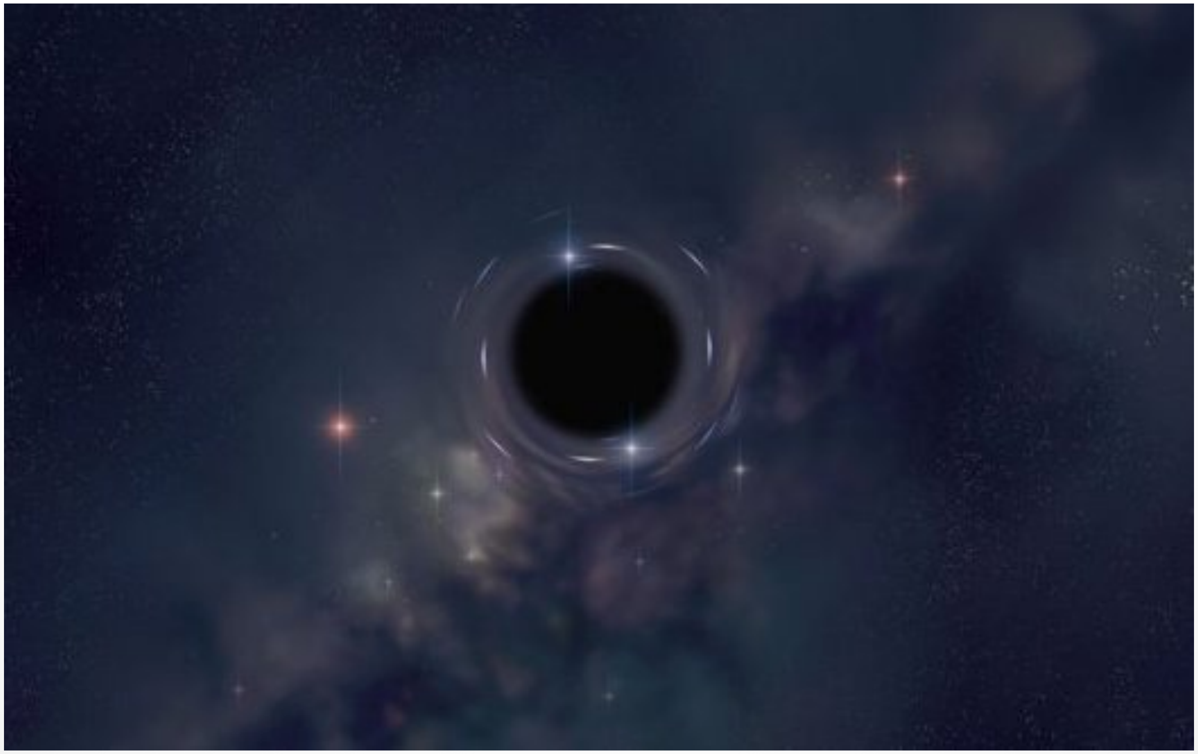
AY2 Announcements

- Quiz 3 will be Nov 14

Last option for stellar evolution

- Initial stellar mass $0.1M_{Sun} – 8M_{Sun}$: White Dwarf supported by e^- degeneracy (WD mass $\leq 1.4M_{Sun}$)
- Initial stellar mass $> 8M_{Sun}$: neutron star supported by neutron degeneracy

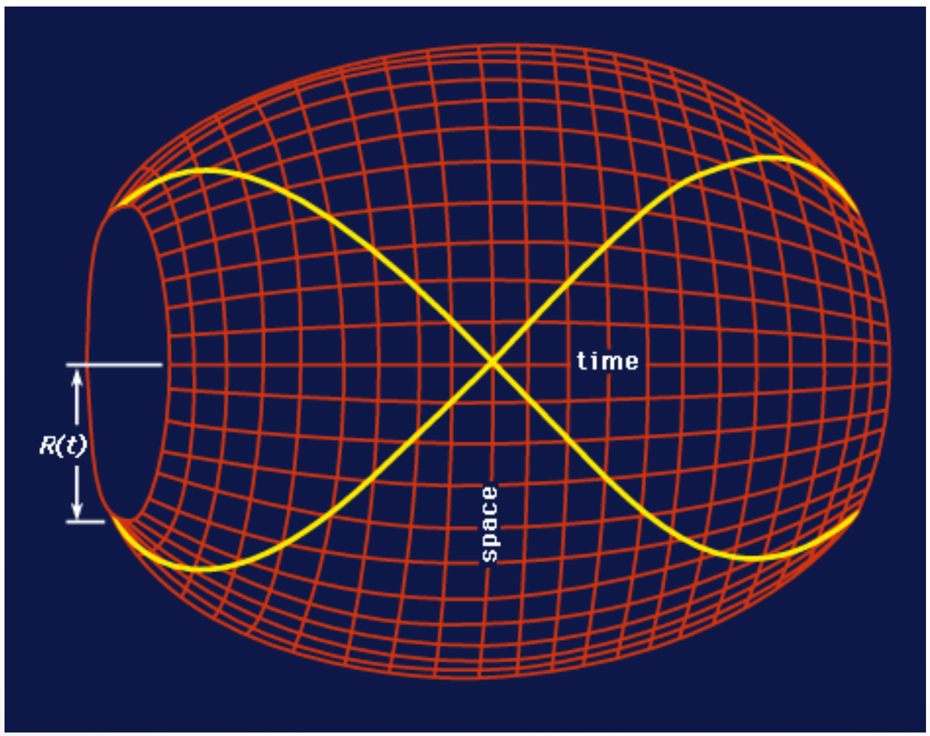


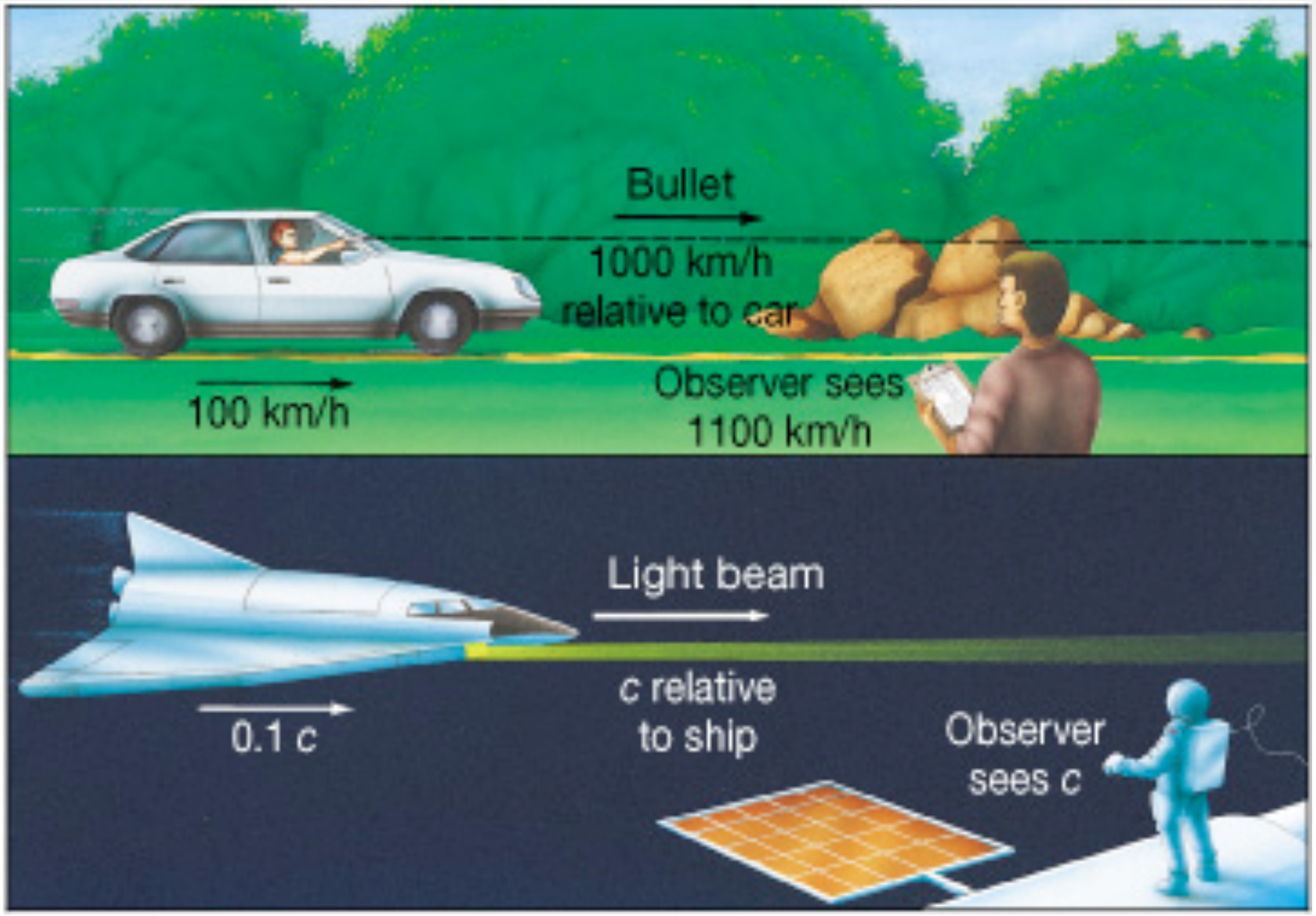
Is there a limit to neutron degeneracy?

- Yes! Gravity wins the final battle. The current best estimate for the maximum mass of a neutron-degenerate star is $3M_{Sun}$.
- If a neutron star exceeds this mass it will collapse into an infinitely small volume called a black hole.
- But, this story starts with Einstein's theories of special and general relativity.

Special Relativity

- Various experiments starting in the late 1800s suggested that the speed of light was constant, *independent of the motion of the observer.*
- This is very counter-intuitive.



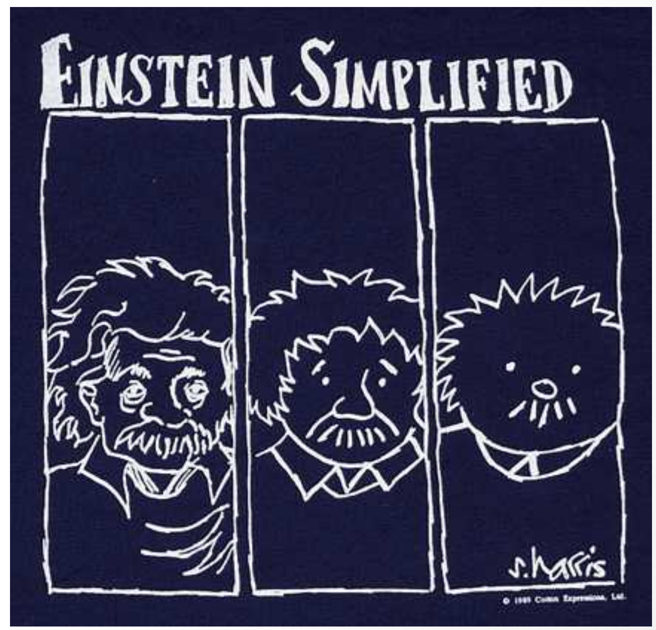


The spaceship traveling in the same direction of a photon measures the photon zooming away at the speed of light NO MATTER how fast the spaceship is traveling!

Special Relativity

- Einstein (and others before him) decided to take the speed of light as an invariant and not make any assumptions about the two properties that go into determining speed:

Space and Time



Time Dilation and Length Contraction

The invariance of the measured speed of light independent of the motion of the observer can be understood if:

(1) Clocks run more slowly as speed increases
(2) Metersticks shrink as speed increases

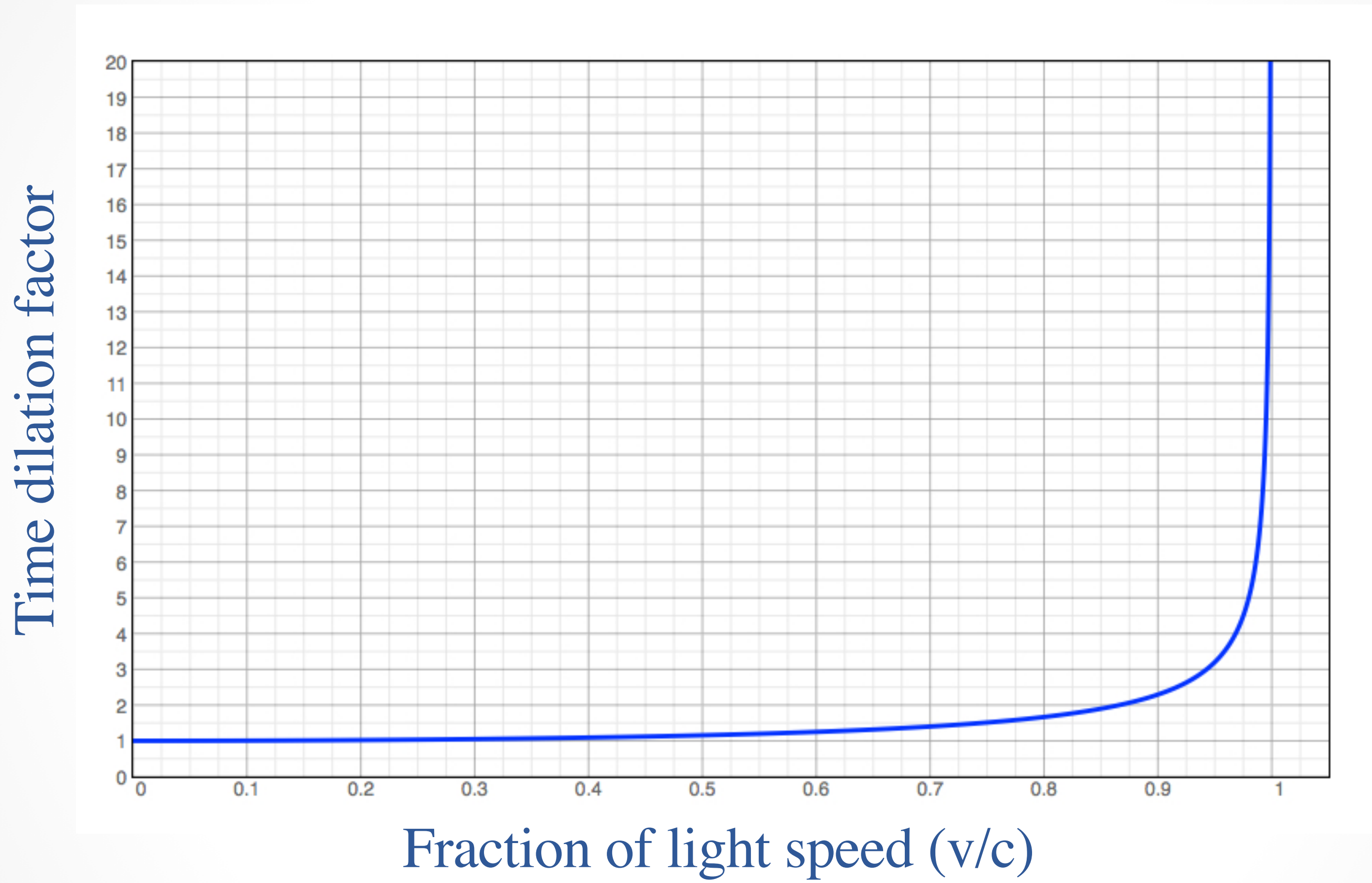
Time Dilation

As your speed with respect to another observer increases, your watch runs more slowly than the observer's watch. This is called `time dilation'

$$T = \frac{T_0}{\sqrt{1-(v/c)^2}}$$

Note, when $v << c$, $T = T_0$

Time Dilation



As v $\rightarrow$ c, v/c $\rightarrow$ 1 and the denominator goes to zero. Dividing by zero gives infinity.

As v approaches c, time grinds to a halt!

Q. Suppose you measure an event that lasts for 1 second by your watch. What will your friend in a spaceship moving at 0.98c measure as the duration of the event?

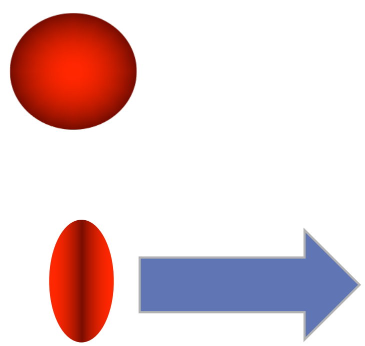
$$T = \frac{T_0}{\sqrt{1-(0.98)^2}} = 5.02T_0$$

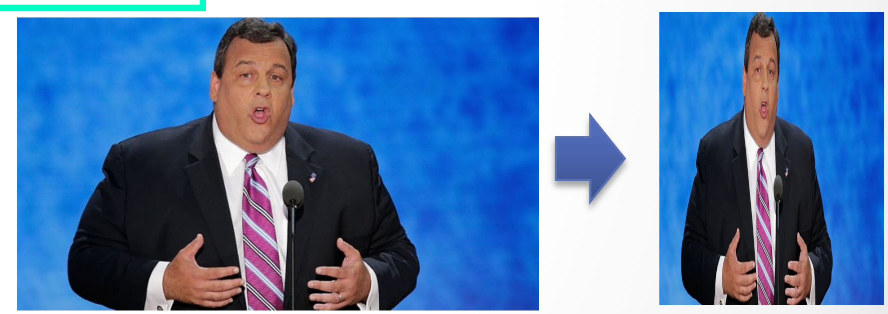
- Time has been stretched by a factor of 5 for your friend.

Length Contraction

- In the same way, metersticks (space) contract in the direction of motion.

$$L = L_0\sqrt{1-(v/c)^2}$$





- But wait, there's more!

Mass

Mass grows with speed.

$$M = \frac{M_0}{\sqrt{1-(v/c)^2}}$$

Constant Speed of Light

- The shrinking rulers and slowing clocks conspire to let observers in any moving frame measure the same speed of light.

Travel beyond the Galaxy will be Difficult

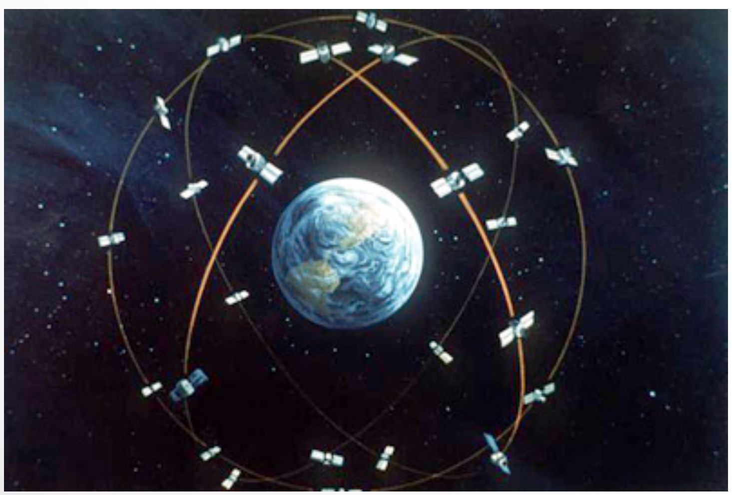
- The slowing clocks and increasing mass conspire to make it impossible for objects with mass to ever reach the speed of light.
- The increasing mass requires an ever-larger force to accelerate to larger speed and the force needed would become infinite. (F=ma)
- Even if you could find the force, your clock would slow and slow and the last step would take an infinitely long time

Is this right?

- Yes! There are many tests of Special Relativity.
- In particle accelerators, mass increase and time dilation effects are routinely measured
- There have been tests flying very accurate clocks in high-speed jets that show time dilation directly.
- We might not be here if not for time dilation in the frame of cosmic rays called muons that get launched at 0.98c and have decay lifetimes stretched by a factor of 5 to allow them to reach the ground

GPS and relativity

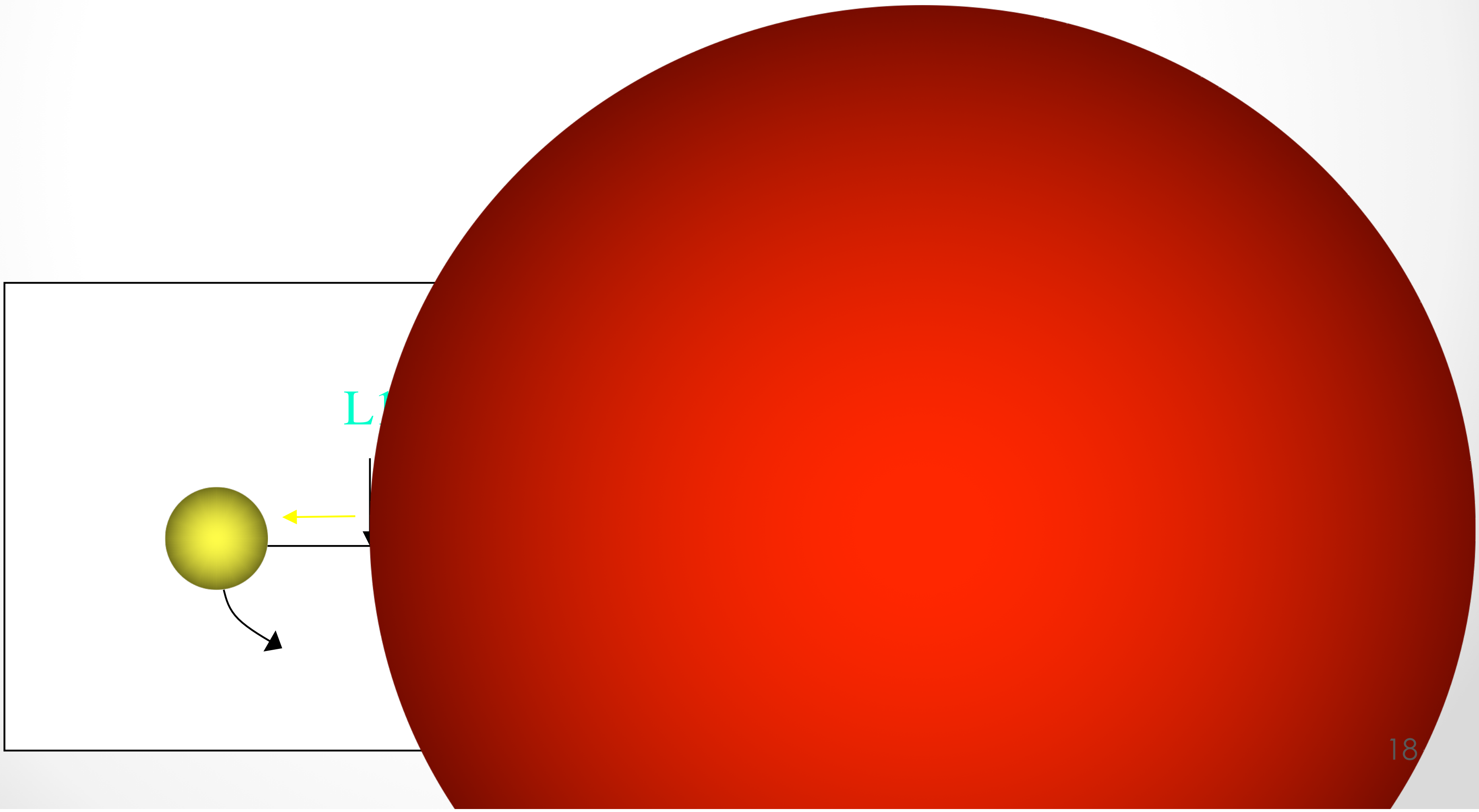
- Commercial GPS requires timing good to ~20 nanosec (20×10^{-9} seconds). The relative speed of GPS satellites to stationary receiver is ~14,000 mph and the time dilation is ~ 7×10^{-6} seconds per day.
- Combined with a General Relativity effect, GPS would be off by ~ 10 km per day if these effects were not accounted for!



Review from last time

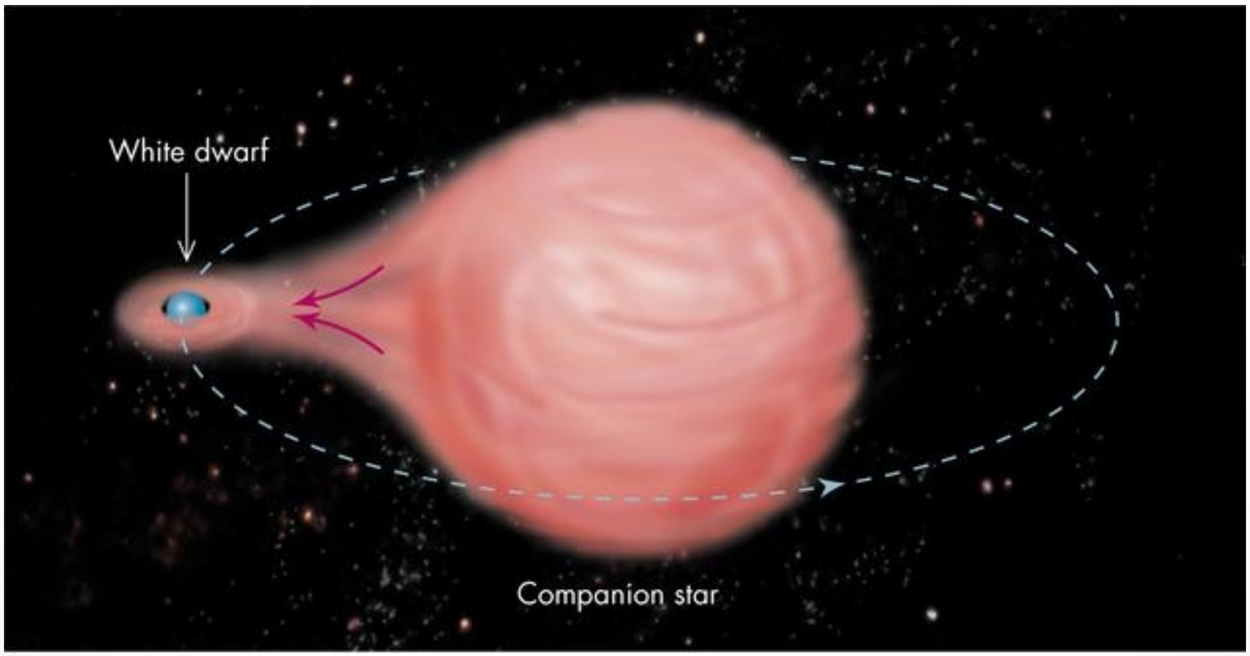
Mass Transfer Binary Systems

- Close binary stars can undergo mass exchange through the L1



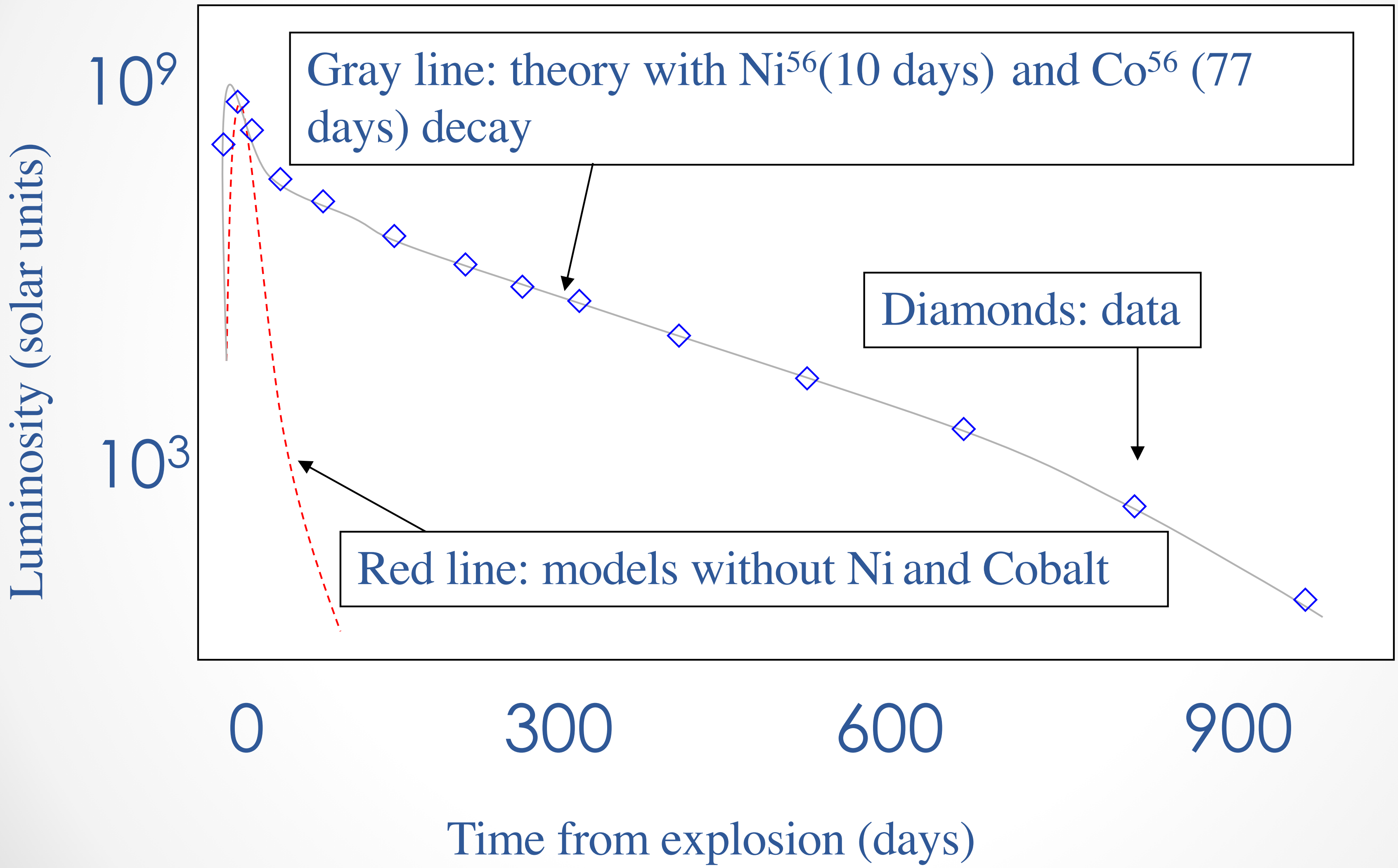
Novae/Supernovae I

Mass transfer onto a White Dwarf can explain Novae and Supernovae I



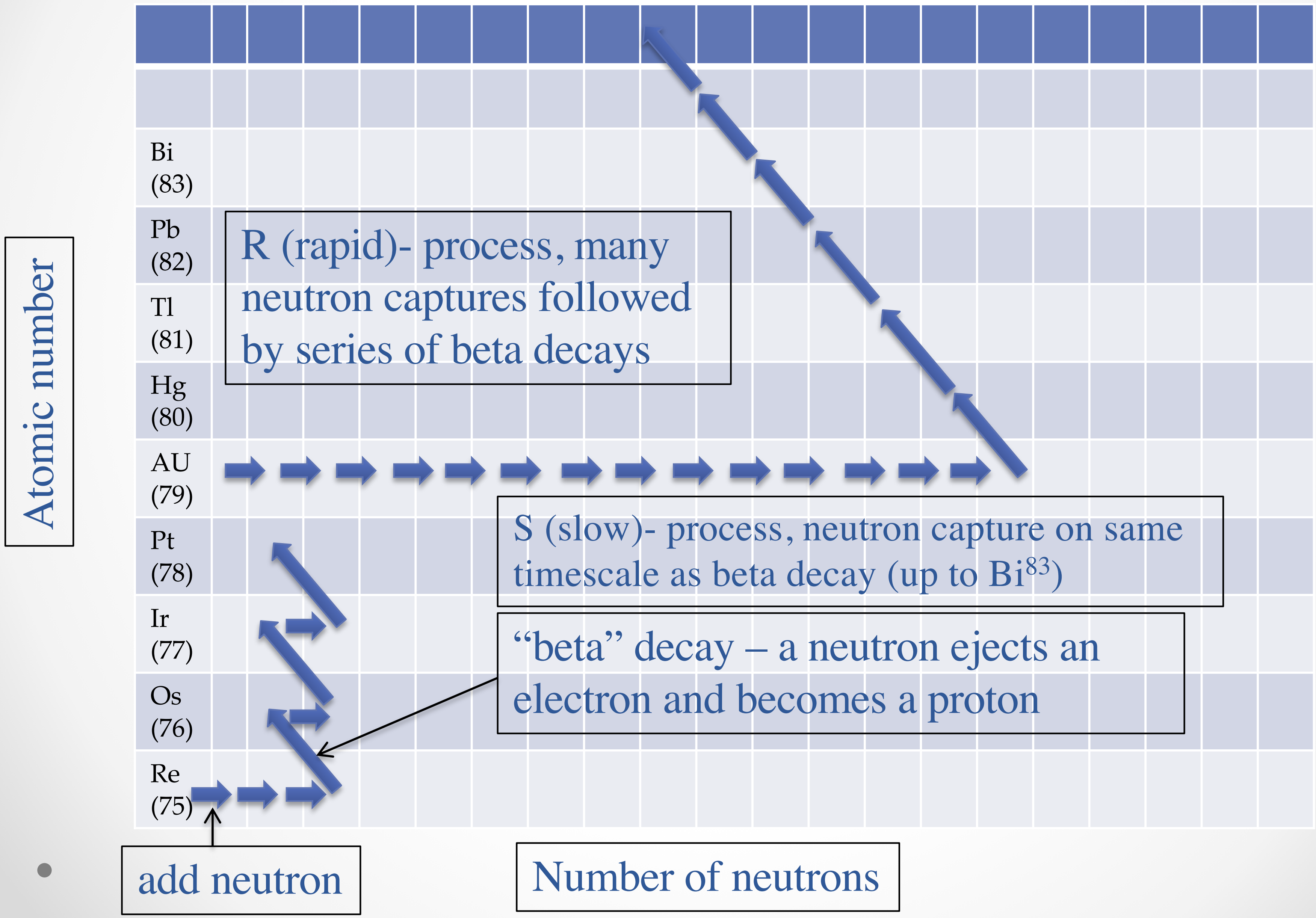
Novae/Supernovae 1

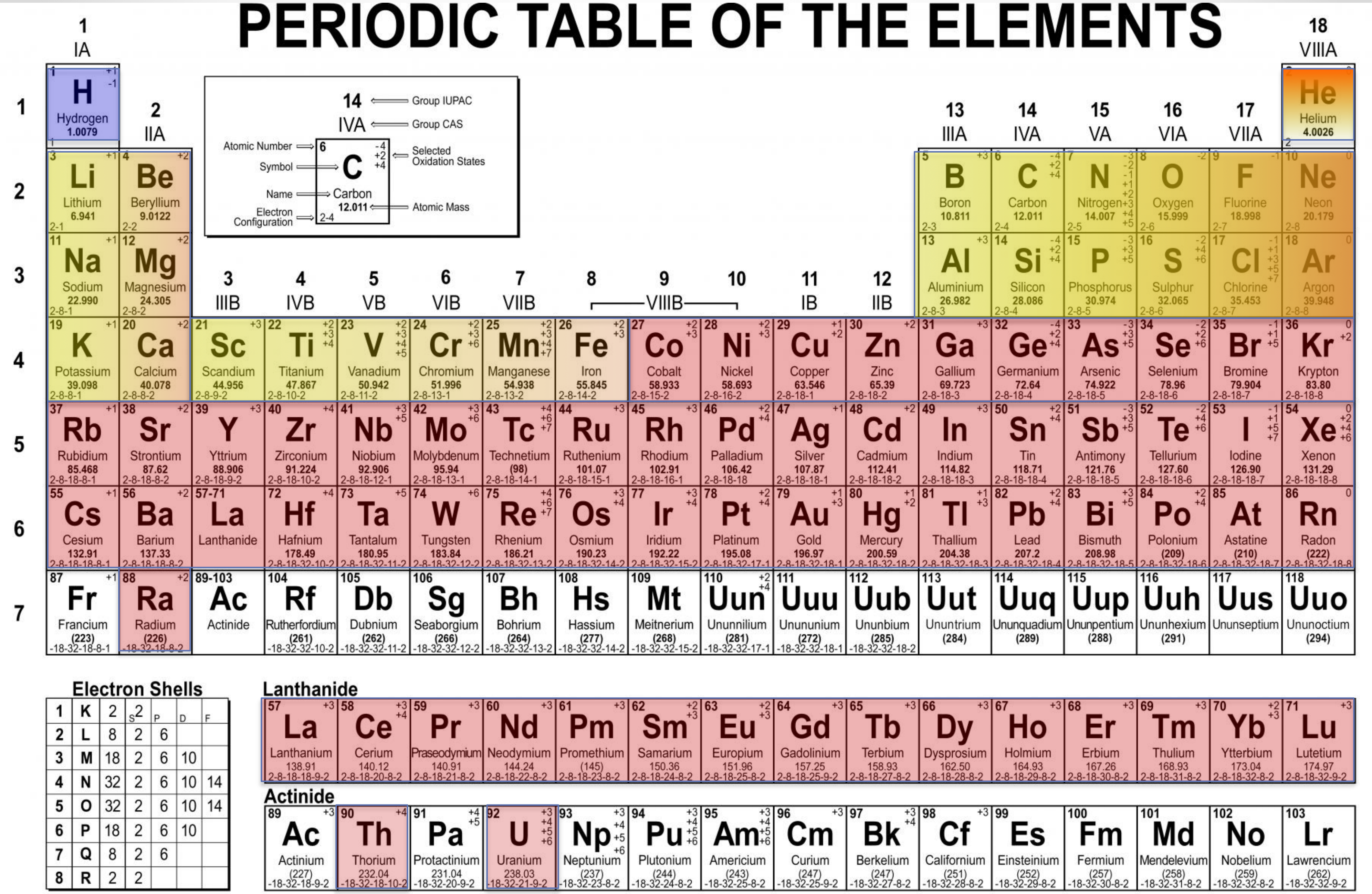
- Nova results from surface detonation of accumulated hydrogen on the surface of the white dwarf
- Supernova 1 results when the accreted material pushes the white dwarf over the Chandrasekar limit for supporting by electron degeneracy against gravity
  - The subsequent collapse and rapid heating cause the entire white dwarf to undergo explosive fusion reactions
  - Predict uniform and very large luminosity
  - Predict the prediction of fusion products up to radioactive Nickel and Cobalt



Gray line: theory with Ni56(10 days) and Co56 (77 days) decay
Diamonds: data
Red line: models without Ni and Cobalt
10^9
10^3
Luminosity (solar units)
0
300
600
900
Time from explosion (days)

S- and R-processes





PERIODIC TABLE OF THE ELEMENTS
14 Group IUPAC
IVA Group CAS
Atomic Number 6
Symbol C
Name Carbon
Electron Configuration 2-4
Atomic Mass 12.011
Selected Oxidation States -4 +2 +4
1 IA
2 IIA
3 IIIB
4 IVB
5 VB
6 VIB
7 VIIB
8 9 10 VIIIB
11 IB
12 IIB
13 IIIA
14 IVA
15 VA
16 VIA
17 VIIA
18 VIIIA
1 2 3 4 5 6 7
1 H Hydrogen 1.0079 1
2 He Helium 4.0026 2
3 Li Lithium 6.941 2-1
4 Be Beryllium 9.0122 2-2
5 B Boron 10.811 2-3
6 C Carbon 12.011 2-4
7 N Nitrogen 14.007 2-5
8 O Oxygen 15.999 2-6
9 F Fluorine 18.998 2-7
10 Ne Neon 20.179 2-8
11 Na Sodium 22.990 2-8-1
12 Mg Magnesium 24.305 2-8-2
13 Al Aluminium 26.982 2-8-3
14 Si Silicon 28.086 2-8-4
15 P Phosphorus 30.974 2-8-5
16 S Sulphur 32.065 2-8-6
17 Cl Chlorine 35.453 2-8-7
18 Ar Argon 39.948 2-8-8
19 K Potassium 39.098 2-8-8-1
20 Ca Calcium 40.078 2-8-8-2
21 Sc Scandium 44.956 2-8-9-2
22 Ti Titanium 47.867 2-8-10-2
23 V Vanadium 50.942 2-8-11-2
24 Cr Chromium 51.996 2-8-13-1
25 Mn Manganese 54.938 2-8-13-2
26 Fe Iron 55.845 2-8-14-2
27 Co Cobalt 58.933 2-8-15-2
28 Ni Nickel 58.693 2-8-16-2
29 Cu Copper 63.546 2-8-18-1
30 Zn Zinc 65.39 2-8-18-2
31 Ga Gallium 69.723 2-8-18-3
32 Ge Germanium 72.64 2-8-18-4
33 As Arsenic 74.922 2-8-18-5
34 Se Selenium 78.96 2-8-18-6
35 Br Bromine 79.904 2-8-18-7
36 Kr Krypton 83.80 2-8-18-8
37 Rb Rubidium 85.468 2-8-18-8-1
38 Sr Strontium 87.62 2-8-18-8-2
39 Y Yttrium 88.906 2-8-18-9-2
40 Zr Zirconium 91.224 2-8-18-10-2
41 Nb Niobium 92.906 2-8-18-12-1
42 Mo Molybdenum 95.94 2-8-18-13-1
43 Tc Technetium (98) 2-8-18-14-1
44 Ru Ruthenium 101.07 2-8-18-15-1
45 Rh Rhodium 102.91 2-8-18-16-1
46 Pd Palladium 106.42 2-8-18-18
47 Ag Silver 107.87 2-8-18-18-1
48 Cd Cadmium 112.41 2-8-18-18-2
49 In Indium 114.82 2-8-18-18-3
50 Sn Tin 118.71 2-8-18-18-4
51 Sb Antimony 121.76 2-8-18-18-5
52 Te Tellurium 127.60 2-8-18-18-6
53 I Iodine 126.90 2-8-18-18-7
54 Xe Xenon 131.29 2-8-18-18-8
55 Cs Cesium 132.91 2-8-18-18-8-1
56 Ba Barium 137.33 2-8-18-18-8-2
57-71 La Lanthanide
72 Hf Hafnium 178.49 2-8-18-32-10-2
73 Ta Tantalum 180.95 2-8-18-32-11-2
74 W Tungsten 183.84 2-8-18-32-12-2
75 Re Rhenium 186.21 2-8-18-32-13-2
76 Os Osmium 190.23 2-8-18-32-14-2
77 Ir Iridium 192.22 2-8-18-32-15-2
78 Pt Platinum 195.08 2-8-18-32-17-1
79 Au Gold 196.97 2-8-18-32-18-1
80 Hg Mercury 200.59 2-8-18-32-18-2
81 Tl Thallium 204.38 2-8-18-32-18-3
82 Pb Lead 207.2 2-8-18-32-18-4
83 Bi Bismuth 208.98 2-8-18-32-18-5
84 Po Polonium (209) 2-8-18-32-18-6
85 At Astatine (210) 2-8-18-32-18-7
86 Rn Radon (222) 2-8-18-32-18-8
87 Fr Francium (223) -18-32-18-8-1
88 Ra Radium (226) -18-32-18-8-2
89-103 Ac Actinide
104 Rf Rutherfordium (261) -18-32-32-10-2
105 Db Dubnium (262) -18-32-32-11-2
106 Sg Seaborgium (266) -18-32-32-12-2
107 Bh Bohrium (264) -18-32-32-13-2
108 Hs Hassium (277) -18-32-32-14-2
109 Mt Meitnerium (268) -18-32-32-15-2
110 Uun Ununnilium (281) -18-32-32-17-1
111 Uuu Unununium (272) -18-32-32-18-1
112 Uub Ununbium (285) -18-32-32-18-2
113 Uut Ununtrium (284)
114 Uuq Ununquadium (289)
115 Uup Ununpentium (288)
116 Uuh Ununhexium (291)
117 Uus Ununseptium
118 Uuo Ununoctium (294)
Electron Shells
1 K 2 2
2 L 8 2 6
3 M 18 2 6 10
4 N 32 2 6 10 14
5 O 32 2 6 10 14
6 P 18 2 6 10
7 Q 8 2 6
8 R 2 2
S P D F
Lanthanide
57 La Lanthanium 138.91 2-8-18-19-9-2
58 Ce Cerium 140.12 2-8-18-20-8-2
59 Pr Praseodymium 140.91 2-8-18-21-8-2
60 Nd Neodymium 144.24 2-8-18-22-8-2
61 Pm Promethium (145) 2-8-18-23-8-2
62 Sm Samarium 150.36 2-8-18-24-8-2
63 Eu Europium 151.96 2-8-18-25-8-2
64 Gd Gadolinium 157.25 2-8-18-25-9-2
65 Tb Terbium 158.93 2-8-18-27-8-2
66 Dy Dysprosium 162.50 2-8-18-28-8-2
67 Ho Holmium 164.93 2-8-18-29-8-2
68 Er Erbium 167.26 2-8-18-30-8-2
69 Tm Thulium 168.93 2-8-18-31-8-2
70 Yb Ytterbium 173.04 2-8-18-32-8-2
71 Lu Lutetium 174.97 2-8-18-32-9-2
Actinide
89 Ac Actinium (227) -18-32-18-9-2
90 Th Thorium 232.04 -18-32-18-10-2
91 Pa Protactinium 231.04 -18-32-20-9-2
92 U Uranium 238.03 -18-32-21-9-2
93 Np Neptunium (237) -18-32-23-8-2
94 Pu Plutonium (244) -18-32-24-8-2
95 Am Americium (243) -18-32-25-8-2
96 Cm Curium (247) -18-32-25-9-2
97 Bk Berkelium (247) -18-32-27-8-2
98 Cf Californium (251) -18-32-28-8-2
99 Es Einsteinium (252) -18-32-29-8-2
100 Fm Fermium (257) -18-32-30-8-2
101 Md Mendelevium (258) -18-32-31-8-2
102 No Nobelium (259) -18-32-32-8-2
103 Lr Lawrencium (262) -18-32-32-9-2

Special Relativity

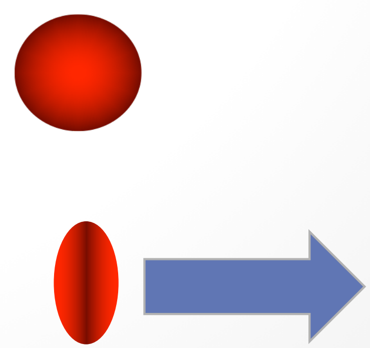
In any "inertial reference frame" the speed of light is always measured to be the same: this is because space and time are different for observers moving at different speeds:

"time dilation"

$$T = \frac{T_0}{\sqrt{1-(v/c)^2}}$$

"length contraction"

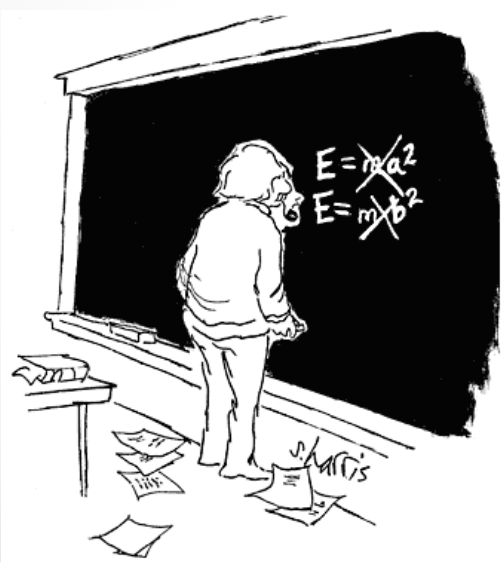
$$L = L_0\sqrt{1-(v/c)^2}$$



Start of New Material

Einstein II: General Relativity

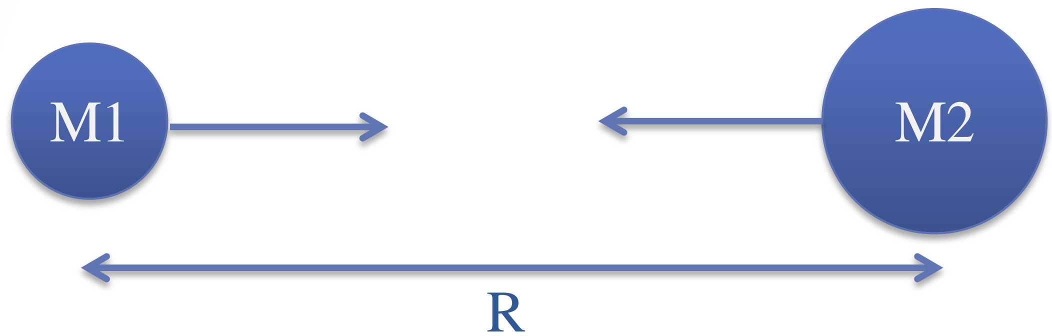
- Einstein's theory of General Relativity is a theory of gravity
- The basic idea is to drop Newton's idea of a mysterious force between masses and replace it with the 4-dimensional ***SpaceTime*** continuum that is warped by the presence of mass

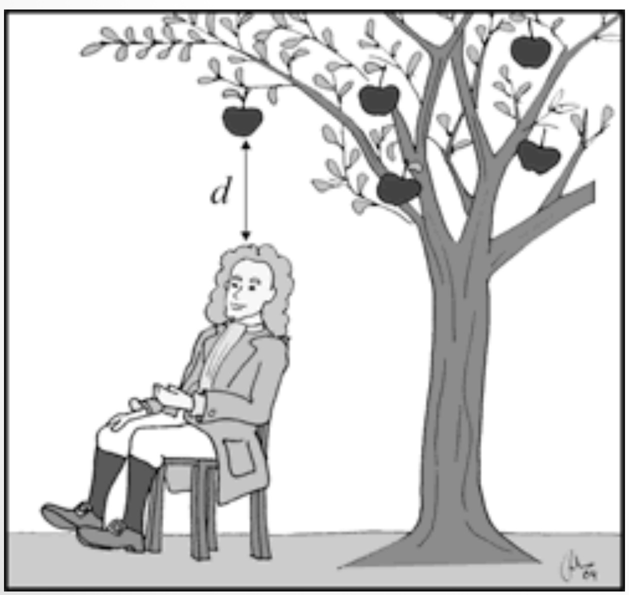


Think about what needs to happen to have an event in the Universe and you can understand the need to specify 4-dimensions

Newtonian Gravity

- Newton proposed a theory of gravity to explain why things fell to Earth and the orbits of planets

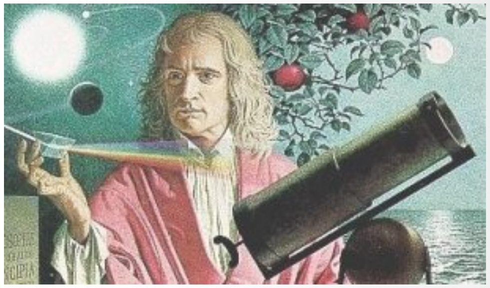


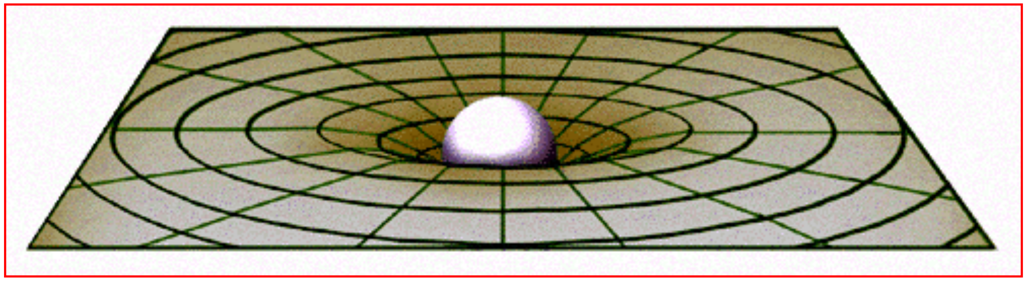


$$Force_{gravity} = \frac{G \times M_1 \times M_2}{R^2}$$

General Relativity

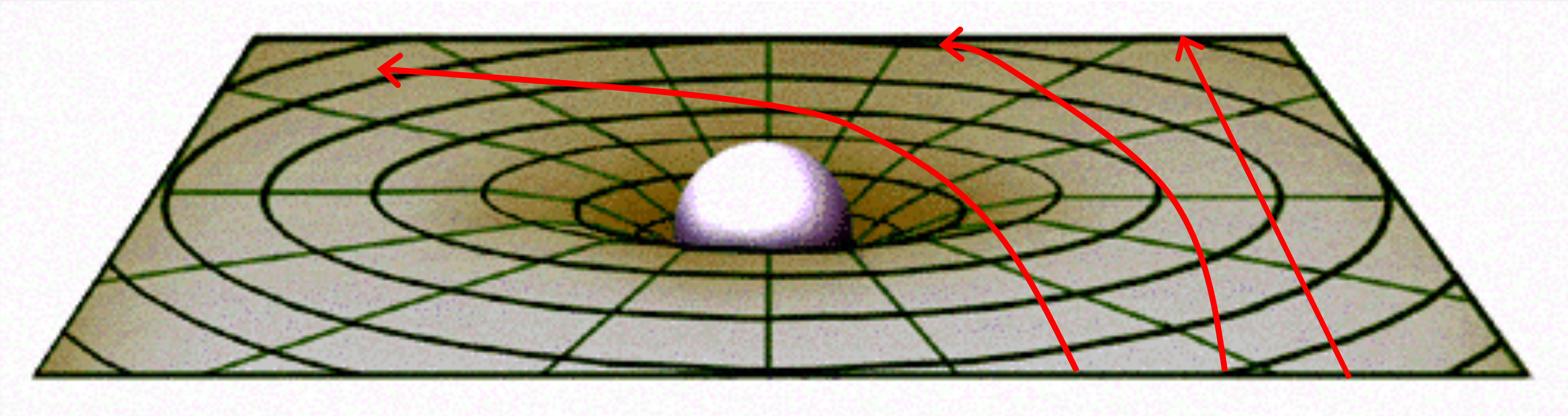
- In GR, mass (or energy) warps the spacetime fabric of space.



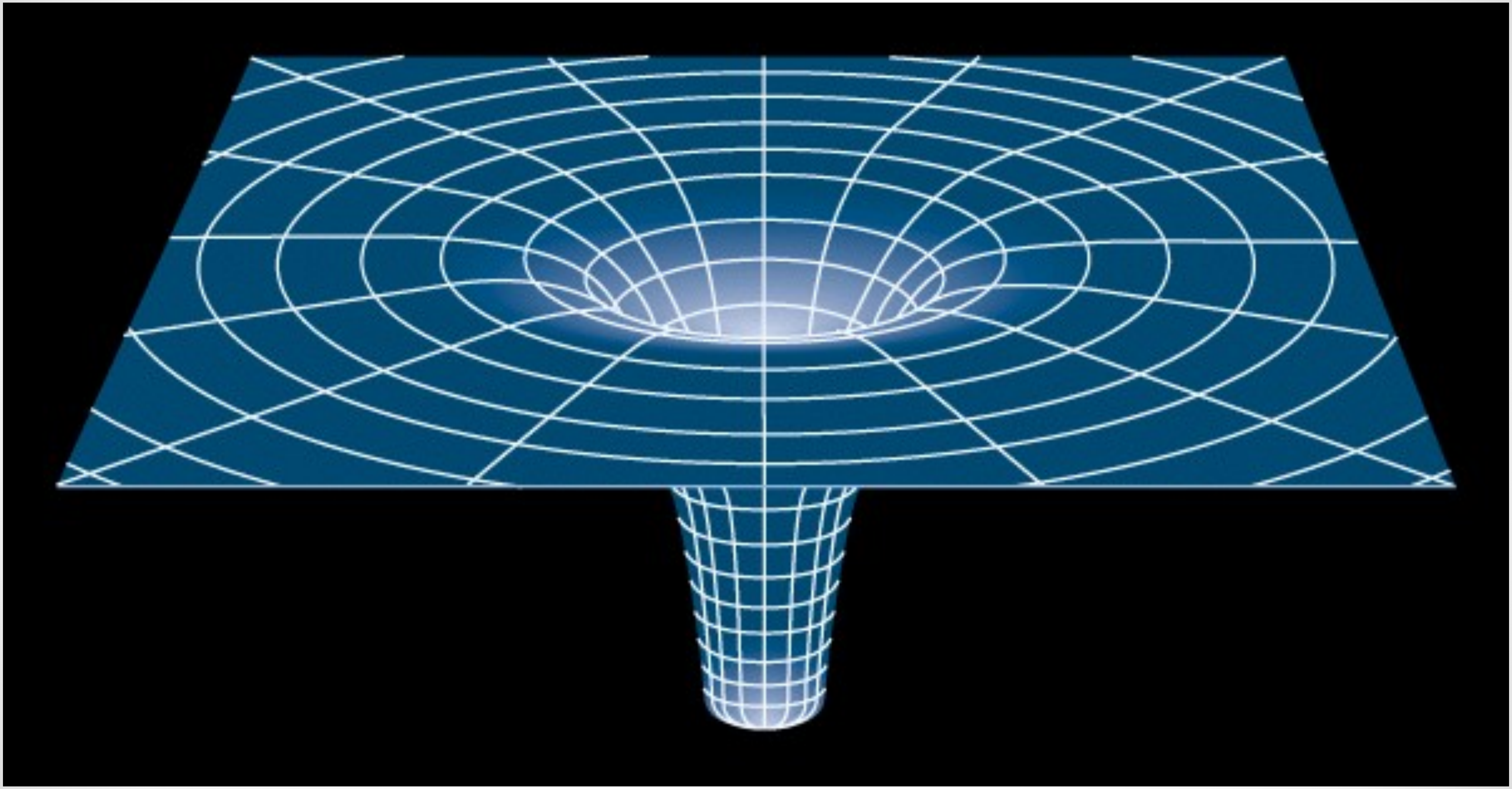


- Orbits of planets around stars are not due to a central force, but rather the planets are traveling in straight lines through curved space

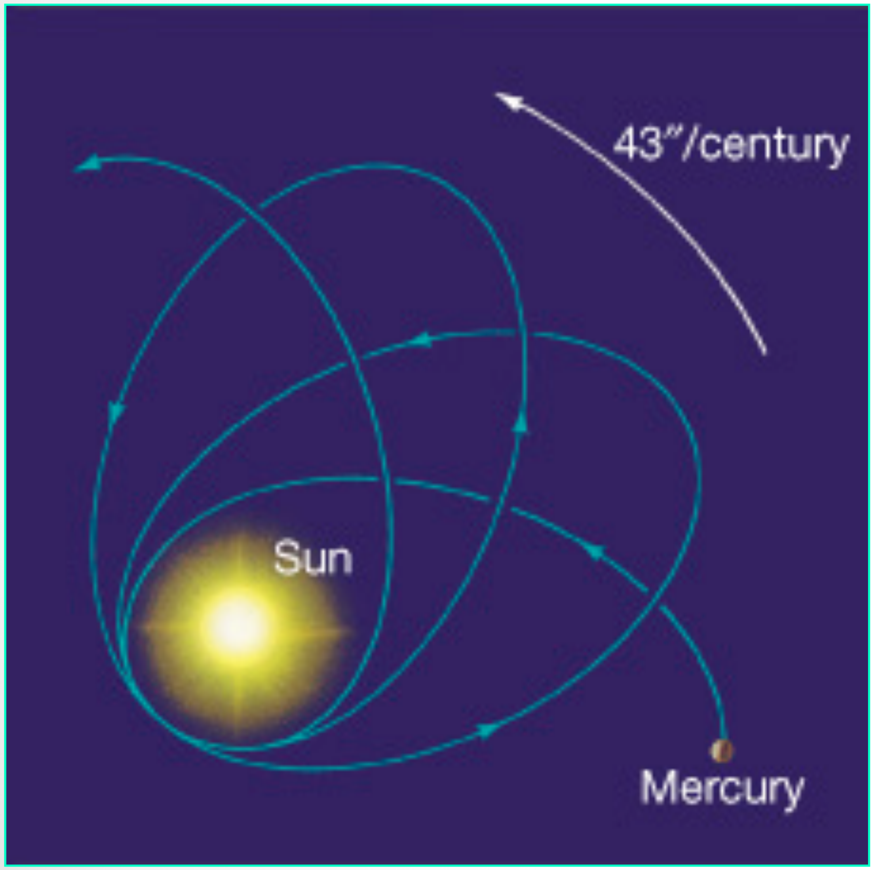
Imagine tossing a shotput onto your bed and rolling marbles at different speeds and distances from the shotput. (also imagine that you have a frictionless blanket on the bed).



The marbles that are moving slowly or close will fall down toward the shotput. If you look from above, it will appear as if the marbles were attracted to the shotput.



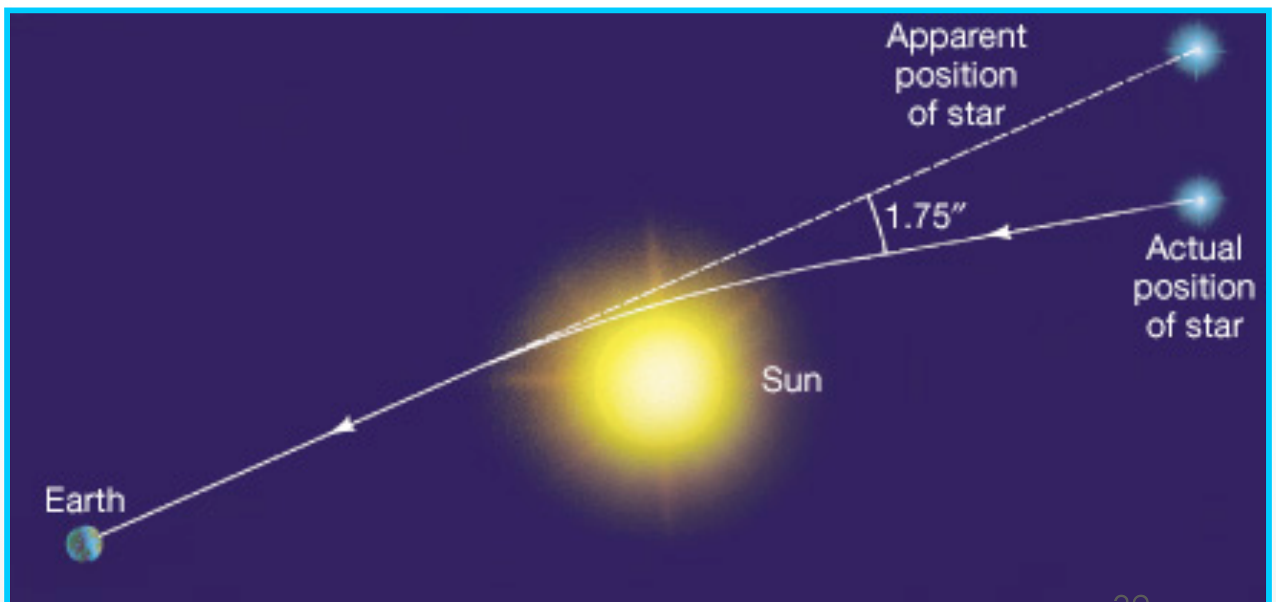
Fabric of Space



- This is a RADICALLY different view of the Universe and gravity
- In regions where space is not strongly curved, GR reduces to Newton's law of gravity
- Einstein pointed out his new theory would explain the Precession of the Perihelion of Mercury

The Deflection of Starlight

- There were several other predictions of GR, one important one was that light rays would also follow straight lines through curved space.



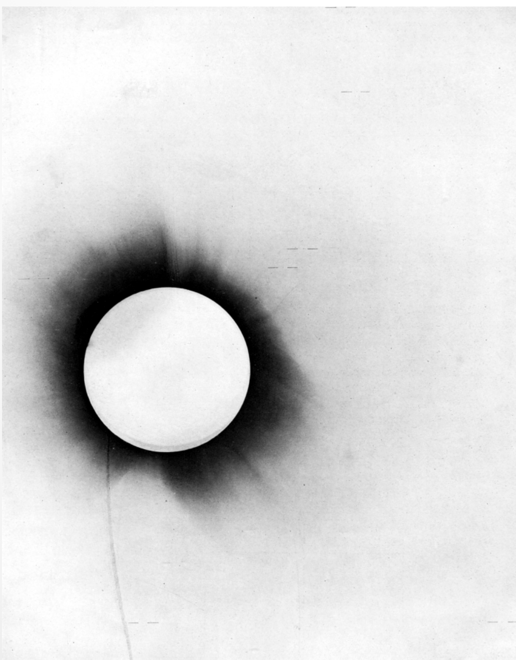
Tests of GR

- GR also predicted that *time would slow* in strongly curved space. This was verified experimentally in 1958.

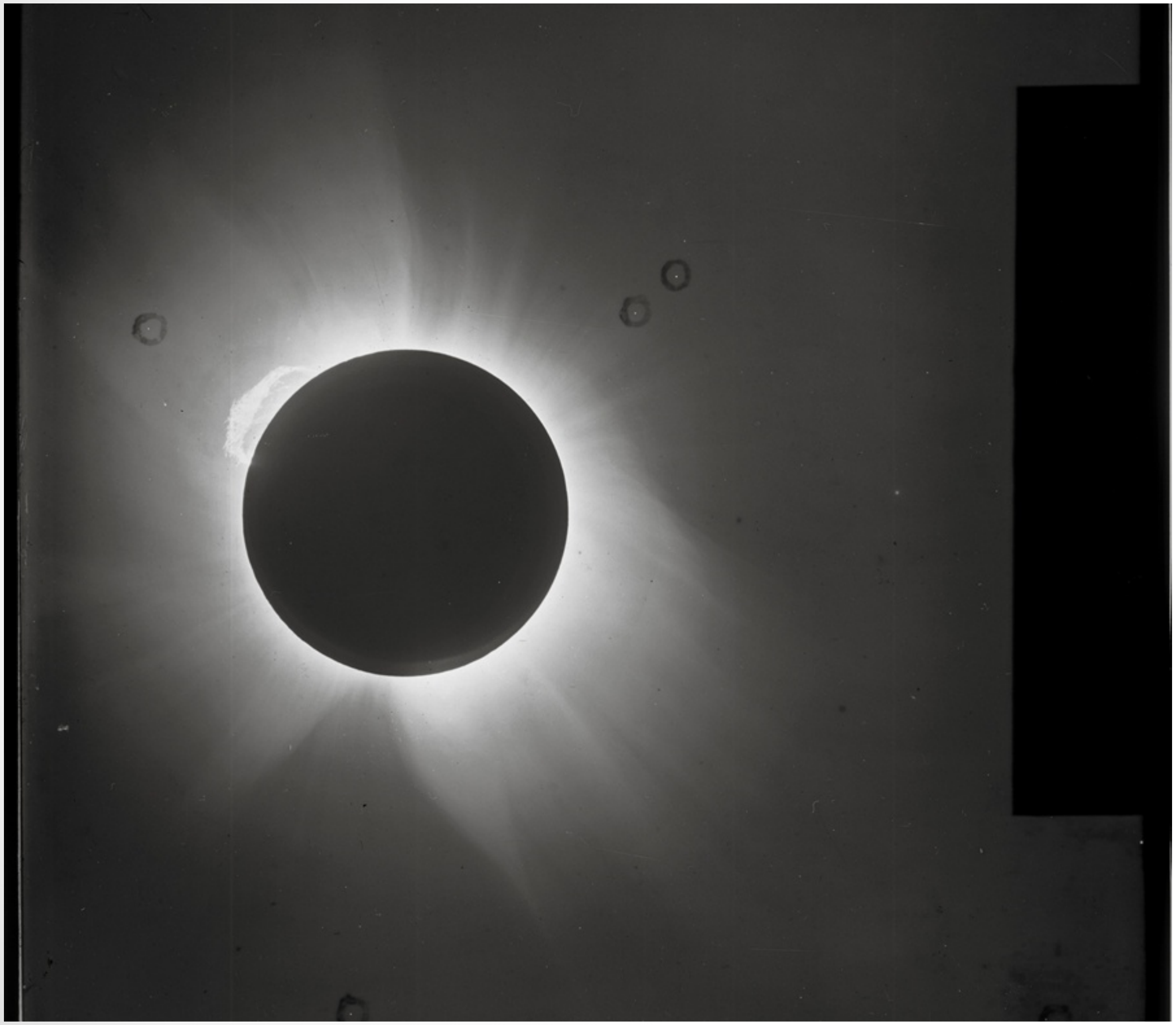
Pound-Rebka experiment essentially measured the rate of time at the top and bottom of a tall building through the effects of gravitational redshift

The Great Test GR

- In 1919, during a total eclipse of the Sun, the deflection of starlight for stars near to the limb of the Sun was measured by Eddington with observations from West Africa and Brazil



- It was announced that Einstein's prediction was correct and it was front-page news worldwide
- However, it was fairly quickly established that the observational errors were too large and the test was inconclusive



* * *

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

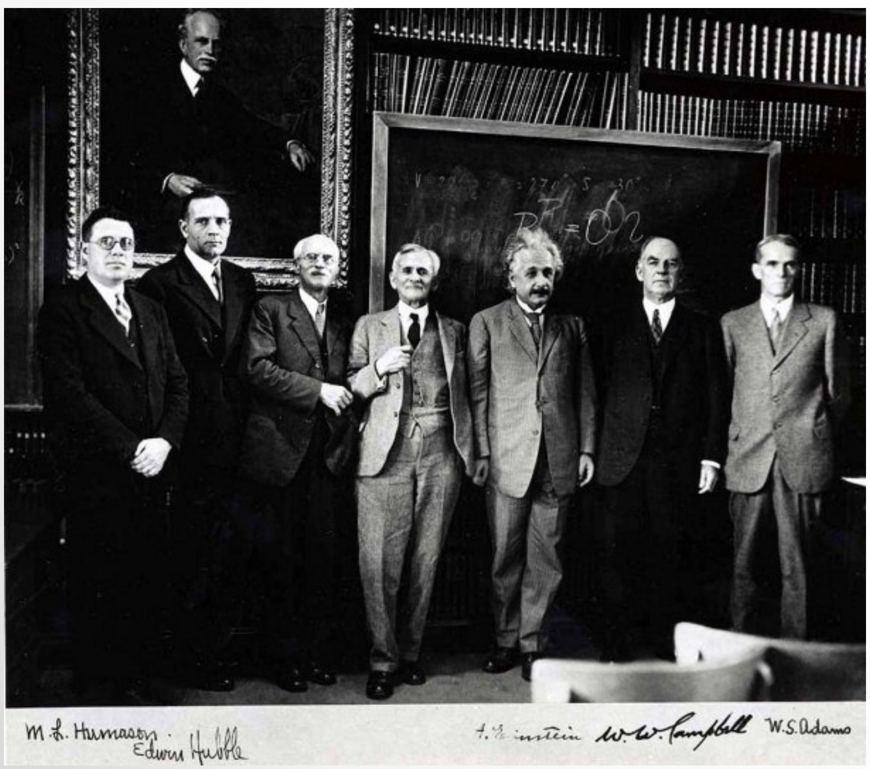
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Special Cable to THE NEW YORK TIMES.

LONDON, Nov. 9.—Efforts made to put in words intelligible to the non-scientific public the Einstein theory of light proved by the eclipse expedition so far have not been very successful. The new theory was discussed at a recent meeting of the Royal Society and Royal Astronomical Society, Sir Joseph Thomson, President of the Royal Society, declares it is not possible to put Einstein's theory into really intelligible words, yet at the same time Thomson adds:

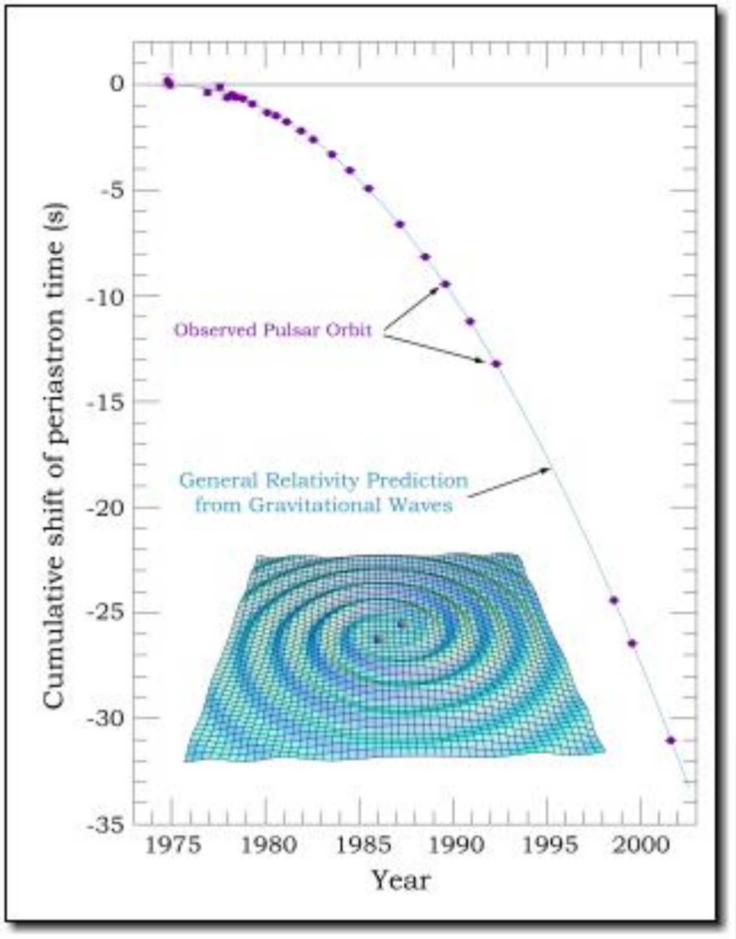
Lick Observatory and GR

The data from the famous eclipse expedition of 1919 weren't good enough to prove or disprove Einstein's theory. Lick Observatory Director WW Campbell made it the goal of the Observatory to carry out the observations that eventually supported GR.



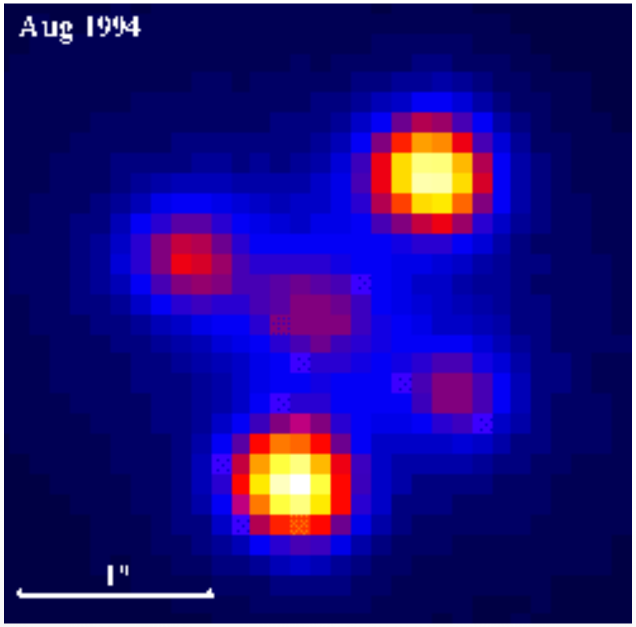
More tests of GR

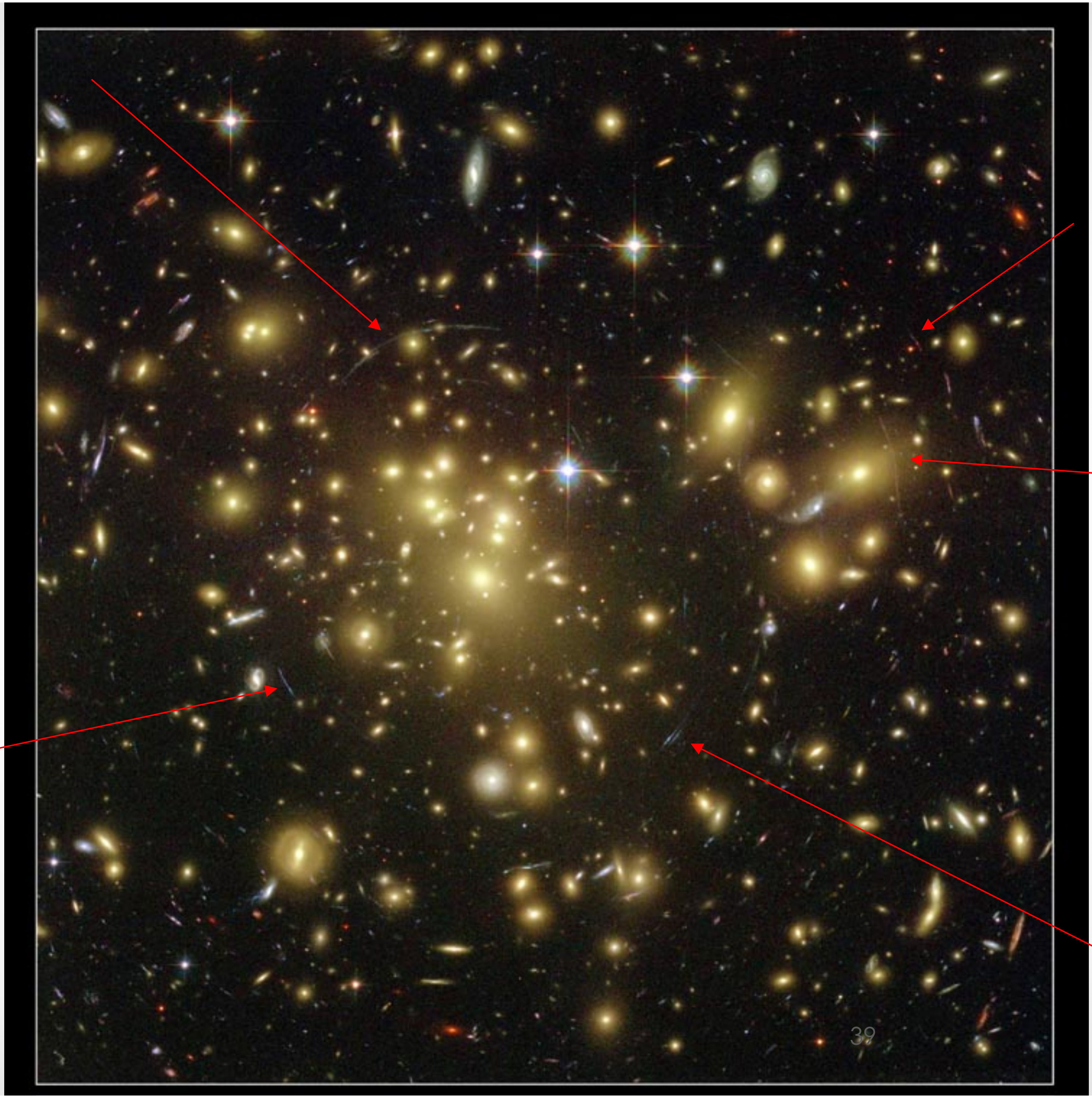
- There is now a long list of predictions made by GR and in every case to date, observations have they have been consistent with the theory.
- Binary pulsar spin down
- Gravitational Waves

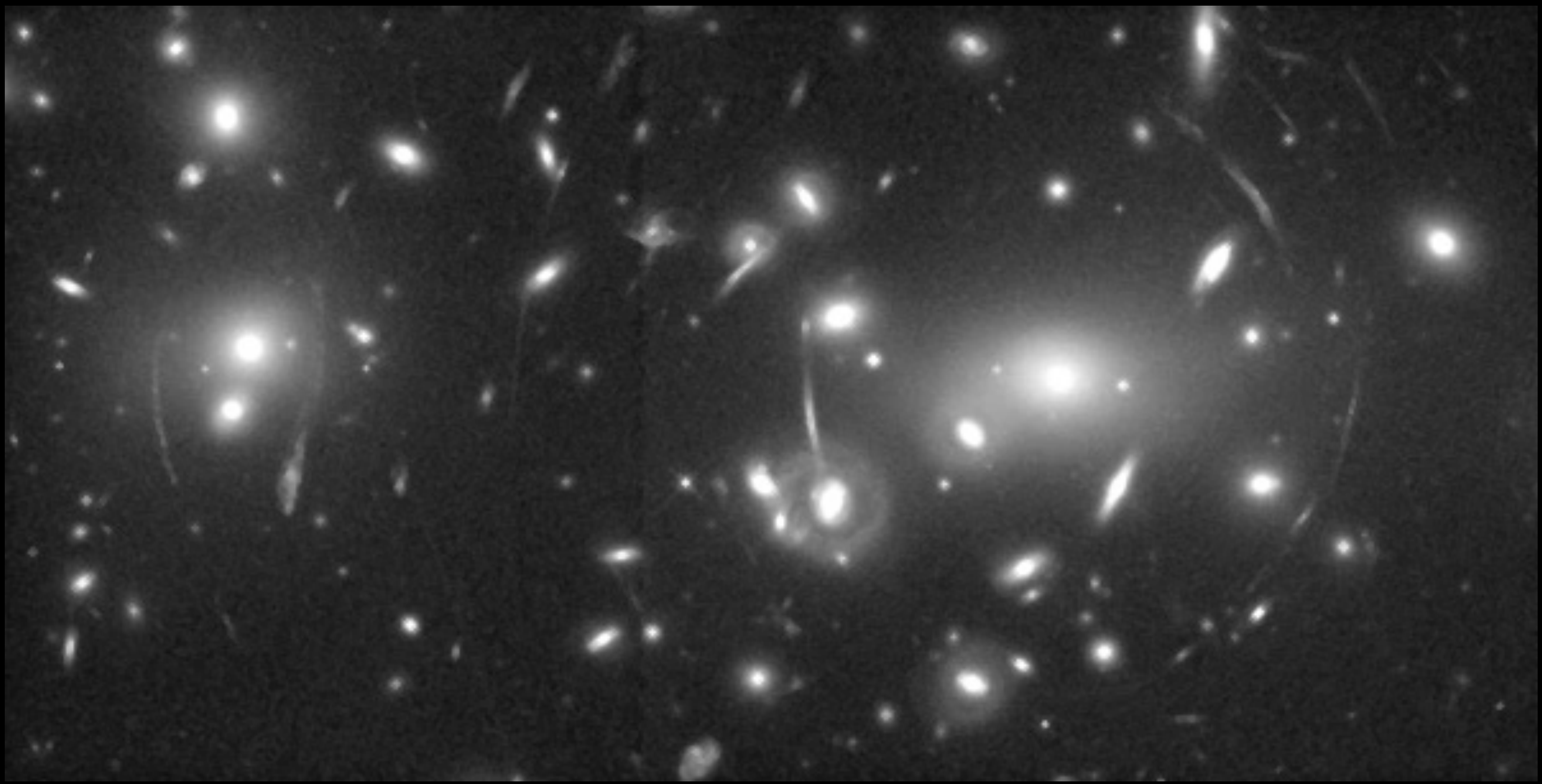


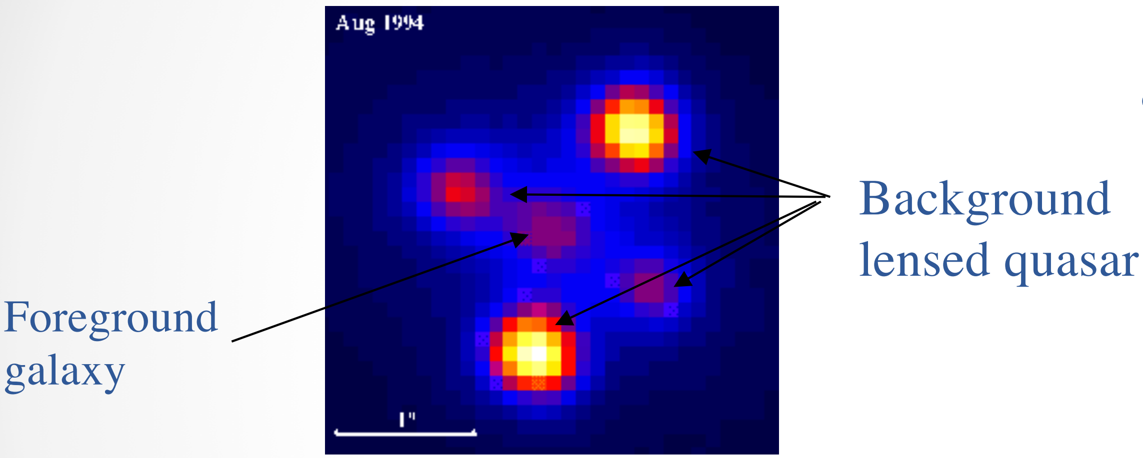
The Bending of Light II

- The bending of light in GR leads to some very useful and interesting phenomenon.
- One is the effect called a gravitational lens.
- The light from a distant galaxy is bent by a large mass along the line of sight to to Earth. If everything is lined up perfectly, you get an "Einstein Ring". Very useful for identifying and measuring "Dark Matter"









- It is rare to have a close-to-perfect alignment. The more common case is to have a set of discrete images.

On to Black Holes

- The second very interesting aspect of light bending in General Relativity is the idea of Black Holes. It starts with the concept of escape velocity.

Escape Velocity

- Imagine feebly tossing a rocketship up in the air. It falls back to Earth because its kinetic energy was less than its gravitational potential energy.
- However, toss it with a larger and larger velocity and it will go higher and higher before falling back to Earth.
- There is a velocity above which it will not return to Earth -- this is the escape velocity.

Escape Speed

- To determine the escape speed from Earth you set the gravitational potential energy equal to kinetic energy and solve for speed

$$\frac{1}{2}mv^2 = \frac{GmM}{R}$$

$$v_{escape} = \sqrt{\frac{2 \times G \times M}{R}}$$

Mass of the escaping object

Mass of the object from which you want to escape

Radius from which you want to escape

Escape Speed II

- Note that the escape speed doesn't depend on the mass of the escaping body.
- For the Earth, put in the mass and radius of the Earth (for escape from the surface of the Earth) and you get:

$$V_{esc} = 11 \text{ km/sec} = 25{,}000 \text{ miles/hr}$$

Escape Speed III

Suppose you increase the mass of the Earth by a factor of 4 without changing its radius. What happens to V_{esc} from the surface of the higher-mass Sun? (iClicker quiz)

A. Escape speed will be higher
B. Escape speed will be lower

$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

$$V_{esc} \propto \sqrt{M}$$

Escape Speed III

Suppose you shrink the Earth to 1/100 of its current radius (at constant mass). What happens to V_{esc} from the surface of the smaller Earth? (iClicker quiz)

A. Escape speed is 1/100 of the original
B. Escape speed is 1/10 of the original
C. Escape speed is 100 times the original
D. Escape speed is 10 times the original

$$V_{esc} = \sqrt{\frac{2GM}{R}}$$

$$V_{esc} \propto \sqrt{\frac{1}{R}}$$

Escape Speed

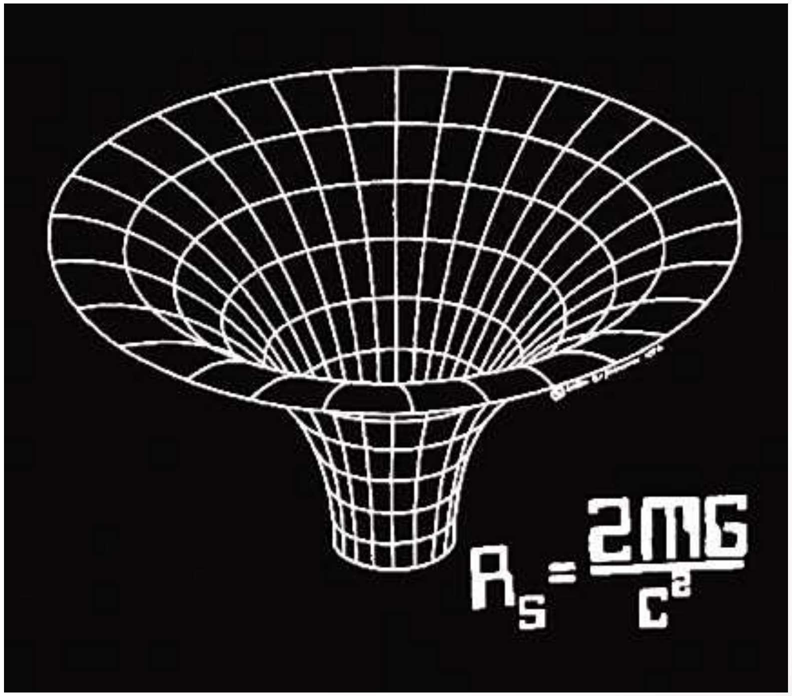
Reduce the radius of the Earth to 1cm and

V_{esc}=c (speed of light)

- In this new theory of Gravity, where photons are affected by gravity, if the escape velocity equals or exceeds the speed of light, that object can no longer be observed. This is a Black Hole

Black Holes

- The critical radius for which an object of a particular mass has an escape velocity of equal to the speed of light is called the *Schwarzschild Radius*.
- The surface at his radius is called the "Event Horizon".



Schwarzschild Radius

- You can easily calculate the Schwarzschild radius for any mass by setting $V_{esc}=c$

$$V_{esc} = c = \sqrt{\frac{2MG}{R_s}}$$

$$c^2 = \frac{2MG}{R_s} \Rightarrow R_s = \frac{2MG}{c^2}$$

- Every object has a radius at which it becomes a Black Hole

Black Holes

- But, it is VERY, VERY difficult to compress an object to its Schwarzschild radius.
- For the Sun, you would have to somehow overcome:
  - thermal pressure
  - e- degeneracy
  - neutron degeneracy

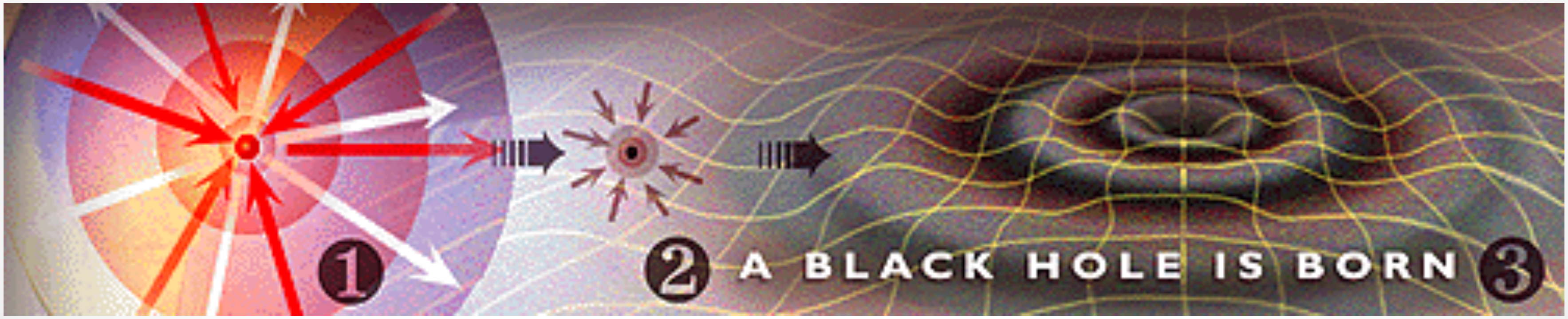
We know of no `cosmic vice' that can do that.

Black Holes

- But, go back to a neutron star and we are building a pretty big vice. Thermal pressure has already been overcome as has e- degeneracy pressure.
- And, there is a limit to the pressure that can be generated by neutron degeneracy. Its hard to calculate, but is probably between $2M_{\odot}$ and $3M_{\odot}$

Black Holes

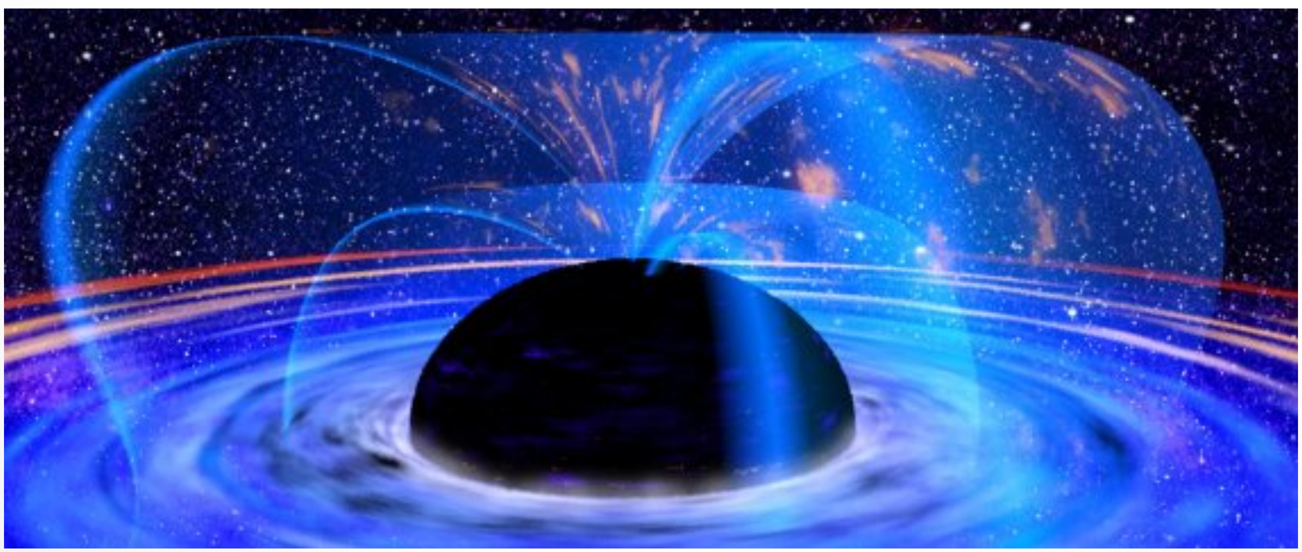
- Think about the 1.4$M_\odot$ n-star core of a SNII explosion. If say 1.6$M_\odot$ of material falls back, the core will exceed the neutron degeneracy limit and undergo collapse to zero volume (what?).



Black Holes

- What is left behind?
  - The gravitational force (i.e. a warp in spacetime) including a "singularity" at the center of the warp
  - An Event Horizon with radius given by

$$R_{Sch}=8.9\text{km (for } 3M_{Sun} \text{ black hole)}$$



Black Hole FAQs

- What would happen if the Sun collapsed into a Black Hole, would the Earth be dragged in?

No, the gravitational force at the distance of the Earth would not change

- Is the Event Horizon a physical boundary?

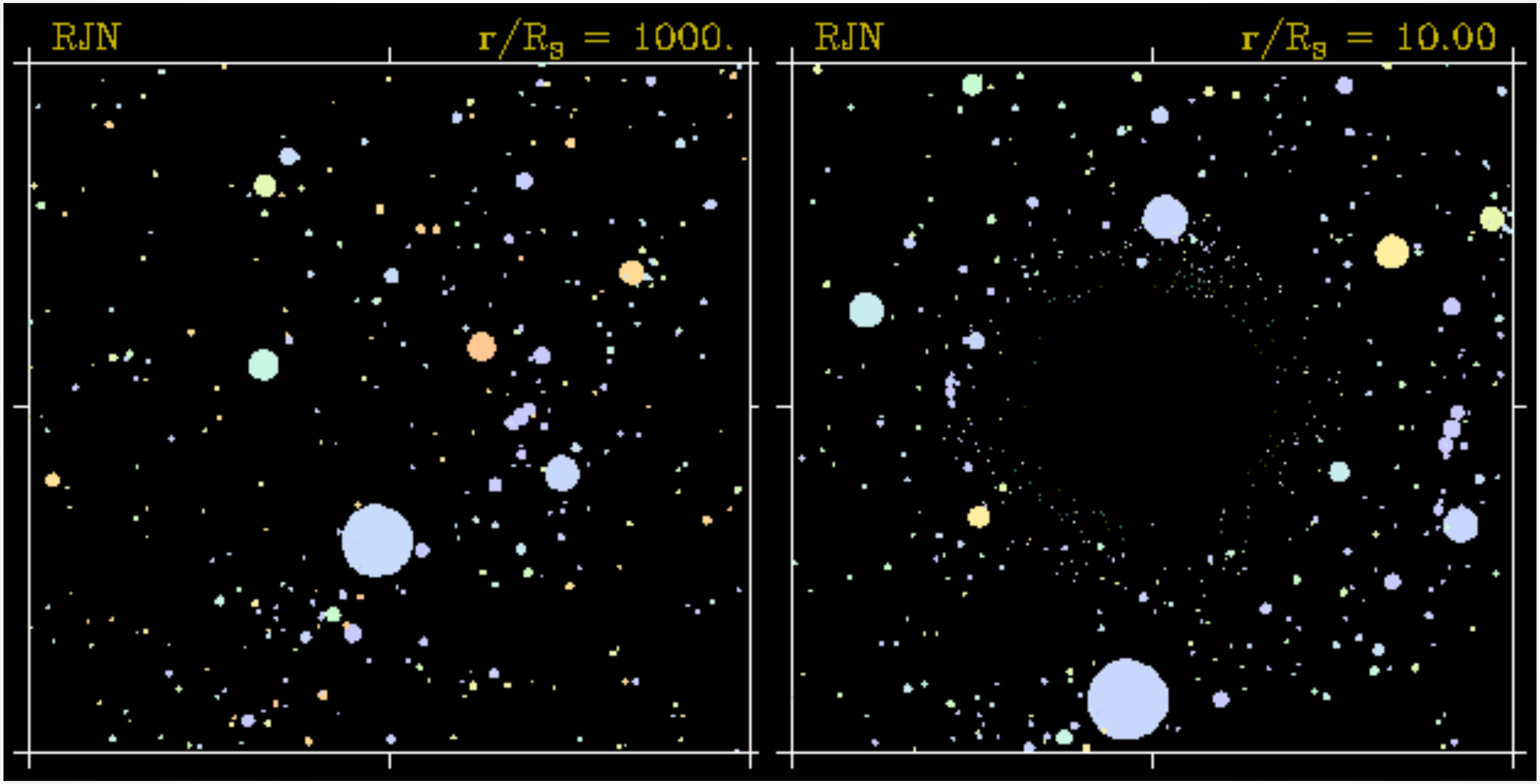
  No, it is the distance from the center where the escape velocity of `c'.

- What happens if a Black Hole absorbs some mass?

  As M increases, the Schwarzschild radius also increases.

- Is there any reason to believe that Black Holes exist? Yes!

This would be great. But not too likely…

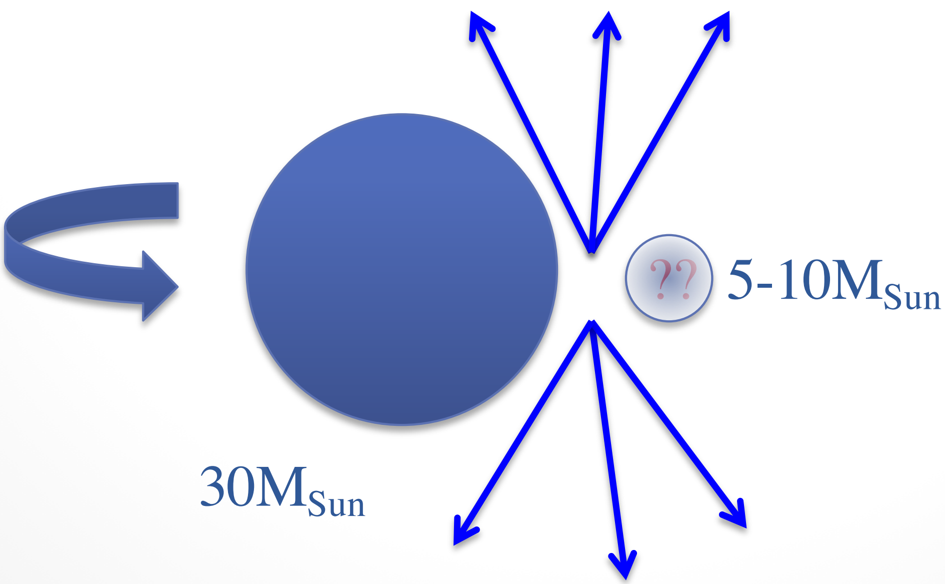


Black Hole Evidence

- The best stellar-mass cases are binary x-ray sources. Cygnus X-1 is a good example.

Black Hole Evidence

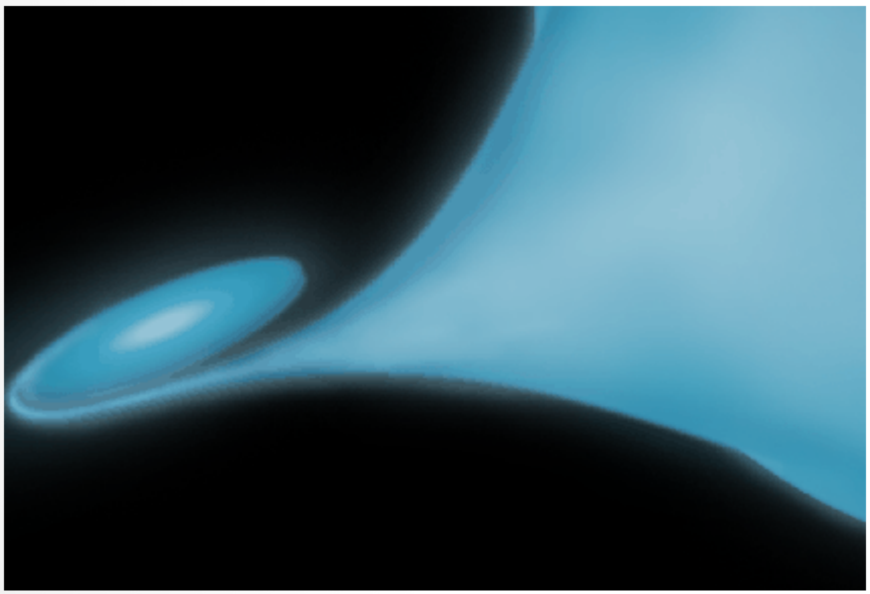
- Cyg X-1 is a bright x-ray source. Look there in the visual part of the spectrum, we see a $30M_{Sun}$ blue main-sequence star which is a spectroscopic binary with a period of 5.6 days.
- The companion has a mass of between 5 and $10M_{Sun}$. What is it?



Cygnus X-1

- There is no sign of the companion at any wavelength (but, remember the x-rays) so what is it?
  1) A red giant would be easily seen
  2) A main-sequence star would be seen with a little effort
  3) Can't be a WD because $M>1.4M_{\odot}$
  4) Can't be a n-star because $M>3M_{\odot}$

Cygnus X-1



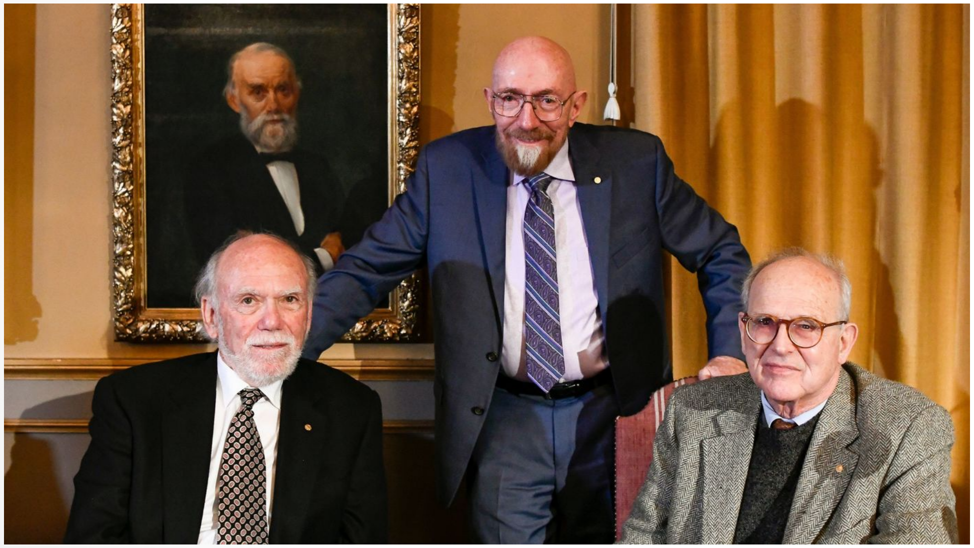
- By elimination, we are left with a black hole
- The x-rays back this up. In an accreting WD we see UV radiation, in a neutron-star we see `soft' x-rays, in Cyg X-1 we see `hard' x-rays because the accreting material falls into a deeper potential well.

Stellar-mass Black Holes

- We now have a few dozen excellent stellar-mass black hole candidates and few people doubt that such objects exist.
- There are also various claims that x-ray transients are black holes accreting little bits of stuff.

LIGO

- Rainer Weiss and Joe Weber started working on an idea from two Soviet physicsts to measure gravitational waves in the 1960s. Kip Thorne and Ron Drever at Caltech started working on the experiment and nature of the expected signals.



Look up Gabriela Gonzales TED talk for more information on GW

- Shotgun marriage at NSF launched LIGO and searched unsuccessfully for Gravitational Waves from 2002 - 2010

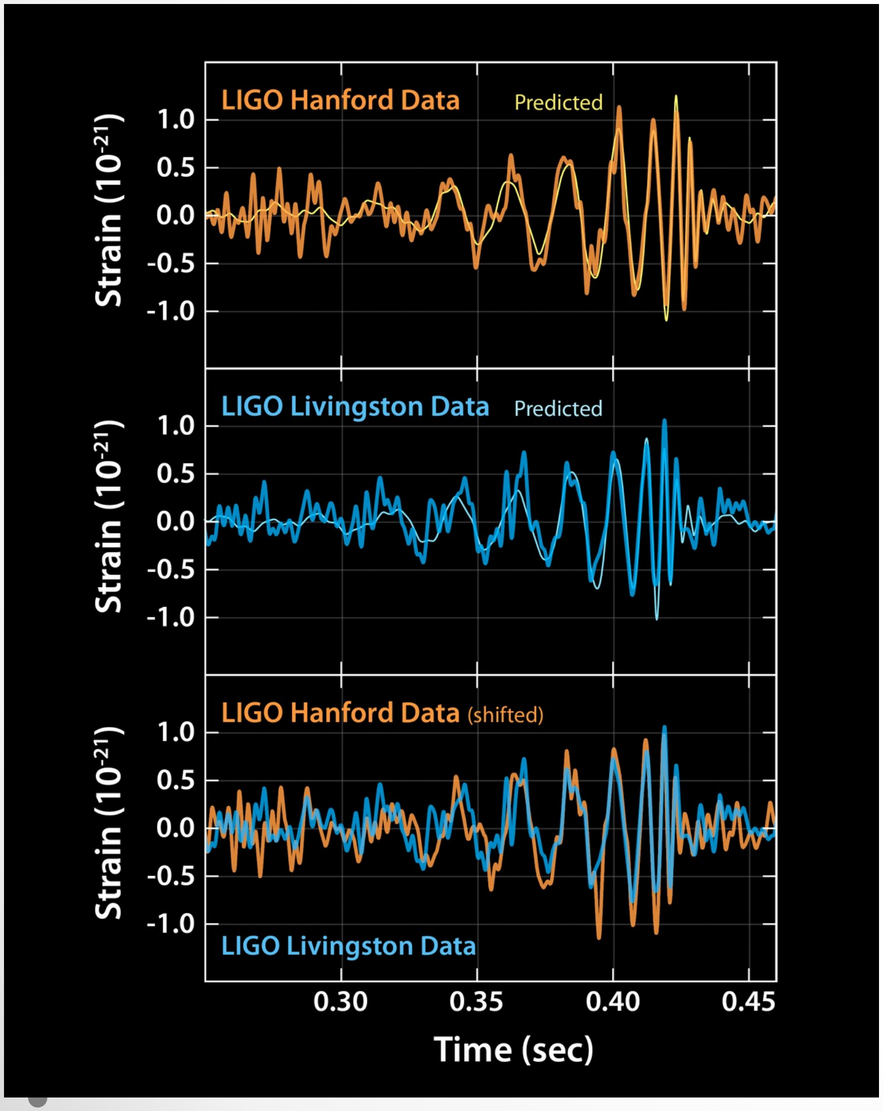
LIGO

Idea is to fire lasers along two 4-km-long arms to produce an interferogram and measure the distances between two mirrors at each end of each arm to about 10^{-4} the diameter of a proton (!!??)

Controlling all sources of vibration to this level is an extremely daunting job

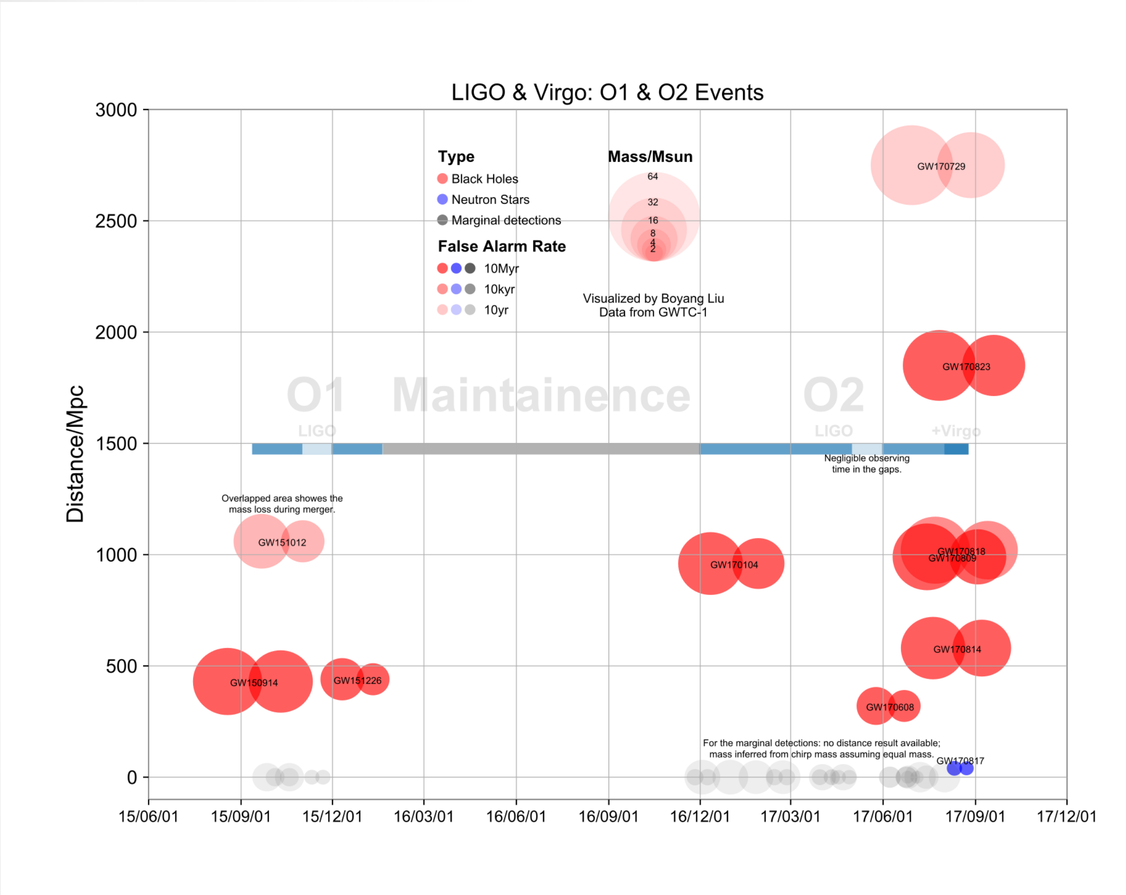
Two independent experiments were built separated by 1900 miles

LIGO success



- 14 Sept 2015, just two days after a major upgrade, the LIGO consortium announced the first detection of gravitational waves
- The signal matched predictions for merging black holes and the "ring down" of the resulting single black hole with amazing accuracy
- The black hole masses of 29 and 36 solar masses each was surprising, but now seems common

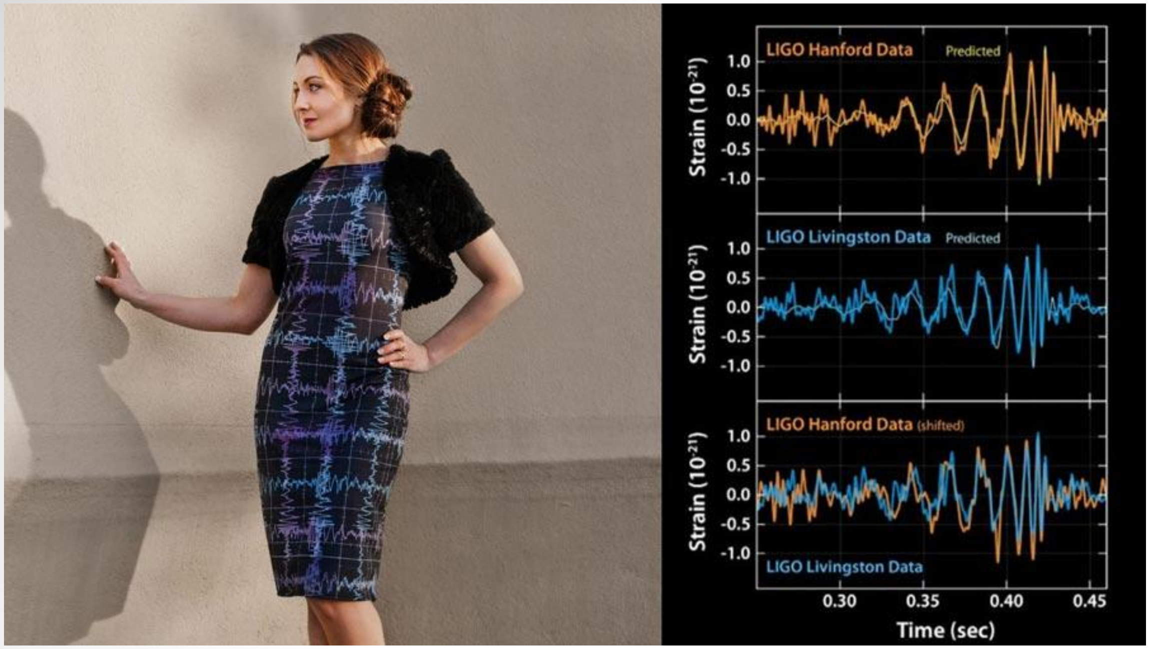
LIGO Black Holes

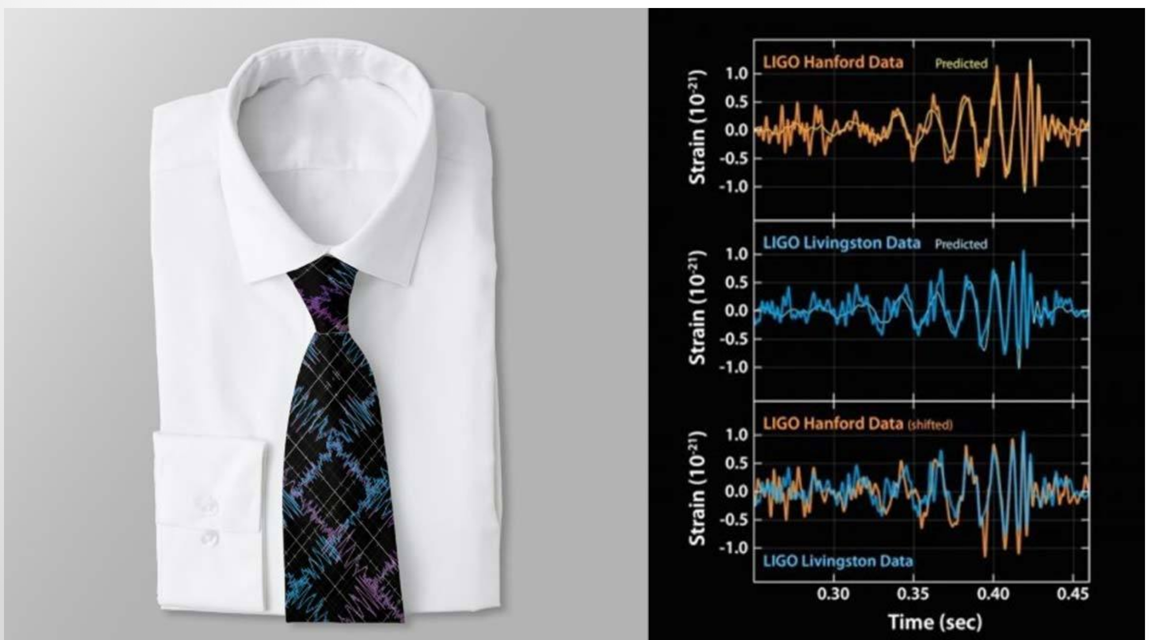


During the first two LIGO observing runs, 10 black hole mergers were discovered

During O3, now underway, the number has doubled

There is a population of 15 – 60 solar mass black holes that had previously eluded detection!





When I was looking up background information on the LIGO discoveries, I started getting targeted ads…

iclicker

Elements heavier than iron (Fe) are primarily produced by what mechanism?

A. The fusion of lighter elements to iron
B. The fission of very heavy elements (i.e. Uranium) into two or more lighter nuclei
C. The addition of neutrons to existing nuclei followed by "beta" decay
D. Helium fusion during the red giant phase of stellar evolution

iclicker

Which is the only true statement about the "event horizon" of a black hole?

A. Time slows to a stop when you reach the event horizon
B. The event horizon is where the gravitational influence of the black holes stops
C. Only black holes with masses greater than $3M_{Sun}$ have an event horizon
D. The escape velocity from a black hole is equal to the speed of light at the event horizon