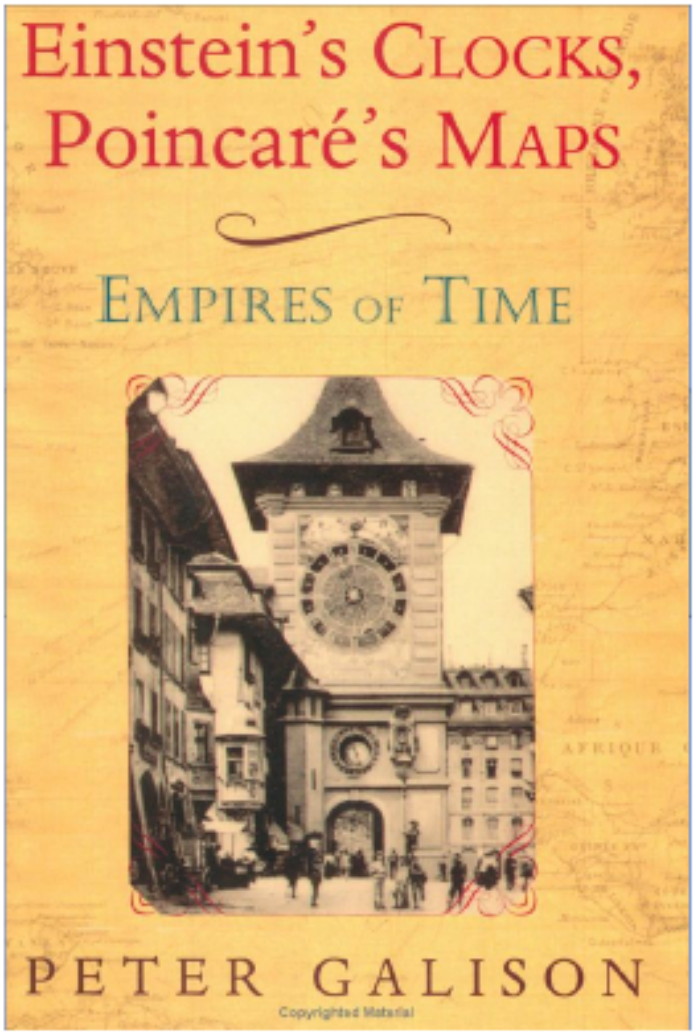
Physics 294H

- Professor: Joey Huston
- email:huston@msu.edu
- office: BPS3230
- Homework will be with Mastering Physics (and an average of 1 hand-written problem per week)
  - **Help-room hours: 12:40-2:40 Monday (note change); 3:00-4:00 PM Friday**
  - **36.73 hand-in problem for next Wed**
- Quizzes by iclicker (sometimes hand-written)
- Average on 2nd exam (so far)=71/120
- **Final exam Thursday May 5 10:00 AM – 12:00 PM 1420 BPS**
- Course website: www.pa.msu.edu/~huston/phy294h/index.html
  - lectures will be posted frequently, mostly every day if I can remember to do so

Interesting book



Year of Physics, March 10, 2005, slide 24

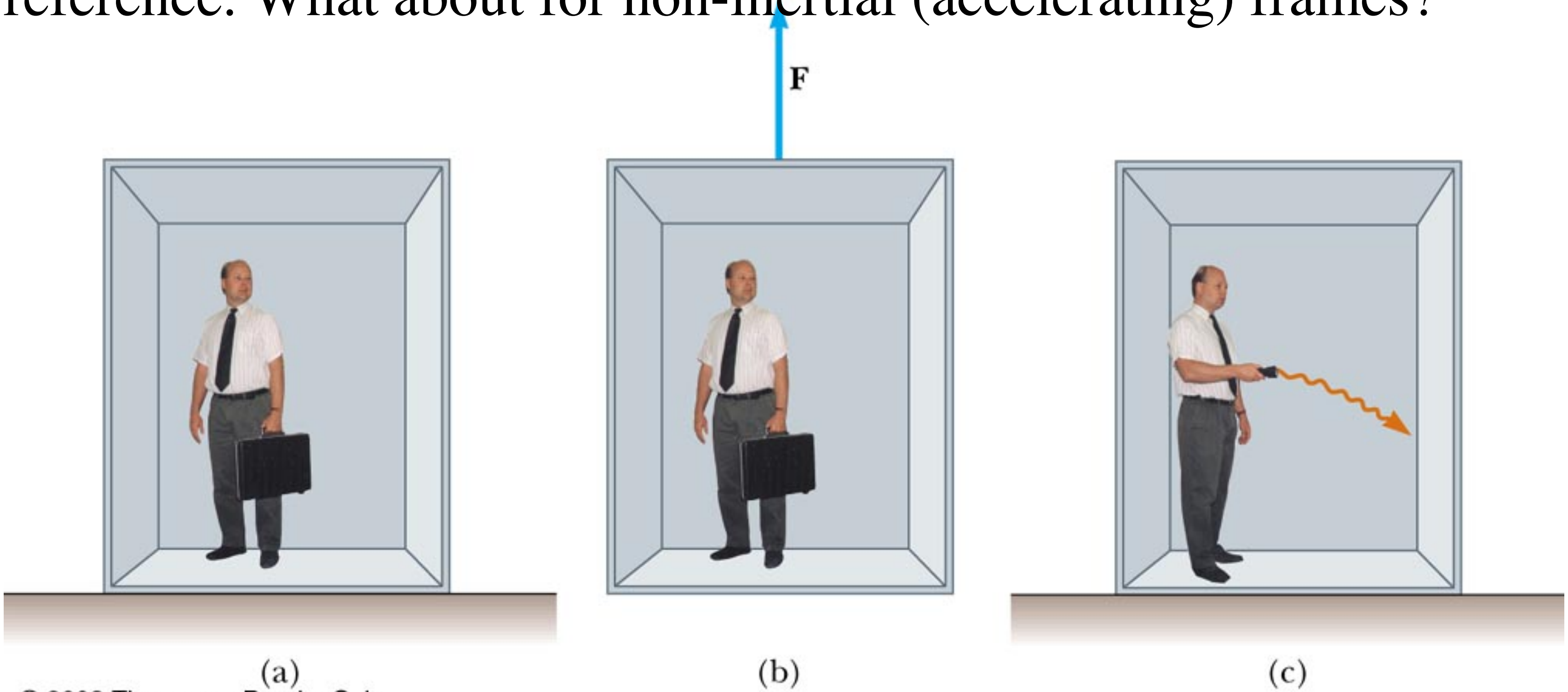
Very interesting section on Einstein's work in the patent office.

It was the synchronization of clocks, a key technological problem of the late 19th century.

Also describes how Poincaré's essays on important open questions in physics led to Einstein's great discoveries of 1905.

General Relativity

We said that special relativity applies for inertial frames of reference. What about for non-inertial (accelerating) frames?

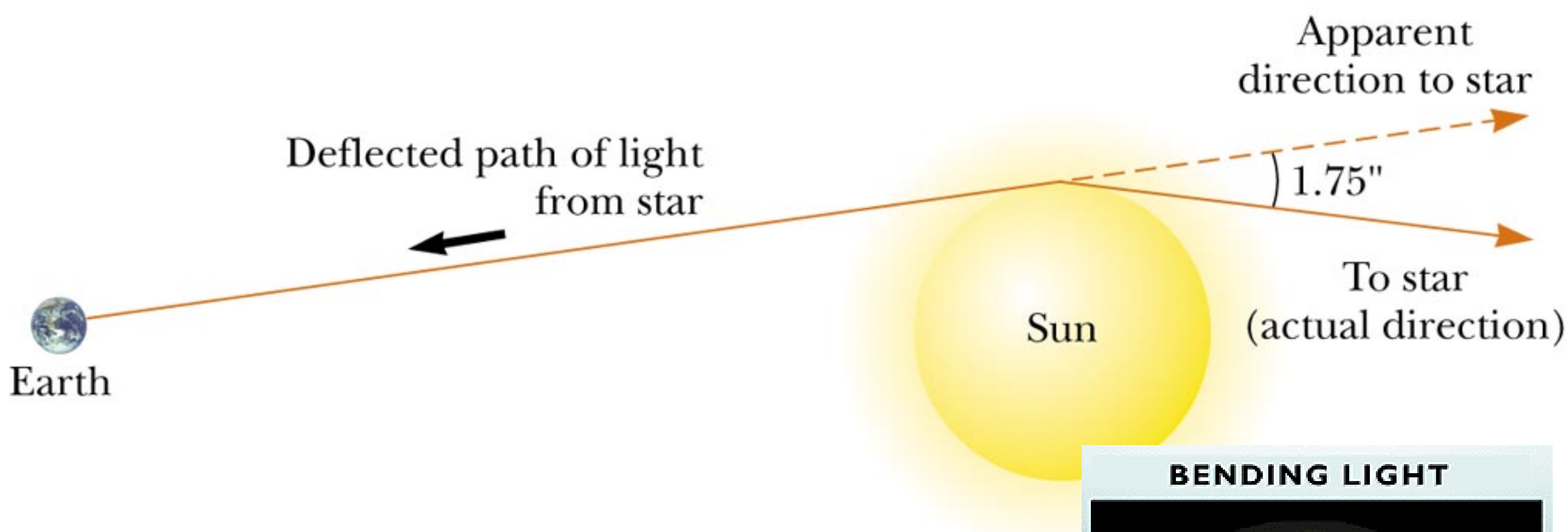


That's the realm of general relativity (also by A. Einstein). His equivalence principle stated that one can not tell the difference between gravity and an accelerating frame of reference.

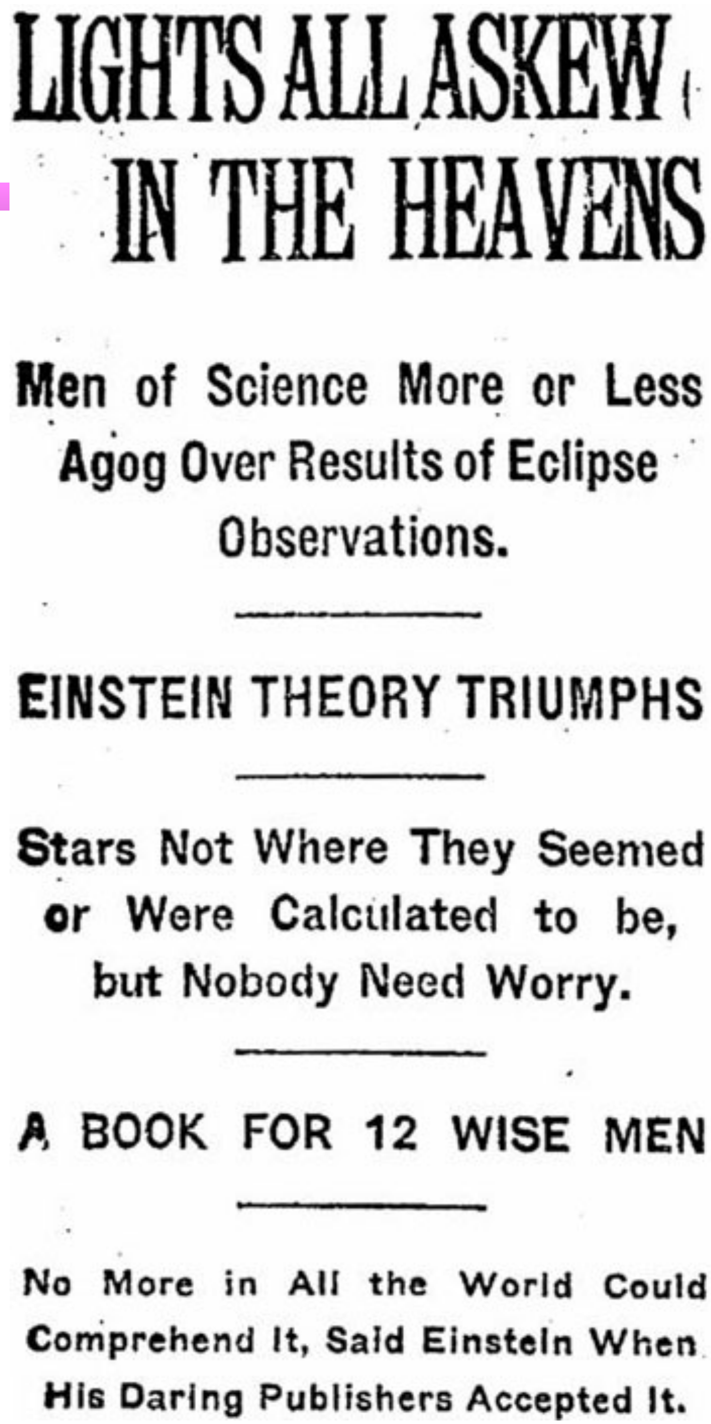
Deflection of starlight by gravity

Energy and mass are equivalent. Starlight has energy; starlight should be affected by gravitational fields.

Einstein's big prediction. Verified by an astronomer (Sir Arthur Eddington) in a total eclipse in 1918.



Einstein became a celebrity.


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

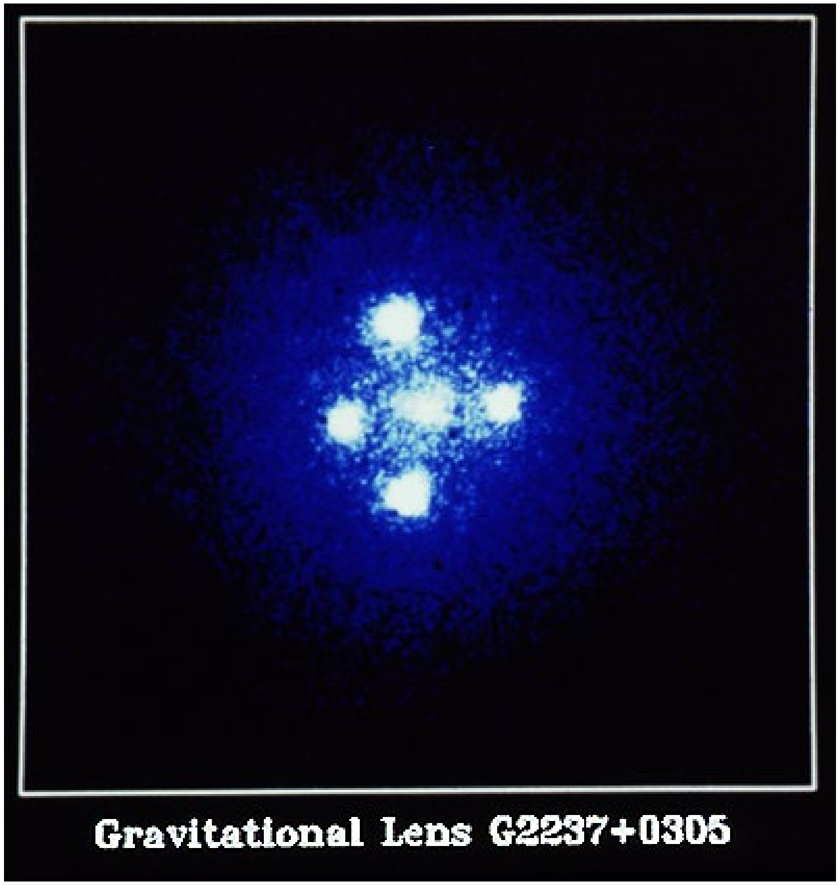
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

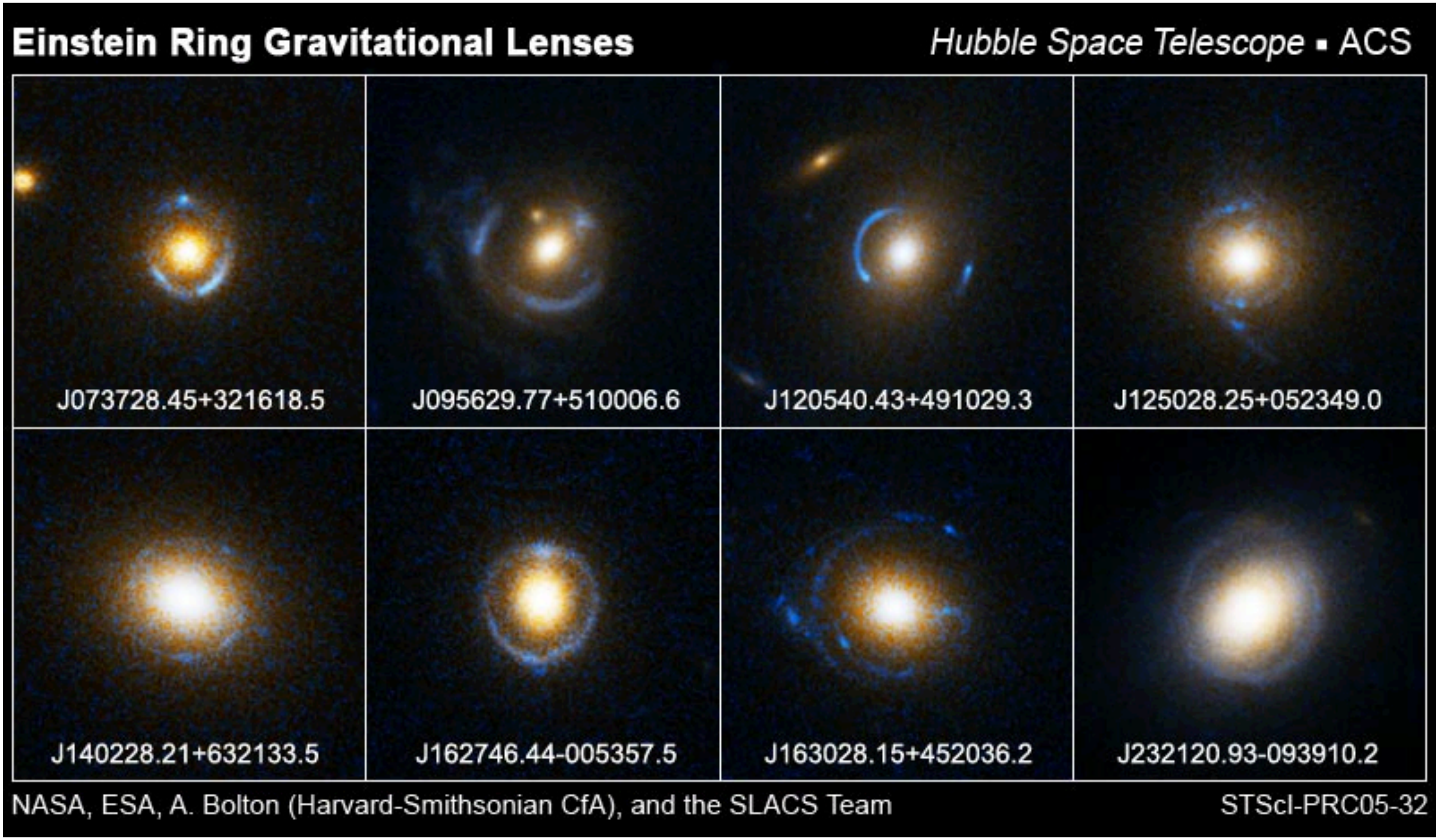
Interestingly enough, the Measurement was supposed to Take place in a 1915 eclipse in Crimea.

Other tests of general relativity: gravitational lensing

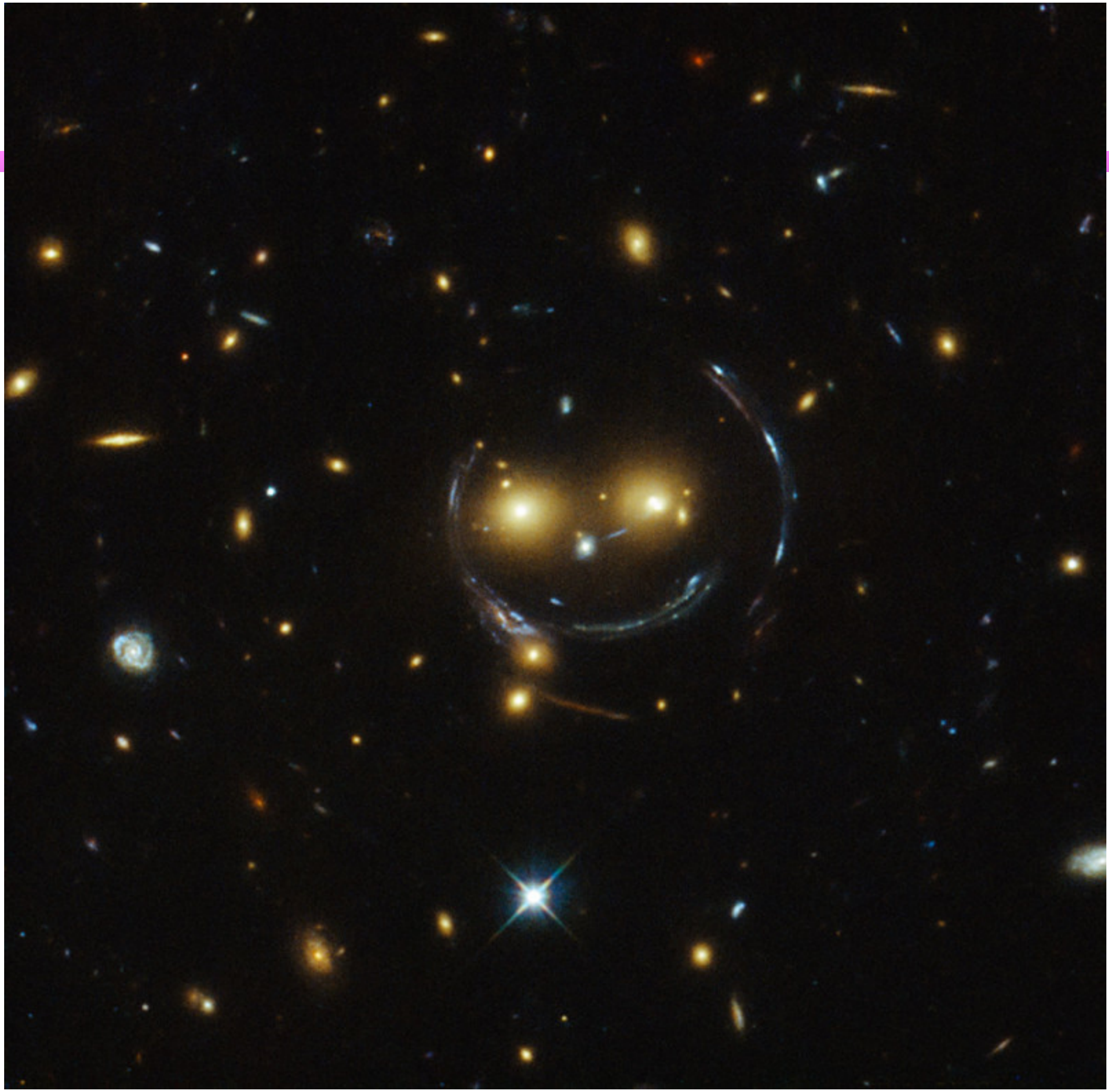
- Four images of the same distant quasar
- The light images are bent by the gravitational effects of an intermediate galaxy

.mov



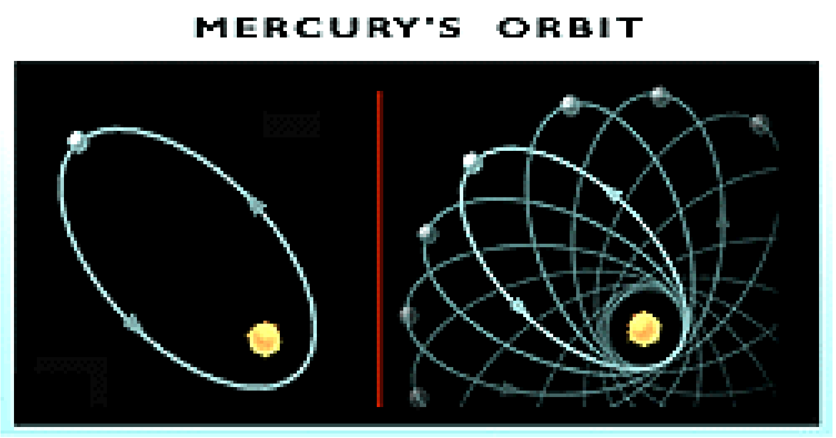


Galaxies a few billion light years away focusing light (into a ring) from galaxies about twice that distance. Perfect alignment results in a ring. Non-perfect alignment results in arcs.



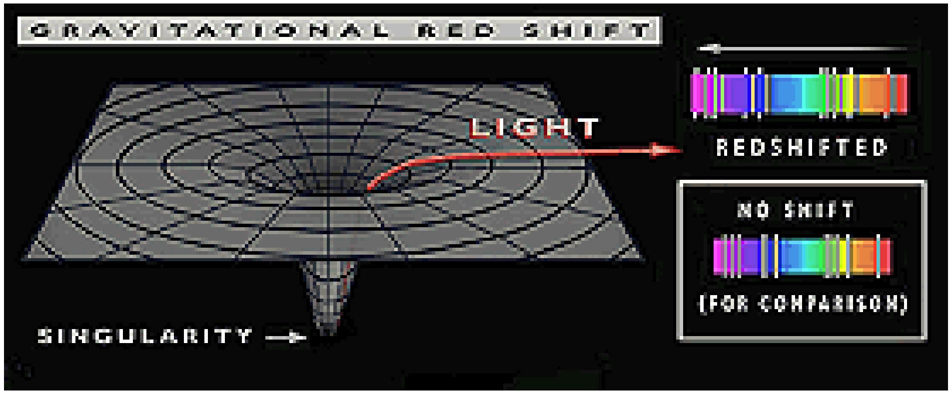
Advance of the perihelion of Mercury

- Since almost two centuries earlier astronomers had been aware of a small flaw in Mercury's orbit around the Sun, as predicted by Newton's laws. As the closest planet to the Sun, Mercury orbits a region in the solar system where spacetime is disturbed by the Sun's mass. Mercury's elliptical path around the Sun shifts slightly with each orbit such that its closest point to the Sun (or "perihelion") shifts forward with each pass. Newton's theory had predicted an advance only half as large as the one actually observed. Einstein's predictions exactly matched the observation.



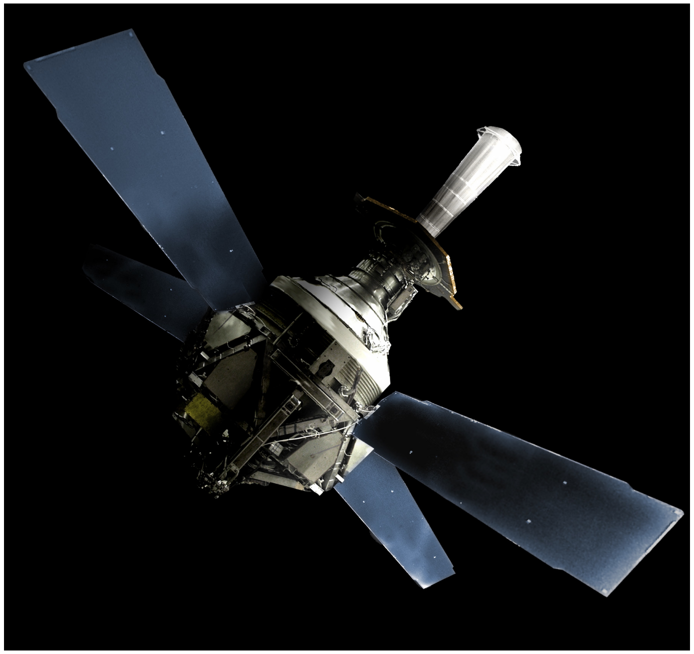
Gravitational redshift

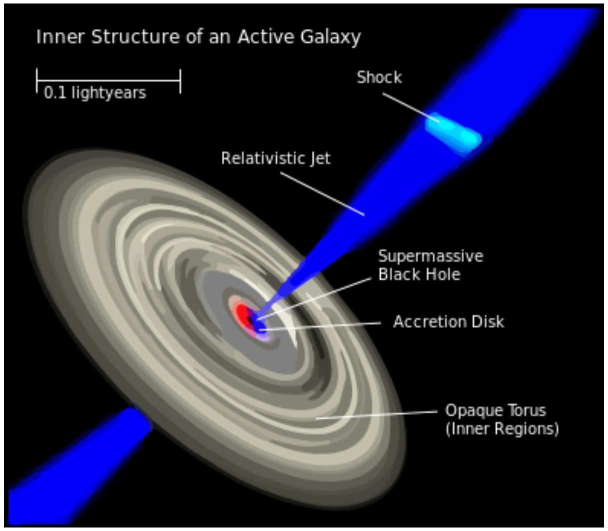
- According to General Relativity, the wavelength of light (or any other form of electromagnetic radiation) passing through a gravitational field will be shifted towards redder regions of the spectrum. To understand this **gravitational redshift**, think of a baseball hit high into the air, slowing as it climbs. Einstein's theory says that as a photon fights its way out of a gravitational field, it loses energy and its color reddens. Gravitational redshifts have been observed in diverse settings.



Frame dragging

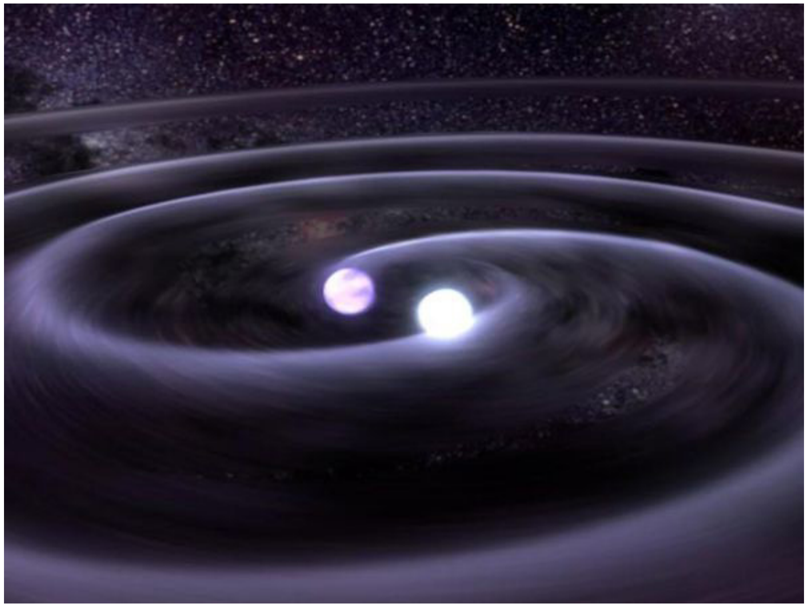
- Frame dragging is an effect on space-time that is due to masses that are non-static, for example rotating
- The rotation of a massive object distorts the space-time metric making the orbit of a nearby object precess
- This does not happen in Newtonian gravity where the gravitation field depends only on its mass, not on its rotation
- This effect was confirmed by the satellite Gravity Probe B
- Also used to explain the production of relativistic jets in active galaxies

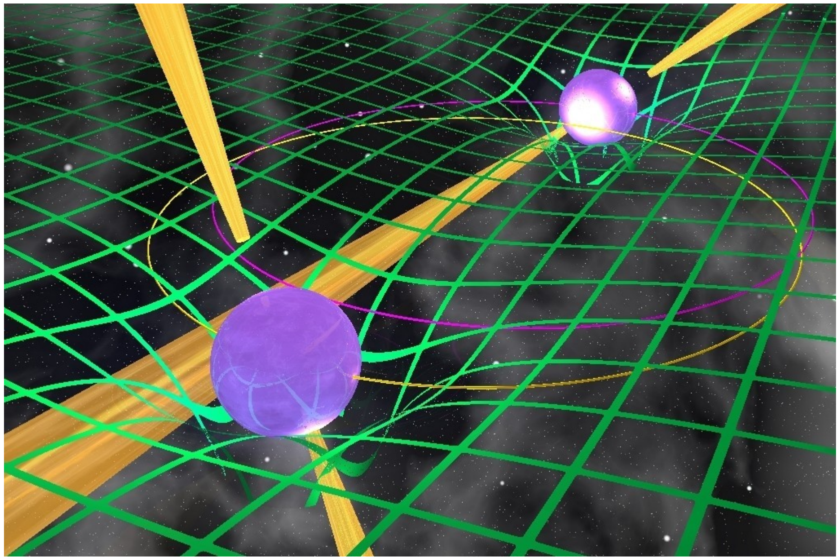




Gravitational waves

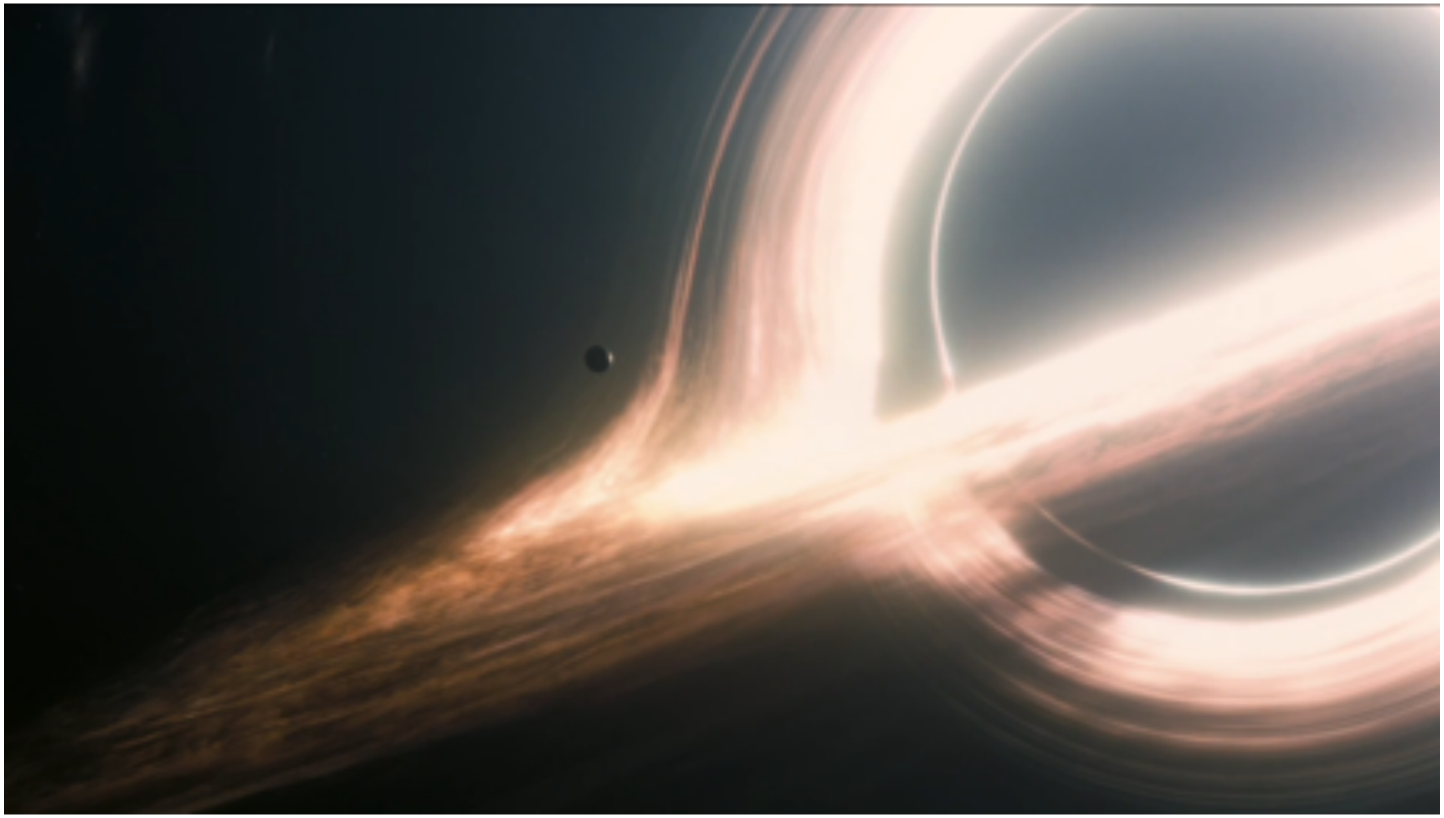
- Hulse and Taylor observed a pulsar (rapidly rotating neutron star) with a period of about 59 ms
- They also observed that there were additional variations with a period of about 7.75 hours, which they interpreted as the pulsar orbiting around another neutron star
- But the orbit was decaying, by about 76.5 microseconds per year, exactly the amount predicted to be carried off by gravitational radiation (7.35×10^{24} Watts)
- They won the Nobel prize in 1974
- Up until this year, this was the best evidence for gravitational waves





Gargantua from Interstellar

- …is supposed to have 100 million times the mass of the Sun
- The Schwarzchild radius is 300 million km (past the orbit of Mars)
- 1 hour on the planet near Gargantua is equal to 7 years on Earth



Time dilation

- Special relativity

$$t_f = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

t_o is proper time

- General relativity (outside of a rotating sphere)

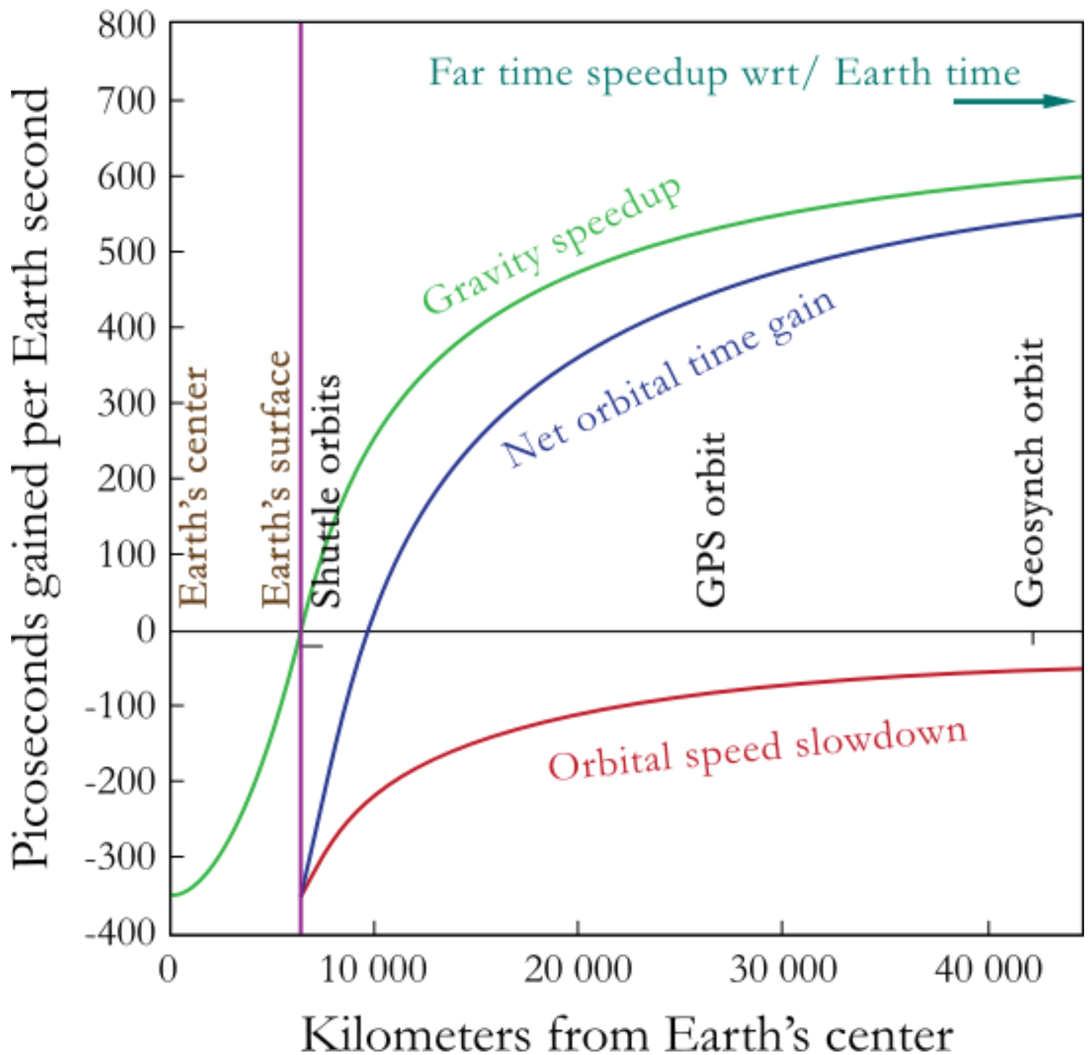
$$t_f = \frac{t_o}{\sqrt{1 - \frac{3}{2}\frac{r_s}{r}}}$$

r_s is Schwarzchild radius

- I don't know the impact of frame dragging on the time dilation; Gargantua is supposed to be rotating at a substantial fraction of the speed of light

Time dilation

- Consider a GPS satellite, in an orbit about 25,000 km above the surface of the Earth
- It is travelling at a speed of several km/sec, so special relativity makes its clock tick more slowly
- But it is in a weaker gravitational field, which makes its clock tick more quickly
- The gravitational effect wins, and time moves more slowly on the Earth than on the GPS satellite
- This effect has to be taken into account in any device using GPS satellites for directions



Einstein field equations

$$G_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

- The Einstein field equations*:* The Einstein field equations (EFE) are the core of general relativity theory. The EFE describe how mass and energy (as represented in the stress-energy tensor) are related to the curvature of spacetime (as represented in the Einstein tensor). In abstract index notation, the EFE reads as shown above where G_{ab} is the Einstein tensor, Λ is the cosmological constant, c is the speed of light in a vacuum and G is the gravitational constant, which comes from Newton's law of gravity.The solutions of the EFE are metric tensors. The EFE, being non-linear differential equations for the metric, are often difficult to solve. The usual strategy is to start with an ansatz (or an educated guess) of the final metric, and refine it until it is specific enough to support a coordinate system but still general enough to yield a set of simultaneous differential equations with unknowns that can be solved for. Metric tensors resulting from cases where the resultant differential equations can be solved exactly for a physically reasonable distribution of energy-momentum are called exact solutions. Examples of important exact solutions include the Schwarzschild solution and the Friedman-Lemaître-Robertson-Walker solution.

Einstein field equations

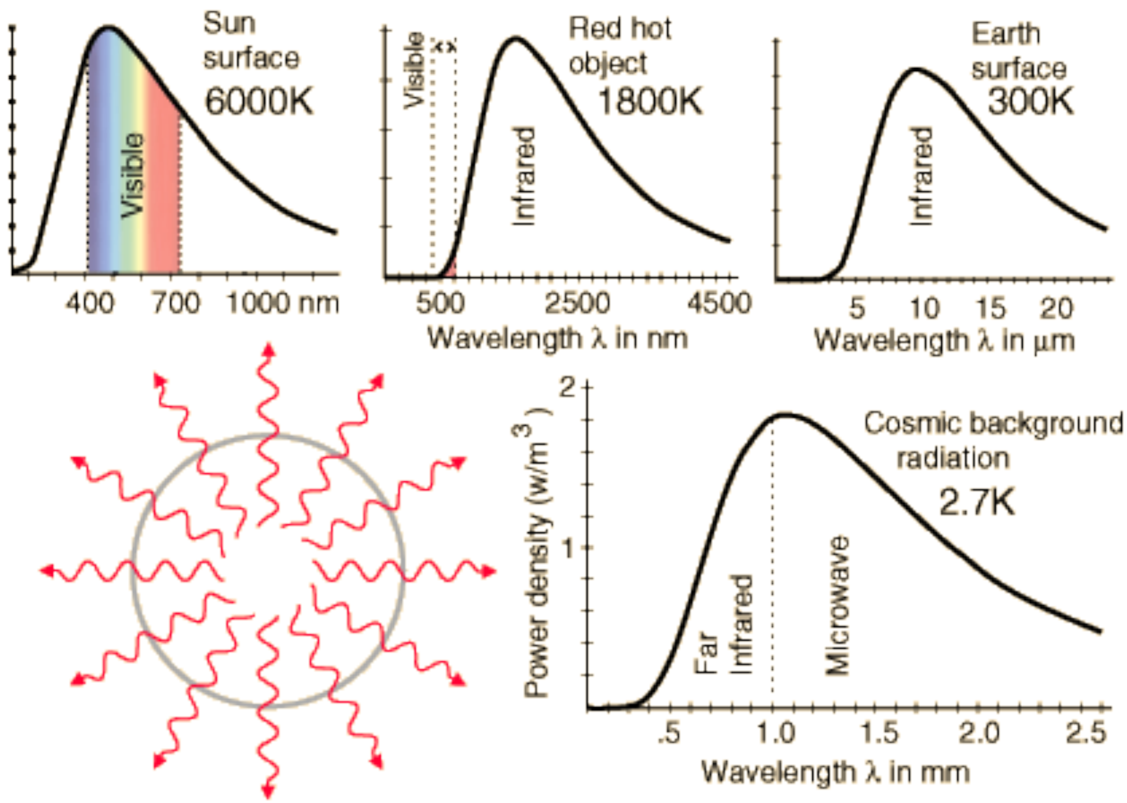
$$G_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

“My greatest blunder.” sincerely, Albert Einstein

…because without the cosmological constant the universe could not be ttatic and would have to be expanding

But in the 1960’s Penzias and Wilson discovered the remnants of the Big Bang that started the universe expanding

What were they really looking for?



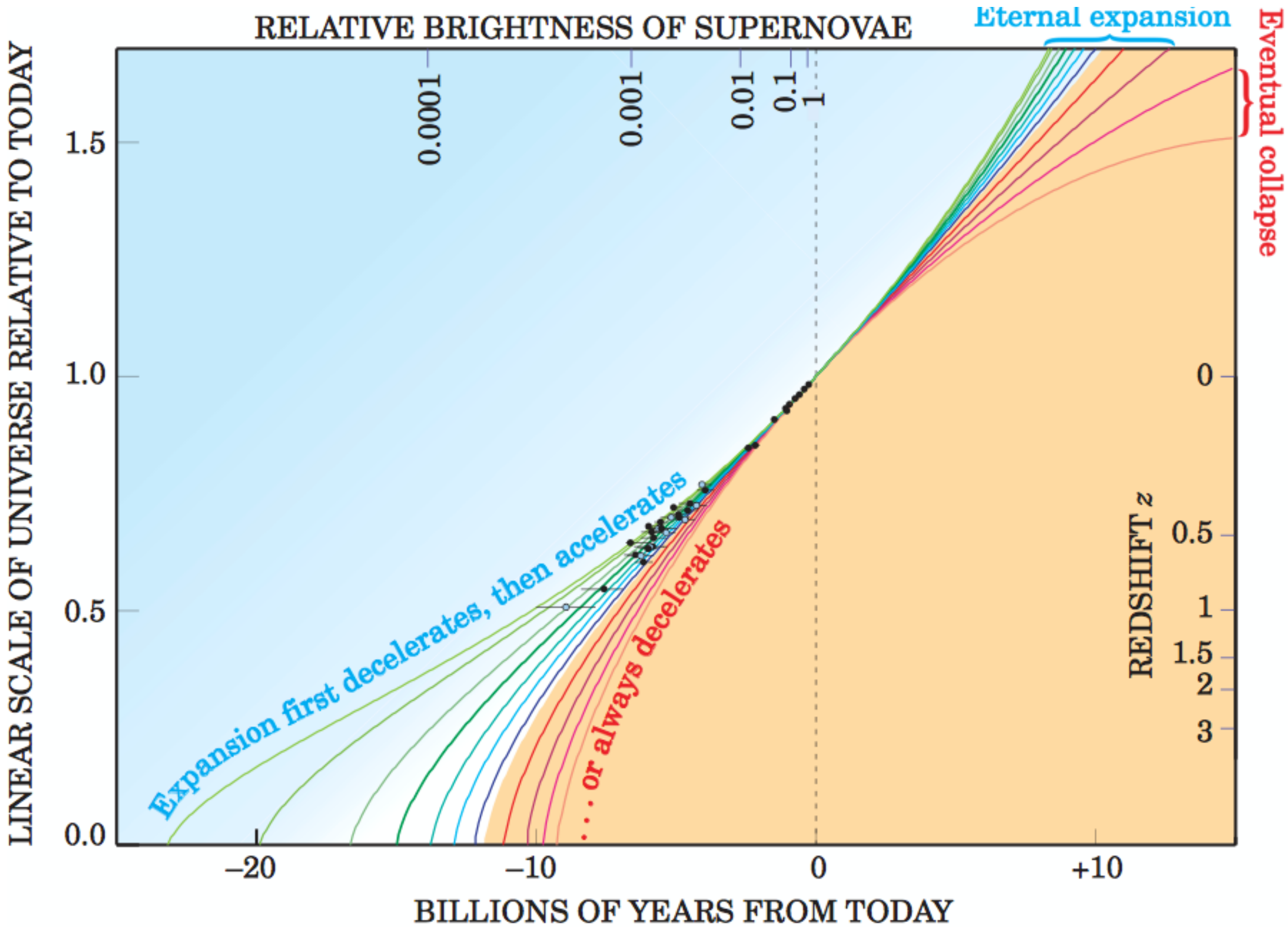
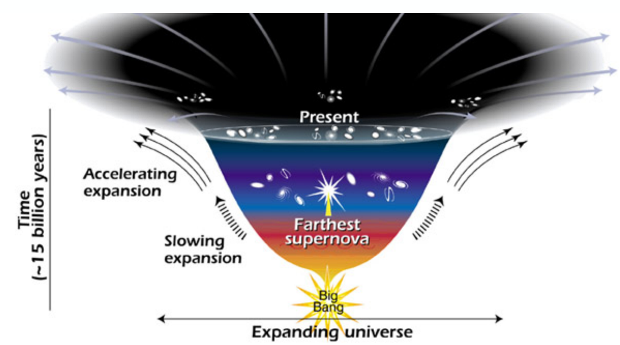
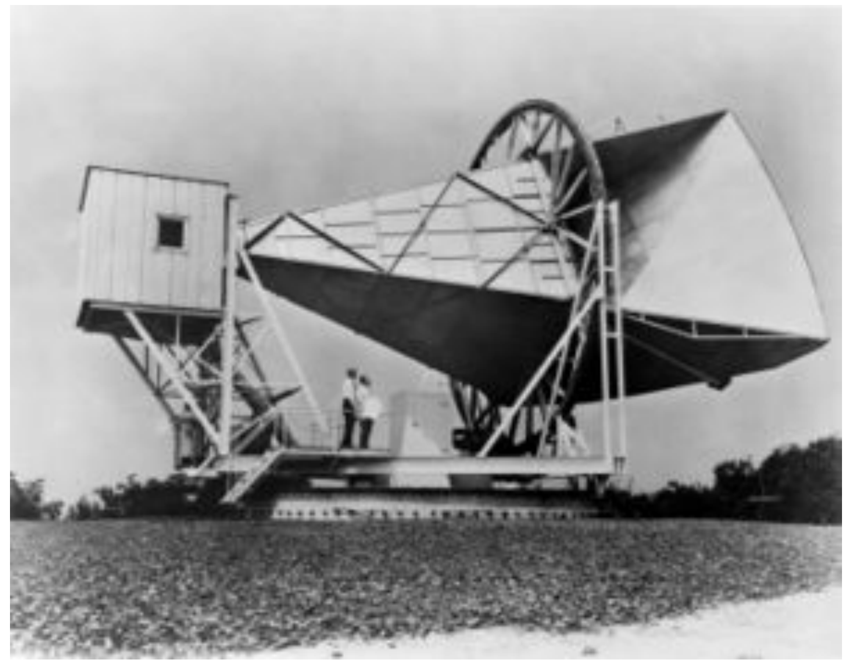


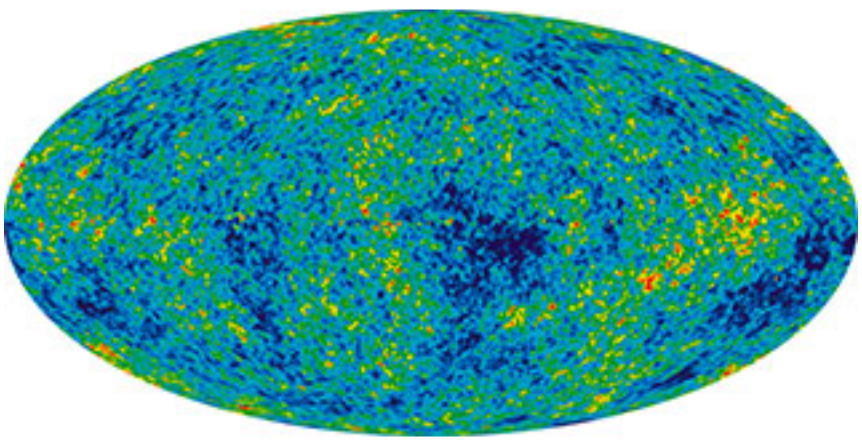
Figure 4. The history of cosmic expansion, as measured by the high-redshift supernovae (the black data points), assuming flat cosmic geometry. The scale factor R of the universe is taken to be 1 at present, so it equals $1/(1 + z)$. The curves in the blue shaded region represent cosmological models in which the accelerating effect of vacuum energy eventually overcomes the decelerating effect of the mass density. These curves assume vacuum energy densities ranging from 0.95 ρ_c (top curve) down to 0.4 ρ_c. In the yellow shaded region, the curves represent models in which the cosmic expansion is always decelerating due to high mass density. They assume mass densities ranging (left to right) from 0.8 ρ_c up to 1.4 ρ_c. In fact, for the last two curves, the expansion eventually halts and reverses into a cosmic collapse.



This diagram reveals changes in the rate of expansion since the universe's birth 15 billion years ago. The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart at a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pushing galaxies apart.

Penzias and Wilson





latest WMAP results

Einstein field equations

$$G_{ab} + \Lambda g_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

"My greatest blunder." sincerely, Albert Einstein

Sung to the tune of "The Times They Are A-Chang
Come gather 'round, math phobes,
Wherever you roam
And admit that the cosmos
Around you has grown
And accept it that soon
You won't know what's worth knowin'
Until Einstein to you
Becomes clearer.
So you'd better start listenin'
Or you'll drift cold and lone
For the cosmos is weird, gettin' weirder.