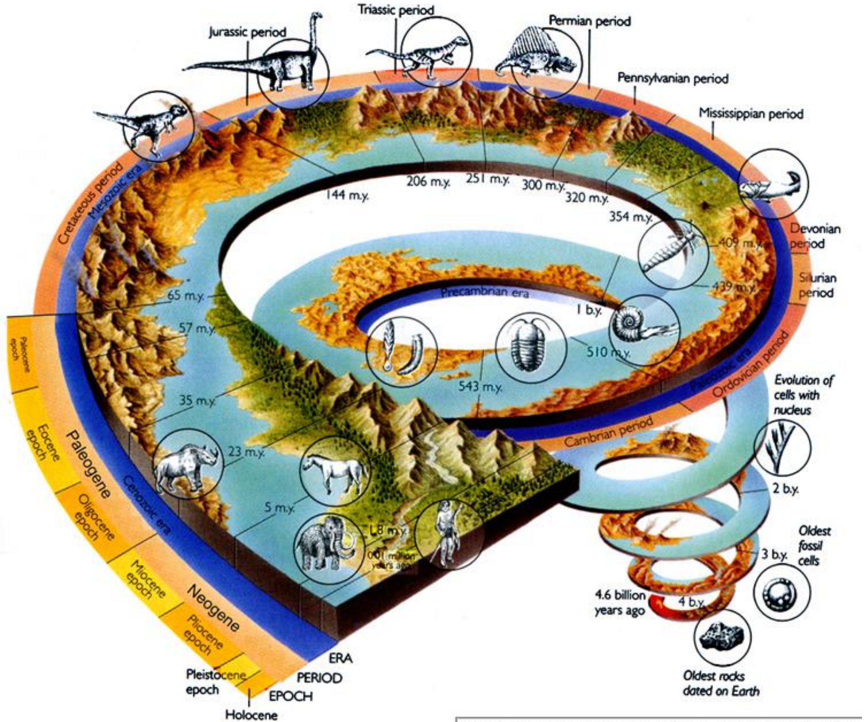
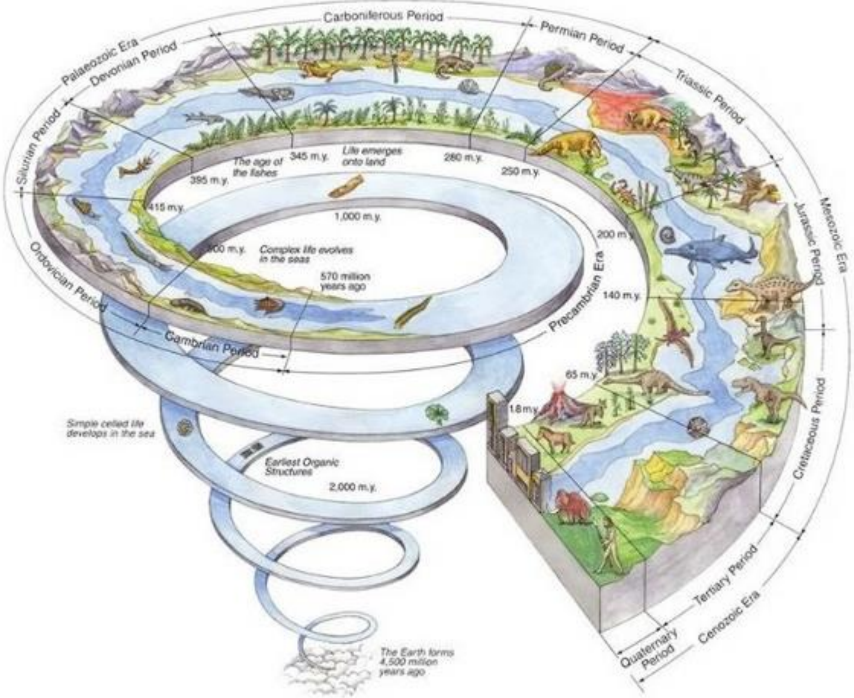
- The origin of life on Earth is still **deeply mysterious**.




Adapted from Press & Siever, 2000, Understanding Earth



# Introduction

- The origin of life on Earth is still **deeply mysterious**.

- However:

  - ✓ The answer seems to be **within the reach of science**, at least *generally*.

  - ✓ **Right conditions** (chemical/solar free energy, organic molecules, liquid water) + increasingly **plausible origin models** ⇒ at least *simple* life is **probable**.

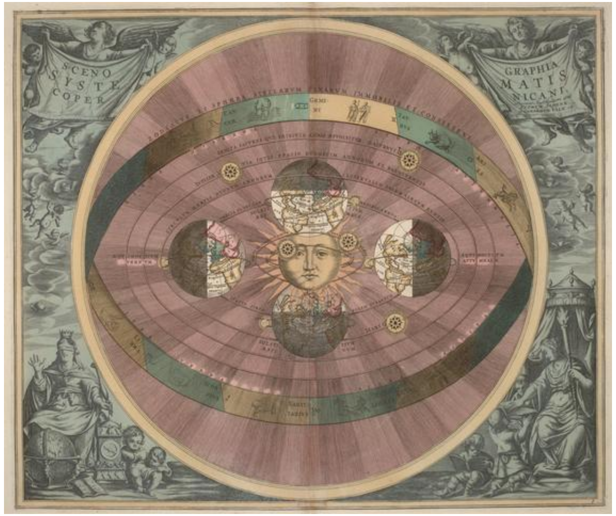
  - ✓ Indeed, if an idea like "dissipation-driven adaptation" turns out to be correct, then under the **right conditions**, life may be an **inevitable consequence** of physics.

  - ✓ If so, and since the laws of physics appear to be the same everywhere, then life should be **common** in those places that have the **right conditions**.

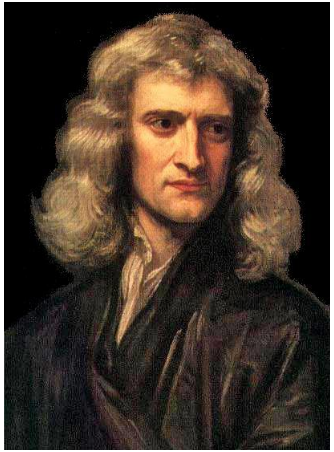
- The question “**Are We Alone**” is of ever increasing interest to scientists.

  ✓ **Why?** The discovery of life of *any* kind (or *not*) beyond the Earth would deeply and forever **change our perspective** of who we are, and what our place in the universe is. This is what science ***does***, e.g.:

  - Discovery of **heliocentrism** (Copernicus, and Newton’s “unification of heavens & Earth”);
  - Discovery of **deep time** and **deep space**;
  - Discovery of **evolution** and **genetics**;
  - Discovery of the **Big Bang** (beginning?);
  - Discovery of the **quantum nature** of the universe (freewill?), etc.

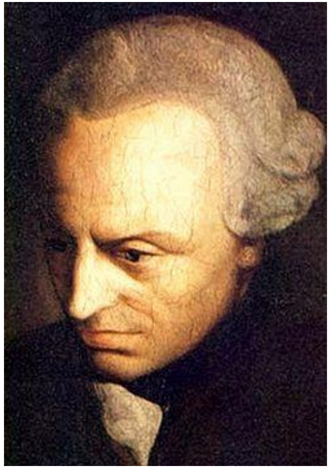


- The question “**Are We Alone**” is of ever increasing interest to scientists.
  - ✓ **Why Now?** Scientists have *always* been interested in this question, but in the last few decades this interest has **dramatically intensified**:
    - We now **know** **there are planets out there**. (Without them, ET life is unlikely.)
    - We now have much better reasons to think that **biology might be universal**.
    - We now have sufficient **technology** to begin **looking for ET life**.
  - ✓ “…the study of life in the universe [astrobiology] is one of the most rapidly growing fields of active scientific research…”—Bennett & Shostak (2012).



- With his discovery of a universal laws of **motion** ($F = ma$) and **gravitation**, Newton "unified the heavens and the Earth". However, he thought the order in our Solar System was initially imposed by God:

> "Gravity explains the motions of the planets, but it cannot explain who set the planets in motion. God governs all things and knows all that is or can be done."—Newton



- In his 1755 book, *General History of Nature and Theory of the Heavens*, the philosopher Immanuel Kant introduced his **nebular hypothesis**, attempting to explain the **origin of the order** in the Solar System.

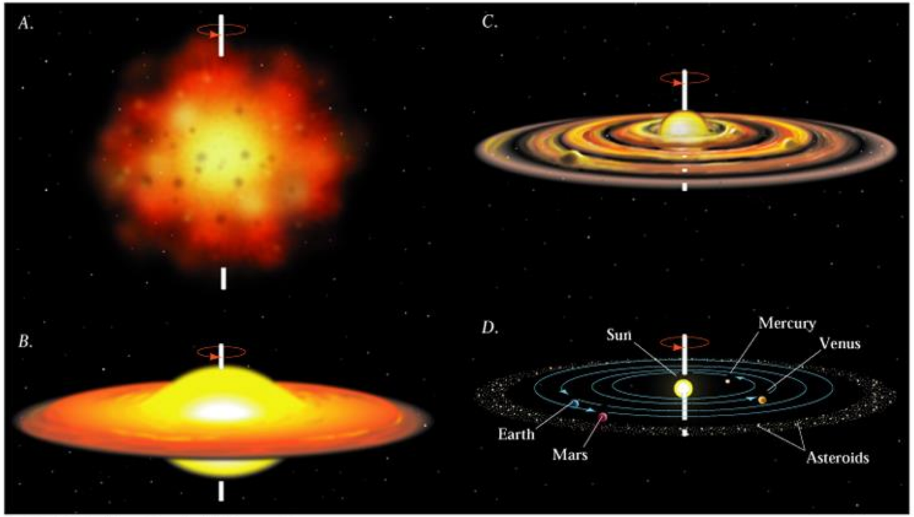
- Since then, the nebular hypothesis has been significantly developed, and provides a simple, **natural** explanation for the formation of stars and planets, not just the Solar System, but **throughout the universe**.

A. Large, relatively dense interstellar cloud of gas and dust, with small random overall rotation, begins gravitational collapse

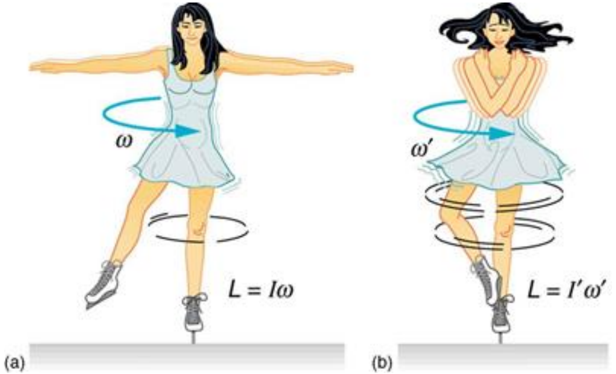
B. Gravitational energy → thermal energy → sparks fusion in protostar. Rotation speeds up & cloud flattens into protoplanetary disk

C. Electrostatic then gravitational clumping in the disk → planetesimals → planets. We now have sophisticated computer models

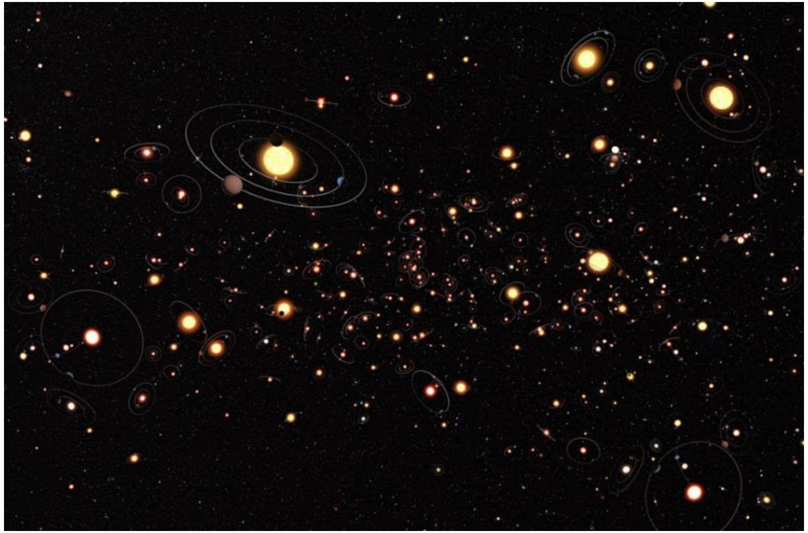
D. Rocky planets form in warm region near star (like Earth); icy & gaseous planets form in cold region far from star (like Jupiter).

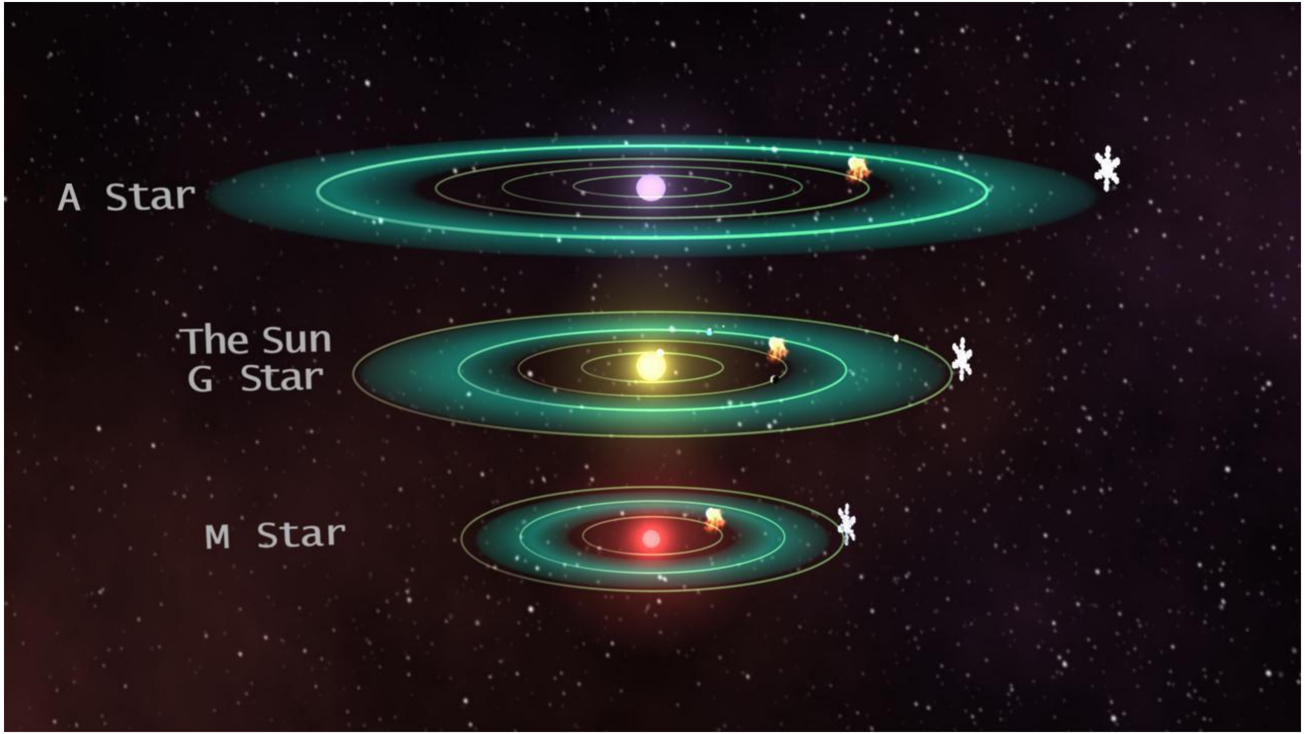





- So scientists expected **virtually all** stars to have planets, but before 1988 the number of **known** *exoplanets* (planets orbiting other stars) was **zero**.
- Since 1988 the number of **known** exoplanets has risen to **more than 2000**. Extrapolating the numbers, **our galaxy contains over 10 billion Earth-like planets orbiting Sun-like stars in the "habitable zone" (i.e., would support liquid water)**!



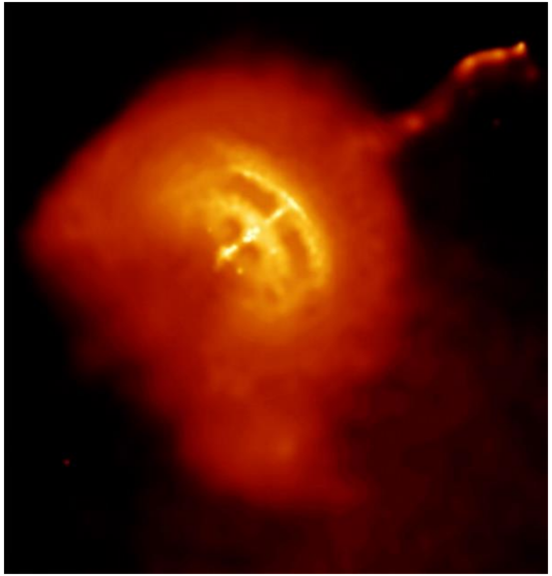



"habitable zone" (not too hot, not too cold → liquid water)

- First discoveries:
  - 1988: Canadian Bruce Campbell & team tentatively discovered a planet in the Gamma Cephei **binary star** system (like Luke Skywalker’s planet Tatooine in Star Wars)

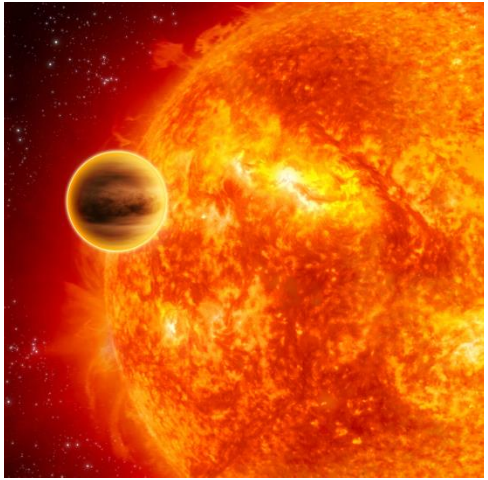
- First discoveries:

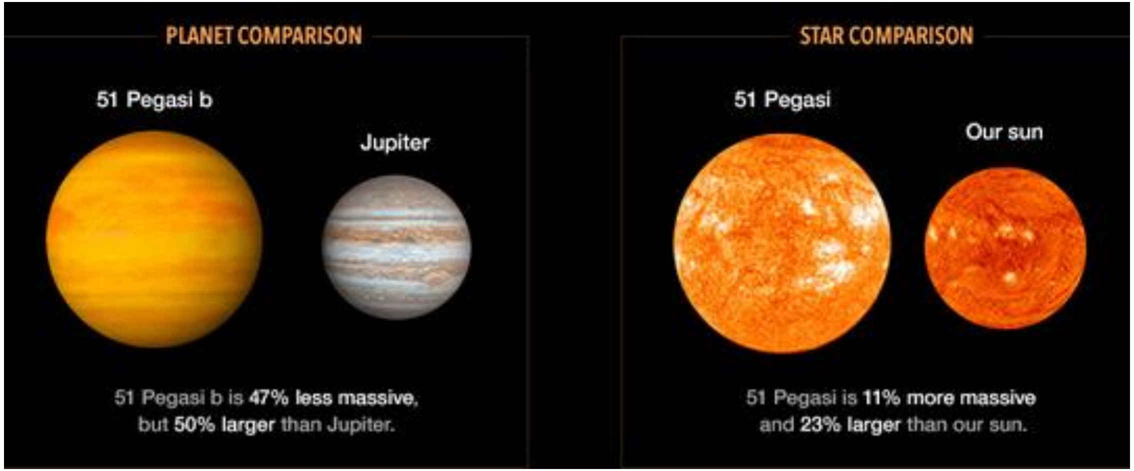
    - 1992: Aleksander Wolszczan and Canadian Dale Frail discovered two planets around **pulsar** PSR1257+12 (rapidly spinning, magnetized neutron star—life not likely!)



- First discoveries:

  - 1995: First exoplanet orbiting a ***main-sequence* star**, 51 Pegasi b (a Sun-like star 51 light years from Earth). Named “Bellerophon” from Greek mythology. At least half the mass of Jupiter, and orbits very close to the star → temperature around 1000 °C. Such “hot Jupiters” challenged existing theories of planet formation → “migration theory”





*Main-sequence* stars: Stably fusing H to He.

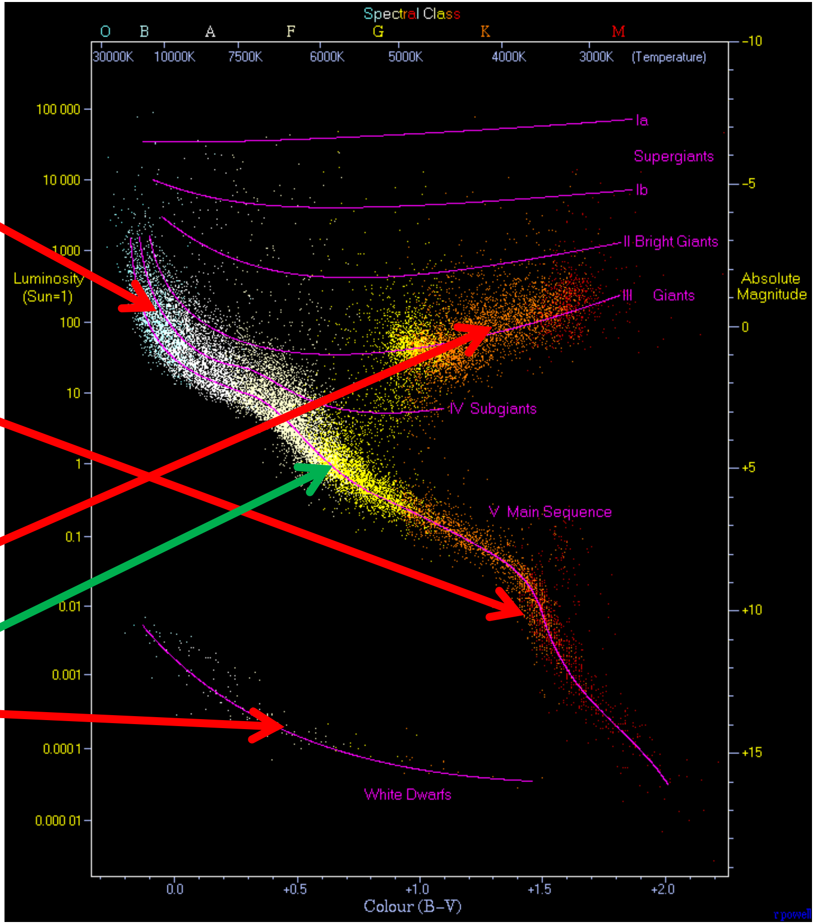
**Blue giants**: Bright & high mass → supernova. Least abundant, and too short-lived for life to likely evolve.

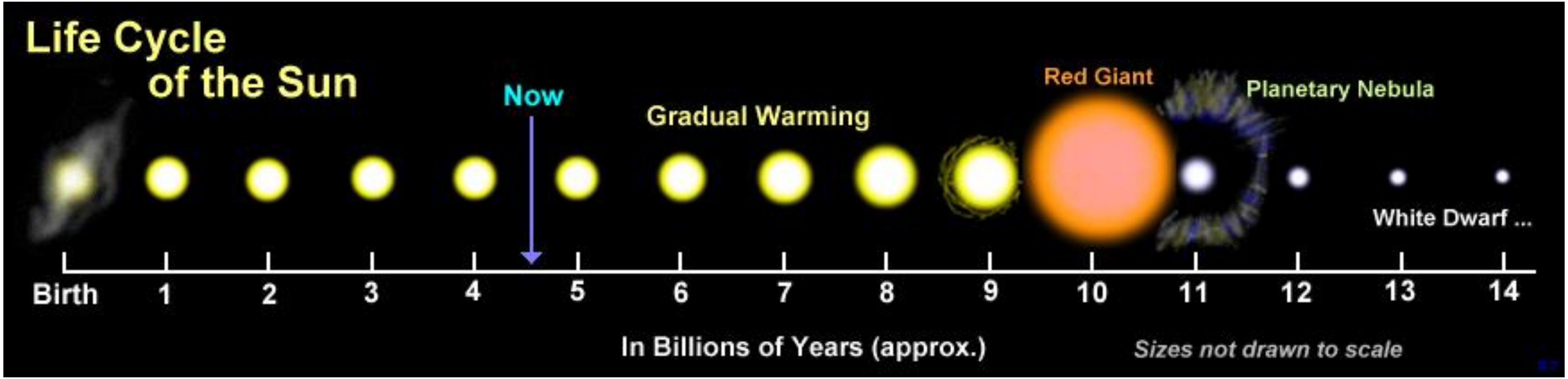
**Red dwarfs**: Dim & low mass → longest-lived and most abundant, but brightness variable & planet must be close → tidal heating and tidal locking. Feasibility for life is currently being debated…

**Giants**: Stars in transition state or death throes.

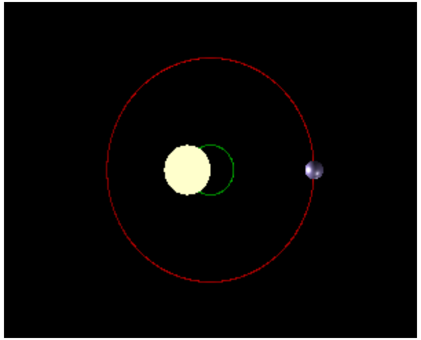
**White dwarfs**: End state of 97% of stars (including Sun); heavier stars end as **neutron star** or **black hole**

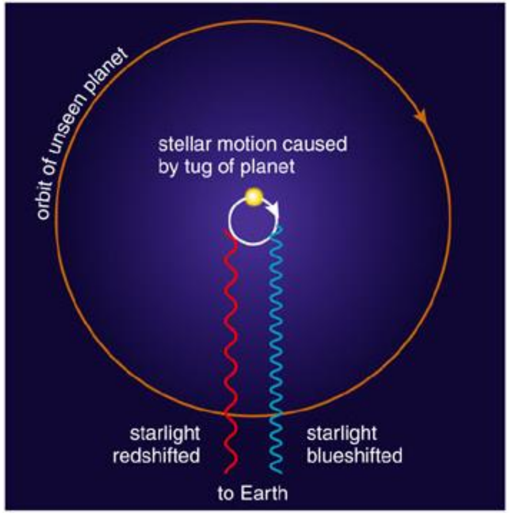
Sun-like stars are "just right"!

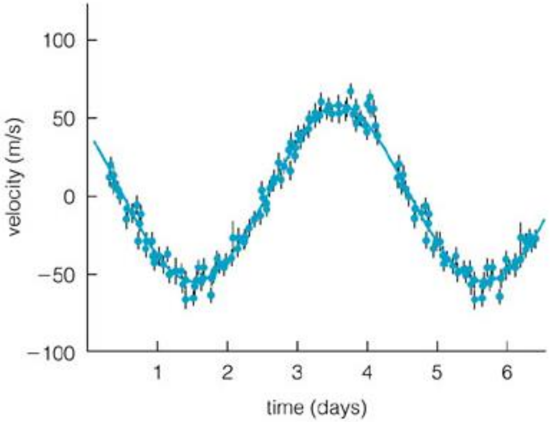


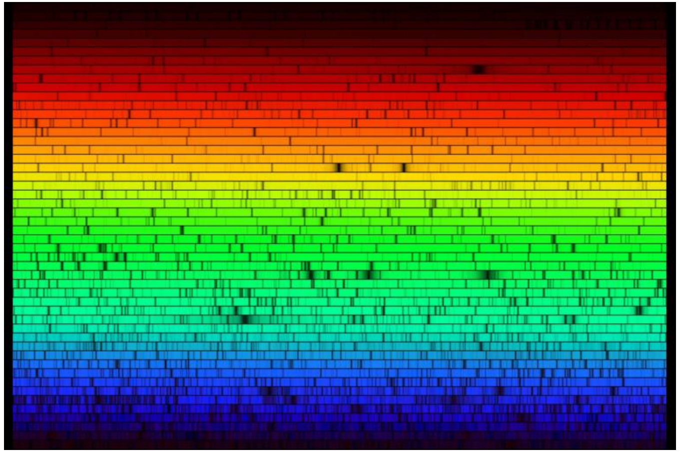

Life Cycle
of the Sun
Now
Gradual Warming
Red Giant
Planetary Nebula
White Dwarf ...
Birth
1
2
3
4
5
6
7
8
9
10
11
12
13
14
In Billions of Years (approx.)
Sizes not drawn to scale

- Exoplanet **detection** methods:
  - **Doppler method**: Planet and star orbit **center of mass** → star *wobbles* → detect periodic shift in *spectrum* of starlight. Gives **mass** of planet (and period → orbital distance by Kepler's third law); best for **high mass planets close to their star**.



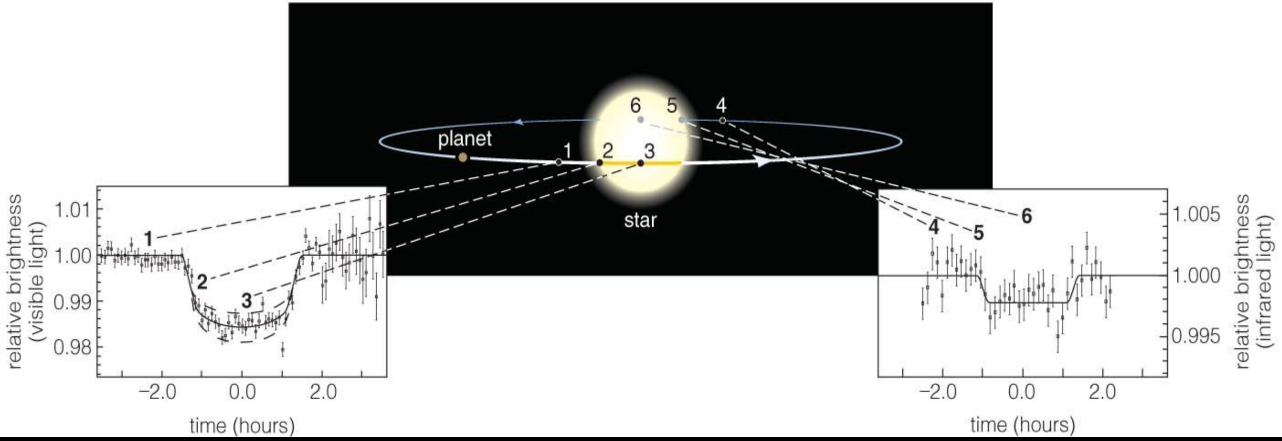


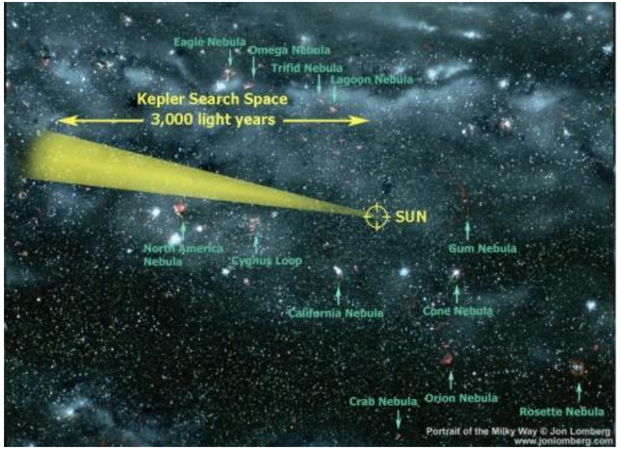
- Exoplanet **detection** methods:

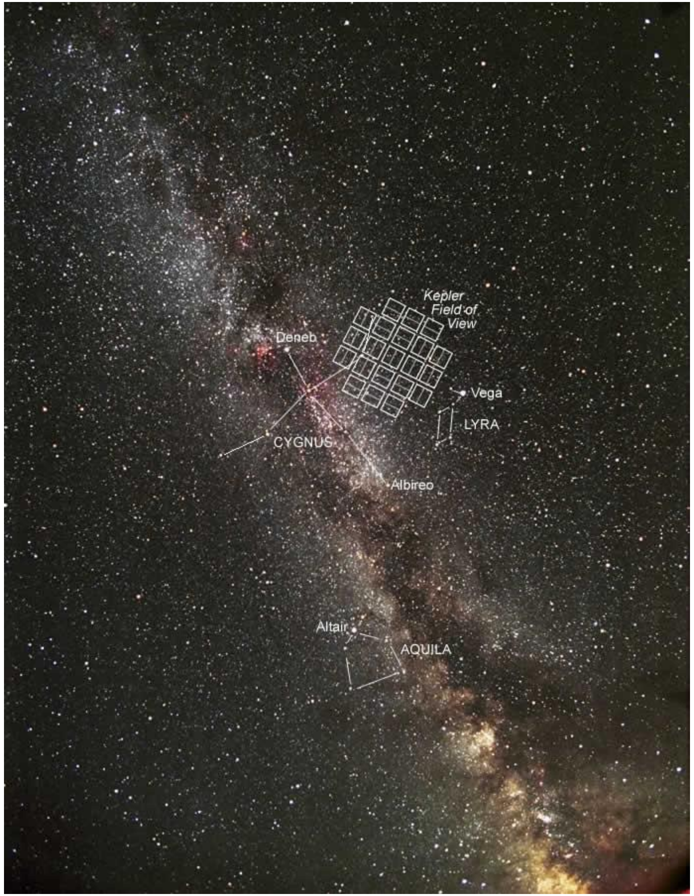
  - **Transit method**: Requires **edge-on** view (probability about 1 in 200)
    - Planet in front of star → reduced visible light → planet **size**
    - (and period → orbital distance by Kepler’s third law)
    - Planet behind star → reduced infrared light → planet **temperature**
    - Can also get some info about **chemicals in the atmosphere**!
    - Can detect also **small mass** (e.g., Earth-like) planets



- Exoplanet **detection** methods:

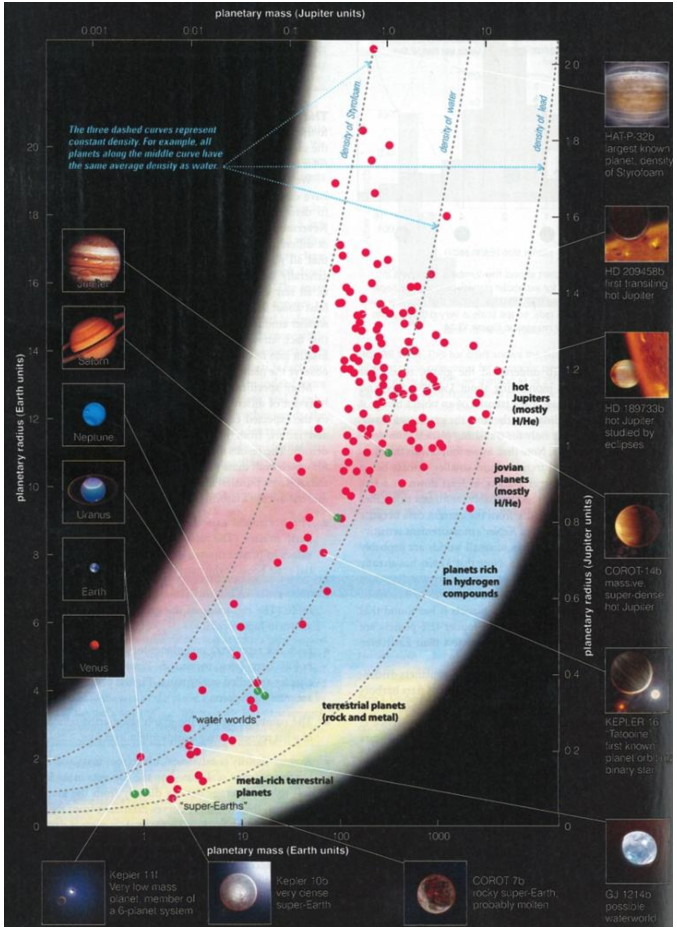
    - **Kepler mission** (transit method): 145,000 main-sequence stars, imaged every 30 minutes to detect brightness changes. As of July 2015, candidate planets = 4,696; **confirmed planets = 1030**. (Added to ≈ 1000 from other planet searches.)



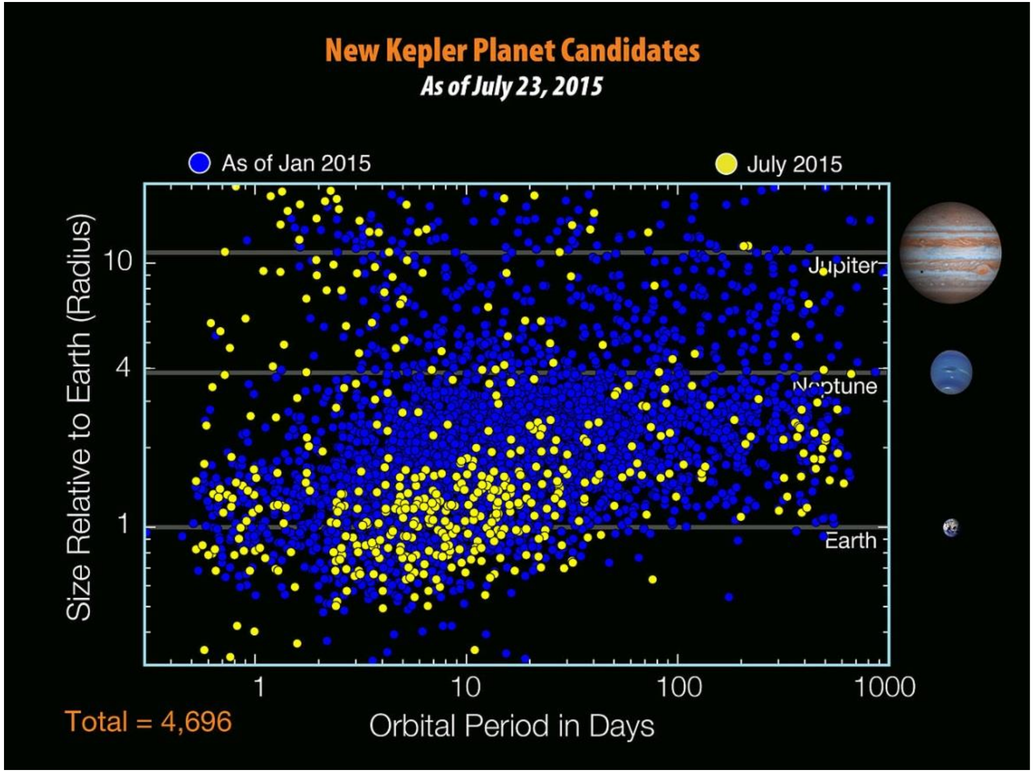



# Exoplanets

- Exoplanet **detection** methods:
  - Combine **both** methods:
    - ✓ Planet **mass** from Doppler
    - ✓ Planet **size** from transit
    - ✓ Gives planet average **density**:
      - **rocky?**
      - **gaseous?**
      - **other?**
  - Lots of **surprises** & **mysteries**!



- “Tons” of **data** (search for ET is now **real**!)



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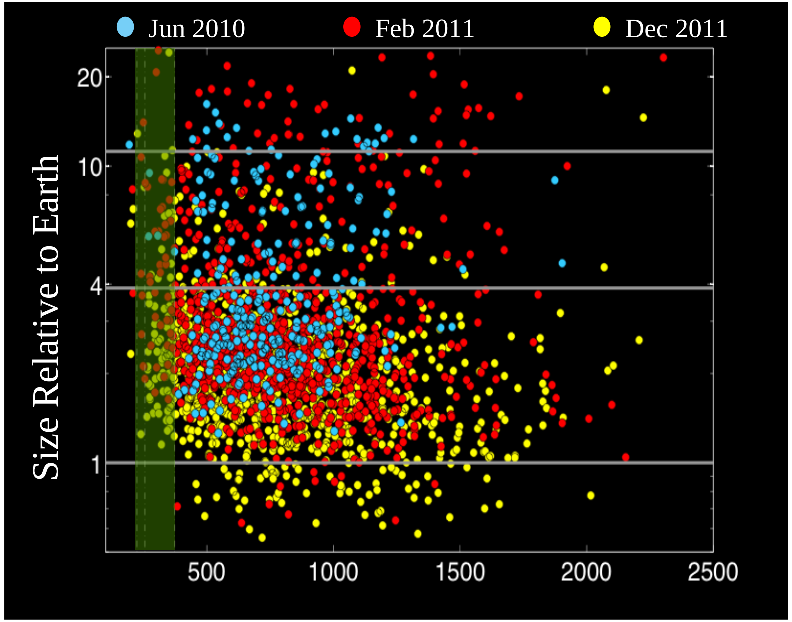
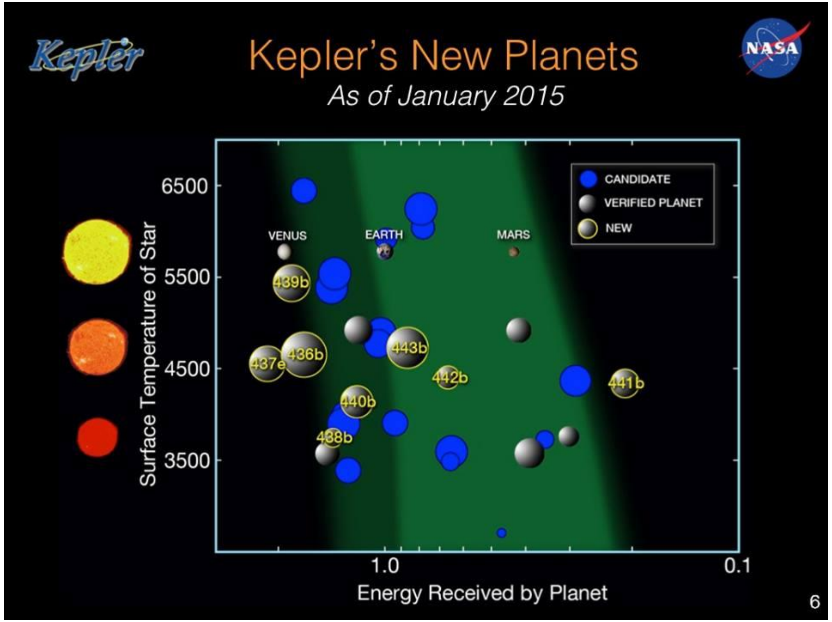


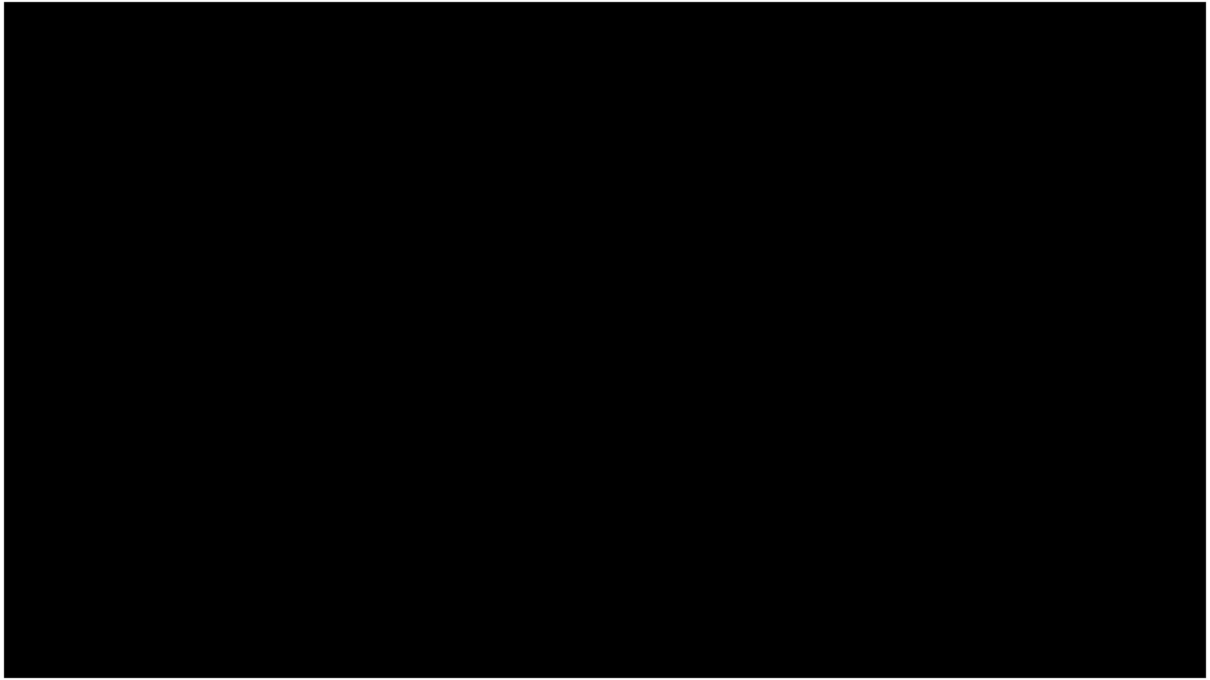

Equilibrium Temperature [K]

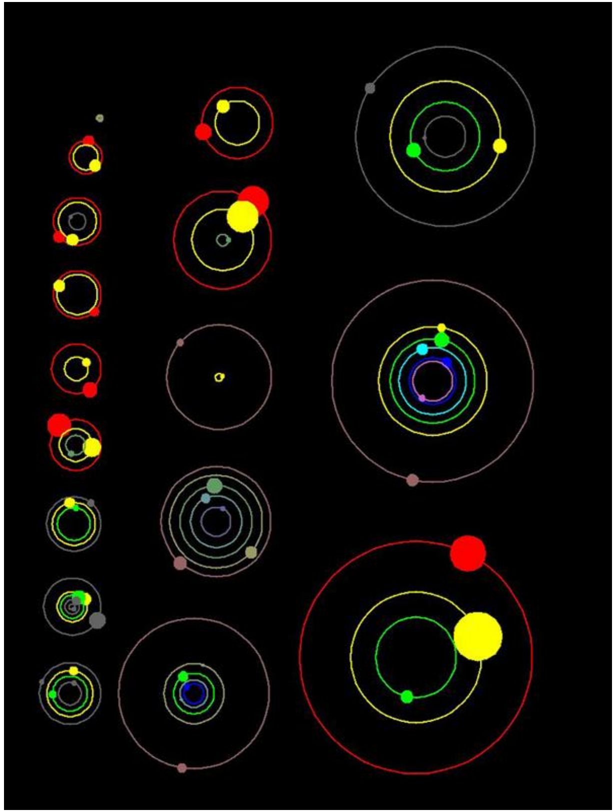



Planet Temperature (Green = “Habitable”)

- “Tons” of **data** (search for ET is now **real**!)

- Amazing variety of planetary systems. Super cool link.

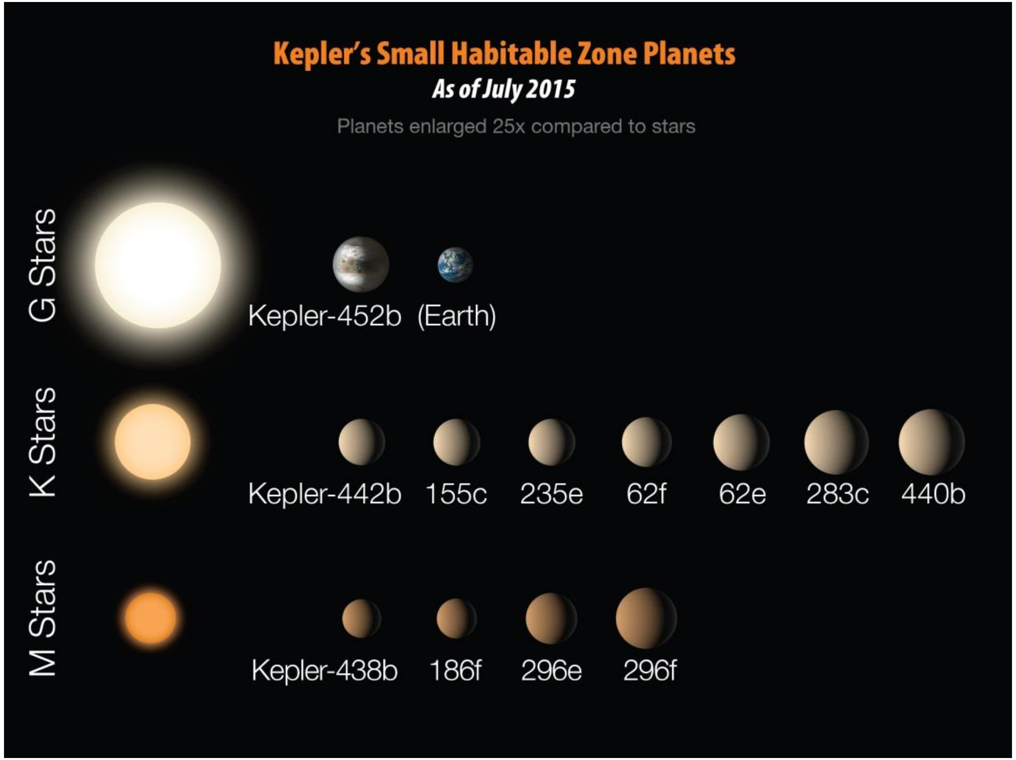




- Latest on search for **habitable** planets:

    - Twelve exoplanet discoveries from Kepler that are **less than twice the size of Earth** and reside in the **habitable zone** of their host star. G stars are **Sun-like**; K and M are smaller and cooler.

    - (The sizes of the planets are enlarged by 25X compared to the stars. The Earth is shown for reference.)



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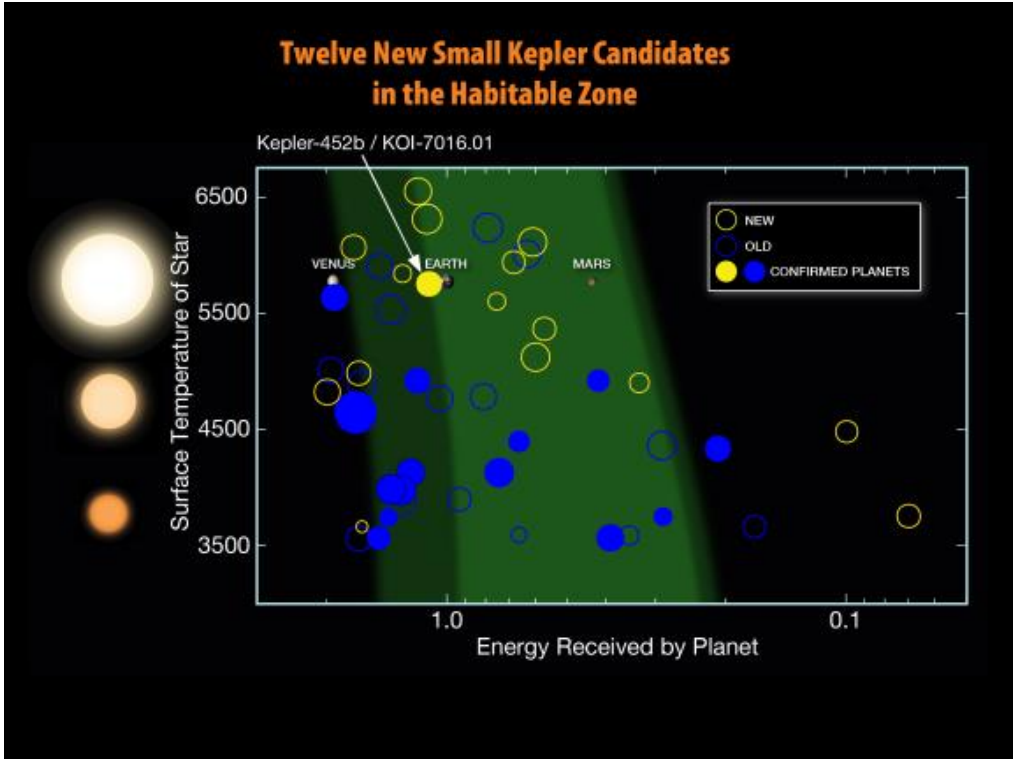
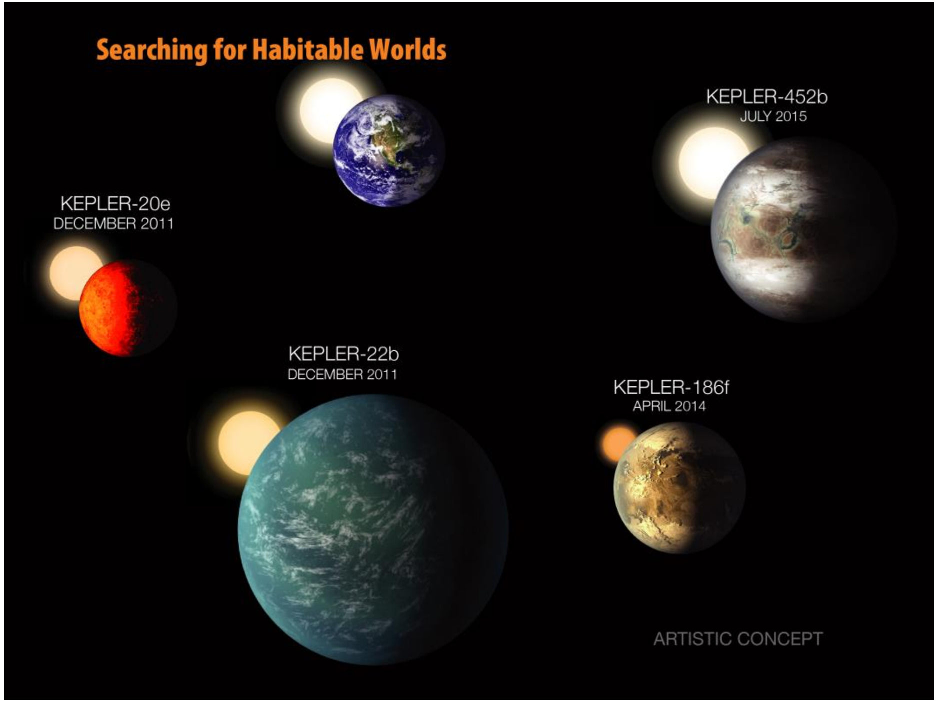


- Latest on search for **habitable** planets:

- Dec 2011: Kepler-20e, first planet **smaller than Earth**, orbits a star slightly cooler and smaller than our Sun every six days. But it is scorching hot and unable to maintain an atmosphere or a liquid water ocean.

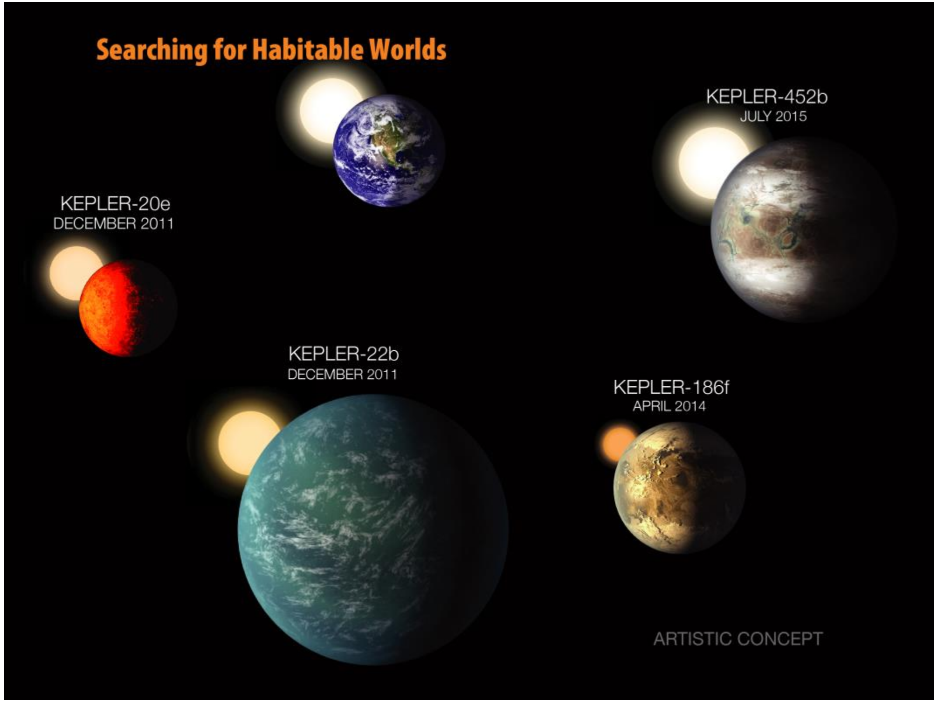
- Dec 2011: Kepler-22b first planet in the **habitable zone** of a sun-like star, but is more than twice the size of Earth and unlikely to have a solid surface ("water world"?).



- Latest on search for **habitable** planets:

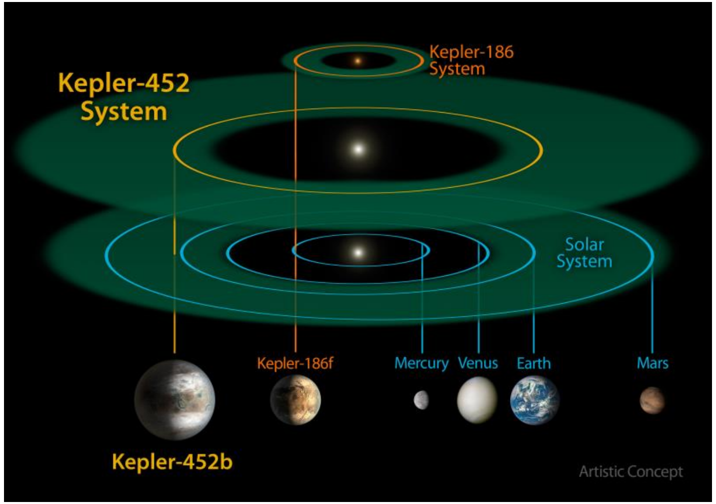
- Apr 2014: Kepler-186f is the **first Earth-size planet** found in the **habitable zone** of a small, cool M dwarf (red dwarf star) about half the size and mass of our sun.

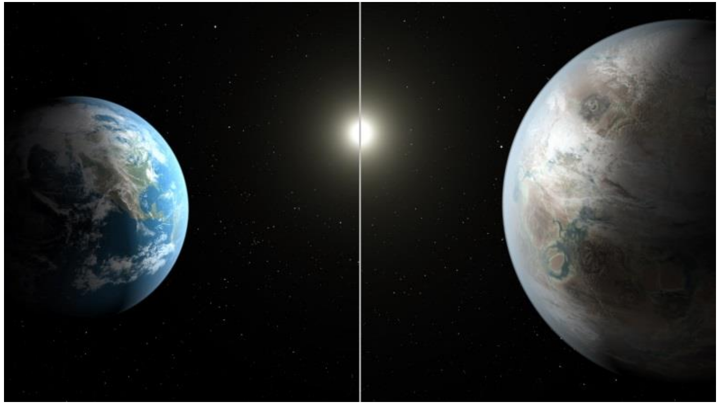
- **July 2015**: Kepler-452b is the first **near-Earth-size world** to be found in the **habitable zone** of a star that is **similar to our Sun**. (All three!)



## Kepler-452b:

- Found 1,400 light-years away in the constellation Cygnus, 452b is the first **near-Earth-size** planet in the **habitable zone** around a **Sun-like star**.
- 385-day orbit. Mass & composition not yet known, but small size suggests likely a **rocky** planet.
- 60% larger diameter than Earth ("**super-Earth**"), 6 billion years old → "bigger, older cousin" to Earth.

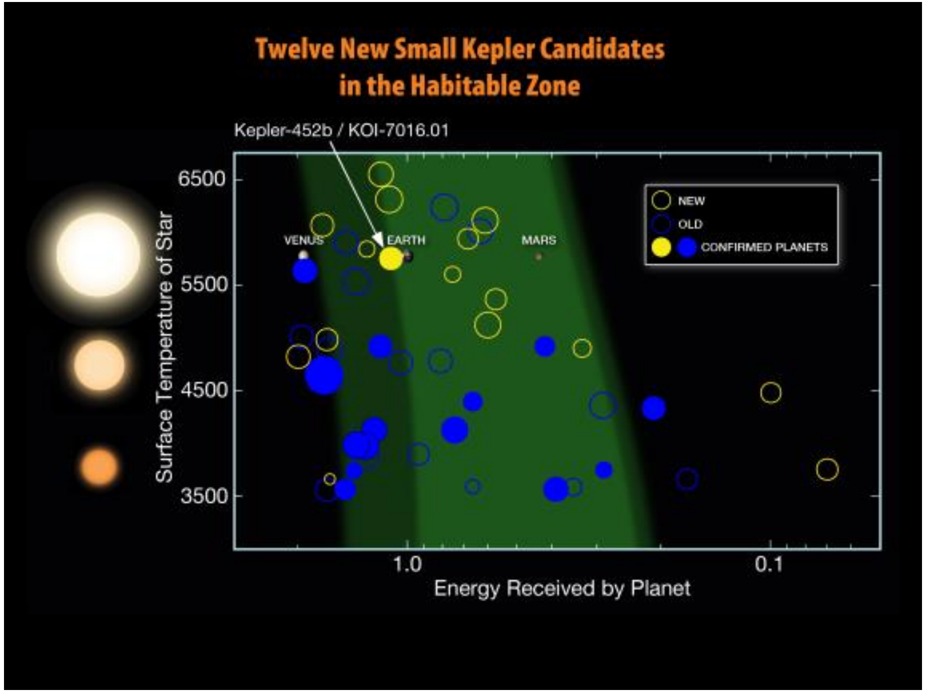


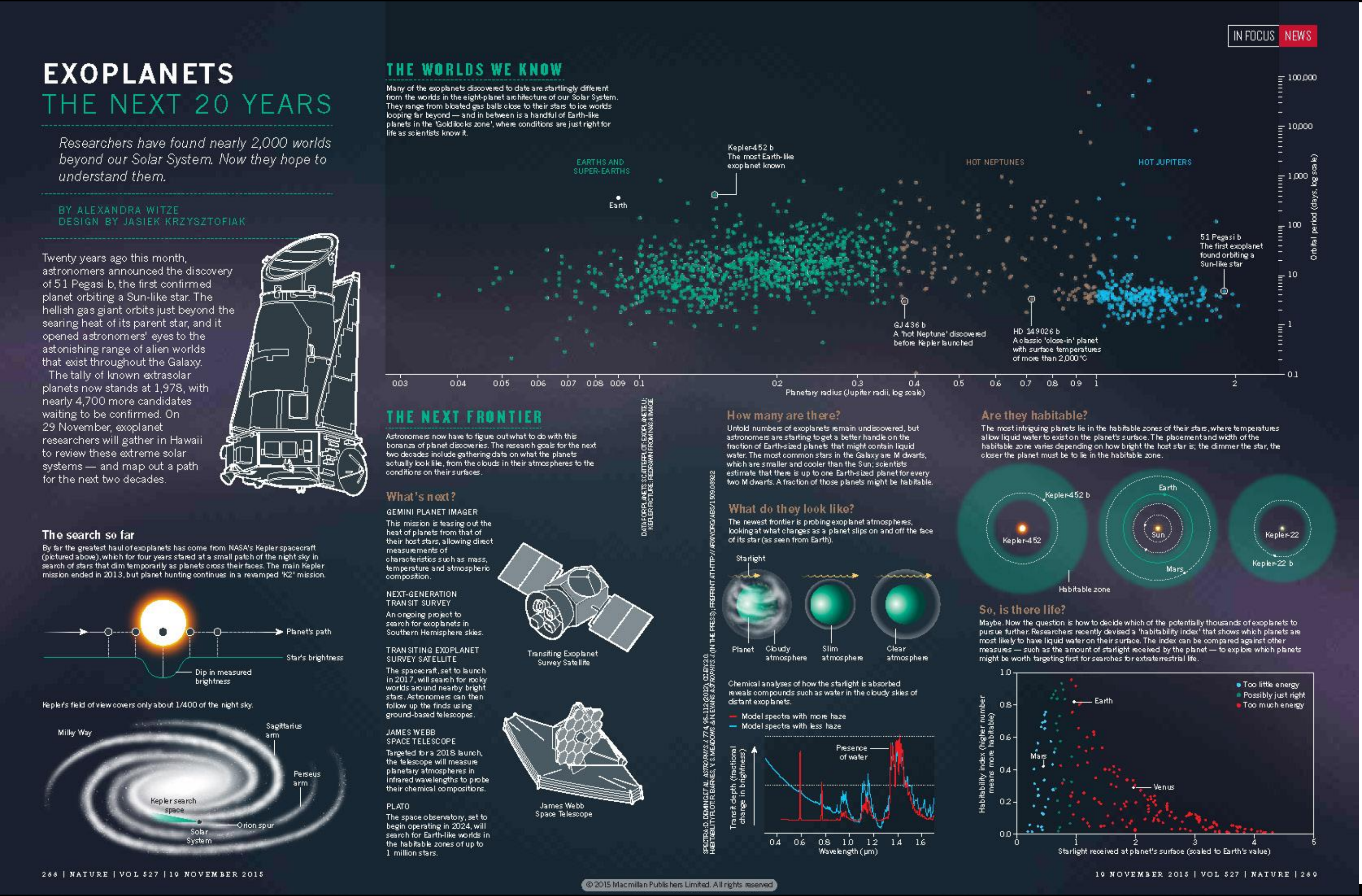



**Kepler-452b:**

"It’s awe-inspiring to consider that this planet has spent 6 billion years in the habitable zone of its star; longer than Earth. That’s substantial opportunity for life to arise, should all the necessary ingredients and conditions for life exist on this planet.”

—Jon Jenkins, Kepler data analysis lead at NASA's Ames Research Center in Moffett Field, California, who led the team that discovered Kepler-452b.




IN FOCUS NEWS

EXOPLANETS
THE NEXT 20 YEARS

*Researchers have found nearly 2,000 worlds beyond our Solar System. Now they hope to understand them.*

BY ALEXANDRA WITZE
DESIGN BY JASIEK KRZYSZTOFIAK

Twenty years ago this month, astronomers announced the discovery of 51 Pegasi b, the first confirmed planet orbiting a Sun-like star. The hellish gas giant orbits just beyond the searing heat of its parent star, and it opened astronomers' eyes to the astonishing range of alien worlds that exist throughout the Galaxy.

The tally of known extrasolar planets now stands at 1,978, with nearly 4,700 more candidates waiting to be confirmed. On 29 November, exoplanet researchers will gather in Hawaii to review these extreme solar systems — and map out a path for the next two decades.

**The search so far**

By far the greatest haul of exoplanets has come from NASA's Kepler spacecraft (pictured above), which for four years stared at a small patch of the night sky in search of stars that dim temporarily as planets cross their faces. The main Kepler mission ended in 2013, but planet hunting continues in a revamped 'K2' mission.



Kepler's field of view covers only about 1/400 of the night sky.



**THE WORLDS WE KNOW**

Many of the exoplanets discovered to date are startlingly different from the worlds in the eight-planet architecture of our Solar System. They range from bloated gas balls close to their stars to ice worlds looping far beyond — and in between is a handful of Earth-like planets in the 'Goldilocks zone', where conditions are just right for life as scientists know it.



**THE NEXT FRONTIER**

Astronomers now have to figure out what to do with this bonanza of planet discoveries. The research goals for the next two decades include gathering data on what the planets actually look like, from the clouds in their atmospheres to the conditions on their surfaces.

**What's next?**

GEMINI PLANET IMAGER
This mission is teasing out the heat of planets from that of their host stars, allowing direct measurements of characteristics such as mass, temperature and atmospheric composition.

NEXT-GENERATION TRANSIT SURVEY
An ongoing project to search for exoplanets in Southern Hemisphere skies.

TRANSITING EXOPLANET SURVEY SATELLITE
The spacecraft, set to launch in 2017, will search for rocky worlds around nearby bright stars. Astronomers can then follow up the finds using ground-based telescopes.

JAMES WEBB SPACE TELESCOPE
Targeted for a 2018 launch, the telescope will measure planetary atmospheres in infrared wavelengths to probe their chemical compositions.

PLATO
The space observatory, set to begin operating in 2024, will search for Earth-like worlds in the habitable zones of up to 1 million stars.



**How many are there?**

Untold numbers of exoplanets remain undiscovered, but astronomers are starting to get a better handle on the fraction of Earth-sized planets that might contain liquid water. The most common stars in the Galaxy are M dwarfs, which are smaller and cooler than the Sun; scientists estimate that there is up to one Earth-sized planet for every two M dwarfs. A fraction of those planets might be habitable.

**What do they look like?**

The newest frontier is probing exoplanet atmospheres, looking at what changes as a planet slips on and off the face of its star (as seen from Earth).



Chemical analyses of how the starlight is absorbed reveals compounds such as water in the cloudy skies of distant exoplanets.



**Are they habitable?**

The most intriguing planets lie in the habitable zones of their stars, where temperatures allow liquid water to exist on the planet's surface. The placement and width of the habitable zone varies depending on how bright the host star is; the dimmer the star, the closer the planet must be to lie in the habitable zone.



**So, is there life?**

Maybe. Now the question is how to decide which of the potentially thousands of exoplanets to pursue further. Researchers recently devised a 'habitability index' that shows which planets are most likely to have liquid water on their surface. The index can be compared against other measures — such as the amount of starlight received by the planet — to explore which planets might be worth targeting first for searches for extraterrestrial life.



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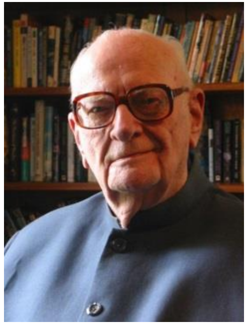
[Nature Infographic](Nature Infographic)

Exoplanet exploration is a **rapidly-developing field**.
See: intriguing exoplanets, latest news, future exoplanets, etc.

- **Brian Cox:** "Think about this:
  - There are **billions** of habitable Earth-like worlds out there in the galaxy, and yet **we are alone**.
  - There are **billions** of habitable Earth-like worlds out there in the galaxy, and **we are not alone**. There are others.
  - One of these statements is true…"

- **Arthur C. Clarke:**
  - "Sometimes I think we're alone in the universe, and sometimes I think we're not. In either case the idea is quite staggering."



- The question "**Are We Alone**" is of ever increasing interest to scientists.

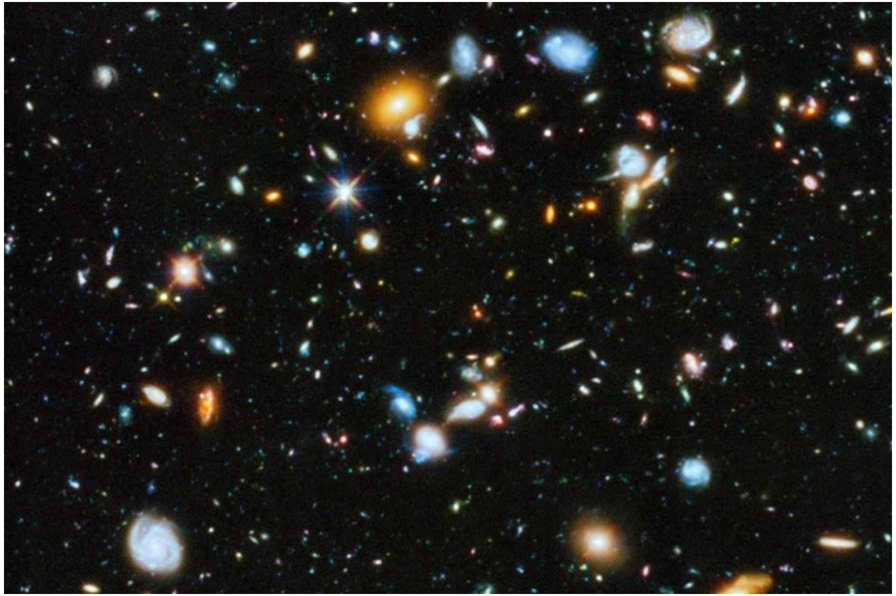
  - ✓ **Why Now?** Scientists have *always* been interested in this question, but in the last few decades this interest has **dramatically intensified**:

    - We now **<u>know</u> there are planets out there**. (Without them, ET life is unlikely.)
    - We now have much better reasons to think that **biology might be universal**.
    - We now have sufficient **technology** to begin **looking for life**.

  - ✓ "…the study of life in the universe [astrobiology] is one of the most rapidly growing fields of active scientific research…"—Bennett & Shostak (2012).

- <u>Reason 1</u>: Everywhere we have looked in the universe, the **laws of physics are the same**.

  - "Everywhere" means in both **space** and **time**: all across the vast space of the observable universe, and back to almost the beginning of time:



Similar galaxies sprinkled throughout space

Same chemicals in the stars, gas, and dust

Same stellar processes (e.g., supernovae)

Same gravity (e.g., orbital motions)

Same electromagnetism (e.g., light)

Same thermodynamics (e.g., CMB)

Laws of physics are being tested at the LHC between $10^{-12}$-$10^{-6}$ seconds after Big Bang!

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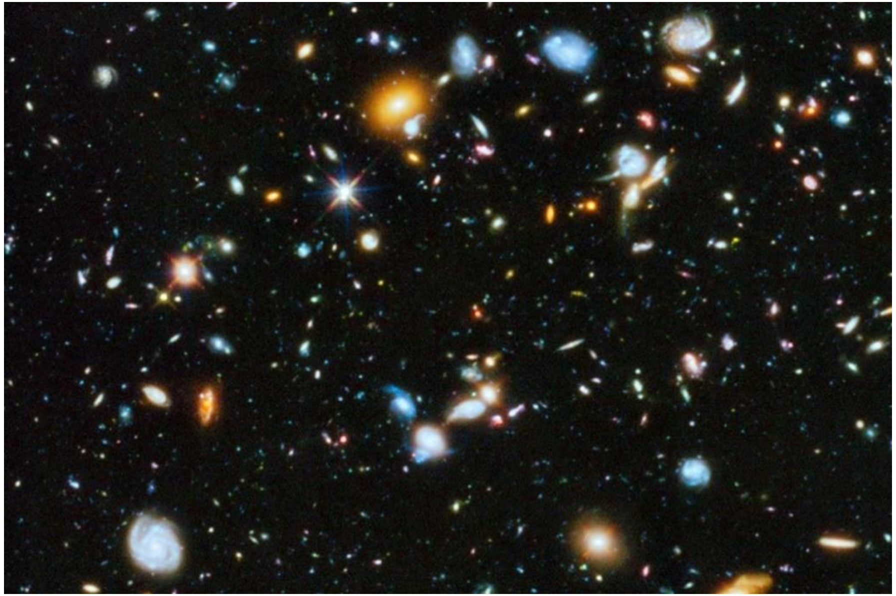
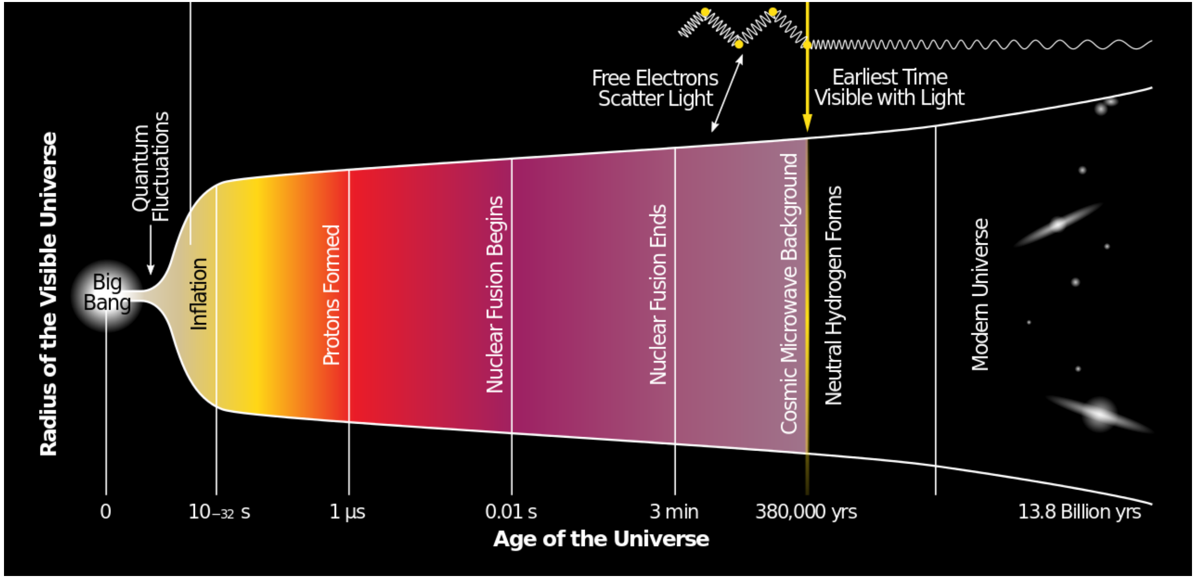


Newton's "unification of the heavens and the Earth" has been **vastly** extended:

It appears that ***all*** the laws of physics we discover here on Earth (e.g., at the LHC) hold **throughout the universe** (not just the laws of motion and gravity in the Solar System)

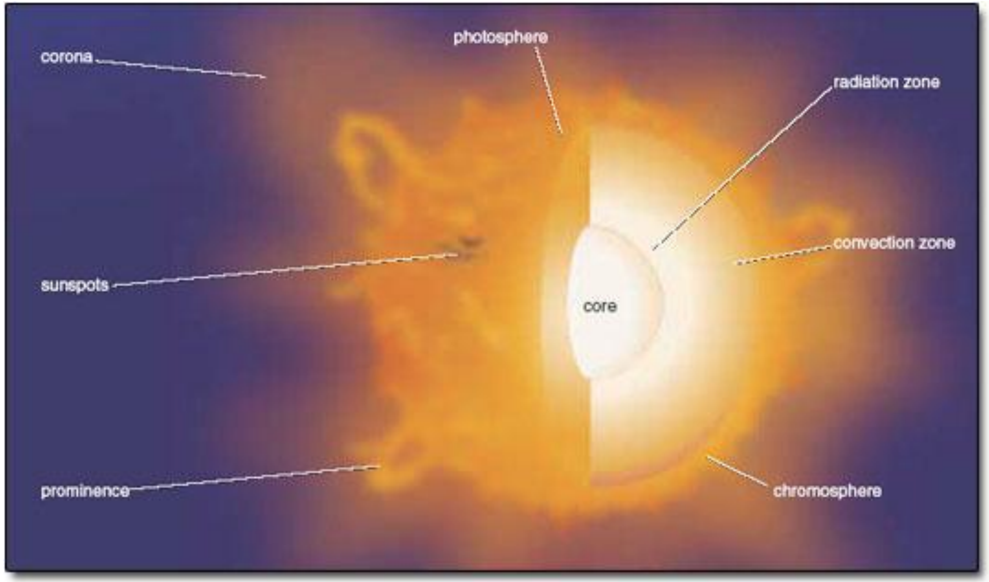
- Reason 1: Everywhere we have looked in the universe, the **laws of physics are the same**.
  - Biology is rooted in chemistry
  - Chemistry is rooted in physics
  - Thus, biology is ultimately rooted in physics. It is ultimately the laws of physics that allow (or disallow) life to emerge in a universe. (E.g.: Even **tiny** changes in certain particle masses or interaction strengths would result in **very** different universes, most of which **could not have life**. More later: "Fine Tuning" & "Anthropic Principle")
  - Thus, if the physics of our universe allowed life to emerge on the Earth, there is no reason to believe that, under similar conditions, life could not emerge on other Earth-like exoplanets orbiting Sun-like stars in their habitable zone.

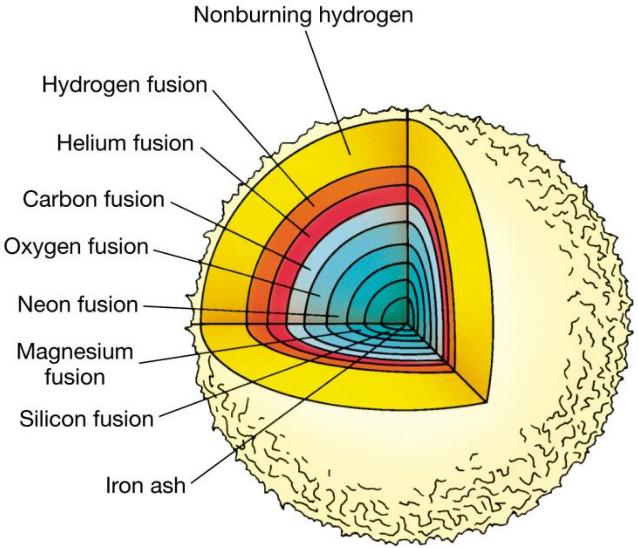
- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.
  - The Big Bang created mainly **hydrogen** (75%) and **helium** (25%) through thermonuclear fusion, within the first three minutes:



- <u>Reason 2</u>: **Organic molecules** form easily and are widespread throughout the universe.

  - The heavier elements up to **iron** (**carbon**, **oxygen**, **silicon**, etc., plus more helium) are forged by thermonuclear fusion in the cores of stars:



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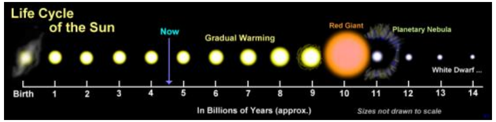
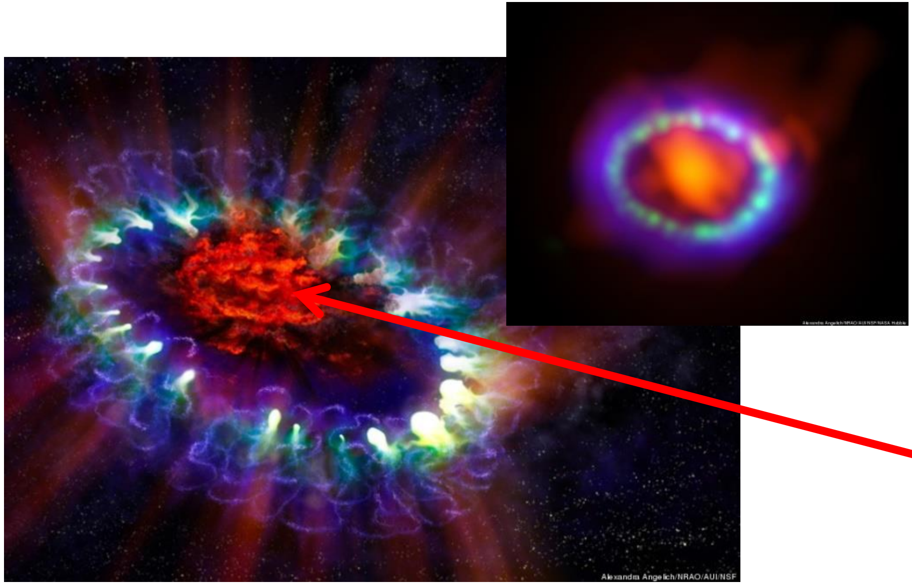



All low-to-medium mass stars (including the Sun) enter a **red giant** phase late in life. Strong stellar winds and "thermal pulses" dredge up the **carbon** and **oxygen** in the core, sloughing off 50-70% of the star's mass. About 1 in 6 are **carbon stars**, that are especially rich sources of sooty, **carbon compounds** (carbon-rich dust like graphite). Article on Image.

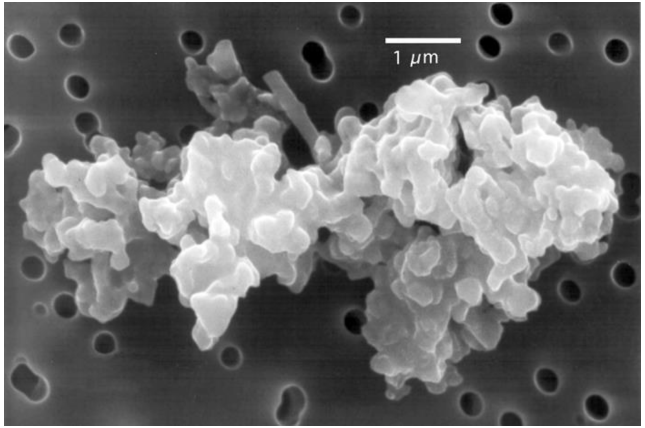
This dust significantly enriches the mainly H & He interstellar medium, and becomes part of future generations of stars and planets.

- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.
  - Elements heavier than **iron** (e.g., **uranium**) are formed in shockwave-induced nuclear fusion and rapid neutron capture in stellar supernovae:

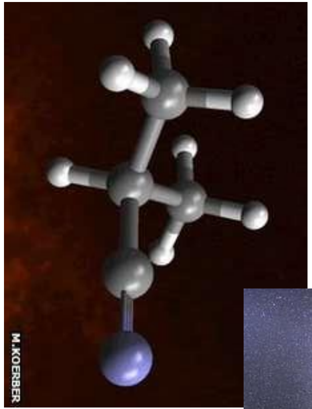



**Supernova 1987A** in the Large Magellanic Cloud: First direct observation of the long-held hypothesis that supernovas are a source of interstellar dust.

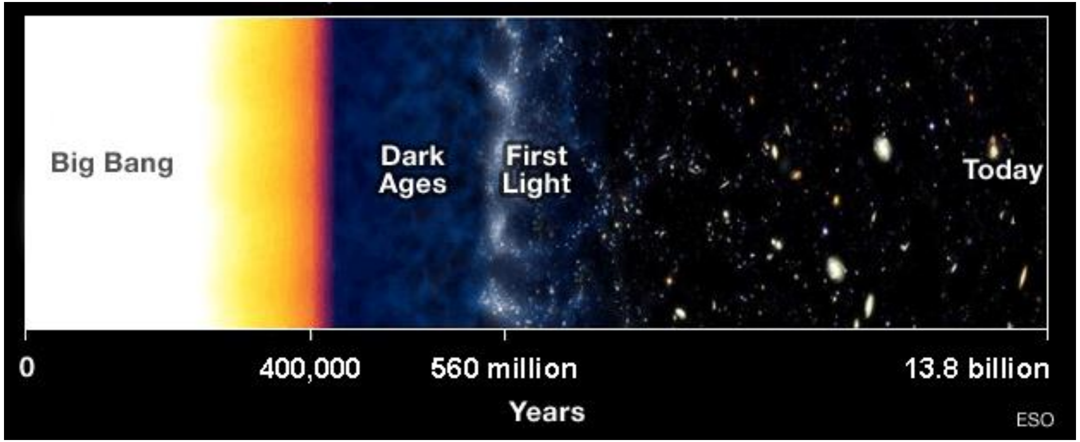
- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.
  - **Organic molecules** form in dusty interstellar clouds and rain down on planets
    - ✓ This was a **surprise**. No one expected chemical reactions in cold, diffuse gasses.
    - ✓ One idea: Nearby stars provide energy for chemical reactions on the surface of "**cosmic dust**" grains (tiny pieces of solid particles composed mainly of carbon, silicon and oxygen).
    - ✓ Another idea: Cosmic rays ionize atoms, and ions are electrostatically attracted to each other, forming more complex molecules.



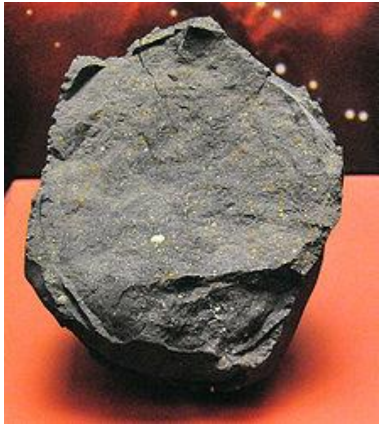
- <u>Reason 2</u>: **Organic molecules** form easily and are widespread throughout the universe.
  - **Organic molecules** form in dusty interstellar clouds and rain down on planets
    - ✓ **Early discoveries**: formaldehyde, methanol, and vinyl alcohol (discovered in 2001)
    - ✓ **Most complex to date** (2014): Iso-proply cyanide:
      - Branched carbon structure [like an amino acid] is closer to the complex organic molecules of life than any previous finding from interstellar space.
      - "So far we do not have the sensitivity to detect the signals from [amino acids] … **The interstellar chemistry seems to be able to form these amino acids but at the moment we lack the evidence**."




- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.
    - **Organic molecules** form in dusty interstellar clouds and rain down on planets
        - ✓ Avi Loeb (2014): has even suggested that the chemistry of life may have begun shortly after the Big Bang, during a "**habitable epoch**" when the universe was only 10-17 million years old (and there weren't any stars yet—a time called the *Dark Ages*).
        - ✓ News article.
        - ✓ Journal article.



- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.
  - **Organic molecules** form in dusty interstellar clouds and rain down on planets
    - ✓ The organic molecules (possibly including amino acids) make their way into **meteorites**, which rain down on planets.
    - ✓ Example: Murchison meteorite contains **common amino acids** such as glycine, alanine and glutamic acid as well as unusual ones like isovaline and pseudoleucine.
    - ✓ A 2010 analysis identified 14,000 molecular compounds including **70 amino acids**, with possibly **millions** of distinct organic compounds.
    - ✓ The quantity of organics from the Late Heavy Bombardment may be **comparable** to those produced by terrestrial sources.

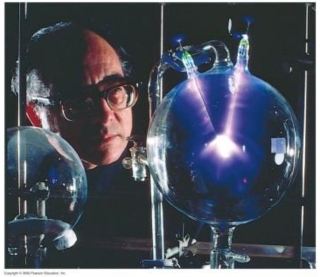


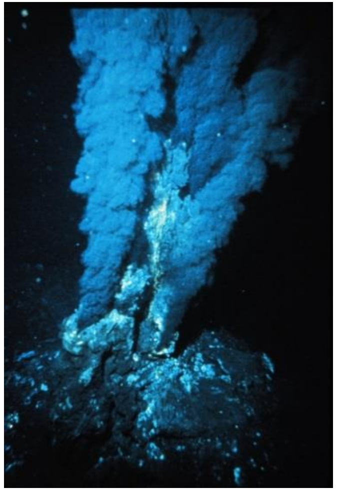
- Reason 2: **Organic molecules** form easily and are widespread throughout the universe.

  - **Organic molecules** are created on Earth:

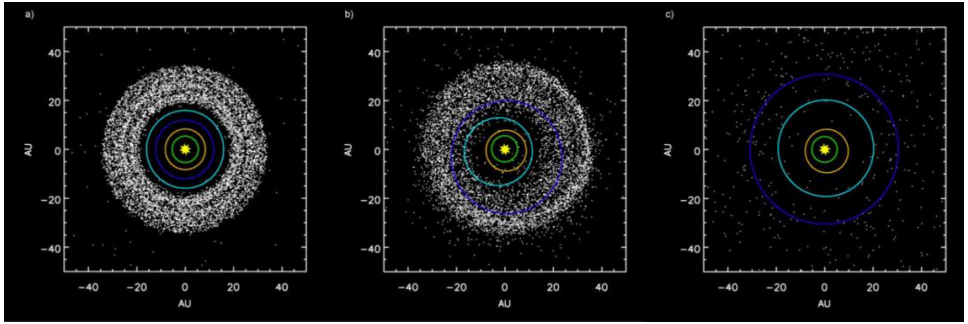
    - ✓ **Energy sources**: Impact shocks, volcanic activity, UV light, lightning, etc. Recall famous Miller-Urey experiment.

    - ✓ **In deep-sea hydrothermal vents**. Everett Shock (NASA astrobiology): "there is an enormous thermodynamic drive to form organic compounds, as seawater and hydrothermal fluids, which are far from equilibrium, mix and move towards a more stable state.” The drive is maximised at around 100–150 °C, precisely the temperatures at which the hyperthermophilic bacteria and thermoacidophilic archaea have been found, at the base of the phylogenetic tree of life closest to the Last Universal Common Ancestor…



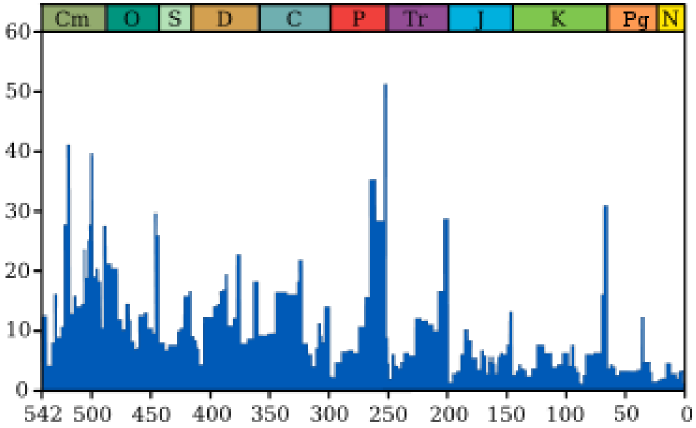


- Reason 3: Life on Earth arose **almost immediately** after the "right conditions" emerged.
    - The Late Heavy Bombardment ended about 3.8 BYA, and life emerged almost immediately after this (fossilized stromatolites date back at least to 3.5 BYA).




    - This suggests the transition from chemistry to biology is **not especially difficult**, and quite possibly life would emerge just as quickly on other worlds in similar conditions.
    - Remember: We have increasingly **plausible origins** scenarios for life on Earth: "exceedingly improbable" has shifted to "not unlikely", to possibly even "inevitable".

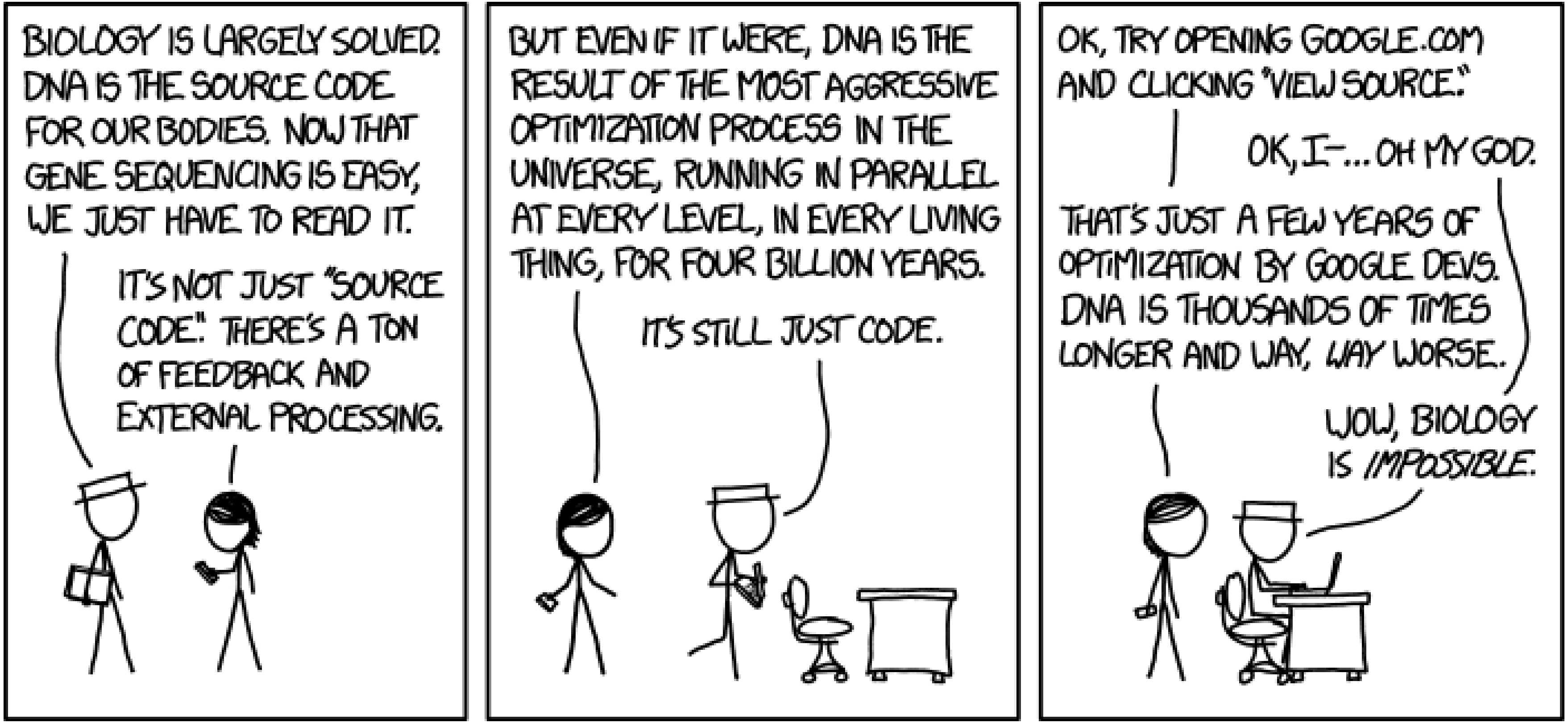
- Reason 3: Life on Earth arose **almost immediately** after the "right conditions" emerged.
  - Also, **life is robust**:
    - ✓ Life quickly "bounced back" after **five mass extinction** events in the last 500 million years (asteroid impacts, volcanism, etc.)
    - ✓ Life can exist in **surprisingly extreme conditions** (extremophiles): extraordinarily hot, acidic, alkaline, dry, high pressure (e.g., in rocks many km underground), etc..
    - ✓ Significantly increases the chances of finding life on **exoplanets**, and also elsewhere in our **Solar System**…




Life inside super dry Antarctic rock

- We have no reason to think that life ought to be rare in the universe, and several reasons to expect it **might be quite common**:
  - Everywhere we have looked in the universe, **the laws of physics are the same**
  - **Organic molecules form easily** and are widespread throughout the universe
  - **Life on Earth arose almost immediately** after the "right conditions" emerged, and can survive under a wide range of extreme conditions (**extremophiles**)

- Videos worth watching:
  - Jack Szostak (Nobel laureate, Harvard): The Origin of Life on Earth (and implications for ET life). Simplified version (to bypass the unfortunate anti-creationist messaging at the beginning, start at 2:39). Trying to create life in the lab. (See also Craig Venter.)
  - Robert Hazen (Carnegie Institution): The Emergence of Life on Earth. Mentions Deep Carbon Observatory at the end. See also this article and this video (rocks & life).


BIOLOGY IS LARGELY SOLVED. DNA IS THE SOURCE CODE FOR OUR BODIES. NOW THAT GENE SEQUENCING IS EASY, WE JUST HAVE TO READ IT.
IT'S NOT JUST "SOURCE CODE." THERE'S A TON OF FEEDBACK AND EXTERNAL PROCESSING.
BUT EVEN IF IT WERE, DNA IS THE RESULT OF THE MOST AGGRESSIVE OPTIMIZATION PROCESS IN THE UNIVERSE, RUNNING IN PARALLEL AT EVERY LEVEL, IN EVERY LIVING THING, FOR FOUR BILLION YEARS.
IT'S STILL JUST CODE.
OK, TRY OPENING GOOGLE.COM AND CLICKING "VIEW SOURCE."
OK, I– ...OH MY GOD.
THAT'S JUST A FEW YEARS OF OPTIMIZATION BY GOOGLE DEVS. DNA IS THOUSANDS OF TIMES LONGER AND WAY, WAY WORSE.
WOW, BIOLOGY IS *IMPOSSIBLE*.

- The question "**Are We Alone**" is of ever increasing interest to scientists.

  - ✓ **Why Now?** Scientists have *always* been interested in this question, but in the last few decades this interest has **dramatically intensified**:

    - We now **know** **there are planets out there**. (Without them, ET life is unlikely.)

    - We now have much better reasons to think that **biology might be universal**.

    - We now have sufficient **technology** to begin **looking for life** (more later…)

  - ✓ "…the study of life in the universe [astrobiology] is one of the most rapidly growing fields of active scientific research…"—Bennett & Shostak (2012).