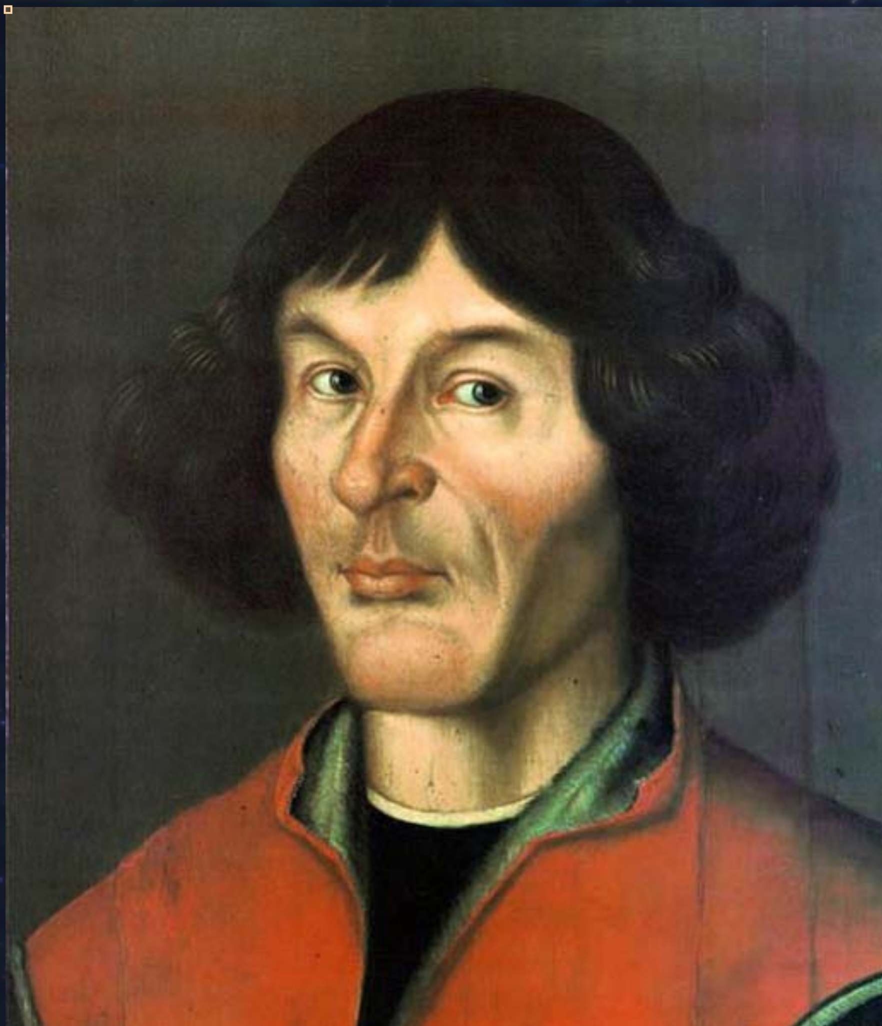
Lecture 2:

Newtonian Gravity and Physics Basics

The "Big Four": Nicholaus Copernicus



(*portrait from Toruń, 16th C*)

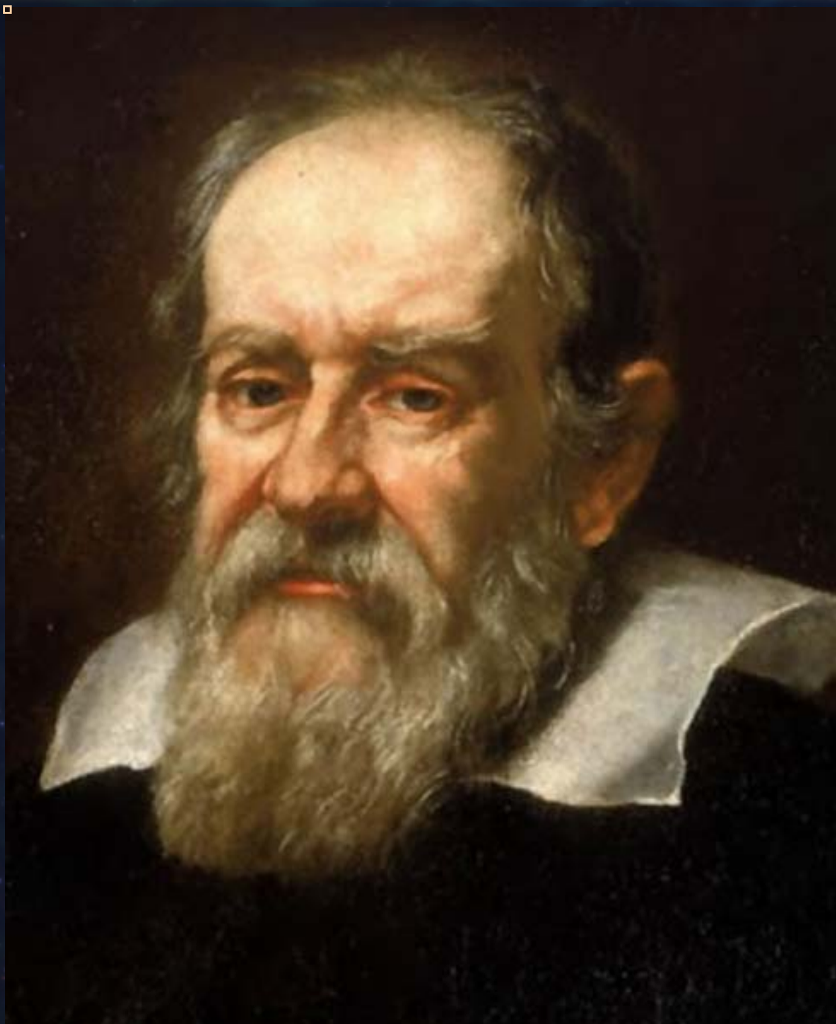
- *Mikolaj Kopernik*
  Poland, 1473-1543
- Primarily active 1512-1540
- Planets orbit the Sun, not Earth
- Assumed circular orbits, from Greek idea of perfection

The "Big Four": Johannes Kepler

(*portrait from 1610*)

- Germany, 1571-1630
- Primarily active 1609-1619
- Formulated 3 laws of planetary motion
  - Planets follow elliptical orbits, not circular
  - Orbits can be described by simple laws

The “Big Four”: Galileo Galilei



(*portrait by Justus Sustermans*)

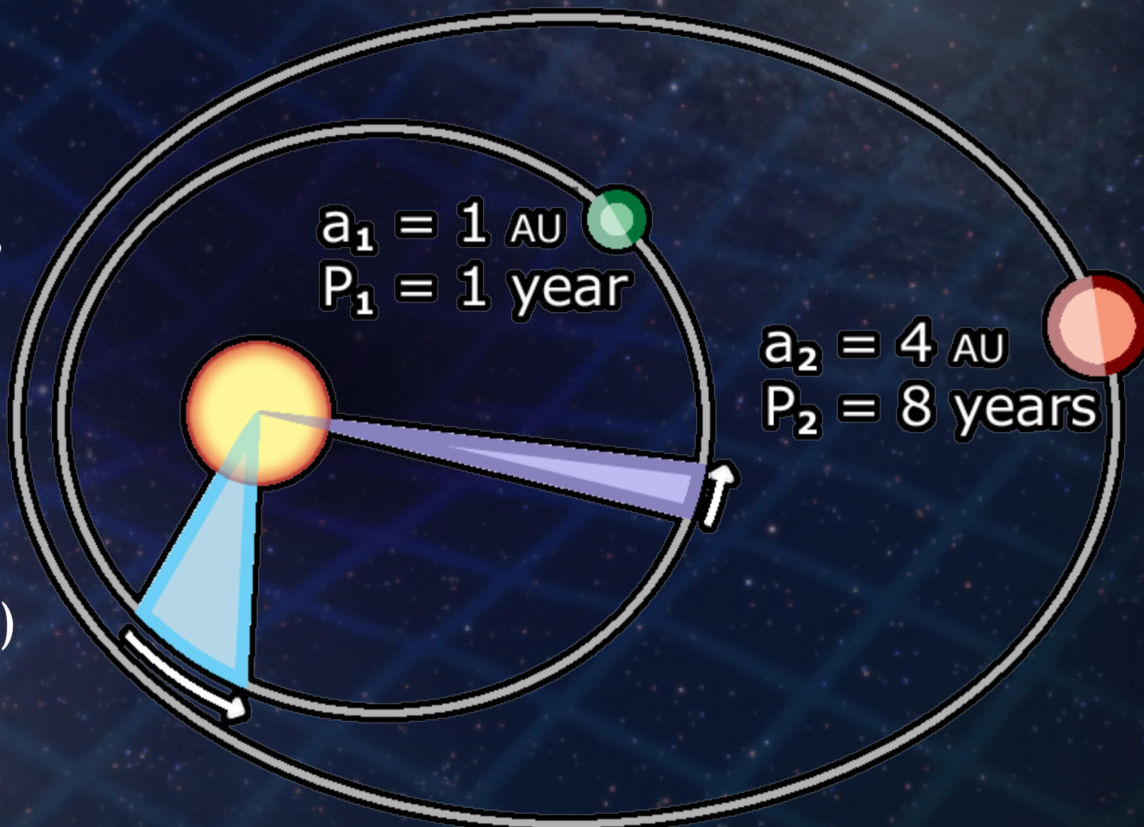
- Italy, 1564-1642
- Described phases of Venus, uneven surface of the Moon, sunspots
- Discovered the 4 largest moons of Jupiter: Io, Europa, Ganymede, Callisto
- Dispelled geocentric theory

Kepler's 3 Laws of Planetary Motion

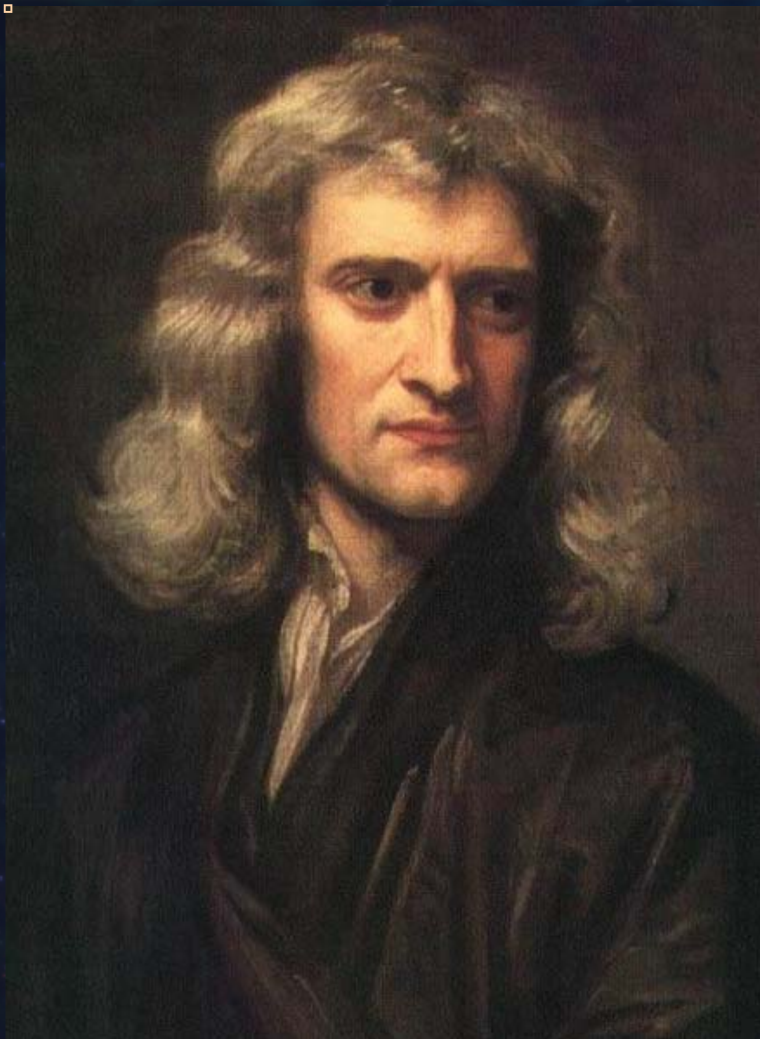
1. Planets revolve in elliptical orbits with the Sun at one focus

2. Planets move faster when closer to the Sun (or, a line sweeps out equal areas in equal times)

3. $P^2 \propto a^3$



The "Big Four": Isaac Newton



(1689 portrait by Godfrey Kneller)

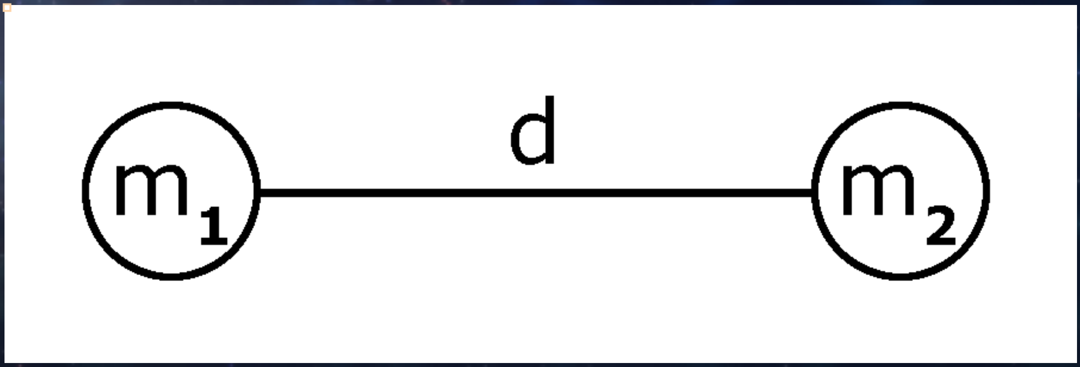
- England, 1643-1727
- Around 1680; worked out laws of motion and theory of gravity

Newton's Laws

1. Every object moves uniformly in a straight line unless acted upon by a force.

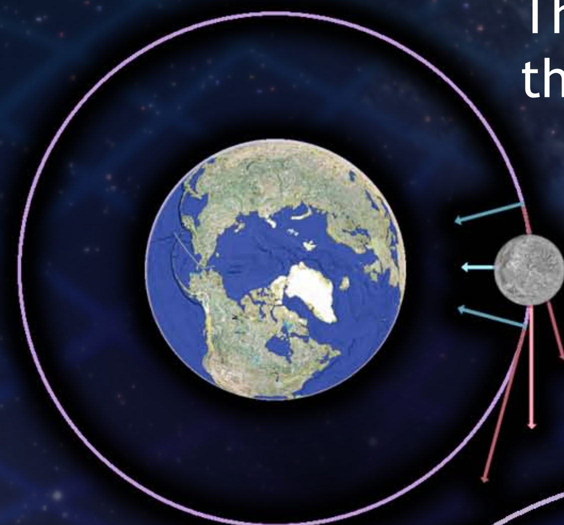
2. When a force acts, the object's velocity changes at a rate proportional to the force and inversely proportional to its mass.

3. $F_{gravity} \propto m_1 m_2 / d^2$



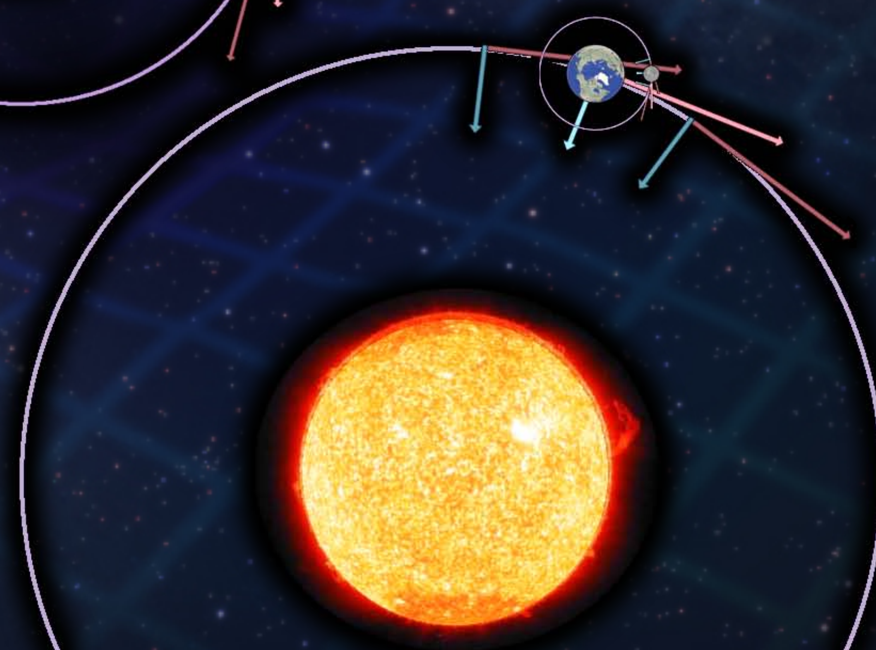
Newtonian Gravity

An apple falling from a tree falls towards the center of mass of the Earth.

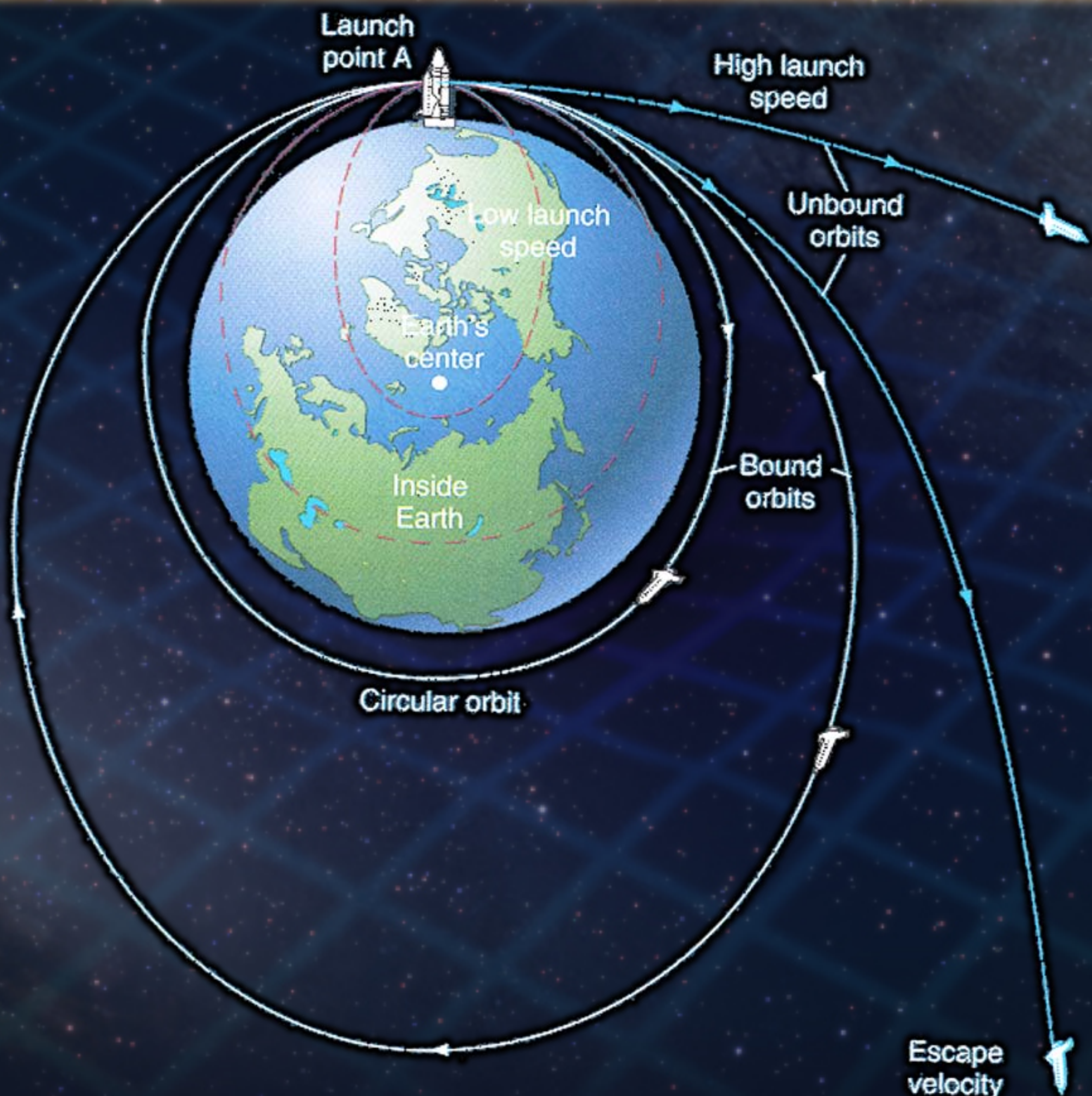


The Moon falls around the Earth...

...just as the Earth-Moon system falls around the Sun.



Newtonian Gravity - Orbits



Newton's Theory – Idea of "Escape Velocity"

- Gravity is a "force"
  - causes acceleration or deceleration (= negative acceleration)
  - g at Earth's surface = 32 ft/sec/sec = 22 mph/sec = 9.8 meters/sec/sec

- Example:
  - throw something up at 66 mph: it stops after 3 sec, then falls back in another 3 sec

- How to calculate gravitational pull of a mass:
  - increases with amount of mass: $2 \times \text{mass} \Rightarrow 2 \times g$
  - decreases with square of distance from center of mass:

    $2 \times \text{distance} \Rightarrow g/4$

Escape Velocity

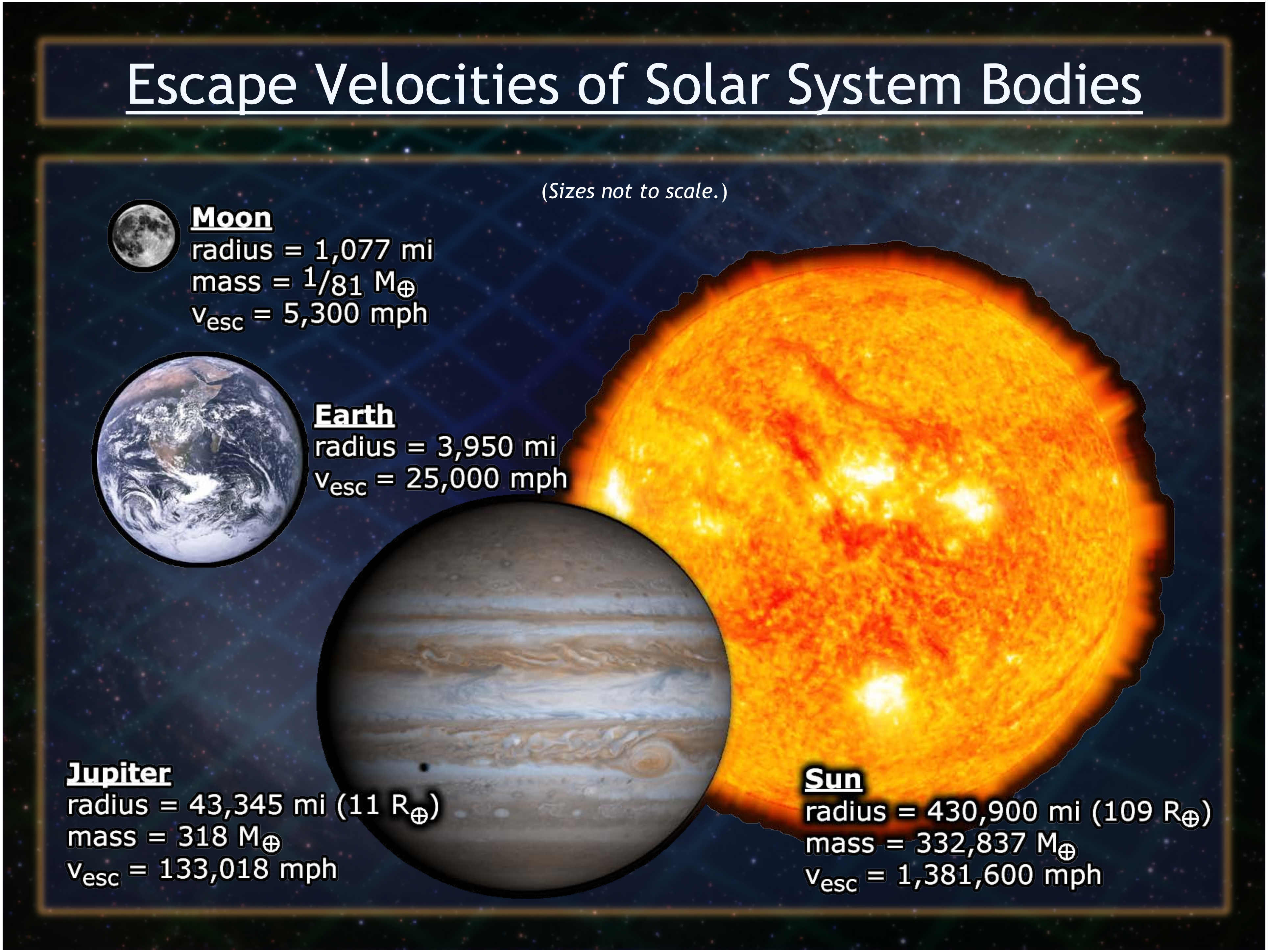
Competition — deceleration vs. weakening of gravity with distance:

$$v_{esc}(\text{Earth}) = \sqrt{2 \times g_{\text{Earth}} \times R_{\text{Earth}}}$$

$$g_{\text{Earth}} = 22 \text{ mph/sec} = 79{,}000 \text{ mph/hour}$$

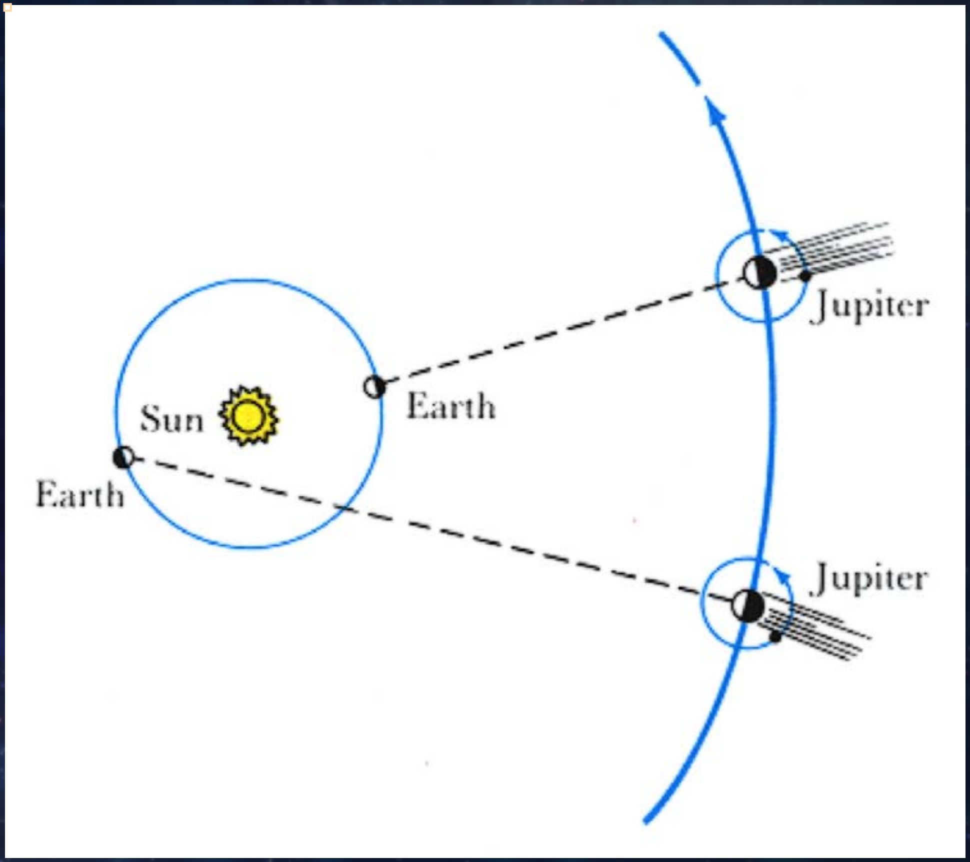
$$R_{\text{Earth}} = 6378 \text{ km} = 3960 \text{ mi}$$

$$v_{esc}(\text{Earth}) = \sqrt{2 \times (79{,}000) \times (3960)} \text{ mph} = 25{,}000 \text{ mph}$$


Escape Velocities of Solar System Bodies
(Sizes not to scale.)
Moon
radius = 1,077 mi
mass = 1/81 $M_\oplus$
v_{esc} = 5,300 mph
Earth
radius = 3,950 mi
v_{esc} = 25,000 mph
Jupiter
radius = 43,345 mi (11 $R_\oplus$)
mass = 318 $M_\oplus$
v_{esc} = 133,018 mph
Sun
radius = 430,900 mi (109 $R_\oplus$)
mass = 332,837 $M_\oplus$
v_{esc} = 1,381,600 mph

Speed of Light

1675: Danish Astronomer **Olaus Roemer** measured the speed of light by timing "transits" of Jupiter's moons.



(Kaufmann, *Universe*, 4th Ed., p.80)

Today this value is known to be

c = 186,000 miles/sec = 300,000 km/sec = 669,600,000 mph

Escape Velocity and the Speed of Light

John Michell (1783), **Pierre-Simon Laplace** (1796):

Question: What happens if the escape speed from an object is greater than the speed of light?

Answer: If light consists of particles of matter, they would not be able to escape.

The Catch: Early 19^{th} century idea was that light is a wave (a disturbance), not a particle — and the black hole idea was forgotten….

…until **Einstein** came along.

Absolute Space, Absolute Time

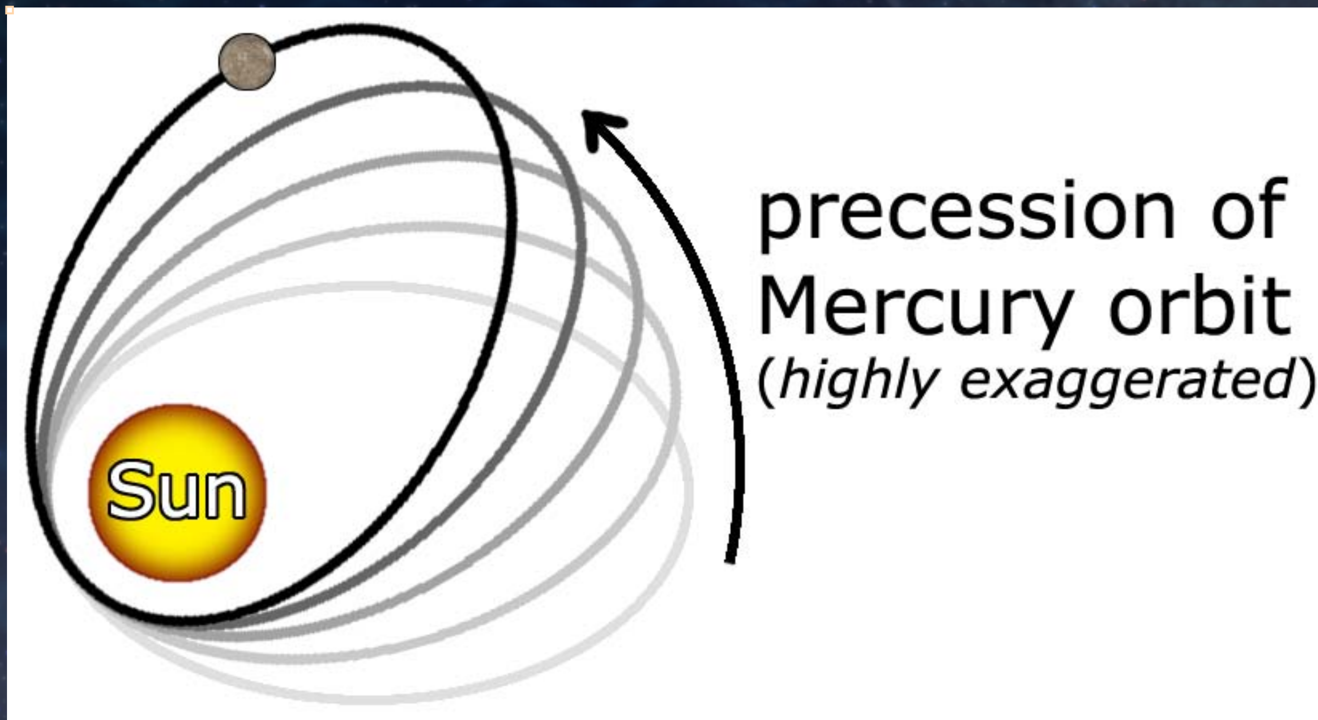
Absolute Space

- All inhabit the same space
- Gives our ideas of length, breadth, height
- All agree on length, breadth,
- height as long as we make sufficiently accurate measurements (regardless of motion)

Absolute Time

- Universal "clock" that ticks forward at the same rate everywhere
- All agree on a span of time as long as we make sufficiently accurate measurements (regardless of motion)

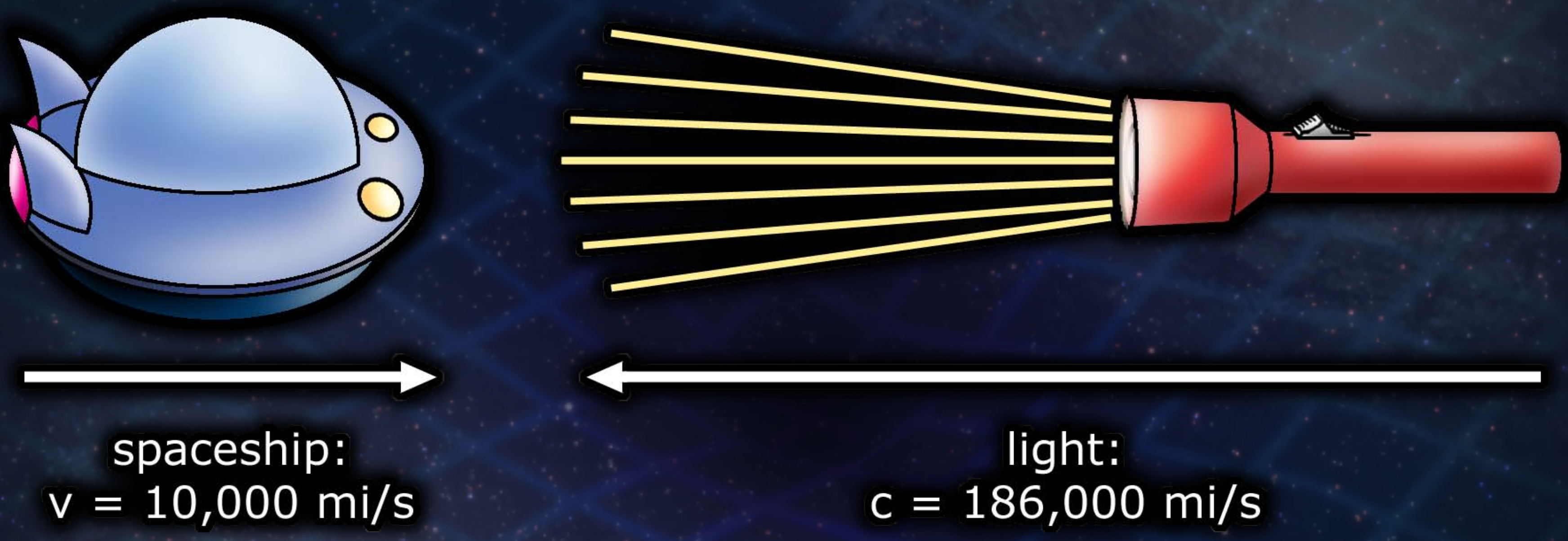
Problems with Newtonian Mechanics



Mercury's orbit precesses by 1.38" per orbit.

After accounting for Jupiter's gravitational effects, there is still an extra 0.10".

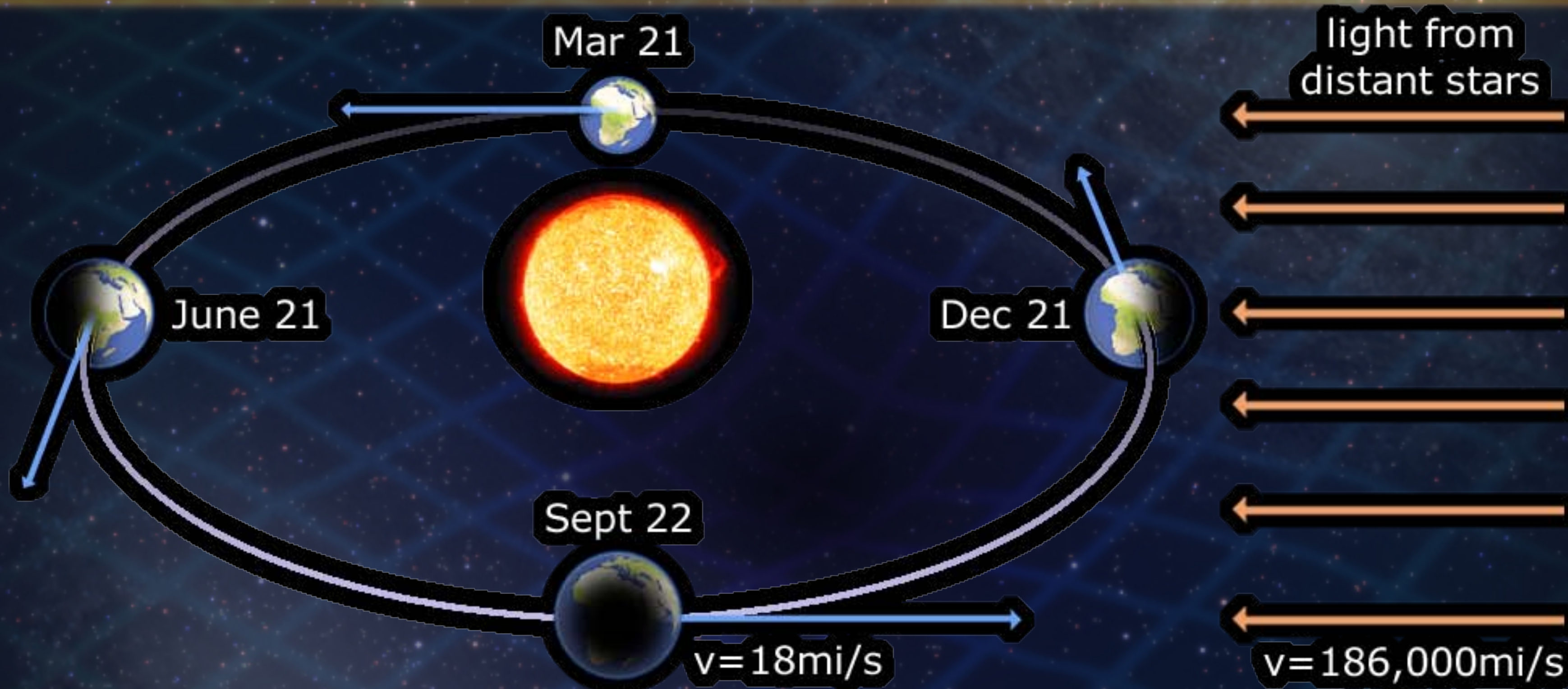
Problems with Newtonian Mechanics



Under Newtonian laws, we expect the speed of light to depend on how you're moving relative to absolute space.

The spaceship pilot would measure the speed of the oncoming light to be 196,000 mi/s.

Problems with Newtonian Mechanics



Under Newtonian laws, we would expect measurements of the speed of distant stars' light to change seasonally:

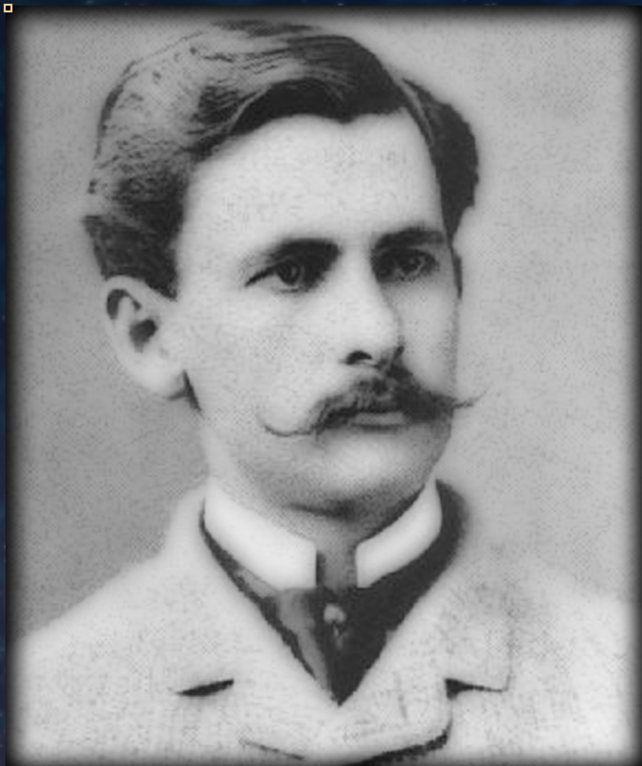
185,982mi/s, on March 21

186,018mi/s, on September 22

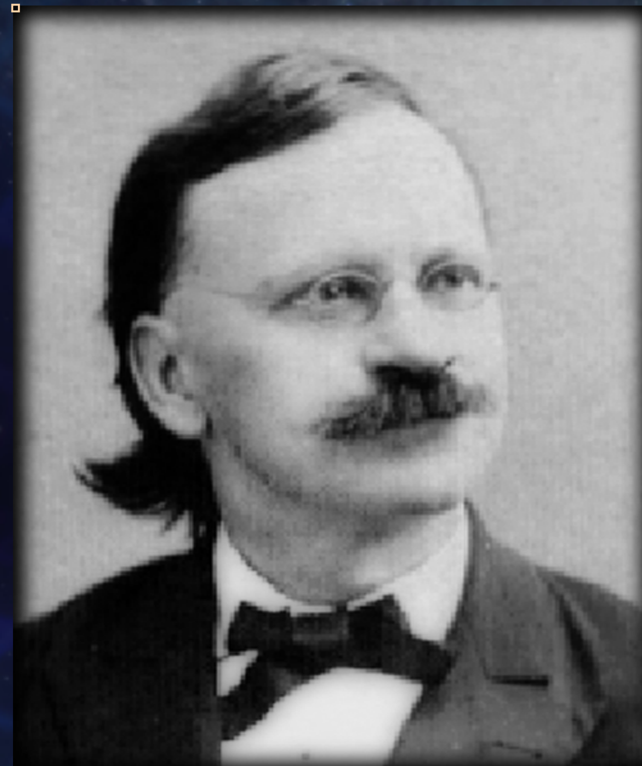
186,000 mi/s, on June 21

186,000 mi/s, on December 21

Problems with Newtonian Mechanics



Albert Michelson

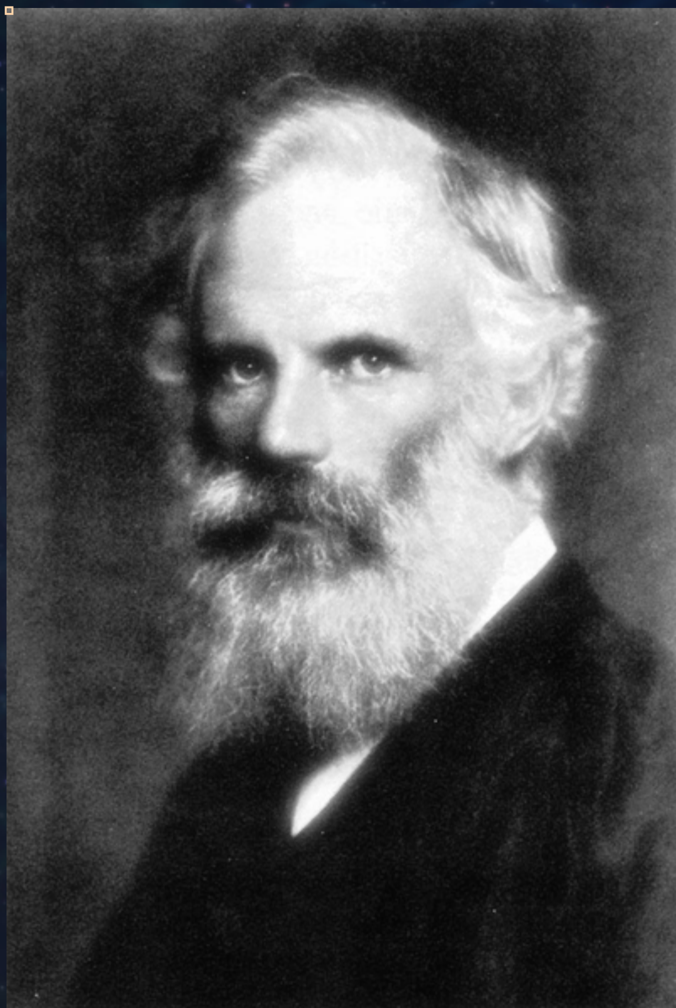


Edward Morley

Tried a clever experiment from 1881-1887 to detect a change in the measured speed of light, and did not see it.

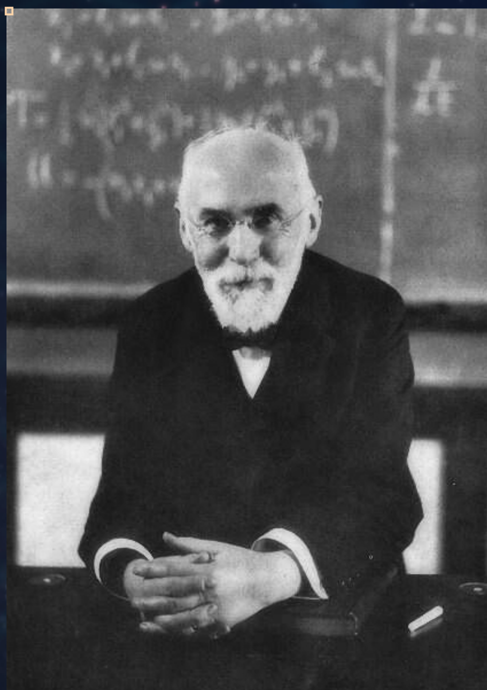
Lecture 3:
Special Relativity

George F. Fitzgerald

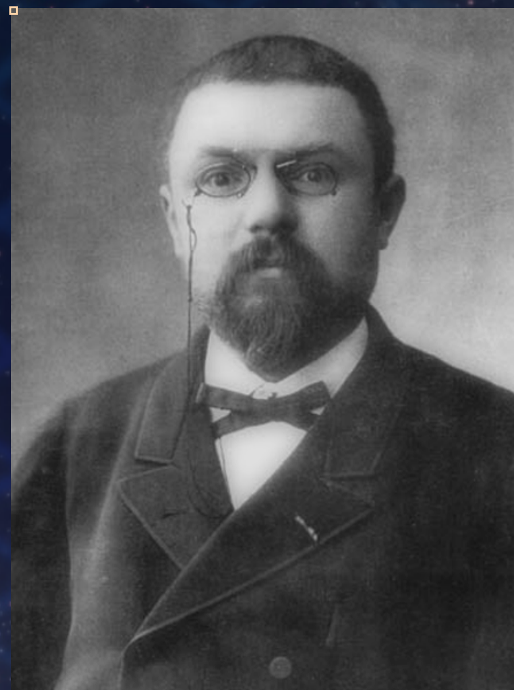


- Irish physicist, 1851-1901
- Became interested in the "mathematical curiosity" presented by the Michelson-Morley experiment, in 1889
- Proposed that objects *contract* as they move through absolute space, by a factor of $(v/c)^2$

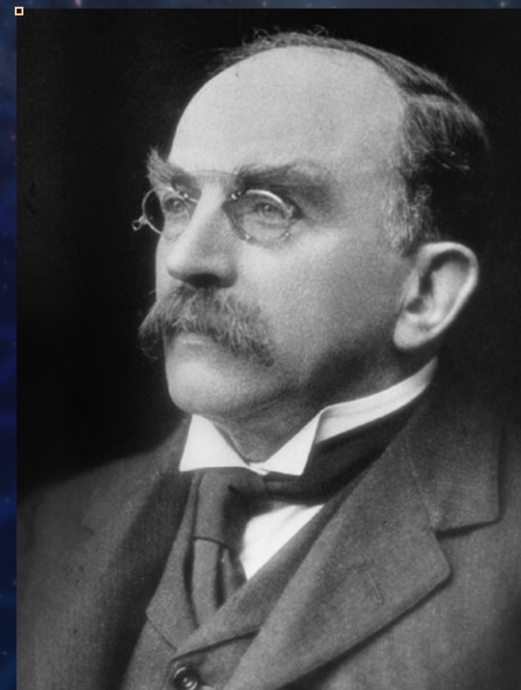
Support for Fitzgerald's Length Contraction



Hendrik Lorentz - Amsterdam



Henri Poincaré - Paris



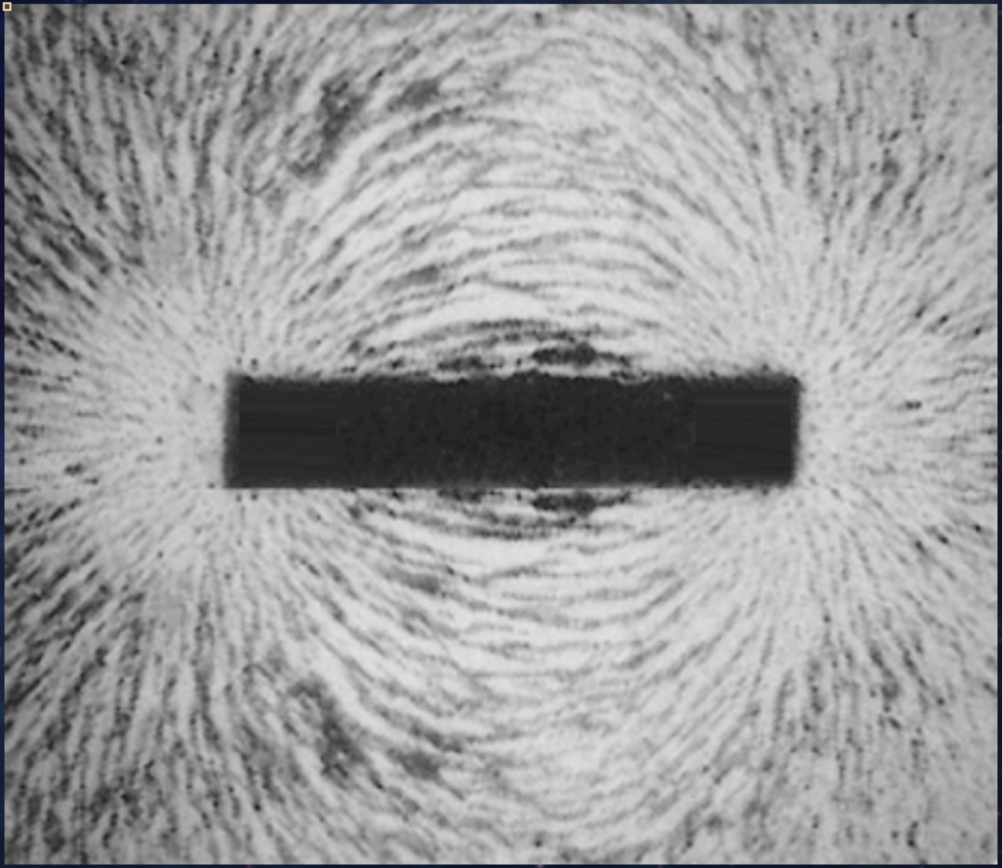
Joseph Larmor - Cambridge

Applied Fitzgerald length contraction to problems in electromagnetic theory.

Electromagnetic Theory

The open field lines problem in magnetism could be solved if, in addition to Fitzgerald length contraction, you also had time running more slowly when you move relative to absolute space.

Motion "dilates" time.



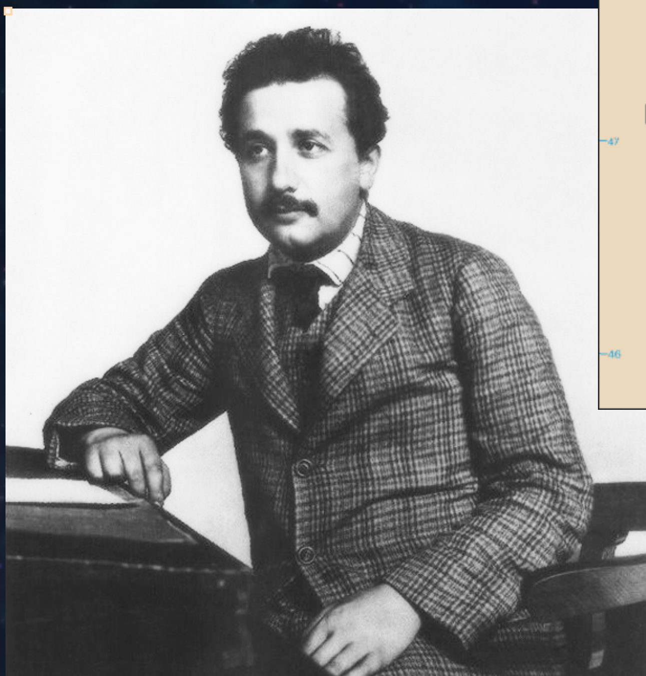
Albert Einstein

"Heretical," in that…

- Mathematics professor Minkowski called him a "lazy dog"
- Irritated his college teachers so much he couldn't get a job in physics
- Turbulent relationship with Mileva Marić, whom his parents hated
- Fathered an illegitimate child with Marić

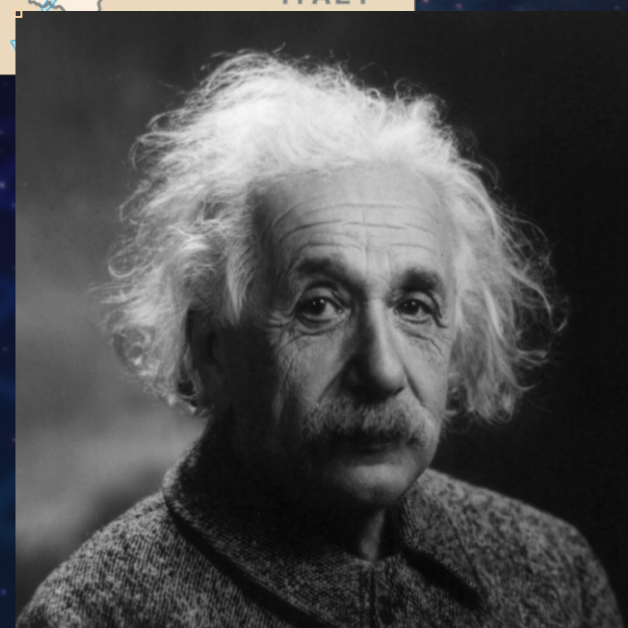
Albert Einstein and Mileva Marić

Albert Einstein



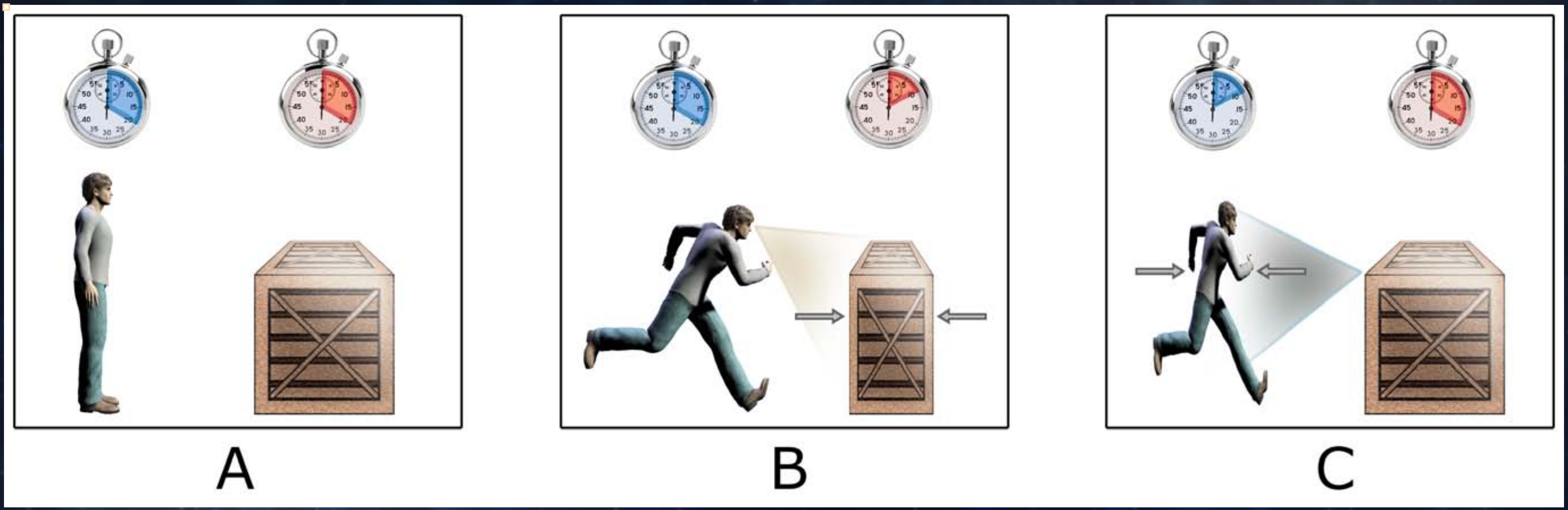
Einstein at the Swiss patent office
Bern - 1905

While working alone, he came to his special theory of relativity in 1905.



Einstein, 1947

Length Contraction and Time Dilation



1. With both the person and the object at rest (**A**), the sizes of each and the passage of time appear “normal” from both perspectives (the person’s and the object’s).
2. The person moving towards the object sees the object contracted along its length (**B**) but not in other directions (by exact amount Fitzgerald needed to explain Michelson-Morley).
3. As the object “sees” the person moving toward it, the person appears contracted in the direction of motion (**C**), but not in other directions, by the same amount as it appeared contracted to the observer.
4. As the person moves toward the object, the object’s flow of time appears slowed (**B**); that is…
   - A clock on it would appear to run slower, or
   - The object “ages” more slowly than the observer.
5. As the object sees the person moving toward it (**C**), it sees the person’s flow of time slowed.
   - A clock on the person appears to run slower.
   - The person ages more slowly than the object.

Why don’t we notice these effects?

At 150 mph:

Time slowed by ≈1 part in 10^{14}
Space contracted by ≈1 part in 10^{14}

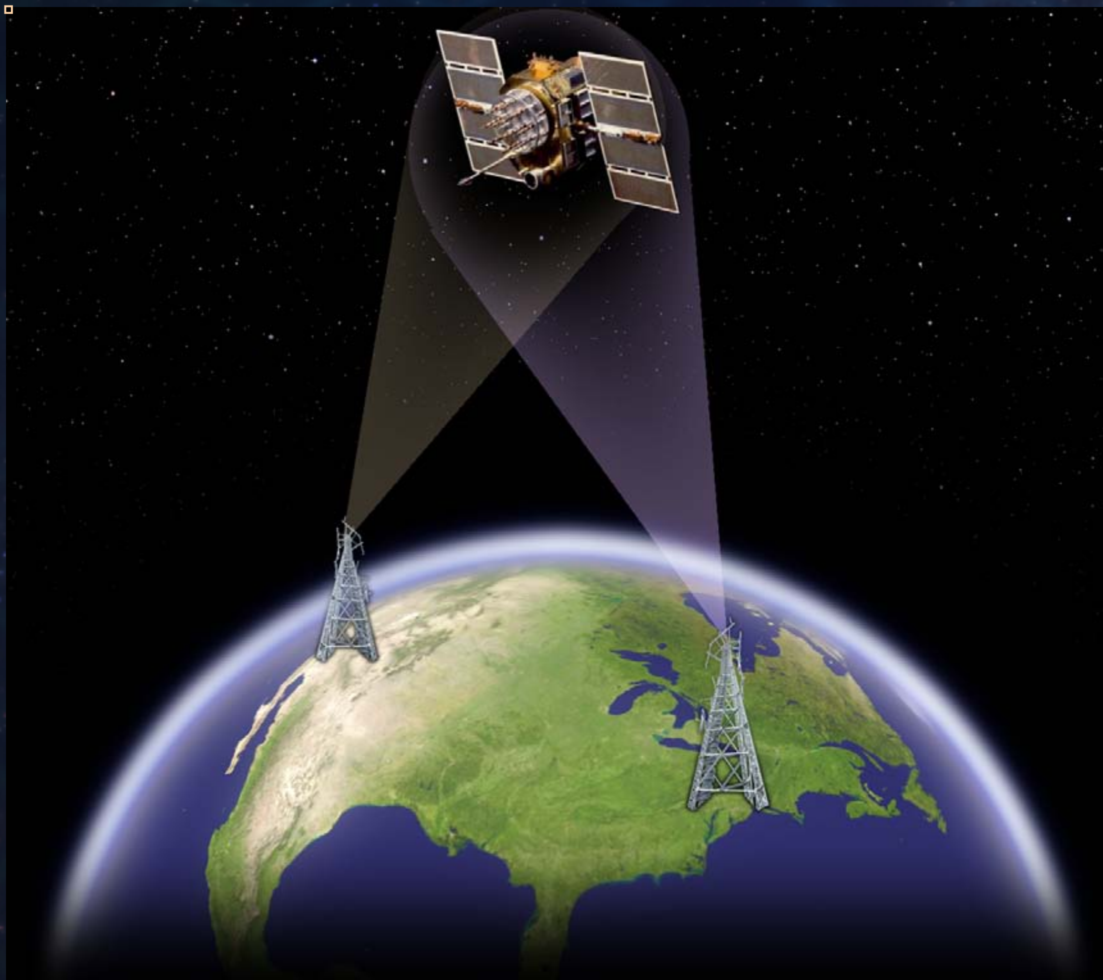
At 87% of c:

(~580,000,000 mph)
Time slowed by factor of 2
Space contracted by factor of 2

We can test that these effects really occur

1. Synchronize 2 atomic clocks, and…
    - Fly one around Earth at high speed, other stays put
    - They'll become no longer synchronized, and disagree by an amount predicted by relativity (≈100 nanoseconds)

We can test that these effects really occur



2. Global positioning system (GPS) satellites: need to include Special Relativity and General Relativity effects or they'll return wrong answers.

They depend on the receipt of radio signals from distant radio transmitters to get position.

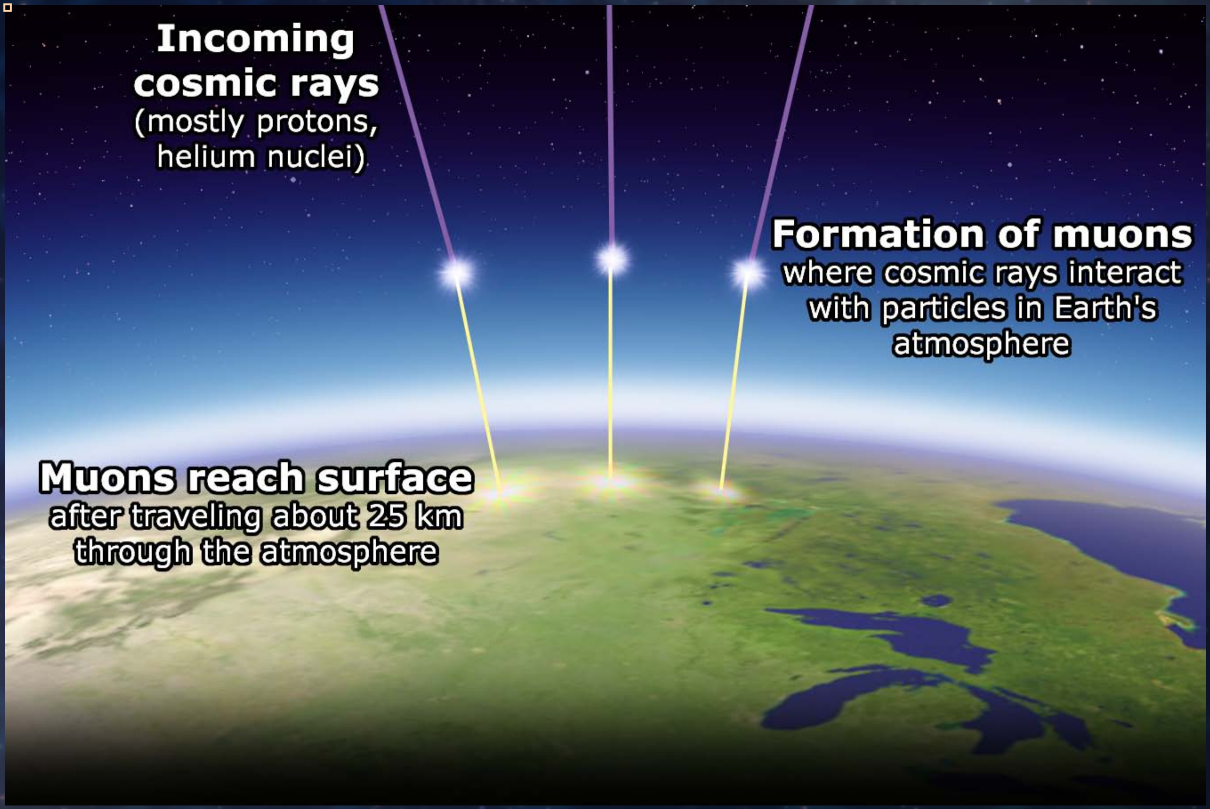
We can test that these effects really occur

3. Some subatomic particles have short lifespans; for example, Muons:

Live for 2.196×10^{-6} s when at rest relative to us, and can only travel up to ≈0.66 km before decaying.

Are formed at heights of about 25 km above the Earth's surface, when cosmic rays strike atmosphere.

But they make it to the Earth's surface!

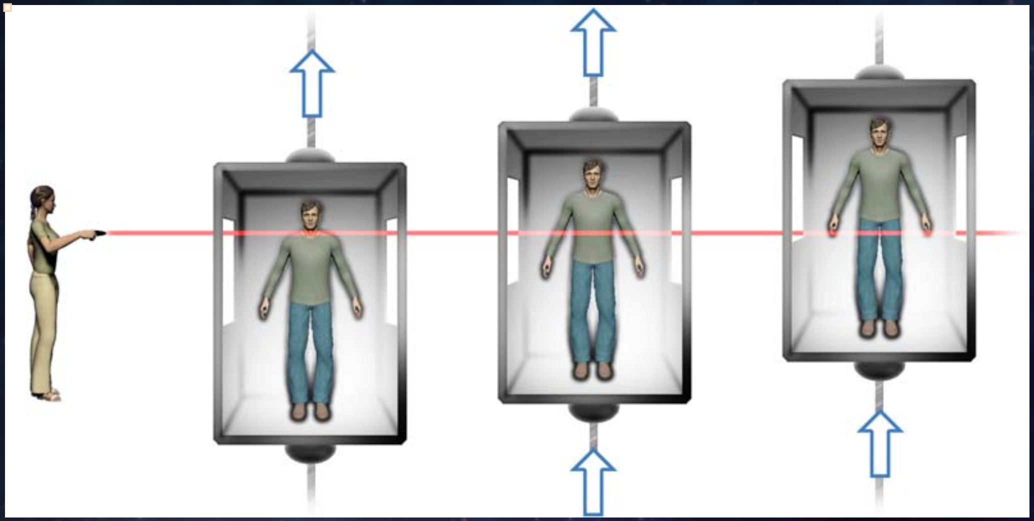


The reason is that the muon sees Earth's atmosphere Lorentz-contracted; or, we see the muon's clock running slow.

Fundamental Principles of Special Relativity

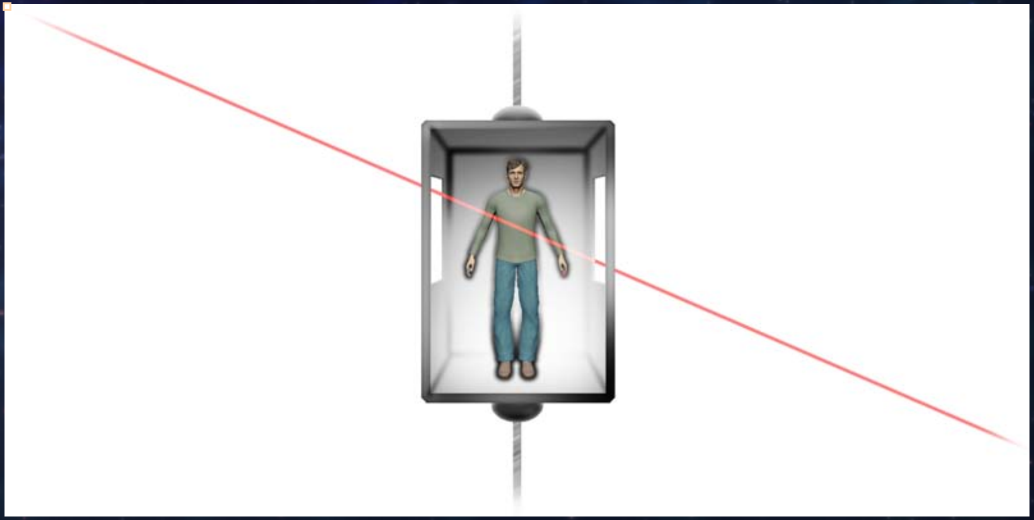
1. The laws of physics do not depend on state of motion.
   - Resounding rejection of absolute space.
   - If the laws of physics didn't treat all states of motion on equal footing, then using the laws of physics we could pick out some "preferred" state of motion and define this to be absolute rest. Then we'd have absolute space again!
2. Everyone who measures the speed of light must get the same answer, *irrespective* of their states of motion.

Aberration of Light

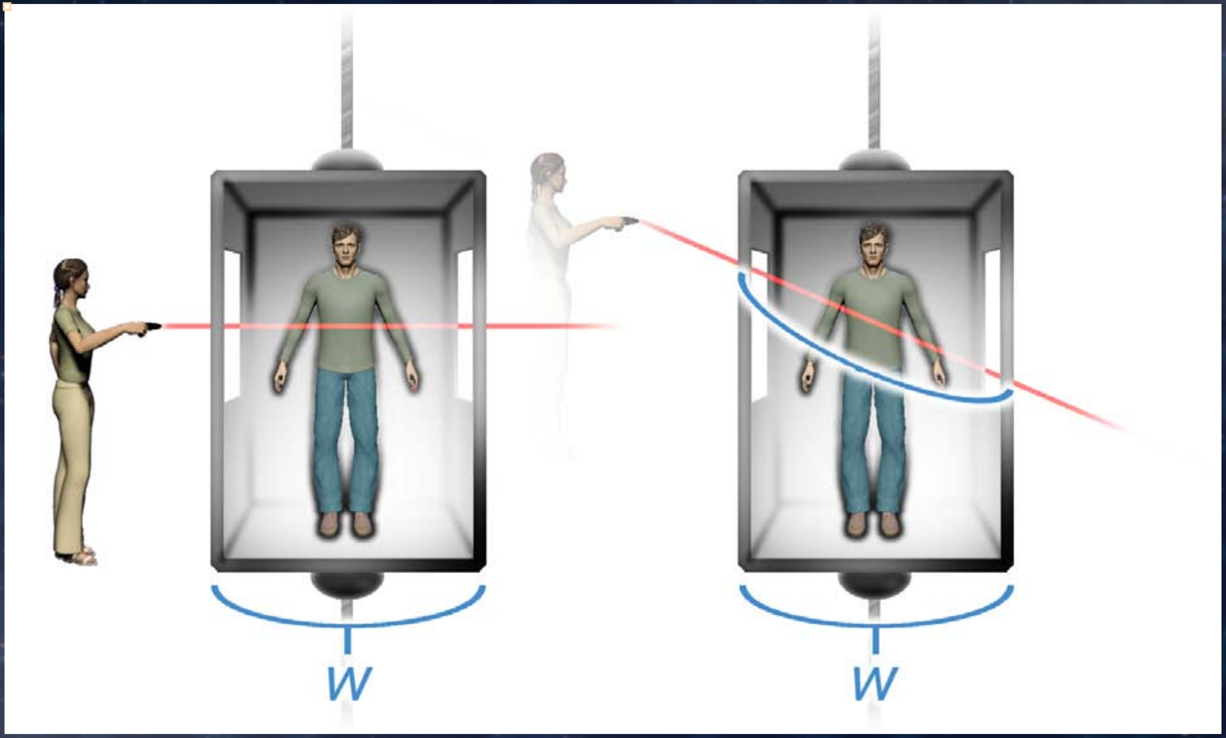


To an outside observer, the laser beam goes straight through the elevator.

The elevator occupant sees the laser beam traveling at an angle.



Aberration of Light



To outside observer:

Distance across box = *w*

Time to cross box = *w*/*c*

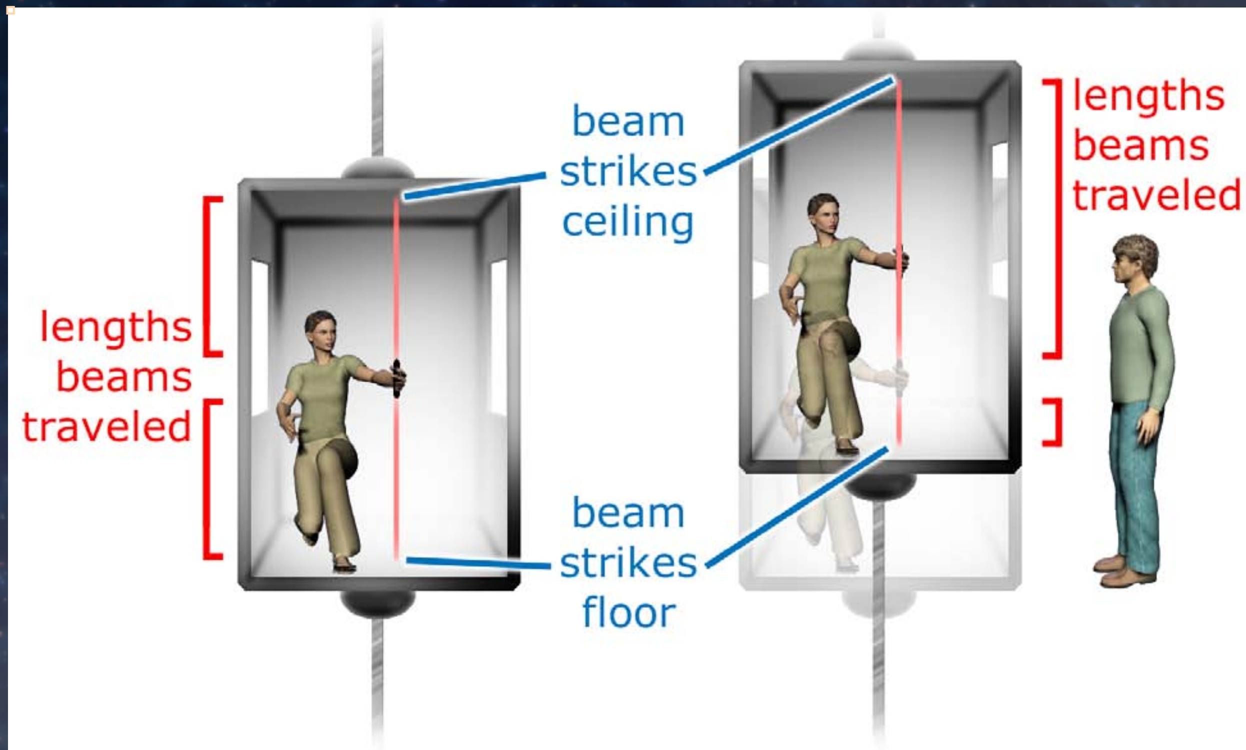
To inside observer:

Distance across box > *w*

Time to cross box > *w*/*c*

Relativity of Simultaneity

A person in an upward-bound elevator with a 2-directional laser pointer:

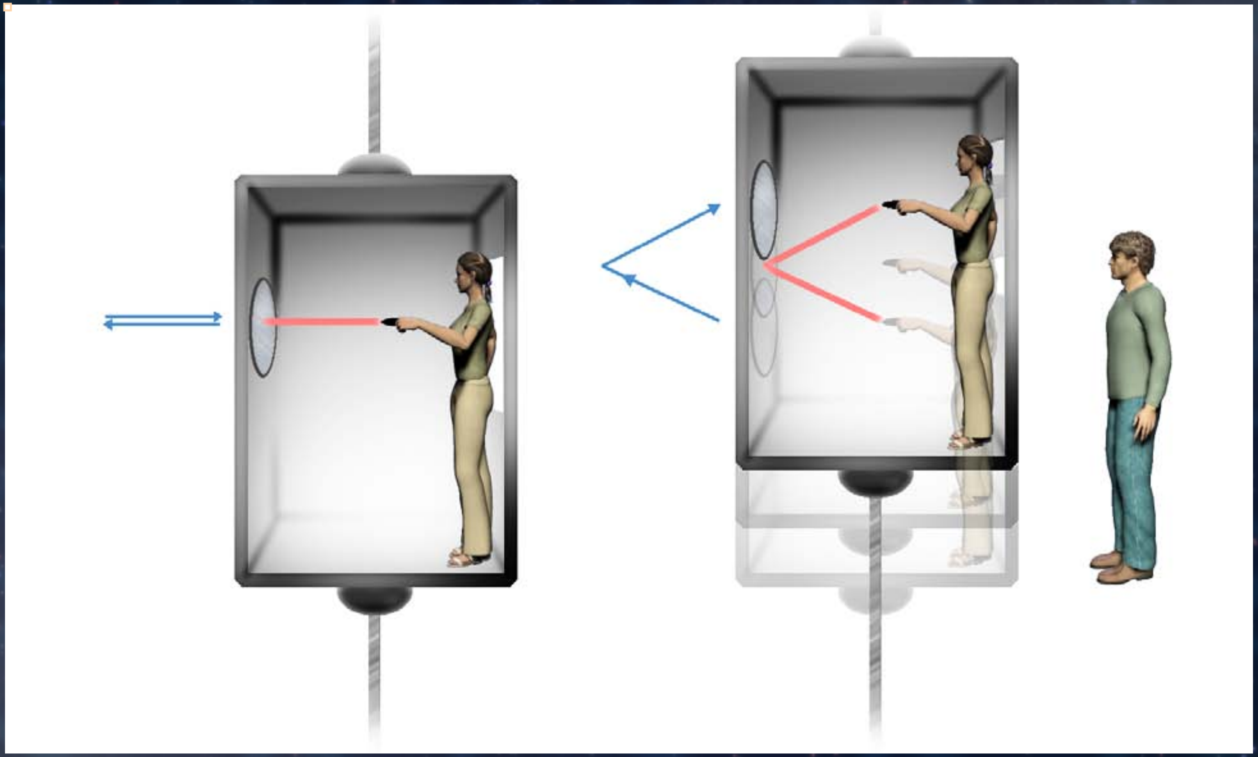


The person inside the elevator sees the beams hit the top and bottom of the car simultaneously.

A person outside the elevator sees the lower beam hit the floor before the upper hits the ceiling.

Time Dilation

A person in an upward-bound elevator with a laser pointed at a mirror:



To an observer outside the car, the interval between the time when the beam is fired and the time when it returns is longer than for the person inside the car.

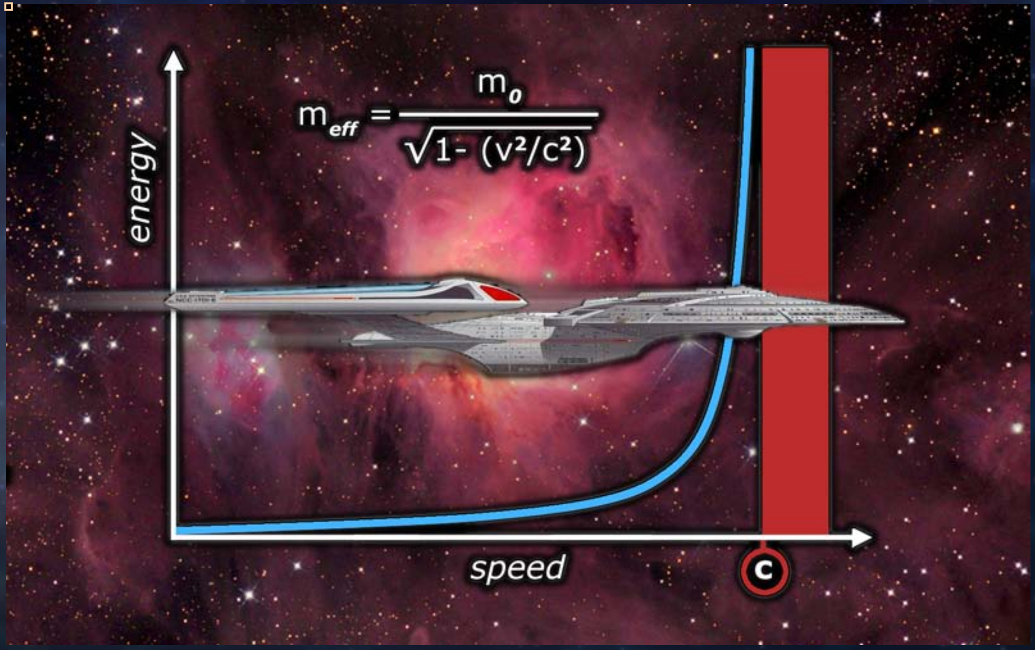
This means that time inside the elevator is dilated: in other words, time appears to pass more slowly inside the elevator.

Implications of Special Relativity

—1—

The inertia of an object increases rapidly as one approaches the speed of light.

No matter how hard you try, ***you cannot exceed c*** (as you approach **c**, the force required to accelerate further approaches infinity).

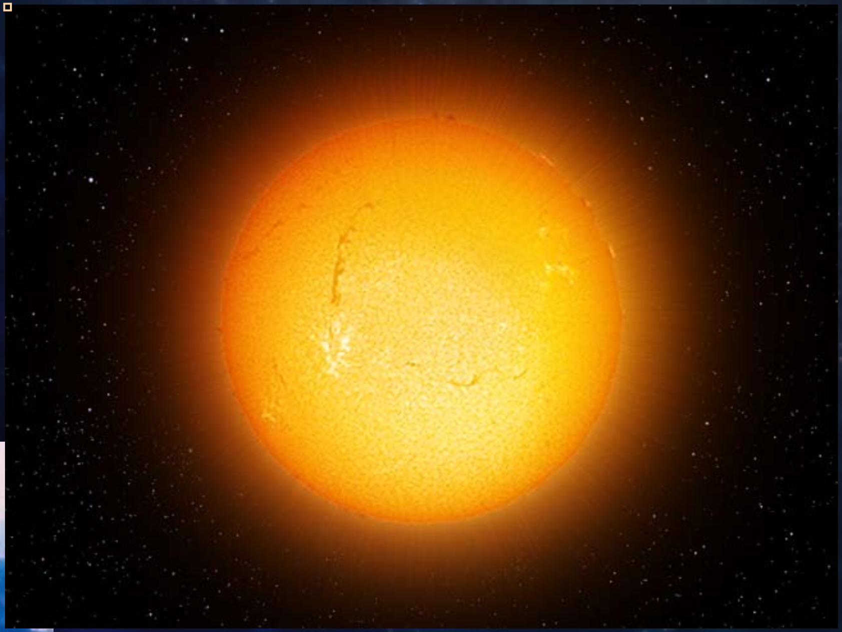


(Graph adapted from "Warp Drive, When?" — *http://www.nasa.gov/centers/glenn/research/warp/warp.html*)

Implications of Special Relativity

—2—

Mass can be converted into energy following the relation $\mathbf{E = mc^2}$. Since $\mathbf{c^2}$ is large, a little mass can make a lot of energy.



This principle explains how the atomic bomb works and how stars shine.

“On the Electrodynamics of Moving Bodies”

Einstein’s 1905 paper introducing Special Relativity

3. *Zur Elektrodynamik bewegter Körper;* von *A. Einstein.*

Daß die Elektrodynamik Maxwells — wie dieselbe gegenwärtig aufgefaßt zu werden pflegt — in ihrer Anwendung auf bewegte Körper zu Asymmetrien führt, welche den Phänomenen nicht anzuhaften scheinen, ist bekannt. Man denke z. B. an die elektrodynamische Wechselwirkung zwischen einem Magneten und einem Leiter. Das beobachtbare Phänomen hängt hier nur ab von der Relativbewegung von Leiter und Magnet, während nach der üblichen Auffassung die beiden Fälle, daß der eine oder der andere dieser Körper der bewegte sei, streng voneinander zu trennen sind. Bewegt sich nämlich der Magnet und ruht der Leiter, so entsteht in der Umgebung des Magneten ein elektrisches Feld von gewissem Energiewerte, welches an den Orten, wo sich Teile des Leiters befinden, einen Strom erzeugt. Ruht aber der Magnet und bewegt sich der Leiter, so entsteht in der Umgebung des Magneten kein elektrisches Feld, dagegen im Leiter eine elektromotorische Kraft, welcher an sich keine Energie entspricht, die aber — Gleichheit der Relativbewegung bei den beiden ins Auge gefaßten Fällen vorausgesetzt — zu elektrischen Strömen von derselben Größe und demselben Verlaufe Veranlassung gibt, wie im ersten Falle die elektrischen Kräfte.

Beispiele ähnlicher Art, sowie die mißlungenen Versuche, eine Bewegung der Erde relativ zum „Lichtmedium“ zu konstatieren, führen zu der Vermutung, daß dem Begriffe der absoluten Ruhe nicht nur in der Mechanik, sondern auch in der Elektrodynamik keine Eigenschaften der Erscheinungen entsprechen, sondern daß vielmehr für alle Koordinatensysteme, für welche die mechanischen Gleichungen gelten, auch die gleichen elektrodynamischen und optischen Gesetze gelten, wie dies für die Größen erster Ordnung bereits erwiesen ist. Wir wollen diese Vermutung (deren Inhalt im folgenden „Prinzip der Relativität“ genannt werden wird) zur Voraussetzung erheben und außerdem die mit ihm nur scheinbar unverträgliche

Lecture 4:
General Relativity

Einstein's Progress in General Relativity

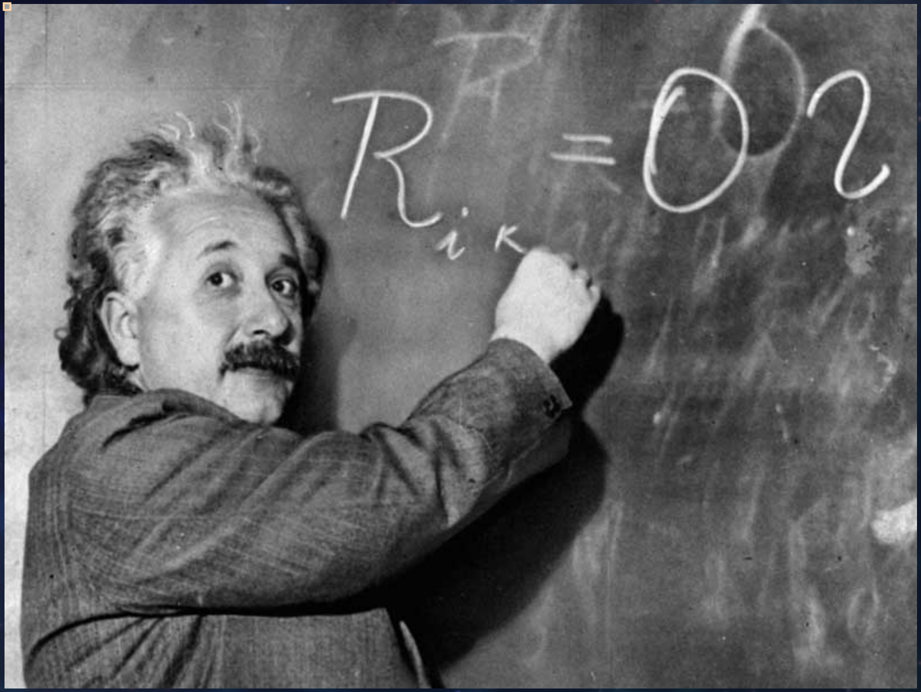
Einstein knew Special Relativity could only treat situations where gravity was not present (i.e., not black holes, among others).

Some highlights:

1907: Made some progress by introducing *Principle of Equivalence*

1908-1911: Worked mainly on atomic physics and radiation; also got a professorship

1911-1915: Struggled with and succeeded in creating a *General Theory of Relativity* with gravity

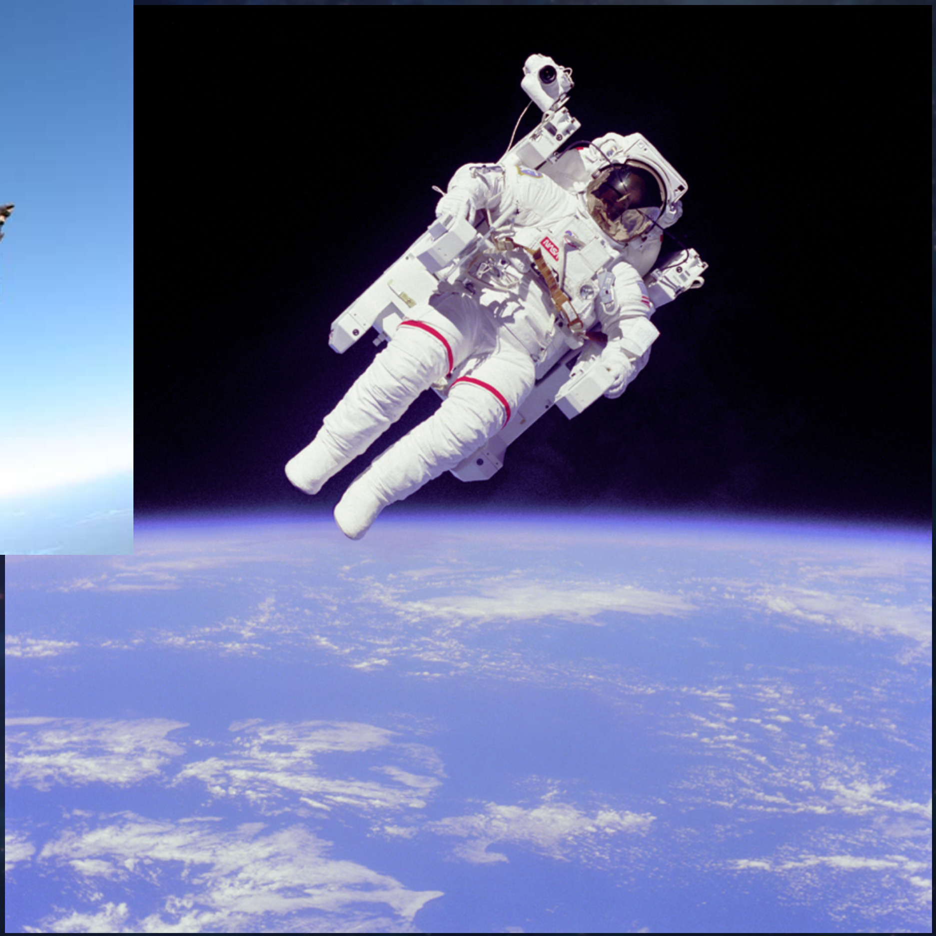


Principle of Equivalence

Einstein thought, "If a person falls freely, he will not feel his own weight."

⇑

The 1000 Islands Skydivers, Gananoque Sport Parachuting Centre (*http://www.skydivegan.com*)

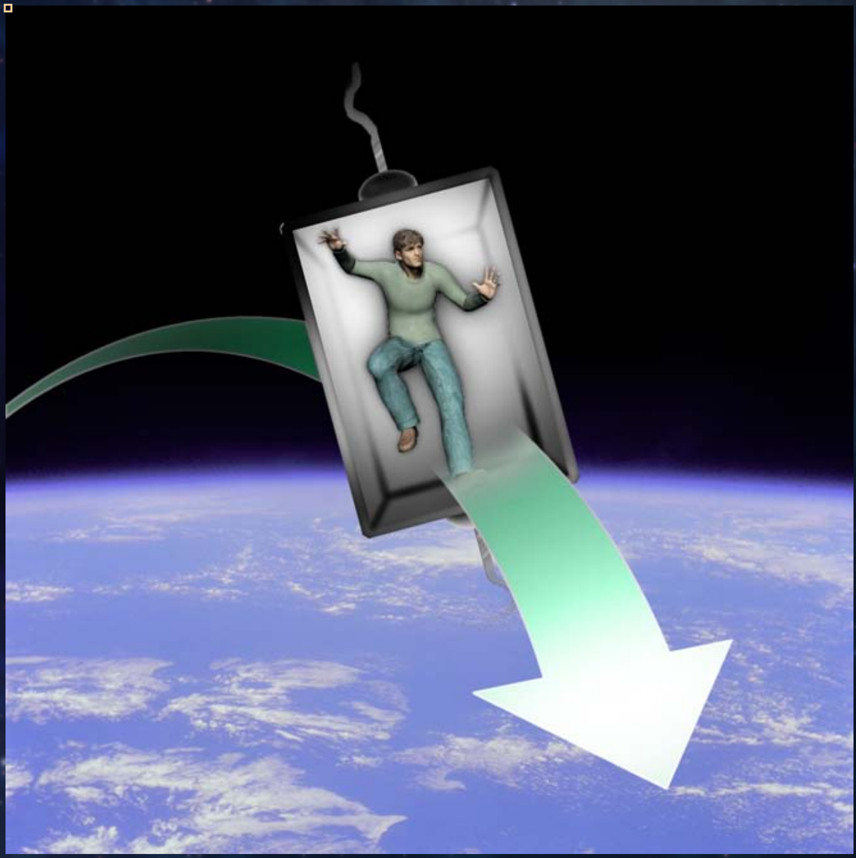


⇒

Astronaut Bruce McCandless II in an untethered manned maneuvering unit (MMU), STS-41-B, 1984 (NASA – *http://www.nasa.gov*)

Principle of Equivalence

If you’re in an elevator car (opaque) falling freely in a gravitational field, you can’t tell this from moving through space at constant velocity.

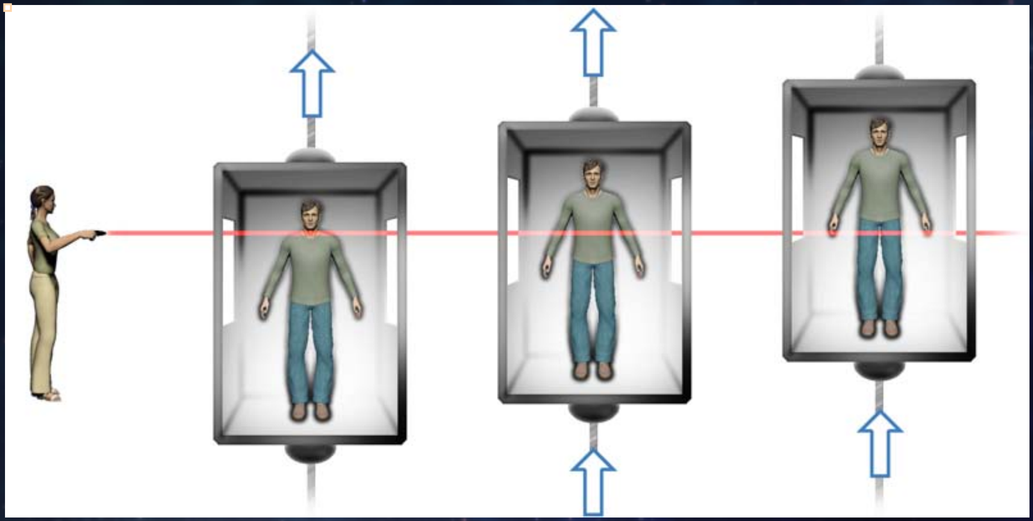


small, freely-falling frame $\Leftrightarrow$ gravity-free frame, moving at constant velocity

Principle of Equivalence

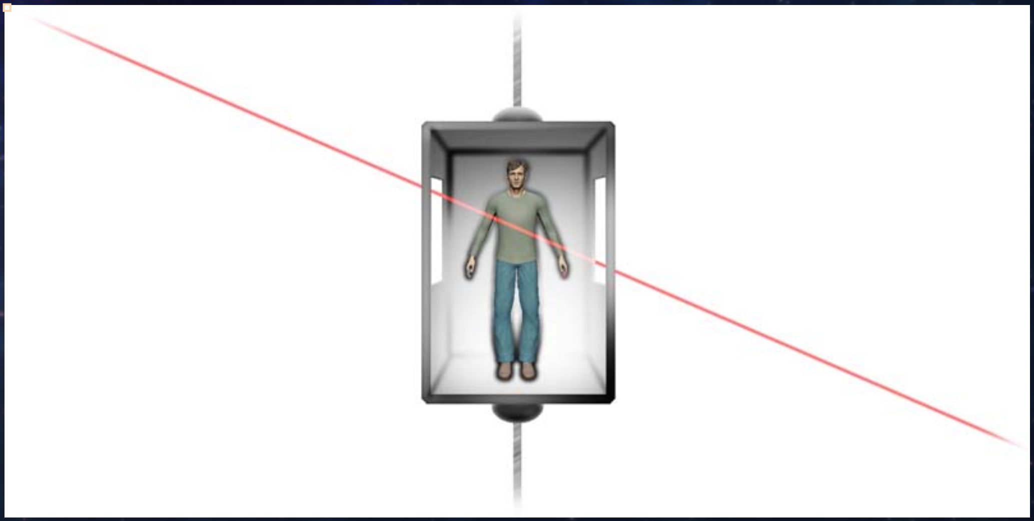
Alternatively, if you’ re sitting stationary in a gravitational field, this is equivalent to accelerating upward in space.

Review: Aberration of Light



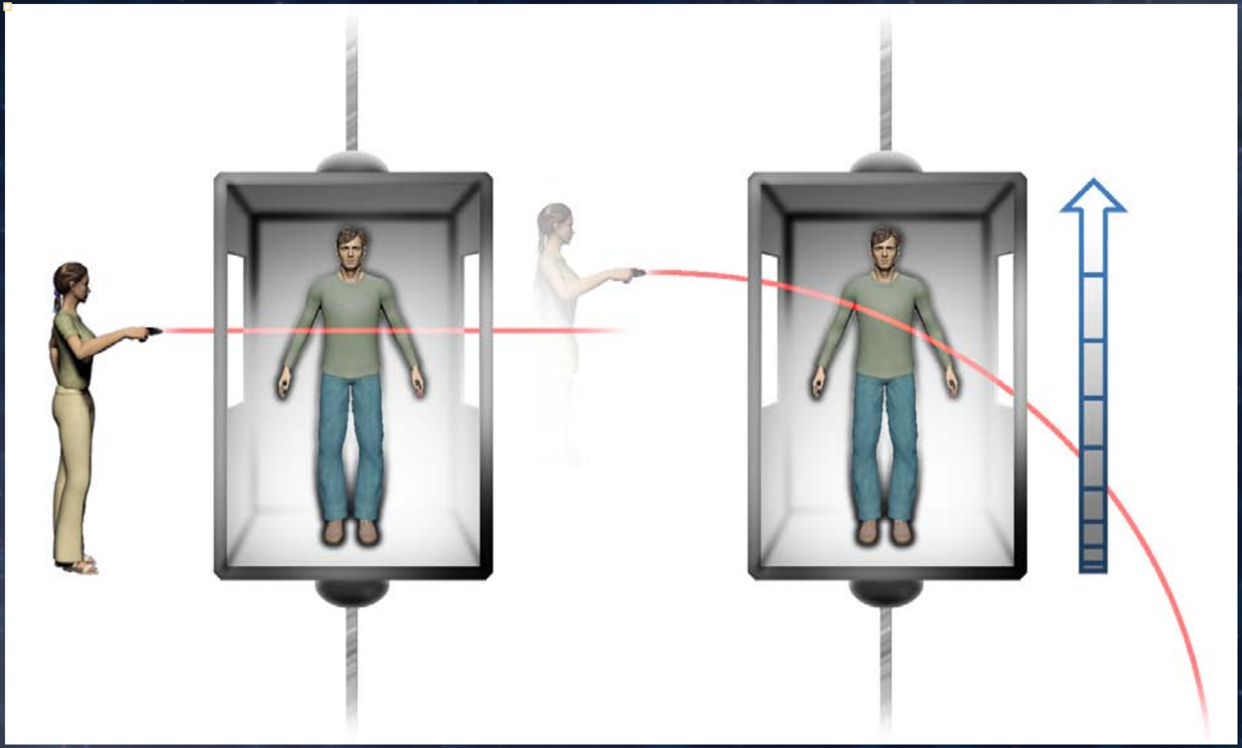
To an outside observer, the laser beam goes straight through the elevator.

The elevator occupant sees the laser beam traveling at an angle.



Principle of Equivalence

A laser beam through the windows of an upward-accelerating elevator:



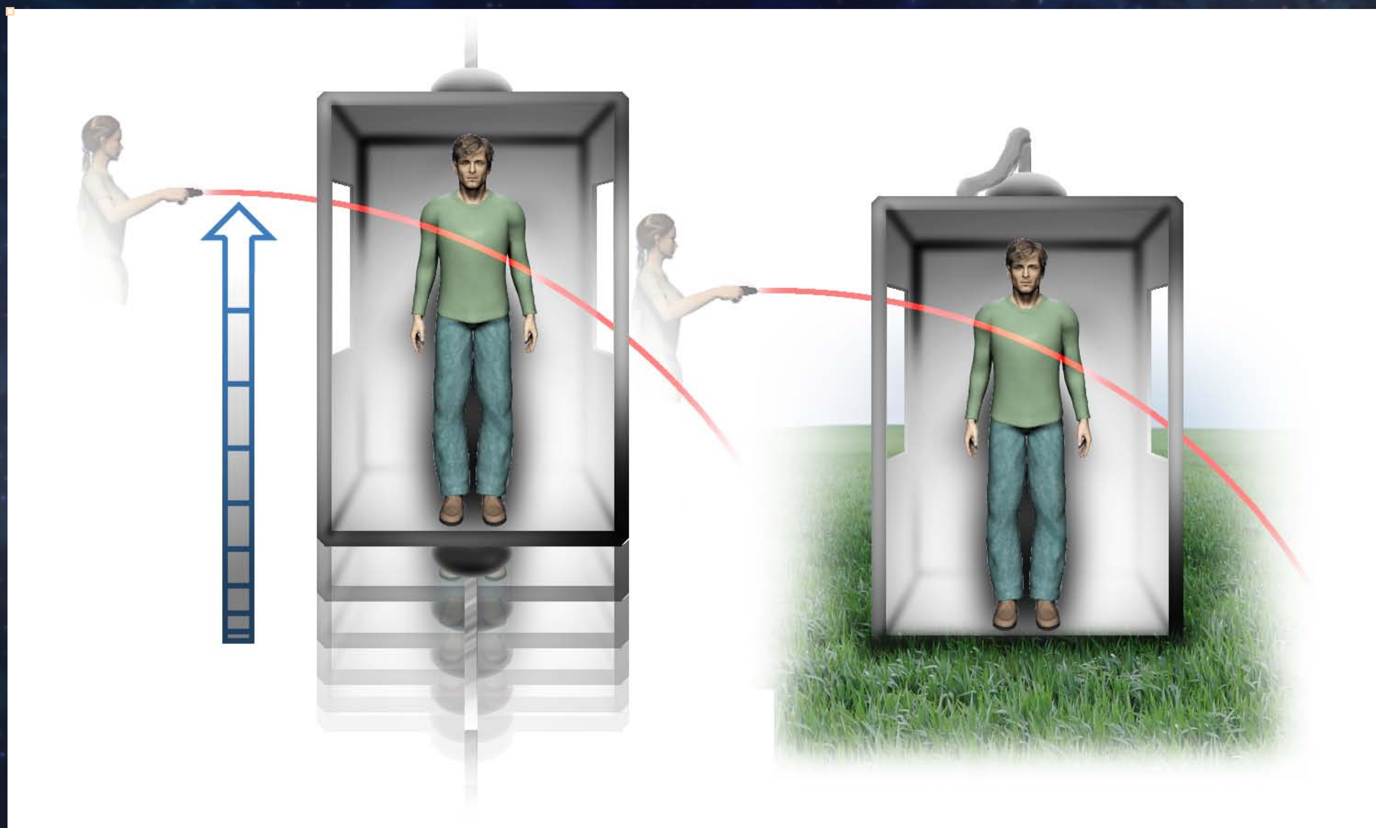
To the outside observer, the beam goes straight through the car, again.

To the car occupant, the beam goes down faster over time; the light path is curved.

Principle of Equivalence

Recall that an elevator accelerating upward is equivalent to a non-moving elevator in a stationary gravity field.

So, gravity can attract light and bend its path!



May 29, 1919 — Solar Eclipse

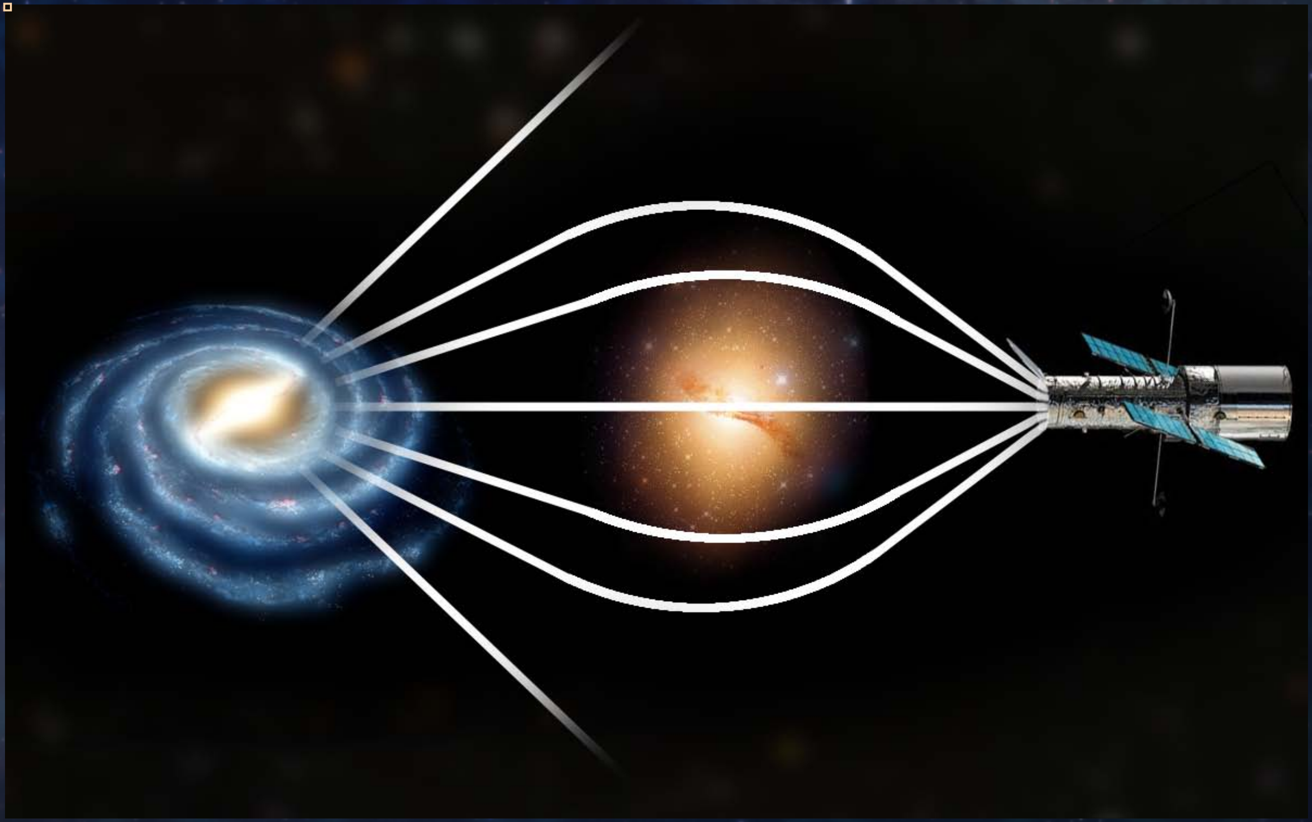
Gravitational bending of the path of light has been shown to be true. The first claim was made by **A.S. Eddington** in a 1919 expedition to the coast of west Africa to see the solar eclipse.

- Einstein predicted a star's apparent position would shift by ≈ 1.75" as it went behind the Sun.
- Eddington said he confirmed General Relativity — an apparent great success for the theory and made Einstein a celebrity.
- In fact, his data were consistent with General Relativity but were inconclusive (at best).
- Today we can measure this effect much better using radio telescopes and distant quasars (we measure 1.75 ± 0.05" or better).

Gravitational Bending of Light

Gravitational bending of light could have spectacular effects for a background galaxy aligned with a foreground galaxy. One might see…

- Multiple images
- Long arcs
- Magnification in size and intensity



Gravitational Bending of Light

An “Einstein Cross” gravitational lens

Gravitational Bending of Light

Multiple images from lensed galaxy behind CL 0024+1654

Gravitational Lens HST • WFPC2
Galaxy Cluster 0024+1654
PRC96-10 • ST ScI OPO • April 24, 1996
W.N. Colley (Princeton University), E. Turner (Princeton University), J.A. Tyson (AT&T Bell Labs) and NASA

Gravitational Bending of Light

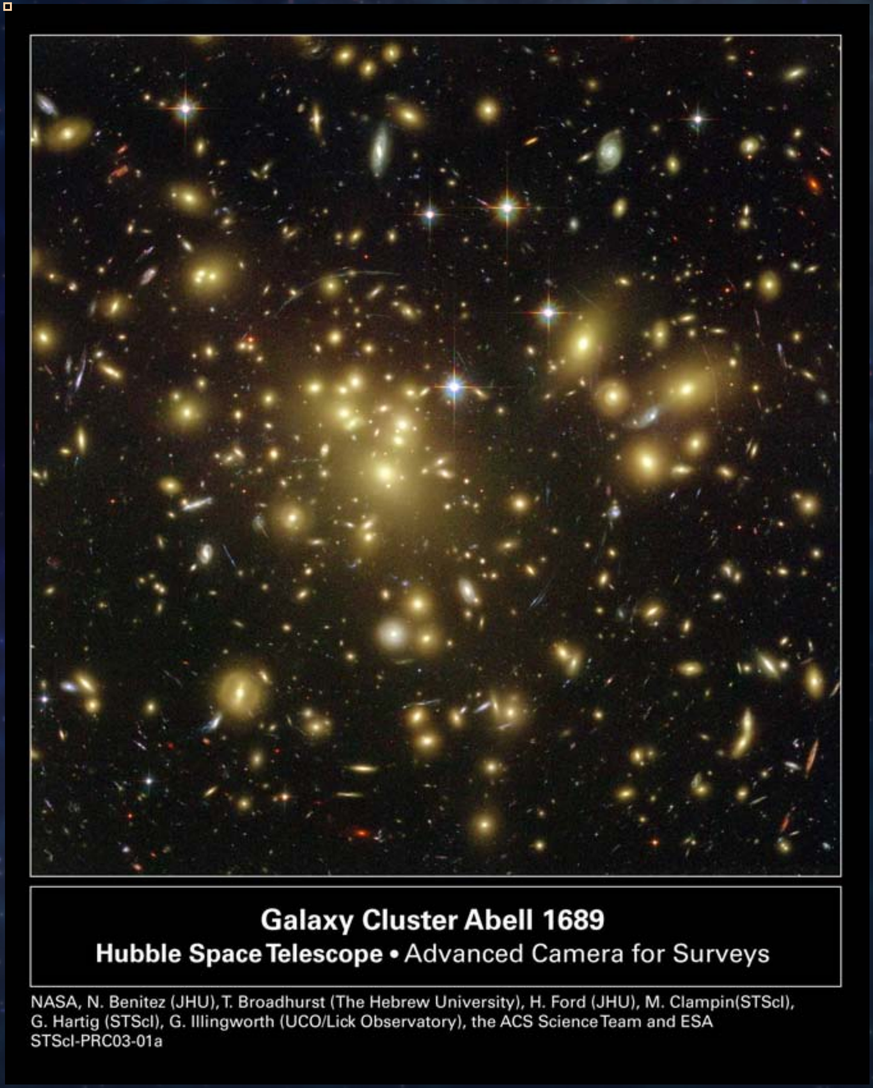
Gravitational lensing by galaxy cluster Abell 2218

Galaxy Cluster Abell 2218 **HST** • WFPC2

NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Gravitational Bending of Light

Gravitational lensing by galaxy cluster Abell 1689



Problems That Bothered Einstein

1. If nothing can propagate faster than light, then how can Newton's gravity act instantaneously at a distance?

   - That is, if at any instant of time two objects are separated by a distance d, then Newton's gravitational law says the force will be $\mathbf{F} \propto (\mathbf{M_1 M_2})/\mathbf{d}^2$.

   - How does the force "know" what to be instantaneously? It would have to send a signal faster than light.

Problems That Bothered Einstein

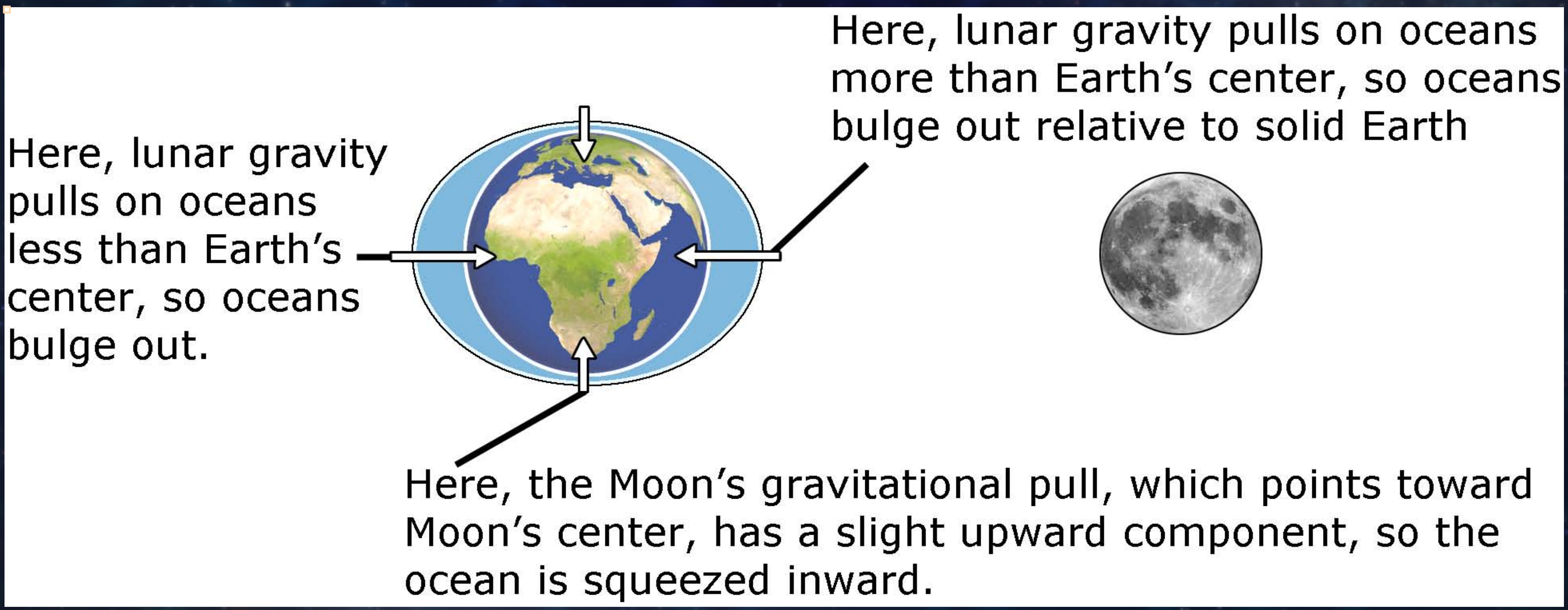
2. Another problem with $\mathbf{F} \propto (\mathbf{M_1 M_2})/\mathbf{d}^2$ is that different observers will not agree on the value of **d**, according to relativity.

   - For Mercury orbiting around the Sun, Mercury will see some lengths as Lorentz-contracted, but the Sun will not.

   - Just like for the muons! We know a muon is made 25 km up in Earth's atmosphere, but the muon "says" it is only made about ≤ 0.66 km up.

Problems That Bothered Einstein

What eventually led Einstein to more insight around 1911 was the consideration of something called "tidal gravity" because it makes the tides on Earth.



As Earth rotates, we get two "high tides" and two "low tides" per day.

Tidal Gravity

The Bay of Fundy at high and low tides, site of some of the greatest differences in high/low tide water levels in the world. Photos by Samuel Wantman, 1972.

High and low tides at Douglas (Juneau), Alaska.
Photos by Daniel Cornwall, 2006.

Problems That Bothered Einstein

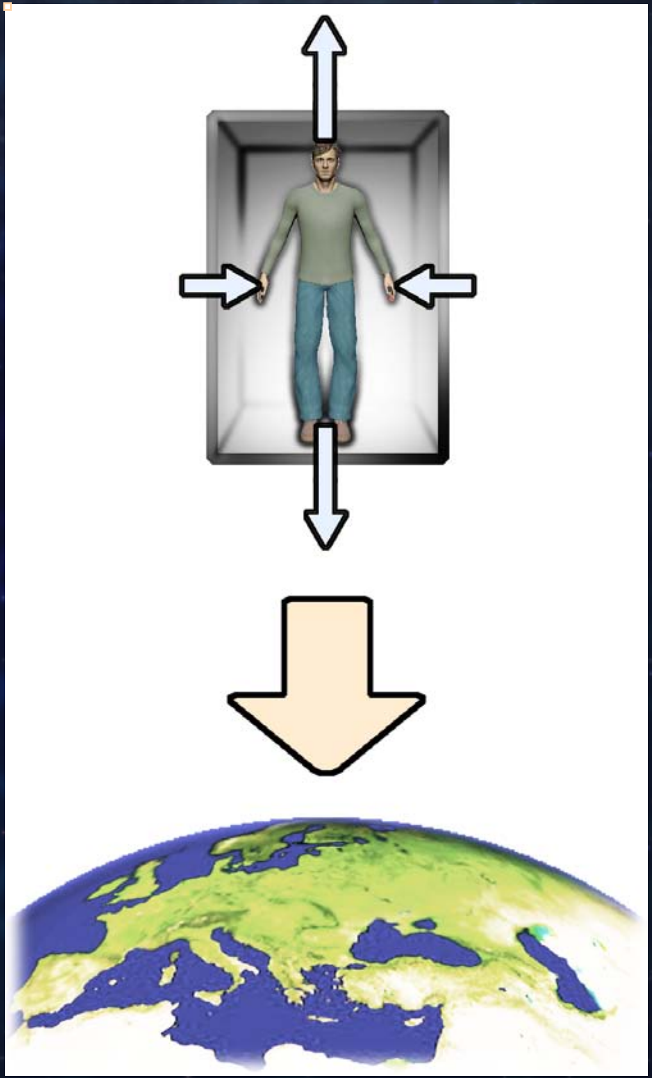
Let's return to Einstein's elevators:

- Gravity's pull is toward the center of the Earth (larger arrow)

- The person in the elevator feels the forces marked with smaller arrows (tidal forces).

Einstein realized this was a problem for his principle of equivalence.

You could discriminate between *falling freely toward a mass* and *moving through space at constant velocity* because in the first case you would feel additional tidal forces.



Lecture 5:

Curvature of Spacetime

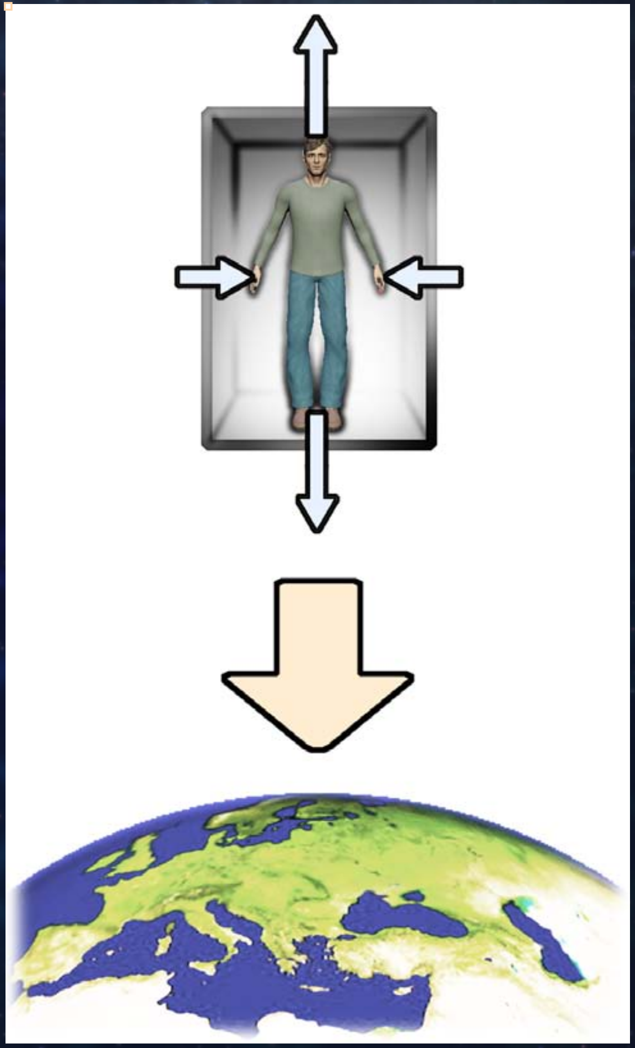
Spacetime Curvature

In the last lecture, we talked about tidal gravity and how this bothered Einstein greatly.

A person in an elevator falling towards Earth (large arrow) feels tidal forces (small arrows).

This violates the principle of equivalence for any finite-sized observer.

These considerations led Einstein ultimately to propose that space and time were “warped” by presence of mass; or, that mass created “spacetime curvature.”



Spacetime Curvature

A 2-D analogy to our 3-D world

2D (planar) geometry

- parallel lines never cross
- sum of the angles in a triangle = 180˚
- Euclid’s postulates hold true

3D, spherical

- lines initially parallel at the
- equator intersect at the poles
- sum of the angles in a triangle > 180˚
- a sufficiently small area is locally flat

Detecting Spacetime Curvature

Karl Friedrich Gauss, from 1818-1832 tried to test for curvature of space by measuring angles for a
3-mountain triangle.

- Mountains: Hohenhagen, Inselberg, Brocken in Germany: 70-110 km apart
- He got 180˚, but this wasn't wildly surprising

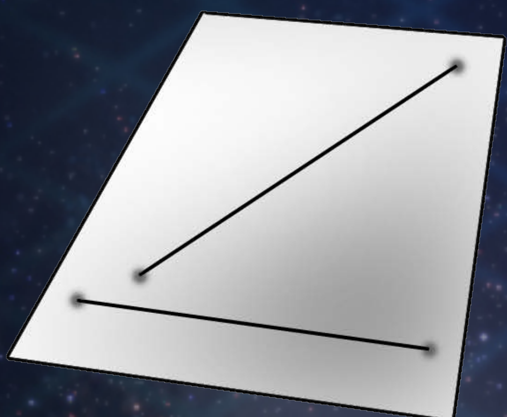
If space were curved strongly enough to allow Gauss to detect the curvature, it would dramatically affect many things – space *is* curved, but not on this scale.

Gauss — 1840 portrait by Christian Albrecht Jensen

Geodesics

Any line, on a curved or flat surface, that is "straight" in that…

1. It is the shortest route between two points
2. In a sufficiently small region the line appears straight in the usual "piece of paper" sense.



On a sphere, a geodesic would be a "great circle" (or part thereof).

The shortest flight between Los Angeles and Tokyo is by Alaska.

Geodesics

Einstein proposed that…

1. **Matter curves spacetime**, and gravity is just a manifestation of that curvature

2. Objects in curved spacetime **always move along geodesics** (unless acted upon by some nongravitational force)

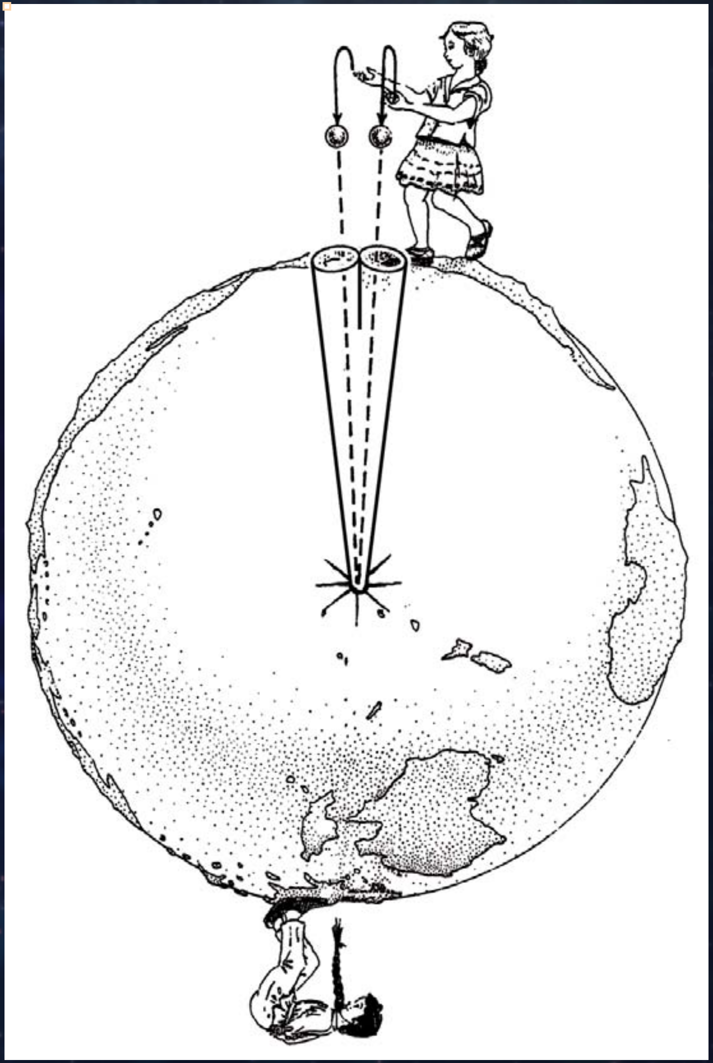
Newtonian vs. Einstein’s Gravity

Imagine throwing two balls into the air on Earth’s surface with precisely parallel trajectories. Each ball then falls back down into a small borehole you’ve drilled into the Earth.

Each ball will fall toward the center of the Earth, and they will hit each other there.

In Newtonian gravity, we would say that tidal gravity acted on the balls.

In Einstein’s gravity we would say that the balls moved along geodesics, but spacetime is curved due to the mass of the Earth, and this caused the balls’ paths to intersect just like the curvature of a globe causes parallel lines to intersect.



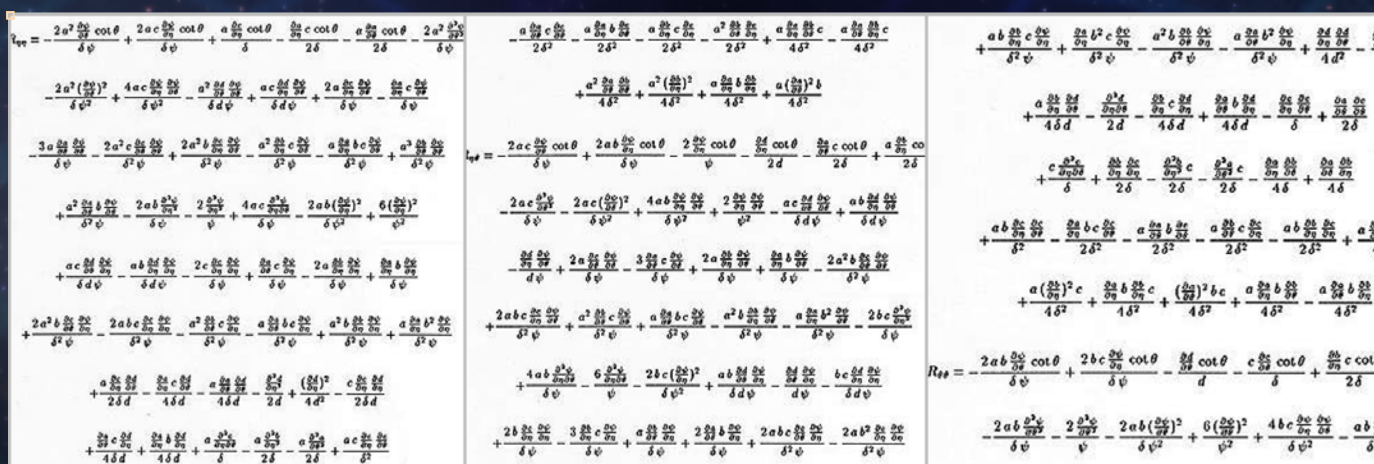
(*Fig. 2.5, from Thorne 1994 - p.110*)

Einstein Field Equations

One might be tempted to say that all Einstein did was "rename" tidal gravity to be spacetime curvature – *so what?*

Actually, he did much more than this, but you need to learn lots of math to appreciate it fully. In particular, Einstein specified a mathematical "law of curvature" that lets one calculate the amount spacetime is curved by any given mass.

$$G^{ab} = \left(\frac{8\pi G}{c^2}\right) T^{ab}$$



Pages of work applying Einstein Field Equations in 2D. (*http://archive.ncsa.uiuc.edu/Cyberia/NumRel/mathmine3.html*)

About this work, Einstein later wrote, "Compared to this problem the original [special] relativity theory is child's play."

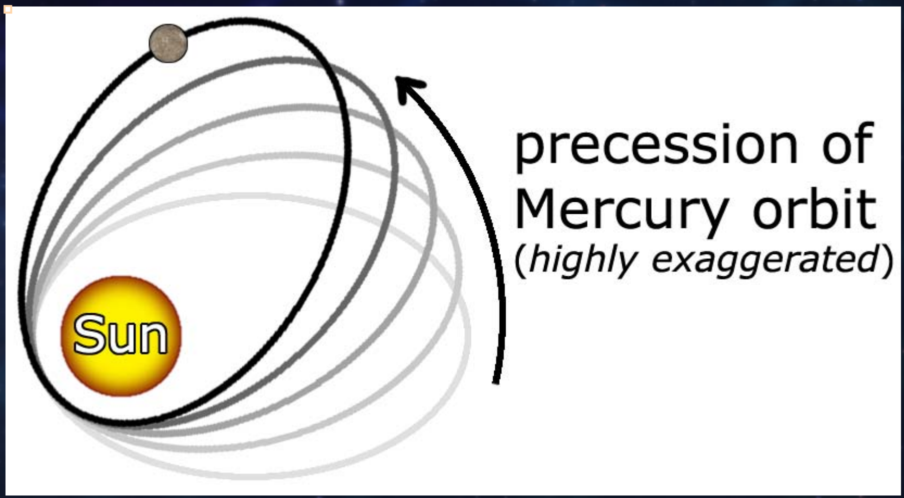
Einstein Field Equations

Einstein's law of curvature gives the right answers while Newton's theory does not!

- Curvature of light paths by the Sun (1.75")
- Account for the 'extra' 0.10"-per-orbit precession of Mercury
- Other "modern" tests confirm Einstein's work, which I'll describe later.

The orbit of Mercury was correctly predicted in November 1915.

When Einstein got this result, he was beside himself with joy. For three days, he was so excited that he couldn't work.

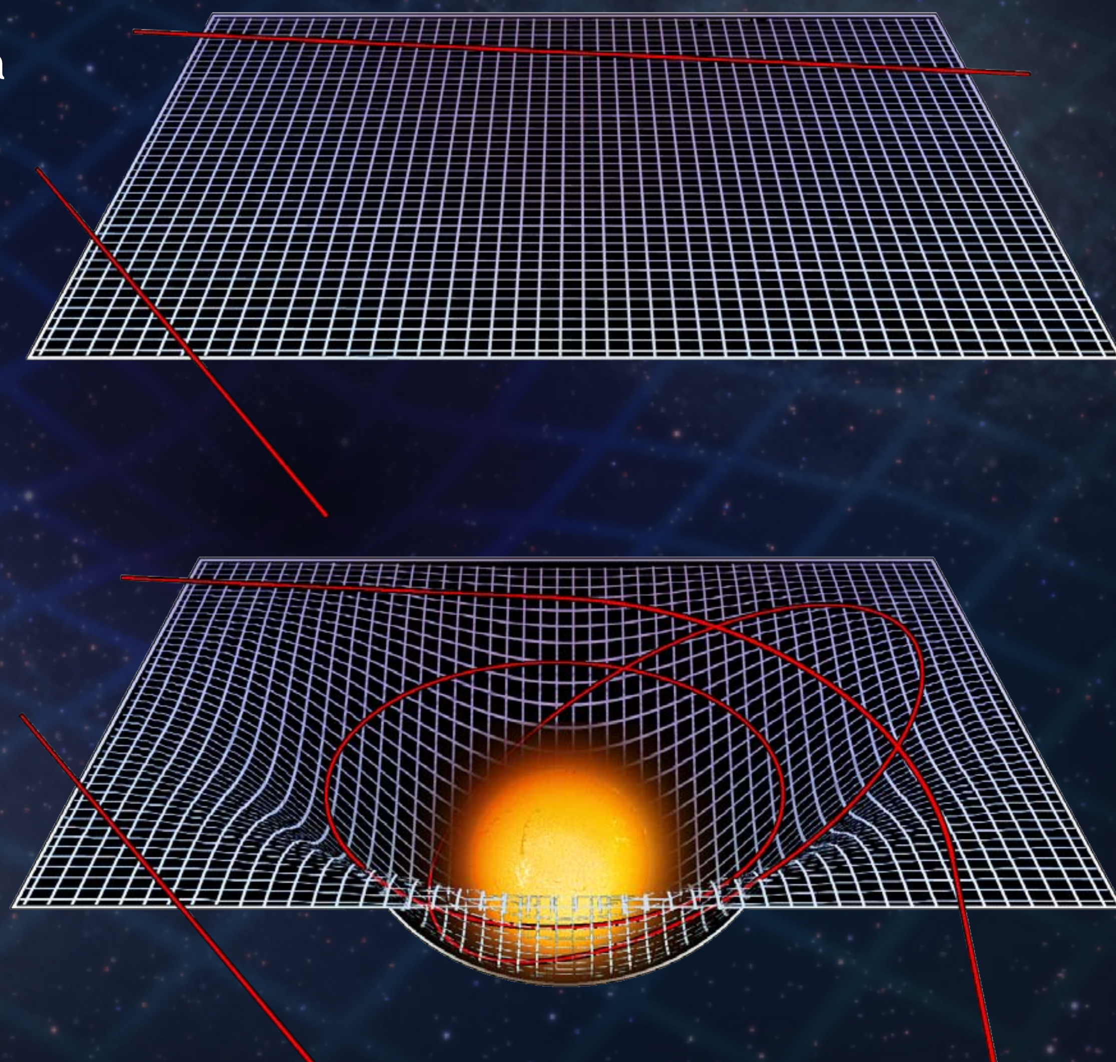


Spacetime Curvature: Rubber Sheet Analogy

A rubber sheet with nothing on it remains flat. If we roll a small ball along it, it will roll in a straight line – analagous to how an object in empty space moves in a straight line.

Now put a massive object on the sheet, and roll a small ball across the sheet near the object. The small ball will roll around the depression and change direction as if a force acted on it.

We can also explain orbits this way — shortest distance between two points. Also, larger masses curve the rubber sheet more — just like spacetime.



Spacetime Curvature

Spiral Wishing Well, from *http://www.spiralwishingwells.com*

Spacetime Curvature

"... .one thing is certain, that in all my life I have never struggled so hard, and that I have been infused with great respect for mathematics the subtler parts of which, in my simple-mindedness, I had considered pure luxury up to now!"

— *A. Einstein, 1912*

Lecture 6:

Schwarzschild's Solution

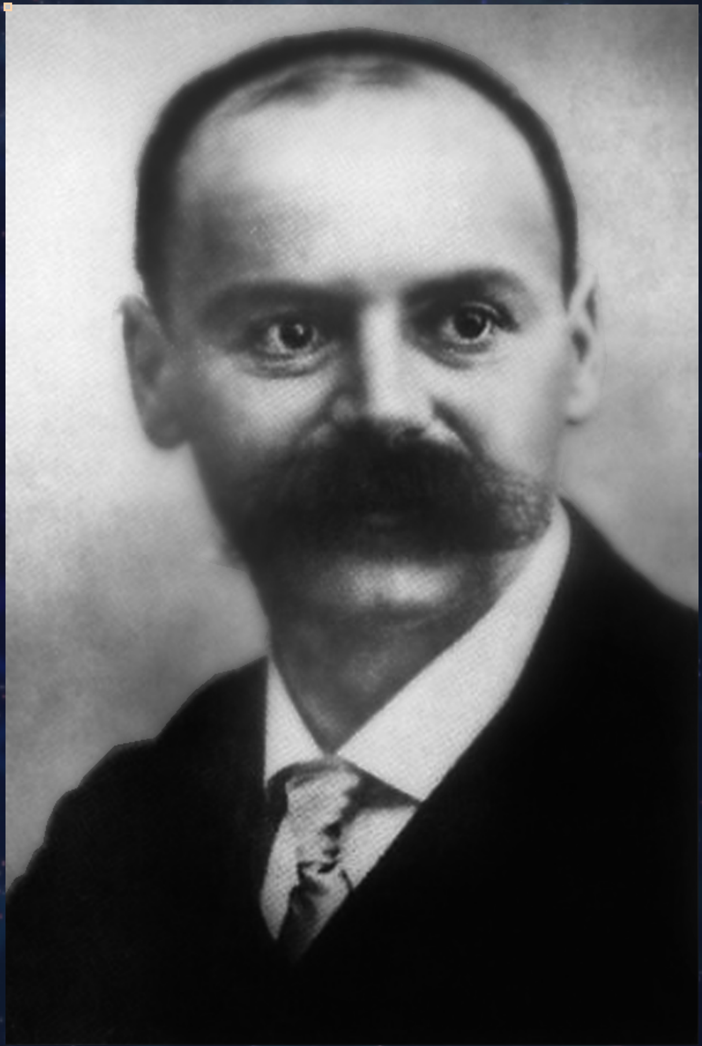
Karl Schwarzschild

Read about Einstein's work on general relativity while serving in the German army on the Russian front during World War I.

Within just 1-2 months, tried to apply Einstein's theory to a star.

Calculated the curvature of spacetime for a spherical, nonspinning star. Einstein was impressed, and presented Schwarzchild's results on January 13, 1916.

His elegant calculation is still used today — the "**Schwarzchild spacetime geometry.**"

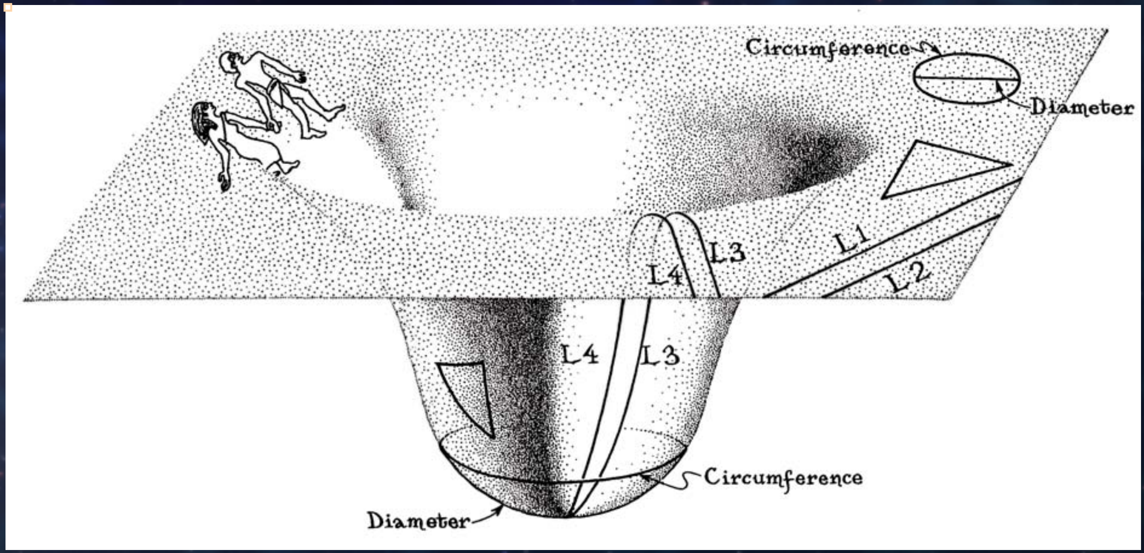


Karl Schwarzschild, 1873-1916

Schwarzschild Spacetime Geometry

A few key points, for this 2D analogy to 4D spacetime:

- 2D beings living in this universe cannot conceive of another dimension
- Far from the lip of the bowl, the local space is "flat" (*e.g.*, L1 and L2 stay parallel)
- But in the bowl, initially parallel lines eventually cross (L3 and L4 are "curved")
- Also, triangles: outside bowl, the sum of the angles = 180°; inside, the sum is > 180°
- Also, inside the bowl, the circumference of a circle is < ($\pi \times$ diameter)



(Fig. 3.2, from Thorne 1994 - p.127)

Embedding Diagram

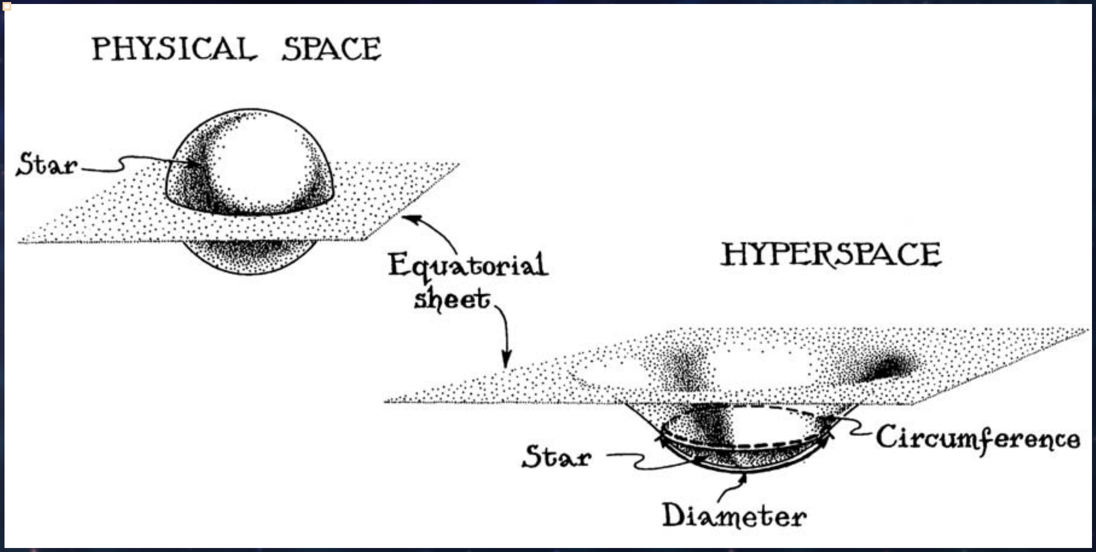
Although the sheet looks flat in the picture, it isn't really flat. The star's mass curves 3D space inside and around the star.

We can discover this curvature by making geometric measurements.

- Straight lines, initially parallel, cross near the star's center
- Angles of a triangle > 180°
- Circumference < ($\pi \times$ diameter)

Quantitative details of "how much" are predicted by Schwarzchild's solution.

We can imagine extracting this 2D sheet from the curved 3D space of our Universe and embedding it in a fictitious 3D "hyperspace."

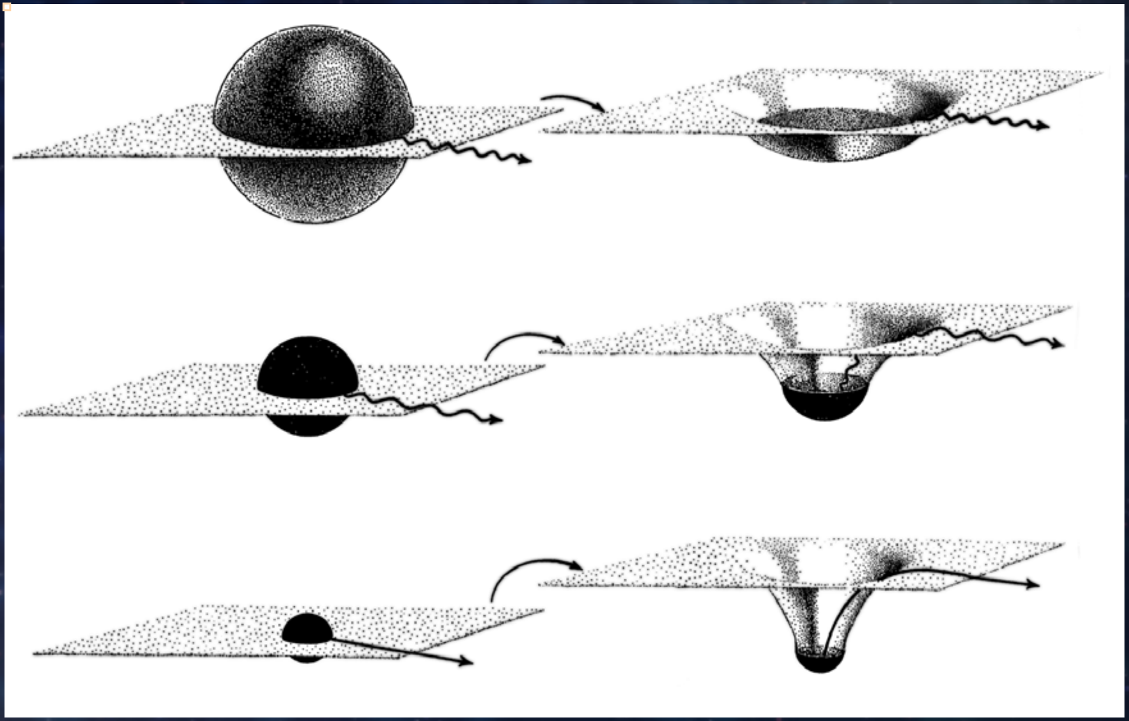


(Fig. 3.3, from Thorne 1994 – p.129)

Embedding Diagram

These effects are small for our Sun – circumference < ($\pi \times$ diameter), by only a few parts per million.

If the Sun had its mass compacted to be smaller and smaller in size, the curvature would get stronger and stronger.



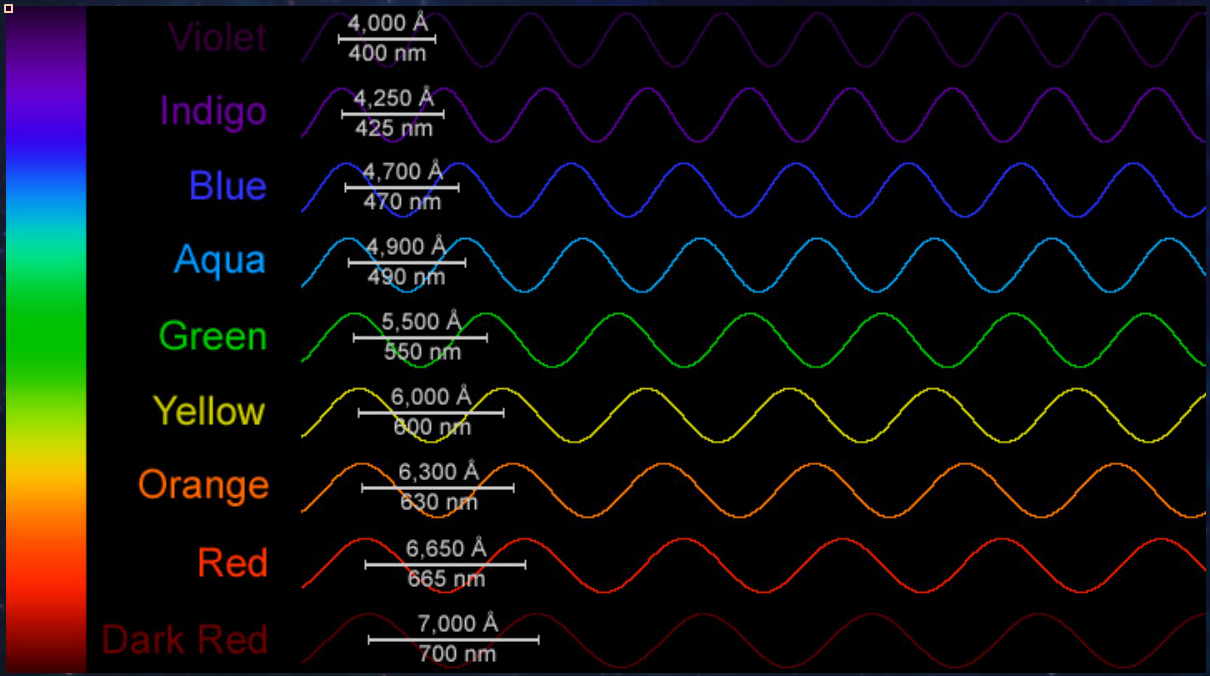
(adapted from Fig. 3.4, from Thorne 1994 - p.132)

This corresponds to the downward dip of the bowl becoming more pronounced.

Gravitational Redshift

Just as gravity extracts energy from an object trying to move away from a massive body, it also extracts energy from light (photons).

For light, less energy = longer wavelength. Blue light has a shorter wavelength than red — hence, the light is "redshifted."



This is a small effect for the Sun — just about two parts per million — too little to make a visible change in color.

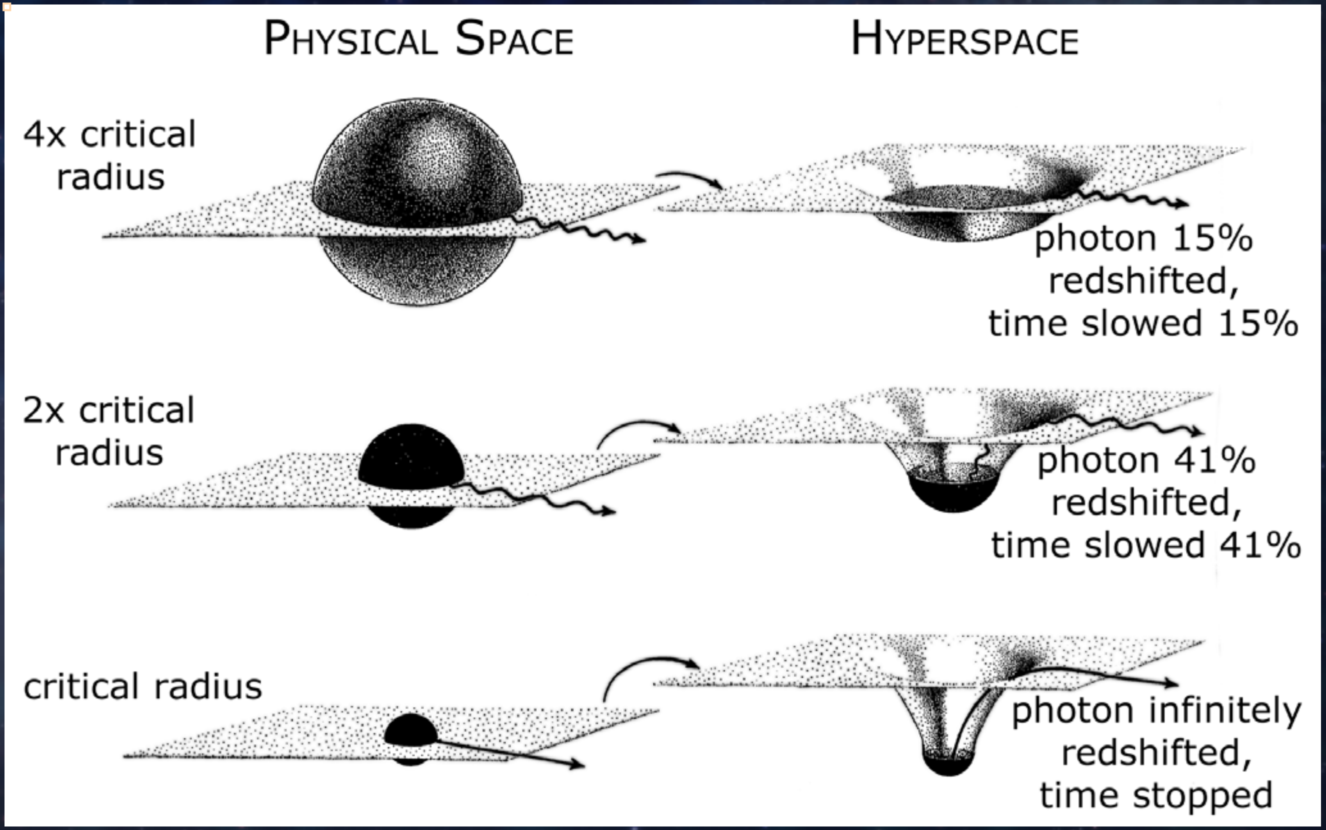
(credit: University Corporation for Atmospheric Research, *http://www.windows.ucar.edu*)

Schwarzschild Radius

The critical radius at which "bad" things start to happen:

$$R_S = 2GM/c^2$$

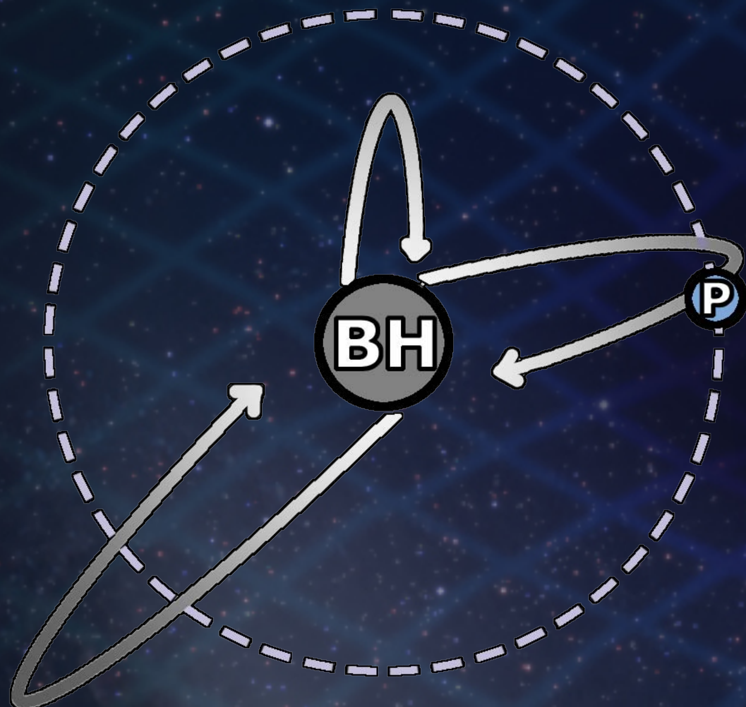
This is equivalent to 3 km of radius per solar mass.



(adapted from Fig. 3.4, from Thorne 1994 – p.132)

Newtonian vs. General Relativistic Black Holes

Newtonian black hole



- Light launched from the surface is always recaptured
- A creature on a nearby orbiting planet would see some light

General relativistic black hole

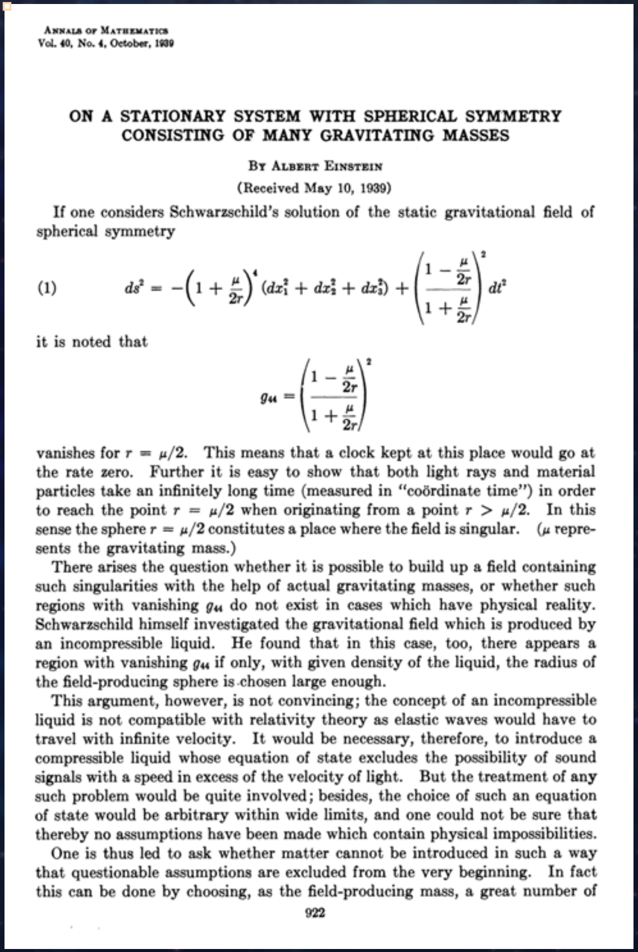
- No light gets out at all
- A creature on a nearby orbiting planet would see nothing
- In fact, infinite redshift occurs in infinitesimal distance!

Reaction to Black Holes

Einstein and Eddington, the world's leading relativists, first tried to ignore black holes, and in the 1930s, switched to denouncing the idea.

In 1939, Einstein published a paper claiming to explain why Schwarzschild singularities could never exist in nature. Einstein's arguments were, in fact, wrong, and it took until the 1950s for physicists to straighten the matter out.

Getting things straight took a better understanding of stars and their fates.



ANNALS OF MATHEMATICS
Vol. 40, No. 4, October, 1939

ON A STATIONARY SYSTEM WITH SPHERICAL SYMMETRY CONSISTING OF MANY GRAVITATING MASSES

BY ALBERT EINSTEIN

(Received May 10, 1939)

If one considers Schwarzschild's solution of the static gravitational field of spherical symmetry

$$ds^2 = -\left(1 + \frac{\mu}{2r}\right)^4 (dx_1^2 + dx_2^2 + dx_3^2) + \left(\frac{1 - \frac{\mu}{2r}}{1 + \frac{\mu}{2r}}\right)^2 dt^2 \tag{1}$$

it is noted that

$$g_{44} = \left(\frac{1 - \frac{\mu}{2r}}{1 + \frac{\mu}{2r}}\right)^2$$

vanishes for $r = \mu/2$. This means that a clock kept at this place would go at the rate zero. Further it is easy to show that both light rays and material particles take an infinitely long time (measured in "coördinate time") in order to reach the point $r = \mu/2$ when originating from a point $r > \mu/2$. In this sense the sphere $r = \mu/2$ constitutes a place where the field is singular. (μ represents the gravitating mass.)

There arises the question whether it is possible to build up a field containing such singularities with the help of actual gravitating masses, or whether such regions with vanishing g_{44} do not exist in cases which have physical reality. Schwarzschild himself investigated the gravitational field which is produced by an incompressible liquid. He found that in this case, too, there appears a region with vanishing g_{44} if only, with given density of the liquid, the radius of the field-producing sphere is chosen large enough.

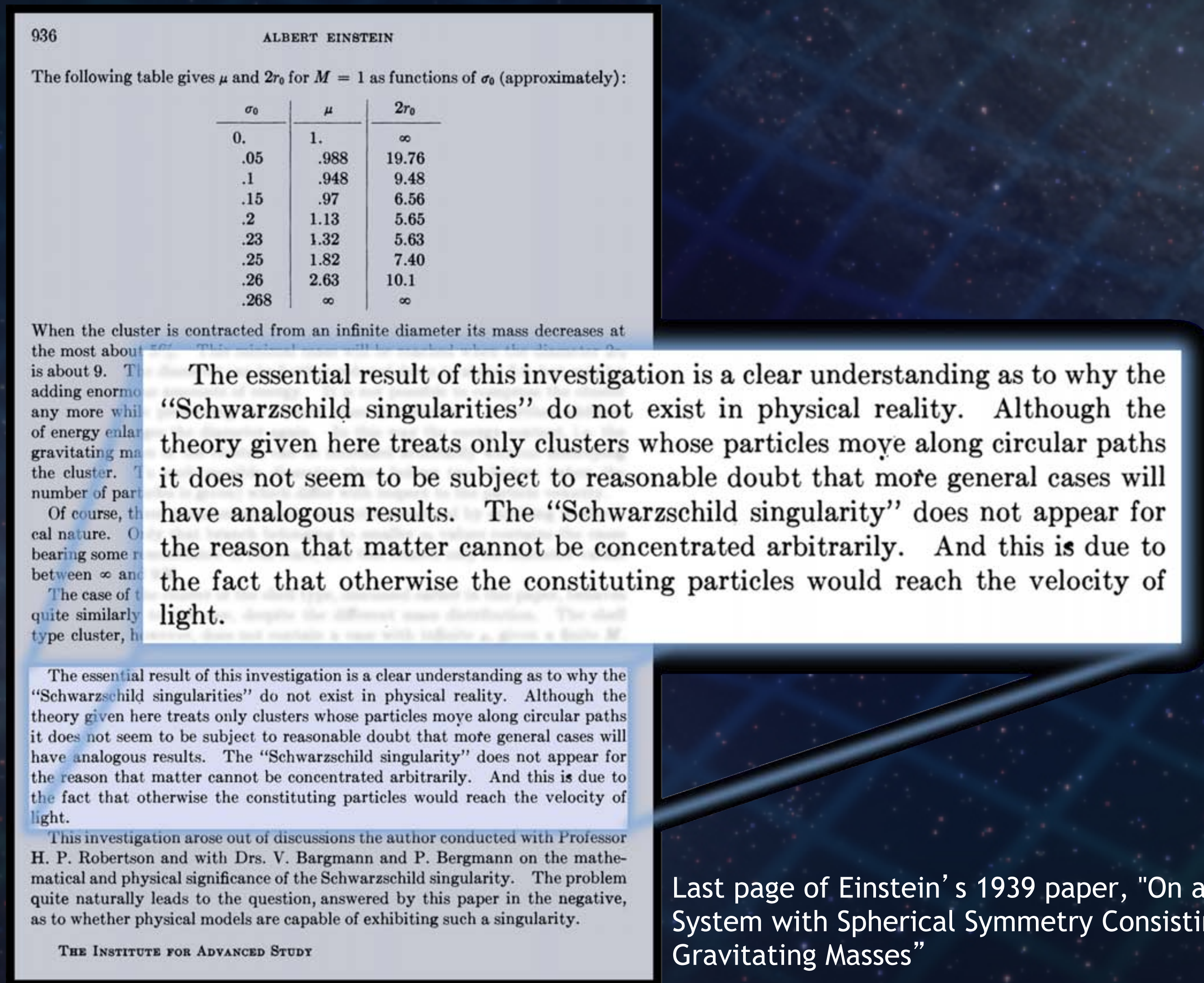
This argument, however, is not convincing; the concept of an incompressible liquid is not compatible with relativity theory as elastic waves would have to travel with infinite velocity. It would be necessary, therefore, to introduce a compressible liquid whose equation of state excludes the possibility of sound signals with a speed in excess of the velocity of light. But the treatment of any such problem would be quite involved; besides, the choice of such an equation of state would be arbitrary within wide limits, and one could not be sure that thereby no assumptions have been made which contain physical impossibilities.

One is thus led to ask whether matter cannot be introduced in such a way that questionable assumptions are excluded from the very beginning. In fact this can be done by choosing, as the field-producing mass, a great number of

922

Einstein's 1939 paper, "On a Stationary System with Spherical Symmetry Consisting of Many Gravitating Masses," which features his criticism of Schwarzschild's singularities.

Reaction to Black Holes



The following table gives μ and $2r_0$ for $M = 1$ as functions of σ_0 (approximately):

σ_0	μ	$2r_0$
0.	1.	∞
.05	.988	19.76
.1	.948	9.48
.15	.97	6.56
.2	1.13	5.65
.23	1.32	5.63
.25	1.82	7.40
.26	2.63	10.1
.268	∞	∞

When the cluster is contracted from an infinite diameter its mass decreases at the most about … is about 9. T… adding enormo… any more whil… of energy enlar… gravitating ma… the cluster. T… number of part…

Of course, th… cal nature. O… bearing some r… between ∞ and…

The case of t… quite similarly … type cluster, h…

The essential result of this investigation is a clear understanding as to why the "Schwarzschild singularities" do not exist in physical reality. Although the theory given here treats only clusters whose particles move along circular paths it does not seem to be subject to reasonable doubt that more general cases will have analogous results. The "Schwarzschild singularity" does not appear for the reason that matter cannot be concentrated arbitrarily. And this is due to the fact that otherwise the constituting particles would reach the velocity of light.

This investigation arose out of discussions the author conducted with Professor H. P. Robertson and with Drs. V. Bargmann and P. Bergmann on the mathematical and physical significance of the Schwarzschild singularity. The problem quite naturally leads to the question, answered by this paper in the negative, as to whether physical models are capable of exhibiting such a singularity.

THE INSTITUTE FOR ADVANCED STUDY

The essential result of this investigation is a clear understanding as to why the "Schwarzschild singularities" do not exist in physical reality. Although the theory given here treats only clusters whose particles move along circular paths it does not seem to be subject to reasonable doubt that more general cases will have analogous results. The "Schwarzschild singularity" does not appear for the reason that matter cannot be concentrated arbitrarily. And this is due to the fact that otherwise the constituting particles would reach the velocity of light.

Last page of Einstein's 1939 paper, "On a Stationary System with Spherical Symmetry Consisting of Many Gravitating Masses"

Lecture 7:

Stellar Fates

Work on Stellar Evolution

Understanding black holes required an improved knowledge of the lives and deaths of stars.

Some of the main people involved were S. Chandrasekhar, F. Zwicky, L. Landau, J.R. Oppenheimer and his students, R.C. Tolman, and J.A. Wheeler.


Chandrasekhar


Zwicky


Landau


Oppenheimer


Tolman


Wheeler

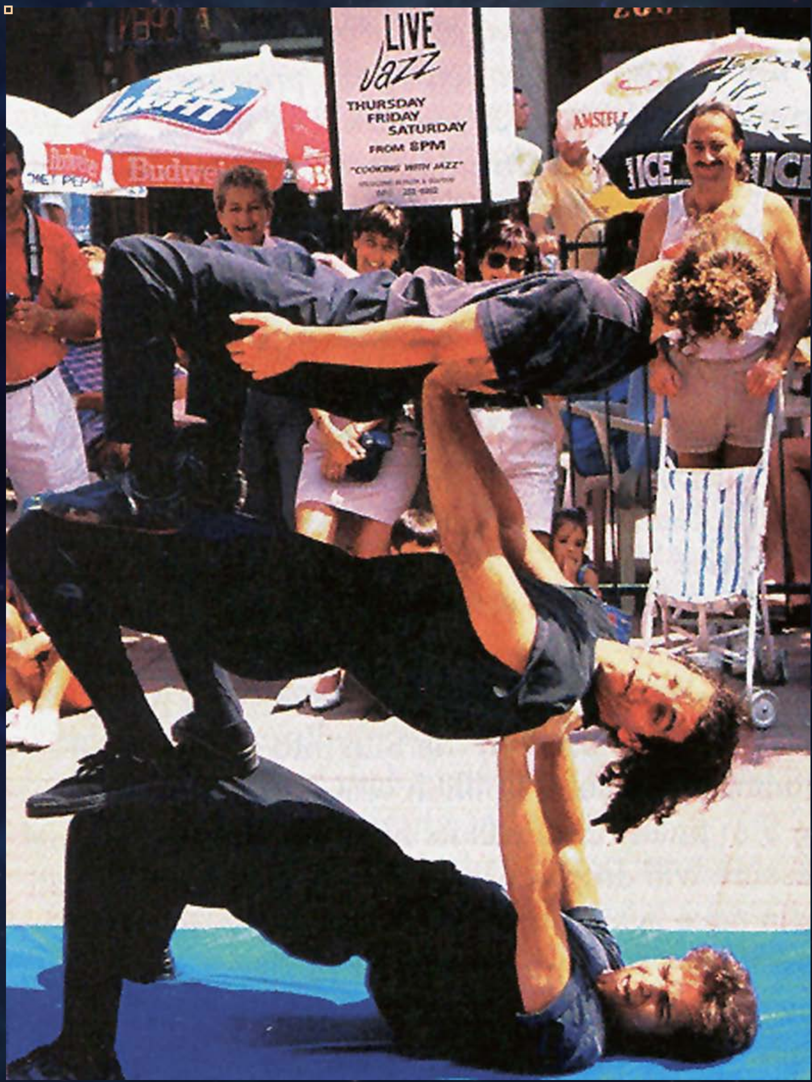
Lives and Deaths of Stars

The life of a normal star is a "battle" of gravity versus fusion. You could say stars are "gravitationally bound fusion reactors."

1. Fusion makes heat and pressure inside the star to prevent gravitational collapse.

2. However, this can't go on forever since energy is escaping as luminosity.

3. Eventually the available fuel supply runs out and the star collapses.



Lives and Deaths of Stars

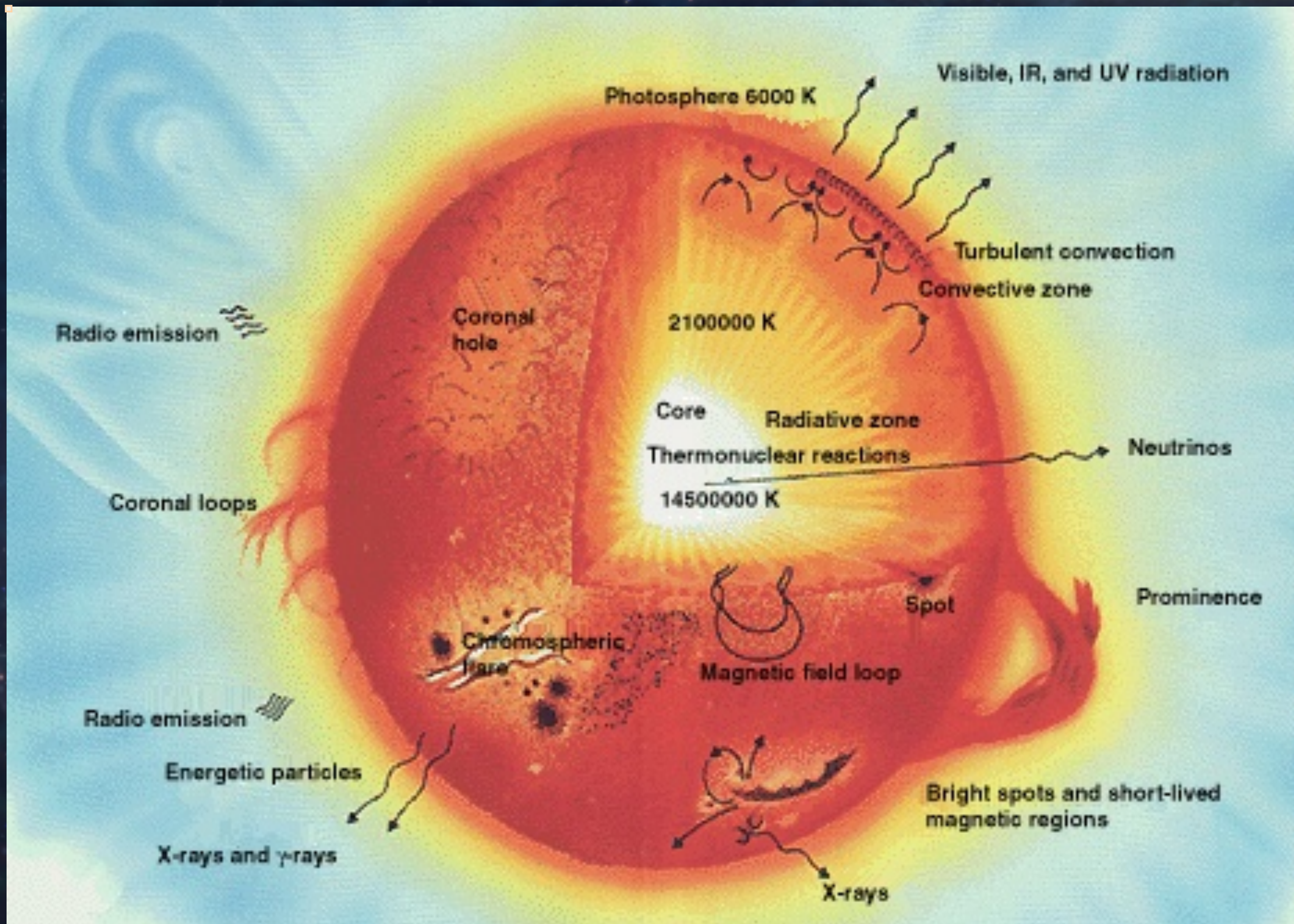


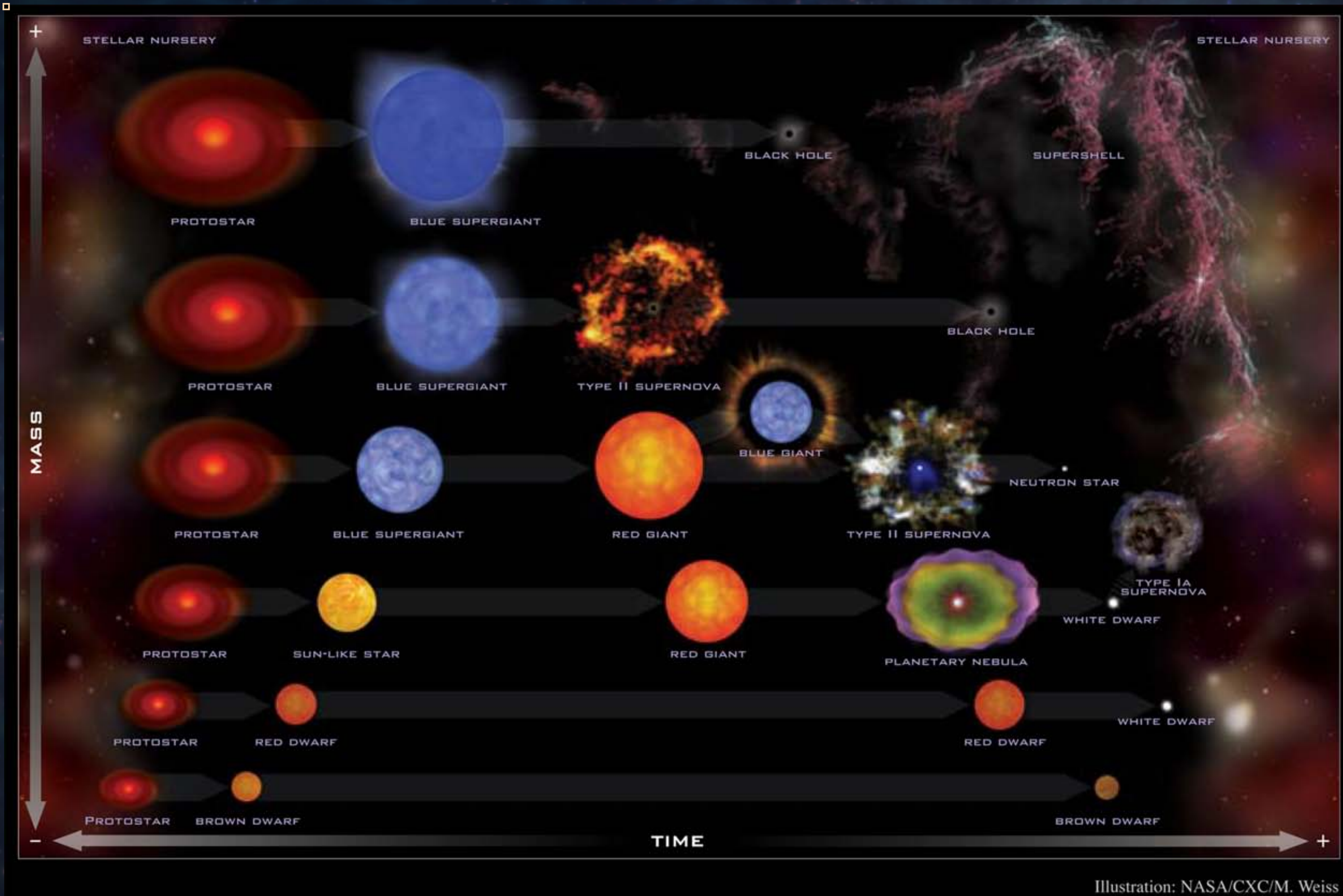
Diagram of a Solar-Type star (credit: *NASA*)

Lives and Deaths of Stars

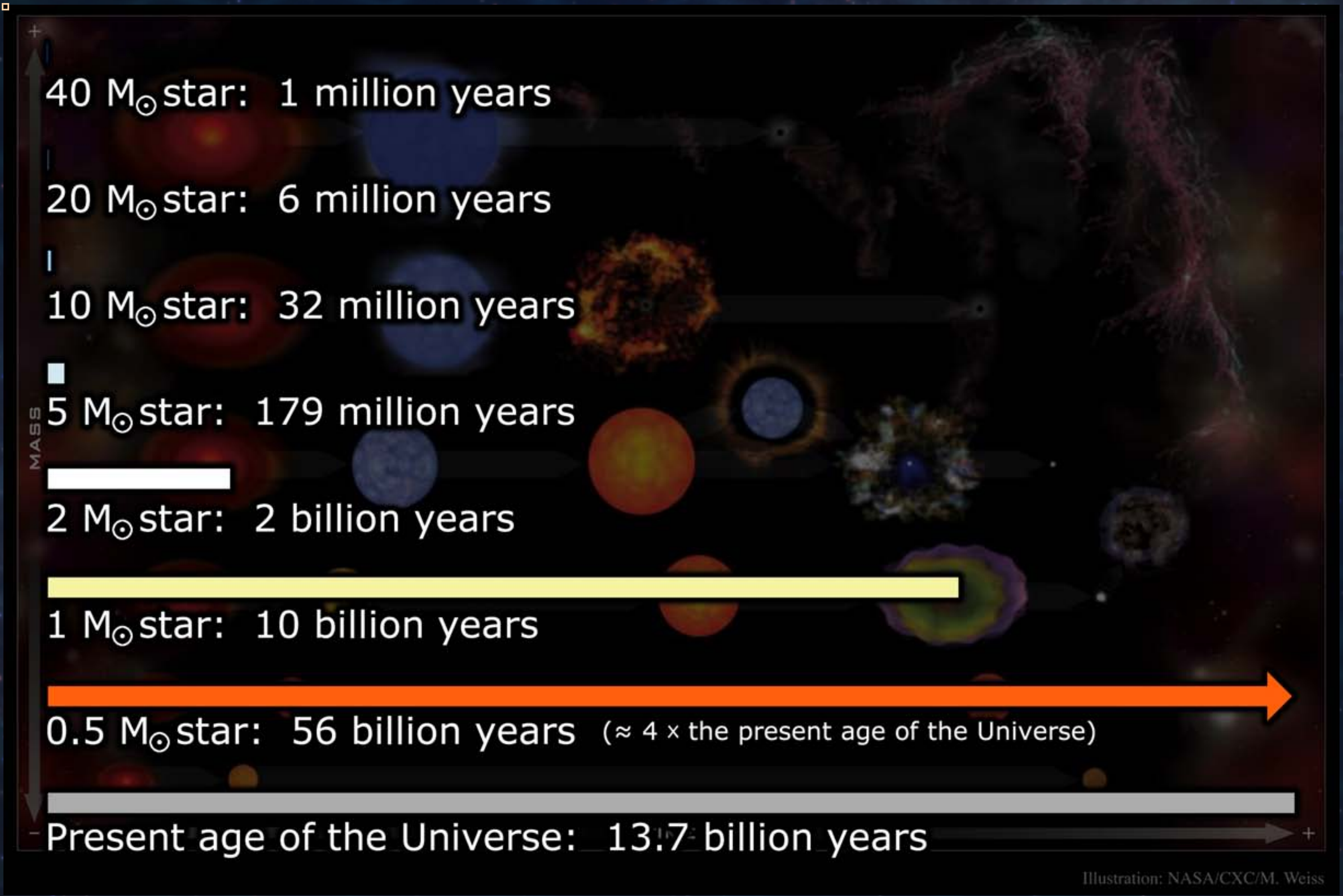
3 basic fates for stars:

1. White dwarf — "electron degeneracy pressure" fights off gravitational collapse; for stars born with about ≤ 8 $M_{\odot}$
2. Neutron star — "neutron degeneracy pressure" fights off gravitational collapse; for stars born with about 8-30 $M_{\odot}$
3. Black hole — nothing fights off gravitational collapse; for stars born with about ≥ 30 $M_{\odot}$

Lives and Deaths of Stars



Lives and Deaths of Stars



(stellar lifetimes estimated using $\tau/\tau_{\odot} \sim (M/M_{\odot})^{-2.5}$, where $\tau_{\odot}=10^{10}$ years)

Eta Carinae

One of the most luminous stars in the galaxy, at ≈ 5 million $L_{\odot}$

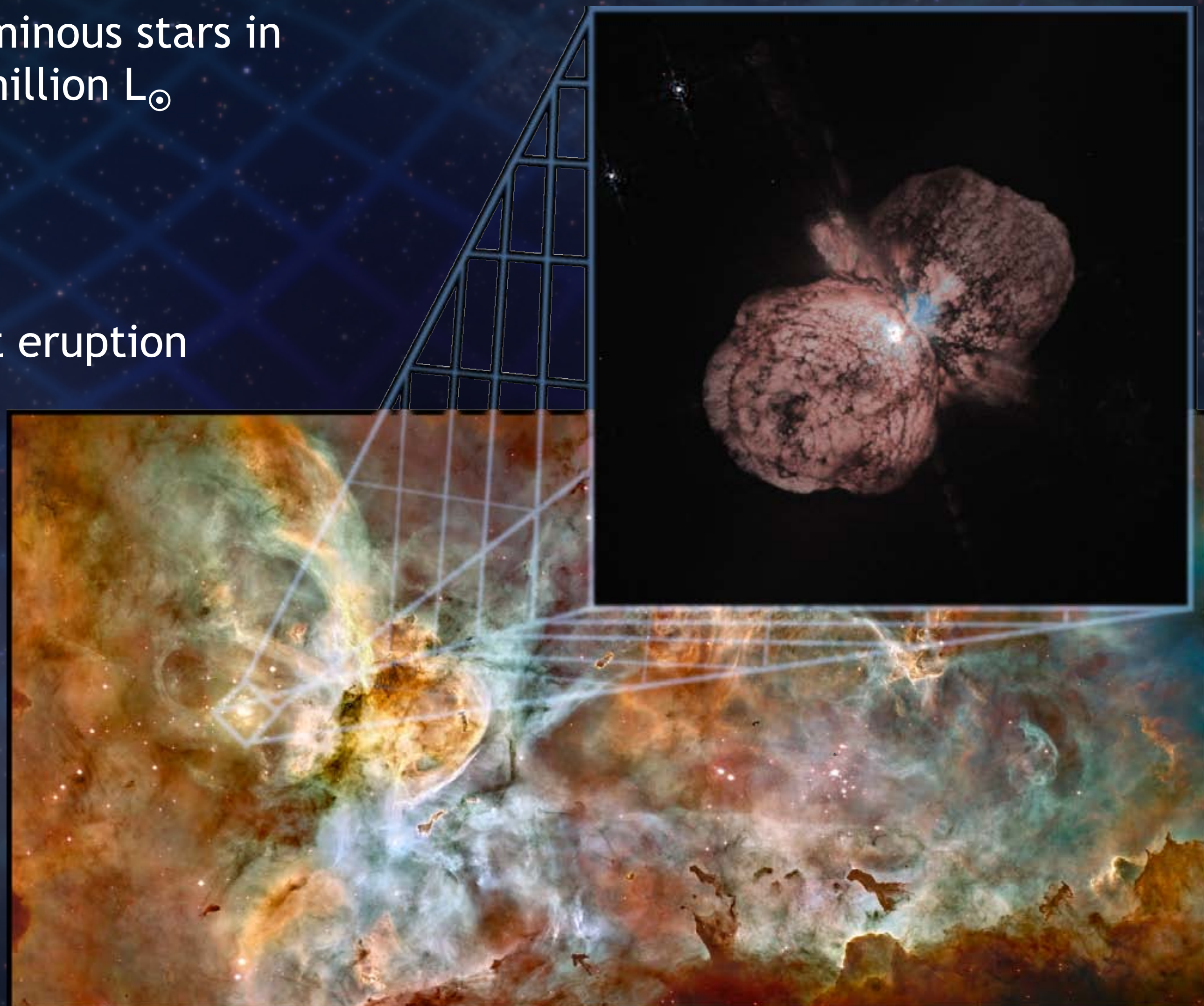
Perhaps ≈100 $M_{\odot}$

Experienced a giant eruption around 1837-1856

Could collapse at any time — probably forming a black hole

⟹

Hubble Space Telescope image of NGC 3372, host nebula to η Carinae (above, right)



Eta Carinae

Arnon Dar and A. De Rújula (2001), “The Threat to Life from Eta Carinae and Gamma-Ray Bursts.”

THE THREAT TO LIFE FROM ETA CARINAE AND GAMMA-RAY BURSTS

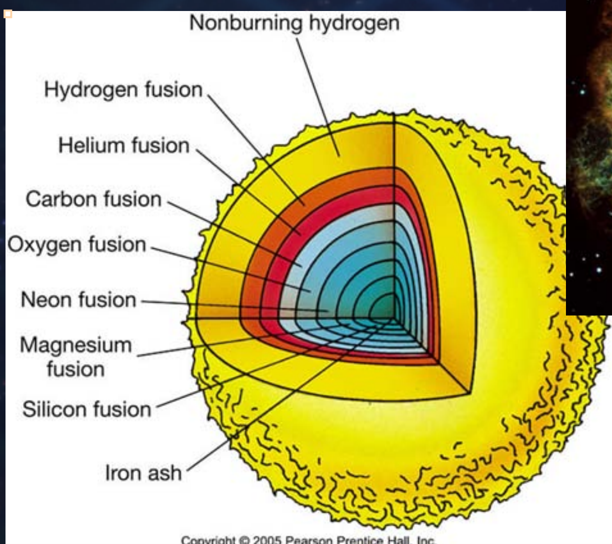
Arnon Dar[1] and A. De Rújula[2]
1. Department of Physics and Space Research Institute, Technion, Haifa 32000, Israel
2. Theory Division, CERN, Geneva 23, Switzerland

Eta Carinae, the most massive and luminous star known in our galaxy, is rapidly boiling matter off its surface. At any time its core could collapse into a black hole, which may result in a gamma-ray burst (GRB) that can devastate life on Earth. Auspiciously, recent observations indicate that the GRBs are narrowly beamed in cones along the rotational axis of the progenitor star. In the case of Eta Carinae the GRBs will not point to us, but will be ravaging to life on planets in our galaxy that happen to lie within the two beaming cones. The mean rate of massive life extinctions by jets from GRBs, per life-supporting planet in galaxies like ours, is once in 100 million years, comparable to the rate of major extinctions observed in the geological records of our planet.

Gamma ray bursts (GRBs) are short-duration flares of MeV γ-rays from outer space that last between a few milliseconds and $\sim$1000 s and occur at a rate of about 3 a day [1]. They were discovered serendipitously in 1967 by the Vela satellites launched by the US to monitor the compliance with the Nuclear Test Ban Treaty, banning nuclear explosions in and above the atmosphere. Their exact locations —and consequently their distance and total energy output— were unknown for 30 years, although their isotropy, established by observations with the BATSE instrument on board the Compton Gamma Ray Observatory satellite (CGRO) strongly suggested [2] cosmological distances [3]. Combined with the observed short-time variability of GRBs, such distances imply an enormous energy release from a small volume, if due to spherical explosions. Alternatively, it was argued that if GRB progenitors are so distant, they must be produced by narrow relativistic jets, from the birth of neutron stars or of black holes [4], [5].

Deaths of Stars

An enormous subject with a fascinating history…



"Onion-skin" model of stellar structure — elemental fusion zones in supergiant stars.

Hubble Space Telescope image of the Crab Nebula — remnant of a 1054 supernova near and bright enough to be visible in daytime on Earth.
Now host to a pulsar.

HST image of the Helix Nebula — gaseous shells thrown off as the central star collapsed to a white dwarf (tiny dot in the center).

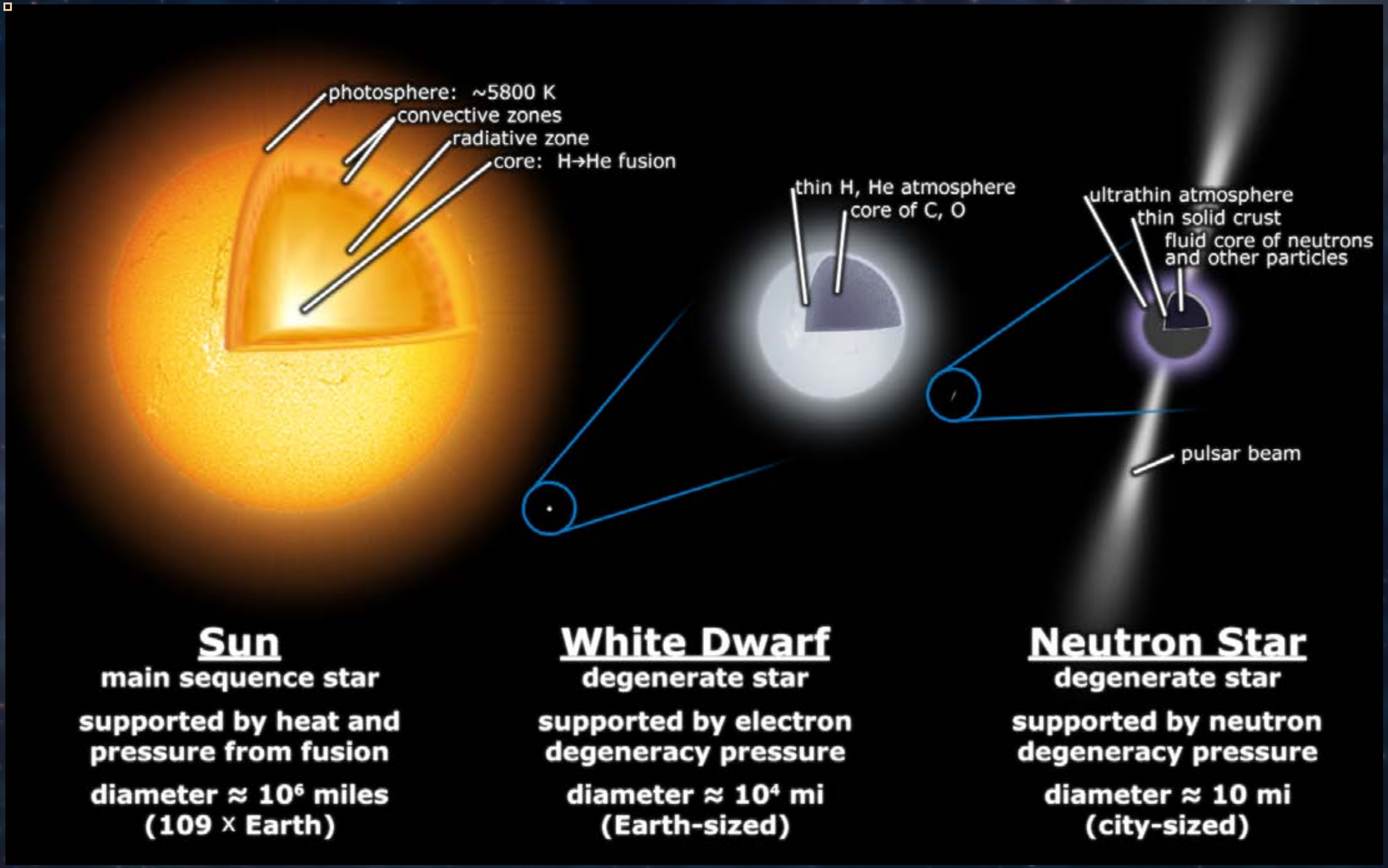
Two Key Ideas

1. Degenerate stars and their maximum mass

2. Black-Hole formation

Degenerate Stars

Both white dwarfs and neutron stars have maximum masses at which they can exist: 1.4 $M_{\odot}$, and ≈ 1.5-3 $M_{\odot}$, respectively.



Note that stars can shed a lot of their mass during their lives via winds and explosions. Stars with about 8 $M_{\odot}$ at birth have about 1.4 $M_{\odot}$ at death, while stars with about 30 $M_{\odot}$ at birth have about 2 $M_{\odot}$ at death.

Quantum Mechanics and Degenerate Stars

Wolfgang Pauli
Austrian theoretical physicist,
1900-1958

Satyendra Nath Bose
Indian mathematical physicist,
1894-1974

Enrico Fermi
Italian nuclear physicist,
1901-1954

Pauli Exclusion Principle

Two types of particles in nature: bosons and fermions, with the difference being that bosons have integer "spin" values, and fermions half-integer.

Bosons

- named after S. N. Bose
- *examples*: photons, gluons, and some atomic nuclei
- "social;" can cluster together

Fermions

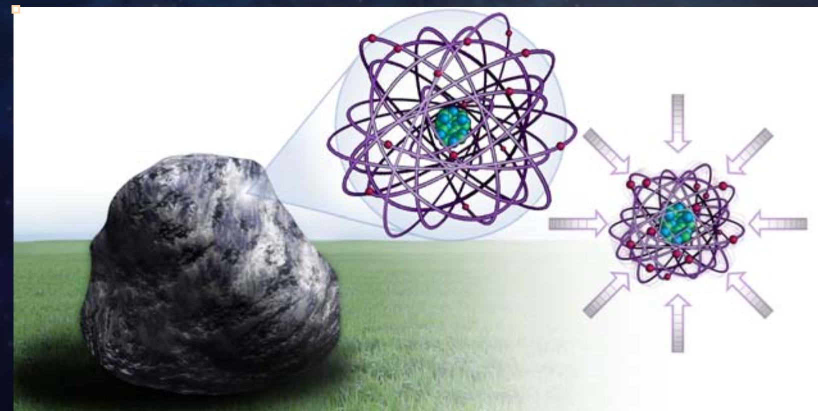
- named after E. Fermi
- *examples*: protons, neutrons, electrons
- "antisocial, claustrophobic;" only one of a kind can exist at a given place with a given velocity

The Pauli Exclusion Principle applies to *fermions*, the antisocial particles.

Pauli Exclusion Principle

- No two fermions can share the same position and velocity.

- If you squeeze matter to 10,000 times the density of rock, the electron cloud around each nucleus gets squashed 10,000-fold.



- With so little space available, the electrons shake uncontrollably, like a claustrophobic human.

- This banging around and kicking against adjacent electrons cannot be stopped — it's forced on the electrons by the laws of QM.

- In this state, the electron is "degenerate."

- The more you squash the matter, the more degeneracy pressure you get.

White Dwarfs

A star where you have gravity squeezing down and electron degeneracy pressure pushing up is a white dwarf; an example is **Sirius B**, a white dwarf orbiting the brightest star in the night sky.

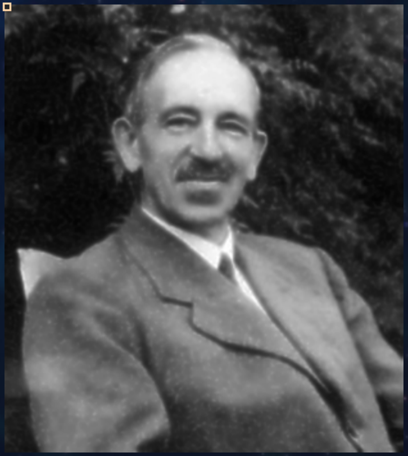
Sirius B is the tiny dot below and right of the center star, Sirius A.

Mass: 1.05 $M_\odot$

Radius: 4900 km ($R_{Earth} \approx 6400$ km)

A density of 60 tons per cubic inch!

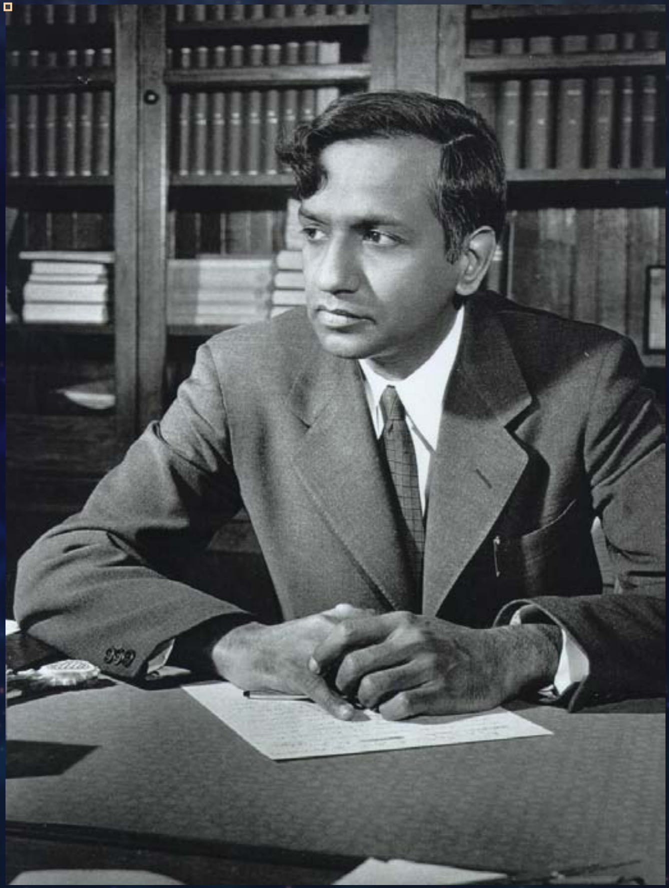
Also, more massive white dwarfs are actually smaller!



British physicist **Sir Ralph H. Fowler**, who solved the mystery of Sirius B in 1926.

The Chandrasekhar Limit

In 1930, Subrahmanyan Chandrasekhar worked out that *no white dwarf can have a mass greater than* **1.4 $M_\odot$** — the Chandrasekhar limit.



Subrahmanyan Chandrasekhar

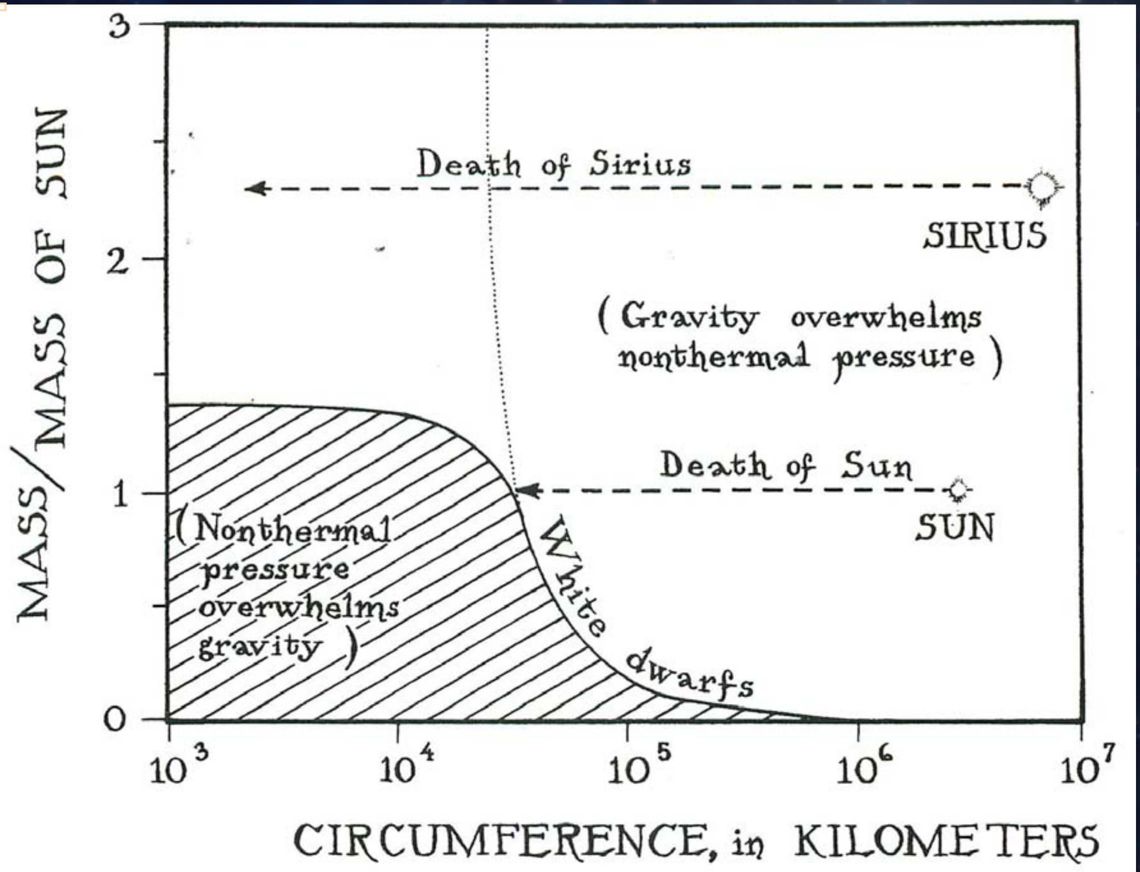
When the electrons in a white dwarf become relativistic, they cannot provide enough pressure to fight off gravity, so the white dwarf will collapse. This occurs at a white-dwarf mass of 1.4 $M_\odot$.

But, what happens to a star more massive than 1.4 $M_\odot$?

The Chandrasekhar Limit

As the Sun's fusion dies (~4.5 billion years from now), it will shrink down to become a white dwarf.

Sirius A, with 2.3 $M_{\odot}$, with no mass loss will appear to shrink forever when its fusion dies, because it's above the Chandrasekhar limit.



(Thorne 1994 - Fig.4.4, p.161)

The Chandrasekhar Limit

In 1934, Eddington attacked Chandrasekhar’s work, saying there must be an error — but Chandrasekhar was right!

38 *Proceedings at Meeting of* [No. 729.

density σ. For ordinary degeneracy $P_e = K\sigma^{5/3}$. But it is generally supposed that this is only the limiting form at low densities of a more complicated relativistic formula, which shows P varying as something between $\sigma^{5/3}$ and $\sigma^{4/3}$, approximating to $\sigma^{4/3}$ at the highest densities. I do not know whether I shall escape from this meeting alive, but the point of my paper is that there is no such thing

$\sigma^{4/3}$, approximating to $\sigma^{4/3}$ at the highest densities. I do not know whether I shall escape from this meeting alive, but the point of my paper is that there is no such thing
as relativistic degeneracy !

seemed to be no way in which a dense star could cool down. Apparently it had to go on radiating for ever, getting smaller and smaller. Soon afterwards Fermi-Dirac statistics were discovered, and Prof. Fowler applied them to the problem and showed that they solved the difficulty; but now Dr. Chandrasekhar has revived it again. Fowler used the ordinary formula; Chandrasekhar, using the relativistic formula which has been accepted

Dr. Chandrasekhar had got this result before, but he has rubbed it in in his last paper; and, when discussing it with him, I felt driven to the conclusion that this was almost a *reductio ad absurdum* of the relativistic degeneracy formula. Various accidents may intervene to save the star, but I want more protection than that. I think there should be a law of Nature to prevent a star from behaving in this absurd way !

from behaving in this absurd way !

If one takes the mathematical derivation of the relativistic degeneracy formula as given in astronomical papers, no fault is to be found. One has to look deeper into its physical foundations, and these are not above suspicion. The formula is based on a combination of relativity mechanics and non-relativity quantum theory, and I do not regard the offspring of such a union as born in lawful

Remarks by Eddington in the Proceedings of the 11 January 1935 meeting of the Royal Astronomical Society

Neutron Stars

Because of the different quantum mechanical behavior for neutrons, neutron stars are even more compact than white dwarfs.

Gravity squeezes the atom so much that it becomes just the nucleus.

Neutron stars have a mass of ≈ 1.4 $M_\odot$ squashed into a radius of ≈ 10 km!

Zwicky

Landau

Oppenheimer

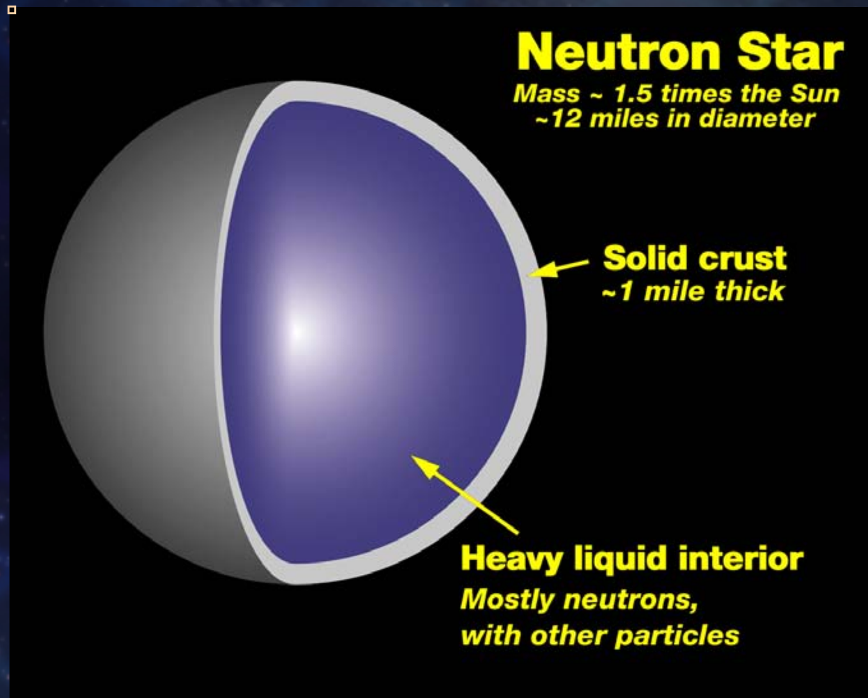
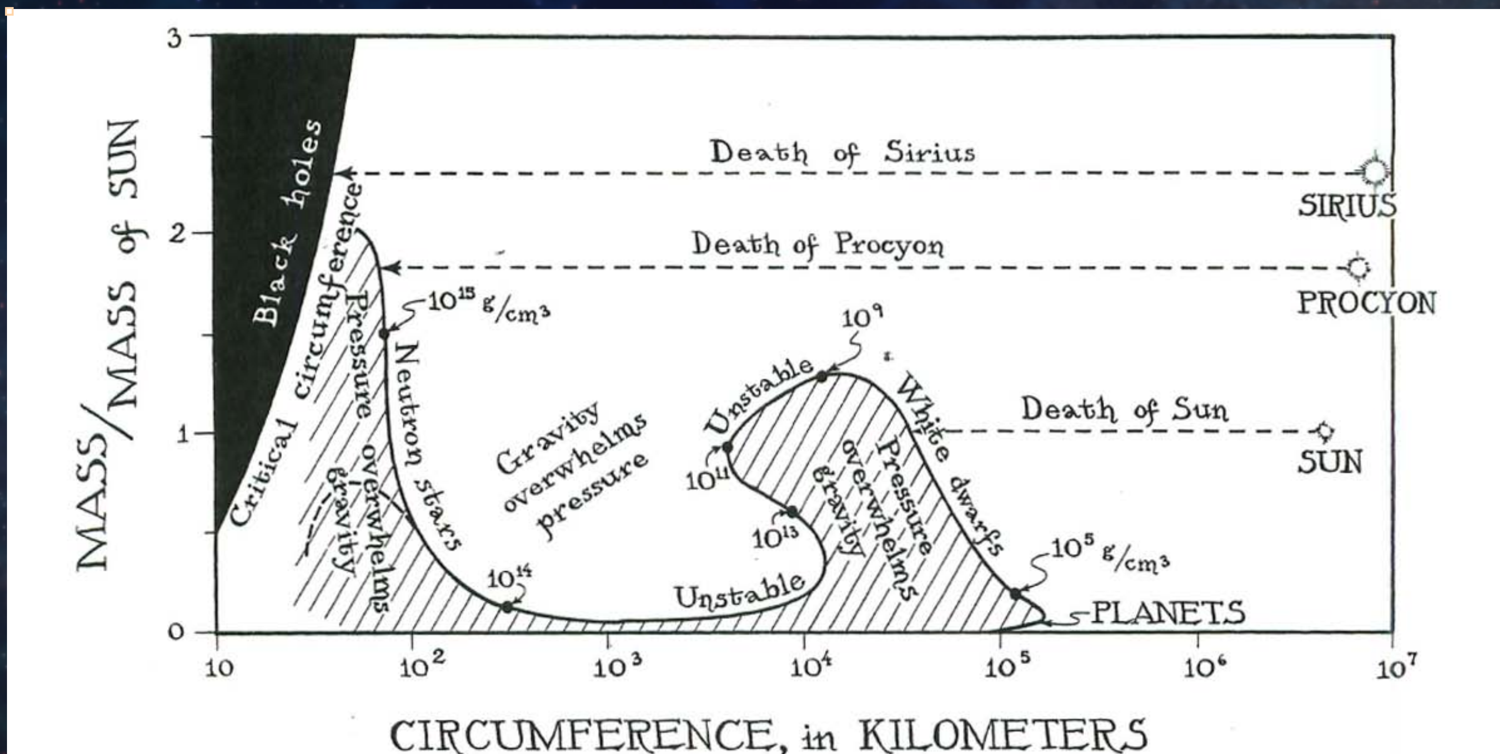


Diagram of the interior of a neutron star.
(*NASA/Marshall Space Flight Center*)

Neutron Stars

Neutron stars have an upper limit to their mass, just like white dwarfs (same ideas apply) — probably in the range of ≈ 1.5 – 3 $M_{\odot}$.



(Thorne 1994 – Fig. 5.5, p.203)

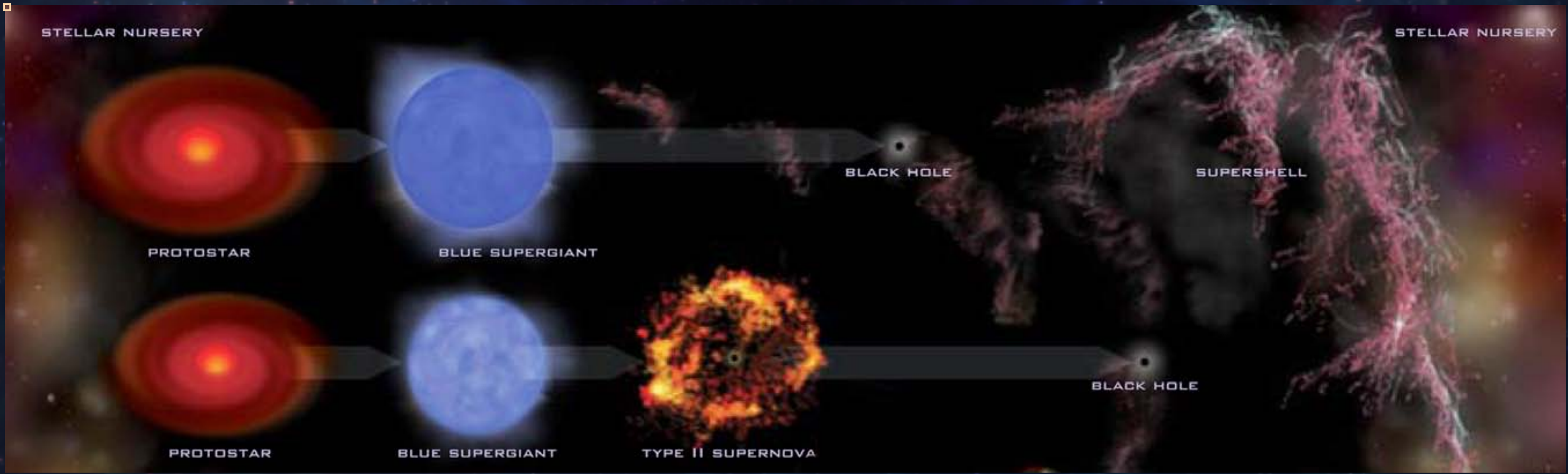
According to their current masses:

Sun → white dwarf, Procyon → neutron star, and Sirius → black hole

Stellar Fates

In reality, mass loss changes this!

But the basic idea is that a star that ends its life with more than ≈ 3 $M_\odot$ is doomed to become a black hole.



Lecture 8:

Black-Hole Formation

Black-Hole Formation

The study of black-hole formation was spearheaded by Robert Oppenheimer and his graduate student, Hartland Snyder.

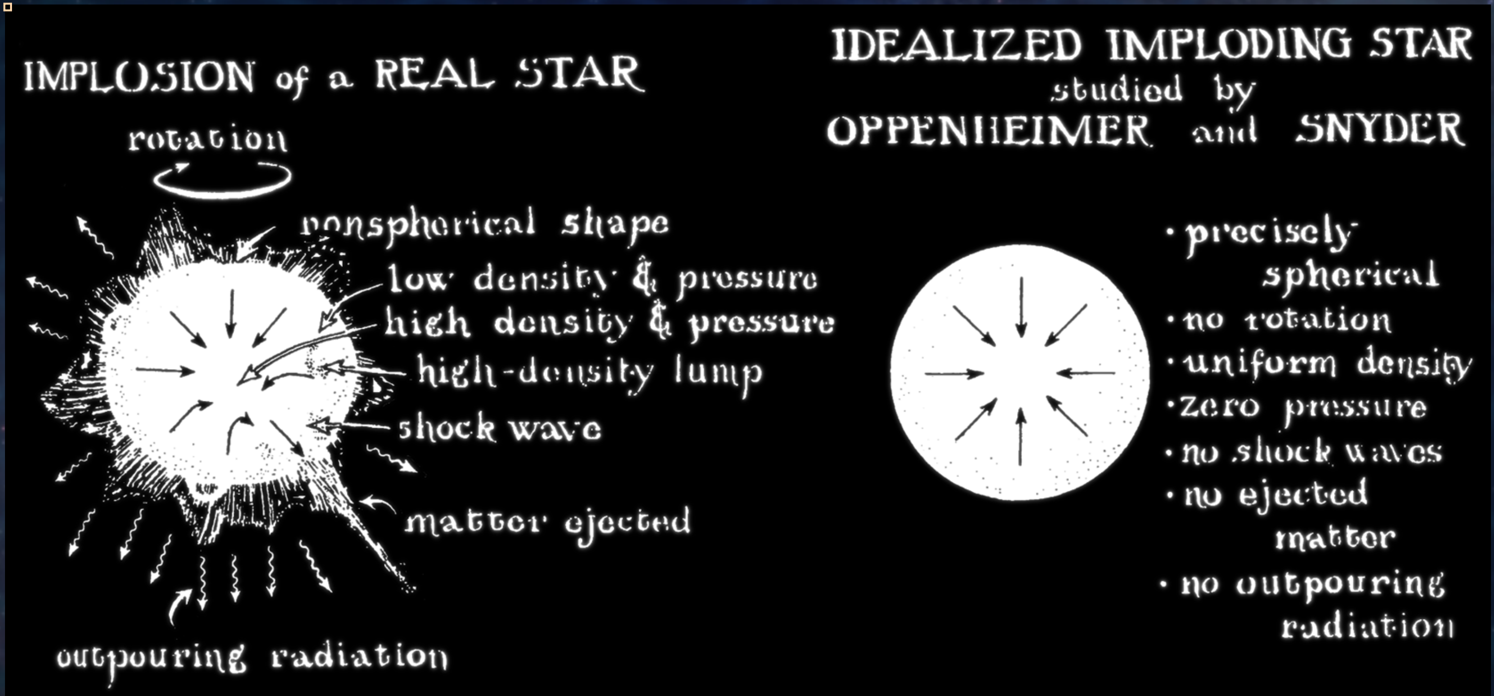
They performed a simplified calculation in 1939 which neglected

- Star spin
- Nonspherical star shapes
- Density changes
- Pressure
- Shocks

Oppenheimer

Black-Hole Formation

Oppenheimer and Snyder only focused on the general relativity effects, and they did these carefully.



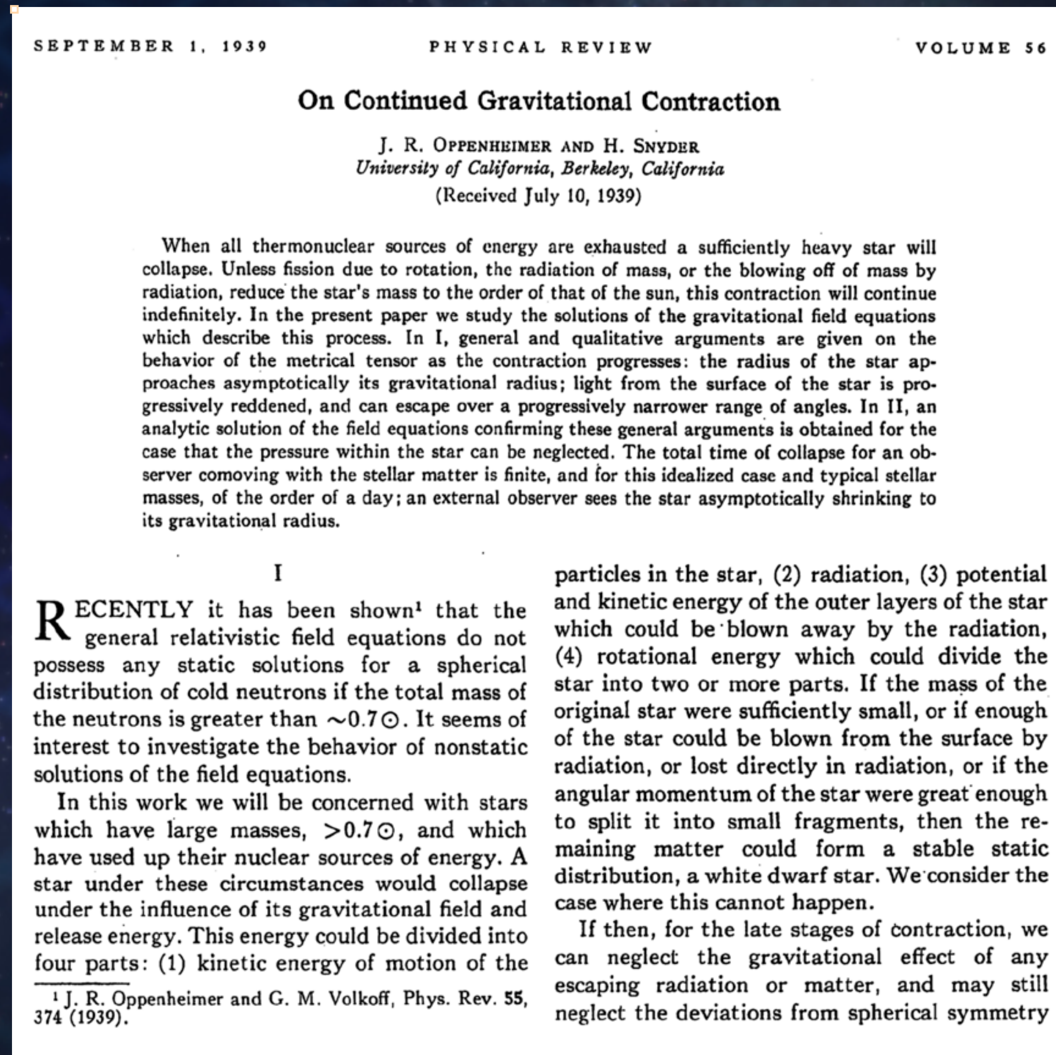
6.3 *Left:* Physical phenomena in a realistic, imploding star. *Right:* The idealizations that Oppenheimer and Snyder made in order to compute stellar implosion.

(Thorne 1994 – Fig. 6.3, p.217)

More recent computer simulations have shown they got the main ideas right in 1939!

Black-Hole Formation

Oppenheimer and Snyder's 1939 paper "On Continued Gravitational Contraction," featuring their initial simplified black-hole calculations.



SEPTEMBER 1, 1939 PHYSICAL REVIEW VOLUME 56

On Continued Gravitational Contraction

J. R. Oppenheimer and H. Snyder
University of California, Berkeley, California

(Received July 10, 1939)

When all thermonuclear sources of energy are exhausted a sufficiently heavy star will collapse. Unless fission due to rotation, the radiation of mass, or the blowing off of mass by radiation, reduce the star's mass to the order of that of the sun, this contraction will continue indefinitely. In the present paper we study the solutions of the gravitational field equations which describe this process. In I, general and qualitative arguments are given on the behavior of the metrical tensor as the contraction progresses: the radius of the star approaches asymptotically its gravitational radius; light from the surface of the star is progressively reddened, and can escape over a progressively narrower range of angles. In II, an analytic solution of the field equations confirming these general arguments is obtained for the case that the pressure within the star can be neglected. The total time of collapse for an observer comoving with the stellar matter is finite, and for this idealized case and typical stellar masses, of the order of a day; an external observer sees the star asymptotically shrinking to its gravitational radius.

I

RECENTLY it has been shown[1] that the general relativistic field equations do not possess any static solutions for a spherical distribution of cold neutrons if the total mass of the neutrons is greater than $\sim 0.7\odot$. It seems of interest to investigate the behavior of nonstatic solutions of the field equations.

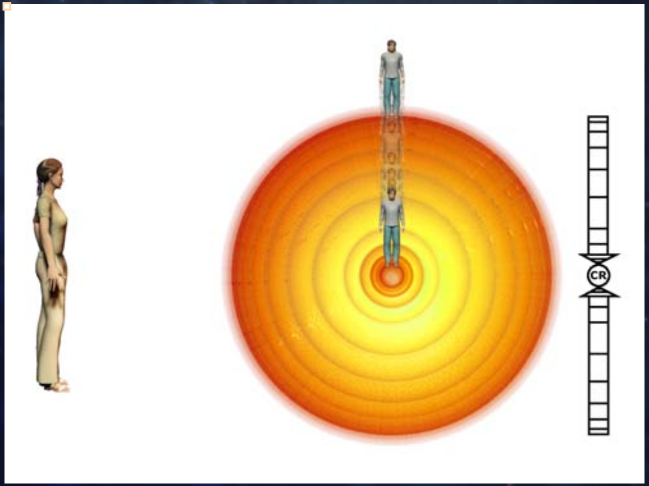
In this work we will be concerned with stars which have large masses, $>0.7\odot$, and which have used up their nuclear sources of energy. A star under these circumstances would collapse under the influence of its gravitational field and release energy. This energy could be divided into four parts: (1) kinetic energy of motion of the particles in the star, (2) radiation, (3) potential and kinetic energy of the outer layers of the star which could be blown away by the radiation, (4) rotational energy which could divide the star into two or more parts. If the mass of the original star were sufficiently small, or if enough of the star could be blown from the surface by radiation, or lost directly in radiation, or if the angular momentum of the star were great enough to split it into small fragments, then the remaining matter could form a stable static distribution, a white dwarf star. We consider the case where this cannot happen.

If then, for the late stages of contraction, we can neglect the gravitational effect of any escaping radiation or matter, and may still neglect the deviations from spherical symmetry

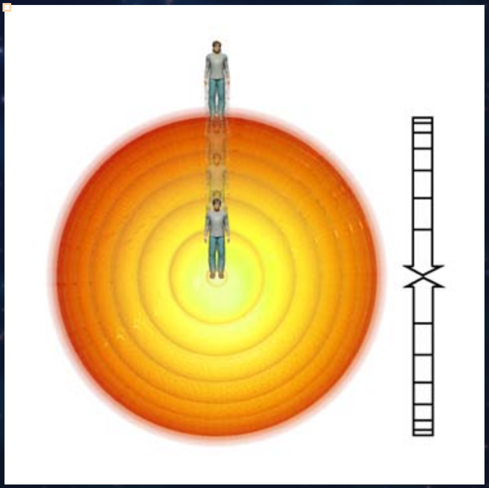
[1] J. R. Oppenheimer and G. M. Volkoff, Phys. Rev. 55, 374 (1939).

Implications of Black Holes

1. Consider first a static, external observer:
   - The star starts collapsing as expected, accelerating like a rock dropped from a rooftop.
   - But when it gets close to the critical radius, the shrinkage slows to a crawl.
   - The shrinking becomes frozen at exactly the critical radius!



2. Now, consider an observer riding inward on the star's surface:
   - This observer does not perceive any time freezing.
   - A normal star, as seen from its surface, implodes in about 1 hour and then keeps imploding past criticality to an infinite-density "crunch."



Singularities, Event Horizons, and the Name, “Black Hole”

By the early 1960s, people believed the Oppenheimer-Snyder calculations.

They wanted to understand the infinite-density “crunch” of the star inside the black hole (that is, the singularity). Unfortunately, to this day, we don’t understand this very well.

We know that the laws of general relativity break down there and must be replaced by **quantum gravity**, but we still don’t have a proper theory of quantum gravity.

Fortunately, what goes on inside the black hole is not of major concern to us right now, since it’s surrounded by the **event horizon**.

What goes on inside the event horizon cannot affect the outside Universe.

What To Call This "Monster?"

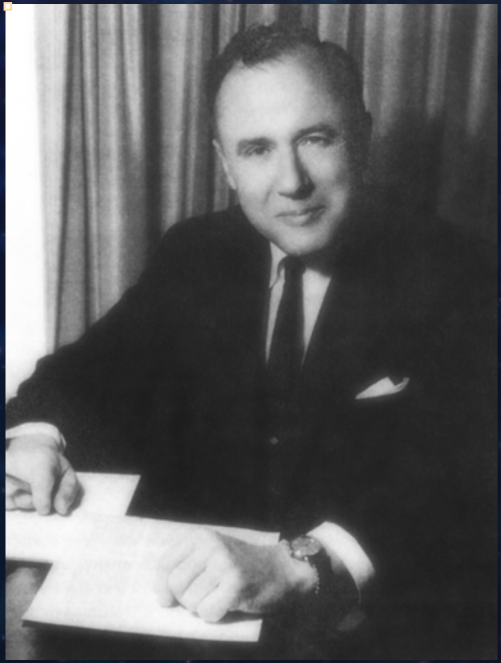
For a while, it was called a "Schwarzchild singularity," then a "collapsed star" (used in the USA) or a "frozen star" (in the then-USSR).

In 1967, Wheeler proposed the term "black hole."

- "Black" because light and other particles cannot get out
- "Hole" because objects will tend to fall into it via gravity, although it's not a "magic vacuum cleaner"
- When objects fall in, its mass grows

⇐

A simulated black hole of 10 $M_{\odot}$ as seen from a distance of 600 km, with the Milky Way in the background.
(*Ute Kraus, Physics Education Group, Universität Tübingen*)



J.A. Wheeler

“Ants on a Membrane” Analogy

Imagine there are six ants on a large rubber membrane.

They communicate using signal balls that roll with a constant speed (like the speed of light).

Regrettably, the ants had not calculated the membrane’s strength. Five ants gathered near the center, and their weight made the membrane start to collapse. They’re trapped – can’t crawl out fast enough to escape.

There is a 6th ant: an astronomer ant with a signal ball telescope.

As the membrane collapses, the trapped ants dispatch signal balls.

The membrane: 1) contracts inward, and 2) sags and becomes curved into a bowl-like shape.

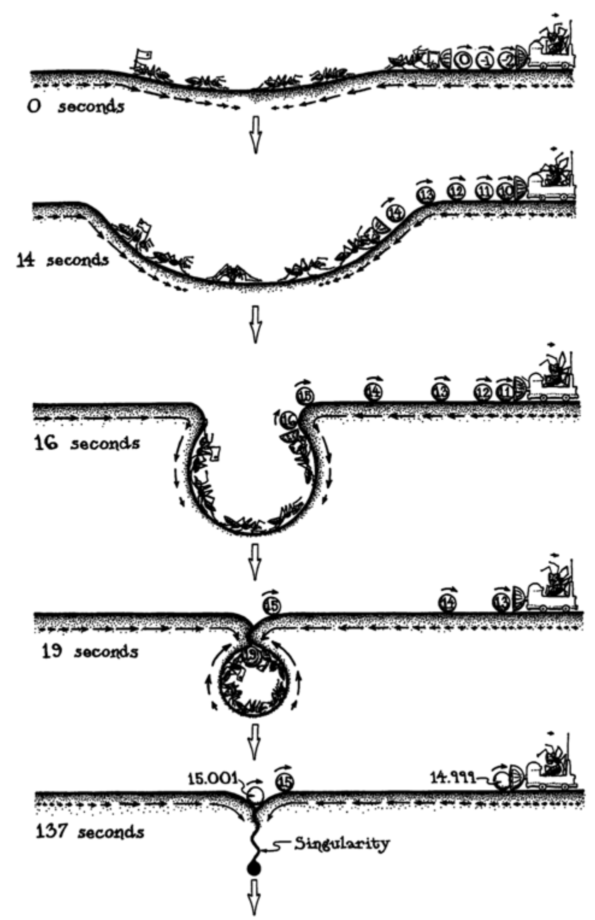
The membrane contracts faster and faster as the collapse proceeds, so the signal balls become more and more widely spaced.

Ball 14.999 arrives after a long delay

Ball 15 stays forever

Ball 15.001 is crushed

Note that the trapped ants don’t see time freezing! (Though they’re probably not too happy when they get squeezed together into such infinitesimally small space)



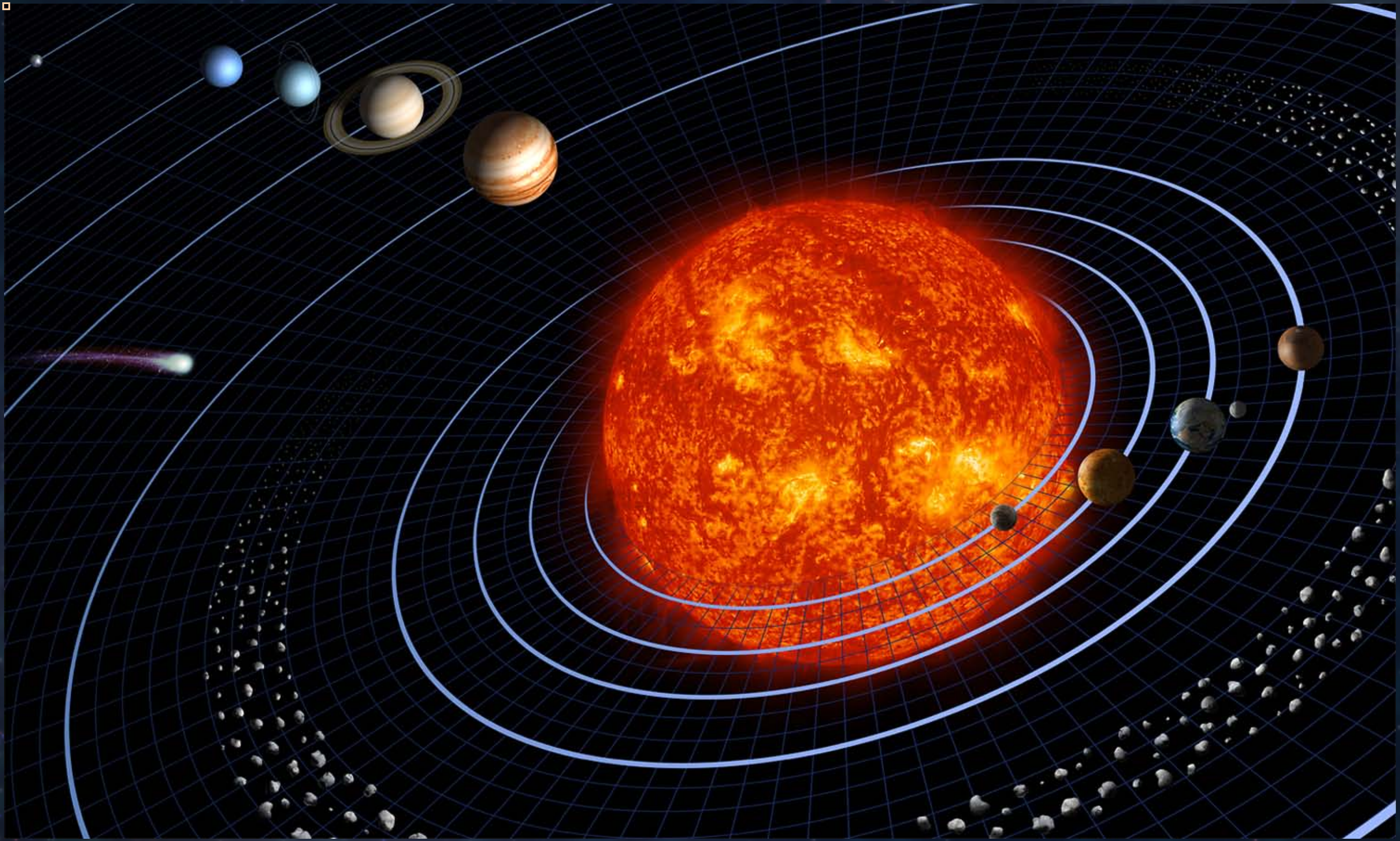
6.6 Collapsing rubber membrane populated by ants provides a fanciful analogue of the gravitational implosion of a star to form a black hole. [Adapted from Thorne (1967).]

(Thorne 1994 – Fig. 6.6, p.247)

Lecture 9:
Finding Black Holes

Finding Black Holes

Finding Black Holes

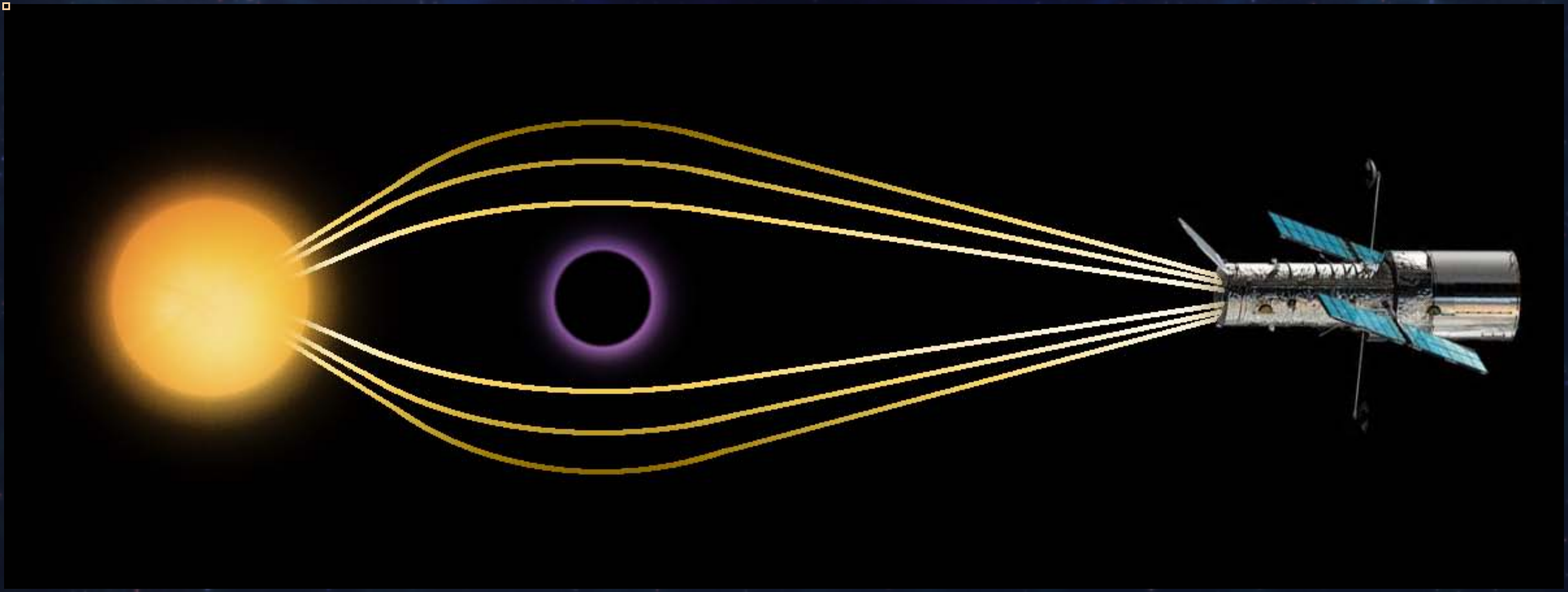


Even the nearest black holes must be outside our Solar System, or else they would disrupt the planetary orbits.

(Solar System image not to scale — *NASA*)

Finding Black Holes

1. Proposed search for moving, black object that blots out background stars. It turns out that **gravitational lensing** causes stars behind black holes to brighten, instead.
   - Can actually increase star's brightness by 10-100 times or more
   - Such events are exceedingly rare, but we are seeing such events today – we use computers to monitor millions of stars



Finding Black Holes

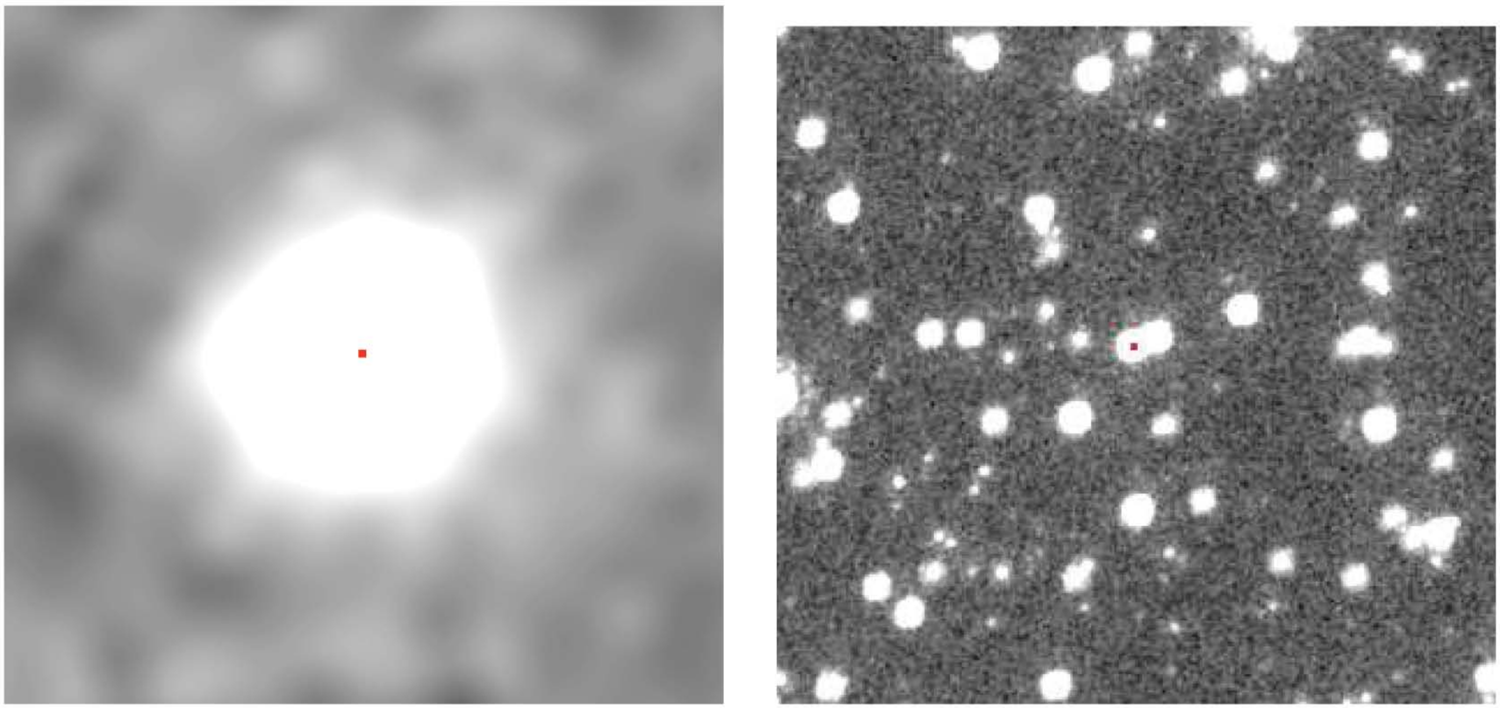


Fig. 8.— The image on the left is the master difference image as described in the text. It has been registered to the same coordinate system as the F814W HST/WFPC2 image shown on the right. The red marks show the centroid of the variable flux in the master difference image and the location of this centroid when transformed to the coordinate system of the HST data. A single, main sequence bulge star is clearly identified as the lensed source star.

(from *Bennett et al. 2002. "Gravitational Microlensing Events Due to Stellar Mass Black Holes."*)

Finding Black Holes

Gravitational Microlensing Events Due to Stellar Mass Black Holes[1]

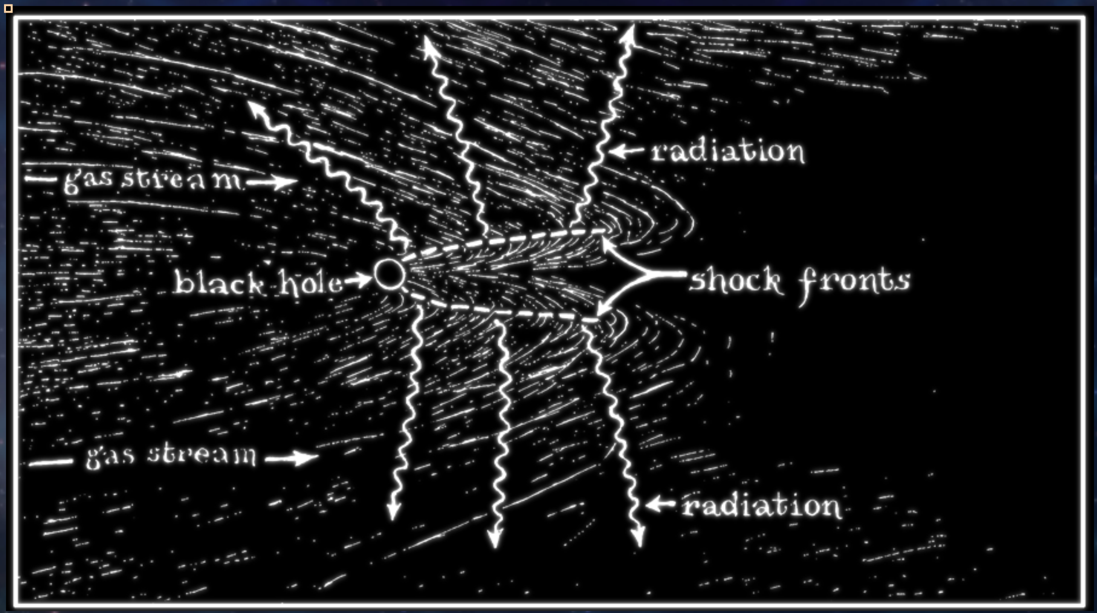
D.P. Bennett[2,3], A.C. Becker[4], J.L. Quinn[2], A.B. Tomaney[5], C. Alcock[3,6,7], R.A. Allsman[8], D.R. Alves[9], T.S. Axelrod[10], J.J. Calitz[11], K.H. Cook[3,7], A.J. Drake[7], P.C. Fragile[2], K.C. Freeman[10], M. Geha[12], K. Griest[13], B.R. Johnson[14], S.C. Keller[7], C. Laws[5], M.J. Lehner[6], S.L. Marshall[7], D. Minniti[15], C.A. Nelson[7,16], B.A. Peterson[10], P. Popowski[17], M.R. Pratt[5], P.J. Quinn[18], S.H. Rhie[2], C.W. Stubbs[3,5], W. Sutherland[19], T. Vandehei[12], D. Welch[20]
(The MACHO and MPS Collaborations)

ABSTRACT

We present an analysis of the longest timescale microlensing events discovered by the MACHO Collaboration during a seven year survey of the Galactic bulge. We find six events that exhibit very strong microlensing parallax signals due, in part, to accurate photometric data from the GMAN and MPS collaborations. The microlensing parallax fit parameters are used in a likelihood analysis, which is able to estimate the distance and masses of the lens objects based upon a standard model of the Galactic velocity distribution. This analysis indicates that the most likely masses of five of the six lenses are $> 1\,\mathrm{M}_\odot$, which suggests that a substantial fraction of the Galactic lenses may be massive stellar remnants. This could explain the observed excess of long timescale microlensing events. The lenses for events MACHO-96-BLG-5 and MACHO-98-BLG-6 are the most massive, with mass estimates of $M/\mathrm{M}_\odot = 6^{+10}_{-3}$ and $M/\mathrm{M}_\odot = 6^{+7}_{-3}$, respectively. The observed upper limits on the absolute brightness of main sequence stars for these lenses are $< 1\,\mathrm{L}_\odot$, so both lenses are black hole candidates. The black hole interpretation is also favored by a likelihood analysis with a Bayesian prior using a conventional model for the lens mass function. We consider the possibility that the source stars for some of these six events may lie in the foreground Galactic disk or in the Sagittarius (SGR) Dwarf Galaxy behind the bulge, but we find that bulge sources are likely to dominate our microlensing parallax event sample. Future HST observations of these events can either confirm the black hole lens hypothesis or detect the lens stars and provide a direct measurement of their masses. Future observations of similar events by SIM or the Keck or VLTI interferometers (Delplancke, Górski & Richichi 2001) will allow direct measurements of the lens masses for stellar remnant lenses as well.

Finding Black Holes

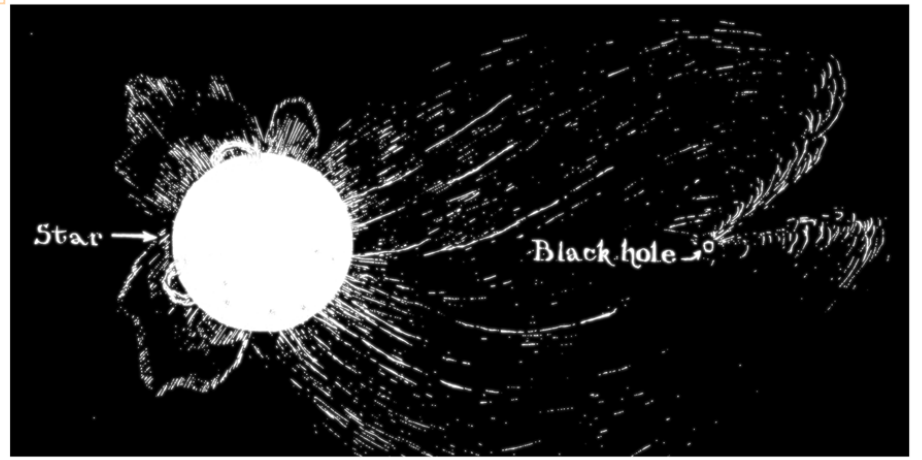
2. Black hole flying through a gas cloud in space.
   - Streams of gas, accelerated to nearly the speed of light by the black hole's gravity, will fly around opposite sides of the hole and crash together at its rear.
   - Will make shocks that heat the gas to X-ray-emitting temperature.
   - We haven't found these yet, but we're still trying!



Salpeter-Zel'dovich proposal for how to detect a black hole.
(*Thorne 1994 – Fig. 8.4, p.307*)

Finding Black Holes

3. Black holes in binary star systems
   - Strong winds of gas (mainly H, He) blow off the surfaces of some stars
   - Let's say the black hole and wind-emitting star are in orbit around each other
     - We'd see an effect just like the previous scenario, except that the wind moves rather than the hole – but motion is relative!
     - The black hole captures some of the wind's gas, heats it at shock fronts, and makes it radiate.
     - The gas is heated to several million degrees, so mostly X-rays would be produced.



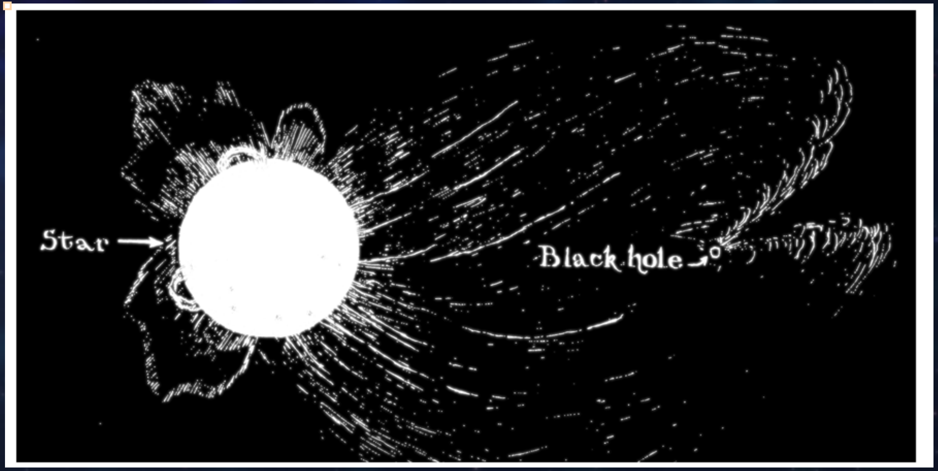
Black hole in a binary system.
(*Thorne 1994 – Fig. 8.5, p.308*)

Finding Black Holes

3. Black holes in binary star systems *(continued)*
   - Zel'dovich and Novikov proposed to search for such objects in 1966; they said:
     - Look for binary stars where normal star is optically bright and faint in X-rays and the black hole is optically dark and bright in X-rays
     - Measure the stars' orbits to get mass information

I.D. Novikov (left) and Y.B. Zel'dovich

Black hole in a binary system.
(*Thorne 1994 - Fig. 8.5, p.308*)



Black Holes in Binary Systems

This has been the most successful method to date, although we're also making progress with the microlensing method.

While X-rays let us "home in" on such a system, they alone do not provide the proof of a black hole. We get the mass by studying the binary orbit and watching the black hole pulling on its companion star.

The key idea is that we learn about "invisible" black holes by measuring their effects via gravity on objects that we *can* see.

This is a common theme that is used again and again in black-hole studies, and astronomy in general.

Accretion Disks

Gas almost never falls directly onto a black hole.

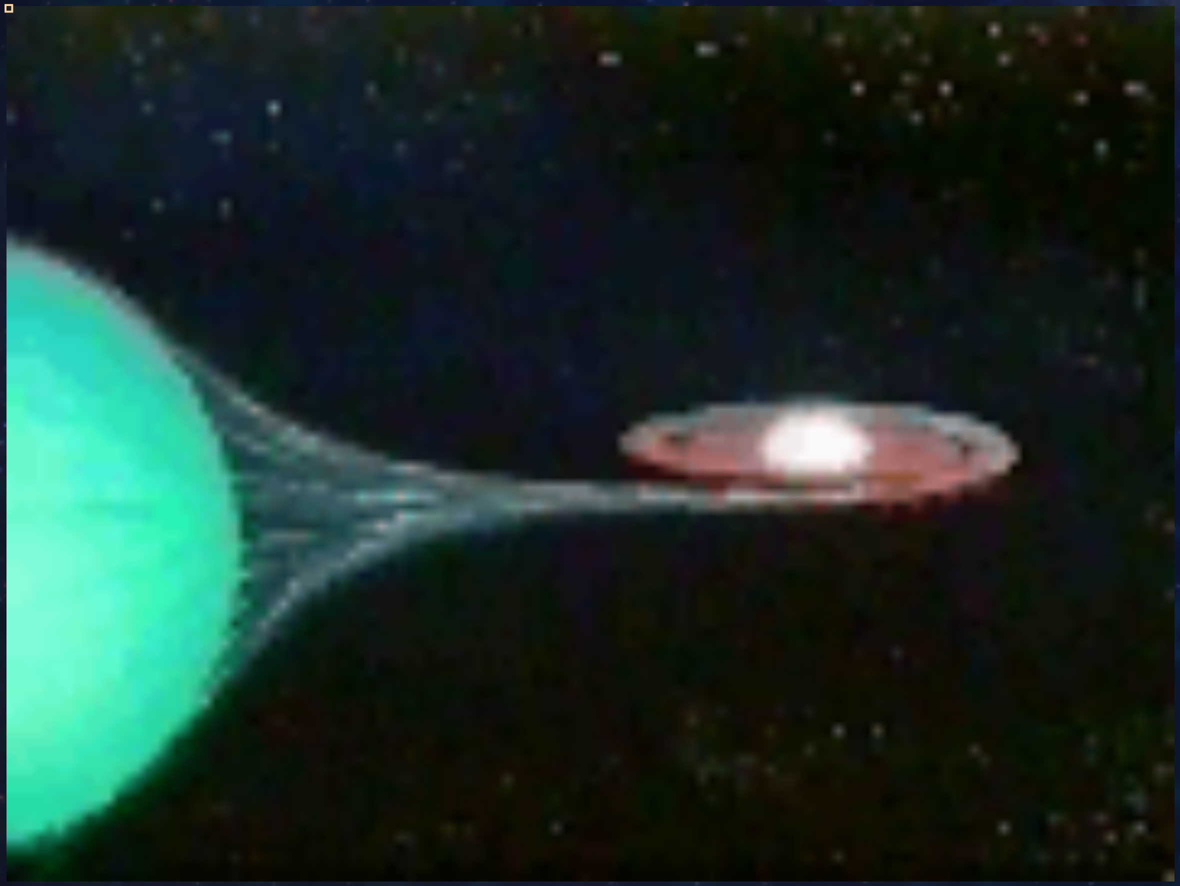
Instead, it forms an **accretion disk** with the black hole at its center.

When a gas stream hits the disk, it makes a bright spot. Black holes can swallow matter via such streams as well as via stellar winds.

(*Dana Barry and Keith Horne, STScI, NASA*)

Accretion Disks

This movie helps to illustrate what goes on as the two stars orbit each other:



- Matter is continuously pulled off the normal star.
- The gas has angular momentum due to the binary orbit.
- We can measure Doppler shifts of the normal star to learn about velocities in the system and hence the stars' orbits and masses.

Accretion Disks

You can think of the accretion disk as a kind of flattened whirlpool or vortex.

(Arthur Rackham, illustration for Edgar Allen Poe's Tales of Mystery and Imagination)

Water in your bathtub makes a vortex as it goes down the drain because it can lose gravitational energy.

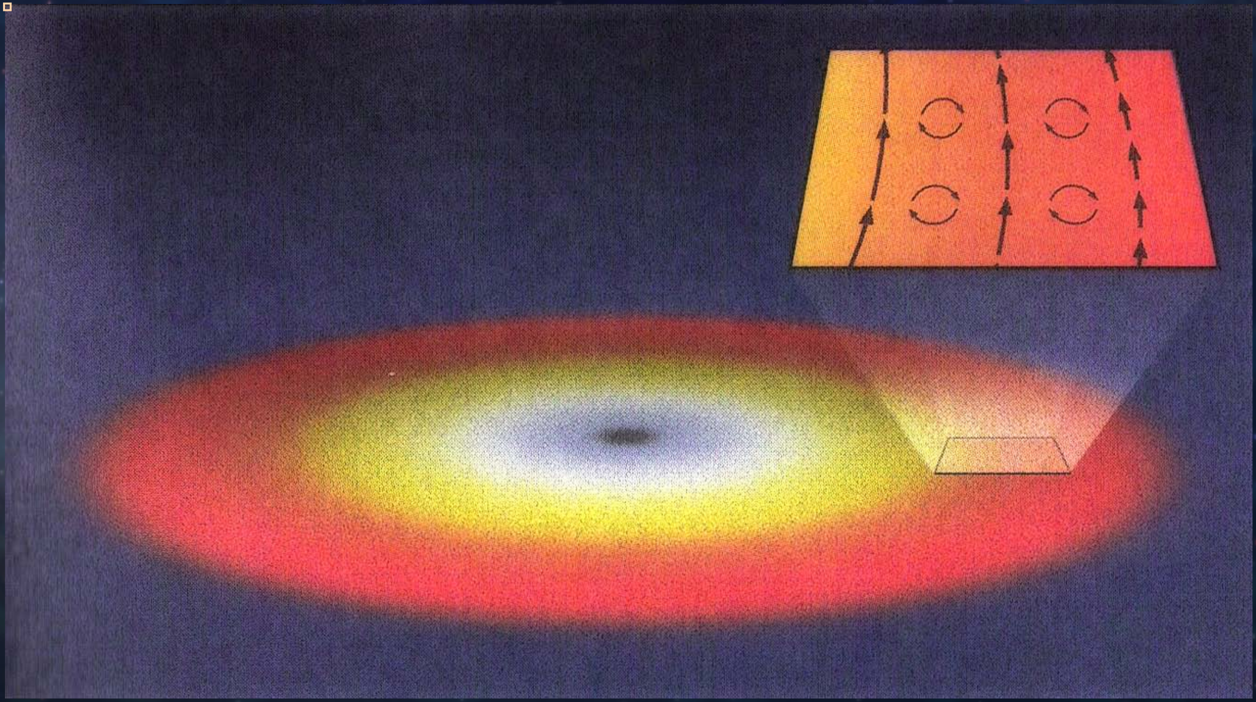
For gas to fall onto a black hole, it must lose angular momentum. This is done by friction, also known as viscosity — just like it is for bathtub water.

The gas closer to the center orbits faster than gas farther out. Frictional effects cause energy to be dissipated and angular momentum to go outward.

Accretion Disks

The material closer to the black hole moves faster, so the frictional dissipation there is greater.

- Inner parts radiate more intensely than outer parts
- Inner parts radiate at shorter wavelengths than outer parts
- Black hole does *not* make radiation



(*from Begelman and Rees 1998, p. 63*)

Accretion Disks

These things can happen for accretion disks around neutron stars, too.

Gravity

↓ *matter swirling inward*

Motion

↓ *friction*

Heat

↓

Radiation

<u>This is the basic chain of forces. It's a very efficient way of making energy:</u>

Fusion efficiency = 0.7%

Black hole accretion efficiency = 5-29%

Compact Objects in Binary Systems

We’ve been able to study a significant number of stellar binary systems with both black holes and neutron stars.

Our ability to determine the compact object’s mass depends on:

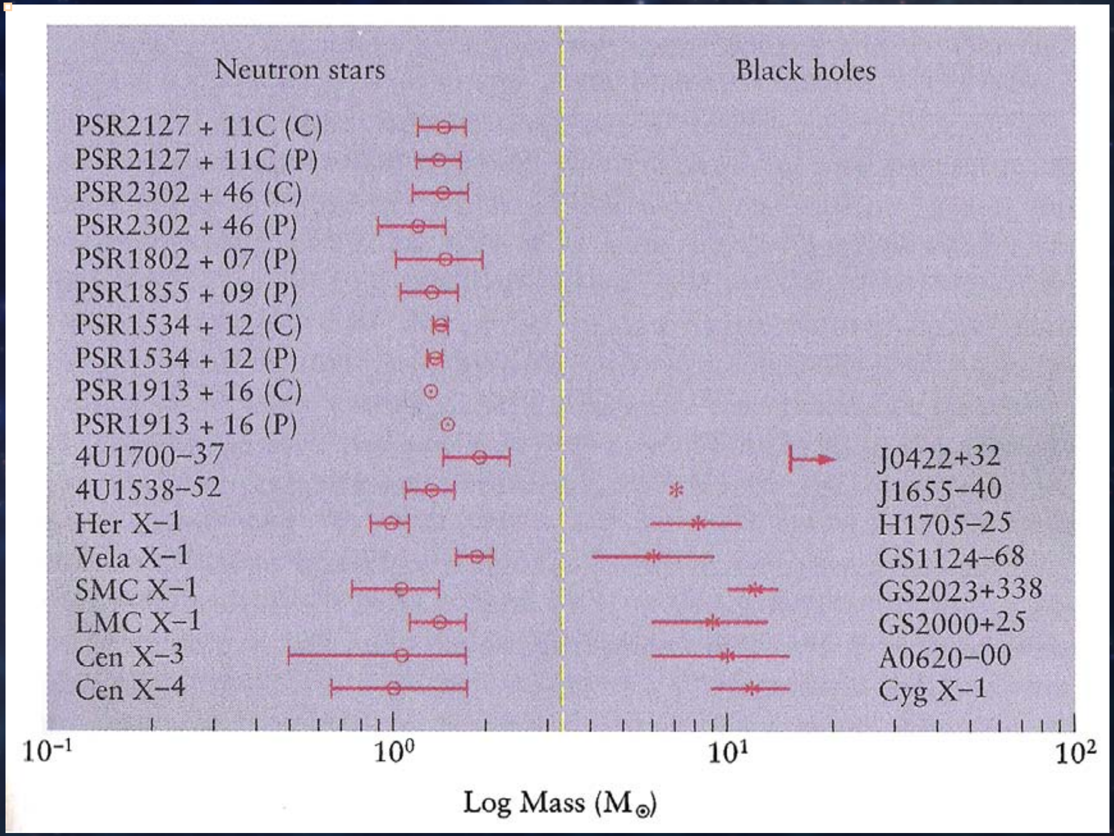
- Orbital period (simple to determine)
- Doppler shift (also simple)
- Mass of normal star (hard)
- Orbital inclination (hard)

Compact Objects in Binary Systems

This plot from Begelman & Rees shows the mass distribution of several neutron star and black hole candidates, based on measurements of their binary system orbits.

- 26 objects are shown, with error bars for their mass uncertainties

- The neutron-star – black-hole mass boundary is given by the yellow dashed line.



(*Begelman & Rees 1998 — p.65*)

Compact Objects in Binary Systems

A recent summary of measurements for the masses of compact objects in binary systems are shown in this figure:

- 34 objects shown in total

- The mass range for a neutron star (≈ 1.5-3 $M_{\odot}$) is framed by vertical parallel dotted lines.

- Remember that a star with a mass greater than ≈ 1.5-3 $M_{\odot}$ upon its death will become a black hole instead of a neutron star.

(*J. Orosz 2002, "Inventory of Black Hole Binaries*")

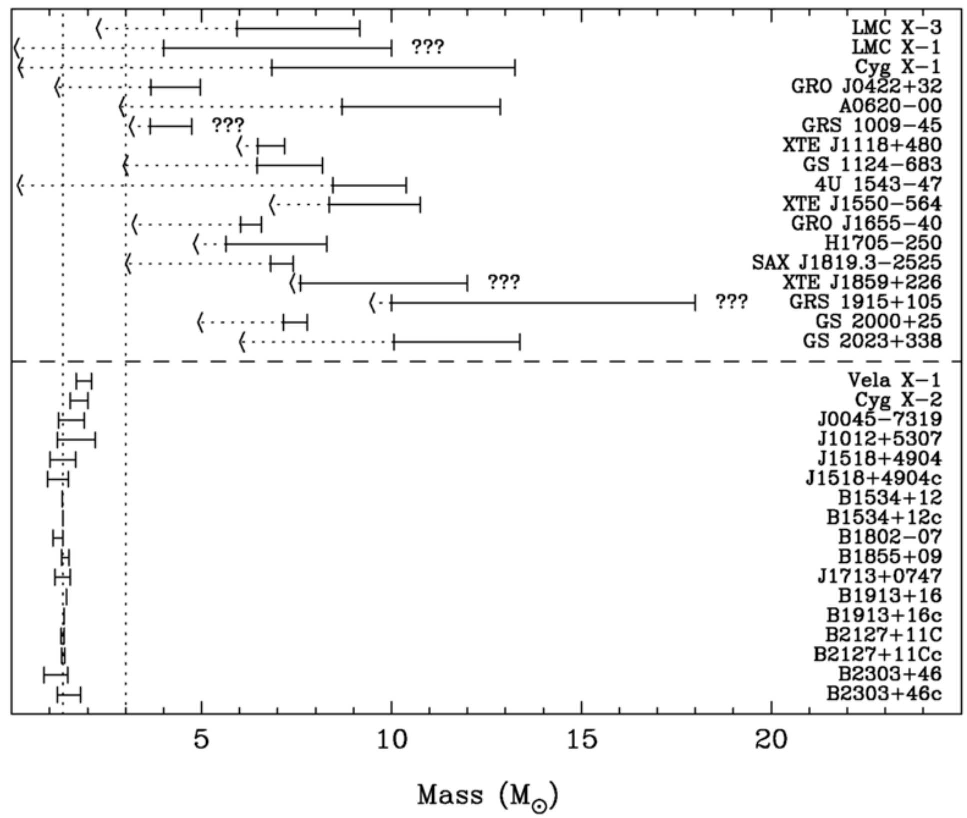


Figure 1. Summary of black hole masses (top, Table 1 and cited references) and selected neutron star masses (bottom, Thorsett & Chakrabarty 1999). The ranges are 1σ in most cases. The arrows in the top indicate the measured mass functions.

Black Holes in Binary Systems

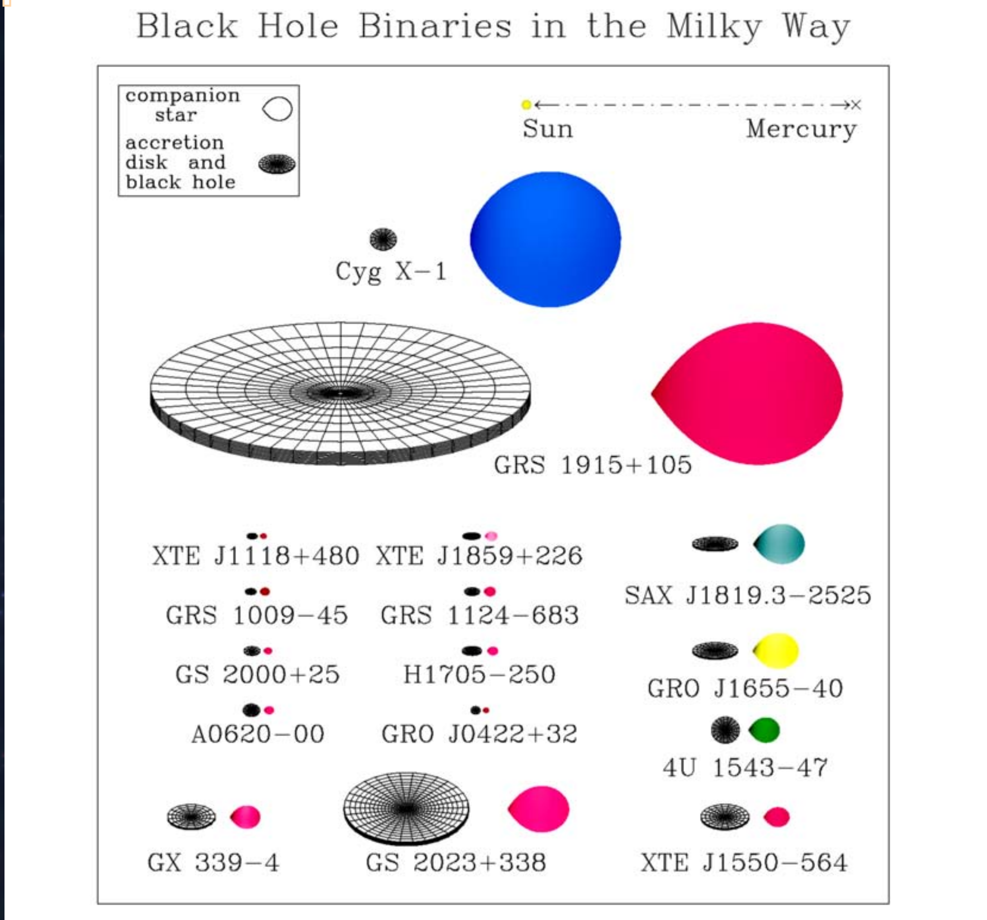


Figure 1: Scale drawings of 16 black-hole binaries in the Milky Way (courtesy of J. Orosz). The Sun–Mercury distance (0.4 AU) is shown at the top. The estimated binary inclination is indicated by the tilt of the accretion disk. The color of the companion star roughly indicates its surface temperature.

The first black hole discovered was Cygnus X-1 (1960s-1970s). Today we have ≈ 16 reliable black holes in binary systems with masses clearly above 3 $M_{\odot}$.

(*J. Orosz, in Remillard and McClintock 2006, "X-ray Properties of Black-Hole Binaries*)

Lecture 10:

Gamma-Ray Bursts

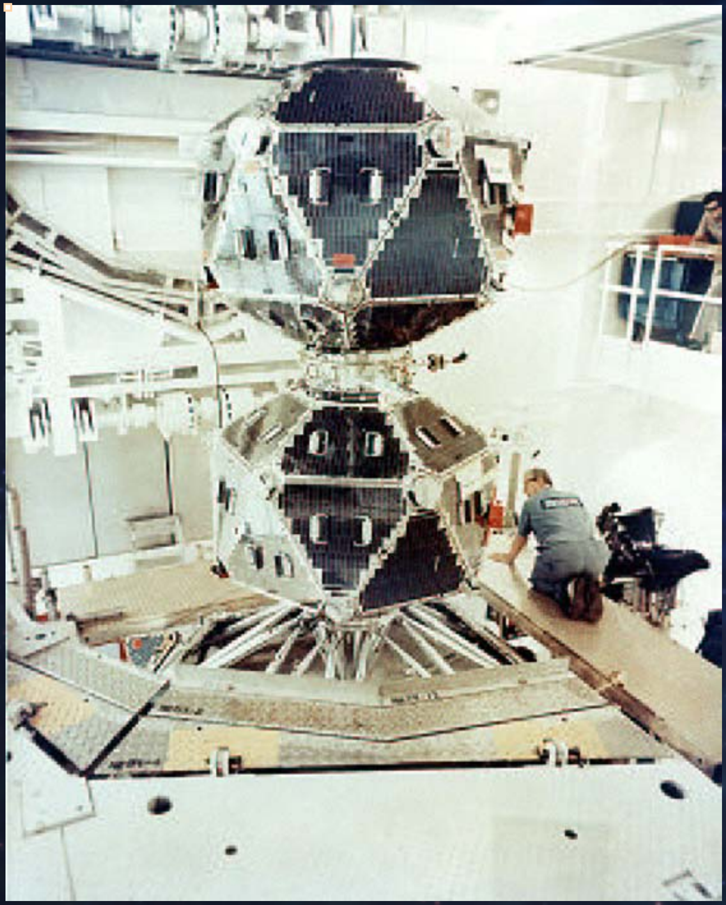
Gamma-Ray Bursts

Sudden, intense flashes of gamma-rays which, for a few blinding seconds, light up an otherwise fairly dark γ-ray sky.

As we'll see, many are likely to indicate black holes being formed.

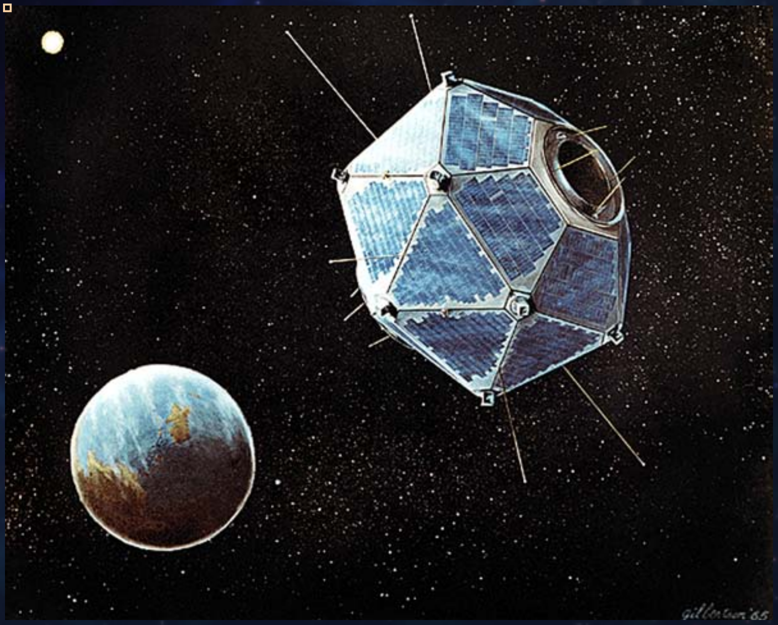
Earliest Observations

The Vela satellites, launched 1969-1973 by the United States, orbited Earth at a great distance — about halfway to the Moon.



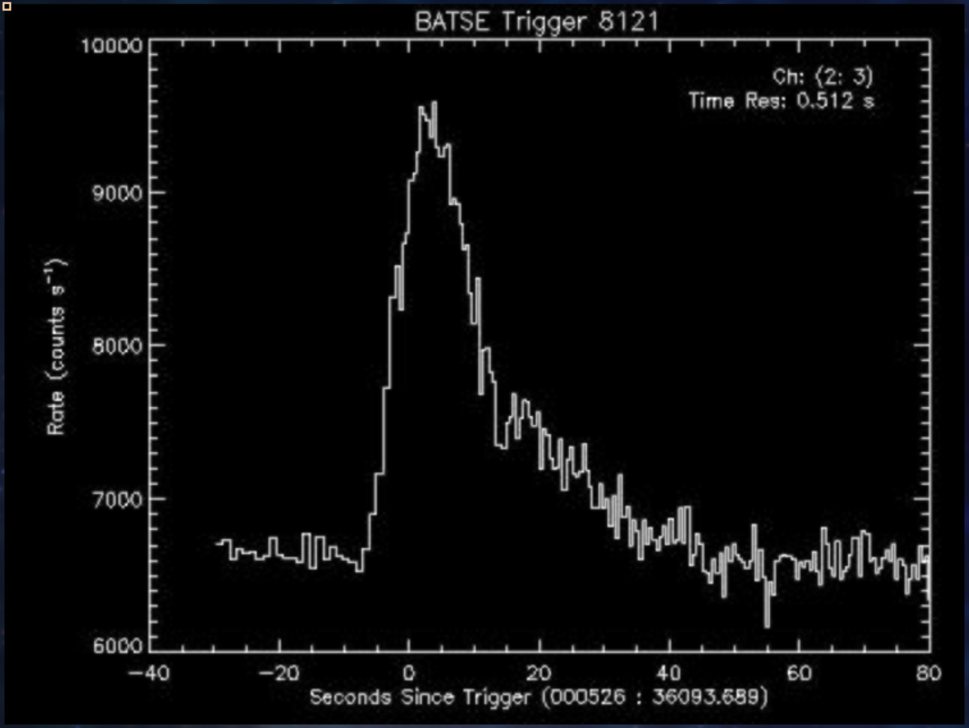
(Vela satellites — *HEASARC, NASA/GSFC*)

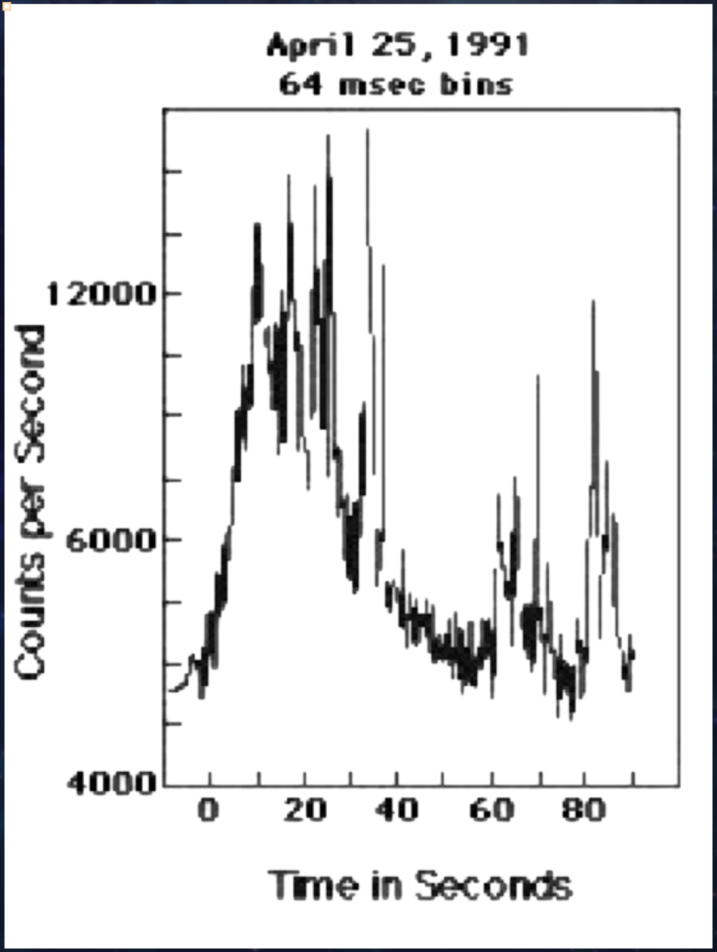
Designed to detect nuclear bomb tests; scientists also wanted to study the astronomical background.



Earliest Observations

In 1973 scientists were highly convinced that they saw γ-ray bursts from outside the Solar System and announced the discovery.





Light curves from gamma-ray bursts.

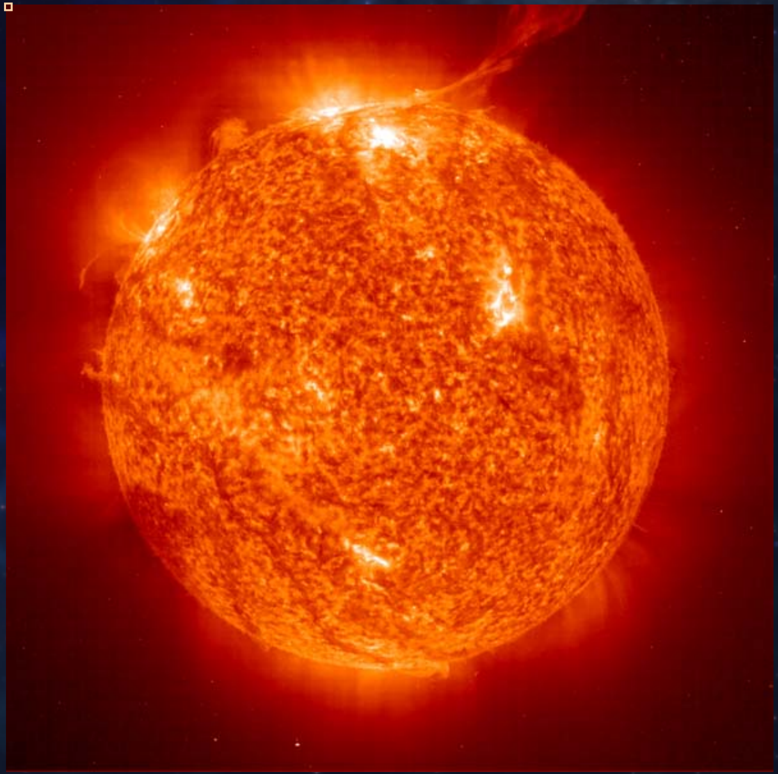
What Are Gamma-Ray Bursts?

Recall what γ-rays are — even higher energy than X-rays.

Gamma-ray bursts last for ≈10-30 seconds. They are erratic and rapidly variable down to timescales of 0.001s.

No two are the same.

Such light curves are seen from solar flares and other exploding things in the Universe – this suggests some catastrophic events are occurring and making energetic γ-rays in the process.



(*NASA*)

What Are Gamma-Ray Bursts?

The main problem in solving the mystery was that we couldn't find counterparts at other wavelengths, so we couldn't figure out the distances to these sources (*e.g.*, with redshift)

- γ-ray detectors typically have had very bad spatial resolution; it's hard to focus γ-rays.
- γ-ray positions often give an error circle of 100+ times the angular size of the Moon.
- So we have millions of possible galaxies and stars that could be the counterpart.
- It's a needle in a haystack, made worse because the needle is only visible for 10-30 seconds!

We didn't even know if the γ-ray bursts were in our Galaxy or in external galaxies.

What Are Gamma-Ray Bursts?

Theorists made up all kinds of crazy models!

- Black-hole collapses
- Relativistic dust grains from interstellar space that crash into the solar wind
- Comets and asteroids crashing into neutron stars
- Advanced extraterrestrial civilizations

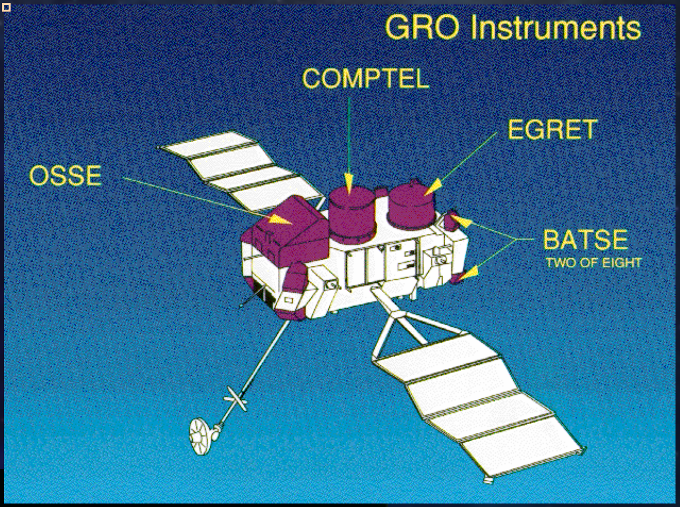
Compton Gamma-Ray Observatory

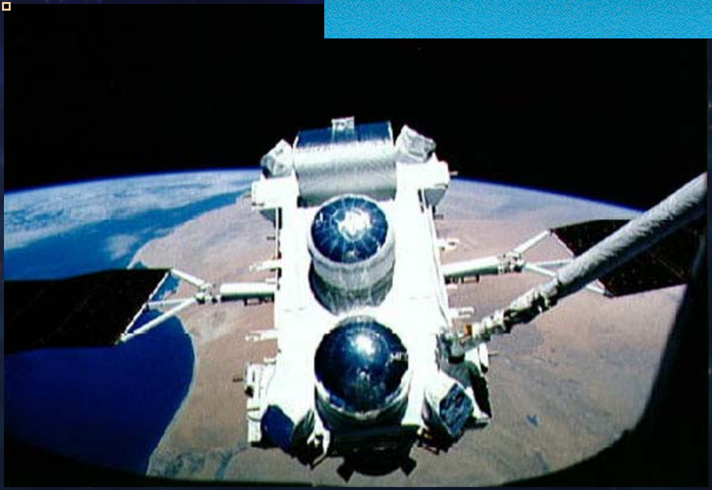
A major advance came in 1991 with the launch of the Compton Gamma-Ray Observatory, one of NASA's "Great Observatories."

Compton carried BATSE, the Burst and Transient Source Experiment. It monitored the whole sky and discovered ≈1 gamma-ray burst per day for 9 years.

In total, it found ≈2700 gamma-ray bursts.

It could measure the spatial distribution of the bursts over the sky — found to be isotropically distributed.





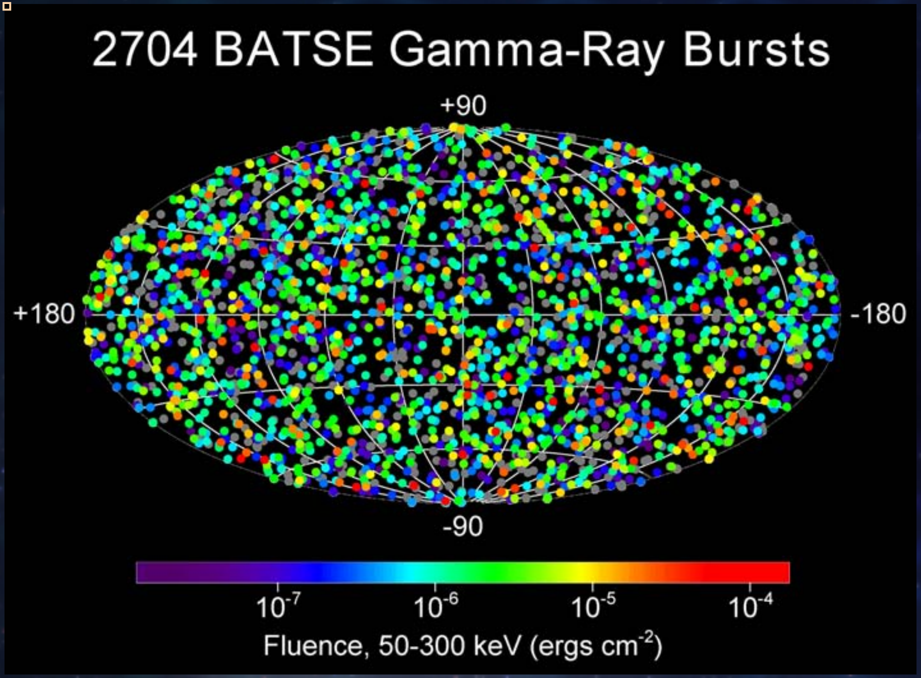
(*above*: instruments on the Compton GRO

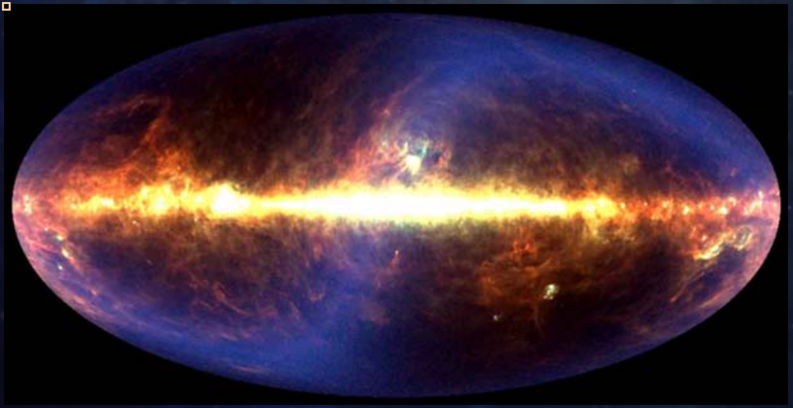
left: CGRO released from the Space Shuttle

NASA/GSFC)

Compton Gamma-Ray Observatory

Compare Compton's gamma-ray bursts distribution to that for our Galaxy.





(*above*: The infrared sky — *COBE / DIRBE*, *NASA*)

(*left*: Distribution of CGRO's detected GRBs — *NASA*)

There was no bias toward the disk of our Galaxy.

This strongly suggested that they originated in galaxies at cosmological distances, since distant galaxies are approximately uniform on the sky.

Recent Studies of Gamma-Ray Bursts

So then we needed to explain the generation of an enormous amount of energy, like that of a supernova, *all in γ-rays*.

This narrowed down the possible models to:

- Two neutron stars orbiting each other crashing together
- A black hole and a neutron star crashing together
- A star core collapsing violently to make a rapidly spinning black hole

The problem was still that there were no counterparts at other wavelengths, so we couldn't bring the techniques and lore of multi-wavelength astronomy to bear.

Revolutionary advances have been made since 1997.

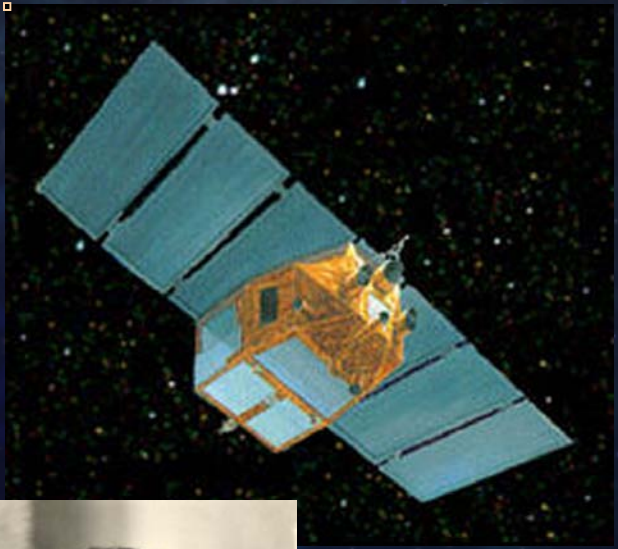
BeppoSAX

BeppoSAX: named after Giuseppe "Beppo" Occhialini; "*Satellite per Astronomia a Raggi X*"

- Had a burst monitor that could detect a weak X-ray signal from GRB → crude position. Then could slew a second instrument onto the general location to refine the position (takes ≈ a day).

- Somewhat risky: we know the γ-rays die after ≈ 10-30 seconds, so what if the X-rays die off too? Than after ≈ 1 day, we'd have nothing to see!

- But it paid off enormously!

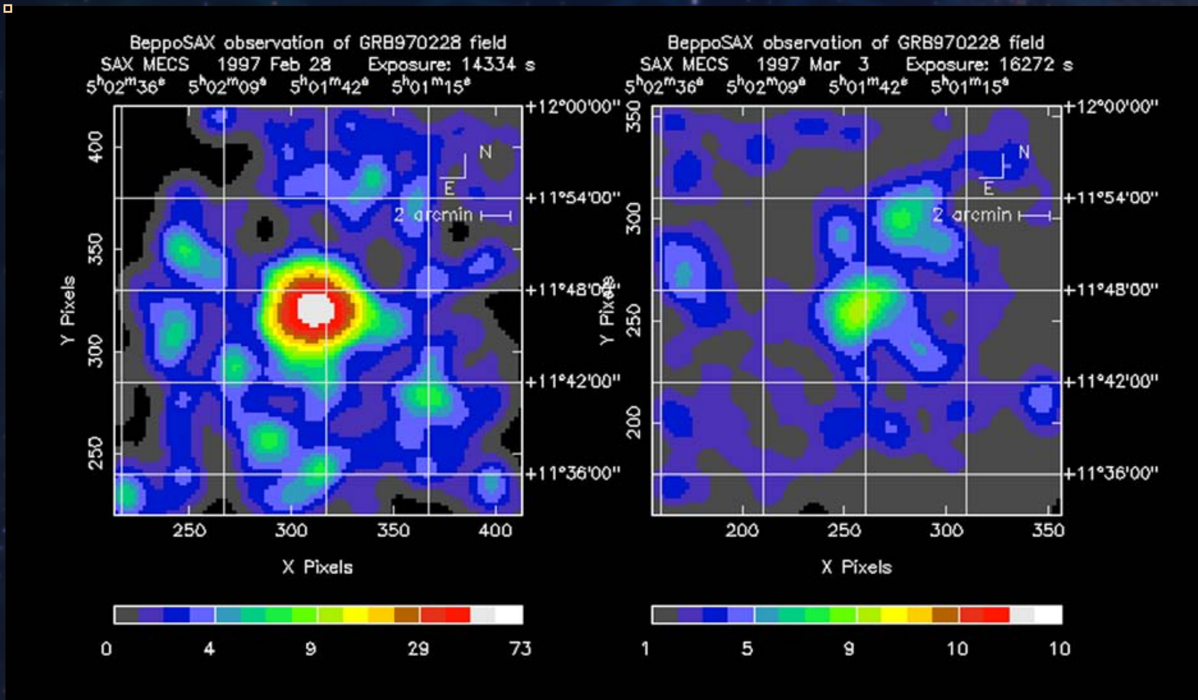


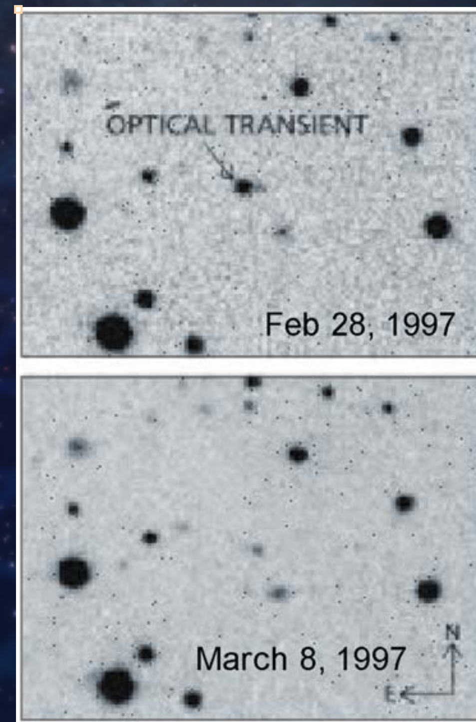
(*above*: BeppoSAX — *Italian Space Agency, ASI*

left: Giuseppe "Beppo" Occhialini)

Gamma-Ray Burst Afterglows

On February 28, 1997, a **Gamma-ray burst afterglow** was discovered.





BeppoSAX found and localized a gamma-ray burst to within a couple arcminutes using an X-ray afterglow that remained visible for days after the γ-rays had shut off.

This let people find an optical transient counterpart to the gamma-ray burst.

Gamma-Ray Burst Afterglows

Why is this important?

- We can get an excellent position optically.
- We can determine the host galaxy.
- We can measure distance via redshift.

Gamma-Ray Burst Afterglows

While GRB 970228 faded too quickly for astronomers to get a spectroscopic redshift, BeppoSAX found more gamma-ray burst afterglows.

GRB 970508 (May 8, 1997) had a redshift distance of ≈ 1 billion ly

GRB 971214 (December 14, 1997) had a redshift distance of ≈ 12 billion ly

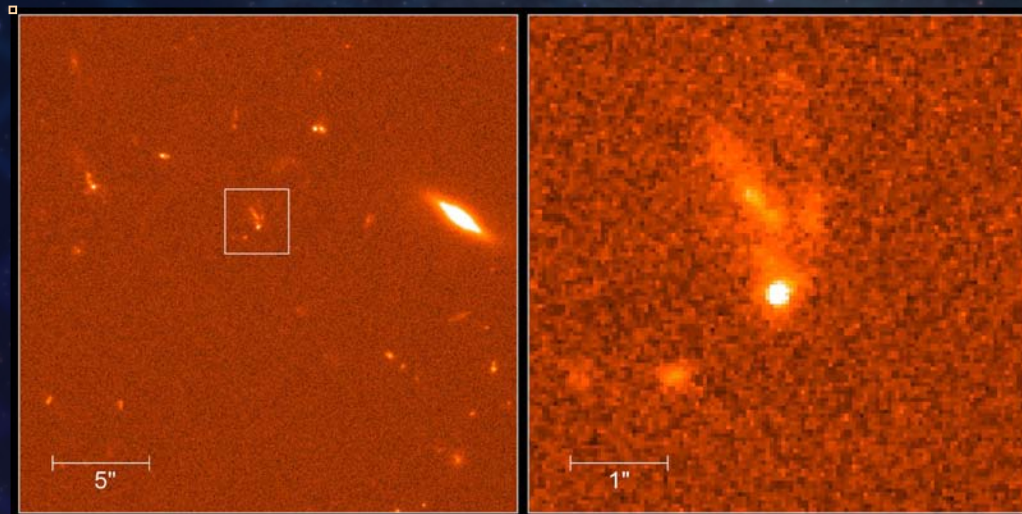
These are enormous distances! They were a substantial fraction of the way across the Universe.

This implies enormous energies — in the most extreme cases, they have many times the luminosity of a supernova.

Gamma-Ray Burst Afterglows

GRB 990123:

- $E_{\gamma\text{-rays}} \approx 3.4 \times 10^{54}$ ergs
- $L_{\text{optical, peak}} \approx 3.3 \times 10^{16}\, L_{\odot}$ (about that of a million normal galaxies!)
- Assuming isotropic emission
- *Nature* 398, 392



(Hubble Space Telescope image of GRB 990123; the distorted shape of the host galaxy is possibly due to a collision between galaxies — *STScI, NASA*)

We've now found many gamma-ray burst afterglows and host galaxies.

Not all gamma-ray bursts have afterglows, but many do.

An X-ray afterglow usually lasts for days, while those in optical and radio wavelengths can last for weeks or months.

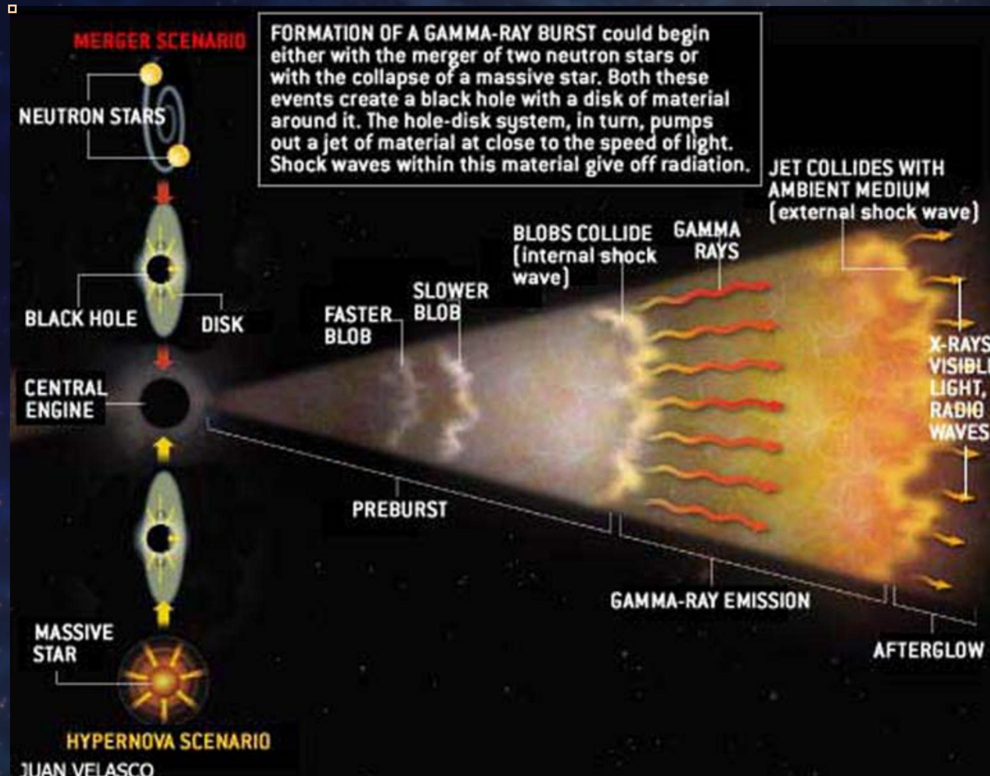
Nature of Gamma-Ray Bursts

So what is going on in these objects?

We don’t know entirely, but we have a good idea.

The process that energizes the event sends a powerful explosion out into the surrounding interstellar gas. This sends a strong shock wave outward at nearly the speed of light.

The shock wave crashes into interstellar gas and makes γ-ray, X-ray, optical and radio emissions. This is called a “fireball” or a “relativistic blast wave.”



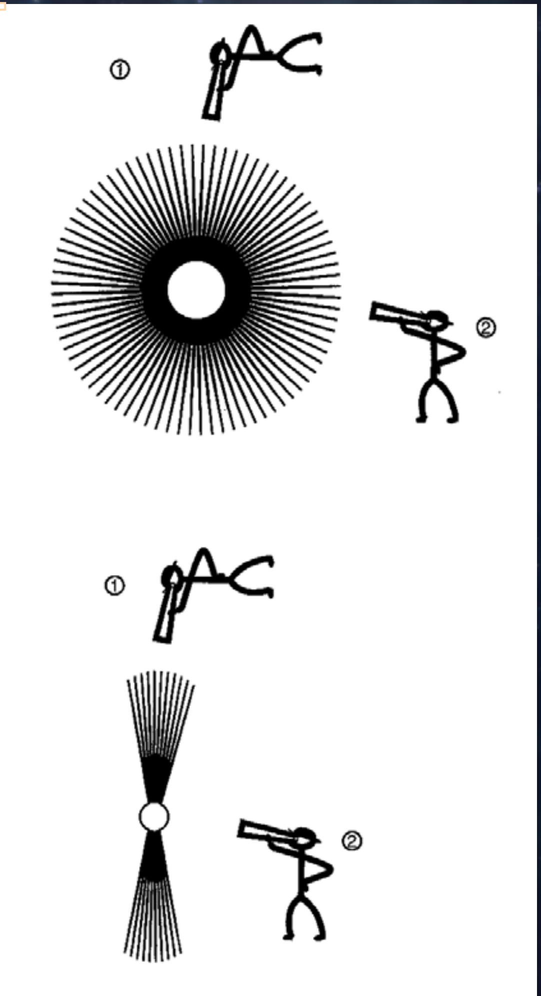
(Diagram of a gamma-ray burst blast wave — *Scientific American, December 2002*)

Nature of Gamma-Ray Bursts

How can we explain these enormous energies?

The emission is probably not equal in all directions but highly collimated. This can help with the energy requirements.

If energy flows into a "jet" filling only 2% of all available directions, then the energy is only 2% of what it would otherwise need to be.



(collimated beam image from *Craig Wheeler's* *Cosmic Catastrophes*)

Nature of Gamma-Ray Bursts

Another cool effect:

If the source of the radiation is moving toward the observer at relativistic speed, then the radiation is preferentially thrown in the direction of the observer; this is called "beaming" or the "headlight effect."

Nature of Gamma-Ray Bursts

If we allow for beaming and time dilation, then the effects are more understandable.

- Not an unreasonable amount of energy needed
- Occurs over a more relaxed timeframe
- Special relativity in action!

But fundamentally we still don't understand why the energy comes out in this highly collimated way.

It may be related to "jets" in active galaxies, which we'll discuss later.

Nature of Gamma-Ray Bursts

Also, what is the “energizing event?”

The favored idea is that gamma-ray bursts arise in a small fraction of stars which undergo some cataclysm when they die — one in a million stars.

“Long” γ-ray bursts (10s – 100s duration) are thought to originate from “hypernovae.”

“Short” γ-ray bursts (0.1s – 1s duration) are thought to originate from the merging of two neutron stars.

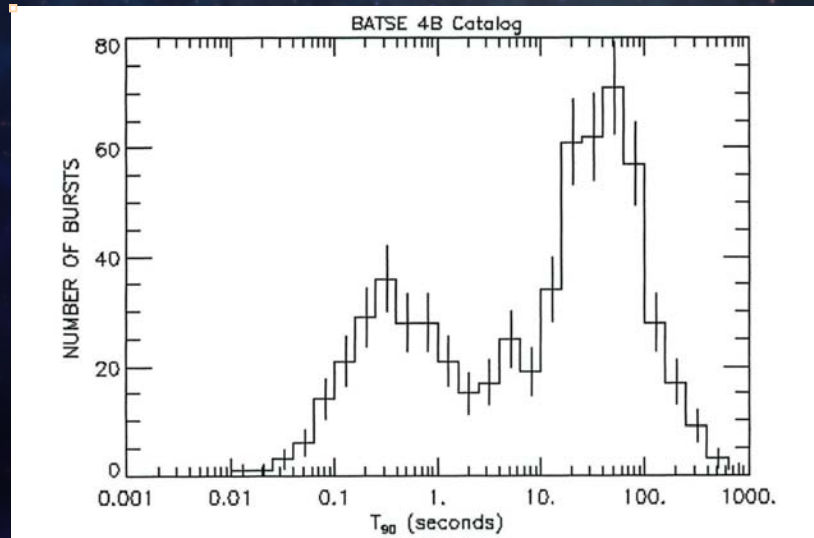


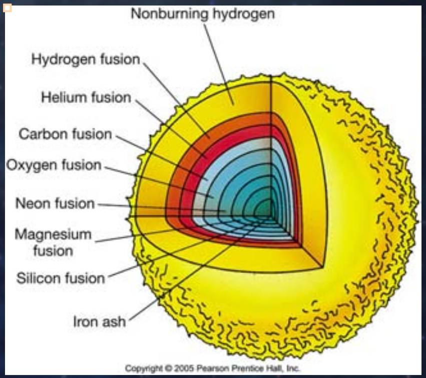
Figure 3: Shown is the bi-modal distribution of GRB durations of the 4B Catague, set by a T90 duration parameter, on lightcurves integrated over all 4 channels ($E >$20keV). (Courtesy of NASA Marshall Space Flight Center, Space Sciences Laboratory.) The population of long bursts is probably associated with young massive stars and, hence, with a redshift of $z = 1 - 2$. This indicates a redshift corrected mean value of the intrinsic duration of about 10-15s. In van Putten & Ostriker (2001), shorts bursts are identified with magnetic regulated hyperaccretion onto slowly rotating black holes, and long bursts with rapidly rotating black holes in a state of suspended accretion. Long bursts are potential LIGO/VIRGO sources of gravitational radiation by gravitational radiation from the torus, derived from the spin-energy of the black hole. This indicates a mean duration of 10-15s of gravitational wave-emissions commensurate with the redshift corrected GRB-event, for a cosmologically nearby sample within the detection sensitivity of LIGO/VIRGO.

(Distribution of gamma-ray burst durations, showing two distinct groups: from ≈0.1 to 1 second, and from ≈10s to several minutes — *NASA, Marshall Space Flight Center*)

Nature of Gamma-Ray Bursts

Long gamma-ray bursts: **Hypernovae**

A massive core collapses into a black hole threaded by magnetic field lines from the star.

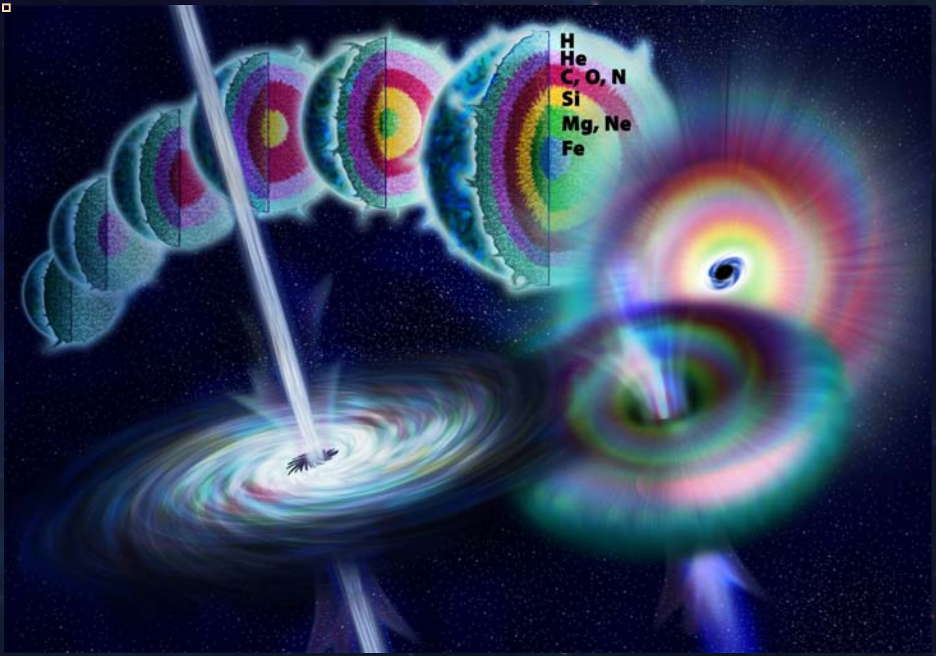


"Onion-skin" model of stellar structure — elemental fusion zones in supergiant stars

- Silicon, carbon, oxygen part of the star in the process of exploding in a supernova

- Black hole threaded by magnetic fields

- Jet punches right out of exploding star



(*N.R. Fuller, NSF*)

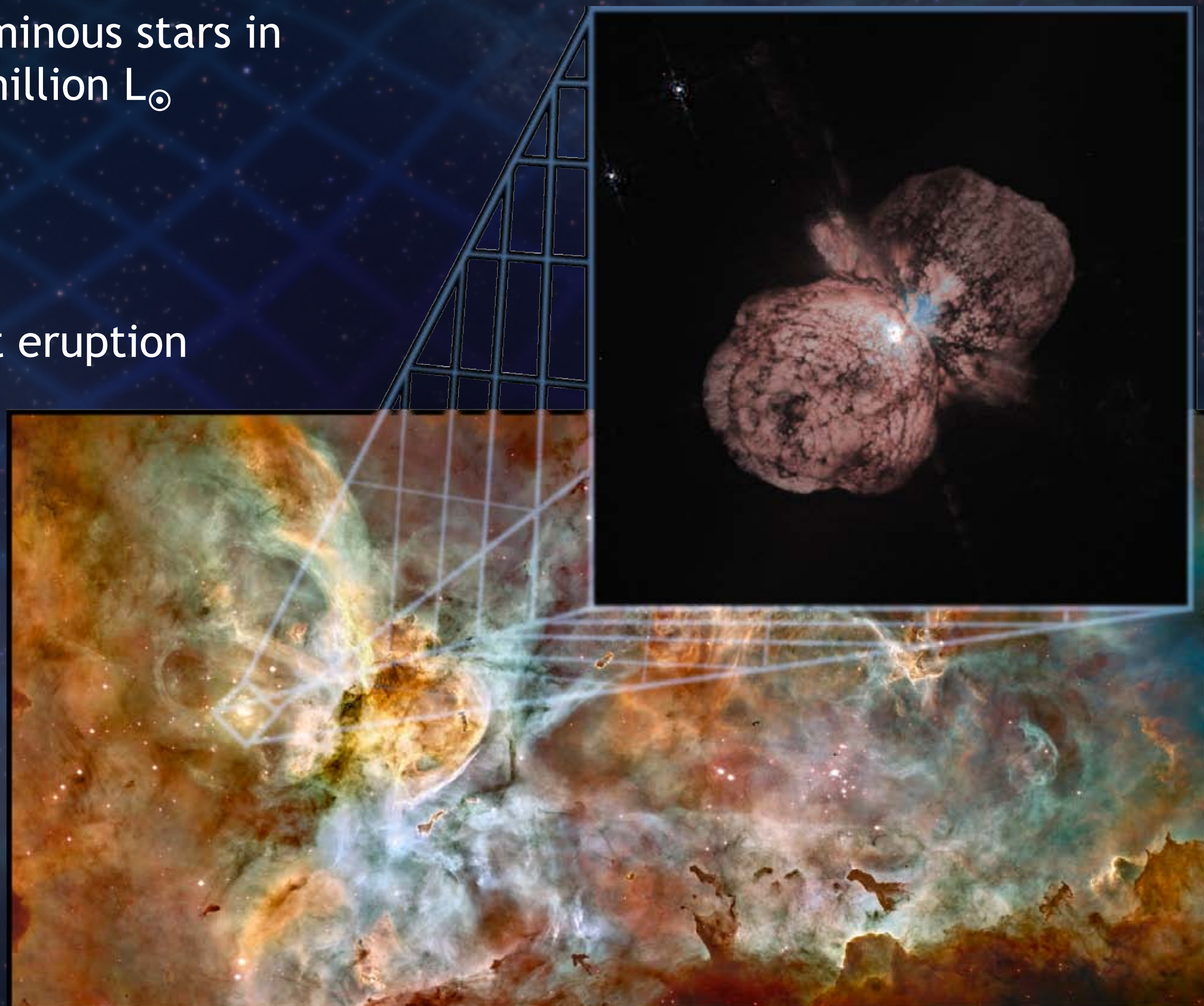
Eta Carinae

One of the most luminous stars in the galaxy, at ≈ 5 million $L_\odot$

Perhaps ≈100 $M_\odot$

Experienced a giant eruption around 1837-1856

Could collapse at any time — probably forming a black hole



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Hubble Space Telescope image of NGC 3372, host nebula to η Carinae (above, right)

Nature of Gamma-Ray Bursts

Short gamma-ray bursts: Black hole + neutron star or two-neutron-star binary mergers

To solve this problem, we mainly need to be able to study the explosion quickly, rather than after 1 to a few days.

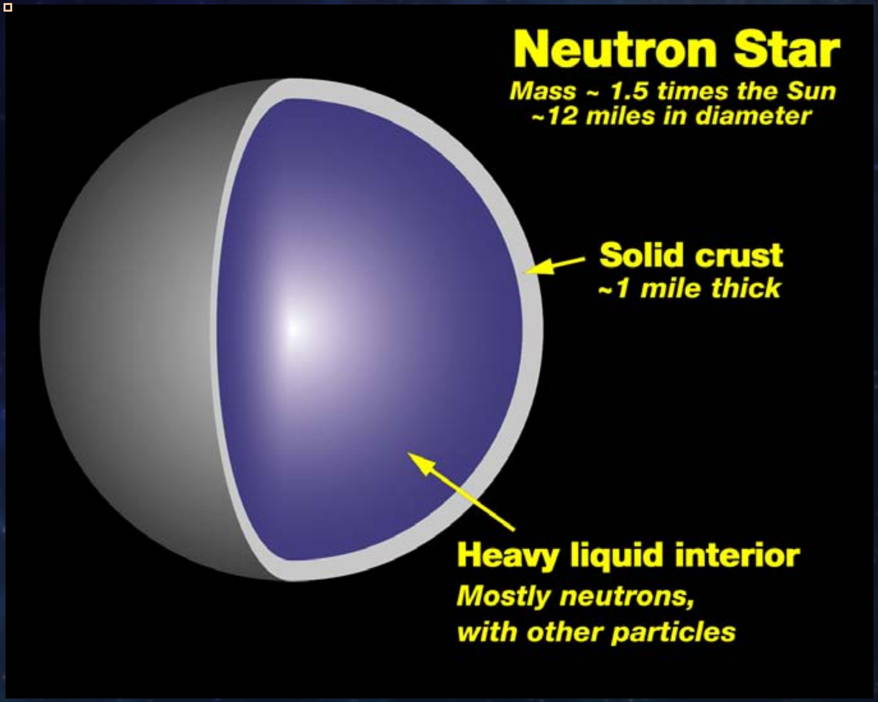


Diagram of the interior of a neutron star.
(*NASA/Marshall Space Flight Center*)

Swift Gamma-Ray Burst Explorer

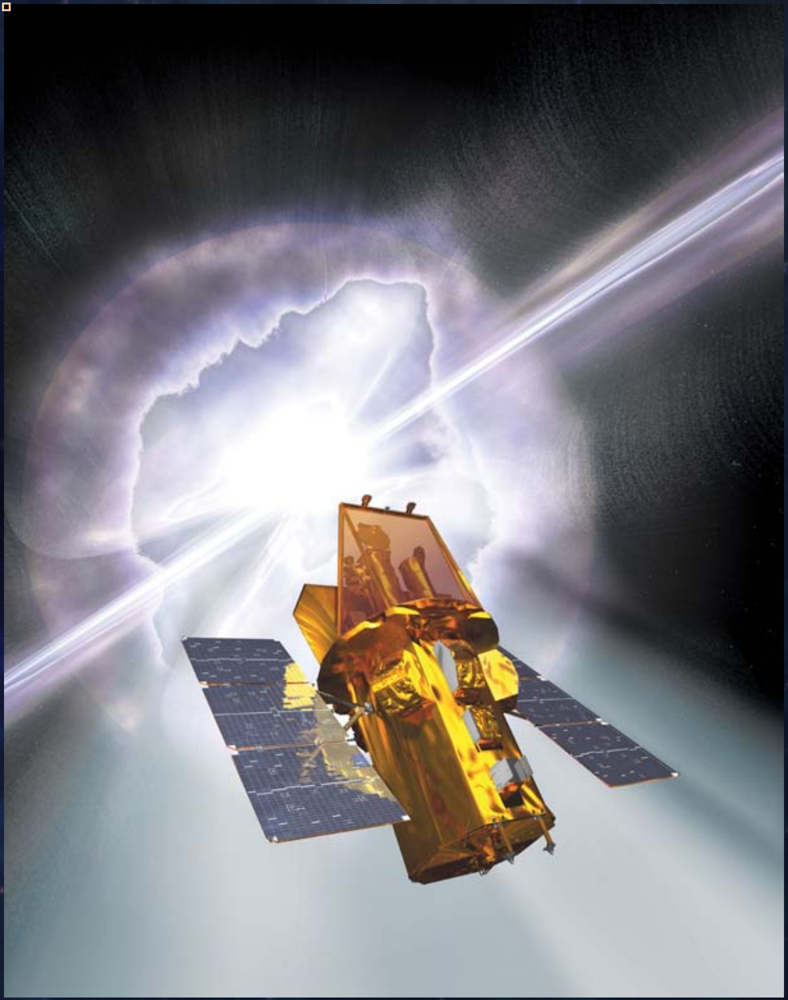
“Catching Gamma-Ray Bursts on the Fly”

- First dedicated gamma-ray burst satellite; launched on a Delta rocket 20 November 2004

- Named after the birds “Swifts,” which can change direction quickly in flight

- Can move to a gamma-ray burst within 1 minute – much faster than before (used to take one to a few days)

- Can observe in gamma-ray, X-ray, optical, ultraviolet



(Artist’s conception of the Swift GRBE — *Spectrum and NASA E/PO, Sonoma State University, Aurore Simonnet*)

Swift Gamma-Ray Burst Explorer

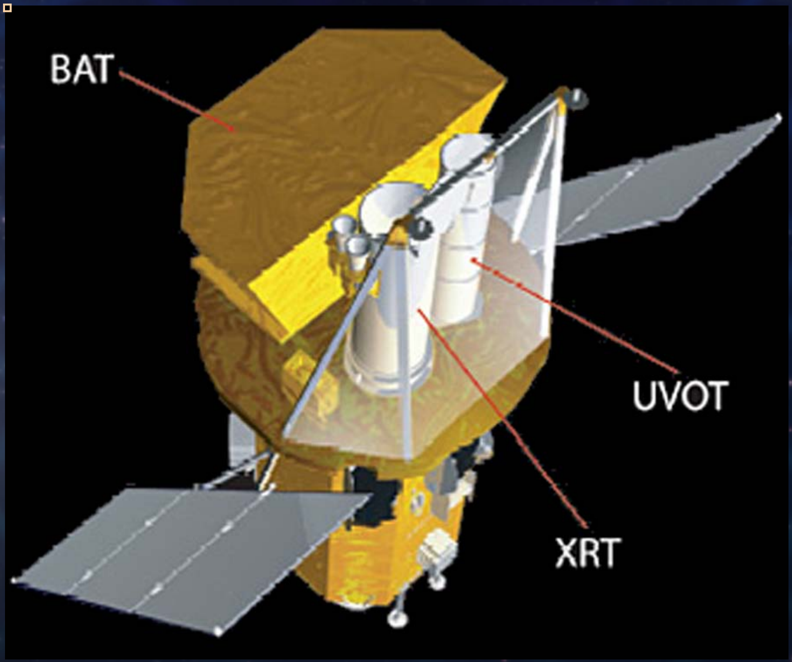
Goals of the Swift Mission:

1. Determine the origin of gamma-ray bursts
2. Classify gamma-ray bursts and search for new types
3. Determine how blast waves evolve and interact with surroundings
4. Use gamma-ray bursts to study the early Universe

Swift Gamma-Ray Burst Explorer

Instruments:

- Burst Alert Telescope (BAT): coded mask, Cd Zn Te; covers ~2 steradians (almost 1/6 of the sky)
- X-ray Telescope (XRT): detects in the range of 0.2–10 keV
- Ultraviolet/Optical Telescope (UVOT): detects from 170–650 nm



(Primary scientific instruments on the Swift GRBE — *NASA* / *GSFC*)

Swift Gamma-Ray Burst Explorer

The Swift mission involves a large collaboration, including Goddard Space Flight Center and Penn State. PSU runs the mission operations center.

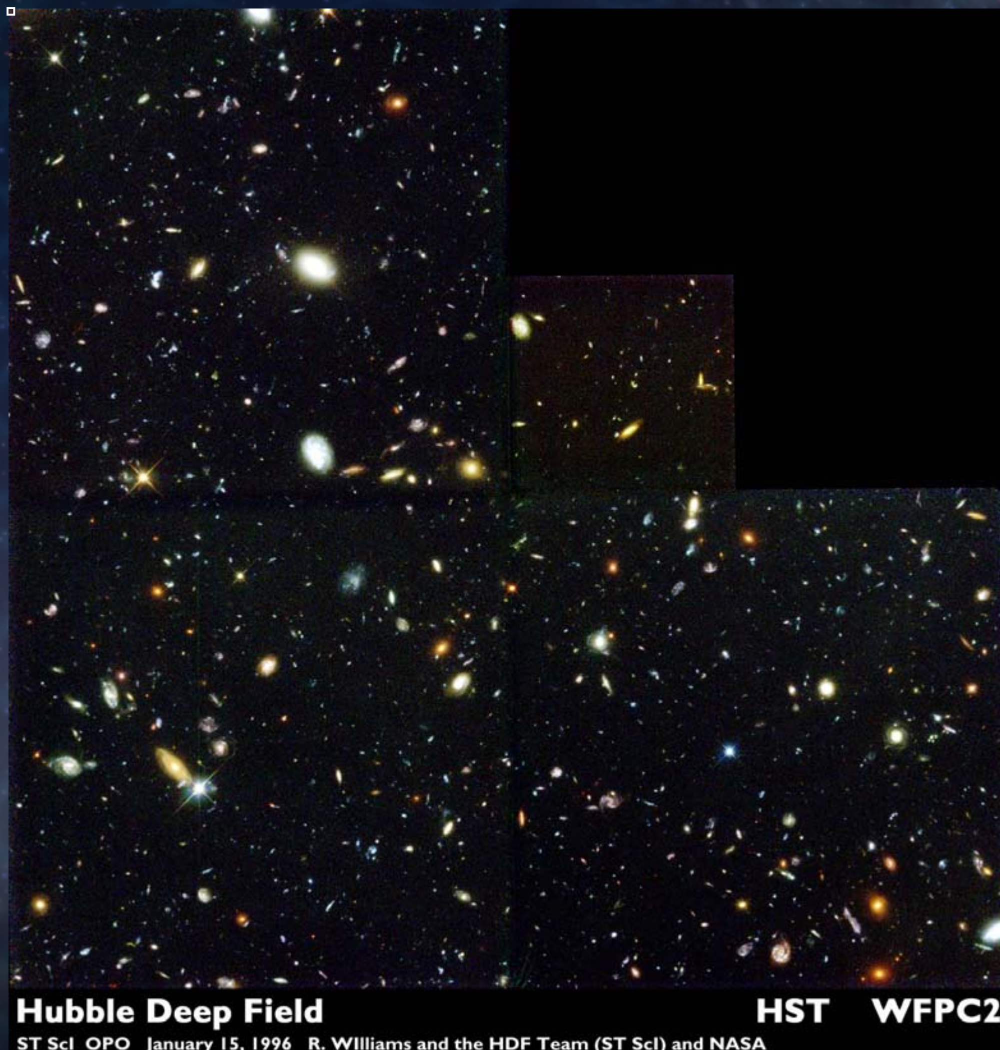
Every couple days, on average, Swift detects a new gamma-ray burst.

Swift's main discoveries so far:

- Clarification of the nature of short versus long gamma-ray bursts
  - "Short" GRBs (0.1–1 second): merging neutron stars
  - "Long" GRBs (10–100 seconds): black hole forming from a massive star
- Most long gamma-ray bursts are associated with supernovae
- Detailed data on flare from nearby magnetar in December 2004
- Most distant gamma-ray burst, GRB 050904, at $z = 6.29$
  (corresponds to ≈ 12.6 billion ly)

Lecture 11:
Galaxies and Their Nuclei

The Hubble Deep Field



Eye on a Dime

The Hubble Ultradeep Field

Brief Review of Galaxy Structure

Disks

Prominent feature in spiral galaxies (like Milky Way)

Stars in nearly circular orbits

Analogies: Solar System, accretion disk

Bulges

Coexist with disks in spirals (central bulge, halo)

Elliptical galaxies: whole galaxy is bulge

Stars in random orbits

Galaxy Disks

Artist's Impression of
Our Galaxy's Disk

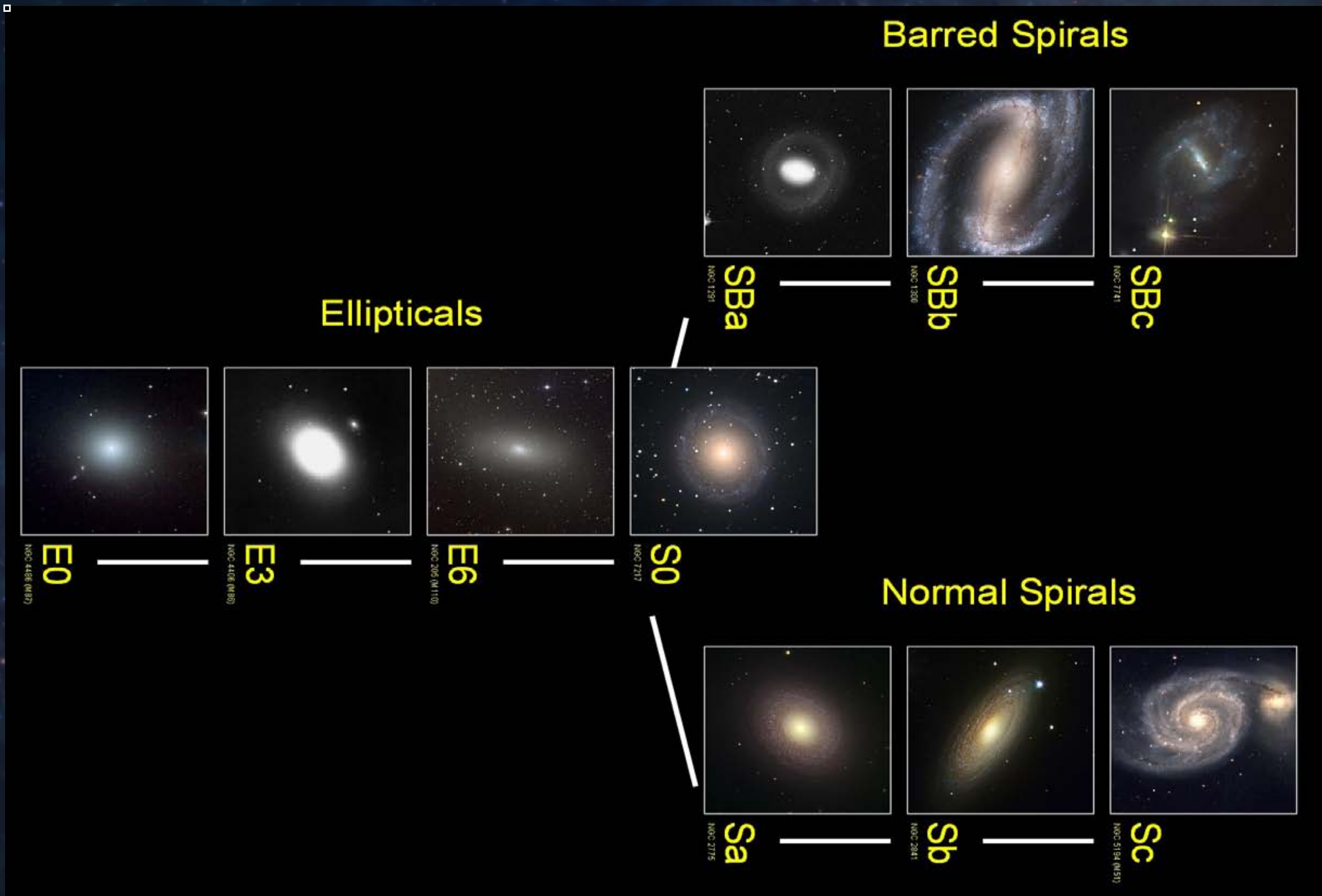
Disk of the
Galaxy NGC 1672

Galaxy Bulges

Sombrero Galaxy – Note the Large Bulge

M87 © Anglo-Australian Observatory
Photo by David Malin

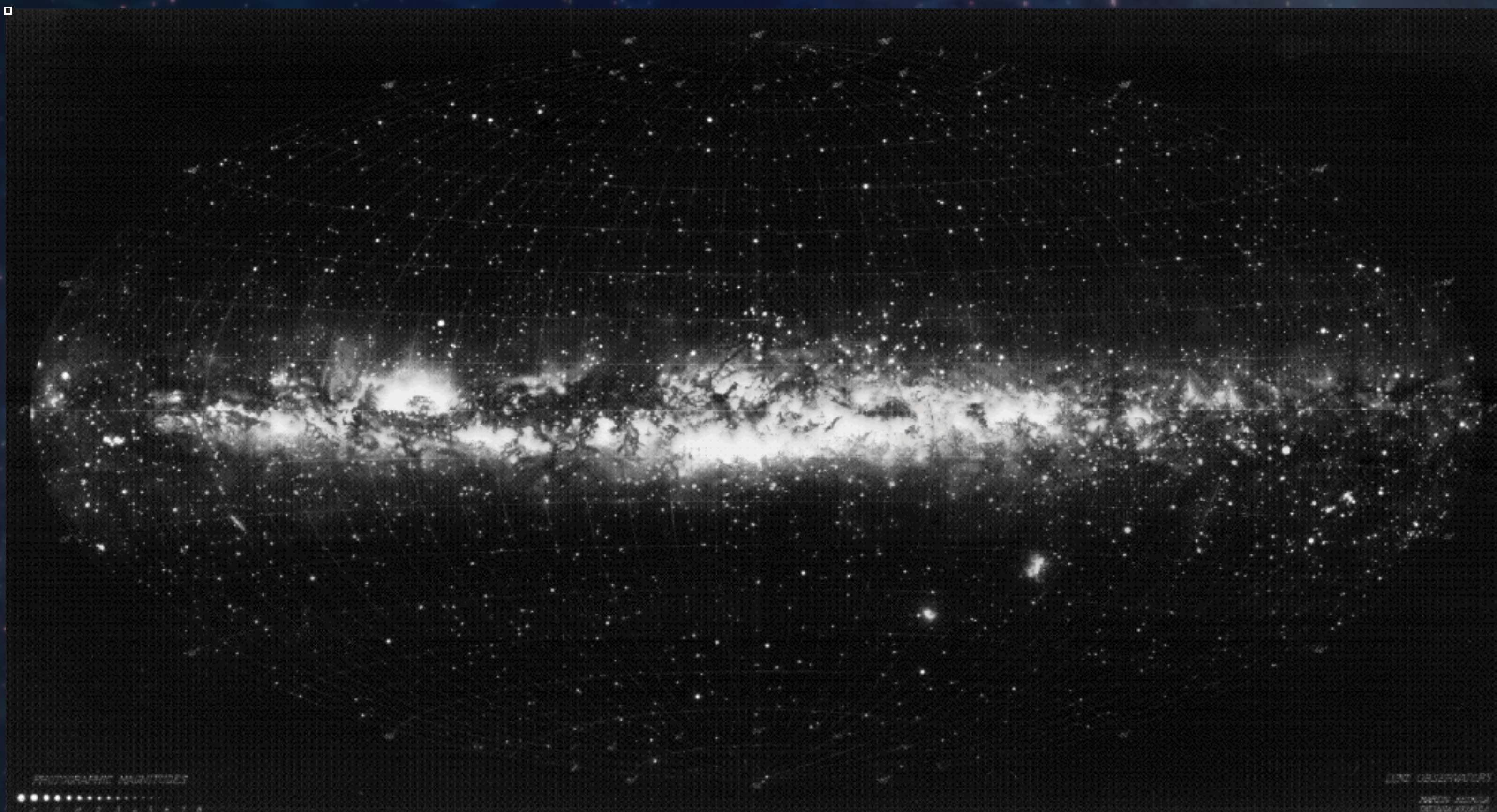
Galaxy Classification



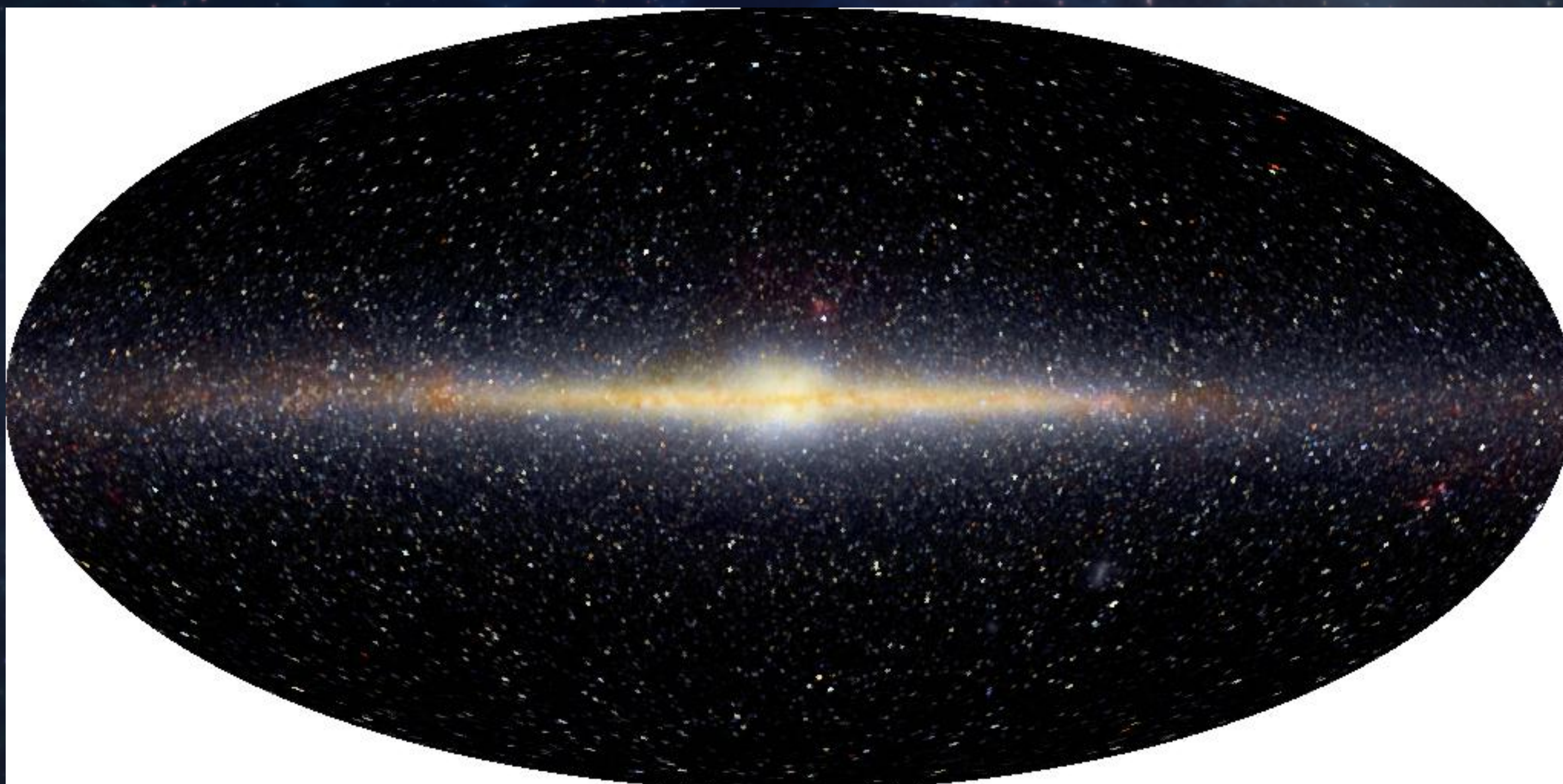
Main Contents of Galaxies

- **Dark Matter** (~80% of halo, smaller proportion of disk)
- **Stars**
  - Large galaxy has 100 billion stars (range 10^7-10^{12} stars)
  - "Collisionless", interact by gravitational forces
- **Gas**
  - > 10% of star mass
  - "Dissipative", tends to form clouds, sink to center
  - Can fall in from outside or escape in wind
- **Dust**
  - About 1% of gas mass, follows gas motion
  - Obscuration

The Milky Way in Optical Light

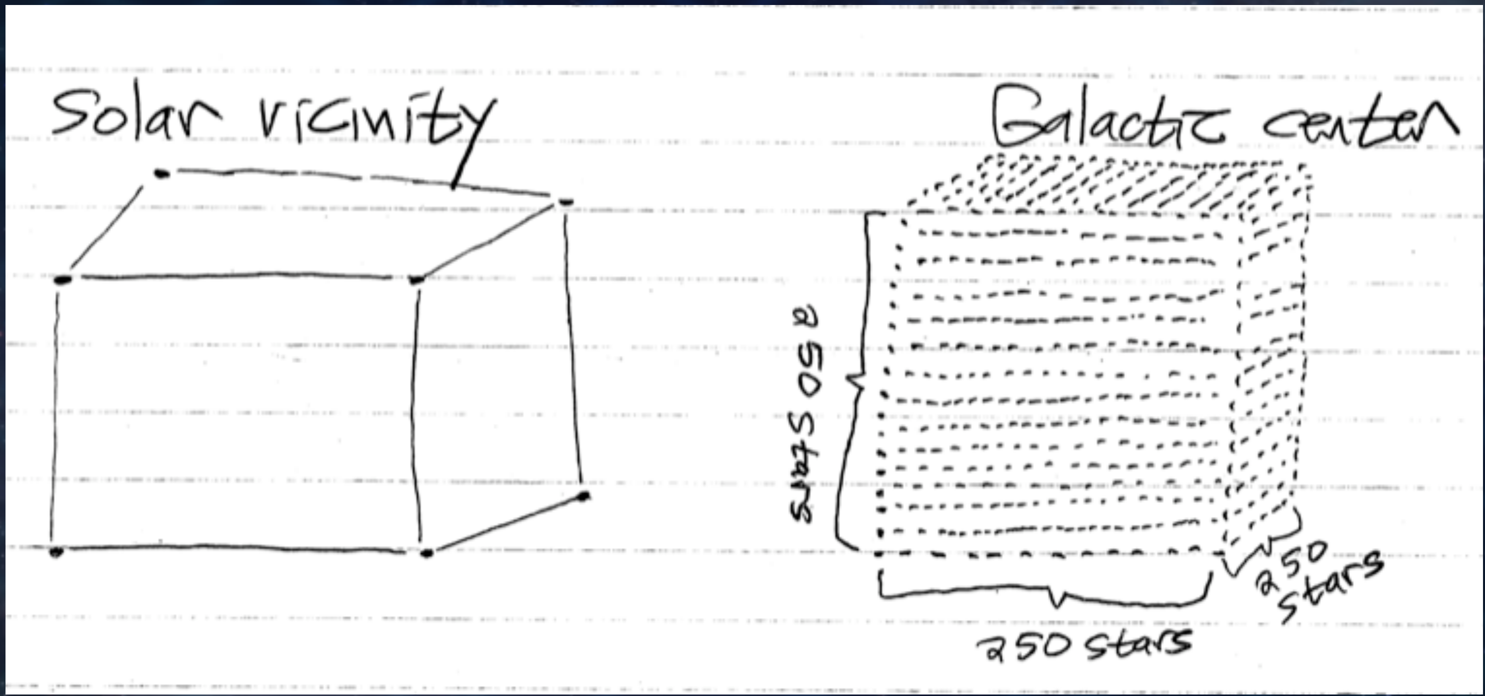


The Milky Way in Infrared Light

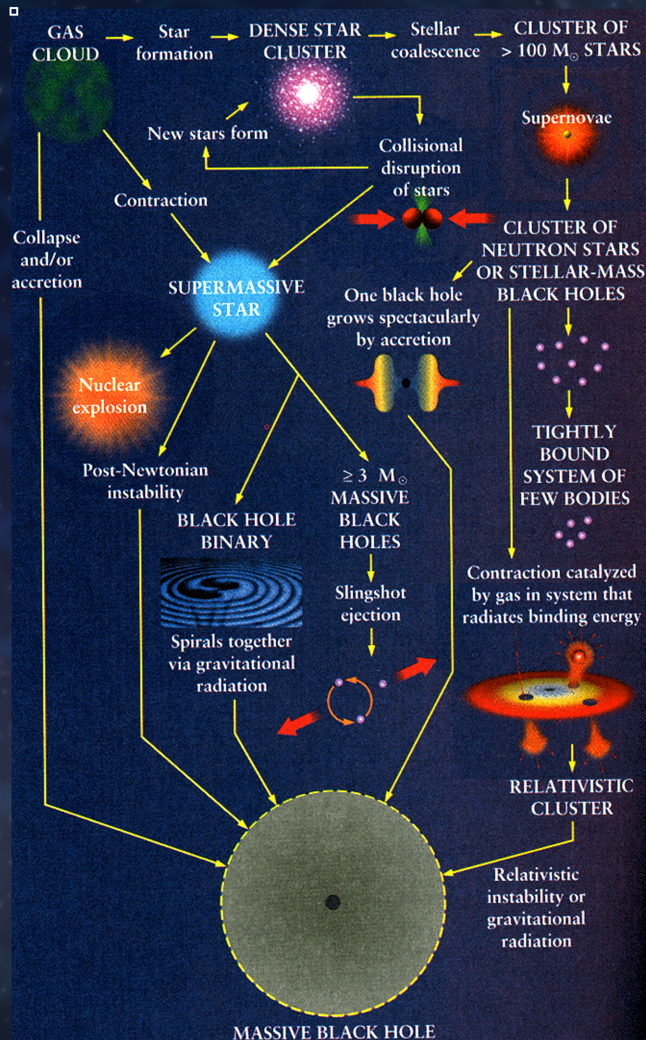


The Galactic Center in the Near Infrared

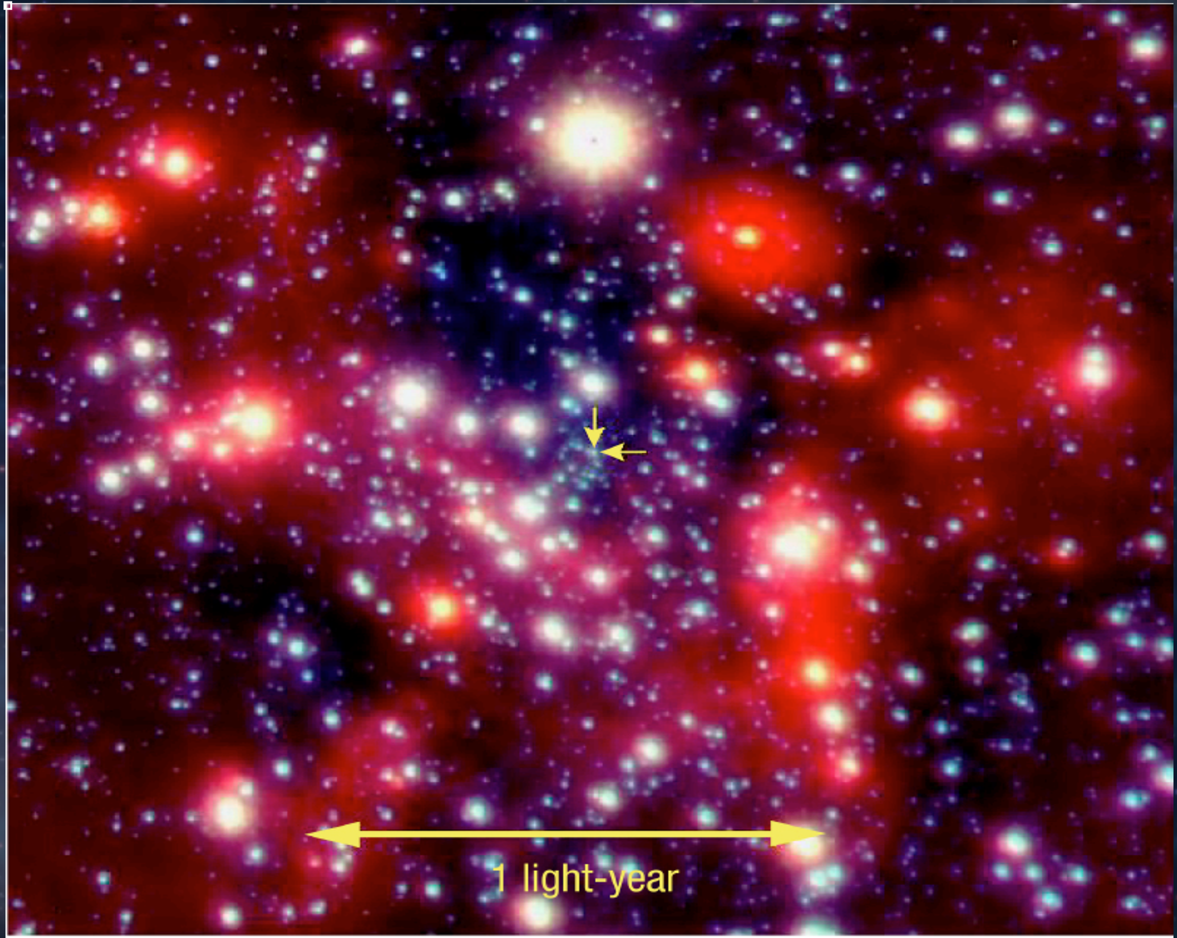
Relative Stellar Densities



Routes to a Supermassive Black Hole



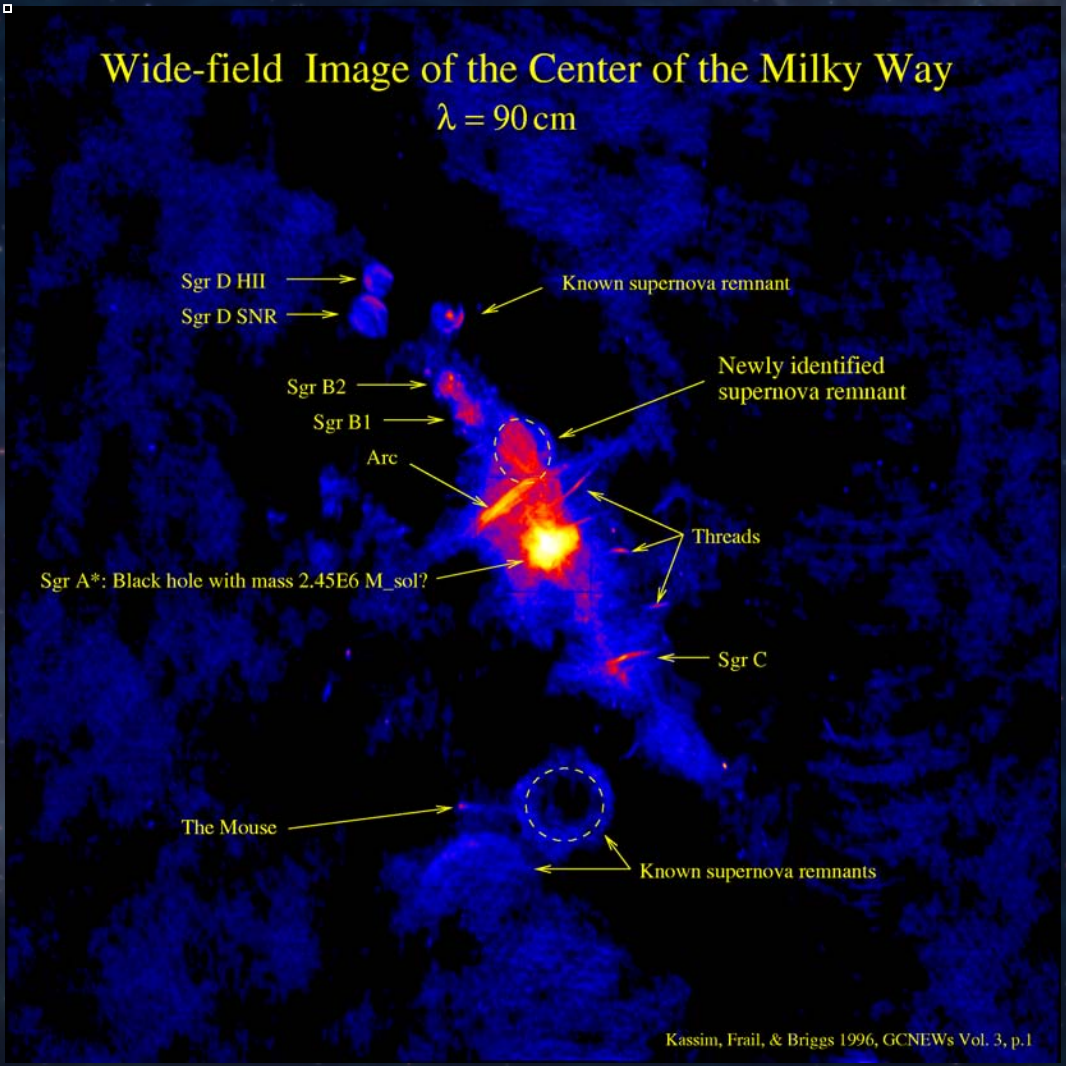
Infrared Image of Galactic Center



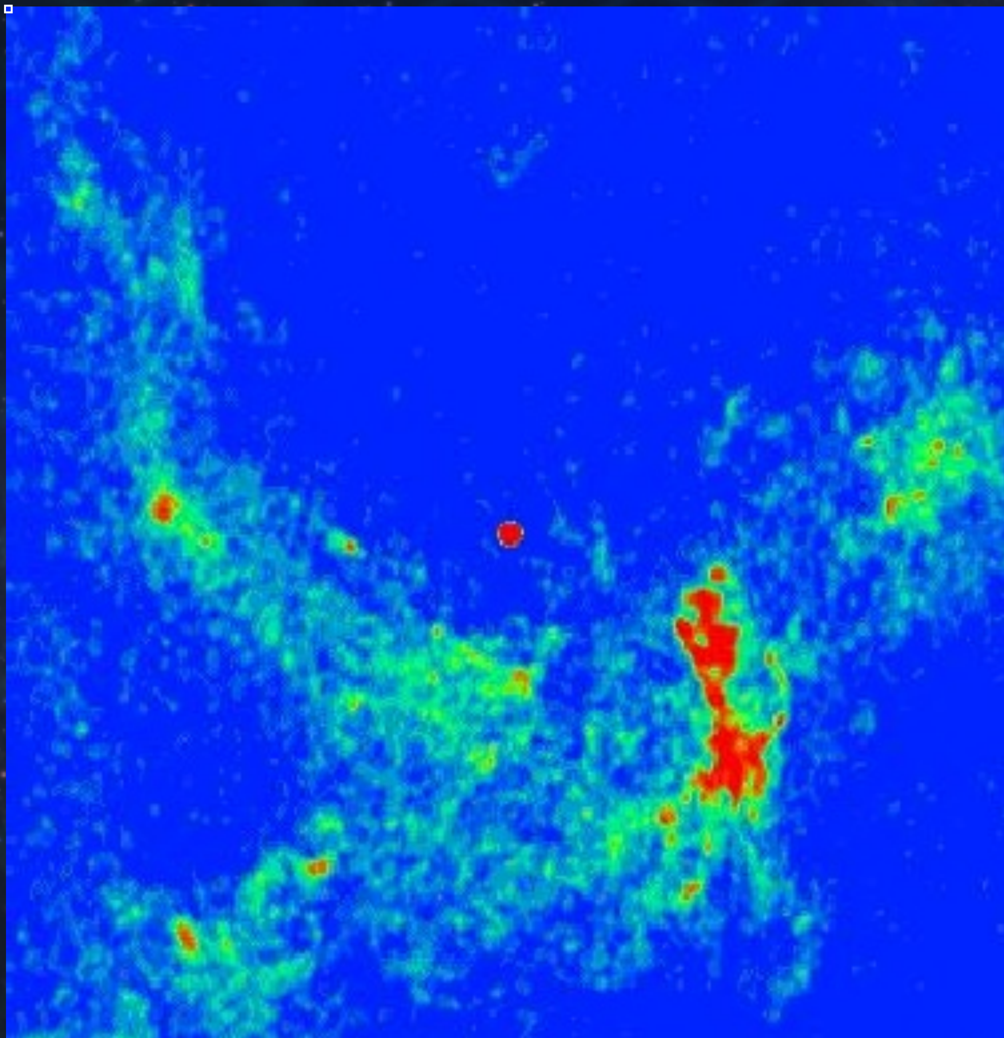
The Centre of the Milky Way
(VLT YEPUN + NACO)

ESO PR Photo 23a/02 (9 October 2002)

The Radio Source Sgr A*

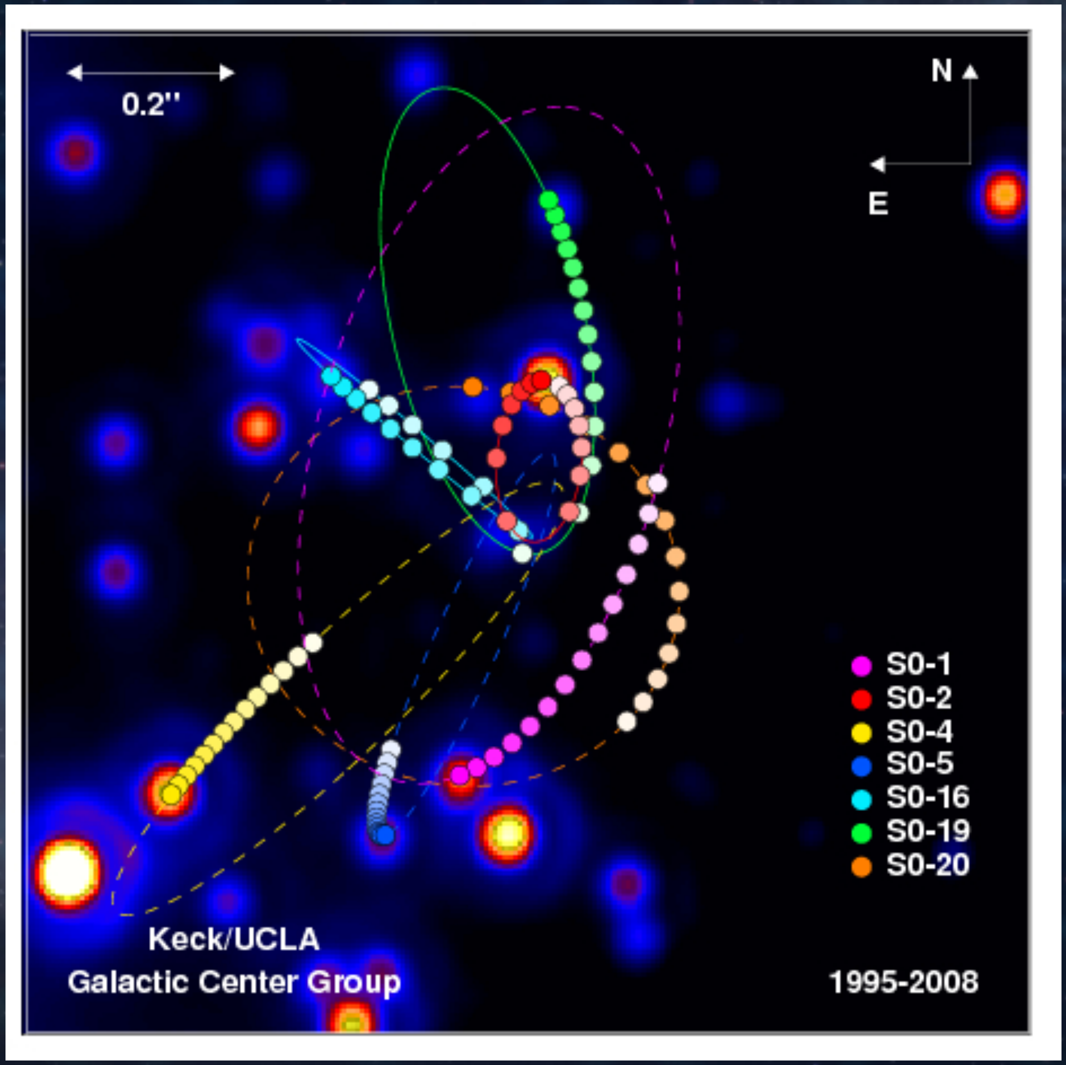


The Radio Source Sgr A*



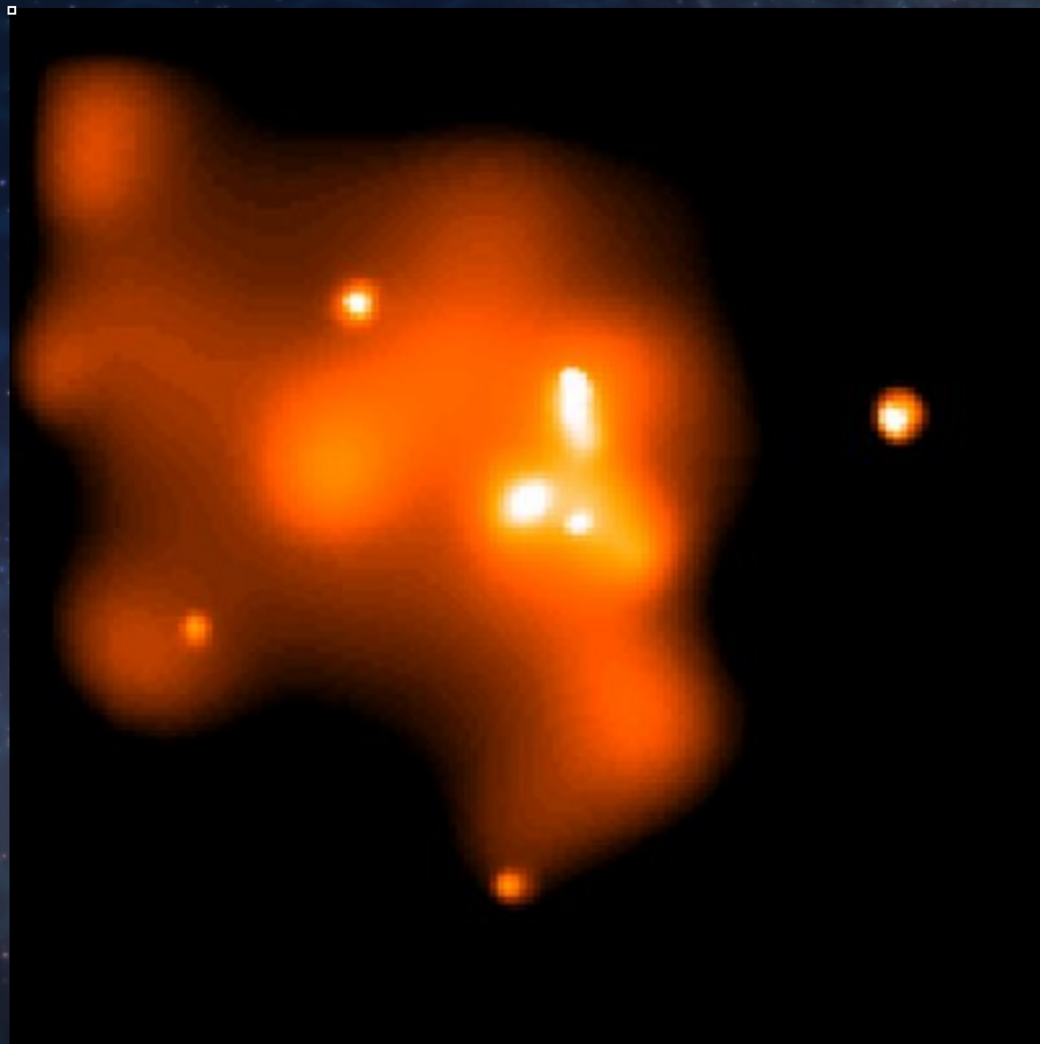
The red dot at the center is Sgr A*

Stellar Motions Near Sgr A*

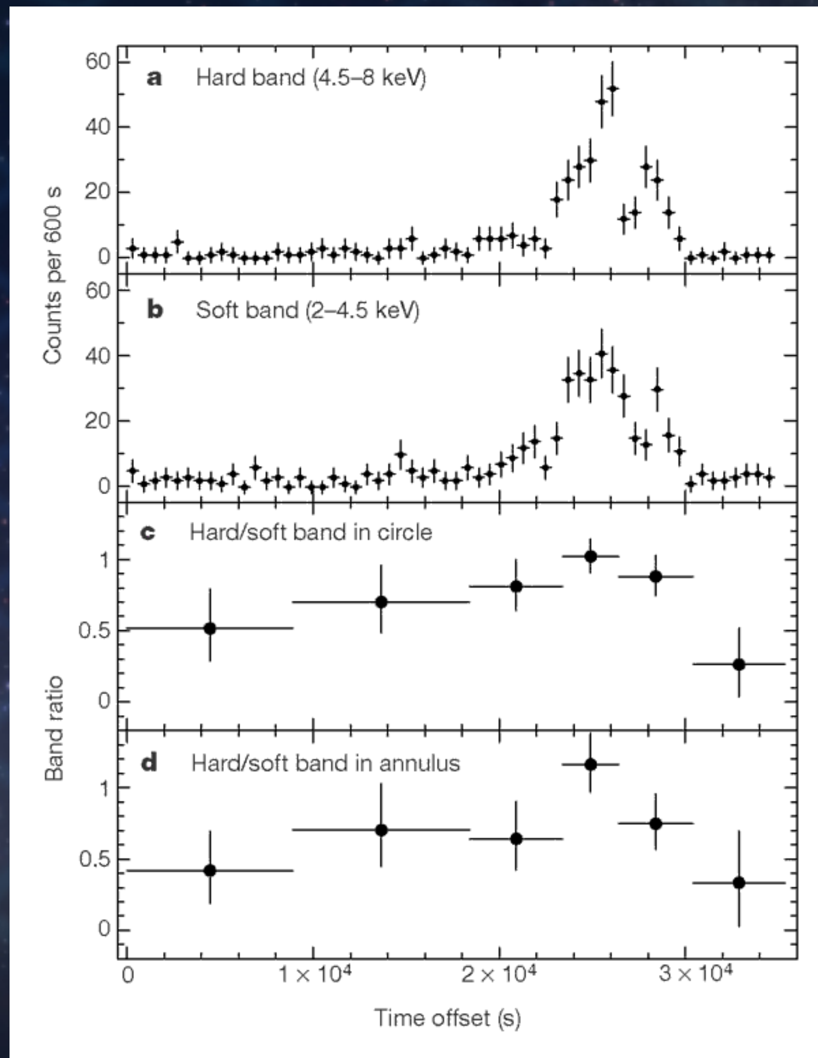


Chandra X-ray Image of Galactic Center

Chandra X-ray Image of Sgr A*



X-ray Flare from Sgr A*



Lecture 12:

Active Galactic Nuclei

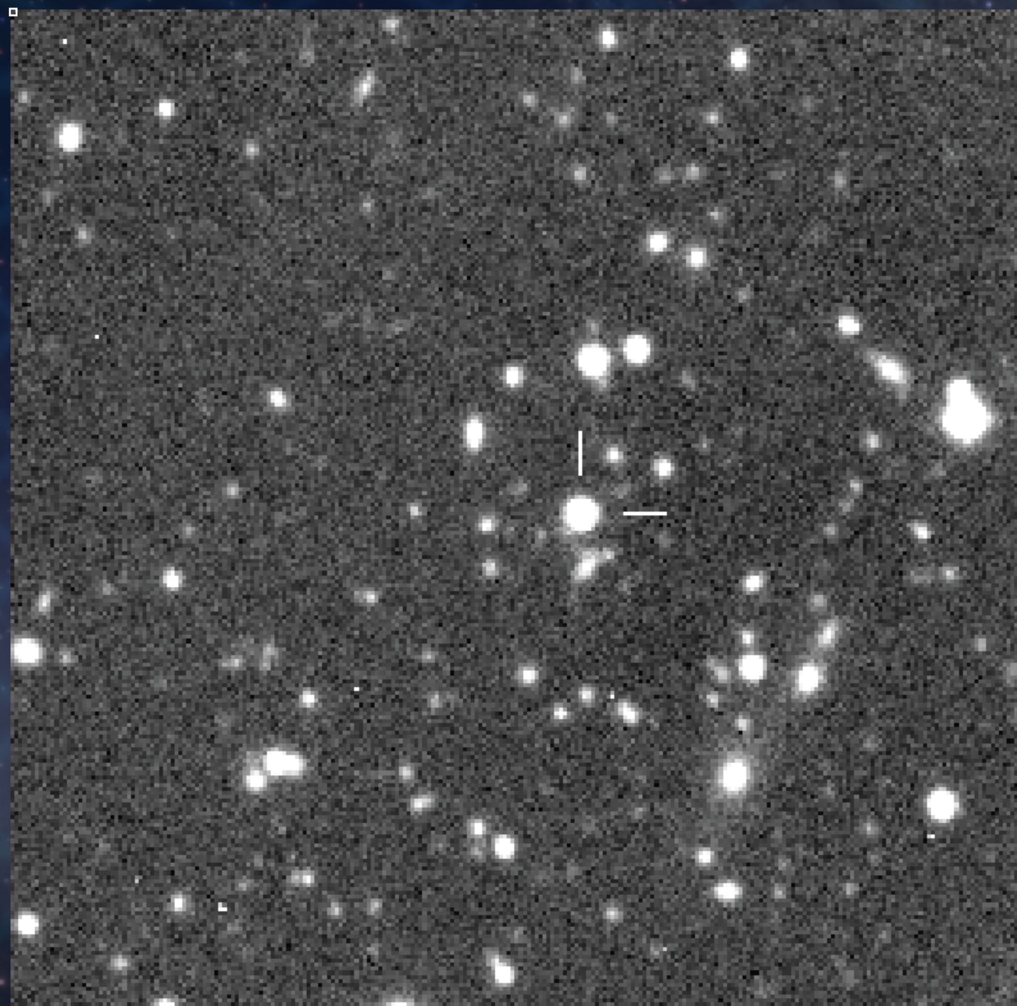
A Brief History of Active Galaxy Studies

Some early events in the history of active galaxy studies

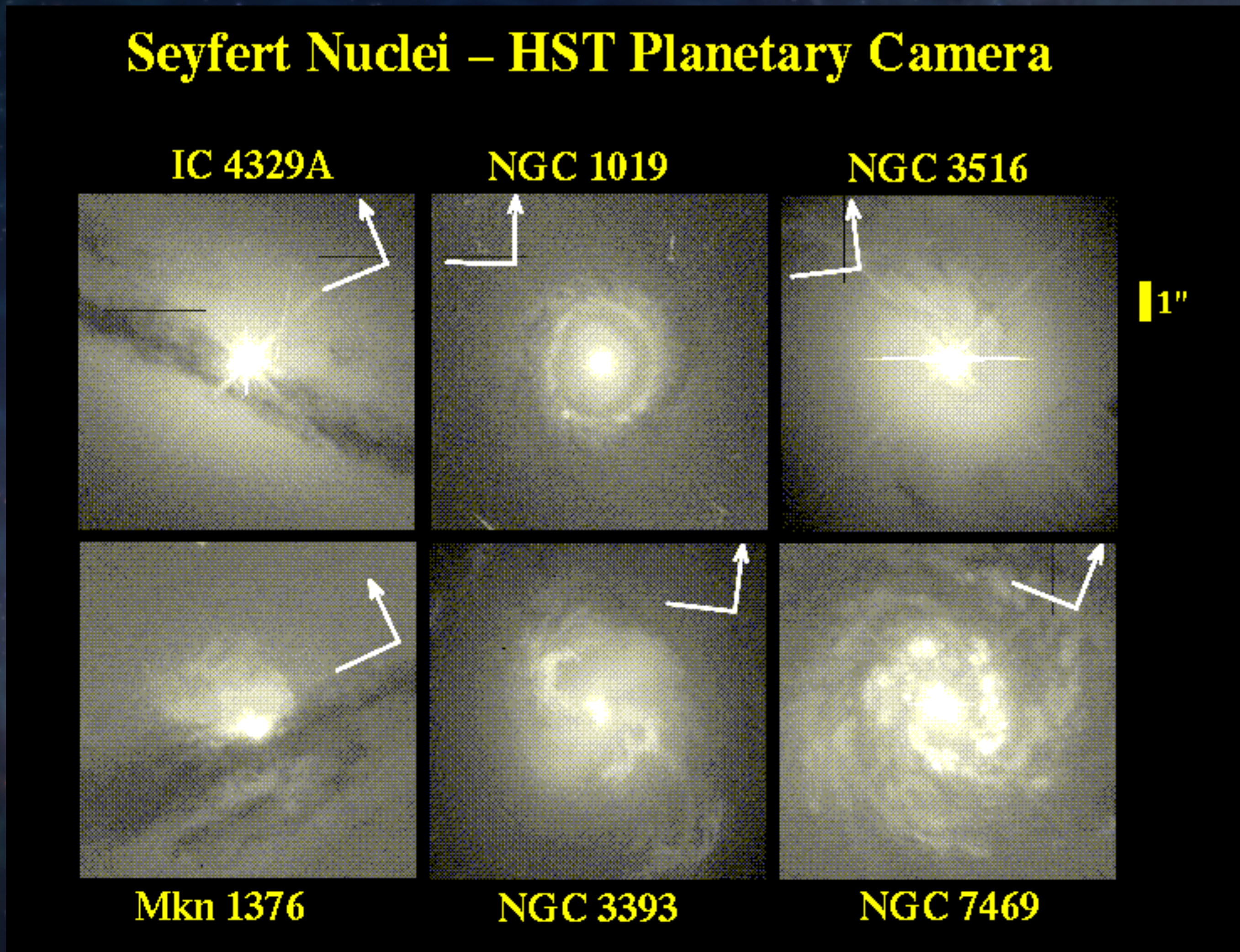
Year	Event
1908	Edward Fath notices strong emission lines from hydrogen, oxygen and neon in the nuclear spectrum of NGC 1068
1924-1929	General realization that galaxies are extragalactic - led by Edwin Hubble
1926	Edwin Hubble notices the nuclear emission line spectra of NGC 1068, NGC 4051 and NGC 4151
1939	Grote Reber discovers the radio source Cygnus A
1943	C.K. Seyfert shows that a fraction of galaxies have strong, broad emission lines and that these galaxies are especially luminous
1954	Walter Baade and Rudolph Minkowski find the counterpart to Cygnus A at $z = 0.057$
1963	Maarten Schmidt discovers 3C273 to have $z = 0.158$
1964	Zeldovich and Salpeter speculate about black holes powering quasars
1967	The term `black hole' is coined by John Wheeler
1969 onward	Serious research on the black hole plus accretion disk model
1971-1974	Identification and study of the first stellar mass black hole in our Galaxy (Cygnus X-1)

John Herschel

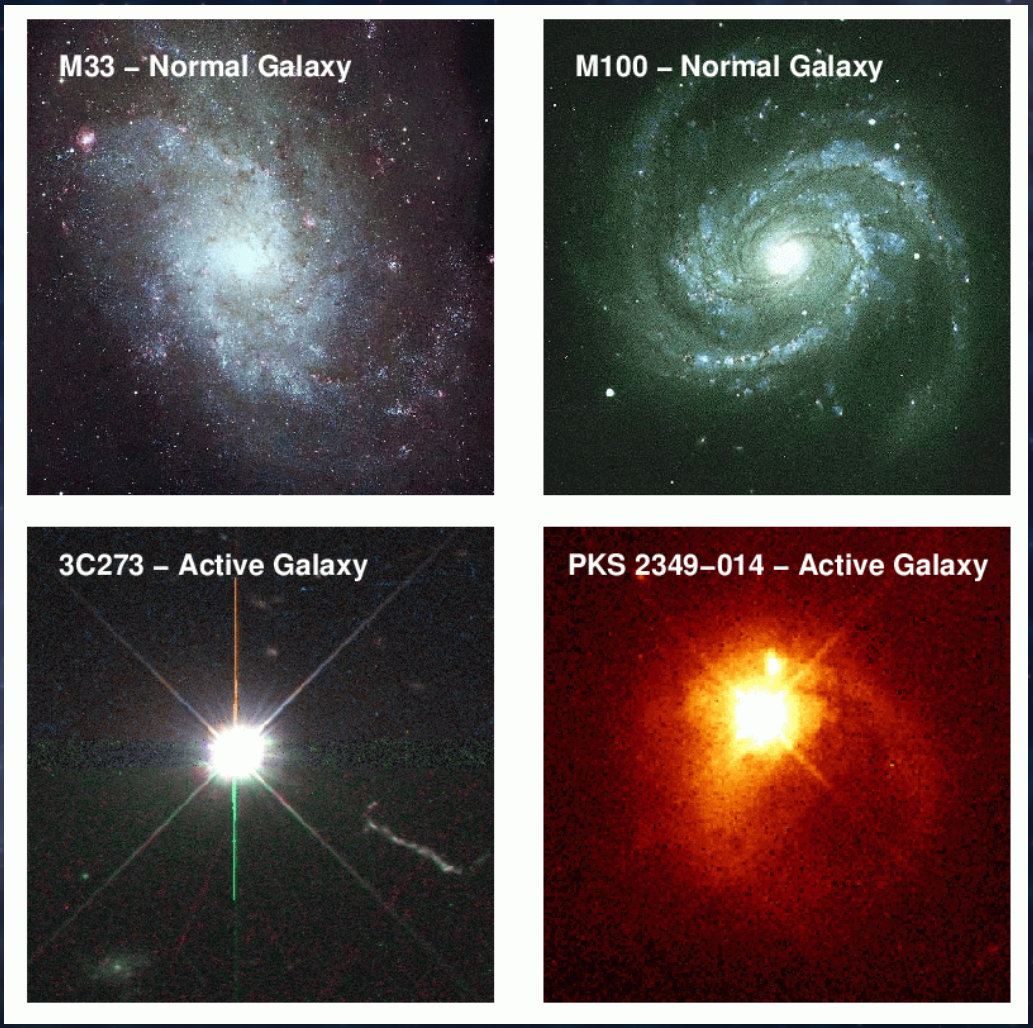
Optical Image of PKS 1117-248



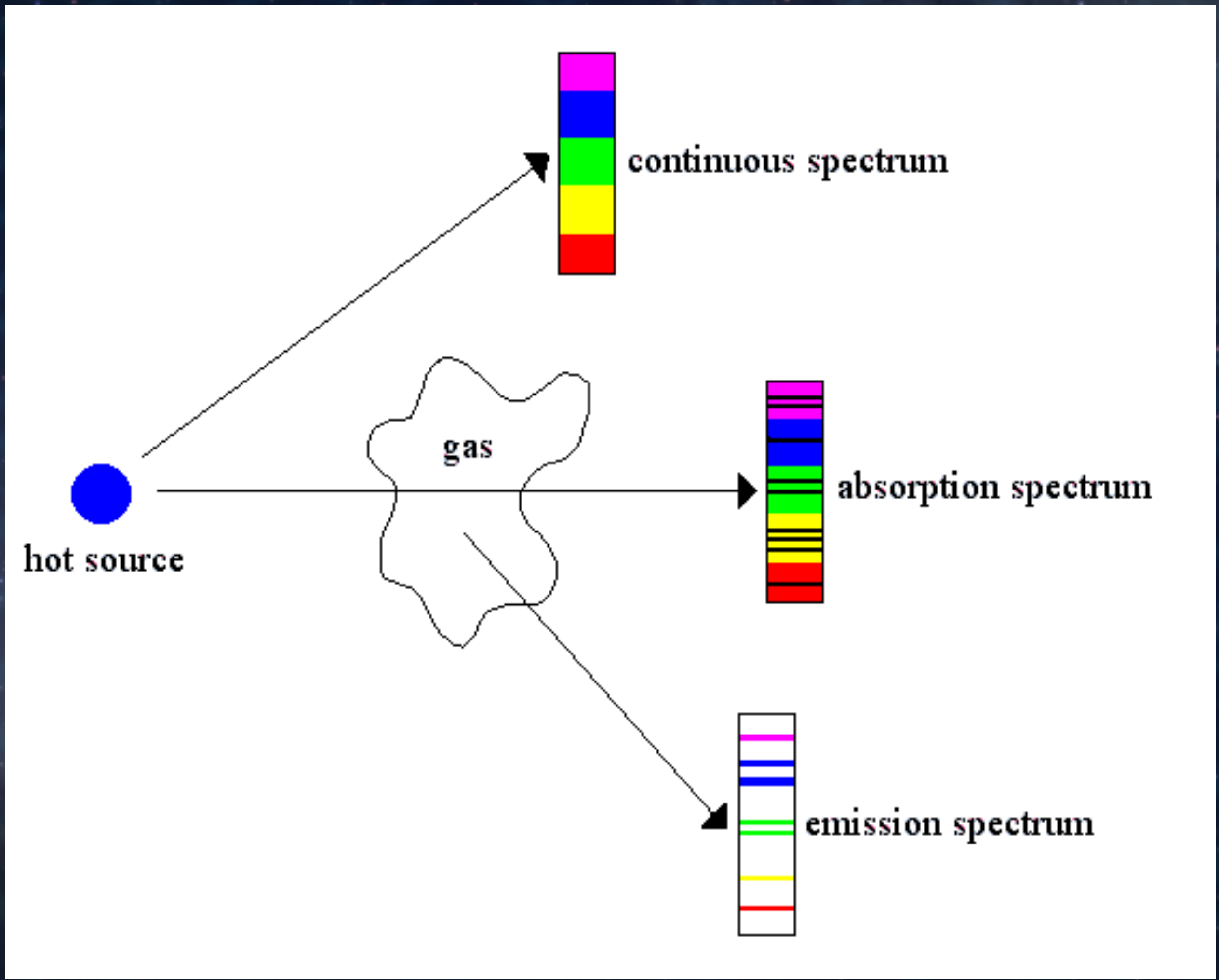
Images of Some Nearby Active Galaxies



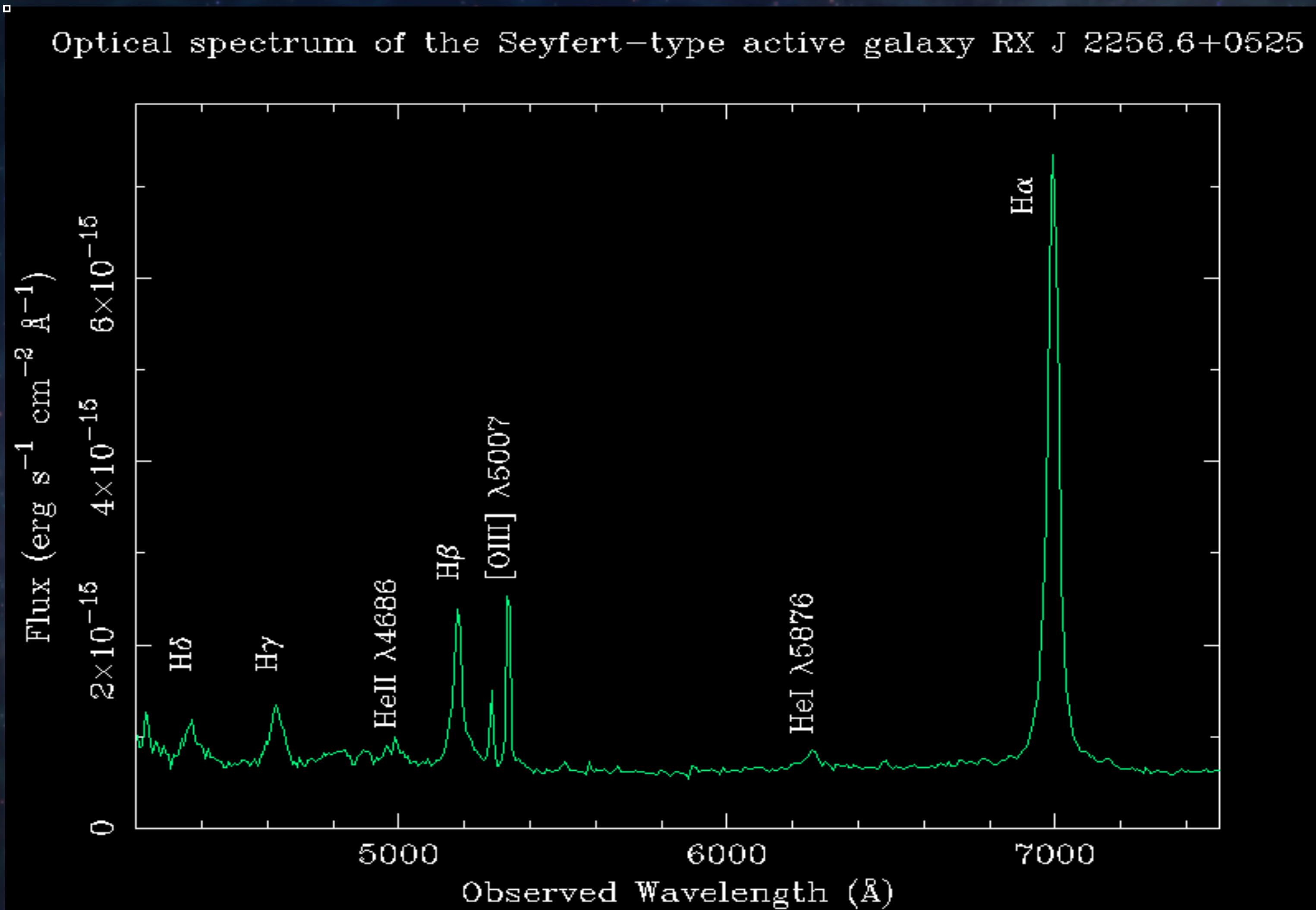
Images of Active vs. Normal Galaxies



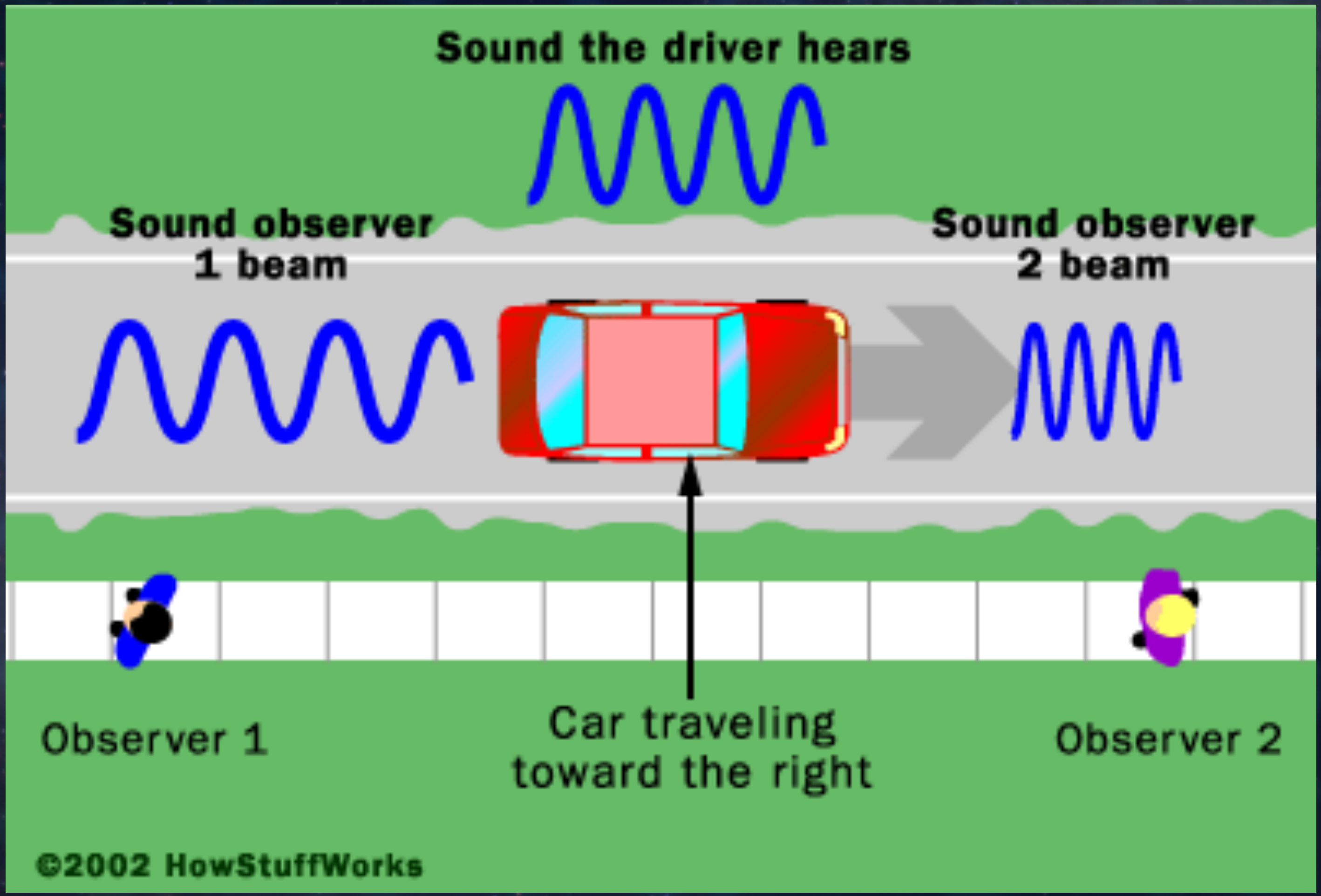
The Three Types of Spectra



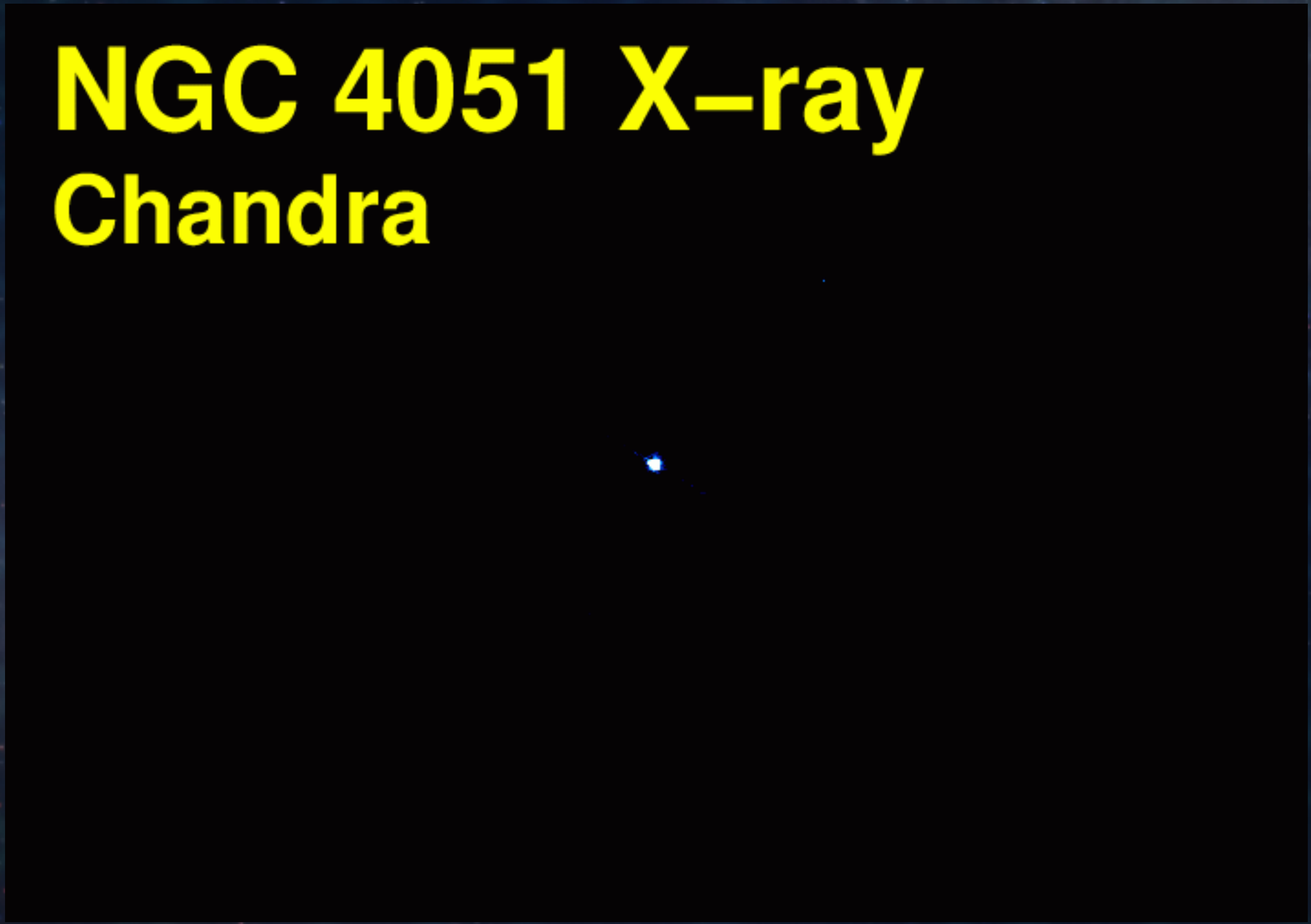
Optical Spectrum of a Typical Active Galaxy



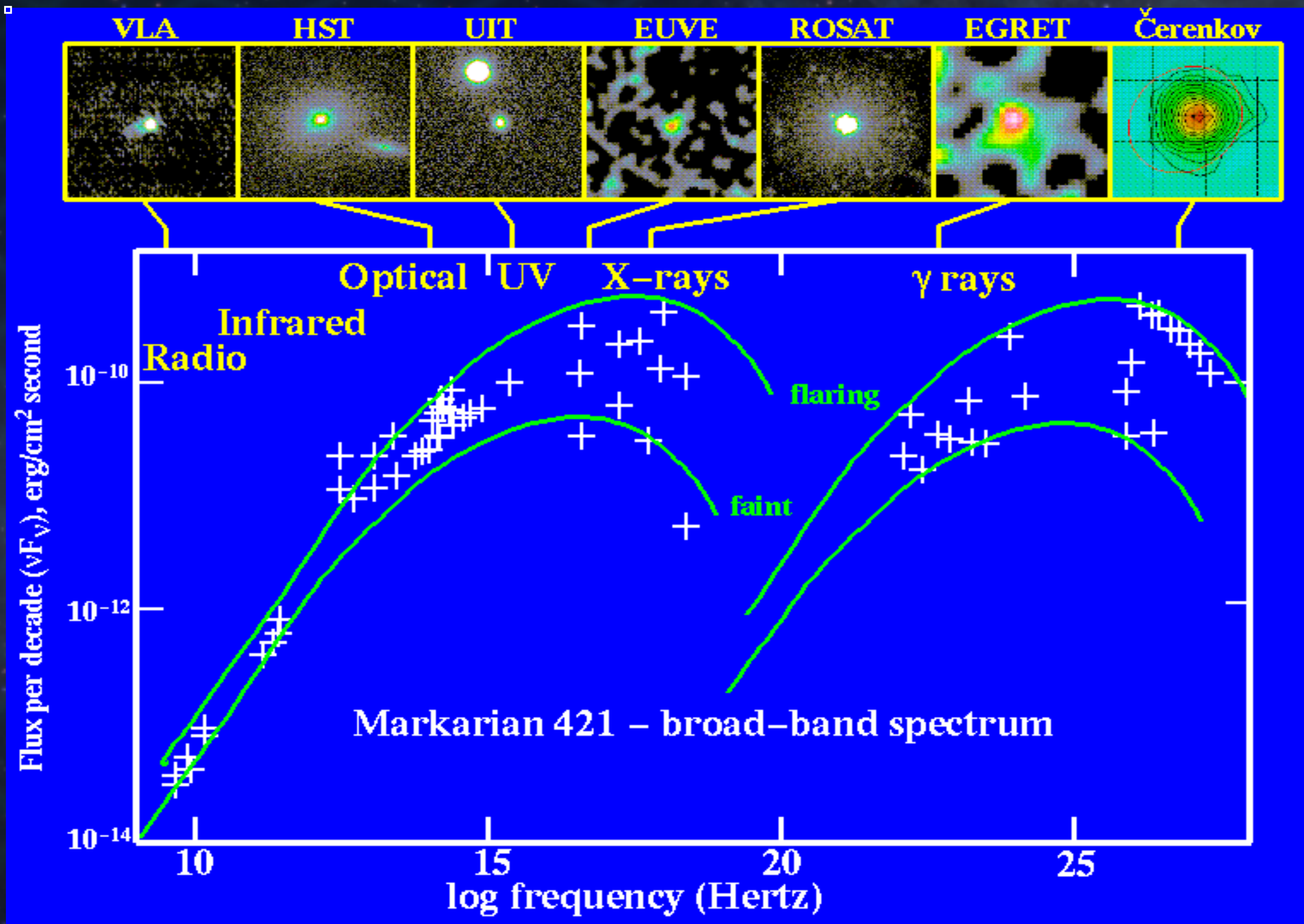
Review of the Doppler Shift



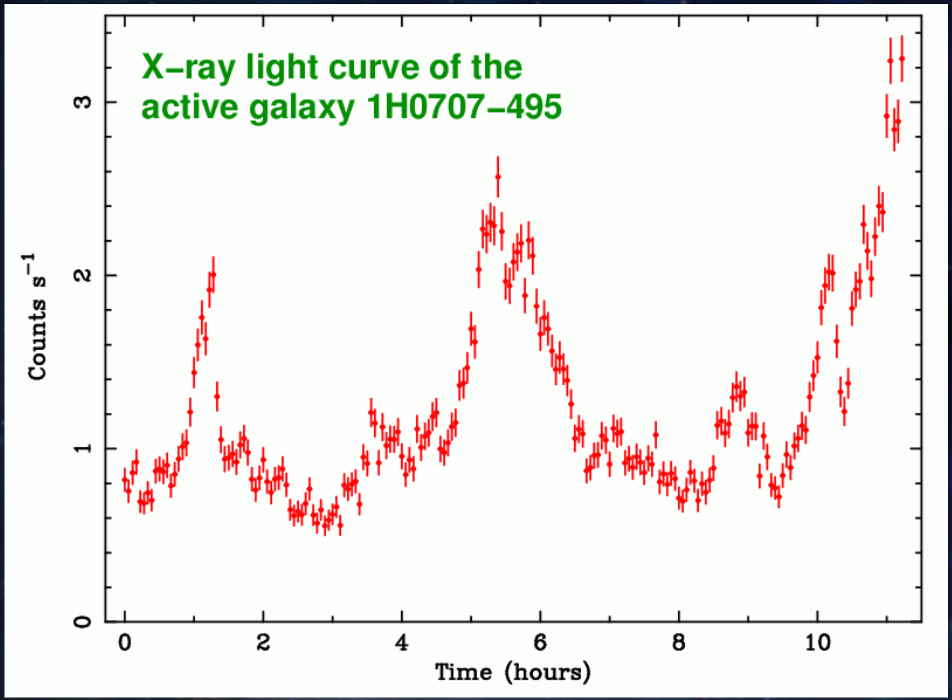
X-rays from an Active Galactic Nucleus

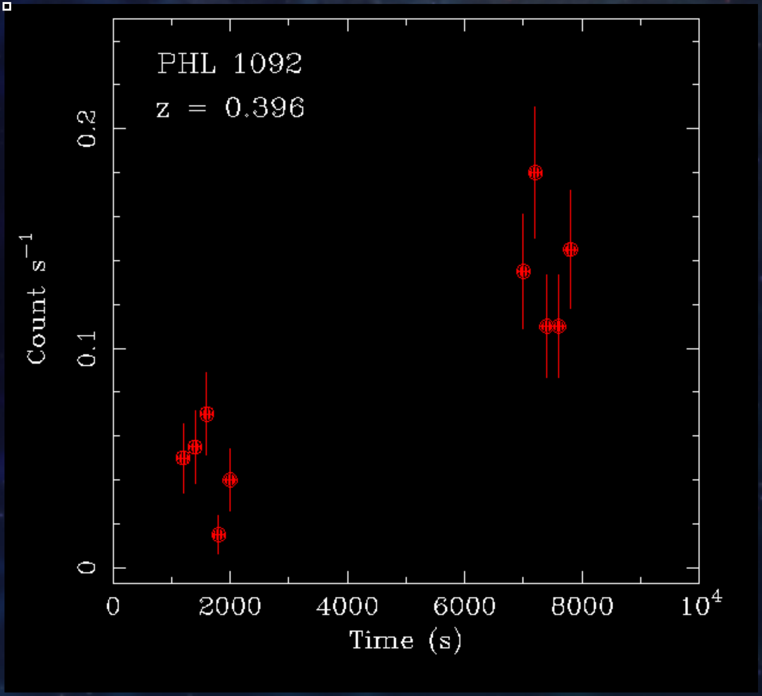


Broad-Band Spectrum of an Active Galaxy

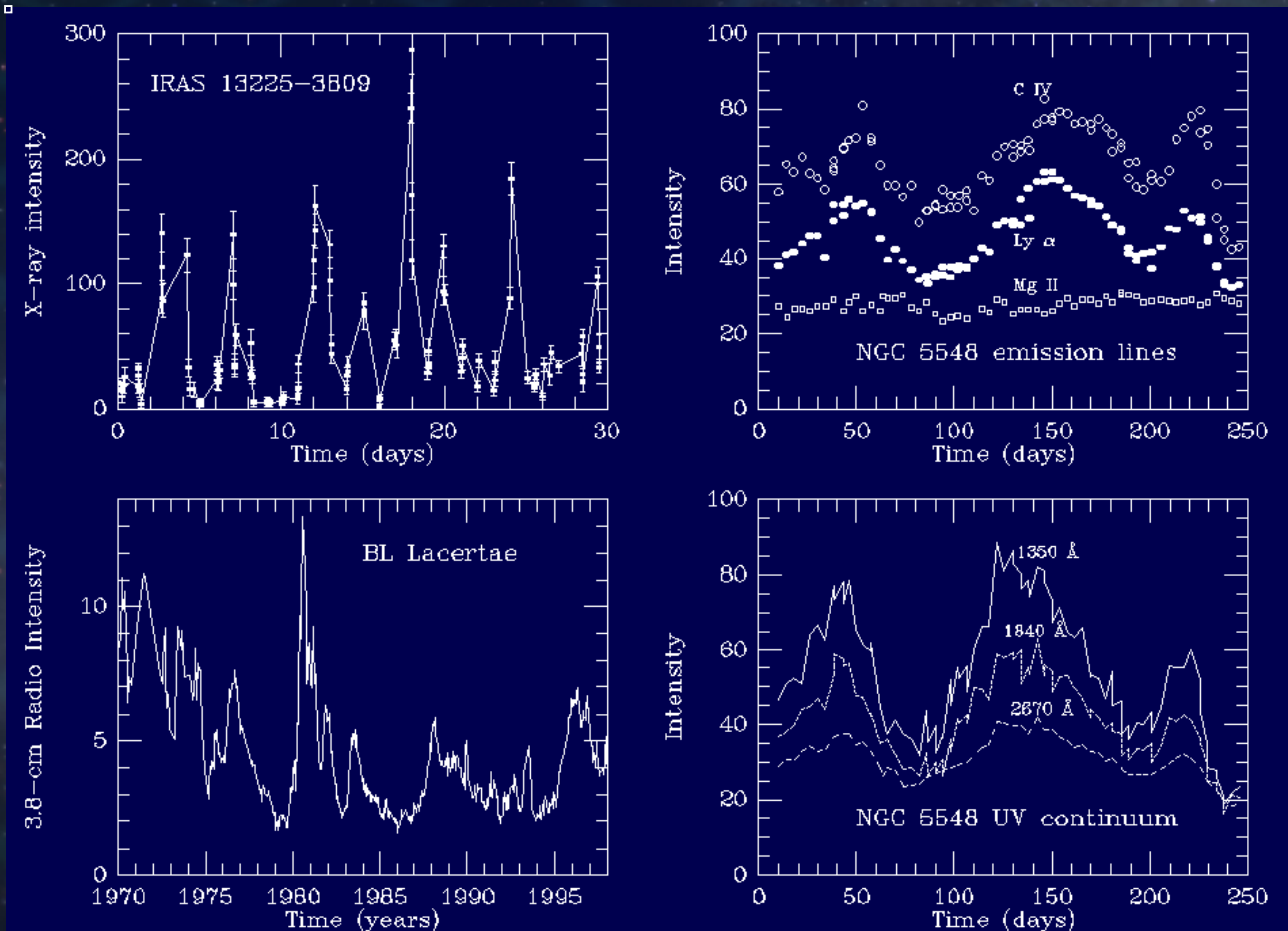


Rapid X-ray Variability of Active Galaxies



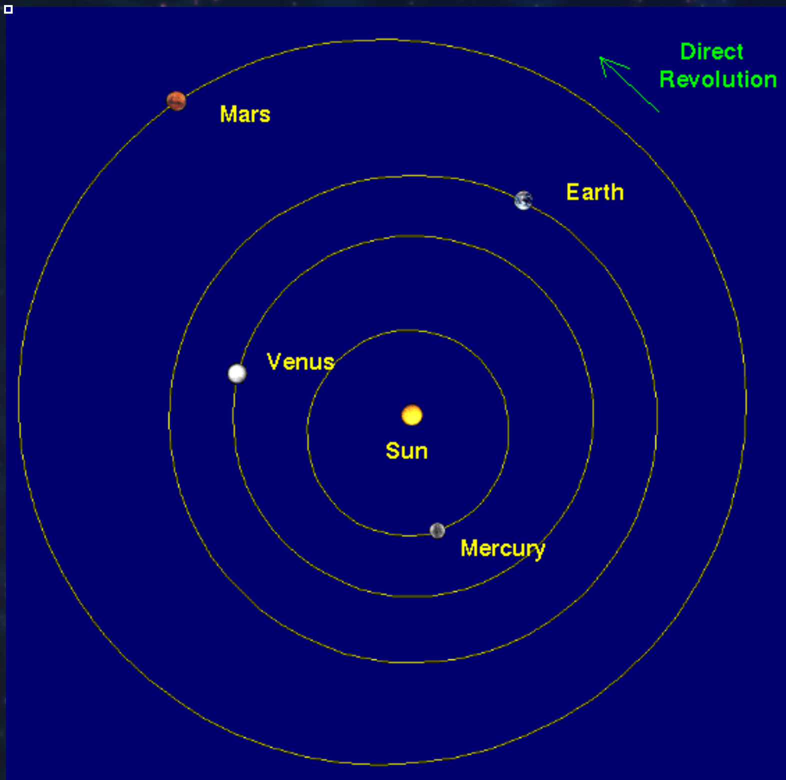


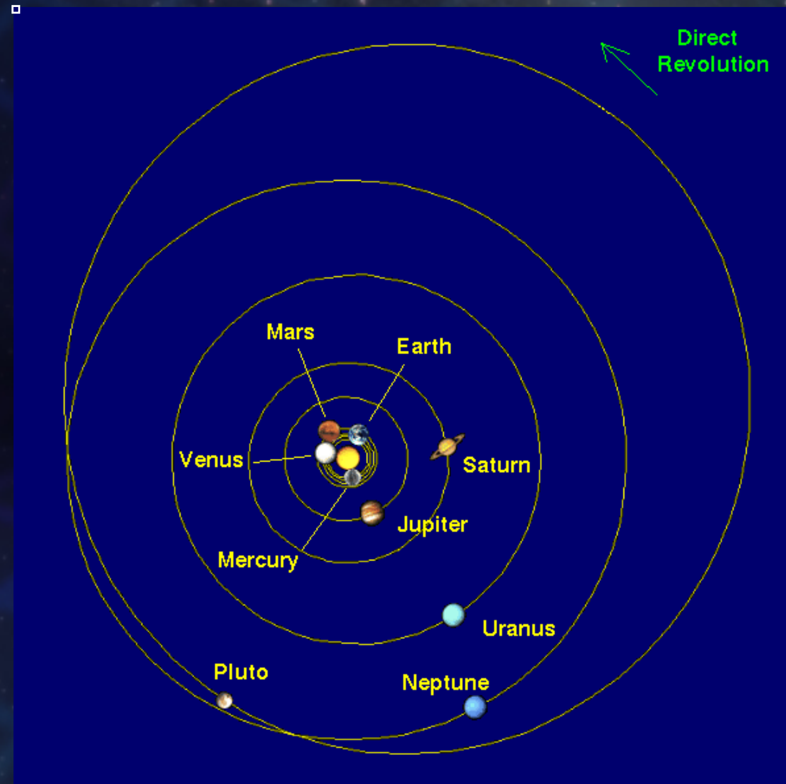
Variability of Active Galaxies



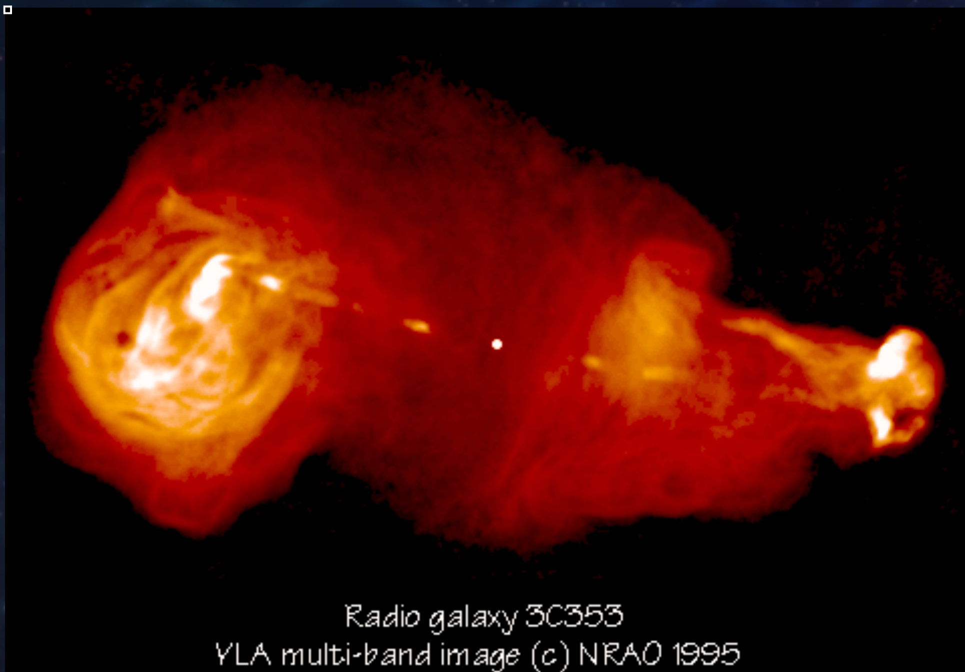
Analogy – A Coherent Crowd Shout

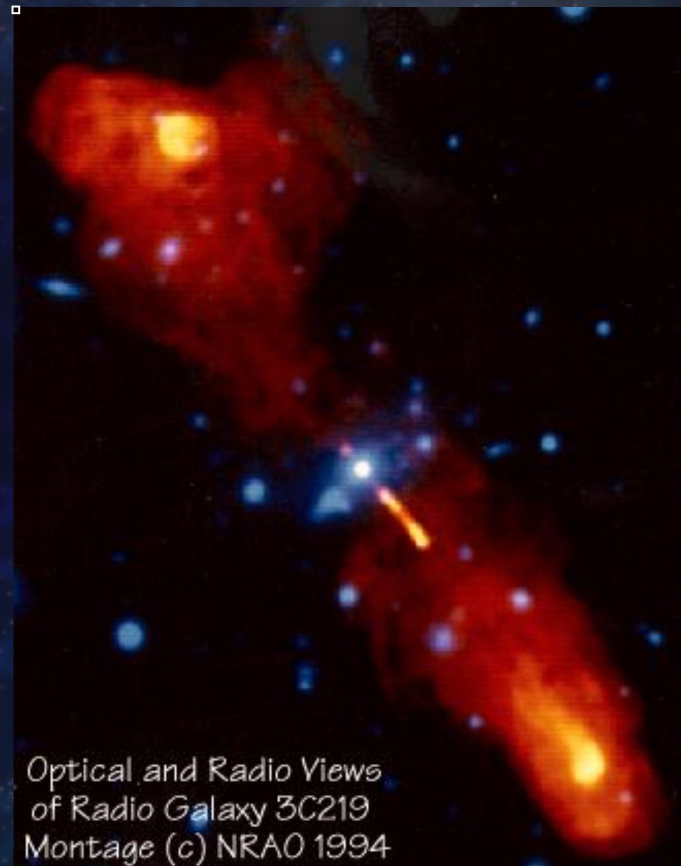
Light Travel Times in the Solar System



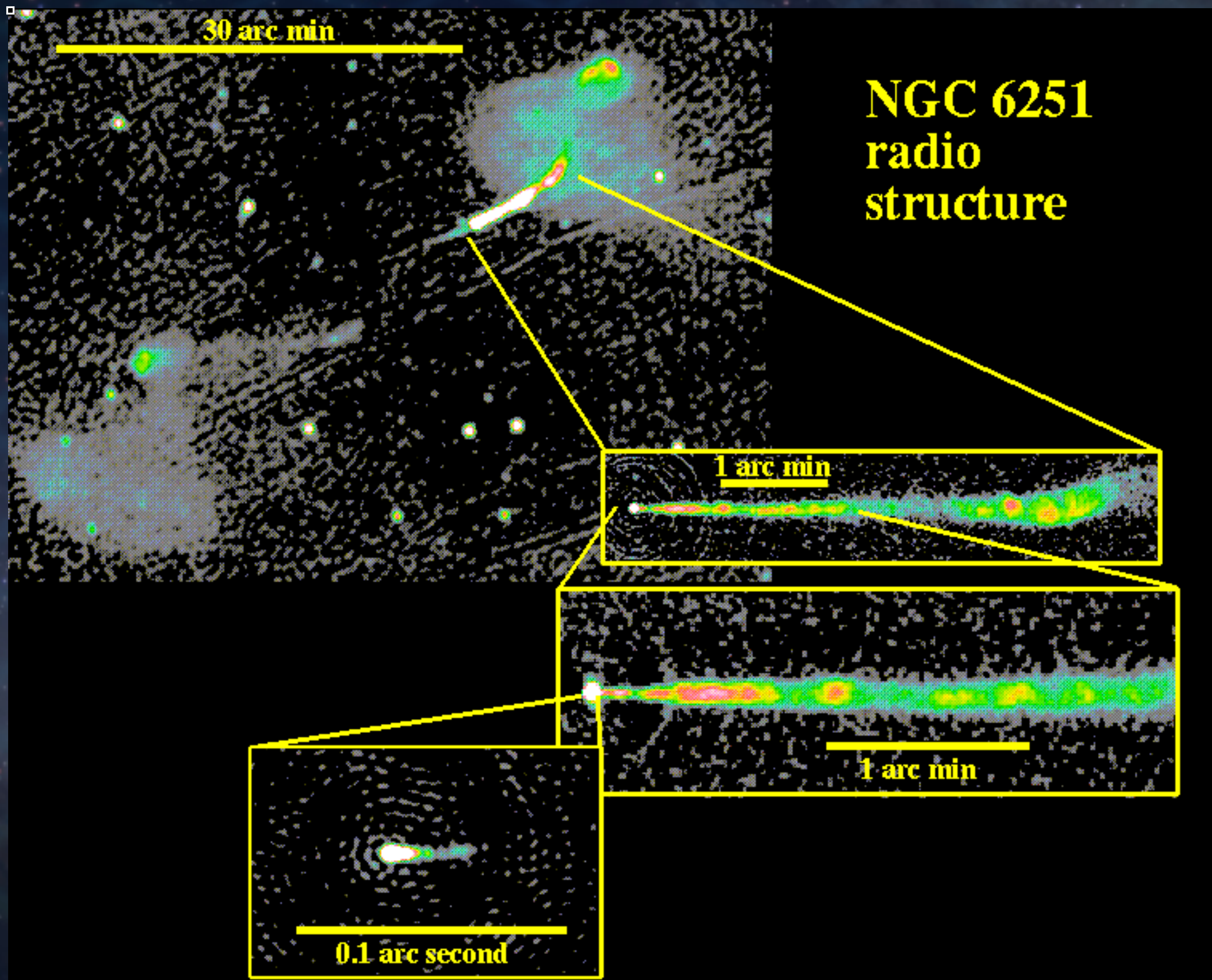


Particle Jets from Active Galaxies

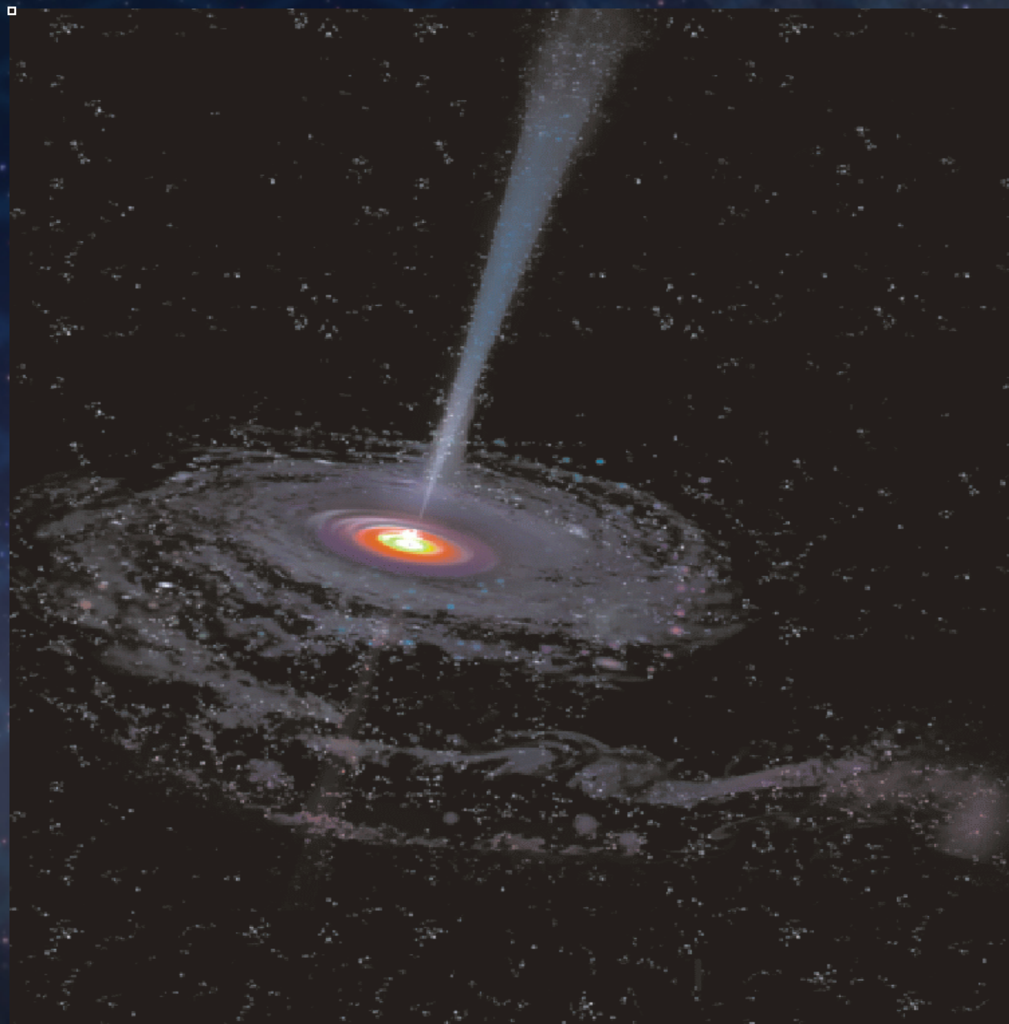




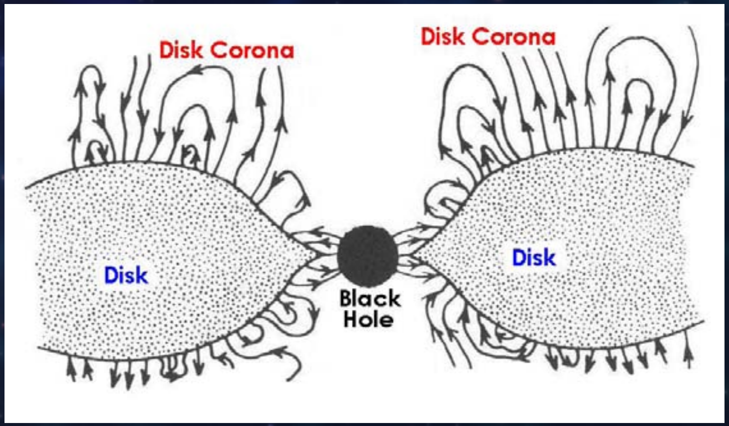
Particle Jets Span a Wide Range of Scales



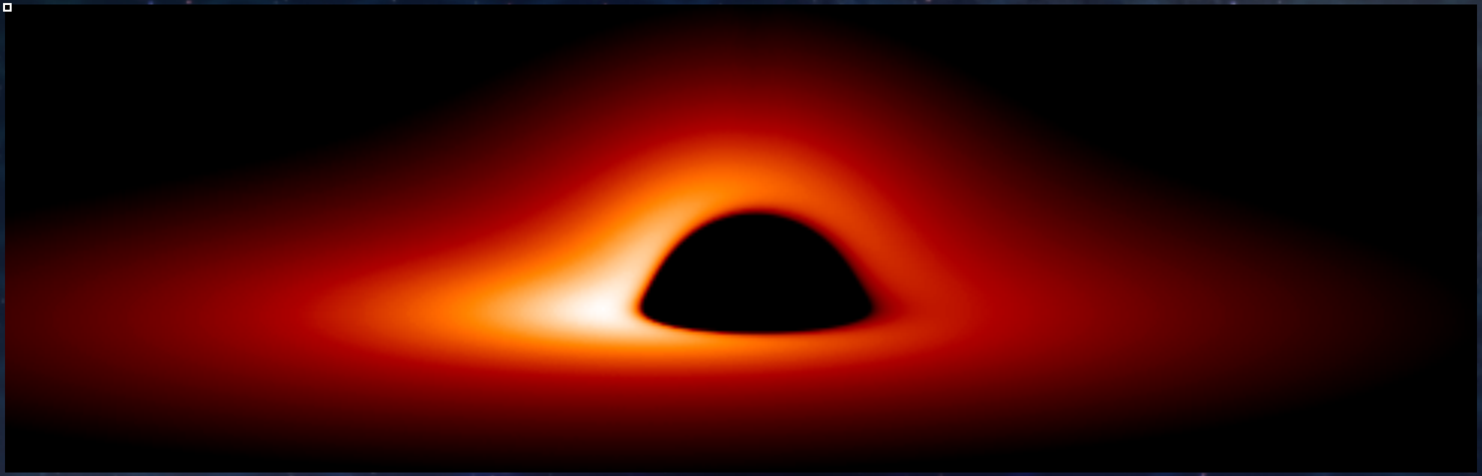
The Black-Hole + Accretion-Disk Model

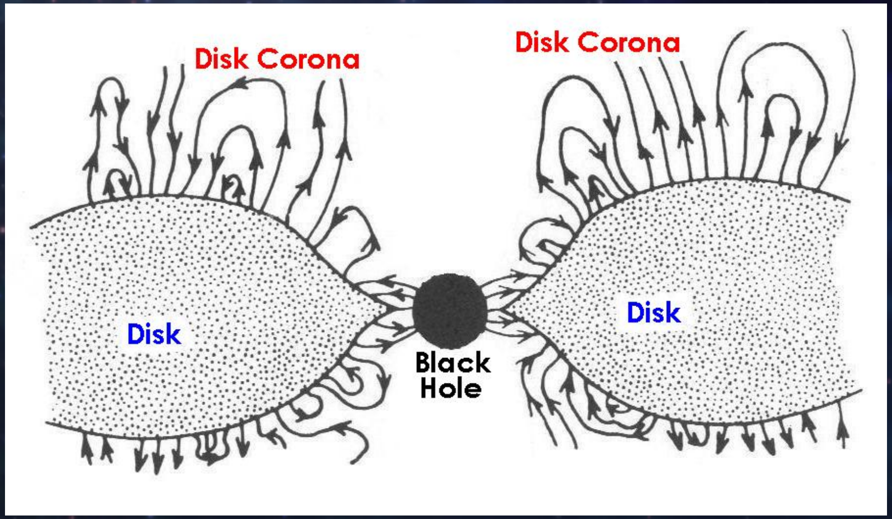


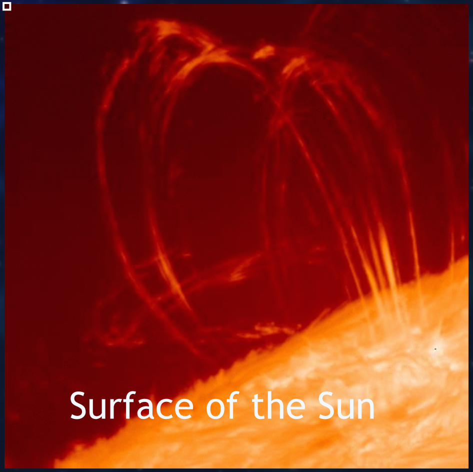
Methods of Power Generation



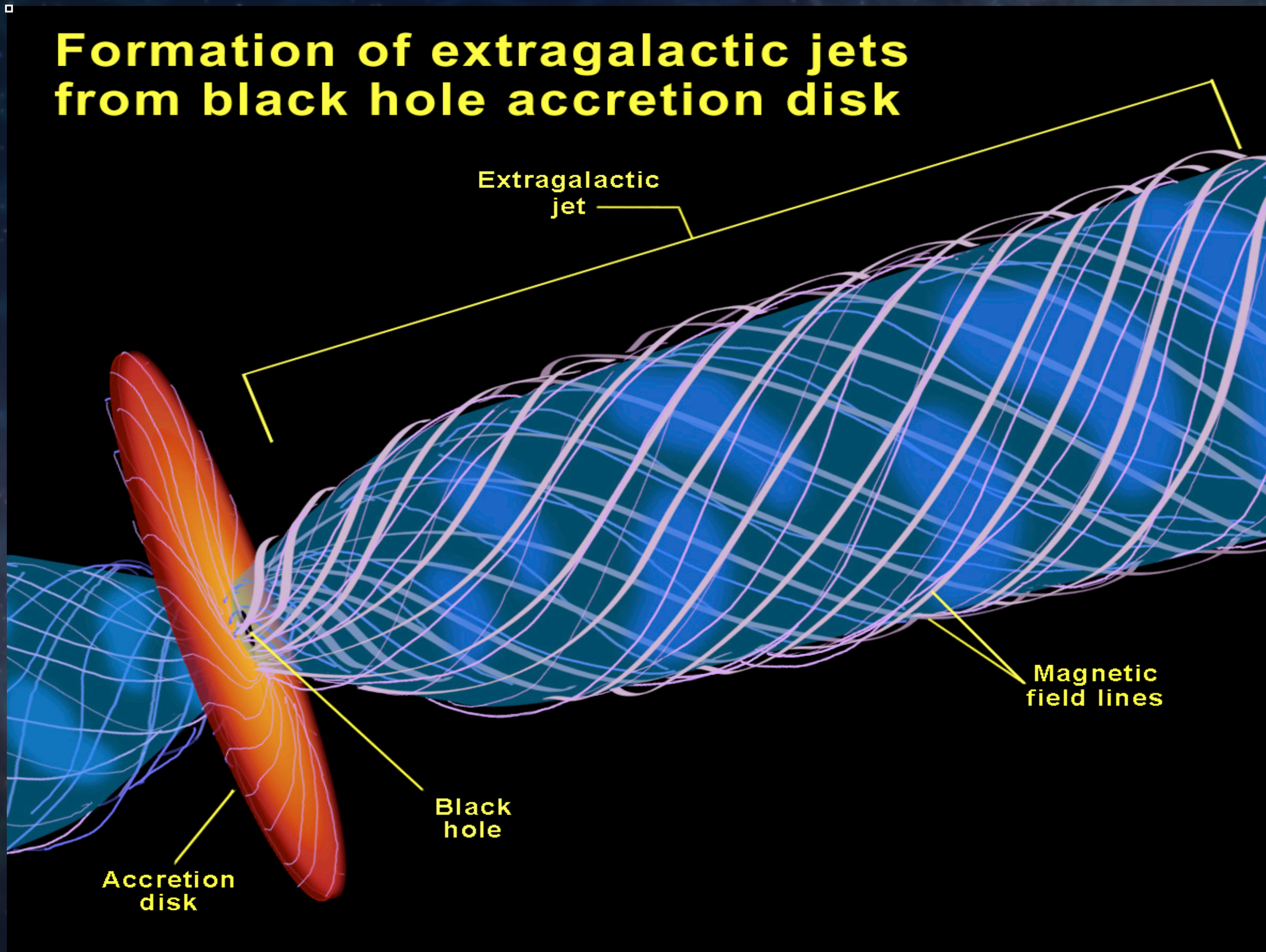
The Innermost Accretion Disk







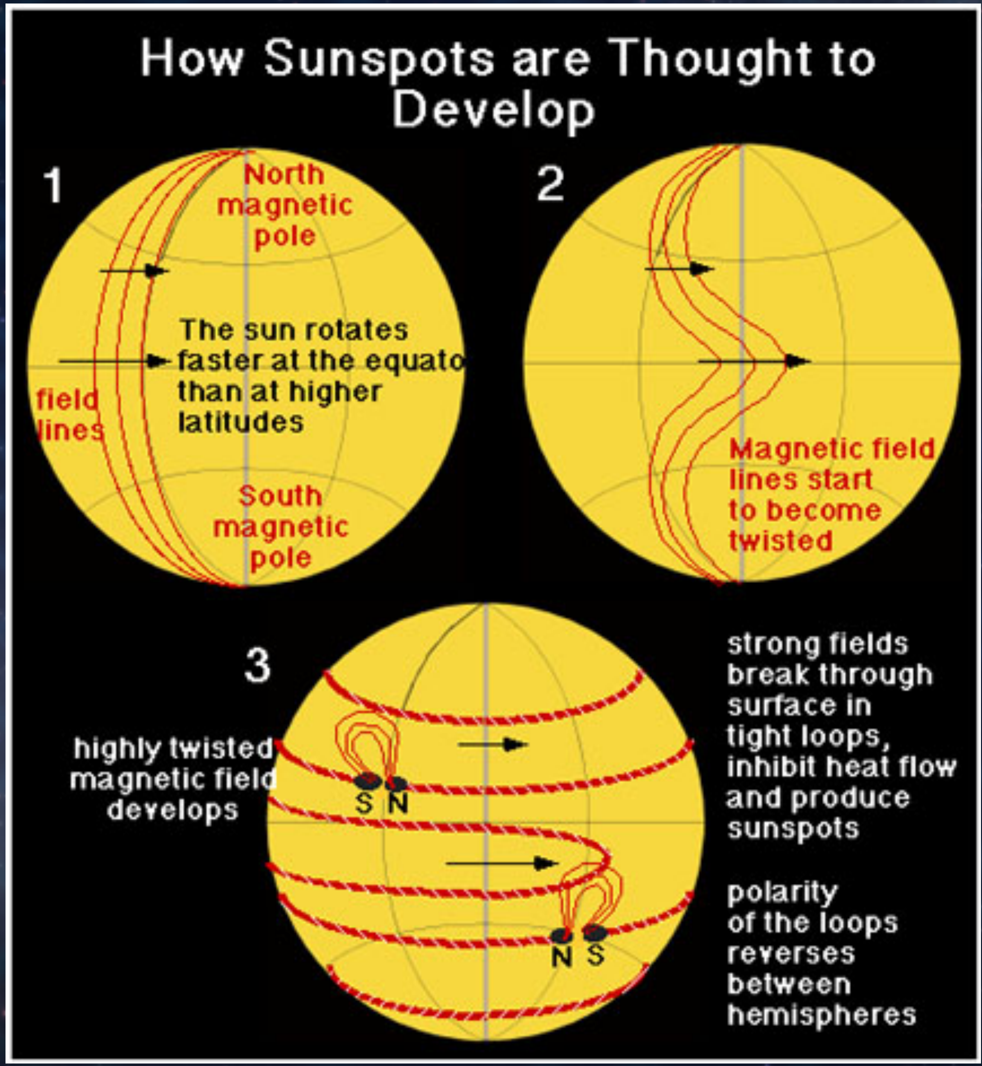
Model for Jet Formation



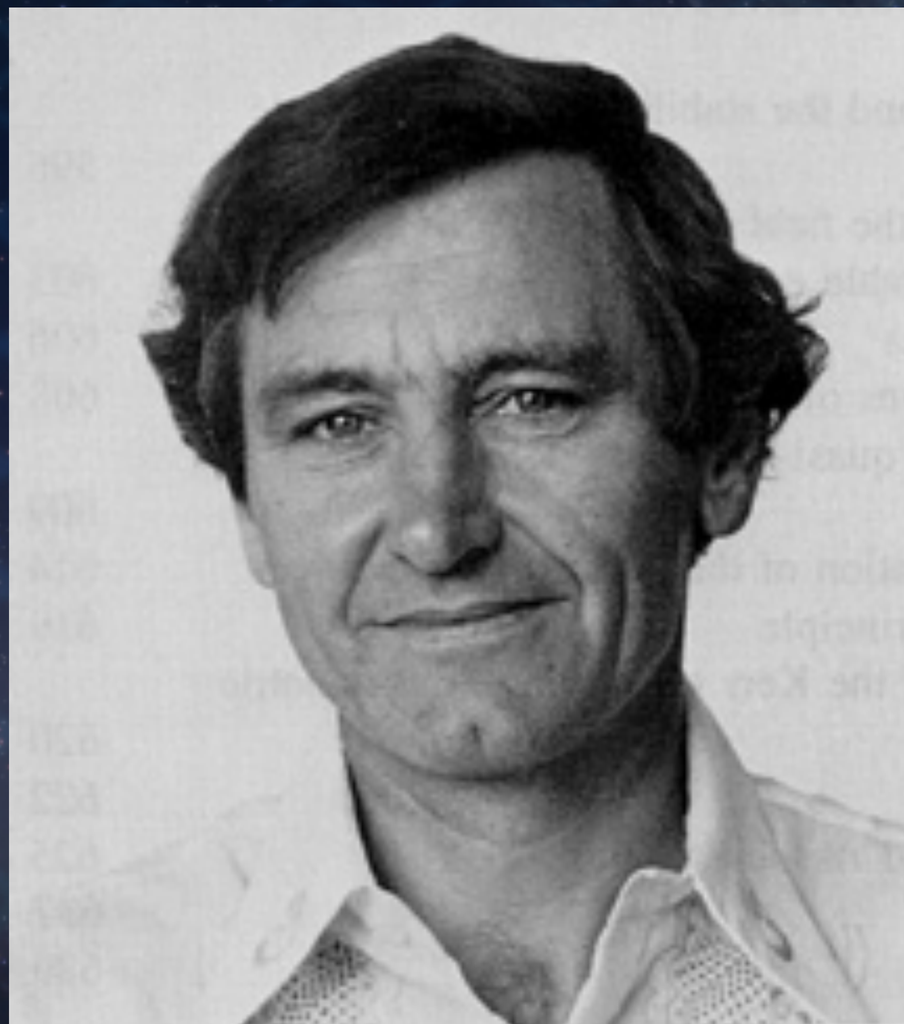
Lecture 13:
Jets

Not These!

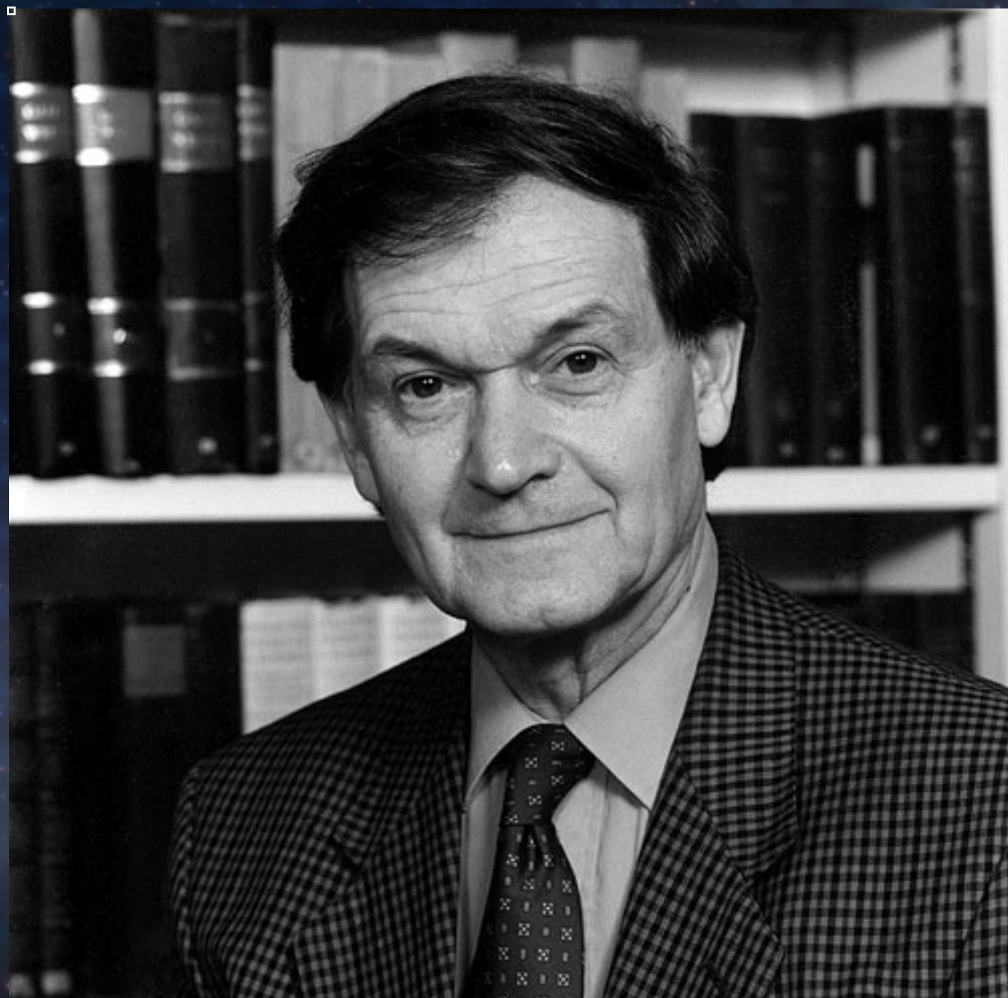
Solar Rotation



Roy Kerr



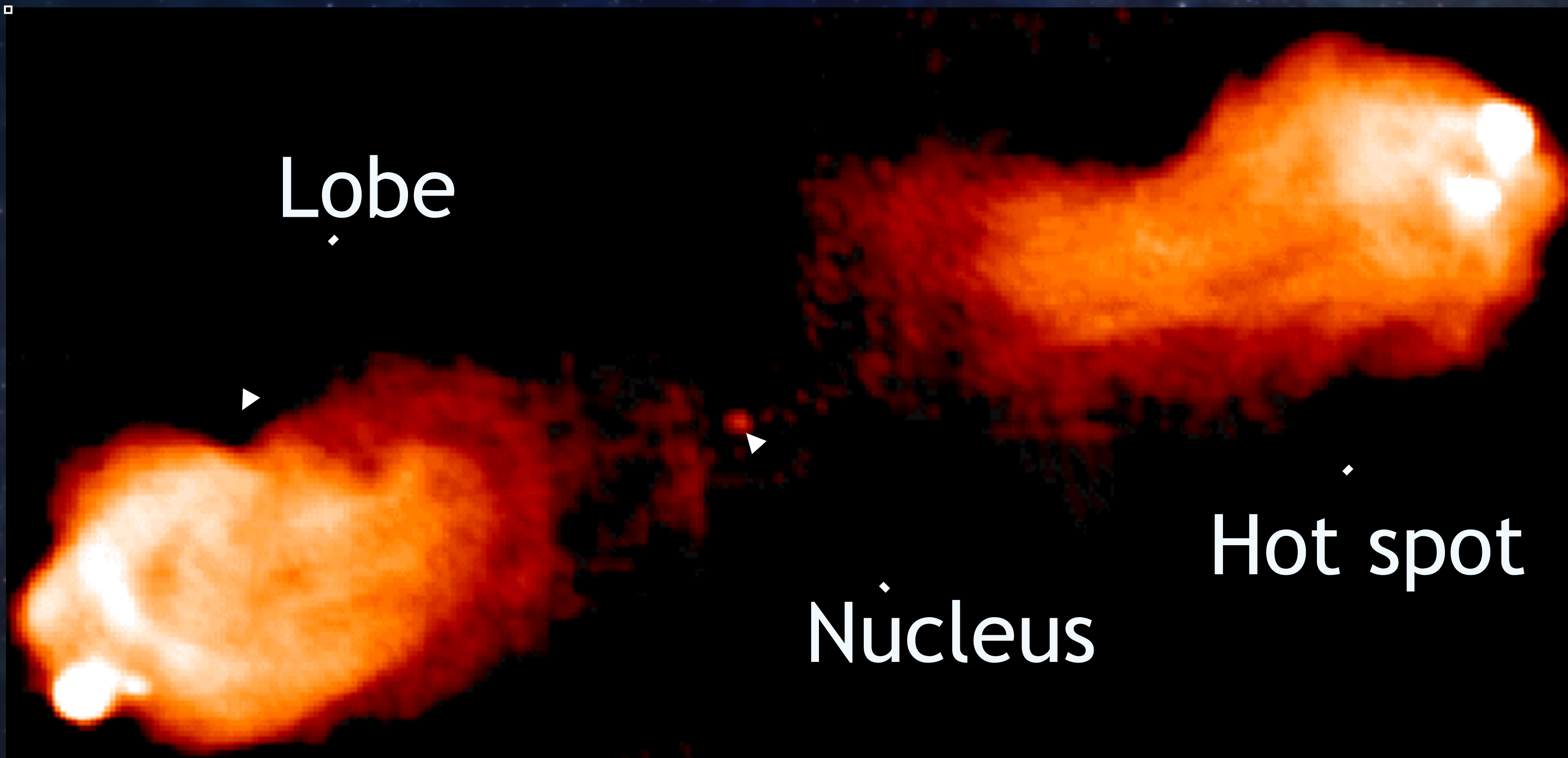
Roger Penrose



Stabilization of a Gyroscope

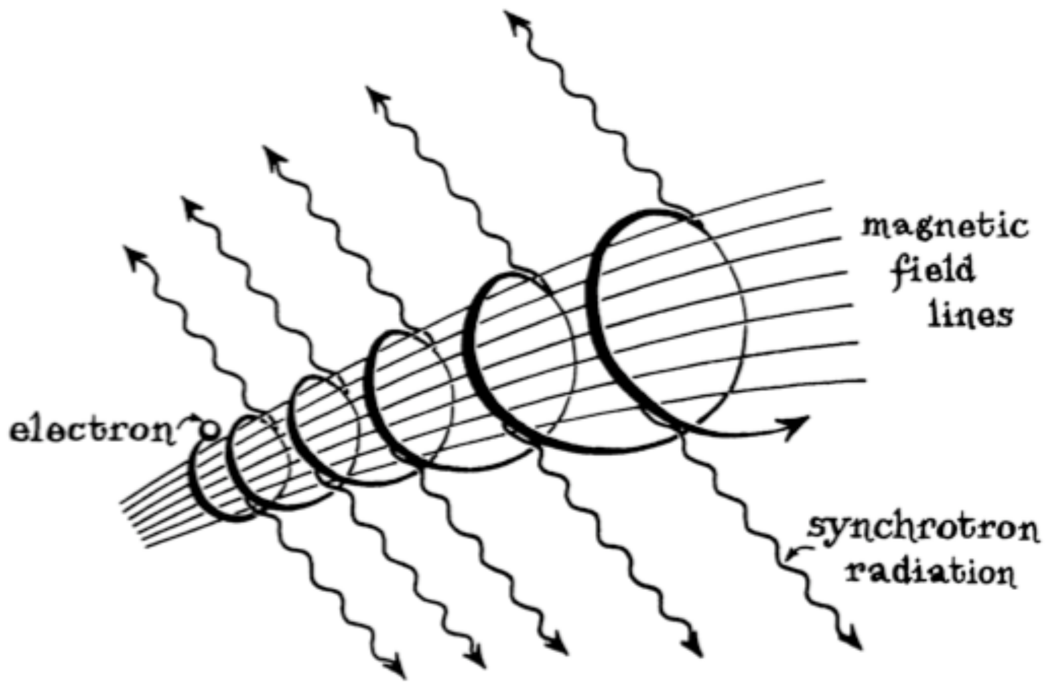
Cygnus A: Example of a Radio Galaxy

21 cm radio image from the VLA



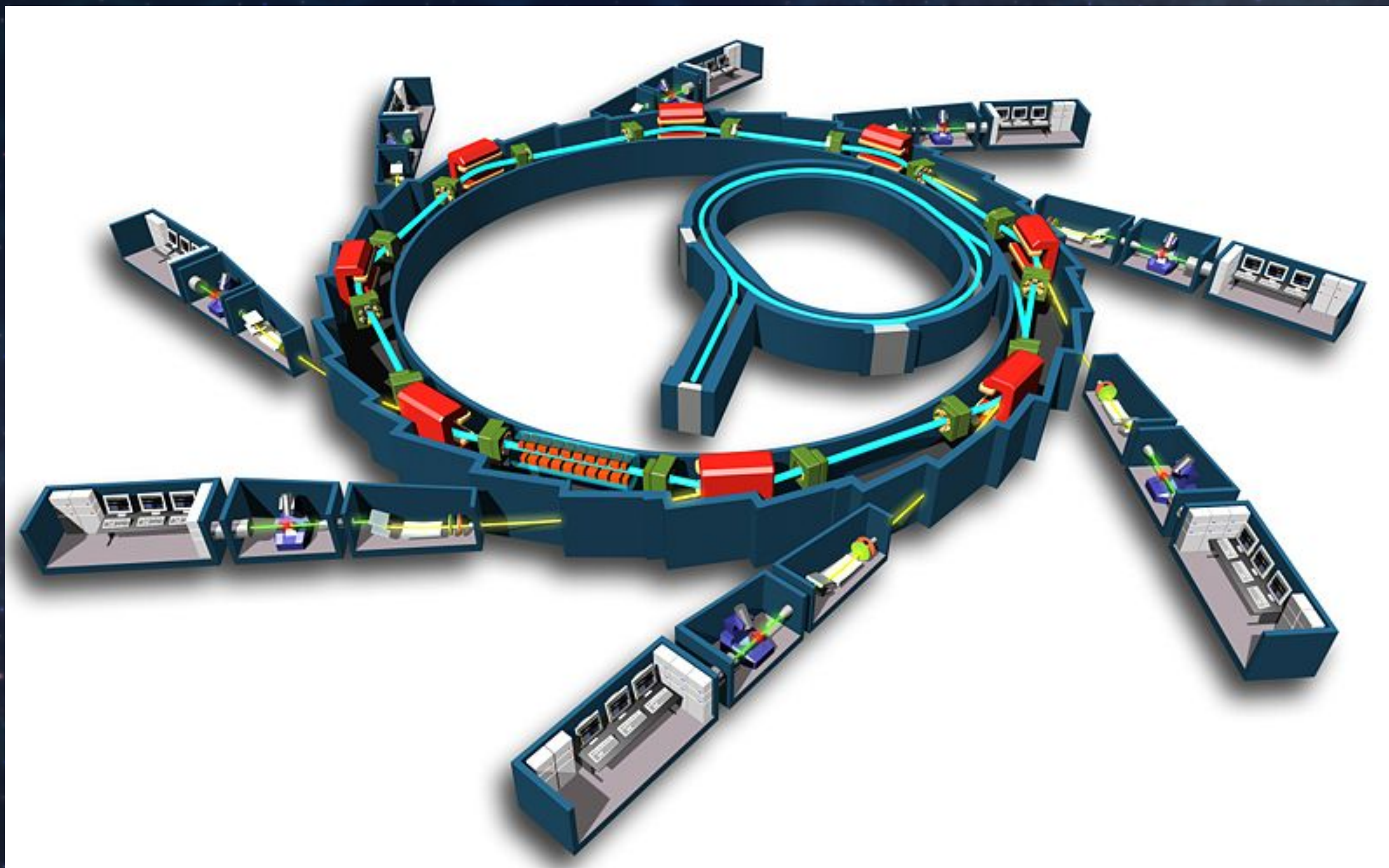
Synchrotron Radiation

9.4 Cosmic radio waves are produced by near-light-speed electrons that spiral around and around in magnetic fields. The magnetic field forces an electron to spiral instead of moving on a straight line, and the electron's spiraling motion produces the radio waves.



From Thorne book

A Synchrotron on Earth

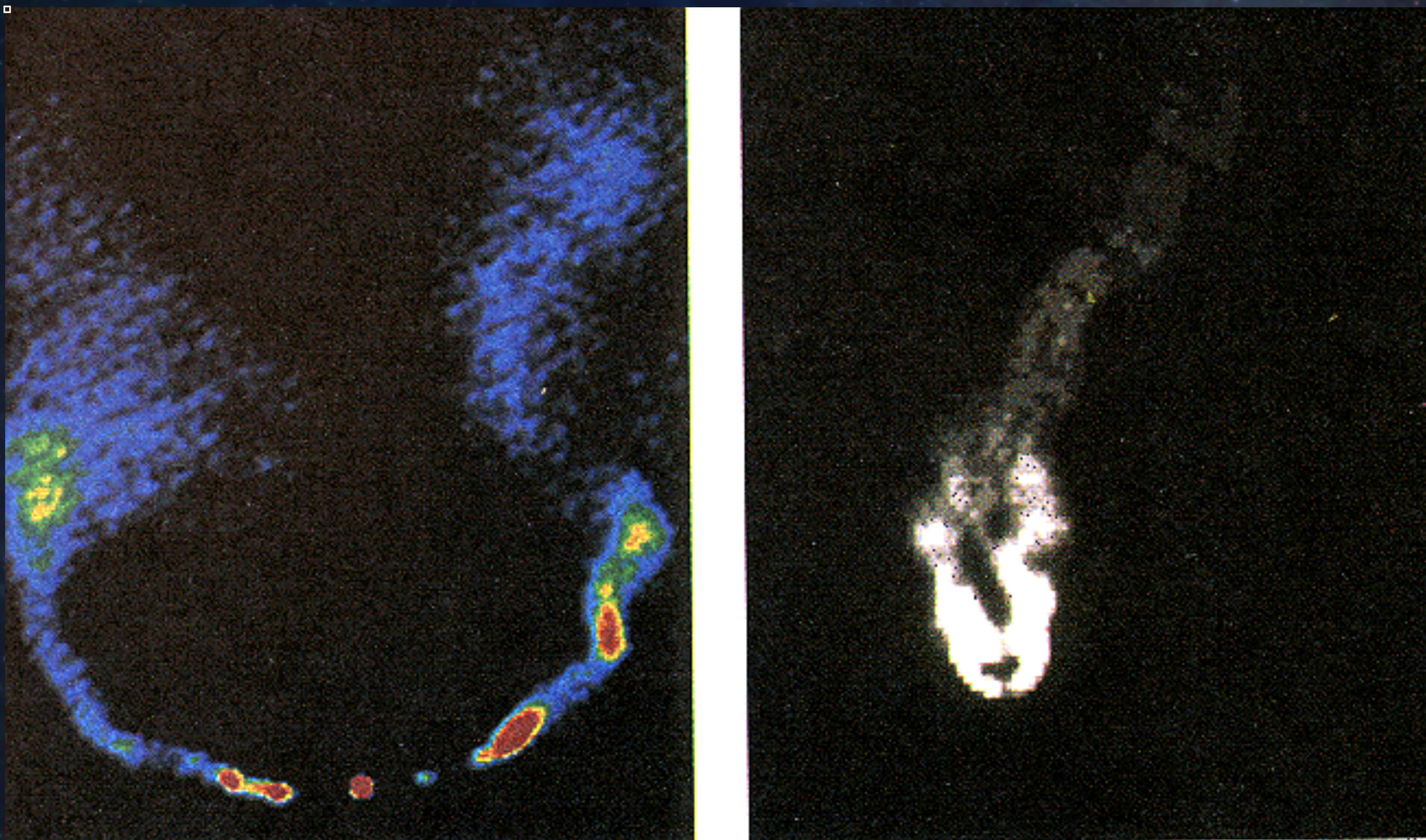


High Resolution Image of Cygnus A

6 cm radio image from the VLA

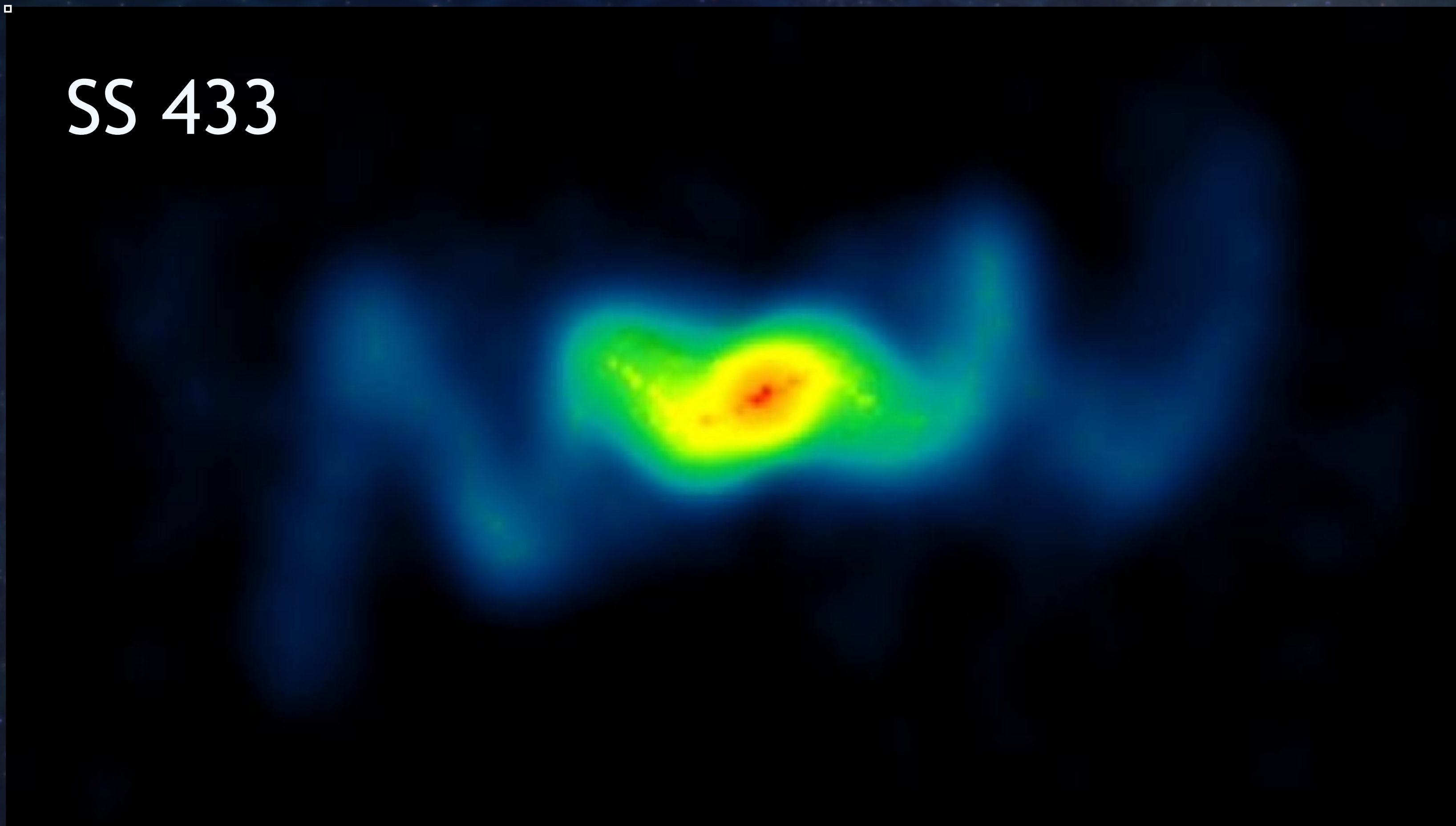
Components of the Cygnus A Radio Emission

NGC 1265 – Radio Source in Galaxy Cluster

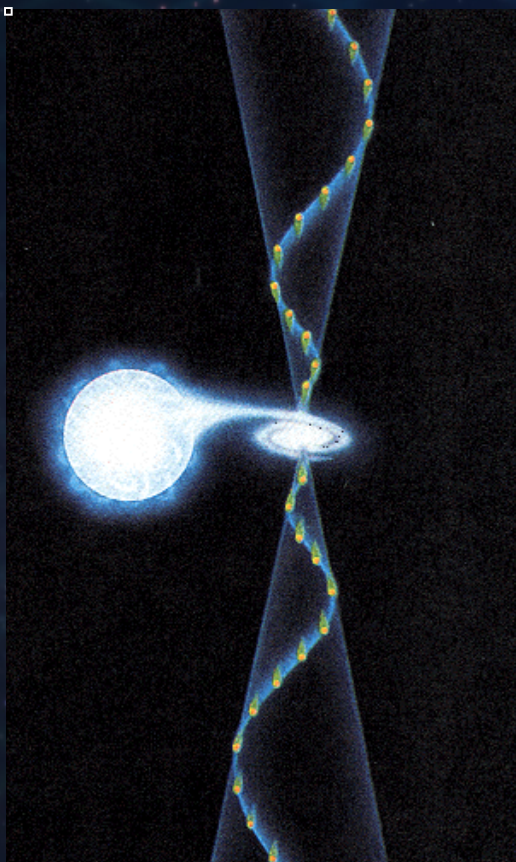


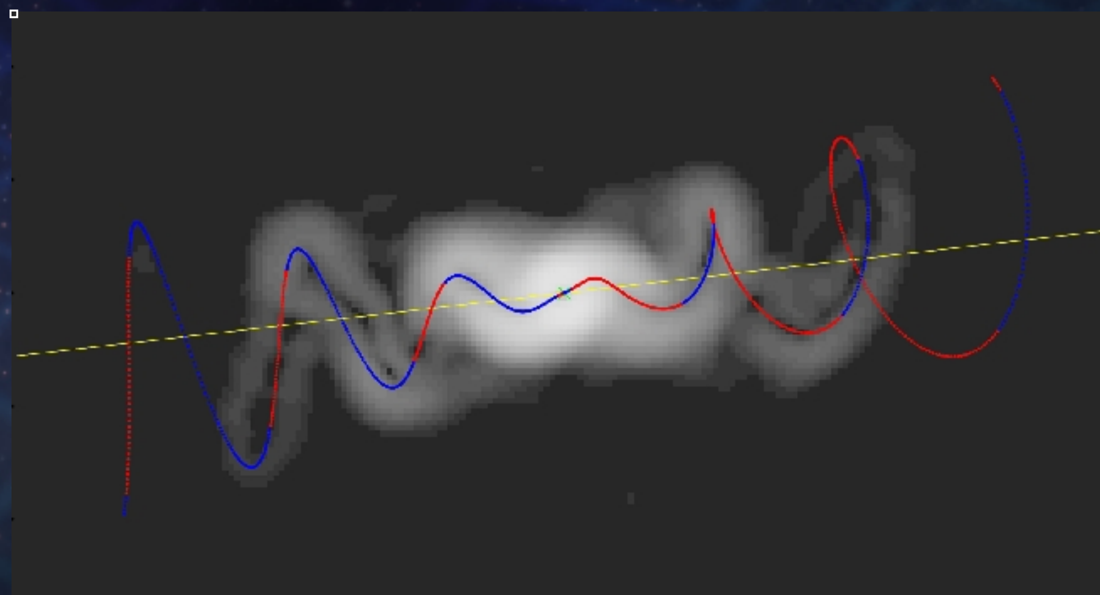
A Smokestack on a Windy Day

Radio Jets from Sources in Our Galaxy

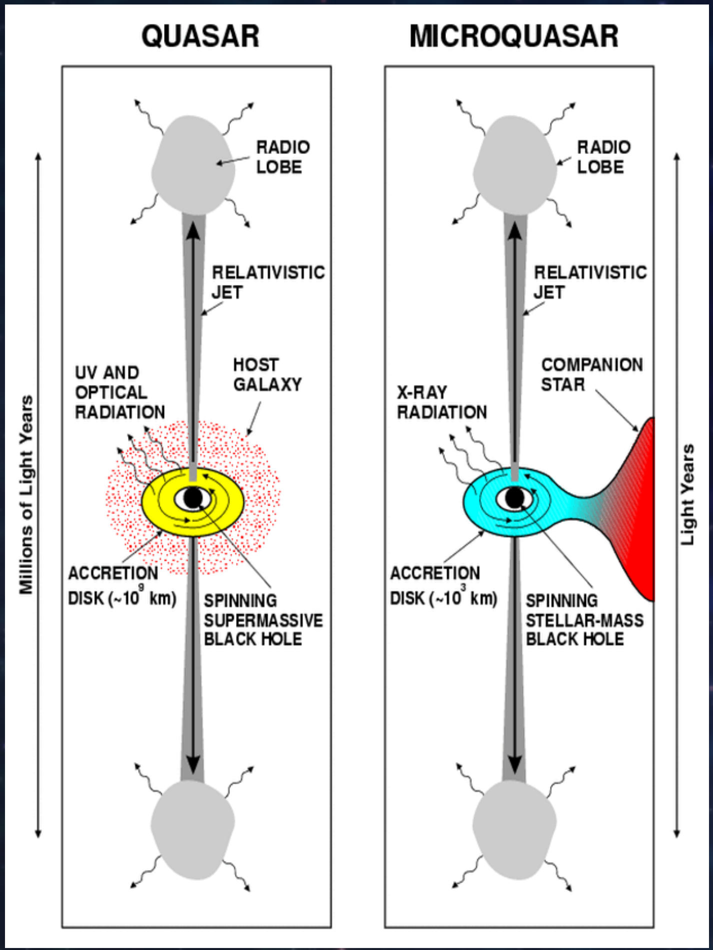


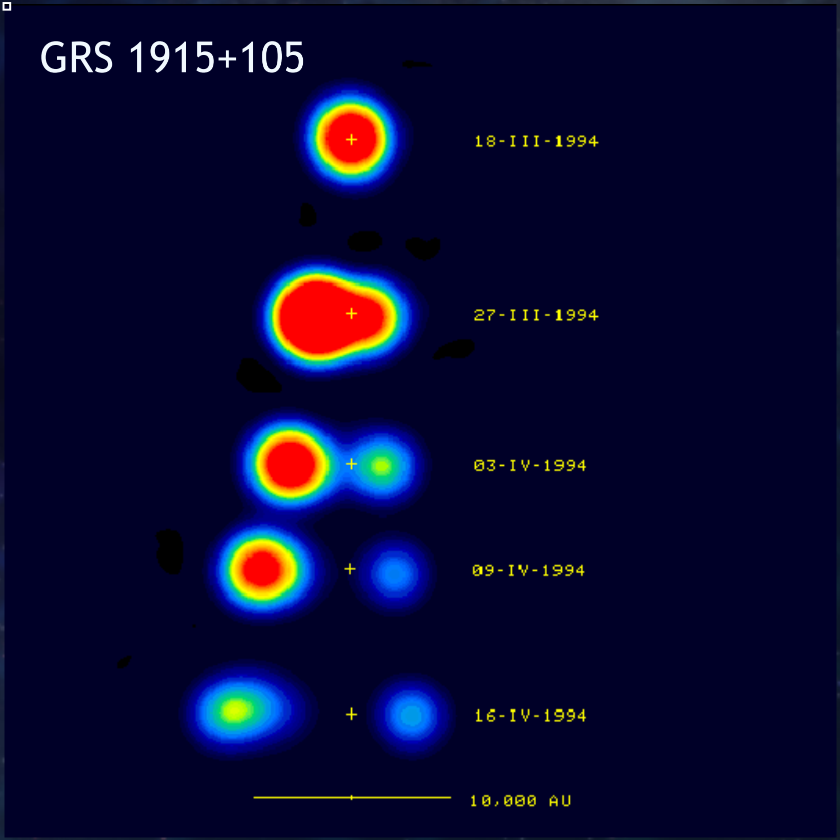
Models for SS 433





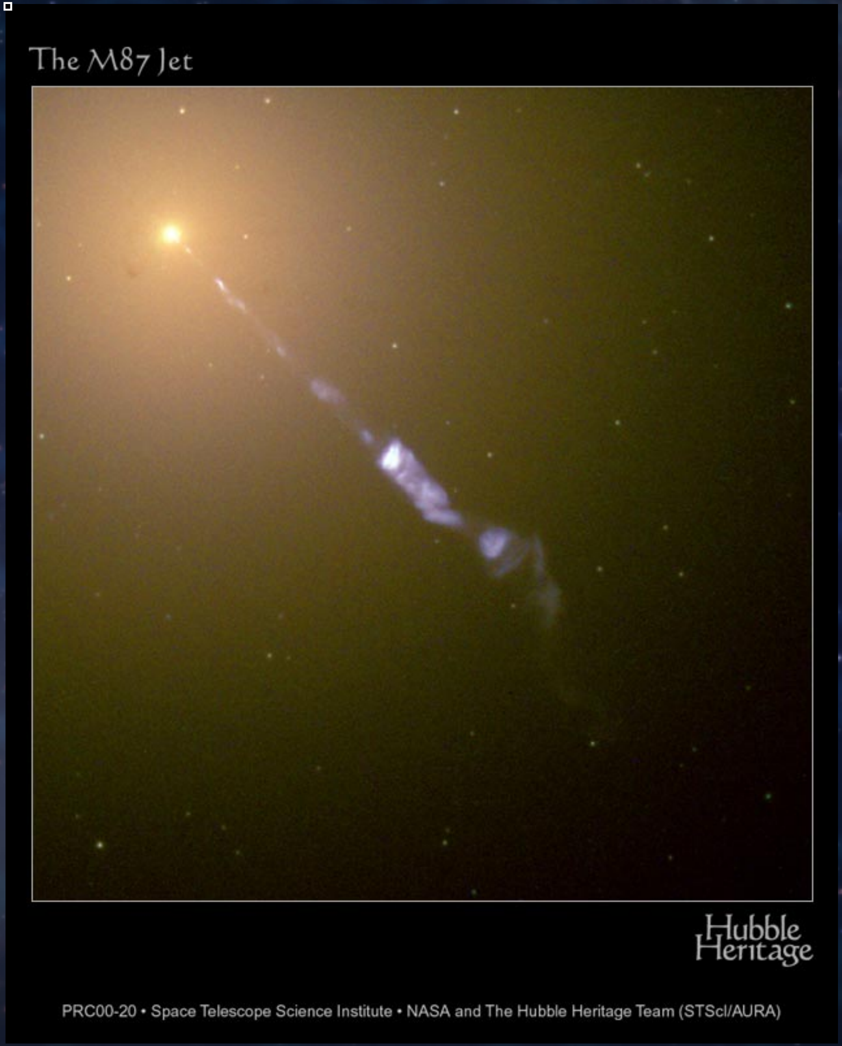
Microquasars in Our Galaxy



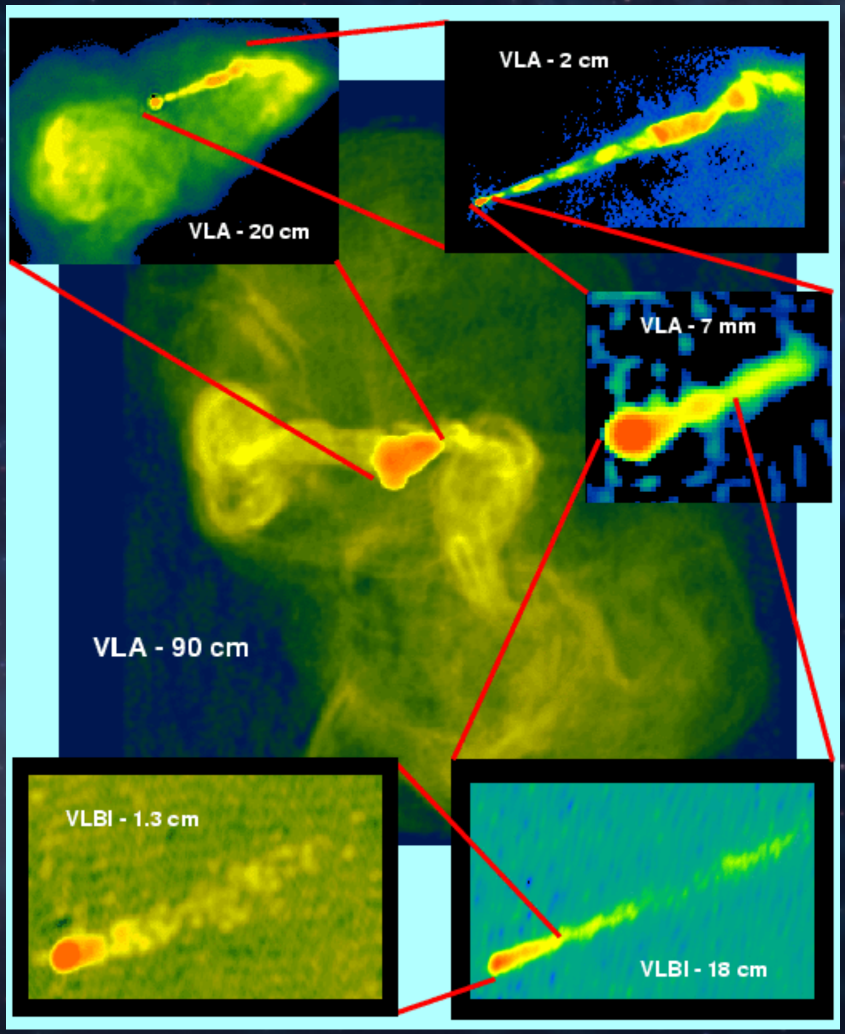


The Giant Elliptical M87 in the Virgo Cluster

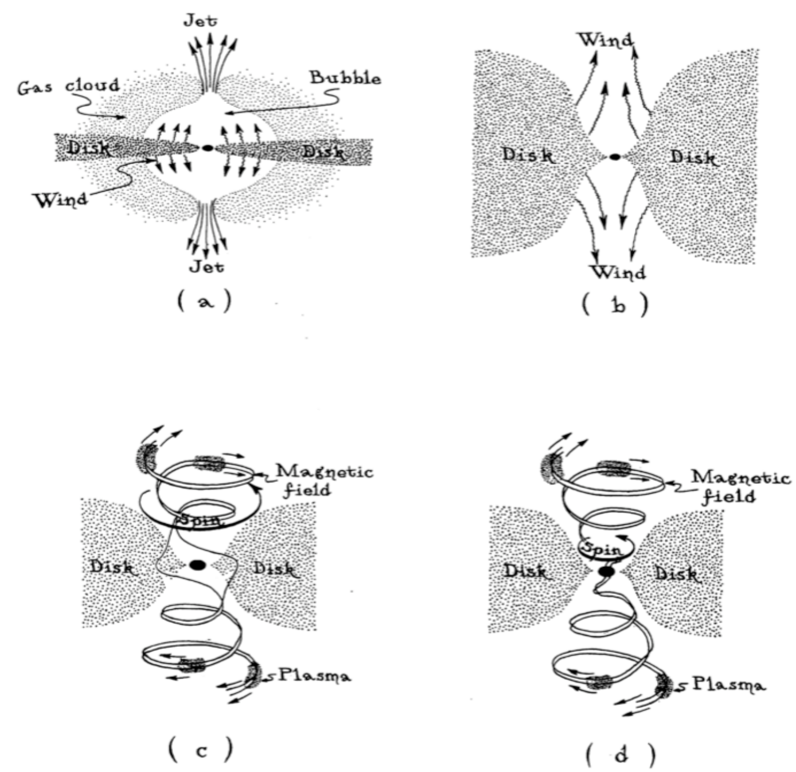
The Optical Jet of M87



Radio Images of the M87 Jet

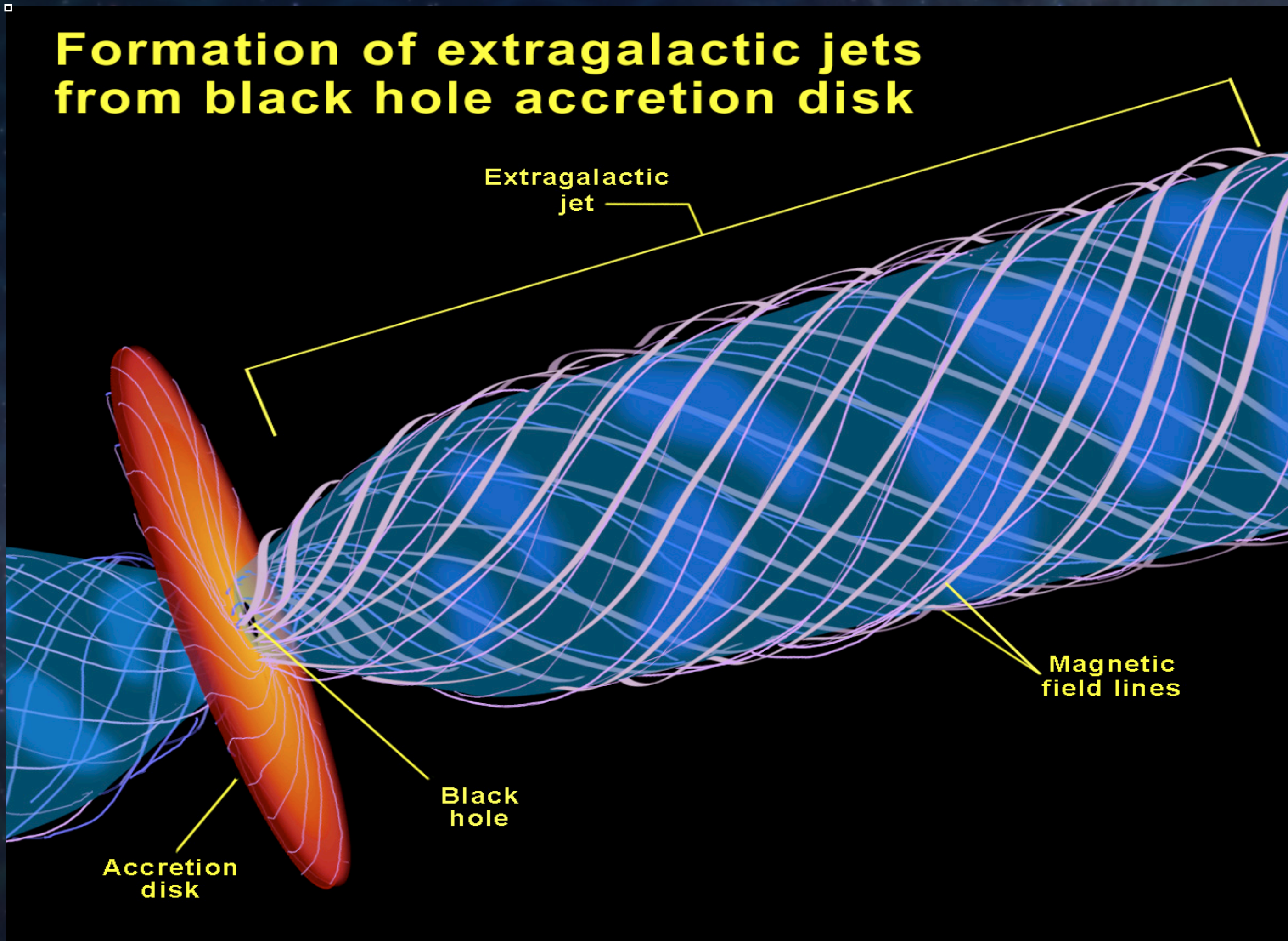


Possible Methods of Jet Creation

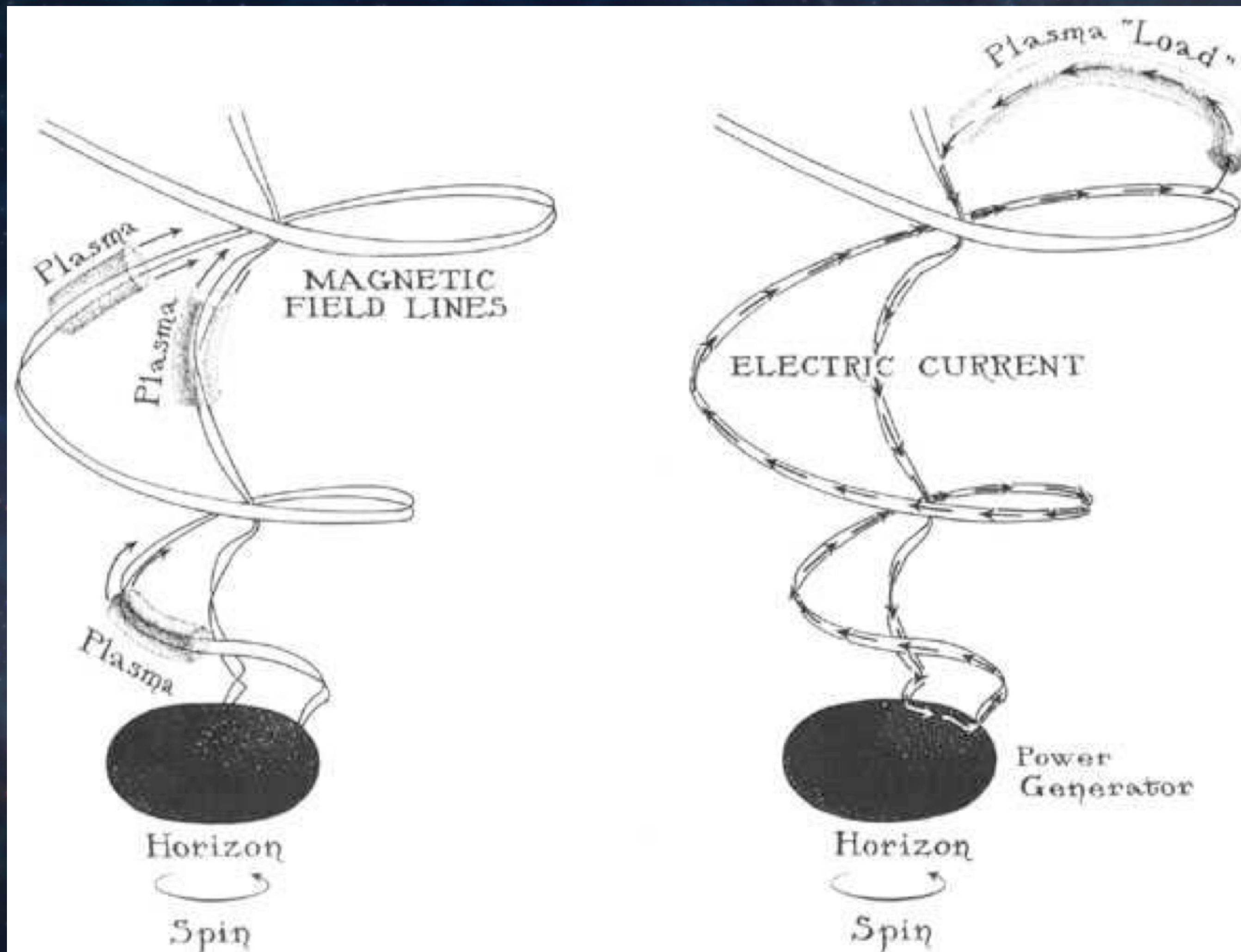


9.7 Four methods by which a black hole or its accretion disk could power twin jets. (a) A wind from the disk blows a bubble in a surrounding, spinning gas cloud; the bubble's hot gas punches orifices through the cloud, along its spin axis; and jets of hot gas shoot out the orifices. (b) The disk is puffed up by the pressure of its great internal heat, and the surface of the puffed, rotating disk forms two funnels that collimate the disk's wind into two jets. (c) Magnetic field lines anchored in the disk are forced to spin by the disk's orbital rotation; as they spin, the field lines fling plasma upward and downward, and the plasma, sliding along the field lines, forms two magnetized jets. (d) Magnetic field lines threading through the black hole are forced to spin by the swirl of the hole's space, and as they spin, the field lines fling plasma upward and downward to form two magnetized jets.

A Magnetically Driven Jet



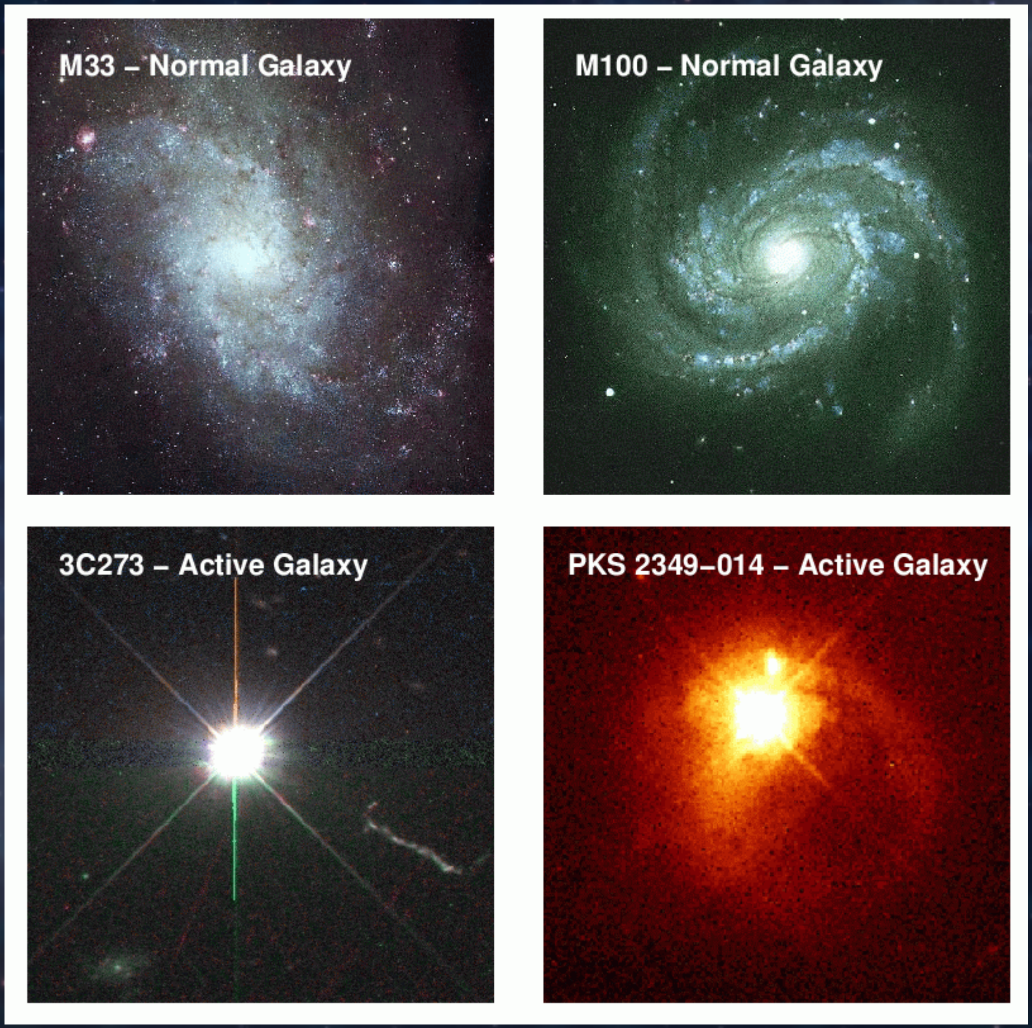
Blandford-Znajek Process



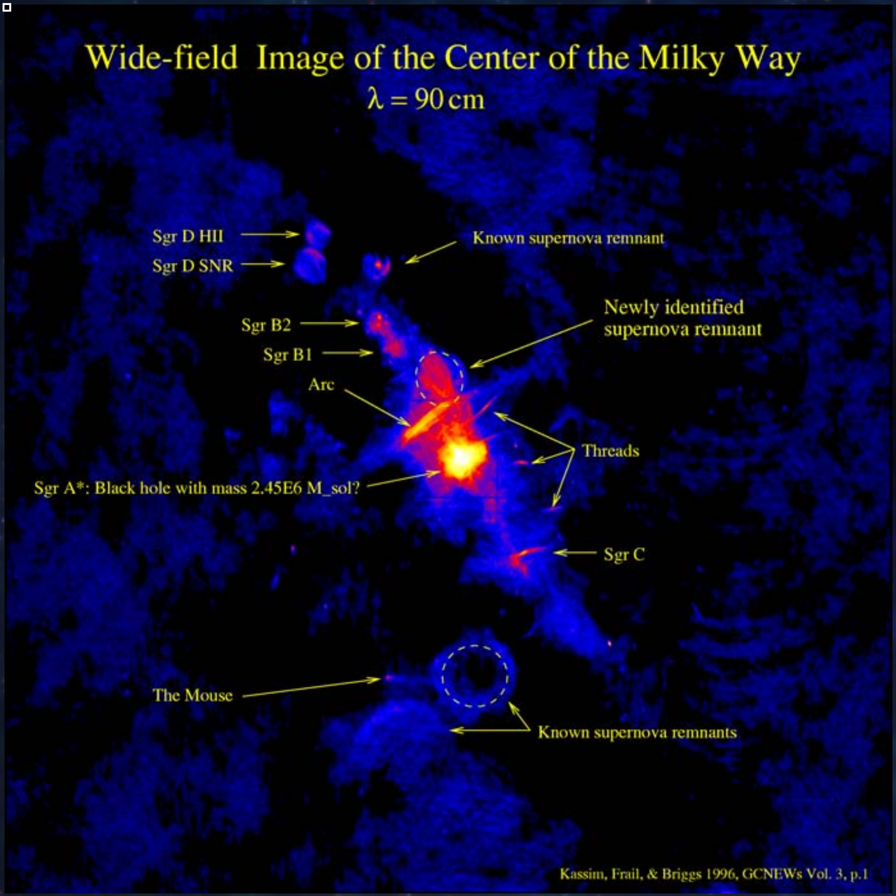
Lecture 14:

Supermassive Black Holes in Hibernation

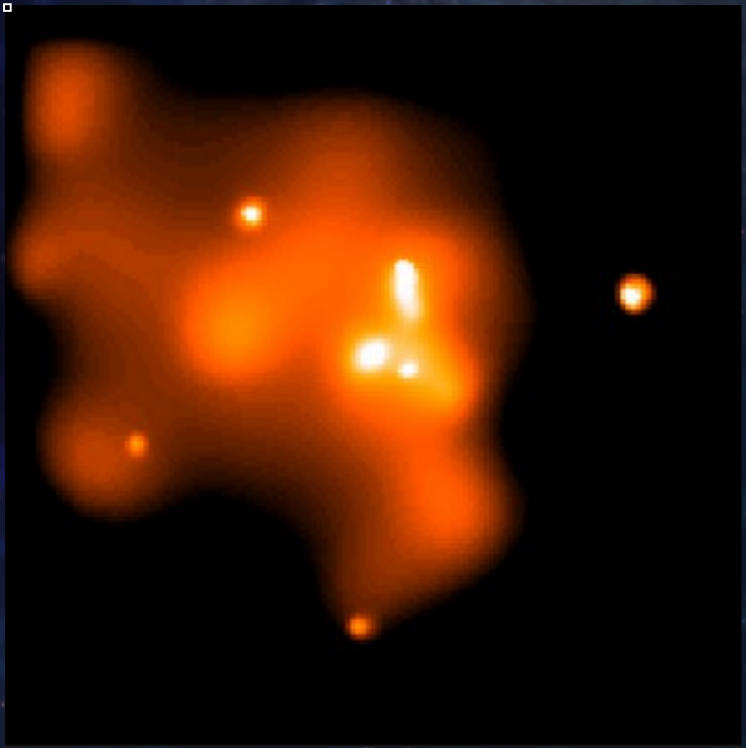
Active and Normal Galaxies



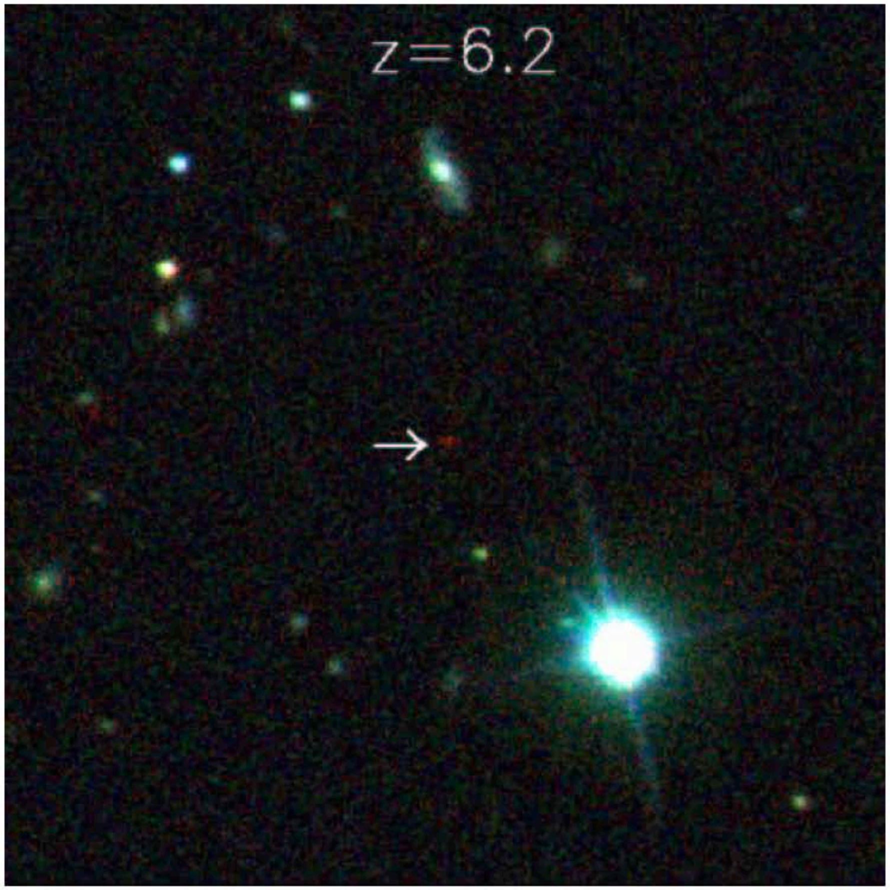
A Starved SMBH in Our Galaxy

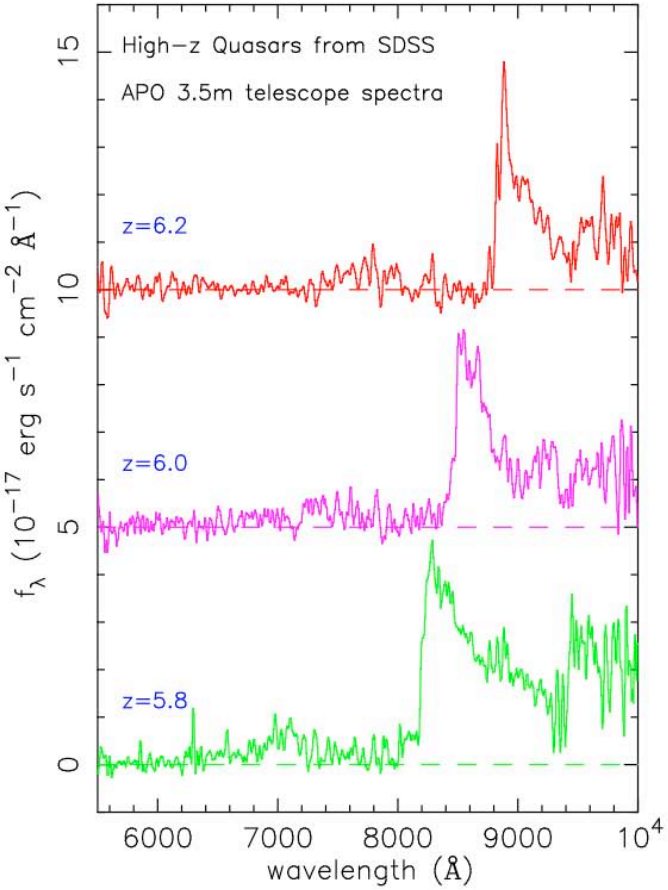


Chandra X-ray Image of Sgr A*



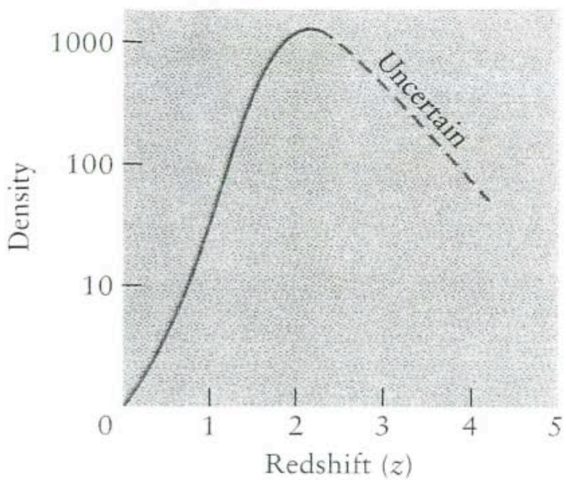
Some of the First Quasars in the Universe





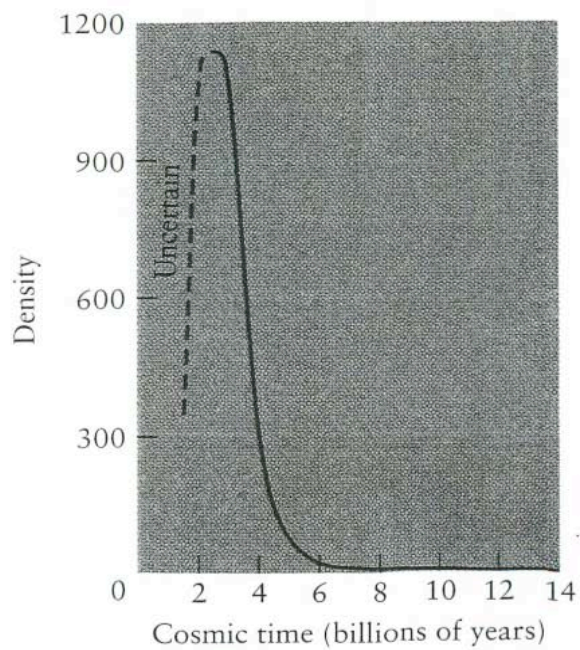
Fan et al. (2001)

Quasar Evolution Over Cosmic Time



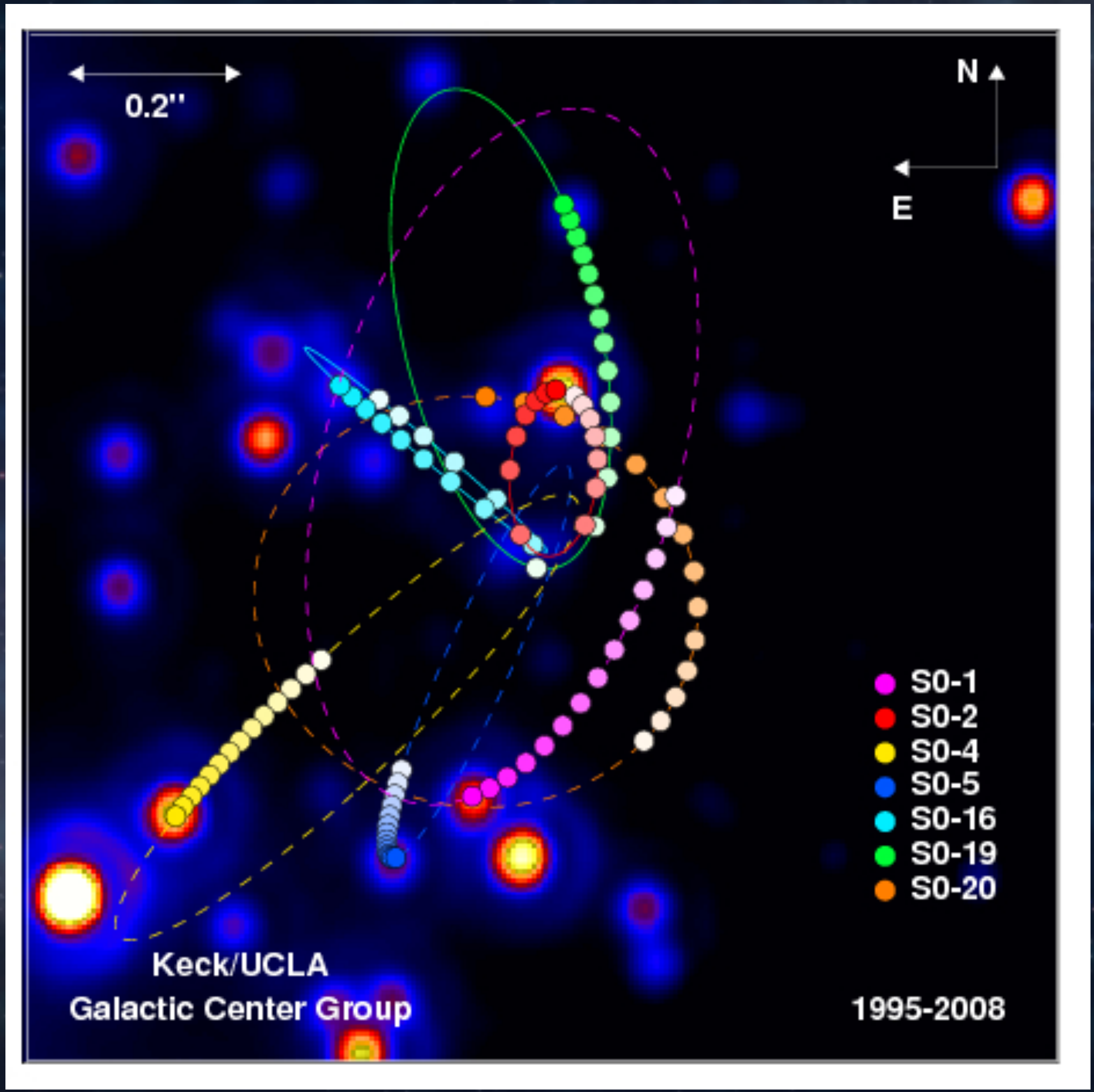
This graph shows how the abundance of quasars has changed with redshift. The vertical scale shows the density of quasars in space relative to their local (z = 0) density. Changes in density resulting simply from cosmic expansion have been removed before plotting the diagram. The pronounced peak that remains shows that quasars were most common at a redshift of 2 to 3.

Changes in the Density of Quasars over Cosmic Time

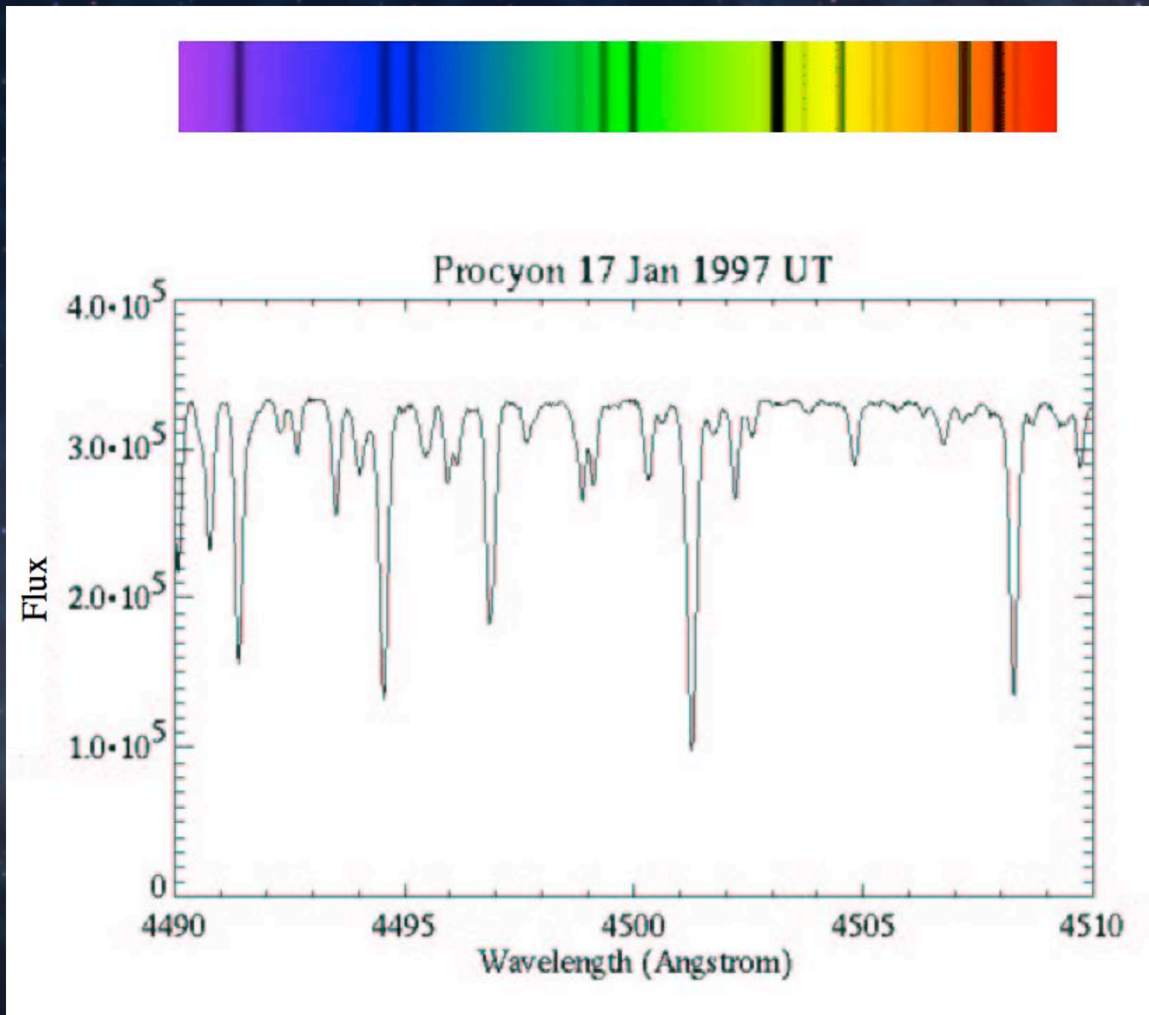


Where are They Now?

SMBH Affecting Star Orbits at Galactic Center

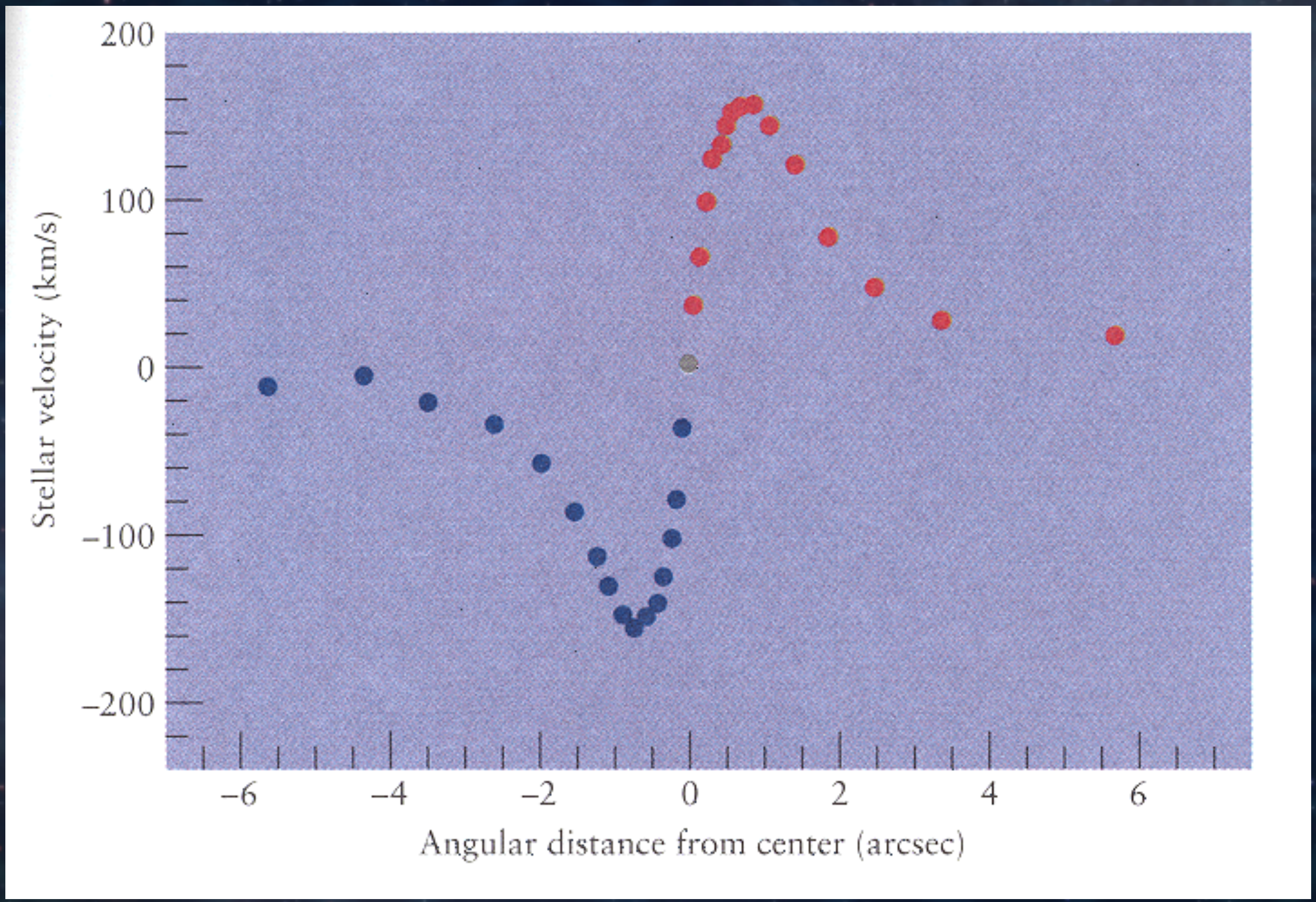


Example of a Stellar Spectrum



The Andromeda Galaxy (M31)

Stellar Motions in Center of M31

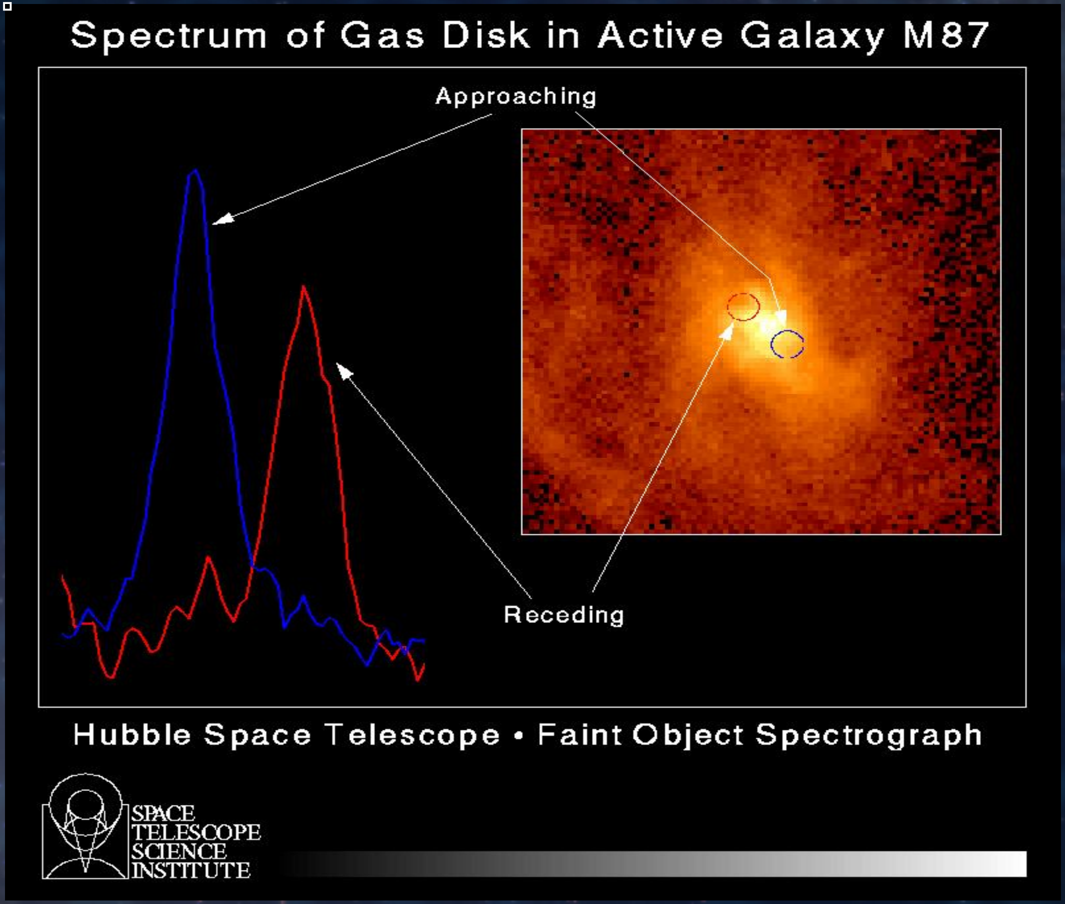


Inferred SMBH mass is ~ 45 million solar masses.

The Sombrero Galaxy

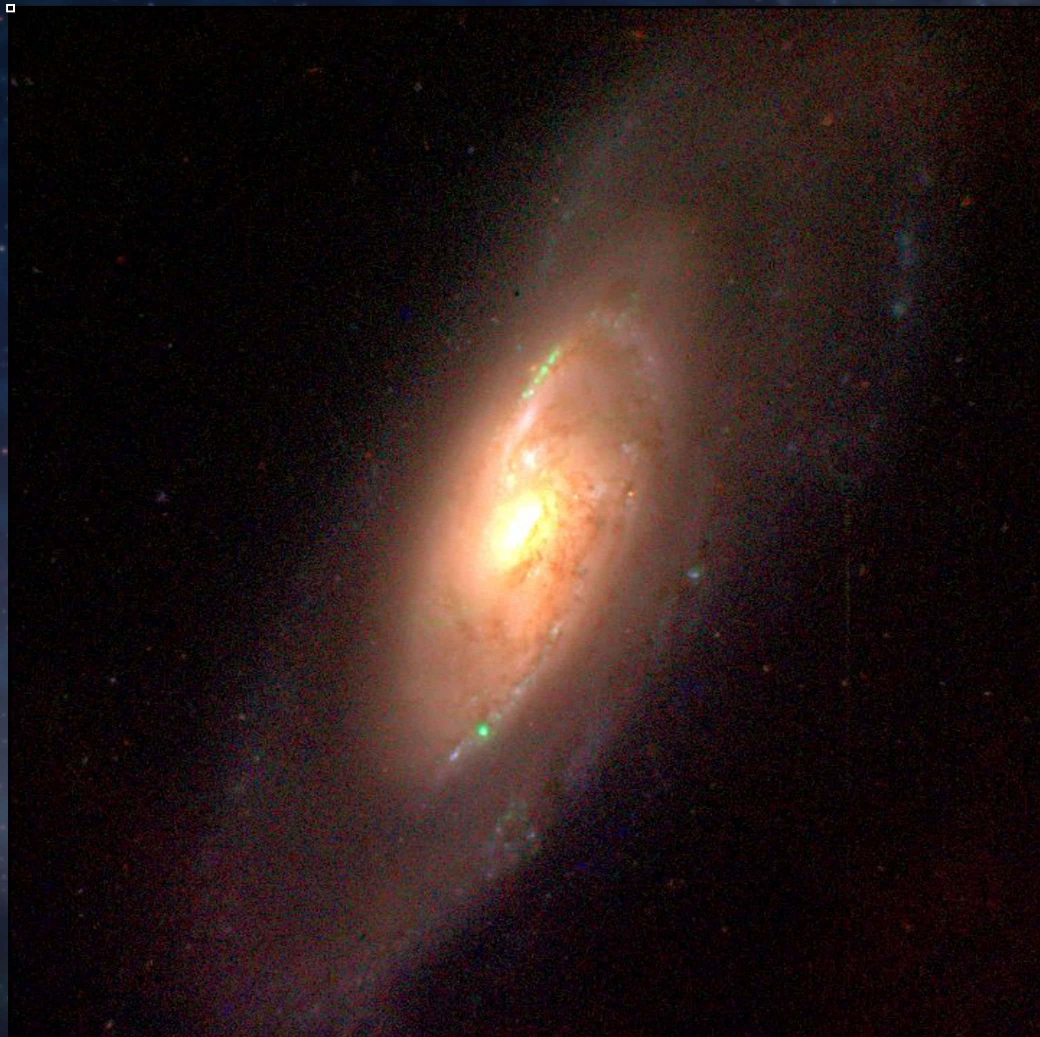
Inferred SMBH mass is ~ billion solar masses.

Rotation of Gas Clouds in M87



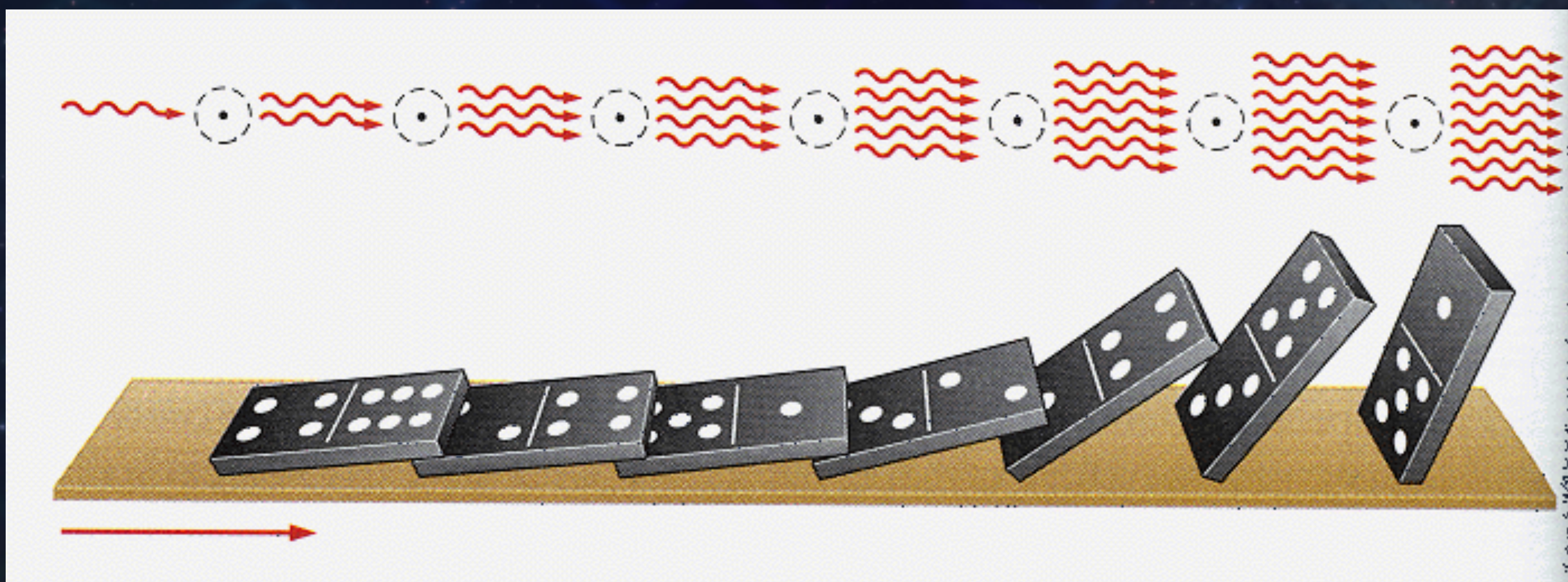
Inferred SMBH mass is ~ 3 billion solar masses.

NGC 4258 – A Maser Disk Galaxy

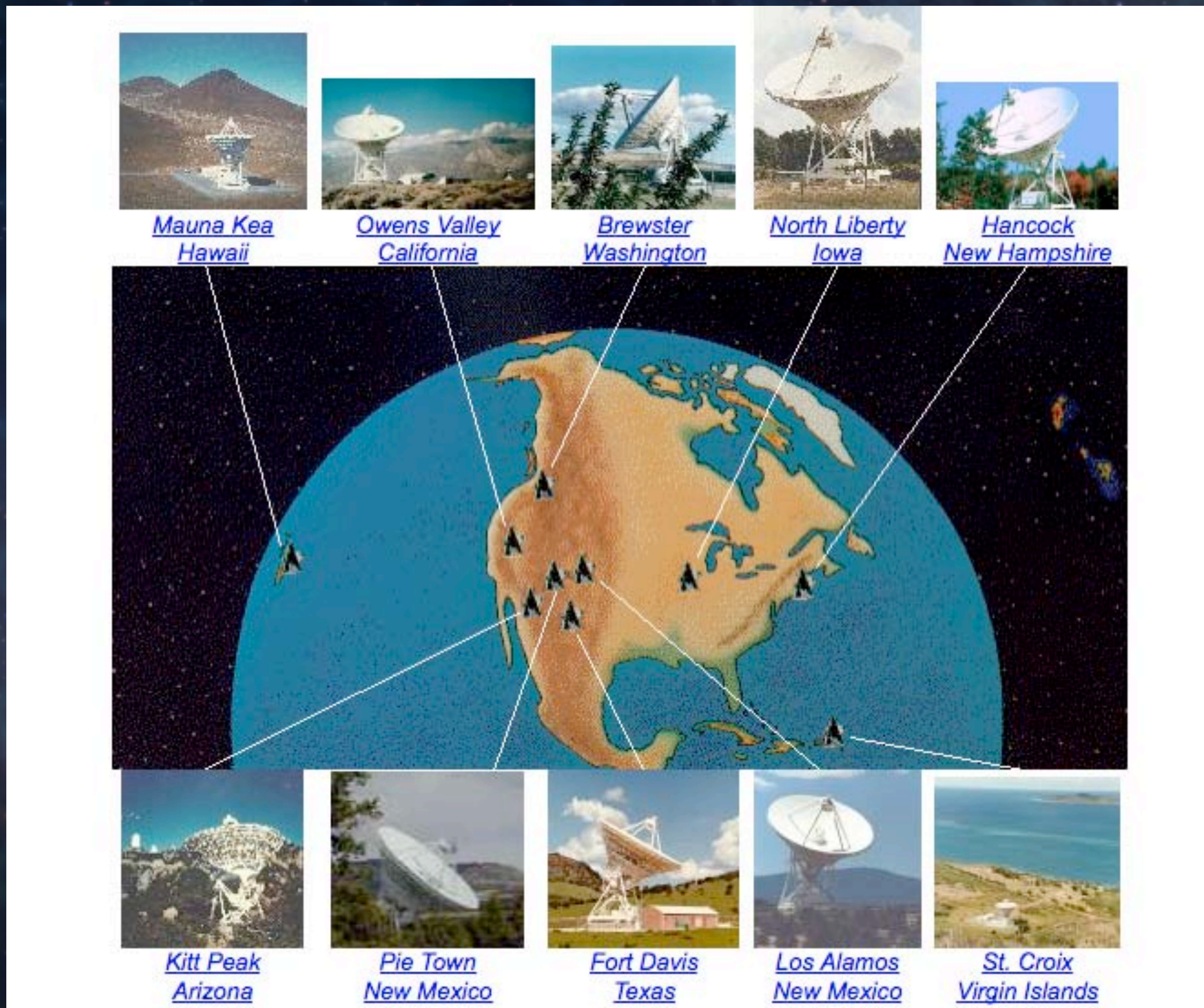


Basic Idea of a MASER

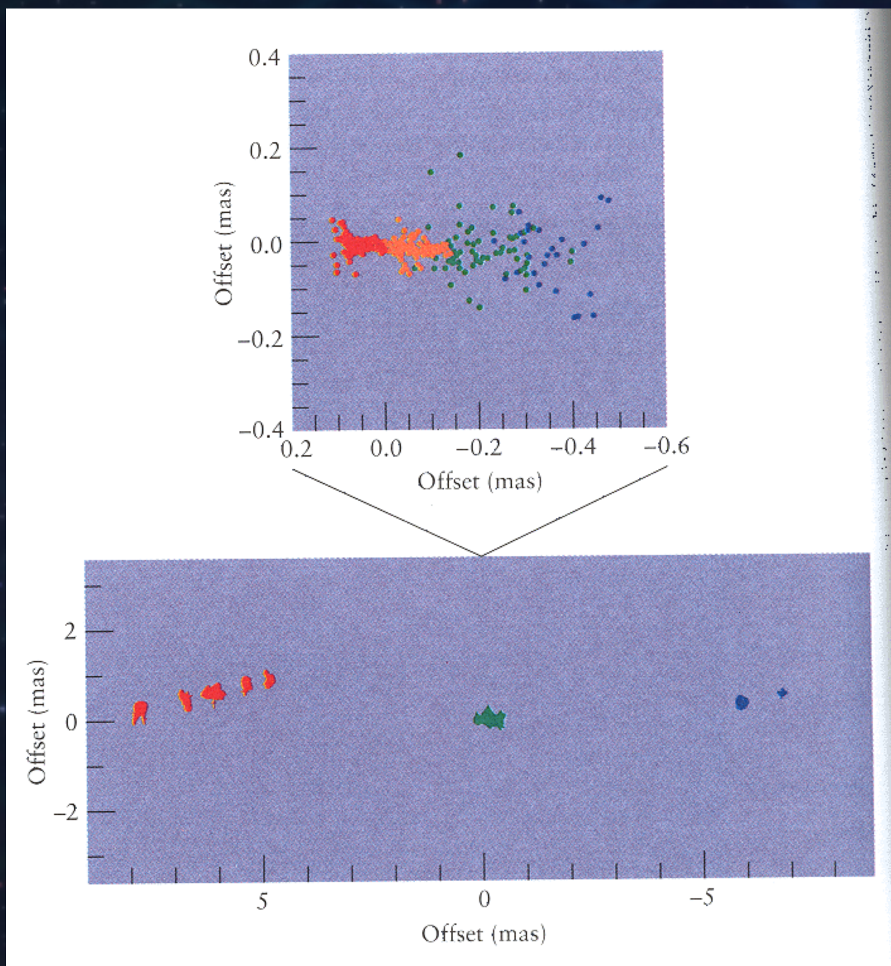
Microwave Amplification by Stimulated Emission of Radiation

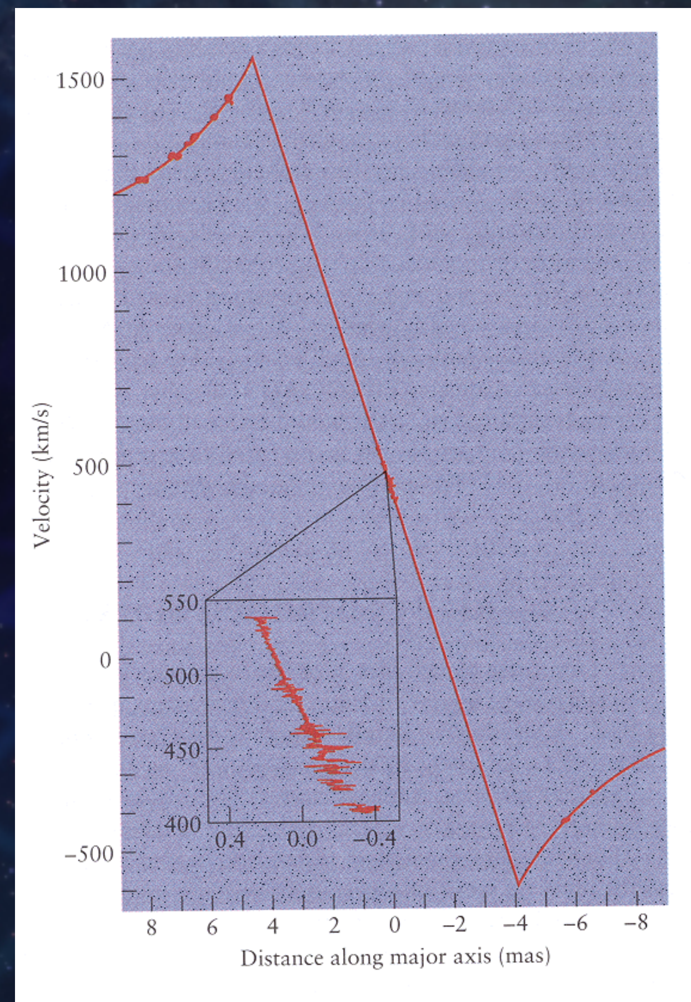


The Very Long Baseline Array

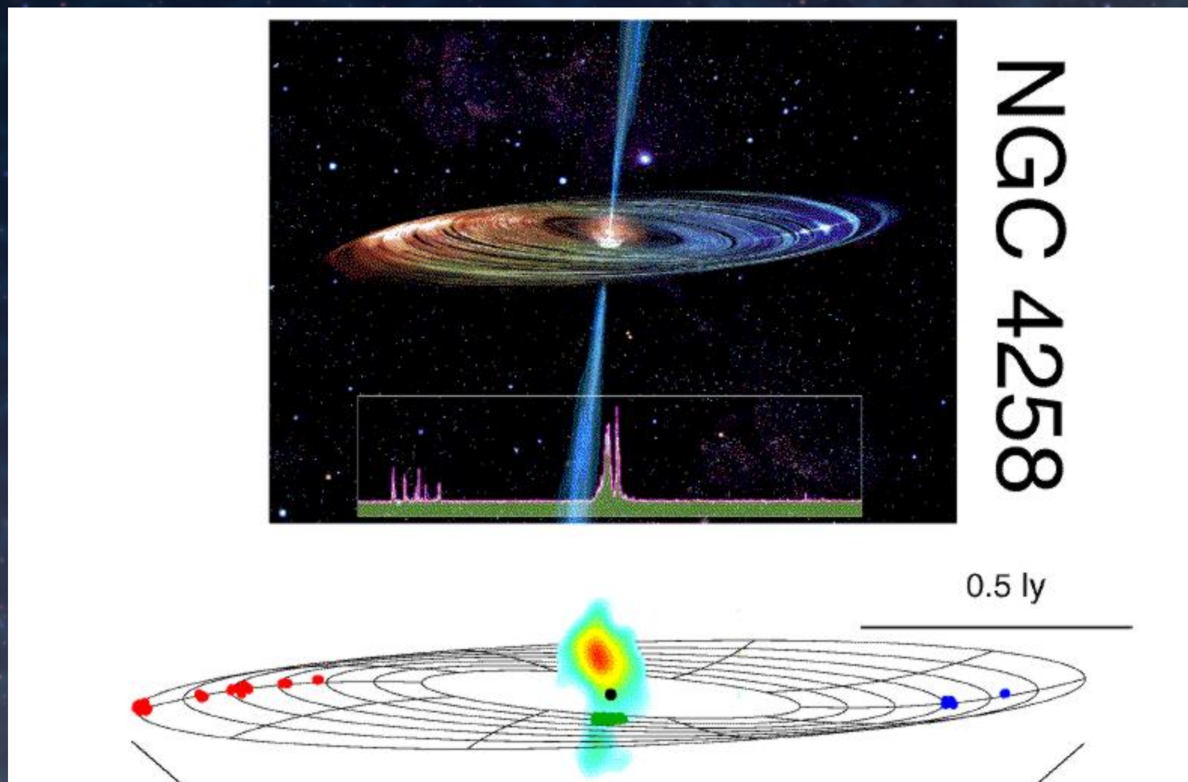


Observed MASERS in NGC 4258



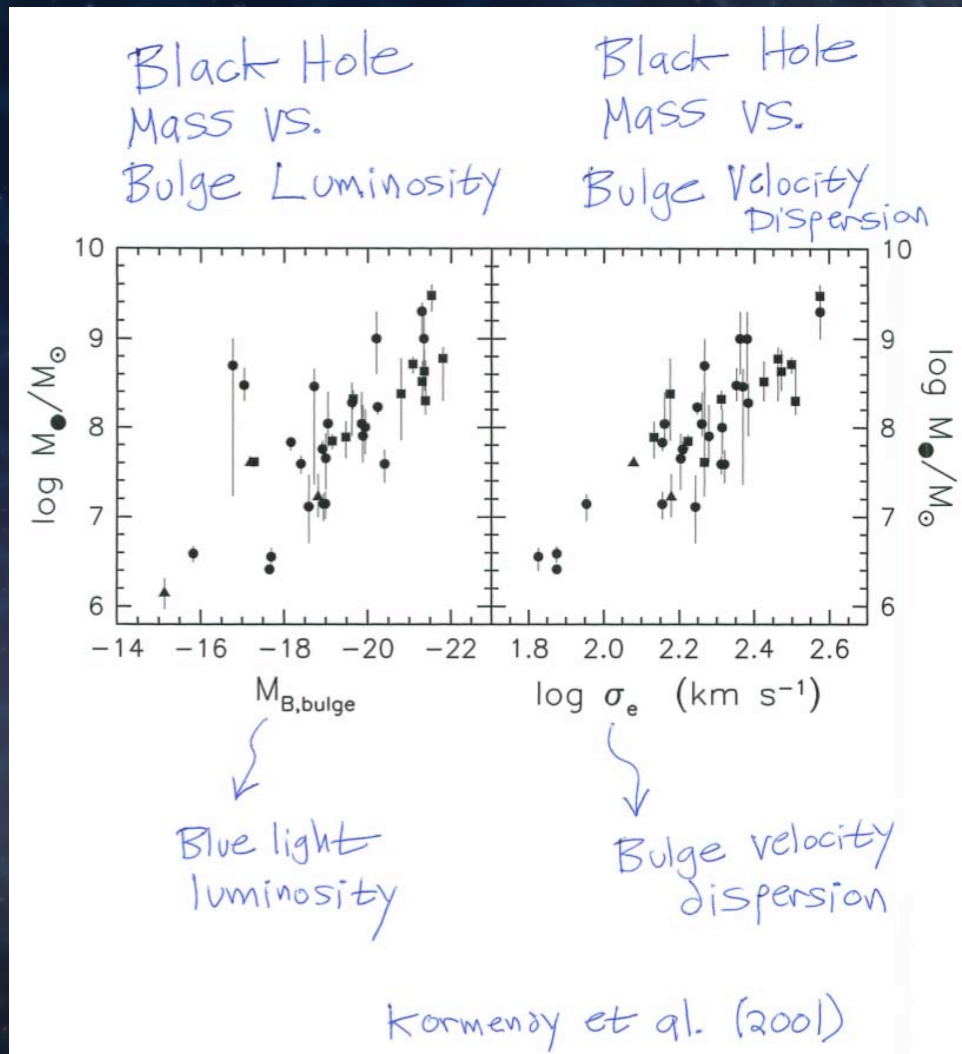


Model to Explain the MASER Observations

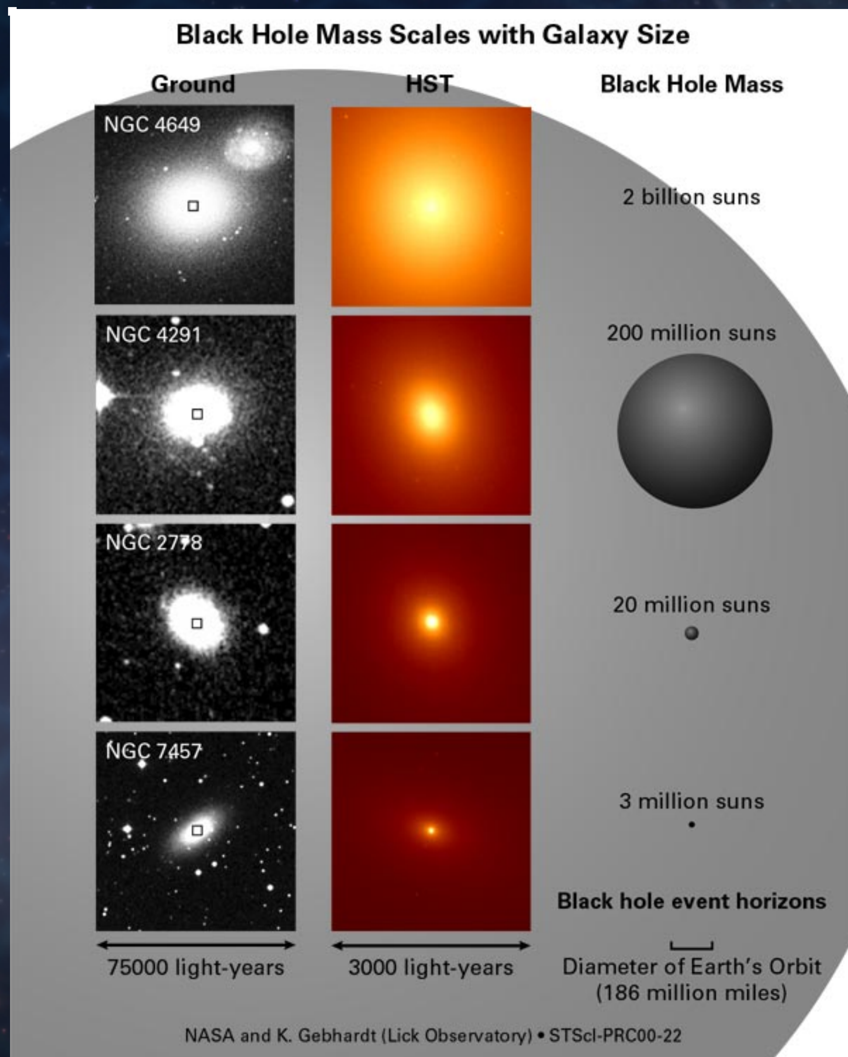


Inferred SMBH mass is 36 million solar masses.

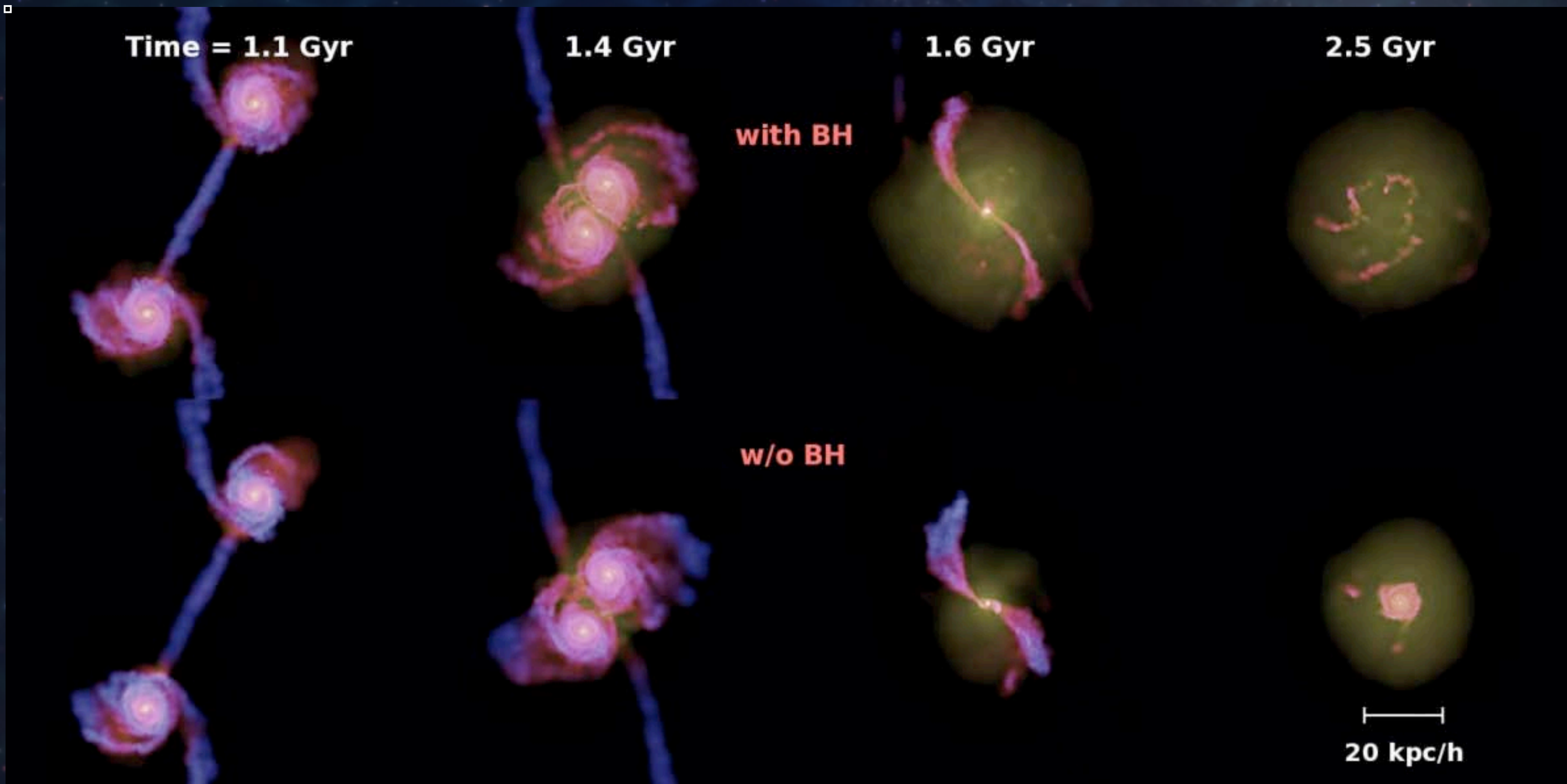
Relations Between SMBHs and Host Bulges



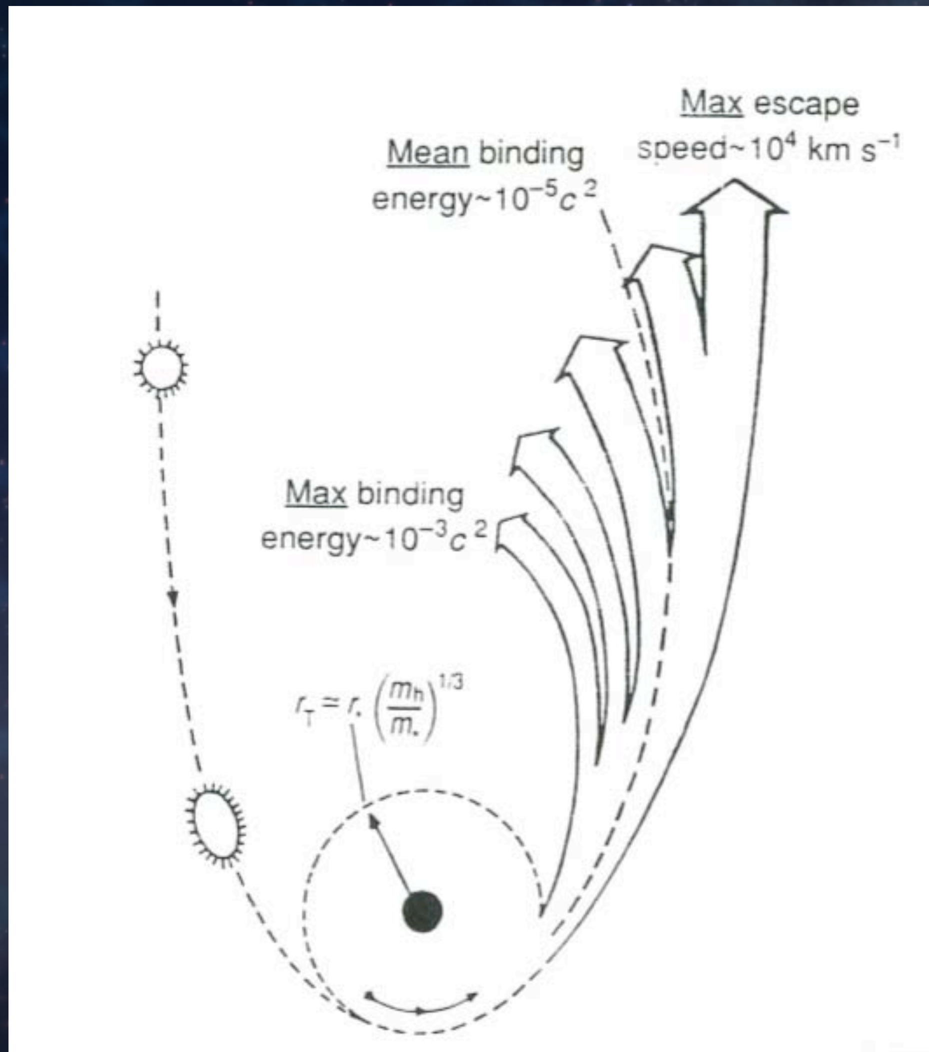
Relations Between SMBHs and Host Bulges



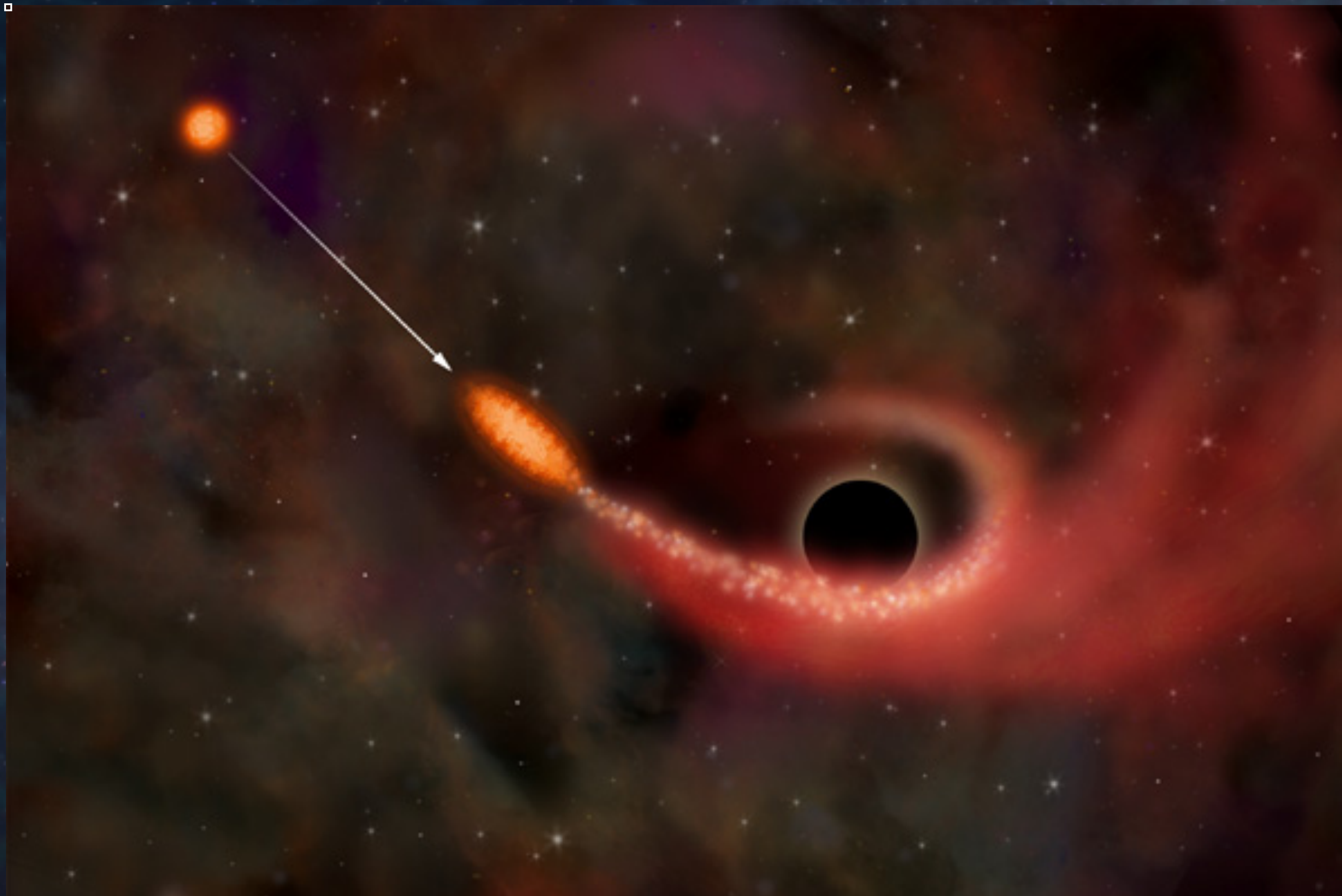
Quasar Winds as a Source of Feedback?



Tidal Disruptions of Stars by SMBHs

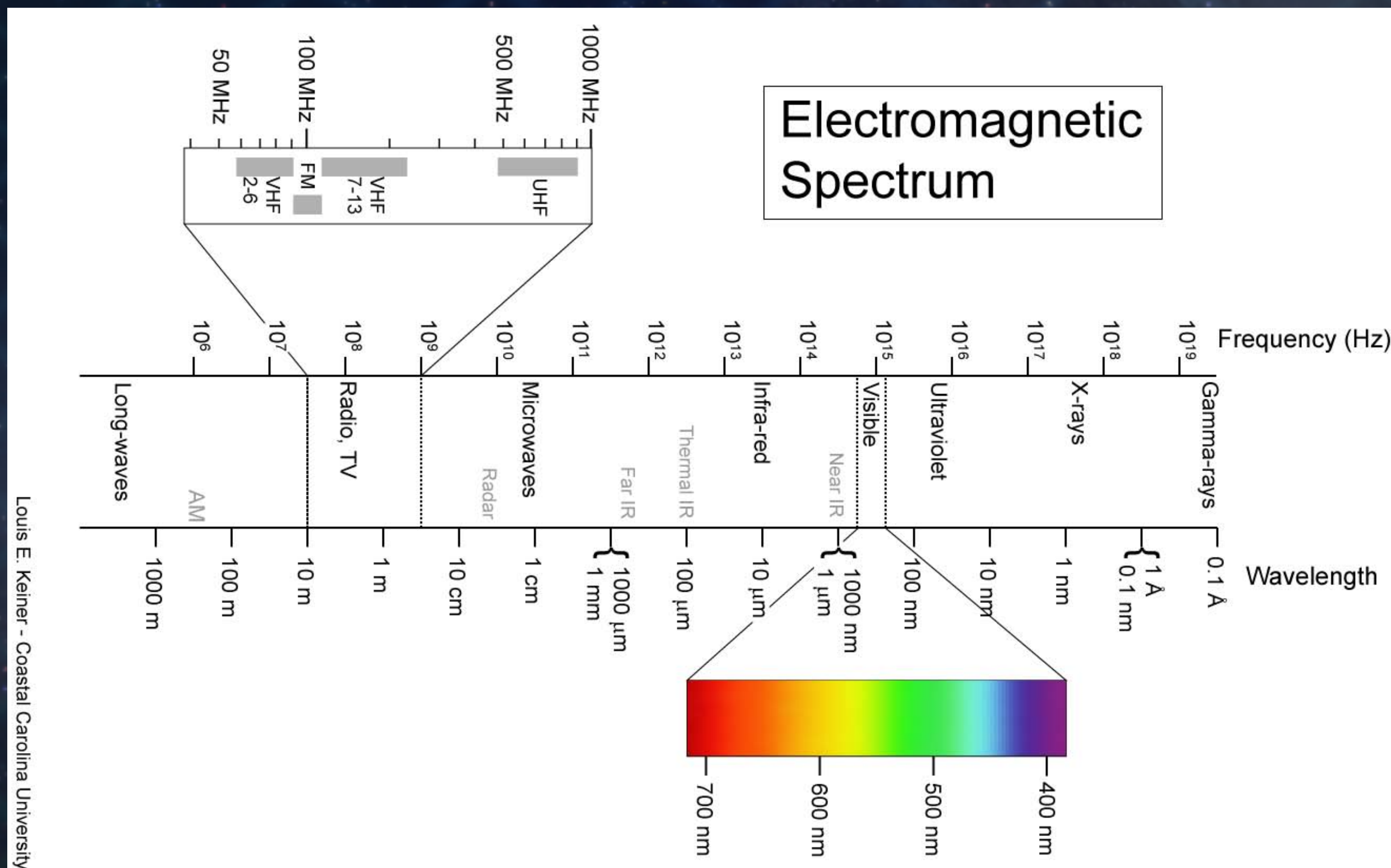


Tidal Disruptions of Stars by SMBHs



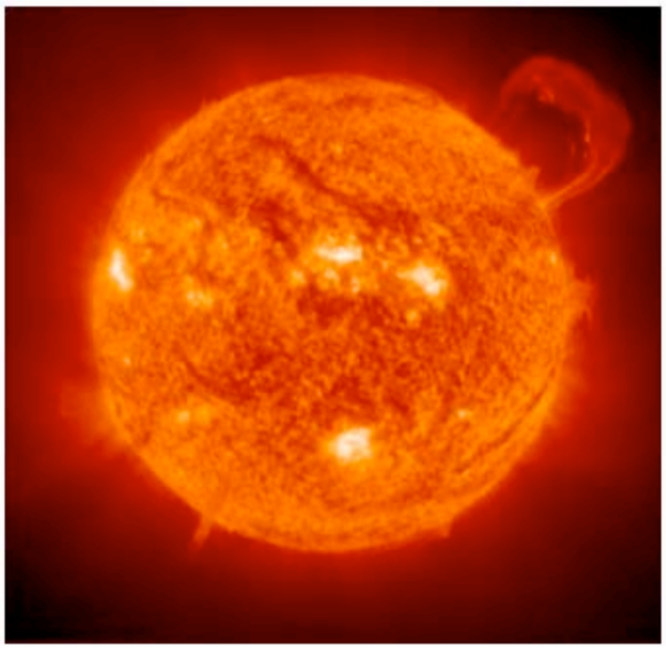
Lecture 15:
Gravitational Waves

Electromagnetic Radiation

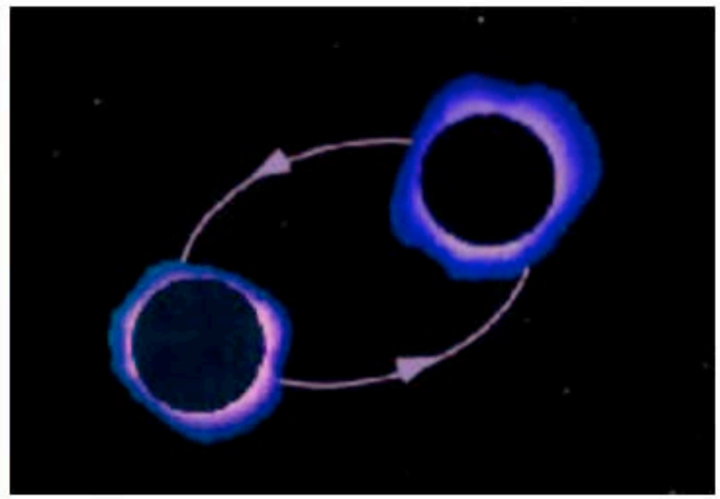


Sources of EM and Gravitational Radiation

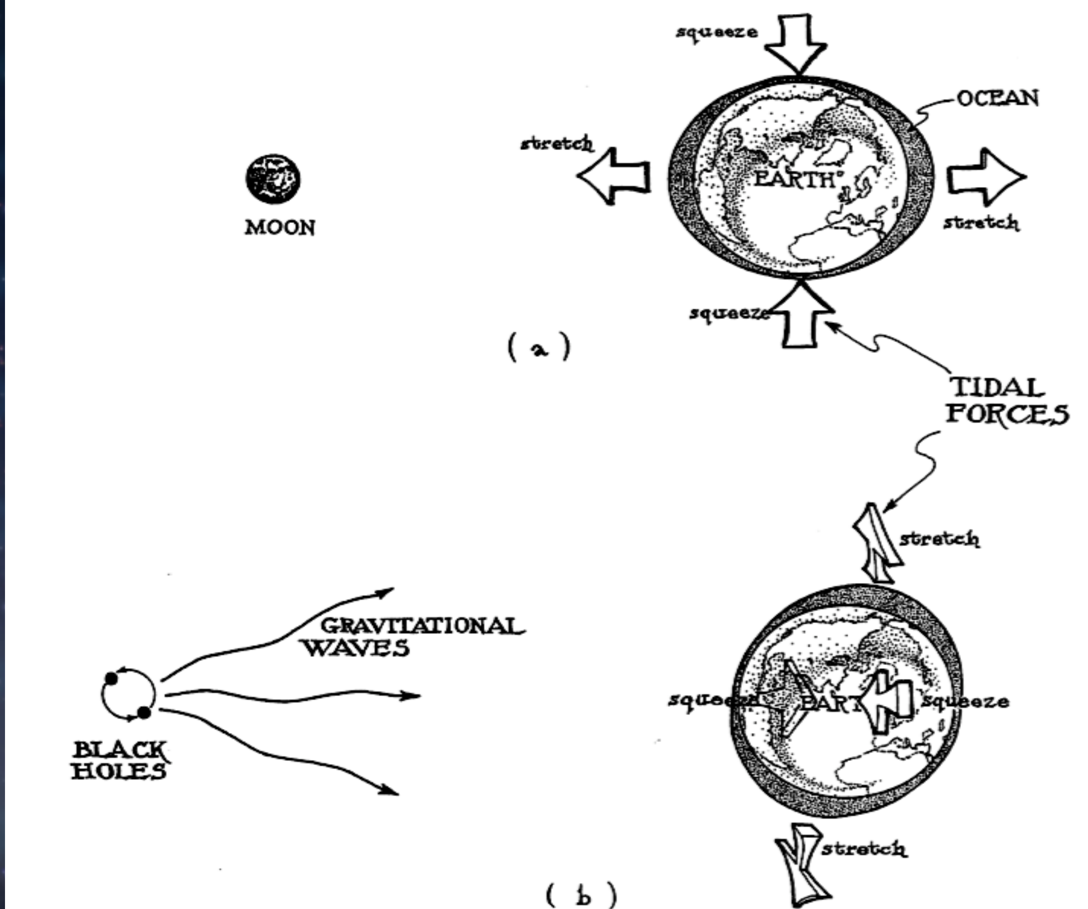
The Sun: A Source of Electromagnetic Radiation



Merging Black Holes: A Source of Gravitational Wave Radiation



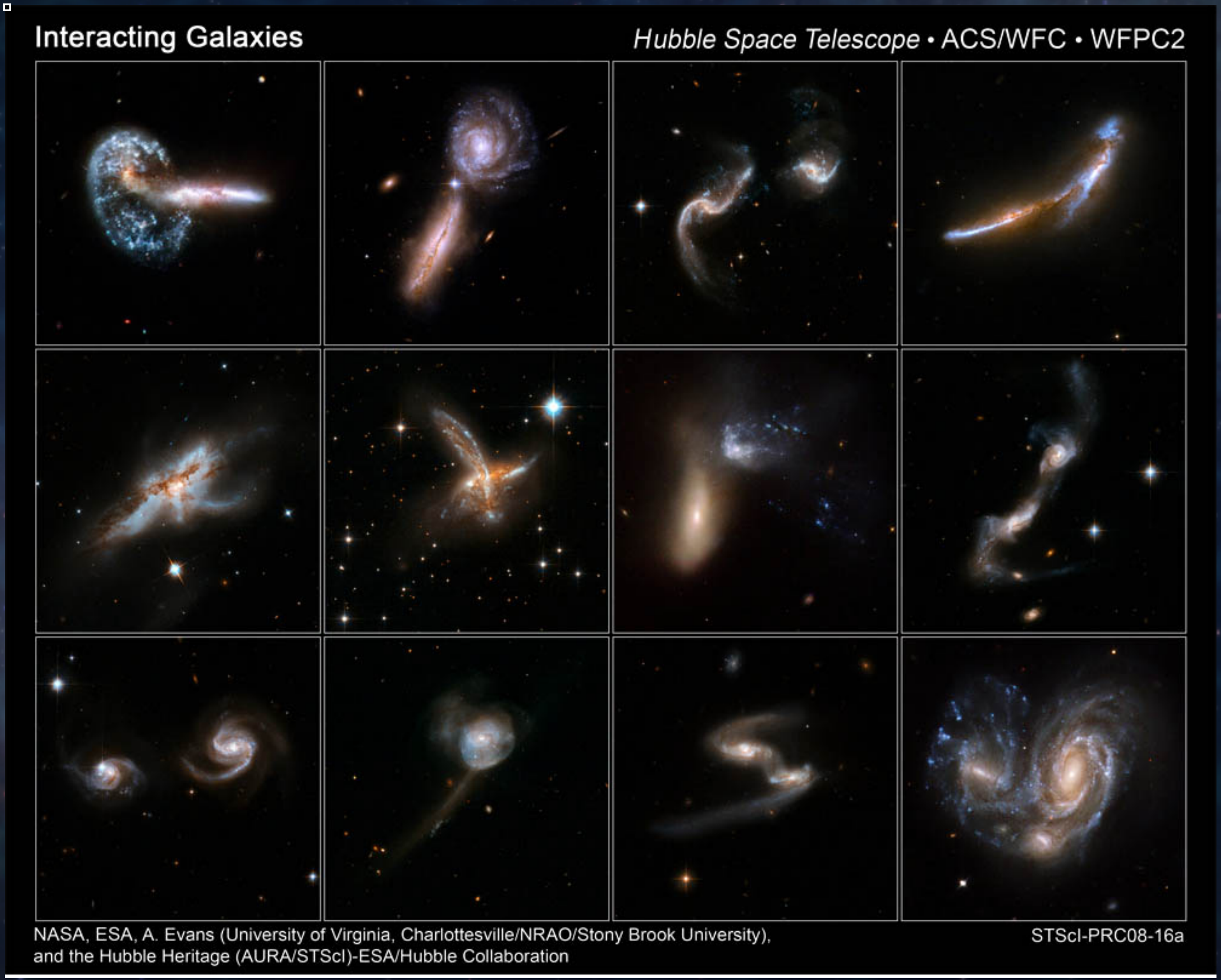
Tidal Forces from Gravitational Waves



10.3 The tidal forces produced by the Moon and by a gravitational wave. (a) The Moon's tidal forces stretch and squeeze the Earth's oceans; the stretch is longitudinal, the squeeze is transverse. (b) A gravitational wave's tidal forces stretch and squeeze the Earth's oceans; the forces are entirely transverse, with a stretch along one transverse direction and a squeeze along the other.

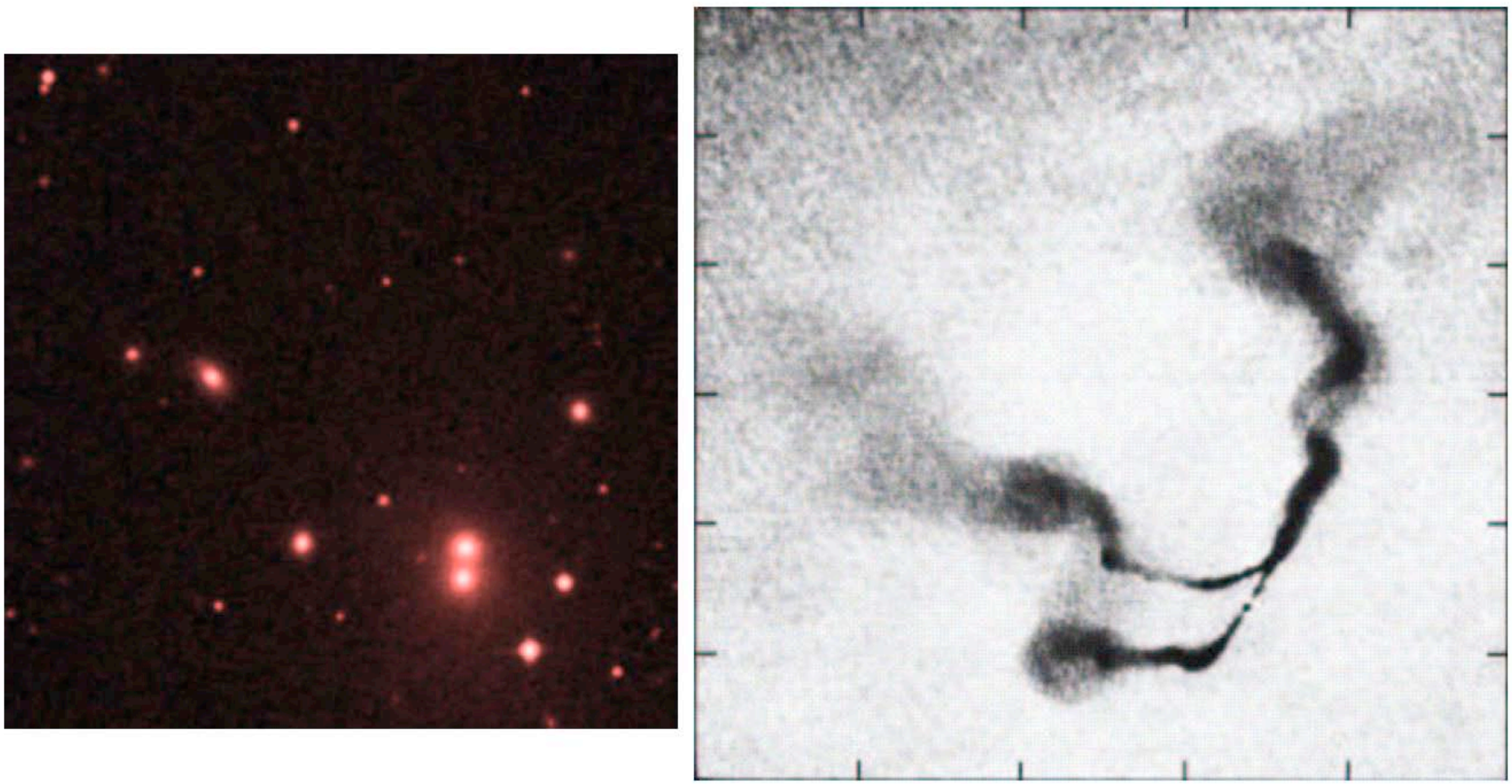
Black-Hole Binary System

Examples of Galaxy Collisions

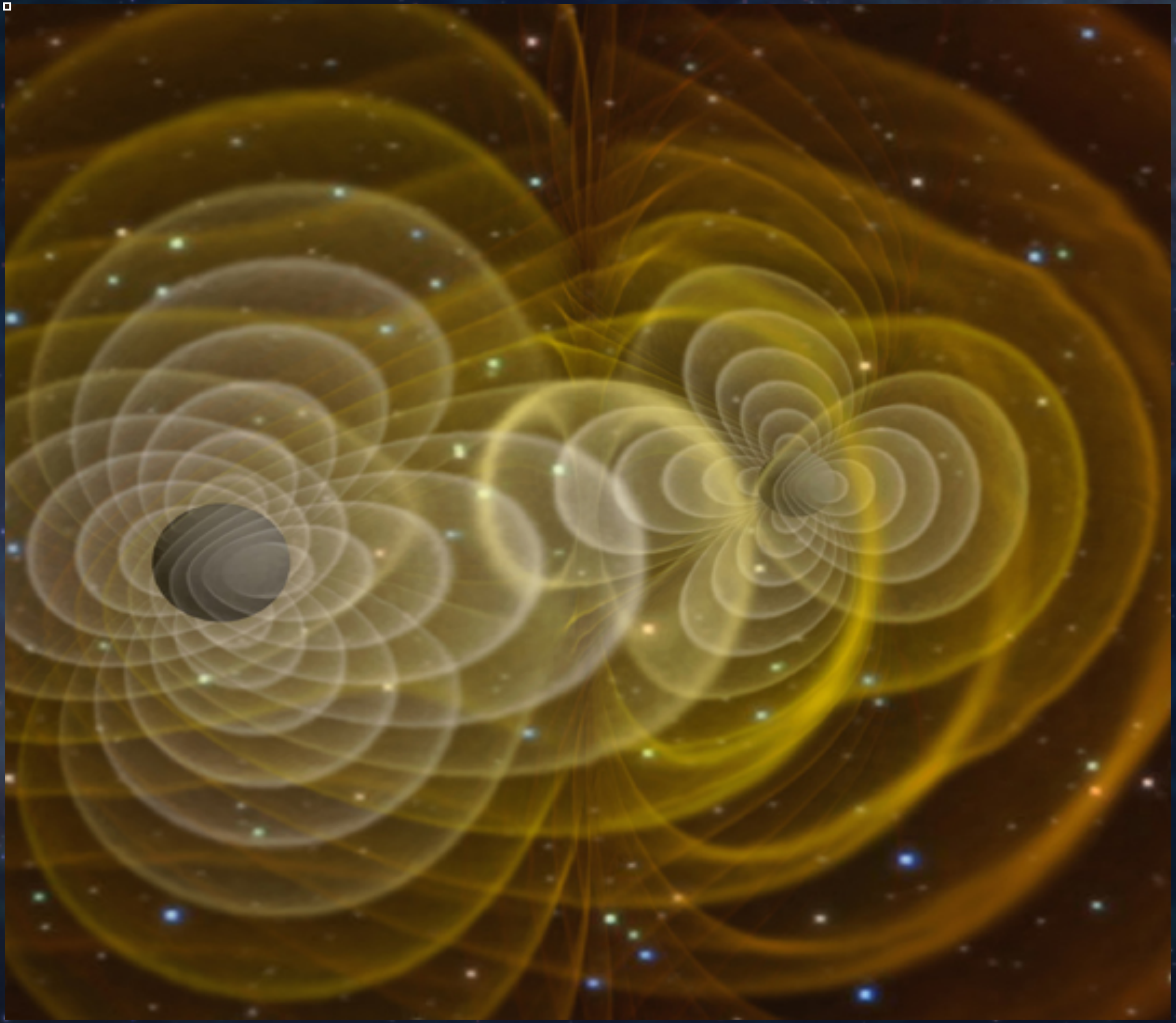


A Future Supermassive Black Hole Binary

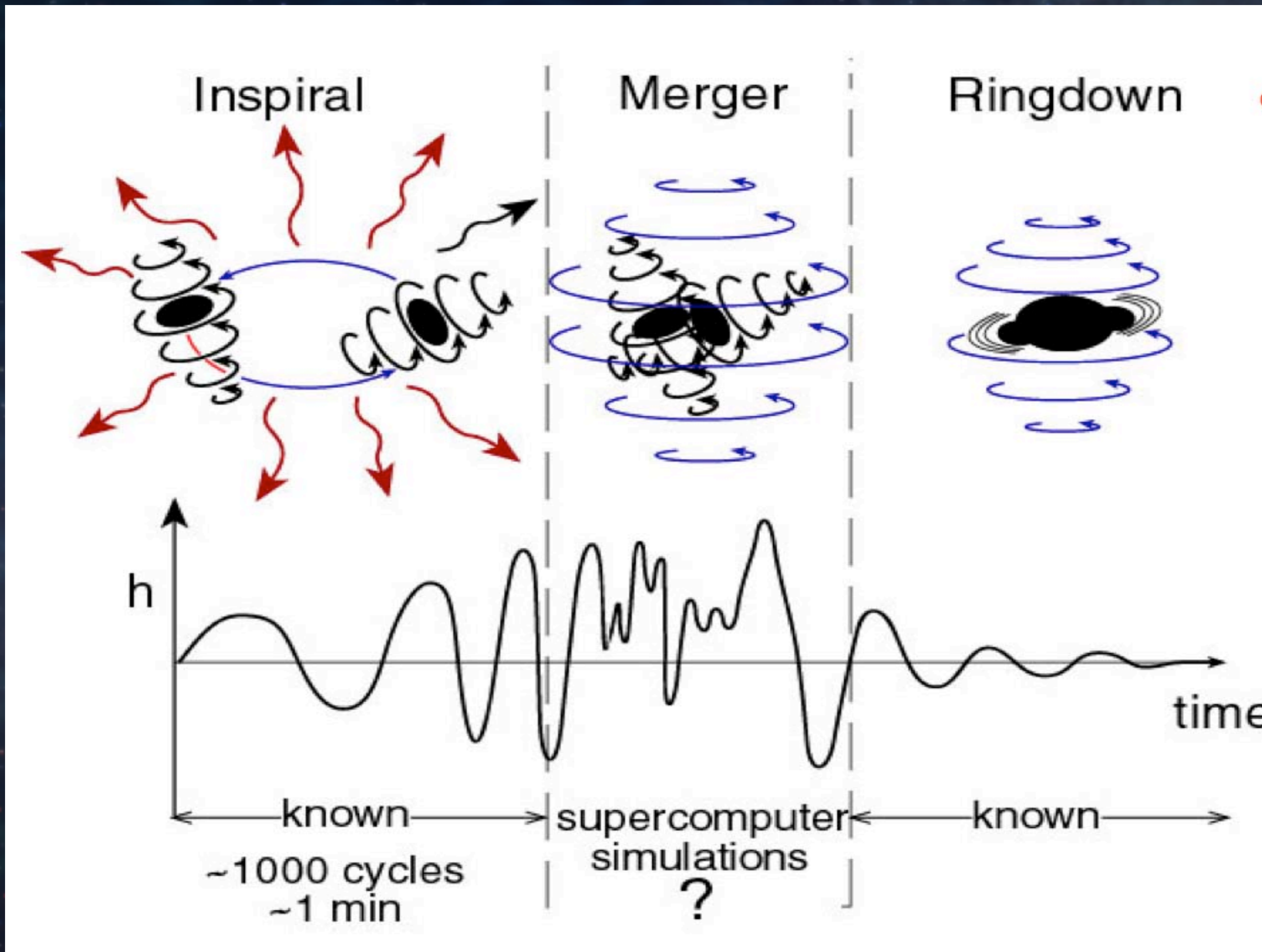
3C75: Prelude to a Supermassive Black Hole Binary?



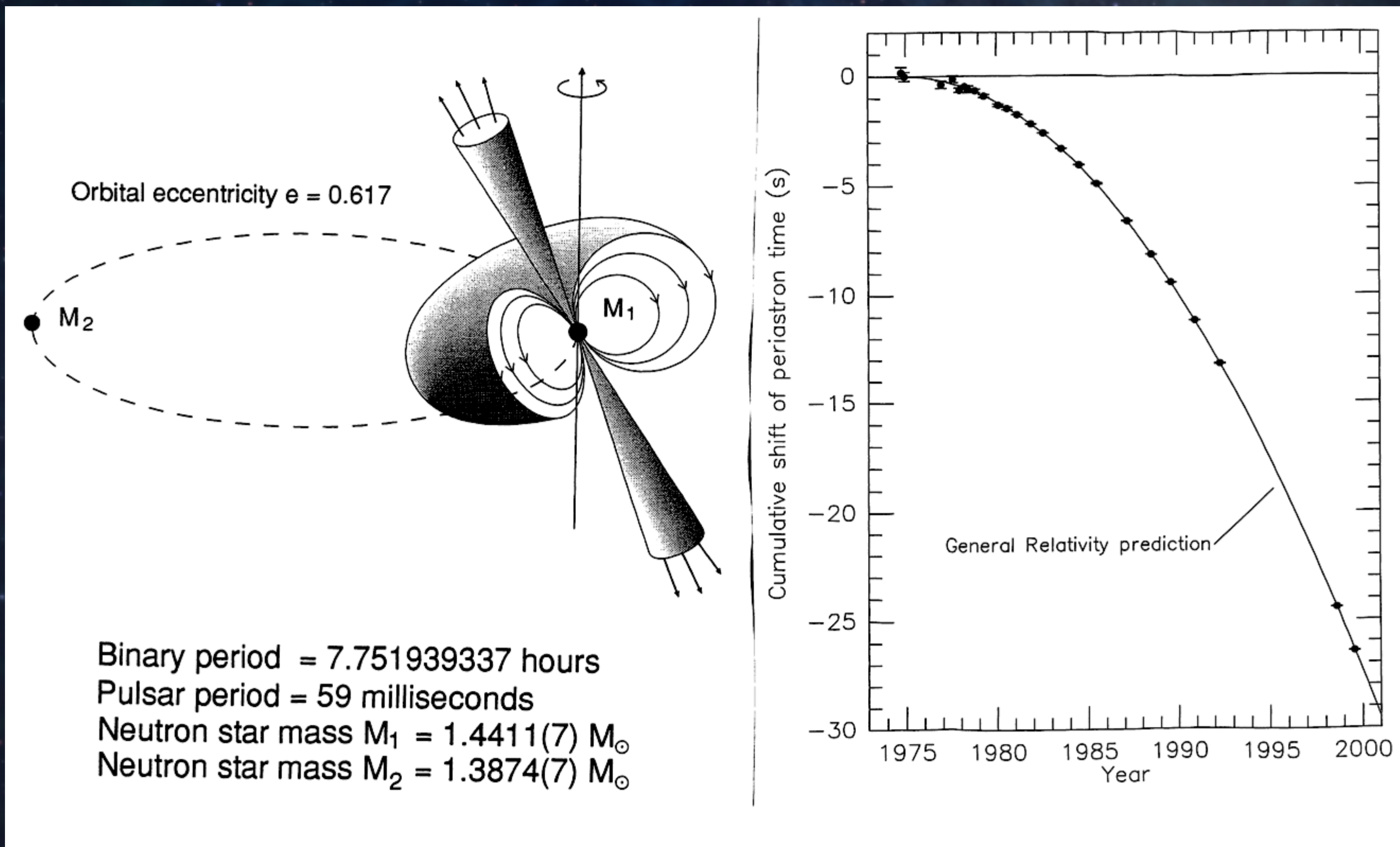
Gravitational Waves from a Binary Black Hole



Merging Black Holes

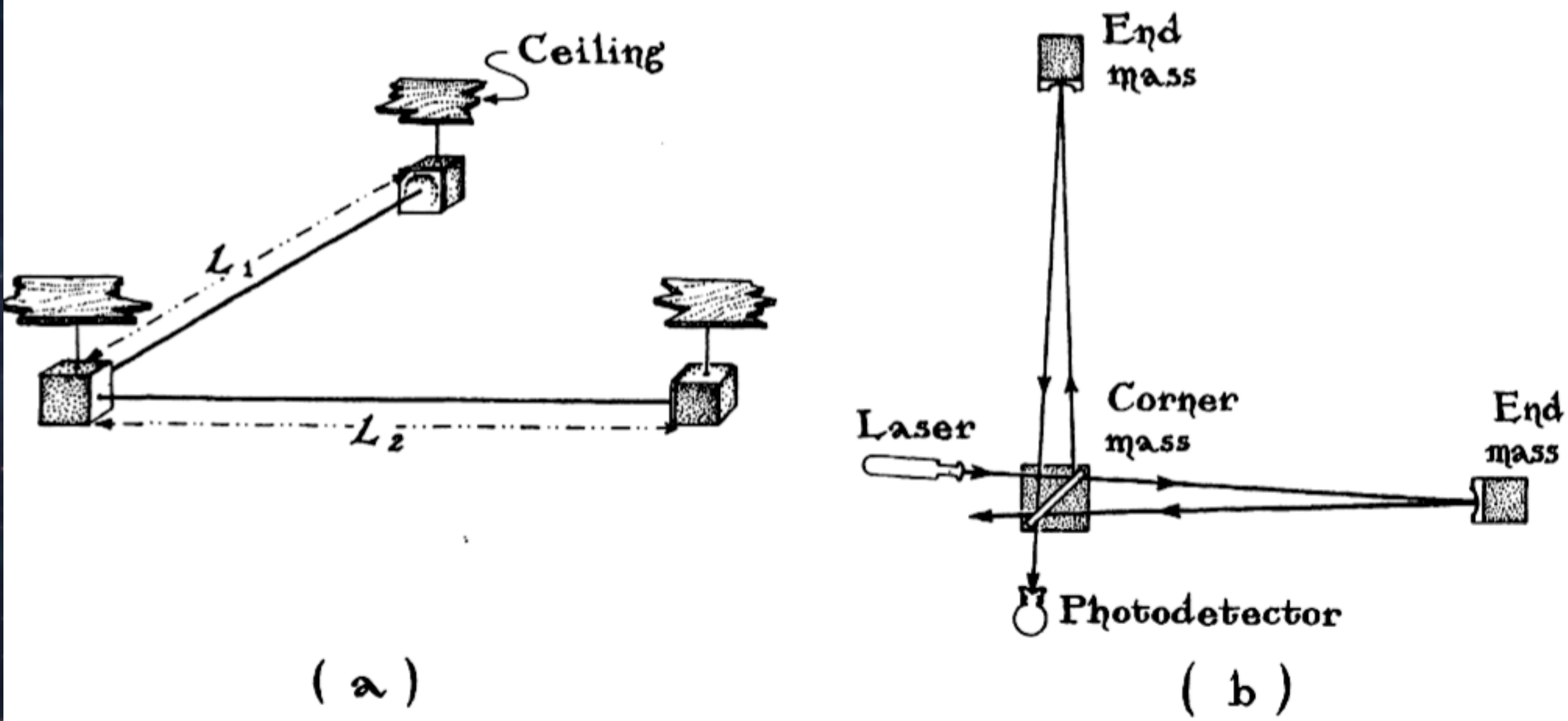


Indirect Evidence for Gravitational Waves



Simplified Gravitational Wave Detector

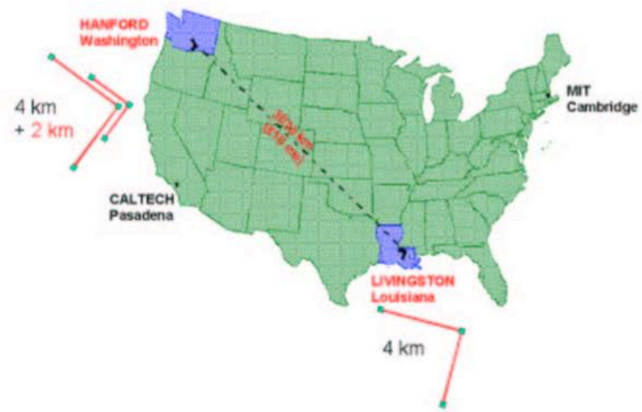
10.6 A laser interferometric gravitational-wave detector. This instrument is very similar to the one used by Michelson and Morley in 1887 to search for motion of the Earth through the aether (Chapter 1). See the text for a detailed explanation.



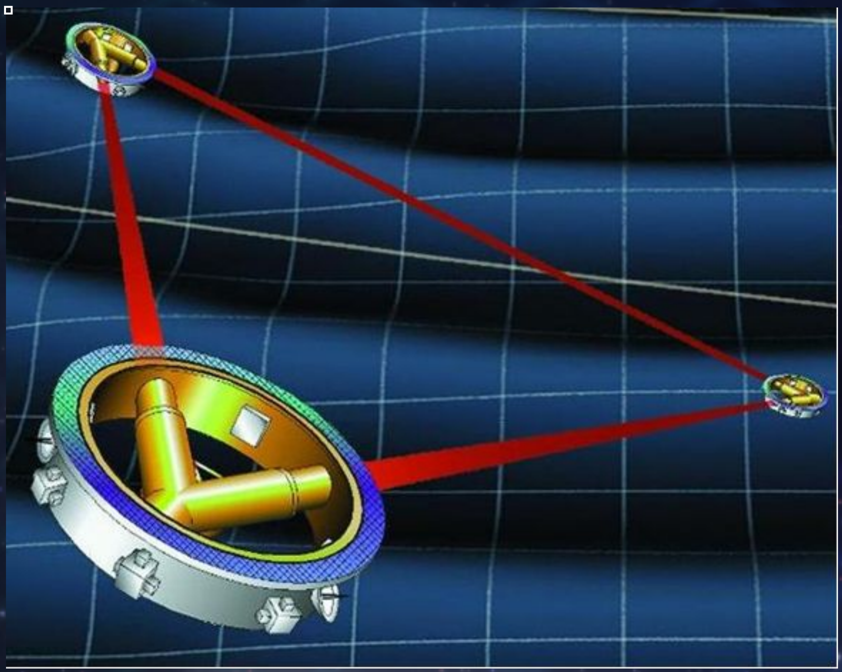
The LIGO Experiment

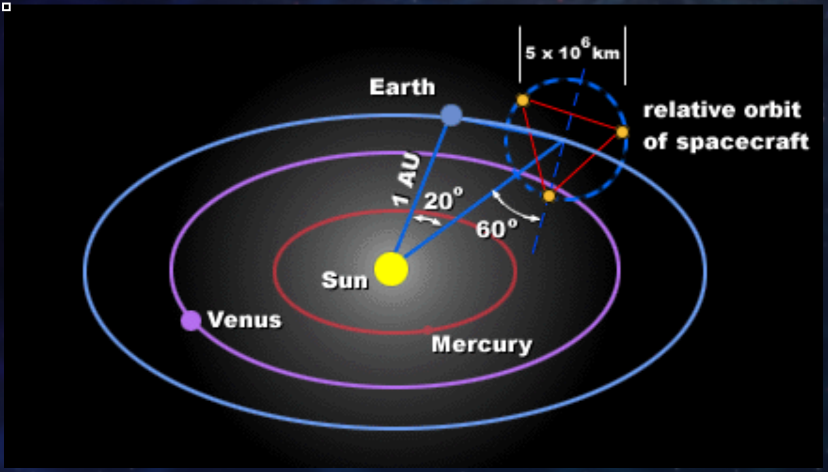
Laser Interferometer Gravitational-Wave Observatory (LIGO)

LIGO Observatories

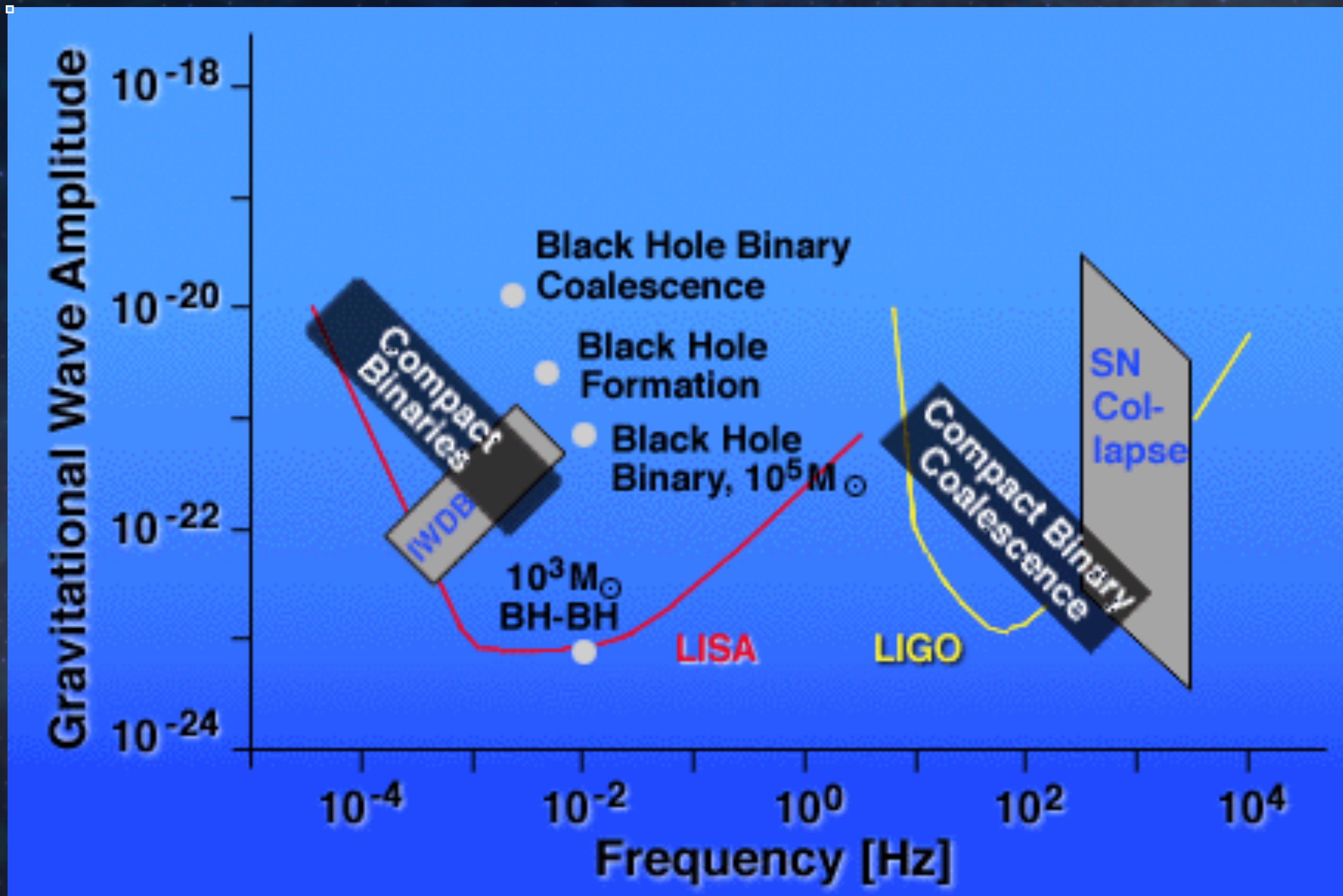


The Proposed LISA Experiment





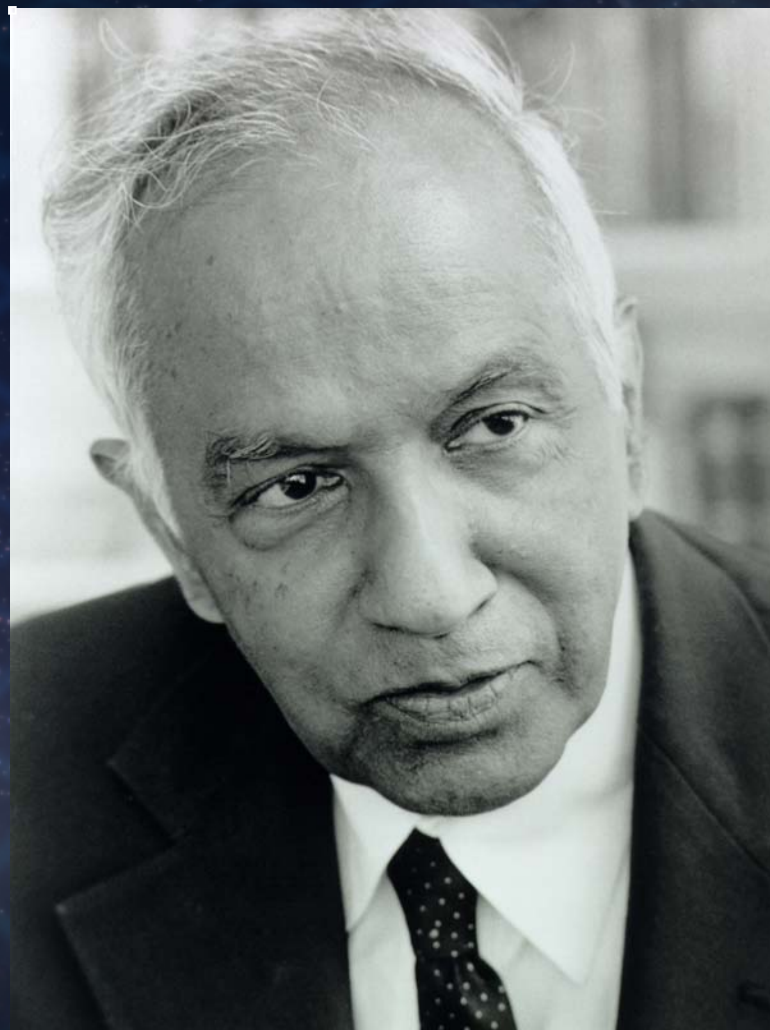
The Spectrum of Gravitational Waves



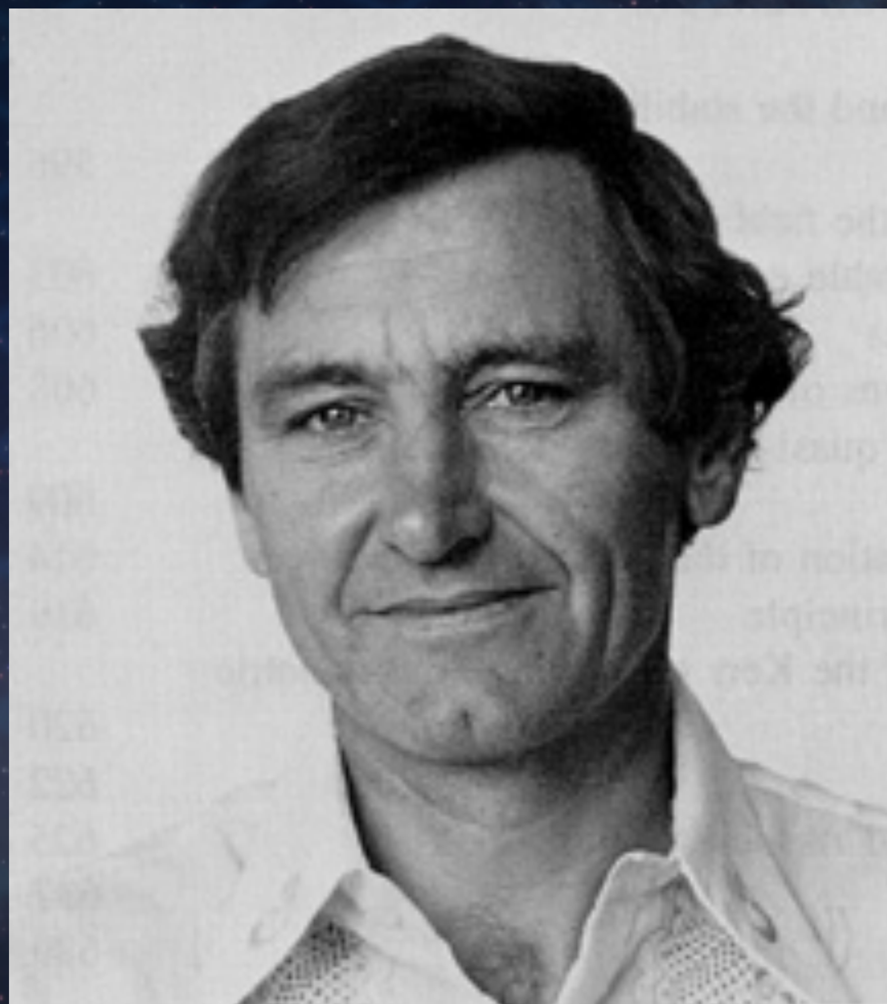
Lecture 16:

Spinning Black Holes and the No-Hair Theorem

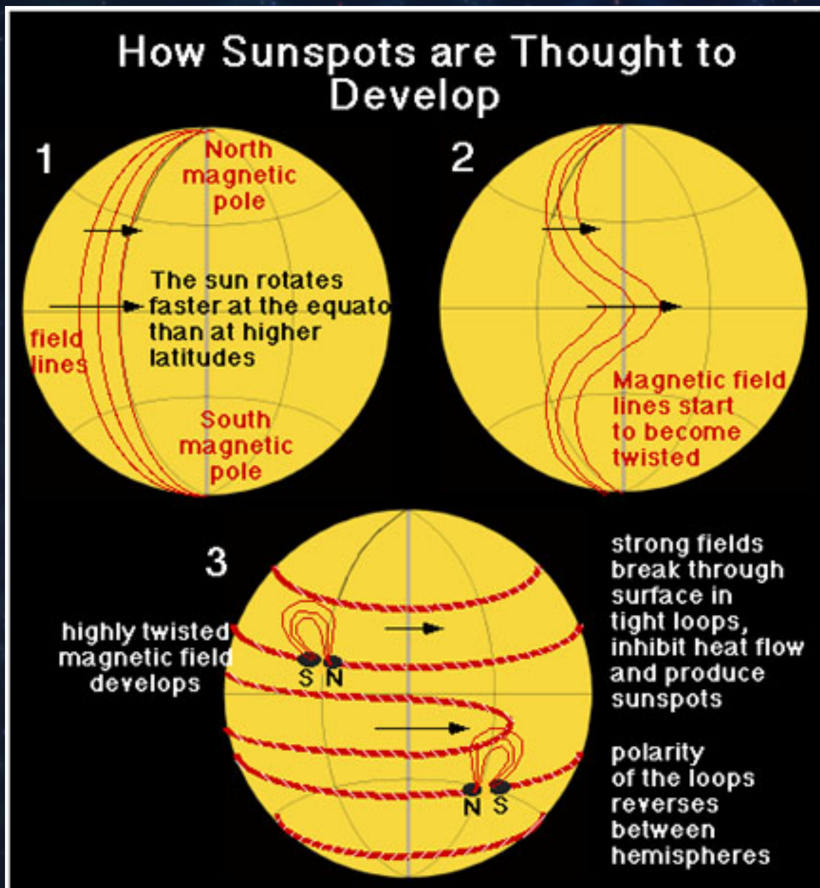
S. Chandrasekhar – “Shattering Experience”



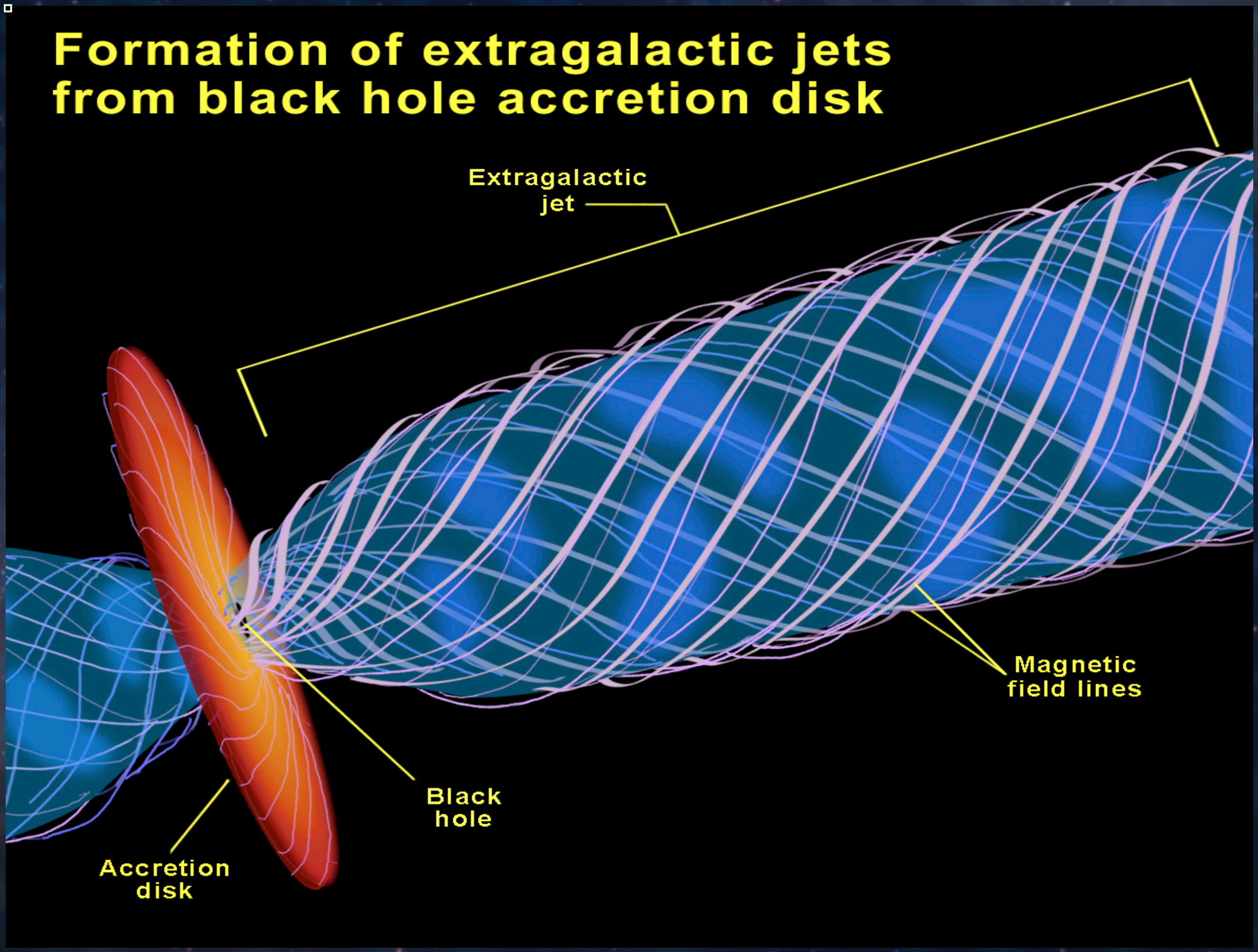
Roy Kerr – Discoverer of Black-Hole Spin



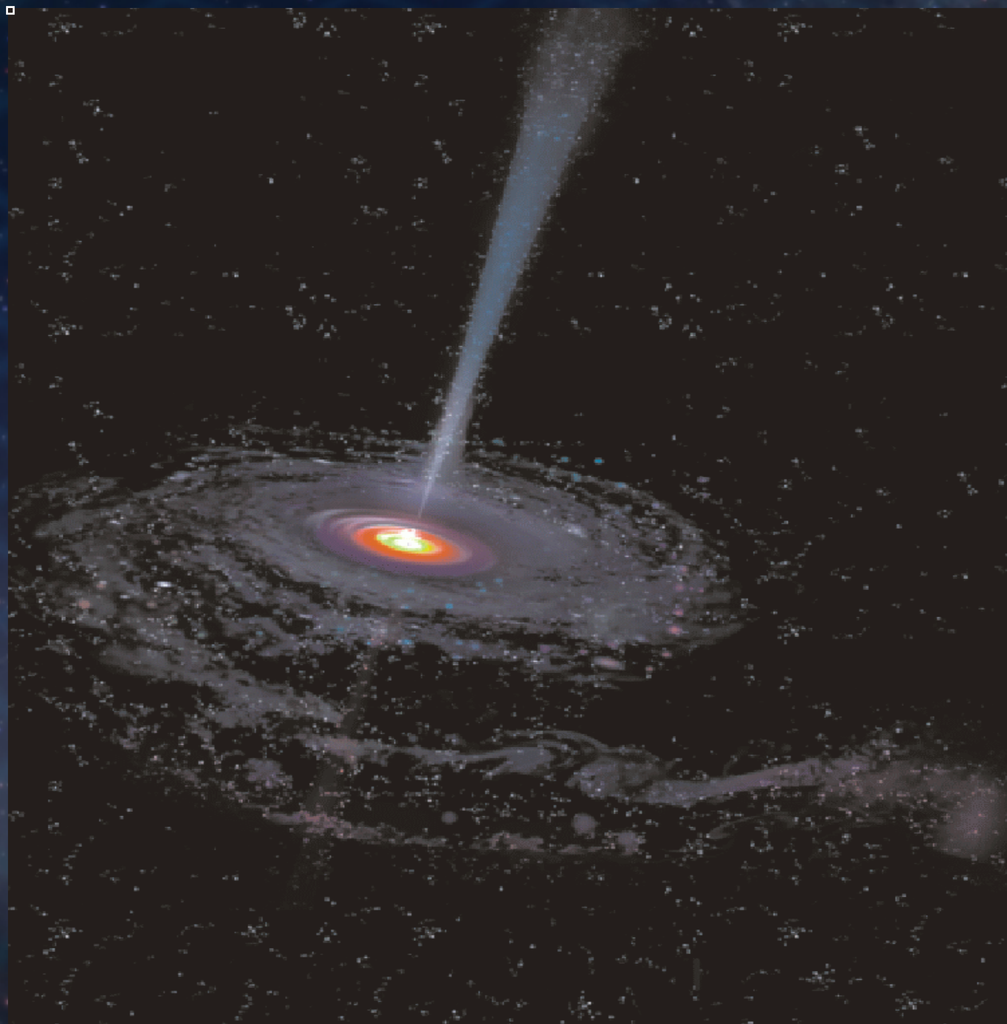
Spinning Stars and Gyroscopic Effect



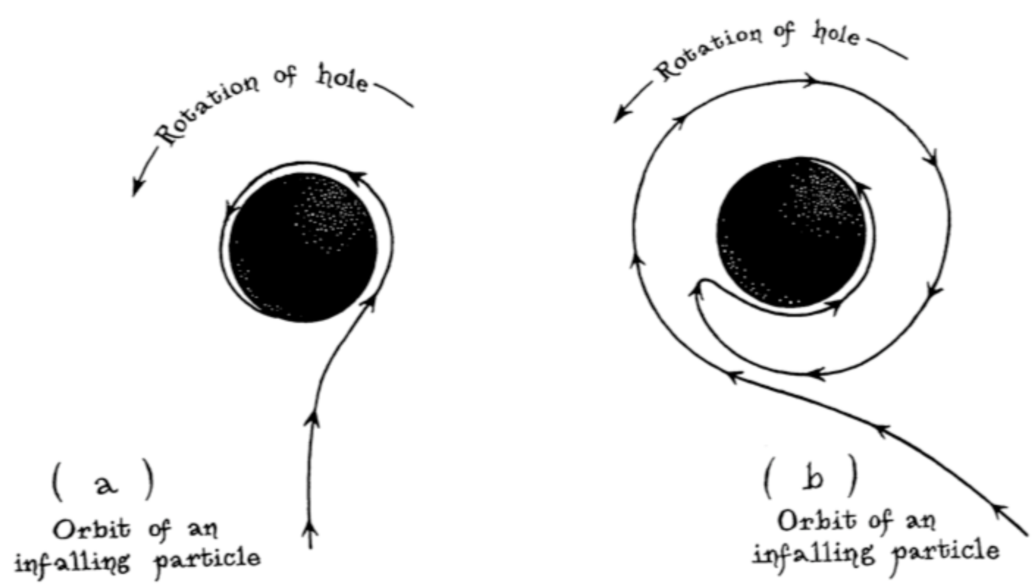
Spin Gives Preferred Axis for Jets



Disk-to-Hole Transfer of Angular Momentum



Trajectories Near Spinning Black Hole

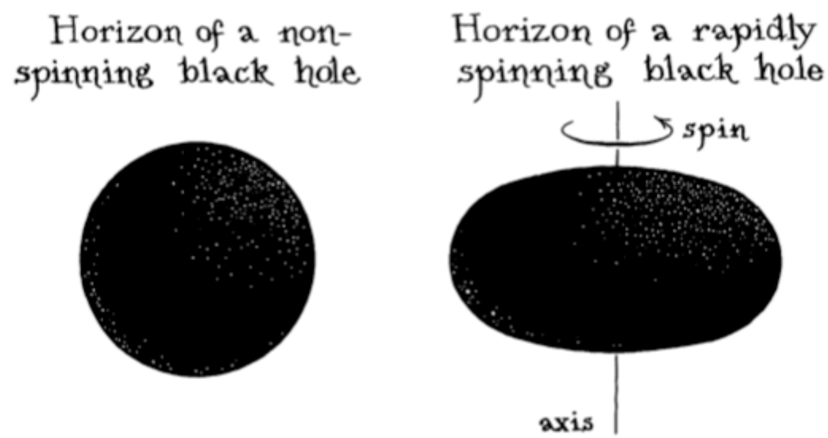


7.8 The trajectories in space of two particles that are thrown toward a black hole. (The trajectories are those that would be measured in a static, external reference frame.) Despite their very different initial motions, both particles are dragged, by the swirl of space, into precisely the same lockstep rotation with the hole as they near the horizon.

from Thorne book

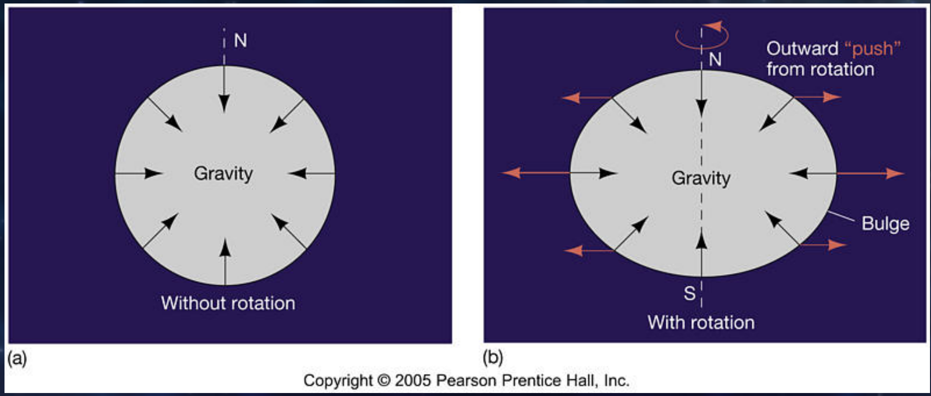
Horizon Shape of Spinning Black Hole

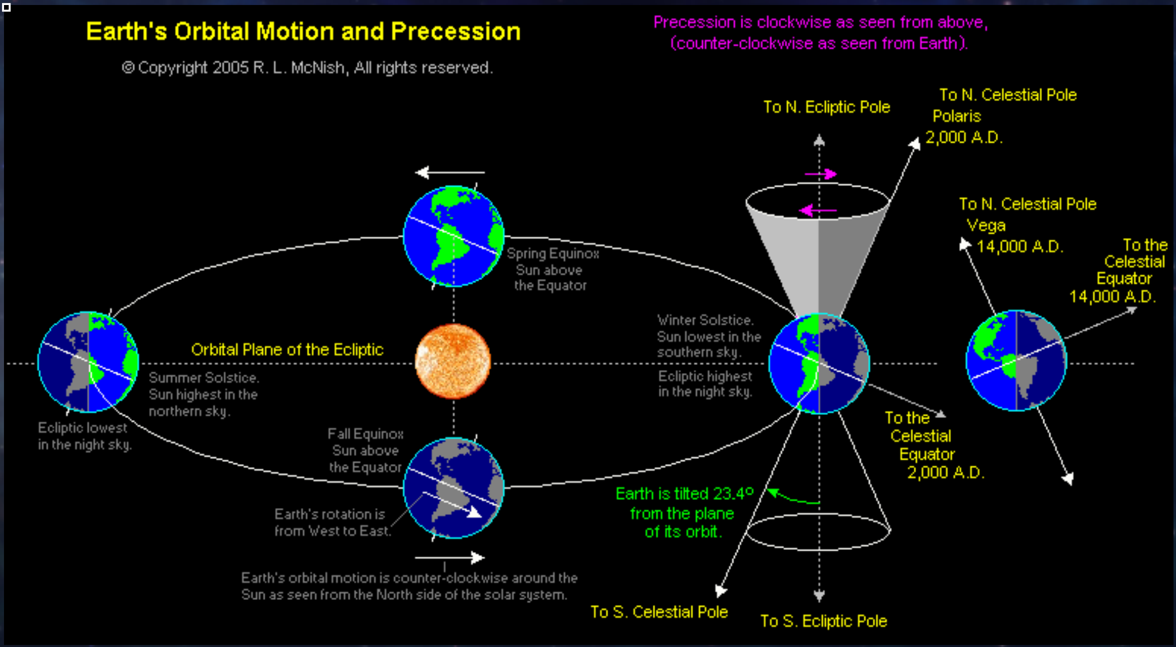
7.9 The shapes of the horizons of two black holes, one *(left)* not spinning, and the other *(right)* spinning with a spin rate 58 percent of the maximum. The effect of the spin on the horizon shape was discovered in 1973 by Larry Smarr, a student at Stanford University who was inspired by Wheeler.



from Thorne book

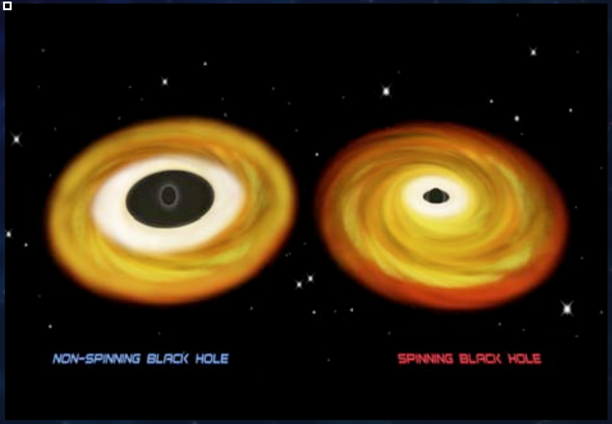
Equatorial Bulges of Planets



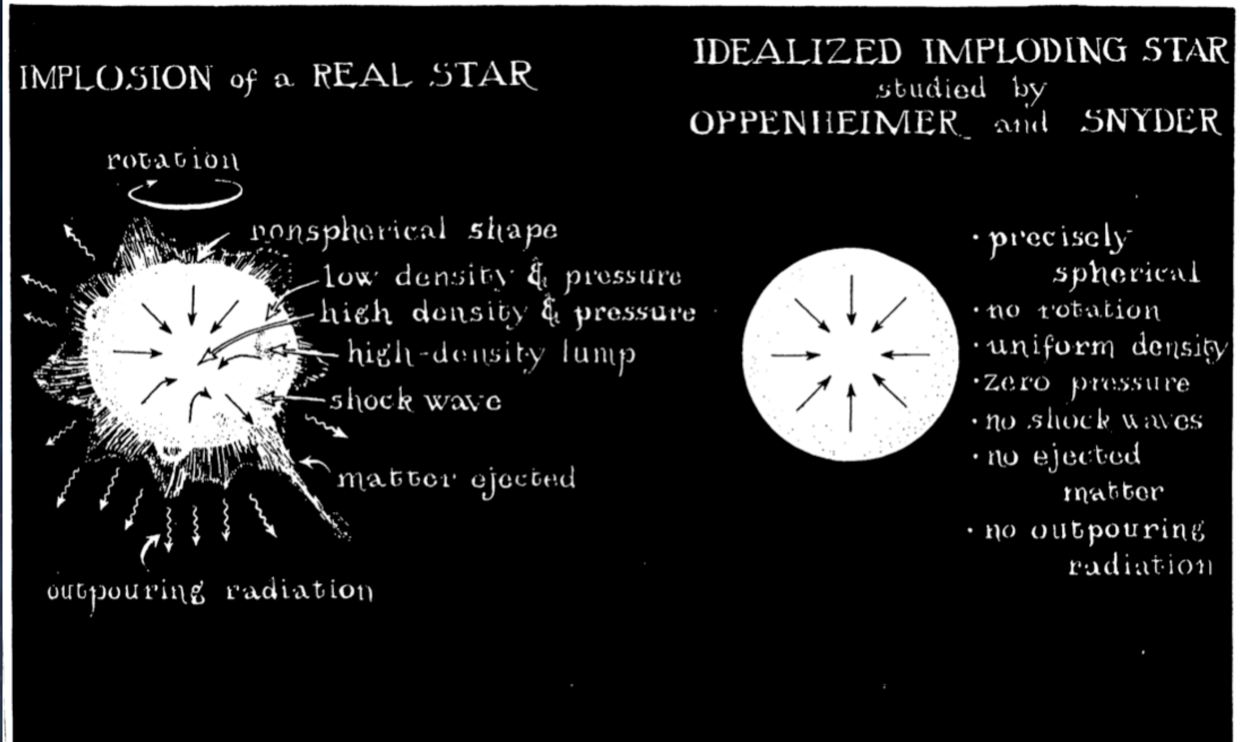


Spinning Black-Hole Accretion is Efficient

Chemical power (gasoline, coal, dynamite)	(1×10^{-6})% of mass can be turned to energy
Nuclear power	~1%
Black hole accretion (nonspinning)	~5%
Black hole accretion (spinning)	~ up to 29%



Implosion of Real vs. Idealized Stars



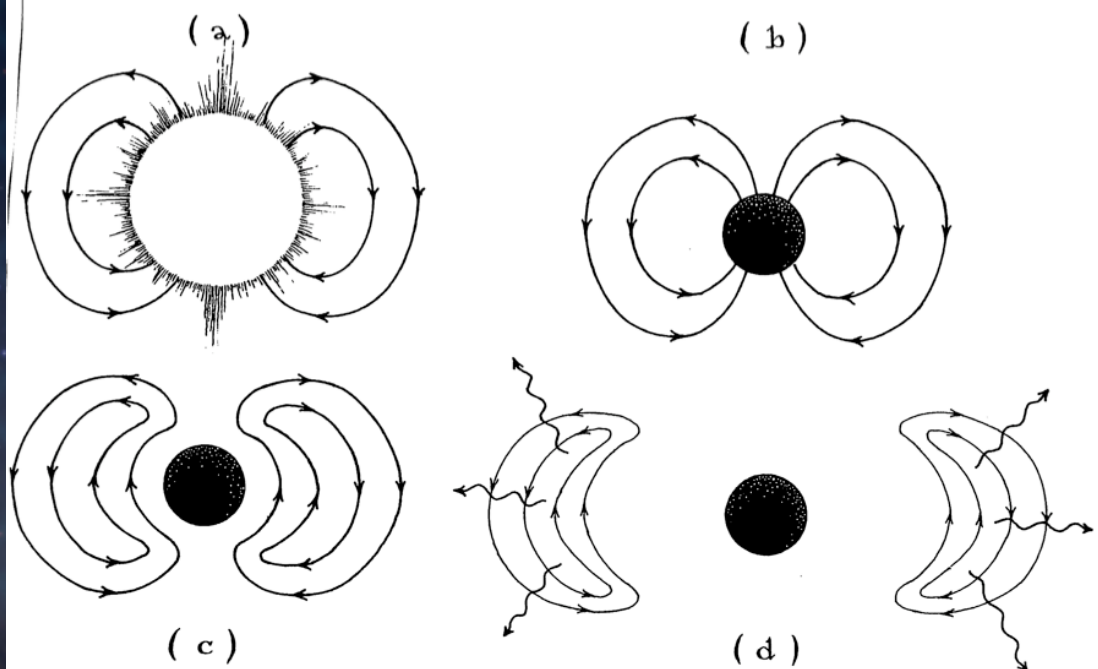
6.3 *Left:* Physical phenomena in a realistic, imploding star. *Right:* The idealizations that Oppenheimer and Snyder made in order to compute stellar implosion.

from Thorne book

Stars Have Magnetic Fields

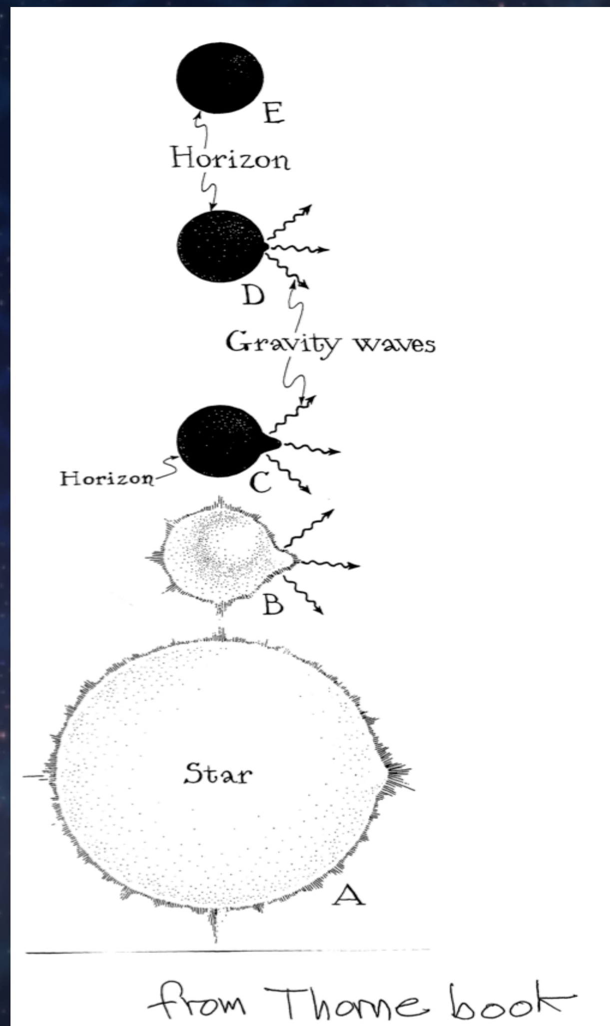
A Black Hole Radiating a Magnetic Field

7.5 A sequence of snapshots showing the implosion of a magnetized star (a) to form a black hole (b). The hole at first inherits the magnetic field from the star. However, the hole has no power to hold on to the field. The field slips off it (c), is converted into electromagnetic radiation, and flies away (d).



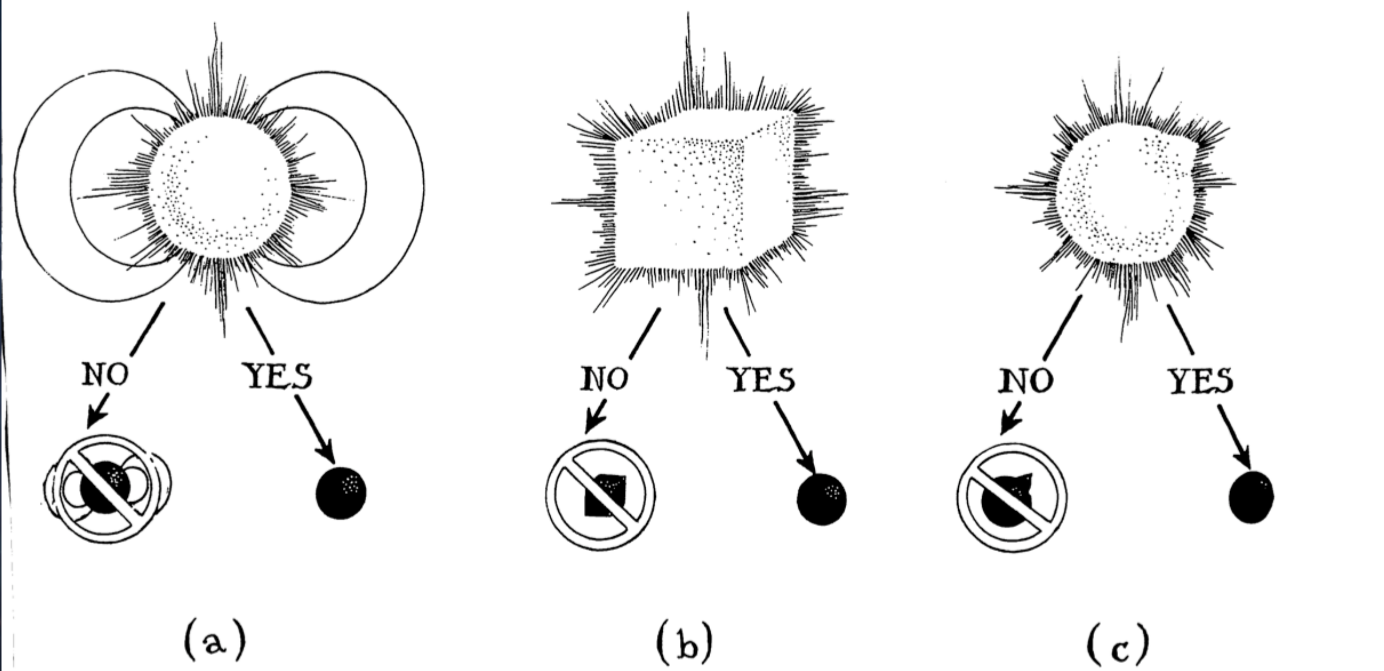
from Thorne book

A Black Hole Radiating a "Mountain"



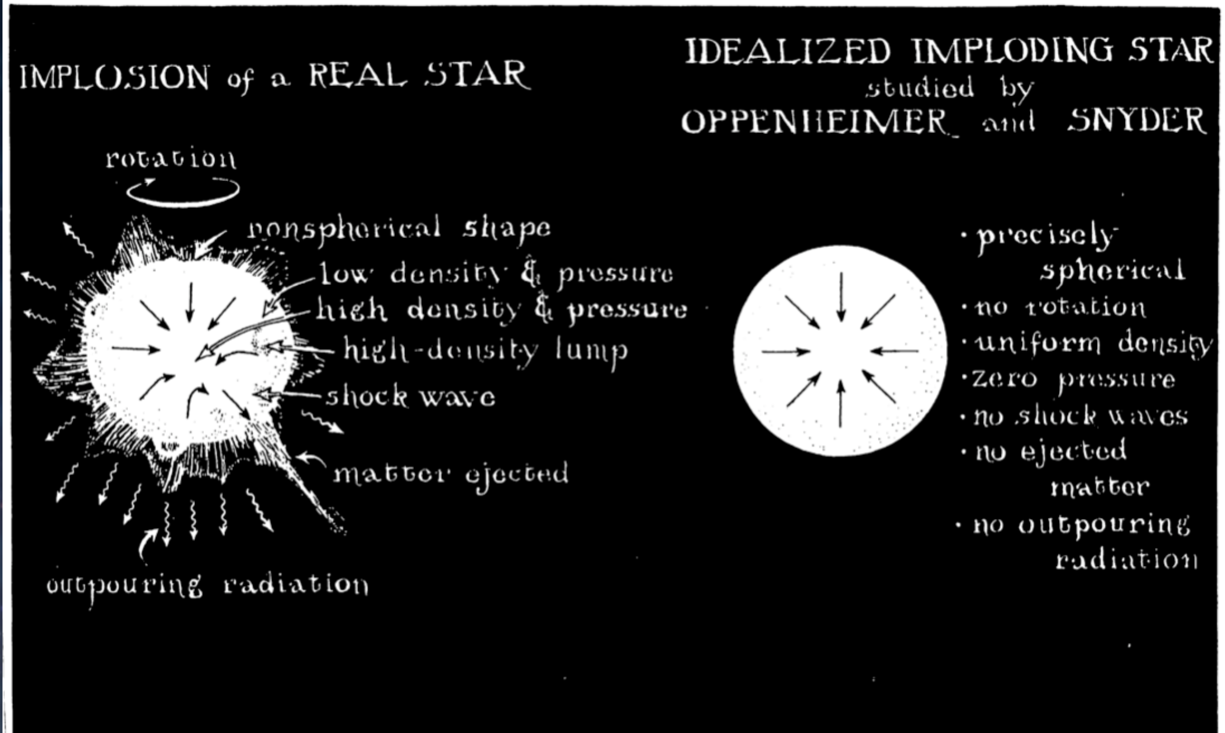
Black Holes Have No Hair

7.3 Some examples of the "no-hair conjecture": (a) When a magnetized star implodes, the hole it forms has no magnetic field. (b) When a square star implodes, the hole it forms is round, not square. (c) When a star with a mountain on its surface implodes, the hole it forms has no mountain.



from Thorne book

Validating the Oppenheimer-Snyder Study

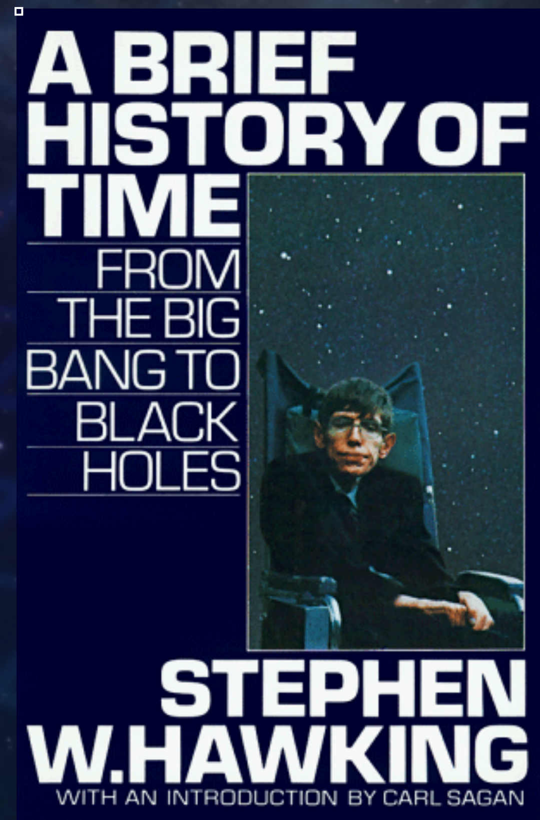


6.3 *Left:* Physical phenomena in a realistic, imploding star. *Right:* The idealizations that Oppenheimer and Snyder made in order to compute stellar implosion.

from Thorne book

Lecture 17:
Black-Hole Evaporation

Stephen Hawking



Thermal History of the Universe

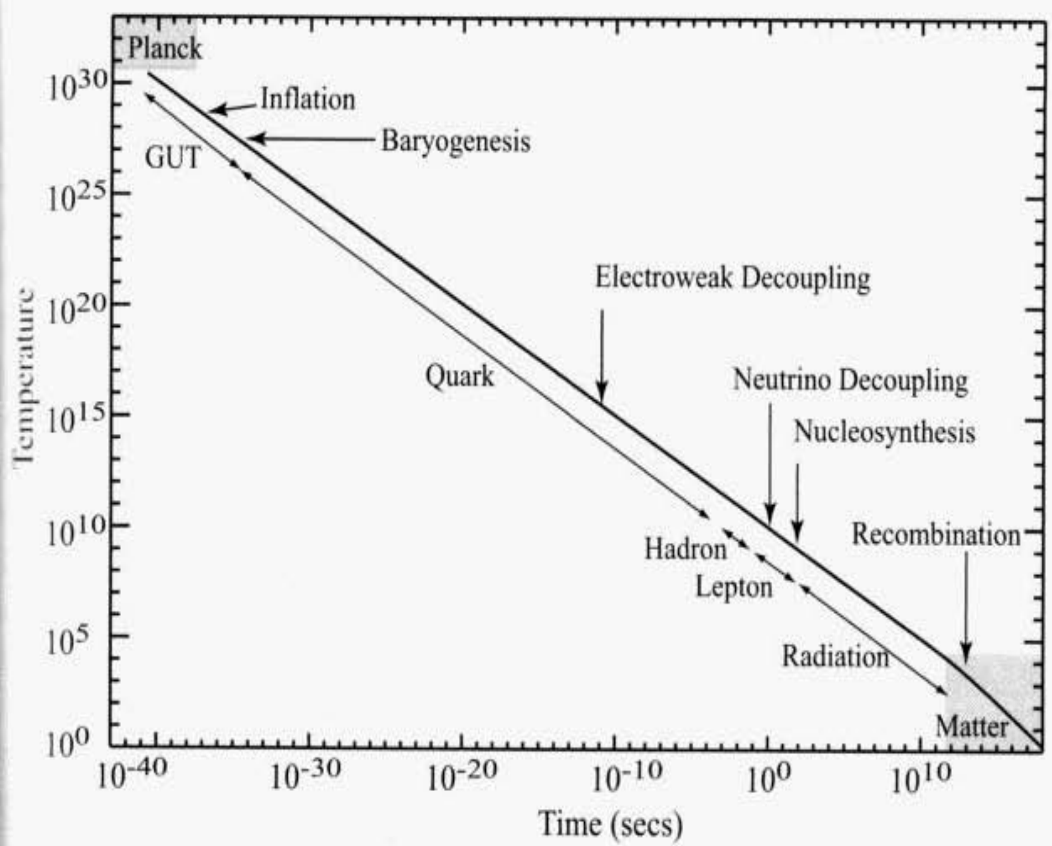
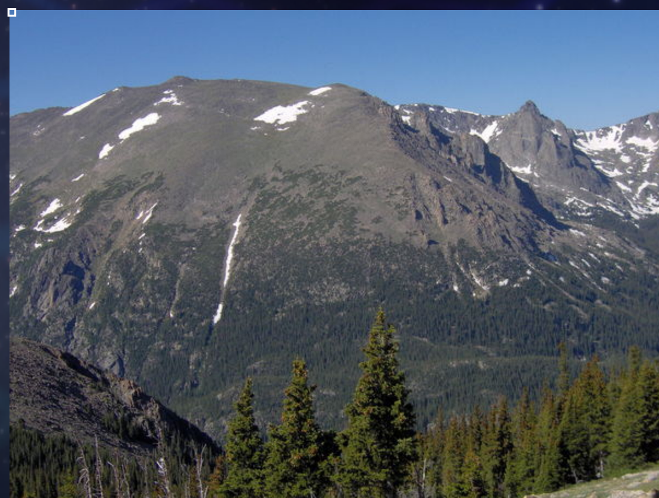


Fig. 12.9 Great moments in the history of the universe. Important events and epochs are shown along a line indicating radiation temperature versus time.

Possible Masses of Primordial Black Holes

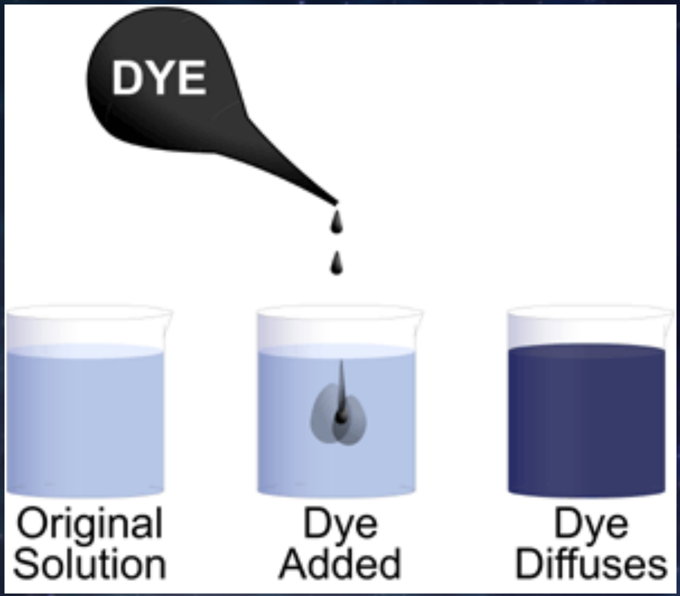


Second Law of Thermodynamics

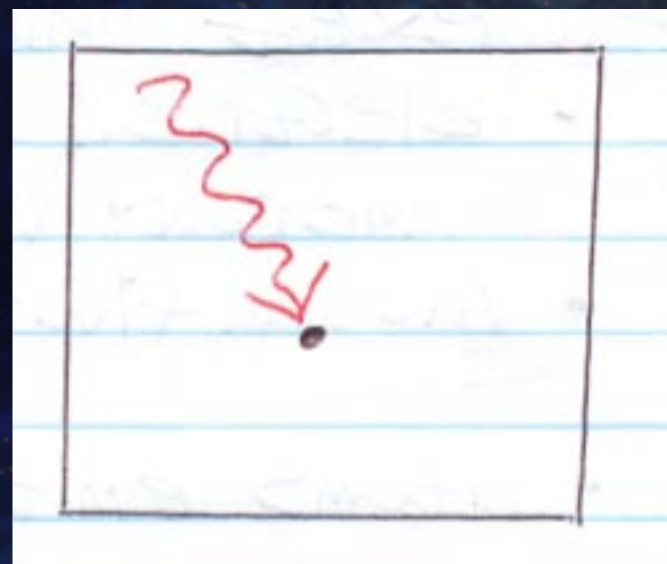
In any region of space, measure the total entropy of everything there. Then wait for as long as you like. Then measure the total entropy again. It will have increased.

Entropy

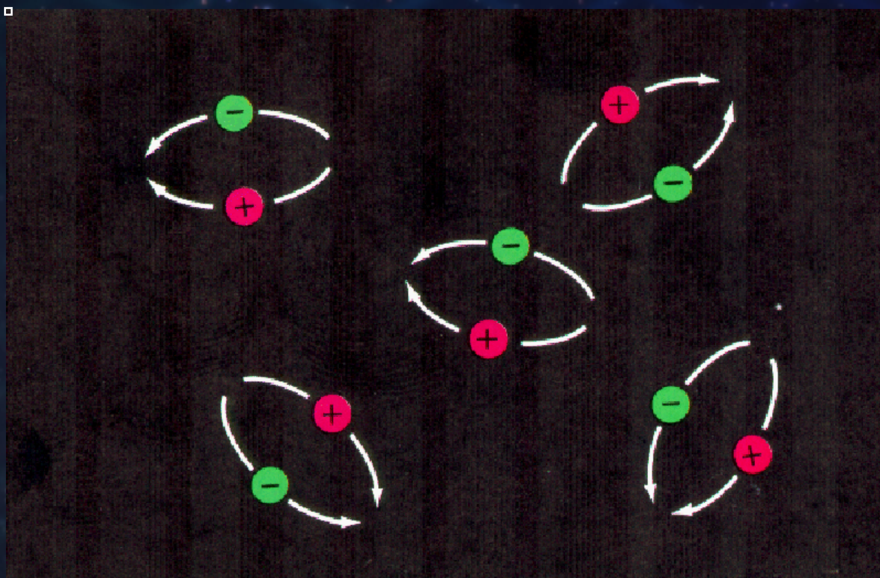
Examples of Entropy Increase

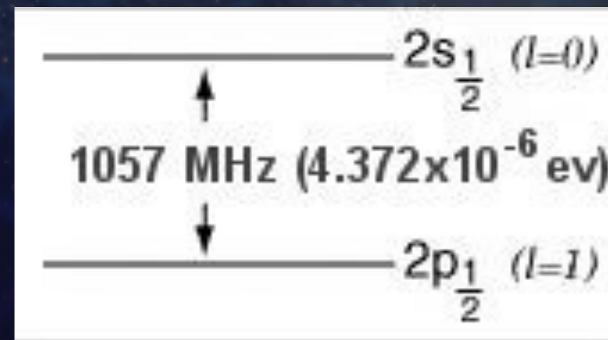


Intrinsic Uncertainty of Nature



Virtual Particles





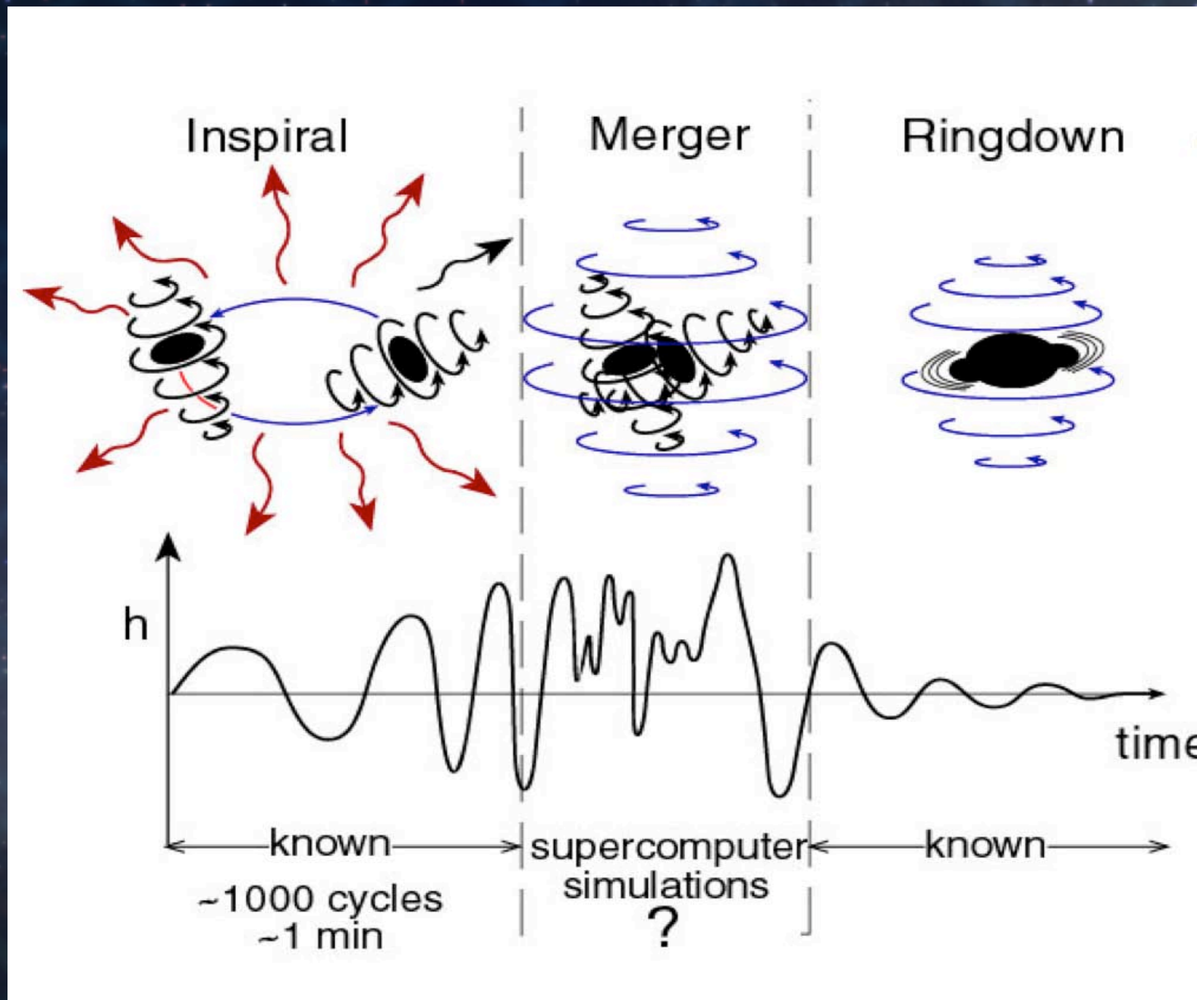
Avoiding a Bounced Check

Second Law of Black-Hole Mechanics

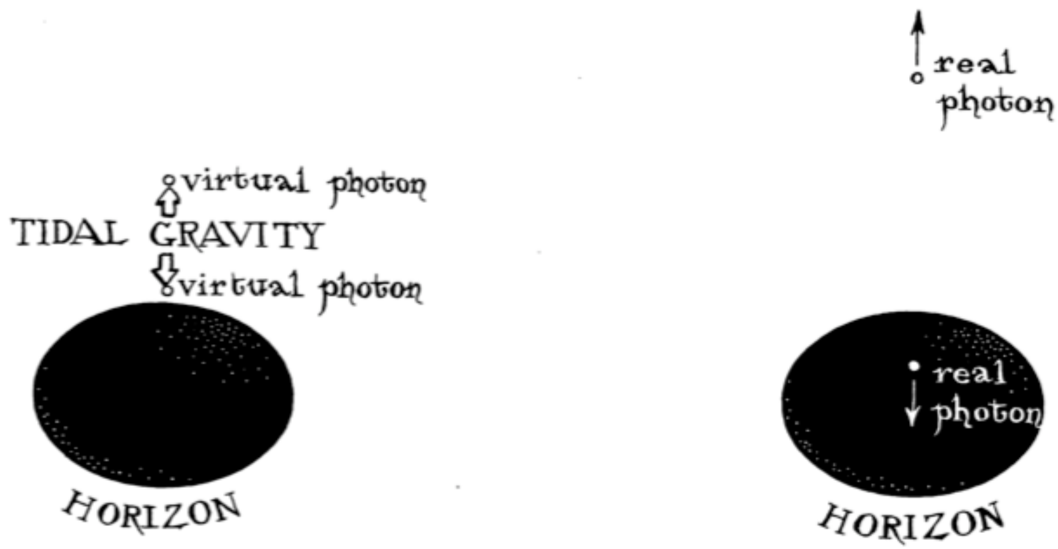
In any region of space, measure the total entropy of everything there. Then wait for as long as you like. Then measure the total entropy again. It will have increased.

In any region of space, measure the total surface area of all the black holes there. Then wait as long as you like. Then measure the total surface area again. It will have increased.

Black-Hole Merger – Surface Area Increases



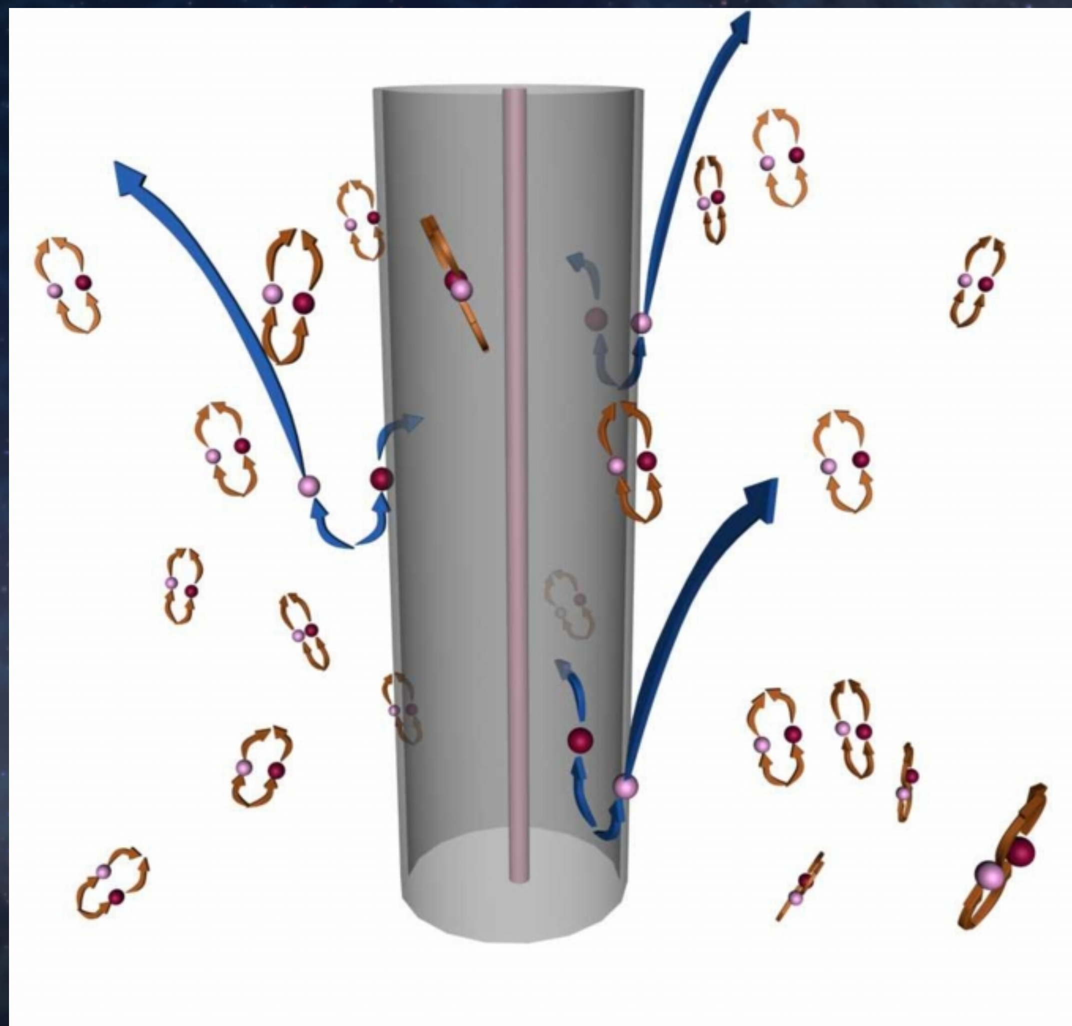
Could Black Holes Radiate?



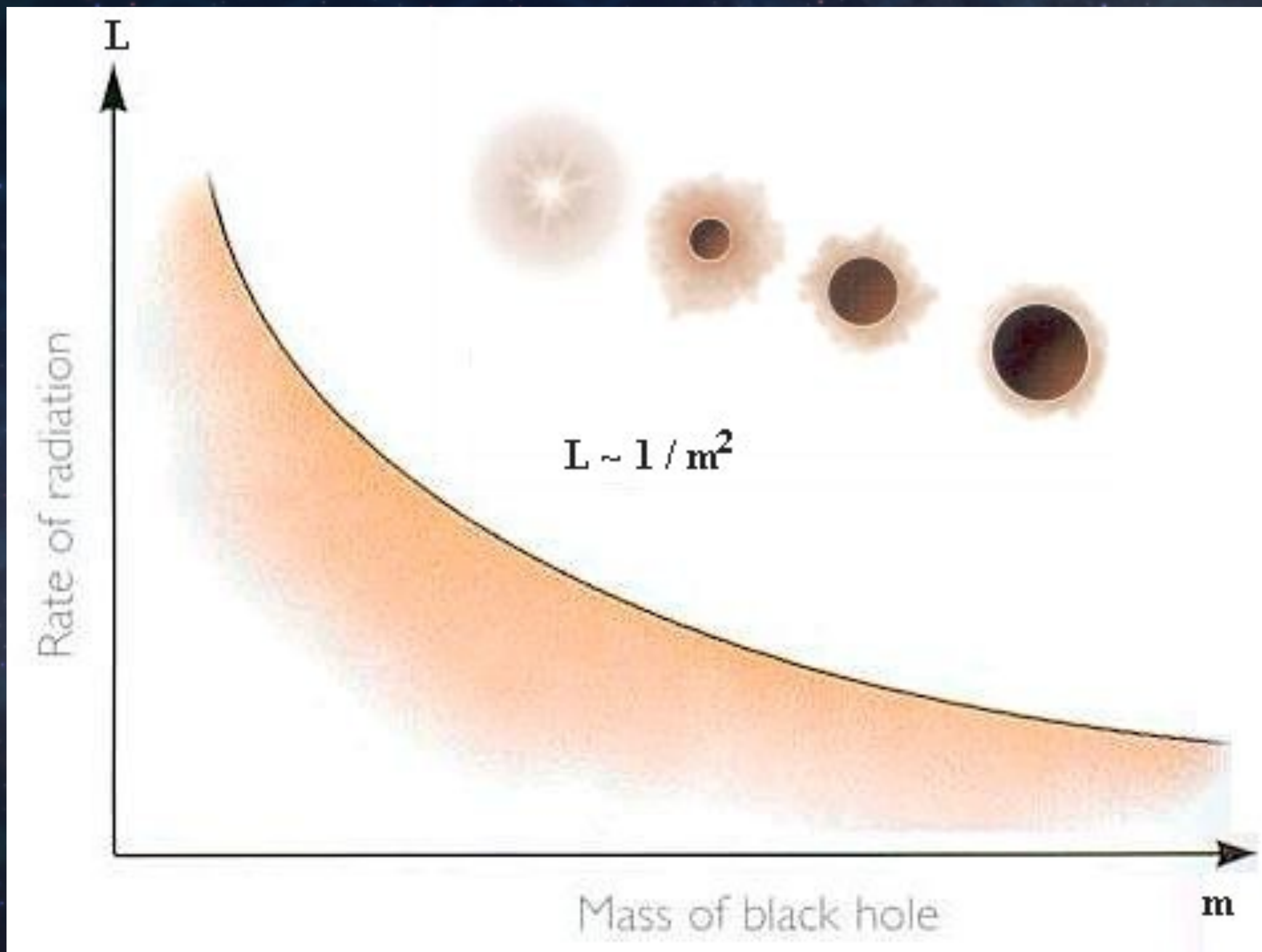
12.2 The mechanism of black-hole evaporation, as viewed by someone who is falling into the hole. *Left:* A black hole's tidal gravity pulls a pair of virtual photons apart, thereby feeding energy into them. *Right:* The virtual photons have acquired enough energy from tidal gravity to materialize, permanently, into real photons, one of which escapes from the hole while the other falls toward the hole's center.

From Thorne book

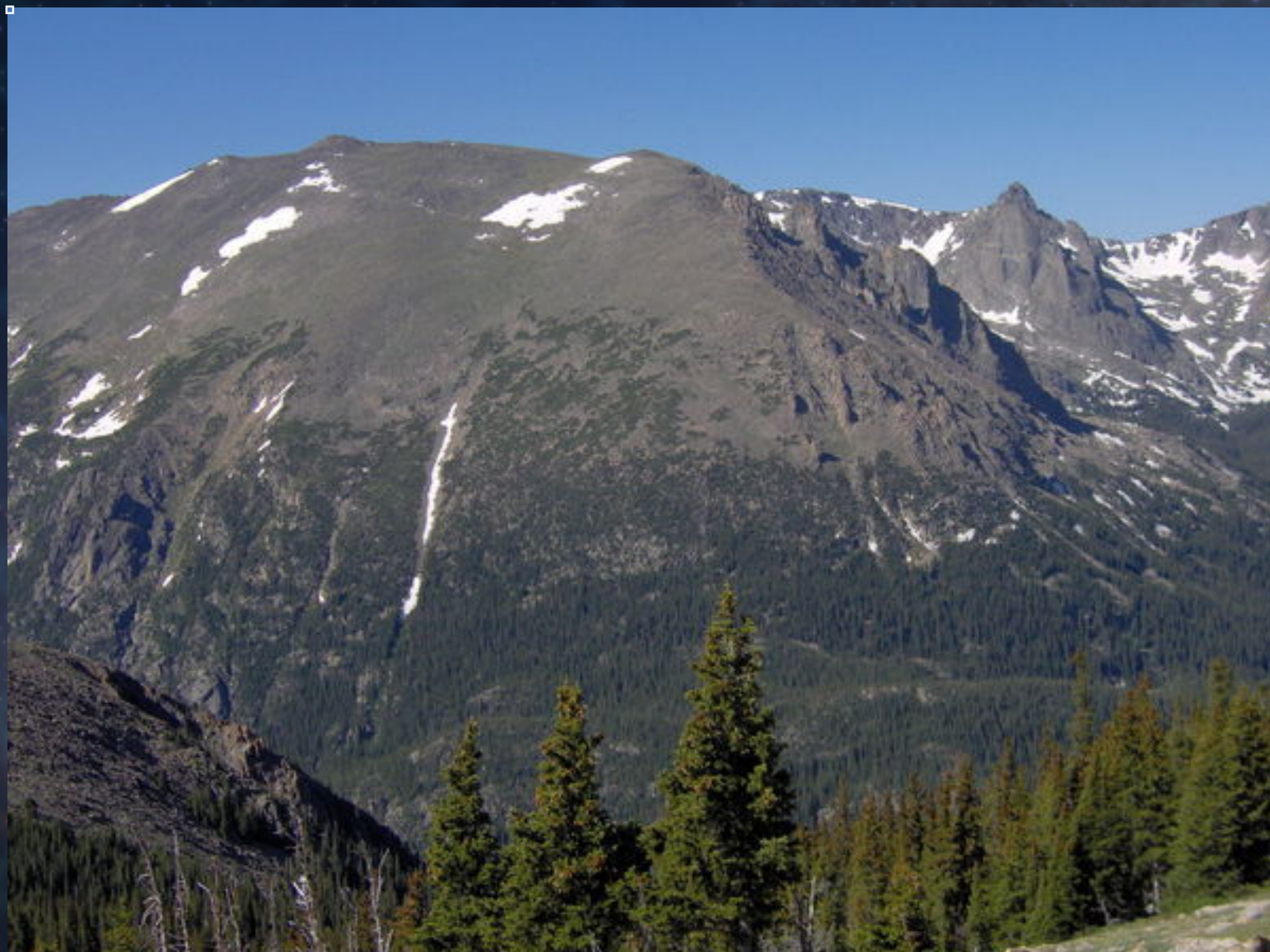
Could Black Holes Radiate?



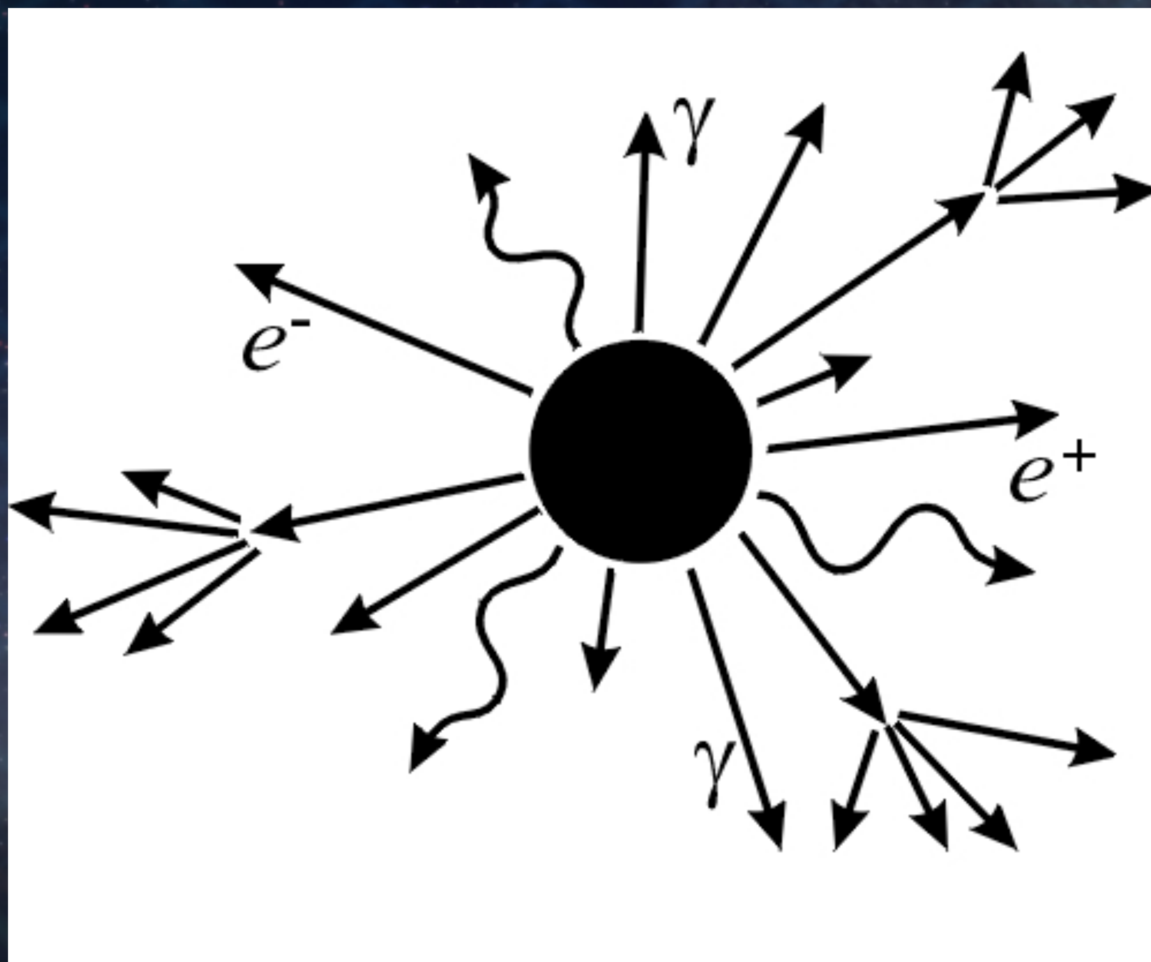
Radiation Rate Depends Upon Mass



Primordial Black Holes Evaporating Today?



Final Moments of an Evaporating Black Hole



Searches for Evaporating Black Holes

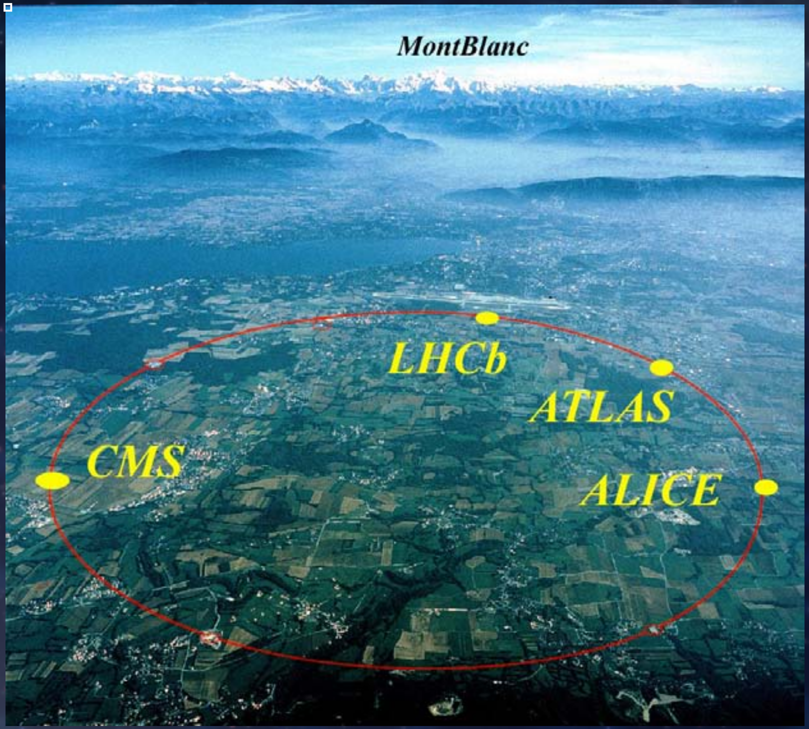
REVIEW ARTICLE

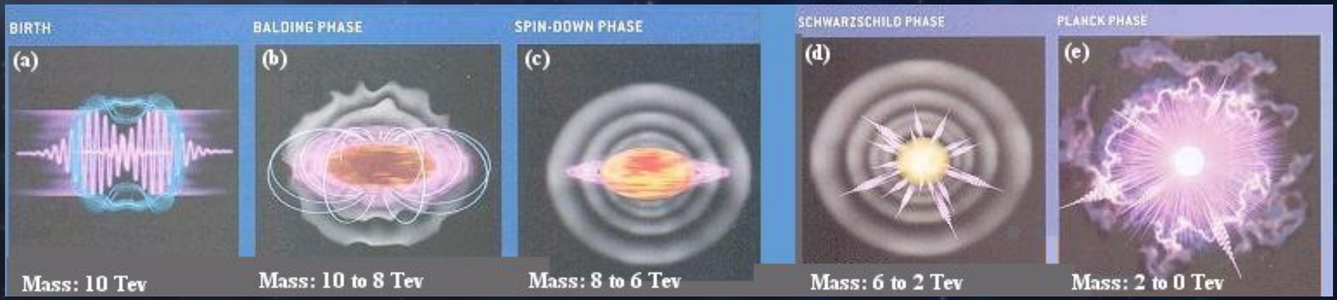
Gamma rays and energetic particles from primordial black holes

F. Halzen, E. Zas, J. H. MacGibbon & T. C. Weekes

Black holes of almost arbitrarily small mass may have formed in the very early Universe. Their presence today would be revealed by the energetic radiation they would produce by means of the quantum-gravitational Hawking mechanism, allowing observational limits to be set on their density today and on their past significance.

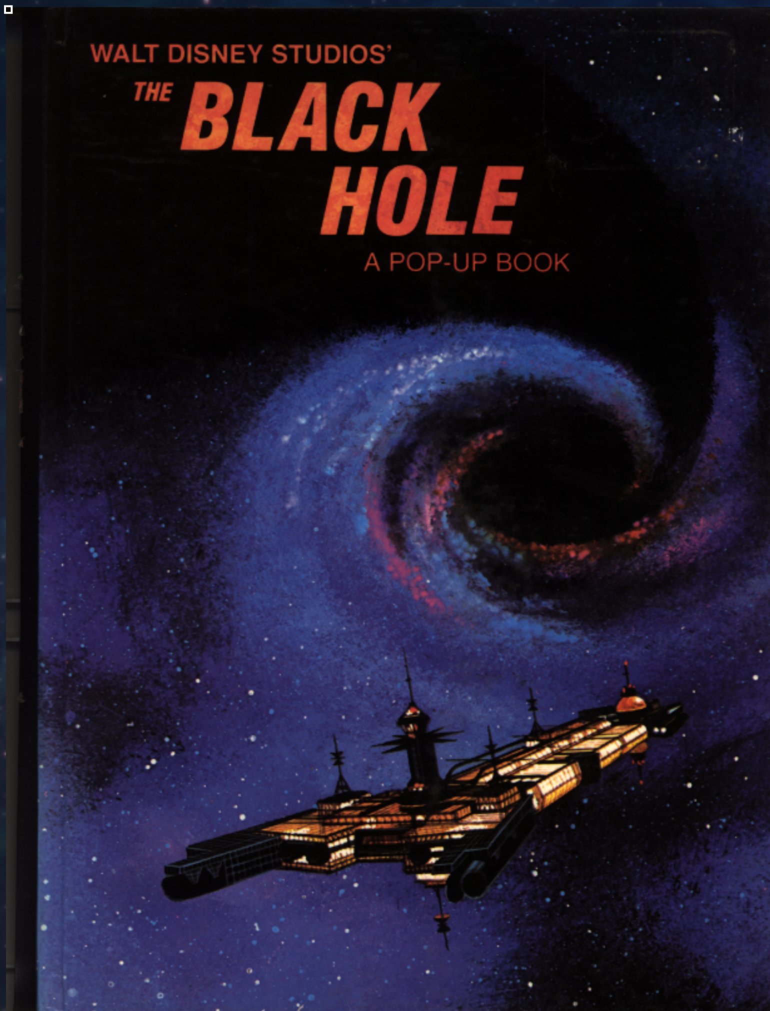
Black Holes from Particle Accelerators?

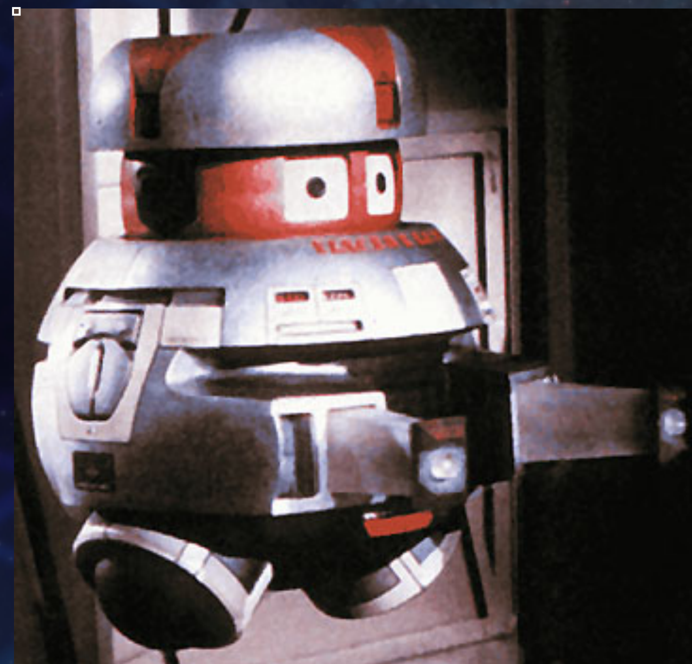




Lecture 18:
Singularities – Inside Black Holes

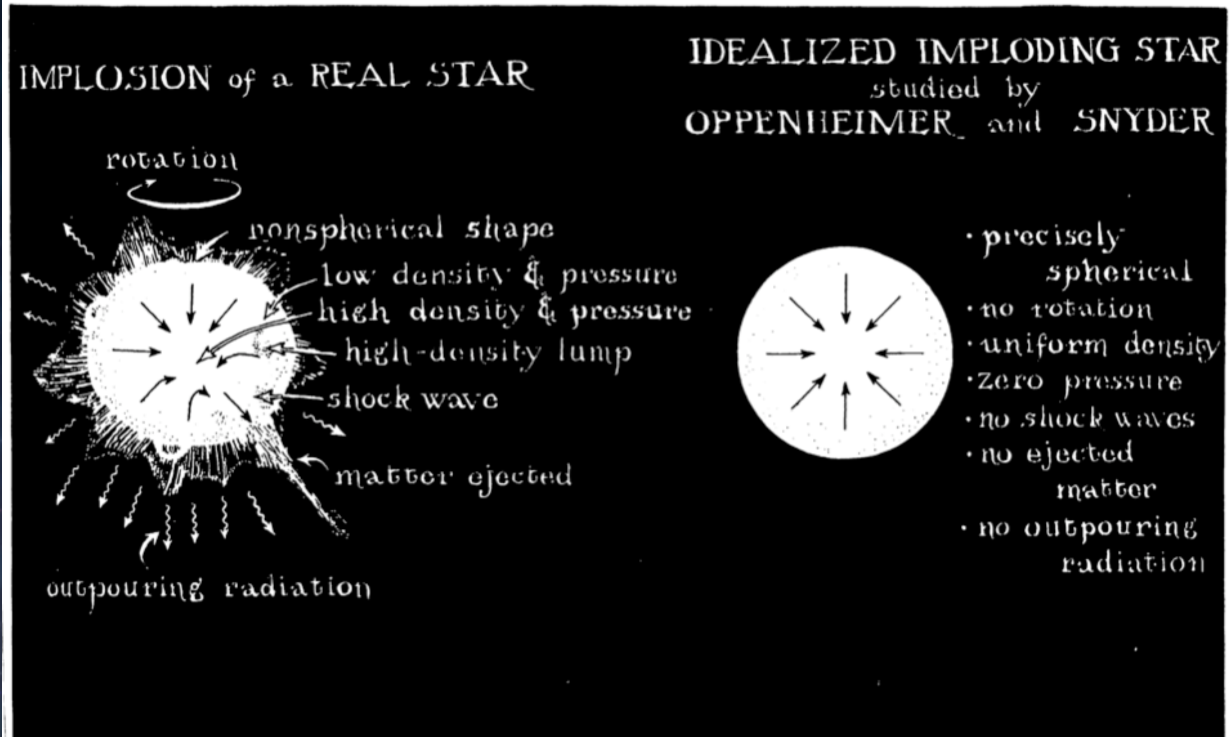
What's Inside a Black Hole?





Singularity Hazard Sign

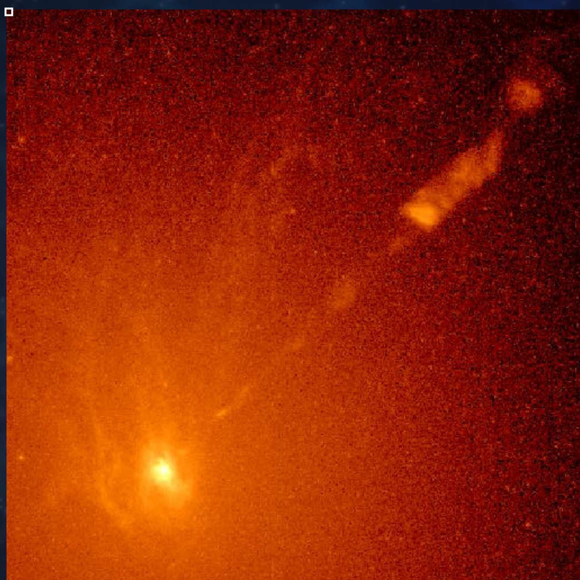
Oppenheimer-Snyder Collapse Calculation



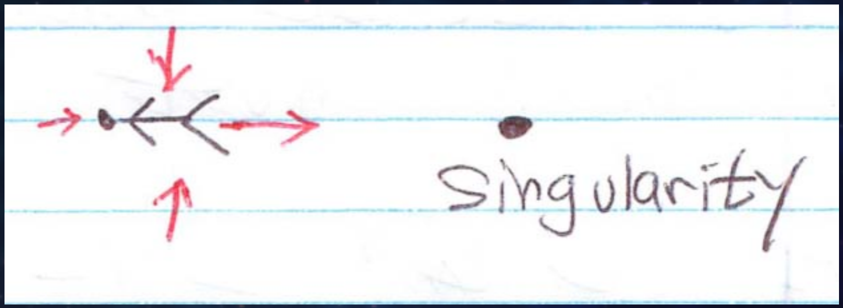
6.3 *Left:* Physical phenomena in a realistic, imploding star. *Right:* The idealizations that Oppenheimer and Snyder made in order to compute stellar implosion.

from Thorne book

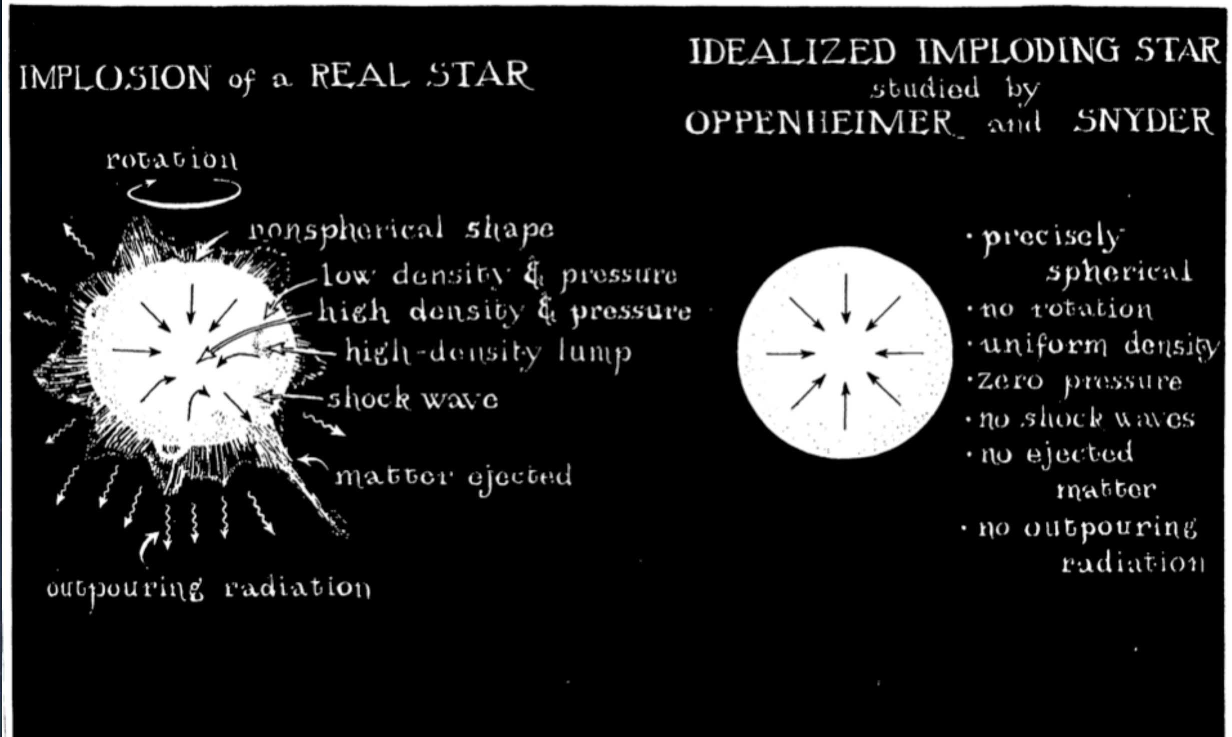
M87 and Sombrero - Very Massive Black Holes



Spaghettification



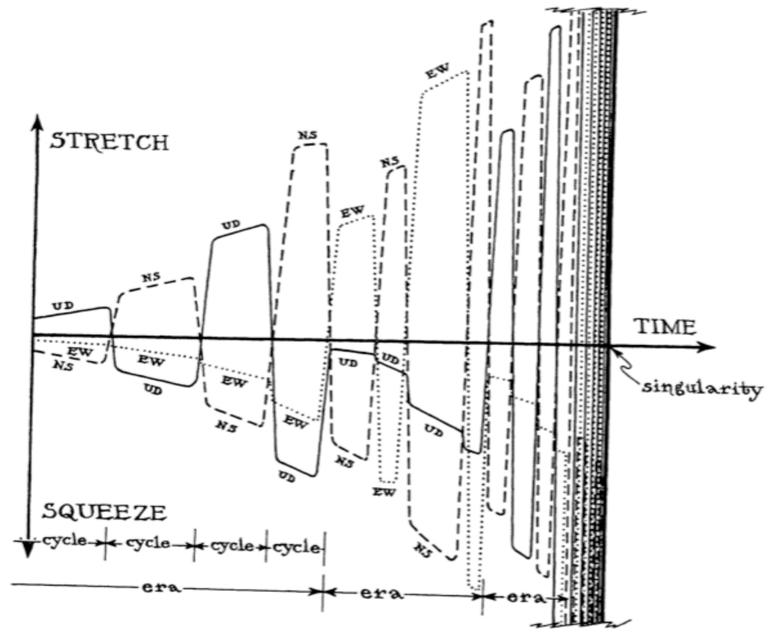
Oppenheimer-Snyder Collapse Calculation



6.3 *Left:* Physical phenomena in a realistic, imploding star. *Right:* The idealizations that Oppenheimer and Snyder made in order to compute stellar implosion.

from Thorne book

Tidal Forces Near BKL Singularity

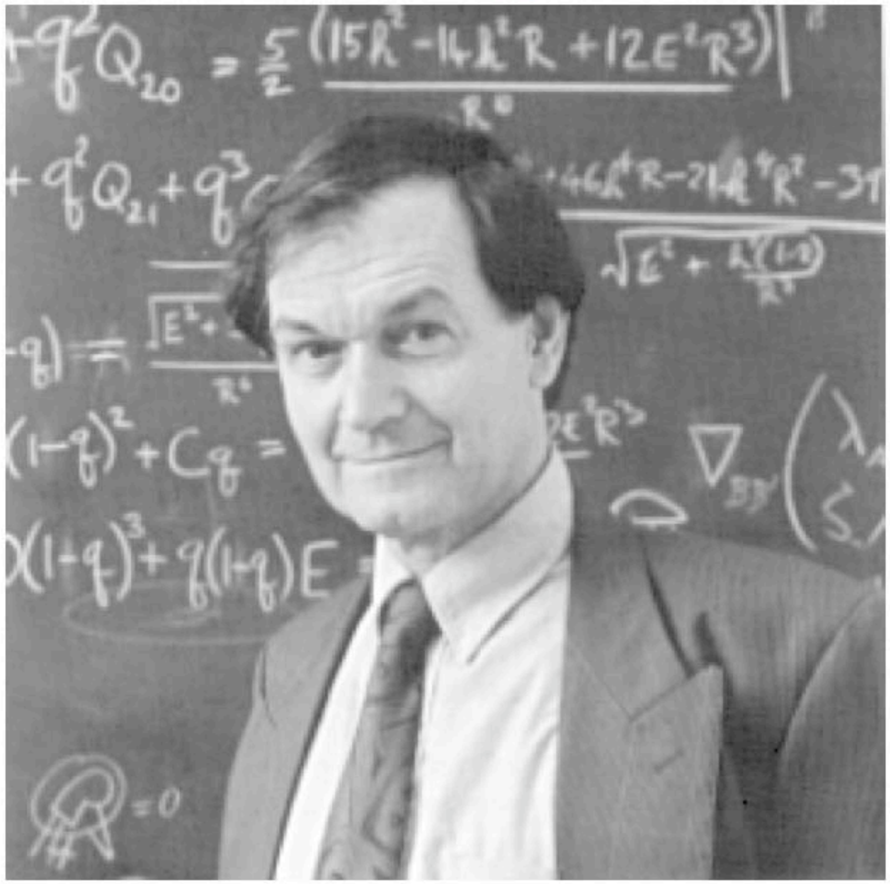


13.6 An example of how the tidal forces might oscillate with time in a BKL singularity. The tidal forces act in different manners along three different, perpendicular directions. These directions, for definiteness, are here called UD (for "up/down"), NS (for "north/south"), and EW (for "east/west"), and each of the three curves describes the behavior of the tidal force along one of these directions. Time is plotted horizontally. At any time when the UD curve is *above* the horizontal time axis, the tidal force is *stretching* along the UD direction, while at a time when the UD curve is *below* the axis, the UD tidal force is *squeezing*. The higher the curve above the axis, the stronger the stretch; the lower the curve below the axis, the stronger the squeeze. Notice the following: (i) At any moment of time there is a squeeze along two directions and a stretch along one. (ii) The tidal forces oscillate between stretch and squeeze; each oscillation is called a "cycle." (iii) The cycles are collected into "eras." During each era, one of the three directions is subjected to a fairly steady squeeze, while the other two oscillate between stretch and squeeze. (iv) When the era changes, there is a change of the steady direction. (v) As the singularity is approached, the oscillations become infinitely rapid and the tidal forces become infinitely strong. The details of the division of cycles into eras and the change of oscillation patterns at the beginning of each era are governed by what is sometimes called a "chaotic map."

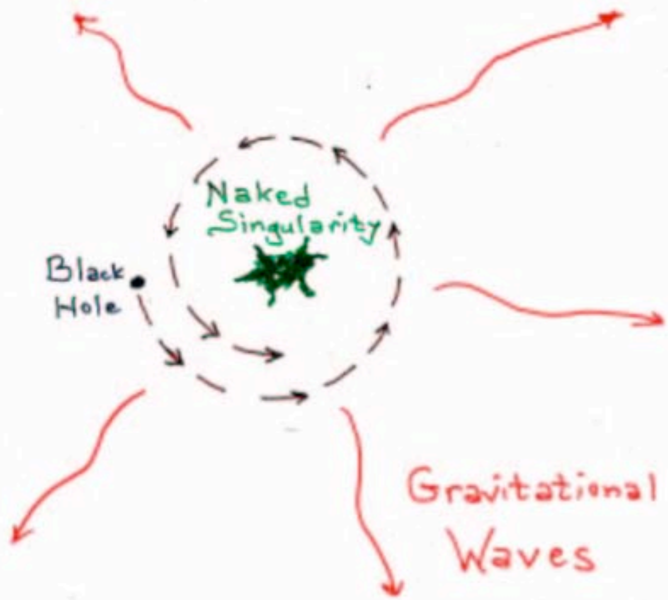
from Thorne book

Roger Penrose – Horizon Implies Singularity

Collapsing stars that make horizons must also make singularities.



Naked Singularities?



Whereas Stephen W. Hawking firmly believes that naked singularities are an anathema and should be prohibited by the laws of classical physics,

And whereas John Preskill and Kip Thorne regard naked singularities as quantum gravitational objects that might exist unclothed by horizons, for all the Universe to see,

Therefore Hawking offers, and Preskill/Thorne accept, a wager with odds of 100 pounds stirling to 50 pounds stirling, that when any form of classical matter or field that is incapable of becoming singular in flat spacetime is coupled to general relativity via the classical Einstein equations, the result can never be a naked singularity.

The loser will reward the winner with clothing to cover the winner's nakedness. The clothing is to be embroidered with a suitable concessionary message.

Stephen W. Hawking   John P. Preskill & Kip S. Thorne

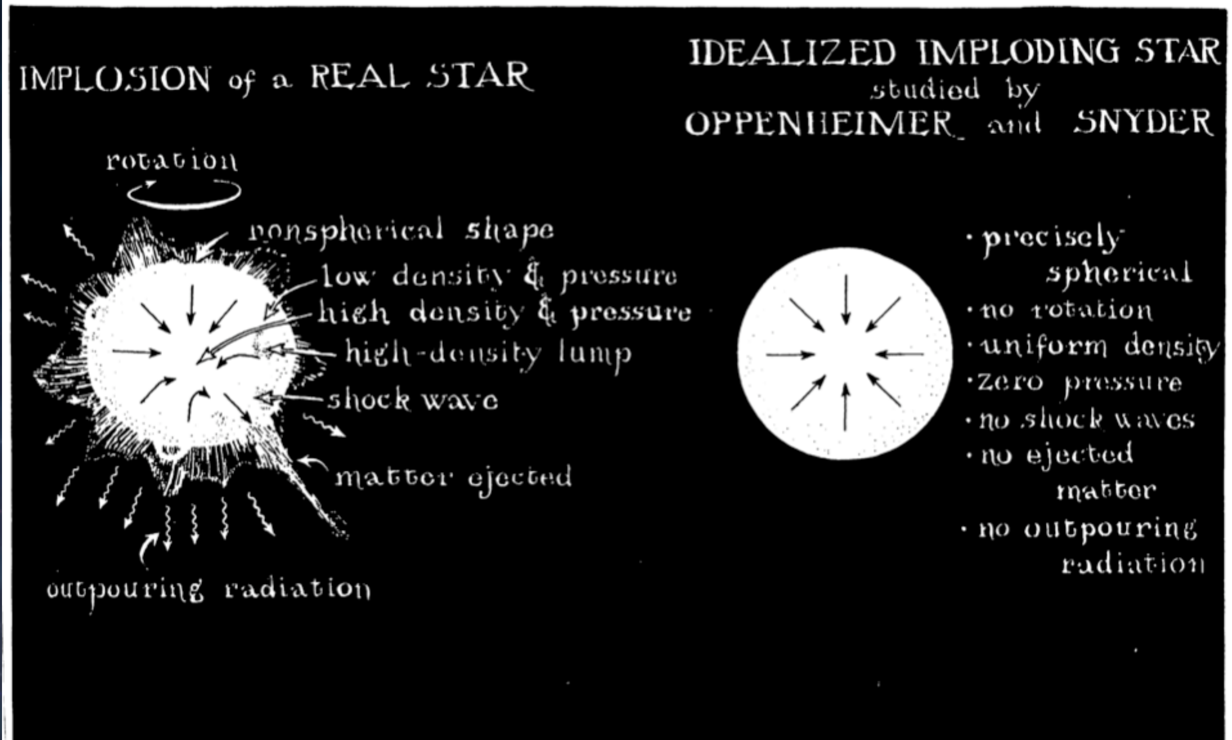
Pasadena, California, 24 September 1991

Hawking has conceded!

Lecture 19:

Black Holes and Child Universes

Oppenheimer-Snyder Collapse Calculation

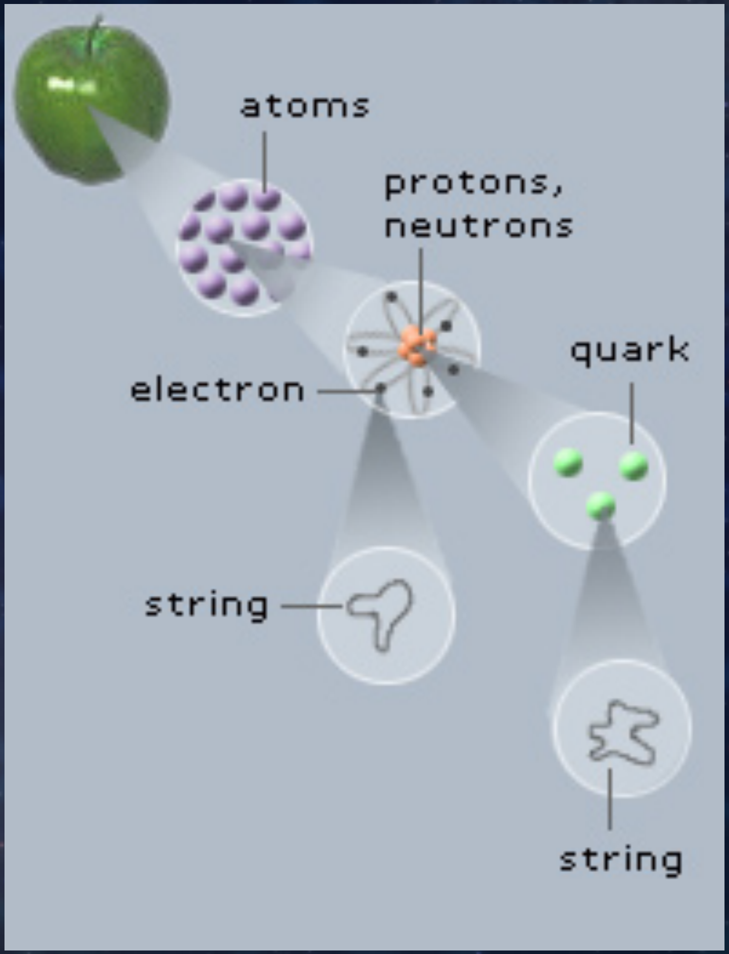


6.3 *Left:* Physical phenomena in a realistic, imploding star. *Right:* The idealizations that Oppenheimer and Snyder made in order to compute stellar implosion.

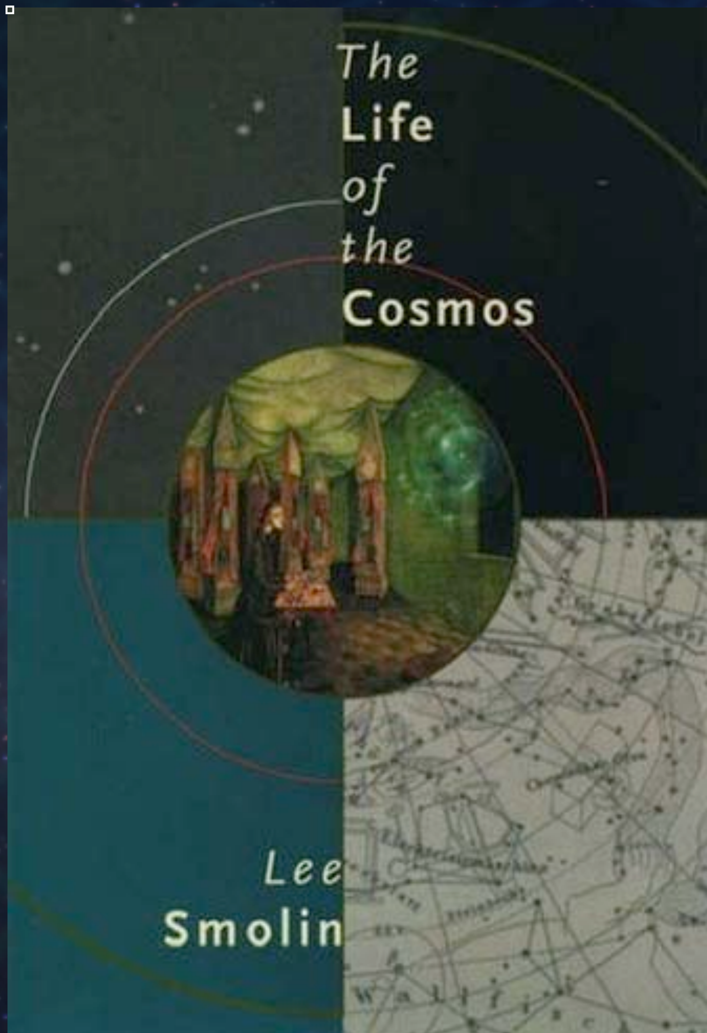
from Thorne book

Singularity Hazard Sign

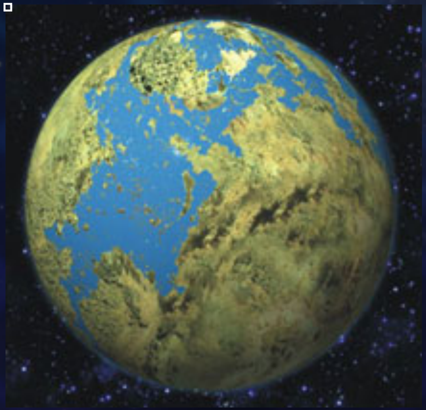
No Proper Theory of Quantum Gravity

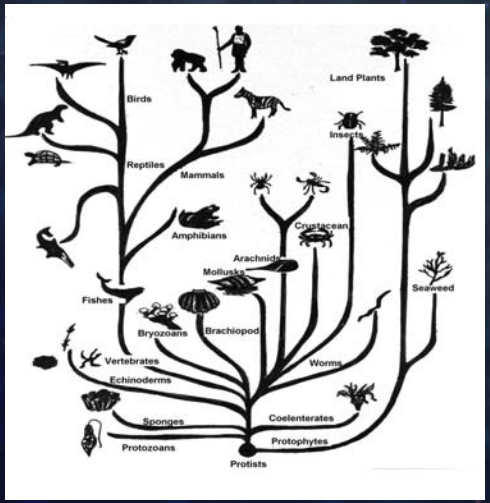


Black Holes and Child Universes?



Contents of a Child Universe





Singularities as Both Beginning and End

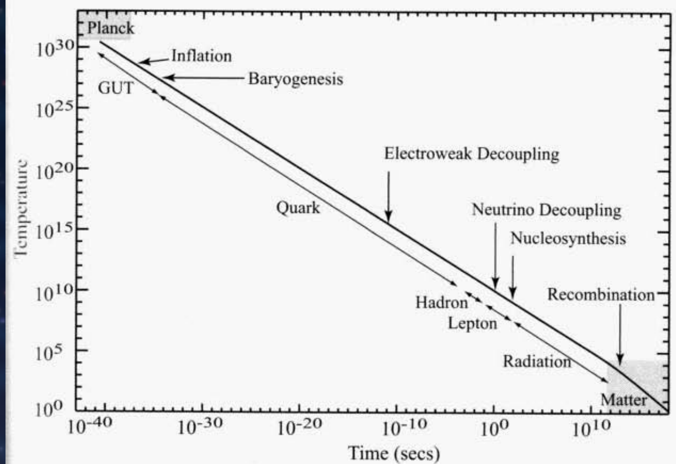
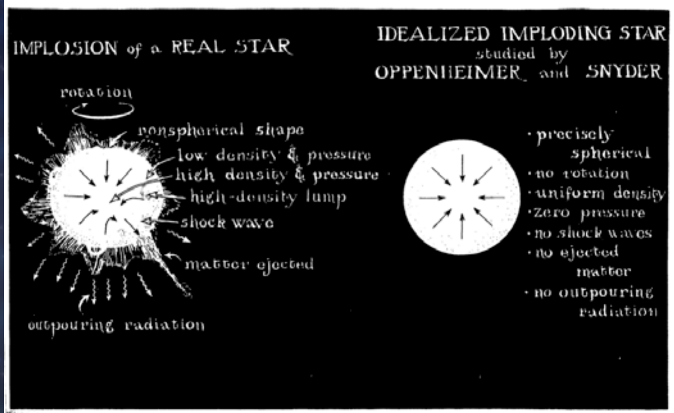


Fig. 12.9 Great moments in the history of the universe. Important events and epochs are shown along a line indicating radiation temperature versus time.

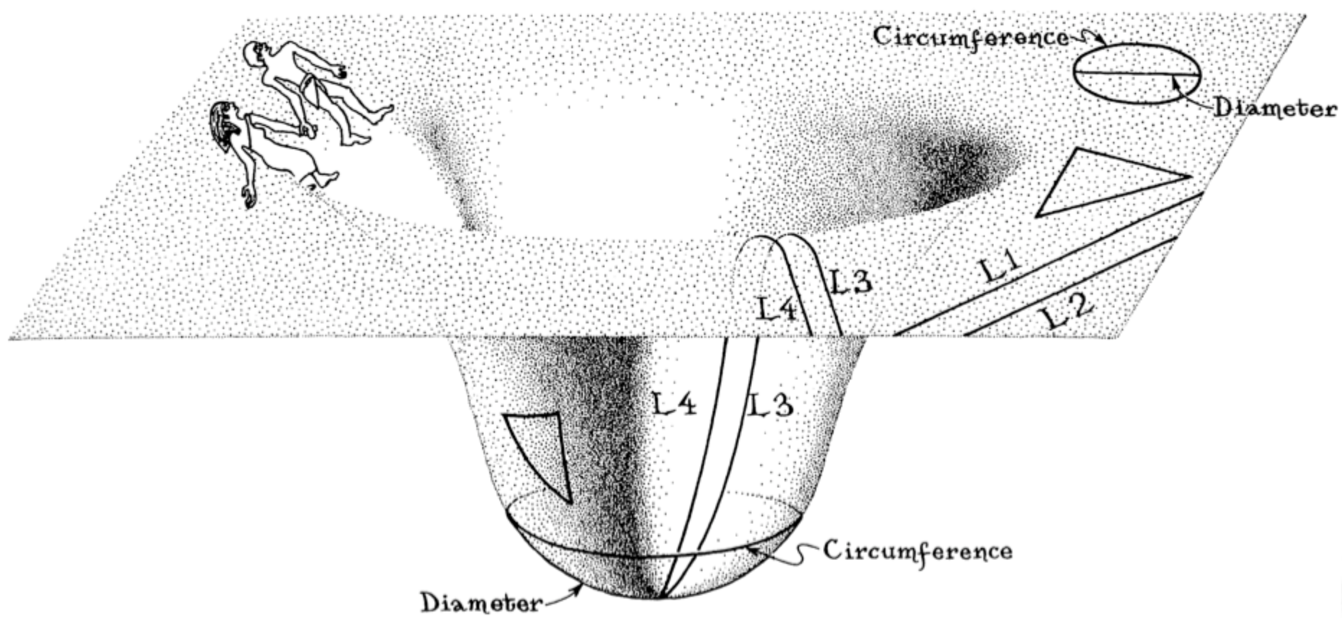


6.3 *Left:* Physical phenomena in a realistic, imploding star. *Right:* The idealizations that Oppenheimer and Snyder made in order to compute stellar implosion.

from Thorne book

A Two-Dimensional Universe

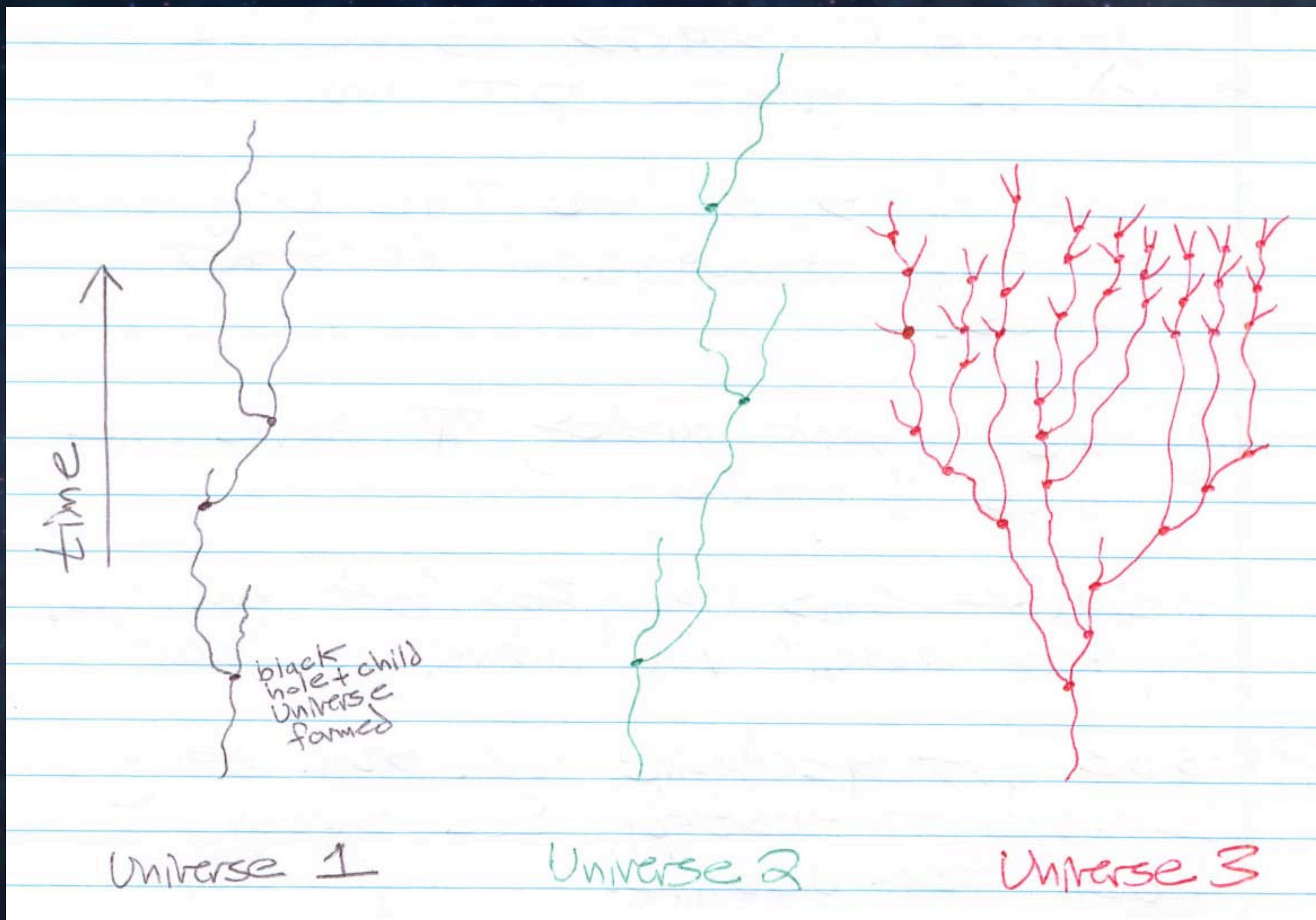
3.2 A two-dimensional universe peopled by 2D beings.



from Thorne book

Many Black Holes in Our Universe

"Natural Selection" of Universes?



Fundamental Constants of Nature

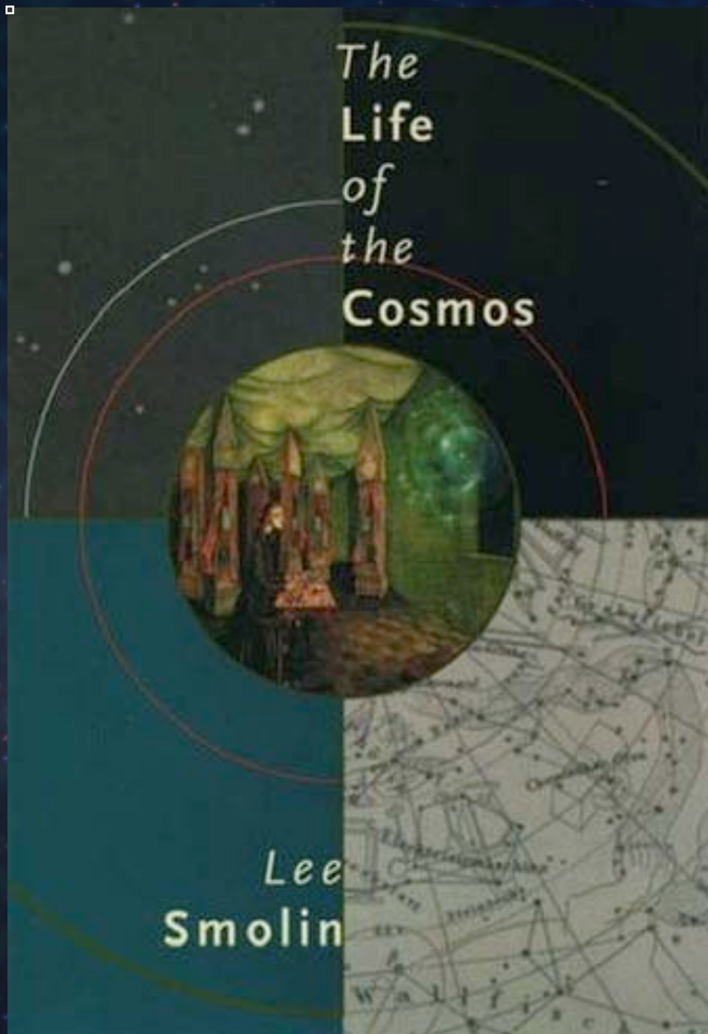
Values of some selected fundamental constants

quantity	symbol	value
constant of gravitation	G	6.67259×10^{-11} cubic metre per second squared per kilogram
speed of light (in a vacuum)	c	$2.99792458 \times 10^{10}$ centimetres per second
Planck's constant	h	$6.6260755 \times 10^{-34}$ joule per second
Boltzmann constant	k	1.380662×10^{-23} joule per kelvin
Faraday constant	$N_A e$	9.648456×10^{4} coulombs per mole
electron rest mass	m_e	9.109389×10^{-31} kilogram
proton rest mass	m_p	$1.6726231 \times 10^{-27}$ kilogram
neutron rest mass	m_n	$1.6749543 \times 10^{-27}$ kilogram
charge on electron	e	4.803×10^{-10} electrostatic unit
Rydberg constant	R	1.09737×10^{5} per centimetre
Stefan-Boltzmann constant	σ	5.67032×10^{-8} watt per square metre kelvin
fine-structure constant	α	$7.29735308 \times 10^{-3}$

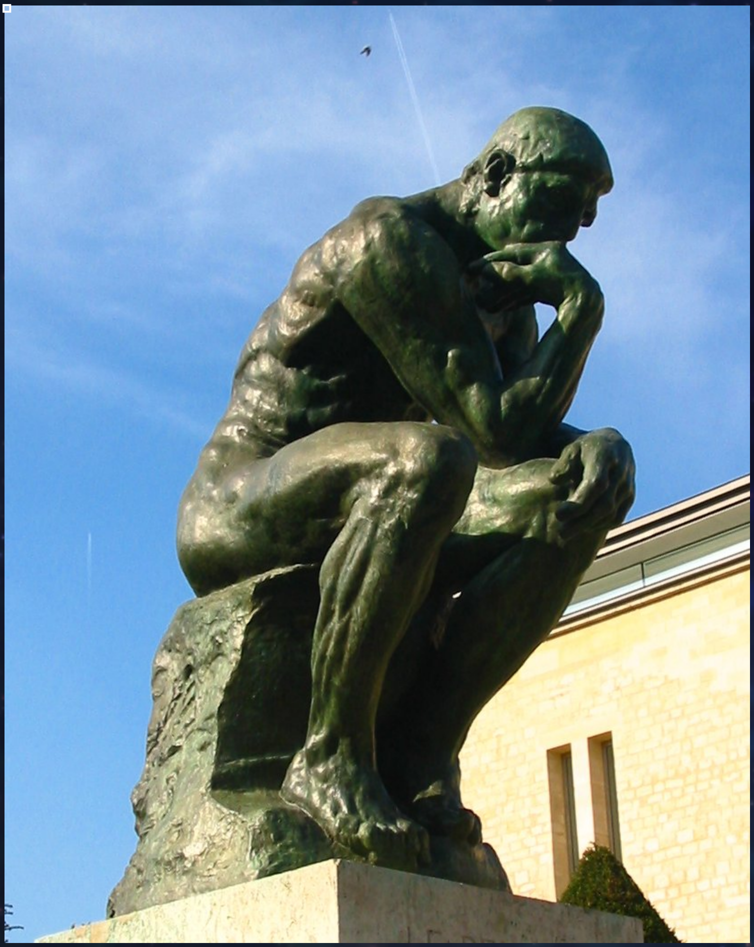
Lecture 20:

Natural Selection of Universes

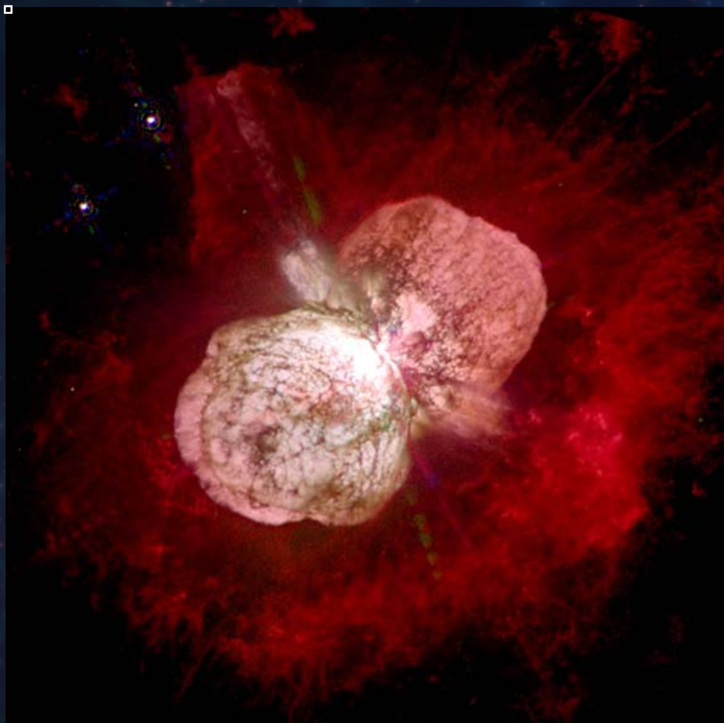
Black Holes and Child Universes?

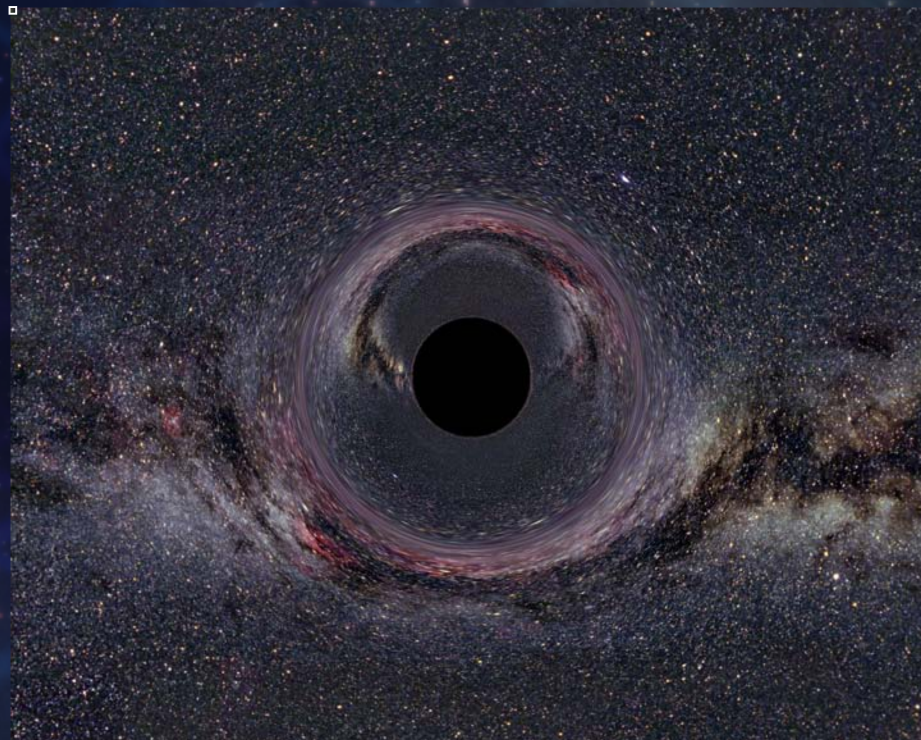


Philosophy or Science?

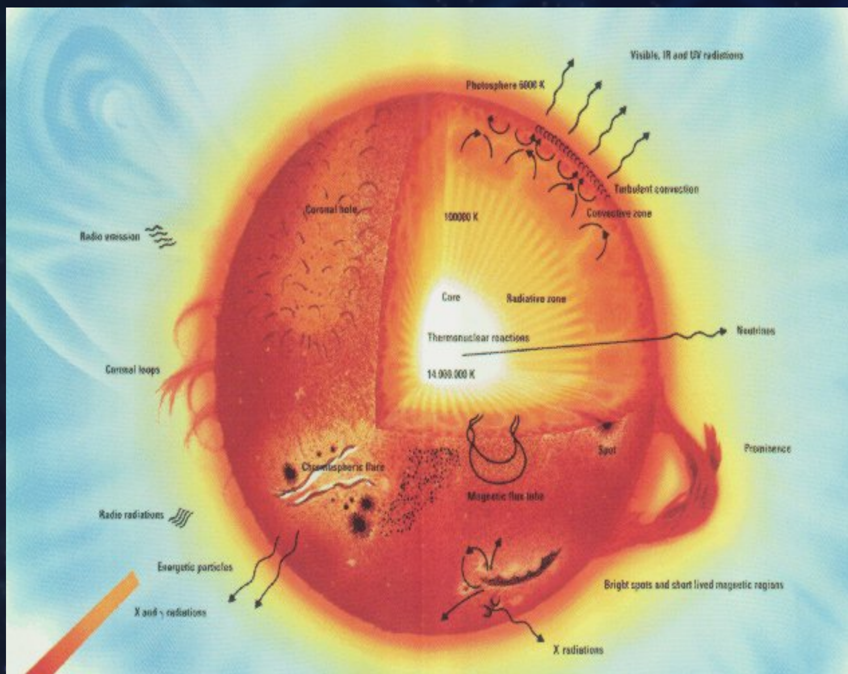


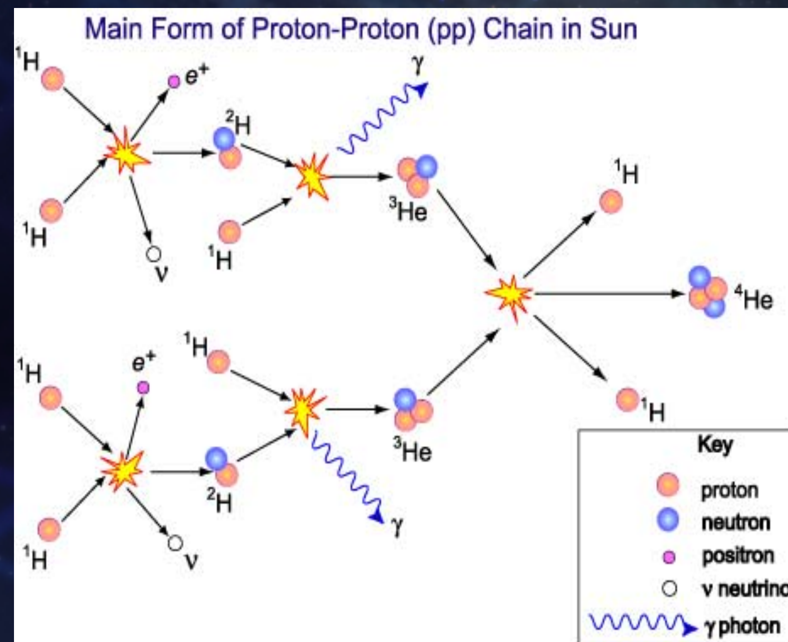
To Make Black Holes, Need to Have Stars



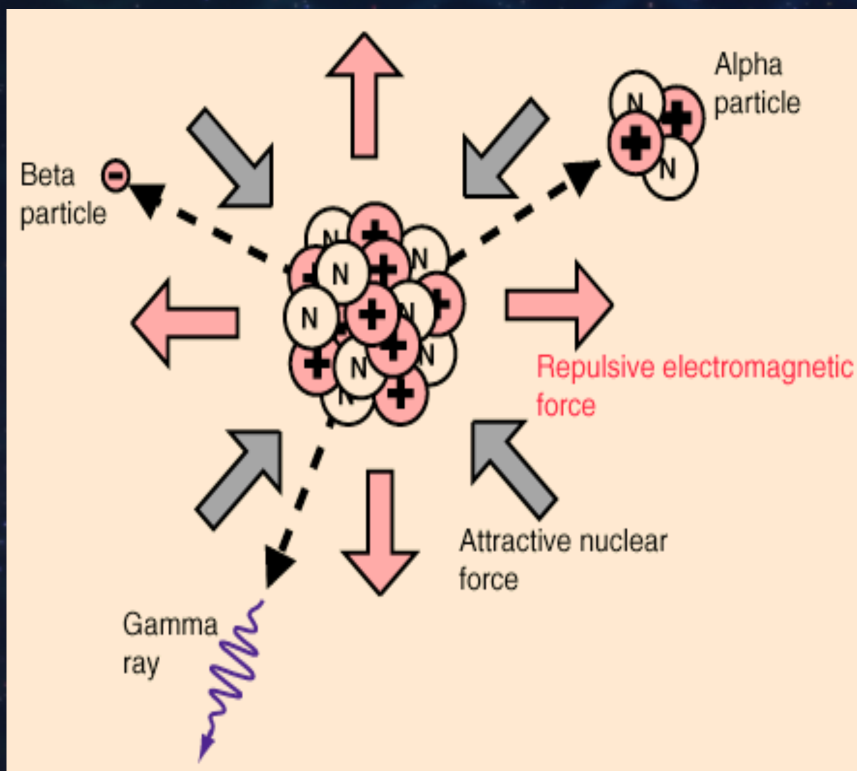


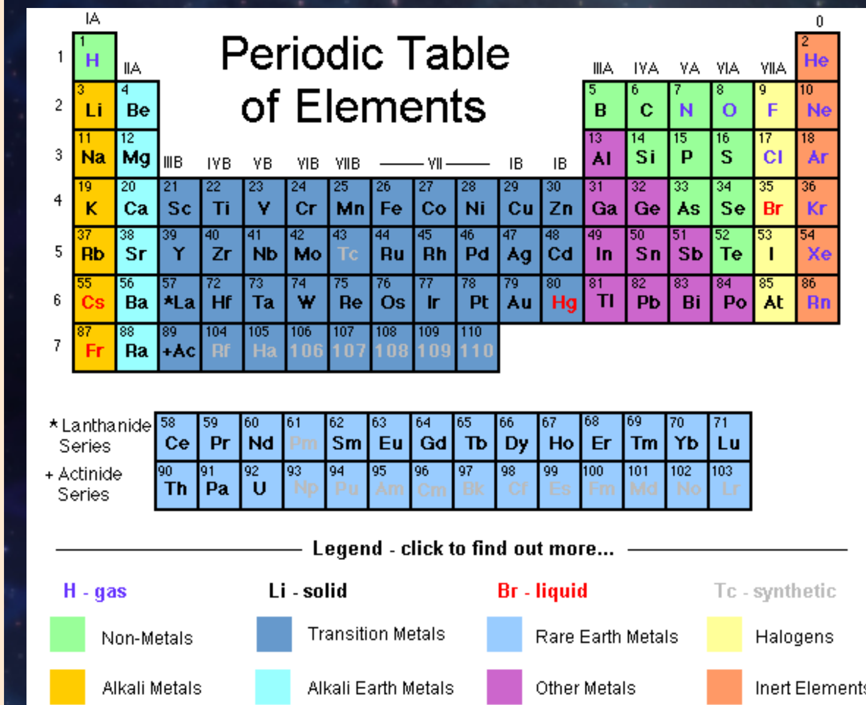
Stars Need Atomic Nuclei for Fusion



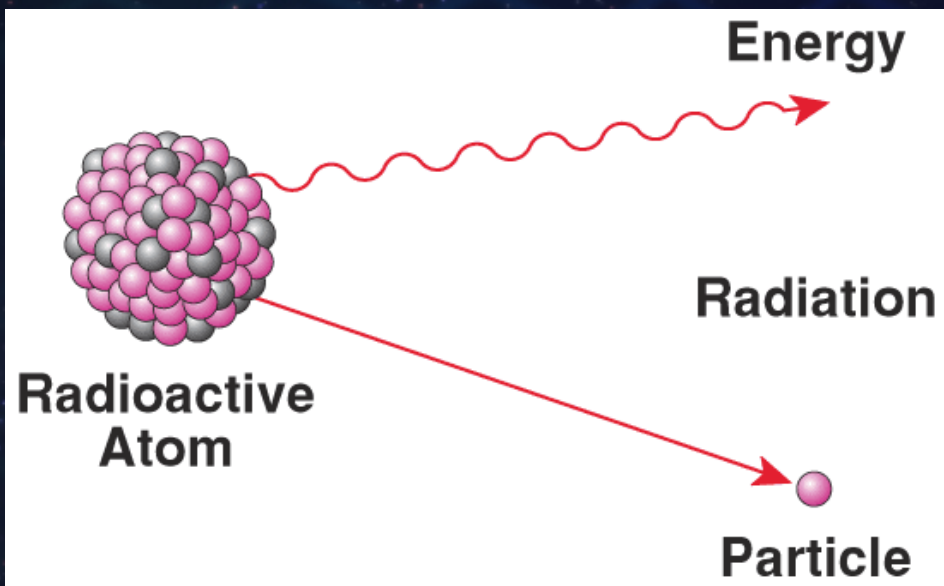


Nuclei Need Balance of Strong and EM Forces





Radioactive Nuclei – Balance Closely Matched



Relative Masses of Proton, Neutron, Electron

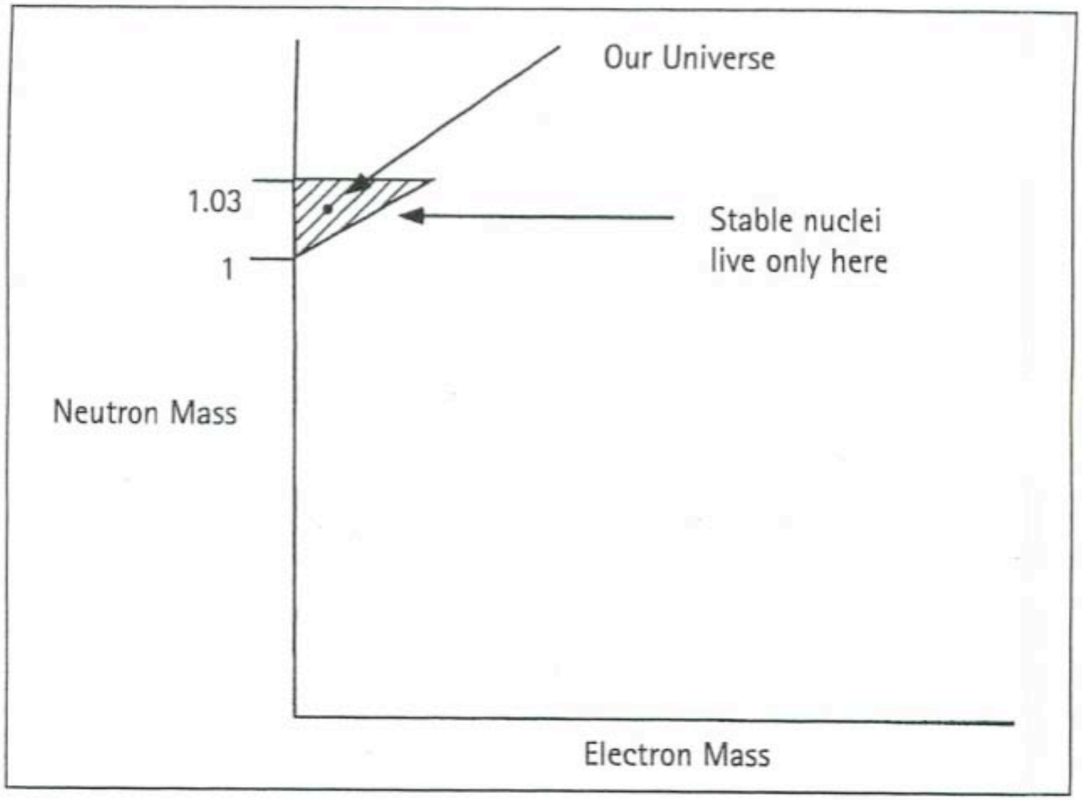
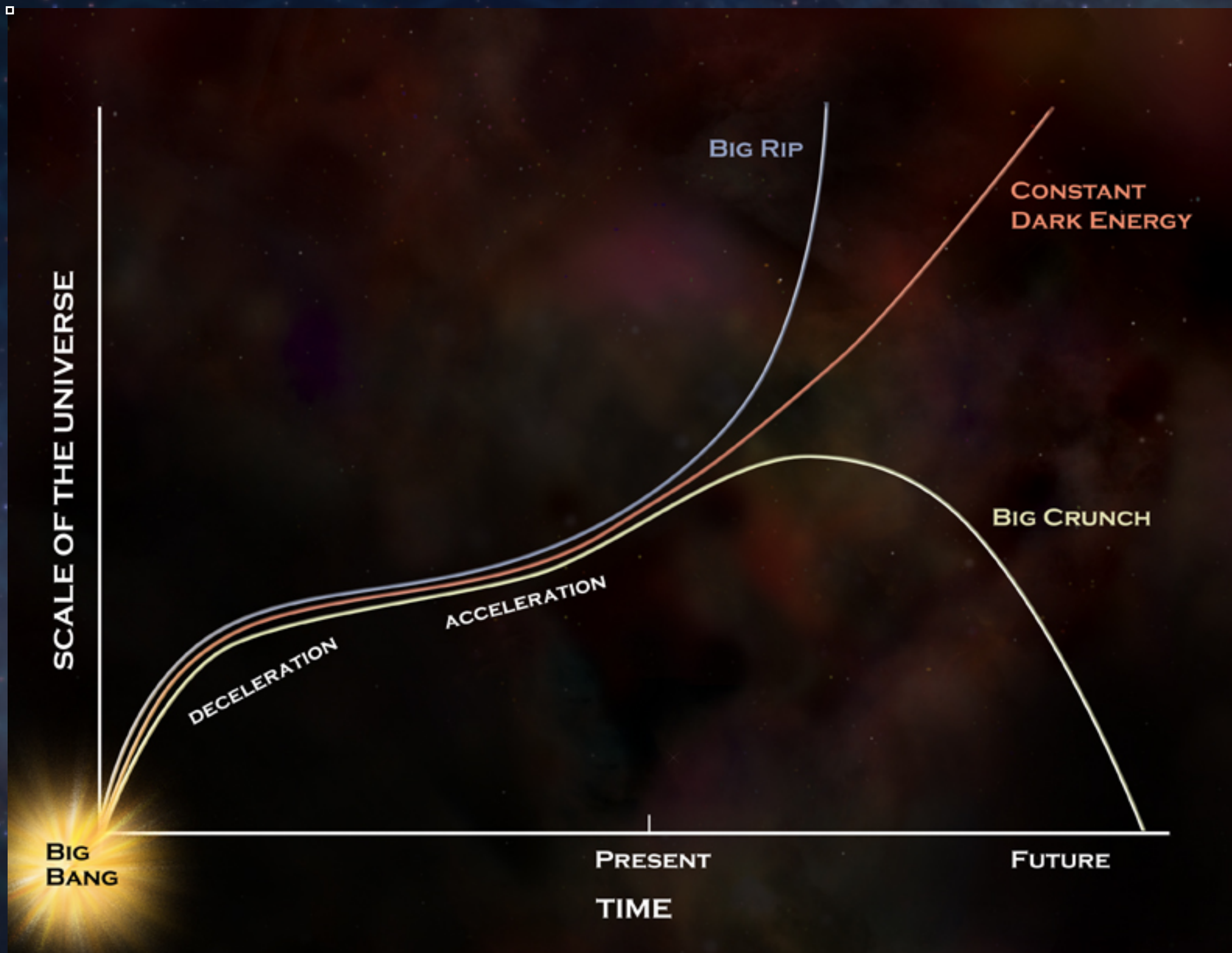


Figure 1 A two dimensional slice of the space of paramenters of the standard model of particle physics, labeled by the value of the neutron and electron masses. The small region correcsponds to values of the parameters in which there are stable nuclei.

Cosmic Expansion Must Allow Star Formation



Role of Cosmological Constant Debated

On cosmic natural selection

Alexander Vilenkin

Institute of Cosmology, Department of Physics and Astronomy,
Tufts University, Medford, MA 02155, USA

Abstract

The rate of black hole formation can be increased by increasing the value of the cosmological constant. This falsifies Smolin's conjecture that the values of all constants of nature are adjusted to maximize black hole production.

The status of cosmological natural selection

Lee Smolin*

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35 King Street North, Waterloo, Ontario N2J 2W9, Canada, and
Department of Physics, University of Waterloo,
Waterloo, Ontario N2L 3G1, Canada

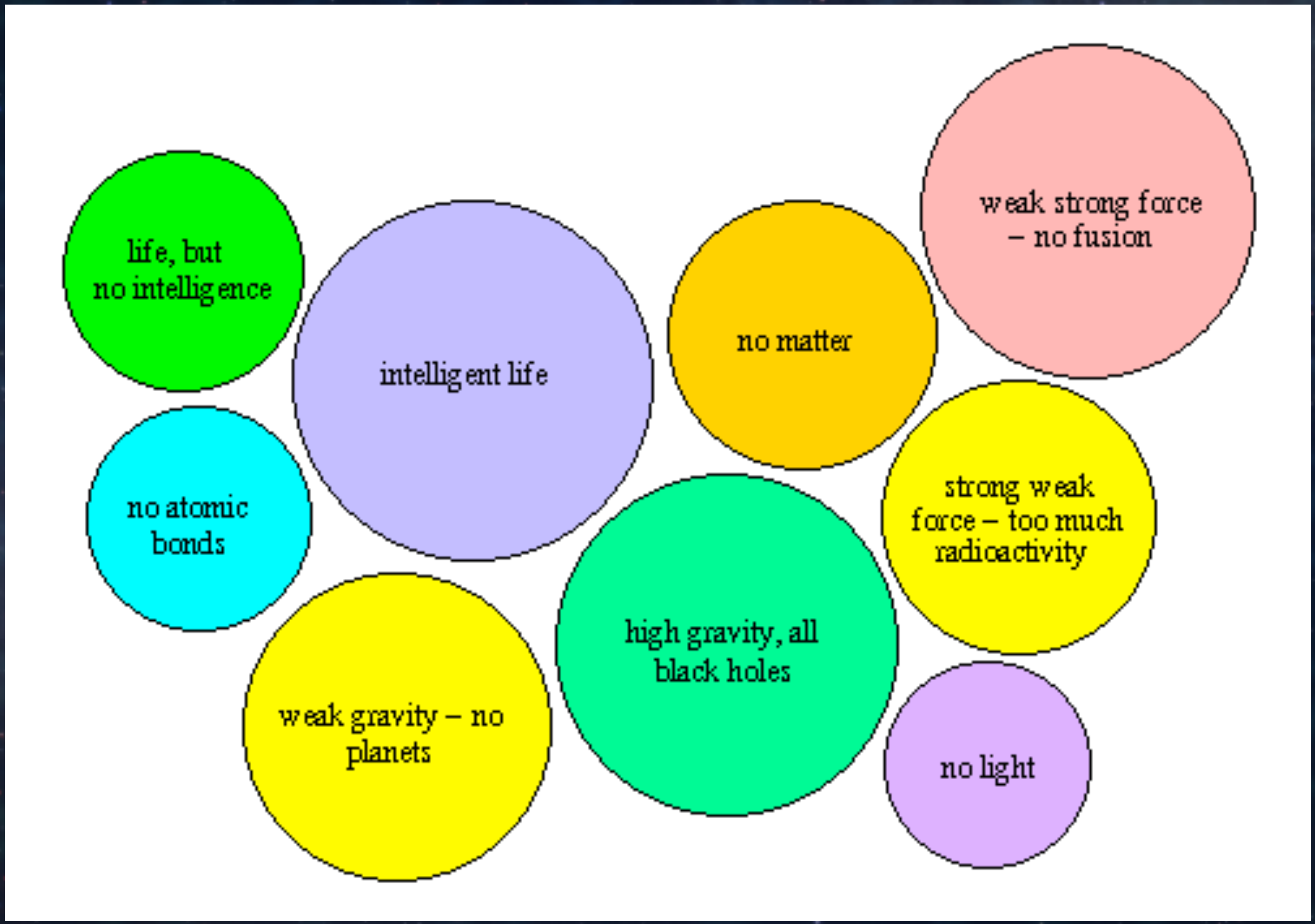
February 2, 2008

Abstract

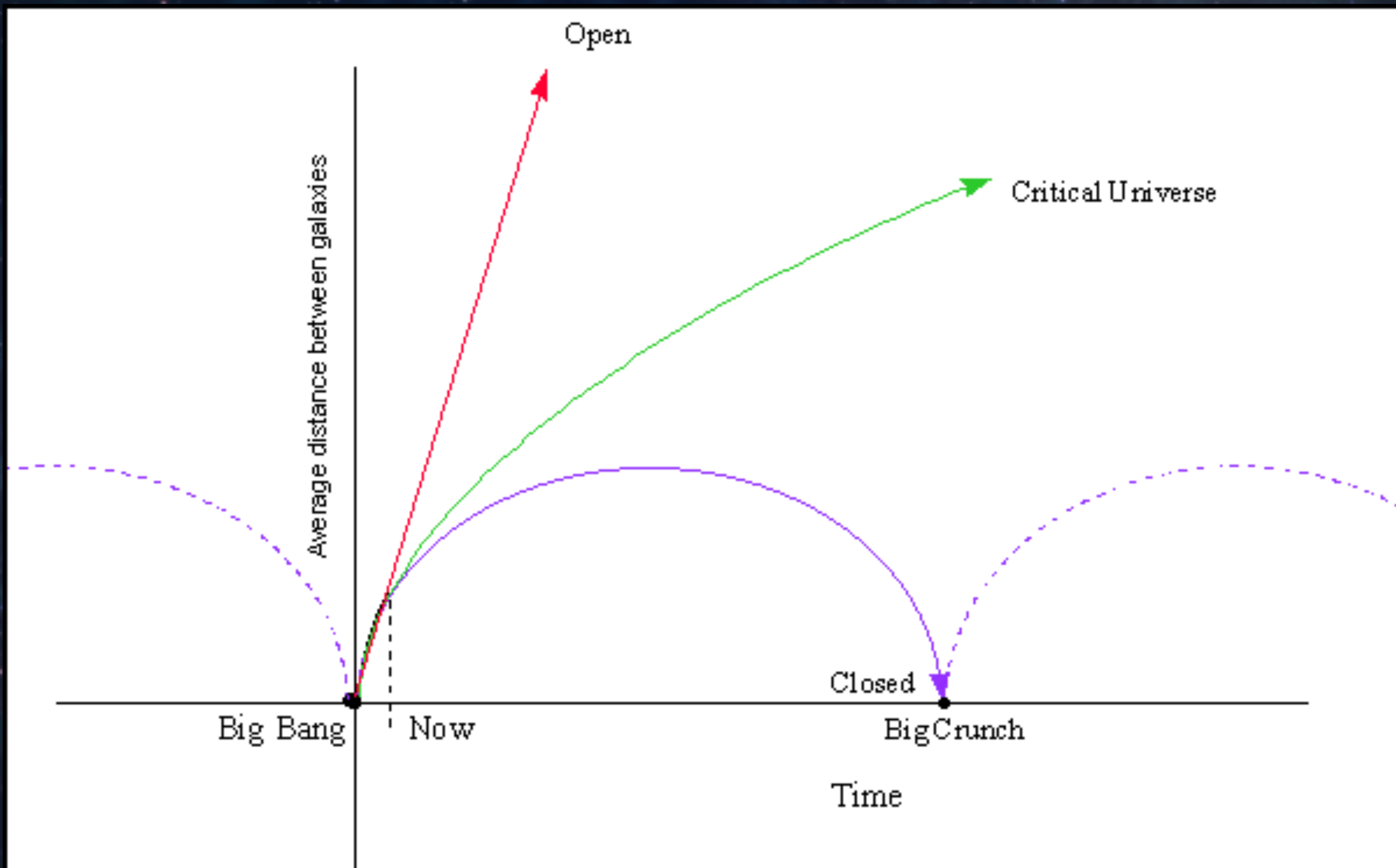
The problem of making predictions from theories that have landscapes of possible low energy parameters is reviewed. Conditions for such a theory to yield falsifiable predictions for doable experiments are given. It is shown that the hypothesis of cosmological natural selection satisfies these conditions, thus showing that it is possible to continue to do physics on a landscape without invoking the anthropic principle. In particular, this is true whether or not the ensemble of universes generated by black holes bouncing is a sub-ensemble of a larger ensemble that might be generated by a random process such as eternal inflation.

A recent criticism of cosmological natural selection made by Vilenkin is discussed. It is shown to rely on assumptions about both the infrared and ultraviolet behavior of quantum gravity that are very unlikely to be true.

A Selection of Universes



What About the First Universe?



Fundamental Constants of Nature

Values of some selected fundamental constants

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A Fitness Landscape for Universes

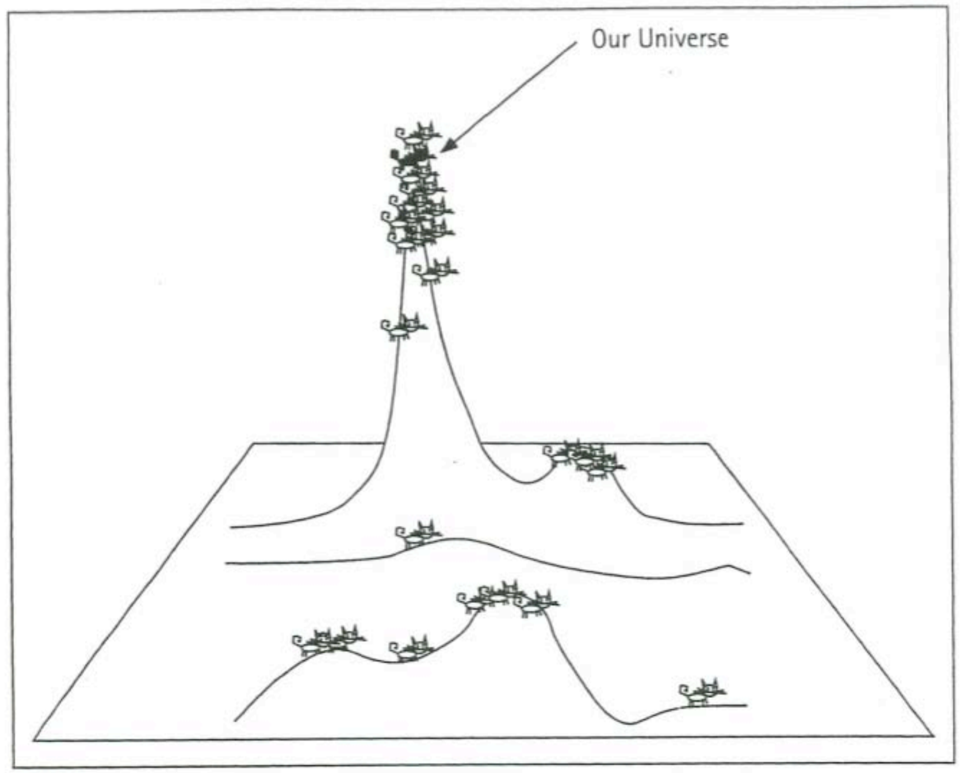

Figure 3 A possible fitness landscape for cosmology on a two dimensional slice of the space of parameters of the standard model. The altitude of the landscape is proportional to the number of black holes a "universe" with each values of the parameters will produce. The cats represent a population of "universes" after a number of "generations."
Drawing courtesy of Saint Clair Cemin.

Fundamental Constants and Black Holes