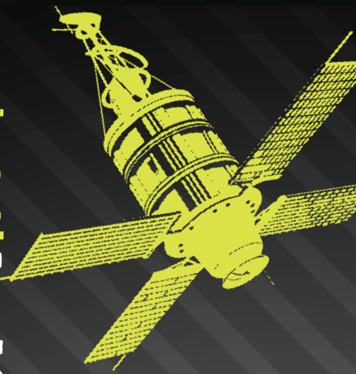
DK

HOW DARK MATTER BUILT THE UNIVERSE

SPACE THE FATAL FRONTIER



MEET THE REAL SHOOTING STARS

QUANTUM PHYSICS AND THE INSANELY TINY

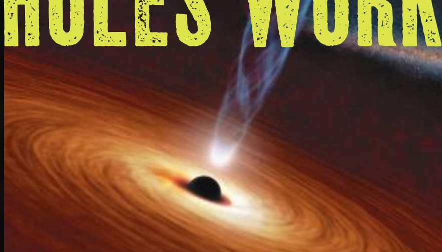
HOW TO CATCH A COMET

ROCKET SCIENCE

FOR THE REST OF US

CUTTING-EDGE CONCEPTS MADE SIMPLE

HOW BLACK HOLES WORK



THE BIG STORY BEHIND THE ATOM

DEATH RAYS FROM OUTER SPACE

BEN GILLILAND

ROCKET SCIENCE FOR THE REST OF US

CUTTING-EDGE CONCEPTS MADE SIMPLE

WRITTEN BY

BEN GILLILAND

CONSULTANT

JACK CHALLONER

DK Penguin Random House

DK LONDON

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First American Edition, 2015
Published in the United States by
DK Publishing
345 Hudson Street
New York, New York 10014

15 16 17 18 19 10 9 8 7 6 5 4 3 2 1
001—275156—04/15

A catalog record for this book is available from the Library of Congress.

ISBN 978-1-4654-3365-7

DK books are available at special discounts when purchased in bulk for sales promotions, premiums, fund-raising, or educational use. For details, contact: DK Publishing Special Markets, 345 Hudson Street, New York, New York 10014 or SpecialSales@dk.com.

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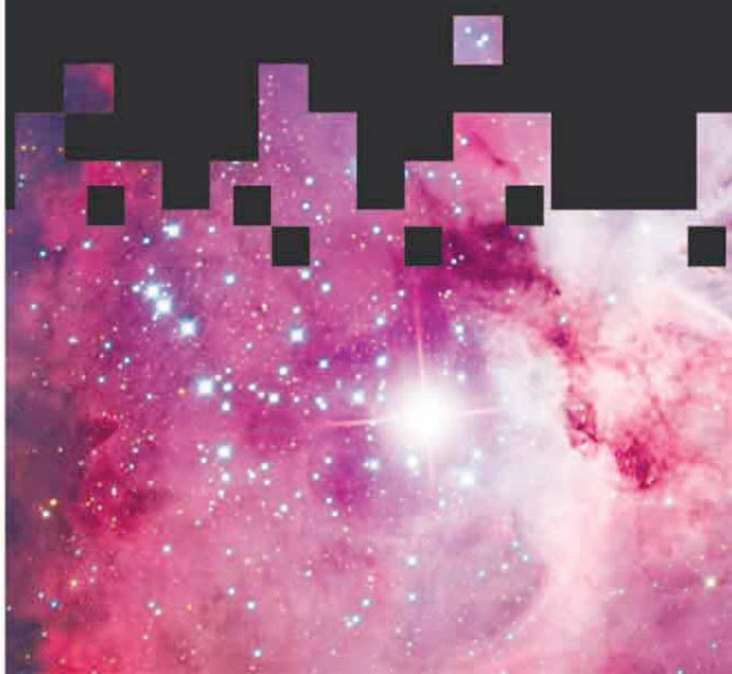

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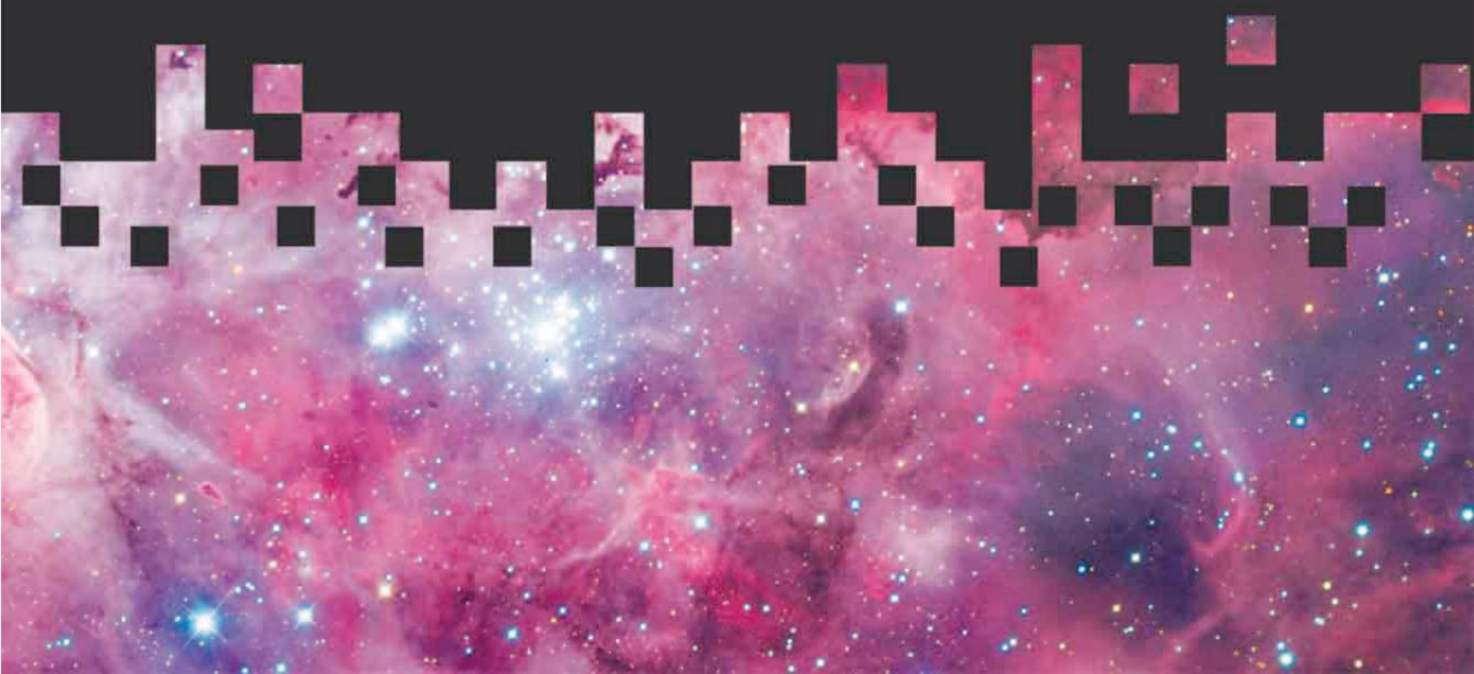

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HOW BIG IS THE UNIVERSE?

THAT BIG WHITE BLOB ON THE RIGHT IS SPIRAL GALAXY NGC 1345 (we will call this one Terry). Terry lives quite close to our very own galaxy, the Milky Way—you might say that they are neighbors. However, closeness is a very relative term indeed. Compared to the **overwhelming vastness** of the universe, Terry lives just a few doors down the road.

But where does he live in relation to you and me? After all, if you live in an apartment building in New York City, a few doors down is just a few paces along the hallway. However, if you live in the middle of the Mojave Desert, reaching your nearest neighbors could mean having to hop onto your scooter for a trip of several miles. Given that the scale of the universe is more like that of the Mojave than that of the Big Apple, you can be sure **Terry does not live as close as the image implies.**

Let us apply some **sense of scale** to the image. The bright star in the image (the one with the word *star* pointing at it) does not actually live in Terry's house—it actually lives in our house (the Milky Way)—so it must be pretty close. But our house is pretty big, so the star is not as close as you might guess. In fact, that pinpoint of light is probably a few thousand light-years away, and that is still a long way off indeed—because **a light-year** is the distance that a photon of light, shooting along at an impressive **11 million miles a minute (18 million kilometers a minute)**, can travel in a year.

Even if it is as close as a thousand light-years away, that star is still at least 5.9 million billion miles (9.5 million billion kilometers) away—that journey would take you about **10 billion years** to complete on your scooter, provided you travel 24 hours a day at the heady speed of 62 mph (100 km/h).

Peer a little deeper into the image and you can see lots of small galaxies that seem to be crowding around Terry. Of course, these galaxies only appear much smaller because they live much farther down the road than Terry—perhaps hundreds of millions of light-years farther down the road.

It is hard (perhaps impossible) for the human brain to comprehend distances of this magnitude, but (in cosmic terms) **we have still barely left the end of the road.** To peer beyond the road and out of town

This is how the distant galaxies crowding Terry look when enlarged

Hubble Ultra-Deep Field

you need a different image. The portrait of Terry was taken by the Hubble Space Telescope using an exposure of about half an hour and, just like using a normal camera, the longer you expose the "film" to light, the more light you gather, and the more light you gather, the fainter the objects you can see.

The image in the top right corner is the **Hubble Ultra-Deep Field.** It is perhaps one of the most profound images ever captured. The image is the result of an exposure amounting to 1 million seconds (11-and-a-half days). Now, when you consider that Terry and his distant neighbors were revealed after a 30-minute exposure, imagine what is revealed after an exposure of more than 11 days. There are 10,000 galaxies visible in this image and the **most distant is located 13 billion light-years away**—that is a journey of 140 million billion years on your interstellar scooter (you might want to pack a sandwich). However, even though you have to travel well beyond the end of the road, out of town, and far out into the distance, even these galaxies really only sit on the cosmic horizon—the universe extends far deeper still.

The universe is not infinite—it does have its limits—but because it is expanding, you could never hope to travel to its end. Even if you were to soup up your scooter to be able to travel at the speed of light, you would still be left playing eternal catch-up with the universe's ever-expanding frontiers. **Suddenly, Terry doesn't seem so far away!**

HOW BIG IS BIG?

When you see an astronomical object afloat in the blackness of space, without a familiar object nearby to provide some scale, it's difficult to appreciate just how big big can be. So we'll start with Earth—home to some 7 billion humans... so quite big—and go from there...

EARTH
Diameter: 7,926 miles (12,756 km)

JUPITER
Diameter: 88,846 miles (142,984 km)

CAT'S EYE NEBULA
Diameter: 2.3 trillion miles (3.78 trillion km)

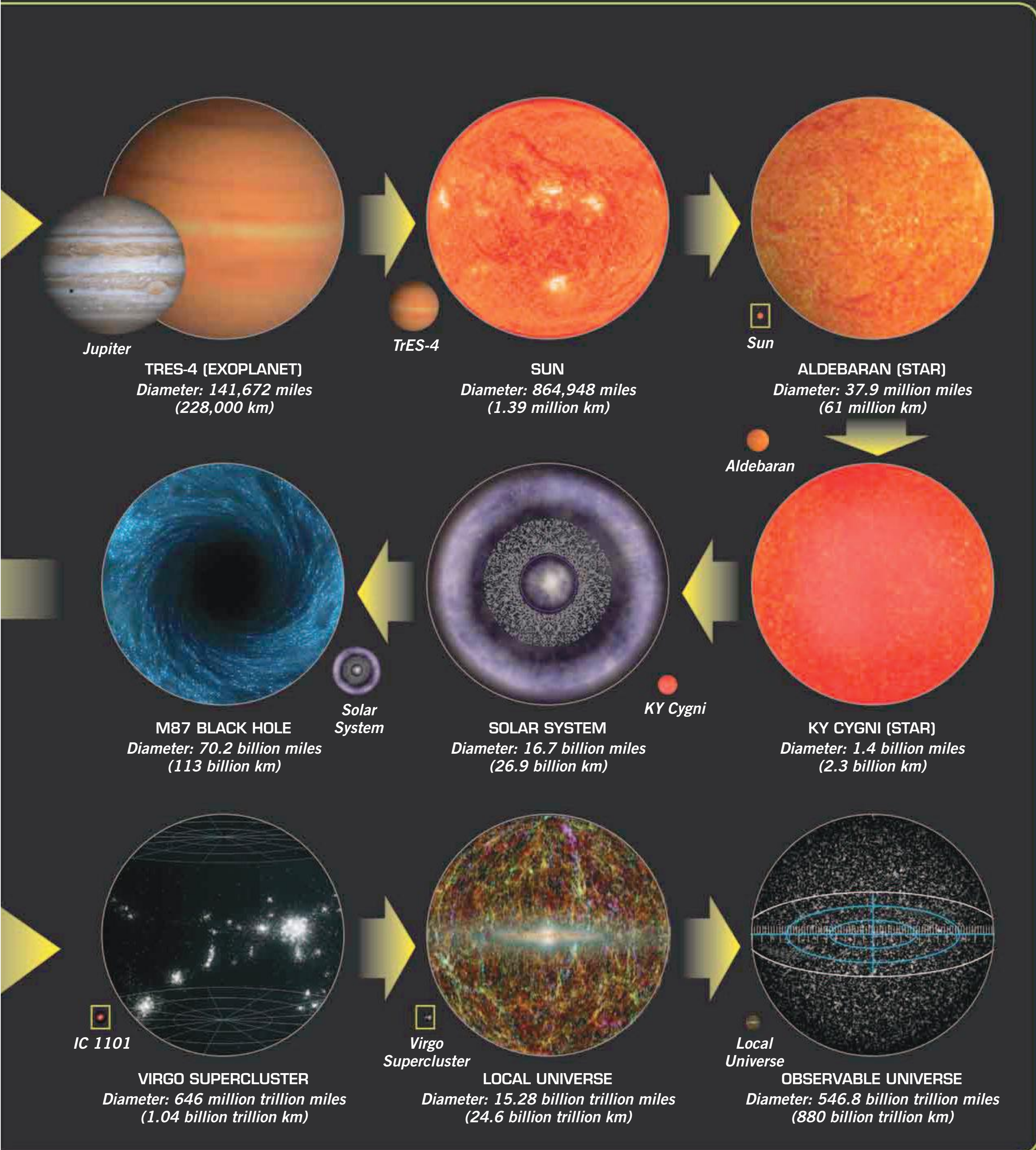
CRAB NEBULA
Diameter: 64.6 trillion miles (104 trillion km)

ROSETTE NEBULA
Diameter: 764.2 trillion miles (1,230 trillion km)

SMALL MAGELLANIC CLOUD (GALAXY)
Diameter: 41,134 trillion miles (66,200 trillion km)

MILKY WAY (GALAXY)
Diameter: 708,363 trillion miles (1.14 million trillion km)

IC 1101 (GALAXY)
Diameter: 32.9 million trillion miles (53 million trillion km)


Jupiter
TRES-4 (EXOPLANET)
Diameter: 141,672 miles
(228,000 km)
TrES-4
SUN
Diameter: 864,948 miles
(1.39 million km)
Sun
ALDEBARAN (STAR)
Diameter: 37.9 million miles
(61 million km)
Aldebaran
KY CYGNI (STAR)
Diameter: 1.4 billion miles
(2.3 billion km)
KY Cygni
SOLAR SYSTEM
Diameter: 16.7 billion miles
(26.9 billion km)
Solar
System
M87 BLACK HOLE
Diameter: 70.2 billion miles
(113 billion km)
IC 1101
VIRGO SUPERCLUSTER
Diameter: 646 million trillion miles
(1.04 billion trillion km)
Virgo
Supercluster
LOCAL UNIVERSE
Diameter: 15.28 billion trillion miles
(24.6 billion trillion km)
Local
Universe
OBSERVABLE UNIVERSE
Diameter: 546.8 billion trillion miles
(880 billion trillion km)

THE STAR THAT REDREW THE COSMOS

AT THE START OF THE 20TH CENTURY, astronomers thought they knew what the universe was all about. It was an island of light, afloat alone in the dark, infinite sea of existence. Measuring about **100,000 light-years** across, it contained about 100 million stars—a fixed, unchanging, and eternal raft of stars sometimes called the Milky Way.

Then, on October 4, 1923, from a dark mountainside in California, a discovery was made that would **redraw the map of the cosmos.** It led astronomy down a path that no one could have imagined or predicted, and would eventually lead the way back **13.8 billion years** to the birth of the universe itself.

From the time of the ancient Greeks to the Age of Enlightenment (nearly 2,000 years later), mainstream belief had it that the **full extent of the universe was contained within a series of celestial spheres,** which encased the focal point, and jewel, of creation—planet Earth. In the 16th century, Polish astronomer Nicolaus Copernicus convinced many people that Earth was not at the center, but was in orbit around the sun—and **discoveries made after the introduction of the telescope to astronomy in 1609 convinced many of the doubters.** The centuries-old map of the heavens was torn up, and the sun found itself suddenly promoted to the position of "center of the universe." But, within just a few short years, its promotion lost its significance and **the sun was relegated to being just one star of many tens of thousands** in a new-model universe called the "Milky Way."

Once astronomers had the universe's "true" size and nature sketched out, the only thing they really had left to do was find stuff floating around within its confines. **They sought new stars, asteroids, or comets,** to which, like the great explorers of old, they could attach their names for the advancement of science and not at all for fame or other such vainglorious pursuits (well, maybe for a bit of glory).

In the latter half of the 18th century, one of the cosmological explorers was a French chap named Charles Messier. Messier was obsessed with finding comets (he would discover 13 in all, with six more codiscoveries) but, as he scanned the heavens, he kept stumbling across **strange fuzzy objects**—fluffy, cloudlike blobs that looked a bit like comets but that did not

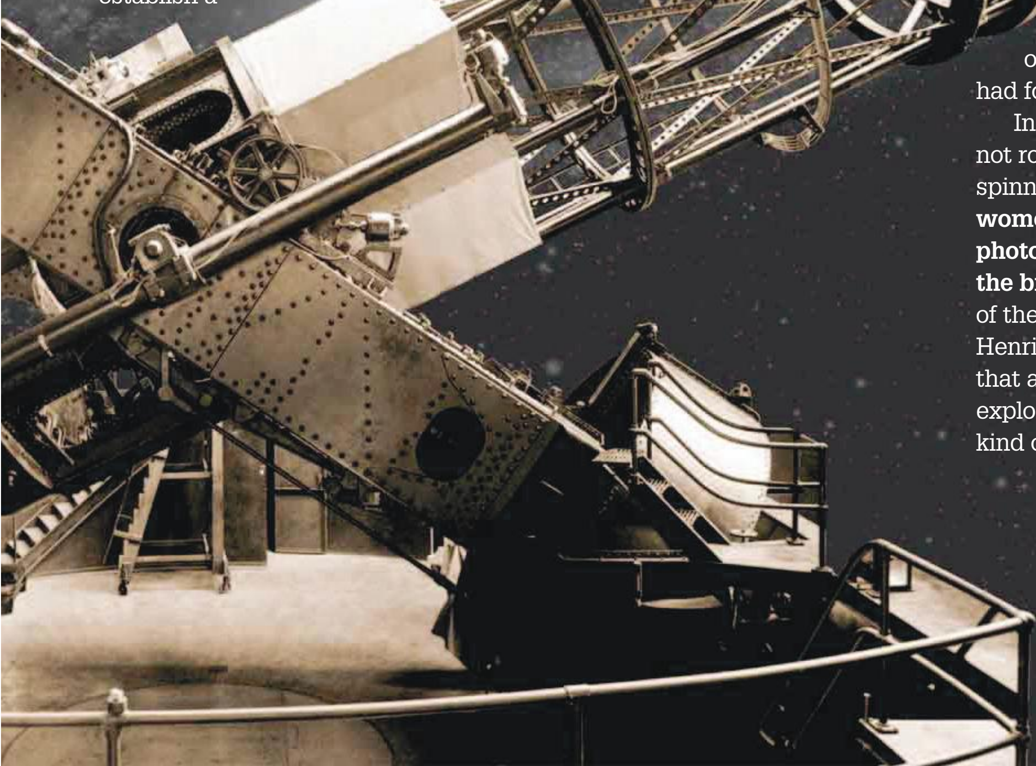
seem to move. To avoid confusing them in the future, Messier compiled a catalog of these **"nebulae"** and, by the time he died in 1817, he had charted the locations of 103 of them.

But what were they? Why did some appear to be shapeless apparitions, while others formed spirals? Were they, as many believed, just insignificant clouds of gas and random groups of stars that floated around inside the Milky Way? Or were they, as the great German-British astronomer William Herschel suggested, **unique island universes located beyond the limits of the Milky Way?** It was this mystery that weighed on the mind of American astronomer Edwin Hubble as he sat peering through the eyepiece of his telescope in 1923, enshrouded in the darkness of the California night.

To settle the debate once and for all, Hubble was determined to establish a reliable distance to the spiral nebulae, and he had the right tool for the job. With a 100 in (254 cm) mirror, the Hooker Telescope at the Mount Wilson Observatory near Los Angeles was the most powerful in the world. Hubble turned its observational might on the **largest of the spiral nebulae—Andromeda** (also known as M31—*M* for "Messier")—in the hope that he might find a particular sort of star that he could use to calculate its distance.

In the 19th century, astronomers had figured out that there is an intrinsic link between the color of a star and its temperature and brightness. If you can accurately identify the color of a star, you can calculate how bright it would appear if you lived on a planet that orbited it. By knowing how bright it should appear and comparing that to its apparent brightness from Earth, you can figure out how far away it is. Known as the **"spectroscopic parallax technique,"** it is a terrifically accurate way to determine distance, but it only really works with relatively nearby stars. The farther starlight has to travel, the more light-obscuring "stuff" (such as dust, which absorbs and reflects light) gets in its way. Eventually, the light that does make it through cannot be trusted to be telling the"truth" about the star it came from. Luckily, just over a decade before Hubble began his survey of Andromeda, a "computer" had found a solution.

In those days, computers were not rooms full of glowing valves and spinning data tapes—they were **women employed to study photographic plates and catalog the brightness of stars.** In 1908, one of these "computers," the American Henrietta Swan Leavitt, discovered that astronomers like Hubble could exploit the properties of a particular kind of star to measure distances



Record breaker:
The Hooker Telescope was the largest telescope in the world when built in 1918. Hubble used it to discover how far away Andromeda is.

accurately over vast distances. Known as "Cepheid variables," these stars vary in brightness—throbbing from bright to dim like **cosmic Christmas-tree lights.** Leavitt discovered that there was a link between how quickly they "throbbed" and their brightness (a Cepheid that takes ten days to go from bright to dim and back again will be brighter overall than one that takes seven days). If Hubble could find a Cepheid within Andromeda and measure its period of variation, he could determine its brightness and use that to calculate its distance.

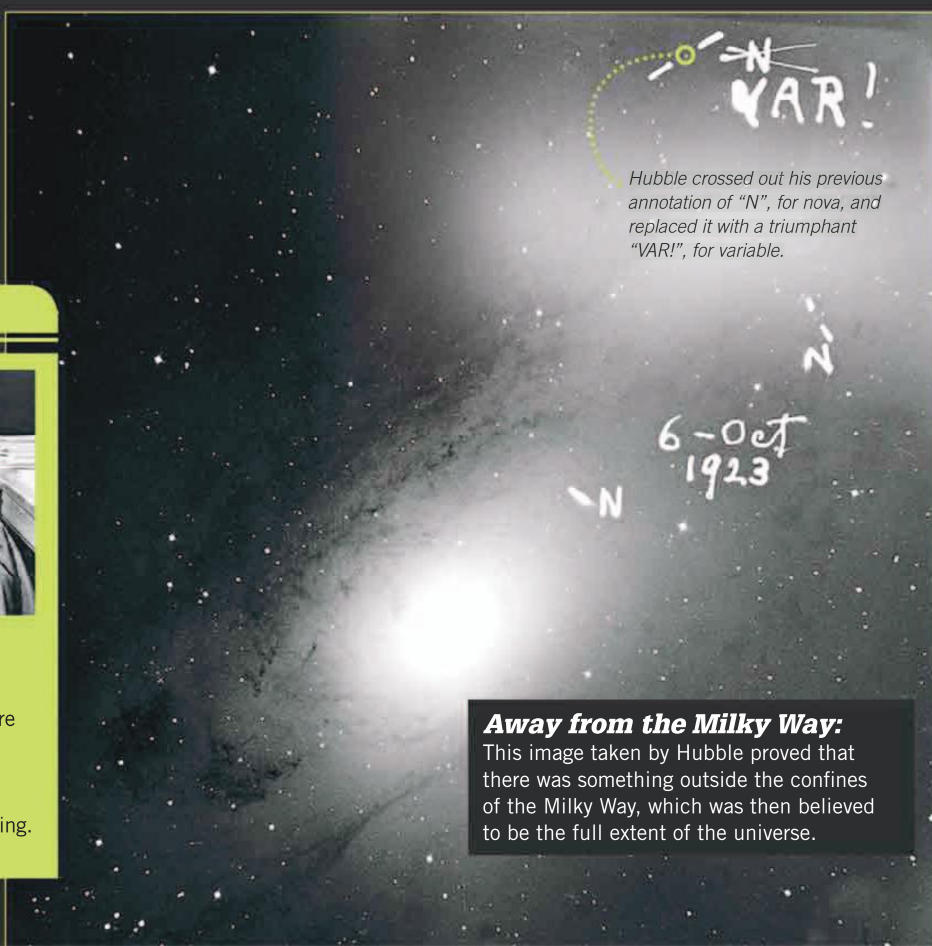
Hubble spent several months in 1923 scanning Andromeda and making long photographic exposures in the hope of resolving an individual star. Pretty much all the stars that were bright enough to be spotted were so-called "novae"—white dwarf stars that suddenly brighten when **intense bursts of nuclear fusion** ignite on their surface (not to be confused with supernovae); these Hubble dismissed by marking an *N* (for "novae") next to the image.

On the night of October 4, 1923, Hubble made a 45-minute exposure that revealed three suspected novae, which he duly marked "N." But two days later he made another exposure, and, when he compared it to the previous image, he realized that one of the *N*s had dimmed faster than it should. Over the following days he made enough observations to determine that the object was a Cepheid variable and he excitedly scribbled out the *N* and replaced it with "VAR!" (for "variable"). The newfound variable's period was 31.4 days—Hubble worked out its luminosity and calculated its distance as about a million light-years—**well outside of the Milky Way and beyond the assumed limits of the universe.**

By the end of 1924, Hubble had found 35 more variable stars in Andromeda (of which 12 were Cepheids). Far from being a small cloud on the fringes of the Milky Way, Andromeda was a whole other galaxy—made small only by the vast distance separating it from Earth. Later, observations of galaxies more distant than Andromeda revealed that they are **all rushing away from each other**—leading to the revelation that **the universe is expanding and was born 13.8 billion years ago in the Big Bang** (Hubble was at the center of that story, too).

EDWIN HUBBLE

Edwin Hubble was one of the most important astronomers of the 20th century. He created a classification system for galaxies, showed that there is something outside of the Milky Way, and discovered a link between a galaxy's redshift and its distance, which proved the universe is expanding.



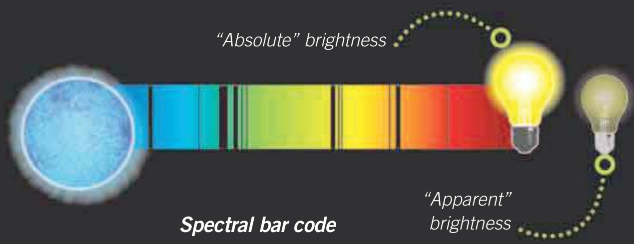
Hubble crossed out his previous annotation of "N", for nova, and replaced it with a triumphant "VAR!", for variable.

Away from the Milky Way: This image taken by Hubble proved that there was something outside the confines of the Milky Way, which was then believed to be the full extent of the universe.

HOW TO MEASURE DISTANCE IN SPACE

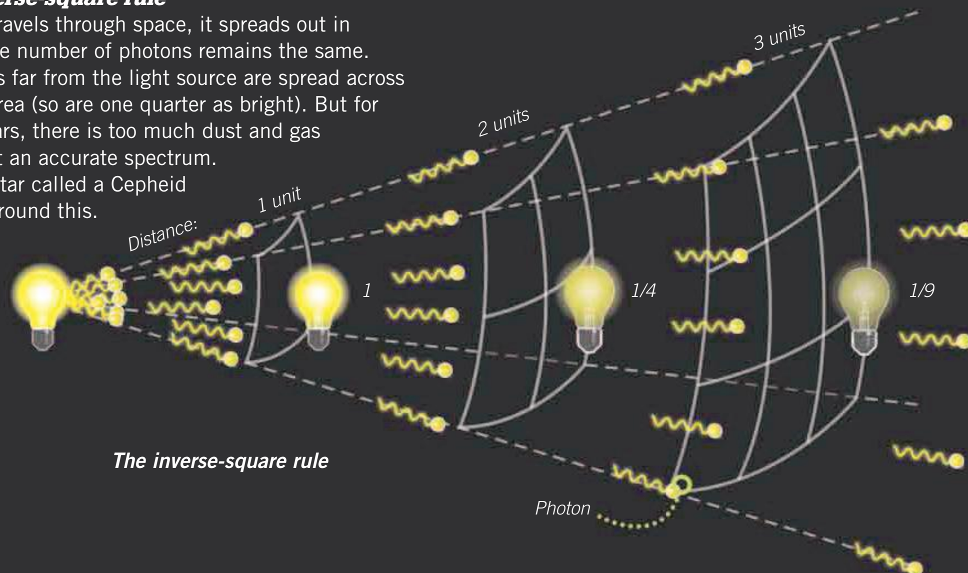
There are no tape measures in space, so astronomers had to come up with more inventive ways to measure distance. One method involves measuring the brightness of a star.

1 ***Spectroscopy***
Using spectroscopy (a technique that splits light into its component colors), astronomers can obtain a spectral bar code, which tells them how bright the star would appear if we were close to it (but not too close). They can then use this "absolute" brightness and compare it to its "apparent" brightness. Then they apply the inverse-square rule to estimate its distance.



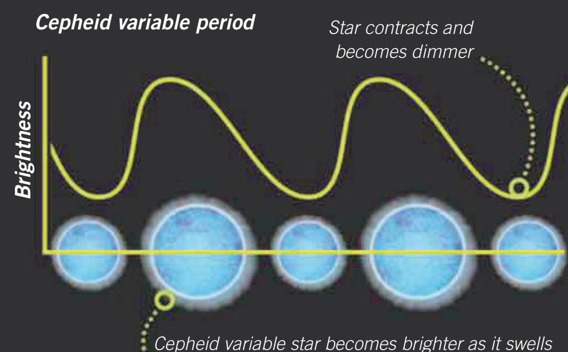
Spectral bar code

2 ***The inverse-square rule***
As light travels through space, it spreads out in a sphere. But the number of photons remains the same. Photons twice as far from the light source are spread across four times the area (so are one quarter as bright). But for really distant stars, there is too much dust and gas in the way to get an accurate spectrum. Hubble used a star called a Cepheid variable to get around this.



The inverse-square rule

3 ***Special stars***
Cepheid variables swell and contract—pulsing from bright to dim and back to bright again over a measurable period. The period is determined by the star's luminosity—the amount of light the star produces. By studying a Cepheid's period, astronomers can determine its absolute brightness and then use the inverse-square rule to measure its distance.

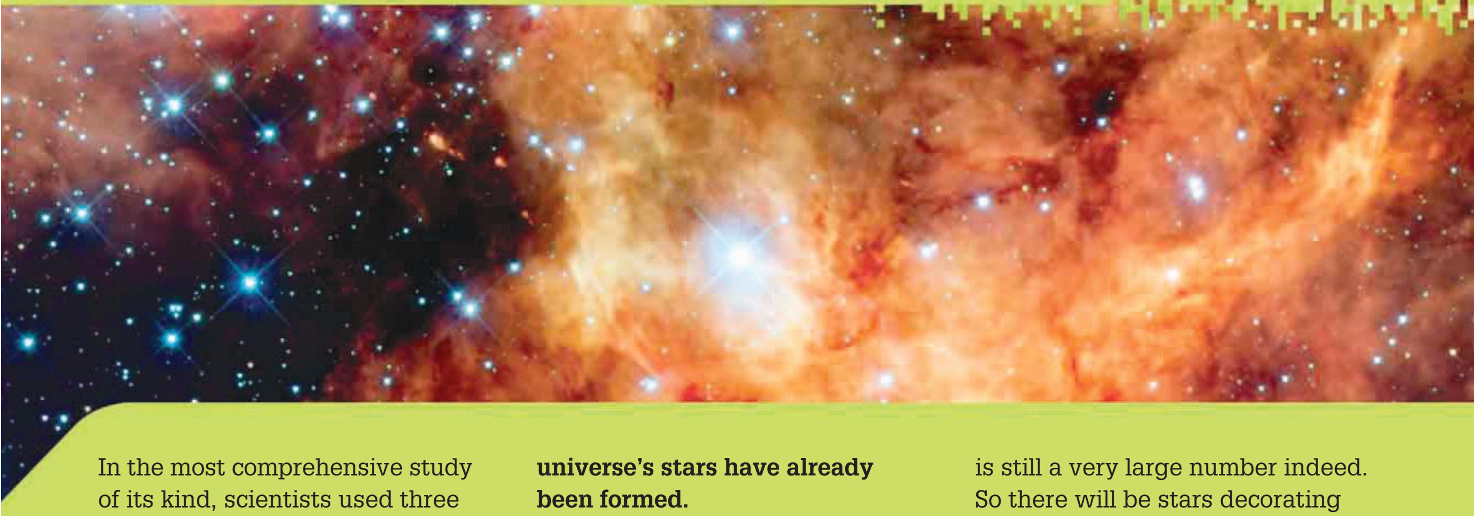
Cepheid variable period


Star cluster:
This star cluster is R136. It can be found in a colossal star-forming nebula called the 30 Doradus Nebula, which is the largest and most prolific stellar nursery in the Milky Way.

EXPANDING UNIVERSE

WE USED TO BELIEVE that stars were eternal and the universe was infinite and immutable, but we now know that this is not the case. From vast clouds of cosmic gas, stars condense, ignite, and burn themselves to death. **Even the universe had a moment of birth, and one day it too will die.** But surely, as long as there is a universe to house them, there will be stars? Maybe not. **Could it be that, one day, mankind's distant descendants will gaze at the night sky and see a starless carpet of perfect black?**

A study from 2012 suggests that the best days of the universe's star formation are long behind it, and that most of the stars left **are now creeping into old age.**



In the most comprehensive study of its kind, scientists used three massive telescopes to look at star-forming galaxies from 4 billion to 11 billion years ago. They used the data to chart the history of star formation in the universe, and found that, **in its early days, the universe was far more prolific in its star-forming activities than it has been in the last few billion years.** In fact, the researchers concluded that **95 percent of the universe's stars have already been formed.**

All stars start off by using hydrogen to fuel their nuclear furnaces and, as the stars age, this hydrogen gets fused into increasingly heavier elements. It seems that there is **just not enough hydrogen left in galaxies to keep forming new stars.**

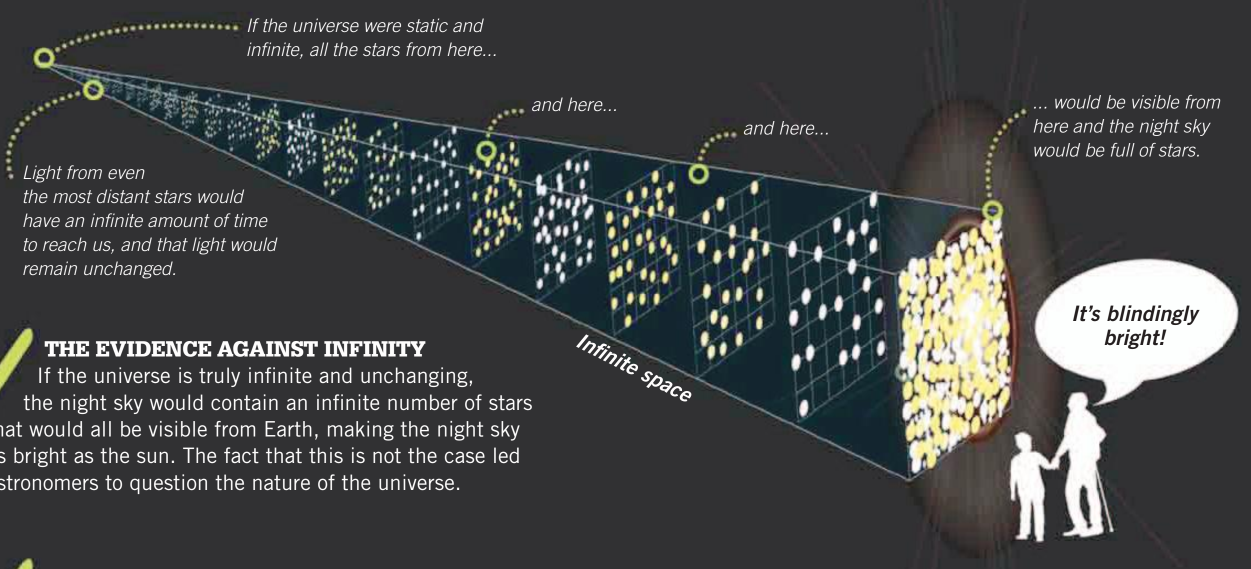
That is not to say that there are not billions of stars yet to be made: A huge drop from a colossal figure is still a very large number indeed. So there will be stars decorating the heavens for some time to come, but **it may be that anything that lies beyond our own galaxy will not be visible from Earth.** According to one theory about the fate of the universe, all those galaxies that make the heavens a more interesting place could be expelled from the night sky as the **expanding universe carries them from sight.**

A BLACK SKY?

In billions of years' time, the light from stars within distant galaxies will be unable to outrun the universe's acceleration, and we will know of nothing beyond the environment of the Milky Way. Although the nearest galaxies will remain gravitationally bound to the Milky Way, and so remain visible, everything else that makes up the universe will recede from sight. On the plus side, Earth will probably be long gone by then...

HOW THE UNIVERSE WILL BANISH GALAXIES

Until the 20th century, it was believed that the universe was eternal, unchanging, and infinite, but there was a problem with this idea—it just did not match the evidence...

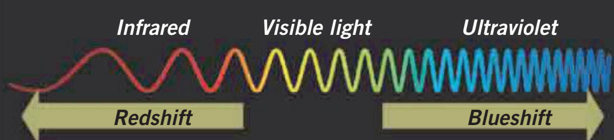


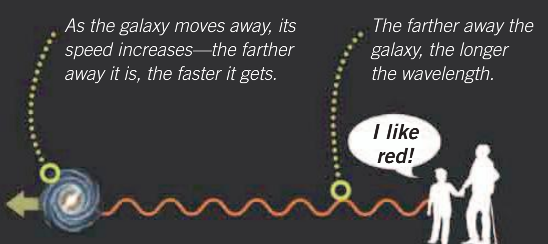
THE EVIDENCE AGAINST INFINITY

If the universe is truly infinite and unchanging, the night sky would contain an infinite number of stars that would all be visible from Earth, making the night sky as bright as the sun. The fact that this is not the case led astronomers to question the nature of the universe.

THE QUICK AND THE RED

Astronomers noticed that the light from distant galaxies was redder than it should have been, with the light appearing redder in more distant stars. Light is part of the electromagnetic spectrum and therefore has a wavelength. Light at the red end of the spectrum has a longer wavelength, and is farther away, than light at the blue end.



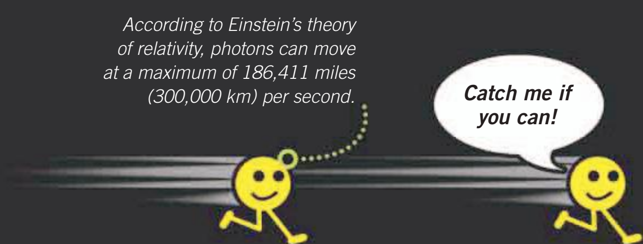


REDSHIFT

The light emitted was being stretched into the red end of the spectrum (called redshift). The answer must be that the galaxies are actually moving.

THE GREED FOR SPEED

The discovery that stars and galaxies are all rushing away from each other led to the revelation that (far from being static) the universe is actually expanding. If it is growing, it must have had a birth (which we now call the "Big Bang"). We cannot see every star that exists because the universe has not been around for long enough for the light from the most distant stars to reach us.

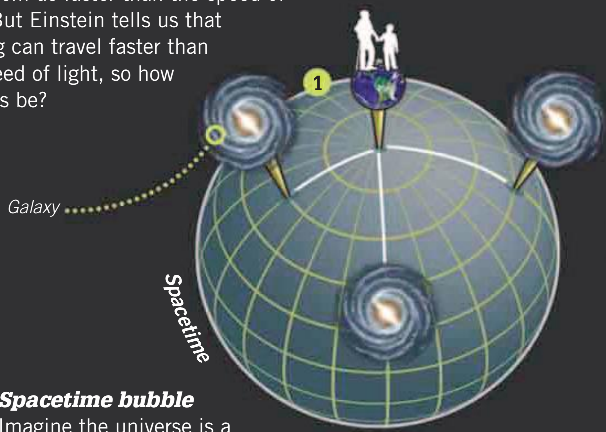


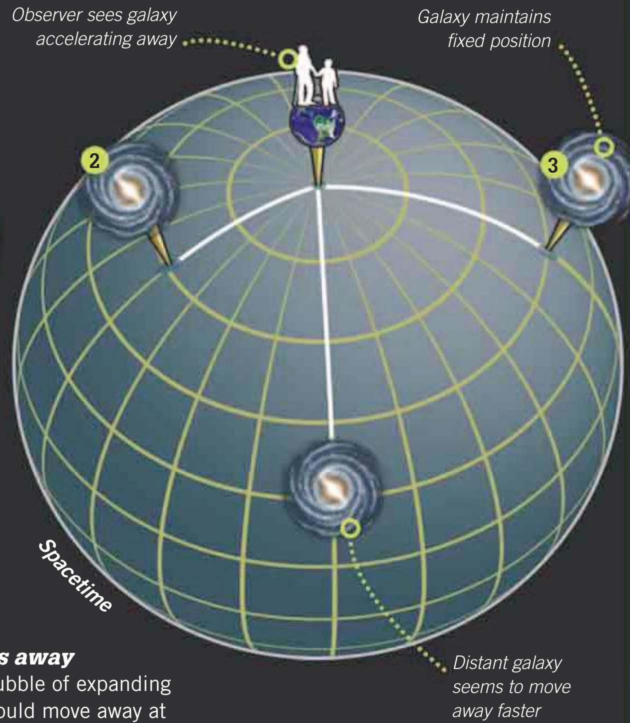
LIGHT SPEED

Light is made up of packets of energy called photons. As they have a maximum speed, light from distant galaxies takes billions of years to reach us.

STANDING STILL AT THE SPEED OF LIGHT

We now know that the rate at which the universe is expanding is accelerating and all those stars and galaxies rushing away from us are getting faster and faster. It is possible that they could eventually appear to be moving away from us faster than the speed of light. But Einstein tells us that nothing can travel faster than the speed of light, so how can this be?





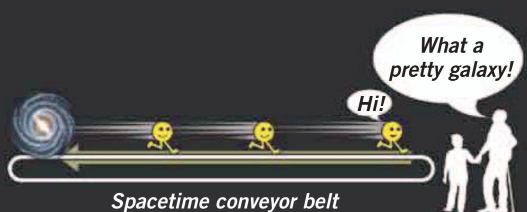
1 ***Spacetime bubble***
Imagine the universe is a bubble of spacetime onto which the galaxies are pinned.

2 ***Expanding universe***
As spacetime expands, the galaxies move apart relative to each other, but, relative to their local patch of spacetime, they have not really moved at all.

3 ***Galaxy moves away***
By riding the bubble of expanding spacetime, a galaxy could move away at faster than light-speed, relative to an observer on Earth.

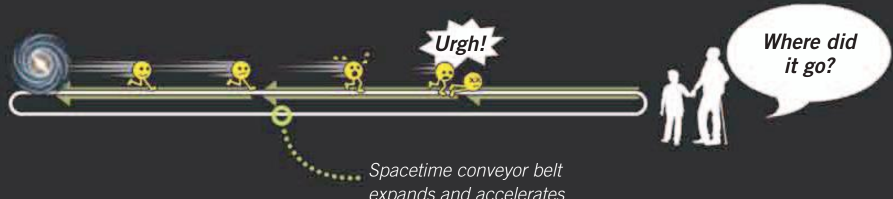
HOW TO MAKE A GALAXY DISAPPEAR

If the space between Earth and the receding galaxy expands faster than the photons of light emitted by stars within it can travel, that light will never reach Earth. Imagine, if you will, that the photons of light are on a spacetime conveyor belt.

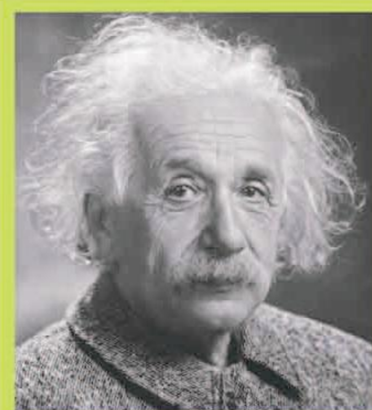


CONVEYOR BELT

As the universe's expansion accelerates, the conveyor belt gets faster and faster. Eventually, the belt is moving faster than the photons can run along it, and they never reach the other end—meaning their light never reaches us.



ALBERT EINSTEIN

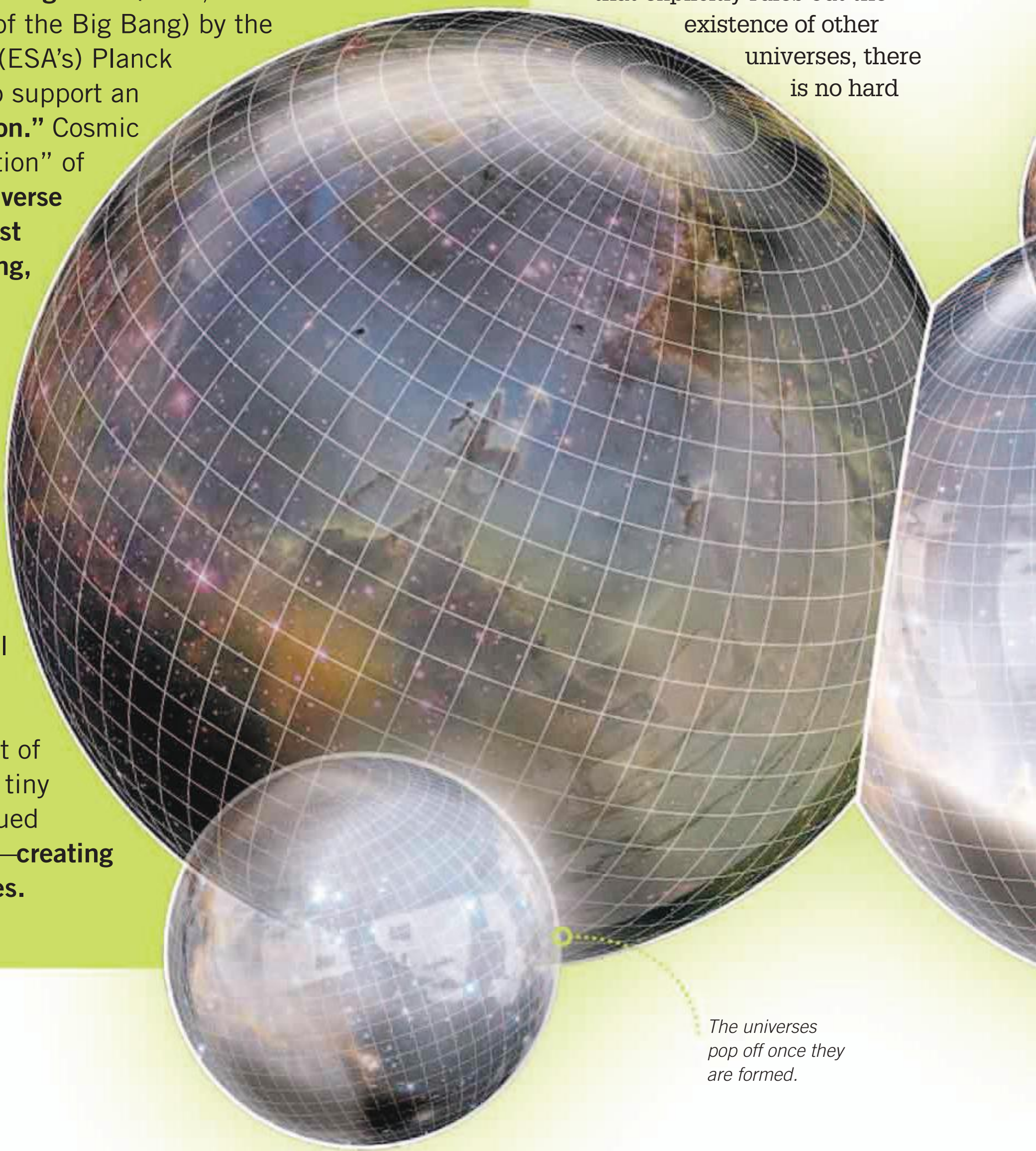


In his theory of special relativity, German-born scientist Albert Einstein revealed that light had a maximum speed limit. As a result, if space is expanding faster than the speed of light, the source of that light will vanish from sight.

WELCOME TO THE **MULTIVERSE**

IS OUR UNIVERSE just one bubble of existence in an infinite **multiverse**? The latest survey of the **cosmic microwave background** (CMB, also known as the radiation afterglow of the Big Bang) by the European Space Agency's (ESA's) Planck space telescope seemed to support an idea called **"cosmic inflation."** Cosmic inflation is a sort of "injection" of energy that **caused the universe to expand exponentially just moments after the Big Bang,** when it was still smaller than an atom. This rapid inflation is seen by many as being the only explanation for the apparent even spread of energy in the early universe (by inflating the teeny tiny universe before it got the chance to spread slowly and get all "lumpy"). But a potential consequence of cosmic inflation is that, while most of the universe slowed down, tiny pockets could have continued their exponential inflation—**creating offshoot "bubble" universes.**

Another tantalizing hint of the **existence of other universes** can be found in Planck's cosmic microwave background survey. There is a mysterious cold spot (pictured below, far right) that, some have suggested, **could be the "imprint" left behind by another universe before it separated from our own.** Although there is nothing in current cosmological theory that explicitly rules out the existence of other universes, there is no hard



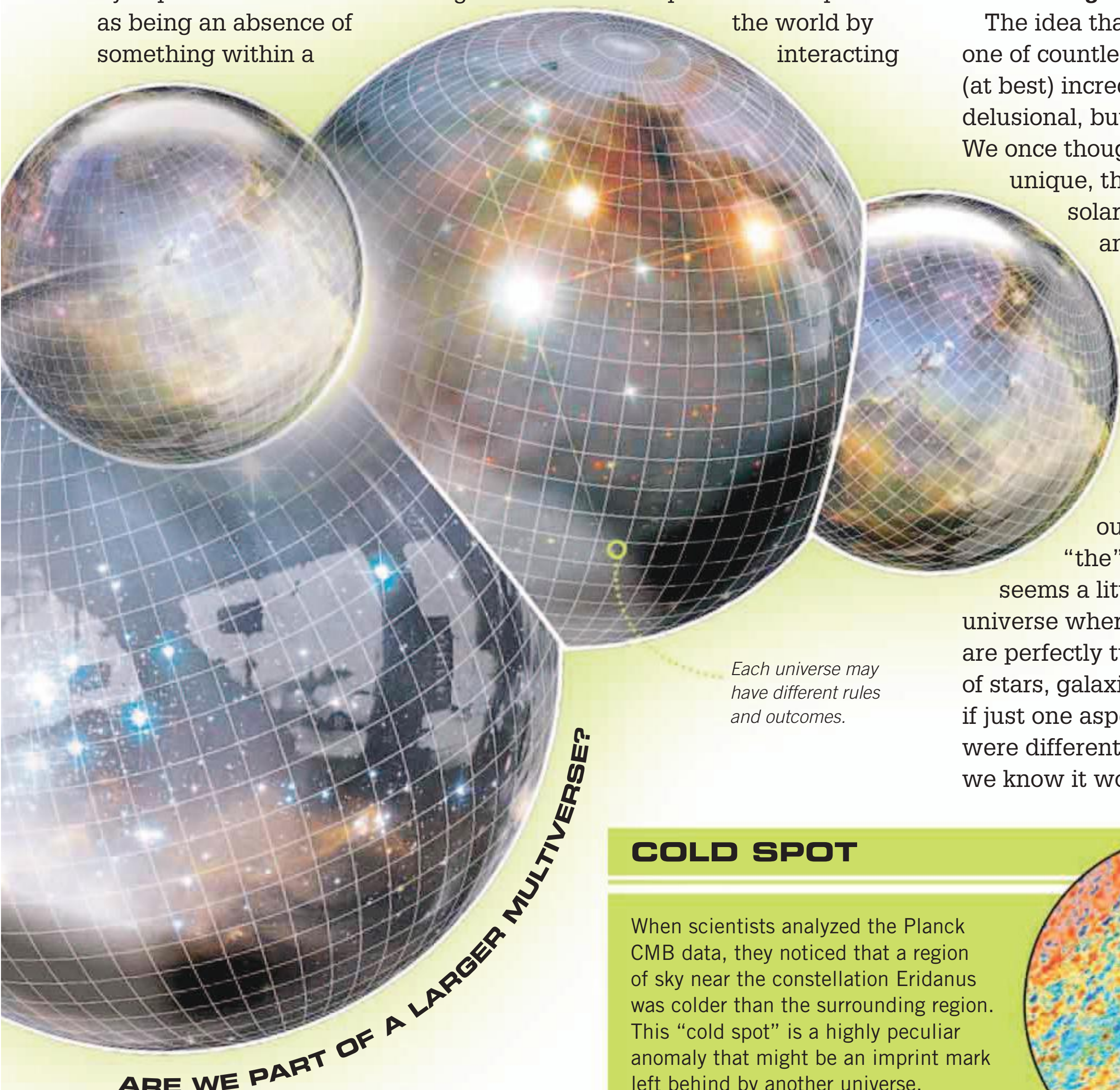
The universes pop off once they are formed.

evidence supporting the idea, either. But **it is fun to imagine that it might be possible.**

One of the most commonly asked questions of Big Bang theorists is **"what came before the Big Bang?"** The standard answer is that there was nothing at all. Normally, we are quite comfortable with the idea of "nothing." We are conditioned by experience to think of nothing as being an absence of something within a given area, but if space itself was created in the Big Bang, there cannot be "nothing" because there is nowhere to put the "something" that does not exist. **Asking what came before the Big Bang is equally meaningless because "time" was created along with space**—you cannot have a "before" because time did not exist. For a species that experiences the world by interacting with time and space, that is **a slightly uncomfortable, brain-blending concept.**

Luckily (depending on your point of view) there are physicists who believe that, far from being the beginning of all things, the Big Bang was just the moment our universe burst from the womb of a parent universe—**just one offspring of a much larger multiverse.**

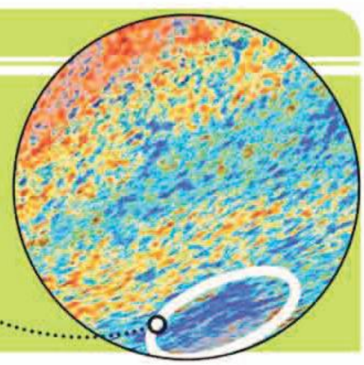
The idea that our universe is just one of countless others might seem (at best) incredible and (at worst) delusional, but remember this: We once thought our planet was unique, then we thought our solar system was unique, and, after that, we thought our galaxy was unique—**is it such a stretch to imagine that our universe is not unique, as we like to believe?** One of the problems with our universe being "the" universe is that it seems a little too perfect. It is a universe where the laws of physics are perfectly tuned for the creation of stars, galaxies, planets, and life—if just one aspect of those laws were different, then the universe as we know it would not exist. It is



Each universe may have different rules and outcomes.

COLD SPOT

When scientists analyzed the Planck CMB data, they noticed that a region of sky near the constellation Eridanus was colder than the surrounding region. This "cold spot" is a highly peculiar anomaly that might be an imprint mark left behind by another universe.



Cold spot

the same problem we once had with our planet.

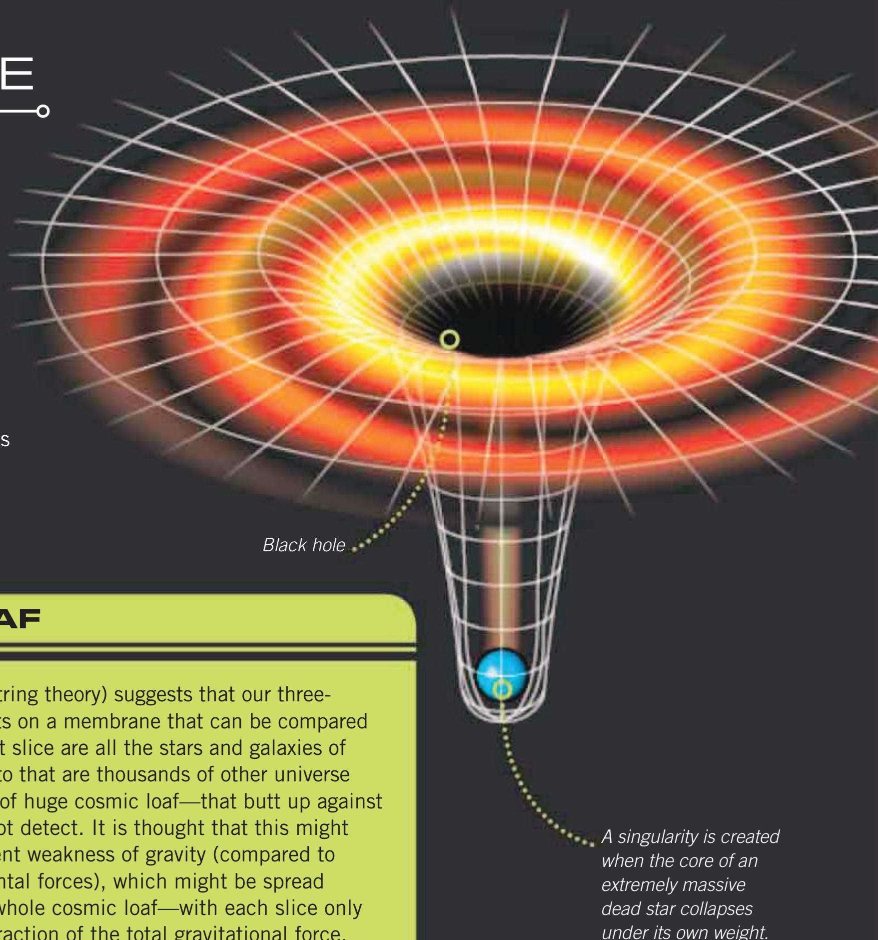
Looked at in isolation, Earth seems to have been perfectly "designed" for the creation of life—just the right distance from just the right sort of star with just the right atmosphere and just the right sort of magnetic field (and so on). Of course, we now know that there are countless other planets out there where conditions are not perfect and where life does not exist. **We were just the winners in the planetary lottery.** The multiverse would solve the problem of our "perfect" universe in the same way. Just as Earth won the planetary lottery, our universe won the cosmological lottery. It seems "perfect" because the conditions within it allowed us to evolve and marvel at its perfection. **But there are countless other universes where conditions were not just right.** You can compare it to a game of cards. If you were allowed to pull just one card from the deck, the chances of pulling out the card you were looking for is quite small, but if you were allowed to go through the whole deck, your card's discovery becomes inevitable. The same applies to the multiverse: With infinite permutations of the laws of physics available, it is inevitable that one would be perfect for life. In many ways, a multiverse is a more comfortable concept to come to grips with than a perfect universe born from the void.

Of course, eventually you have to ask where the first of these ancestor universes came from, and **you are right back where you started!**

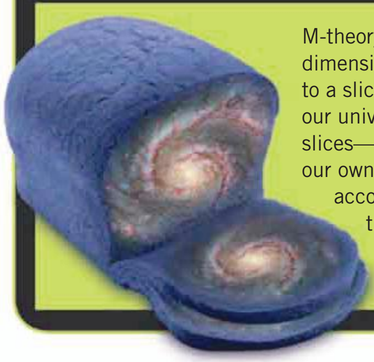
CHILDREN OF THE BLACK HOLE

Another theory is that our universe was born within a black hole and that black holes within our cosmos are creating universes of their own.

1 ***Black hole***
This is a black hole. She is quite happy munching her way through all the light and matter that strays too close to her irresistible gravitational pull. At her heart is a tiny ball of concentrated matter called a singularity, which gets increasingly compact as it gains mass, until it reaches near-infinite density.



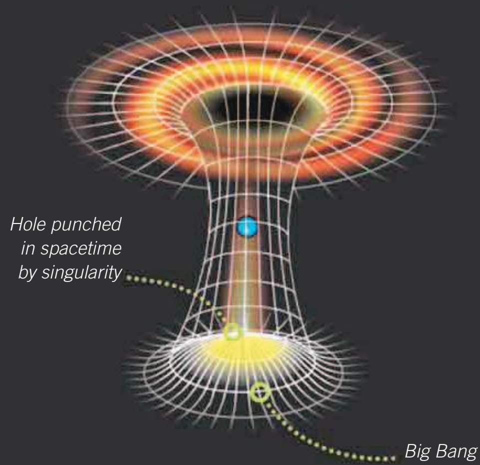
SLICED MULTIVERSE LOAF



M-theory (an offshoot of string theory) suggests that our three-dimensional universe exists on a membrane that can be compared to a slice of bread. On that slice are all the stars and galaxies of our universe, but parallel to that are thousands of other universe slices—arranged in a sort of huge cosmic loaf—that butt up against our own but that we cannot detect. It is thought that this might account for the apparent weakness of gravity (compared to the other fundamental forces), which might be spread out through the whole cosmic loaf—with each slice only experiencing a fraction of the total gravitational force.

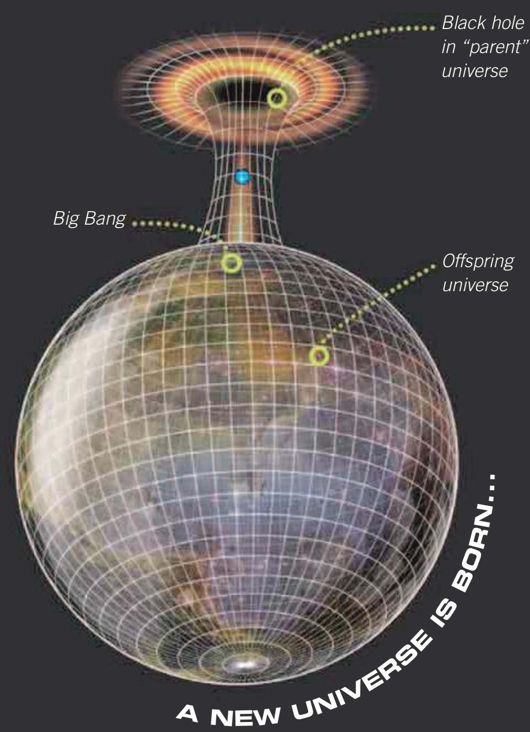
2 *Singularity bounces back*

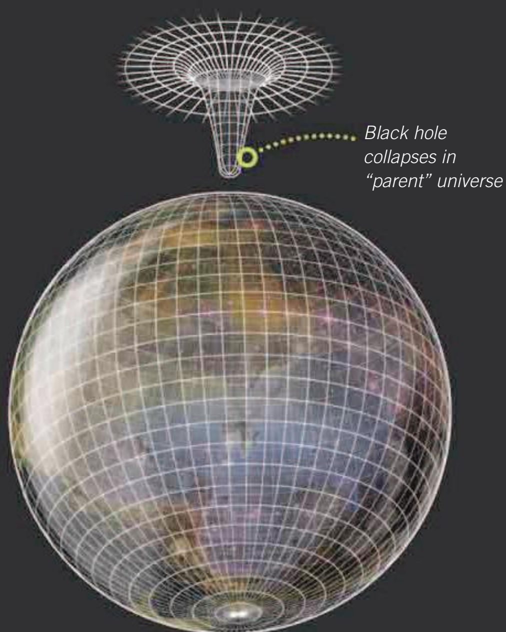
At this point, the standard theory suggests that space and time become so heavily distorted at the singularity that time stops. But one theory says that the singularity “bounces back” and punches a hole in spacetime (the fabric of the universe).



3 *Big Bang*

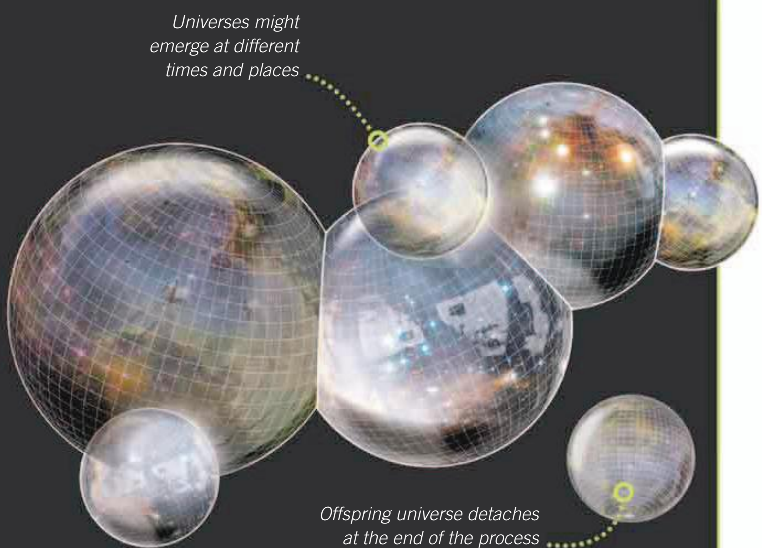
Here, the singularity begins to expand—creating a “Big Bang” from which a new universe is born, where the laws of physics might be slightly different from those of its parent universe.





4 *Time stops in singularity*

Back in the parent universe, just as time starts in the new universe, time stops at the singularity. Eventually, the original black hole collapses—severing the umbilical cord to the offspring universe.



5 *Multiverse*

There might be an infinite chain of universes, but only a few in which the laws of physics are conducive to life.

WE'RE ALL **DOOMED!**

MORE THAN 400 MILLION YEARS AGO, Earth was a very different place from today. The climate, encouraged by excessive levels of greenhouse gases, was hot enough to ensure that no water was locked away at the poles. **Sea levels were a great deal higher than today** and, in the balmy waters, sea life had exploded—dominating life on Earth.

Then this all changed. Inexplicably, the climate cooled, glaciers formed at the poles, sea levels plummeted, and more than 85 percent of Earth's species died out. The Late Ordovician mass extinction, as it has come to be known, was **one of the most catastrophic extinction events in the planet's history.** But what caused the climate to take such a dramatic U-turn?

One explanation is that Earth was the **unwilling recipient of a massive dose of gamma radiation gifted to us by a distant star dying a violent death.** Gamma ray bursts (GRBs) are the most powerful cosmic explosions we know of. When a massive star explodes in a supernova explosion, sometimes, as if in a fit of raw fury, **the star will spew intense beams of deadly gamma radiation into the cosmos.**

If Earth was at the receiving end of such an outburst all those millennia ago, gamma radiation would have wreaked havoc on the planet. It would have **destroyed the protective ozone layer, and blanketed the planet in a suffocating layer of smog** that would have blocked sunlight and sent the climate into a tailspin, resulting in the **death of more than three-quarters of life on Earth.** Well, get your best apocalypse trousers on, because if some scientists are to be believed, **Earth could be on the receiving end of another dose of gamma rays soon.**

Eight thousand light-years away, in the constellation of Sagittarius (the Archer), a dying star could have us locked in its sights. WR 104 is a Wolf-Rayet binary star system composed of **two truly massive stars engaged in an orbiting death dance.** Due to their size (equivalent to as many as 20 suns each), both stars are living on borrowed time and will soon **die the sort of violent death that only truly colossal stars can.** But one is a very special sort of star called a Wolf-Rayet star.

WOLF-RAYET STARS ARE THE MOST MASSIVE AND BRIGHTEST STARS KNOWN

When this star dies, not content with an understated supernova, its core will collapse to form a black hole that, through a fierce collusion of forces, **will vent two beams of gamma radiation along the star's poles and out into space—possibly toward us.**

Since WR 104 was discovered in 1998, arguments have swung back and forth as to whether it has us in its sights. Now two astronomers at the Keck Observatory in Hawaii have suggested that we could be better aligned with the so-called "Death Star's" poles than we might find comfortable.

As the two stars orbit each other, they vent huge quantities of material that spread out to create a spiral pattern. When we look at the spiral from Earth, we appear to be seeing it face-on—**meaning the star's poles could be pointing at our little blue planet.**

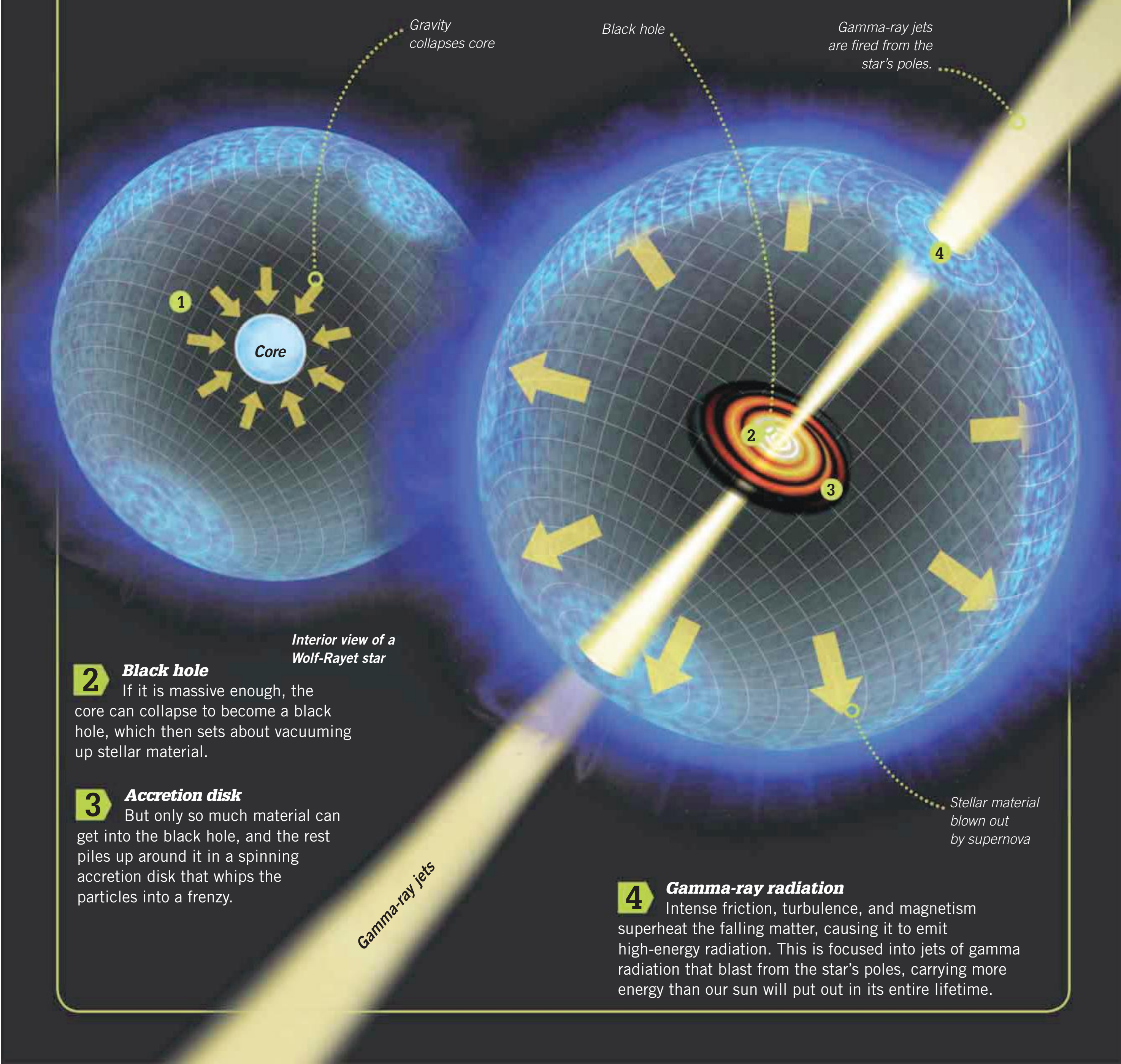
Although the star could go boom at any time in the next 500,000 years, the slightest misalignment of even a few degrees would see the beam sail by harmlessly. So we might not be so doomed after all.

MEET THE REAL "DEATH STAR"...

WR 104 consists of two stars, both of which are extremely massive and counting down to their imminent demise. But it is the Wolf-Rayet star that could create the potentially lethal gamma-ray burst.

1 *Crushed core*

When a star runs out of fuel, nuclear reactions shut down in its core. For a star as massive as a Wolf-Rayet, this causes the star to explode as a supernova, and the core to collapse catastrophically under the weight of its own gravity.



Interior view of a Wolf-Rayet star

2 *Black hole*

If it is massive enough, the core can collapse to become a black hole, which then sets about vacuuming up stellar material.

3 *Accretion disk*

But only so much material can get into the black hole, and the rest piles up around it in a spinning accretion disk that whips the particles into a frenzy.

4 *Gamma-ray radiation*

Intense friction, turbulence, and magnetism superheat the falling matter, causing it to emit high-energy radiation. This is focused into jets of gamma radiation that blast from the star's poles, carrying more energy than our sun will put out in its entire lifetime.

EARTH IN ITS SIGHTS...

A blast of gamma-ray radiation would have a catastrophic effect on the atmosphere and life on Earth. Though we can't do much to stop it from happening, we might just be able to see if it's coming our way...

1 ***Big winds***
When the stellar wind from one star meets the wind from the other, the charged particles are compressed into a shock front, where dust particles can form.

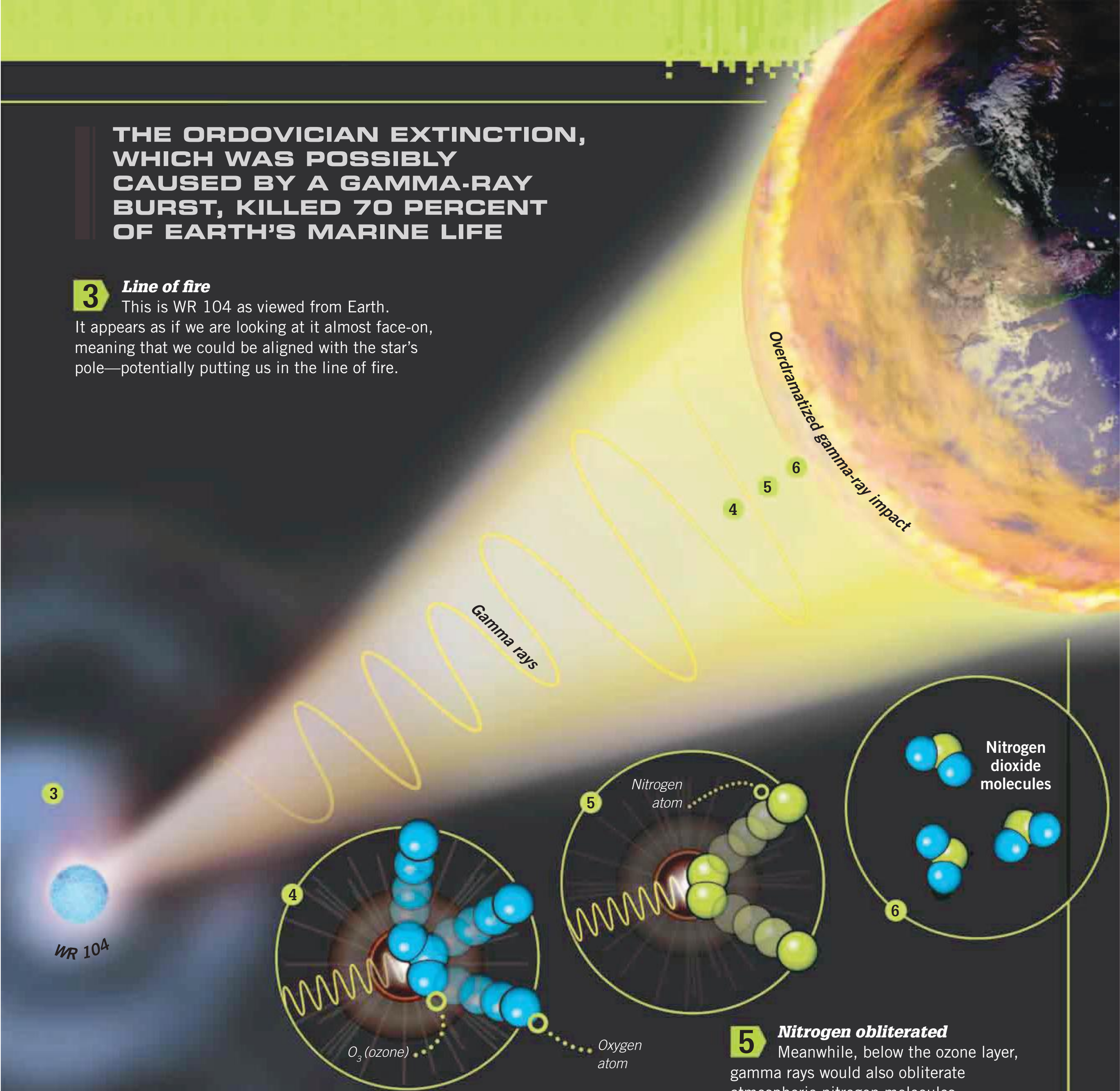
2 ***Dust tail***
As the stars orbit each other, they carry the dust with them, creating a tail of gas that spirals away from the center (like water thrown from a lawn sprinkler). The dust spiral is aligned with the stars' equators—meaning the stars' poles are on either side of the dust spiral.

DEATHLY FACTS

- Wolf-Rayet stars can be more than 200 times as massive as the sun and more than 100,000 times as bright.
- They are also extremely hot. Compared to the sun's balmy 18,032°F (10,000°C) surface temperature, Wolf-Rayet stars can exceed 90,032°F (50,000°C).
- Their extreme mass means they are short-lived (taking just one million years to exhaust their fuel).
- Pressure from intense nuclear reactions in their cores means they have a great deal of trouble holding themselves together—spewing out about two billion trillion tons of material (about three Earth masses) into space in a 10 million mph (16 million km/h) solar wind.

THE ORDOVICIAN EXTINCTION, WHICH WAS POSSIBLY CAUSED BY A GAMMA-RAY BURST, KILLED 70 PERCENT OF EARTH'S MARINE LIFE

3 ***Line of fire***
This is WR 104 as viewed from Earth. It appears as if we are looking at it almost face-on, meaning that we could be aligned with the star's pole—potentially putting us in the line of fire.



5 ***Nitrogen obliterated***
Meanwhile, below the ozone layer, gamma rays would also obliterate atmospheric nitrogen molecules.

4 ***Ozone layer shattered***
If Earth were struck by gamma radiation from WR 104, the gamma rays would shatter ozone molecules in the upper atmosphere—depleting the ozone layer (which protects us from ultraviolet radiation from the sun) by 30–50 percent. It would take years for it to recover.

6 ***Doomed Earth***
The nitrogen and oxygen atoms would then combine to form nitrogen dioxide: a major component of smog. This would block sunlight and lead to rapid global cooling, dissolve into the oceans, and fall from the sky as acid rain.

CATCH UP WITH THE STELLAR SPEED DEMONS

A SHOOTING STAR JUST DOES NOT LIVE UP TO the beauty of its name. It promises a flaming stellar projectile fired from the cannon of the gods, but in reality a shooting star is less a colossal spherical inferno and more **a speck of cosmic dust that lost a battle with friction.** Luckily, the universe (that great purveyor of baffling wonderment) **has some real shooting stars up its sleeve.**

Sometimes called rogue, runaway, or even hypervelocity stars, these are stars that have been liberated from the gravitational bonds of the galaxy, and **set free to travel the cosmos at almost unimaginable speeds.**

Since the first one was sighted in 2005, dozens of these intergalactic speed demons have been found **careering around the cosmos like stellar drag racers.**

Most of the Milky Way's hundred billion or so stars orbit the galactic center at a relatively pedestrian 400,000 mph (640,000 km/h) or so, but **hypervelocity stars can be traveling at 2 million mph (3.2 million km/h) and some might be streaking along at many times that speed.** Hypervelocity stars move so fast that **they can exceed the escape velocity of the galaxy** (the speed needed to overcome the pull of gravity). This is no mean feat because the object they are escaping is a supermassive black hole that weighs in at four million times the mass of our sun—which is a lot of gravity to overcome.

Why do these stars go "rogue" in the first place? When their existence was first proposed, astronomers believed their discovery would confirm the then-theoretical existence of a black hole at a galaxy's heart because **only a supermassive black hole could provide the gravitational "kick" needed to accelerate a massive star to hypervelocity speeds.**

Close to the galactic center, gravity is so extreme that stars in this region are whipped into superfast orbits that see them **whizzing along their elliptical highways at more than a million miles per hour.** It is a delicate balancing act that, if disturbed, could see the star being sucked to its doom or flung into the dark expanse of intergalactic space.

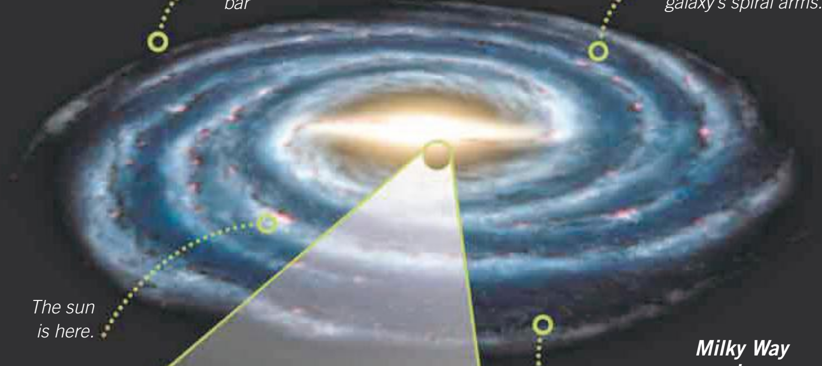
EVEN AT HYPERVELOCITIES, A STAR WOULD TAKE ABOUT 10 MILLION YEARS TO TRAVEL FROM THE CENTER OF THE MILKY WAY TO ITS EDGE

ALPHA CAM

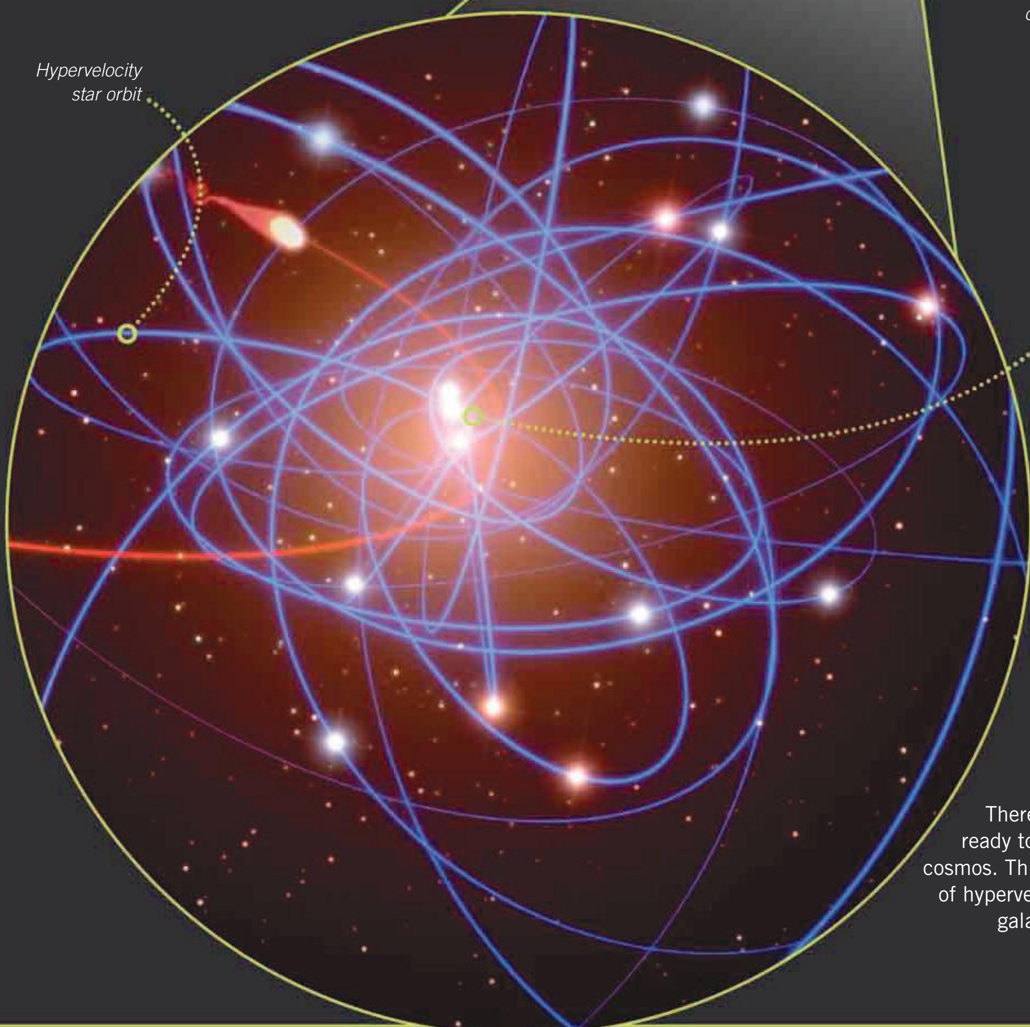
One of the fastest hypervelocity stars yet discovered is called Alpha Camelopardalis, or Alpha Cam. In this image, taken by NASA's WISE space telescope, the red smudge is a band of glowing gases heated up by the shock wave created by the star as it streaks through the cosmos. Its speed has been estimated at between 1.5 and 9.4 million mph (2.4 and 15 million km/h)—at that speed it would take just over a second to travel from London to New York.

INSIDE **THE GALAXY**

At the center of the Milky Way there is a colossal black hole with the mass of four million suns. More distant stars, like our sun, orbit the galactic center at about 450,000 mph (720,000 km/h), but a closer star can orbit at millions of miles per hour. It is thought that for even such a speedy star to be kicked out of the galaxy, it must be part of a binary, or multiple, star system.



Milky Way galaxy



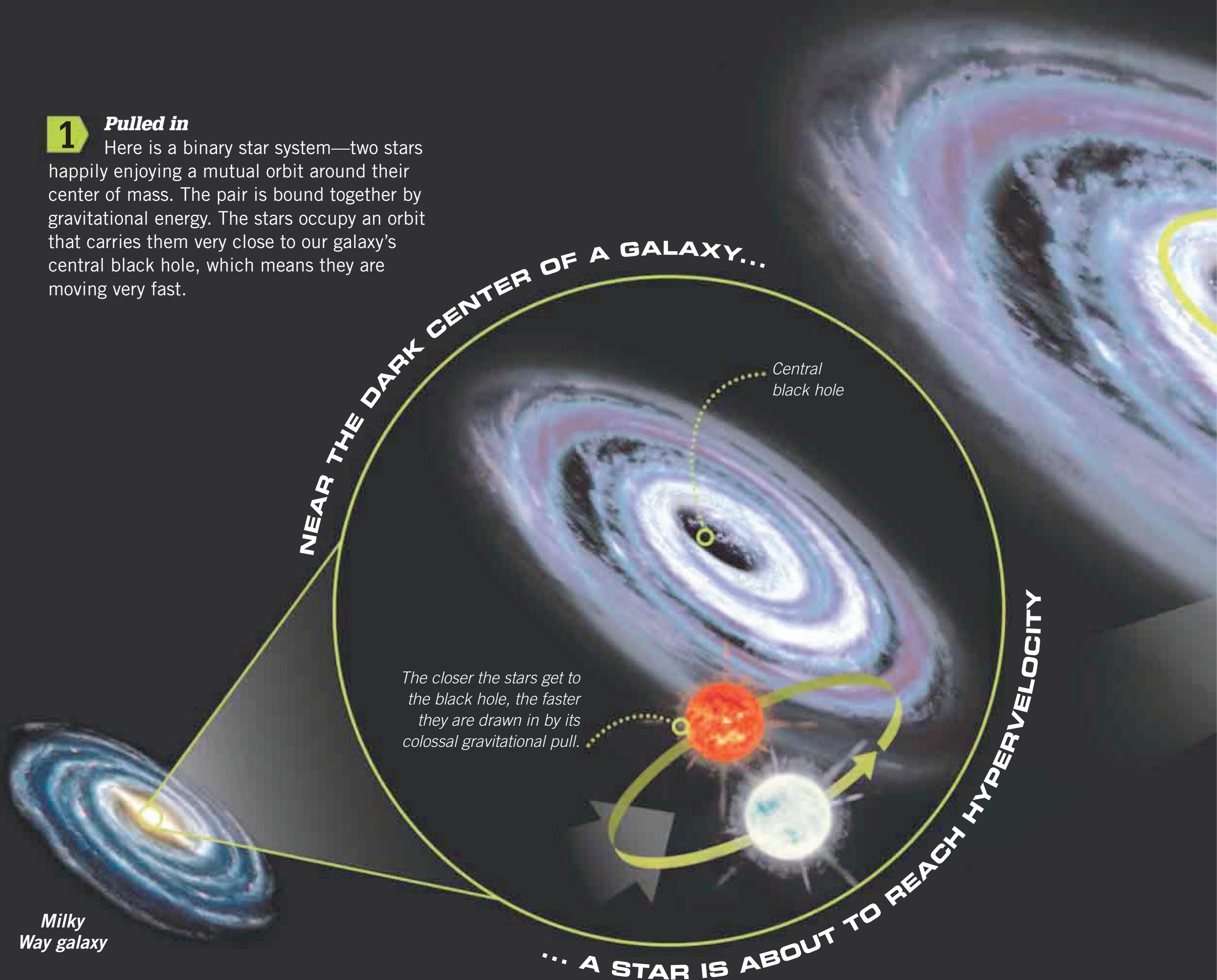
STAR MAP
There is no shortage of stars ready to be catapulted into the cosmos. This map shows the orbits of hypervelocity stars orbiting the galaxy's central black hole.

HOW HYPERVELOCITY STARS ARE **THROWN OUT OF THE GALAXY**

The existence of hypervelocity stars was first proposed in 1988, but the first was not discovered until 2005. We now know that these rogue stars travel so fast that they can escape the gravitational confines of the galaxy that bore them, and travel out into intergalactic space. Here's how...

ASTRONOMERS THINK THAT ONE HYPERVELOCITY STAR IS BOOTED OUT OF THE GALAXY EVERY 10,000 YEARS

1 ***Pulled in***
Here is a binary star system—two stars happily enjoying a mutual orbit around their center of mass. The pair is bound together by gravitational energy. The stars occupy an orbit that carries them very close to our galaxy's central black hole, which means they are moving very fast.



2 *Torn apart*

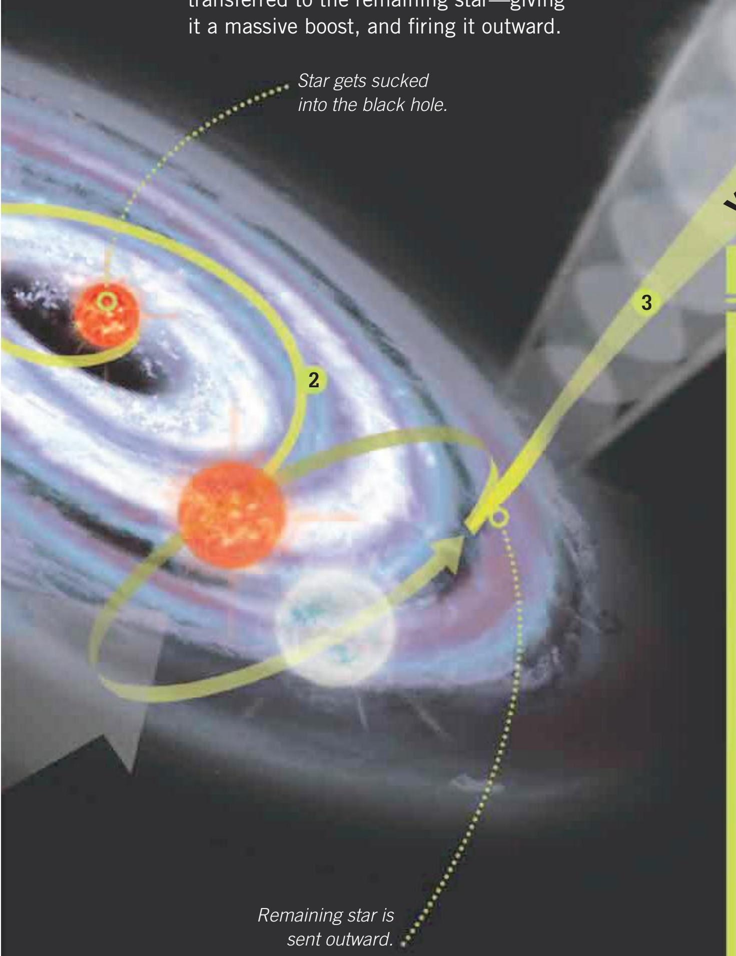
But if they stray too close, the black hole's colossal gravitational energy can overwhelm the energy that binds the stars together, and tear them apart. One star is captured, and falls into the black hole.

3 *Speed boost*

Before they are torn apart, the two stars were orbiting at great speed. When the pair's gravitational bond is broken, all the energy and angular momentum within the system is transferred to the remaining star—giving it a massive boost, and firing it outward.

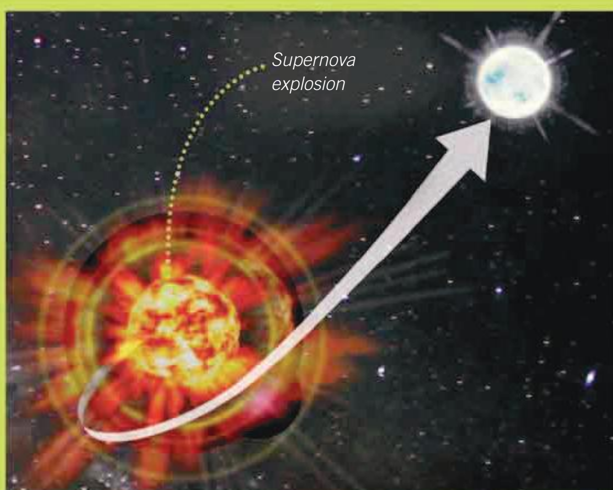
4 *Hypervelocity!*

The star's initial orbital speed, combined with the extra energy and momentum, accelerates the star to up to 9.4 million mph (15 million km/h) and flings it out of the galaxy. It wanders the universe as a stellar speed demon.



SUPERNOVA SLINGSHOT

But the black-hole-slingshot model does not fit for all hypervelocity stars. Some seem to have been "spat out" from more distant regions of the galaxy, and many of them contain chemicals that could only have come from a supernova explosion. One explanation for this is that these stars were once part of an extremely rapidly rotating binary pair of stars. When one of the pair exploded as a supernova, the gravitational release combined with the extra "shove" of the explosion gave the remaining star enough speed to escape the galaxy.



MEET THE SMELLY DWARF

IN A UNIVERSE POPULATED BY THE BIZARRE and unusual, it takes a special talent to be singled out as a **space oddity,** but if there is one celestial object that deserves this moniker, it is the **lowly brown dwarf.**

Stuck in a strange no man's land between stars and planets, and accused of being dull, **smelly** (their atmosphere is rich with **eggy hydrogen sulfide** and **urine-smelling ammonia**), and underachieving loners, brown dwarfs are one of the universe's most maligned objects—a sort of cosmic hobo if you will.

Formed from the collapse of clouds of gas and dust, brown dwarfs start their lives full of **the promise of stardom.** But they never manage to gather enough mass to ignite full-blooded hydrogen fusion in their cores and, instead of becoming blazing stars surrounded by supplicant planets, they resemble enormous Jupiter-like planets—**doomed to billions of years of cold obscurity.**

Brown dwarfs are so unlike stars that their existence was only actually confirmed in 1994, after decades of speculation. Although they begin life as hot, dense almost-stars, without a functioning nuclear furnace in their cores, brown dwarfs hemorrhage heat into the frigid vacuum of space and quickly become **too cold to be seen by conventional telescopes.** Luckily, although they can be feebly cold by stellar standards, they are warmer than the space that surrounds them, which makes them visible to infrared telescopes. But this does not make them easy to find.

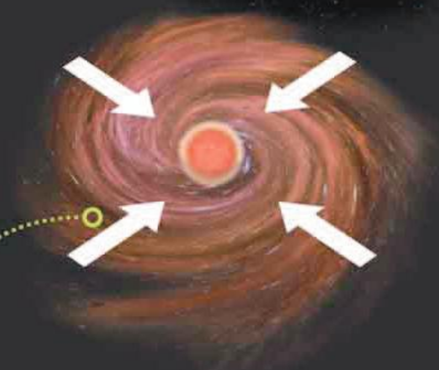
A young brown dwarf can be hot enough to be mistaken for the smallest stars and an old brown dwarf can be cold enough to be mistaken for a Jupiter-like gas giant. So instead of thinking of brown dwarfs as being the hobos of the universe, **perhaps we should imagine them as cosmic double agents**—surely they deserve that much?

THE BROWN DWARF: A STELLAR DROPOUT

The early careers of brown dwarfs and stars are very similar—both are formed from the gravitational collapse of clouds of interstellar gas and dust—but, somewhere along the line, a brown dwarf drops out of the stellar university and lives the rest of its life labeled as a "failed star."

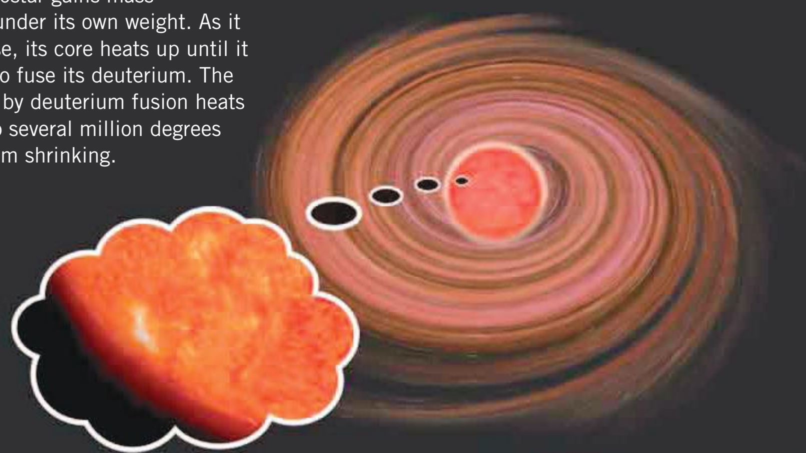
1 ***Gas-and-dust cloud***
Here is a cloud of interstellar gas and dust. It is mostly made up of hydrogen and helium, with small amounts of deuterium (also known as "heavy hydrogen") and lithium. The center is slightly denser than its surroundings, and this acts as a sort of seed around which a star can grow.

2 ***Protostar***
The extra gravitational pull of the seed draws in material from the cloud until a young protostar is formed.



Cloud material is drawn into the center

3 ***Deuterium fusion***
The protostar gains mass and contracts under its own weight. As it gets more dense, its core heats up until it is hot enough to fuse its deuterium. The energy created by deuterium fusion heats the protostar to several million degrees and stops it from shrinking.



4 ***Empty fuel tank***
But here its dreams of stardom end. It soon runs out of deuterium fuel, and it has not gained enough mass to keep the fusion going (it takes a lot more energy to fuse hydrogen).

5 ***Cooling off***
With no new energy being created in its core, it starts to shrink and cool.

Unused gas and dust drift away

6 ***Similar looks***
Eventually the brown dwarf becomes almost identical to a gas giant planet.

7 ***Undetectable***
In time, it will cool completely and become almost undetectable.

FAILED STAR? OR OVERACHIEVING PLANET?

Gas giant planets, brown dwarfs, and stars are all made of pretty much the same ingredients: about 90 percent hydrogen and 10 percent helium. So is it fair to call a brown dwarf a failed star, or can we call it an overachieving planet instead?

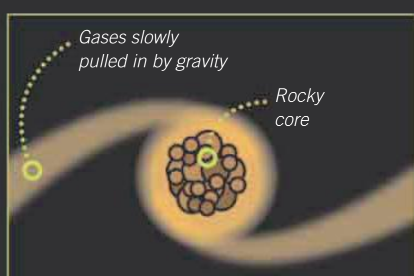
HEAT: THE STAR QUALITY

Here are three objects that are made of the same stuff and are about the same size. Jupiter is the largest planet in our solar system, Gliese 229B is a fairly typical brown dwarf, and OGLE-TR-122B (yes, that is its name) is the smallest star yet discovered.

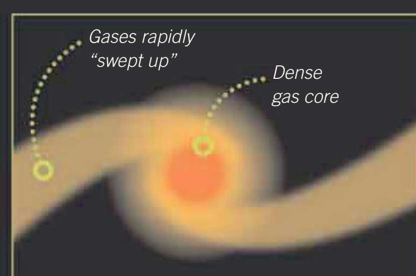
JUPITER, GAS GIANT PLANET	GLIESE 229B, BROWN DWARF STAR	OGLE-TR-122B, SMALL STAR
Mass: 1 Jupiter mass	**Mass:** 40 Jupiter masses	**Mass:** 96 Jupiter masses
Temperature: -229°F (-145°C)	**Temperature:** 1,346°F (730°C)	**Temperature:** 4,500°F (2,500°C)
Despite its size, Jupiter is not particularly dense, so it does not have enough mass to force the atoms that make it up to fuse together. This means it is pretty darn cold.	Gliese 229B is far more massive than Jupiter. The gravitational force of the extra mass is enough to make deuterium atoms fuse in its core—generating heat for a short time.	OGLE-TR-122B is more than twice as massive as Gliese 229B. This creates enough core pressure for hydrogen fusion to take place—creating heat for many millions of years.

BUILT LIKE A STAR (AND MAYBE A PLANET)

It was assumed that Jupiter-like gas giants formed more like planets than stars. In recent years, gas giants have been discovered outside our solar system that are too young to have been "built" like planets. So, if some planets are built like stars, we might be able to call brown dwarfs planetary overachievers.



OLD THEORY: ACCRETION MODEL
The gas giant starts off as a baby rocky planet, but, over millions of years, its rocky core becomes wrapped in gases left over from the formation of their star. This requires the planet to have a rocky core, which brown dwarfs do not. Under this model, brown dwarfs remain "failed stars."



NEW THEORY: COLLAPSE MODEL
Gas giants form from the collapse of the gas disk of a still-growing star. In place of a rocky core, the planet grows around a seed of dense gas. This is similar to how stars and brown dwarfs are formed. Under this model we could call brown dwarfs "overachieving planets."

IT IS THOUGHT THAT THERE MIGHT BE AS MANY AS 30–100 BILLION BROWN DWARFS IN OUR GALAXY ALONE

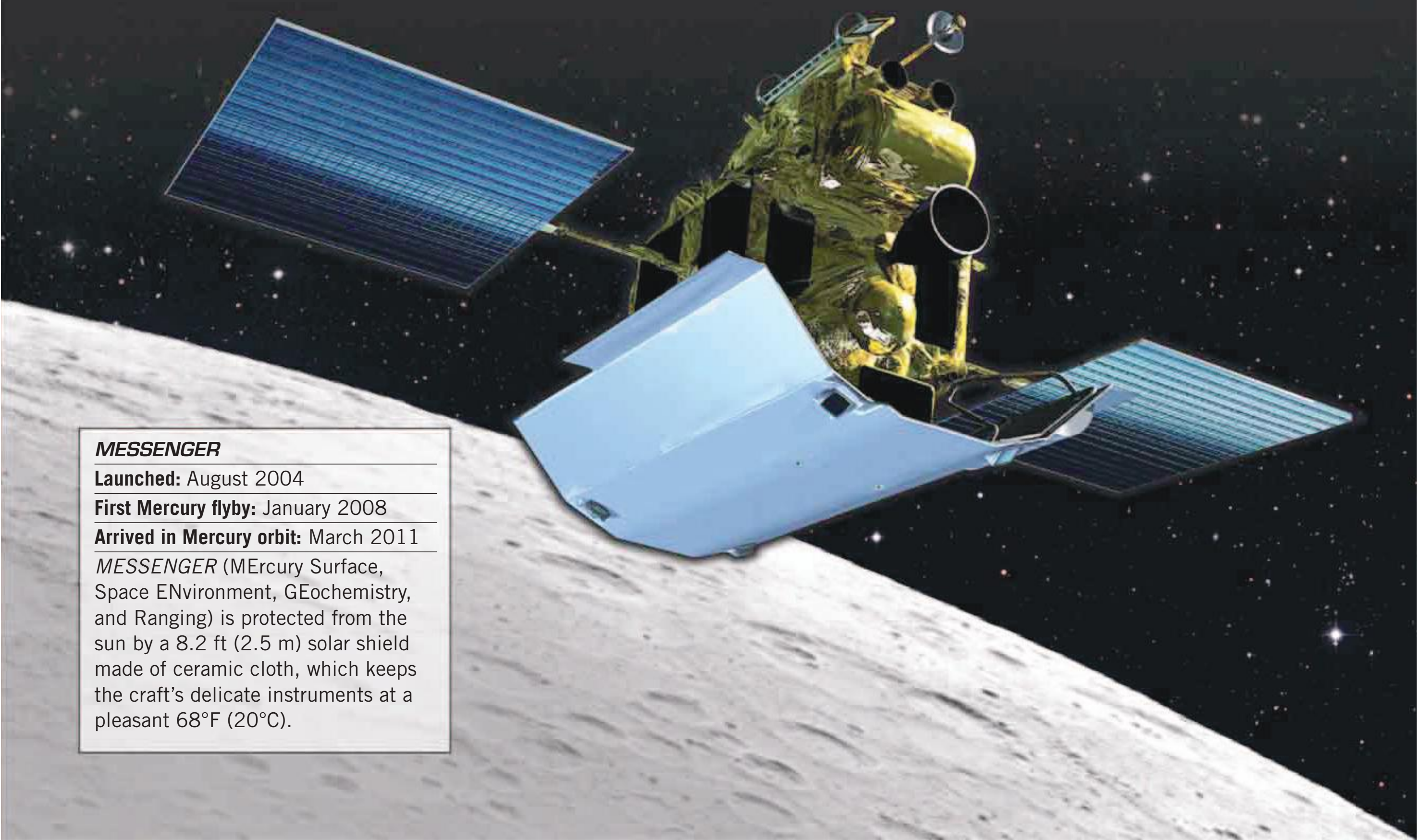
MERCURY'S SECRETS

WHEN ANCIENT ASTRONOMERS observed the tiny planet that lives on the doorstep of the sun, they saw how quickly it seemed to shoot across the heavens. So the Romans named it after the god Mercury—**the swift messenger.** When the scientists of the 21st century decided to send the first spacecraft to orbit Mercury, they saw no reason to break the tradition, **so they named the craft *MESSENGER*.**

MESSENGER was launched in 2004, and, since moving into orbit in early 2011, **the spacecraft has captured nearly 100,000 images** and revealed new information about Mercury, which, even many thousands of years since its discovery, has always been one of the **least understood planets in our solar system.**

Mapping Mercury:
All we had were close-up pictures of one half of Mercury's surface until *MESSENGER* made its first flyby of the planet in 2008. *MESSENGER* has now mapped more than 99 percent of the planet.

THE SUN-FACING SIDE OF *MESSENGER*'S SHIELD REACHES TEMPERATURES OF 700°F (360°C)



MESSENGER

Launched: August 2004

First Mercury flyby: January 2008

Arrived in Mercury orbit: March 2011

MESSENGER (MErcury Surface, Space ENvironment, GEochemistry, and Ranging) is protected from the sun by a 8.2 ft (2.5 m) solar shield made of ceramic cloth, which keeps the craft's delicate instruments at a pleasant 68°F (20°C).

The reason we know so little about Mercury is simple—**it is uncomfortably close to the sun.** It is difficult to study from afar, because telescopes like Hubble are blinded by the sun's glare and any probe sent to Mercury must contend with temperatures that swing from a searing 680 °F (360 °C) to a frigid -256 °F (-160 °C). *Mariner 10* was previously the only craft to make the journey—it snapped a handful of images of the planet as it whizzed past in 1974.

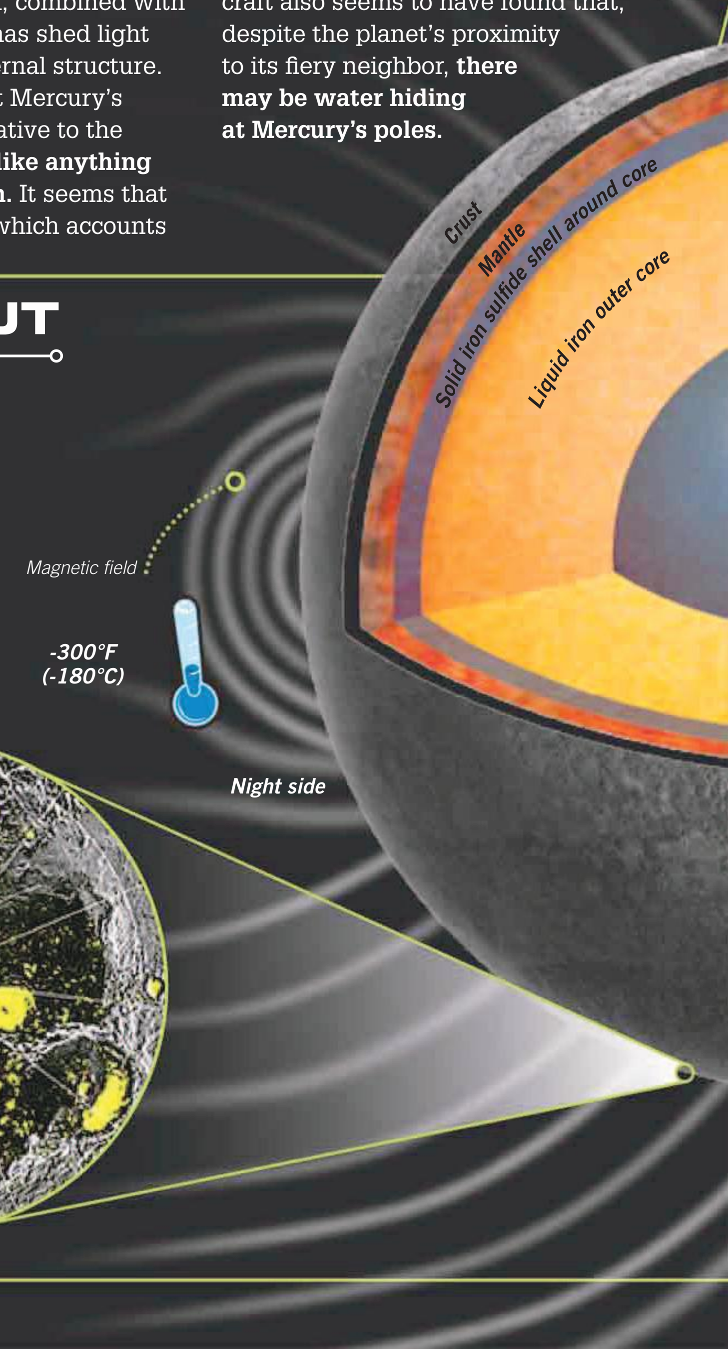
Thirty years after *Mariner 10*, *MESSENGER* was sent to shed light on this most illuminated of planets. After a year in orbit, *MESSENGER*'s findings are **revealing Mercury to be a most surprising and complex little world.**

Data from *MESSENGER* has allowed scientists to build the first precise model of Mercury's gravity field, which, combined with topographic data, has shed light on the planet's internal structure. It has revealed that Mercury's enormous core (relative to the planet's size) is **unlike anything in the solar system.** It seems that the complex core, which accounts for 85 percent of the planet's diameter, consists of a solid iron core, sitting within a ball of molten iron and encased by a sphere of solid iron sulfide (sort of like a giant iron Ferrero Rocher chocolate... or Ferrous Rocher).

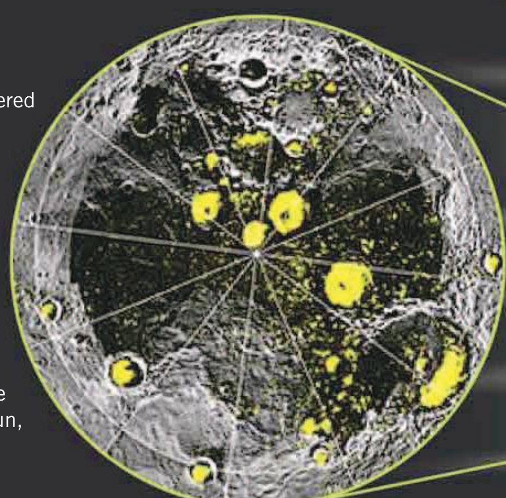
Perhaps most surprisingly, the craft also seems to have found that, despite the planet's proximity to its fiery neighbor, **there may be water hiding at Mercury's poles.**

MERCURY **INSIDE OUT**

Mercury is only slightly bigger than Earth's Moon and is the closest planet to the sun. During its long 58-hour day (a year lasts just 88 days) the surface is superheated to 800°F (430°C), while at night temperatures drop as low as -300°F (-180°C). Despite its proximity to the sun, Mercury's reflective surface and lack of atmosphere mean it isn't the solar system's hottest planet—nearby Venus has that dubious honor.

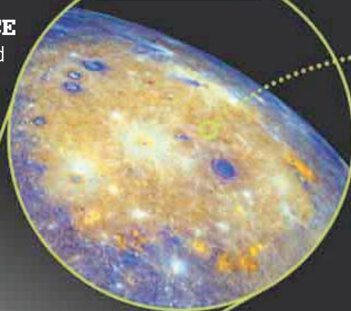


WATER AT THE POLES?
In the 1990s, astronomers discovered patches that reflected radar rays sent from Earth near Mercury's poles. At the time, it was suggested that water ice could be hiding in the cold, permanently shadowed craters. Scientists have compared these bright radar patches with new images taken by *MESSENGER* and they seem to match up perfectly—suggesting that, despite Mercury's close proximity to the sun, water may be hiding at its poles.



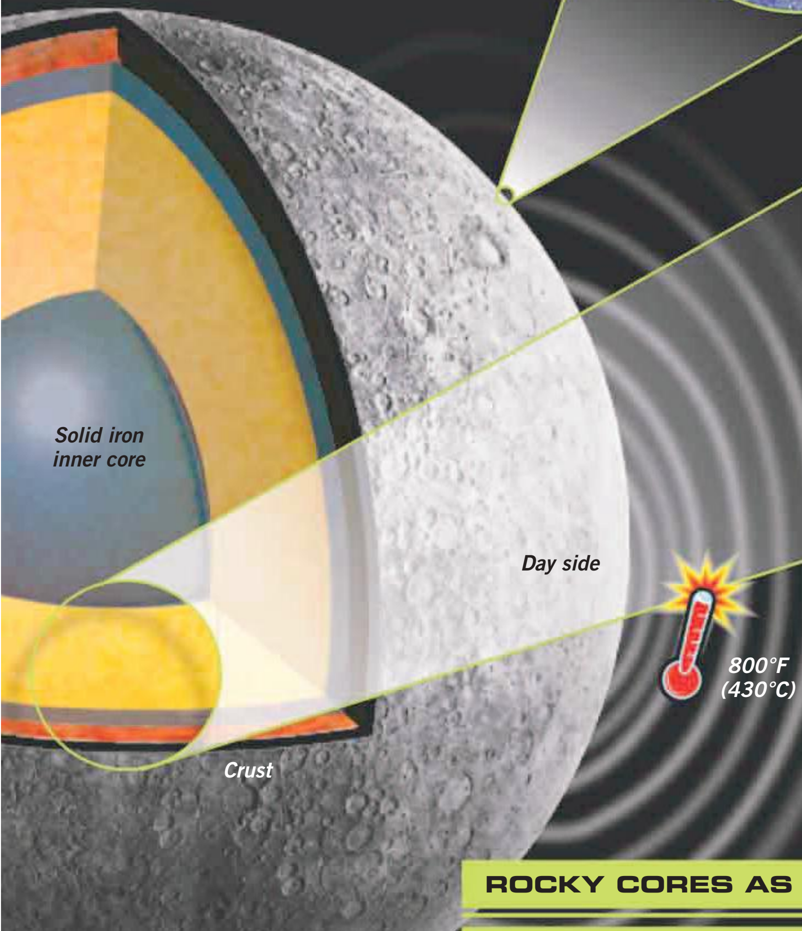
THE SURFACE

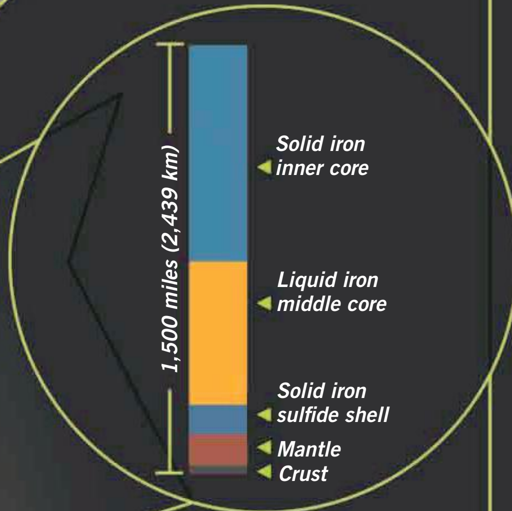
Before *MESSENGER*, many scientists believed that the planet had cooled off quickly after its formation and had been geologically dead for billions of years. *MESSENGER*'s findings seem to indicate that geological processes continued for some time after the planet's formation.



Moving on up

The floor of the Caloris Basin—an impact crater created about 4 billion years ago—has risen since it was formed, suggesting that an active interior within Mercury pushed the floor up.

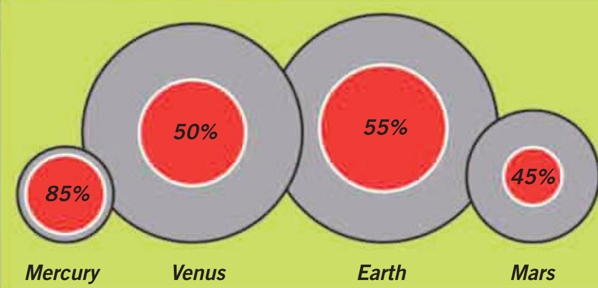




A MOST UNUSUAL CORE

Gravitational measurements from *MESSENGER* suggest that Mercury's iron core is even bigger than previously thought. *MESSENGER* has also revealed that the iron core has an unusually complex structure. The area above it is much denser than the rocky mantle, although not as dense as iron, which could mean that the central core is encased in a shell of iron sulfide 125 miles (200 km) thick—a situation not seen in any other planet.

ROCKY CORES AS A PERCENTAGE OF DIAMETER



Compared with the other rocky planets, Mercury has an unusually large core for its size. In fact, it would be fair to say that it is more core than planet. The core accounts for 42 percent of the planet's volume—Earth's core is only 17 percent of its volume.

HOW TO CATCH A COMET

MAN HAS ALWAYS HUNTED. Even before prehistory ditched the *pre* part of its name and became just history, hunters were using long and **sharp pointy things** to spear fish. But sometimes the fish slipped off the end. Then some bright spark had the idea of putting a barbed end on the sharp pointy thing and **the harpoon was born.** For centuries, the harpoon was the weapon of choice for hunting at sea, but lately it has fallen out of vogue. NASA is planning to rehabilitate the harpoon, but instead of hunting whales at sea, **they will be hunting comets in space.**

Astronomers are fascinated by comets. These frozen chunks of dust and ice were formed when the solar system was still a baby (that is well before history, prehistory, or any other sort of history) and they have remained unchanged ever since. As such, **they are like frozen time capsules**, crammed full of information about the origins of the solar system.

Bright flash:
This image of Comet Tempel 1 was captured by NASA's Deep Impact mission. The bright flash is the result of an impactor that was deliberately smashed into the comet so that the debris thrown out could be studied.

Astronomers would love to get **their hands on a sample of comet and unlock its secrets.** To make their wish a reality, NASA will be equipping a comet-hunting spacecraft called *OSIRIS-REx* with a harpoon, and to complete the historical synergy, they will fire it from a crossbow.

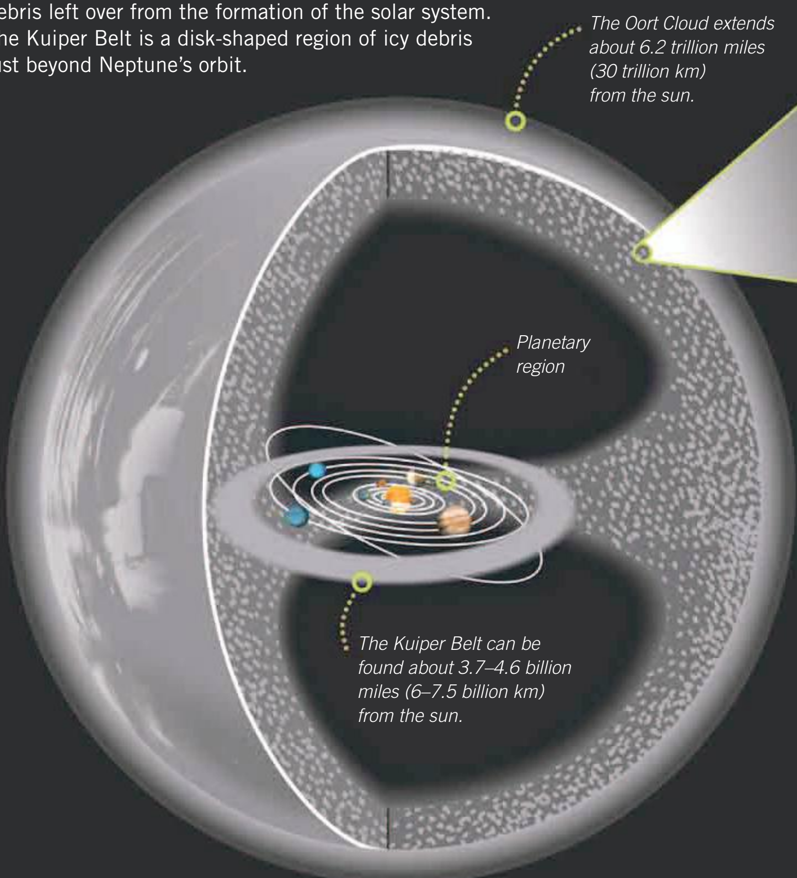
A comet can move through space quite quickly—about 150,000 mph (240,000 km/h)—so landing a craft on its surface is a bit tricky. **The craft, which is slated to launch in 2016, will use a 6.5 ft (2 m) crossbow to fire a high-speed harpoon** with a special hollowed-out tip into the comet's surface.

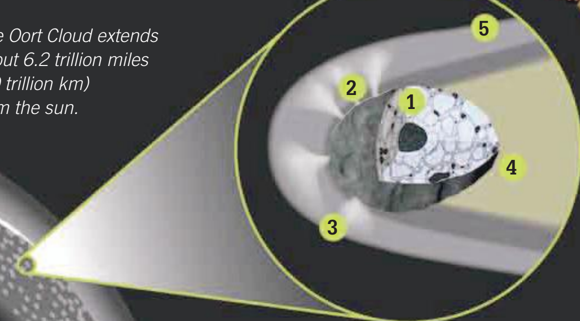
The harpoon will grab a sample from inside the comet and then the sample will be winched back to *OSIRIS-REx* and returned to Earth. However, comet hunting is not as straightforward as you would think. So "Call me Ishmael" and check out our comet-hunting guide.

THE HUNTER'S GUIDE TO COMETS...

Comets can be tricky little blighters, but, like all "big game" hunts, knowing your quarry is half the battle. First, you need to know where to find them. Like male lions, comets are kicked out of their homeland to wander alone. They come from two regions.

THE OORT CLOUD AND THE KUIPER BELT
The Oort Cloud is an immense spherical cloud of rocky debris left over from the formation of the solar system. The Kuiper Belt is a disk-shaped region of icy debris just beyond Neptune's orbit.





Anatomy of a comet

1 ***Nucleus***
Always aim for the heart. A comet's heart is a "dirty snowball" of water ice, frozen carbon dioxide, methane, and ammonia.

2 ***Jets of gas and dust***
Gas and dust vent from the comet as the sun vaporizes the comet's ice.

3 ***Coma***
The coma is a cloud of dust and vapor that surrounds the nucleus.

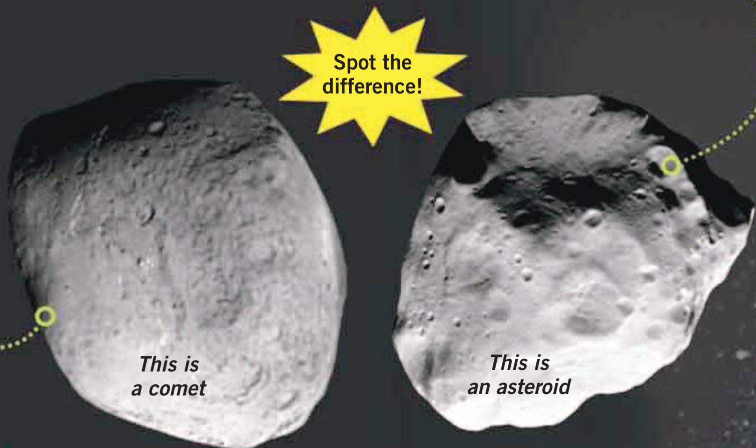
4 ***Dust tail***
A trail of dust particles.

5 ***Ion tail***
The ion tail consists of charged particles pushed away from the comet by the solar wind, and can extend many tens of millions of miles from the comet.

EXPERT TIPS TO HELP YOU BAG YOUR PRIZE

Just because you know where to find them, don't think for one second that it's going to be plain sailing from here on out. Here's some dos and don'ts for any prospective hunter to keep in mind.

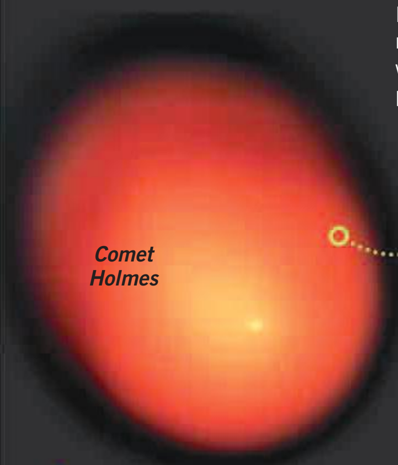
Dead ringer
Asteroids and comets are almost indistinguishable. Comets spend 99 percent of their lives looking like asteroids.



Not very comety
Without the sun's warmth, the water and gases that form the comet's telltale tail stay frozen solid—locked away in the comet's nucleus. In short, it doesn't look very comety.

DON'T BE FOOLED BY LOOKS

So you think you know a comet when you see one? Well, think again. They only adopt their full comety plumage when they pass close to the sun. Because comets have such huge orbits, they spend most of their time a long way from the sun's warmth. So if you are not careful, a comet could pass right by you and you would never know.



Vented gas cloud
The cloud is created by gas that vents out of the comet when it is warmed by the sun.

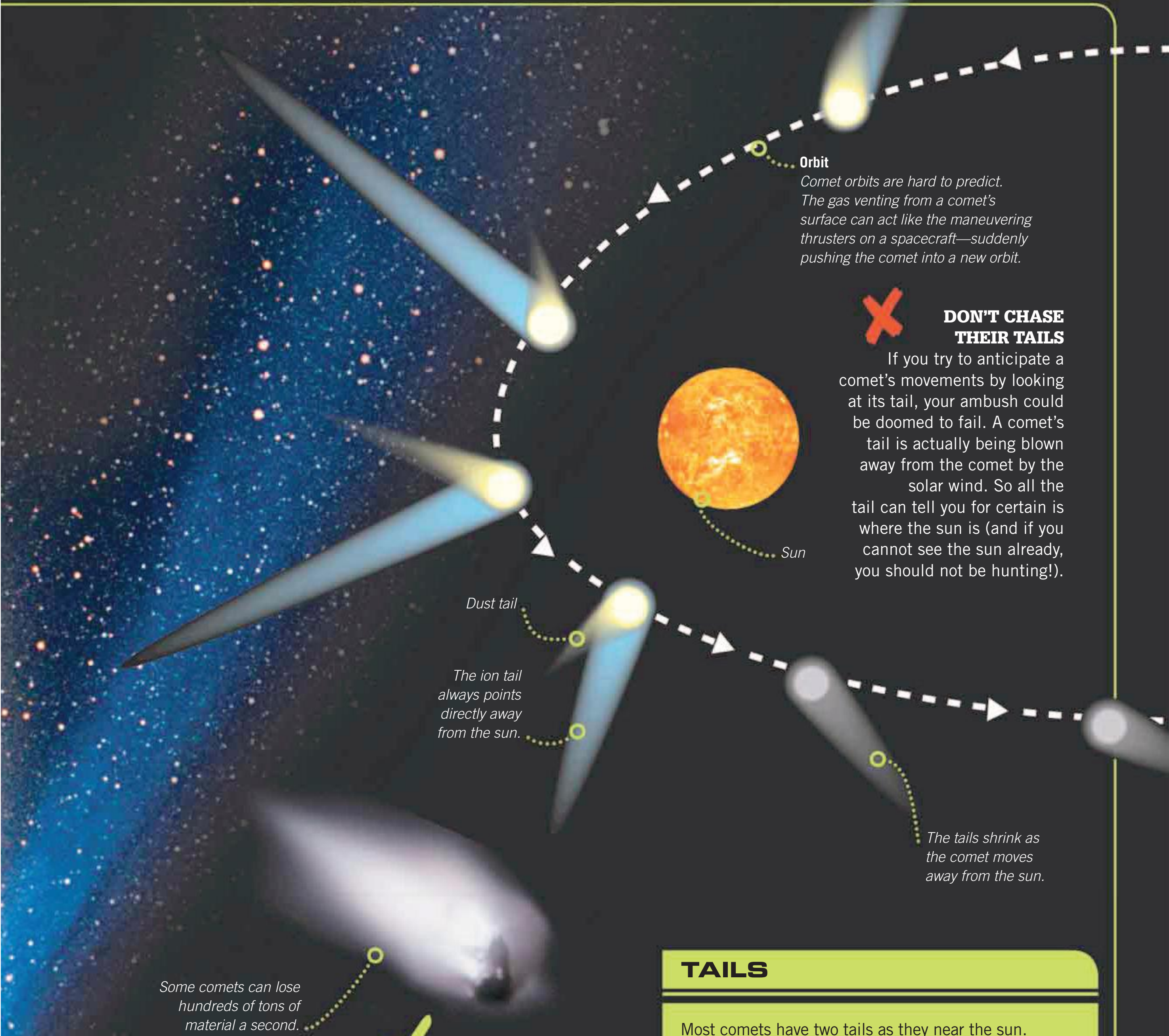
DO PREPARE YOURSELF

If you think you can wait for a comet to pass by before you shoot it, think again. Comets can come from deep space, which gives them plenty of time to pick up speed. You will either need to get in front of the comet to shoot it as it streaks toward you (not recommended), or you will need to match the comet's speed yourself.

DON'T BE TRICKED BY SIZE

When you do get your quarry in your sights, do not be fooled by its size—it is not as big as it looks. Most of what you can see is a cloud of gas, with the nucleus being a tiny speck somewhere in the middle. If you do not aim for the comet's tiny heart, your harpoon will just sail harmlessly through.

COMETS CAN MOVE 70 TIMES FASTER THAN A BULLET



DON'T CHASE THEIR TAILS

If you try to anticipate a comet's movements by looking at its tail, your ambush could be doomed to fail. A comet's tail is actually being blown away from the comet by the solar wind. So all the tail can tell you for certain is where the sun is (and if you cannot see the sun already, you should not be hunting!).

DO STRIKE QUICKLY

A successful hunter is a patient hunter, but do not be too patient or your prize will vanish before your eyes. As comets are essentially giant lumps of ice, every time they pass the sun, they melt a little bit. All the gas that makes a comet so spectacular is actually its lifeblood venting away into space. Eventually, all the ice and gas that holds it together will be gone and your comet will disintegrate.

TAILS

Most comets have two tails as they near the sun. The ion tail is made up of gas ions (atoms whose electrons have been stripped away by the solar wind). The ions get all excited by the sun's radiation, and emit blue light. The dust tail is made of dust released from the comet's surface. Dust particles are heavier than the gas ions—left behind in the orbit, they appear as a curved tail as the comet changes direction.

SATURN'S AMAZING RINGS

IN THE COURT OF THE PLANETS, red-eyed King Jupiter reigned supreme. Nothing rivaled his size, the violence of his atmosphere, the pull of his gravity, or the number of moons he held subject to his will. For billions of years his **only rival in the heavenly sphere was Saturn,** who, although a gas giant himself, could never rival Jupiter's might.

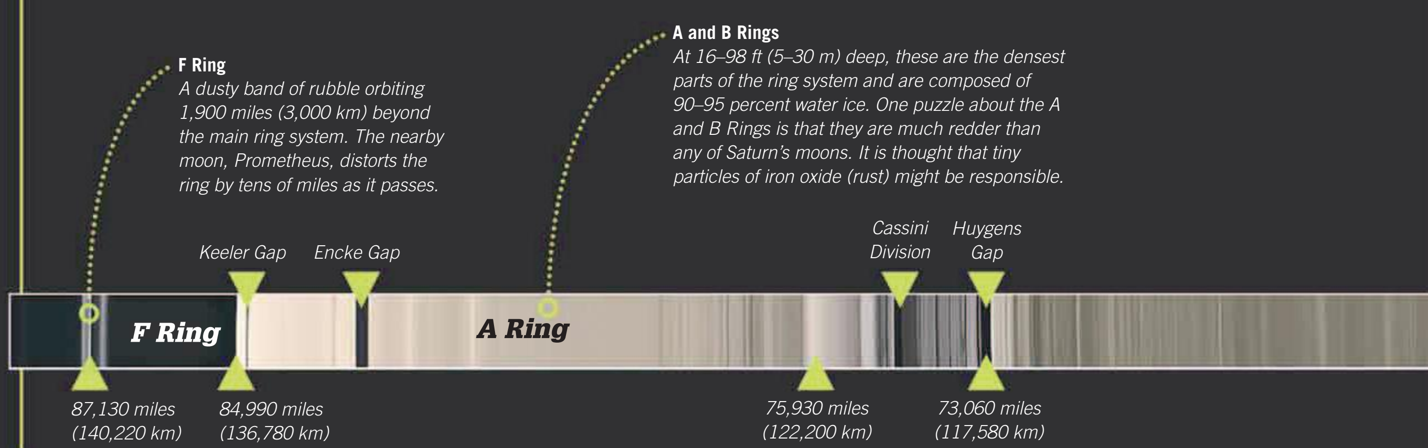
So, like many a subordinate royal sibling, Saturn sought to outdo his relation in the only way he could. He gathered sparkling jewels, which he laid about himself in delicate rings; he became the dandy of the heavenly court; **he became the king of bling.**

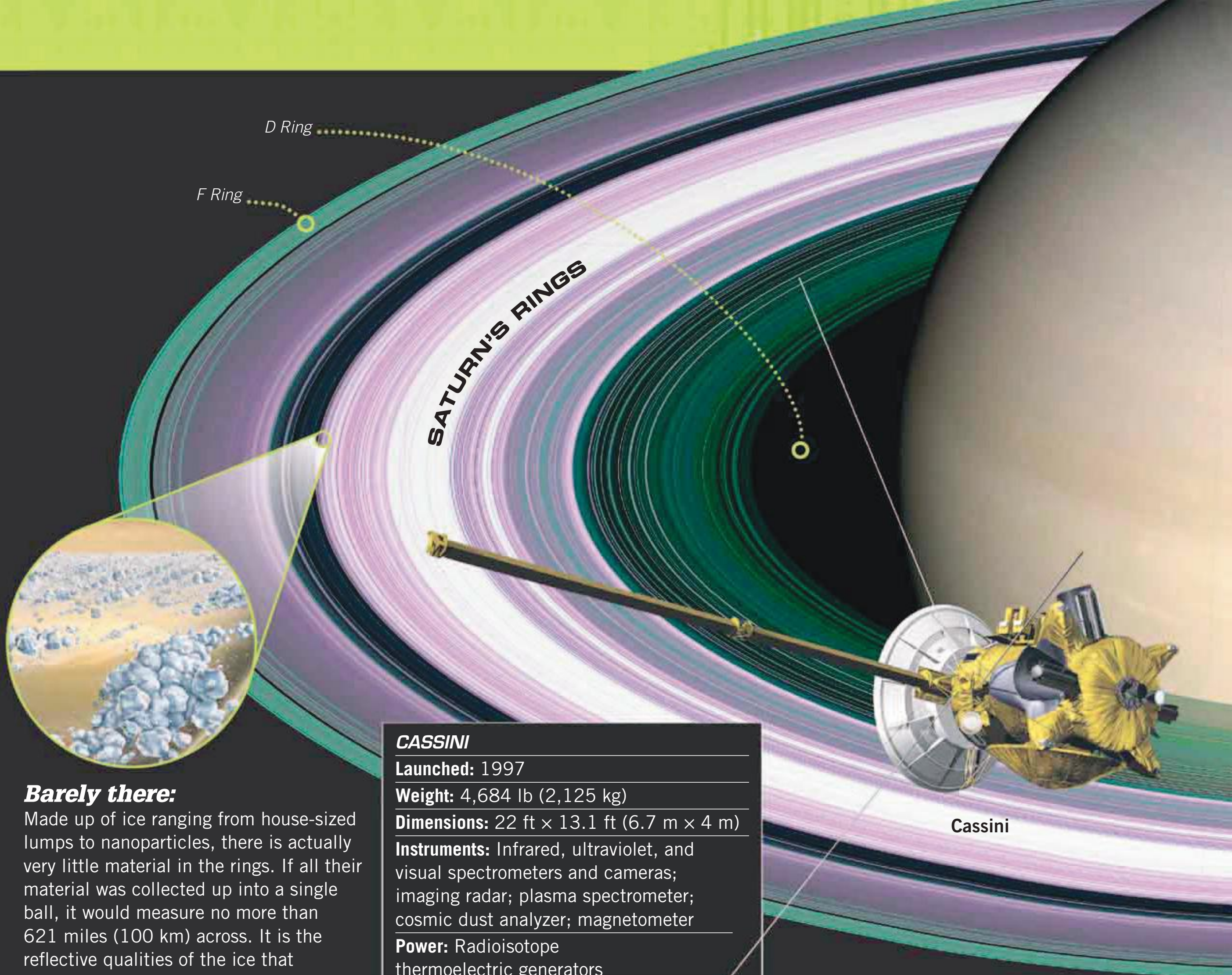
But for millions of years his efforts went unnoticed by the peoples of the lowly rock-planet Earth, until one day, 400 years ago, a little Italian chap named **Galileo Galilei** turned a telescope to the heavens and proclaimed that Saturn had handles.

It took a few more years and some slightly more powerful telescopes before mankind identified Saturn's rings for what they were: **one of the most beautiful phenomena in the solar system.** But still Saturn was not happy—he knew the stunning complexity of his finest decoration could never be appreciated from afar, so he brooded, awaiting the adulation his finery deserved.

Then, in 2004, he got his wish when a tiny machine sent by the humans to study his magnificence arrived. The machine was a probe called *Cassini* and it has revolutionized our understanding of Saturn and his glorious rings. It revealed the rings to be an elegantly complex system where **glittering beads of ice collide, reform, and collide again** (ensuring that the rings stay nice and shiny).

It revealed **moons acting as shepherds,** keeping the rings in check. Other, tiny moons pull material out into trailing tails in some places, and cut lines though the rings, while their gravity decorates the edges with waves in others. Meanwhile, vain Saturn's gravity **tears apart** any ice that clumps into pieces so large that they might threaten the aesthetic of his design.





Barely there:
Made up of ice ranging from house-sized lumps to nanoparticles, there is actually very little material in the rings. If all their material was collected up into a single ball, it would measure no more than 621 miles (100 km) across. It is the reflective qualities of the ice that makes Saturn's rings so luminous.

CASSINI
Launched: 1997
Weight: 4,684 lb (2,125 kg)
Dimensions: 22 ft × 13.1 ft (6.7 m × 4 m)
Instruments: Infrared, ultraviolet, and visual spectrometers and cameras; imaging radar; plasma spectrometer; cosmic dust analyzer; magnetometer
Power: Radioisotope thermoelectric generators

RINGS' **ANATOMY**

The main rings consist of thousands of ringlets, with each ringlet made up of millions of particles of ice, each an individual satellite orbiting the planet at up to 50,000 mph (80,000 km/h). The rings are split by large gaps, which are caused by the gravitational influence of some of Saturn's moons orbiting outside the ring system.

C Ring
A wide but faint ring that is only about 16 ft (5 m) deep. Its particles are known to be dirtier than the other rings, which is probably caused by pollution from meteoroids.

D Ring
Saturn's innermost ring is its thinnest and faintest. It extends into Saturn's highest atmospheric clouds.

Cross-section of Saturn's rings

THE SEARCH FOR ALIEN LIFE

IN THE 16TH CENTURY, the Italian philosopher-cum-astronomer Giordano Bruno speculated that stars (which, at that time, were thought to be little more than God's way of decorating the firmament) were in fact suns, around which might be **"an infinity of worlds of the same kind as our own."**

Sadly, Bruno's heretical speculations led to him being **burned at the stake** by the Catholic Inquisition (not solely for his astronomical thinking), but he would not be the last great thinker to suggest that **Earth might not be the only world in the heavens capable of nurturing life**—English scientist Isaac Newton had similar thoughts 100 years later.

It was not until the early 1990s that the existence of the first extrasolar planet (exoplanet) was definitively confirmed—although unconfirmed discoveries had been staggering in since 1988. Since then, **confirmed exoplanet discoveries have risen into the thousands,** with thousands more awaiting confirmation.

The first such planets to be found were mostly supersized Jupiter-like worlds with little hope of harboring anything but the most robust single-celled alien life. But in recent years improved detection techniques and a new generation of space telescopes are allowing scientists to build a catalog of **earthlike worlds that might just be capable of supporting alien life.** The most prolific of these exoplanet hunters is NASA's Kepler Space Telescope.

Since its launch in 2009, **Kepler has spotted thousands of exoplanet candidates** (planets awaiting independent confirmation). Just a few hundred of those are Earth-sized worlds, which are outnumbered by the so-called "super-Earth" planets (rocky planets with up to ten times the mass of Earth).

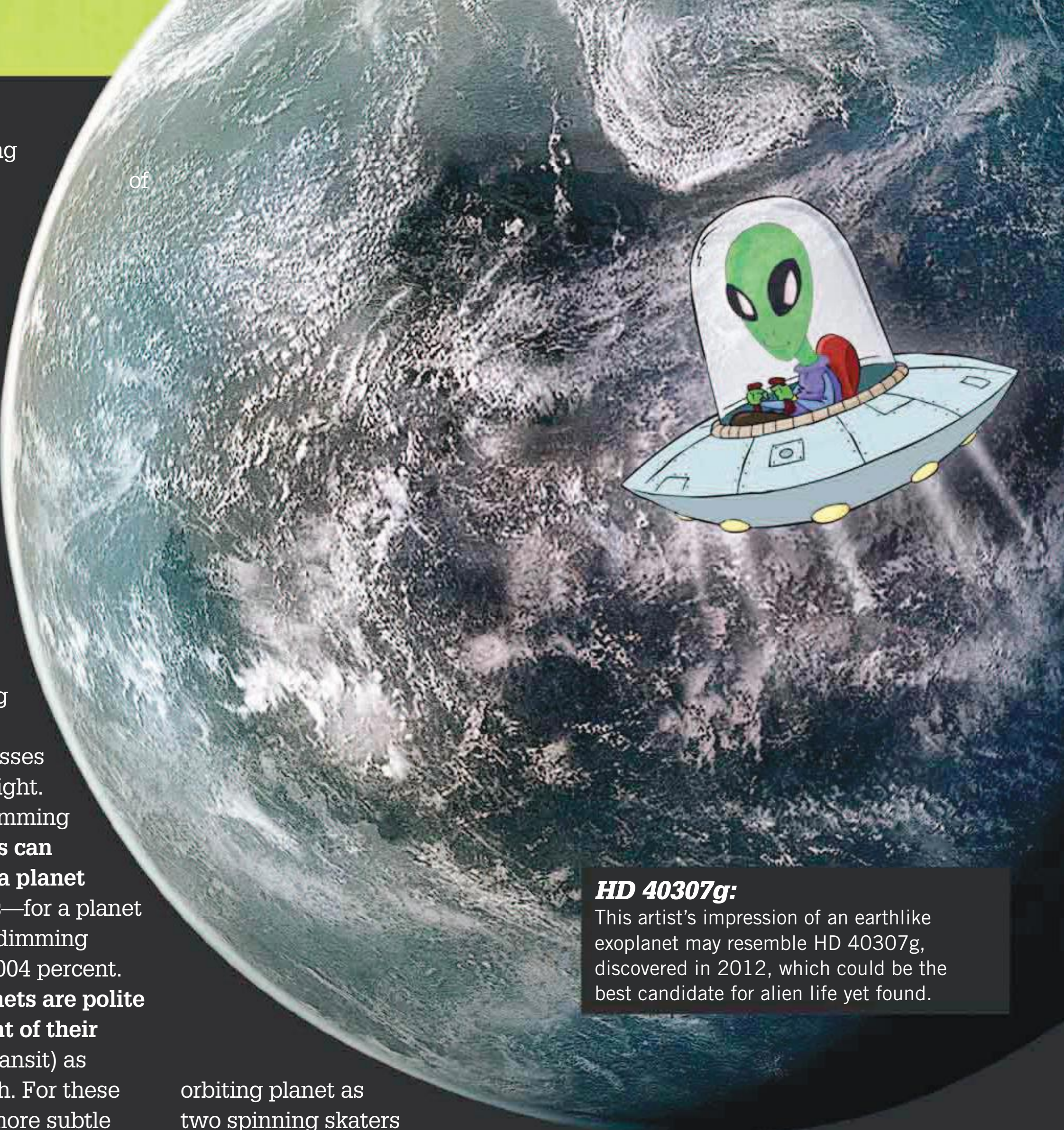
But, when it comes to searching for extraterrestrials, size and composition are not everything—**if a planet lacks liquid water and a stable atmosphere, chances are it cannot support life.** A planet that orbits its parent star too closely will be too hot, and one whose orbit carries it too far away from its star will be too cold for water to exist in its life-supporting liquid state. We call the bit in between the **"Goldilocks zone,"** and when we strip away all the discovered exoplanets that fall outside it, we are left with just a few confirmed potentially habitable worlds.

One reason for the ambiguity in the status of many of these discoveries is distance. Telescopes like Kepler search for exoplanets in orbit around stars that can be thousands of light-years away from Earth. At this distance, a star (a giant nuclear furnace whose surface is burning at tens of thousands of degrees) is quite

PSR B1257+12B: The first confirmed discovery of an exoplanet was made in 1992. This world orbits a pulsar 1,000 light-years from Earth.

easy to spot, but finding a planet (a small lump of rock) is a much more complicated prospect. To make matters worse, that tiny dark planet is being outshone by the star it orbits. In short, finding an earthlike exoplanet is like trying to spot a mosquito as it flies across a floodlight several miles away. Kepler does this by looking for the almost-imperceptible dimming that occurs when the planetary mosquito passes across its stellar floodlight. From the amount of dimming it detects, **astronomers can infer the existence of a planet and estimate its mass**—for a planet the size of Earth, that dimming might be as little as 0.004 percent.

But **not all exoplanets are polite enough to pass in front of their parent star** (called a transit) as we look at it from Earth. For these tricky little blighters, more subtle techniques are required. Europe's dedicated planet-hunter, the High Accuracy Radial Velocity Planet Searcher (HARPS)—an instrument attached to an Earth-based telescope in Chile—**can detect the tiny "wobble" that occurs in a star's motion when it has a planet orbiting it.** Imagine a star and its orbiting planet as two spinning skaters with unequal masses (with the star being the more massive one). If they link arms, the smaller one goes around in a larger circle, but can cause the more massive one to be thrown slightly out of balance as it spins. A planet orbiting a star is just like that added weight—its **gravitational pull causes the star to wobble slightly.** This wobble means that the star is moving back and forth relative to Earth. When the wobble carries the star away from us, the wavelength of its light is stretched toward the red end of the spectrum (redshift); when the star wobbles toward us, the light's wavelength is squeezed into the blue end of the spectrum (blueshift). The more massive the planet, the greater the shift—but, for small, earthlike exoplanets, the amount of shift is barely perceptible. Luckily,



HD 40307g:
This artist's impression of an earthlike exoplanet may resemble HD 40307g, discovered in 2012, which could be the best candidate for alien life yet found.

THE OLDEST EXOPLANET DISCOVERED SO FAR, PSR B1620-26B, IS ALMOST 13 BILLION YEARS OLD

HARPS is sensitive enough to track these spectral changes. In its nine years of service, **HARPS has found 75 exoplanets.** Most have been uninhabitable super-Earths or gas giants, but in January 2012 the HARPS team announced the discovery of an exoplanet that sits comfortably within its star's habitable zone. The planet, HD 40307g, is the outermost of six worlds in orbit around a star about 42 light-years away called HD 40307. It orbits its star at a similar distance as Earth is from the sun, enjoys similar levels of solar energy, and is likely to be a rocky world about seven times the mass of Earth. **There is also a good chance that it will have oceans of liquid water and a stable atmosphere.** Though it is 42 light-years away from us, HD 40307g is, relatively speaking, on our cosmic doorstep. This puts HD 40307g in range of future life-seeking exoplanet hunters.

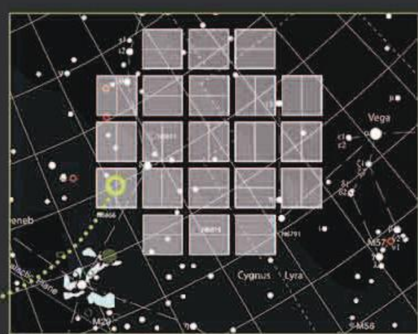
HOW TO **FIND AN EXOPLANET**

Finding a tiny planet in orbit around a star so distant that, from Earth, it appears as little more than a white speck is challenging enough. Determining whether that planet could possibly harbor life would seem to be impossible. Luckily, astronomers have a few tricks up their sleeves.

FIND A GOOD SPOT

A star field without any "bright" stars is needed so they do not blind the instruments. Kepler, for example, is searching the Cygnus star field, where it is monitoring 100,000 stars. Cygnus is ideal because it contains many stars that are similar to our sun.

Search grid

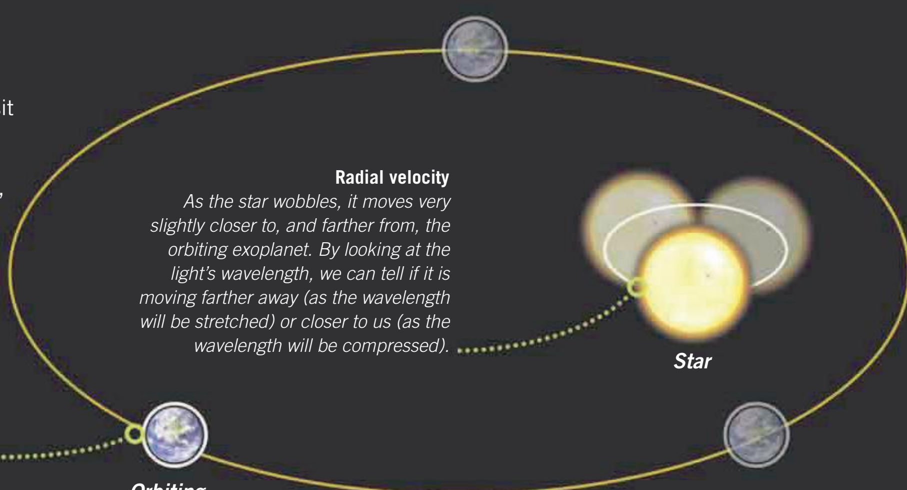


Cygnus star field

"ROGUE PLANETS" ARE WORLDS THAT HAVE BEEN EJECTED FROM THEIR PLANETARY SYSTEM, AND ARE DOOMED TO WANDER ALONE IN THE DARK

FIND THE PLANET

There are two main ways to find a planet. The first, mentioned earlier, is the transit method—where we wait for the planet to cross the star, causing it to dim slightly. The second involves the technique of astrometric detection, which detects radial velocity (the wobbling of the star). Both determine the presence of planets by looking for subtle changes in the appearance of the parent star.



Radial velocity

As the star wobbles, it moves very slightly closer to, and farther from, the orbiting exoplanet. By looking at the light's wavelength, we can tell if it is moving farther away (as the wavelength will be stretched) or closer to us (as the wavelength will be compressed).

Star

Astrometric detection

As a planet orbits its star, the planet's gravity ever-so-slightly pulls the star from side to side—causing it to wobble.

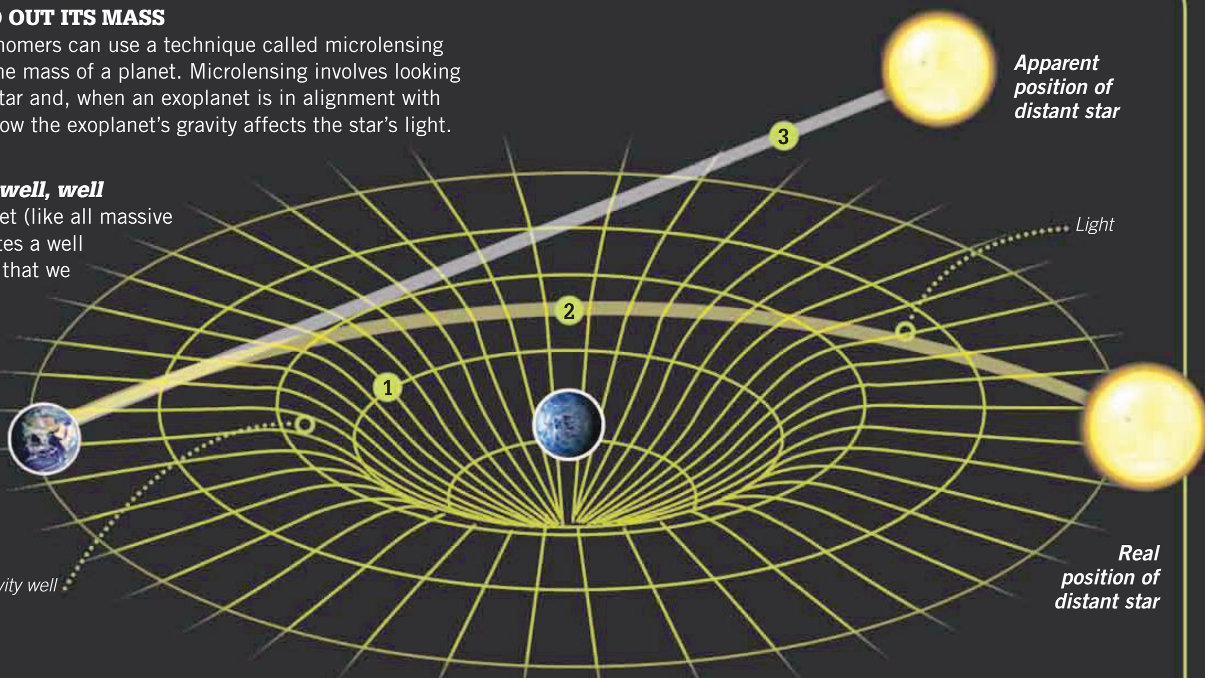
Orbiting exoplanet

FIND OUT ITS MASS

Astronomers can use a technique called microlensing to work out the mass of a planet. Microlensing involves looking at a distant star and, when an exoplanet is in alignment with it, studying how the exoplanet's gravity affects the star's light.

1 *Well, well, well*

A planet (like all massive objects) creates a well in spacetime that we call gravity.



2 *Bending light*

Einstein showed us that light is affected by gravity, just like anything else, and is bent as it passes a massive object.

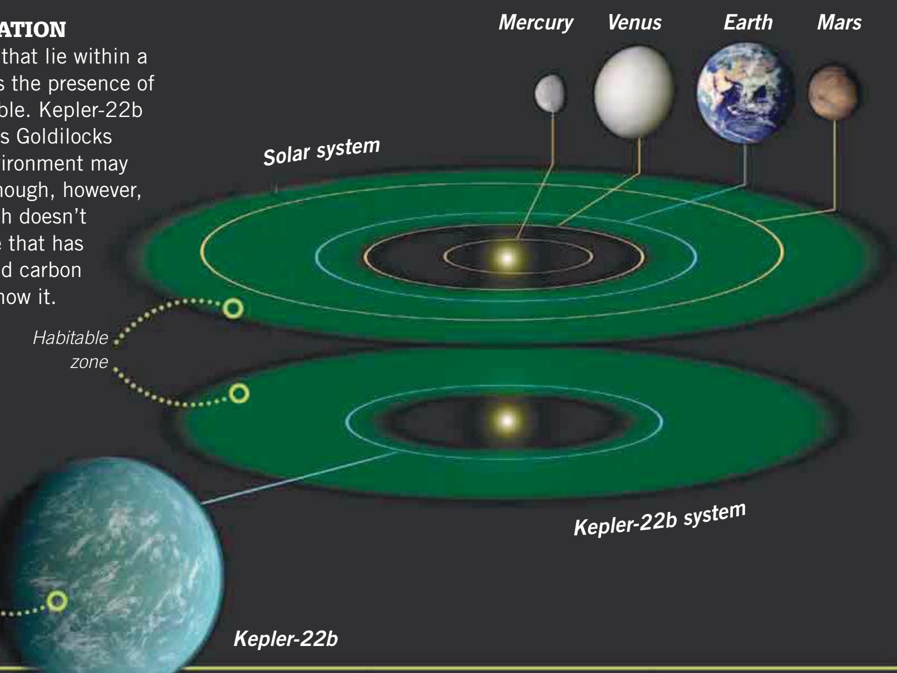
Microlensing to determine a planet's mass

3 *Shifting stars*

When looking at distant stars, astronomers can figure out the planet's mass by how much it bends the stars' light—the more the stars seem to shift position, the greater the planet's mass.

LOCATION, LOCATION, LOCATION

Only exoplanets of the right size that lie within a distance of their parent star that permits the presence of liquid water are considered to be habitable. Kepler-22b is one such planet that is within its star's Goldilocks zone, and astronomers think that its environment may be similar to Earth's. This may not be enough, however, as the same could be said of Mars, which doesn't harbor life. A planet with an atmosphere that has evidence of water (H_2O), oxygen (O_2), and carbon dioxide (CO_2) could support life as we know it.



Life, Jim, as we know it

The final confirmation of whether or not Kepler-22b is supporting life will be evidence of chemical biosignatures. Abundant life will affect the chemistry of the planet's atmosphere. For example, lots of vegetation will absorb light in certain recognizable wavelengths.

THE HOSTILE BLUE PLANET

FLUNG AROUND its parent star at 248,549 mph (400,000 km/h), the exoplanet HD 189733b is so close to the stellar furnace that its year lasts just 2.2 Earth days. Flayed by solar winds, **its atmosphere is stripped away and blasted into space by extreme ultraviolet and X-ray radiation** at the rate of 1,000 tons every second. The scorched atmosphere that survives the onslaught is rent by 4,350 mph (7,000 km/h) winds laden with silicate particles, which become **supersonic shards of molten glass, propelled sideways.**

Indeed, if there is one exoplanet that deserves to have the blues, it is HD 189733b, which is rather apt as it has become the **first exoplanet to have its true color determined** and, in line with that rather labored setup, that color is blue.

Located about 63 light-years away, HD 189733b (which we will call **Howlin' Dave**) is (relatively speaking) right on our cosmic doorstep. It also happens to be one of the closest exoplanets that can be seen crossing the face of its star—making it the **most studied of all the alien planets.**

As a gas giant called a "hot Jupiter," Howlin' Dave is typical of most exoplanet discoveries—being big and hot (close to their stars) makes them relatively easy to spot. But this is **the first time astronomers have been able to measure an exoplanet's color** and imagine how it would actually look through the window if you were able to fly past.

The planet's color, which has been described as a **"deep cobalt blue,"** is thought to come from clouds laden with reflective particles that contain silicon—raindrops of molten glass that scatter blue wavelengths of light. It adds to a growing portrait of Howlin' Dave.

In 2007, scientists using NASA's Spitzer Space Telescope studied Howlin' Dave and produced one of the first temperature maps of an exoplanet. It revealed a Janus-like world, with **one face tidally locked in a permanent furnace-facing gaze and the other hidden in eternal darkness.** The two sides differ in temperature by hundreds of degrees, driving the atmospheric turbulence that results in the planet's extreme winds.

In 2012, NASA's Swift satellite saw hydrogen atoms being torn from the planet's atmosphere at 300,000 mph (482,803 km/h) by powerful solar winds—that is what happens when you orbit just 2.4 million miles (4 million km) from your star, Dave. Earth orbits the sun at a far more sensible 93 million miles (150 million km).

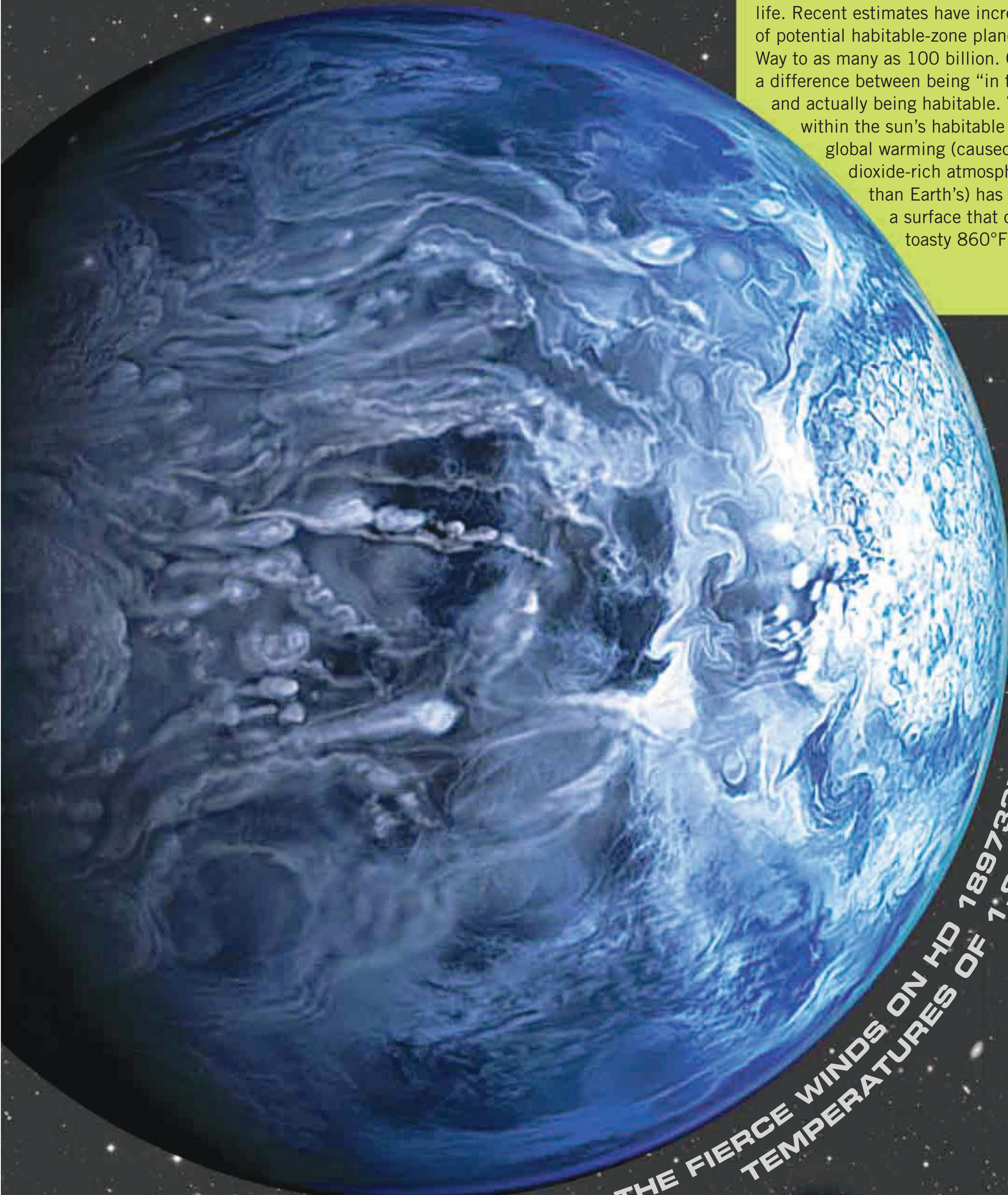
In 2013, astronomers turned the European Southern Observatory's pragmatically named Very Large Telescope on the planet and detected **water molecules in its atmosphere—the first time good old H_20 had been found on an exoplanet**.

So Howlin' Dave is a bit like the stars of one of those "look at me, I'm a freak!" shows on TV—he was dealt a bad hand, but he is scientifically interesting and he is getting his five minutes of fame.

HD 189733b:
As the first exoplanet to have its true color measured, HD 189733b's peaceful azure hue belies its true turbulent nature.

WE WANT ALIENS!

The golden egg of exoplanet research would be the discovery of a planet capable of supporting life. Recent estimates have increased the number of potential habitable-zone planets in the Milky Way to as many as 100 billion. Of course, there is a difference between being "in the habitable zone" and actually being habitable. Venus sits neatly within the sun's habitable zone, but runaway global warming (caused by a toxic carbon-dioxide-rich atmosphere 93 times denser than Earth's) has left the planet with a surface that can reach a toasty 860°F (460°C).

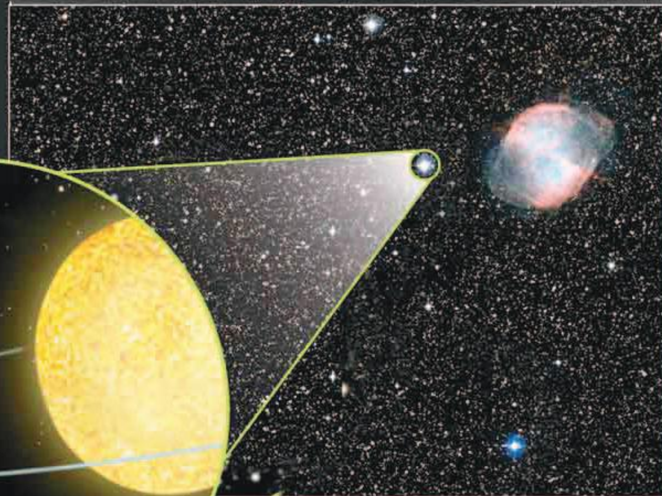


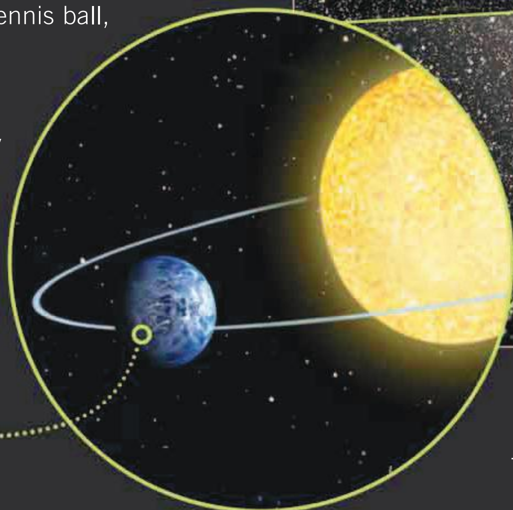
THE FIERCE WINDS ON HD 189733B CAN REACH TEMPERATURES OF 1,800°F (1,000°C)

HOW FAR AWAY?

At a mere 63 light-years away, HD 189733b is close to us in astronomical terms, but that is still quite a long way. One light-year is 5.88 trillion miles (9.46 trillion km), which means that Howlin' Dave is 370 trillion miles (596 trillion km) away. To get an idea of the distance, if we scaled down the galaxy so that the sun was reduced to the size of a tennis ball, Earth (shrunk to the size of a grain of sand) would be 26 ft (8 m) away. HD 189733b (shrunk to the size of a cherry pit) would be 19,803 miles (31,870 km) away—almost six times the distance from London to New York.

The area of sky covered in this image is roughly equivalent to the width of your little finger held at arm's length.

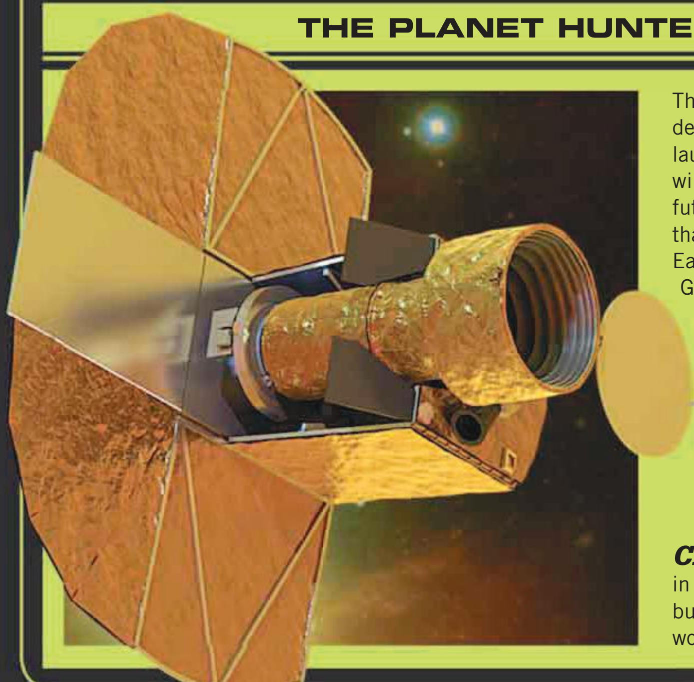




This artist's impression shows HD 189733b in orbit around its star.

Hubble's view: Shown here is Howlin' Dave's parent star, HD 189733, as seen by Hubble. That we know anything about a planet that orbits this tiny white speck is impressive—that we know so much is pretty awesome.

THE PLANET HUNTER



The European Space Agency (ESA) has just authorized the development of a new planet-hunting satellite mission. Due for launch in 2017, the CHaracterising ExOPlanet Satellite (CHEOPS) will be tasked with building a catalog of potential exoplanets for future life-detecting missions to target. Scientists have estimated that, in our galaxy alone, there are tens of billions of rocky, Earth-sized planets, many of which are lying inside their stars' Goldilocks zone—meaning the existence of life beyond Earth is not just possible, but that it might be inevitable and common. Whether any of that life is anything other than self-replicating slime is another matter, but, given the almost incomprehensible scale of the universe, the odds of there being a "proper ET" somewhere out there look pretty healthy.

CHEOPS: Due to begin operations in 2017, ESA's CHEOPS planet-hunter will build a catalog of potentially life-supporting worlds for future life-hunters to exploit.

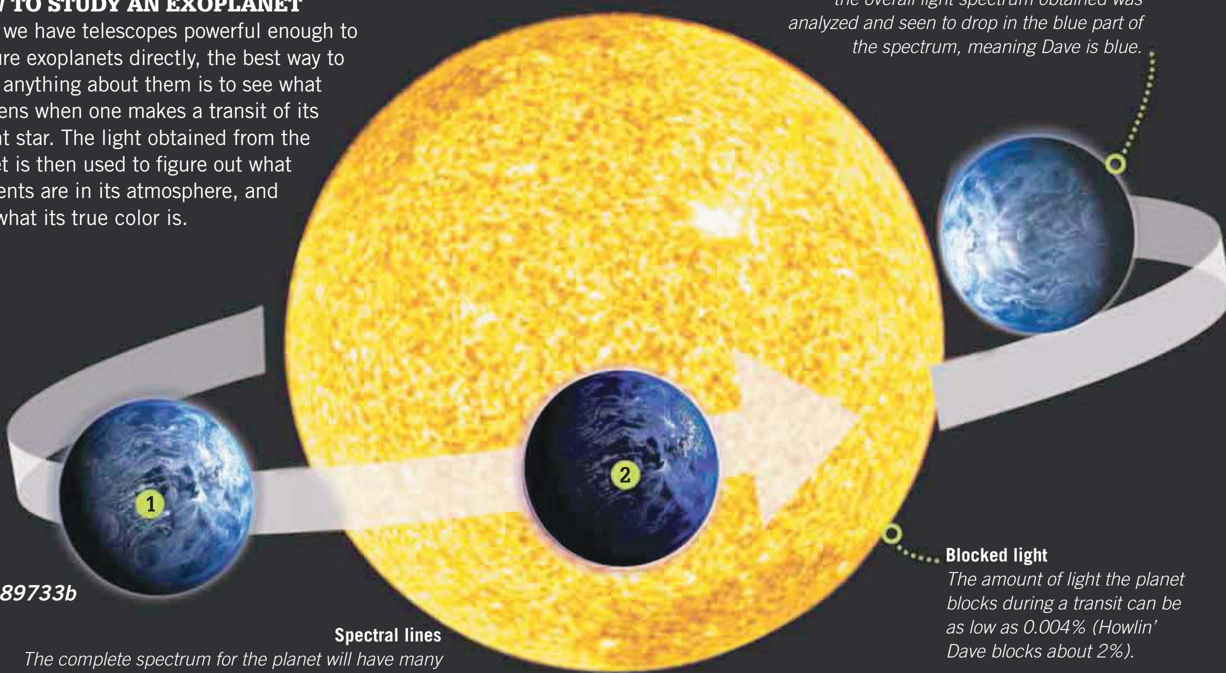
COLOR ANALYSIS

Every chemical element absorbs and emits certain frequencies of light. Splitting starlight into a spectrum reveals lines that correspond to the elements of which the star is made—like a chemical bar code. The same technique, called spectroscopy, can also be used, with appropriate cunning, to work out the composition of the atmosphere of an exoplanet, and sometimes even something about its surface and its true color.

THE NEXT GENERATION OF TELESCOPES WILL ALLOW ASTRONOMERS TO SEARCH EXOPLANET ATMOSPHERES FOR THE CHEMICAL SIGNATURES OF LIFE

HOW TO STUDY AN EXOPLANET

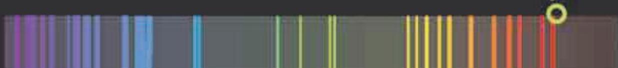
Until we have telescopes powerful enough to capture exoplanets directly, the best way to learn anything about them is to see what happens when one makes a transit of its parent star. The light obtained from the planet is then used to figure out what elements are in its atmosphere, and also what its true color is.



True color
When Howlin' Dave had passed behind his star, the overall light spectrum obtained was analyzed and seen to drop in the blue part of the spectrum, meaning Dave is blue.

Blocked light
The amount of light the planet blocks during a transit can be as low as 0.004% (Howlin' Dave blocks about 2%).

Spectral lines
The complete spectrum for the planet will have many spectral lines. By looking for each element's specific bar code within the spectrum (in this case oxygen), astronomers can identify the elements present.



Oxygen emission spectrum

Oxygen absorption spectrum

1 ***Emission***
When the planet is fully illuminated, elements in the surface and atmosphere reflect (emit) certain frequencies of light. By studying the reflected light, scientists can work out what elements are present on the planet. This is because each element has its own emission spectrum, which is like a bar code that spans the full length of the reflected light.

2 ***Absorption***
As the planet passes in front of the star, light from the star passes through the planet's atmosphere. By the time it has passed through, some of the light has been absorbed by the elements in the atmosphere. By looking at the absorption spectra from various elements, we can determine which elements did the absorbing.

THE SPACE ROCK THAT "KILLED" PLUTO

BACK IN 2006, the world of astronomy was **torn asunder** by the controversial decision to **demote Pluto.** Overnight, the planet was stripped of its status, and became a dwarf planet. Many astronomers, who felt the decision had been usurped by a minority, were furious (as were countless students who had labored to memorize the planetary mnemonic "My Very Educated Mother Just Served Us Nine Pizzas").

The trouble started back in 2005, when astronomers discovered another world hiding in the darkness of the Kuiper Belt that seemed to be **even bigger than Pluto.** The world was named Eris—after the Greek goddess of chaos and strife—and it has been living up to its name ever since.

Its discovery sparked a debate about the definition of a planet that could have seen the number of "planets" in our solar system swell to 14 or more, but instead, in 2006, it saw Pluto being chopped off the end of the planetary roll call. **The arguments have been raging ever since.**

Then, in 2010, astronomers measured Eris's girth with greater accuracy and, yet again, it caused trouble. Eris, as it turns out, is actually **significantly smaller than was first estimated**—small enough to pass the Kuiper Belt crown back to Pluto.

The difference is tiny: Eris is a mere 2.5 miles (4 km) narrower than Pluto. But it was enough for the "promote Pluto" trumpets to start sounding once again. Unfortunately, the planet's demotion was not based on its Kuiper ranking alone, and all the other reasons for its fall from grace still stand—**its wacky orbit** and its tiny size relative to "real" planets.

Also, given the margin of error that comes with measuring a tiny, dark object 39 times farther from the sun than Earth, its size ranking could still change. Intriguingly, the new measurements have shown Eris to be 25 percent more massive (the term "weight" does not apply in space) than Pluto—**implying that Eris contains more rock than icy Pluto.**

So, until something changes, the new mnemonic in Pluto's absence is "Mean Very Evil Men Just Shortened Up Nature."

THE DWARF PLANET SEDNA IS SO FAR AWAY THAT IT TAKES 11,400 YEARS TO MAKE ONE ORBIT OF THE SUN

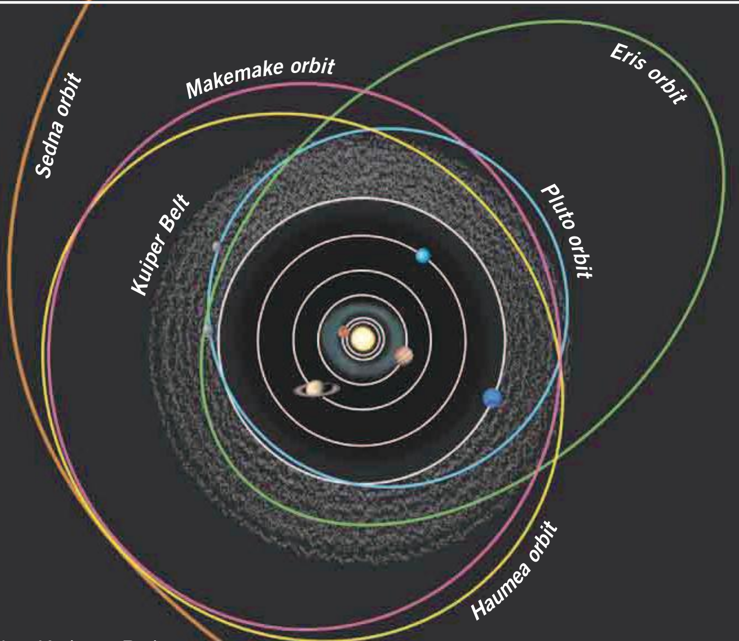
Eris:
The architect of Pluto's downfall, Eris, looks back on the distant sun in this artist's impression.

NEW HORIZONS

After nearly ten years and 3 billion miles (5 billion km), NASA's *New Horizons* spacecraft is due to fly past Pluto and its moons in July 2015. It will provide us with our first close-up study of Pluto and will, finally, determine its size once and for all. It will then continue on into the Kuiper Belt.

Launched: 1997
Weight: 1,025 lb (465 kg)
Width: 8.2 ft (2.5 m)
Power: Nuclear (radioisotope thermoelectric generator)
Max speed: 45,000 mph (72,420 km/h)

MEET THE DWARF PLANETS



1. PLUTO
Discovered: 1930
Diameter: 1,457 miles (2,344 km)
Pluto is named after the ancient Roman god who ruled the underworld.

2. ERIS
Discovered: 2005
Diameter: 1,454 miles (2,340 km)
Eris is the ancient Greek goddess of chaos, strife, and discord.

3. HAUMEA
Discovered: 2003
Diameter: 1,218 miles (1,960 km) at its widest point
This egg-shaped rock is named after a Hawaiian fertility god.

4. MAKEMAKE
Discovered: 2005
Diameter: approx. 1,180 miles (1,900 km)
The Polynesian god of fertility gives this rock its name.

5. SEDNA
Discovered: 2004
Diameter: 733–1,118 miles (1,180–1,800 km)
The Inuit goddess of the sea gives this dwarf planet its name.

The Kuiper Belt is often called our solar system's final frontier. It is a disk-shaped region of icy debris about 3.7–4.6 million miles (6–7.5 billion km) from the sun. Over 1,000 Kuiper Belt objects have been discovered in the belt, almost all of them since 1992.

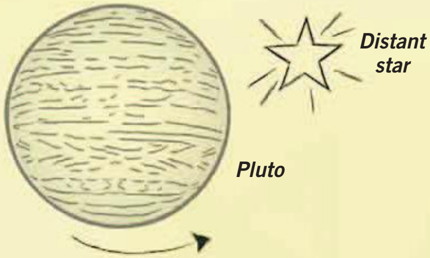
Sedna's orbit makes it one of the most distant objects in the solar system

The unusual suspects: Thousands of rocks, one lineup, no planets.

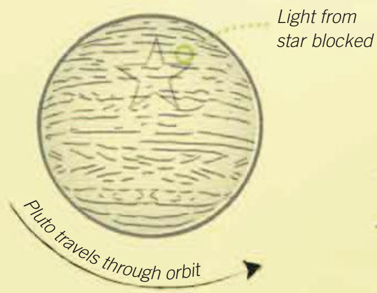
MEASURING SOMETHING YOU CAN BARELY SEE

In the past few years, new data seems to have revealed that Eris might actually be smaller than Pluto after all. But is it really? And how do we know? Let's investigate!

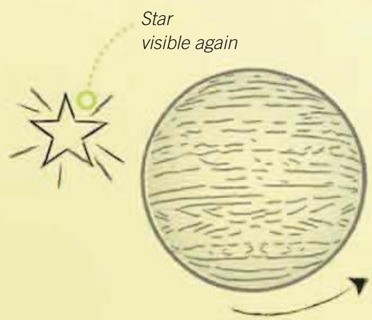
HOW HAS ERIS SHRUNK?
It has not—its size was just overestimated. The first measurements of Eris's size were based on how bright it appeared and the amount of light it reflects. This gave a diameter of about 1,490 miles (2,400 km)—bigger than Pluto.



1 ***Distant star***
Astronomers look for a distant star on the far side of Pluto.



2 ***Blocking light***
As Pluto moves through its orbit, it crosses the star, blocking its light.

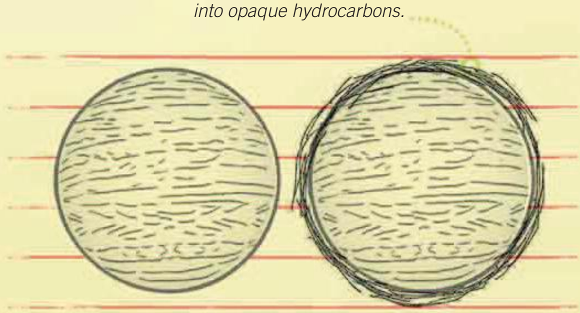


3 ***Diameter measured***
By measuring how long it takes for the star to reappear, astronomers can calculate Pluto's diameter.

SO WHAT HAPPENED?
Recently astronomers had a chance to measure a stellar occultation (above), which is much more accurate. Astronomers need to measure at least two instances of stellar occultation, from different locations, to accurately gauge an object's size. Using this method, the new measurement for Eris is a far-smaller diameter of about 1,454 miles (2,340 km).

SO ERIS IS DEFINITELY SMALLER THAN PLUTO?
Erm... no. Even though the generally accepted measurement for Pluto is 1,490 miles (2,400 km), this is far from definitive. The trouble with using the occultation method is that Pluto has a light atmosphere, which is enough to mess around with occultation measurements. Pluto's atmosphere therefore makes the planet appear bigger than it is (since an occultation measurement relies on the amount of light being blocked), so the information we have is probably misleading. Dang!

Atmospheric methane
Sunlight causes the methane in Pluto's atmosphere to decompose into opaque hydrocarbons.



Without opaque atmosphere ***With opaque atmosphere***

THE FIRST HUMAN IN SPACE

PIONEER 10: THE LITTLE SPACECRAFT THAT COULD

ENGAGE WARP DRIVE!

GRAVITY LENSING TO SEE THE COSMOS

MAPPING THE MILKY WAY

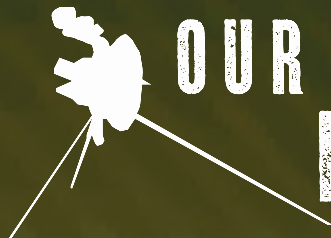
IS THERE LIFE ON MARS?

COLONIZING MARS

SPACE: THE FATAL FRONTIER

ESA'S ROSETTA COMET CHASER

VOYAGER: OUR DISTANT EMISSARY



TO BOLDLY GO

LOOKING BEYOND MARS FOR LIFE

DETECTING KILLER ASTEROIDS

A WEBB TO CATCH THE OLDEST STARS

THE FIRST **HUMAN IN SPACE**

AT 6:07 A.M. ON APRIL 12, 1961, Yuri Gagarin, a 26-year-old astronaut from the USSR, left the surface of Earth and traveled into space—**becoming the first human to escape the confines of our planet and extend humankind's reach into the heavens.**

The announcement left the US space program reeling. The USSR's **"Space Race"** rival was due to launch its first human into space a few weeks later, but their astronaut, Alan Shepard, had to settle for being the first American in space.

Cosmonaut Yuri Gagarin in the cockpit of his Vostok 1 *spaceship*

"CIRCLING THE EARTH IN MY ORBITAL SPACESHIP, I MARVELLED AT THE BEAUTY OF OUR PLANET... LET US SAFEGUARD AND ENHANCE THIS BEAUTY, NOT DESTROY IT"

YURI GAGARIN

Vostok-K: Gagarin's *Vostok 1* craft was launched into orbit on a Vostok-K rocket. The Vostok-K had failed on its first launch just four months before Gagarin's mission.

The launch into the unknown from Baikonur, Kazakhstan

Gagarin's five-ton spaceship, *Vostok 1,* was **carried into space on board a converted ballistic missile,** which propelled the plucky space navigator to speeds in excess of 17,000 mph (27,000 km/h) from a launch in a remote region of Kazakhstan.

At the heady altitude of 203 miles (327 km), his craft then proceeded to orbit Earth—a journey that took just 89 minutes to complete. **A mere 108 minutes after leaving the planet in obscurity, Gagarin returned safely to Earth as a national hero** and an international celebrity.

Unknown to Gagarin, during the launch, the second stage of the rocket burned for longer than planned—**thrusting the *Vostok 1* orbiter into a higher orbit than was intended.** This meant that, had his braking engine failed, it would have taken Gagarin's craft 15 days to fall back to Earth, as there was no backup. This would have been five days longer than his food and life-support system would have allowed.

Nor was the return to Earth as smooth as intended. During reentry, a valve within the braking engine failed to close completely, which let some fuel escape—**causing the engine to shut down a second too early.** Gases were vented that caused the craft to enter into a violent spin. Also, the technical module failed to separate completely from the reentry section.

Fortunately, the spin subsided and the heat created during reentry burned through the cable that still connected the technical module—**allowing Gagarin to jettison the craft's main hatch and eject from the vehicle** at an altitude of 4.3 miles (7 km), and return safely to terra firma.

A VOYAGE AROUND THE WORLD...

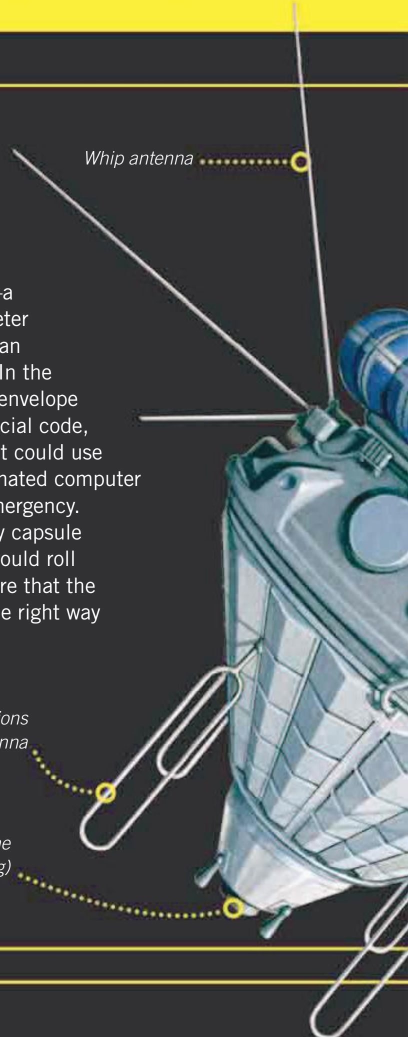
Yuri Gagarin was selected from an elite group of Soviet pilots, known as the “Sochi Six,” to become the first human to be launched into space and orbit Earth. Despite his piloting pedigree, Gagarin was really just a passenger on board the *Vostok 1* spacecraft—because of the uncertainty about how spaceflight would affect him, the craft was controlled remotely from Earth. His flight lasted just 108 minutes but, in that time, he orbited the planet, saw the sun rise and set, and, most importantly, landed back on Earth alive and well.

LAIKA

In November 1957, a stray dog named Laika became the first living thing to be sent into space. Sent by the USSR, the plucky hound safely orbited Earth for seven days, proving that it was possible for a creature to survive a launch and live in space. Unfortunately, there was no plan to bring her back and, after seven days, Laika was put to sleep before her oxygen supply ran out.

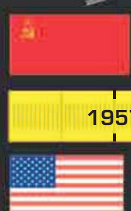
VOSTOK 1

The craft was made up of two modules—a 7.5 ft (2.3 m) diameter reentry capsule and an equipment module. In the cabin, there was an envelope that contained a special code, which the cosmonaut could use to override the automated computer system in case of emergency. The spherical reentry capsule was weighted so it would roll into position to ensure that the craft was pointing the right way during reentry.



SPACE RACE

On October 4, 1957, the world (and the US in particular) was stunned by the news that the USSR had successfully launched the world’s first orbiting satellite, *Sputnik 1*, into space. The Space Race had begun. In the early years, the race was the USSR’s to lose—after *Sputnik*, it put the first living creature into Earth orbit (Laika) and then the first human (Gagarin). The US, determined that it would achieve the ultimate first, threw everything at the race to put the first man on the moon...



1957

October 4
USSR launches the first space satellite, *Sputnik 1*.

November 3
USSR launches Laika into orbit on board *Sputnik 2*.

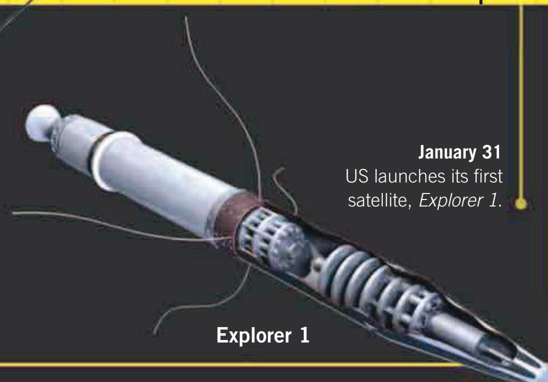
1958

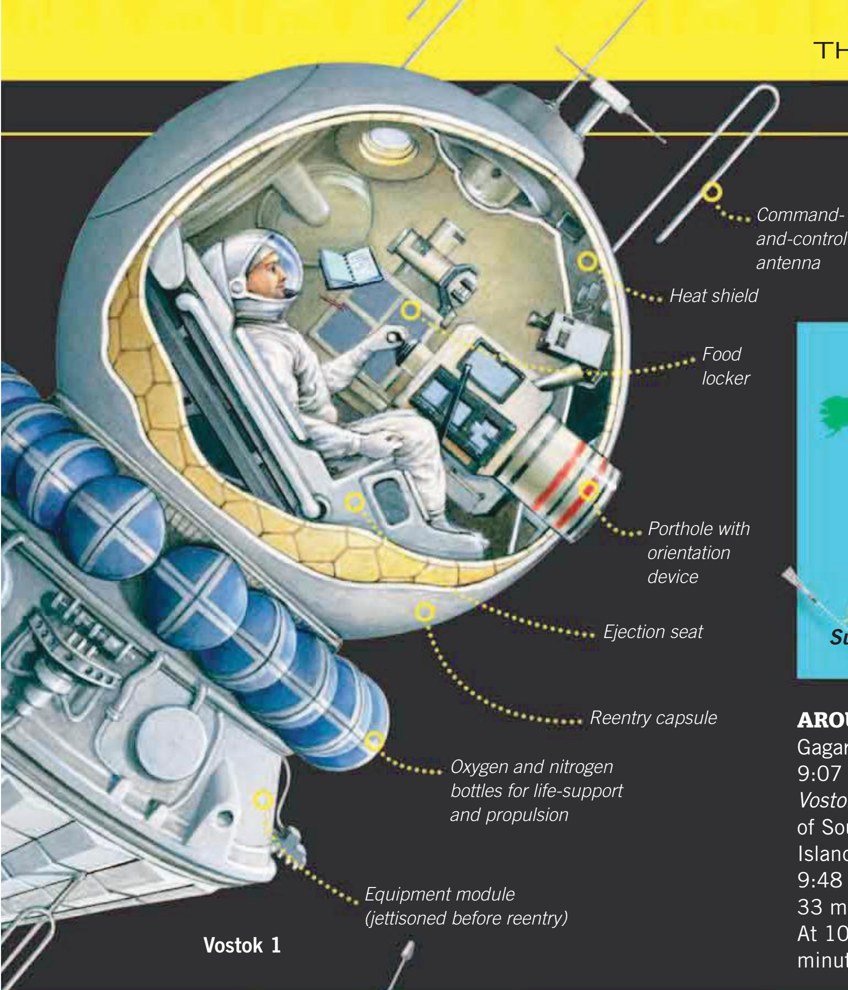
January 31
US launches its first satellite, *Explorer 1*.

March 5
Explorer 2 fails during launch.

March 17
The first solar-powered satellite, *Vanguard 1*, is launched.

May 15
Sputnik 3 is launched.





Vostok 1

"THE EARTH IS BLUE. HOW WONDERFUL. IT IS AMAZING"

YURI GAGARIN

AROUND THE WORLD IN 108 MINUTES

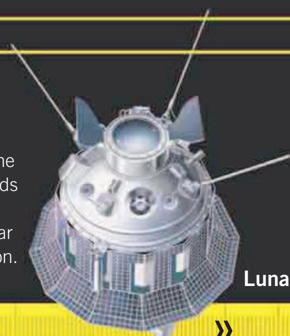
Gagarin was launched from Baikonur, Kazakhstan, at 9:07 a.m. local time, and reached orbit ten minutes later. *Vostok 1* passed over the Pacific Ocean to the southern tip of South America and, as Gagarin approached the Hawaiian Islands, he watched the sun set. He crossed the equator at 9:48 a.m. and then, as he passed over the South Atlantic, just 33 minutes after he watched it set, he watched the sun rise. At 10:25 a.m., *Vostok 1* fired its reentry engines and, ten minutes later, the craft began its descent back to Earth.

January 2 The first man-made object to orbit the sun, *Luna 1*, is launched.

Luna 2

September 12 *Luna 2* is launched. It hits the moon on September 13, becoming the first man-made object to do so.

October 4 *Luna 3* orbits the moon, and sends back the first images of the far side of the moon.



Luna 3

April 12 Yuri Gagarin becomes the first man in space and the first to orbit Earth.

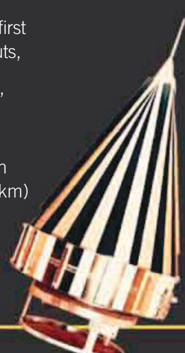
1959 » 1960 » 1961 »

October 1 The National Aeronautics and Space Administration (NASA) is formed.

October 11 NASA's first spacecraft, *Pioneer 1*, is launched.

March 3 *Pioneer 4* passes within 37,500 miles (60,000 km) of the moon's surface.

April 2 NASA selects its first group of astronauts, dubbed the "Mercury Seven."



Pioneer 4

April 1 The first successful weather satellite, *Tiros 1*, is launched.

August 18 The first camera-equipped spy satellite, *Discoverer XIV*, is launched.

November 8 John F. Kennedy is elected as the 35th president of the United States, and sets NASA the goal of landing a man on the moon before 1970, a goal achieved in 1969.

PIONEER 10: THE LITTLE SPACECRAFT THAT COULD

Helium vector magnetometer
Measures and maps Jupiter's magnetic field.

UNTIL ABOUT 40 YEARS AGO, the farthest any man-made object had ventured into space was Mars, but it was clear that **going farther would present a series of challenges.** Beyond Mars, there lay an 110 million mile (180 million km) wide barrier of rocks of all sizes, barreling through space at tens of thousands of miles per hour—called the asteroid belt. Any craft that ventured in could be damaged by huge rocks, or possibly be **pelted with tiny rocks that could wreck its instruments.**

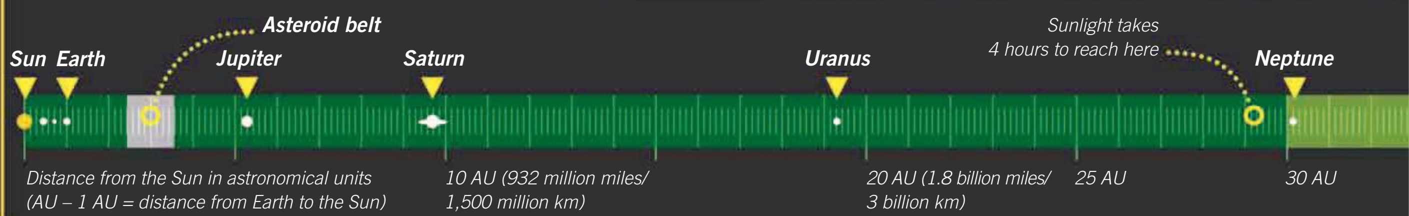
Then, a little over 42 years ago, NASA put the theory to the test. Launched on March 2, 1972, *Pioneer 10* left Earth on a mission to study Jupiter. To reach the planet, it would have to **traverse the asteroid belt.** A few months later, *Pioneer 10* entered the belt but, instead of being smashed to a metallic pulp, it sailed through without a hitch. It turned out that, far from being a densely packed highway of rocky death, the asteroid belt was mostly empty space. The solar system was now ours to explore.

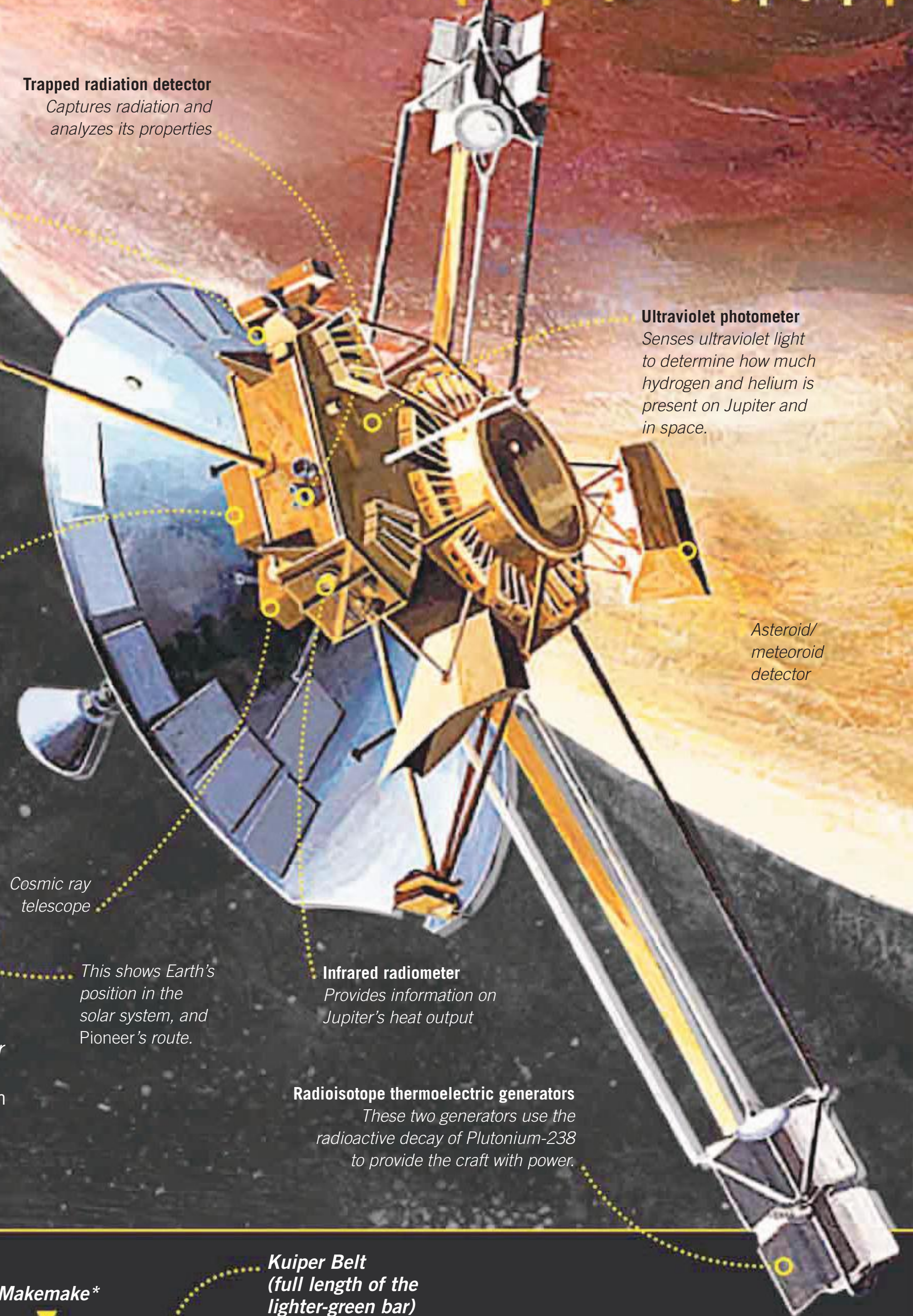
Pioneer 10 went on to become the **first man-made object to study Jupiter and the first to cross the orbits of Saturn, Neptune, Uranus, and Pluto.** Long after its intended 21-month lifespan had been exceeded, *Pioneer 10* kept on trucking until 2003, when, at the outer limits of our solar system and 7.5 billion miles (12.2 billion km) from home, it sent its last transmission. *Pioneer 10* (and its sister craft, *Pioneer 11*, launched in 1973 to visit Saturn) was one of the **great space adventures,** and it paved the way for many more.

IT WILL TAKE MORE THAN 2 MILLION YEARS FOR *PIONEER 10* TO PASS ALDEBARAN, THE NEAREST STAR ON ITS TRAJECTORY

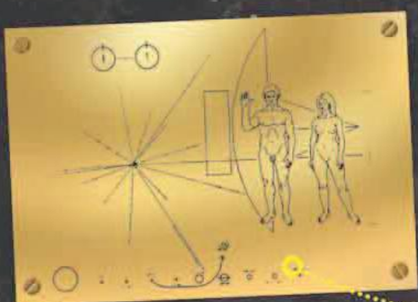
BUSTING OUT!

Until *Pioneer 10*, the farthest mankind had extended his reach was Mars. The *Pioneer* probes went much, much farther...





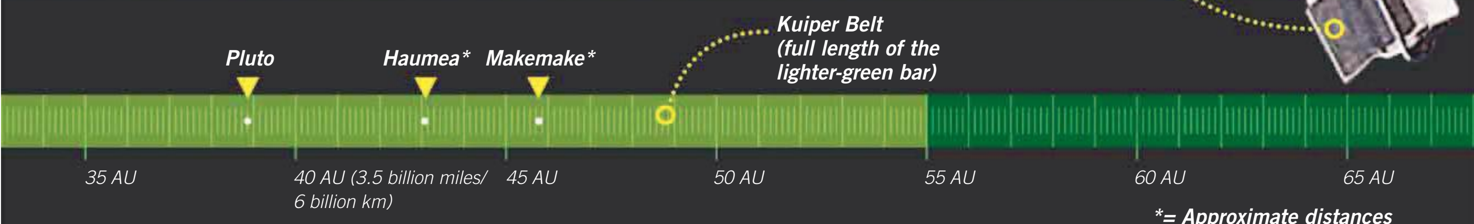
PIONEER
Launched ***Pioneer 10***: March 1972 ***Pioneer 11***: April 1973
Mass (both craft): 571 lb (259 kg)
Antenna (both craft): 9 ft (2.75 m)



This shows Earth's position in the solar system, and Pioneer's route.

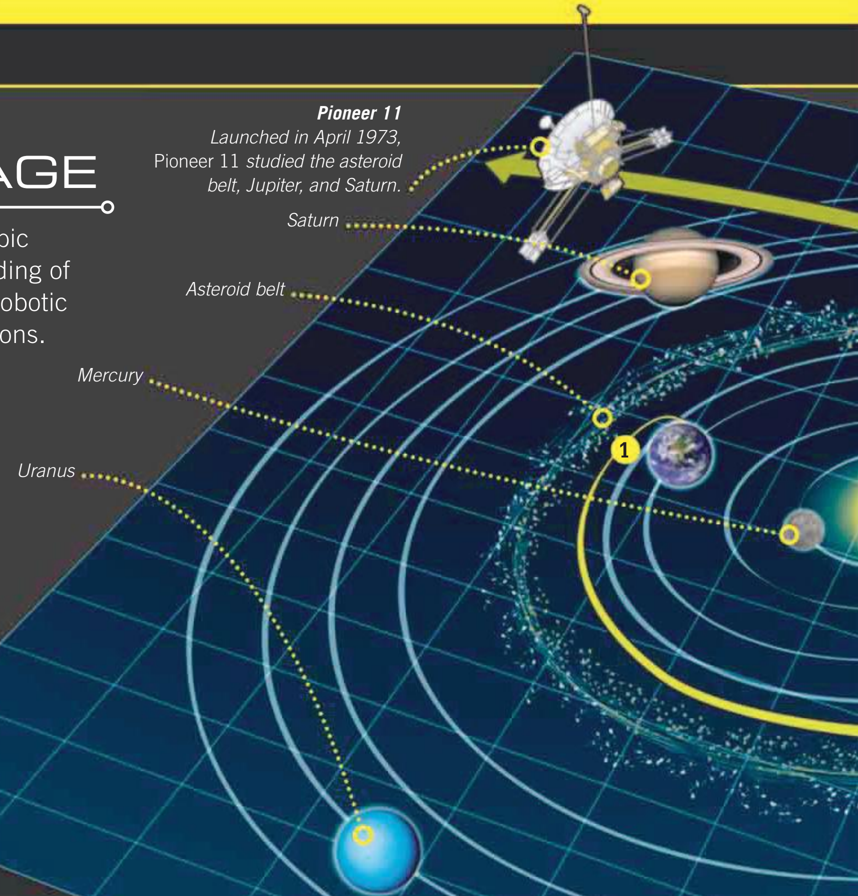
The* Pioneer *plaque:

Gold-anodized aluminum plates (above) were fixed to both *Pioneer 10* and *Pioneer 11*. They were designed to communicate the location and appearance of the human race as well as information about the spacecrafts' origins—in case the probes were intercepted by extraterrestrials.



PIONEER'S FANTASTIC VOYAGE

The voyage of the *Pioneer* probes was a truly epic achievement that revolutionized our understanding of the solar system and paved the way for future robotic explorers, such as NASA's iconic *Voyager* missions.



1 *Launch from Earth*

Pioneer 10 was launched on a three-stage Atlas-Centaur rocket from Florida in March 1972. The craft reached 32,400 mph (52,140 km/h), making it the fastest man-made object to leave Earth. At this speed, *Pioneer* could pass the Moon in 11 hours and cross the orbit of Mars in just 12 weeks.

2 *Asteroid belt*

Pioneer 10 entered the asteroid belt in July 1972. At the time, it was thought that the belt was densely populated with asteroids cannoning through space at 45,000 mph (72,400 km/h). Scientists were worried that *Pioneer* would be unable to navigate safely through and, like a blind hedgehog on a highway, would be smashed to smithereens.

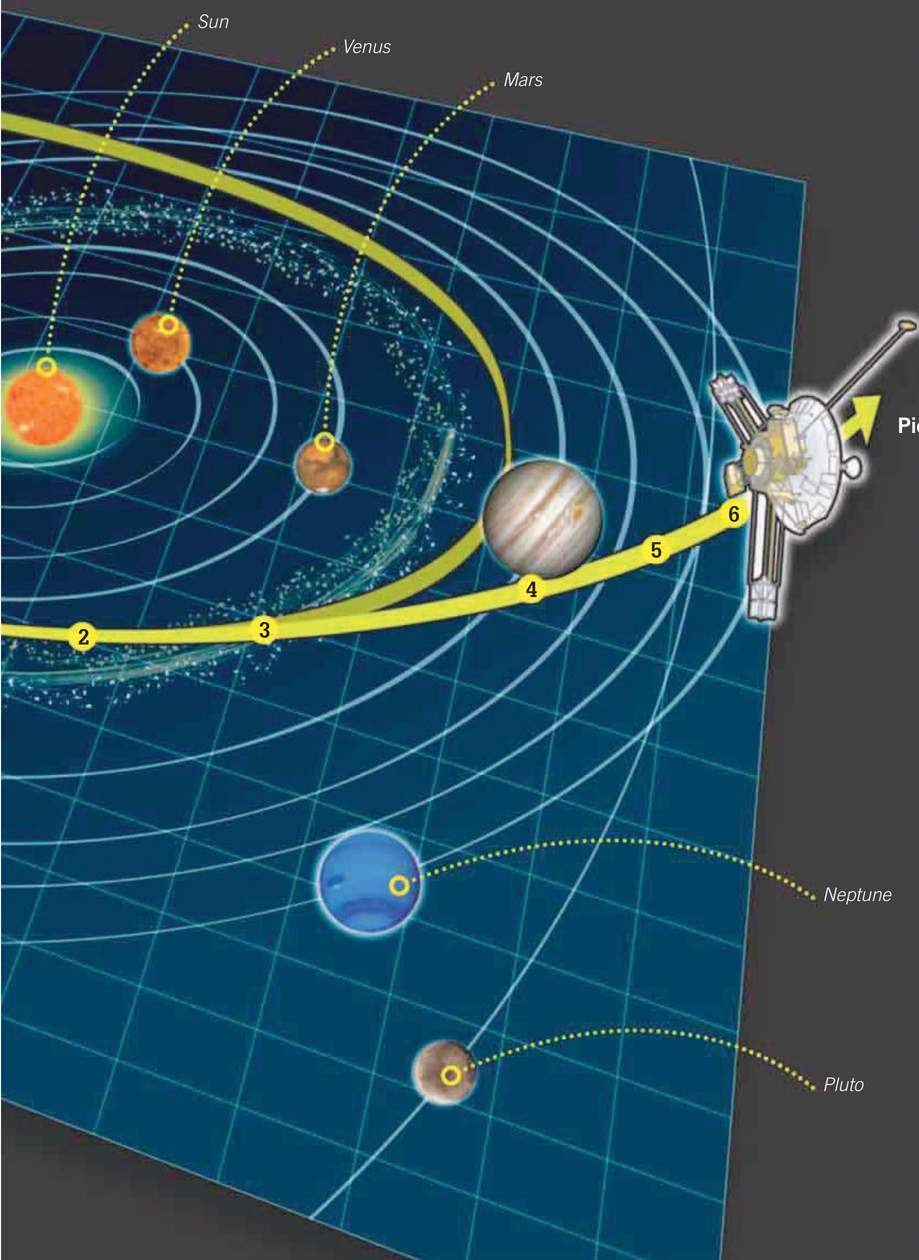
3 *Leaving the asteroid belt*

Pioneer passed safely out of the asteroid belt in February 1973. It had shown the belt to be actually quite sparsely populated. The revelation opened the door for future deep-space exploration.

4 *Jupiter*

In December 1973, *Pioneer 10* passed by Jupiter, becoming the first craft to photograph and make direct observations of the red-eyed gas giant. *Pioneer 10* charted Jupiter's intense radiation belts, studied its magnetic field, and confirmed the fact that Jupiter radiated more heat than it absorbed from the sun.

Pioneer 10's *image of Jupiter:* At its closest approach, the craft passed within 82,177 miles (132,252 km) of the planet's outer atmosphere. Under the pull of Jupiter's gravity, *Pioneer 10* was accelerated to 82,000 mph (132,000 km/h).

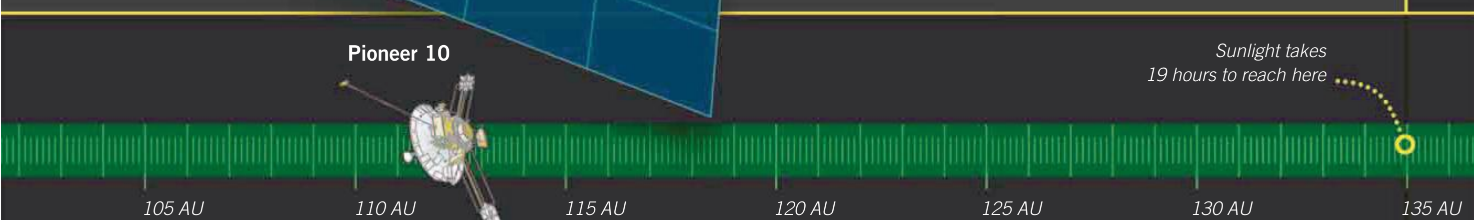


5 ***Pluto***
Pioneer 10 became the first man-made object to pass the orbit of Pluto when it traveled past in April 1983. Pluto's irregular orbit meant it was closer to the sun than Neptune in 1983.

6 ***Neptune***
The craft crossed the orbit of Neptune in June 1983. Soon after, *Pioneer 10* became the first man-made object to depart the inner solar system.

MISSION FACTS

- *Pioneer 10* continued to take readings of the outer regions of the solar system until its science mission officially ended on March 31, 1997.
- On April 27, 2002, *Pioneer 10* sent its last decipherable signal.
- By April 2015, based on its last-known speed, *Pioneer 10* reached 112 AU, and *Pioneer 11* reached 92 AU.
- Each year, both *Pioneer* craft travel about 3,100 miles (5,000 km) less than scientists calculate that they should. With no air to slow the craft down (space, after all, is a vacuum), scientists have struggled to come up with an explanation for this anomaly. Proposed solutions have varied from the mundane—gas leakage from the craft or heat radiation—to the much more dramatic suggestion that this reveals flaws in our understanding of gravitational physics.

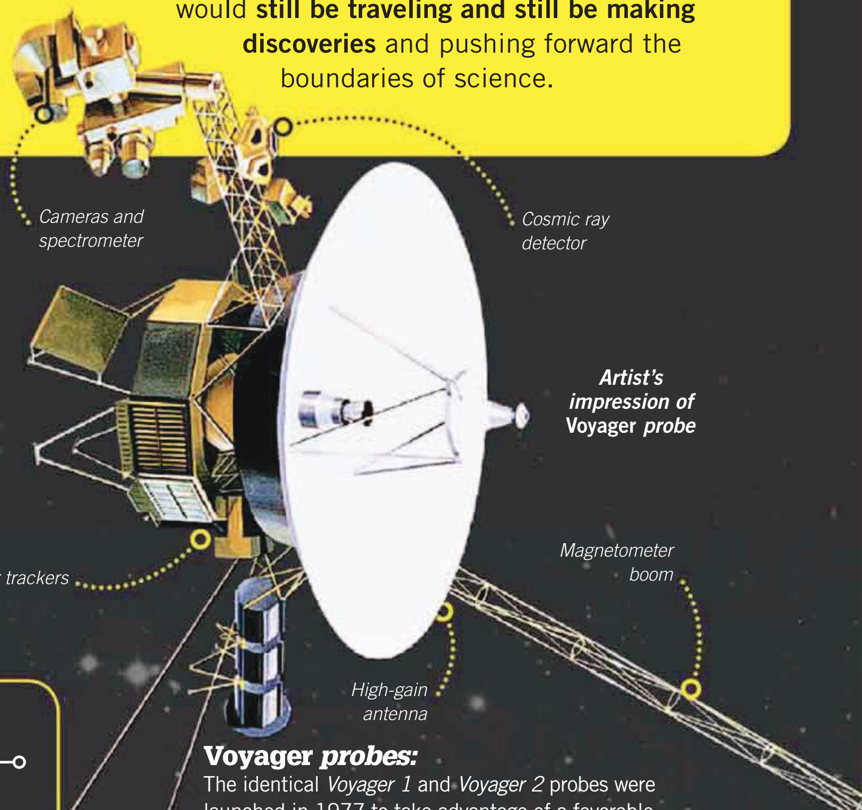


***= Approximate distances**

VOYAGER: OUR DISTANT EMISSARY

IN THE LATE 1970S, an extremely rare event took place: the orbits of the outer planets of the solar system—Jupiter, Saturn, Uranus, and Pluto—aligned in such a way that it would be possible for a pair of spacecraft to visit and study them. To take advantage of this **once-in-every-175-years opportunity,** NASA launched the twin *Voyager* probes on a "grand tour of the planets" in 1977.

No one could have guessed that, almost four decades later, the (by then) rickety old probes would **still be traveling and still be making discoveries** and pushing forward the boundaries of science.



Artist's impression of* Voyager *probe

VOYAGER

Launched
Voyager 1: September 5, 1977
Voyager 2: August 20, 1977

Mass: 1,600 lb (721.9 kg)

Current speed
Voyager 1: 38,000 mph (62,000 km/h)
Voyager 2: 34,500 mph (55,500 km/h)

Distance from Earth in 2015
Voyager 1: 12 billion miles (19.3 billion km)
Voyager 2: 9.9 billion miles (15.9 billion km)

Voyager *probes:*
The identical *Voyager 1* and *Voyager 2* probes were launched in 1977 to take advantage of a favorable alignment of the planets. They were designated to study the planetary systems of Jupiter and Saturn but, four decades later, they are still traveling through space.

TRAVELING FAR

It may not be obvious from all those artist's impressions of closely packed planets, but the solar system is a vast place, and since 1977 the *Voyager* probes have traveled a long, long way...

Now, nearly four decades and about 12 billion miles (19.3 billion km) later, *Voyager 1* is leaving our solar system behind and **passing into the dark, unexplored expanse of interstellar space.**

For some years now, data beamed back from *Voyager 1* (data that takes more than 16 hours to reach Earth) has hinted that the venerable machine **might finally be passing the outer limits of our solar system.** But things are not quite what scientists expected them to be.

A SIGNAL TRAVELING AT THE SPEED OF LIGHT TAKES ABOUT 13 HOURS ONE WAY TO REACH *VOYAGER 2*, AND 16 HOURS TO REACH *VOYAGER 1*

Scientists define the limits of our solar system as the point at which the solar wind (a stream of charged particles flowing out from the sun at supersonic speeds) runs out of steam—in other words, **the solar system ends where the sun's influence ends.** While it has the strength, the solar wind pushes against the gas and dust of interstellar space and inflates a giant "bubble" of charged particles and magnetic fields called the heliosphere. At the edge of this bubble, scientists had expected to find a pressure boundary called the heliopause, where the solar wind smashed into the interstellar medium like a bucket of water thrown against a wall.

In 2010, *Voyager 1* seemed to reach this point, but the craft's instruments indicated that the wind had just stopped dead—instead of a maelstrom of clashing solar particles, there was **just a stagnant pool of stationary particles.**

This countered everything that existing models of the solar system had predicted. This led scientists to reassess how they think about the heliosphere, and **researchers suggested that *Voyager 1* was not as close to the interstellar boundary as suspected.**

Analysis of more data collected in 2010 found further anomalies at the edge of the heliosphere. Scientists had expected that, as solar wind slowed, **the heliosphere's magnetic field would fluctuate** and scramble any high-energy cosmic rays trying to pass through it. But as the magnetic field became more chaotic, the number of high-energy particles actually increased. Researchers then suggested that the magnetic field may actually be acting as a sort of particle accelerator that picks up particles from within the heliopause and whips them up into a high-energy frenzy.

Around 2012, the craft began to detect a dramatic drop in the number of solar particles it was finding and a huge increase in the amount of cosmic radiation, which suggested that the craft was about to become the first man-made object to leave the solar system—**as it successfully did in 2013!**

VOYAGER DISKS

Both of the *Voyager* craft carry identical 12-inch gold-plated disks that include:

- 117 pictures of Earth, the solar system, and various plants and animals.
- Greetings in 54 languages—including one in Mandarin, saying, "Hope everyone's well. We are thinking about you all. Please come here to visit when you have time"—and a brief hello from some humpback whales.

THE VOYAGE FROM HOME...

A rare planetary alignment made the *Voyager* probes' "grand tour" possible, but no one could have imagined how far they would travel.

1 *Launch from Earth*
Voyager 2 is launched in August 1977—with *Voyager 1* following a few weeks later in September.

2 *Say cheese!*
Voyager 1 takes the first spacecraft photograph of the moon and Earth in a single frame in September 1977.

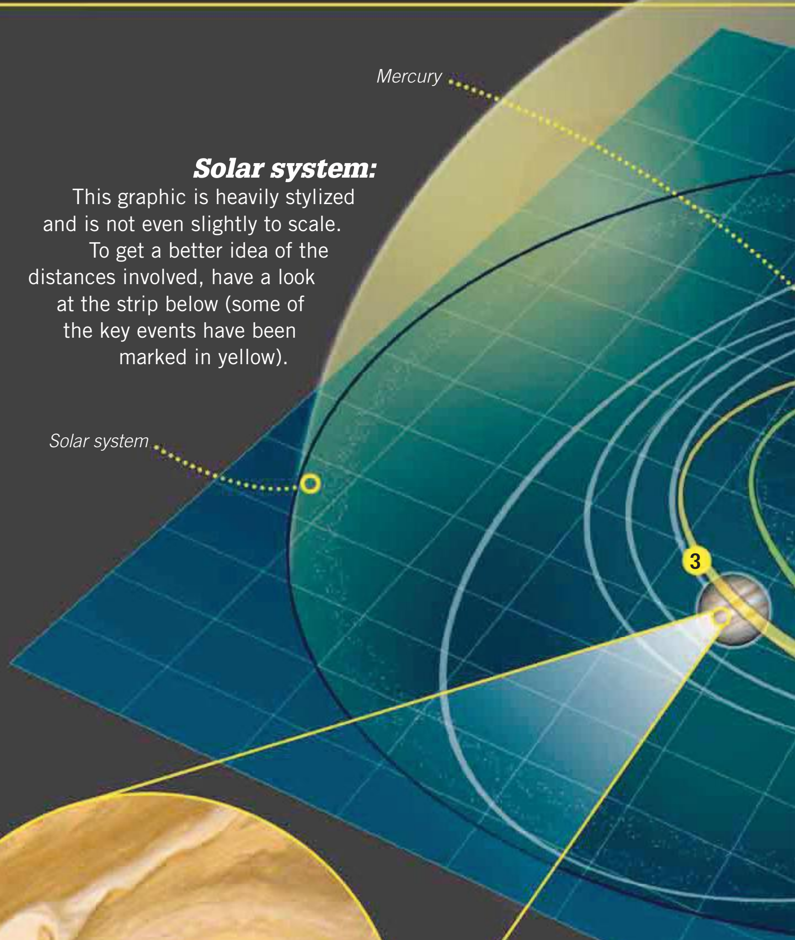
3 *Jupiter*
Voyager 1 makes its closest approach to Jupiter in March 1979, followed by *Voyager 2* in July.

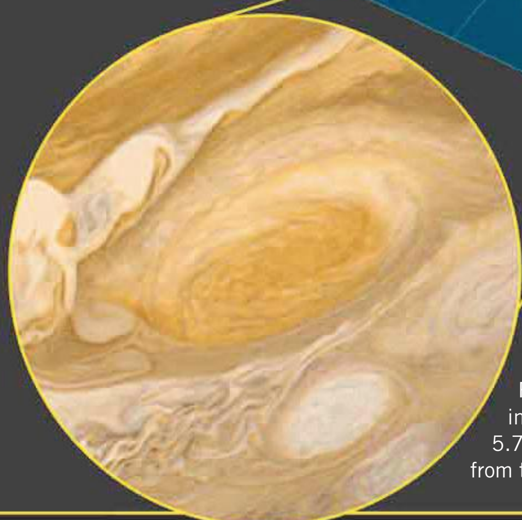
4 *Saturn*
Voyager 1 flies by Saturn in November 1980, with *Voyager 2* chugging past in August the following year.

5 *Uranus*
Voyager 2 becomes the first spacecraft to visit Uranus in January 1986.

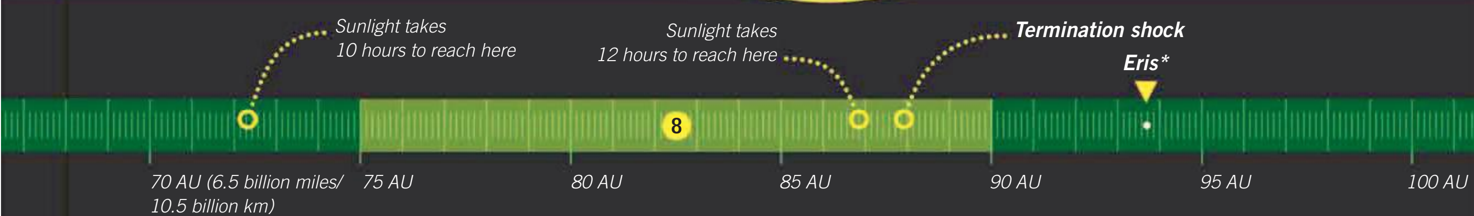
6 *Neptune*
Voyager 2 becomes the first spacecraft to visit Neptune in August 1989.

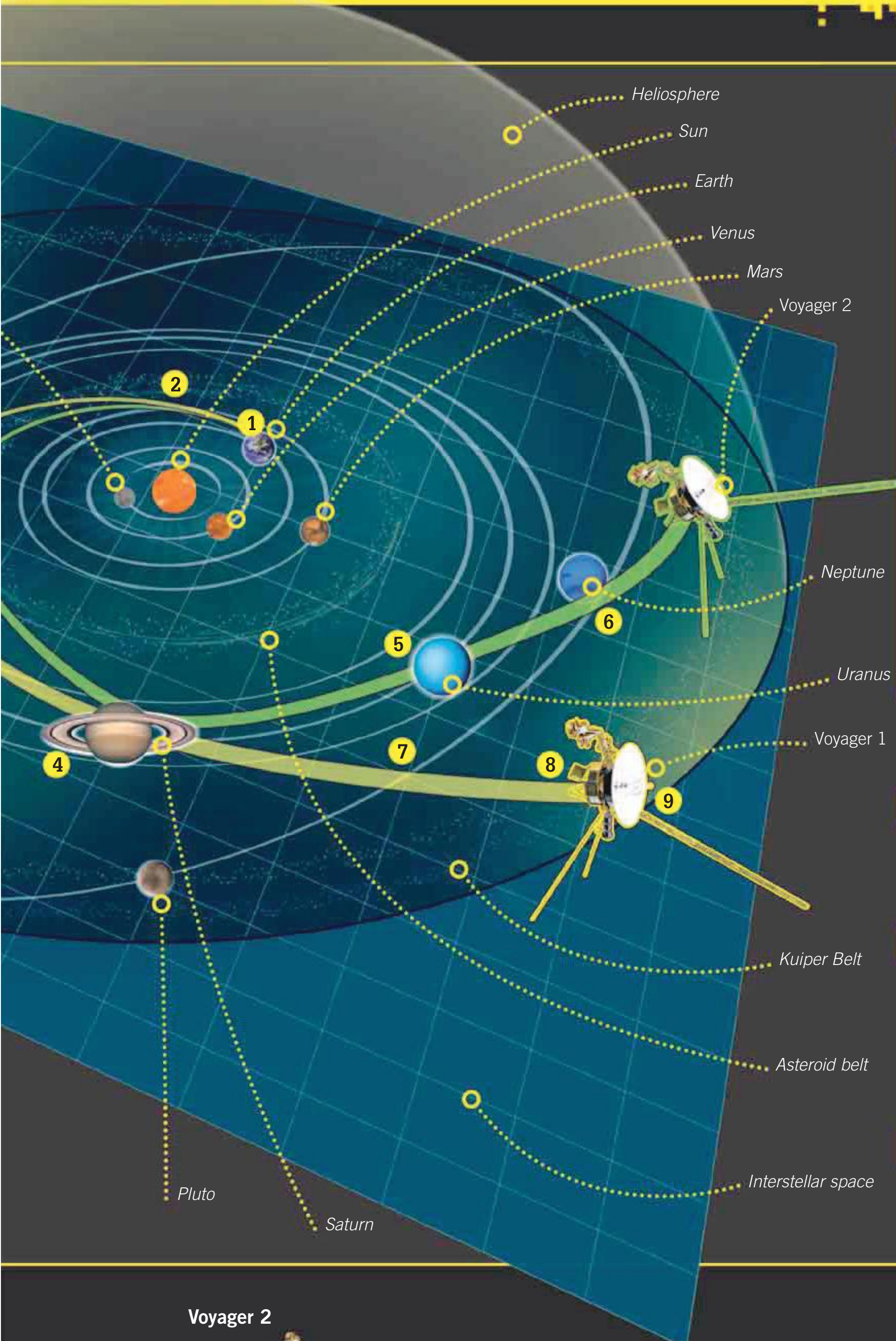
Solar system:
This graphic is heavily stylized and is not even slightly to scale. To get a better idea of the distances involved, have a look at the strip below (some of the key events have been marked in yellow).





Jupiter:
This image of Jupiter's Great Red Spot was taken by *Voyager 1* in 1979, when the spacecraft was 5.7 million miles (9.2 million km) from the gas giant.





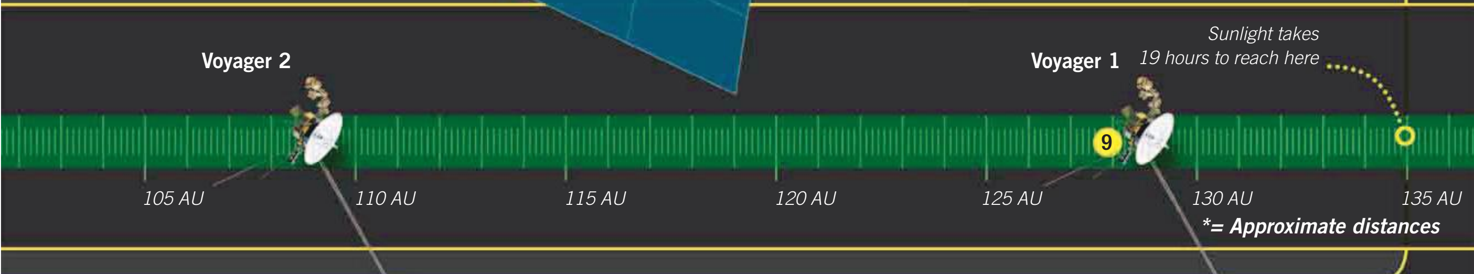
LOOKING BACK

In 1990, NASA turned *Voyager 1*'s camera back toward Earth. From a distance of 3.7 billion miles (6 billion km), Earth was revealed as just a "pale blue dot"—"a mote of dust suspended on a sunbeam," as American scientist Carl Sagan described it.

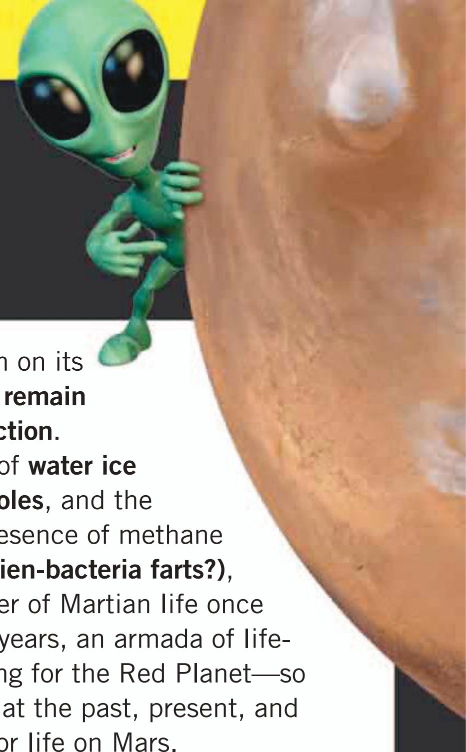
7 ***Pale Blue Dot image***
At about 3.7 billion miles (6 billion km) from Earth, *Voyager 1* snaps what is often called the "Pale Blue Dot" image.

8 ***Termination shock***
Voyager 1 crosses the termination shock (the region of space where the solar wind drops from supersonic speeds and interacts with interstellar space) in December 2004. *Voyager 2* crosses it almost three years later, in September 2007.

9 ***Bye-bye, Voyager!***
Voyager 1 finally passes through the heliosphere and leaves the solar system on September 12, 2013.



IS THERE LIFE ON MARS?



AN ITALIAN ASTRONOMER turned his telescope toward Mars in 1877, and what he saw prompted speculation about **advanced Martian civilizations** that lasted almost a century. It was not until NASA's *Mariner 6* and *7* probes traveled to the Red Planet in 1969 that Mars was revealed to be the desolate "almost-Earth" we know today.

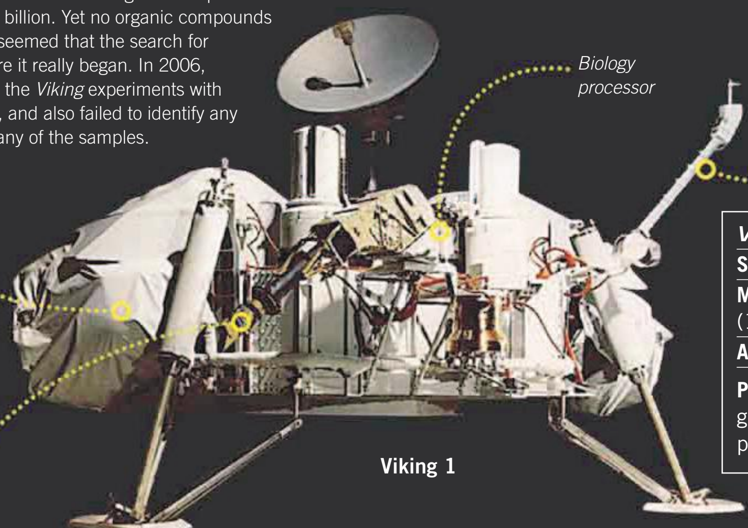
Further investigations revealed that **Mars lost hold of its atmosphere billions of years ago**—leaving only a tenuous carbon dioxide atmosphere. Then the life-hunting *Viking* landers of the 1970s probed the Martian soil and came up empty-handed. It seemed that life on Mars (even on its smallest scale) would **remain the stuff of science fiction**.

Recent discoveries of **water ice around the planet's poles**, and the so-far-unexplained presence of methane in isolated regions **(alien-bacteria farts?)**, have raised the specter of Martian life once again. In the coming years, an armada of life-hunters will be heading for the Red Planet—so here is a special look at the past, present, and future of the search for life on Mars.

1975 » 1980 » 1985

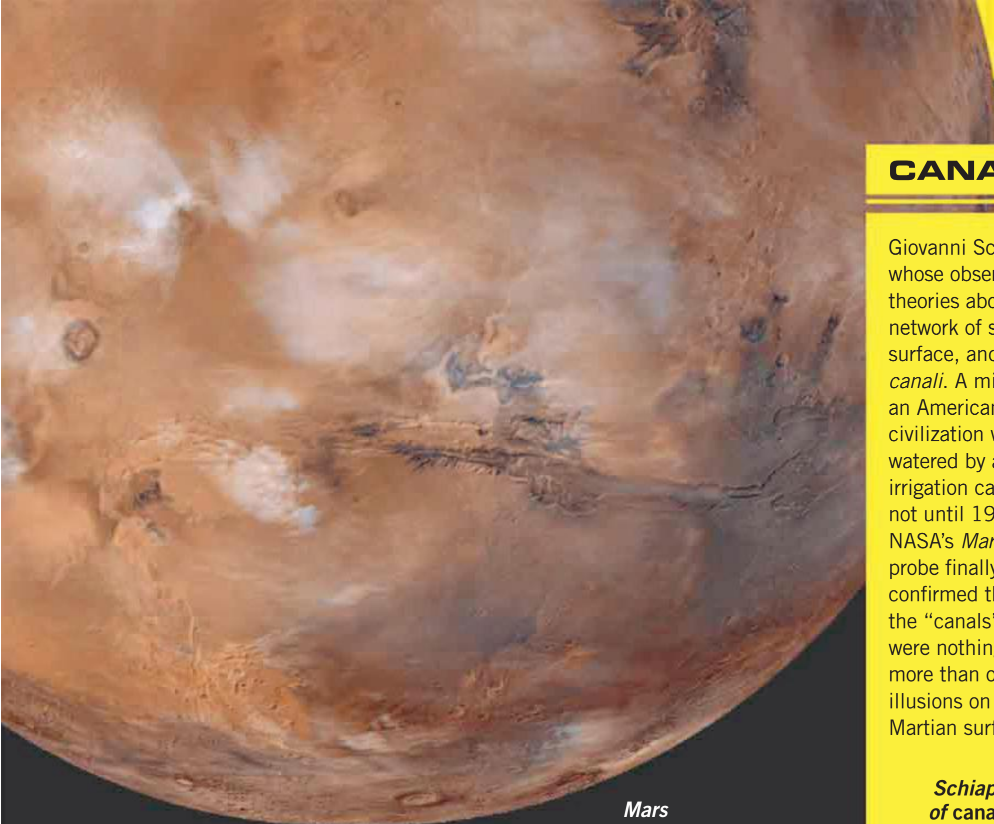
1975: *Viking 1* and *Viking 2*
Launched in 1975, *Viking 1* and *Viking 2* were the first dedicated attempts to find signs of Martian life. The craft performed tests designed to detect signs of life. One test involved scooping up Martian topsoil and heating it to 932°F (500°C). *Viking* then analyzed the vaporized dirt for signs of organic molecules. The test was sensitive to levels of organic compounds of only a few parts per billion. Yet no organic compounds were ever found. It seemed that the search for life had ended before it really began. In 2006, scientists replicated the *Viking* experiments with samples from Earth, and also failed to identify any organic material in any of the samples.

THE VIKING LANDERS WERE DESIGNED TO LAST FOR ONLY 90 DAYS ON MARS, BUT THEY BEAMED IMAGES AND DATA TO EARTH FOR MANY YEARS



Viking 1

VIKING
Size: 8.2 ft × 8.2 ft (2.5 m × 2.5 m)
Mass: 5,132 lb (2,328 kg); 3,185 lb (1,445 kg) of that was fuel
Arms: Up to 9.8 ft (3 m), telescopic
Power: Two radioisotope thermal generators (RTG) containing plutonium-238



Mars

CANALS AND *CANALI*

Giovanni Schiaparelli was the Italian astronomer whose observations of Mars in 1877 led to theories about life there. Schiaparelli spotted a network of straight lines crisscrossing the Martian surface, and described them as channels, or *canali*. A mistranslation led Percival Lowell, an American astronomer, to imagine a Martian civilization whose crops were watered by a network of irrigation canals. It was not until 1969 that NASA's *Mariner* probe finally confirmed that the "canals" were nothing more than optical illusions on the Martian surface.

Schiaparelli's drawing of* canali *on the Martian surface

1990 1995

1996: Martian fossils

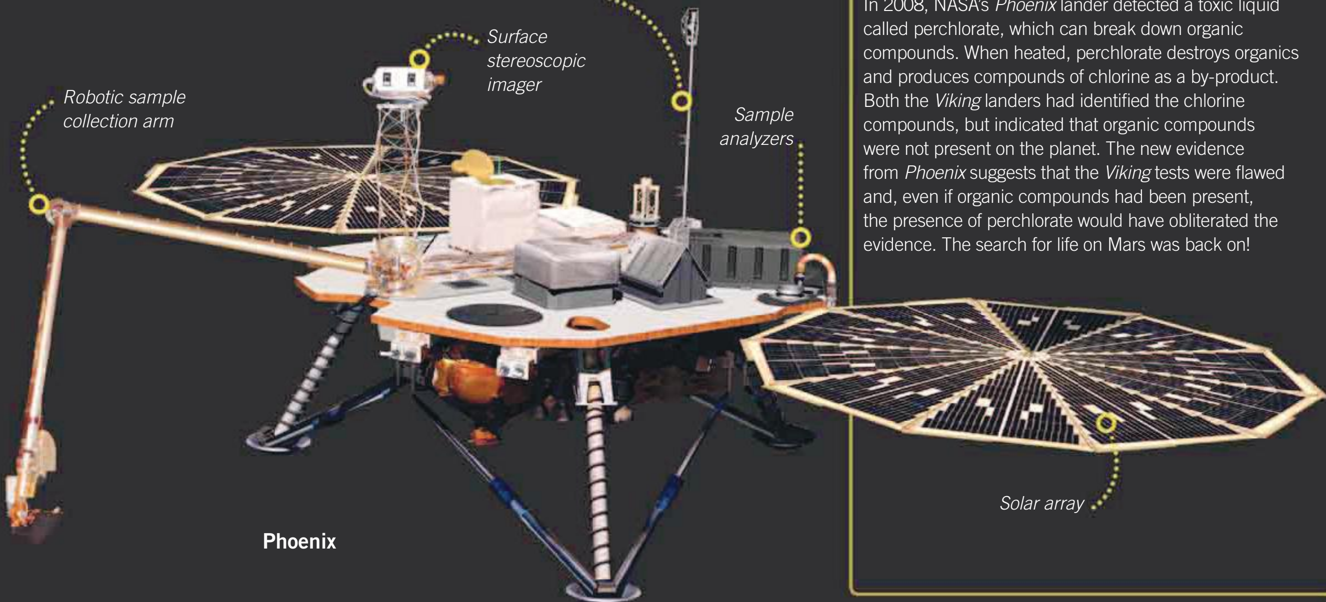
On August 6, 1996, NASA announced the discovery of evidence of fossil life in a meteorite that originated from Mars and had landed on Earth 13,000 years ago. Under the scanning electron microscope, structures were revealed that seemed to be fossilized Martian bacteria. The finding remains controversial, with some scientists claiming the fossils were just the result of earthly contamination. Recent studies have found that cracks in the meteorite are filled with carbonate materials that suggest the presence of water on Mars about four billion years ago. Complex organic compounds—called polycyclic aromatic hydrocarbons—have also been identified that point to a biological origin. Interestingly, these have been found deep within the rock, where contamination is unlikely.

Fossilized Martian bacteria?

LIFE, JIM, BUT NOT AS WE KNOW IT

Perhaps the search for life in extreme environments such as Mars should begin on Earth? All over our planet we have found life, not clinging on, but actually thriving in some of the most inhospitable environments—such as deep in Arctic ice. In 2008, the European Space Agency (ESA) sent 664 examples of these extremophiles to the International Space Station (ISS). For 18 months, two-thirds of the samples were exposed to the vacuum, massive temperature swings, and desiccating conditions of open space. The rest were exposed to a thin carbon dioxide atmosphere that simulated the Martian environment. Many of the samples survived the ordeal, with one of the stars of the show being a strange, pond-dwelling creature called a tardigrade, which can survive temperature swings ranging from -457ºF (-272ºC) to 302ºF (150ºC).

Tardigrade



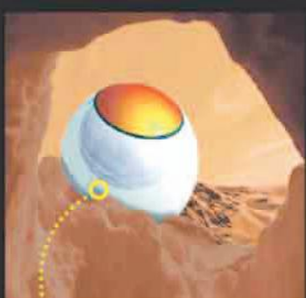
Phoenix

2008: *Phoenix* reignites search for life
In 2008, NASA's *Phoenix* lander detected a toxic liquid called perchlorate, which can break down organic compounds. When heated, perchlorate destroys organics and produces compounds of chlorine as a by-product. Both the *Viking* landers had identified the chlorine compounds, but indicated that organic compounds were not present on the planet. The new evidence from *Phoenix* suggests that the *Viking* tests were flawed and, even if organic compounds had been present, the presence of perchlorate would have obliterated the evidence. The search for life on Mars was back on!

2000 » 2005 »

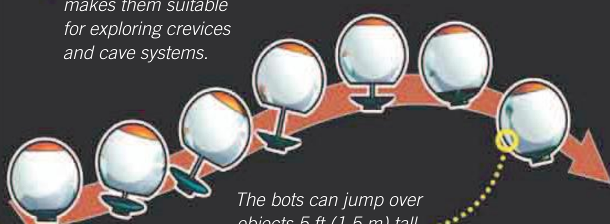
FUTURE WEAPONS OF EXPLORATION

Ever since the first man-made craft set down on the Martian surface, Mars exploration has been dominated by static landers or lumbering rovers. In the future, however, planetary explorers might be much smaller...

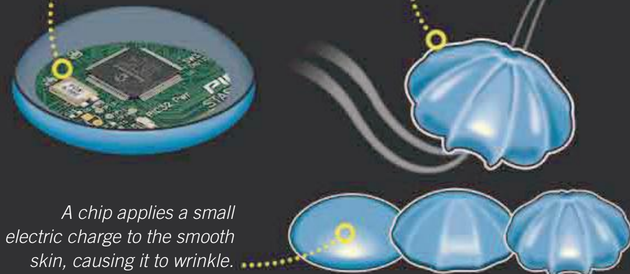


The bots' spherical shape makes them suitable for exploring crevices and cave systems.

MICROBOT SWARM
These tiny spherical robots could be dropped by the thousands on the Martian surface, where they would operate as a swarm to locate and explore caves. Just 5 in (12 cm) wide, the individual robots use a powered leg to hop, bounce, and roll their way across difficult terrain.



The bots can jump over objects 5 ft (1.5 m) tall.



Each nanobot consists of a polymer skin covering a 0.04 in (1 mm) computer chip.

The wrinkled skin allows the nanobot to be picked up by the wind.

A chip applies a small electric charge to the smooth skin, causing it to wrinkle.

NANOBOT DUST SWARM
Currently under development, these potential Martian explorers would be no larger than a grain of sand. Clouds of "smart dust" containing up to 30,000 nanobots could be dispatched into the Martian atmosphere, where, taking advantage of Mars's low gravity (just 38 percent of Earth's), they would be carried by the wind.

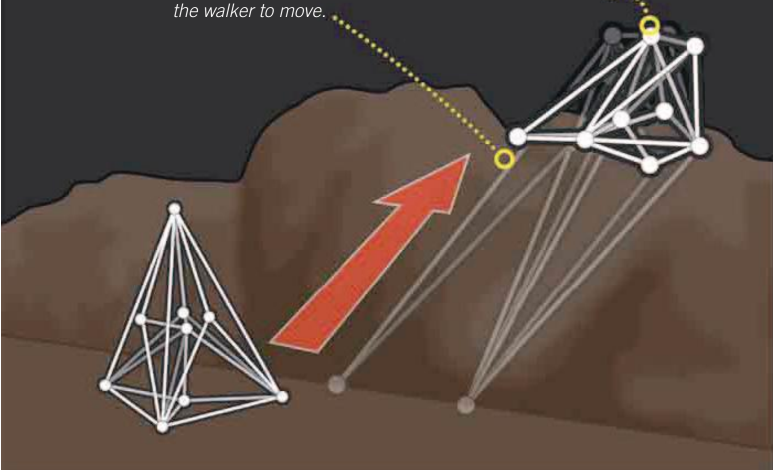
2012: *Curiosity*
In September 2013, NASA announced that *Curiosity* had detected "abundant, easily accessible" water in the Martian soil. The robotic explorer had found that the red surface of Mars contains about two percent water by weight—meaning that future colonists could (in theory) extract about two pints of water from every cubic foot of Martian dirt—meaning that the life on Mars could soon be us!

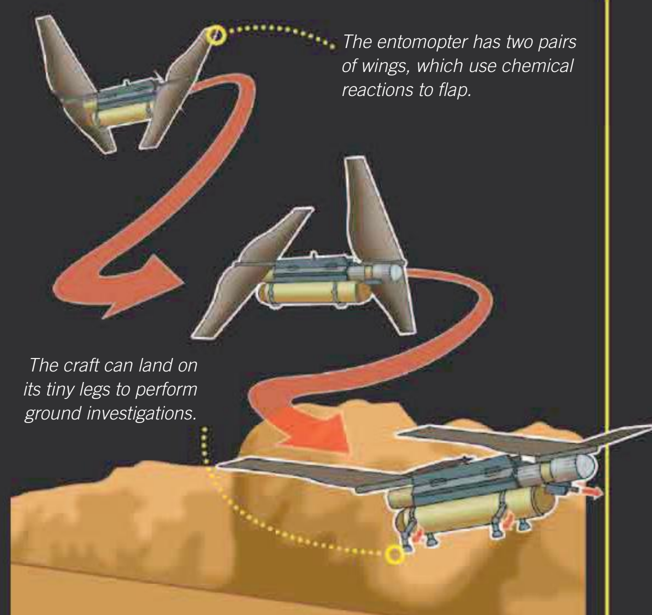
Curiosity

2010 » 2015 » 2020

TETRAHEDRAL WALKERS

Developed by NASA, the Addressable Reconfigurable Technology (ALT) walker consists of intelligent nodes connected by extendable struts. Motors in the nodes are used to expand or retract the connecting struts to change the walker's shape. This also means that, if the walker were damaged, it would be able to fix itself by removing damaged sections and rejoining to undamaged nodes.





INSECT-INSPIRED ENTOMOPTERS

Designed as part of NASA's Institute for Advanced Concepts, the entomopter is a flying robot modeled on a hawk moth. The Martian atmosphere is too thin (one percent of Earth's) for fixed-wing aircraft, but is perfect for a lightweight flapping vehicle.

COLONIZING **MARS**

BY 1970, AMERICA had the moon under its belt and the **human exploration of other worlds** was riding high in the imagination of the earthbound masses. Predictions of **lunar colonies** by the late 1970s and **Martian colonies** by the 1980s were tossed around the media as if their planning and execution were no more troublesome than building a highway.

By today, Mars was supposed to be a **"New Earth"** where humans no longer tenuously inhabited Martian outposts, but thrived in autonomous cities where generations were born, lived, and died, having never known the blue skies of Mother Earth. Obviously this is not the case today, nor is it likely to be for a very long time.

However, we might soon see the dispatch of those first Martian pioneers and the settlement of those first outposts—even if they are three decades too late. In 2010, NASA announced **an initiative to move space flight and exploration to the next level.**

The plan has been dubbed the **"Hundred Year Starship"**—and that is about it (as they have not been forthcoming with many details)—and has received funding from NASA and its wacky research arm, the Defense Advanced Research Projects Agency (DARPA).

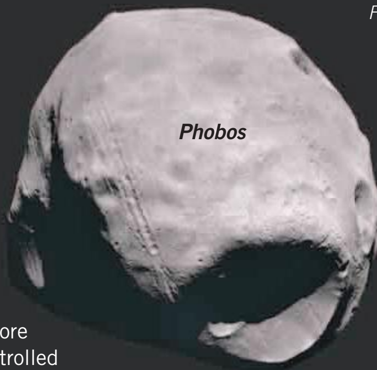
The idea is to develop a **new form of spacecraft** that would cut the journey time to Mars (currently a prohibitive six to nine months) and, arguably more importantly, cut the cost. Under discussion is a propulsion system called **"microwave thermal propulsion."** A craft powered in such a way would have its energy "beamed" via microwaves, or lasers, directly from Earth. Such beams would heat its propellant directly and push the craft forward—thus eliminating the massive amounts of fuel it would otherwise have to carry with it (which is heavy, and heavy stuff costs a lot to get off the ground).

Halving the distance that a manned craft might need to travel would also cut costs. How? Well, by making it a **one-way trip for the astronauts on board.**

The NASA proposal suggests that the best way to conquer Mars might be to land the first pioneers on the Red Planet—or initially on its moon, Phobos (see right)—and then **leave them there, forever.** That is not to say that they would be dumped and then left to fend for themselves. They would be **periodically resupplied from Earth with basic necessities,** but otherwise they would be encouraged to become increasingly self-sufficient. Despite the "no return" clause, NASA is not expecting to have any trouble recruiting volunteers.

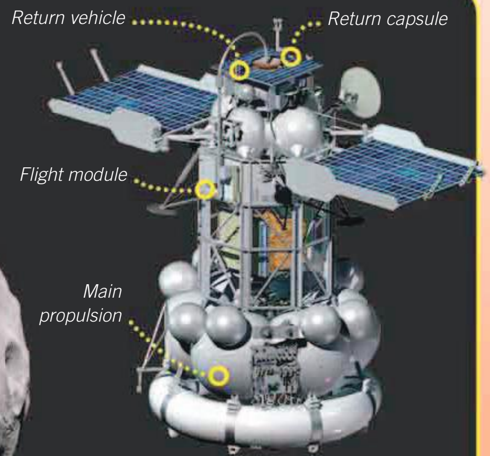
PHOBOS: A PERFECT FRONTIER POST?

Measuring just 17.3 miles (28 km) wide, with just two-billionths of Earth's mass, Mars's largest moon is little more than an asteroid. It has no atmosphere at all and its gravity is infinitesimally small. It is also very close to Mars—at a distance of just 5,826 miles (9,377 km)—all of which might make it a perfect Martian "jumping off" point.



WEAK GRAVITATIONAL FIELD

Using Phobos as a base camp, scientists could explore the surface of Mars with telescopes and remote-controlled rovers. And, because its gravitational field is so weak, landing is a cinch and taking off wouldn't require much energy. This would make it cheaper and easier to send spacecraft from Earth to Phobos (then ferry humans and materials down to Mars) than to send them directly to the Martian surface.

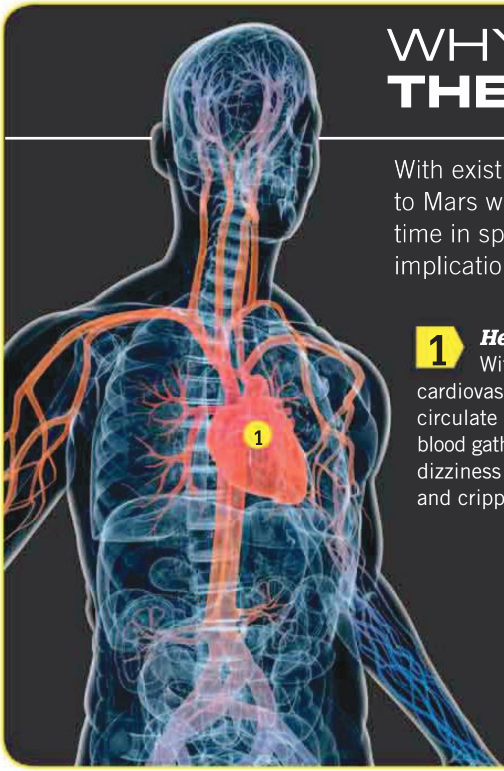


PHOBOS-GRUNT

In 2011, Russia launched *Phobos-Grunt* (meaning "Phobos-soil") to take samples from Phobos and return them to Earth. The mission failed, but in 2012 a repeat mission was announced—to be carried out in 2020.

COLONISTS WILL HAVE TO DEAL WITH RAZOR-SHARP DUST THAT WILL MUCK UP MACHINERY AND SPACE SUITS

On Mars: This artist's impression shows a pioneering astronaut zipping around on a scooter on the Red Planet.



WHY WE NEED TO SPEED THE JOURNEY UP A BIT

With existing propulsion technologies, the journey to Mars will take up to nine months. This amount of time in space can have some pretty serious health implications for any would-be Martian pioneer.

1 ***Heart's not in it***
Without gravity to push against, your cardiovascular system will weaken and no longer circulate as it did on Earth—so most of your blood gathers in your torso and brain. This means dizziness and nausea, but high blood pressure and crippling headaches are not far behind.

2 ***Brain flashes***
As you watch Earth become smaller and Mars grow larger, your view might occasionally be obscured by flashes of white light as high-energy cosmic rays slash though your brain. These rays may also cause cancer, and damage your brain and nervous system.

LOST IN SPACE

Of all the missions launched toward the Red Planet, about two-thirds have either been blighted with technical problems, or been lost completely. Here are the missions that have fallen afoul of the "Curse of Mars."

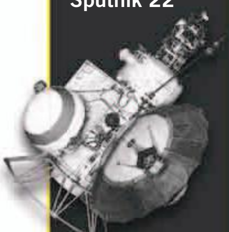
1960, USSR
Marsnik 1 and 2: Mars flyby missions—both lost to launch failures.

1964, USA
Mariner 3: Mars flyby—spacecraft housing failed to open following launch. Unable to deploy its solar panels, the craft ran out of power. It is still orbiting the sun.


Mariner 3

1960 » 1965 » 1970 » 1975 » 1980

Sputnik 22



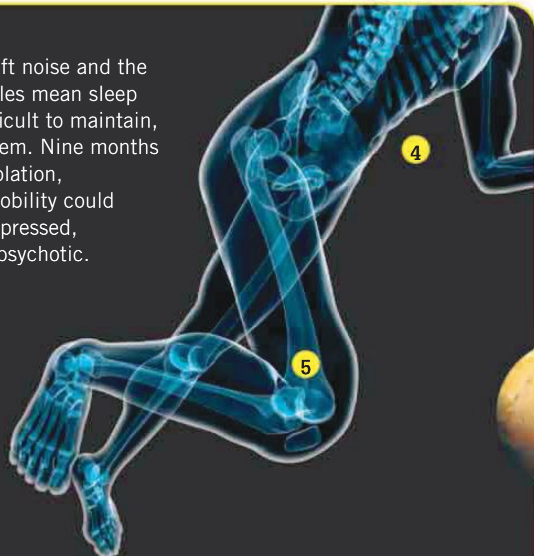
1962, USSR
Sputnik 22: Mars flyby—launch failure. Destroyed in low-Earth orbit.
Mars 1: Mars flyby—contact lost en route to Mars.
Sputnik 24: Mars lander—destroyed in low-Earth orbit.

1969, USSR
Mars 1969A: Mars orbiter and lander—launch failure. Lost in explosion.
Mars 1969B: Mars orbiter and lander—launch failure. Lost in launchpad explosion.

1971, USA
Mariner 8: Mars orbiter—lost during launch failure.


Mariner 8

1973, USSR
Mars 4: Mars orbiter—reached Mars but failed to fire braking thrusters and the craft overshot the planet.
Mars 6: Mars lander—reached Mars but lander was lost on descent.
Mars 7: Mars lander—reached Mars but lander separated three hours too early and overshot the planet.



3 *Space blues*

Constant spacecraft noise and the absence of day-night cycles mean sleep rhythms will become difficult to maintain, so fatigue can be a problem. Nine months is a long time and the isolation, monotony, and limited mobility could leave you dangerously depressed, anxious, and potentially psychotic.

4 *No exercise*

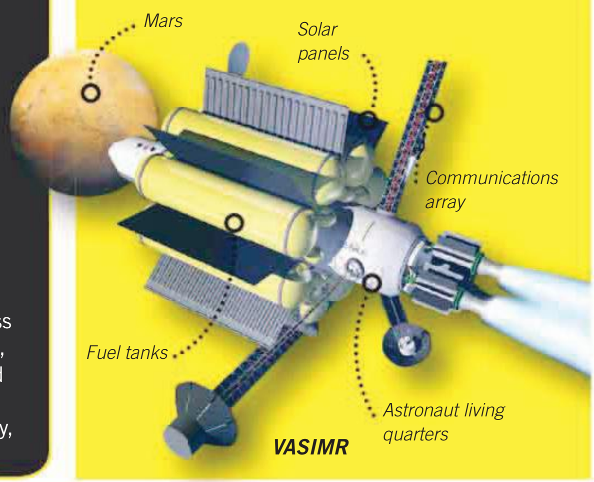
With little opportunity to exercise, the muscles in your flabby, underused limbs will atrophy, making movement awkward and painful.

5 *Bad bones*

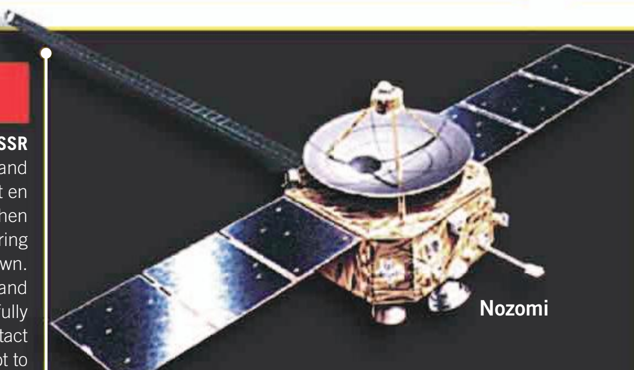
More than 200 days of near-total weightlessness causes your bones to excrete calcium and phosphorus, meaning they have lost as much density as they would during a lifetime on Earth—making your bones fragile and prone to fracture. No longer compressed by gravity, your vertebrae can separate, causing backaches.

VASIMR

Existing rocket technologies are too slow for effective Martian colonization. Experimental technologies, such as the (awesomely named) Variable Specific Impulse Magnetoplasma Rocket (VASIMR), could reach speeds of 119,925 mph (193,000 km/h) and get to Mars in 39 days. But this is still 20 to 30 years away.



1988, USSR
Phobos 1: Mars orbiter and Phobos lander—lost en route to Mars when command failure caused steering thrusters to shut down.
Phobos 2: Mars orbiter and Phobos lander—successfully entered Mars orbit but contact was lost during attempt to deploy the landers.

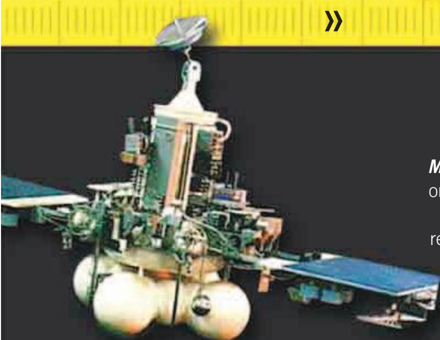


Nozomi

1998, Japan
Nozomi: Mars orbiter—failed to achieve Mars orbit due to electrical failure.

1998, USA
Mars Climate Orbiter: Mars orbiter—communication problem caused craft to break up in Martian atmosphere.

1990 1995 2000 2005



Phobos 2

1992, USA
Mars Observer: Mars orbiter—contact lost three days before reaching Mars orbit.

1996, Russia
Mars 96: Mars orbiter and lander—lost during launch failure.

1999, USA
Mars Polar Lander and Deep Space 2: Mars lander and surface penetrator—lost during descent to the planet's surface.

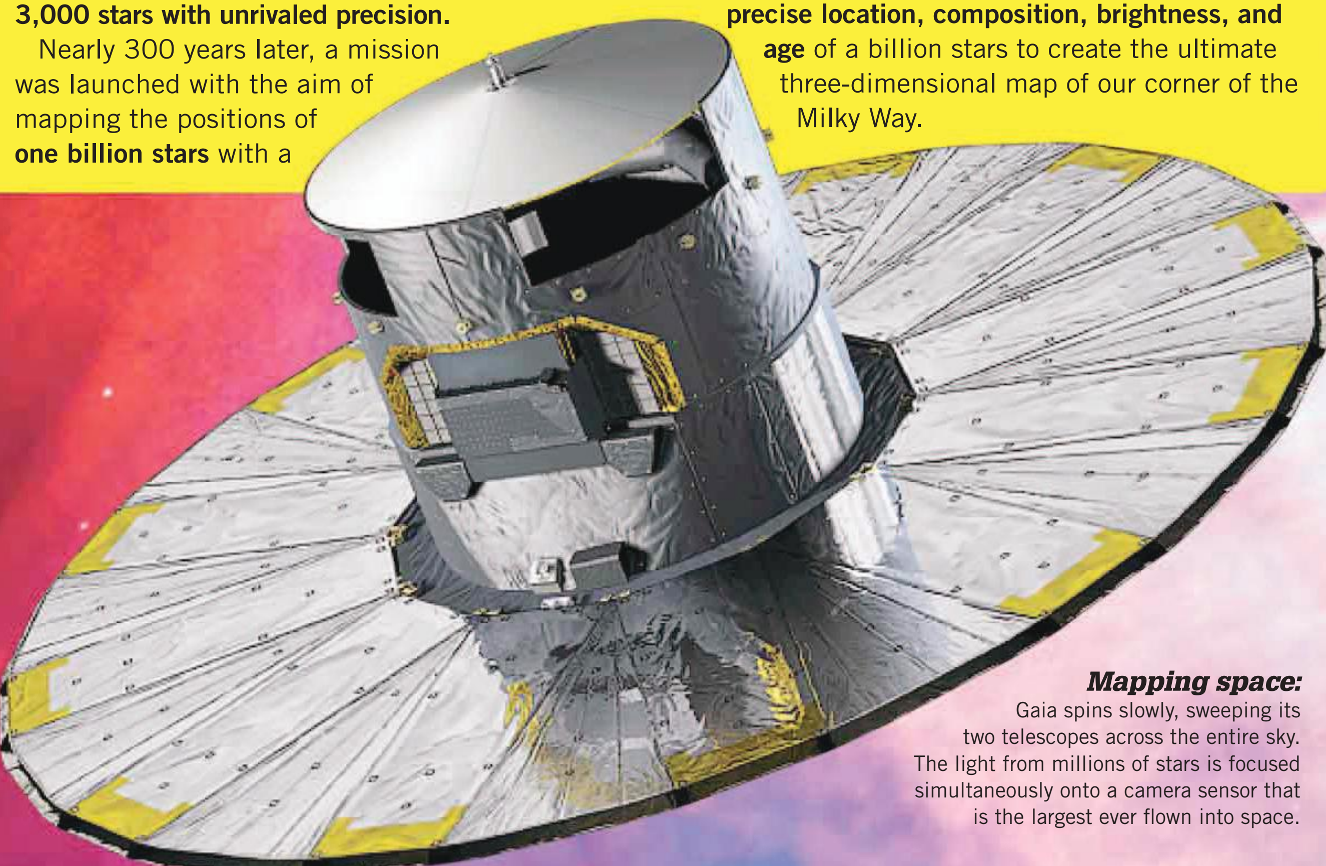
2003, Britain
Beagle 2: Mars lander—lost during descent to the planet's surface.

MAPPING THE MILKY WAY

IN 1676, THE ENGLISH ASTRONOMER ROYAL, John Flamsteed, sat down to compile the first catalog of star positions to be recorded with the aid of a telescope. He spent **an incredible 43 years dedicated to the task** and, by the time the final catalog was published in 1725 (six years after his death), he had **recorded the positions of nearly 3,000 stars with unrivaled precision.**

Nearly 300 years later, a mission was launched with the aim of mapping the positions of **one billion stars** with a level of accuracy that would have made Flamsteed's head explode—and it plans to do so **in just five years.**

Launched on December 20, 2013, the European Space Agency's (ESA's) Gaia spacecraft was one of the **most ambitious space-charting missions ever conceived.** From its position 932,000 miles (1.5 million km) from Earth, Gaia will map the **precise location, composition, brightness, and age** of a billion stars to create the ultimate three-dimensional map of our corner of the Milky Way.



Mapping space: Gaia spins slowly, sweeping its two telescopes across the entire sky. The light from millions of stars is focused simultaneously onto a camera sensor that is the largest ever flown into space.

GAIA PINPOINTS THE POSITION OF STARS WITH AN ACCURACY A HUNDRED TIMES GREATER THAN ANY EXISTING STAR CATALOG

For a lucky 150 million of those stars, Gaia aims to chart how they are moving through space. Their exact speed through the galactic medium will be measured as well as their motion relative to Earth—building a three-dimensional map that will allow astronomers to **trace the origins and evolution of the Milky Way and even provide clues about its ultimate fate.**

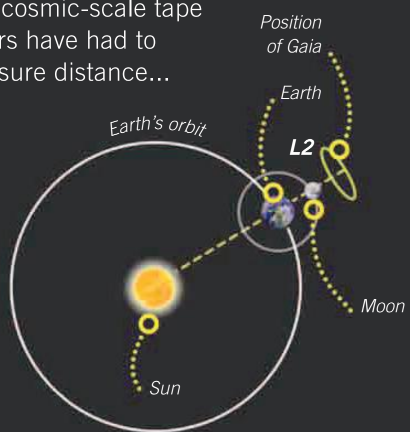
As if this was not ambitious enough, Gaia's remarkable near-billion-pixel camera will simultaneously **map the locations of thousands of asteroids, comets, planetary systems, supernovae, and even distant galaxies.**

Gaia is armed with two telescopes that will sweep the sky to a depth of 20,000 parsecs, or 65,200 light-years—generating so much data that it will take the number-crunching power of a supercomputer to process it.

The level of precision needed to make these measurements requires absolute stability, so the craft has no moving parts and has a skeleton made of silicon carbide, which does not expand or contract when the temperature fluctuates.

SEEING STARS FROM DIFFERENT ANGLES

There are no road signs or handy cosmic-scale tape measures in space, so astronomers have had to develop clever techniques to measure distance...



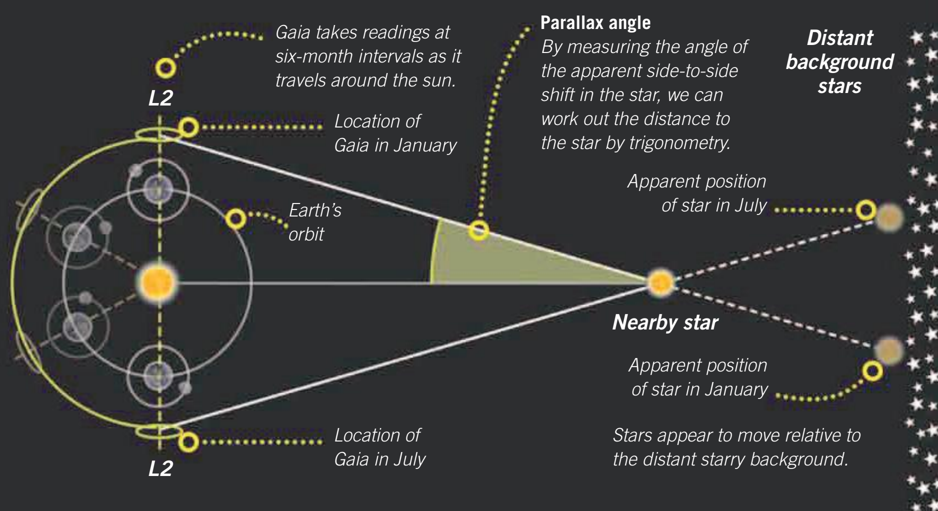
GAIA MEASURES THE POSITIONS AND MOVEMENT OF UP TO 8,000 STARS EVERY SECOND, TO AN ACCURACY EQUIVALENT TO A COIN SITTING ON THE MOON'S SURFACE

STAYING STILL

Gaia sits in an area of space called a Lagrange point. The spacecraft occupies Lagrange 2 (L2), which is located beyond the moon's orbit away from the sun. Here the sun's gravity and Earth's cancel each other out—allowing Gaia to remain relatively stationary.

THE PARALLAX EFFECT

Gaia will take advantage of the "parallax effect" to measure the distance to stars. Close one eye and hold your finger in front of your face and note where it appears relative to the background. If you swap eyes, you will see the finger jump to the side, even though it hasn't moved. This is the parallax effect, and it happens because your eyes see things from slightly different angles. Gaia takes readings at different positions, and combines them to find the correct distance.



DETECTING **KILLER ASTEROIDS**

GENERALS HAVE KNOWN for millennia that to prevail in battle, you must study your enemy—as the great Chinese military tactician Sun Tzu wrote in the 6th century BCE: **"know thy enemy and know thyself, you can win a hundred battles."** It is a lesson that has been put to use on battlefields all over the world, but now it is time to move the lesson to a larger field of battle: space itself.

As the meteor that exploded over the Russian region of Chelyabinsk Oblast in 2013 reminded us, the pale blue dot we call Earth is really rather small and vulnerable. That meteor **injured some 1,500 people and damaged more than 4,300 buildings across six cities.** The damage was impressive, but more impressive was the size of the offending space rock—it measured a mere 98 ft (30 m) across—**a speck of dust compared to some of the asteroids hoofing about in the space above our heads.**

So what can we do to prevent this from happening again? Well, in the case of the Russian meteor, probably not much—**it was just too small to spot before it entered the atmosphere**—but we might be able to do something about the larger rocks that we can detect.

Studies suggest that there are some 4,700 near-Earth asteroids

EARTH IS STRUCK BY AN ASTEROID THE SIZE OF A FOOTBALL FIELD APPROXIMATELY EVERY 2,000 YEARS

measuring in at more than 320 ft (100 m), and although none are expected to hit Earth in the next 100 years, it would be folly not to prepare for the worst. Detection is the first line of defense because once we know where they are, we can predict their orbits decades in advance—giving us lots of time to rally our forces.

However, to defend effectively against a potential killer asteroid, **we must first know what they are made of and how they work.**

Two new "know thy enemy" missions have been announced by space agencies on both sides of the pond. On the American side, NASA will have the grandly named *OSIRIS-RE*x—which will return an asteroid sample to Earth—and on the European side, ESA will have the slightly geriatrically named AIDA—which will study the effects of crashing a spacecraft into an asteroid.

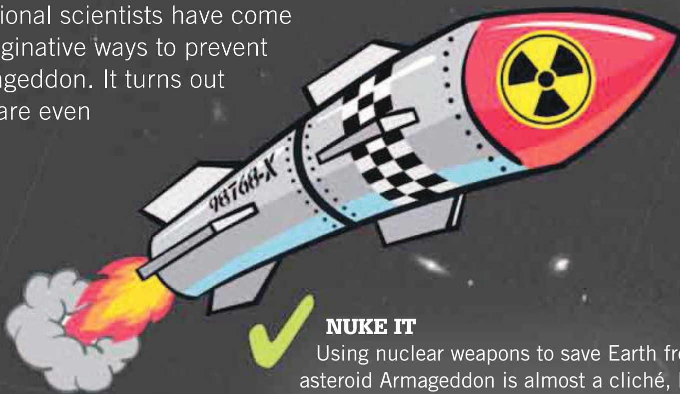
Once we figure out our foe, **how do we go about protecting ourselves from a supersonic lump of rock the size of a mountain?** Well, there are a few ideas...

OSIRIS-REx:
NASA's *OSIRIS-REx* will launch in 2016, with the goal of studying asteroid 101955 Bennu (previously named 1999 RQ36) and collecting a sample for return to Earth by 2023.

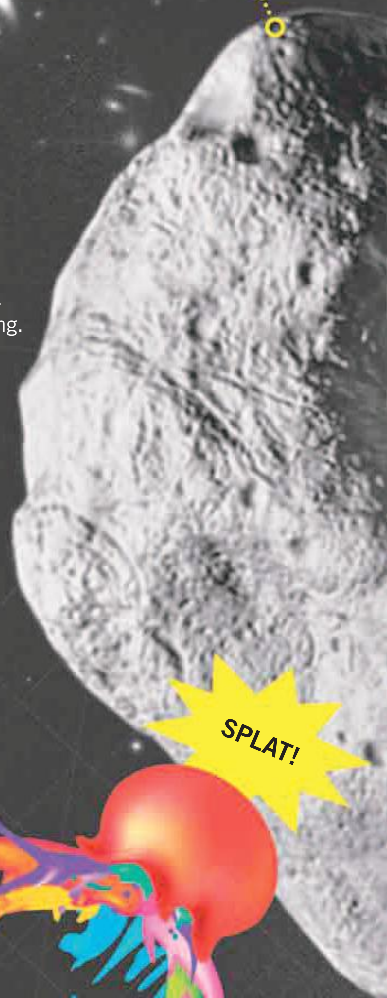
Asteroid 101955 Bennu

HOW TO DEFLECT **A KILLER ASTEROID...**

In disaster movies, fictional scientists have come up with all sorts of imaginative ways to prevent asteroid-induced Armageddon. It turns out that real-life solutions are even more bizarre...

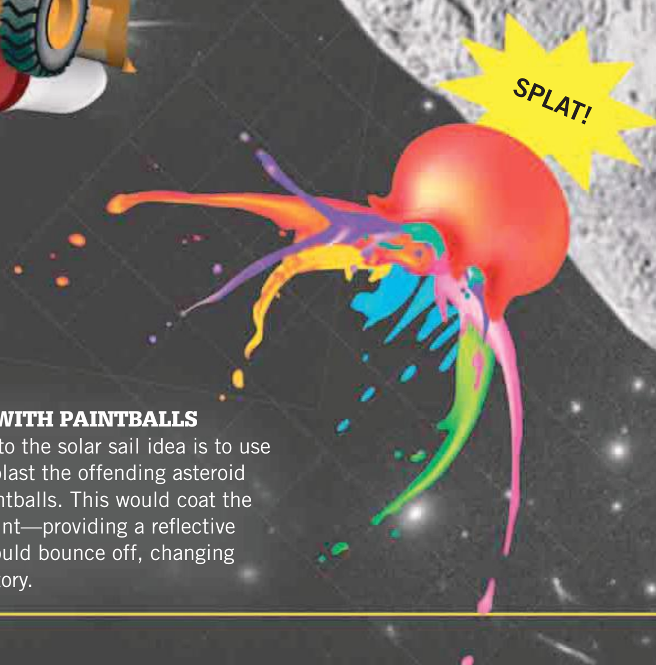


A nearby nuclear explosion would heat one side of the rock, causing material to vaporize.

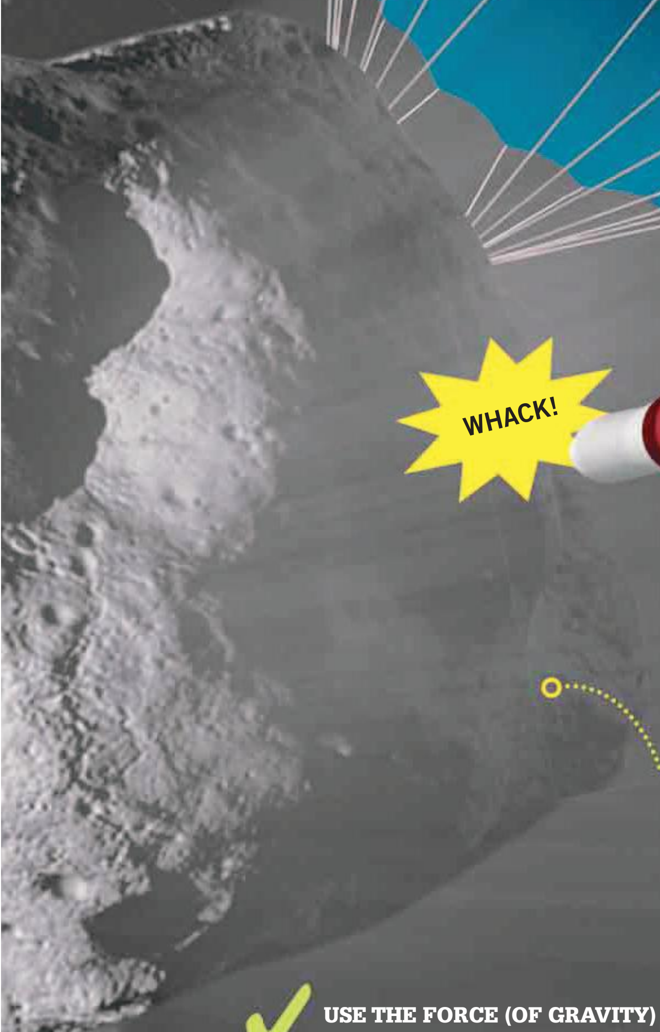


NUKE IT
Using nuclear weapons to save Earth from asteroid Armageddon is almost a cliché, but a direct hit would probably only serve to break the asteroid into many deadly chunks. A better option might be to detonate the warhead near the asteroid. Of course, this would require a little forward planning.

GET PUSHY
If you have ever watched a tiny tugboat maneuver a huge ship into harbor, you might see the merit of the next idea: Use a spacecraft to push the asteroid away. It really is as simple as it sounds (well, sort of). All you need to do is fly a spacecraft equipped with ion thrusters to the asteroid and push the space rock into a nice, safe trajectory. In 15–20 years, you'll be totally safe!



PEPPER IT WITH PAINTBALLS
An alternative to the solar sail idea is to use a spacecraft to blast the offending asteroid with five tons of paintballs. This would coat the rock in a layer of paint—providing a reflective surface that light would bounce off, changing the asteroid's trajectory.



SAIL TO SAFETY

Every second, the sun fires a billion billion billion billion billion photons out into space, and each one of those photons is a tiny packet of energy that you can use to push stuff around. Solar sails with huge reflective panels could be attached to a menacing asteroid, with the sail being used to catch and bounce photons back in the opposite direction. Each photon imparts a tiny bit of momentum to the sail, which can gently change the course of a giant space rock.

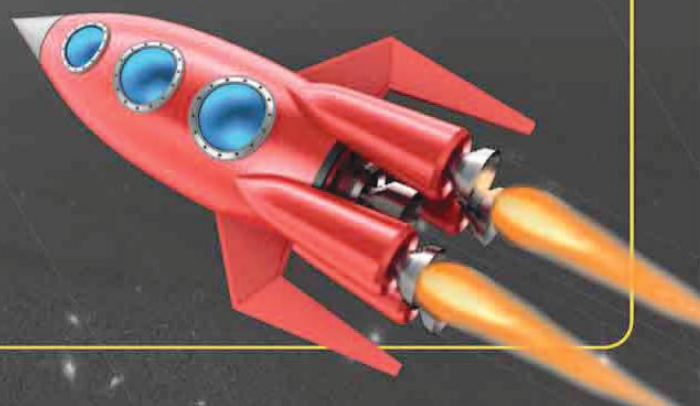
WHACK IT

Anyone familiar with snooker or pool can confirm that when you whack a ball with a cue, it shoots off in the opposite direction. Perhaps we need to think of an asteroid as a giant, lumpy pool ball and just whack it away from Earth. Luckily, you do not need a giant space-cue to get the same effect—a heavy object fired at great speed into the space rock would do the trick.

Asteroids can travel at close to 62,500 mph (100,000 km/h), and trying to hit it with a smaller object moving at about 18,750 mph (30,000 km/h) might just be tricky!

USE THE FORCE (OF GRAVITY)

Everything that possesses mass, even a small thing like a grain of sand, has a gravitational pull. You could take advantage of this by placing a spacecraft in orbit around an asteroid and using its gravity to "tug" the rock into a non-Earth-destroying orbit. All you have to do is get your spacecraft close enough, and its feeble gravity will exert enough pull to move the asteroid out of harm's way. Unfortunately, it will take at least 15 years to deflect the asteroid.



LOOKING BEYOND MARS FOR LIFE

MARS DOMINATES the search for life beyond Earth, but a growing number of scientists believe that our efforts should be directed toward a world that seems **a most unlikely candidate for extraterrestrial life**—Enceladus, the sixth-largest moon of Saturn.

For life (as we know it) to evolve and survive, it requires **three essential ingredients—water, energy, and organic chemicals.** But how can a tiny frozen moon so far from the sun possibly possess any of these ingredients?

Ingredient one: Water

Enceladus's northern hemisphere is heavily cratered and looks like any other moon, but its southern hemisphere is a little bit special. It is almost completely bereft of craters, which means that **the surface must be undergoing constant change.** Its cracked and scarred surface is riven by colossal canyons. Directly over the south pole are Enceladus's famous **"tiger stripes"—**four massive tears in the icy surface more than 85 miles (140 km) long and hundreds of yards deep that resemble tectonic fault lines on Earth.

In 2005, scientists working on NASA's *Cassini* mission discovered **vast plumes of water being vented from the tiger stripes**—like giant frozen volcanoes spewing ice instead of molten rock. The ice geysers of Enceladus (there

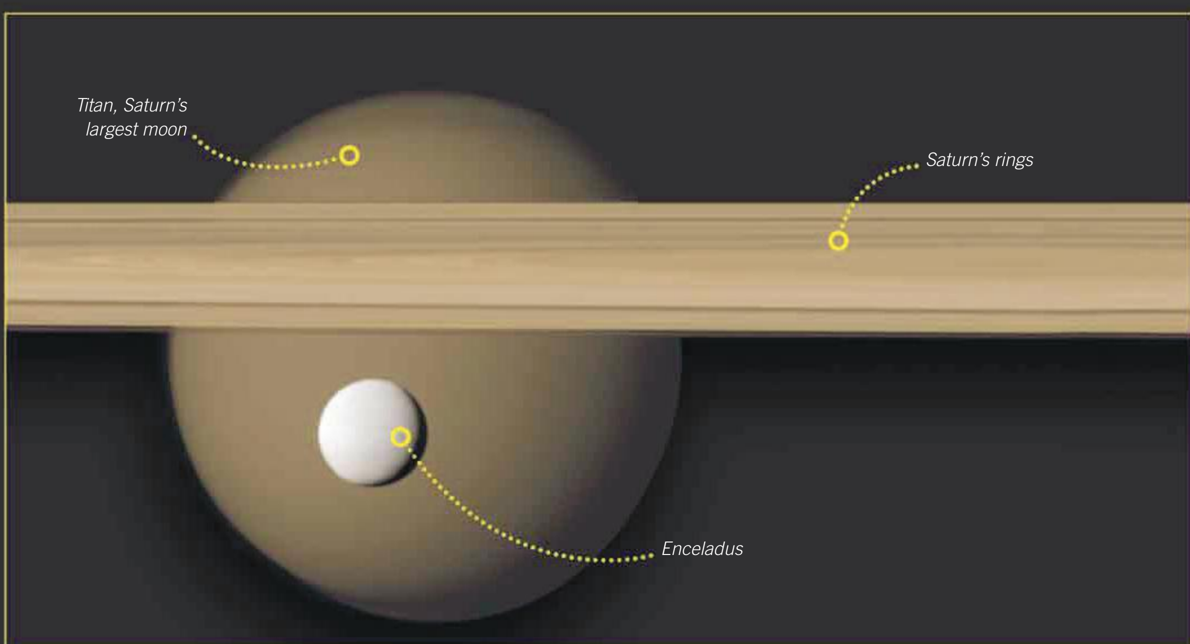
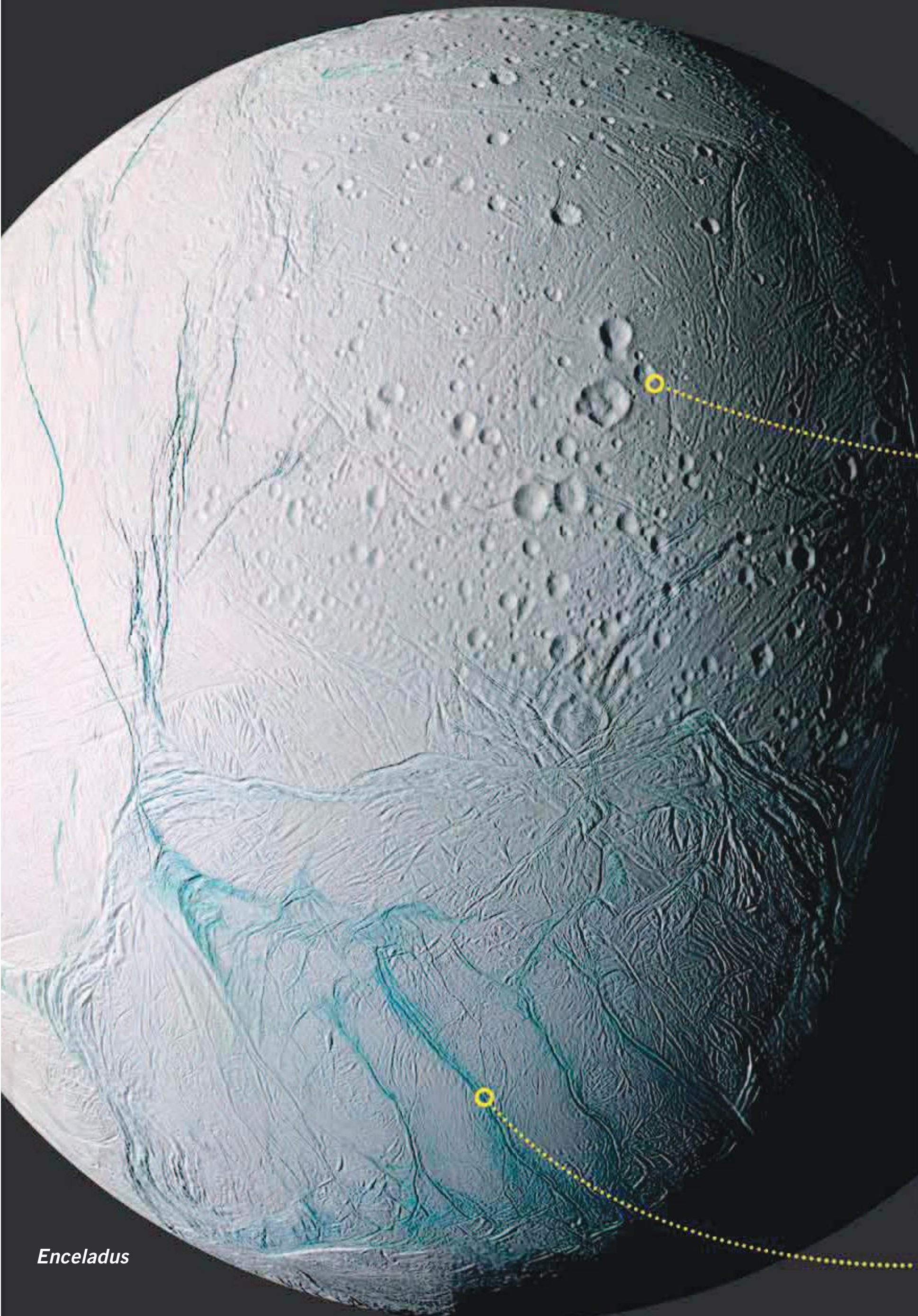


***Image of Enceladus taken by* Cassini**

are more than 100 of them) burst through the moon's frozen surface at 800 mph (1,300 km/h) and blast 440 lb (200 kg) of water vapor thousands of miles into space every second. As it encounters the frigid vacuum of space, the liquid water instantly freezes into tiny ice crystals. Much of this falls back to Enceladus as snow, which accumulates over millions of years to form **snow drifts up to 328 ft (100 m) deep** and gives the moon a white surface that reflects almost all of the sun's feeble rays back into space—making Enceladus the most reflective object in the solar system. But not all of it falls as snow; **some of the ice spreads out into space and wraps around Saturn, forming the planet's great E Ring.** More relevant for our recipe for life is the fact that the geysers would not be possible unless there were **liquid water beneath Enceladus's icy surface.**



Enceladus

ICY PLUMES

So far, astronomers have found 101 geysers on Enceladus venting water vapor and ice from near the moon's south pole. *Cassini* took this spectacular shot of the ice plumes, backlit by the sun.

Ingredient two: Energy

Being too small to generate its own internal heat and so far from the warmth of the sun, **Enceladus should be frozen solid.** What was causing that ice to melt? When Cassini investigated Enceladus's "tiger stripes" with its thermal imaging cameras, it discovered that the stripes sat over **"hot spots" that are much warmer than the rest of the moon.** Heat is relative, of course. These "hot" zones are about -139°F (-95°C), which on Earth is pretty cold, but 869 billion miles (1.4 billion km) from the sun and on a moon with an average temperature of -328°F (-200°C), it is almost balmy.

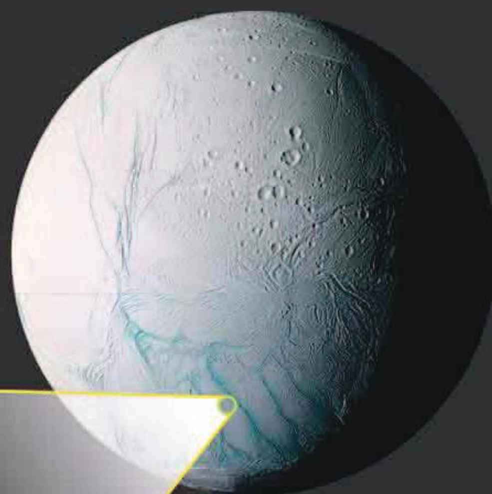
But where is the energy coming from? At such a great distance from the sun, you can be sure it is not coming from there. The answer lies in that most enigmatic of forces: gravity. Any object that orbits another exerts a gravitational influence on that object called the tidal force. Earth pulls on the moon and the moon pulls on Earth. Although much smaller than Earth, **the moon's gravitational pull is strong enough to distort Earth's solid rock crust**—lifting it by 7.8 in (20 cm) with every pass. If a relatively small object like the moon can distort Earth, just imagine what Saturn does to tiny Enceladus. Saturn is about 95 times more massive than Earth and Enceladus is only one-sixth the size of the moon.

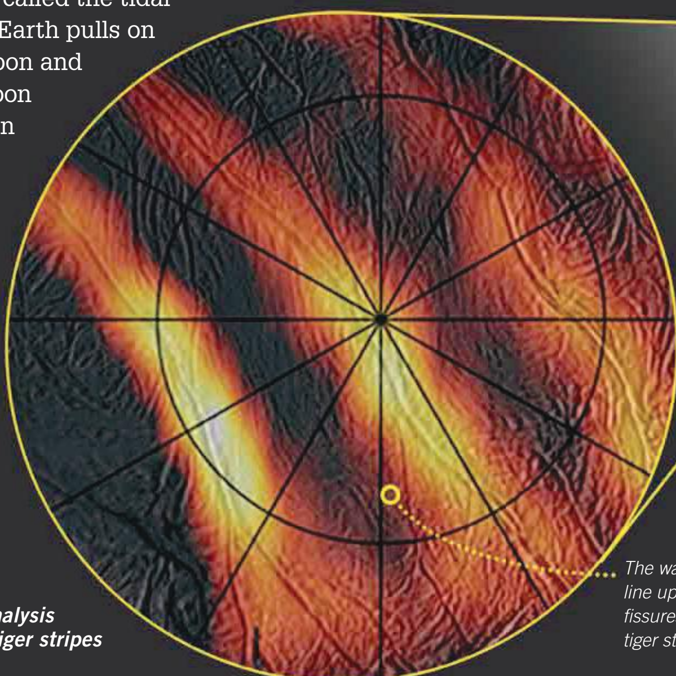
Enceladus travels around Saturn in an elliptical orbit, which means that, as the moon moves closer to and farther away from Saturn, **tidal forces are continually stretching and squashing Enceladus like a ball of putty.** This constant internal movement creates friction that, as anyone who has ever enjoyed a carpet burn can attest, generates energy in the form of heat. **This heat is enough to melt Enceladus's icy interior** and create a small underground ocean of liquid water.

Ingredient three: Organic compounds

Some of *Cassini*'s visits to Enceladus pass as close as 13 miles (21 km) to the moon's surface. This has enabled *Cassini* to **fly through the heart of the plumes and analyze the gas and ice.** In the process it detected a cocktail of organic compounds—ammonia, methane, carbon dioxide, acetylene, and other hydrocarbons. All these ingredients are thought to have made up the prebiotic soup from which life eventually emerged on Earth. **But could life have formed in a frigid subterranean ocean that is so distant from our life-nurturing sun?**

It depends on your expectations of what alien life will be. If you are hoping for extraterrestrial dinosaurs or cuddly, exponentially replicating fur balls, then you will be sorely disappointed. But **if you lower your ET aspirations to include microbial life, then you've got a shot.** There have been several microbial ecosystems discovered on





Heat analysis of the tiger stripes

The warmest areas line up with the fissures called tiger stripes.

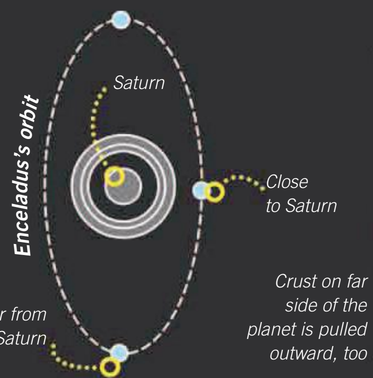
Earth that could provide a blueprint for possible Enceladian life. One group of singled-celled life, called archaea, are able to thrive in the most extreme of environments. Known as methanogens (because they give off methane as a by-product of their metabolism), they have been **found living locked away from oxygen and sunlight under miles of ice in Greenland.** Such microbes have been discovered surviving on the energy from the chemical interaction between different kinds of minerals and even living off the energy produced by radioactive decay in rocks.

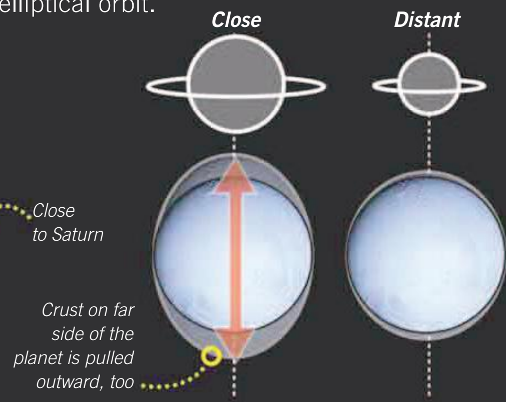
THE TIGER STRIPES ARE EMITTING AN ENORMOUS AMOUNT OF ENERGY—ABOUT 16 GIGAWATTS, WHICH EQUATES TO ABOUT 20 COAL-FIRED POWER PLANTS

So Enceladus has the three basic ingredients in the recipe for life—water, energy (warmth), and organic chemicals—and we know that microbial life can survive just about anywhere, but does life exist below the moon's cue-ball surface? Only a dedicated sampling mission can hope to answer this question, but it is an intriguing thought, is it not?

HOW TIDAL FORCES COULD CREATE AN OCEAN ON ENCELADUS

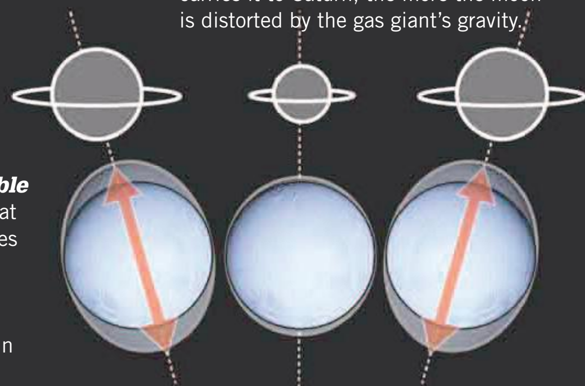
The interior of Enceladus should be frozen solid, so what is melting the ice? The answer lies in its giant companion, Saturn, and the moon's elliptical orbit.





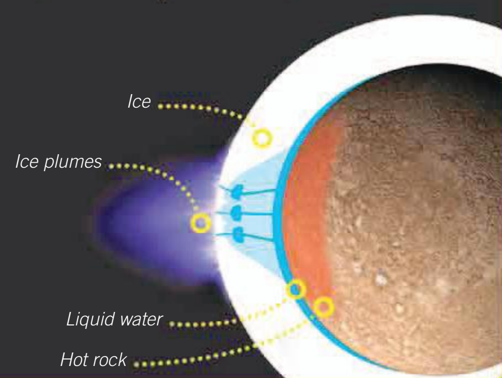
1 Elliptical orbit Enceladus moves in an elliptical orbit around Saturn.

2 Distance from Saturn The closer Enceladus's orbit carries it to Saturn, the more the moon is distorted by the gas giant's gravity.



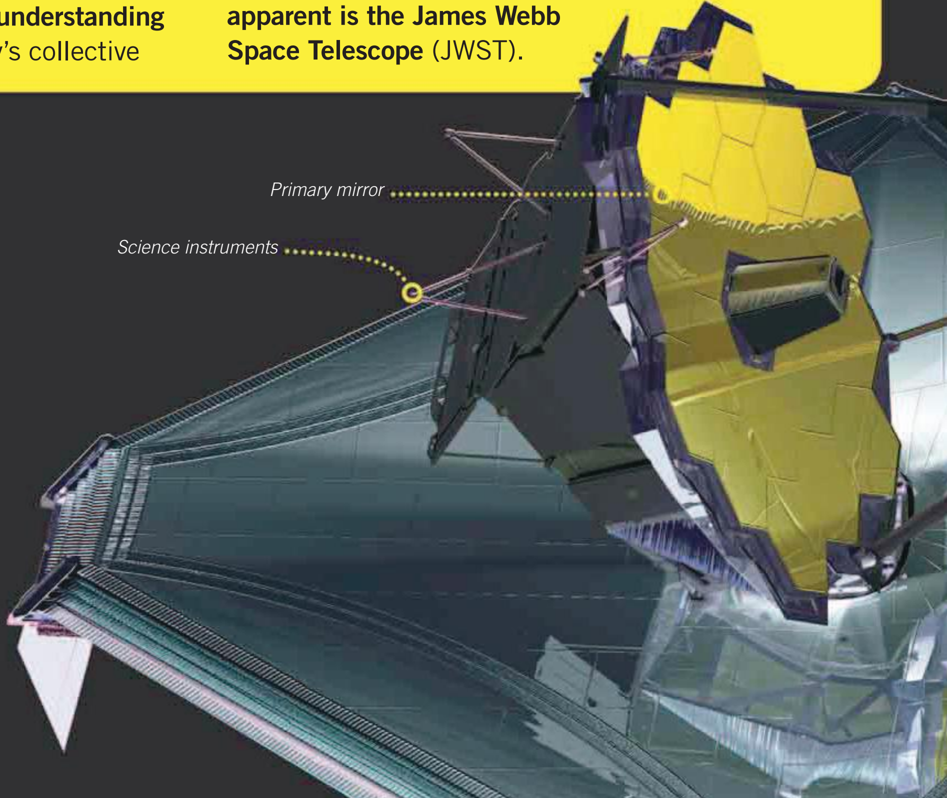
3 Wobble wobble It is thought that Enceladus also wobbles slightly as it orbits (called libration)—meaning the moon is stretched and pulled in different directions.

4 Stretching out All this stretching creates friction within Enceladus—generating heat, which melts the ice and creates a subsurface ocean. The water from this ocean travels up through the ice and collect in caverns beneath the tiger stripes before venting out into space.



A WEBB TO CATCH THE OLDEST STARS

IN THE KINGDOM OF TELESCOPES, there is no denying that the Hubble Space Telescope is king. From the moment of its launch (well, from the moment its faulty optics were fixed with the addition of a set of space spectacles), it has beamed back images that have **revolutionized our understanding of the cosmos**, tapped into humanity's collective imagination, populated the coffee tables of the world with countless pictorial tomes, and titillated the planet's computer users with an endless stream of astro screen savers. But even legends must one day step aside and cede their title to the next generation. **Hubble's heir apparent is the James Webb Space Telescope** (JWST).



But transitions of power rarely run smoothly, and **Webb's ascension has certainly not gone according to plan**. Since it was first conceived in 1996, it has been delayed (from an initial launch date of 2013 to 2018), run over budget by billions of dollars (from \$3.6 billion to \$9.1 billion), and **even been canceled**, but it seems, at last, that Webb is finally on course to assume its heavenly throne.

In 2013, the European Space Agency (ESA) announced that it had completed the second of the two instruments it is contributing to NASA's mighty orbiting observatory. Called the Near-InfraRed Spectrograph, or NIRSpec, it is an infrared camera that will be **sensitive enough to detect light that has been traveling across space for 13.6 billion years**—revealing the very first stars and galaxies to flare into life just 400 million years after the Big Bang. It follows hot on the heels of Europe's other contribution—the British-designed and built Mid-Infrared Instrument (MIRI).

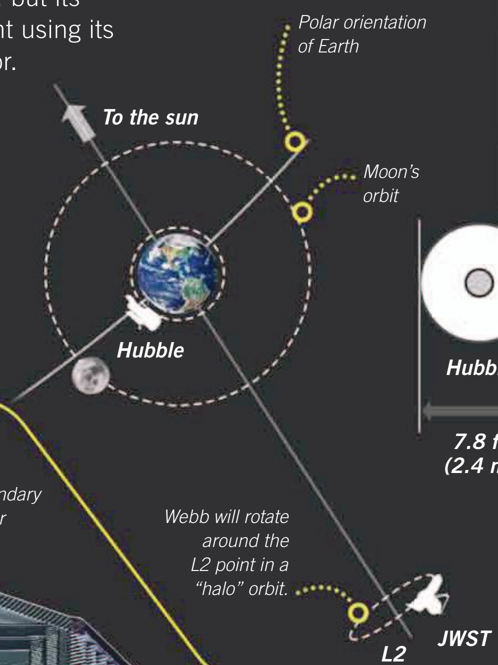
Studying the universe in infrared will also allow astronomers to pierce the opaque gloom of cosmic dust that obscures so much of the cosmos, **revealing objects that Hubble is simply blind to**. NIRSpec's spectrometer will give Webb the power to study the atmospheres of distant worlds and discern their chemical composition—**a first step toward finding alien life**.

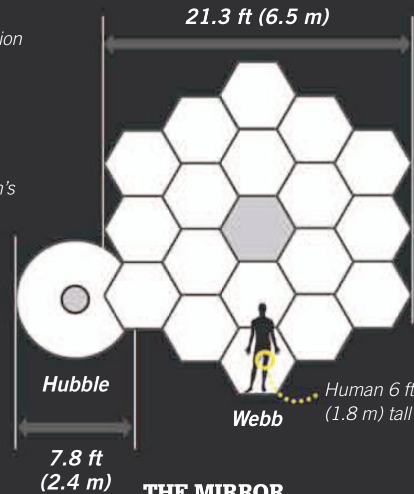
James Webb Space Telescope

JWST VS. HUBBLE

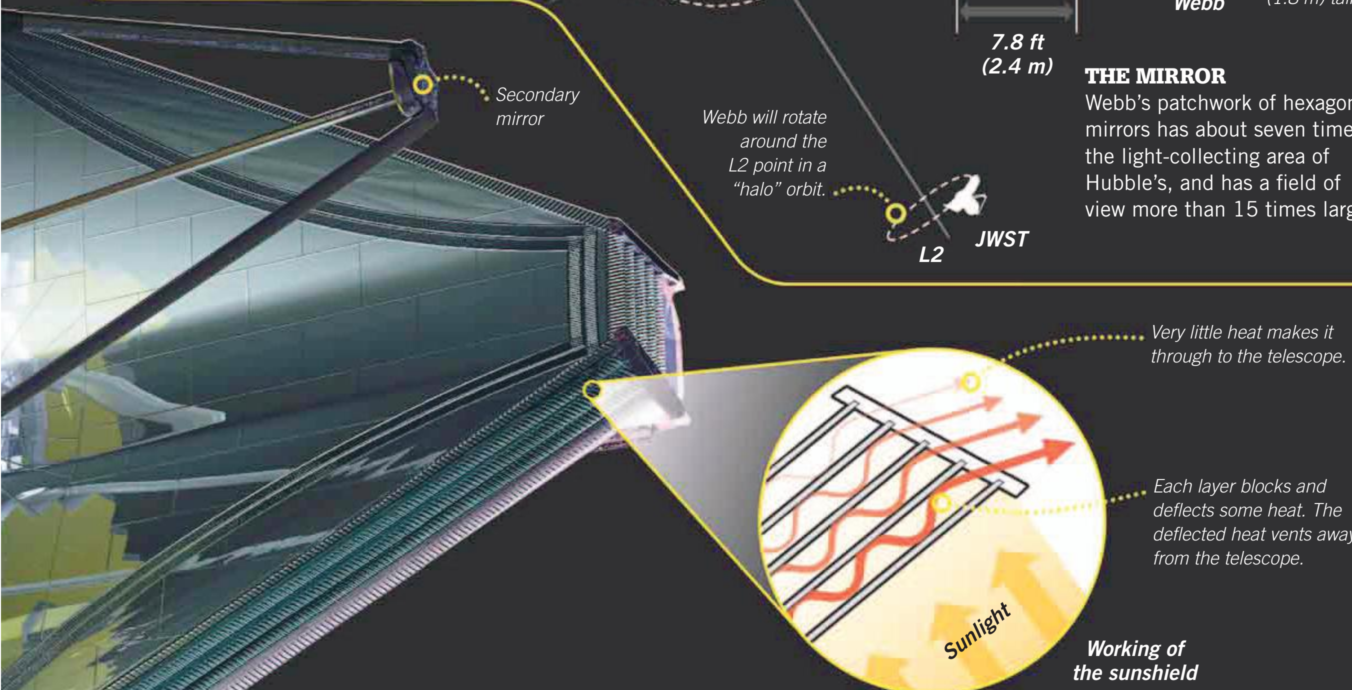
Like Hubble, Webb will see visible light, but its real talent will be capturing infrared light using its enormous 21.3 ft (6.5 m) primary mirror.

THE ORBIT
Webb will not orbit close to Earth, like Hubble—instead, it will inhabit an area in space called a Lagrange point. Webb will occupy Lagrange 2, which is a region about 930,000 miles (1.5 million km) from Earth, where the sun's gravity and Earth's gravity cancel each other out—allowing the craft to remain relatively stationary.





THE MIRROR
Webb's patchwork of hexagonal mirrors has about seven times the light-collecting area of Hubble's, and has a field of view more than 15 times larger.



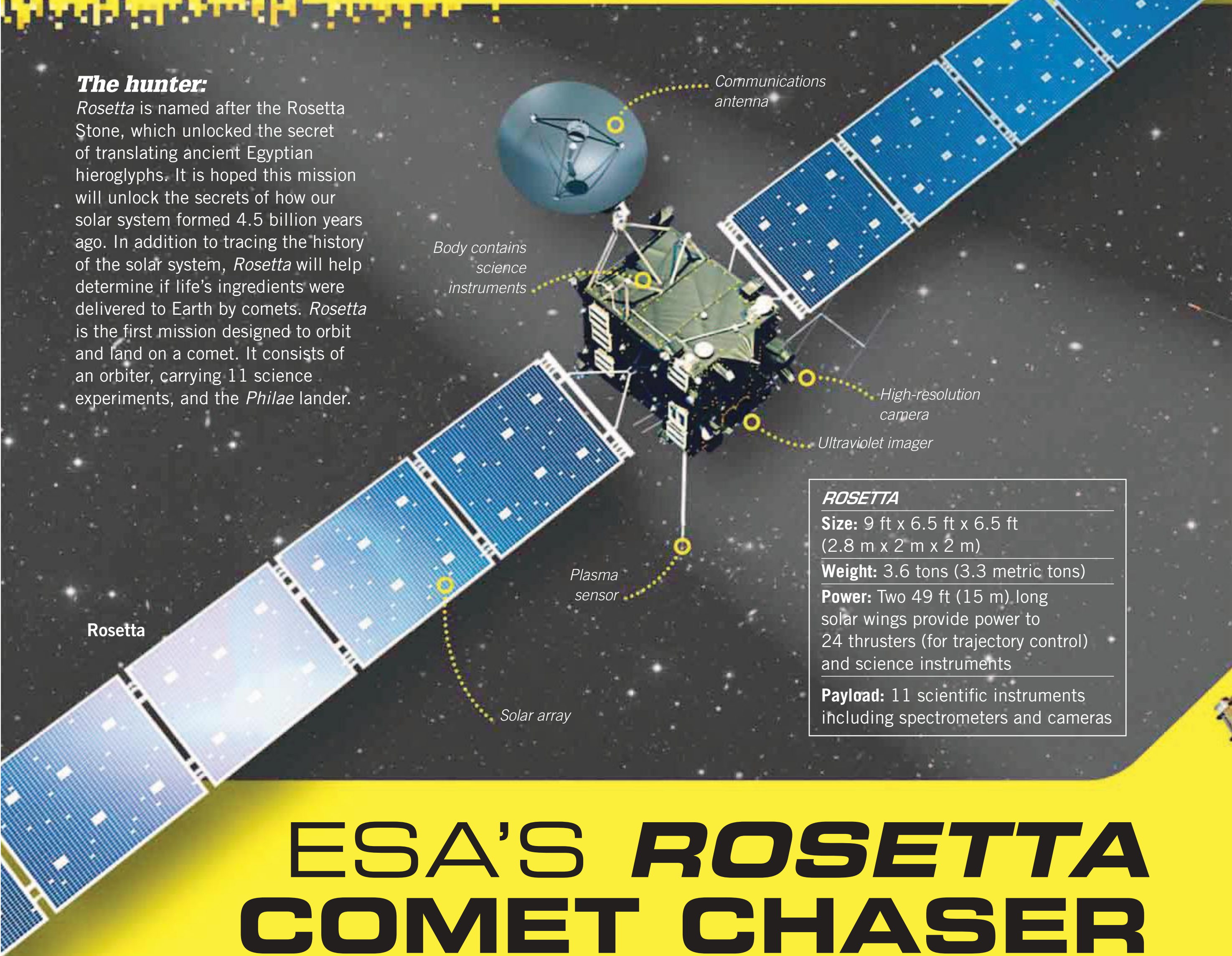
Webb is a very different beast from Hubble. More of an **interstellar sailing ship** than a telescope, Webb's colossal light-collecting mirrors sit atop a sunshield the size of a tennis court and, once unfolded to their full spread, the **array of hexagonal mirrors will dwarf Hubble's single mirror**.

Nor will Webb have access to the sort of home comforts that Hubble has enjoyed in its Earth-hugging orbit. Webb will be well beyond the reach of the servicing missions that have repaired and upgraded Hubble, and, should anything go wrong, **it will be well beyond any sort of help at all**. They do say it is lonely at the top.

JWST'S GOALS

- Search for light from the first stars and galaxies to form after the Big Bang.
- Study galaxy formation and evolution.
- Study planetary systems and the origins of life.

The hunter:
Rosetta is named after the Rosetta Stone, which unlocked the secret of translating ancient Egyptian hieroglyphs. It is hoped this mission will unlock the secrets of how our solar system formed 4.5 billion years ago. In addition to tracing the history of the solar system, *Rosetta* will help determine if life's ingredients were delivered to Earth by comets. *Rosetta* is the first mission designed to orbit and land on a comet. It consists of an orbiter, carrying 11 science experiments, and the *Philae* lander.



ROSETTA

Size: 9 ft x 6.5 ft x 6.5 ft (2.8 m x 2 m x 2 m)

Weight: 3.6 tons (3.3 metric tons)

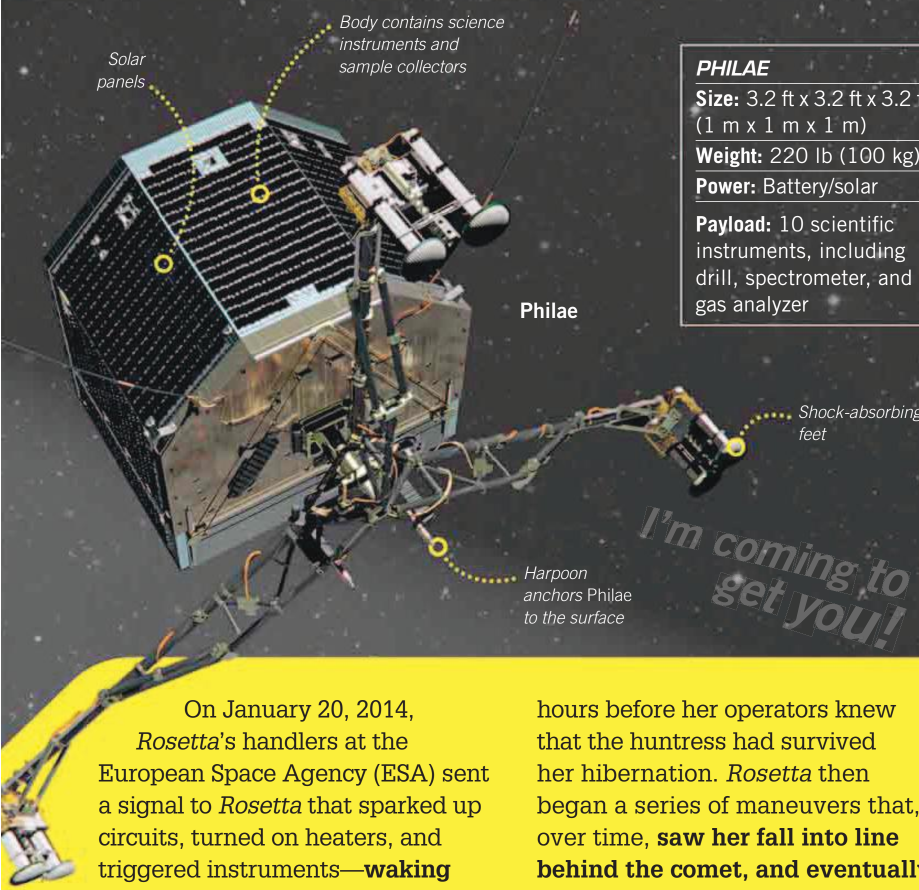
Power: Two 49 ft (15 m) long solar wings provide power to 24 thrusters (for trajectory control) and science instruments

Payload: 11 scientific instruments including spectrometers and cameras

ESA'S ***ROSETTA*** COMET CHASER

SOMEWHERE IN THE FRIGID BLACKNESS of deep space, a hunter is preparing to be stirred from her slumber. She has spent **ten long years chasing down her prey,** and now, after a journey of almost 4.35 billion miles (7 billion km), she is on the brink of ensnaring her quarry. When *Rosetta* set out, she was **hopelessly outpaced by her prey,** but, after four tours of the inner solar system (stealing gravitational energy from the planets she encountered along the way), her speed of more than 83,885 mph (135,000 km/h) is more than a match for the object in her sights.

But the hunt had been exhausting and, millions of miles from home, the sun had been too weak to sustain her, so, **for about two and a half years she was hibernating**—rationing her reserves for the final pursuit.



PHILAE
Size: 3.2 ft x 3.2 ft x 3.2 ft (1 m x 1 m x 1 m)
Weight: 220 lb (100 kg)
Power: Battery/solar
Payload: 10 scientific instruments, including drill, spectrometer, and gas analyzer

The hound:

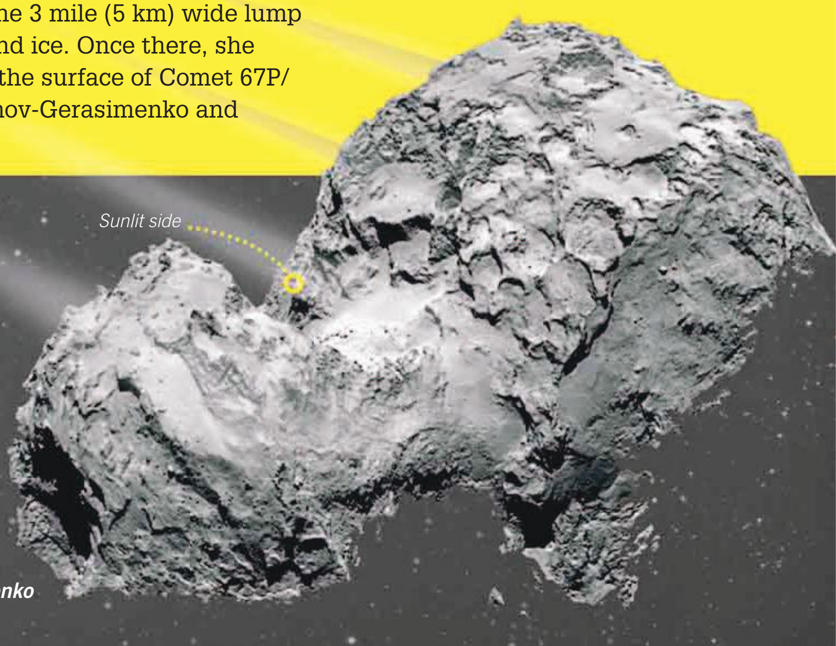
The lander is named after the island Philae in the Nile River, where an obelisk was found that helped decipher the Rosetta Stone. The *Philae* lander is the first spacecraft to make a soft landing on the surface of a comet. It piggybacks along with *Rosetta* until it arrives at the comet—where it ejects, unfolds its legs, and descends. On landing, *Philae* anchors itself to the surface by firing a harpoon into the surface. A small drill allows *Philae* to take samples, which are analyzed to determine the comet's composition.

On January 20, 2014, *Rosetta*'s handlers at the European Space Agency (ESA) sent a signal to *Rosetta* that sparked up circuits, turned on heaters, and triggered instruments—**waking the hunter at precisely 10 am.**

After two and a half years sleeping in the freezer, it took some time for *Rosetta*'s instruments to wake up fully and send a message to Earth. There were several tense hours before her operators knew that the huntress had survived her hibernation. *Rosetta* then began a series of maneuvers that, over time, **saw her fall into line behind the comet, and eventually catch up in August 2014.** She gradually entered into an orbit around the 3 mile (5 km) wide lump of rock and ice. Once there, she mapped the surface of Comet 67P/Churyumov-Gerasimenko and unleashed her "hound," *Philae*. *Philae* was armed with a harpoon that it used **to spear the comet and secure itself to the surface.** The probe then deployed a drill to extract samples of the comet to be studied by its panoply of scientific instruments.

The quarry:

Rosetta's target is Comet Churyumov-Gerasimenko. A remnant of the formation of the solar system, this 2.5 mile (4 km) wide lump of rock and ice was discovered in 1969, but has been knocking around for 4.5 billion years. By the time *Rosetta* caught up with Churyumov-Gerasimenko, the comet was some 372 million miles (600 million km) from the sun and its nucleus was quite dormant, but as it approaches the sun, the comet will warm up and its ices will "boil" off (sublimate)—forming the comet's trademark tails.

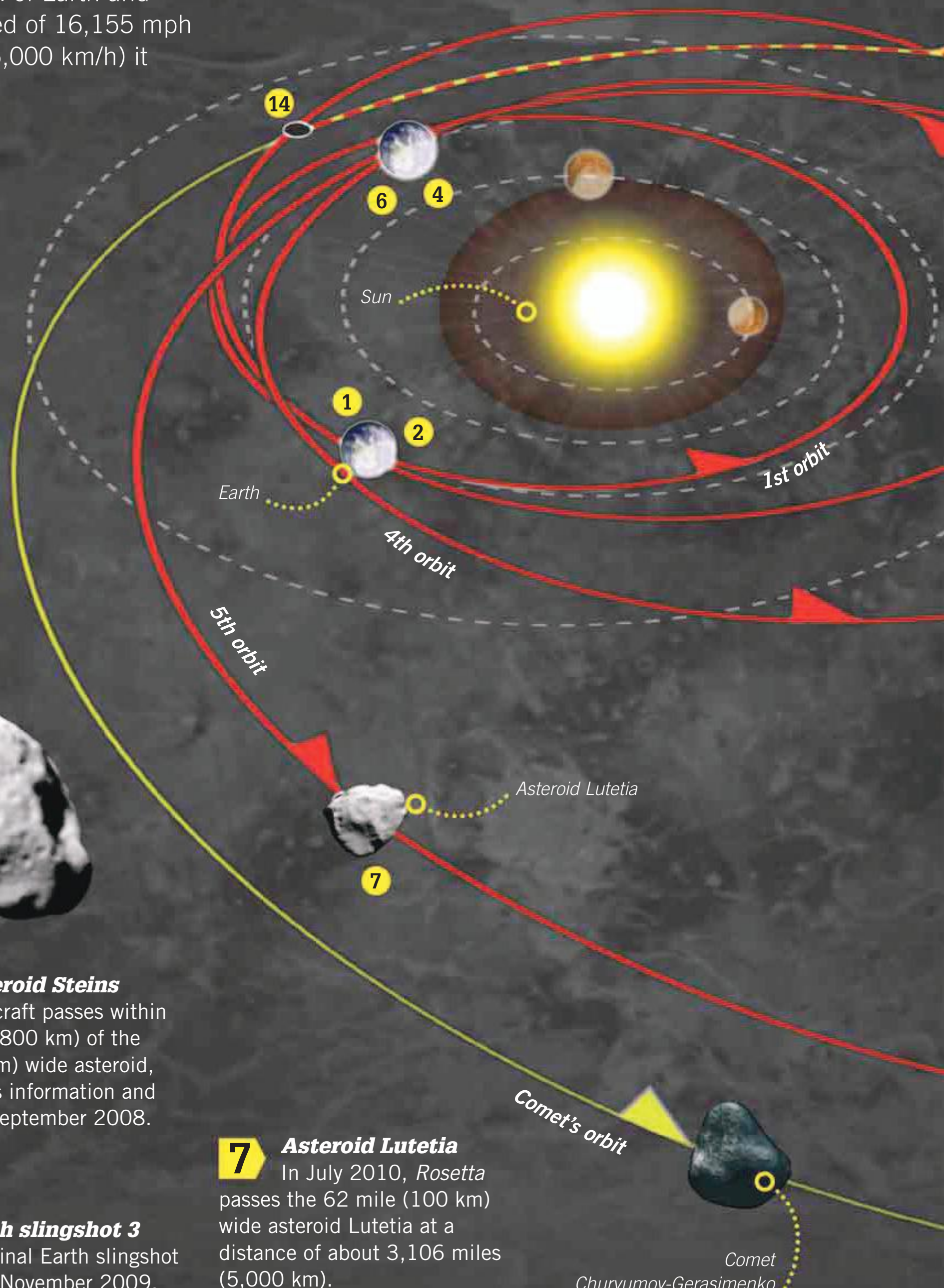


Comet Churyumov-Gerasimenko

THE **CHASE...**

By the time Rosetta caught up with comet Churyumov-Gerasimenko, the craft had completed almost five circuits of the inner solar system and covered a distance of more than 4 billion miles (6.5 billion km). Along the way, the craft used the gravitational pull of Earth and Mars to accelerate from its launch speed of 16,155 mph (26,000 km/h) to the 83,885 mph (135,000 km/h) it needed to chase down the comet.

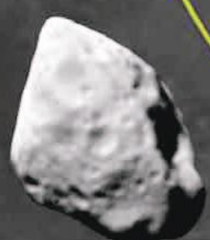
14 ***Toward the sun***
In December 2014, *Rosetta* accompanies the comet as it travels toward the sun. As the comet warms, its ices "sublimate" (pass straight from solid to gas) and are ejected at supersonic speeds. *Rosetta* records and studies these changes.



1 ***Blast off!***
Rosetta launches from Kourou, French Guiana, on board an Ariane 5 rocket in March 2004.

2 ***Earth slingshot 1***
A year after launch, the craft uses Earth's gravity to accelerate.

3 ***Mars slingshot 1***
February 2007.

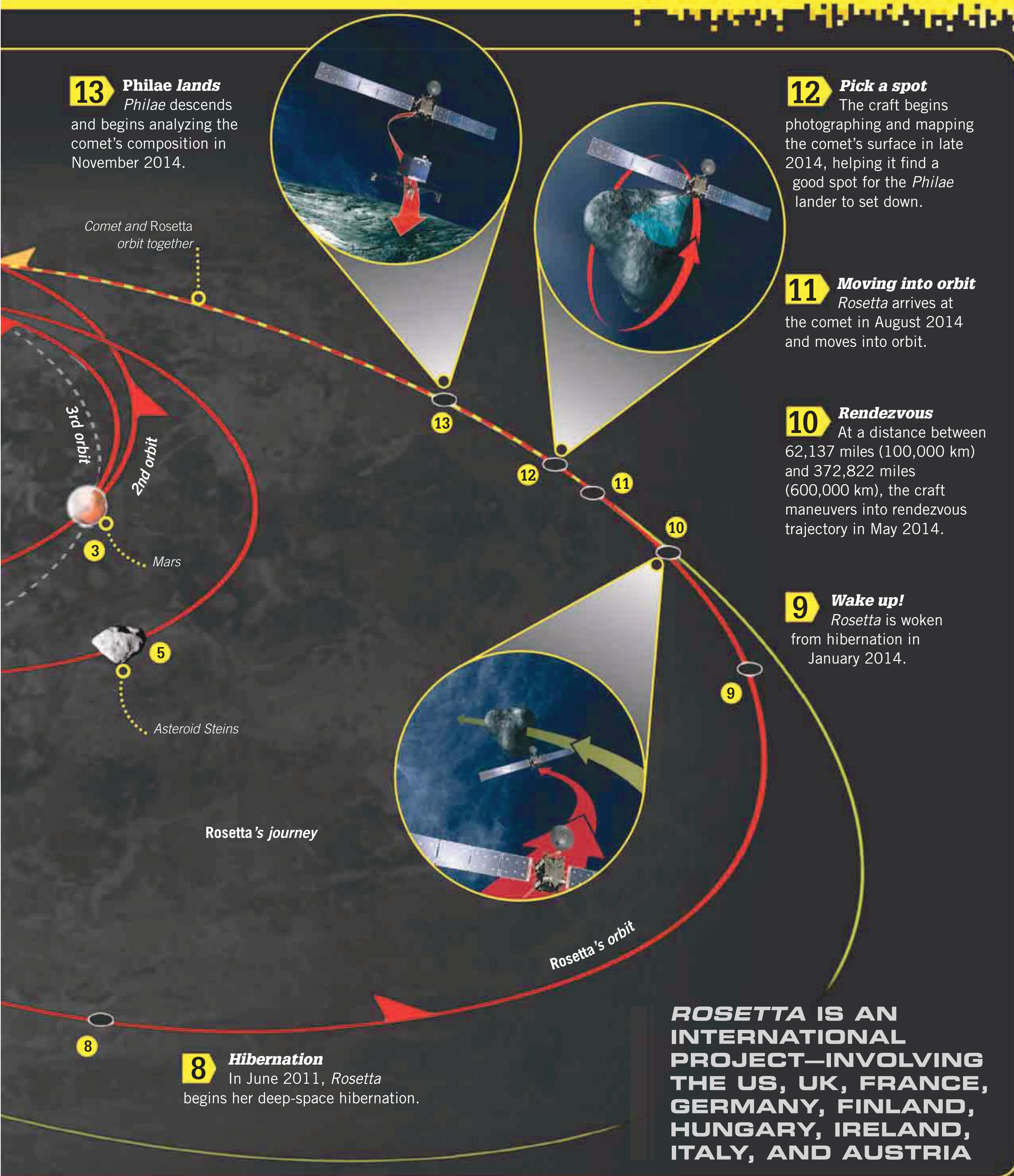


4 ***Earth slingshot 2***
November 2007.

5 ***Asteroid Steins***
The craft passes within 497 miles (800 km) of the 3 mile (5 km) wide asteroid, and collects information and images in September 2008.

6 ***Earth slingshot 3***
The final Earth slingshot happens in November 2009.

7 ***Asteroid Lutetia***
In July 2010, *Rosetta* passes the 62 mile (100 km) wide asteroid Lutetia at a distance of about 3,106 miles (5,000 km).



13 Philae *lands*
Philae descends and begins analyzing the comet's composition in November 2014.

12 *Pick a spot*
The craft begins photographing and mapping the comet's surface in late 2014, helping it find a good spot for the *Philae* lander to set down.

11 *Moving into orbit*
Rosetta arrives at the comet in August 2014 and moves into orbit.

10 *Rendezvous*
At a distance between 62,137 miles (100,000 km) and 372,822 miles (600,000 km), the craft maneuvers into rendezvous trajectory in May 2014.

9 *Wake up!*
Rosetta is woken from hibernation in January 2014.

8 *Hibernation*
In June 2011, *Rosetta* begins her deep-space hibernation.

***ROSETTA* IS AN INTERNATIONAL PROJECT—INVOLVING THE US, UK, FRANCE, GERMANY, FINLAND, HUNGARY, IRELAND, ITALY, AND AUSTRIA**

GRAVITY LENSING TO SEE THE COSMOS

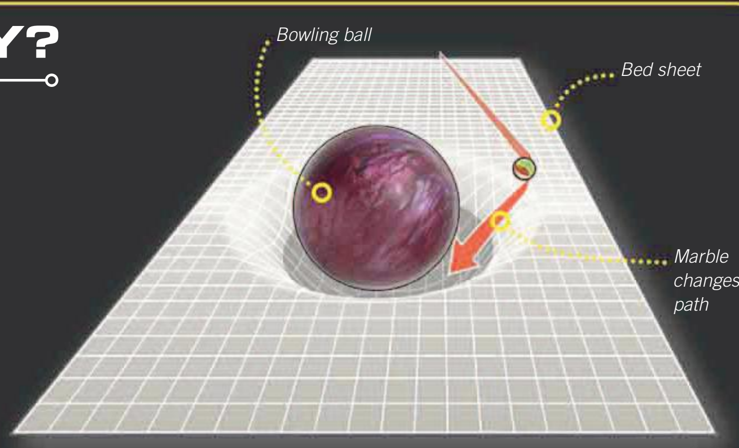
IT MIGHT SEEM COUNTERINTUITIVE, but the best way to see an object in the most distant recesses of the cosmos is to make sure that you have a nice big galaxy nearby that **completely blocks your view.** Confused? Well, in the weird world of astronomy, not only can you see a distant object parked squarely behind a massive galaxy, but you can see it **bigger and brighter** than you could by using even the very best of telescopes. The phenomenon, known as gravitational lensing, takes advantage of the fact that massive objects warp the fabric of the universe in such a way that light from a distant object is actually bent around the obscuring object, and focused on the other side—much **like light passing through a lens.**

Unlike a conventional lens, a gravitational lens **creates multiple images of the same object from different angles**. This is because the galaxy's gravity pulls in light from angles that would have seen it travel elsewhere in space. These multiple clues provide far more information than a single observation could. By understanding how long it took the light that makes up each image to travel along each path and its speed, researchers could calculate how far away the galaxy is, the overall scale of the universe, and how it is expanding.

Gravitational lensing also works at smaller scales and can be used for planet-hunting. A nearby star, for example, can be used to infer the presence of planets orbiting stars too distant to capture directly and even allows astronomers to figure out the planet's mass. **The results seem to confirm that dark energy (much hated by many astronomers) exists, and that it is accelerating the universe's expansion.**

WHAT IS GRAVITY?

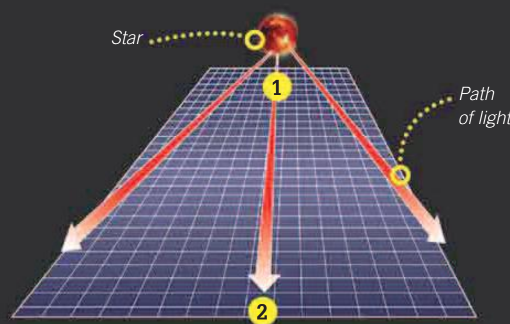
Imagine the universe to be like a bedsheet. If you place a bowling ball on the sheet, it will make a depression in the fabric. If you roll marbles along the sheet, they will roll into the depression made by the bowling ball. The exact same thing happens in the universe. A heavy object such as a star, or galaxy, bends the fabric of the universe (known as spacetime). All lighter objects traveling through spacetime will be drawn into (or toward) the depression caused by the mass of that object. This is gravity.



BED SHEET UNIVERSE
The gravitational pull of stars and galaxies distorts the Universe, just as this bowling ball distorts this sheet.

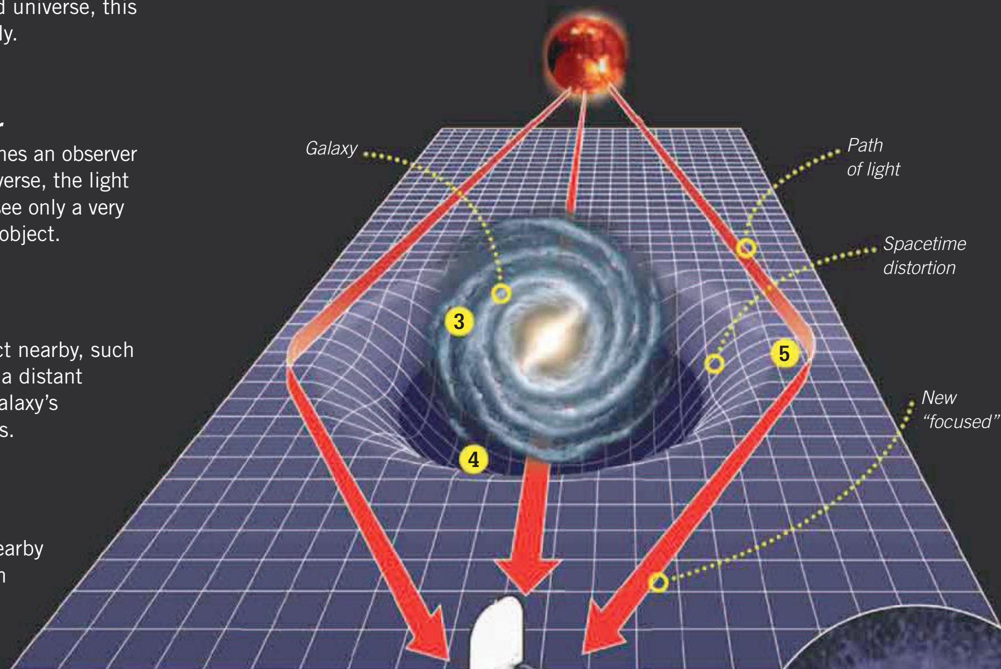
USING A **GALAXY AS A SPY GLASS...**

It is not just stuff like planets (or marbles) that feel the effects of gravity – even light finds itself drawn towards massive objects. If the object is massive enough, it can act like a lens – light rays are bent around it, gathered, and focused – a phenomenon known as gravitational lensing.



1 ***Even spread***
Light leaves a distant astronomical object, such as a star or quasar or galaxy. In a clear and uncluttered universe, this light will spread out evenly.

2 ***Getting dimmer***
By the time it reaches an observer on the far side of this universe, the light is so diminished that we see only a very dim image of the original object.

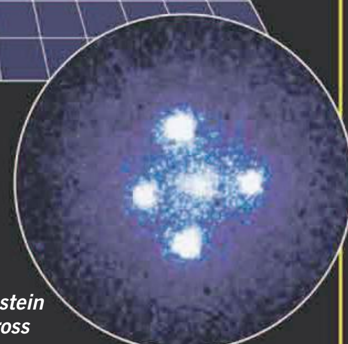


3 ***Gravity lens***
When a large object nearby, such as another galaxy, blocks a distant object, you can use the galaxy's gravitational pull as a lens.

4 ***Warped space***
The mass of the nearby galaxy warps spacetime in the galaxy's vicinity.

5 ***Focusing light***
Light traveling from the distant star "falls" toward the distortion created by the nearby galaxy. This pulls in light that would otherwise have spread out, bending it around the galaxy—in effect "focusing" the light on the other side.

Hubble Space Telescope



Einstein cross

6 ***Final image***
This means that the observer (in this case, the Hubble Space Telescope) sees a much brighter image of the distant star as more light reaches it. This image is distorted, however, as the rays show the image from different angles.

7 ***Einstein cross***
A spectacular example of one sort of gravitational lensing resulted in an "Einstein cross"—where a quasar (center) and four images of it can be seen.

ENGAGE WARP DRIVE!

IN THE 20TH AND 21ST CENTURIES, when a traveler wanted to traverse the country in comfort and style, they took their trusty camper van. Powered by a 1.6-liter air-cooled engine, it transported its occupants on hundreds of road trips. But **by the 23rd century**, travelers were no longer content with highways and boring food and were aiming for the stars.

They soon realized that the van's trusty gasoline engine was not up to the job **(it would take millions of years just to reach the nearest star)**, so someone invented the **"warp drive,"** fitted it to their ride, and the "interstellar" camper van was born. We are all familiar with *Star Trek*'s interstellar ship, the USS *Enterprise*, which allows Kirk and Spock to zip between stars, but surely warp-driven campers are **also the stuff of science fiction?**

If you want to travel between different star systems (without dying of old age along the way), **you need to move faster than the speed of light**. Unfortunately, Einstein proved that you cannot do this because the energy required eventually becomes infinite.

In 1994, a Mexican theoretical physicist named Miguel Alcubierre came up with **a theoretical faster-than-light propulsion method called the Alcubierre drive**. Using the Alcubierre drive, the fabric of space is manipulated to expand behind the camper and contract in front of it. Safe inside a bubble of stationary space, the camper van would be able to traverse the universe at faster-than-light speeds **without ever physically moving**. Everything was looking good for the future of the interstellar camper van (leaving aside the practicalities of "warping" space and time).

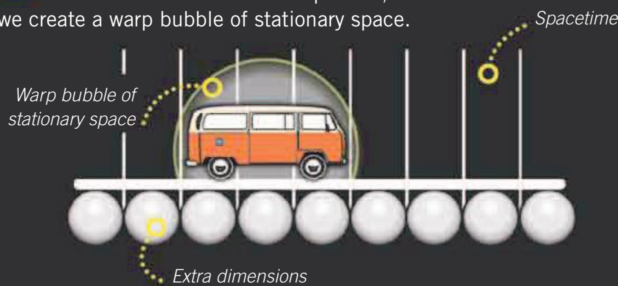
Then scientists used supercomputers to simulate a faster-than-light journey made using an Alcubierre drive and came to a disturbing conclusion: When the camper van stops, **it will destroy everything at its destination**.

Of course, the fact that a warp drive could turn out to be the ultimate doomsday device is the least of its problems. Alcubierre's original design called for the creation of a "negative energy" bubble that **would distort the fabric of spacetime around it**—just as a massive object like Earth does, but in a much more extreme fashion. Unfortunately, an impossible amount of energy would be required to make such a bubble. It would also require some sort of "exotic matter" (which exists only in theory and, by definition, violates the laws of physics) in an amount equal to **ten billion times the total mass of the observable universe**—that is a lot of matter, by the way. In theory, you can get around this by taking advantage of an area of physics called string theory, but it will be some time before you can swap your internal combustion engine for a warp drive.

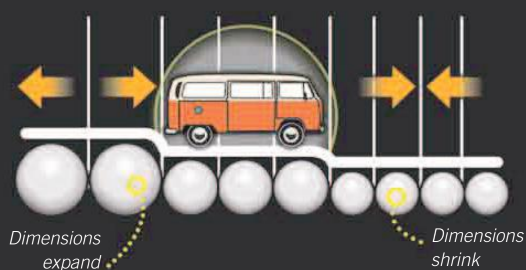
HOW A WARP DRIVE **MIGHT WORK...**

String theory predicts that there are many more dimensions—perhaps as many as 26—than the four we are familiar with. If this is true, it might be possible to manipulate these extra dimensions to bend space and time at will.

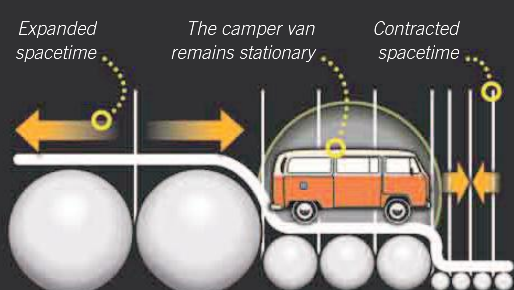
1 ***Bubble bobble***
Around our interstellar camper van, we create a warp bubble of stationary space.



2 ***Squashing space***
By squashing the dimensions in front of the bubble, and expanding them behind it, the camper van will be carried though space, as if on a wave.



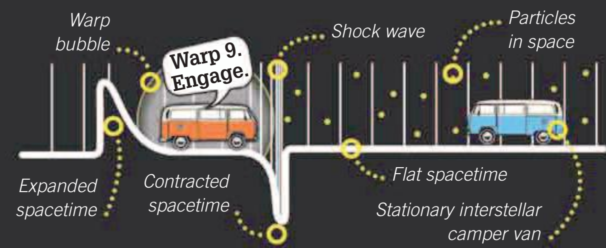
3 ***Comfortable ride***
Inside the van, the passengers are not subjected to massive acceleration forces and the van does not violate any fundamental laws of physics.



... OR PERHAPS **DESTROY YOU**

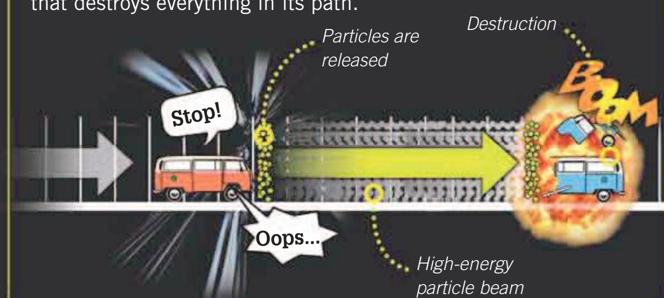
Warp travel might allow future space explorers to cover vast distances, but it might come with a rather deadly side effect...

1 ***Shock wave ahead!***
The warp bubble travels through space, carrying the interstellar camper van along with it. Ahead of it, spacetime is so heavily distorted that a shock wave forms (like the wave that forms ahead of the bow of a ship).



2 ***A full vacuum***
Even though it seems empty, space is full of all sorts of different particles. As the warp bubble moves through space, it picks these up. Some enter the bubble, but others become trapped in the shock wave.

3 ***Kabooooom!***
These trapped particles pick up huge amounts of energy as they are swept along. When the warp bubble stops, the particles are released in a high-energy beam that destroys everything in its path.



SPACE: THE FATAL FRONTIER

SO, AFTER DECADES of careful budgeting, you finally bought your very own interstellar camper van. You are a month into your trip to Mars—to boldly camp on the plains of Amazonis Planitia (with stunning views of Olympus Mons)—when disaster strikes. **Billions of tons of radiation**, spewed into space by a colossal solar storm, is bearing down on you.

With no time to move out of its path, the best you can do is **lower your sun visors and hope for the best.** As billions of supercharged particles blast through your body, shattering DNA and obliterating your bone marrow, you have time to regret buying the embroidered seat covers instead of that radiation shield option. Your irradiated, blister-covered corpse is found months later by an itinerant asteroid miner. **You are quite dead.**

If only you had equipped your vehicle with a mini-magnetosphere plasma radiation shield, things might not have gone so badly. Designed in the early decades of the 21st century, the radiation shield **re-created the magnetic bubble that protects Earth from the worst of the sun's high-energy hissy fits.** The device consists of superconducting coils that are supercooled and charged with high-voltage currents to generate a magnetic bubble around the vehicle. This bubble is then filled with a low-density plasma (electrons and protons stripped from hydrogen atoms) that interacts with the magnetic field to create **a cocoon of protective electric currents.** If you'd had one, the electric field would have been able to absorb or deflect the worst of the solar storm—saving your life.

The device has a long history. First suggested in the 1960s as a means to protect astronauts on long voyages, early designs were dismissed because the electric field would have needed to be too large to be practical. With this issue fixed, the shield proved its worth in the 2030s when early lunar and Martian colonists used versions of it to protect their craft and on-surface habitats. **You should have listened to the salesman.**

But how does solar radiation affect the human body, you ask? High-energy particles such as protons and electrons are known as ionizing radiation. They are so energetic that **they can pass clean through the human body**, dumping energy and knocking electrons from atoms (ionizing them). High-energy protons in particular strike molecules in living tissue and break them apart, like teeny tiny bowling balls. Being in the path of a powerful solar event, like a coronal mass ejection (CME), is like **having a neutron bomb go off next to you.** Ionizing radiation wreaks havoc with the structure of DNA that is not easily fixed—creating errors that can lead to cancer. Fast-growing cells like hair follicles, skin, and bone marrow are particularly vulnerable—leading to hair loss, vomiting, diarrhea, bleeding gums, loss of immune defenses, and accelerated aging.

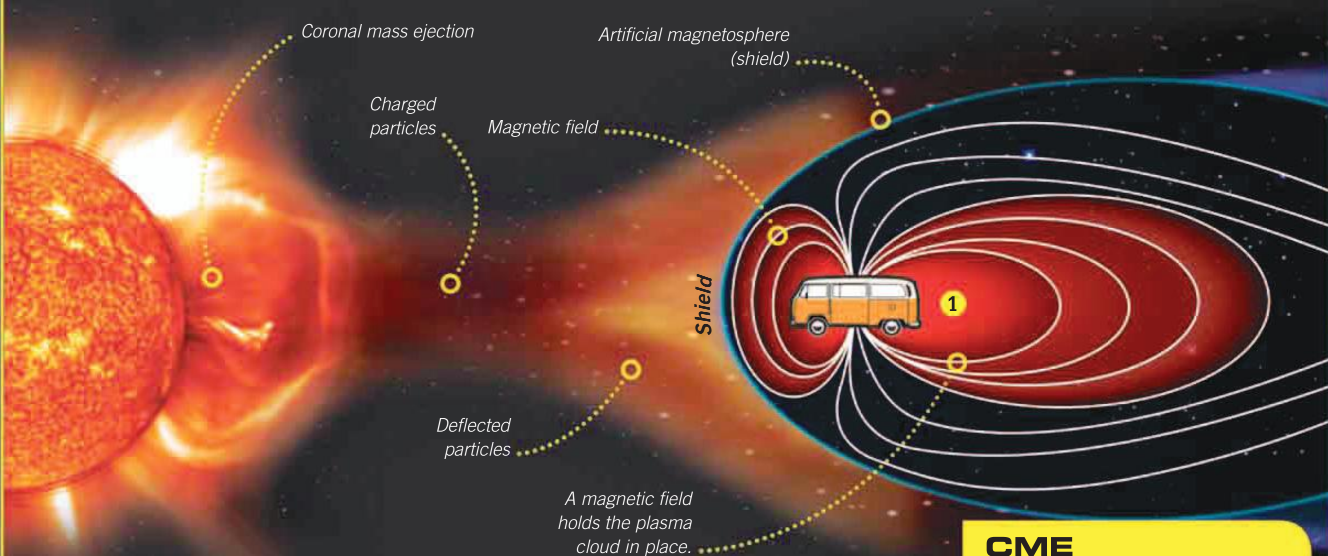
For reasons still not understood by science, crew members wearing red shirts are particularly badly affected and often perish first.

RAISE SHIELDS!

In space, the thin steel shield of the camper van offers no protection from high-energy protons. Even several inches of metal would be pretty useless because protons could cut right through it. In fact, such shielding could be more dangerous than none at all, as protons passing through it can knock neutrons from the shield's atoms—irradiating the occupants with secondary radiation. Several yards of shielding might work, but would be prohibitively heavy. Another solution is required...

EVEN A SMALL SOLAR FLARE EXPLODES WITH THE ENERGY OF MILLIONS OF 100-MEGATON HYDROGEN BOMBS

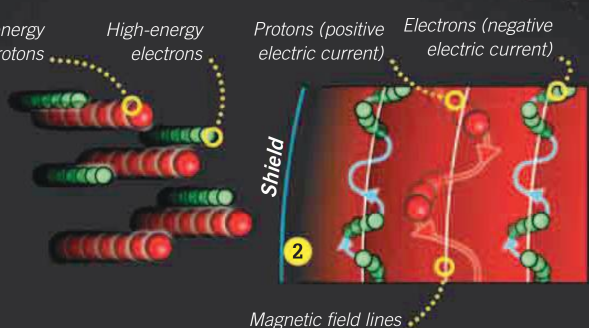
1 *Electric gas* The camper van is equipped with a high-voltage machine that tears hydrogen atoms into their constituent protons and electrons. The hot, electrically charged gas (plasma) is then pumped into space around the craft.



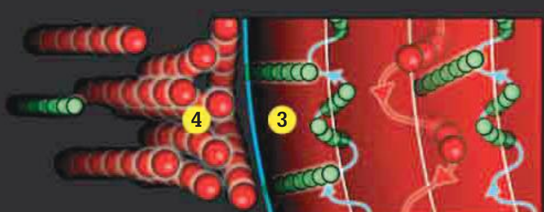
CME

Coronal mass ejections (CMEs) are the most powerful events in the solar system. A single CME can throw 10 billion tons of charged particles (mostly protons and electrons) into space—covering an area as wide as 30 million miles (48 million km).

2 *Positive and negative* Electric currents run through the plasma bubble—with negatively charged electrons flowing one way (spiraling around the lines of the magnetic field) and positively charged protons flowing the other.



3 *Solar wind* When the supercharged particles of the solar wind strike the shield, the electrons are captured by the magnetic field and start flowing along the magnetic field lines—boosting the electric current and the shield's effectiveness.



4 *Protected* The high-energy protons are either stopped completely or deflected by the shield, and flow around the spacecraft—forming a bubble in the solar wind in which the spacecraft is protected.

LEAP SECOND

IT IS ONLY A THEORY

DEATH RAYS FROM OUTER SPACE

CURIOSITY: SCIENCE'S HEART

WHY DOES ANYTHING EXIST?

THE STORY OF THE PULSAR

WHAT IS DARK MATTER?

DARK MATTER BUILDS THE UNIVERSE

A WEIRD, ALMOST PERFECT UNIVERSE

IS GLASS A LIQUID?

GRAVITY SLINGSHOT

HELIUM SHORTAGE

THE APPLIANCE OF SCIENCE

WE ARE ALL MADE OF STARS

DOING THE BLACK HOLE TWIST

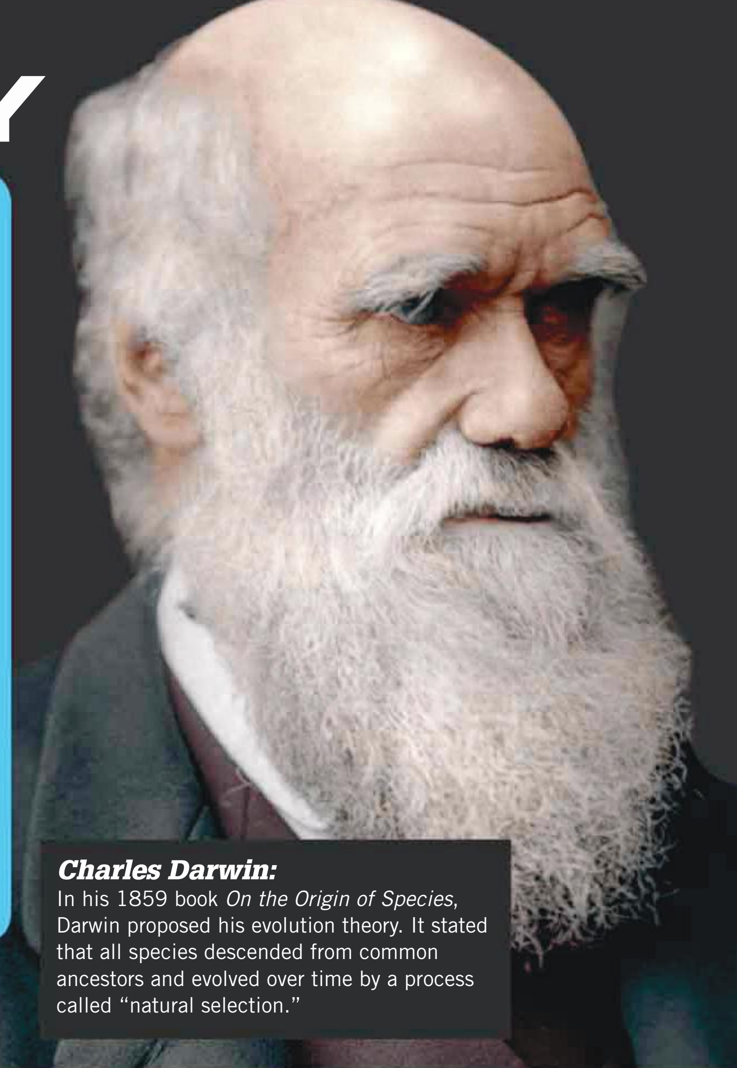
WHY IS GRAVITY SO WEAK?

IT IS ONLY A THEORY

SOMETIMES YOU CANNOT HELP THINKING that scientists do not want nonscientists to understand what they are talking about. It is as if they protect their knowledge from the great unwashed by hiding it behind **a minefield of jargon, technical terms, and unpronounceable Latinisms,** and, as if that were not enough, they have a final line of defense—a smoke screen of linguistic subterfuge in which **everyday words become double agents imbued with confusing and contradictory meanings.**

Of course, this is not the case at all. **Scientists do want to communicate their discoveries**—it is just that sometimes they seem to do so in a slightly different language.

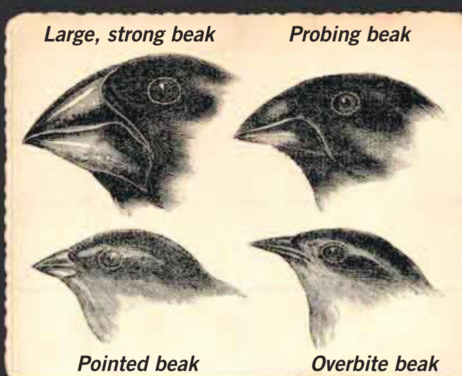
Let us take a look at some words that mean one thing to us but might mean something very different to scientists: ***hypothesis, law,* and *theory.*** And then let's see how they work.



Charles Darwin:
In his 1859 book *On the Origin of Species*, Darwin proposed his evolution theory. It stated that all species descended from common ancestors and evolved over time by a process called "natural selection."

EVOLUTION: A PROPER THEORY

In 1835, British naturalist Charles Darwin noted that finches living on different islands of the Galápagos Islands had different beak shapes. Each beak seemed ideally suited to exploit the food source available on each island—finches with large, strong beaks (perfect for nut-cracking) lived on islands with lots of nuts, but, on islands where insects were the main food source, the finches had slender, pointy beaks.



HYPOTHESIS:
In his book *On the Origin of Species,* Darwin suggested that a creature's body was sculpted by its environment. Those with features that were best suited to where they lived were more likely to survive, and to pass on those features to their offspring. Over great expanses of time, these small changes could add up to create entirely new species.

Hypothesis

This one is nice and easy and is exactly what you would expect it to be. **A hypothesis is the first rung on the ladder of scientific inquiry. It is an idea, or a best guess, that is formulated to explain observations.** For example, Bob, Sally, and Jake see a curtain flapping around and moving (seemingly) independently of its surroundings. Bob hypothesizes that the movement is being caused by a nearby open window. Sally hypothesizes that there might be somebody hiding behind the curtain whose movements are creating the observed effect. Jake hypothesizes that it must be caused by an invisible, incorporeal spirit.

Bob can test his hypothesis by checking for an open window and then trying to replicate the observation—if the curtain moves when the window is open and stops when it is closed, he can be fairly certain his hypothesis is correct. Sally can test hers by checking the curtain for a hidden curtain-twitcher—if no one is present, she can formulate an alternative hypothesis. Jake has made an untestable hypothesis—he cannot detect or measure the ghost, so he cannot remove or include its "influence" to test for a result. He might take note of Bob's results and conclude that the open window was the culprit, or he might say the window was only open because the spirit made it so. **Bob and Sally are being scientific—Jake is not.**

IN SCIENCE, A THEORY IS NOT JUST A HUNCH OR A BEST GUESS—IN FACT, IT IS VERY MUCH THE OPPOSITE (NO, NOT A WORST GUESS)

Making it law

This where meanings start to get a little muddled. In our society, a law is the pinnacle of a set of rules—a law is the umbrella under which rules reside. But, in science, a law is really only the second rung on the inquiry ladder. **Scientific laws are a description of how something works under specific circumstances.** Taking our example, having successfully tested his open-window hypothesis several times, Bob formulates a "law of open windows," which states that an open window will cause a curtain to flap around. Jake will dispute the law because Bob cannot disprove the presence of the curtain-twitching spirit.

Bob's law only describes how the curtain behaves when the window is open; it does not explain what is causing it to behave that way—for that, he has to formulate a theory.

Theory is king

A theory is one of the pinnacles of science and is what scientists like Bob strive to make out of their hypotheses and laws. **A theory usually includes several different hypotheses and laws**—each of which must have withstood

LAW: Biological species change from one kind to another.

PREDICTION: For a theory to be successful, it must make testable predictions. Darwin predicted that fossils would be found that would "fill in the gaps"—if one species evolved into another, there must be evidence of the halfway point in its evolution, when it possessed features belonging to both its ancestors and its future descendants.

EVIDENCE: Just two years after Darwin published *On the Origin of Species,* a fossil was discovered that would become the poster child for evolution: *Archaeopteryx*. Halfway between its dinosaur ancestors and its bird descendants, *Archaeopteryx* shared features belonging to both—just as Darwin predicted.

Archaeopteryx: Discovered in 1861, *Archaeopteryx* is seen as the "missing link" between dinosaurs and birds.

all attempts to prove them false. **Theories explain observations and laws by providing the mechanism that makes them work.**

Going back to our example, Bob is happy with his "law of open windows," but, as he tests it further, he notices that the rate of the curtain's movement is not constant—sometimes it moves a lot and other times it barely moves at all—so he looks for a mechanism that explains why the curtain moves at all. He develops another hypothesis that suggests that varying air movements outside the open window could account for the variation. He tests this by measuring the air speed outside the window and comparing it to how much the curtain moves. He discovers that there is a connection and develops the "law of air-connected movement," which states that there is a direct correlation between wind speed and curtain movement.

After further testing, Bob discovers that the curtain's movements are also affected by how far open the window is—so he creates a law for this, too. **But all of these laws still lack an explanation of the underlying mechanism that causes the curtain to move.**

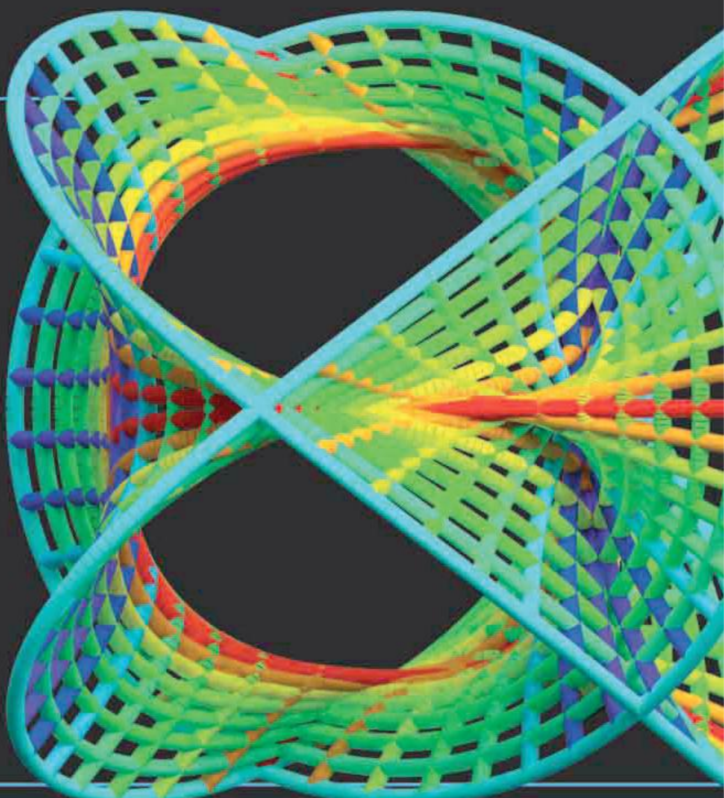
FOR A THEORY TO BE SUCCESSFUL, IT MUST MAKE PREDICTIONS THAT CAN BE TESTED AND INDEPENDENTLY DUPLICATED

After much consideration and many, many more tests, Bob realizes that there must be something within the air itself—something invisible to the naked eye that acts on the material of the curtain, is more energetic in fast-moving air, and is restricted by the aperture of the open window. Based on his evidence, Bob concludes that there must be invisible small bits of matter within the air that, although tiny, can move the curtain when given enough energy. He names the unseen matter after the Latin word for "a small bit"—*particula*—and he calls his new theory the "theory of curtain-moving particles."

Happy with his work, Bob publishes his theory and leaves it to other scientists to search for direct evidence of the existence his "particles."

STRING THEORY: THE THEORY THAT **ISN'T A THEORY**

Two of science's greatest and most successful theories—quantum physics and general relativity—don't work together. Quantum physics fits all the criteria for a theory by predicting and testing effects in the tiny world of particles. Likewise, general relativity works perfectly for predicting and testing how gravity works in the big world of planets, stars, and galaxies. But they are incompatible—gravity can't be explained in the quantum world—and there must be a reason.



Change is good

Some people think that if a theory has to be updated or changed, it must be flawed or incorrect. They point out that theories like evolution are always undergoing revisions and are full of gaps in the evidence.

But they misunderstand what a theory is. A theory can be compared to a car. A car has many complex moving parts that perform many different individual tasks, but they all work in harmony to make the car function. Just as a mechanic can upgrade individual parts, add some parts, and take others away without changing the function of the car as a whole, so **scientists can upgrade, replace, and remove hypotheses and laws without changing the overall truth of the theory.** That is the beauty of a scientific theory.

Even seemingly "perfect" theories are subjected to constant tests and observations—if parts are found wanting, they are refined and (if need be) replaced altogether. Science is sometimes accused of self-protectionism and wanting to preserve the status quo to maintain its illusion of infallibility. But **scientists do not test theories to confirm them—they test them to break them.** You will never hear about the scientist who verifies for the 239,000th time Newton's prediction that a feather will fall at the same speed as an anvil in a vacuum. But the chap who finds evidence that gravity is not what we thought it was will become a household name.

GREGOR MENDEL

Born in the modern-day Czech Republic, Gregor Mendel is known as the "father of modern genetics." Farmers had been selectively breeding specific traits into their livestock and crops for generations, but the mechanism wasn't understood. Mendel spent eight years experimenting with 10,000 pea plants and concluded that traits are inherited through distinct units called genes. Genes are inherited in pairs—one from each parent. Each gene is either dominant or recessive, with the dominant gene determining the offspring's inherited traits. He worked out a series of laws of heredity, which made predictions that were later tested and replicated by other scientists.

Calabi-Yau manifold:
If they do exist, it is thought that the extra dimensions predicted by string theory would be tightly curled around each other, possibly taking a shape akin to a Calabi-Yau manifold.

HYPOTHESIS: »
String theory suggests that what we think of as particles of matter are actually vibrating one-dimensional energy strings. Strings vibrating at different frequencies adopt different states—at one frequency one could be an electron, while at another frequency it could be a photon—resulting in different particles. Likewise, the forces of nature, including gravity, are a manifestation of these vibrations.

LAW: »
Erm… there are none.

PREDICTION:
This is also where string theory falls flat as a bona fide theory—it makes no (as yet) testable predictions. True, it predicts that there may be many more dimensions than the four we are familiar with—up to 26 dimensions that are curled up so tightly (at a subatomic level) that we are unaware of their existence. The dimensions would exist at such a small scale that it would be impossible to detect them—even with the most powerful of machines.

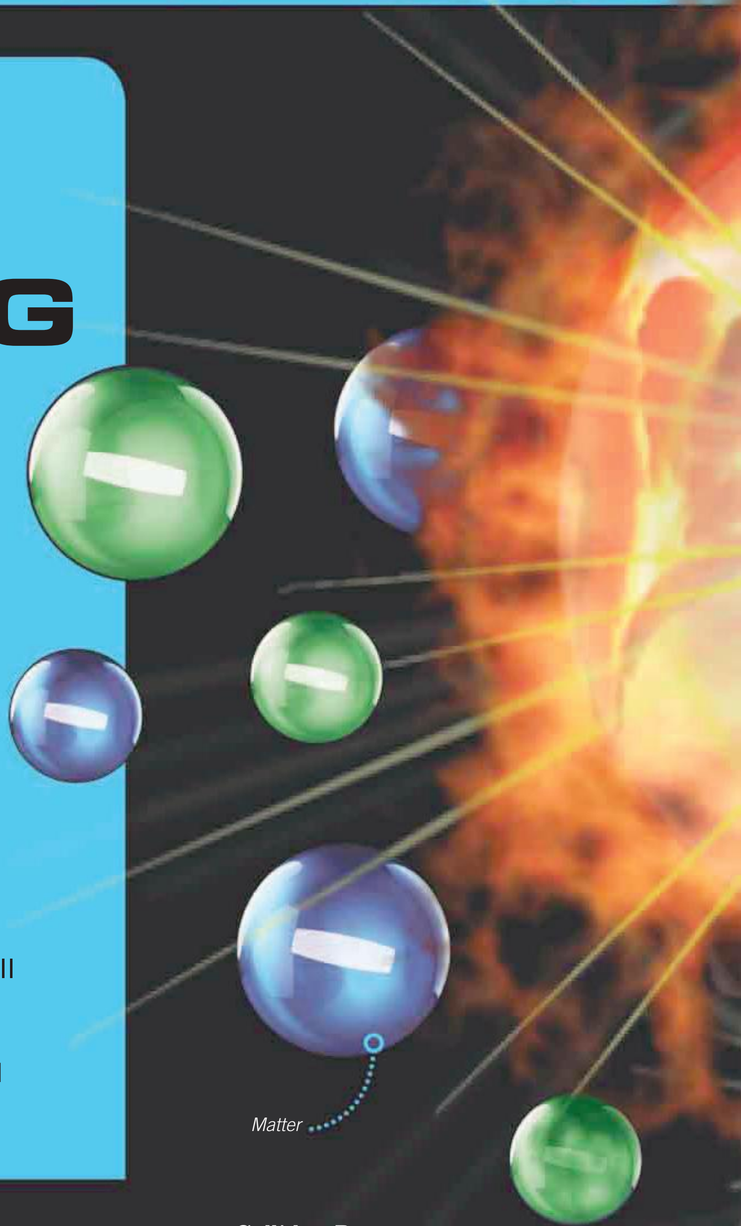
It also predicts that the familiar subatomic particles should have been created in the Big Bang with an accompanying set of heavyweight cousins, but that these would have disappeared (or decayed) within moments of their creation. Unless these so-called supersymmetry particles are created and detected (before they vanish) in the likes of the Large Hadron Collider, this prediction is also untestable. »

EVIDENCE:
There is none. Thus, string theory should not be called a theory.

WHY DOES ANYTHING EXIST?

AT THE DAWN OF EXISTENCE, a mighty war was waged. Two forces faced each other: **matter and antimatter.** Perfect twins separated at birth, but opposite in every way. Neither would be content until the other was annihilated and wiped from the face of existence. Their armies matched each other, particle for particle, and **their mutual destruction should have been assured.**

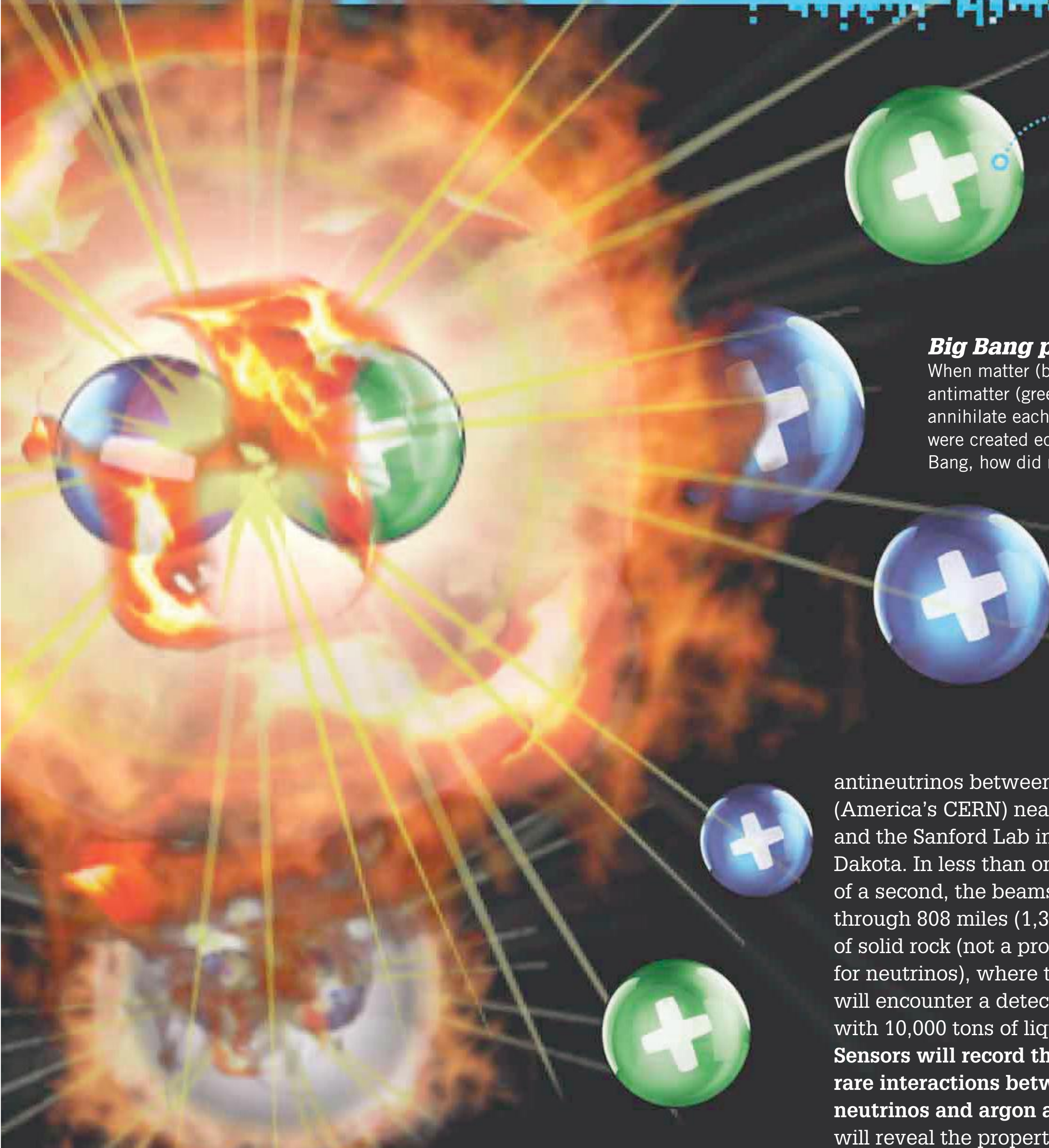
Yet, against all odds, **matter somehow gained the advantage and emerged victorious.** Our best understanding of the physics of the Big Bang tells us that matter and antimatter were created in equal quantities and, when they made contact in the (far smaller and far denser) baby universe, all of their combined mass should have been violently transformed into pure energy. Why and how matter survived the encounter is **one of the most profound mysteries in modern science.**



The current theory is that, although matter and antimatter were created as almost perfect mirror images, there must have been some tiny imbalance, or blemish, that meant that **some were not perfect reflections.** This difference, however tiny, might have been enough to give matter the edge. Scientists have already found a small crack in the mirror, called charge-parity violation, which means that, in some cases, the symmetry of the antimatter reflection becomes broken—**resulting in a particle that is not the perfect opposite of its matter twin.** This "broken symmetry" means that one particle could have an advantage over the other.

This has so far only been witnessed in a tiny number of the particles that are put to the test in the likes of the Large Hadron Collider. But now scientists are pinning their hopes on a less-tested particle—the neutrino.

The neutrino is almost absurdly evasive—it is virtually massless, carries no electric charge, barely interacts with normal matter, and can **spontaneously change its identity,** literally on the fly. It also happens to be one of the most numerous particles in the universe,



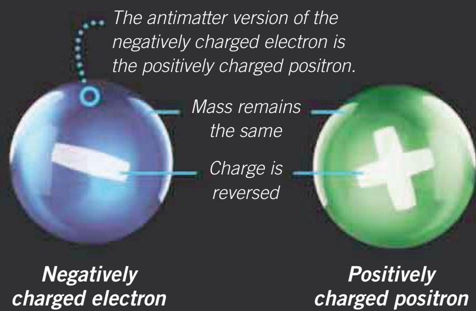
Big Bang problem:
When matter (blue) and antimatter (green) meet, they annihilate each other. So if they were created equal in the Big Bang, how did matter survive?

so if it can be found to be breaking symmetry, **it might be enough to explain matter's rise to power.**

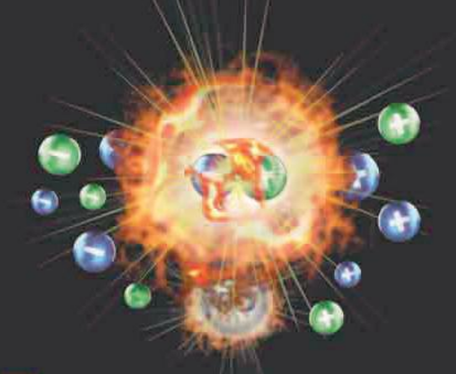
The Long-Baseline Neutrino Experiment (LBNE) is still on the drawing board, but, when completed around 2025, it will send beams of neutrinos and antineutrinos between Fermilab (America's CERN) near Chicago, and the Sanford Lab in South Dakota. In less than one-hundredth of a second, the beams will pass through 808 miles (1,300 km) of solid rock (not a problem for neutrinos), where they will encounter a detector filled with 10,000 tons of liquid argon. **Sensors will record the extremely rare interactions between neutrinos and argon atoms.** This will reveal the properties of the neutrinos and their antimatter cousins—allowing scientists to compare the results. However, the interactions will be so infrequent that **it might take a decade to collect enough data** to discover any matter/antimatter asymmetry.

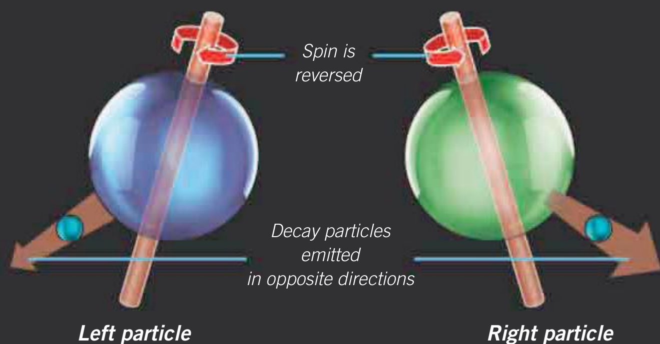
BALANCED **SYMMETRY**

The Big Bang created matter and antimatter together in equal measure. In a perfectly symmetrical universe, where charge and parity are perfectly mirrored, every matter particle would have had an antimatter particle, ensuring their mutual destruction. But that didn't happen...



2 *Charge reversal*
At its most superficial level, the antimatter version of a matter particle is one where the mass remains the same, but the electrical charge is reversed. Other properties, such as spin, must also be reversed.



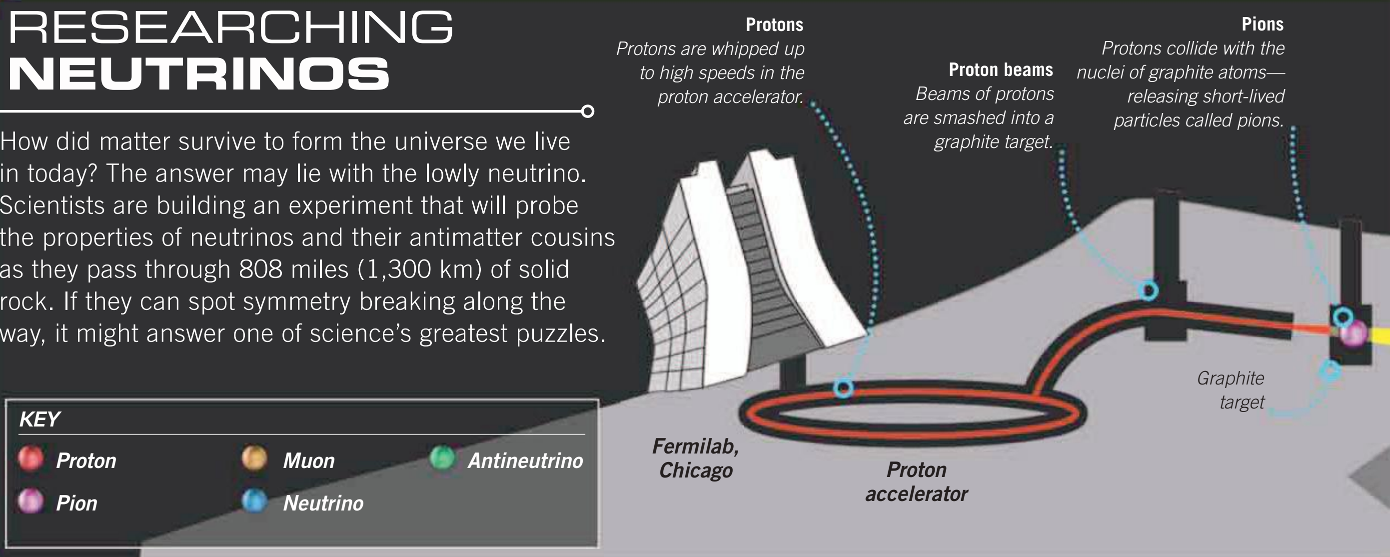


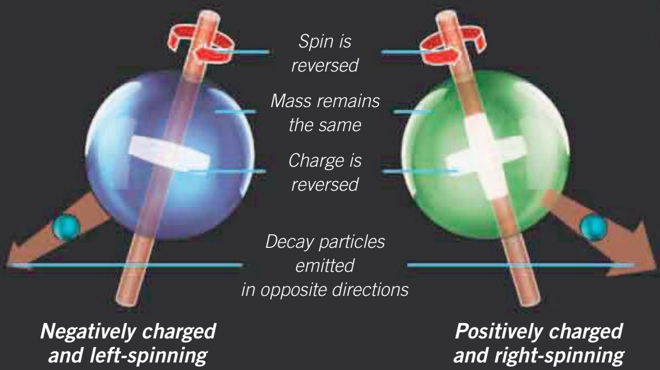
1 *After the bang*
The equal amount of matter and antimatter meant that matter should have been obliterated before anything like stars or planets (or even dust) could have formed—leaving a universe filled with radiation and nothing else.

3 *Parity reversal*
On the left is a particle that spins to the right, and emits a particle to the left when it decays. Its antimatter partner spins to right, and emits its decay particle to the right. This balancing is known as parity.

RESEARCHING **NEUTRINOS**

How did matter survive to form the universe we live in today? The answer may lie with the lowly neutrino. Scientists are building an experiment that will probe the properties of neutrinos and their antimatter cousins as they pass through 808 miles (1,300 km) of solid rock. If they can spot symmetry breaking along the way, it might answer one of science's greatest puzzles.





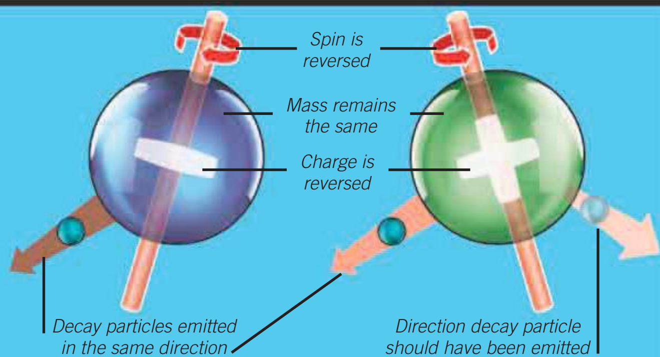
4 *Charge-parity symmetry*

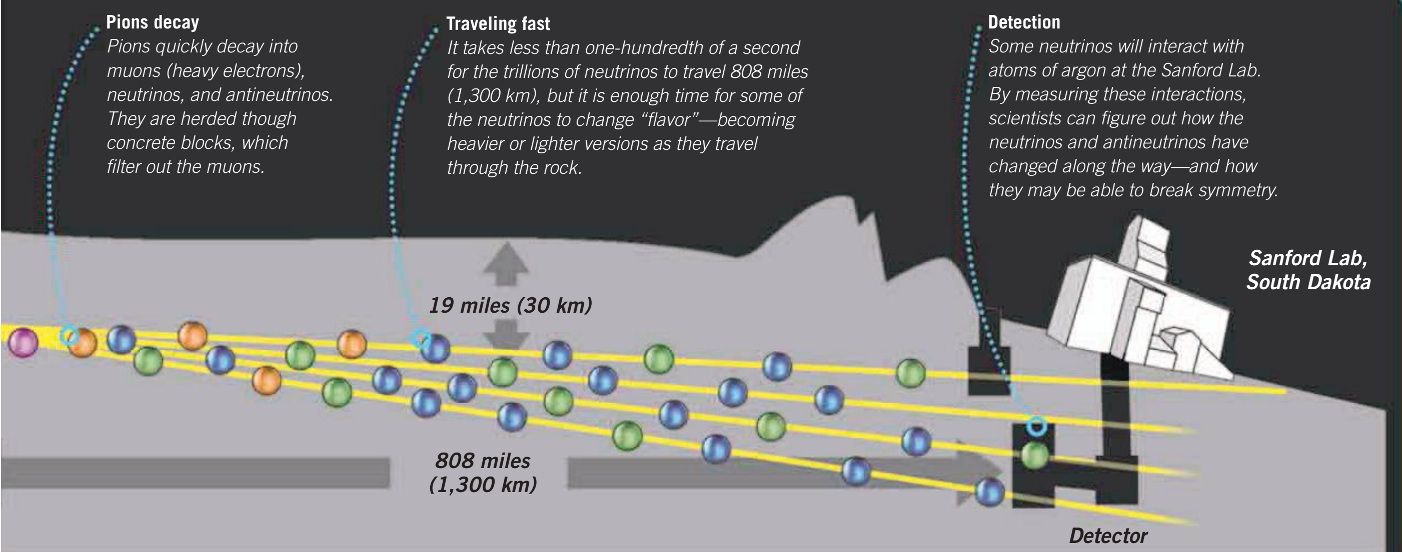
The perfect antimatter particle is one that is an exact mirror image of its matter equivalent—having both its charge and parity reversed. This is known as charge-parity symmetry, and is what we would expect from the early universe.

EVERY SECOND, HUNDREDS OF BILLIONS OF NEUTRINOS PASS RIGHT THOUGH YOUR BODY—AS IF YOU AREN'T THERE

VIOLATING SYMMETRY

We now know that symmetry can be broken. Sometimes an antimatter particle will violate symmetry—perhaps by emitting its decay particle in the same direction as its matter partner, or by decaying at a different rate. If enough violations occurred after the Big Bang, it might explain why matter survived. By behaving differently from their antimatter equivalents, it is possible that particles with broken symmetry just took a little bit longer to decay, stuck around longer, and so won the day for matter. So far, these symmetry violations have only been seen to occur less than 0.1% of the time—not enough to give matter the upper hand, which is where neutrinos come in.





LEAP SECOND

APPROXIMATELY ONCE EVERY YEAR AND A HALF a little extra tick is added to our clocks as the world's official timekeepers decide to **add a "leap second" to the end of the month.** Like a leap year, this leap second is added to bring our clocks back into sync with the rotation of Earth.

The length of a day is determined by Earth's rotation, and one full rotation equals one full day. **But the speed of Earth's rotation is not constant**—ocean tides pulled back and forth by the moon's gravity, churning molten materials deep in Earth's bowels, earthquakes, and even friction from wind all add up and force the planet to give up a tiny bit of its rotational energy. **In other words, Earth slows down, and our clocks need to compensate for this.**

World time: All sorts of cosmic and terrestrial phenomena conspire to slow the rotation of Earth. Leap seconds are added to compensate for Earth's lagging chronometers.

That's not to say that our planet is not a good timekeeper. Left to its own devices, the day would only lengthen by one millisecond every 100 years, but geological forces, such as earthquakes, can cause the clock to slow. Over millennia, all those tiny increases add up and **in 400 million years or so, a day will be 26 hours long.**

The custodians of humanity's timekeeping are a group called the International Earth Rotation and Reference Systems Service (IERS). These time lords use a global network of radio telescopes called the Very Large Baseline Interferometry (VLBI) network **to measure the speed of Earth's rotation to within a millionth of a second.**

In general, one leap second is added every year or two, but **unusual activities in Earth's core since 1999 have meant that only two leap seconds have been added in this time** (the last was added in 2008).

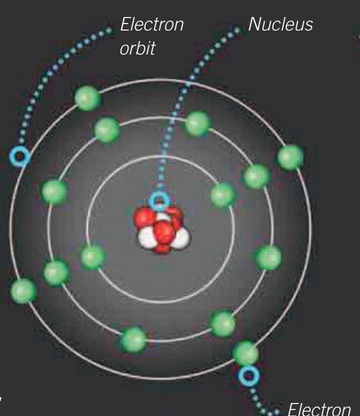
But why should we care? Would it matter if we let the odd millisecond slide by? True, you and I cannot perceive these variations, and even if we could, it would not really matter. But things like satellite navigation systems have to be able to chart the passage of time so accurately that **these tiny changes do make a difference.**

HOW DO WE MEASURE **TIME SO PRECISELY?**

For millennia, mankind was perfectly happy using the sun to chart the passage of time. But, as technology advanced, so too did our need to track time with ever-increasing accuracy. Today's atomic clocks are so precise, that they lose less than one second in 300 million years. Here's how they do it:

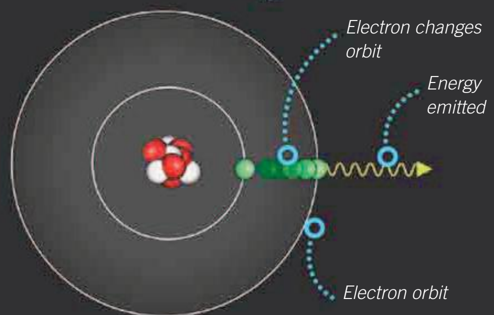
1 *Jumping electrons*

In an atom, the electrons that surround the nucleus move in orbits that occupy different levels. The electrons can jump between levels.



2 *Changing levels*

An electron that gains energy moves up a level, and one that loses energy drops down a level. It requires a very specific amount of energy to make the jump. The energy is emitted as electromagnetic radiation at a certain frequency.



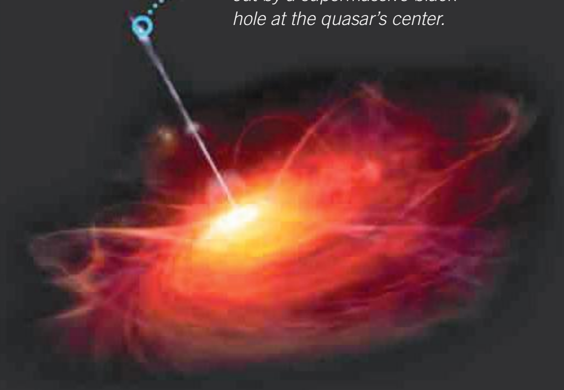
Cesium fountain clock
This is the world's most accurate atomic clock—losing less than one second in 300 million years.

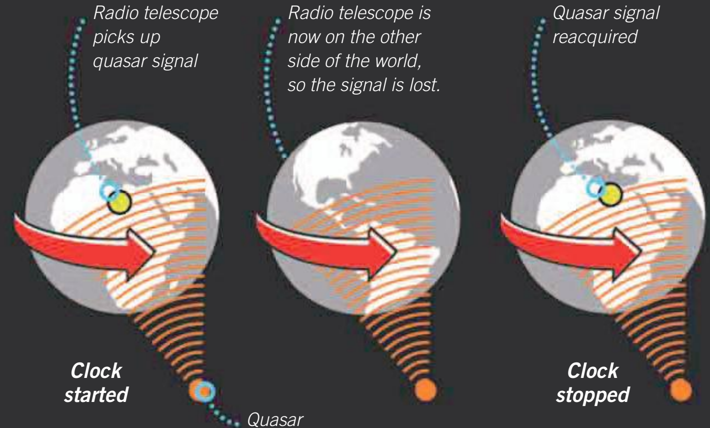
3 *Atomic clock*

An atomic clock uses this wave frequency to chart time (just like an old-fashioned clock uses a pendulum). But, whereas a pendulum only ticks once a second, an atom "ticks" millions of times a second. This means that an atomic clock can chart the passage of time with extreme accuracy.

HOW DO WE KNOW HOW **FAST EARTH ROTATES?**

How do you judge how fast something is moving when, relative to you, it does not seem to be moving at all? Well, you need to look beyond the object you want to measure and try to judge its speed relative to more distant objects. Imagine an ant sitting on the surface of a slowly spinning playground merry-go-round. If he were to look at just the merry-go-round's surface, it would seem that the merry-go-round was stationary. But if he looked out into the rest of the playground, he could judge how fast the merry-go-round was moving by measuring how long it took for the swings to pass by, and then (ahem) swing back into view. In the absence of a set of galactic swings, scientists use distant quasars to measure Earth's rotation.





BRIGHT LIGHTS FROM AFAR

Quasars are distant, energetic objects. They are intense sources of X-rays as well as visible light and can shine two trillion times brighter than our sun (that is 100 times brighter than our galaxy). Most quasars are more than 3 billion light-years away, but they can be even further out than that. Because they are so distant, a quasar's position remains fixed relative to Earth and forms a steady and precise reference point.

MEASURING EARTH'S ROTATION

Scientists use a network of widely spaced radio telescopes to measure Earth's rotation and an ultraprecise atomic clock. Several radio telescopes are pointed toward a distant quasar. When the quasar signal is detected by the telescopes, the time is recorded. As Earth rotates, the telescopes lose the quasar signal. At the end of one full rotation, the quasar signal is reacquired and the time is recorded again, which is then used to give a precise measurement of Earth's rotation.

WHAT WILL HAPPEN IN AN EXTRA LEAP SECOND?

Your body will produce more than **2.5 million red blood cells**

Mosquitoes will infect ***8 people*** with ***malaria***

About ***40 stars*** will end their lives in a ***supernova explosion***

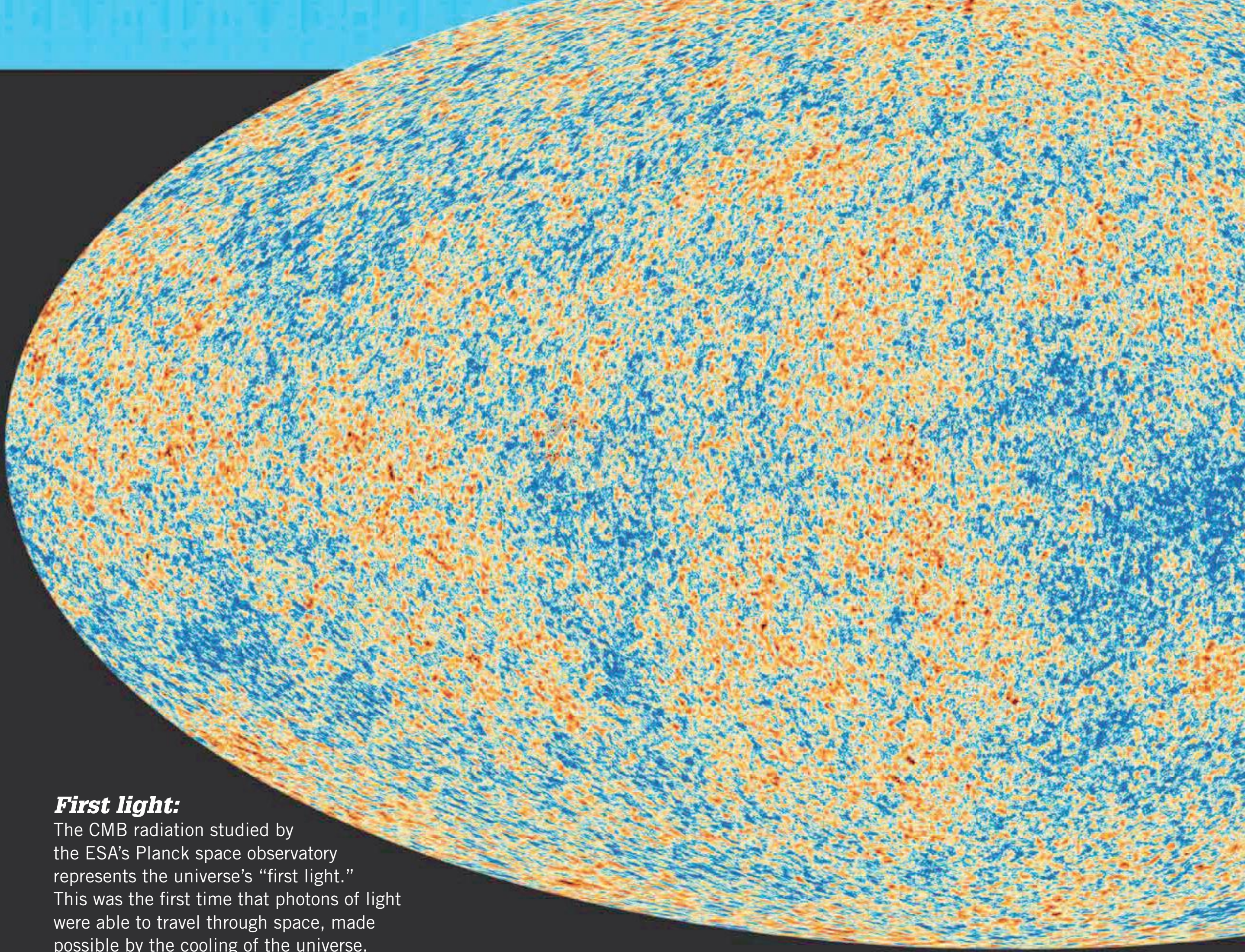
29,000 bananas will be eaten

Lightning will strike earth ***99,500 times***

255,000 TOILETS will be flushed

A hummingbird will flap its wings up to ***200 times***

Hens will lay 2,200 eggs



First light:
The CMB radiation studied by the ESA's Planck space observatory represents the universe's "first light." This was the first time that photons of light were able to travel through space, made possible by the cooling of the universe.

A WEIRD, ALMOST **PERFECT UNIVERSE**

THE COSMIC MICROWAVE BACKGROUND (CMB) dates from about 380,000 years after the Big Bang and represents **the "first light" of the universe**—released when it had cooled enough to allow photons of light to travel unimpeded through space for the first time.

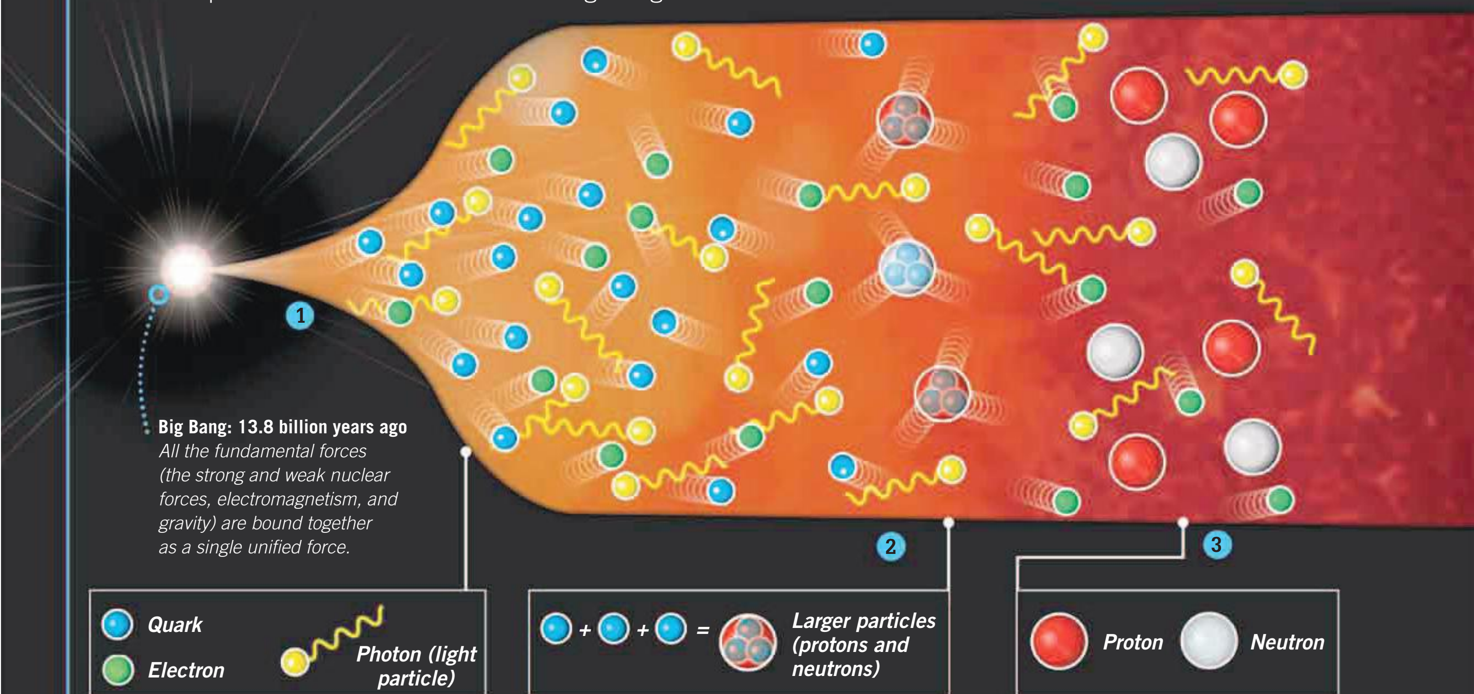
When the light from the CMB began its journey, **the entire universe was even hotter than the melting point of iron,** and its energy was emitted as heat—also known as infrared radiation. But, as the universe expanded, the wavelength of the light was stretched (a bit like how a wavy line drawn on a rubber band becomes stretched when the band is pulled).

The CMB reveals how evenly spread matter and energy were in the early universe. It also shows how uniform the temperature was: Although the colors look dramatic (blue is colder and orange is warmer), they actually represent **temperature differences of less than a hundred-millionth of a degree.**

This uniformity of temperature couldn't have been created by a universe that expanded slowly, so is seen as evidence that **the universe underwent a period of startlingly rapid, faster-than-light expansion known as cosmic inflation.** By expanding faster than light and information can travel, **space overtook energy's ability to react to the change**—so, like a rabbit caught in headlights, energy became "fixed" in its preinflation state. The only thing missing at this early stage is "dark energy", the mysterious agent thought to be driving the universe apart at an ever-increasing rate.

CMB: THE FINGERPRINT OF INFLATION

Planck's map of the CMB seems to confirm a key part of the Big Bang theory called cosmic inflation. The concept of inflation was added to the Big Bang theory in the 1980s to explain the almost perfectly even spread of energy and matter revealed by earlier studies of the CMB.



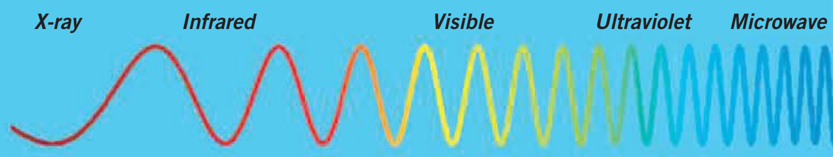
1 Inflation: 0.000000000000000000 0000000000000000001 seconds after the Big Bang
Space, time, matter, and energy are all bundled up in an impossibly small, infinitely dense, insanely hot fireball. The Big Bang breaks down the unified force, and powers the exponential inflation of the universe.

2 Fundamental particles: 0.000000000000000000000000000 000001 seconds later
Energy congeals into matter and the first particles—quarks, electrons, and neutrinos (and their antimatter twins)—are born. These matter opposites collide and annihilate each other, releasing huge numbers of photons.

3 Protons and neutrons: 0.000001 seconds later
As the temperature drops, colliding quarks can join together without being torn apart immediately by all that energy. Quarks combine (via the strong nuclear force) in sets of three to form the first protons and neutrons.

CHANGING WAVELENGTH

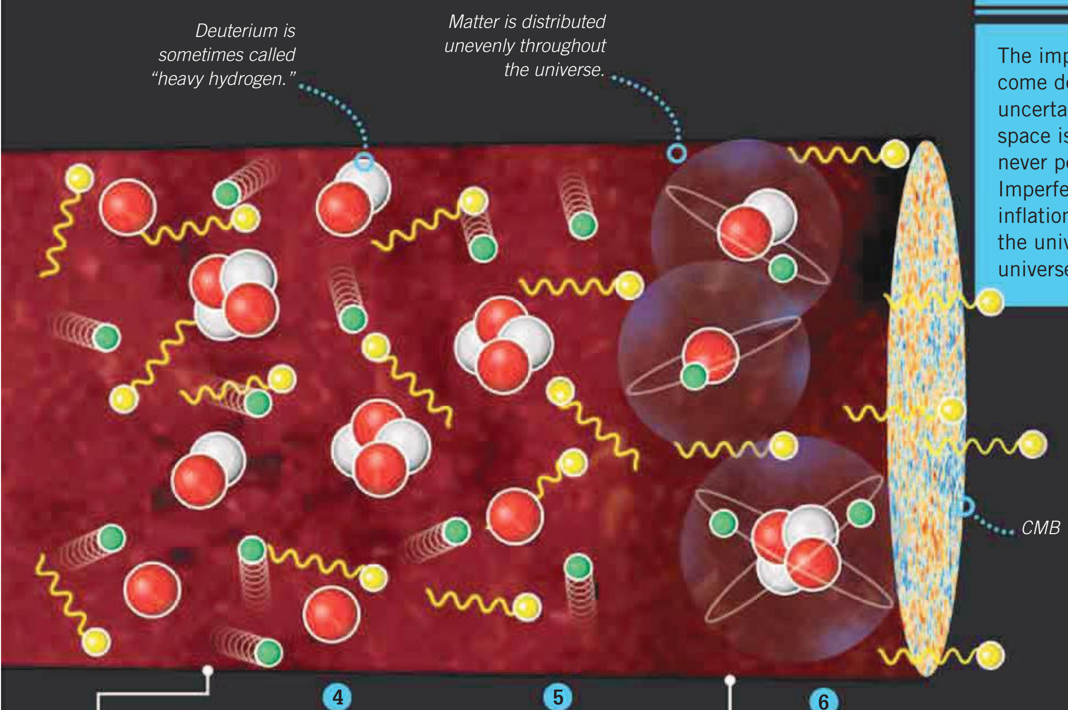
When the light from the CMB began its journey 13.81 billion years ago, the universe was hot, and its energy was emitted as infrared radiation. But, as the universe expanded, the wavelength of the light was stretched. This stretching has caused its wavelength to move into the microwave part of the electromagnetic spectrum, which is what Planck is designed to detect.

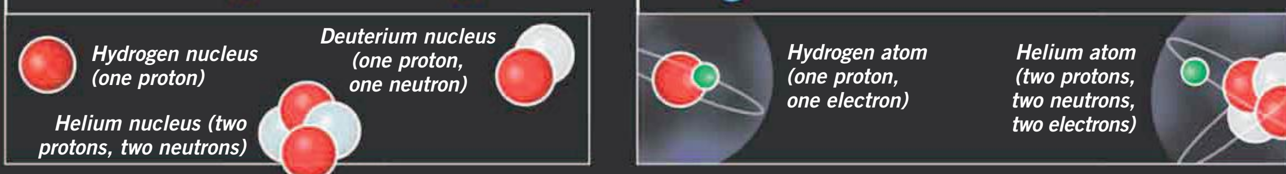


The electromagnetic spectrum

UNEVEN UNIVERSE

The imperfections in the universe might come down to something called quantum uncertainty, which tells us that empty space is never truly empty, and therefore never perfectly smooth and regular. Imperfections present at the moment of inflation would have expanded along with the universe and been imprinted on the universe from that moment forward.





CMB IMPERFECTIONS
If matter and energy had been spread perfectly evenly, the universe we know today would not exist. The temperature fluctuations in the CMB reflect the tiny differences in density and distribution of matter (more matter, more heat). These denser patches had just a little more gravitational pull than their surroundings and accumulated enough matter for the first stars to form.

4 *Nuclei: from 3 minutes until about 377,000 years*

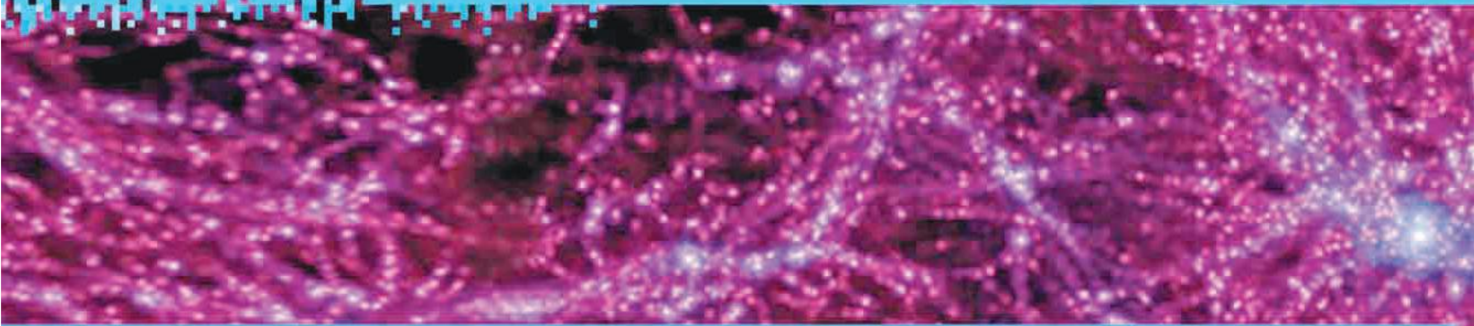
When the temperature has dropped to about a billion degrees, colliding protons and neutrons can combine through nuclear fusion to form the nuclei of the simplest chemical elements—hydrogen and helium.

5 *Opaque era: from 3 minutes until about 377,000 years*

During this era, the universe is filled with a hot, opaque soup of atomic nuclei and electrons, called plasma. All of the photons created through matter/antimatter annihilations are trapped within the plasma.

6 *Stable atoms: 377,000 years later*

The universe cools enough to allow the positively charged atomic nuclei to capture the negatively charged electrons—becoming neutral. With all the nuclei stabilized, photons can travel unimpeded and the universe becomes transparent.



WHAT IS **DARK MATTER?**

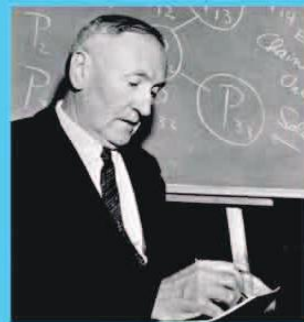
THE HISTORY OF MANKIND'S RELATIONSHIP WITH THE COSMOS is one of repeated revelations that our place within it is far smaller than we had believed. Once, we thought that Earth was the center of all, and the universe was little more than a **window dressing for the night sky.** Then astronomers revealed our planet to be just one lump of rock traveling around a sun that is just one star among many hundreds of billions of others in an unremarkable galaxy that is just one among countless billions more.

In a historical heartbeat, **we went from being the kings of a palatial universe built just for us to an invisible smudge on a speck of matter**, orbiting a mote of incandescent dust, caught in a swirling eddy, lost in the dark ocean of the cosmos.

Dark matter:
This is a computer simulation of the cosmic web of interconnecting filaments thought to underpin the structures of the cosmos. Most of the web is made of invisible dark matter, but about 4 percent is "normal" matter (the stuff the stars and planets are made of).

FRITZ ZWICKY

Fritz Zwicky was a brilliant Swiss astronomer who, besides dark matter, proposed the existence of supernovae (a name he coined), neutron stars, and galaxy clusters. He also developed some of the earliest jet engines.



Then, just as it was looking as if we had found our (albeit reduced) place in the universe, **astronomers realized that the way the universe was behaving did not tally with everything we knew to be in it—something was missing.** So they took measurements and made calculations and concluded that **more than 95 percent of the matter and energy in the universe was missing.** (Well, it was not missing—it was definitely there. We just could not see it.)

Humanity's slide down the greasy pole of significance was now complete—a smudge on a speck orbiting a mote of glowing dust in a galaxy afloat in a vast ocean **that makes up just four percent of the universe.** Yet, rather than damaging our resolve, each revelation of the vastness of the cosmos has only fueled our need to understand it better. **Now the hunt is on to find the missing portion of the universe.**

Why do we think most of the universe is hiding?

In 1933, a Swiss astrophysicist, Fritz Zwicky, was studying a galaxy cluster (a group of galaxies bound together by gravity). He observed the motions of the galaxies within the cluster and applied Newton's laws to estimate its gravitational mass. But when he came to estimate the amount of visible mass within the cluster (by measuring the light emitted by the stars within it, extrapolating their mass, and adding it all together), **his figures fell drastically short of his first estimate—the visible mass accounted for only a fraction of the cluster's gravitational mass.** Furthermore, there was not enough visible mass to generate the gravity needed to hold the cluster together (the galaxies should have been flying apart but they were not). **He concluded that there must be something invisible and undetectable making up all the missing mass—dark matter.**

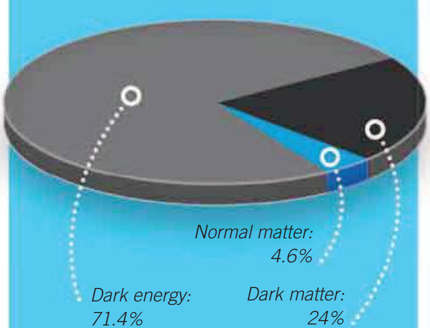
Wimps inherit the universe

Zwicky's conclusions were initially greeted by the astronomical community with a combination of skepticism and ridicule, but, as the years rolled on, evidence for the existence of dark matter began to mount up. **Today, it is almost universally accepted that something beyond our current understanding of physics is at work in the cosmos.** What is not universally accepted though is what form this mysterious something will take. **The term "dark matter" is really just a placeholder name for whatever it is eventually revealed to be** (rather like the code name an electronics manufacturer might give a gaming console while it is under development).

One of the favorite dark matter candidates is something called a WIMP, or Weakly Interacting Massive Particle. WIMPs are thought to be extremely abundant in the universe—a billion are estimated to pass through your body every second. As their name would suggest, **WIMPs are expected to possess a lot of mass—possibly the same as an entire atomic nucleus.** Luckily for us, like all wimps, they are really quite shy and barely interact with normal matter—just one out of the many trillions that whiz through you every year might interact with an atomic nucleus within your body.

DARK ENERGY

Dark matter, which makes up about 24 percent of the universe, should not be confused with dark energy, which accounts for 71.4 percent of it. In many ways, dark energy is dark matter's opposite—whereas dark matter holds the universe together, dark energy is a mysterious force that is fueling its ever-accelerating expansion.



Their shyness makes WIMPs a perfect dark matter candidate because **something that barely interacts with normal matter would be all but invisible to those of us made of normal matter.** Also, because they are thought to be so massive, they might account for all that mass that we cannot see—they might not physically interact with matter, but their mass means that **matter can feel their gravitational influence** (which is how we know dark matter exists at all).

IN 2003, NASA OBSERVED A CLOUD OF HOT GAS AROUND A GALAXY CLUSTER THAT WAS ESTIMATED TO CONTAIN A DARK MATTER MASS EQUIVALENT TO MORE THAN A HUNDRED TRILLION SUNS

Unfortunately, the very qualities that make WIMPs ideal dark matter candidates make them **extremely difficult to find**—but, fortunately, not impossible. Once again, the clue is in their name: they are known as "weakly interacting" particles (not "never-interacting"), which means that **every so often they do interact with normal matter**—we just need to catch the moment that a WIMP smashes into an atom of matter. If one does hit an atom, it will nudge the nucleus and give it a dose of energy that the atom doesn't want. **The atom gets rid of the energy by emitting a photon and some electrons that create a flash of light that can be detected by sensors.**

Finding a WIMP

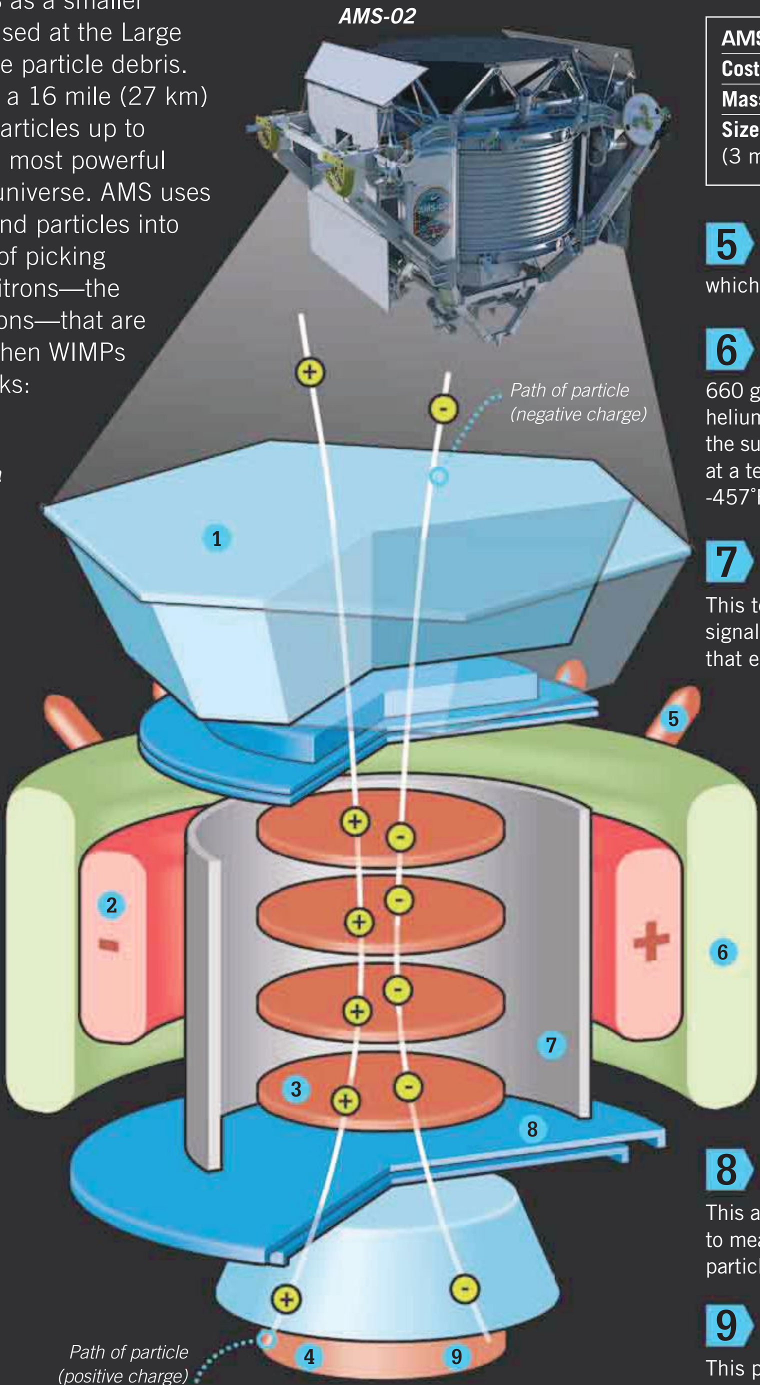
Scientists around the world are now racing to be the first to find this sort of direct evidence of WIMP interactions. To have any hope they need to maximize the chance that a WIMP will collide with an atomic nucleus, and the best way to do this is to use **something very dense so there are lots of atoms packed together as tightly as possible.**

They also need to build their detectors deep underground to filter out particles of ordinary matter and eliminate the chance that a non-WIMP particle will muddy the results. One such detector, called **DarkSide-50, was completed in early 2014 beneath the Gran Sasso mountains in Italy.** But waiting for a WIMP to come out of its shell in a cave isn't the only method of tracking them down. **Another way is to look to the skies.**

It is thought that all the WIMPs that have ever existed were created a fraction of a second after the Big Bang. Some of them will have decayed into their smaller constituent particles and **some will have been destroyed in high-energy collisions with other WIMPs.** It is hoped detectors launched high into Earth's atmosphere and space will find the particle remnants of the decayed or exploded WIMPs. Scientists working on a dark matter hunter—the Alpha Magnetic Spectrometer (AMS-02), currently installed on the International Space Station—**have hinted that they have found strong evidence supporting the existence of dark matter.** The discovery has sent shock waves through the entire scientific community.

CAN DARK MATTER BE FOUND?

You can think of the AMS as a smaller version of the detectors used at the Large Hadron Collider to analyze particle debris. But, instead of relying on a 16 mile (27 km) ring of magnets to whiz particles up to speed, it uses the world's most powerful particle accelerator: the universe. AMS uses a series of magnets to bend particles into its detectors in the hope of picking up the electrons and positrons—the antimatter twins of electrons—that are expected to be spat out when WIMPs collide. Here's how it works:



AMS-02 Cutaway view

AMS-02
Cost: $2bn
Mass: 15,432 lb (7,000 kg)
Size: 9.8 ft × 9.8 ft × 9.8 ft (3 m × 3 m × 3 m)

1 *Transition radiation detector (TRD)*
The TRD identifies the sort of particle entering the device. It can tell the difference between an electron and a proton (an electron emits X-rays as it passes through). Without the TRD, the AMS would not be able to tell the difference between a positively charged proton and the electron's antiparticle—the positively charged positron.

2 *Superconducting magnet*
This bends the path of charged particles so they can be identified—a negatively charged particle will bend toward the positive pole, and a positively charged particle will bend toward the negative pole.

3 *Silicon trackers*
These four devices track the path of particles as they are bent by the magnet.

4 *Electromagnetic calorimeter*
The total energy of the particles is measured here.

5 *Star trackers*
These tell the AMS which way it is pointing.

6 *Helium tank*
The helium tank contains 660 gallons (2,500 liters) of helium. This is used to keep the superconducting magnet at a temperature of about -457°F (-272°C).

7 *Anticoincidence counter*
This tells the AMS to ignore signals from stray particles that enter through the sides.

8 *Time-of-flight counter*
This acts like a stopwatch to measure each particle's speed.

9 *Ringing imaging Cherenkov detector*
This precisely measures the velocity of each particle.

WHY IS GRAVITY SO WEAK?

ON THE FACE OF IT, GRAVITY would seem to be a pretty impressive force—after all, it is responsible for the formation of planets, stars, and galaxies. Earth and all the other planets of our solar system are held on an invisible leash and forced by gravity to orbit the sun. But despite all of this, when compared to the other fundamental forces, **gravity is very puny.**

Gravity is a product of mass—the more massive the object is, the greater its gravitational influence. **Gravity pulls matter toward an object's center of mass**—planets and stars are round because they are made up of atoms of matter that are **jostling to get as close as possible to a central point.**

Weak gravity:
Despite the moon's substantial mass, an astronaut can overcome the gravitational pull of millions of trillions of tons of rock with a gentle push of a foot.

What stops all that matter from reaching the center is the electromagnetic force interacting with all those atoms. **Gravity is powerless against the overwhelming strength of electromagnetism.**

For gravity to overcome the electromagnetic force you need a truly massive object—such as a star. Only in the center of a star is gravity strong enough to force atoms to overcome their electromagnetic repulsion. **But why is gravity so much weaker than the other forces?** No one really knows—and that irritates the hell out of scientists.

Extra dimensions

To explain the mismatch between gravity and the other forces, **physicists have suggested that there may be extra dimensions** beyond the three that we are familiar with—up and down, left and right, forward and backward.

For physicists, **an extra dimension is just another direction in space** on top of the three that we humans use to navigate the world. The extra dimensions are hidden from us because of the way we perceive the universe. String theory **predicts that there are up to 26 dimensions** and that the extra dimensions are hidden from us because they are curled up in really (really, really) small loops.

If that sounds bizarre, imagine an acrobat balancing on a tightrope. In essence, he is occupying a one-dimensional world, in which he can move only backward and forward. Now, imagine a flea on the same tightrope. The flea can move backward and forward on the rope, but he can also walk sideways and walk around the rope. The flea is living in a two-dimensional world, but one of these dimensions is a tiny closed loop. **The acrobat can't detect the second dimension, just as we can't detect dimensions beyond the three we move about in.** Also, just as we are trapped within our three-dimensional world, so is everything we use to measure the world around us—such as light and sound. **With nothing interacting with these other dimensions, we have no way of detecting them.**

What does this have to do with gravity?

Physicists have a very effective theoretical framework to describe how the universe works at the quantum level, called the "standard model." **The theory neatly explains what the fundamental particles do and how they interact with the other fundamental forces.** But, try as they might, physicists just cannot get gravity to fit.

SCIENTISTS ARE STILL LOOKING FOR A "UNIFIED THEORY" OF PHYSICS THAT WILL TIE TOGETHER EINSTEIN'S RELATIVITY AND QUANTUM MECHANICS

Although all the other fundamental forces are trapped in our three-dimensional world, **gravity is thought to be free to travel through these extra dimensions.** As it spreads out through all the extra dimensions it becomes increasingly diluted—making its effect on our three-dimensional world much weaker.

So how can we test this?

Well, according to the standard model, **each of the fundamental forces has a special sort of particle called a force carrier associated with it.** These are like messenger boys that carry instructions to other particles, telling them how to be influenced by the force.

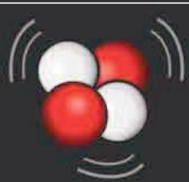
It is thought that gravity must also have a force carrier particle, called the "graviton." Sadly, we have never actually seen a graviton, which is where particle colliders like the Large Hadron Collider (LHC) come in.

When the LHC smashes protons together, all sorts of particle scraps fly out of the energy maelstrom. Given enough energy, **there is a chance that (if it exists) a graviton will be spat out from the collision.** If gravity does permeate all those extra dimensions, there is a chance that **the newly produced graviton will immediately disappear as it escapes into one of them.**

So our best chance of detecting the extra dimensions (which we can't see) is to find (from among all the other particle mess) a graviton (which may or may not exist) disappearing from our plane of existence.

That is the LHC's next big task. **Sounds like a doozy.**

FUNDAMENTAL FORCES



STRONG NUCLEAR FORCE

Power: 1,000,000,000,000, 000,00,000,000,000,000, 000,000,000 times stronger than gravity

Reach: Subatomic

Force carrier: Gluon

This binds matter together. It can't reach very far, but is strong enough to hold protons together within an atom, even though their positive charge is pushing them apart.

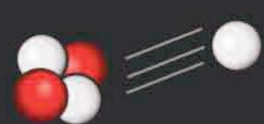
ELECTROMAGNETIC FORCE

Power: 10,000,000,000,000, 000,000,000,000,000,000, 000,000 times stronger than gravity

Reach: Infinite

Force carrier: Photon

Electromagnetism is perhaps the most familiar force, as it encompasses everything from magnetism, to light, to the radio waves we communicate with.



WEAK NUCLEAR FORCE

Power: 100,000,000,000,000, 000,000,000,000,000,000 times stronger than gravity

Reach: Subatomic

Force carrier: W and Z bosons

This is the force responsible for radioactive decay. It allows an atom to change by taking on or losing particles.

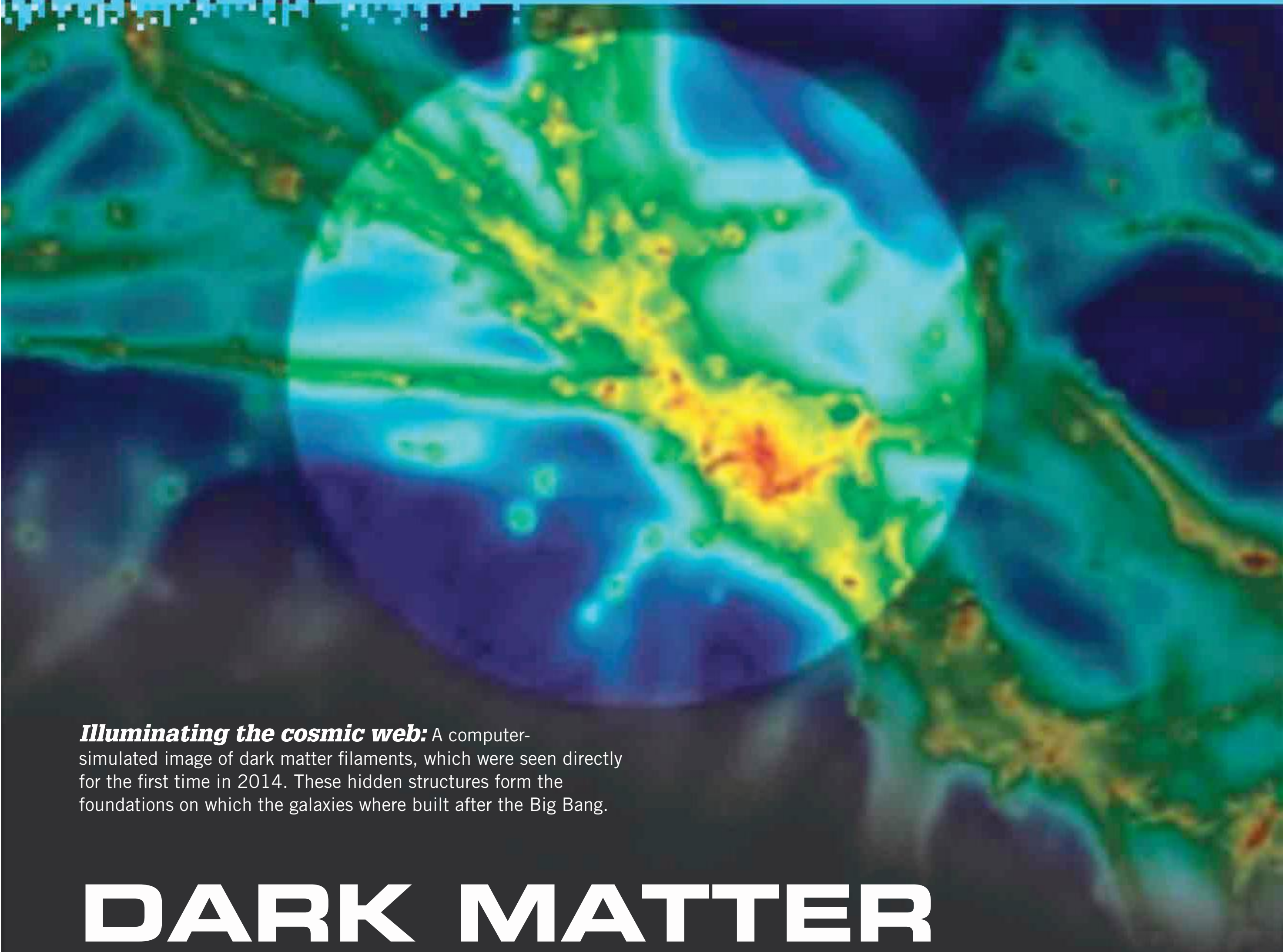
GRAVITY

Power: Really weak

Reach: Infinite

Force carrier: Graviton (not yet discovered)

Gravity has a powerful effect on planets and stars, but has almost no influence on matter at the quantum level.



Illuminating the cosmic web: A computer-simulated image of dark matter filaments, which were seen directly for the first time in 2014. These hidden structures form the foundations on which the galaxies where built after the Big Bang.

DARK MATTER BUILDS THE UNIVERSE

WHEN YOU LOOK UP at the stars that pepper the night sky, or at images of distant galaxies, **you would be forgiven for thinking that they float alone as isolated oases of light in the vast empty ocean of space,** but is the desolate blackness as barren as it appears?

Scientists have believed for some time that **the isolation of the galaxies is actually an illusion.** Instead, they are all connected by a cosmic web of interlinking filaments—huge, invisible highways that carry cold, diffuse gases into the galaxies as fuel for their stellar furnaces.

A legacy of the Big Bang and the tiny energy fluctuations that formed in the universe's first moments of life, **this cosmic web is thought to have formed the foundations on which the stars and galaxies were built.**

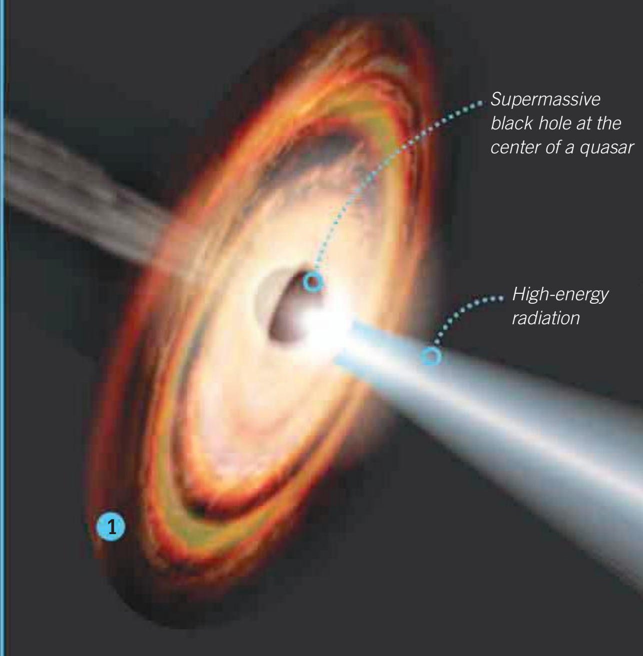
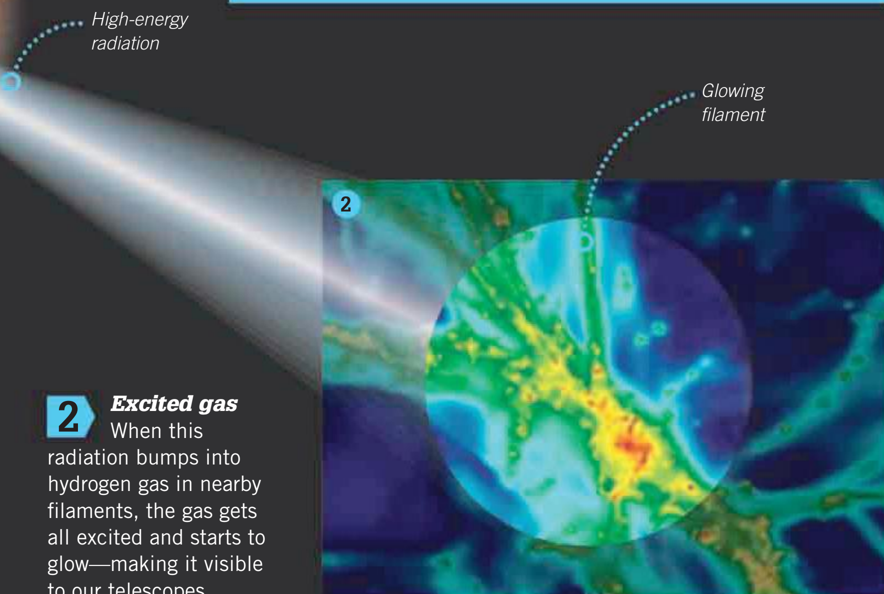
Most of the web (about 84 percent) is made of invisible dark matter, which **can only be detected indirectly** by measuring the effects its gravity has on the matter (gases, dust, stars, and so on) that we can see. **Luckily, the filaments contain, and are surrounded by, hydrogen gas.** Usually, this gas is too cold and thinly spread to detect with telescopes, but if it is bombarded with energy, it can be made to glow (like the gases inside a fluorescent light tube).

Now, with the help of a supermassive black hole, these **cosmic filament gases have been observed directly** by astronomers using the 32.8 ft (10 m) wide Keck telescopes in Hawaii.

Illuminated by a nearby quasar (a galaxy with an active black hole that spews out high-energy radiation) called UM 287, the gases are allowing scientists to see the web's filamentary structure for the first time—**confirming the existence of this vestigial remnant of the Big Bang.**

THE WEB

Scientists have believed for some time that space is not nearly as empty as it appears. Instead, all the stars and galaxies are connected by a vast cosmic web of interlinking filaments...

1 Gas accumulation
Clumps of matter (mostly hydrogen gas) accumulate where the filaments intersect—forming stars, which collect to make galaxies. One sort of galaxy, called a quasar, has an active supermassive black hole at its center, which pumps high-energy radiation into the space around it.

2 Excited gas
When this radiation bumps into hydrogen gas in nearby filaments, the gas gets all excited and starts to glow—making it visible to our telescopes.

GLOWING QUASAR

In this image, the bright white blob is a quasar. The blue fuzz is glowing hydrogen gas in the surrounding filaments—the first time this has been seen directly. It might not look like much, but this fuzzy blue blob is 2 million light-years wide—in contrast, our Milky Way galaxy is “just” 100,000 light-years in diameter. Although extremely diffuse, the hydrogen gas in this image weighs in at the mass equivalent of a thousand billion Suns.

HOW THE WEB WAS SPUN

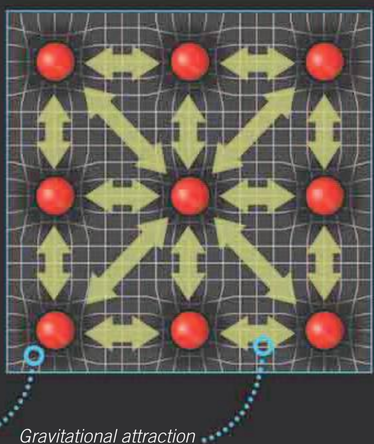
Following its birth in the Big Bang, the universe was a roiling soup of blazing plasma. Eventually, this settled down and cooled—forming stable atoms of hydrogen (with some helium and a little lithium). As the universe expanded, this spread out to become a diffused cloud of gas...

GENERAL RELATIVITY

Albert Einstein's theory of general relativity shows us that gravity is a by-product of mass. Objects with mass (everything from stars and planets to tortoises and particles) bend the fabric of space around them (spacetime)—making "dents" that other, less massive objects "fall" into. The greater the mass, the deeper the dent and stronger the gravitational pull.

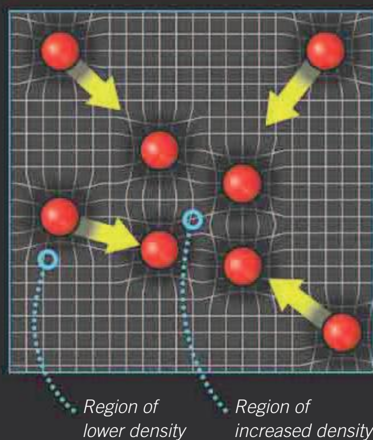
1 *Stationary*

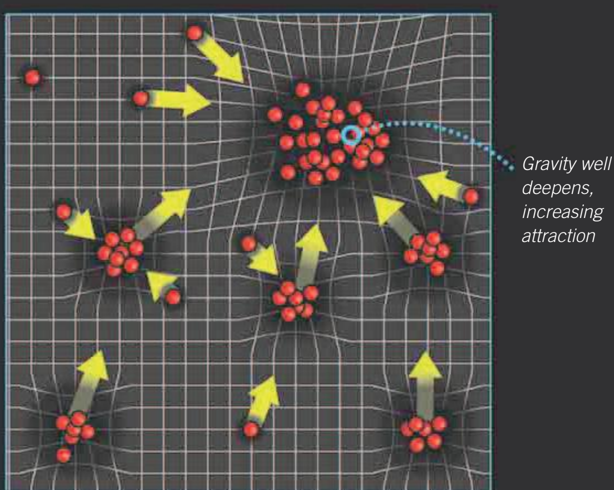
If this cloud had been spread perfectly evenly, gravity would have acted perfectly evenly on each particle within it. With every particle being pulled (and pulling) the same amount in every direction, they would have remained perfectly stationary.



2 *Density*

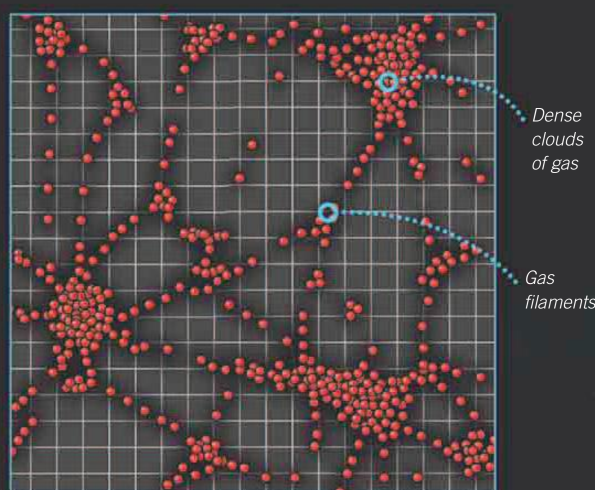
But matter within the cloud was not spread perfectly evenly. There were tiny imperfections—regions where matter was a little more, or a little less, dense. Regions of higher density exerted slightly more gravitational pull—so particles in less dense regions were drawn toward more dense regions.





3 *Gravitational dents*

The more mass that accumulated in one region, the deeper the gravitational "dent" it made in spacetime, and the more mass it attracted.

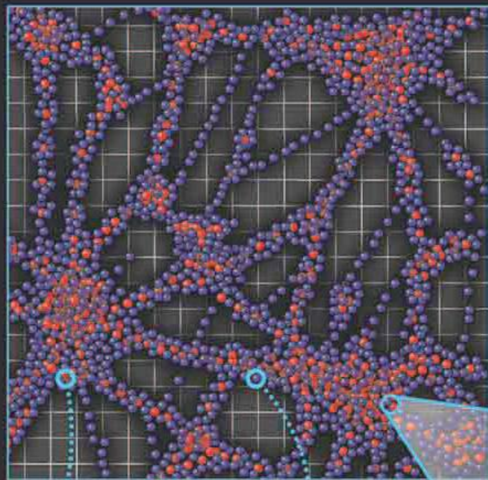


4 *Clouds and filaments*

Over millions of years, gas in these regions accumulated into increasingly dense clouds, with connecting filaments. The densest clumps became nurseries for the very first stars and galaxies.

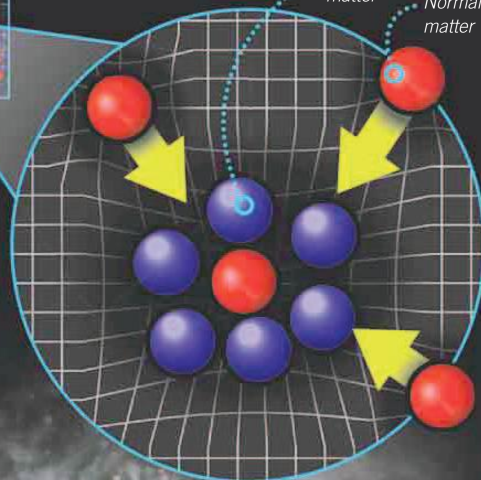
5 *The true cosmic web*

The rapid collapse of gas into the complex web of filaments and dense gas clouds could not have been achieved by the mass of "normal" matter alone. There was too little, spread too evenly over too much space to provide the mass needed to pull everything together so quickly. Luckily, there was lots of dark matter kicking around—with more than enough mass to get the ball rolling. Once these invisible dark-matter particles attached to the gas clouds and filaments, the true cosmic web was revealed.



6 *The dark force*

Dark matter outnumbers normal matter by about six atoms to one. Only dark matter has enough gravitational oomph to collapse to form complex structures. Even if normal matter had been able to pull itself together, without the dark-matter web holding it in place, it would have been torn apart by the expansion of the universe.



7 *Forming galaxies*

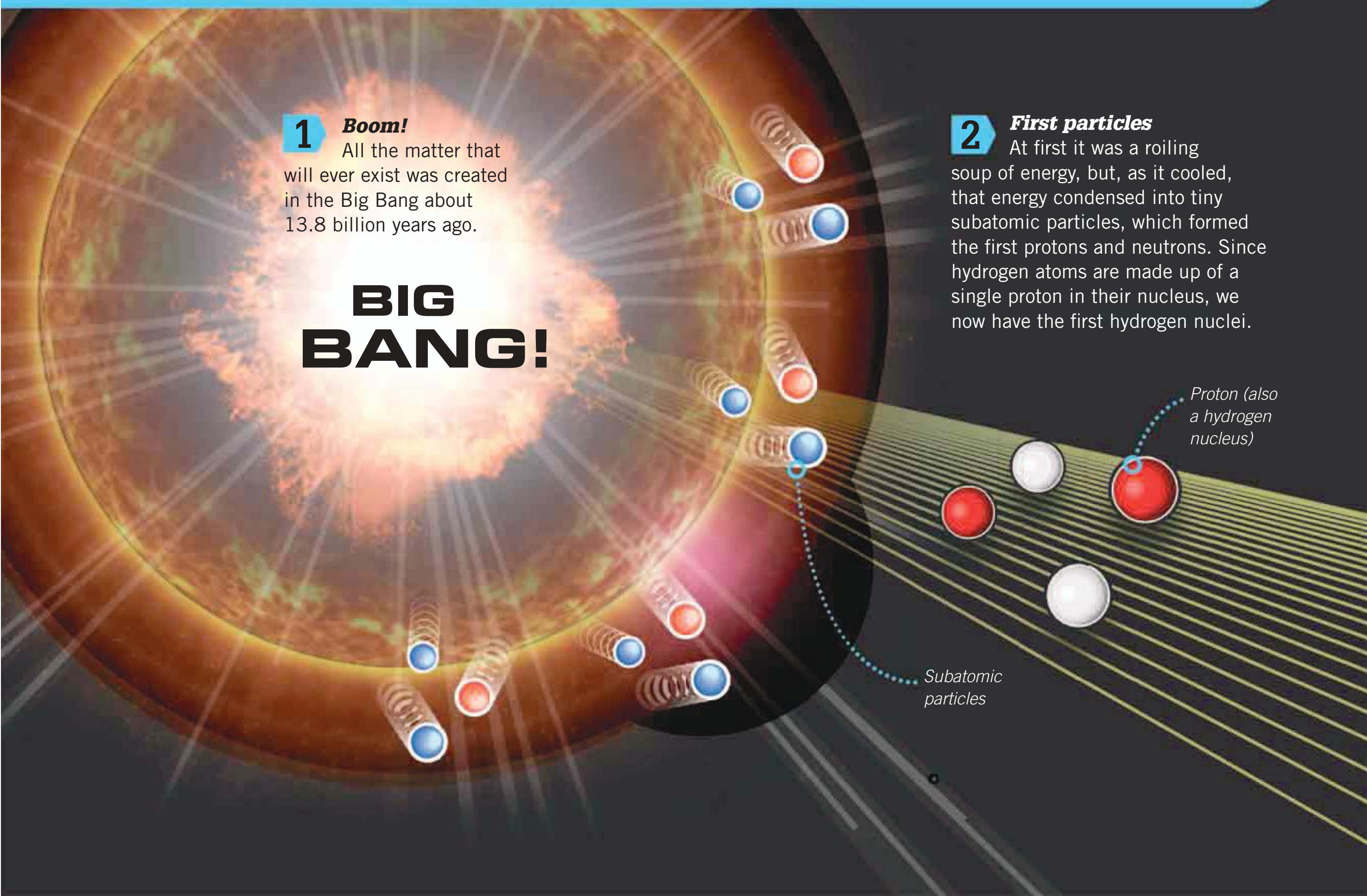
It was the cosmic web of dark matter that gave normal matter the gravitational foundations it needed to accumulate and build the cities of stars we call galaxies. The interconnecting filaments behave like a transportation system—moving matter into the cities to be used to build new stars.

Sharpless 2-106 star-forming region

WE ARE ALL MADE OF STARS

IN THE BEGINNING, THERE WAS THE VOID. The universe was formless and empty, and darkness was over the surface of the deep. Then there was light and the light was good. **The light was energy and from that energy came matter.** But the matter was simple and disparate, which was not good. Then matter was drawn together and **the first stars illuminated the darkness.** From within the belly of the inferno, simplicity begat complexity and the first heavy elements were born. Hydrogen begat helium. Helium begat carbon and oxygen. Carbon begat magnesium and aluminum and these begat silicon and iron.

Heavy with their elemental progeny, the stars burst forth and spread their seed into the darkness. **From the stars' seed came forth the sun and Earth.**



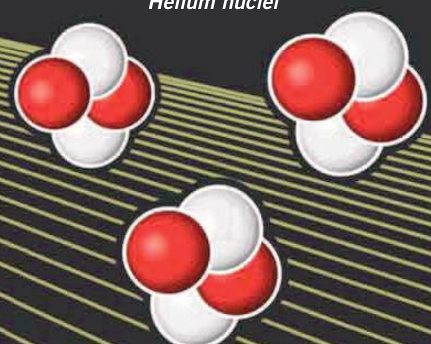
On the land, hydrogen married oxygen and **together they became water.** The elements came together and created complex chemicals and these in turn created amino acids. From the amino acids was brought forth life and **soon the waters were pregnant with living creatures.**

The living creatures were fruitful, increasing in number and filling the waters of the seas, the lands of Earth, and the vaults of the sky.

One of these creatures, called a human being, looked to the heavens and asked, **"Where did I come from?"**

BY THE TIME THE UNIVERSE HAD COOLED, IT WAS MADE UP OF ABOUT 75% HYDROGEN AND 25% HELIUM

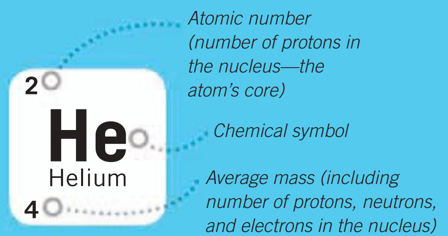
3 ***Helium nuclei***
At this point, the universe was still very hot and dense—enough to squeeze some of those protons and neutrons together to create the first helium nuclei.

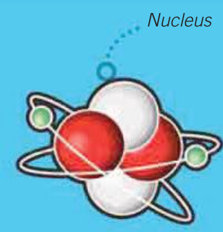


Helium nuclei

PERIODIC TABLE GUIDE

Elements are arranged in a specific order in the Periodic Table, based on increasing atomic number.

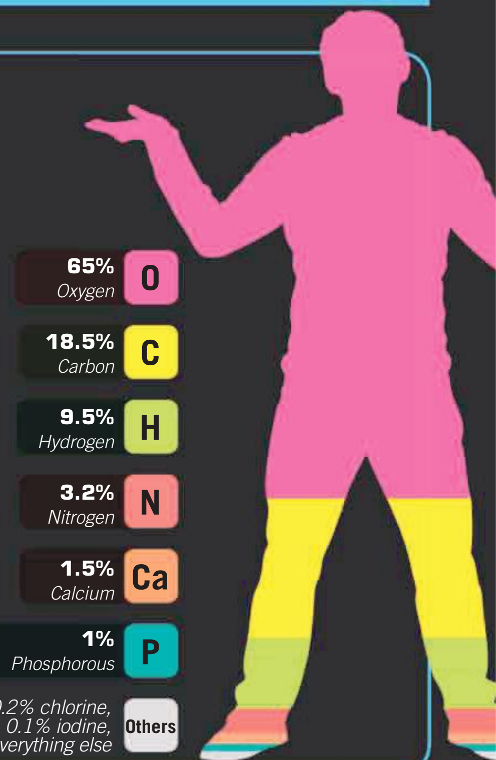




Helium atom (two protons, two neutrons and two electrons)

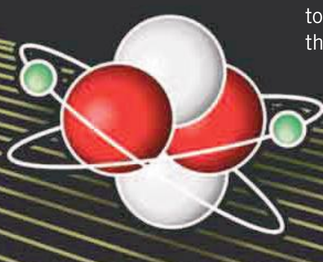
WHAT ARE WE MADE OF?

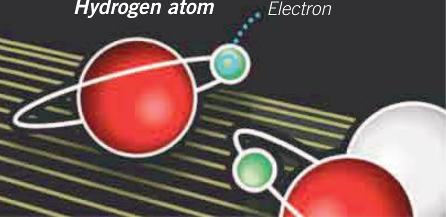
An element is a substance that cannot be broken down into any simpler substance by physical or chemical means. This diagram shows the elements that make up the human body by percentage of mass. Only hydrogen was made in the Big Bang—the rest was cooked up in the stars.



4 ***First atoms***
The universe cooled down a little more and the electrons—subatomic particles with a negative charge that were made in the Big Bang—were attracted to the positively charged protons, forming the first hydrogen and helium atoms.

Helium atom



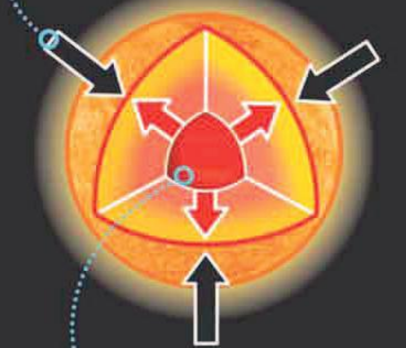


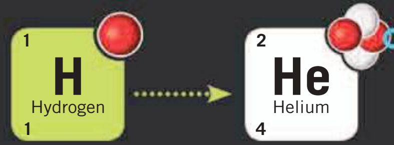
Hydrogen atom

STARS: PARTICLE PRESSURE COOKERS

As the famous American science communicator Carl Sagan once said, "We are all made of star stuff." The following shows just how this is true.

(Note: The processes that create some of the heavier elements are vastly more complex than alluded to here.)





1 *Heat and gravity*

In its core, a main-sequence star is fighting a battle between heat—created in the star when hydrogen atoms fuse to create helium—and gravity. Fusion creates energy because the mass of the new helium particle is less than the combined mass of the hydrogen atoms that made it. The leftover mass is released as energy, in the form of light and heat.

2 *Fusion stopped*

Eventually the star exhausts its supply of hydrogen, and fusion shuts down in the core. With no more heat being released, gravity gains the upper hand and starts to crush the star's core.

3 *Red giant*

Even though the core is crushed, the rest of the star expands as its gases cool and the star becomes a red giant.

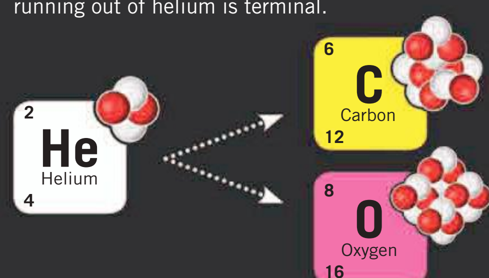
> "THE NITROGEN IN OUR DNA, THE CALCIUM IN OUR TEETH, THE IRON IN OUR BLOOD... WE ARE MADE IN THE INTERIORS OF COLLAPSING STARS"
> CARL SAGAN

4 *Fusion restarted*

As the core collapses, the pressure and temperature within it rise until fusion can start again—this time with the helium it made earlier. With helium burning away nicely, the collapse is halted and the star settles down into the next stage of its life.

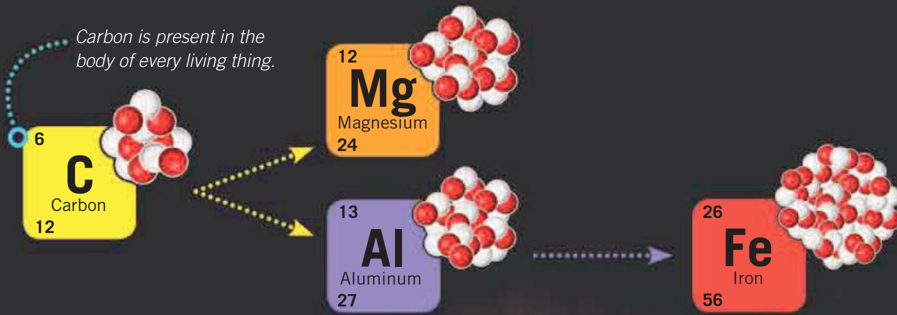
5 *New elements*

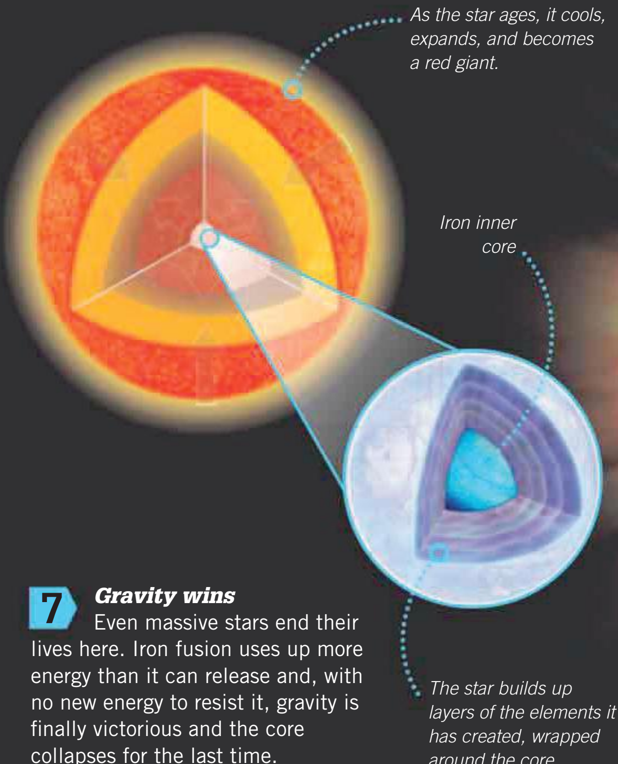
Helium fusion creates two new elements that will turn out to be very useful when building your body—oxygen and carbon. But before very long (about a million years or so), the star runs out of helium to burn as well. For a star like our sun, running out of helium is terminal.



6 *Repeat, repeat, repeat*

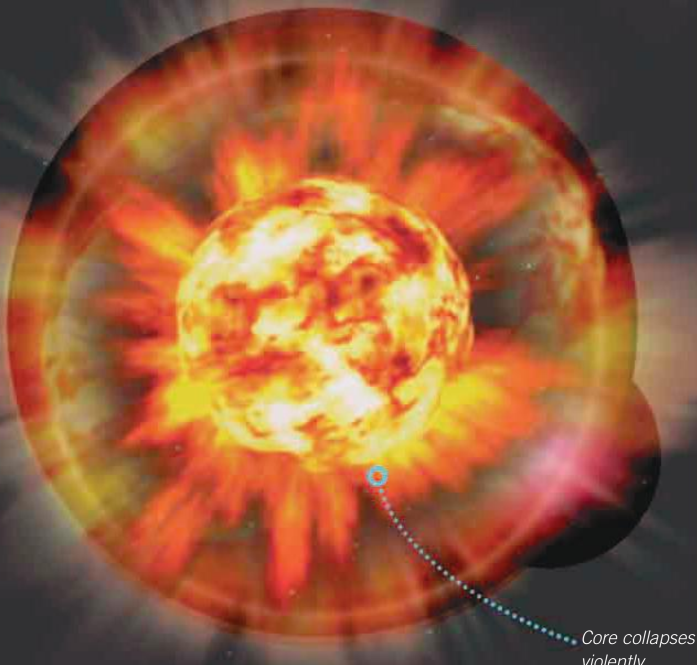
For a star more massive than our sun, after helium is burned out, fusion begins anew. The carbon made earlier by the star is fused to create heavier elements such as magnesium, sodium, and aluminum. The processes of fusion, fuel exhaustion, core collapse, and reignition are repeated again and again—each time creating heavier elements until, finally, iron is created.





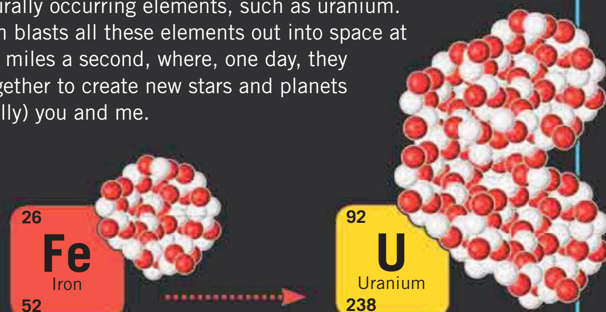
7 *Gravity wins*

Even massive stars end their lives here. Iron fusion uses up more energy than it can release and, with no new energy to resist it, gravity is finally victorious and the core collapses for the last time.



8 *We are all made of stars*

But even this is not the end of the story. The last violent collapse of the core triggers an explosive shock wave that blasts through the star. The shock wave carries so much energy that even iron is fused to create the heaviest naturally occurring elements, such as uranium. The explosion blasts all these elements out into space at thousands of miles a second, where, one day, they will come together to create new stars and planets and (eventually) you and me.



WHAT ABOUT OUR SUN?

In about five billion years, the sun will start to run out of hydrogen fuel. It will slowly expand to be about 260 times the size it is now to become a red giant star. This process will swallow the inner rocky planets and, about 7.5 billion years from now, Earth will also be incinerated.

THE STORY OF THE PULSAR

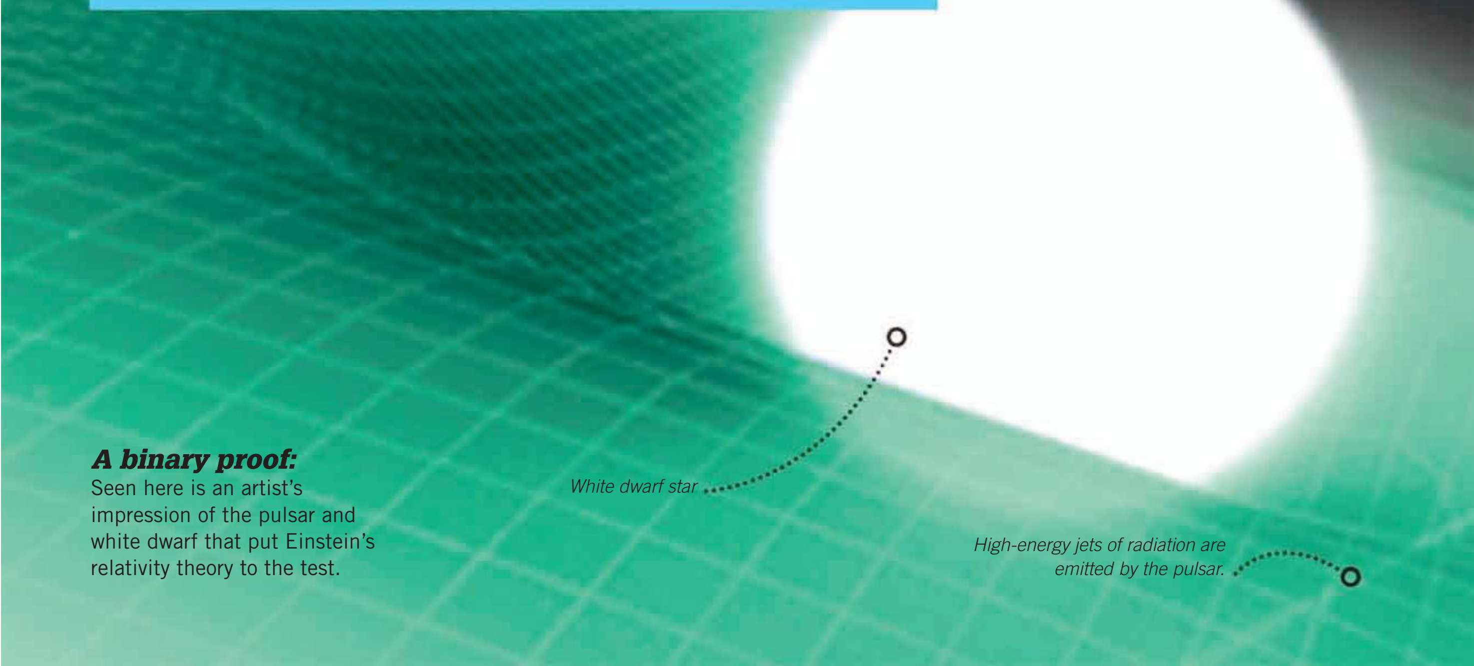
ALBERT EINSTEIN'S THEORY OF GENERAL RELATIVITY (GR), which describes how gravity is the result of mass, energy, and the curvature of spacetime, has passed every test thrown at it since it was thought up in 1915. But, despite its success, **relativity is not expected to be the last word on gravity.** Although it makes superbly accurate predictions for everyday gravitational objects, relativity **has not been tested in more extreme circumstances.**

You do not get much more extreme than the pair below. The larger object is a fairly unremarkable white dwarf star, but the smaller one, **a newly discovered pulsar,** is an extremely remarkable object indeed.

Imagine an object that could sit quite happily in the center of New York City, and that you could walk around in just a few hours. Now imagine that bundled up inside it are **enough atomic nuclei to make two suns.** Picture its surface burning away at millions of degrees as it shoots high-energy jets of radiation out into space at millions of miles per hour. **That is extreme.**

The pulsar, PSR J0348+0432, along with its far less massive companion, is part of a **binary system** in which the two members orbit each other every 2.46 hours. As they plow through space, **they dig gravitational pits in the fabric of spacetime and push up gravity waves,** which spread out into space. According to GR, the binary will lose energy in the process of making those waves and, as such, their orbits will decay, causing them to move closer together.

This prediction has been tested by astronomers using the European Southern Observatory's Extremely Large Telescope in northern Chile. They found that over 12 months of observations, the binary's orbit slowed by eight-millionths of a second, which may not sound like a lot, but it is exactly the amount predicted by GR.



A binary proof:
Seen here is an artist's impression of the pulsar and white dwarf that put Einstein's relativity theory to the test.

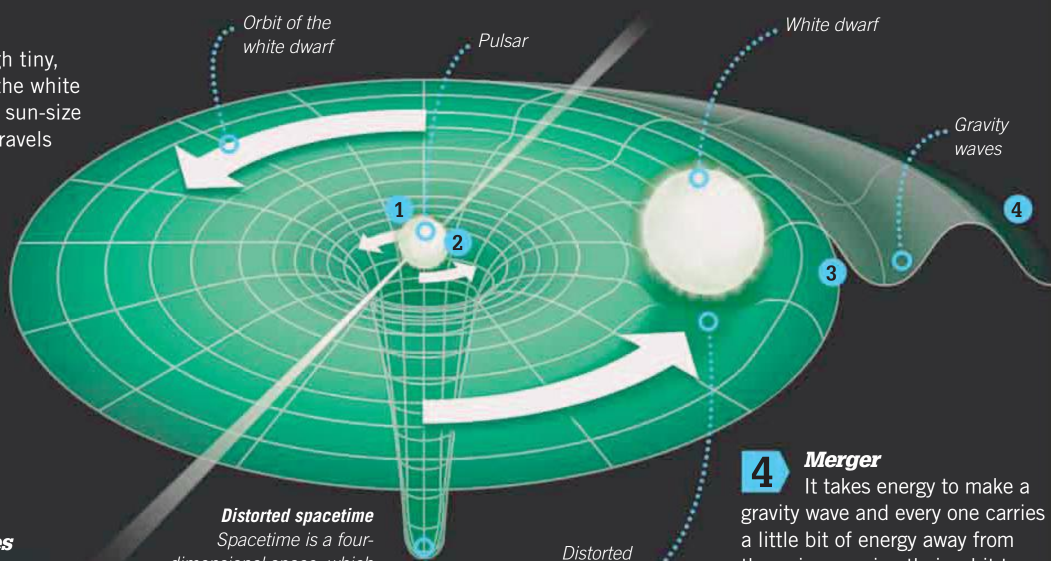
"STIRRING UP" **GRAVITY WAVES**

Einstein's theory of relativity tells us that gravity is the result of a massive object distorting the fabric of the universe (spacetime) around it. The greater the mass, the larger the "dent" made in spacetime and the greater its gravitational influence.

1 ***Binary system*** The pulsar, although tiny, is far more massive than the white dwarf (the spent core of a sun-size star), so the white dwarf travels around the pulsar.

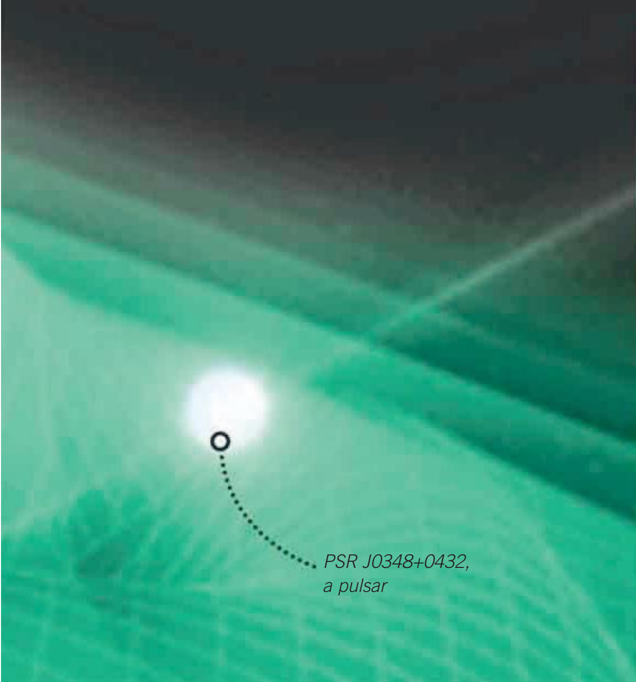
2 ***Orbit*** The pair orbit together around their shared center of mass (an imaginary point where their gravity balances out), which, because it is much more massive, is close to the center of the pulsar.

3 ***Spacetime waves*** As they orbit, they push up waves in spacetime (like a finger stirring the surface of water) that travel out into space.



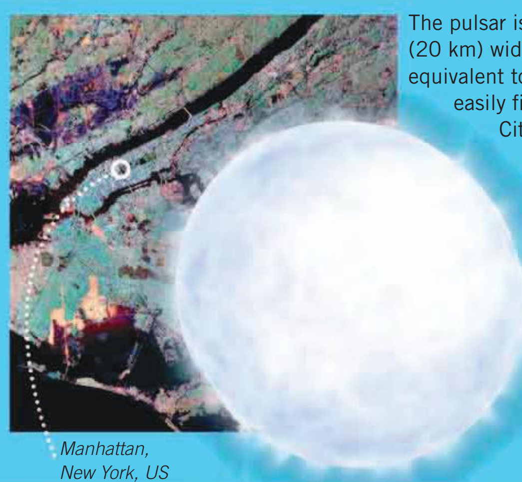
Distorted spacetime *Spacetime is a four-dimensional space, which adds the dimension of time to the three dimensions of length, width, and height.*

4 ***Merger*** It takes energy to make a gravity wave and every one carries a little bit of energy away from the pair—causing their orbit to shrink. In about 400 million years, the white dwarf and pulsar will have lost so much energy that they will merge together.



PSR J0348+0432, a pulsar

MASSIVE MASS



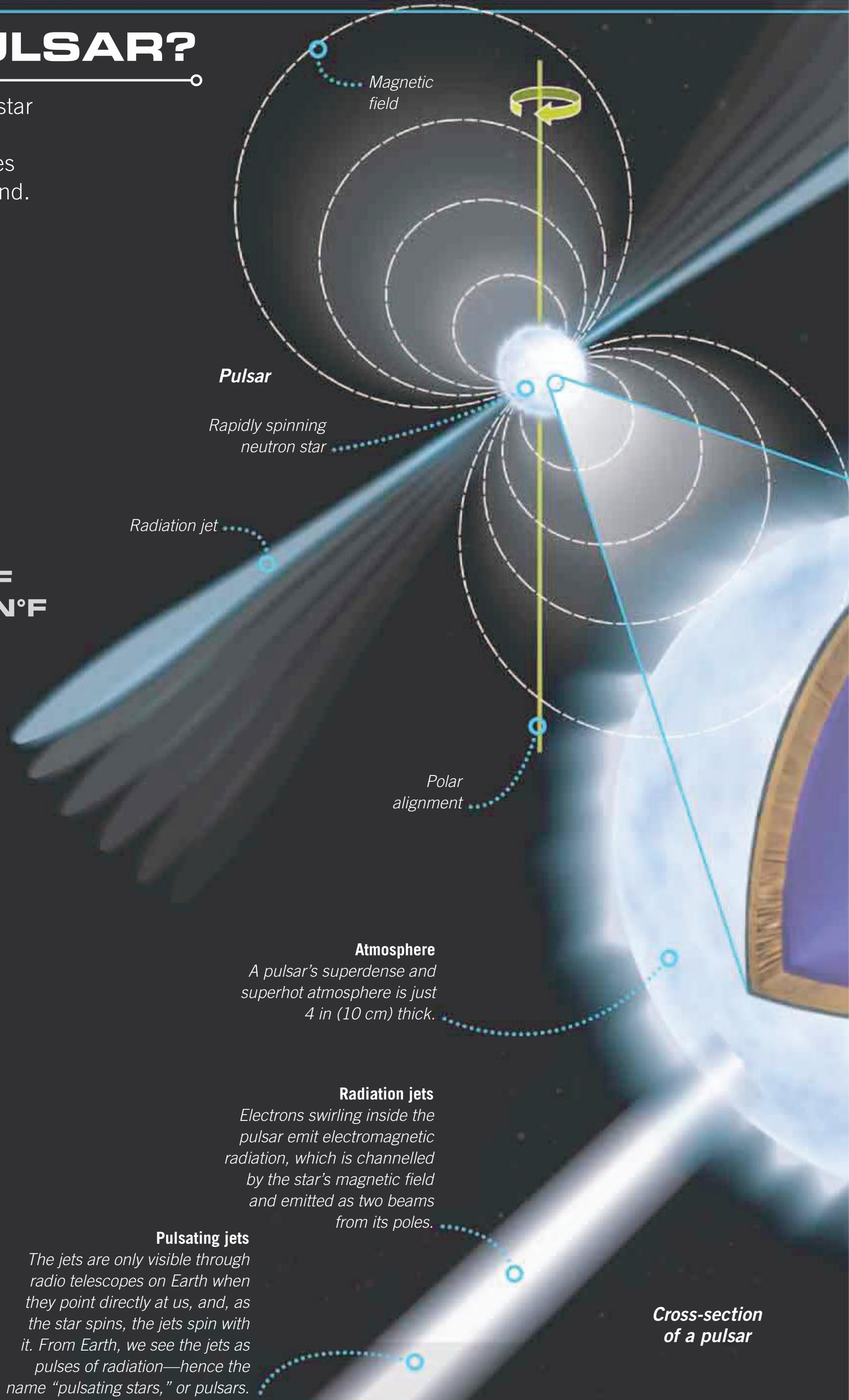
Manhattan, New York, US

The pulsar is only 12.5 miles (20 km) wide, but has a mass equivalent to two suns. It would easily fit over New York City. That's equivalent to having 660,000 planet Earths squashed up inside a sphere small enough for you to cycle around!

WHAT IS **A PULSAR?**

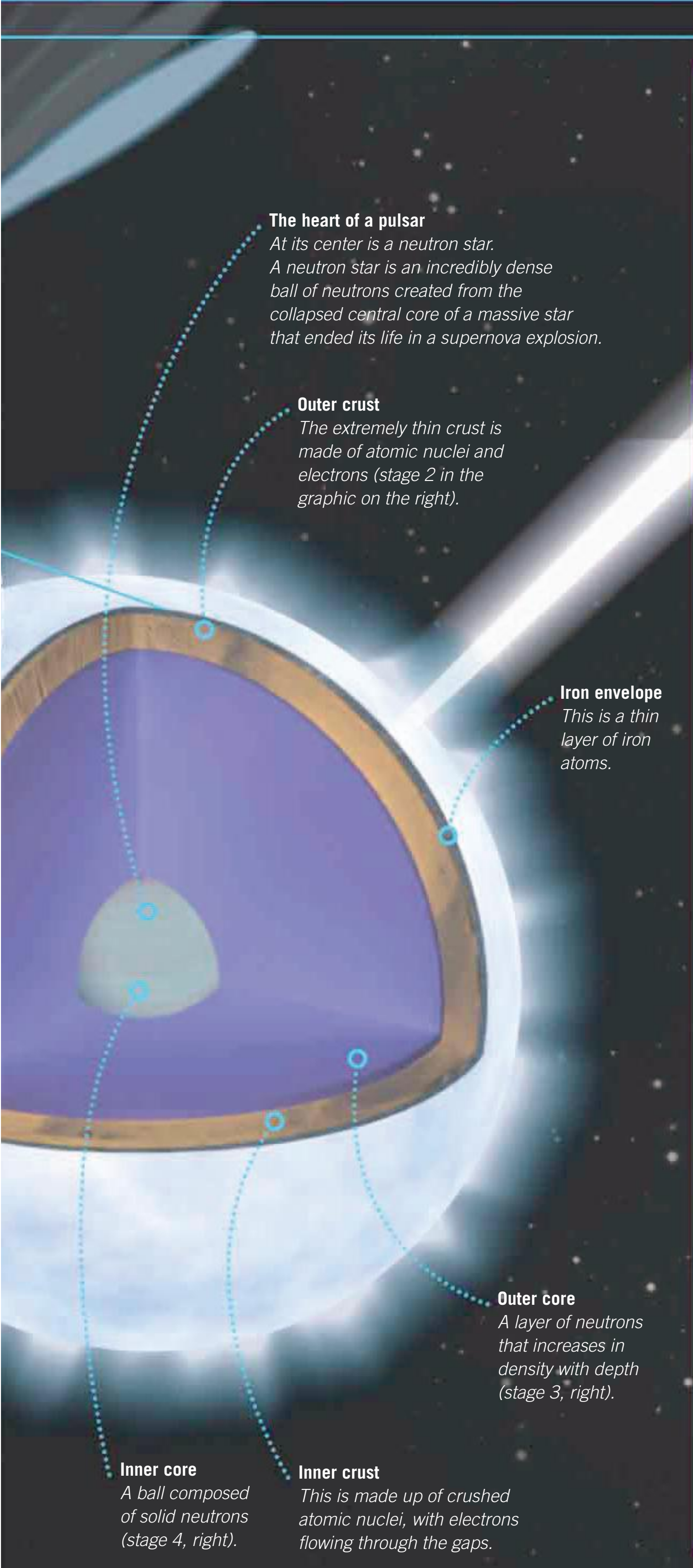
A pulsar is a rapidly spinning neutron star with a colossal magnetic field. It emits jets of electromagnetic radiation at rates of up to one thousand pulses per second. If a neutron star exceeds three solar masses, instead of creating a pulsar, its gravity becomes so extreme that it will collapse to become a black hole.

PULSARS HAVE AN ATMOSPHERE THAT CAN REACH TEMPERATURES OF ABOUT 3.6 MILLION°F (2 MILLION°C)



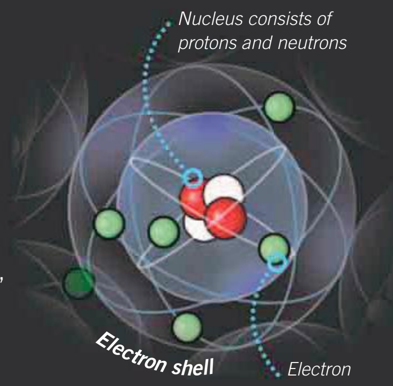
MASSIVE ATTACK

A pulsar's gravity is so extreme that, if you were to land on one, you would weigh about 7 billion tons. But you would not really get the chance to worry about your sudden weight gain because, as you approached the star, you would be stretched into a piece of human spaghetti and fall toward its surface at more than 4 million mph (6.4 million km/h). You would then be crushed into a speck of matter smaller than a grain of salt and assimilated into the star's surface.

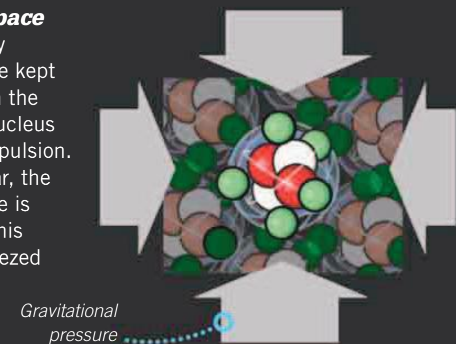


HOW TO BE **MASSIVE, YET TINY**

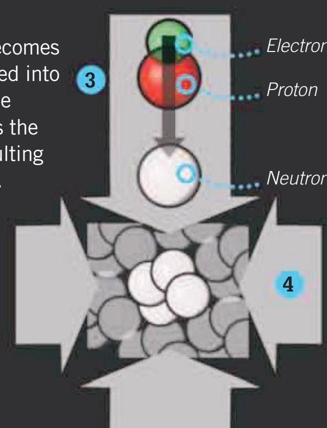
1 ***Empty atom***
An atom consists of a nucleus, made up of protons and neutrons, which is orbited by a cloud of tiny electrons. Atoms are mostly empty space (if an atomic nucleus was the size of the one on this page, you would have to scale the electron shell up to the size of a cathedral).



2 ***Squeezed space***
The negatively charged electrons are kept at this distance from the positively charged nucleus by electromagetic repulsion. But, in a neutron star, the gravitational pressure is so extreme that all this empty space is squeezed out of the atom.



3 ***Neutron formed***
Eventually, the pressure becomes so large that electrons are squeezed into the protons—making neutrons (the electron's negative charge cancels the positive charge of the proton, resulting in an electrically neutral neutron).



4 ***Neutron star***
The end result is a star made entirely of tightly packed neutrons, which is basically a ball of solid, superconcentrated matter that can pack the mass of an entire mountain range on Earth into a few square centimeters.

IF HUMANITY WERE SQUASHED IN THIS MANNER, WE WOULD BE REDUCED TO THE SIZE OF A SUGAR CUBE

DOING THE BLACK HOLE TWIST

SO YOU ARE LISTENING TO THE HIT PARADE on the radio and busting some moves on the rug-clad dance floor of your living room. A quick glance at your reflection in the glass of your patio doors confirms the **true extent of your awesomeness.** Overcome with exuberance, you perform a spectacular pirouette (or whatever the cool kids call them these days).

Unfortunately, the **surprisingly high frictional coefficient** between your cozy slipper socks and the rug causes it to gather up beneath your feet and, before you know it, you have a rug wrapped around your leg. Everything that was on the rug is likewise **dragged violently inwards**, and half a living room's worth of remote controls, discarded socks, and **one confused cat** is hurled toward you... yup, sometimes spinning sucks.

Supermassive black hole: Every galaxy is thought to house a supermassive black hole at its center. Each is powered by a singularity (an almost infinitely dense point in spacetime with the mass of millions or billions of suns).

But if you think that the cat has it bad, spare a thought for **anything unfortunate enough to be too close to a black hole** when one of these cosmic Travoltas does the twist. Because instead of messing up a mere woven floor covering, **a black hole drags the very fabric of the universe along with it,** and you can imagine what that does to anything unfortunate enough to be occupying that particular region of the spacetime rug.

Luckily for astronomers wanting to investigate black holes, which by definition are black and therefore virtually invisible, the "twisted spacetime carpet" effect allows them to study black holes indirectly by **looking at the effect they have on the space around them.** Black holes—particularly supermassive ones, which can be found strutting their stuff at the center of most galaxies—interest astronomers as they hold clues to how galaxies evolved in the first place.

Astronomers have recently made a supermassive breakthrough by finding a new way **to measure how fast black holes spin.** Armed with the European Space Agency's XMM-Newton satellite, they took a look at a supermassive black hole with the mass of 10 million suns that lies at the heart of a galaxy 500 million light-years away.

A BLACK HOLE DRAGS THE VERY FABRIC OF THE UNIVERSE ALONG WITH IT

Like many black holes, it is **surrounded by a spinning disk of gas and dust** that sits like a picnic, spread out across the spacetime rug waiting to be devoured. By looking at the picnic (also **known as an accretion disk**) the team could determine how far the inner edge of the disk was from the black hole.

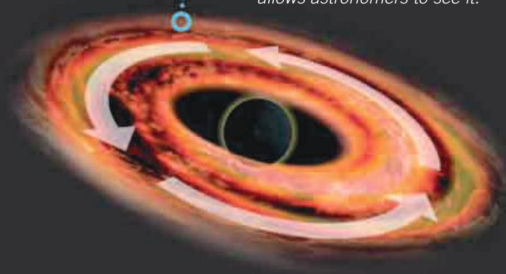
This distance tells astronomers how fast the black hole is spinning because **material in the disk is drawn closer as the black hole's spin increases.** The disk was found to be far from the edge of the black hole, which means that, for the moment at least (bearing in mind it is 500 million light-years away so they are studying it as it appeared half a billion years ago), it is spinning at the relatively slow speed of "only" half the speed of light.

But who cares how fast a black hole spins? Well, if you think a pair of rubber-soled socks can make a mess of a carpet, just take a look at what a spinning black hole can do...

HOW BLACK HOLES WORK...

A black hole is a collapsed remnant of a dead star's core. It is in a star's nature to spin and, when it dies, this spin is transferred to its core. As it collapses under the weight of its own gravity, the core's spin accelerates. By the time it has become a black hole, it can be spinning at almost the speed of light.

This is a supermassive BLACK HOLE...

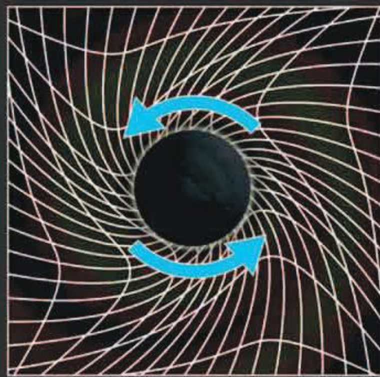


1 ***Heart of the matter***
At a black hole's heart, locked away from time and space, there is a teeny tiny singularity—a speck smaller than an atom that contains the mass of millions of suns.

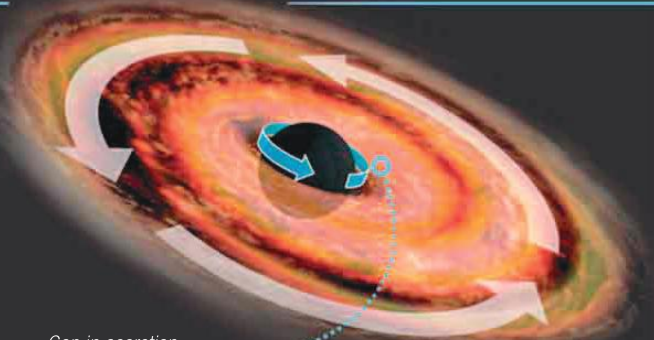
2 ***So much mass***
With all that mass, the black hole bends the fabric of the universe, making a gravitational dent so deep that not even light can escape it.

3 ***Uncompact disc***
The accretion disk is a swirling disk of gas and dust that builds up around the black hole. If the black hole is just chilling out, the orbital momentum of the material in the disk stops it from falling in.

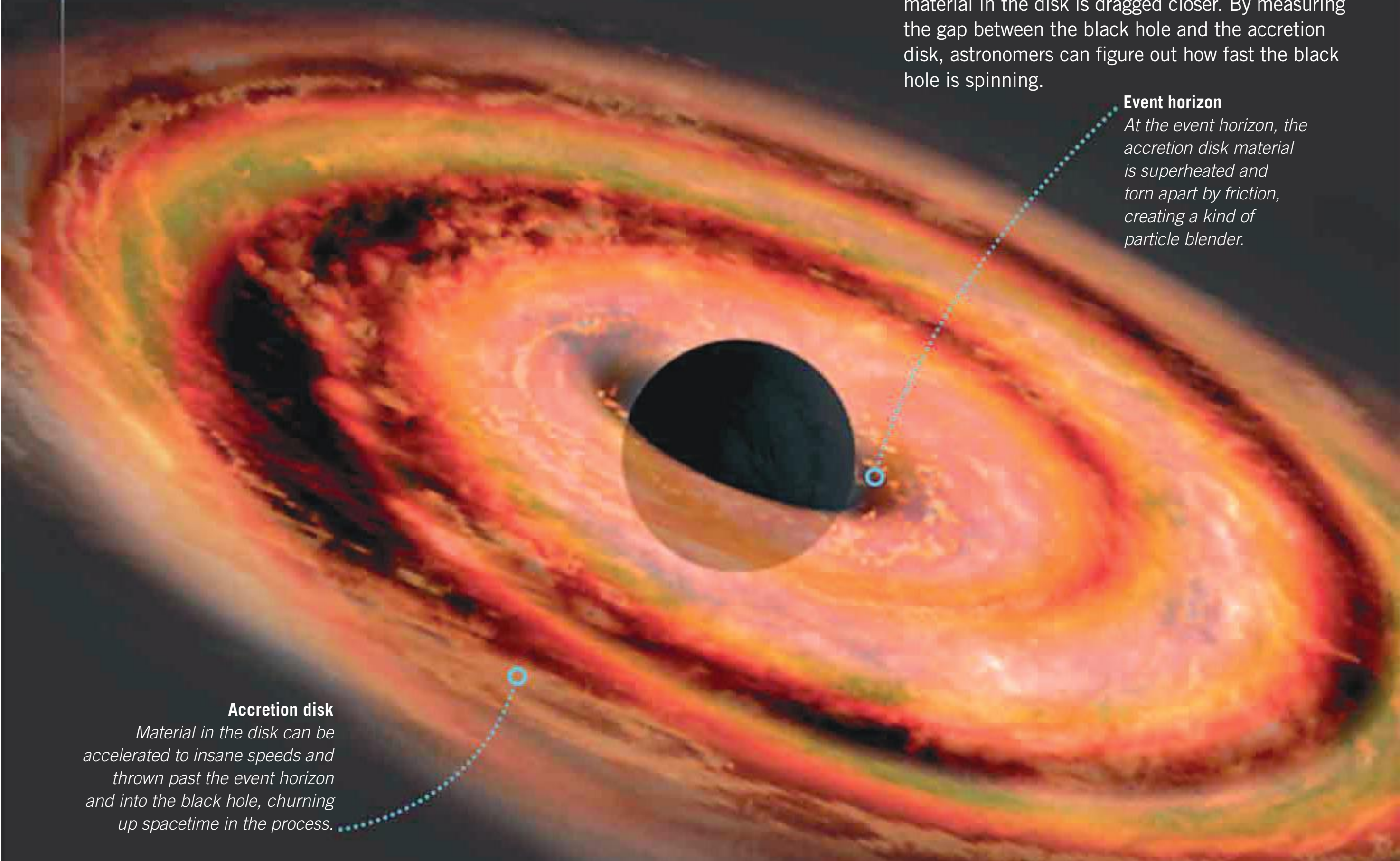
4 ***Spin, spin, spin***
As the black hole spins, it drags the fabric of the universe (spacetime) around with it. Space itself gets all twisted up around it, like a sheet caught in a spinning drill bit—a process known as frame-dragging.



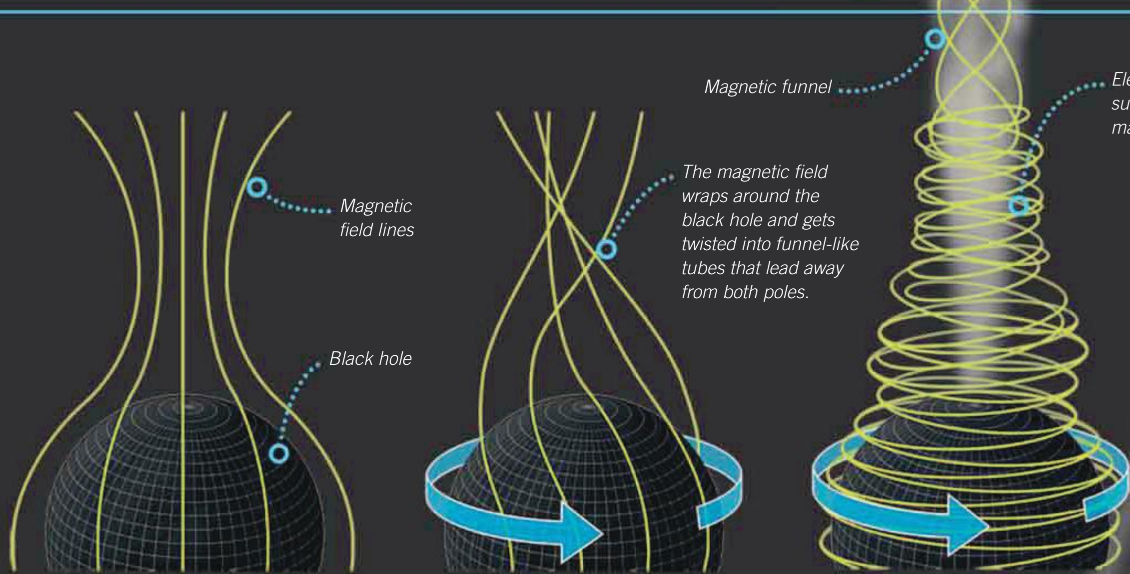
Spacetime dragged around black hole



5 ***A real drag, man***
The faster the black hole spins, the more the material in the disk is dragged closer. By measuring the gap between the black hole and the accretion disk, astronomers can figure out how fast the black hole is spinning.



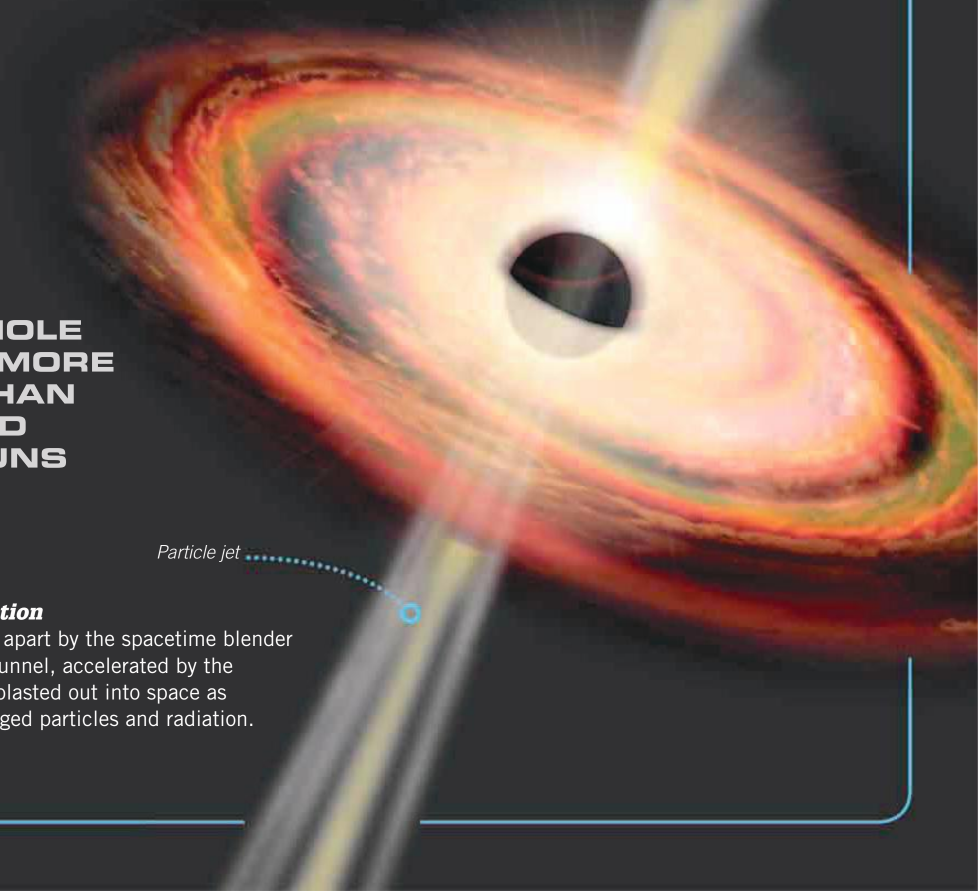
6 ***No escape***
The event horizon is the point where the black hole's gravity becomes so extreme that not even light can escape. Beyond it, spacetime is falling into the black hole faster than the speed of light. This is why light cannot escape—space is flowing inward faster than light can move outward.



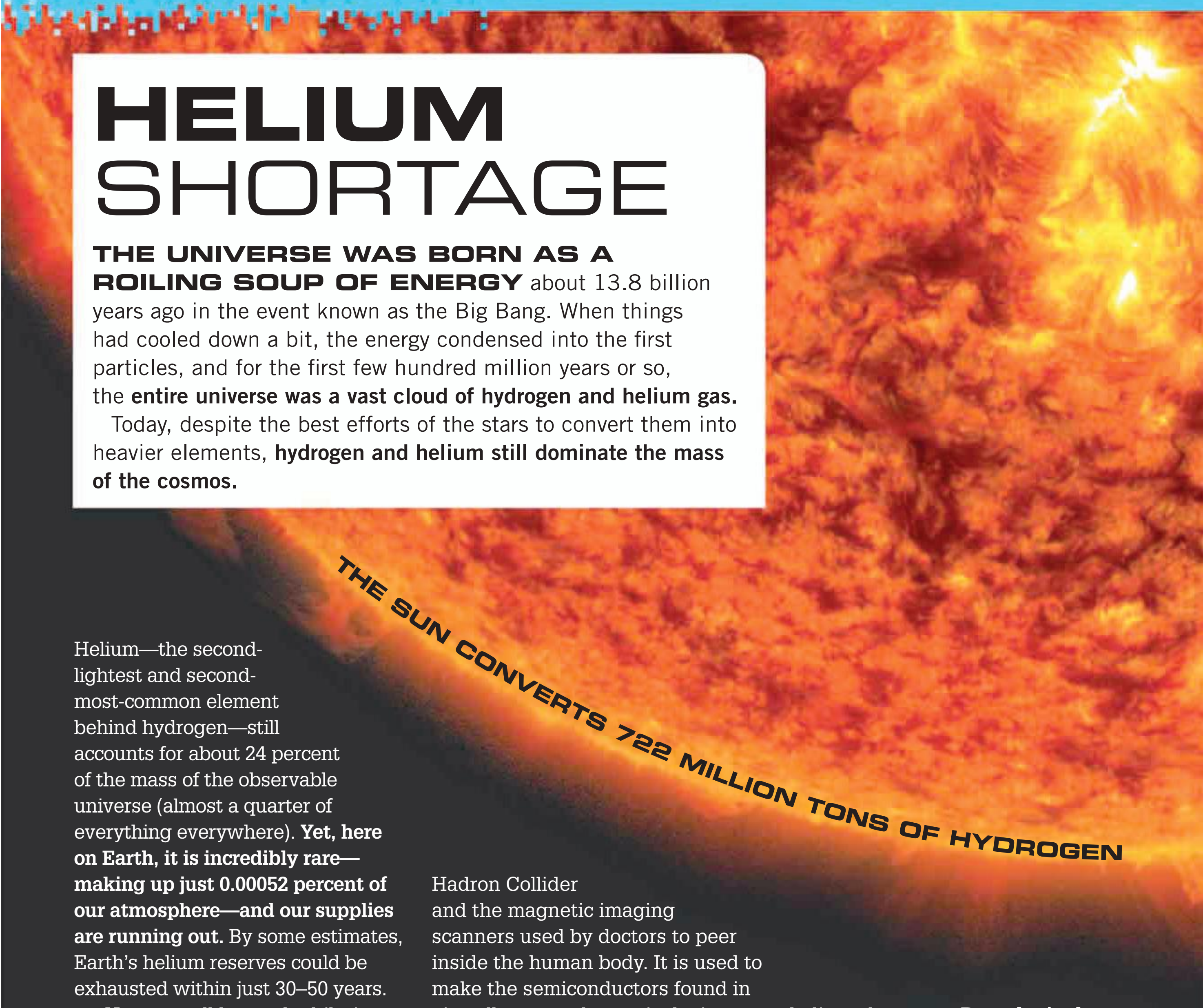
Magnetic field lines dragged around black hole

7 ***Magnetic mash-up***
To make matters worse, the black hole has a superpowerful magnetic field that also gets churned up in the spacetime carousel. Electrons unleashed in the particle blender are gathered up by the magnetic field, creating powerful electric currents that surge through the magnetic field lines.

A BLACK HOLE CAN EMIT MORE ENERGY THAN A HUNDRED BILLION SUNS



8 ***Radiation station***
Particles pulled apart by the spacetime blender are sucked up by the funnel, accelerated by the electric currents, and blasted out into space as focused beams of charged particles and radiation.



HELIUM SHORTAGE

THE UNIVERSE WAS BORN AS A ROILING SOUP OF ENERGY about 13.8 billion years ago in the event known as the Big Bang. When things had cooled down a bit, the energy condensed into the first particles, and for the first few hundred million years or so, the **entire universe was a vast cloud of hydrogen and helium gas.**

Today, despite the best efforts of the stars to convert them into heavier elements, **hydrogen and helium still dominate the mass of the cosmos.**

THE SUN CONVERTS 722 MILLION TONS OF HYDROGEN

Helium—the second-lightest and second-most-common element behind hydrogen—still accounts for about 24 percent of the mass of the observable universe (almost a quarter of everything everywhere). **Yet, here on Earth, it is incredibly rare—making up just 0.00052 percent of our atmosphere—and our supplies are running out.** By some estimates, Earth's helium reserves could be exhausted within just 30–50 years.

Now, we all know the hilarity that ensues when a party-balloon-toting joker uses the gas to perform dubious Mickey Mouse impressions, but, believe it or not, helium has a serious side.

Capable of remaining liquid at temperatures as low as -452°F (-269°C), it is the most effective refrigerant in the world. It cools the superconducting magnets that power the likes of the Large Hadron Collider and the magnetic imaging scanners used by doctors to peer inside the human body. It is used to make the semiconductors found in virtually every electronic device you take for granted – and the fiber-optic cables essential for high-speed Internet, communications, and TV need the cooling power of helium to prevent signal-destroying bubbles from forming during their manufacture. **So running out of helium is certain to cause us a few problems.** In fact, in 2012, medical scanners at some British universities were all affected by helium shortages. But **why is there so little of it on Earth when the cosmos is literally swimming in the stuff?**

Its main problem is its inert chemical nature. Chemical elements form bonds by sharing electrons, which they do to achieve a sort of Zen-like state of electromagnetic balance. A helium atom has two negatively charged electrons in its shell, and it really doesn't need any

INTO 717 MILLION TONS OF HELIUM EVERY SINGLE SECOND

Image of the active sun made using ultraviolet light emitted by ionized helium atoms

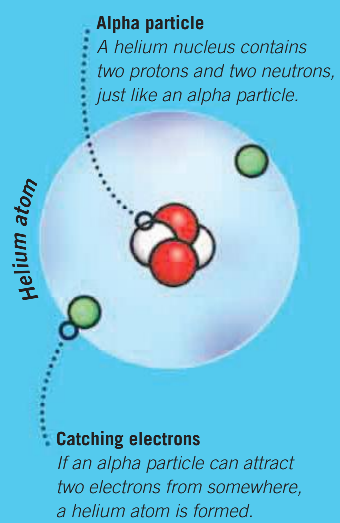
more (it can be considered to be "full")—which means **it has no incentive to bond with other elements.** Also, because it is so light, any that finds its way into the atmosphere eventually just drifts off into space—a quality that also makes it devilishly difficult to store.

Virtually all our helium comes from underground—as a by-product of the decay of naturally occurring radioactive elements like uranium—with the largest reserves being in Texas. Unfortunately, the United States (which holds 80 percent of the world's reserves) has been selling off helium cheaply since 1998—leading to frivolous usage and wastage. You can get it from the decay of tritium (a radioactive isotope of hydrogen), but the US stopped making that in 1988.

Luckily, if we do run out of helium on Earth, **there are plenty of other places in the solar system that have loads of it...**

HELIUM ATOM

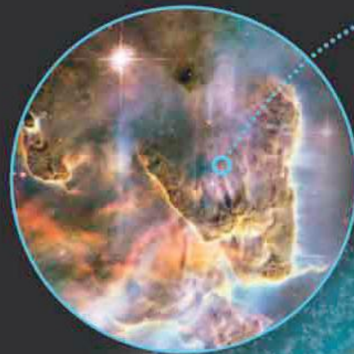
Helium is one of only two natural elements that has never been observed bonding to another to create a compound. Earth's atmosphere contains less than five parts per million of helium, which is resupplied from the decay of radioactive elements on Earth and from cosmic rays. Radioactive elements decay into lighter elements by emitting alpha particles—which are made up of two protons and two neutrons, just like a helium nucleus.

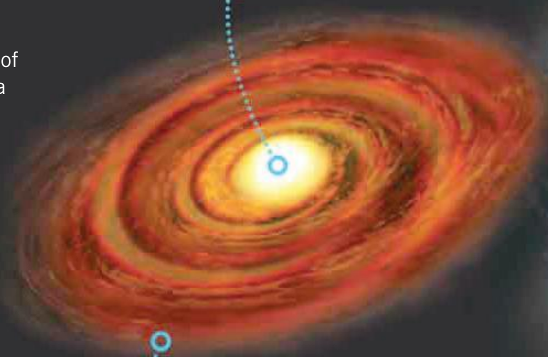


HOW THE SUN **STOLE OUR HELIUM**

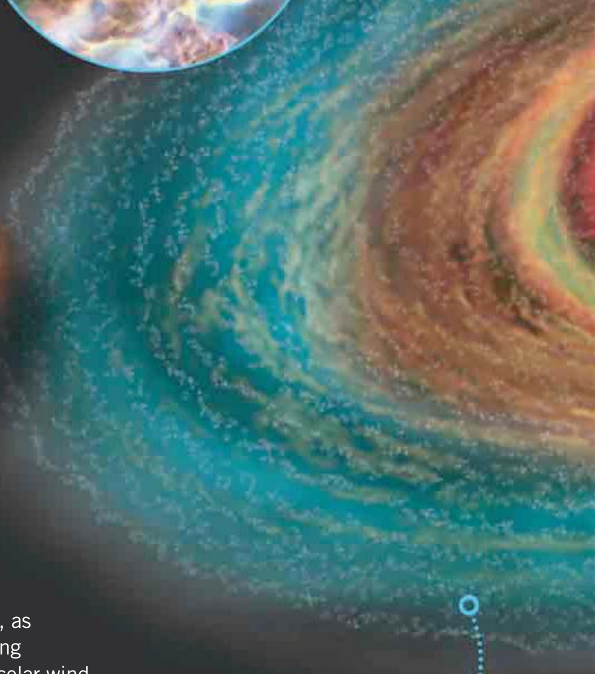
Helium is the second-most-plentiful element in the universe, and there's no shortage of it in the solar system either. The sun contains about 614 million billion billion tons of helium and it makes hundreds of millions of tons more every second. So why is there a shortage here on Earth?

1 *Gassy origins*
Our solar system began life in a giant cloud of gas and dust known as a star-forming nebula.

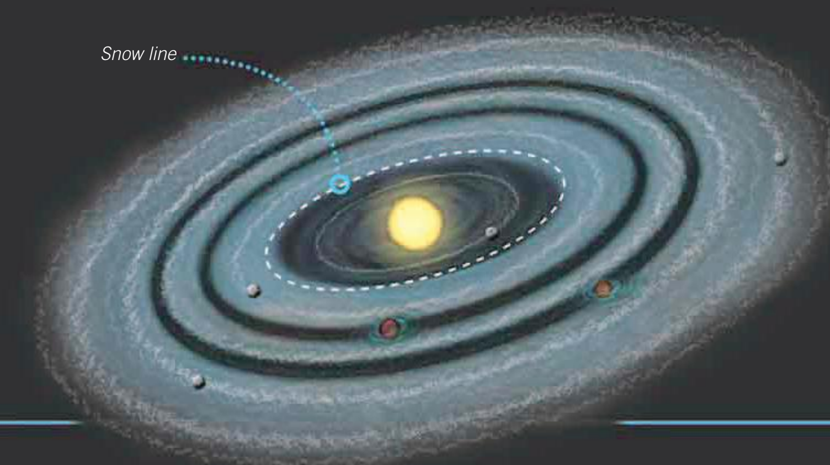




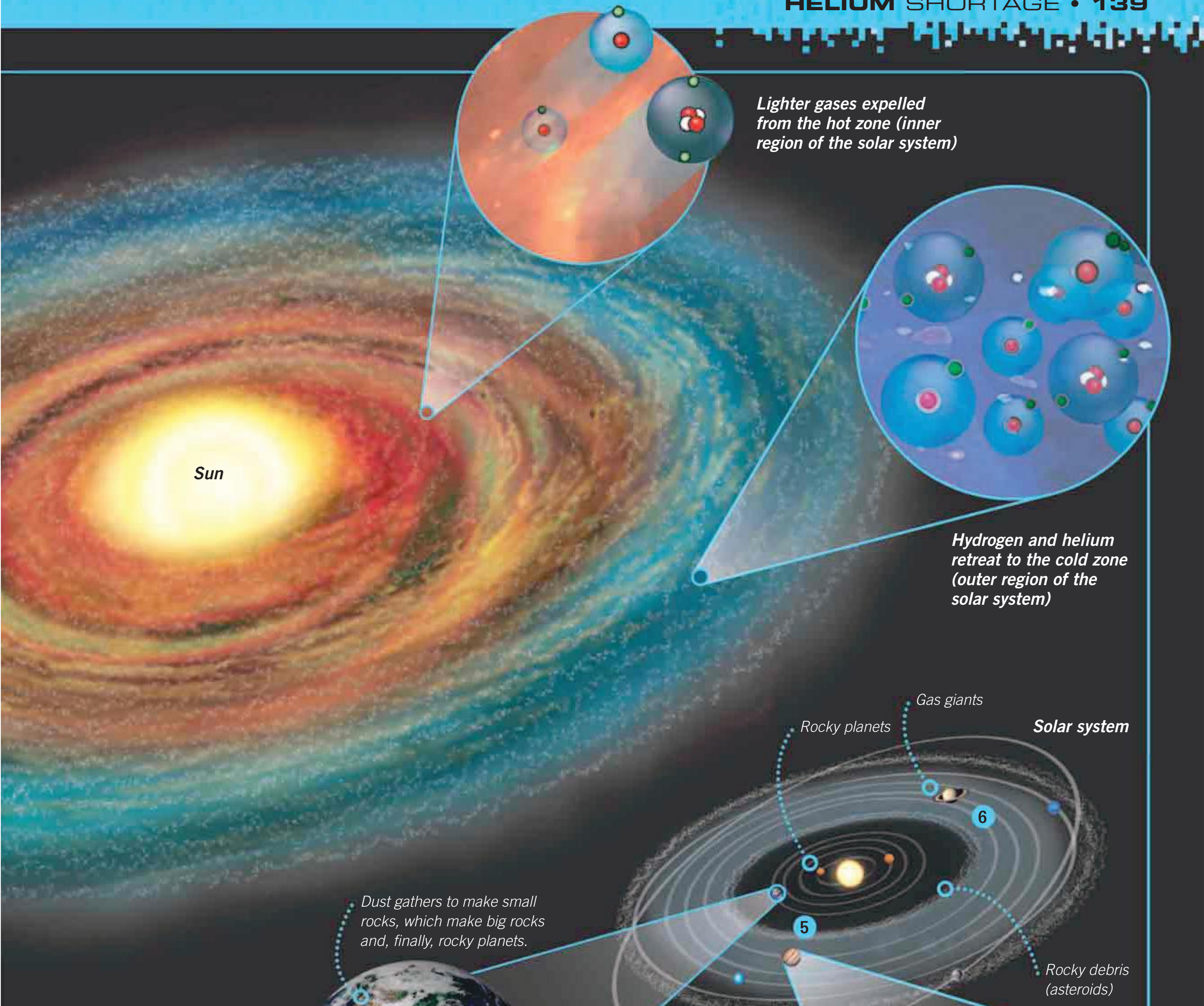
2 *Hungry sun*
Gravity caused part of the cloud to collapse into a swirling disk of gas. At the center, a protostar that became our sun began to grow. The baby sun was hungry for power and, as it grew, it absorbed 99.86 percent of the mass of the disk—leaving just 0.14 percent for the planets to fight over.



3 *Solar wind*
But it was not a fair fight because, as the sun grew in strength, it started blasting high-energy radiation into the disk. This solar wind pushed all the lighter elements away—banishing all the hydrogen and helium to the outer regions of the disk.

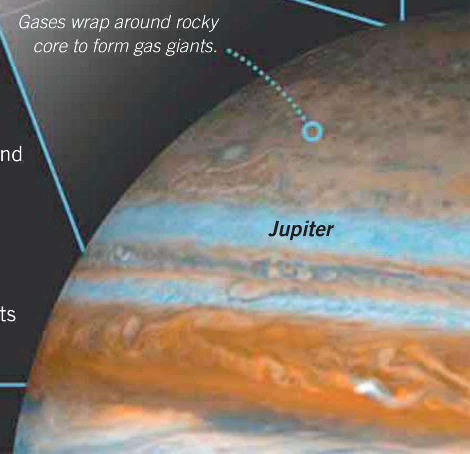


4 *Snow line*
A dividing line was created, called the "snow line." Inside the snow line, only the elements heavy enough to resist the solar wind remained—creating a "hot," rocky wasteland.



5 *In the hot zone*

Forced to grow within the "hot zone," the four planets could gather no gases and were reliant on visitors from beyond the snow line, like comets, to deliver the lighter elements. But, because helium is so unreactive, very little of it arrived, leaving these planets—which included Earth—almost helium-free. These four planets became known as the rocky planets.



6 *In the cold zone*

Meanwhile, on the far side of the snow line, baby planets found themselves in a gaseous nirvana. They wrapped themselves in decadent coats of gassy hydrogen and helium—locking away 99 percent of the solar system's remaining mass. These four planets became known as the gas giants.

DEATH RAYS FROM OUTER SPACE

BACK IN 1901, SOME ENGLISH SCIENTISTS noticed a puzzling thing while experimenting with the radioactive element radium **(radioactivity itself had only been discovered five years earlier).** They were measuring its radioactivity using a gold-leaf electroscope, which used an electric field to hold two strips of gold leaf apart.

When "radium rays" entered the device, they ionized the air around the gold leaf, which allowed electrical charge to escape—the more radiation present, the less charge the gold leaf held and the closer the two strips would move together.

The scientists noticed that, even when the electroscope was removed from the radium, it still lost electrical charge. **Somehow radiation was coming from somewhere else.** Nor was this an isolated event. Laboratories all over the world were reporting the same phenomenon.

Most scientists at the time believed that the radiation must have been coming from minerals in the ground. But, in 1910, a German physicist, Theodore Wulf, took an electroscope to the Eiffel Tower and tested ionization levels at ground level and at the top of the tower. He found that **the effect was actually stronger at high altitude**—the radiation was not coming from the ground. **It was a mystery worthy of Indiana Jones** (if Indiana Jones were a detector-brandishing physicist and not a whip-wielding archaeologist)—enter our hero: Austrian physicist, Victor Hess.

Hess had the idea that the ionizing radiation was coming from the sky rather than from the ground. He built new measuring devices that could survive the temperature and pressure changes that occur at high altitude—then **he took to his hot-air balloon.** The physicist's initial trips in 1911 and 1912 were promising. He found that, although levels of ionizing radiation initially fell, the higher he traveled, the higher the levels became—and, at a height of several miles, ionization was many times greater than at ground level. Hess concluded that **"a radiation of very high penetrating power enters our atmosphere from above."**

But where was it coming from? One obvious candidate was that great nuclear fusion factory in the sky—the sun. On April 12, 1912, Hess took to his balloon once again, but this time, he made his trip during a total eclipse of the sun. If the sun was the source of the mysterious emissions, the levels should drop right off when the moon passed across and blocked the radiation. But the levels measured by Hess did not decrease at all. **He concluded that the radiation was not coming from the sun and must be coming from farther out in space.** Hess's findings were confirmed in 1925 by American physicist Robert Milikan, who dubbed the mysterious radiation **"cosmic rays."** In 1936, Hess and Milikan shared the Nobel Prize in Physics for the discovery. They shared the prize with American physicist Carl D. Anderson, who had discovered the positron (the antimatter version of an electron)—a discovery that stemmed from cosmic ray research.

After more than one hundred years of research into cosmic radiation, you would think we would have it pretty much figured out, but **even today, there is a lot we still do not understand**—such as exactly where it comes from. Whatever the source turns out to be (supernovae, black holes, and starburst galaxies are hot favorites), we do know that it makes the Large Hadron Collider—built by the European Organization for Nuclear Research (CERN) near Geneva, Switzerland—**look like a particle peashooter,** as these cosmic rays can carry 1,000 times more energy.

Dangerous combination: Cosmic radiation is made up of about 89 percent hydrogen nuclei, about 10 percent helium nuclei, and about 1 percent really tiny stuff, such as electrons, and the nuclei of heavier elements.

DESTROYER!

Cosmic radiation is made up of extremely energetic particles traveling at close to the speed of light. Some of these can possess the same energy as a tennis ball traveling at 100 mph (160 km/h). All this energy can cause a lot of problems…

• Cosmic rays can damage the electronic circuits of spacecraft by causing computer memory bits to "flip" or microcircuits to fail. It can also harm astronauts' DNA. NASA estimates that every week spent in space shortens their life expectancy by a day.

• Some scientists think that many of Earth's extinction events could have been partly caused by cosmic radiation. High levels may have caused genetic mutations—making organisms less able to cope with environmental changes.

WHERE DO COSMIC RAYS COME FROM?

Because the particles that make up cosmic radiation are electrically charged, they are deflected by magnetic fields. So, as they journey through the galaxy, their paths become scrambled—making it virtually impossible to trace their origins. But that is not to say we don't have some idea…

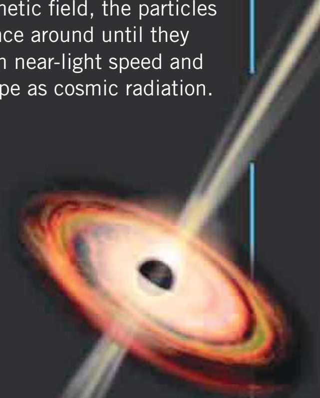
Crab Nebula (supernova remnant)

SUPERNOVAE

It's possible that, when a massive star explodes, the expanding shock wave accelerates the charged particles that are emitted. Trapped inside the remnant's magnetic field, the particles bounce around until they reach near-light speed and escape as cosmic radiation.

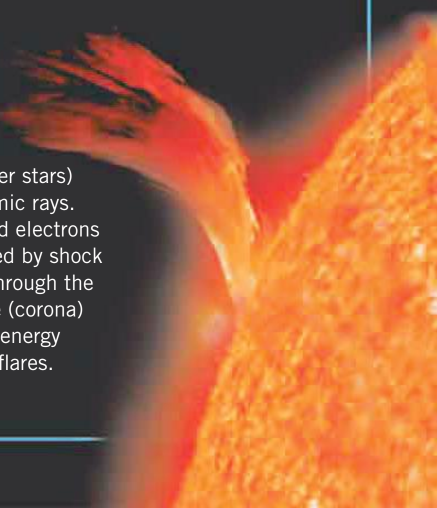
BLACK HOLES

It is thought that the highest-energy cosmic rays are created by supermassive black holes. When matter, or even a star, is devoured by a black hole, it can be spewed out in colossal jets at near-to-light speeds.



STARS

The sun (and other stars) can produce cosmic rays. Atomic nuclei and electrons can be accelerated by shock waves traveling through the sun's atmosphere (corona) and by magnetic energy released in solar flares.

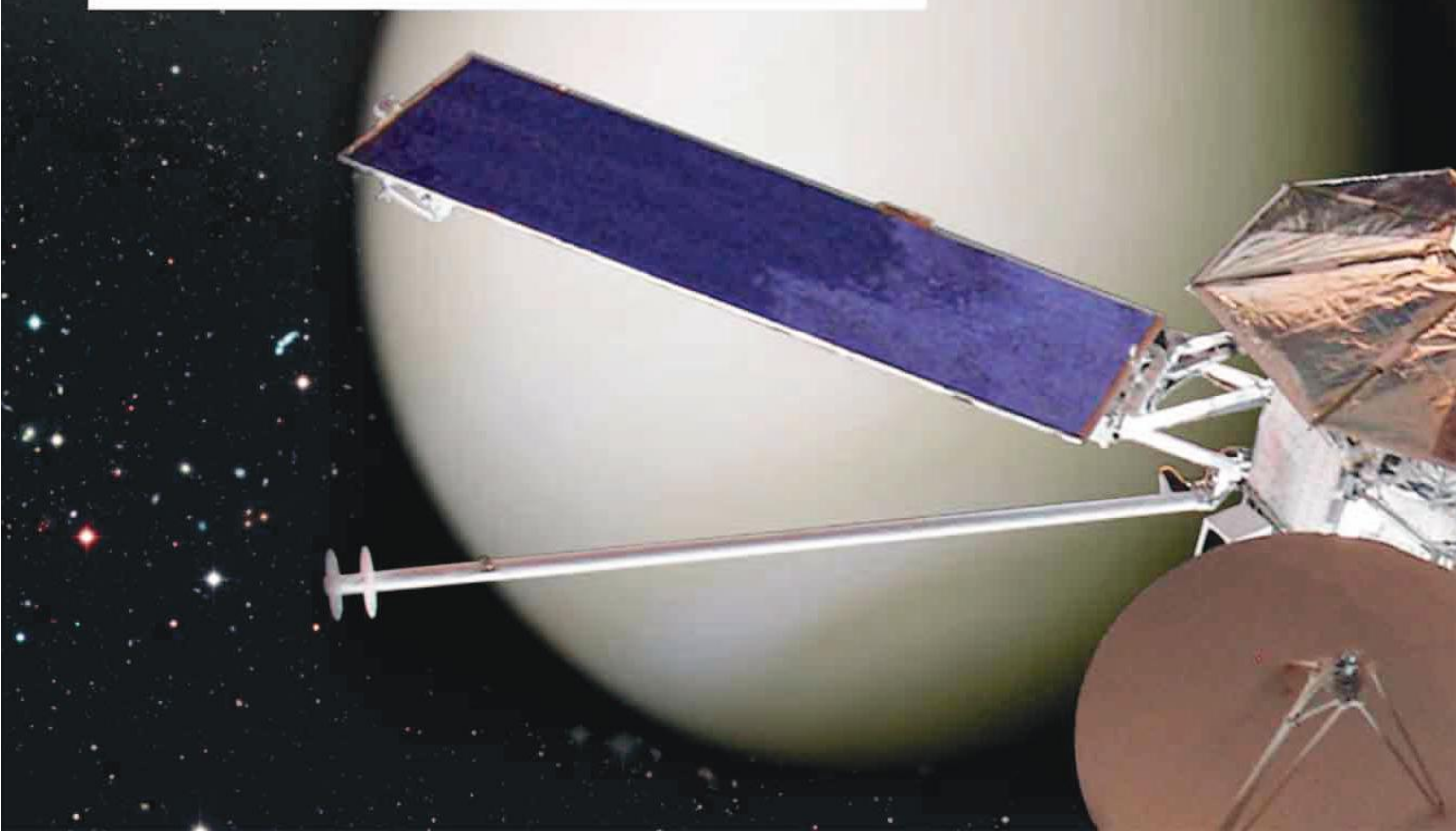


GRAVITY SLINGSHOT

WE ARE USED TO THINKING OF SPACEFLIGHT as a struggle against gravity. After all, it takes vast, towering rockets filled with hundreds of tons of explosive liquids and gases just to give light aircraft–sized vehicles enough thrust to break free of the bonds of Earth's gravity.

Even if you are lucky enough to make it into space, there are still endless gravitational hurdles to overcome. Contrary to what Sir Isaac Newton believed, gravity is not caused by two massive objects pulling on one another. Instead, **gravity is a by-product of the dents and distortions made by massive objects in the fabric of the universe.** A truly massive object, like a planet, makes a pretty big dent, and, when a less massive object, like a spacecraft, strays too close, it finds itself "falling" into that dent—it might look as if the spacecraft is being "pulled" toward the planet, but really it is "falling" toward it.

The solar system is littered with these gravitational pitfalls—**a satellite falls toward Earth, Earth falls toward the sun, and, in turn, the sun falls toward the center of the Milky Way.** The only way to stop this fall from becoming a direct plunge is to move through space fast enough to ensure that your momentum keeps you aloft.



You can think of the sun's gravity as being a little like a wineglass. If you drop an olive into the glass, it will fall straight to the bottom, but if you spin the glass, you can give the olive enough momentum to roll around the sides without falling in (like a planet orbiting the sun). Decrease the momentum and its orbit will fall closer; increase it and its orbit moves farther away. **If you continue to increase the speed, eventually the olive will move so fast that it will achieve "escape velocity" and fly from the glass.**

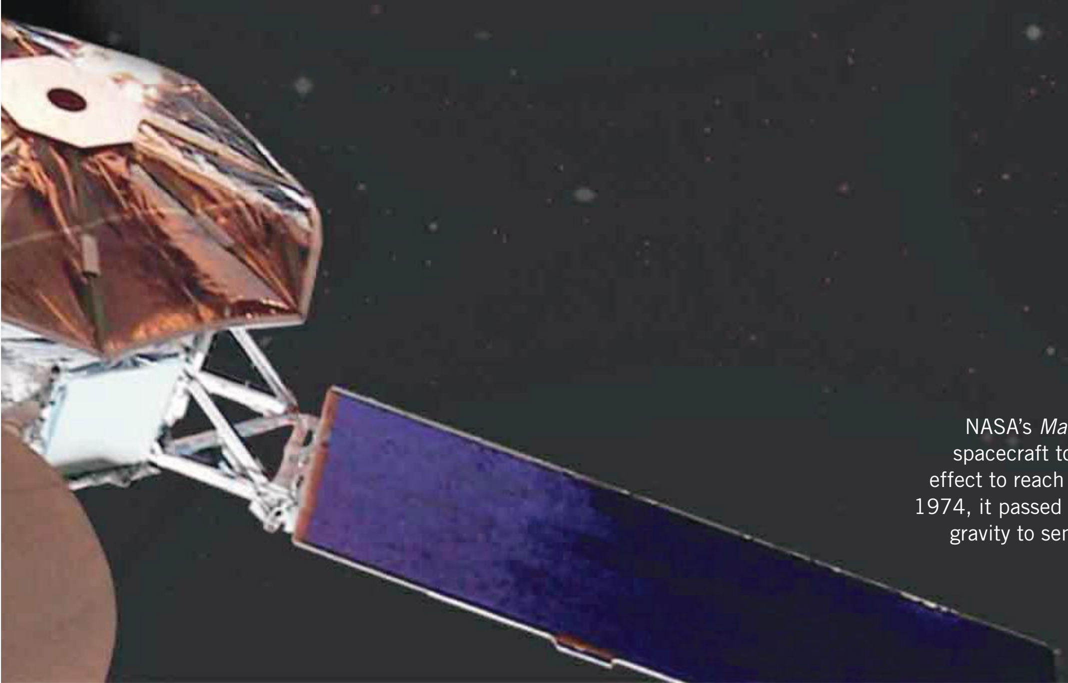
A spacecraft leaving Earth has been given enough momentum to escape Earth's gravity wineglass, but if it wants to travel into deep space, **it has to find enough momentum to escape the sun's gravitational dent, too.** Using rockets is not practical because they would need so much heavy fuel that it would be prohibitively expensive just to leave Earth—so **scientists came up with a clever trick called a "gravity assist" maneuver.**

Also known as the "slingshot" maneuver, the technique was first used successfully 40 years ago by NASA's *Mariner 10* Mercury probe. Instead of struggling against the gravitational pull of the planets, during a gravity assist, a spacecraft uses a planet's (or a series of planets') gravity to give it a speed boost. By falling toward a planet that is falling toward the sun, **a spacecraft can "steal" enough momentum to travel against the sun's gravitational pull.** So you could say that spaceflight is not flying at all: it is just falling, with style!

***MARINER 10* WAS THE FIRST CRAFT TO USE SOLAR WIND AS A MEANS OF PROPULSION AFTER ITS THRUSTERS RAN LOW ON FUEL**

YURI KONDRATYUK

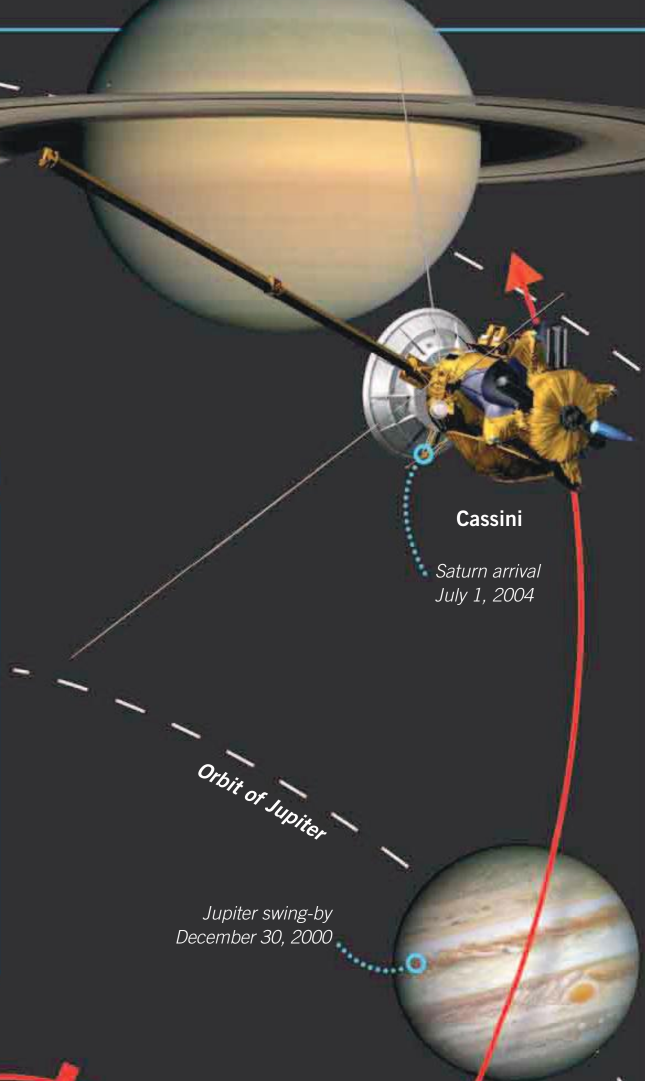
The method of using a celestial body's gravity to accelerate and decelerate was suggested by Ukrainian scientist and engineer Yuri Kondratyuk in his elaborately titled paper "To Whoever Will Read This Paper in Order to Build an Interplanetary Rocket." The paper was dated 1918–19, but published in 1938—so it may have preceded the work of a German-born Russian scientist, Friedrich Zander, who made a similar suggestion in 1925. The idea was refined by NASA scientist Michael Minovitch for *Mariner 10*'s trip to Venus and Mercury in 1973.



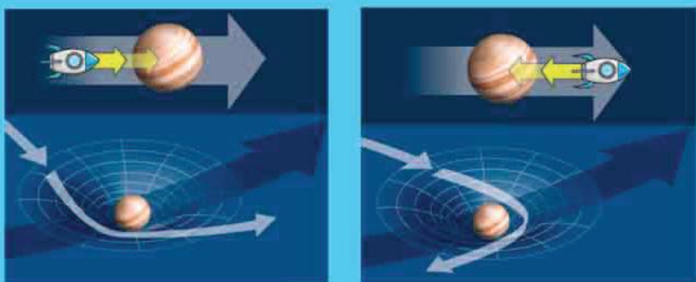
Mariner 10*:*
NASA's *Mariner 10* probe became the first spacecraft to use the gravitational slingshot effect to reach another planet. On February 5, 1974, it passed by Venus and used the planet's gravity to send it on its way toward Mercury.

USING GRAVITY TO GO FASTER

Gravitational assist maneuvers, or slingshots, are an essential part of space exploration. By stealing gravitational energy from a planet, a spacecraft can reach much higher speeds, using less fuel, than would be possible using rockets alone.



SPEED UP, SLOW DOWN

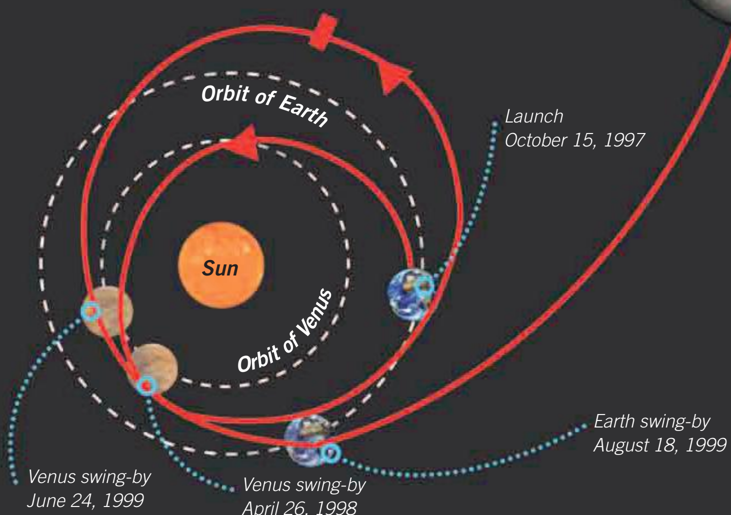


Speeding up: If the spacecraft approaches from behind a planet, it gets a gravitational tow and "slingshots" around the back—gaining speed.

Slowing down: Assists can also be used to slow a spacecraft. By approaching the planet from the front, the craft uses the planet's gravity like an anchor to slow itself.

CASSINI'S TRAJECTORY

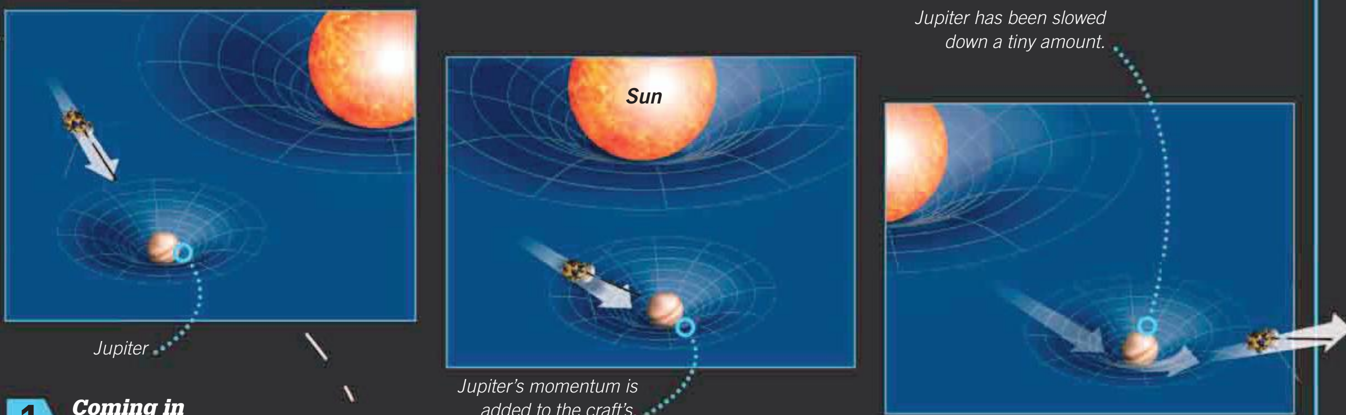
NASA's Saturn-exploring *Cassini-Huygens* spacecraft weighed in at 6.2 tons—too heavy for even the most powerful rockets to provide enough thrust to counter the sun's gravitational pull. To provide the extra boost it needed, *Cassini*'s 6.7-year route took it twice past Venus and once past Earth and Jupiter. With each planetary fly-by, *Cassini* stole a little momentum to give it the boost it needed to break away from the sun's gravity and reach Jupiter.



AN ADVANCED INTERSTELLAR CRAFT MAY ONE DAY USE THE GRAVITY OF TWO NEUTRON STARS TO ACCELERATE TO THE ASTONISHING SPEED OF 181 MILLION MPH (291 MILLION KPH)

SUPER SLINGSHOT

Using gravity to get a speed boost sounds straightforward: a spacecraft is accelerated by a planet's gravity and leaves moving faster than it arrived. But, from the planet's viewpoint, the craft also has to leave that planet's gravity and, in the process, it appears to be slowed down to its original preapproach speed. So where is the boost coming from? It all becomes clear from the sun's point of view...



1 *Coming in*
From the sun's point of view, the craft approaches the planet (in this case, Jupiter) at its normal speed.

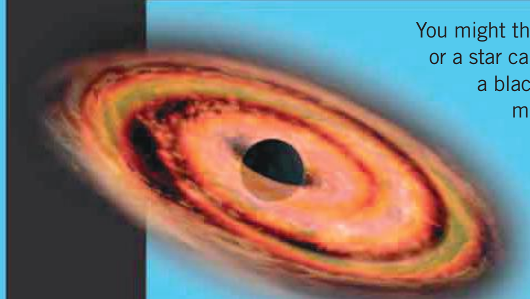
2 *Gravity well*
The craft accelerates as it falls into Jupiter's gravity well. Jupiter's gravity is now acting on the craft, pulling it with the gas giant as it orbits the sun.

3 *Gained momentum*
The question of where the boost comes from is all about perspective. It is like a tennis ball being hit at a moving train: If you were on the train, the ball would appear to bounce back at the speed it was thrown. If you were beside the track, you would see that the ball added the train's speed to its own as it bounced off.

SATURN MISSION

The *Cassini-Huygens* mission was launched on October 15, 1997, and arrived at Saturn in July 2004. The *Huygens* probe, built by the European Space Agency (ESA), entered the atmosphere of Saturn's largest moon, Titan, and parachuted to the surface—taking detailed readings of the atmosphere and capturing the first images of the moon's surface. *Cassini*'s mission is to explore the Saturnian system—focusing on Saturn's rings and icy moons. The craft has made many orbits of Saturn and flybys of Titan, and is expected to continue operating and making discoveries until at least 2017.

BLACK HOLE NO-GO



You might think that if the gravity of a planet or a star can be used to boost a spacecraft, a black hole that contains the mass of millions of stars would make the ultimate slingshot machine. Unfortunately, black holes are so massive, and spacetime becomes so heavily distorted around them, that it would take more energy to escape the pull of a black hole than could ever be added by its motion.

IS GLASS A LIQUID?

GLASS IS ALL AROUND US. It is the window we gaze out of longingly on a warm summer day, and it is the computer screen behind which lurks the work that prevents us from going outside. It is the modern office building in which we toil and it is the empty bottle of wine we discard at the end of a long week. **In the modern world, glass is ubiquitous, essential, and deeply mysterious.**

The mystery of glass started when people looked at centuries-old windows and observed that **their panes seemed to be thicker at the bottom.** This **led to speculation that glass is a liquid** that in short timescales seems to be solid but that, over centuries, acts like warm toffee—flowing downward into the encouraging arms of mother gravity.

Shattered glass:
It's generally seen as common sense that liquids can't shatter—if they could, it would make diving into a swimming pool a rather hazardous pastime. So it stands to reason that glass, which definitely shatters, can't be a liquid... or does it?

This, of course, was not true. If glass was so fluid, older glass objects—like millennia-old drinking vessels—would have long ago melted into glassy puddles. The thickening observed in old windows is **simply a result of the manufacturing processes of the time,** which involved spinning molten glass out into sheets, which created glass with thick edges.

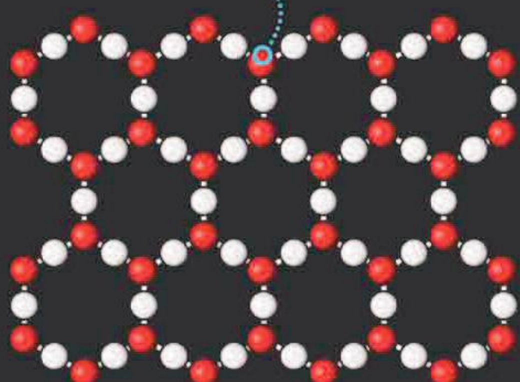
But the mystery does not end there. When you look at glass on a molecular level, **it does indeed appear to be more liquid than solid.** In a solid, the molecules are arranged in neat and rigid shapes, but in glass, the molecules are arranged in an almost random jumble—like a liquid. In fact, **structurally there is almost no difference between a liquid and glass.** Glass is made by cooling a liquid below its freezing point. As the temperature drops, the molecules become more sluggish and the liquid becomes more viscous until they become almost motionless and the glass is formed.

But, unlike a solid whose molecules stop moving, the molecules in glass never really stop. It is this lack of transition between its phases that has led many physicists to argue that glass is neither a liquid nor a solid, but is instead in a sort of in-between state known as an "amorphous solid."

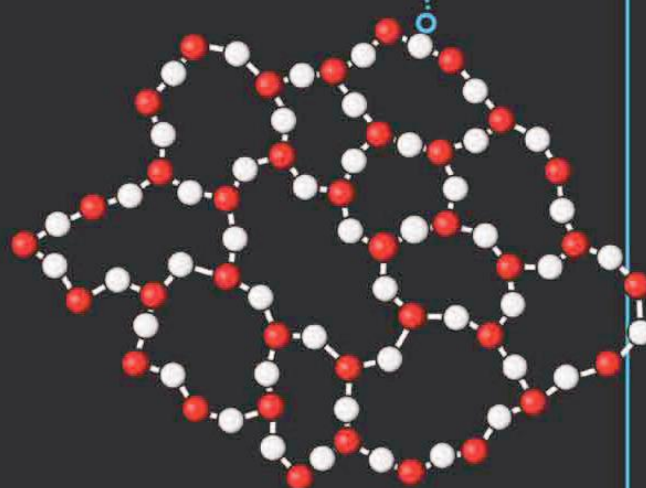
IF GLASS IS A LIQUID, IT WOULD TAKE 100,000,000,000,000,000, 000,000,000,000,000 YEARS FOR A PANE TO SAG SLIGHTLY

WHAT MAKES **GLASS DIFFERENT?**

Glass's molecular structure sits somewhere between a liquid and a solid. Its molecules are jumbled randomly, similar to those in a liquid. But they move a lot slower, to the point where they are almost not moving at all, in a similar state to a solid.



Molecular structure of a solid

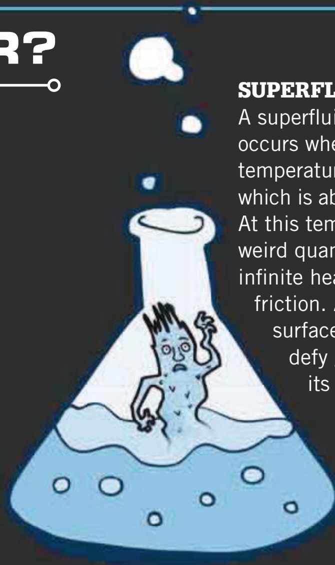


Molecular structure of glass

WHAT'S THE MATTER?

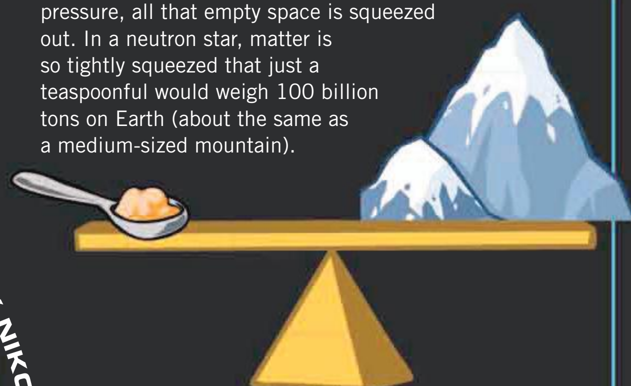
Unlike most substances, which change from their liquid state to their solid state at a set temperature—water solidifies into ice at 32°F (0°C)—the temperature at which glass forms depends on how quickly it is cooled from its molten state. The slower you cool it, the lower the temperature at which it changes into glass and the more dense that glass will be—cool it quickly and it changes into a solid while it is still much hotter. Whether you believe that this makes it a solid or a liquid, or both, glass isn't the only weird state of matter...

SUPERFLUIDS
A superfluid is a phase of matter that occurs when helium is supercooled to temperatures close to absolute zero, which is about -459.67°F (-273.15°C). At this temperature, its atoms exhibit weird quantum effects that give it infinite heat conductivity and zero friction. A superfluid isn't affected by surface tension and can seemingly defy gravity by "climbing" out of its container.



DARK MATTER
This is a mysterious form of matter that makes up 83 percent of the matter mass of the universe. Because it doesn't interact with the electromagnetic force, it doesn't emit or absorb radiation—meaning it is invisible and (so far) impossible to detect directly. It has been detected indirectly through its gravitational effects on objects we can see (like stars and galaxies).

DEGENERATIVE MATTER
Under "normal" conditions, atoms are made up of almost entirely empty space (the space between an atomic nucleus and its electron cloud can be likened to a mosquito inside a cathedral). When matter is subjected to intense pressure, all that empty space is squeezed out. In a neutron star, matter is so tightly squeezed that just a teaspoonful would weigh 100 billion tons on Earth (about the same as a medium-sized mountain).

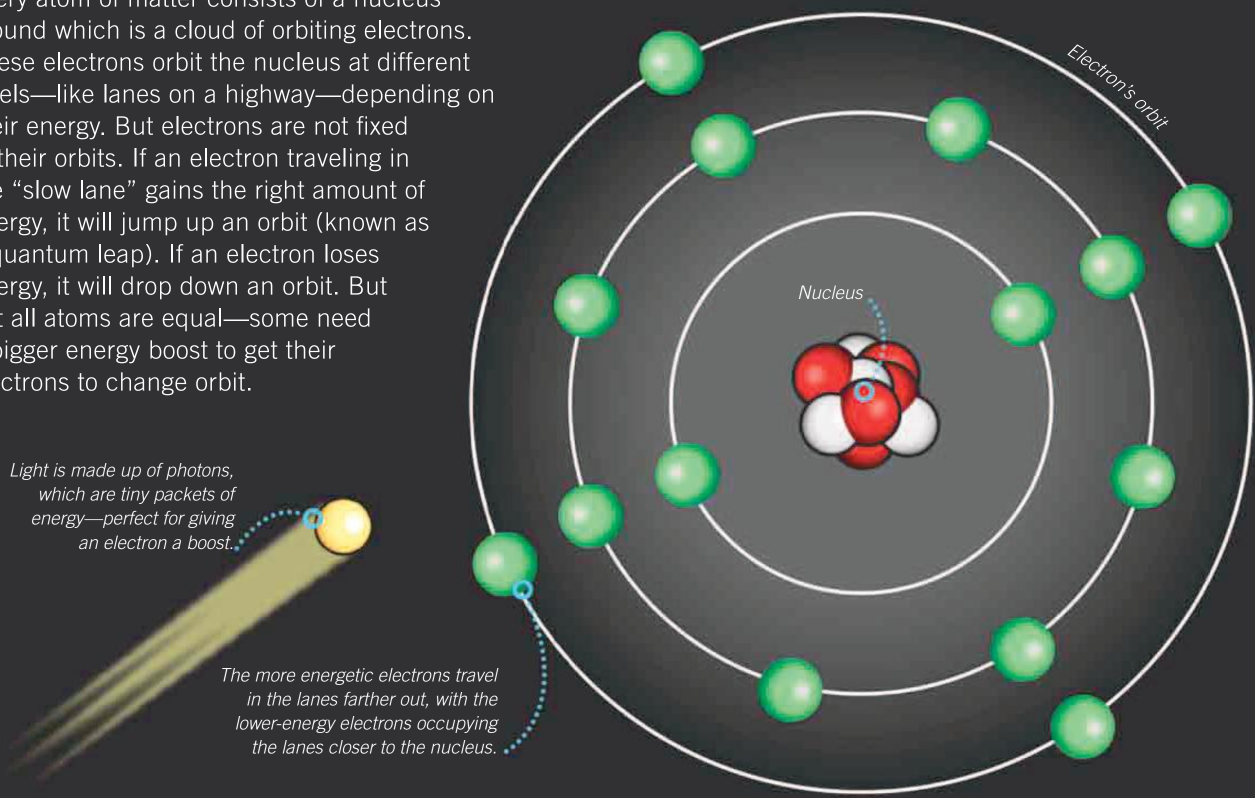


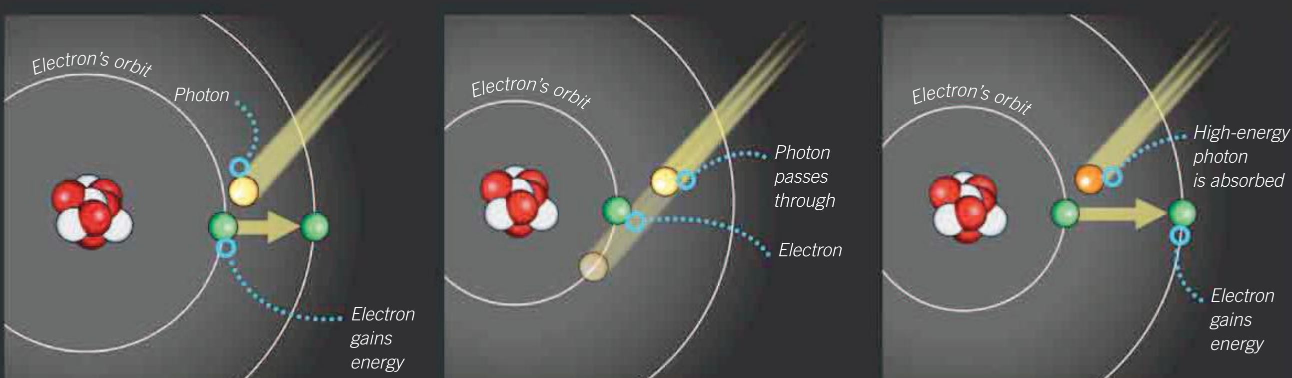
PLASMA GLOBES WERE INVENTED BY NIKOLA TESLA

PLASMA
When atoms are heated to extremely high temperatures, their electrons become so energetic that the nucleus can no longer hold on to them. This creates a soup of atomic nuclei and "free" electrons called a plasma. Because the electrons are "free," plasmas conduct electrical currents and produce magnetic fields. Lightning is a good example of a plasma conducting electric currents, but plasma globes demonstrate the same thing.

WHY IS GLASS TRANSPARENT?

Every atom of matter consists of a nucleus around which is a cloud of orbiting electrons. These electrons orbit the nucleus at different levels—like lanes on a highway—depending on their energy. But electrons are not fixed in their orbits. If an electron traveling in the "slow lane" gains the right amount of energy, it will jump up an orbit (known as a quantum leap). If an electron loses energy, it will drop down an orbit. But not all atoms are equal—some need a bigger energy boost to get their electrons to change orbit.





Opaque atom

NONTRANSPARENT
When a photon comes into contact with the electrons of an opaque (nontransparent) substance, the electron gains enough energy from the photon to jump up a level in its orbit. The photon is absorbed—so light cannot pass through.

Glass atom

TRANSPARENT GLASS
In glass, it takes a lot more energy to make the electrons jump up to the next level (called the energy gap) than a photon can provide. The electron does not absorb the photon—so the photon of light can pass through.

Glass atom with high-energy photon

ULTRAVIOLET
However, some photons are more energetic than others. Glass might be transparent to visible light, but higher-energy light (such as ultraviolet) has enough energy to kick glass's electrons up a level. This makes glass opaque to higher-energy light.

CURIOSITY: SCIENCE'S HEART

HUMANITY IS AN INHERENTLY CURIOUS SPECIES. From the moment of our birth, we seek to understand ourselves, the world we inhabit, and all the space beyond. **Curiosity defines us.** The need to ask *what if?, why?,* and *how?* liberated us from the limits of an existence driven by survival alone and allowed us to become **the first species in the history of the planet to try to understand how the world works.**

Perhaps the ultimate expression of our curiosity is science. If curiosity is raw instinct, then science is curiosity channeled, focused, and refined—curiosity can survive without science, but science cannot survive without curiosity. **Remove curiosity from science and you tear out its beating heart.**

Yet scientific research can be costly, which has thrown up the argument that only scientific research that has a commercial value should be funded. Indeed, this argument believes that all other scientific endeavors are not valuable at all. In short, people who jump on this this train of thought want to **remove curiosity from science altogether.**

On the face of it, that might seem to make sense—after all, in these cash-strapped times, it is frivolous to fund money-pit projects like space telescopes when governments can back something that can be packaged, marketed, and sold for a profit. Nor is this a view limited to government policy-makers. Peer into the great World Wide Web and you will not have to dig too deep to find people asking such questions as **"Why spend billions on particle colliders or space telescopes when there are people dying of starvation, cancer, or war?"** Sure, if you look at great curiosity-driven science projects superficially, it may be difficult to see how they might benefit humanity beyond the "frivolous" quest for understanding—after all, how can $3 billion spent trying to get a better view of a distant galaxy possibly have any effect on your daily life?

But the fact is, most of our modern world is built on the foundations of science driven only by *what if?, why?,* and *how?*

When Scottish physicist James Clerk Maxwell performed his experiments with electricity and magnetism in the late 19th century, **he was not aiming for something as base as personal profit or even anything as lofty as benefiting society.** Yet his electromagnetic tinkerings now form the foundations of our entire economy and society. Everything from computers, the Internet, satellites, mobile phones, and televisions to life-support machines, medical scanners, and machines that go "ping" owe their existence to science for curiosity's sake.

A century ago, when British scientist William Bragg investigated the strange patterns created by X-rays as they scattered from crystalline substances, he did not do it with the aim of creating a technique (X-ray crystallography) that would reveal the structure of DNA and revolutionize the fields of medicine, chemistry, physics, and engineering—**he did it out of curiosity and the desire to reveal something new about the way the world works.**

A more recent example is the discovery of graphene. Graphene is a material made of a single layer of carbon atoms that is 200 times stronger than steel and able to conduct electricity like nothing else. It is expected to replace silicon in microprocessors and should make it possible to build computers a hundred times faster than those today. Batteries made of graphene will charge hundreds of times faster than conventional batteries—**meaning a smartphone could charge in 30 seconds** and an electric car with a flat battery could be ready to drive away in minutes.

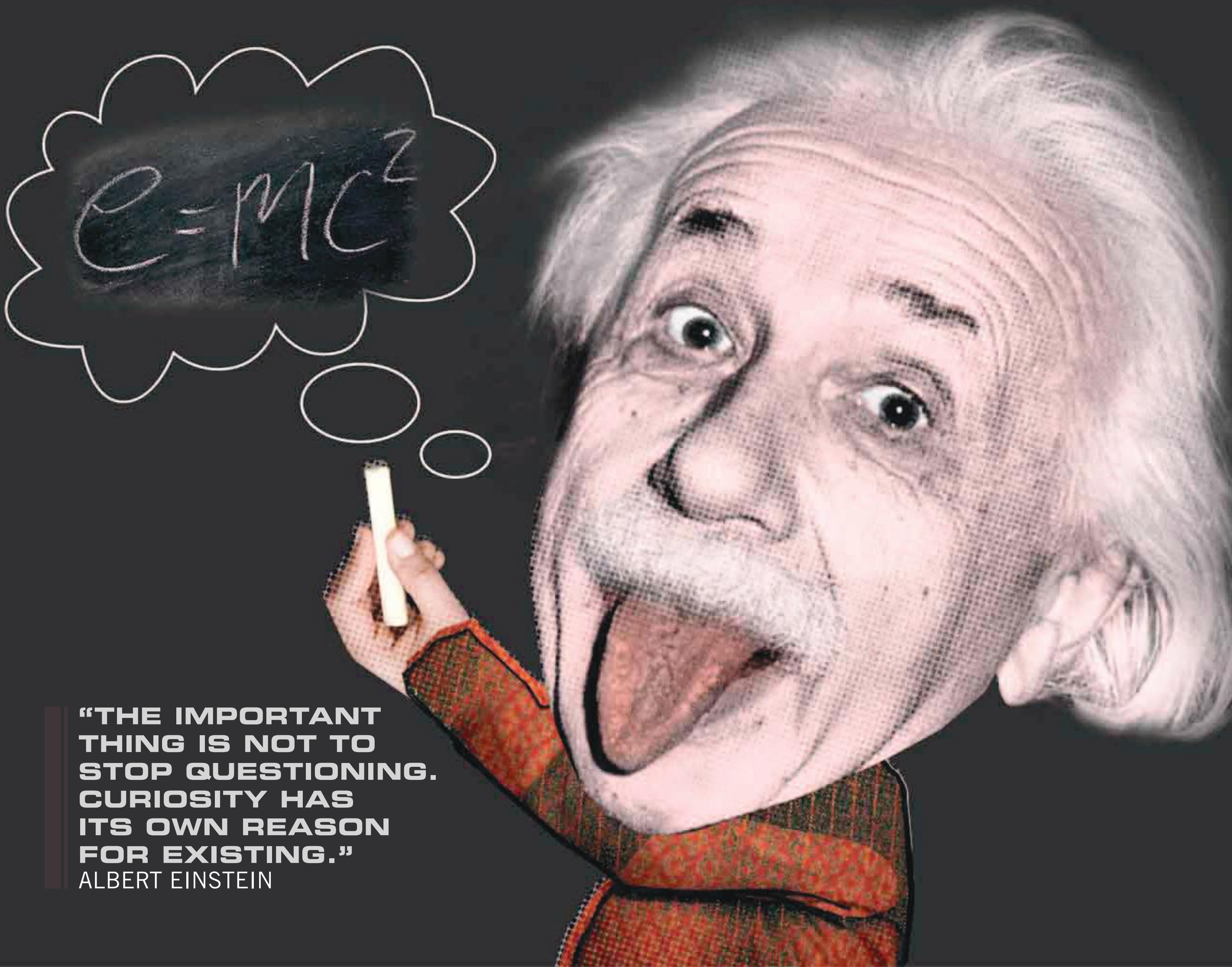
But graphene was not discovered by scientists looking to revolutionize electronics, but by two Russian guys at Manchester University playing around with sticky tape and a block of graphite—just to see how thin they could get it.

Examples like these are legion, but what would happen if Maxwell, for example, were to approach a research council today and **ask for funding "just" to see how something works?**

CURIOSITY AND ALBERT EINSTEIN

It was curiosity that drove Einstein to do his work. Yet, even without an economic goal, his work has made billions for companies and governments and helped build our modern world:

- His work on the photoelectric effect made it possible to build all the televisions, DVD and CD players, digital cameras, and remote controls ever sold.
- He created a formula to measure the size of molecules dissolved in liquids that has been used by chemists to create the shaving creams and toothpastes you use every morning.
- His theory of general relativity helps keep the atomic clocks used by GPS satellites synchronized so you do not drive off a cliff.



"THE IMPORTANT THING IS NOT TO STOP QUESTIONING. CURIOSITY HAS ITS OWN REASON FOR EXISTING."
ALBERT EINSTEIN

Well, if he were to ask those who seek only direct commercial returns from the world of science, he might very well be turned down. But does this law of unanticipated returns apply to all the sciences?

Much has been written about the spin-offs from large-scale physics research, so we thought we would explore those other cosmology mainstays—astronomy and space exploration. While it is quite easy to see how something like physics can have a long-term impact on our society, **it is perhaps more difficult to see how astronomy and space exploration could have much of an effect on those of us shackled to the surface of Earth.** Sure, it is hard to argue that the discoveries of supermassive black holes and radiation-spewing neutron stars have much effect on Mr. Joe Public, but in order to make those discoveries, **astronomers often have to invent new instruments and techniques that produce spin-off technologies that can (and do) have more tangible applications.**

And let us not overlook the power that **big science projects can have to inspire the next generation of scientists and engineers** to want to become that next generation. If we sideline curiosity and turn science into a just-for-profit enterprise, we will breed a generation of nine-to-five technicians and lose the Maxwells, Einsteins, and Braggs who harness curiosity and create scientific revolutions.

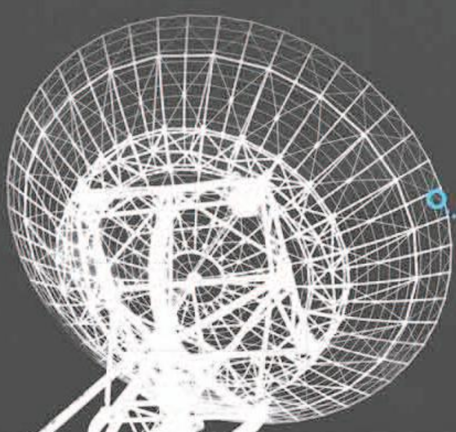
SOME SPACEY **SPIN-OFF TECHNOLOGIES**

Space exploration brings unique challenges that require solutions to be developed by engineers and scientists. Some find unexpected applications here on Earth.

“THE ALCHEMISTS IN THEIR SEARCH FOR GOLD DISCOVERED MANY OTHER THINGS OF GREATER VALUE.”
ARTHUR SCHOPENHAUER (PHILOSOPHER)

WIRELESS TECHNOLOGY
Techniques developed in the 1970s to analyze signals from radio telescopes were adapted two decades later—by the same scientists—to reduce interference in radio-based computer networks. Wireless technology, commonly known as “Wi-Fi,” is now at the heart of modern wireless Internet communications.

Internet connections in Asia



Wireless technology has helped us go from searching the heavens to searching the Internet.

SUNGLASSES
Without Earth’s atmosphere to act as a filter, astronauts working in space are subjected to high levels of solar radiation—especially ultraviolet, which can cause permanent damage to the eyes. To protect astronauts’ sight, NASA developed special coatings in the 1980s that blocked harmful radiation. Some commercial sunglasses use the same technology.

Coatings, designed to protect the sight of astronauts working in space, now look after yours when relaxing on a beach.

In space, there are no wall sockets.

Cordless power drill

Driving on the moon may not have been a game, but the technology has made computer games more fun.

CORDLESS TOOLS

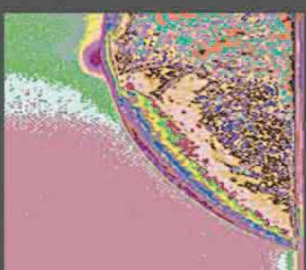
Portable, self-contained power tools were originally developed to help Apollo astronauts drill for moon samples. Back on Earth, this technology has led to the development of such tools as the cordless vacuum cleaner, power drill, hedge trimmers, and grass shears.

JOYSTICK CONTROLLERS

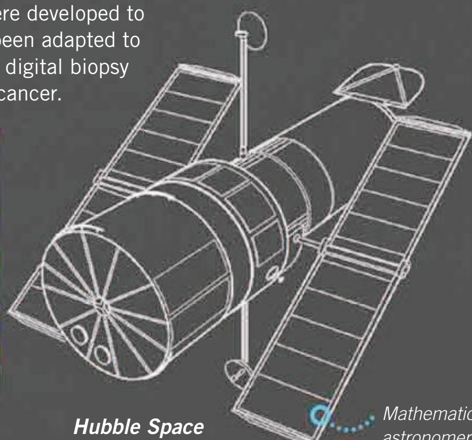
When NASA developed the Apollo Lunar Rover, they needed to develop an intuitive system that would allow the spacesuit-encumbered astronauts to steer and control the vehicle. They came up with the "joystick," which is used today to control everything from computer games to disability vehicles.

MEDICAL IMAGING

The Hubble Space Telescope needs to be supersensitive to collect faint light from distant stars. The charge-coupled devices (CCDs), which convert light into digital files, were developed to meet Hubble's needs and have been adapted to greatly improve the sensitivity of digital biopsy machines used to detect breast cancer.



Microscopic image of biopsy done using Hubble-derived CCD technology

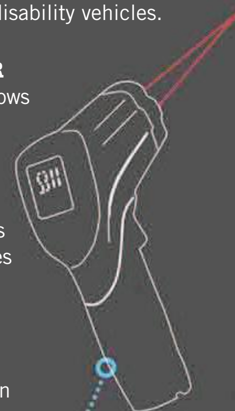


Hubble Space Telescope

Mathematical algorithms, used by astronomers to analyze all the data collected by telescopes, have been used to improve medical imaging.

EAR THERMOMETER

The ear thermometer allows doctors to measure body temperature with accuracy and minimal invasion, but the technology started out as an astronomy tool. It uses a lens to detect infrared radiation (or heat)—in miniature, it is used to take your temperature but, in a telescope, it can detect the birth of stars.



Infrared thermometer

Designed to take the temperature of stars, now it's taking yours!

FIREFIGHTING

Engineers have developed a water pump that allows firefighters to extinguish a blaze in one-sixth of the time it would have previously taken. The pump—which also uses just a fraction of the water—makes use of vortex technology designed to pump fuel into rocket engines.

WATER PURIFICATION

Water is essential to life, but it is much too heavy to be transported into space in large enough quantities for astronauts to live on. NASA developed filtration technologies that turned waste water from respiration, sweat, and urine into drinkable water. The technology is now being put to use in water-starved developing countries.

Water filter

X-RAY CRYSTALLOGRAPHY

THE CERTAINTY OF UNCERTAINTY

THE WORLD OF THE INSANELY TINY

QUANTUM GRAVITY

SEEKING SUPERSYMMETRY

THE STORY OF THE ATOM

ATTACK OF THE MICRO BLACK HOLES

TEENY TINY, SUPERSMALL STUFF

HIGGS BOSON: A BLUFFER'S GUIDE

PARTICLE ACCELERATORS

DISCOVERING THE NEUTRON

THE STORY OF **THE ATOM**

THE STORY OF THE ATOM BEGINS in ancient Greece in the 5th century BCE, when a tunic-clad thinker named Democritus formulated the idea that **matter might be comprised of tiny particles that were *atomos*, or indivisible.** These "atoms" could not be broken up because there were no particles any smaller.

For more than two thousand years, there was not much action in the story of atomic science, until finally, **in the early 19th century, an English physicist and chemist named John Dalton formulated his own "atomic theory."** Dalton's atom was much the same as the ancient Greek's, but he went on to suggest that the different elements were made of atoms of different sizes and that **the elements could be combined to create more complex compounds.** Dalton was also the first person to make a serious attempt to calculate the atomic mass of some of the chemical elements and to introduce a system of chemical symbols.

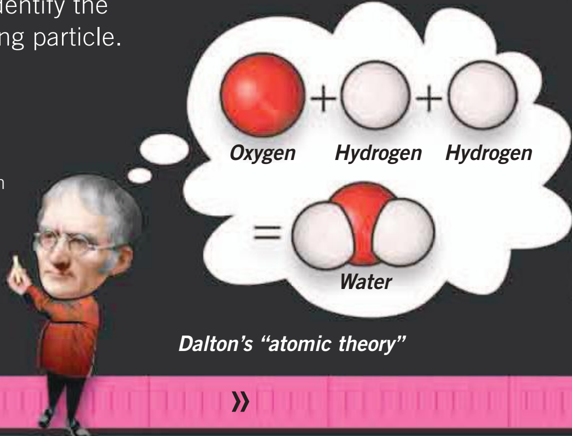
The next big step took place in 1897. A British physicist named Joseph John Thompson was trying to figure out the nature of cathode rays—a mysterious blast of electromagnetic radiation emitted by a cathode (the negative part of an electrical conductor) within a vacuum tube. When he applied a positive charge, he noticed that the rays were attracted to it—**meaning that they must carry a negative charge.**

But the real breakthrough came when he calculated their mass and discovered that **they were about 1,800 times less massive than even the lightest atom** (hydrogen).

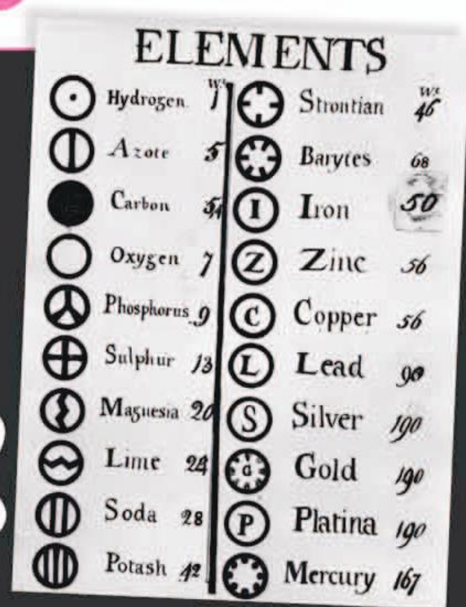
THE SEARCH FOR **STRUCTURE**

In the 19th century, scientists thought they had got to the heart of matter. But by the 20th century, ideas about atoms had been revolutionized and the challenge was to identify the structure of this puzzling particle.

1803: John Dalton proposed that the elements could be combined to create chemical compounds.



Dalton's "atomic theory"



John Dalton's table of elements

1800 1850

Since they were so small, he concluded that they must have come from inside atoms—**the indivisible atom must be divisible.**

Thompson called these tiny negatively charged particles "electrons" and incorporated them into a revolutionary new model of the atom. He knew that atoms are neutral (carrying no overall electrical charge) so, to balance out the negative electrons, **he imagined the atom as being a sort of cloud of positive charge peppered with electrons—like pieces of plum in a plum pudding.**

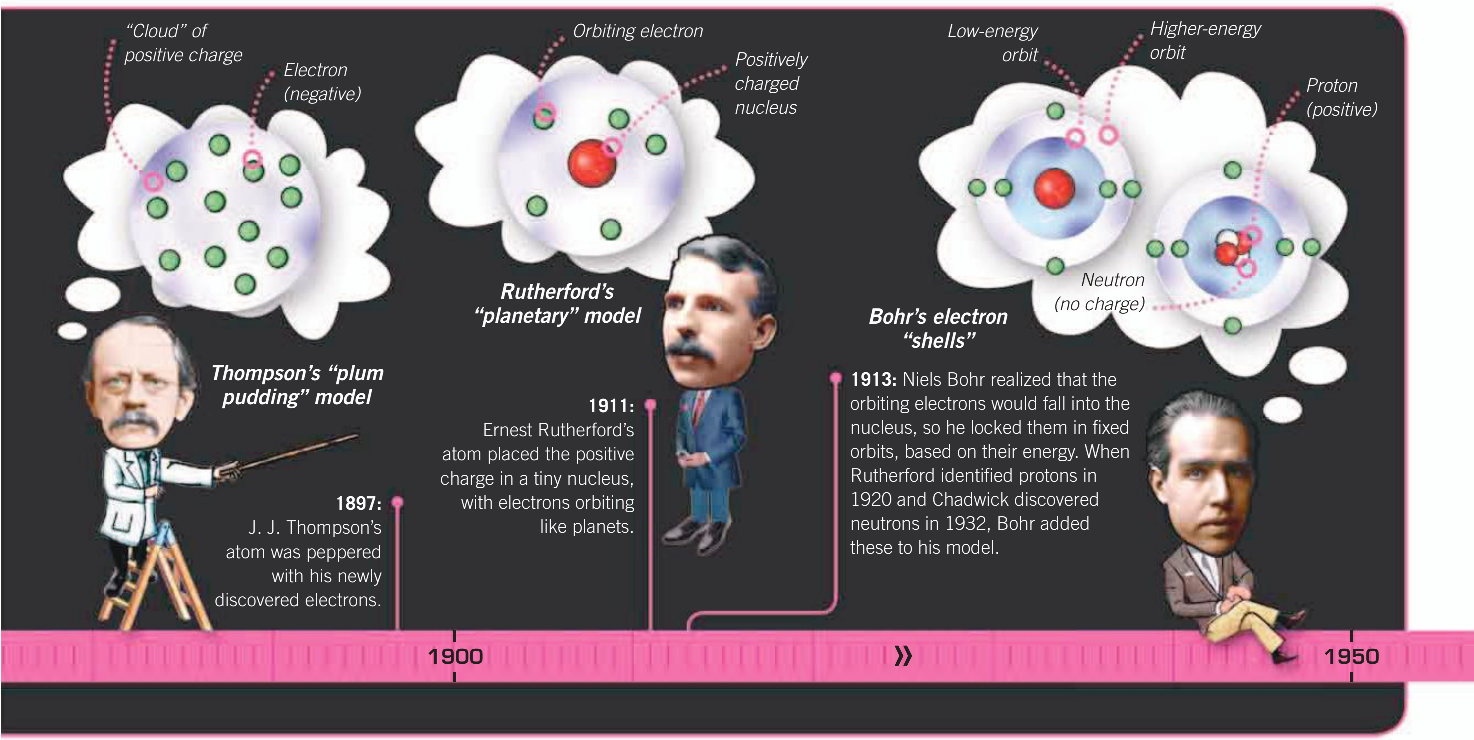
Although Thompson went on to win the Nobel Prize in Physics for his discovery of the electron, **his plum pudding model of the atom would only last about 10 years.** In 1909, a New Zealand–born physicist, Ernest Rutherford, was looking over the results of an experiment performed by two of his students when he spotted a flaw in Thompson's atomic model. The students, Hans Geiger and Ernest Marsden, were experimenting with radiation by firing positively charged particles at a piece of gold foil. Based on Thompson's model of the atom, they had expected the particles to shoot virtually unimpeded through the positive cloud of the atom, which, although positively charged, should have been diffuse enough to allow the heavier particles to barge through.

"IT WAS ALMOST AS INCREDIBLE AS IF YOU HAD FIRED A FIFTEEN-INCH SHELL AT A SHEET OF TISSUE PAPER AND IT CAME BACK AND HIT YOU"
ERNEST RUTHERFORD, DESCRIBING THE RESULTS OF THE GOLD FOIL EXPERIMENT

Instead, they saw that, while many of the particles did pass through, some were deflected and a very small number of the others bounced right back. This led Rutherford to conclude that **the atom must possess an extremely localized concentration of positive charge at its center.**

Rutherford proposed that **the nucleus was made up of distinct units of matter that he called "protons,"** and he placed Thompson's electrons into scattered orbits around the nucleus like planets orbiting the sun.

Under Rutherford's new "planetary model," the atom was revealed to be made up almost entirely of empty



MOST OF AN ATOM IS EMPTY SPACE—AN ATOM THE SIZE OF EARTH WOULD HAVE A NUCLEUS ABOUT THE SIZE OF A FOOTBALL STADIUM

space, with most of its mass concentrated in the tiny nucleus. But he had a problem: **What was stopping the negatively charged electrons from being pulled into the positively charged nucleus?**

To get around this, he dug into the toolbox of Newtonian physics and suggested that, just as the planets are kept in orbit by acceleration gained from the sun's gravity, **electrons must be undergoing constant acceleration, which stops them from falling out of orbit.**

Unfortunately, old-fashioned **Newtonian physics does not cut the mustard in the quantum world,** and this is where Niels Bohr enters the story. It was Bohr who saw the quantum flaw in Rutherford's otherwise ingenious atomic model.

A few decades earlier, Scottish physicist J. C. Maxwell had shown that when an electric charge is accelerated, it loses energy by emitting radiation (a process exploited by X-ray machines). Along with others, Bohr realized that Rutherford's accelerating electrons would lose energy by the same process and quickly fall into the nucleus. As this does not happen, **something else must be keeping an atom's electrons in check.**

On March 6, 1913, Bohr explained his modifications to the planetary model in a letter to Rutherford. Building on the work of German physicist Max Planck, who showed that there was a limit to how far something could move or be divided at the quantum level, Bohr proposed that **electrons are restricted to fixed orbits depending on their energy.** Electrons with the least energy occupy the lowest orbit and those with the most energy occupy the highest orbits. **Electrons can only move between these orbits, or shells, by gaining or losing energy**.

But, in the mid-1920s, a whole new branch of physics, pioneered by the likes of Louis de Broglie, Erwin Schrödinger, and Werner Heisenberg, was entering the scene—quantum mechanics. In this weird new world, **the orbiting electrons became clouds of "possibility," in which they exist in all positions of their orbit at all times** (as both a particle and a wave) until observation forces them to assume position.

The last (slightly less weird) piece of the puzzle was revealed in 1932 when the British physicist **James Chadwick discovered a neutral partner to Rutherford's proton within the atomic nucleus: the neutron.**

Physicists at last had a pretty accurate model of the atom to work with, but it was far from complete. **The indivisible atom that had been divided into protons, neutrons, and electrons would later be further divided into fundamental particles** (except for the electron, which is as small as stuff gets). And so it was that the atom turned out to be more fascinating than anyone imagined.

NIELS BOHR

Danish physicist Niels Bohr won the Nobel Prize in Physics in 1922, and his model of atomic structure remains the basis of the physical and chemical properties of the elements. Like many of his generation, he was deeply affected by the events of World War II, and in later life he worked for the peaceful application of atomic physics.

ELECTRON CLOUD MODEL

By 1926, with the arrival of quantum mechanics, electrons were no longer thought of as orbiting particles but as waves. This led to a more abstract model of the atom, devised by the Austrian quantum physicist Erwin Schrödinger. He used the term "electron clouds" to describe where electrons were most likely to appear. This illustration shows a carbon atom with two electron clouds, colored yellow and blue, to represent their different orbital paths.

Electron cloud model of carbon

DISCOVERING **THE NEUTRON**

THE NEUTRON IS HALF OF THE ULTIMATE DOUBLE ACT. It's the particle equivalent of Oliver Hardy—**the neutral straight-man to the proton's charged-personality**. Like all great double acts, the neutron and proton spent years plugging away in anonymity until, one day, they were discovered, plucked from obscurity, and thrust onto center stage.

The proton and neutron can be **found at the heart of every atom** (apart from hydrogen, which possesses just one lonely proton) and **without them matter as we know it could not exist.** Although the most fundamental of double acts, they did not find fame together. The proton enjoyed the first taste of celebrity, while the neutron was more reluctant to step into the limelight.

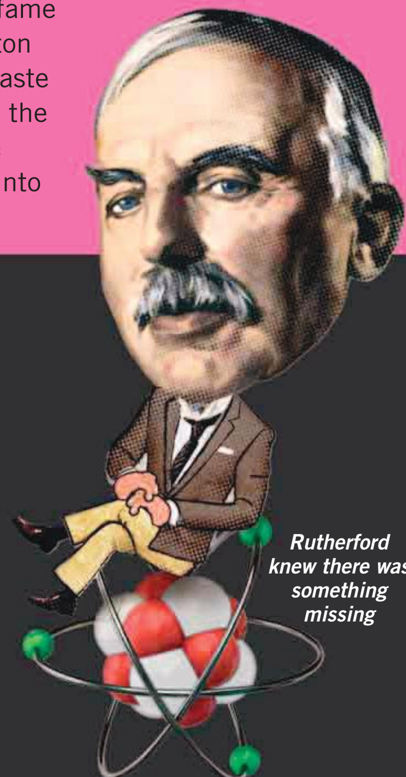
Discovered in 1919 by New Zealand physicist Ernest Rutherford, the proton was initially encouraged to embark on a solo career as the only particle within the atomic nucleus. Like all great celebrities, the proton was known to be accompanied by a crowd of fans—known as electrons. **The electrons were employed to keep the atom well balanced and neutral** (being negatively charged, they balanced out the proton's positive nature).

For a while the arrangement seemed to work, but it soon became clear that **something did not add up.** The trouble was that an atom's atomic number did not always tally with its atomic mass—it was like there were more performers on stage than the billing had advertised.

To account for this discrepancy, Rutherford suggested that there might be **an as-yet-unseen performer at work within the atom,** another particle that had about the same mass as the proton but, rather than being electrically charged, **possessed no charge at all.** This neutral particle would not upset the balance between the positive proton and the negative electrons. The hunt for the neutron was on and the man to find it was Rutherford's assistant, British physicist James Chadwick.

But, being neutrally charged, the neutron was rather difficult to locate. Fortunately, discoveries in Europe would provide just the trail of bread crumbs that Chadwick needed to track the neutron down.

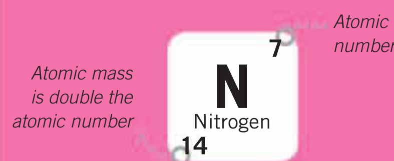
In 1930, researchers in Germany discovered that if you bombard the element beryllium with alpha particles (particles with two protons and two neutrons—like a helium atom but without the electrons), **a strange neutral radiation was emitted that could penetrate matter.** The discoverers of this phenomenon thought it was just garden-variety gamma radiation, but Chadwick was not convinced and **believed that it was actually a particle.**



Rutherford knew there was something missing

WHAT'S MISSING?

On the periodic table, the atomic number refers to the number of protons found in the atom's nucleus. But the atomic mass is often more than twice that—meaning that the proton was not alone in the nucleus.



But his initial attempts to track down the particle in a cloud chamber (the usual method) proved fruitless. Then, in France, researchers discovered that if a lump of paraffin wax was placed in the path of the neutral radiation, **protons were knocked out.** To Chadwick, this was **proof that a particle was at work.**

Anyone who has ever played (or watched) pool or snooker can understand why Chadwick came to this conclusion. Imagine the atoms within the paraffin are pool balls. If you blow (our imaginary gamma radiation) on the pool balls, you might succeed in moving a few of the balls but not much else. If you instead fire the cue ball (our neutrons) at the balls, you will see that **some balls are knocked out of the pack, just like the protons knocked from the paraffin atoms.**

Chadwick replicated the paraffin experiment and he not only confirmed that **the neutral radiation was indeed a particle** but also, by tracing the paths and energies of the dislodged protons, was able to figure out that the particle must have about the same mass as the protons dislodged.

At last, the neutron had been discovered and, in addition to sharing the limelight with the proton, it went on to become a star in its own right. **The discovery of the neutron made possible the nuclear age.** Its ability to penetrate an atom's nucleus meant that it could be used to tear atoms apart and release the energy within (nuclear fission). Without Chadwick's discovery, there would have been no nuclear bomb (OK, so it's not all good) and no nuclear power plants.

Aside from helping to blow up Pacific islands, the neutron also has more benign talents and **is an extremely useful tool for probing the atomic structure of matter.** Its ability to penetrate matter means it can tell us exactly where the atoms and molecules are within a material and how they behave.

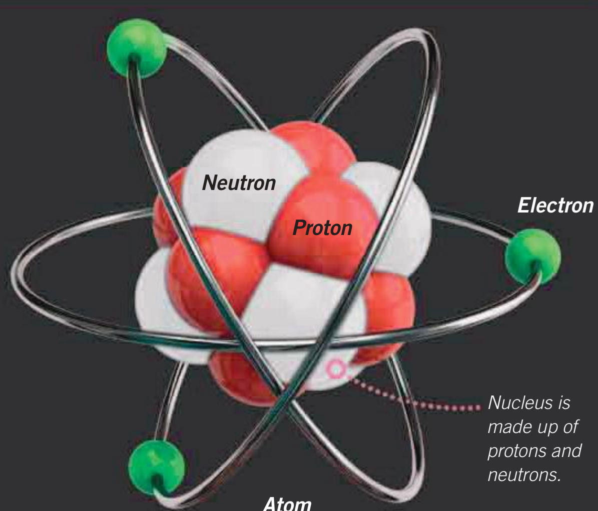
If you think particle science is limited to the esoteric (such as what caused the Big Bang), you would be mistaken. At facilities like the Institut Laue-Langevin (ILL) in Grenoble, France, neutrons are used like supercharged X-rays to understand the world at the

JAMES CHADWICK

In June 1932, James Chadwick's paper announcing the discovery of the neutron was published by the Royal Society, and in 1935 he was awarded the Nobel Prize in Physics. As a result of his discovery, scientists across the world started bombarding all types of materials with neutrons. One such material was uranium, and the result was nuclear fission. During World War II, Chadwick was the head of the British team working on the Manhattan Project in the US, which led to the atom bomb.

WHAT'S INSIDE **AN ATOM?**

We used to think the atom was as small as things get—which is why the Greeks called them "atom," from *atomos*, meaning "indivisible." Atoms are made up of a nucleus (of protons and neutrons) and electrons, which orbit the nucleus. A neutron is (as its name suggests) electrically neutral, while protons carry a positive charge and electrons carry a negative charge. A neutron and proton are about the same size. They both dwarf the tiny electron (the mass of a proton is about 1,840 times that of an electron).



atomic level. At ILL, the neutron has been used to develop **magnetic soap for mopping up oil spills, targeted cancer treatments, and new ways to combat viral and bacterial infections.** It has even helped make aircraft safer by finding structural defects hidden well beyond the reach of the human eye.

And how does ILL create the neutrons it uses? They have **their very own nuclear reactor** that feeds high-intensity beams of neutrons to an array of 40 instruments, which are used by some 1,200 researchers from over 40 countries every year.

The ILL is just one of the stages on which the neutron has performed in the 80 years that have allowed its meteoric rise from obscurity to be **one of the premier particle A-listers.**

CHADWICK CALCULATED THE MASS OF A NEUTRON AS 1.0067 TIMES THAT OF A PROTON, THUS SOLVING THE MYSTERY OF THE MISSING ATOMIC MASS

HOW NEUTRONS **PENETRATE MATTER**

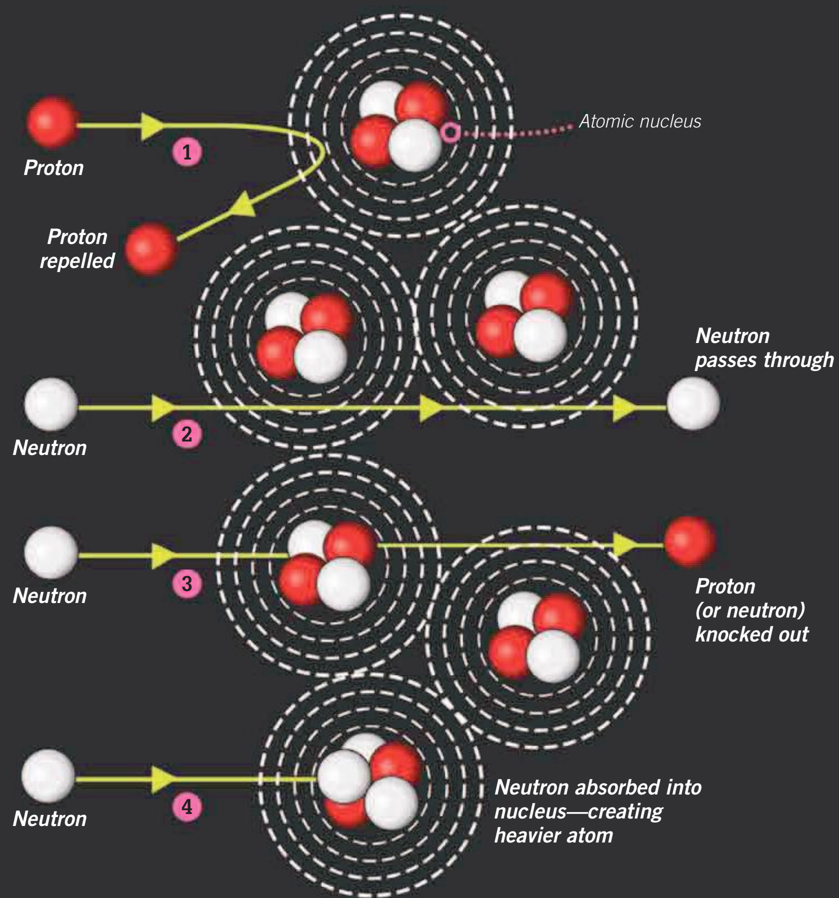
Having no charge, the anonymous neutron can pass undetected right to the heart of matter, where other particles fail.

1 ***Repellent protons*** Being positively charged, protons are repelled by the electrical forces in atomic nuclei. This means that protons are pretty bad at penetrating matter.

2 ***Slipping past*** A neutron's lack of electrical charge allows it to slip past an atom's charged field like an anonymous fan with a backstage pass. Neutrons can even pass through sheets of heavy metals, such as lead.

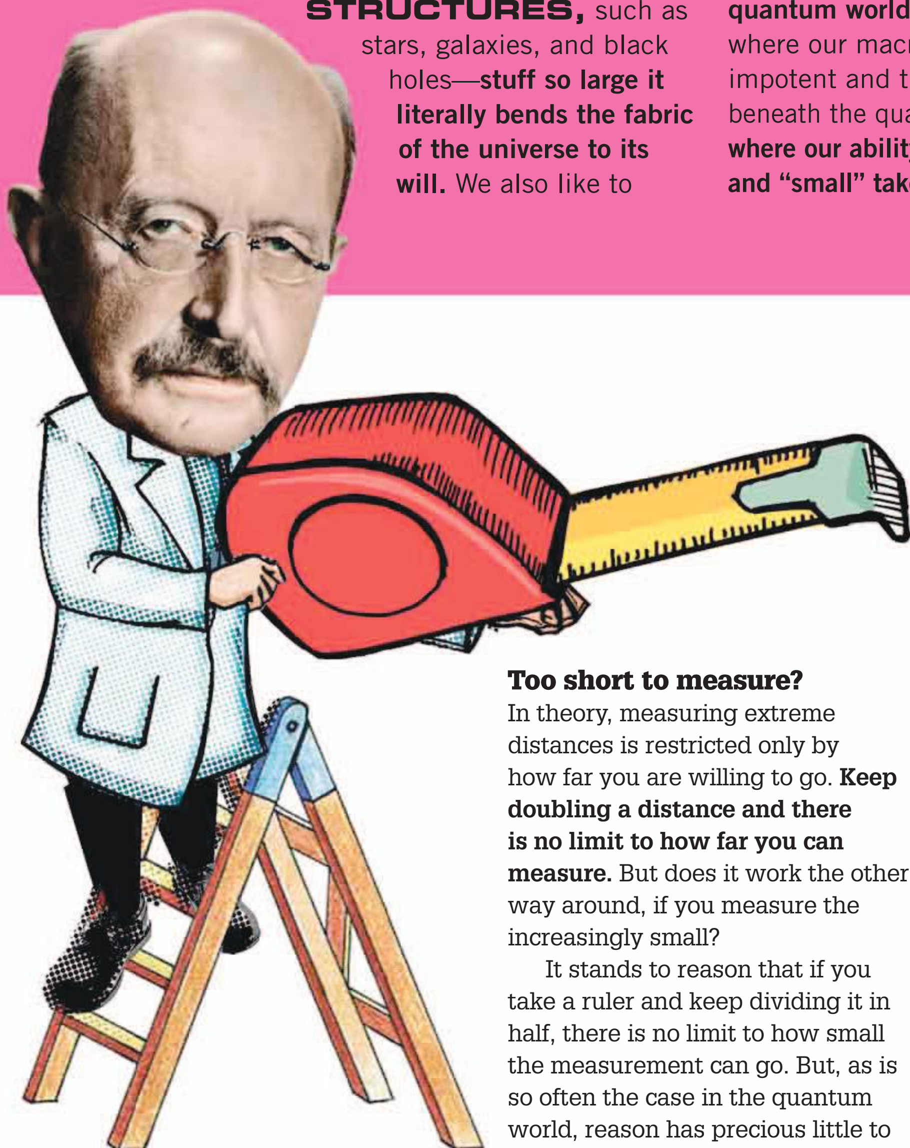
3 ***Strike!*** When a neutron collides with a nucleus, it can act like a cue ball striking a pack of balls and knock particles out of the nucleus.

4 ***No way out*** Sometimes the neutron will become trapped in the nucleus, transforming it into a heavier form of the same atom.



THE WORLD OF THE INSANELY TINY

THIS BOOK IS FULL OF INSANELY IMMENSE COSMIC STRUCTURES, such as stars, galaxies, and black holes—**stuff so large it literally bends the fabric of the universe to its will.** We also like to indulge in a little brain blending by talking about **the world of the unimaginably small—the quantum world of the atomic and subatomic,** where our macroscopic view of reality is rendered impotent and the illogical reigns supreme. But beneath the quantum lurks another level of reality **where our ability to quantify reality breaks down and "small" takes on a whole new meaning.**



The Planck length is the limit of how small things can go

Too short to measure?

In theory, measuring extreme distances is restricted only by how far you are willing to go. **Keep doubling a distance and there is no limit to how far you can measure.** But does it work the other way around, if you measure the increasingly small?

It stands to reason that if you take a ruler and keep dividing it in half, there is no limit to how small the measurement can go. But, as is so often the case in the quantum world, reason has precious little to do with it. Let us say you were to take a ruler (which for some bizarre reason measures 5.3 ft/1.6 m in length) and divide it into 10 pieces. Now take one of those 10 pieces and divide that into 10 pieces, and so on. **In theory, you could repeat the exercise 34 times, but that is as far as you could go** and no force in the universe could enable you to divide it further. **This "last word" in measurement units is called the Planck length,** named after the father of quantum theory, physicist Max Planck.

The Planck length is 5.3 ft (1.6 m) divided by ten 35 times, a number with 34 zeros after the decimal point, which is really very small indeed and, as it turns out, as small as it is possible to go. **At this scale, the laws of physics we use to describe gravity, space, and time become useless.** If two somethings were to be separated by less than one Planck length, there would be no way to determine which something was where.

For the most part, we experience the universe through interaction with the electromagnetic spectrum

(wavelengths of light, radio, and X-rays, for instance). Our eyes see where something is because they collect light photons that have interacted with the object (by bouncing off or being emitted).

All of the electromagnetic spectrum is transmitted by packets of energy called photons that have particular wavelengths—photons with more energy, like X-rays, carry more energy and have shorter wavelengths than light photons. The shorter the wavelength of the photon, the smaller the object that photon can interact with—if it cannot interact, you cannot detect it. **The Planck length is so short that we could never create a photon with a short enough wavelength to interact with it**—therefore, we can never measure anything smaller. Even if we could create a photon with such a short wavelength, **it would carry so much energy, in such a small area, that it would collapse into a black hole** before it could return any useful information.

> **"ANYONE WHO IS NOT SHOCKED BY QUANTUM THEORY HAS NOT UNDERSTOOD IT"**
>
> NIELS BOHR, DANISH PHYSICIST

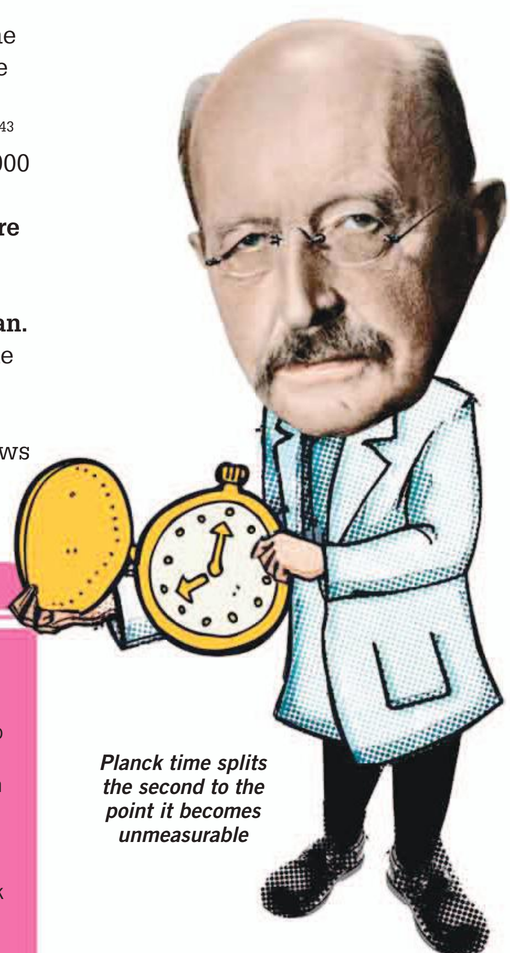
Just a tick

Time, theoretically, can tick onward forever, but wind it back to its smallest increments—past the second, microsecond, and picosecond—and eventually you come to **the smallest possible increment: the Planck time.**

The Planck time is the smallest unit of time that can, in theory, be measured. One Planck time is the amount of time it takes a photon of light (traveling, naturally, at the speed of light) to cross a distance of one Planck length. One unit of Planck time is equal to about 10^{-43} seconds (or, 0.000000000000000000 0000000000000000000000001 seconds)—**it is so short that there are more Planck times in one second than there have been seconds since the universe began.** Anything that happens before the hands of the Planck clock move on by one unit is, by definition, unmeasurable, a quality that allows all sorts of quantum mechanical weirdness to take place.

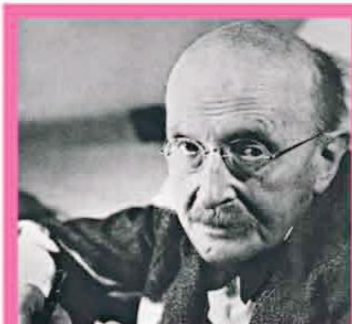
According to quantum theory (in particular, Heisenberg's uncertainty principle), **if you cannot see it happen, then anything can happen**, a concept that naughty children and bankers sometimes try to apply to the nonquantum world. In this "gray" zone of accountability, particles of matter can "borrow" energy from the quantum vacuum and "pop" into existence literally from nowhere.

As long as the particles "pop" back out of existence and return



Planck time splits the second to the point it becomes unmeasurable

MAX PLANCK



German theoretical physicist Max Planck was a professor at Berlin University, where he worked with his friend and collaborator, Albert Einstein. Between them, they were responsible for the two most revolutionary theories of 20th-century physics: Planck for quantum theory and Einstein for the theory of relativity. Planck was a talented musician. He sang and also played the piano, organ, and cello. Einstein sometimes accompanied him on the violin. In 1918, Planck was awarded the Nobel Prize in Physics.

their borrowed energy before the Planck time limit expires, the laws of "conservation of energy" (which state that energy cannot be created or destroyed) have not been violated. Perhaps the strangest outcome of the Planck time is that, because time cannot be measured within the Planck unit, **time as we think of it does not exist in the quantum realm.**

Since you and I are made of particles built of quantum "stuff," **time does not really "exist" as a tangible, measurable phenomenon for us either.** Even those who keep our clocks ticking as accurately as possible admit that **they do not measure time, they just define it.**

The seething vacuum

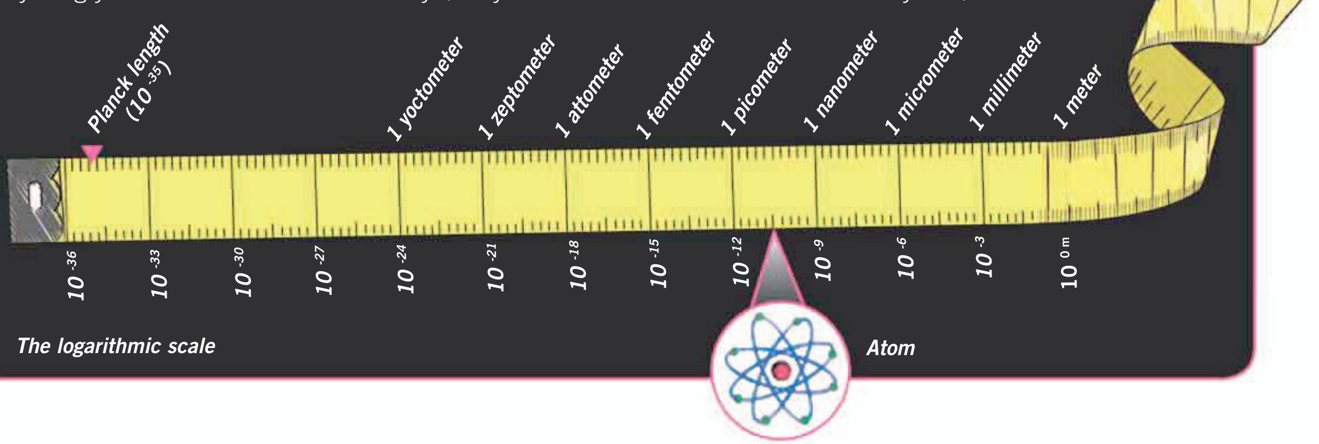
The discovery that space and time cannot be broken down beyond a certain point has implications for the way we understand the universe. It shows that, because time and space each have a minimum dimension, at its most fundamental level **the universe is built from tiny quantifiable units, or quanta,** which is where the science of "quantum" mechanics gets its name. Even the most featureless expanses of the universe (the void, or the vacuum) are built from these quanta.

At the quantum level, "empty space" is never truly "empty," and the concept of a vacuum being a complete absence of something falls apart. **A vacuum just appears empty to us because there is no energy or matter that we can measure.** But beyond the measurable, in the quantum vacuum, **empty space is seething with virtual particles** that bubble up, live very (very, very, very) briefly on borrowed energy, and pop away again—something that physicists call "the quantum foam."

According to Planck, the quantum vacuum is full of virtual particles

HOW SMALL IS SMALL?

It would be impossible to show the Planck length to scale here, so let's start with an atom. This atom is 0.0000000003 ft (0.0000000001 m) in diameter (about 100,000 times smaller than anything you can see with the naked eye). If you were to try to measure the diameter of this atom in Planck lengths by counting one Planck length every second, it would take you about 10 million times the current age of the universe (that is 10 million times 13.8 billion years).



The logarithmic scale

THE CERTAINTY **OF UNCERTAINTY**

QUANTUM MECHANICS IS ONE OF THE MOST SUCCESSFUL BRANCHES OF PHYSICS, when it comes to accurate explanations and testable predictions. It provides **the theoretical framework that allows scientists to describe how matter behaves at the subatomic level**. But despite its astonishing successes, quantum mechanics has an unfortunate side effect. It can induce the cerebral equivalent of **dropping a jellyfish into a blender** and transform the human brain into a quivering mess of gelatinous denial. To say that it is weird is an understatement of galactic proportions, and perhaps the weirdest of all quantum mechanics' predictions is something called **"Heisenberg's uncertainty principle."**

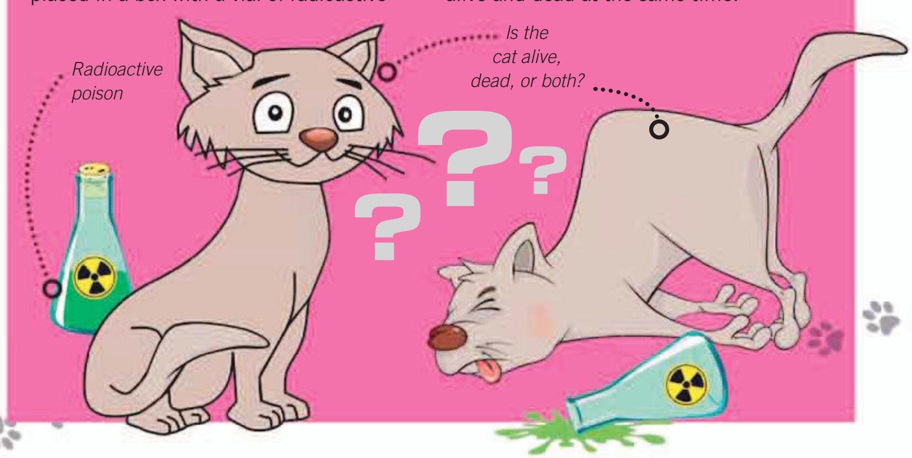
Devised by genius German physicist Werner Heisenberg in 1927, the uncertainty principle states that, in the quantum world, **it is impossible to know simultaneously where a particle is and how fast and where it is going.** You can know its position or you can know its momentum, but you cannot know both. OK, so perhaps that does not sound so very strange, but the reason behind it is very strange indeed.

Particles like electrons are not the discrete, spherical lumps of matter (like teeny tiny ball bearings) we imagine them to be. In quantum mechanics, **a particle is a wavy smudge of spread-out potential.** It exists as a combination of all possible states, each state a combination of things like position, speed, and energy. Quantum mechanics perfectly describes particles using a bit of mathematical wizardry known as a "wave function," which includes the likelihood of each state. However, when you want to make an observation of something, the system takes on one of the possibilities and the wave function collapses. It's a bit like rolling a die. As it scoots along the tabletop the numbers are a blur. Only by stopping the die can you "force" it to choose a number.

This indeterminate nature of the stuff that makes up the world around us did not sit well with scientists—after all, who wants to believe that the particles you are made of exist in state of quantum flux? **Even the physicists who created quantum mechanics were uncomfortable with its predictions,** which led Erwin Schrödinger to create his famous "cat in a box" thought experiment.

SCHRÖDINGER'S CAT

"Schrödinger's cat" is a thought experiment devised by Austrian physicist Erwin Schrödinger to demonstrate the absurdity of quantum mechanics. A cat is placed in a box with a vial of radioactive poison that will release a deadly gas when a single particle decays. Until the moment the box is opened and the state of the cat is revealed, the cat can be said to be both alive and dead at the same time.



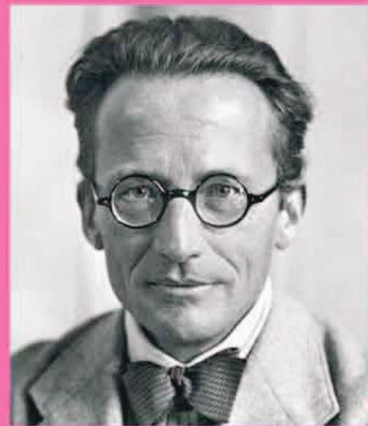
For decades, some scientists have expected (and hoped) **that uncertainty would one day be proved false** and that predictability would be returned to the universe. But in 2013 their hopes were dashed by physicists working at the University of York, who published **a paper that would reinforce Heisenberg's description of the limits imposed by uncertainty.** By constructing a theoretical experiment, in which measurements of particles with known values were compared with those of particles whose states were unknown, they found that the errors in their measurements matched those in Heisenberg's original predictions.

OK, so it was a lot more complicated than that, but **their conclusion could prove to be a boon for quantum cryptography.** Messages encoded in such a fashion would in theory be unbreakable because any attempt to "see" the message would force the multiple-state quantum bits that make it up to "collapse" to a single state (thus ruining the message).

"I THINK I CAN SAFELY SAY THAT NO ONE UNDERSTANDS QUANTUM MECHANICS"

RICHARD FEYNMAN, WINNER OF THE 1965 NOBEL PRIZE IN PHYSICS

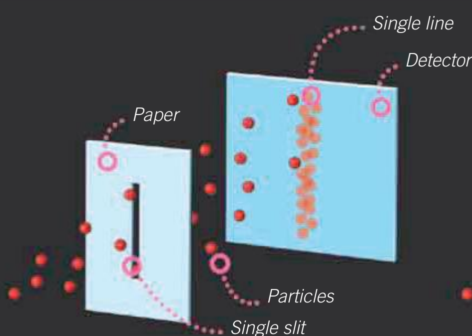
SCHRÖDINGER



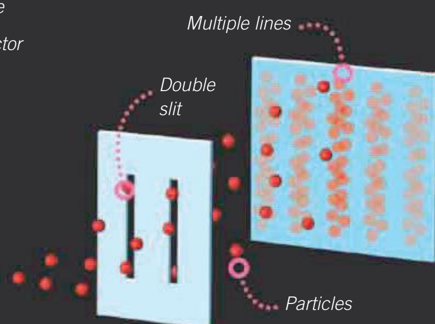
Austrian Erwin Schrödinger was one of the great theoretical physicists of the 20th century. Known to oppose Nazism, he fled his job at Berlin University, and was living in Oxford, England, when he won the Nobel Prize in 1933 for his work on wave mechanics. He had a cat named Milton.

THE INDECISIVE PARTICLE

Depending on how you look at it, light appears to have the properties of both a wave and a particle. When we test for wavelike properties, it behaves like a wave, but when we test for particlelike properties, it behaves like a particle. It seems to have multiple identities and exist in multiple locations at the same time. Can you feel your brain starting to quiver?



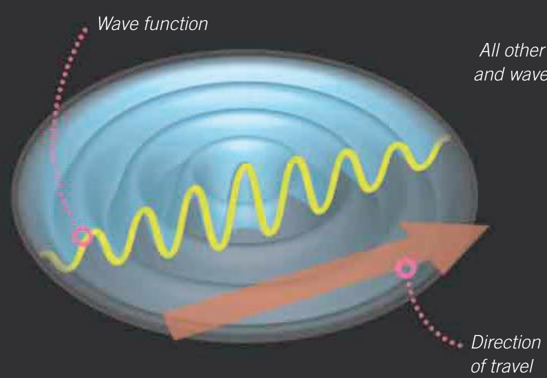
1 *A single slit*
This is what happens when you shoot light particles (photons) through a slit in a piece of paper. As you would expect, they pass through the slit and leave a single vertical mark on a detector at the back—just as if you had fired a bunch of marbles through it.

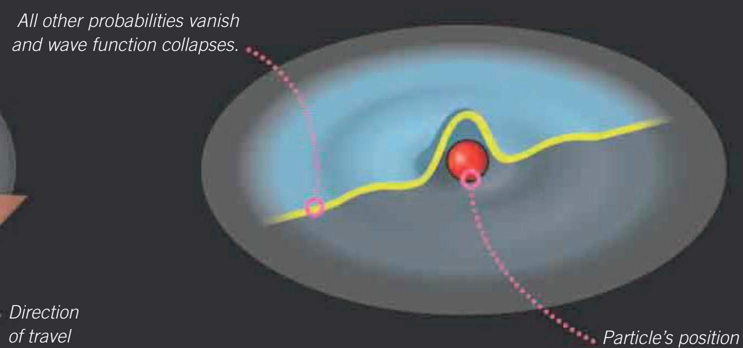


2 *Double slit*
So what happens if you make another slit? You would expect the particles to leave two matching lines, but instead there are many lines. How is this possible?

A CLOUD OF PROBABILITY

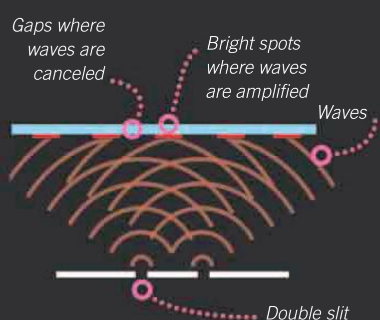
At the quantum level, matter does not really exist in a fixed state. Instead, it is a cloud of "probability" called the "wave function." This ability to exist in multiple states is called "superposition." Instead of thinking of a particle as a defined point of mass, it is more like a region of wavy potential smeared across space.

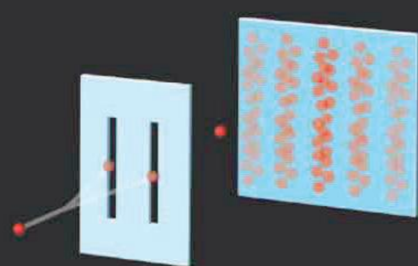


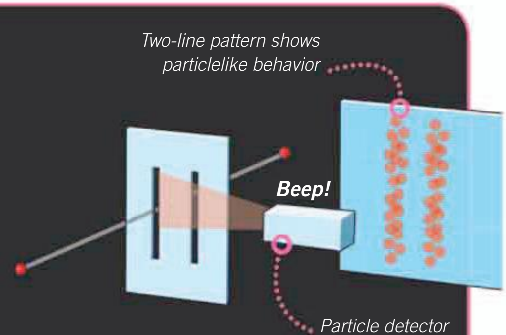


TRAVELING WAVE
Like all waves, a particle wave is spread over a large area, so it has no definite position (peaks and troughs are regions where the probability of the particle occurring increase), but it does have direction. As a wave, we can know a particle's direction of travel, but we cannot know its position.

IN POSITION
In the same way, if we try to measure the position of the particle, the wave function collapses and we can no longer measure its direction of travel. This inability to measure all of a particle's properties is called "Heisenberg's uncertainty principle."







3 ***Wave behavior***
The only explanation is that the particles are behaving like a wave. When a wave passes through two slits, it spreads out from two fronts, which then overlap. When the peak of one wave meets the trough of another, they cancel each other out. When two peaks meet, they amplify each other. This creates an interference pattern identical to the lines left by the particles.

4 ***Curiouser***
Weirder still, if you fire just one particle at a time through the slits, you still get an interference pattern. This means that each single photon must have passed through both slits at the same time and then created an interference pattern as a wave.

5 ***And curiouser***
If that was not weird enough, let us install a detector at the slits, which beeps every time a particle passes through one of the slits. It will see each particle pass through just one slit, but the detector at the back will have just two lines on it.
It is the same test as before, but this time there is no interference pattern. Baffling.

SEEKING SUPERSYMMETRY

THE STANDARD MODEL OF PHYSICS, which describes the quantum world of particles and the stuff that they are made of **is one of the most successful theories in science**. Since it was first thought up in the 1960s and 1970s, it has made hundreds of predictions that have been successfully tested—the most recent of which was the discovery of the Higgs boson (the particle representative of the Higgs field, which imbues particles with mass).

Despite its success in the quantum realm, **the standard model (SM) only explains one aspect of the universe**—gravity, space, and time do not fit. One theory that seeks to integrate the SM with the workings of the universe at large is known as "supersymmetry" (SUSY). This is a collection of theories that predicts that, **for every particle in the SM, there exists a hidden, supersized partner.**

HIGGS HICCUP

Although the discovery of the Higgs boson supported the standard model, it also raised a new problem. Calculations based on the standard model predicted that the Higgs boson would have much more mass than it was discovered to have. A Higgs with a more massive "superpartner" (a Higgsino) would compensate for this. But the Higgs was also too "light" to fit with some supersymmetry predictions. One model predicts there should be five Higgs bosons (and related superparticles)... leaving physicists with one Higgs down and four to go.

Physicists are **hoping the Large Hadron Collider (LHC) will do for supersymmetry what it did for the Higgs boson.** After its highly successful initial run, the LHC underwent an upgrade in 2015 that saw its power double—and it will need every watt of that power to find a superparticle (sparticle). At their least massive, **these are predicted to be some 10,000 times more massive than a proton**—and they are likely to be much heavier.

Most sparticles are predicted to be highly unstable and, even if they are made in the LHC, **they will decay into a myriad of lighter particles within a fraction of a moment.** So, just as they did with the equally fleeting Higgs particle, physicists will have to pick through the decay debris in the hope that they can identify SUSY as the cause.

Like the hunt for the Higgs, the search for SUSY is likely to be a laborious process of **continually refining the energy band in which it may or may not be found** (the more massive the particle, the more energy is required to make it).

Even if the LHC fails to find anything after its upgrade, it will not mean SUSY is not out there, just that we are looking in the wrong place (energy) or for the wrong thing (it might decay into unexpected particles). But **if evidence remains elusive, physicists will face a tough choice**—to abandon the decades-old and heavily invested theory, or keep patching up a theory that may never yield direct evidence of its existence.

Whether SUSY's demise is mourned or not depends on who you talk to. For every physicist who sees an inherent beauty and elegant simplicity in the theory, there is another who sees her as **a Frankenstein-like patchwork of cobbled-together, workaround fixes**.

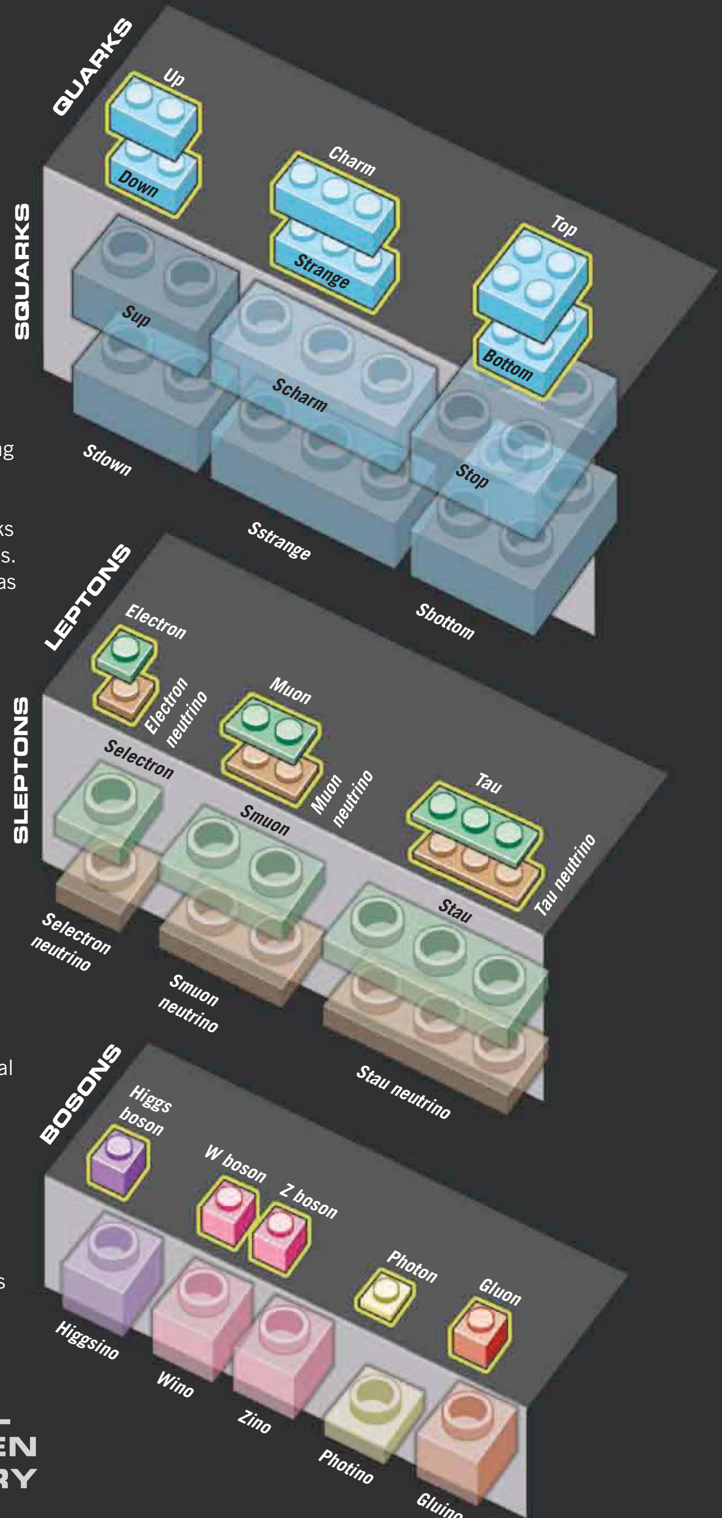
Collider upgrade:
The Large Hadron Collider is currently undergoing a comprehensive upgrade.

THE BUILDING BLOCKS OF MATTER (AND THEIR SUSY "COUSINS")

According to the standard model (SM) of particle physics, atoms are made of particles that, in turn, are made of fundamental particles. There are two families of fundamental particles—quarks and leptons. All matter is made up of a combination of two quarks ("up" and "down") and the lepton called the electron. The rest are usually only "seen" in high-energy particle collisions or in the moments after the Big Bang. Supersymmetry (SUSY) is an extension of the SM in which every fundamental particle has a "twin" (or partner) particle. If they exist, these superparticles (or sparticles) will have much more mass than their SM cousins.

FUNDAMENTAL PARTICLES

As far as we know, fundamental particles are the smallest building blocks of matter. They are divided into two groups: fermions (quarks and leptons) and bosons. Almost every particle has an antimatter version, identical except that it has the opposite electrical charge.



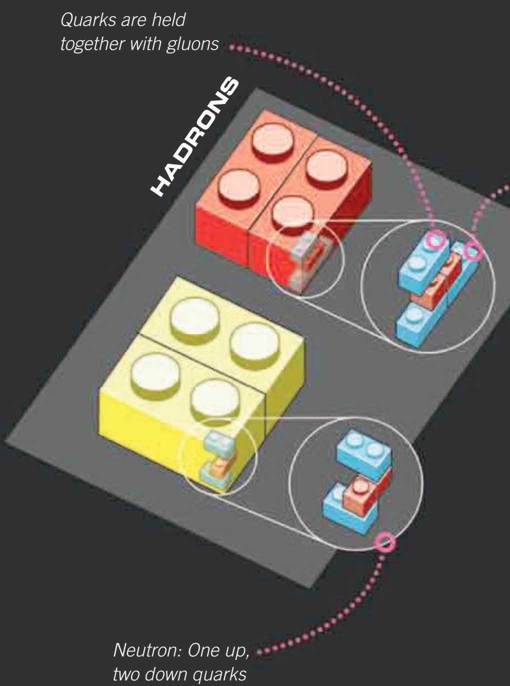
HOW BIG IS "MASSIVE"?

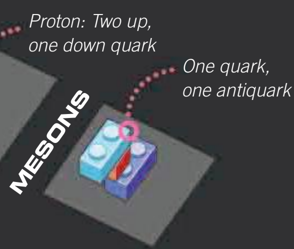
Based on the fact that the LHC has yet to turn up a sparticle at the energy it can search at, the lowest limit (for the least massive) would be about 10,000 times the mass of a proton (about the same as the difference between a mouse and a grand piano).

FORCE REACTIONS

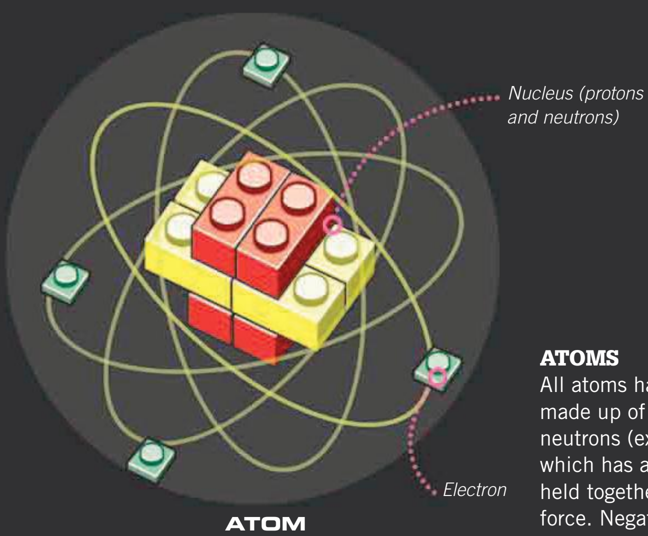
Each of the fundamental forces of nature (electromagnetism, the strong nuclear force, the weak nuclear force) interacts with the fundamental particles through the exchange of force carrier particles called bosons.

THE STANDARD MODEL HAS MADE SO MANY SUCCESSFUL PREDICTIONS THAT IT IS OFTEN REFERRED TO AS "THE THEORY OF ALMOST EVERYTHING"





COMPOSITE PARTICLES
These are particles made up of two or more fundamental particles. The most familiar composites are the positively charged proton and electrically neutral neutron, which are made of three quarks held together by gluons. Composite particles made of quarks are known as hadrons.



ATOMS
All atoms have a nucleus made up of protons and neutrons (except for hydrogen, which has a single proton) held together by the strong force. Negatively charged electrons orbit the nucleus. It is the electrons that allow atoms to bond together to create molecules.

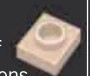
QUARKS
• All of the matter in the universe is made of a combination of up and down quarks.
• All particles composed of quarks are called hadrons (Greek for "heavy")—hence the name of the Large Hadron Collider.
• Quarks come in six "flavors," which have different properties and masses.

SQUARKS
The quark's more massive supersymmetry partner.

LEPTONS
• The most familiar lepton is the electron.
• Leptons are not made up of quarks (or indeed of anything smaller).
• The muon and tau are heavy electrons.

• Another lepton is the neutrino, a ghostly, almost-massless particle that hardly interacts with matter.

SLEPTONS
The superparticle versions of the leptons—includes selectrons (left) and snuetrinos (right).



BOSONS
• Bosons are the particle messengers that tell other particles how to interact with the fundamental forces.

• The gluon mediates the strong nuclear force and is responsible for holding quarks together to form protons and neutrons.

• The photon is a tiny package of energy that carries the electromagnetic force, which affects any fundamental particle carrying a charge.

• W and Z bosons mediate the weak nuclear force, which is responsible for radioactive decay.

• Until recently, the Higgs boson was the missing piece of the SM. It is the particle representative of the Higgs field, which gives mass to quarks and leptons (collectively known as fermions).

HIGGS BOSON: A BLUFFER'S GUIDE

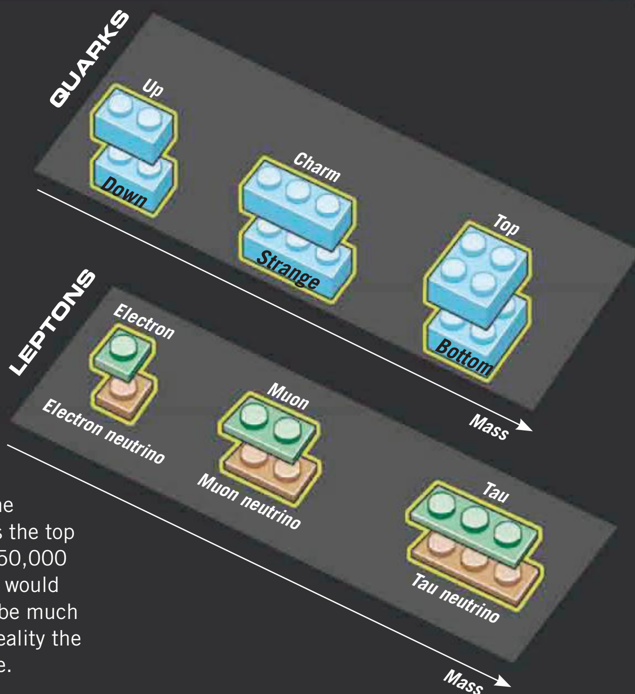
ON JULY 4, 2012, physicists at the European Organization for Nuclear Research (CERN), in Switzerland, home of the Large Hadron Collider (LHC), **announced the discovery of a new particle** that weighed in at about 125–126 GeV—that's about 130 times heavier than a proton. Two separate experiments had both detected the particle, with one data set achieving "five sigma" certainty (a one-in-3.5-million chance of error) that the particle was present. **The discovery was a vindication of the hugely expensive and massively ambitious LHC project,** built to find the mysterious particle. So what is the Higgs boson all about, and **how did scientists know what they were looking for before they found it?** Here is a "bluffer's guide."

LHC impact: This conceptual artwork imagines the rays emitted from particle collisions in the LHC.

The Higgs boson was summoned into theoretical existence in the 1960s, to plug a gap in a theory that was almost perfect—the "standard model" of particle physics. The standard model has been highly successful. It can provide explanations and make predictions about how the counterintuitive quantum world of physics works. **But it couldn't explain one thing—why the fundamental particles have mass** (it also can't explain dark energy and dark matter, but you can't have it all). According to the standard model, all the fundamental particles should have been born in the Big Bang without any mass at all. So how did the smallest building blocks of the cosmos summon mass as if from nowhere? **The Higgs boson is seen as the answer to this problem.** It is the physical emissary of an all-pervading field that interacts with fundamental particles to give them the mass we know they have.

THE **MISSING MASS**

According to the standard model, every object is made up of matter, which has mass. But the problem with this model is that it does not explain why the particle "building blocks" that make up matter do not have enough mass to account for the whole. It is like building a spaceship from six blocks, each of which has a mass of 1, and discovering that its total mass is 500. Something does not add up.



MASSIVE, MORE OR LESS

To add to the confusion, the standard model cannot explain why some particles have so much more mass than others. The lightest particle is the electron. The heaviest particle is the top quark, with a mass more than 350,000 times that of the electron. Logic would dictate that the top quark must be much larger than the electron, yet in reality the particles are about the same size.

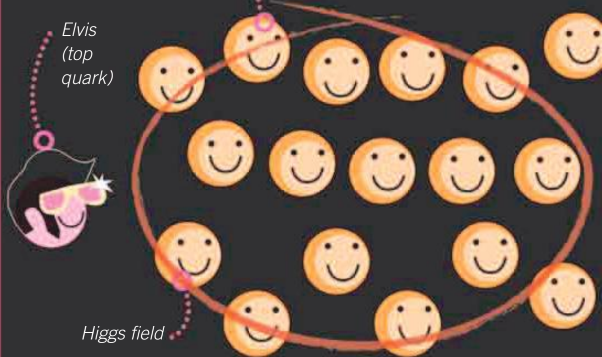
Higgs believed particles acquired mass from a "force field"

WHY A BOSON?

A group of physicists, including Peter Higgs, proposed that the universe is permeated by a sort of invisible force field. As particles travel through this "Higgs field," they interact with it and appear to acquire mass—the greater the interaction with the field, the greater their mass. We know from quantum theory that every field has an associated "force reaction" particle, called a boson, which acts like a messenger to transmit the effect of the field to the particle. So if there is a Higgs field, there must be a Higgs boson.

MASSIVE ATTACK—HOW HIGGS GIVES PARTICLES MASS

As with all things in quantum physics, the reality can only be described in abstract terms and complex mathematics. Not being quantum physicists, we will have to make do with an analogy—here using Elvis and his fans as the different particles, which of course is a huge oversimplification, but perhaps easier to grasp.



1 *An even field*
Imagine the Higgs field is a room filled with particle Elvis fans. The fans represent the Higgs boson and are spread out evenly across the room.

2 *Enter Elvis*
Their hero, Elvis (representing a top quark), enters the room. The fans gather around and slow him down. He loses momentum and energy, but gains mass.

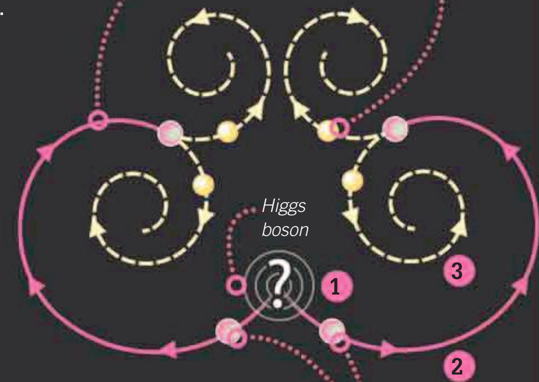
3 *Much less attractive*
When an Elvis impersonator (or electron) enters the room, the fans are not fooled and pretty much ignore him. With little to slow him down, he barely loses energy and gains almost no mass. In the same way, the more a particle interacts with the Higgs field, the more energy it loses, and the more mass it gains.

FIVE SIGMA

The Higgs boson discovery was given the "five sigma" seal of approval. *Five sigma* might sound like the title of a bad 1960s science fiction movie, but for physicists it represents success. A "sigma" is a measure of how likely it is that a result was due to chance. When physicists think they have found a reading that might be the Higgs boson, they repeat the experiment and look for the same reading. The more often they get the same result, the more the likelihood that it was a fluke is reduced. Only when the chance of it being a fluke is reduced to almost zero will they be able say with confidence that they have found the Higgs. A five sigma result means there is only a one-in-3.5-million chance it is wrong.

SEARCHING FOR AN INVISIBLE **NEEDLE IN A HAYSTACK**

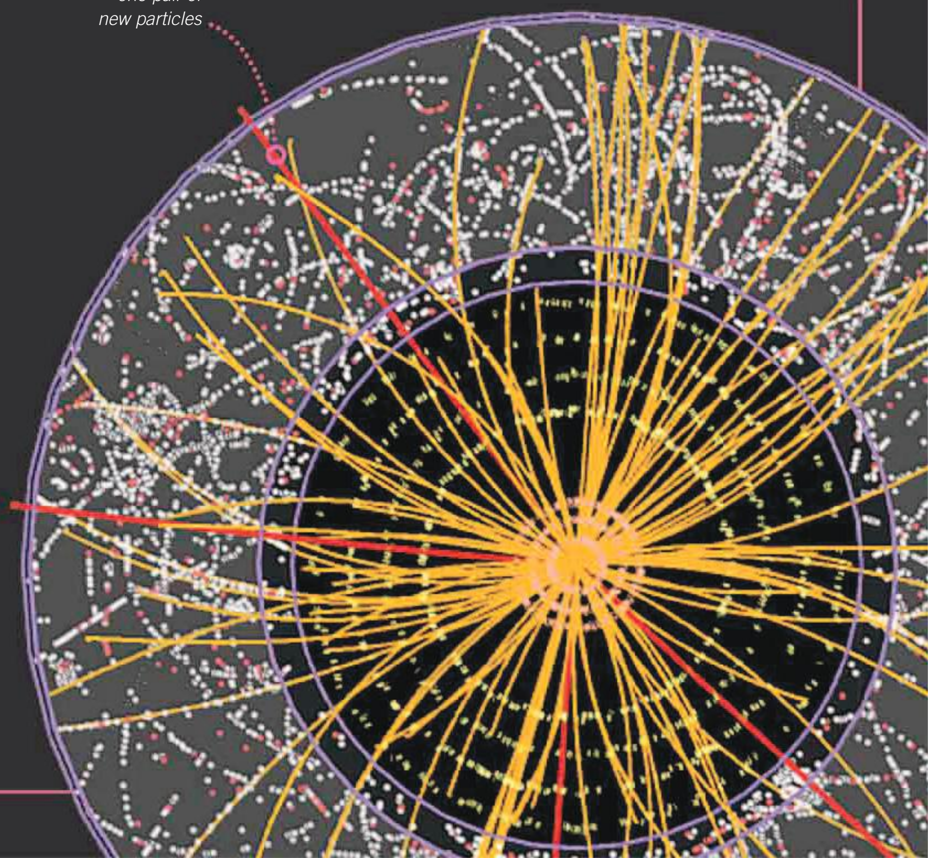
To find evidence of the Higgs field, physicists look for the physical manifestation of that field—the Higgs boson. But they can't spot the Higgs boson directly, so instead they try and predict what sort of particles the Higgs will decay into and look for evidence of those. The action all takes place in the LHC.



1 ***Colliding protons***
The LHC accelerates two beams of protons to 99.9999991 percent of the speed of light (at this speed they complete 11,000 laps of the LHC's 16.7 mile (27 km) circumference every second). The collisions occur with so much energy that the physical laws that hold particles together (the "standard model") break down. Detectors trace and analyze the particles that emerge from the collisions.

2 ***Making tracks***
Unfortunately, even if the collisions do spit out a Higgs boson, it will vanish almost as soon as it appears and decay into two different particles (in physics, decay means a particle turns into two lesser particles, not goes moldy and stinks up your fridge). Physicists study the tracks of these lesser particles.

3 ***New particles***
To complicate matters further, when you smash two protons together, you get all sorts of particles being created—each of which will also decay. This image is a snapshot of one proton collision—all those lines and dots represent the particles that are created and their subsequent tracks. Imagine how difficult it is to find something in all that mess, when you do not know exactly what you are looking for.



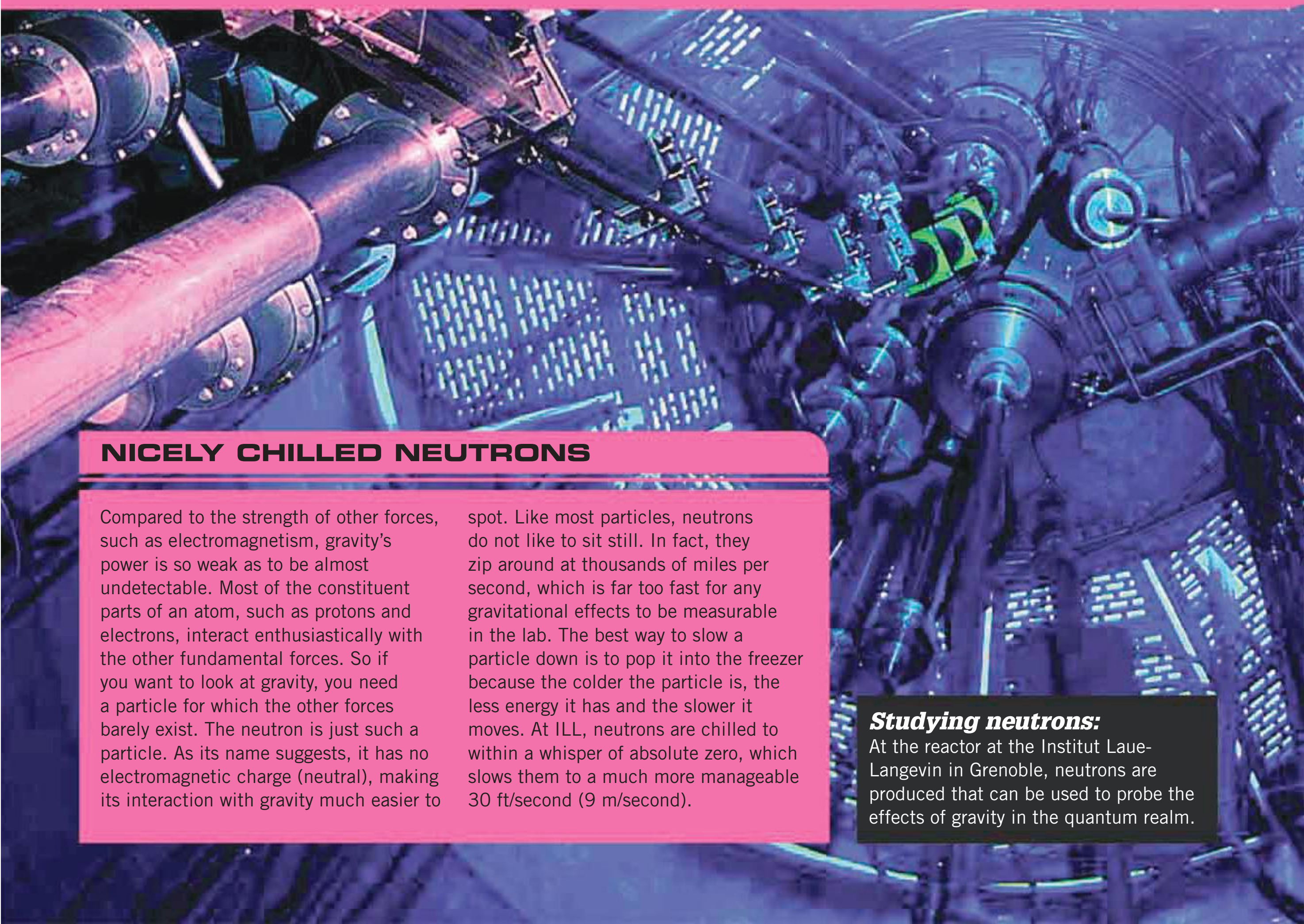
THE LHC IS DESIGNED TO GENERATE NEARLY A BILLION PROTON COLLISIONS EVERY SECOND, WHICH ARE ANALYZED BY 3,000 COMPUTERS

QUANTUM GRAVITY

ON THE FACE OF IT, TESTING HOW GRAVITY AFFECTS THE WORLD AROUND YOU seems like a straightforward proposition. All you have to do is pick something up—perhaps a cannonball, or a turtle—and then let it fall. OK, not a turtle.

But **what if you are a physicist with a pocket full of subatomic particles** and you want to know how gravity affects these smaller-than-small building blocks of nature? After all, **you cannot pick up a neutron with your quantum tweezers, then drop it and expect to see what happens**. Well, you could travel to the Institut Laue-Langevin (ILL) in Grenoble, France.

At ILL, the physicists are neutron wizards who can literally bend particles to their will, and they are using their powers to **probe the mysteries of gravity within the quantum realm**.



NICELY CHILLED NEUTRONS

Compared to the strength of other forces, such as electromagnetism, gravity's power is so weak as to be almost undetectable. Most of the constituent parts of an atom, such as protons and electrons, interact enthusiastically with the other fundamental forces. So if you want to look at gravity, you need a particle for which the other forces barely exist. The neutron is just such a particle. As its name suggests, it has no electromagnetic charge (neutral), making its interaction with gravity much easier to spot. Like most particles, neutrons do not like to sit still. In fact, they zip around at thousands of miles per second, which is far too fast for any gravitational effects to be measurable in the lab. The best way to slow a particle down is to pop it into the freezer because the colder the particle is, the less energy it has and the slower it moves. At ILL, neutrons are chilled to within a whisper of absolute zero, which slows them to a much more manageable 30 ft/second (9 m/second).

Studying neutrons:
At the reactor at the Institut Laue-Langevin in Grenoble, neutrons are produced that can be used to probe the effects of gravity in the quantum realm.

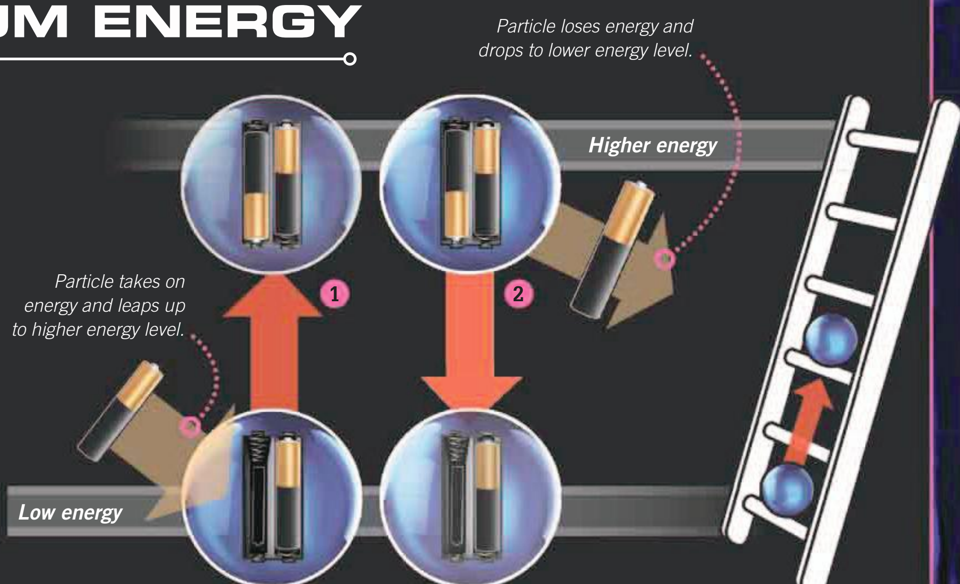
Scientists at ILL have developed a groundbreaking technique, the first results of which were published in March 2014, to **slow down neutrons from their usual Concorde-like speed to a more sedate Usain Bolt–like pace**. At this speed, they can treat the neutrons a little like cannonballs and watch how they fall to Earth.

But **why do we need to know how something as small as a neutron interacts with Earth's gravity?** Quantum mechanics does a great job of telling us how stuff works in the world of the very, very small. Our theories of gravity (Newton's and Einstein's) do a top job telling us how stuff works in the world of the large. But **we still do not know how gravity works at a subatomic scale**. The hope is that, by measuring how particles like neutrons interact with gravity, physicists will be able to **unite quantum mechanics and gravity into a single theoretical framework**.

With rules for how particles usually interact with gravity, scientists can search for **anything unusual that might point to the existence of undiscovered particles** and forces, which might tell us more about one of the great mysteries in science today: **What are dark matter and dark energy made of?**

THE WEIRD WORLD **OF QUANTUM ENERGY**

We are used to thinking of energy as being a sliding scale—you can have lots, little, or anything in between. There is no finite limit to how much you can have. In the quantum world of particles things are very different. Here, energy comes in discrete units, or quanta (hence "quantum"), which particles can absorb, or emit, to reach certain energy states—rather like rungs on an energy ladder.



POWER UNITS
You can think of energy quanta as being a little like batteries that particles use to power their climb up the energy ladder.

1 ***Moving up***
A particle on the lowest rung can absorb one quantum battery and use its energy to leap to a higher rung—a "quantum leap."

2 ***Going down***
A particle on a higher rung can shed a quantum battery to move to a lower rung.

STEP BY STEP
Just as you cannot cut a battery in half and expect it to work, a particle cannot absorb or shed less than one quantum unit. It cannot occupy a space between rungs on the energy ladder, any more than your foot can on a real ladder.

HOW TO MEASURE QUANTUM GRAVITY

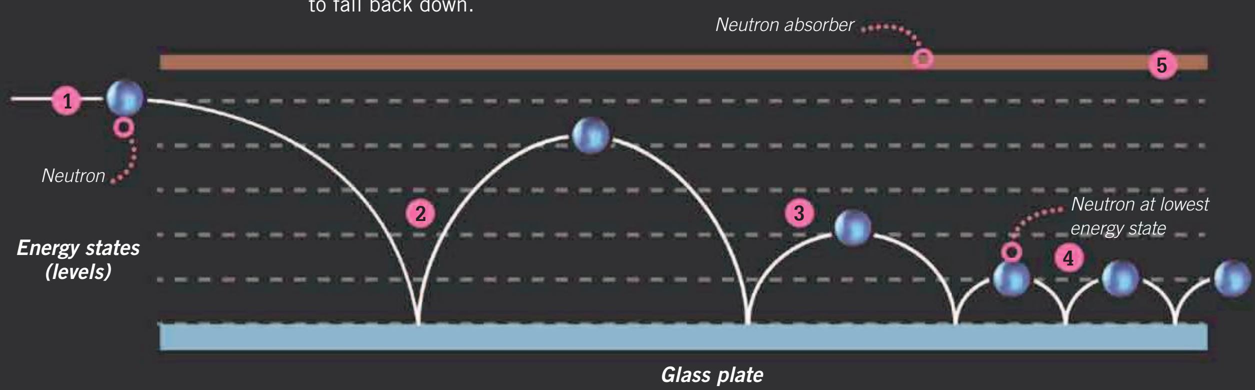
You need to determine a scale before you can measure something—try using a ruler that has no centimeters or inches. For quantum systems, you need to be able mark your ruler with levels of energy states.

1 *Cold start* At the ILL, a beam of cold neutrons travels above a polished glass plate. Each particle is full of gravitational potential energy that wants to fulfill its potential by falling to Earth.

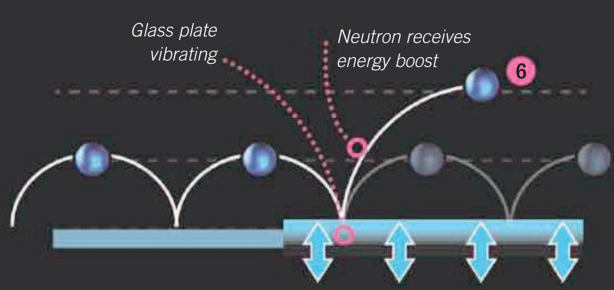
2 *The pull of gravity* As an object falls under the influence of Earth's gravity, its potential energy is converted into kinetic (movement) energy. When it bounces back up, kinetic energy turns into potential energy. When all the energy is converted, the neutron begins to fall back down.

3 *Bouncing back* For the neutron, each bounce back up is like scaling the energy ladder. But with each bounce, it loses energy, which means it cannot climb as high.

4 *Minimum energy* If a neutron behaved like a ball, it would lose energy on each bounce until it simply rolled along. But because neutrons obey quantum laws, a neutron's "bounce" stops getting smaller when it reaches its minimum energy state.



5 *Neutron absorber* Above the neutron beam is an absorber that soaks up neutrons that strike it. As the absorber is lowered, it encounters neutrons at different energy states and absorbs them, reducing the number exiting at the far end. With each dip in neutrons, the energy level is noted. The point at which no neutrons make it out marks the lowest gravitational state.



6 *Energy boost* With only neutrons in their lowest energy state passing over it, the glass plate is made to vibrate. This adds energy to the neutrons so they jump to a higher energy state. Only if the plate vibrates at the right frequency will it add just the amount of energy needed to boost a neutron up. If too high or low, the neutron stays in its lowest energy state.

NEW PROJECTS

By measuring the frequency at which the neutrons jump up, physicists can tell what the energy difference is between the two states, allowing them to measure how much the neutrons are being affected by gravity and how much energy they are getting from the gravity field. This technique makes it possible to study with extraordinary precision how gravity operates in the quantum realm and determine if there are any as-yet-undiscovered forces at work. It will also allow physicists to search for evidence of new particles without having to rely on large, hugely expensive "brute force" experiments such as the Large Hadron Collider.

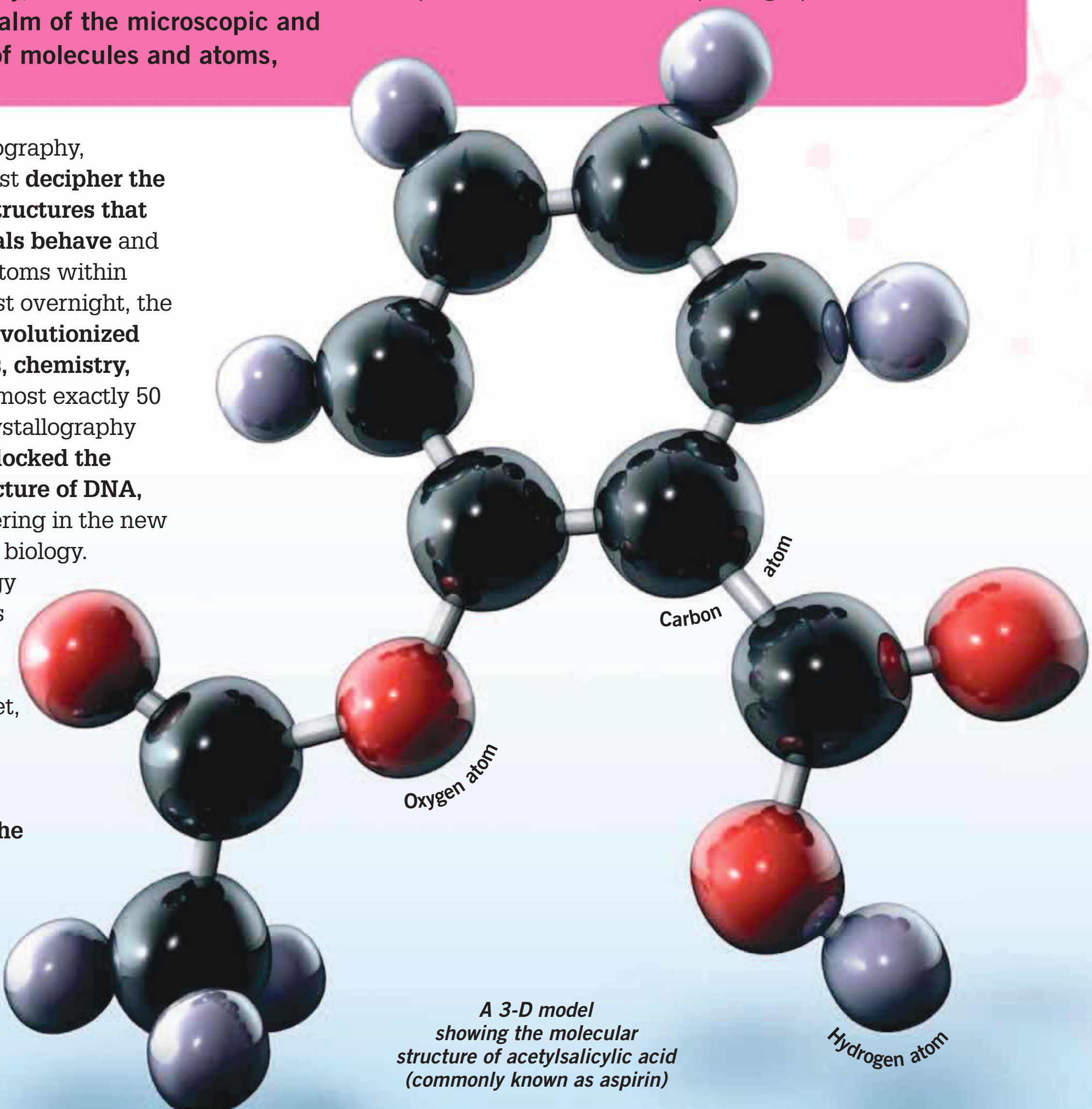
X-RAY CRYSTALLOGRAPHY

IN 1913, BRITISH PHYSICIST WILLIAM HENRY BRAGG and his son, William Lawrence Bragg, made what is probably the most important discovery you've never heard of. They invented a technique, called X-ray crystallography, that allowed scientists to **look beyond the realm of the microscopic and into the kingdom of molecules and atoms,** revealing the hidden mechanisms that drive the world in which we live.

For the first time, **scientists were able to photograph atoms** by bombarding a crystallized sample with X-rays and then decoding the patterns left behind on photographic film.

Using X-ray crystallography, scientists could at last **decipher the hidden molecular structures that govern how materials behave** and figure out how the atoms within them interact. Almost overnight, the Braggs' discovery **revolutionized the fields of physics, chemistry, and biology.** And almost exactly 50 years later, X-ray crystallography was the key that **unlocked the mystery of the structure of DNA,** the code of life, ushering in the new science of molecular biology.

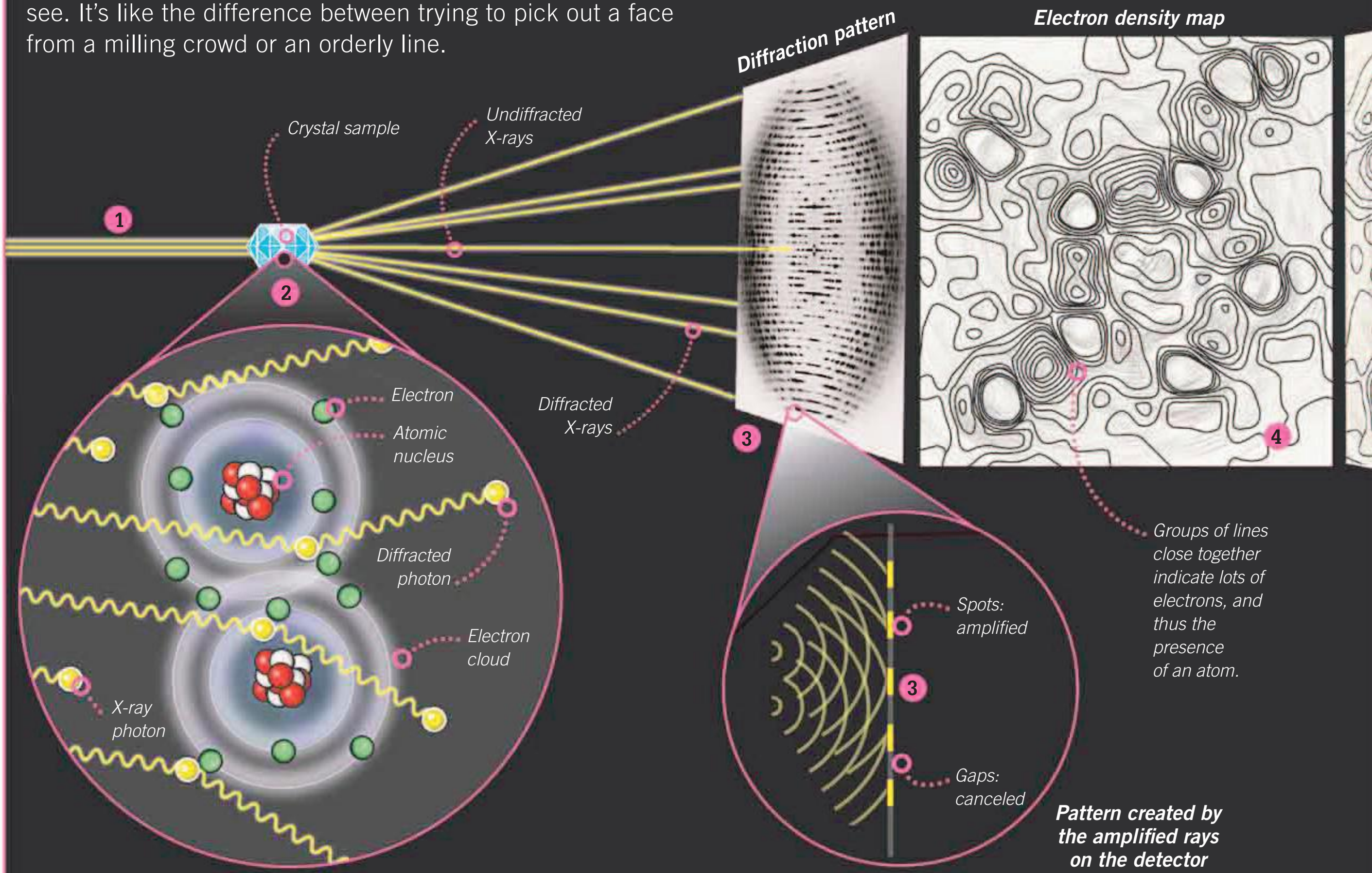
From biotechnology and pharmaceuticals to the planes we fly in and the fuels that power our planet, **there is virtually no area of our modern world that does not owe something to the discoveries of X-ray crystallography.**



A 3-D model showing the molecular structure of acetylsalicylic acid (commonly known as aspirin)

HOW X-RAY CRYSTALLOGRAPHY REVEALS HIDDEN STRUCTURES

Here's how X-ray crystallography makes it possible to "see" something as small as an atom. The sample to be studied must first be refined, purified, and concentrated to form a crystal. That's because in a crystal the molecules are organized into regular, repeating units, which make them easier to see. It's like the difference between trying to pick out a face from a milling crowd or an orderly line.



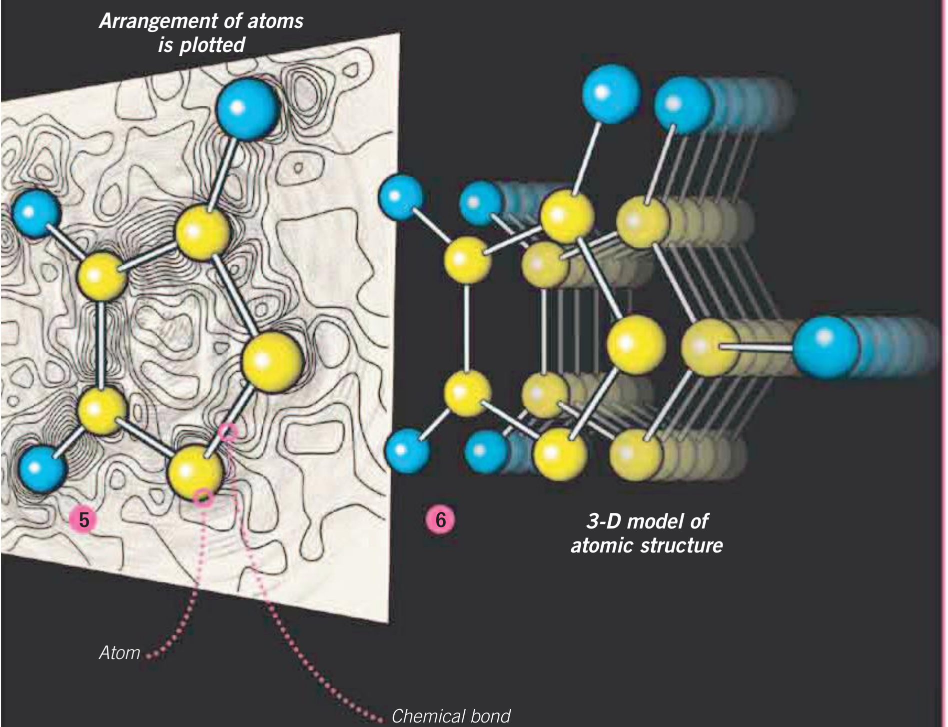
1 *Light beam* A beam of X-rays is fired at the sample. Part of the electromagnetic spectrum (which includes visible light), X-rays are made up of packets (or particles) of energy called photons, but they also behave like waves.

2 *Diffraction* Most photons pass straight through the crystal, but the paths of some photons will be diffracted (made to change direction) as they strike the electrons in the atoms.

3 *Pattern of spots* The diffracted X-rays interact (or interfere) with each other. Some will be amplified and some canceled out. The amplified rays will appear as spots on the detector, and these build up to create a pattern.

4 *Gradient map* As the spots were caused by photons diffracted by electrons, scientists can create a gradient map that plots how electrons are distributed within the sample. The higher the concentration of electrons, the closer the lines appear on the map.

THE BRAGGS ARE THE ONLY FATHER AND SON TO SHARE A NOBEL PRIZE. THEY ALSO HAVE A MINERAL NAMED AFTER THEM, CALLED BRAGGITE



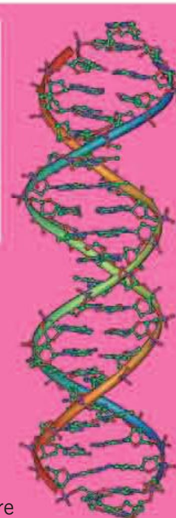
AN AVERAGE GRAIN OF SAND HAS SOME 80 BILLION BILLION SILICA ATOMS—ALMOST CERTAINLY MORE THAN THE NUMBER OF GRAINS OF SAND ON THE BEACH IT CAME FROM

5 ***Interpretation***
From the electron density, scientists can work out the position of atoms in the sample (where there are lots of electrons, there is an atom) and how they are bonded (through electron interactions). They can also work out which chemical element each atom belongs to (the higher the atomic number, the larger the electron cloud).

6 ***3-D model***
By rotating the sample and taking images from different angles, scientists can build up a picture of the entire sample and construct a 3-D model of the molecule's complete atomic structure.

THE X FACTOR

X-ray diffraction image of DNA



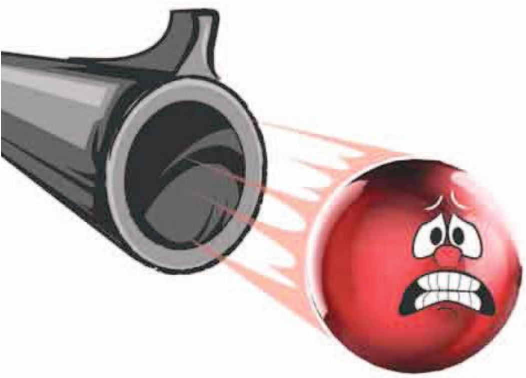
DNA double helix

Perhaps the most famous scientific breakthrough made possible by X-ray crystallography was the discovery of the double helix structure of DNA. Above is the original "Photograph 51" that led the American scientist James Watson and the British scientist Francis Crick to make their Nobel Prize–winning discovery in 1953. The image, captured by Rosalind Franklin and Raymond Gosling in 1952, shows a distinctive X that Watson and Crick recognized as being the telltale sign of a helix.

PARTICLE ACCELERATORS

THE LARGE HADRON COLLIDER (LHC) at the European Organization for Nuclear Research (CERN) is in many ways like a particle sniper rifle. **It fires some of the smallest components of matter into each other at colossal speeds with exquisite precision,** so physicists can study the even smaller components that come flying out.

There can be no doubt that **the LHC is a machine in a class of its own.** It's the most ambitious, technologically demanding, expensive, and powerful particle sniper rifle ever built. **But there is always a new model on the drawing board**—a next-generation machine ready to surpass its predecessor.



Despite its success in finding one of its main targets, the Higgs boson, in 2012, **the LHC was not working at its full operating potential at the time.** When CERN's particle-colliding beast was switched off for upgrades in 2013, it was only **running at a little over half-power—eight trillion electron volts (8 TeV).** When firing on all 14 of its TeV cylinders, its mission will be to find the answer to **the big question for physics—what is dark matter?**

Dark matter is so called because it is invisible, or "dark," and its existence can only be inferred from its gravitational effect on things we can see. **It is thought to make up about 24 percent of the universe,** so there is a lot of it.

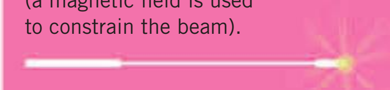
The challenge is to find a particle that has not been seen, cannot be detected directly, could exist in multiple forms (after all, normal matter is not made up of just one sort of particle), and may not exist at all. If that sounds like an exercise in quixotic futility, remember that **they have done this before with the Higgs boson.** But, even operating at full power, the mighty LHC may not be up to the task. It might give some hints about the nature of dark matter, and help focus the hunt, but we may have to wait for the next generation of particle sniper rifles before scientists are able to train their sights on the elusive substance.

Proposals for a new machine include building a giant linear accelerator, or linac (perhaps the most sniper rifle–like accelerator), which would hurl particles down **a 30 mile (50 km) long tunnel** along with a sort of supersized LHC **with a 60 mile (100 km) long accelerator ring.**

Including planning, it took **30 years and more than $8 billion to build the LHC**. So, to build a more ambitious machine than the most ambitious machine ever built, **planning cannot start too early.**

TYPES OF TRACKS

LINEAR (LINAC)
A linac uses electromagnetic waves to accelerate particles down a long, straight track to collide with a target (a magnetic field is used to constrain the beam).



CIRCULAR (SYNCHROTRON)
This accelerates particles around a circular track using electromagnets.

COMBINATION
Most large particle accelerators (like the LHC) are a combination of linear and circular accelerators.

DARK MATTER MACHINE

Here is a simple guide to the journey of protons through the LHC. Around the main ring are four areas—ATLAS, LHCb, ALICE, and CMS—where experiments are carried out on the speeding particles.

1 *Running start*
Protons set off at 33 percent of the speed of light in a linear accelerator.

2 *Speeding up*
In a booster ring they are bumped up to 91.6 percent of the speed of light.

3 *Faster...*
The protons move into a 2,296 ft (700 m) synchrotron and are boosted to 99.93 percent of the speed of light.

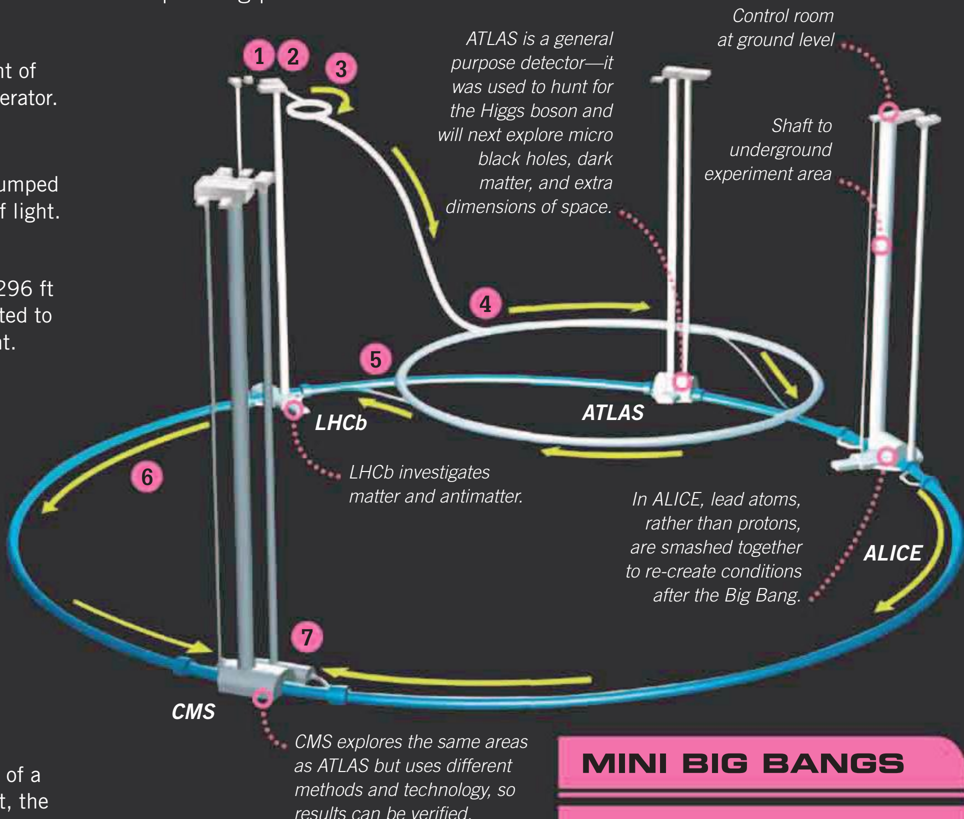
4 *Going underground*
They then shoot 131 ft (40 m) underground into a 4.3 mile (7 km) long ring where they are accelerated to 99.9998 percent of the speed of light.

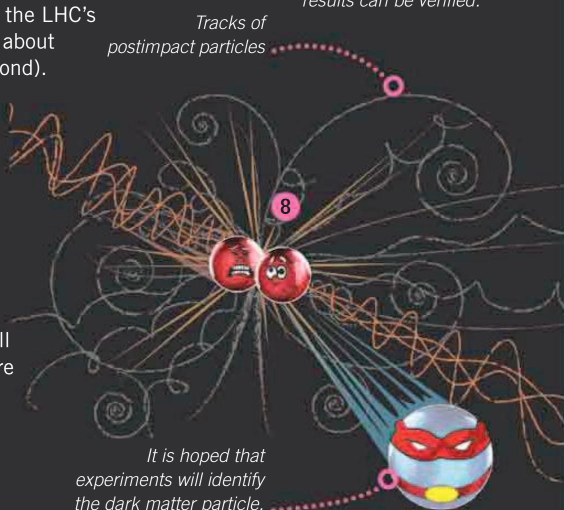
5 *The path splits*
Two streams of protons are fed into the LHC and circulate in opposite directions.

6 *Final surge*
To get that last 0.0001991 of a percent closer to the speed of light, the protons are again boosted around the LHC's 16.7 mile (27 km) ring (covering about 11,000 laps of the ring every second).

7 *Impact!*
At 99.9999991 percent of the speed of light, the two beams are smashed together within the four experiment areas.

8 *Making tracks*
In the energy maelstrom, all sorts of particle building blocks are created. Most are too short-lived to detect, but, by tracing their characteristic tracks, physicists can infer the properties of the particles that created them.





MINI BIG BANGS

Physicists are not just looking for bits of broken proton kicked out by the impact—like shards of glass and metal thrown from a wrecked car. They are also looking for particles that have been created from the intense pressure and energy found in the dense subatomic fireballs (a million times hotter than the center of the sun) formed at the point of collision. This is why scientists talk about the LHC "re-creating conditions at the time of the Big Bang": they really do create mini Big Bangs, in which the colliding protons melt into the same sort of hot and dense fundamental particle soup as the one from which the universe emerged.

THE LOST **ELEMENTS**

Scientists will also be training the sights of their particle accelerators at other, more practical problems, such as the chemical elements that make up the universe.

The periodic table of elements is an icon—a list of atomic attributes that is as elegant as it is practical. As an at-a-glance guide to every chemical element, it is the scientific equivalent of the London Tube map. But it is far from complete. It is supposed to be the full list of all 98 naturally occurring chemical elements (and 20 synthesized ones) but, according to some estimates, there are somewhere between 3,500 and 7,000 elements missing.

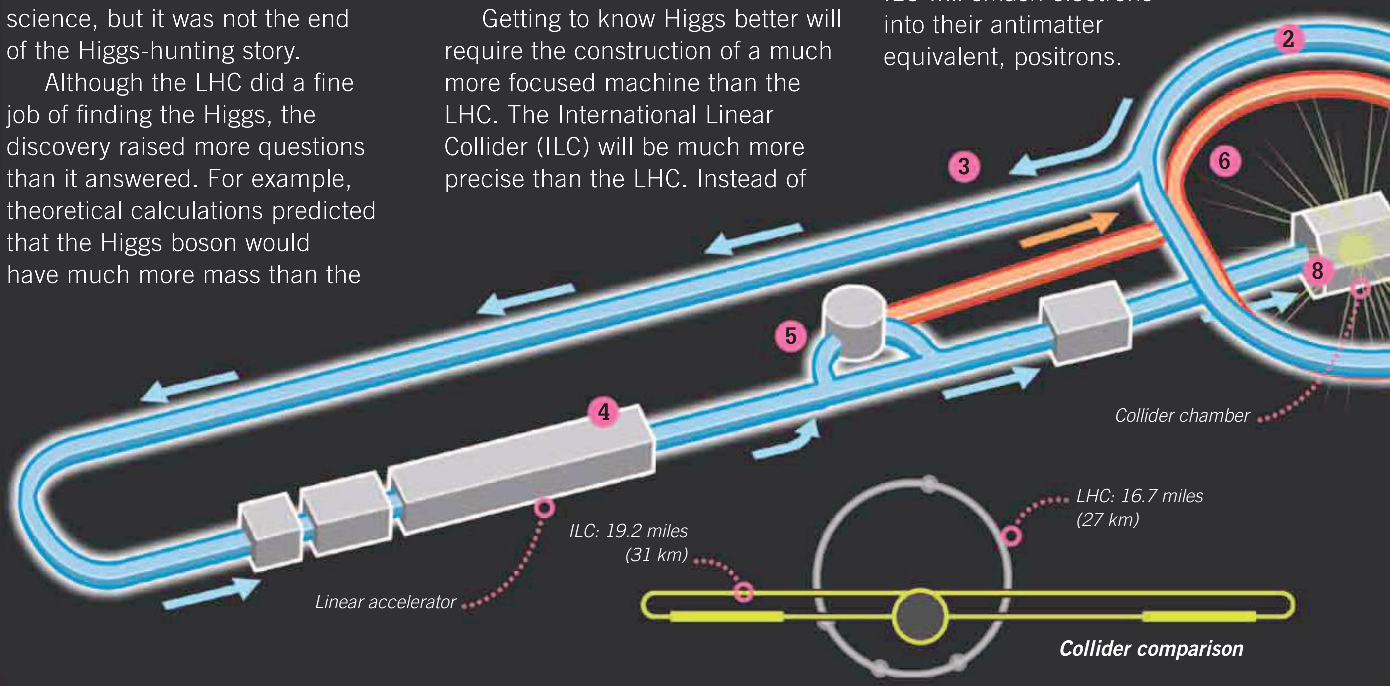
Now scientists are preparing to build two new particle snipers that will hunt down these "lost elements." To find them, scientists will have to re-create the violence of a supernova here on Earth. The first accelerator will be built in Germany, at the Facility for Antiproton and Ion Research (FAIR). The site of the second (whose acronym sounds like a bladder medication), the European Isotope Separation On-Line facility (EURISOL), has not been decided. By smashing atoms of heavy elements, such as uranium, into each other (or into fixed targets), they will create temperatures more than a million times hotter than the sun, and enough pressure, they hope, to produce some of the missing short-lived chemical elements, which they can then measure before they decay.

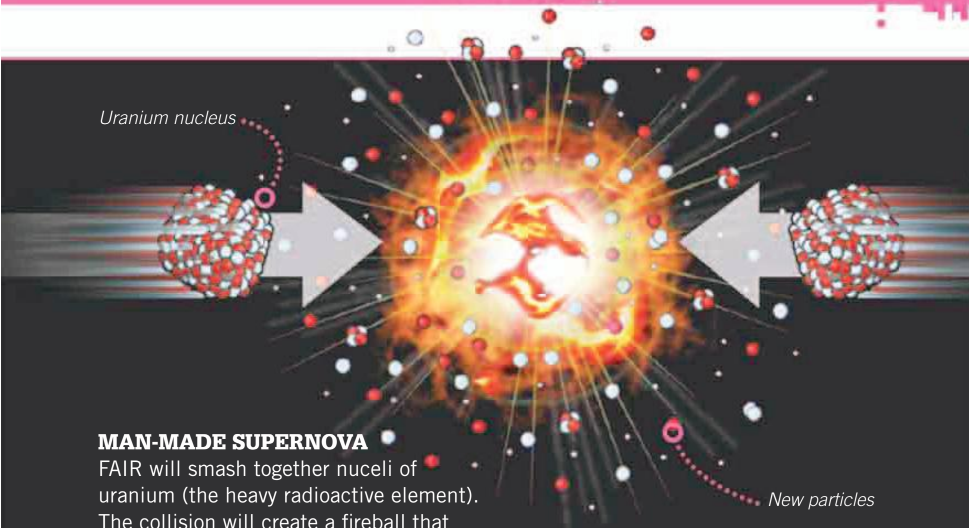
ILC: THE ULTIMATE **PARTICLE SNIPER**

The discovery of the Higgs boson in 2012 was a vindication of the expense of the LHC and a triumph of theoretical and experimental science, but it was not the end of the Higgs-hunting story.

Although the LHC did a fine job of finding the Higgs, the discovery raised more questions than it answered. For example, theoretical calculations predicted that the Higgs boson would have much more mass than the particle discovered at CERN, raising the possibility that the LHC's Higgs is just one member of a larger Higgs family (of perhaps five Higgs).

Getting to know Higgs better will require the construction of a much more focused machine than the LHC. The International Linear Collider (ILC) will be much more precise than the LHC. Instead of smashing protons together—which is a bit messy because they are made of smaller particles—the ILC will smash electrons into their antimatter equivalent, positrons.

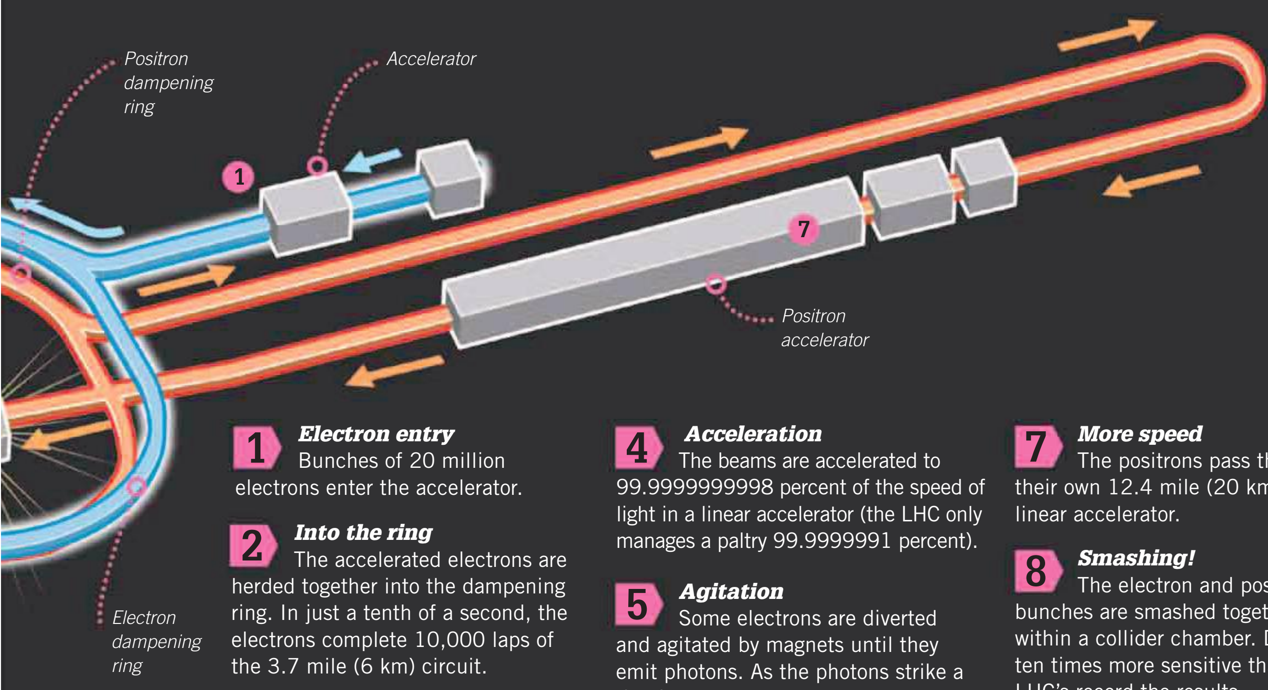




MAN-MADE SUPERNOVA
FAIR will smash together nuceli of uranium (the heavy radioactive element). The collision will create a fireball that briefly reproduces the extreme heat and pressure of a supernova explosion, creating around 1,000 new particles.

BURNOUT

All the chemical elements heavier than iron are forged in the insane high-temperature, high-pressure conditions that exist when a star explodes as a supernova. Although the stable elements stuck around long enough to build the planets—and you and me—the vast majority were so unstable, they lasted just a trillionth of a trillionth of a second before they decayed into lighter, more stable elements and were lost forever.



1 *Electron entry*
Bunches of 20 million electrons enter the accelerator.

2 *Into the ring*
The accelerated electrons are herded together into the dampening ring. In just a tenth of a second, the electrons complete 10,000 laps of the 3.7 mile (6 km) circuit.

3 *Compression*
When they leave, each bunch of electrons has been compressed into a beam just 0.01 in (0.3 mm) long and thinner than a human hair.

4 *Acceleration*
The beams are accelerated to 99.9999999998 percent of the speed of light in a linear accelerator (the LHC only manages a paltry 99.9999991 percent).

5 *Agitation*
Some electrons are diverted and agitated by magnets until they emit photons. As the photons strike a titanium alloy target, the target's atoms emit more electrons and some positrons.

6 *Rounding up*
The positrons are corralled into focused bunches in their own dampening ring.

7 *More speed*
The positrons pass through their own 12.4 mile (20 km) long linear accelerator.

8 *Smashing!*
The electron and positron bunches are smashed together within a collider chamber. Detectors ten times more sensitive than the LHC's record the results.

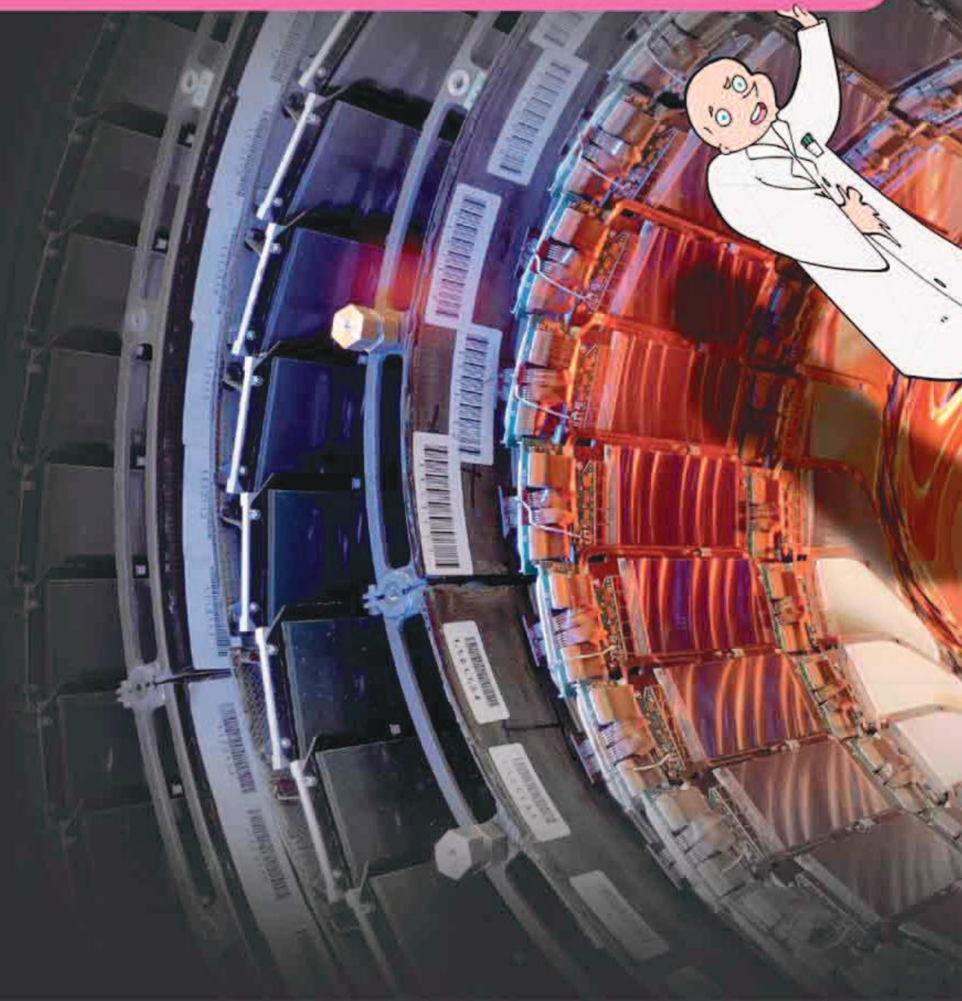
ATTACK OF THE MICRO BLACK HOLES

BLACK HOLES ARE AMONG THE MOST EVOCATIVE and fascinating phenomena in the cosmos. Born from the collapsing cores of massive stars, they are the ultimate expression of gravity's power—**bending the fabric of space and time so absolutely that not even light can escape their clutches.** In their most massive incarnations, they lurk at the center of every galaxy—**able to dictate the movements of stars and, if these stray too close, strip away their gaseous flesh.** Black holes are awesome and terrifying objects.

It is fortunate then that they can only be found in the deep recesses of outer space... **but imagine if, during some sort of perverse science experiment, we were to make one here on planet Earth.**

When the Large Hadron Collider (LHC) was gearing up for its record-breaking high-energy particle collisions in 2008, **fear was rife that a deadly side effect of the collisions would be the creation of microscopic black holes.** Set free by the magnetic fields of the collider, the micro black holes would fall into the bowels of Earth, where, nurtured in a womb of planetary material, they would grow, becoming increasingly massive **until they sucked up Earth and humanity along with it.**

Earth is still here, so it would appear that the fear was unfounded. But it might surprise you to learn that some scientists hope that micro black holes will one day be detected in the aftermath of some of the LHC's particle collisions.



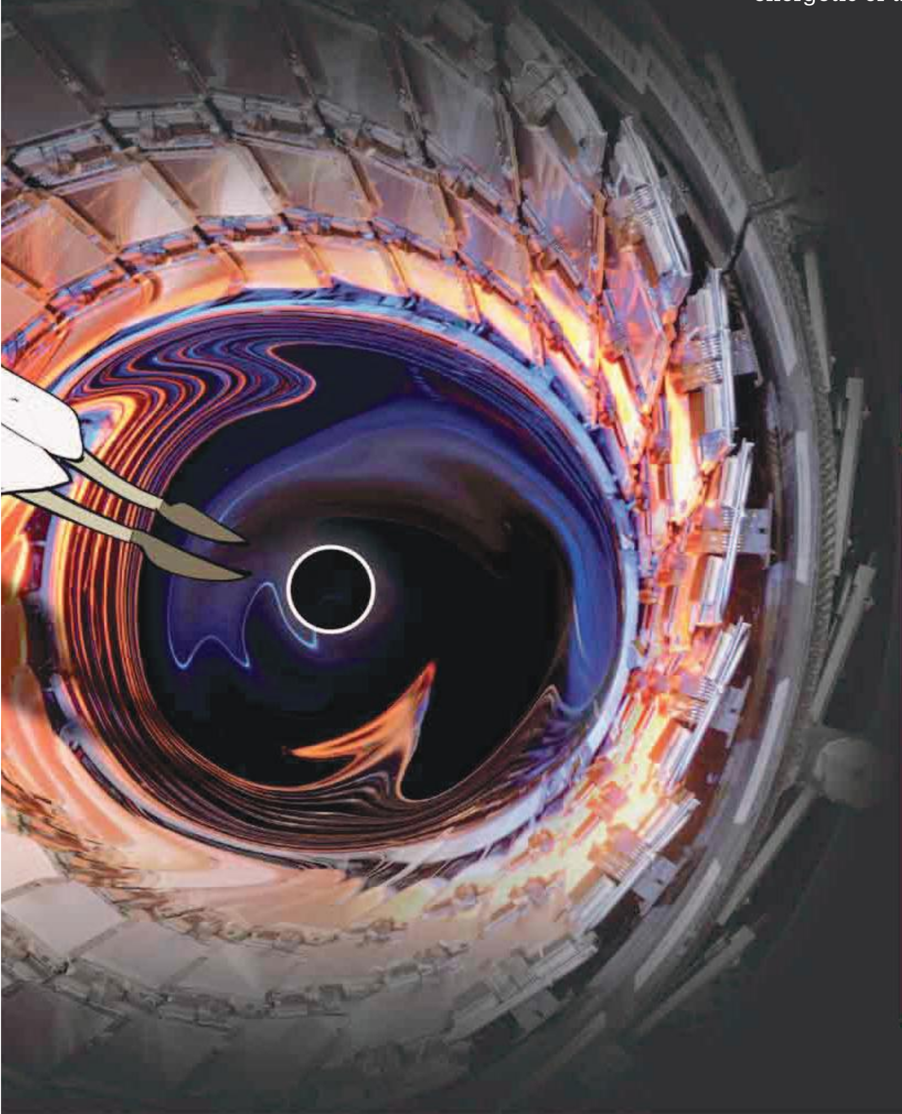
Lost in the LHC: Some feared micro black holes would be created by particle collisions in the LHC.

You cannot be serious?
Why would anyone wish for something so scary? **It all comes down to the continuing search to understand gravity.** For big stuff, like the stars, planets, and you and me, gravity's effects are beautifully described by good old-fashioned Newtonian physics and by Einstein's theory of general relativity. But for really small stuff, like atoms and their subatomic building blocks, gravity's effects stubbornly defy explanation.

The biggest problem is **gravity's apparent weakness compared with the other fundamental forces,** such as electromagnetism. Gravity might have the power to sculpt galaxies, but **the gravitational pull of an entire planet can be overcome by something as feeble as a child's magnet.** Under this framework, gravity is just too weak for even the most energetic of the LHC's particle collisions to result in the formation of a micro black hole.

But there is a theory that seeks to explain gravity's lack of muscle. **String theory predicts that, instead of there being just three dimensions of space, there might be as many as 26,** all curled in tightly bound knots and too small to be detected by our limited three-dimensional brains. The idea goes that, while the other fundamental forces are bound in three dimensions, gravity is free to roam all dimensions and, as such, becomes increasingly diluted.

When two particles collide at almost the speed of light, their energy is concentrated into a tiny space. **If extra dimensions do exist, gravity within that tiny space might be strong enough to allow the formation of a micro black hole.** If gravity can allow the formation of a micro black hole, then the next



DEFYING GRAVITY

Gravity is so weak that you can overpower it yourself. Just grab a couple of nails and place them on a table. Gravity is using all its strength to pull the nails as close as possible to Earth's center of mass. Then take a small magnet and watch in awe as its electromagnetic force easily dismisses the gravitational force of an entire planet and lifts the nails.

A magnet is all you need to defy Earth's gravity

Swallowed up?:
There's no danger Earth will be swallowed up by a black hole made in the LHC.

question is, **will a man-made black hole doom us all?** The short answer is no, and here's why.

Micro means really tiny

Microscopic black holes are so-called because they are really, really tiny. **Producing a black hole is all about taking mass and squeezing it until it falls below the "Schwarzchild radius"**—the threshold at which gravity causes the object to collapse in on itself. You need a lot of mass to create even a modest black hole—**Earth would squash down to a black hole the size of a marble.**

In the LHC, the ingredients for a potential black hole are in short supply. **It would be created with the mass of less than a couple of protons,** so any resulting black hole would be unimaginably small.

They won't devour the planet

The idea that **a matter-devouring black hole would be tempted to "fall" to the center of Earth** is, arguably, a logical conclusion, but it is also wrong. If a teeny tiny black hole were to be created and then liberated from the magnetic confines of the LHC, it would be traveling at much the same speed as the particles from which it was created. Since this is close to the speed of light, **the black hole is far more likely to shoot off into space.** Whether the course of its planetary exit takes it straight out into the atmosphere or through Earth's core is largely irrelevant. It's so inconceivably small that **it would take longer than the current age of the universe to devour just a gram of our precious planet.**

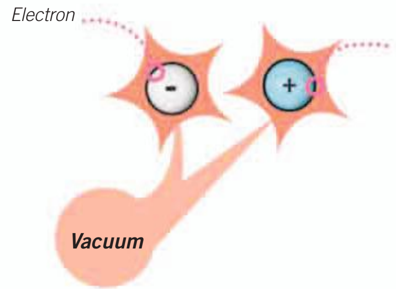
They evaporate really quickly

Time and velocity are the least of the obstacles faced by micro black holes with planet-devouring ambitions. **The greatest hurdle is their insanely short lifespans.**

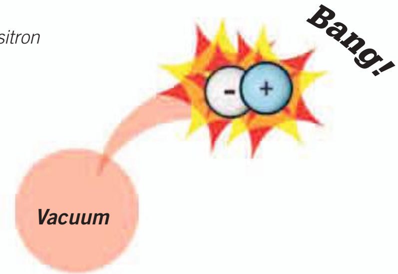
Black holes are famed for their "everything in, but nothing out" nature, so you would be forgiven for thinking that a black hole of any size could only ever get bigger. But British physicist Stephen Hawking says otherwise. In 1974, he realized that all black holes actually emit radiation, now known as Hawking radiation, which causes them to

VIRTUAL PARTICLES

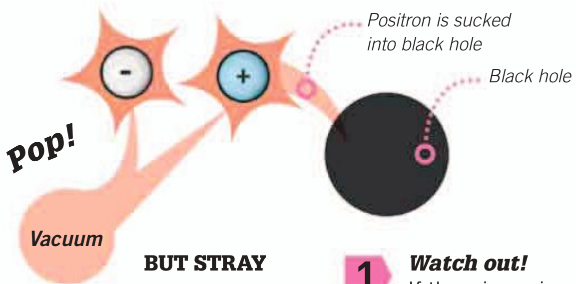
So-called "virtual particles" are born with an energy debt that they have to repay before the Planck time limit expires. Normally they do this by annihilating each other in a flash of energy that repays their quantum vacuum debt.



1 ***Pop-up particles*** A virtual particle pair is created owing energy to a vacuum.

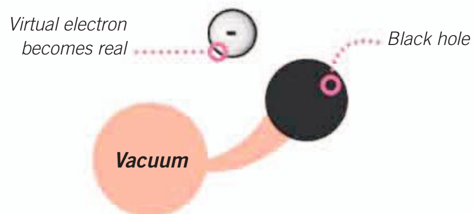


2 ***Over in a flash*** Usually, the particles annihilate each other and release energy back to the vacuum.



BUT STRAY TOO CLOSE TO A MICRO BLACK HOLE...

1 ***Watch out!*** If there is a micro black hole nearby, it sucks up a virtual particle, which is then lost to space and time.



2 ***Energy debt*** The black hole "owes" energy to the vacuum and loses energy. As the virtual electron becomes real, it makes the black hole radiate energy.

lose energy continuously, which leads to their evaporation.

But **if matter and energy cannot escape a black hole, how does it lose energy and matter?** Well, it comes down to a peculiar quirk of quantum mechanics. This tells us that **empty space is never truly empty.** On the smallest scales, it is a bubbling sea of quantum fluctuations from which pairs of particles can be created seemingly from nothing.

Heisenberg's uncertainty principle tells us that the shorter the amount of time you look at something, the less certain you can be of what is going on—**"if you cannot see it happening, anything is possible."** In quantum physics, the shortest period of measurable time is called "Planck time". Anything that happens within that time is, by definition, unmeasurable. If this is so, the uncertainty principle tells us that nothing is impossible.

With no "rules" to prevent it, particle pairs (electrons and their antimatter opposites, positrons) can "borrow" energy from the vacuum and pop into existence (see panel, above). But, if they are created too close to a micro black hole, one of the pair can be "sucked up" and lost to space and time. At that point, the remaining particle is forced to become a bona fide particle, and the black hole is left saddled with the energy debt of the particle it swallowed. Since debt is always a negative value, it effectively takes on negative energy, which is subtracted from the energy it has stored away. In this way, the micro black hole radiates energy (carried away by the virtual particle made real) and it evaporates too quickly to swallow even a small scientist in the LHC, let alone planet Earth.

THE EXPECTED LIFESPAN OF A MICRO BLACK HOLE IS LESS THAN ONE OCTILLIONTH OF A NANOSECOND

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ACKNOWLEDGMENTS

DK WOULD LIKE TO THANK:
Victoria Pyke for proofreading,
and Carron Brown for the index.

The publisher would like to thank the following for their kind permission to reproduce their photographs:

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