Albert Einstein's Revolution

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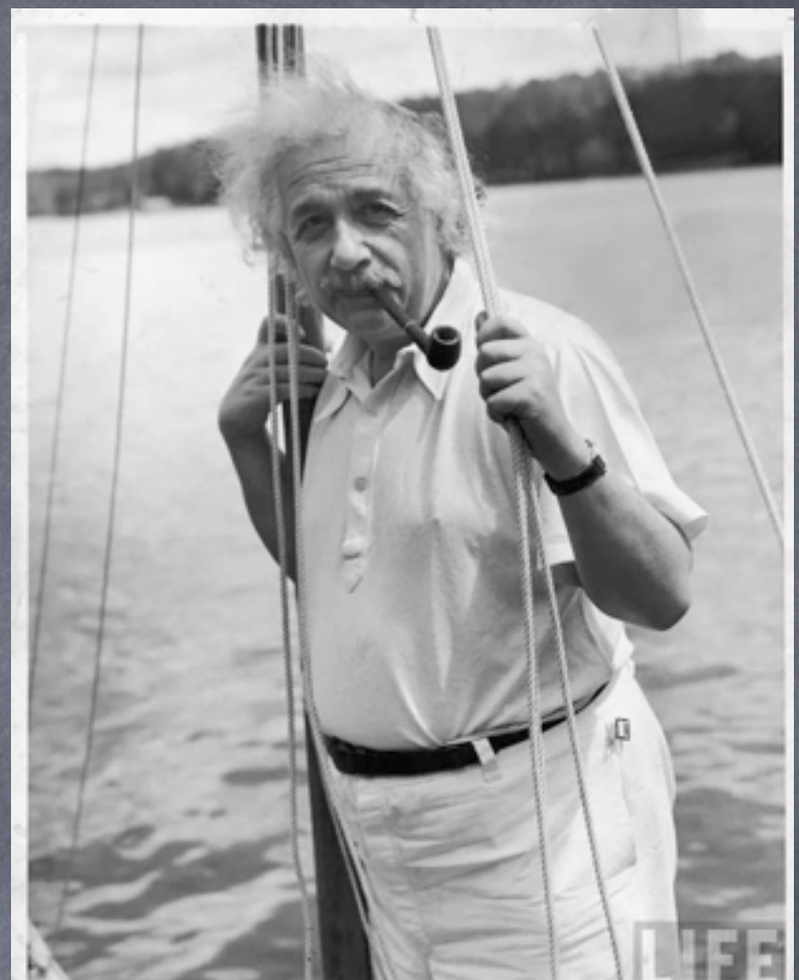
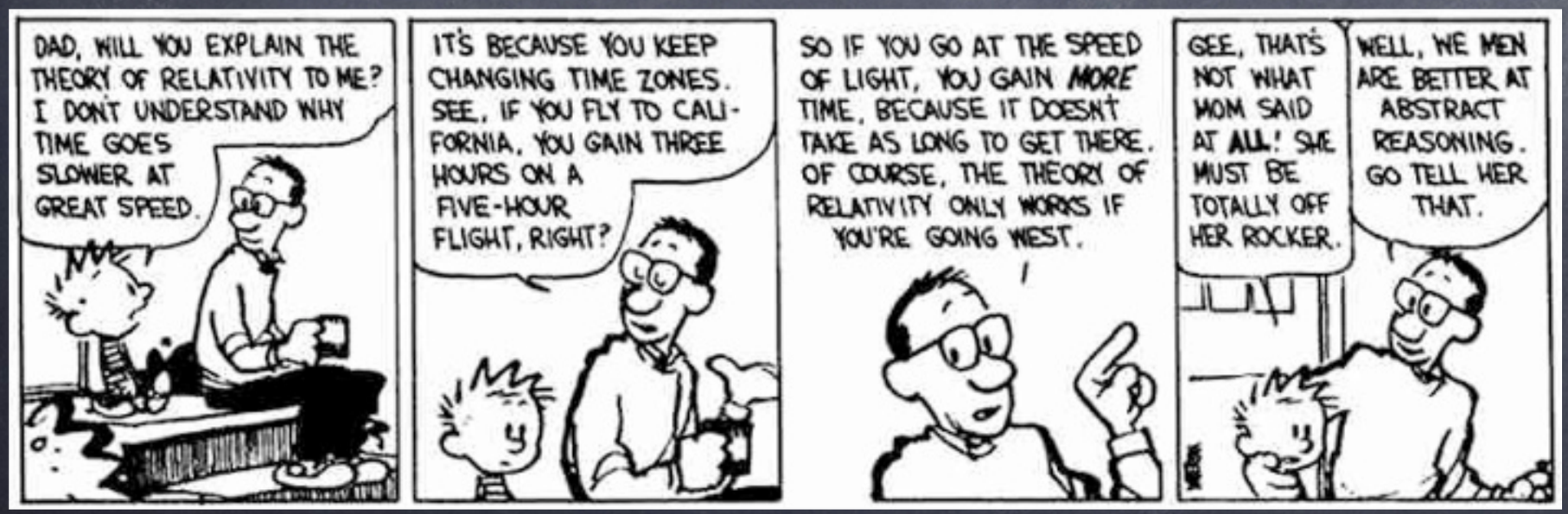
10/25/13



Albert Einstein, 1879–1955



Outline

I. Relativity: a brief description

II. 1905: The Annus mirabilis papers

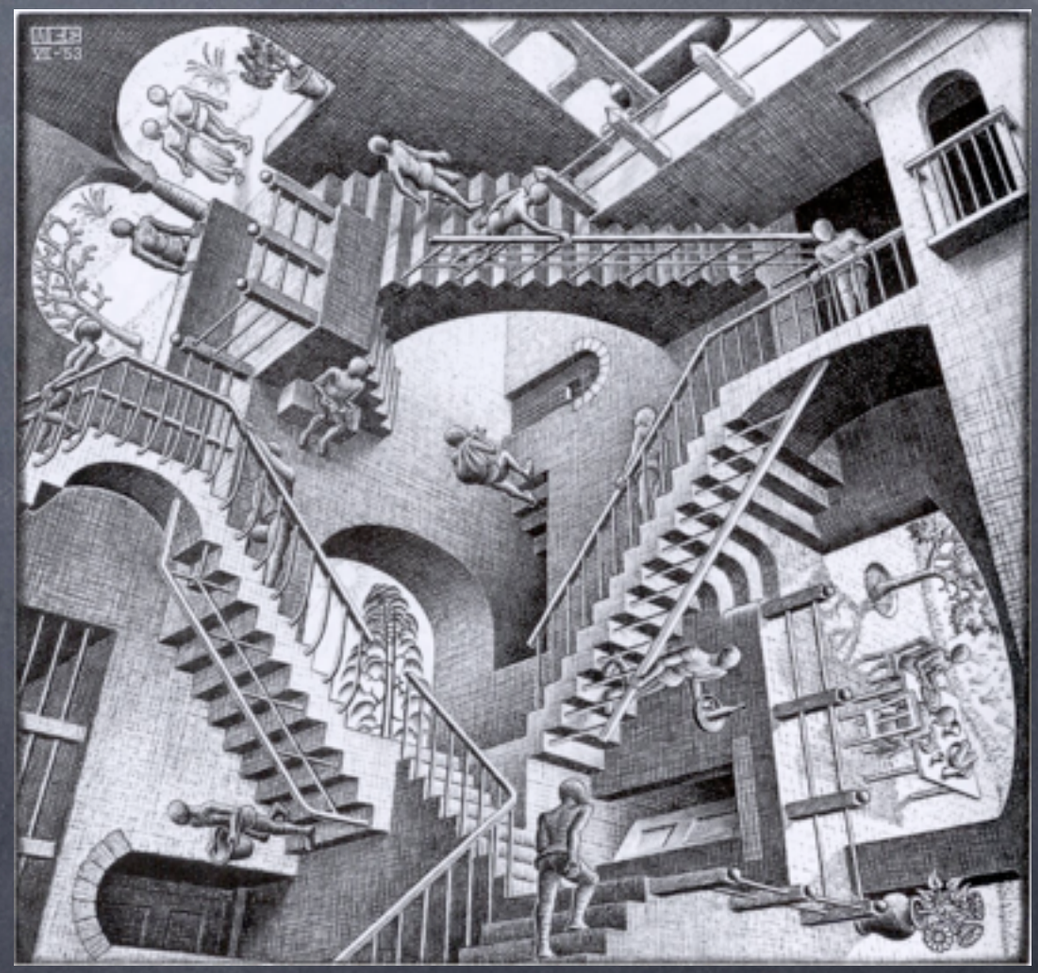
III. Proofs, consequences, & paradoxes

IV. Where did it come from?

V. The expanding universe of ideas

I. Relativity: a brief description

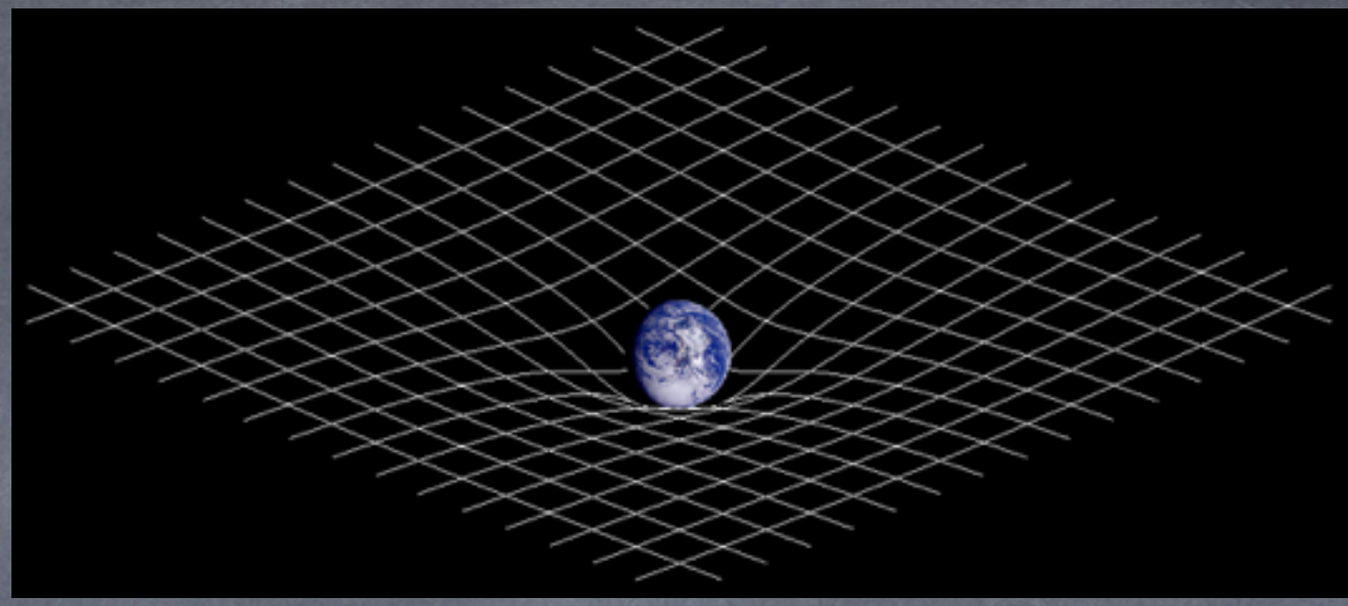
- Einstein's two theories of Relativity - Special & General
  - Special Theory of Relativity (SR, 1905)
    - Speed of light (c) independent of motion of source & observer
    - Spacetime is 4-dimensional.
    - Time intervals & lengths depend on velocity
    - c = ultimate speed limit
    - There is no absolute state of motion
    - Unification of electricity & magnetism
    - $E = mc^2$
    - Restricted to observers with constant velocity

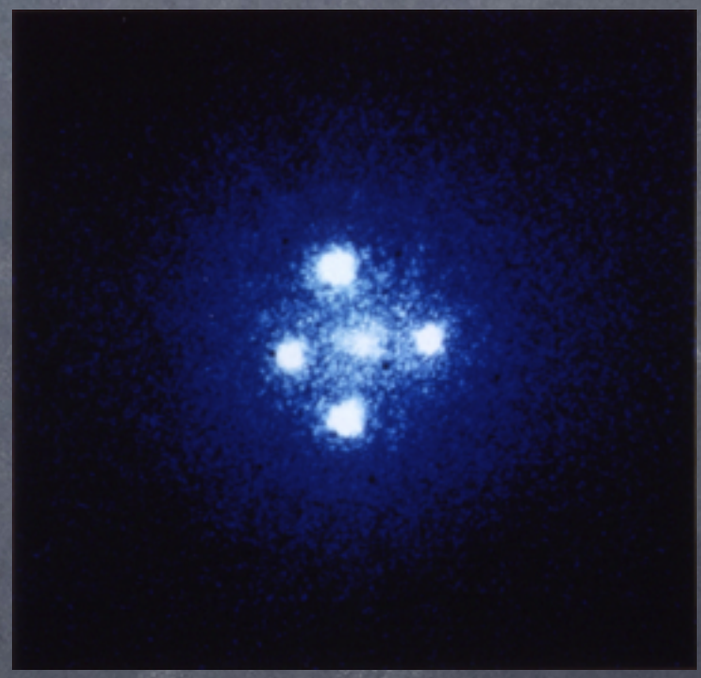


- General Theory of Relativity (GR, 1916)
  - Matter & energy curve spacetime:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

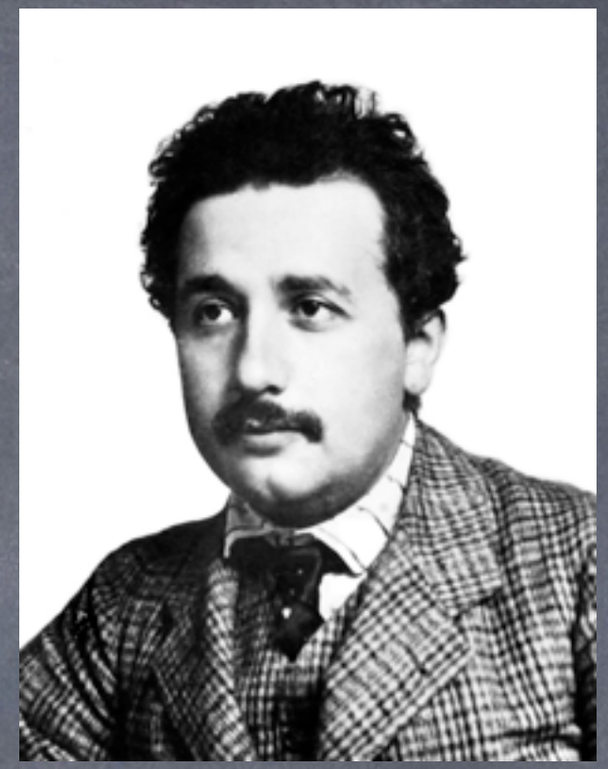
  - Gravity bends light.
  - Gravitational lenses
  - Black holes
  - Gravitational time dilation
  - Gravitational waves
  - Big Bang & expansion of universe





Einstein Cross
4 quasars lenses by
foreground galaxy

II. 1905: The Annus mirabilis papers



Einstein in 1905

- Albert Einstein (1879–1955) was a Swiss patent examiner in 1905.
- With almost no connection to physics community, published 4 groundbreaking articles in Annalen der Physik.
- "On a Heuristic Viewpoint Concerning the Production and Transformation of Light".
  - His proposal of light quanta (photons) for which he rcvd. 1921 Nobel Prize.
- "On the Motion of Small Particles Suspended in a Stationary Liquid, as Required by the Molecular Kinetic Theory of Heat").
  - Brownian motion - proof of the (controversial) atomic theory of matter.
- ...& 2 papers on Relativity...

1905: The Annus mirabilis papers

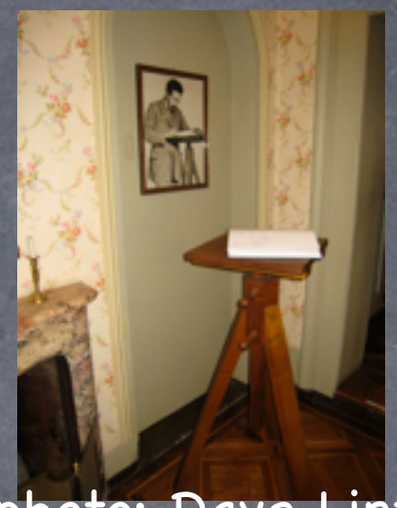
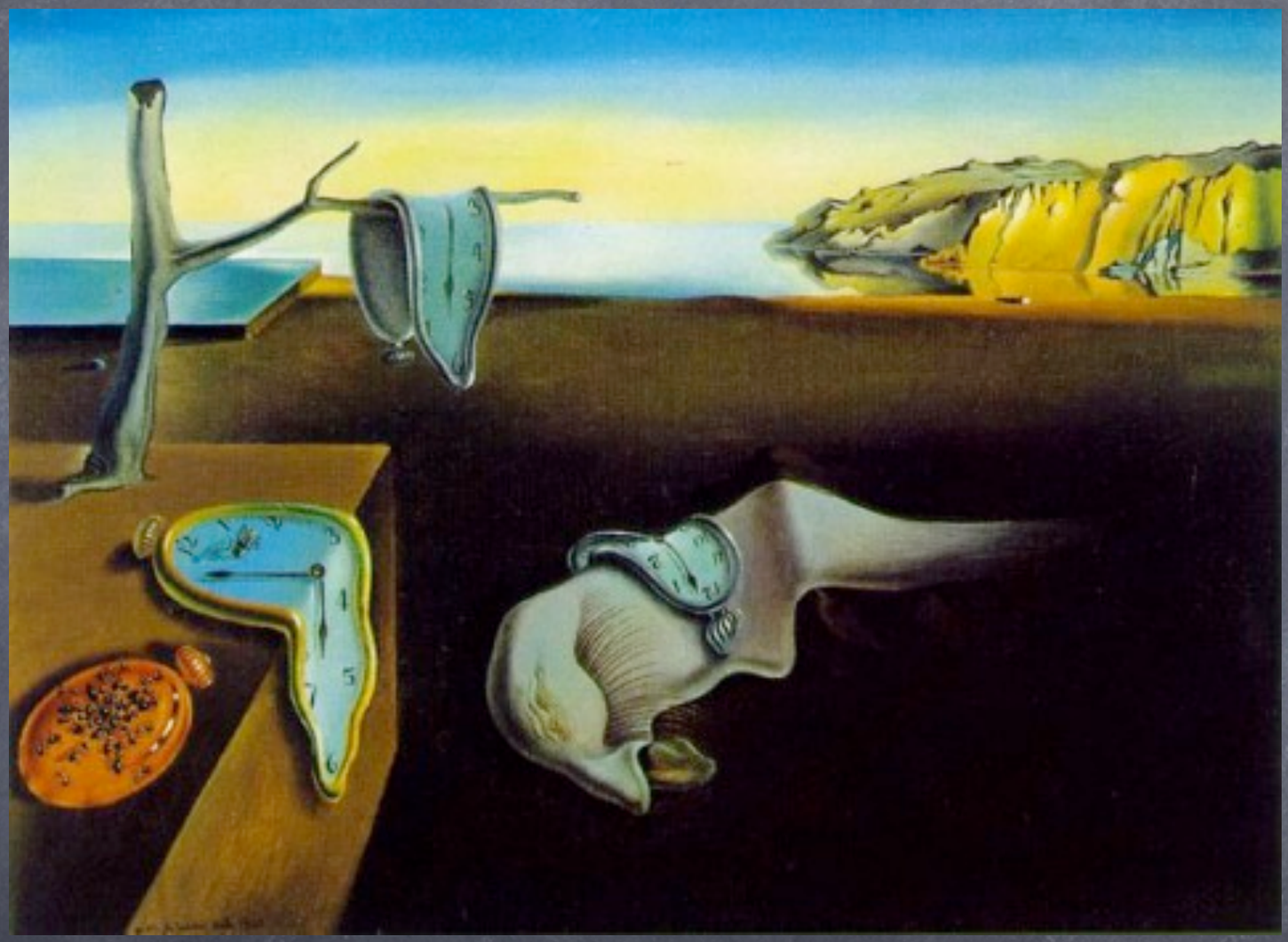


photo: Dave Linton

- "On the Electrodynamics of Moving Bodies".
  - Special Theory of Relativity
  - Postulates that all the laws of physics (including electromagnetism) are the same in all references frames moving with constant velocity (contrast pre-Galileo view).
  - No such thing as absolute rest or motion - all motion is relative!
  - As a consequence, time must be different for different observer.
- "Does the Inertia of a Body Depend Upon Its Energy Content?".
  - $E = mc^2$

III. Proofs, consequences, & paradoxes

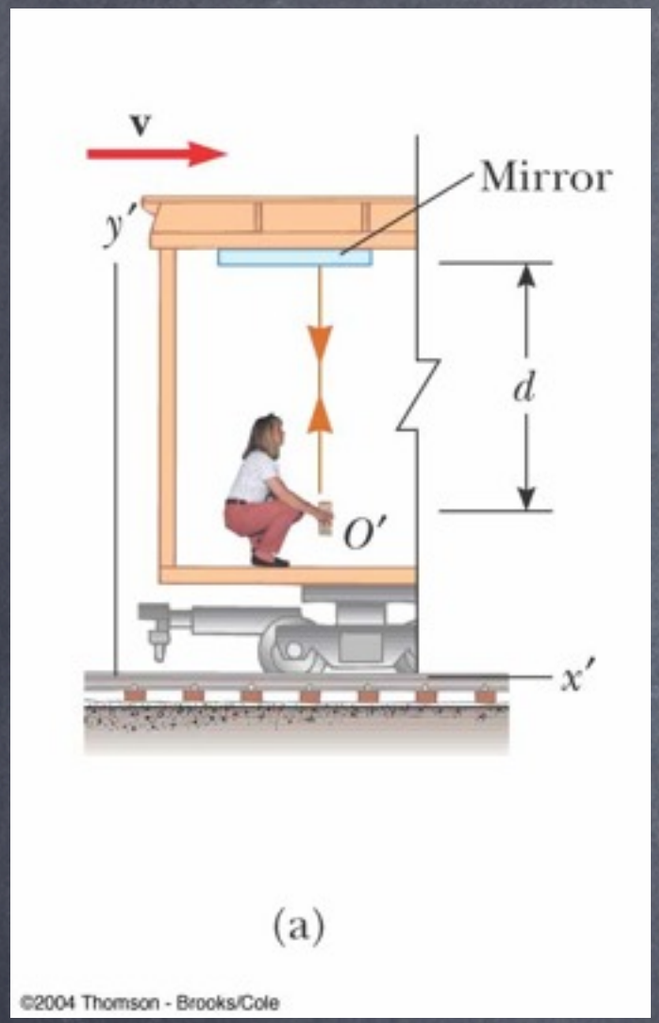
Time dilation

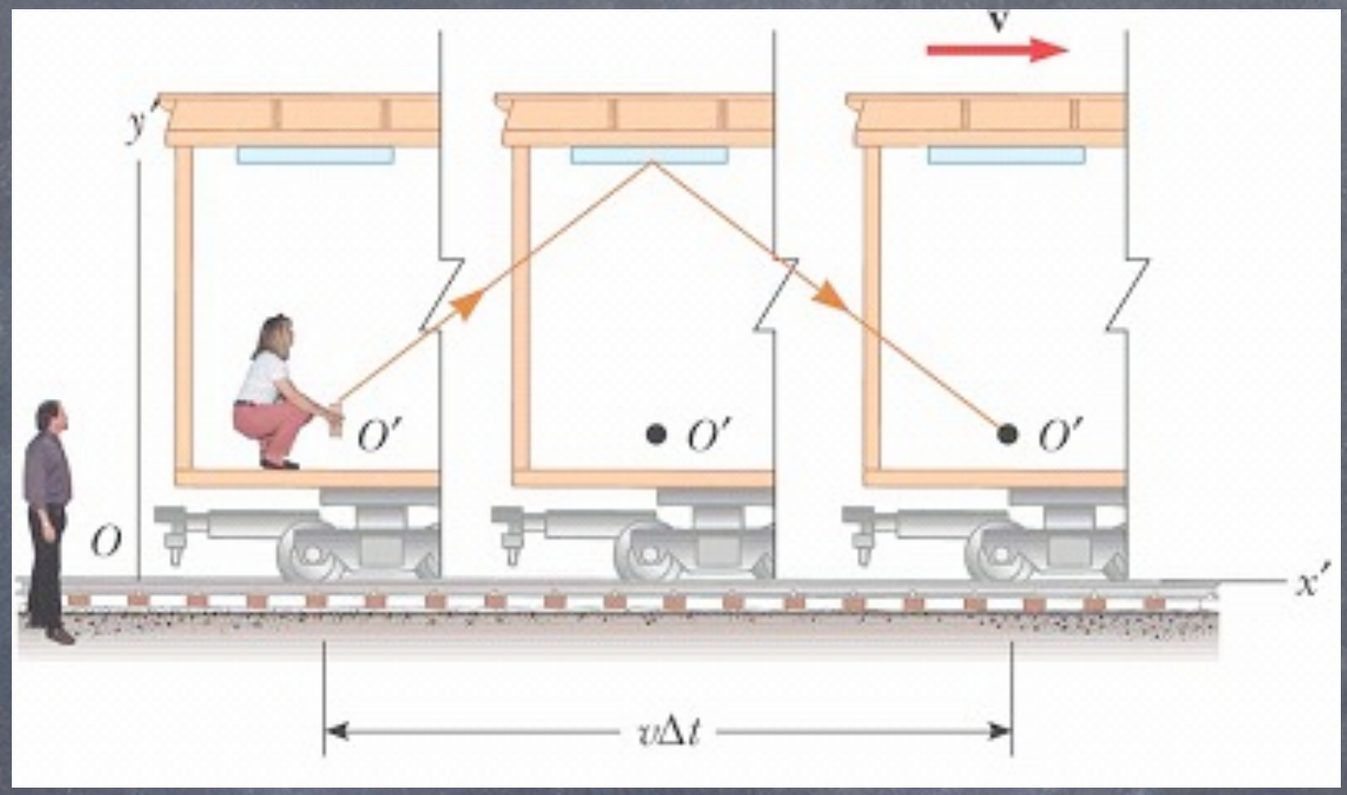


- In order for all observers to see the same speed of light, time must run at different rates for different observers.

Time dilation

- Gedankenexperiment using "light clock".

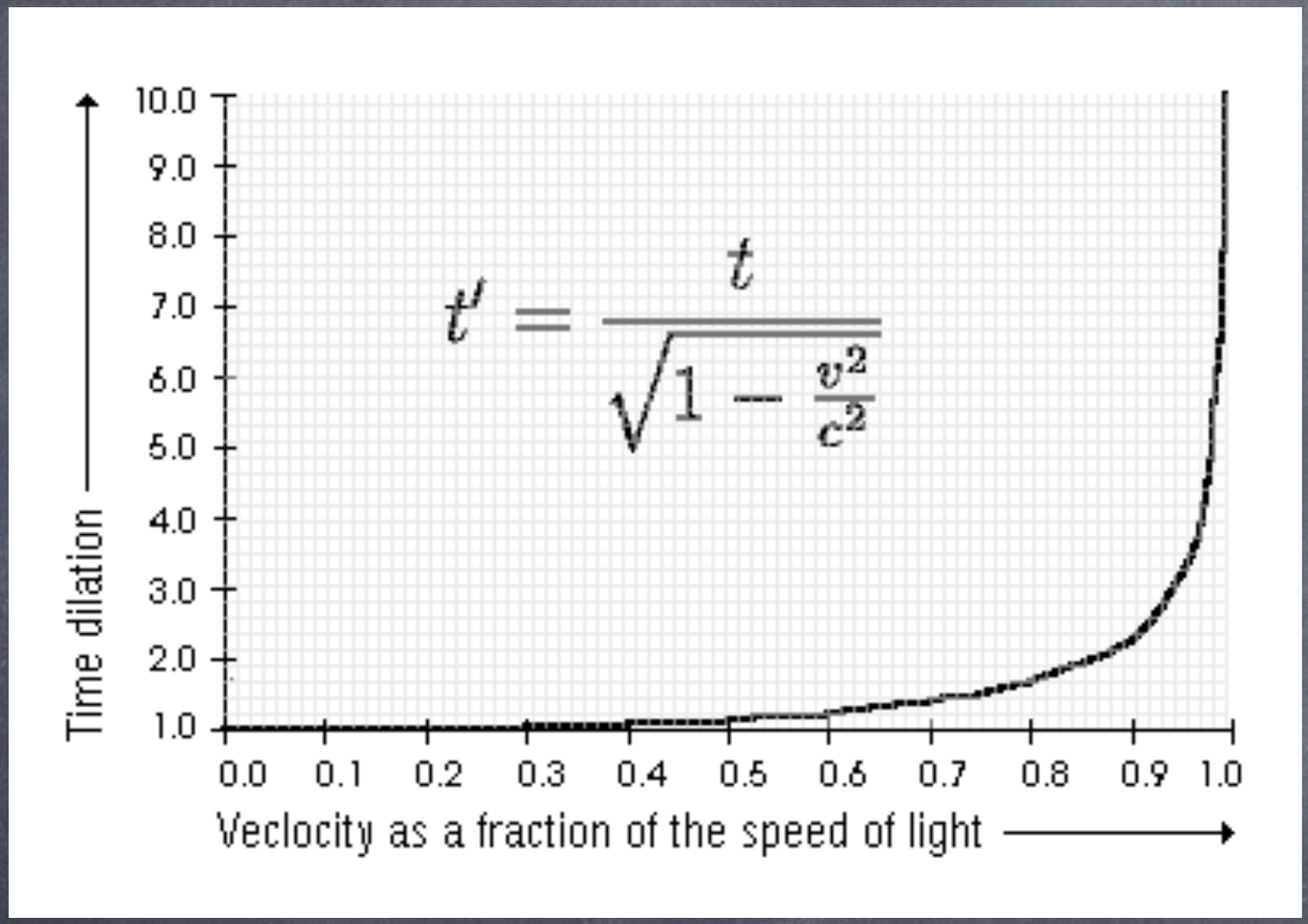




- Light goes up & down in time Δt.
- Both see same speed c, but stationary observer sees longer distance, so longer Δt.
- So time (itself) runs at different rates for different observers!

Time dilation

- Simple math (time = distance/speed) gives factor by which time is slowed down:



- You have to be going close to the speed of light for it to be noticeable.
- But is it even true?

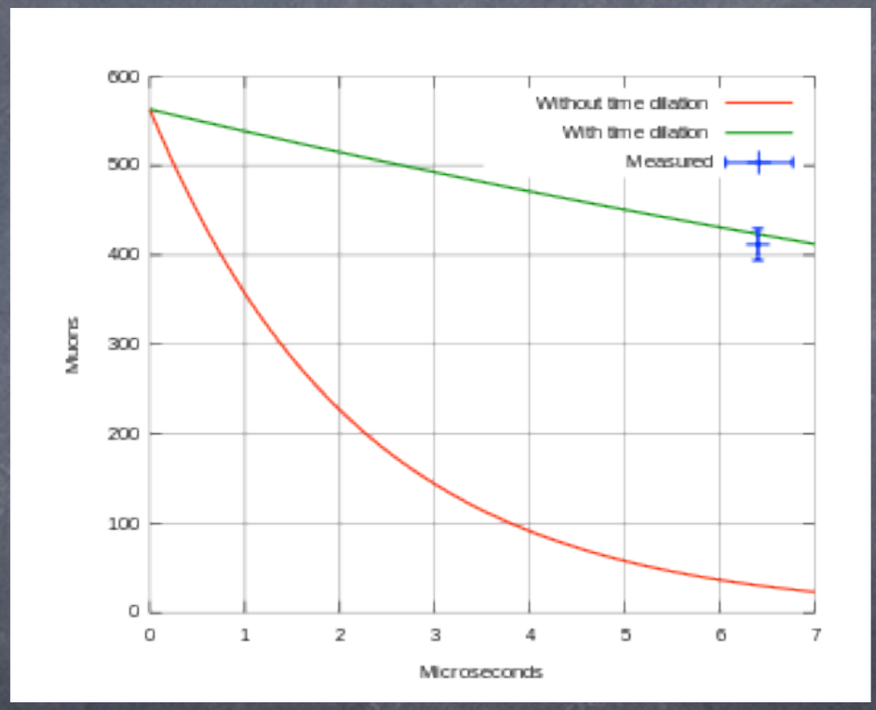
The Hafele-Keating experiment (1971)

- Atomic clocks were flown around the world to the east & west & compared to clocks that stayed in one place.

- (Small) time discrepancies consistent with Relativity.

Frisch-Smith muon experiment (1963)

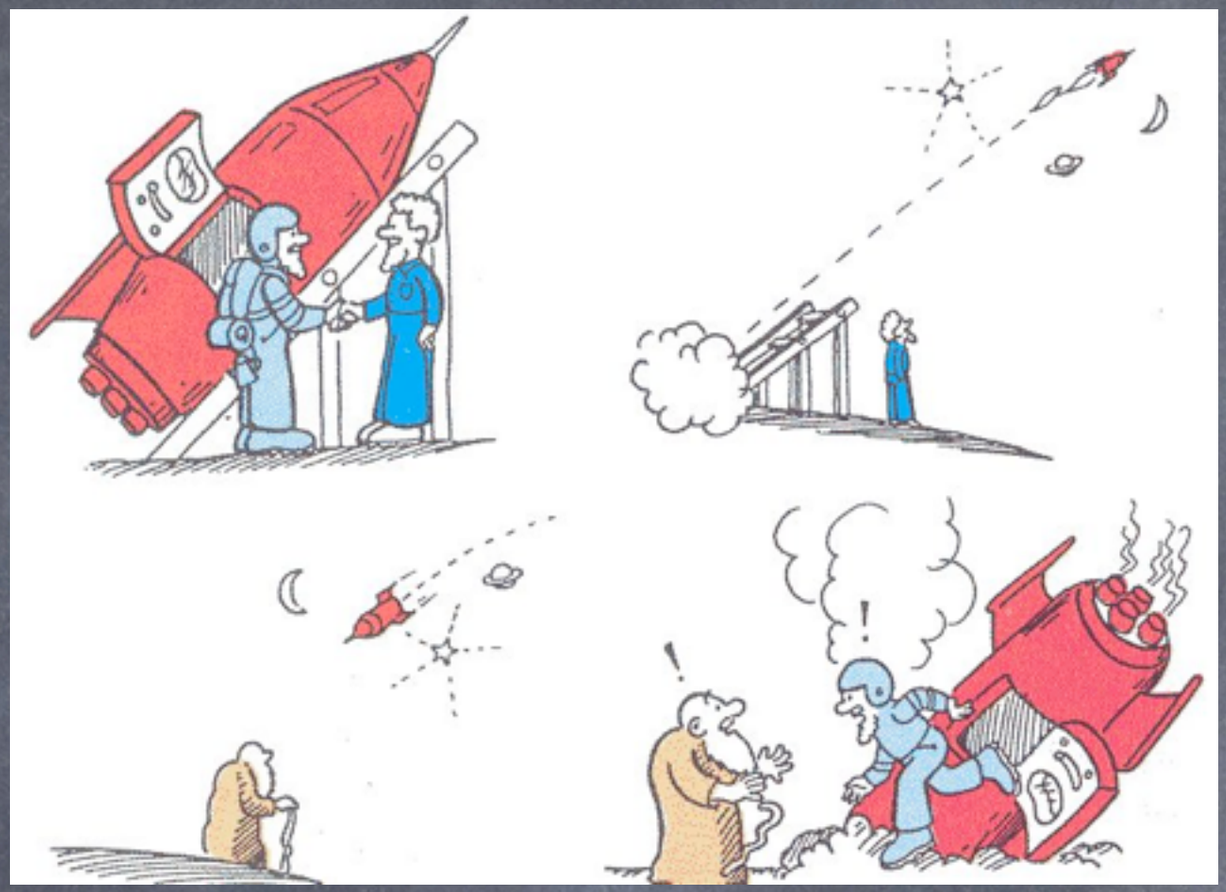
- Muons are particles with a lifetime of 2.2 μs, produced by collision of cosmic rays with atoms in upper atmosphere.
- Without time dilation, they would decay before reaching Earth.
- Some muons traveled at 99.5% of c, giving a time dilation factor ~9.
- Results confirm relativistic time dilation.



- Also - GPS would not work if equations of relativity were not correct!

- No observer will ever observe his own time to go slower. All biological processes - time itself - is slowed.

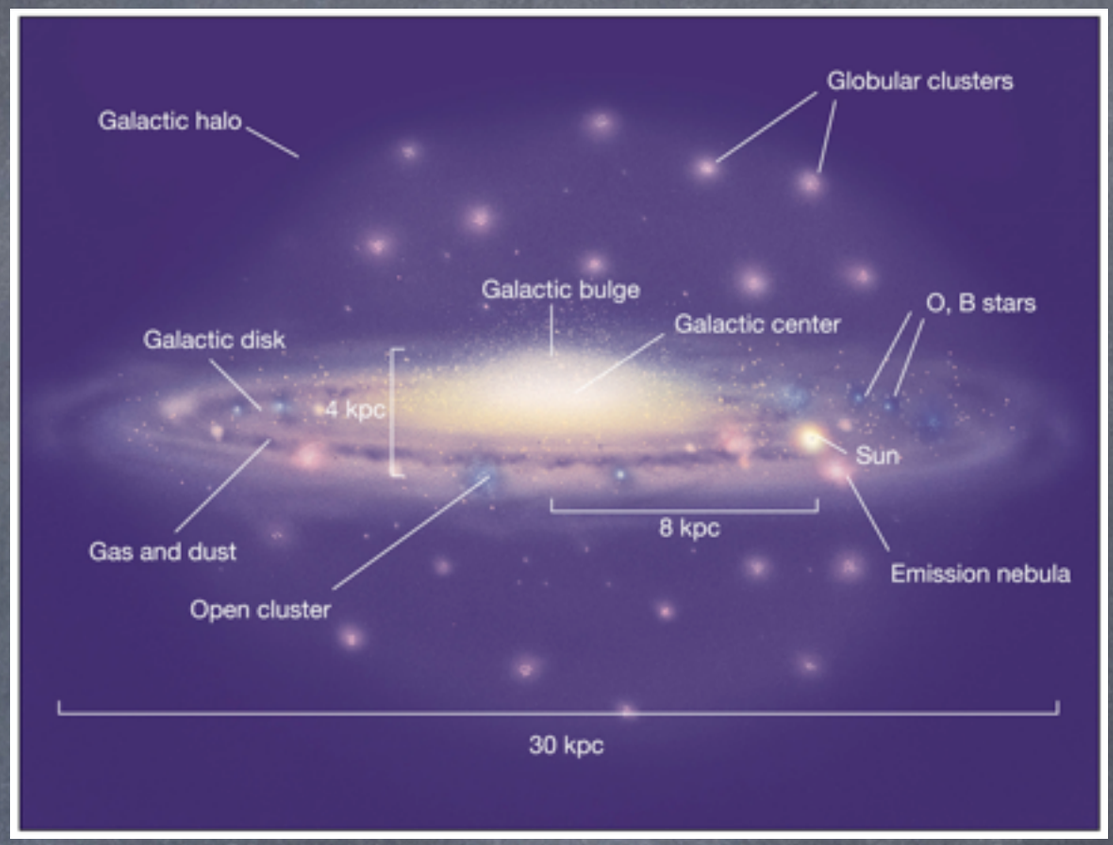
And now - the famous Twin Paradox!



- One twin stays on Earth, one makes a trip to a distant star, at close to the speed of light.
- Elapsed time is much longer for Earthbound twin.
- (From rocket point of view, it's the Earth twin who is moving. But it is not symmetrical, since only the traveling twin accelerates.)

A trip to the center of the galaxy?

- 26,000 light-years away.
- On light-year = distance light travels in one year at 186,000 miles/second, or about 6 trillion miles.
- Without time dilation, it would take 26,000 years, even at the speed of light.
- With time dilation, the trip could hypothetically be made in a human lifetime.
- But the energy requirements may make it impossible.



Length contraction

- A moving object is observed to be contracted along the direction of motion by the factor $\sqrt{(1-v^2/c^2)}$.

- Ladder Paradox: 10-ft garage has automatic doors at front & back. 12-ft ladder carried through garage at 0.6 c (length contraction factor = 0.8). Is the ladder ever in the garage with both doors closed?

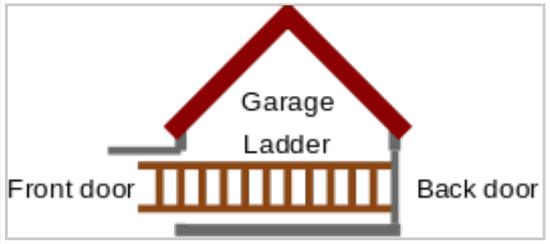


Figure 1: An overview of the garage and the ladder at rest

- A: yes or no, depending on frame of reference!

  - In garage frame, ladder is 0.8*12 = 9.6 ft long. Front door closes before rear door opens.

  - In ladder frame, garage is 0.8*10 = 8 ft long. Front door closes after rear door opens.

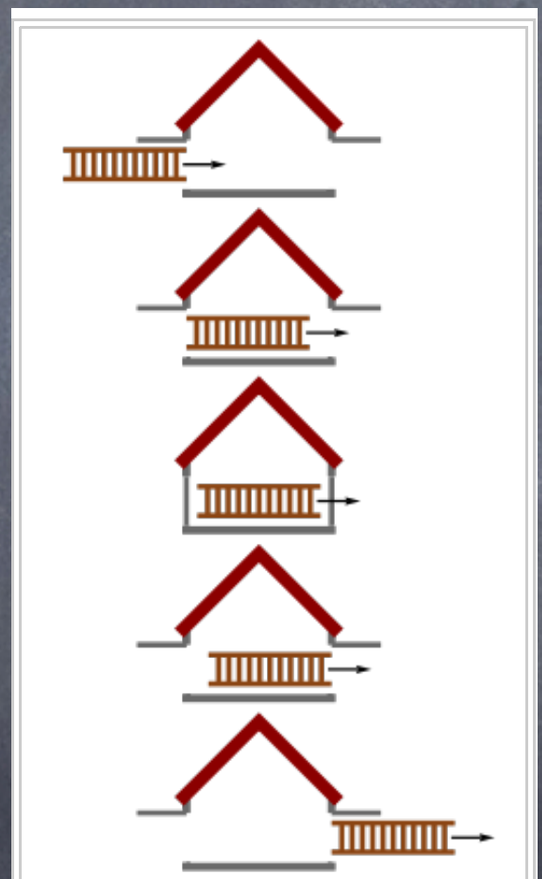


Figure 4: Scenario in the garage frame: a length contracted ladder entering and exiting the garage

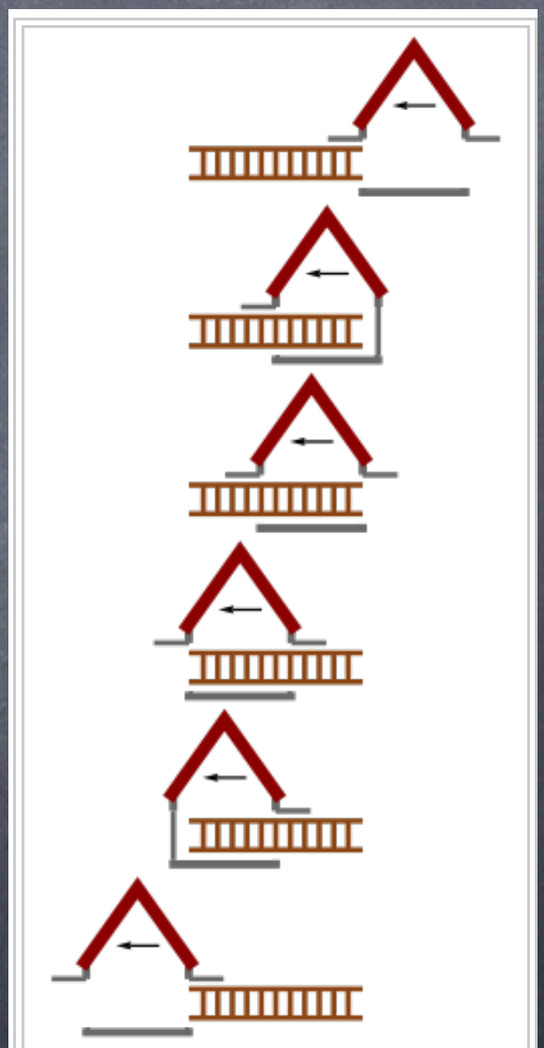
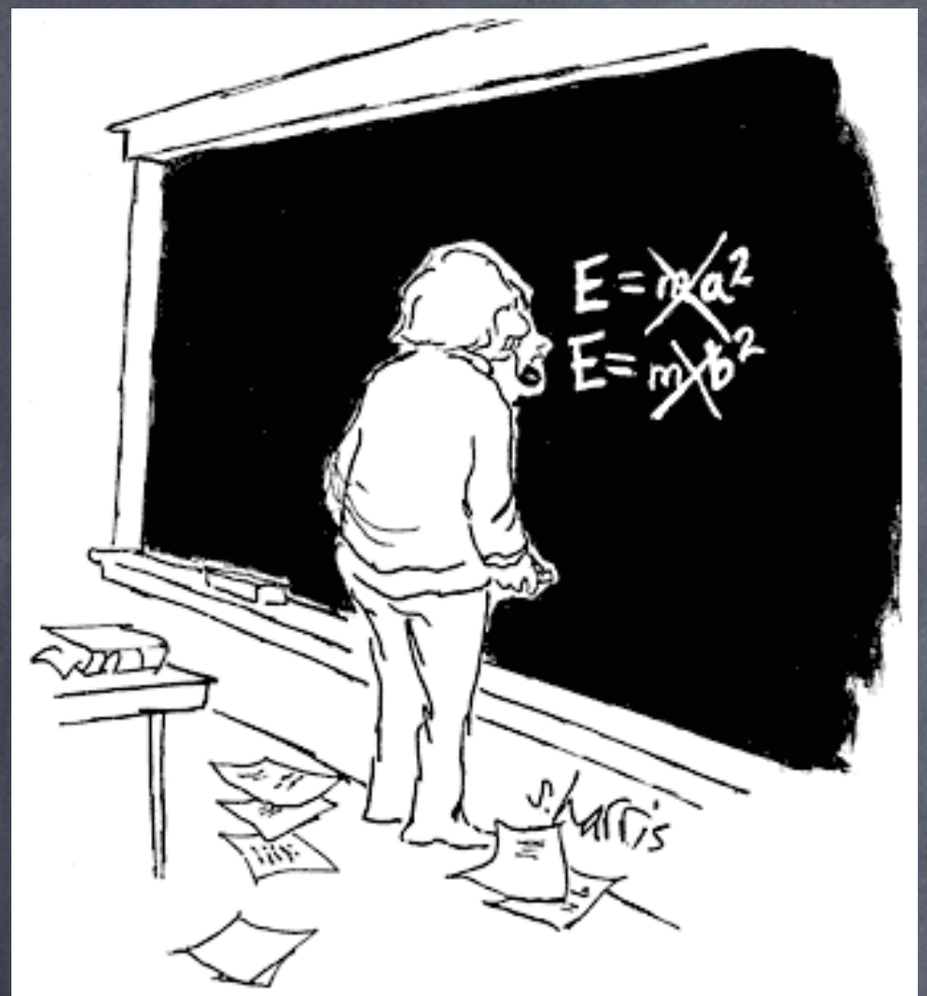


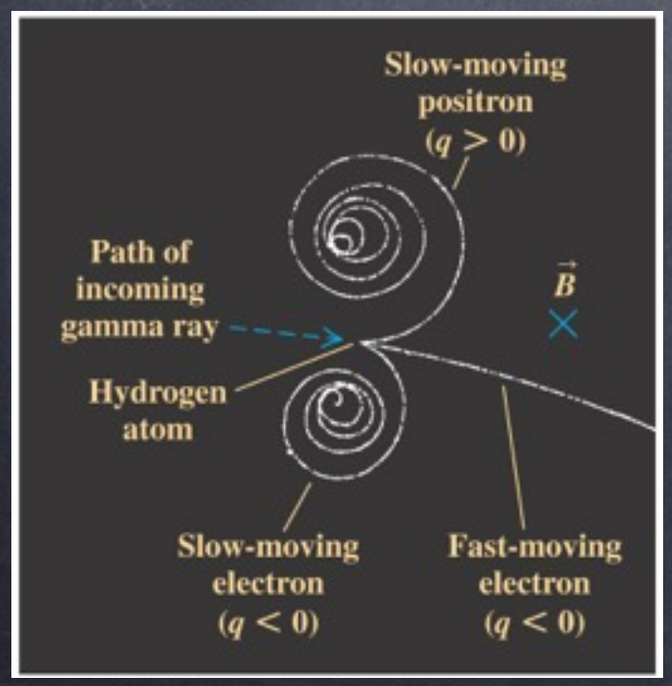
Figure 5: Scenario in the ladder frame: a length contracted garage passing over the ladder

The most famous equation of the 20th Century!



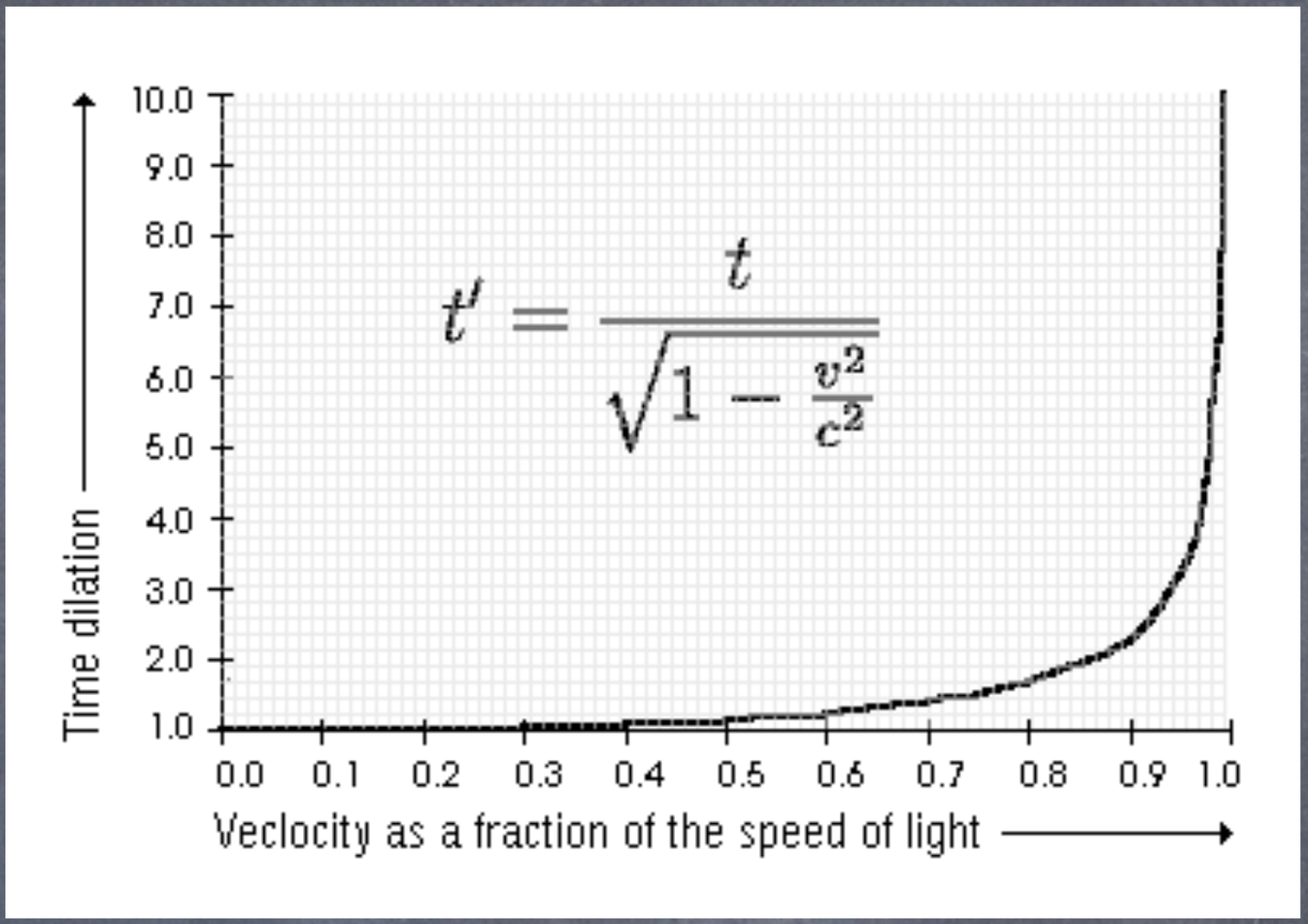
- Mass & energy are 2 forms of the same thing, & can be converted from one to the other.

- Think of mass as highly concentrated energy.
- Wind up a spring, its mass slightly increases (very slightly, since $c^2 = 9 \times 10^{16}$ in metric units).
- Mass defect ~10^{-9} in chemical reactions, ~10^{-4} for nuclear.
- m(u+u+d) < 2% m(p)



- In accelerators, particles are created from energy.

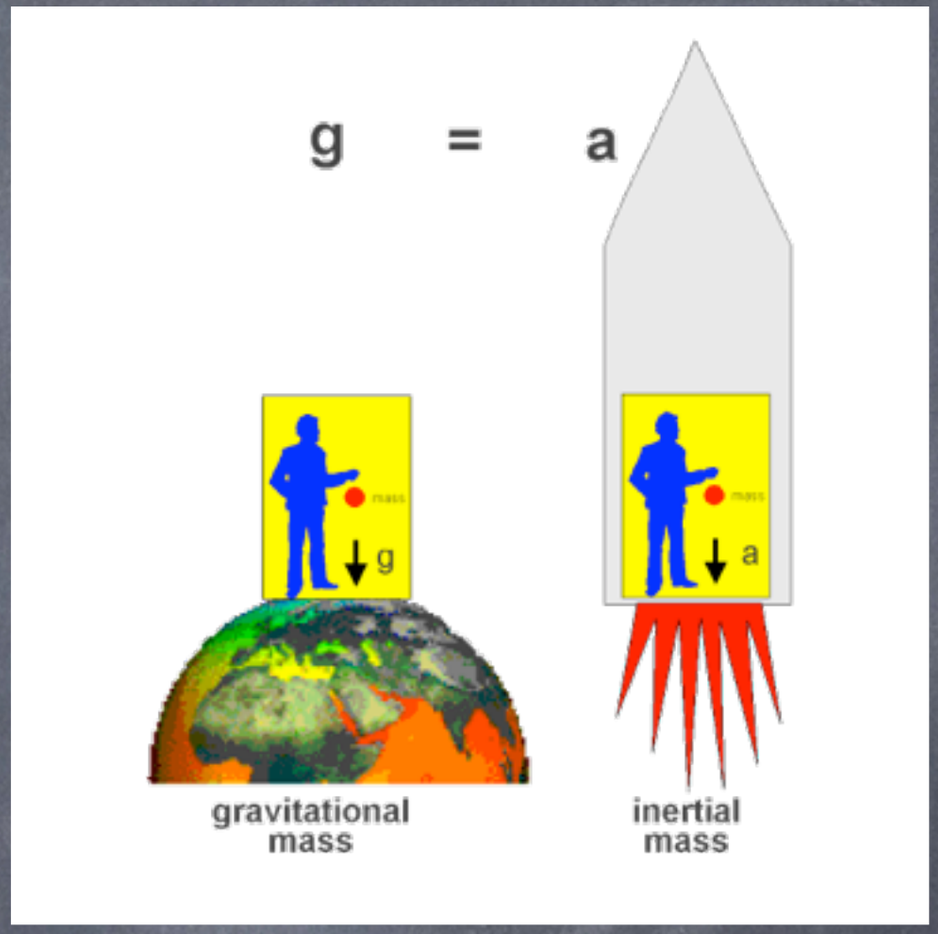
More fun stuff!

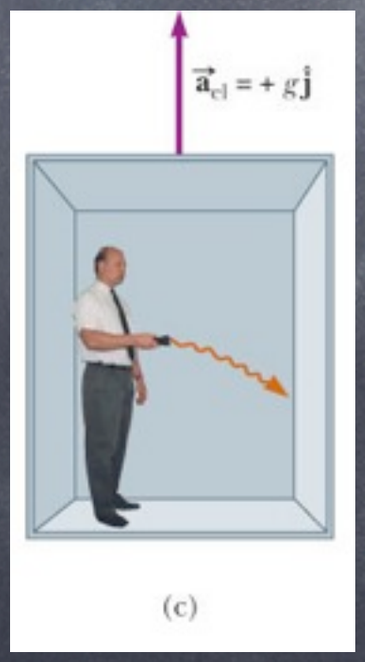


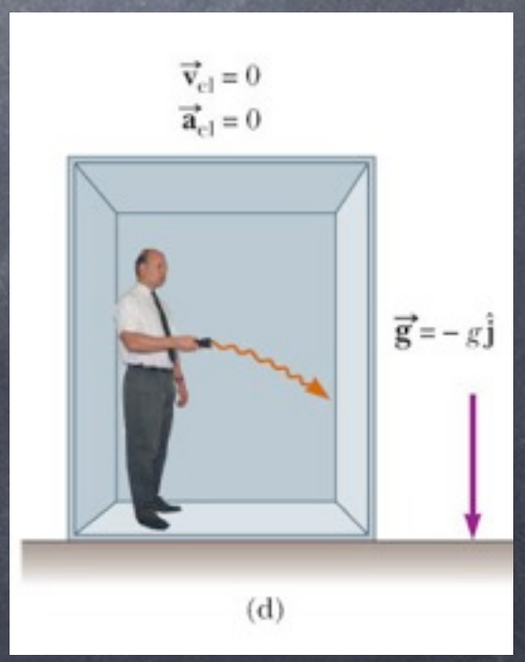
- $E = mc^2$ is for an object at rest. For a moving object the total energy is $\gamma\, mc^2$, where the relativistic γ factor is the same one used for time dilation & length contraction.
- So it would take an infinite amount of energy to accelerate an object to c.
- We could say that the mass of an object increases with speed, but in modern usage, mass means rest mass.

General Relativity (1916)

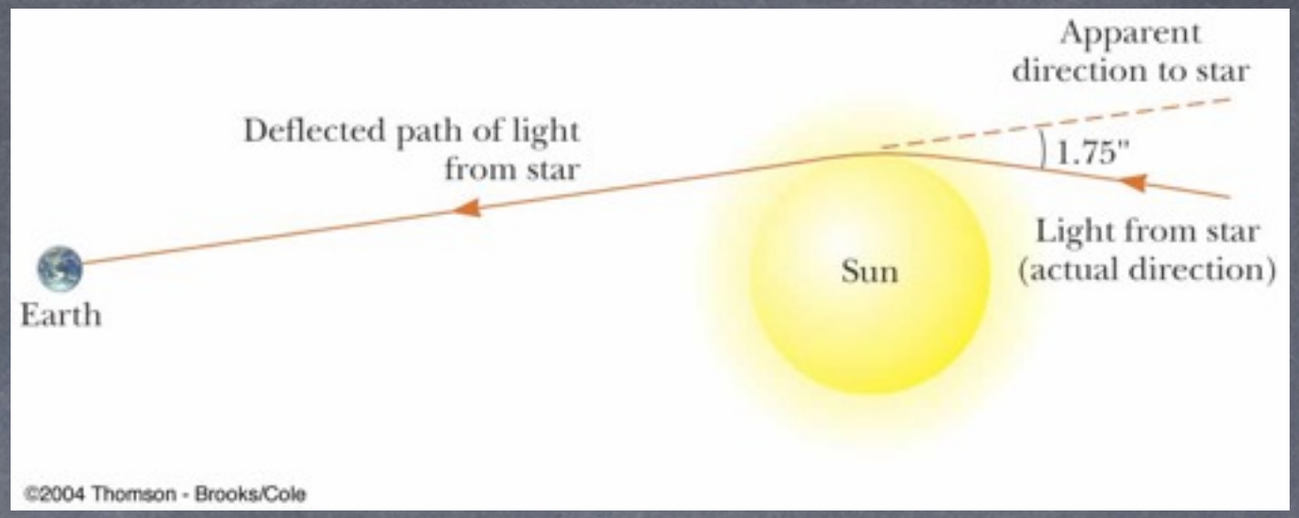
- Special Relativity is restricted to constant velocity.
- General Relativity based on Principle of Equivalence: the effects of acceleration are indistinguishable from those gravity (so GR is a theory of gravity).
- Explains the "coincidence" of gravitational & inertial mass.
- Predicts gravitational light-bending.



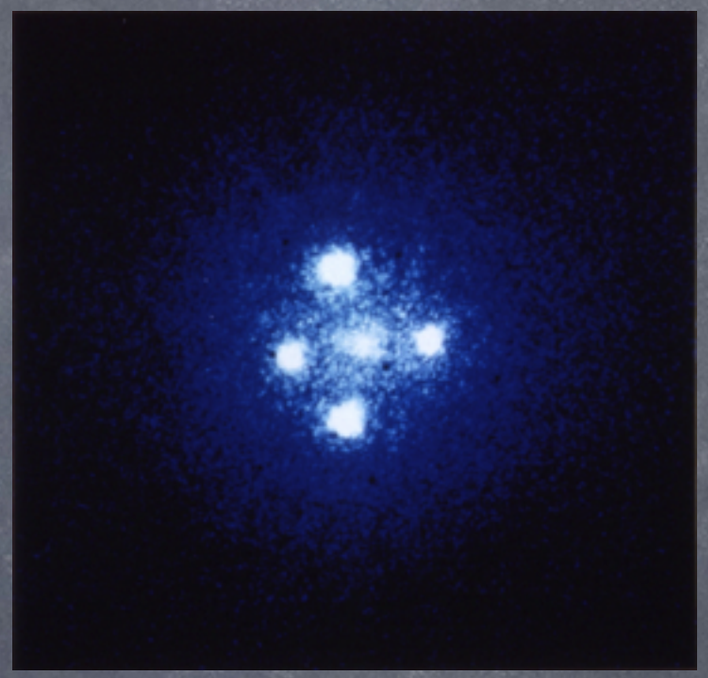




- Gravitational light-bending due to Sun verified during eclipse of 1919.



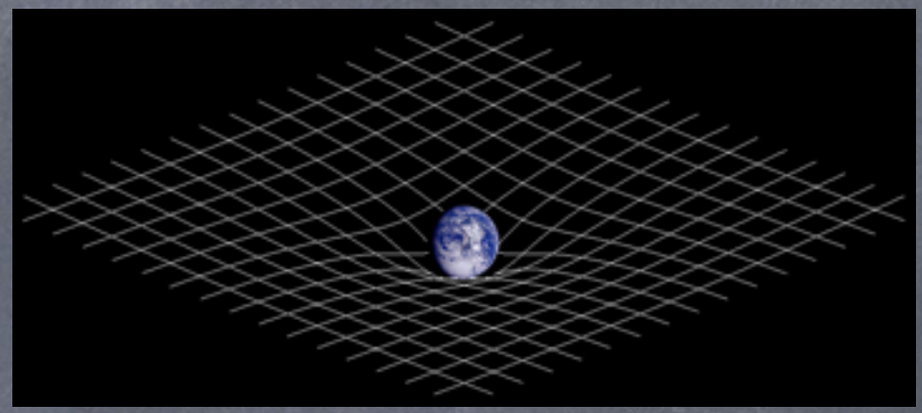
- Gravitational lensing



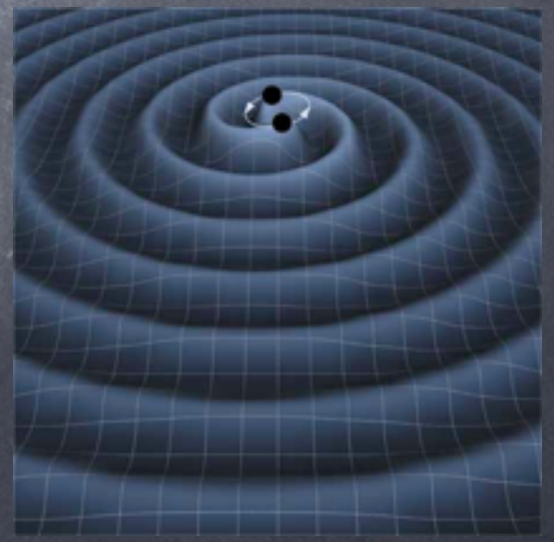
Einstein Cross
4 quasars lenses by
foreground galaxy

- GR is a theory of gravity: matter & energy curve spacetime.
- GR also explained details of orbit of planet Mercury.
- Gravitational waves: not yet detected directly, but indirectly in orbit of double pulsar (& other systems).

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

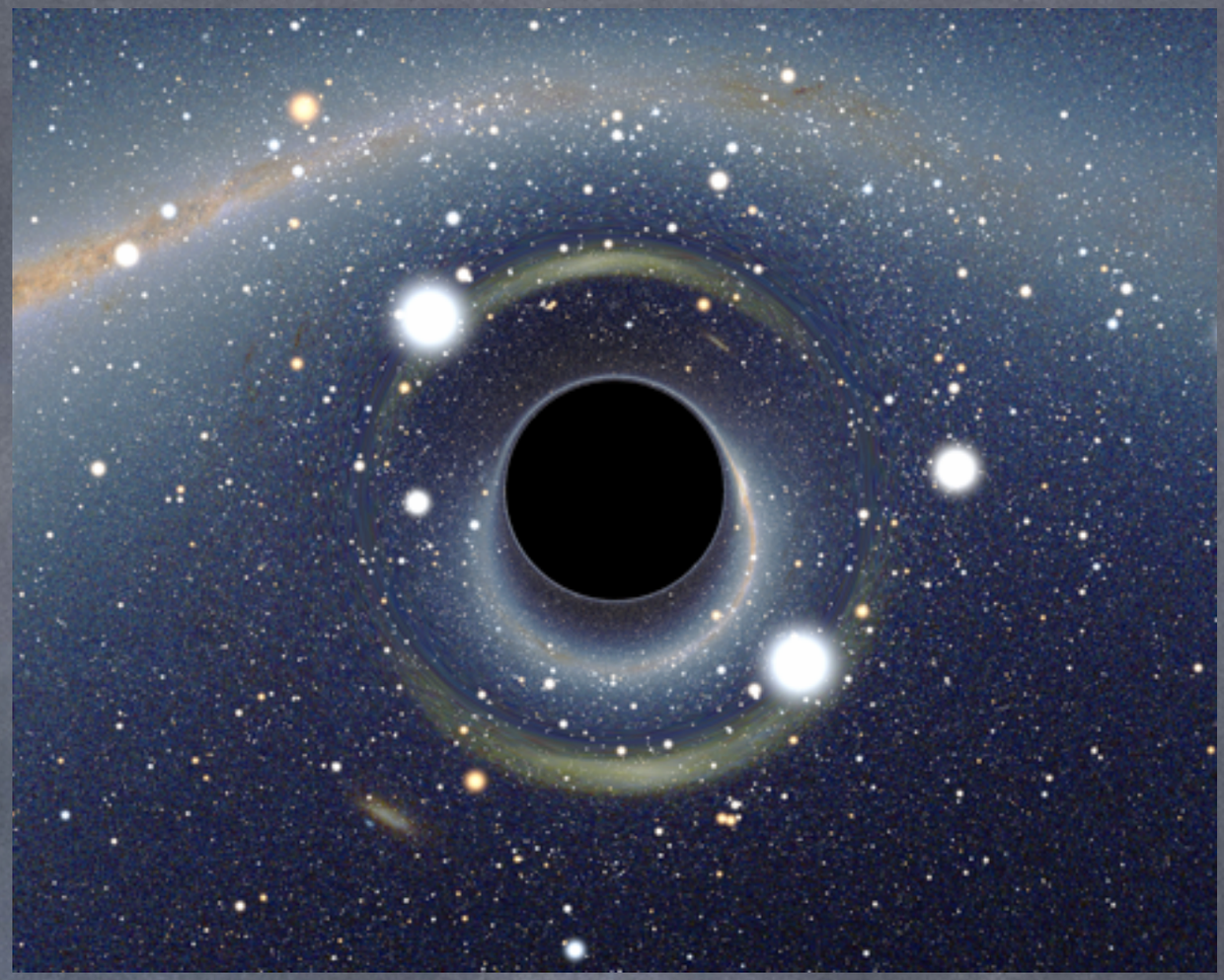


Laser Interferometer Gravitational-Wave Observatory (LIGO)



Black Holes

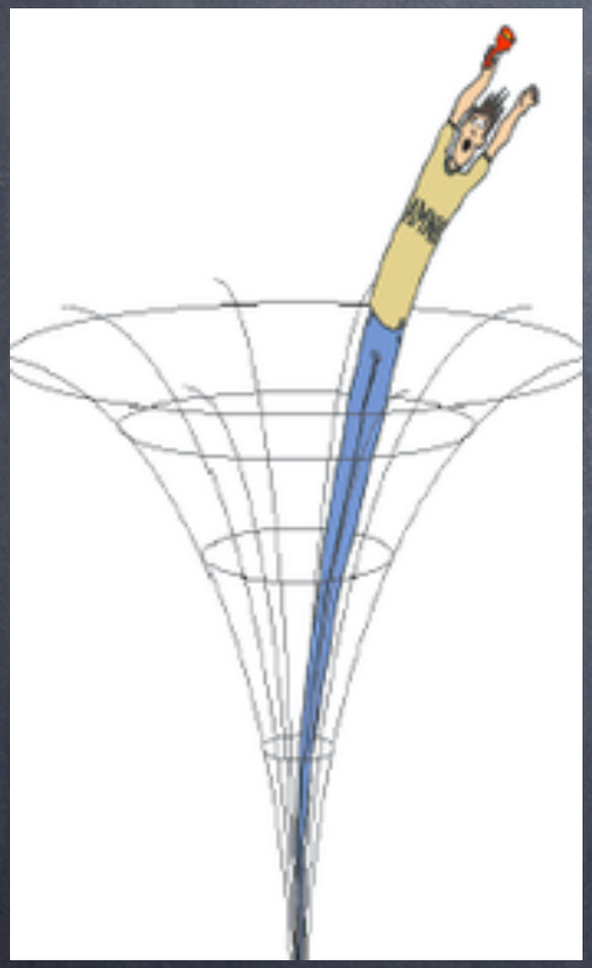
- When enough mass is put into a small enough space, nothing, not even light, can escape.
- Have been observed, both stellar-mass & supermassive (at centers of galaxies).
- Our Milky Way galaxy has a black hole of mass 4.1 million solar masses at its center.

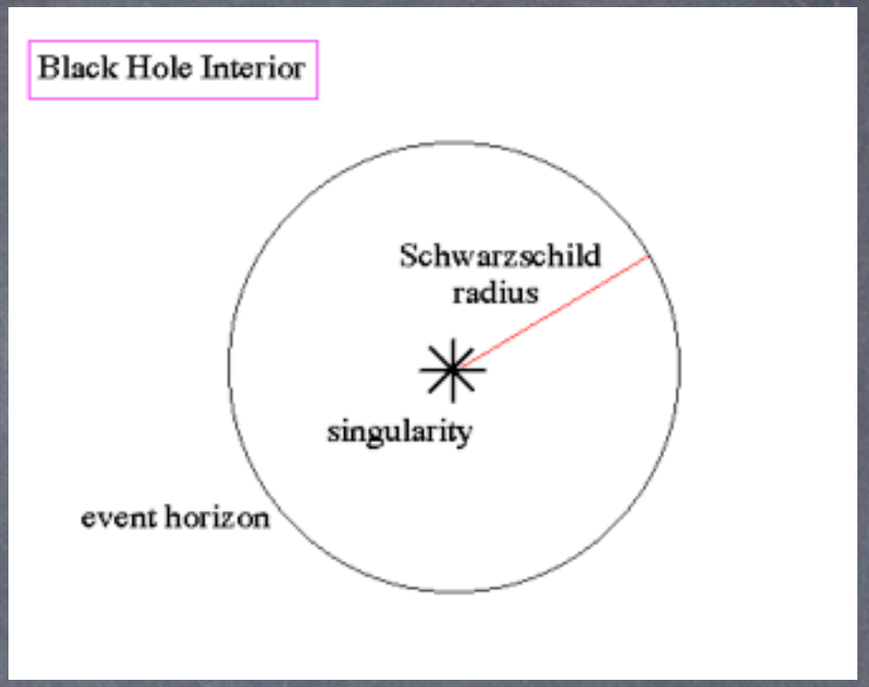


Black Holes

- A black hole consists of an event horizon (the point of no return) surrounding a singularity (point of (near) infinite density).

- Trip into a black hole fatal for the traveler.



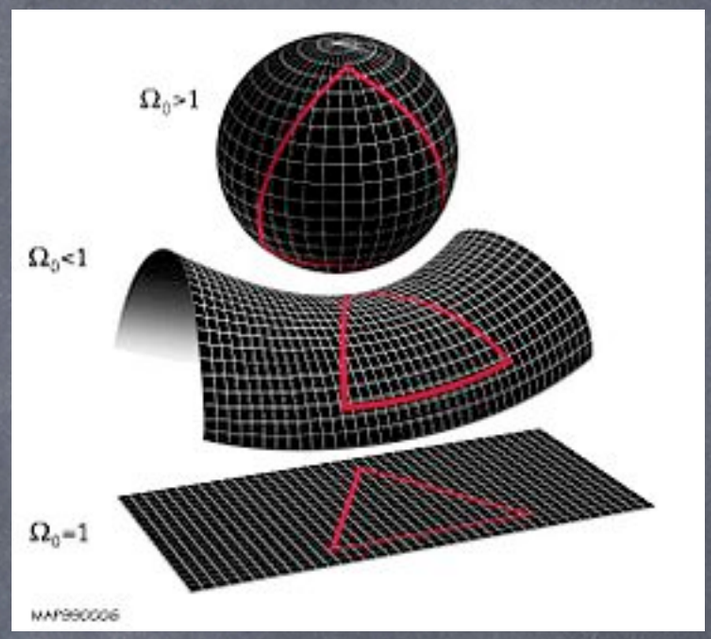


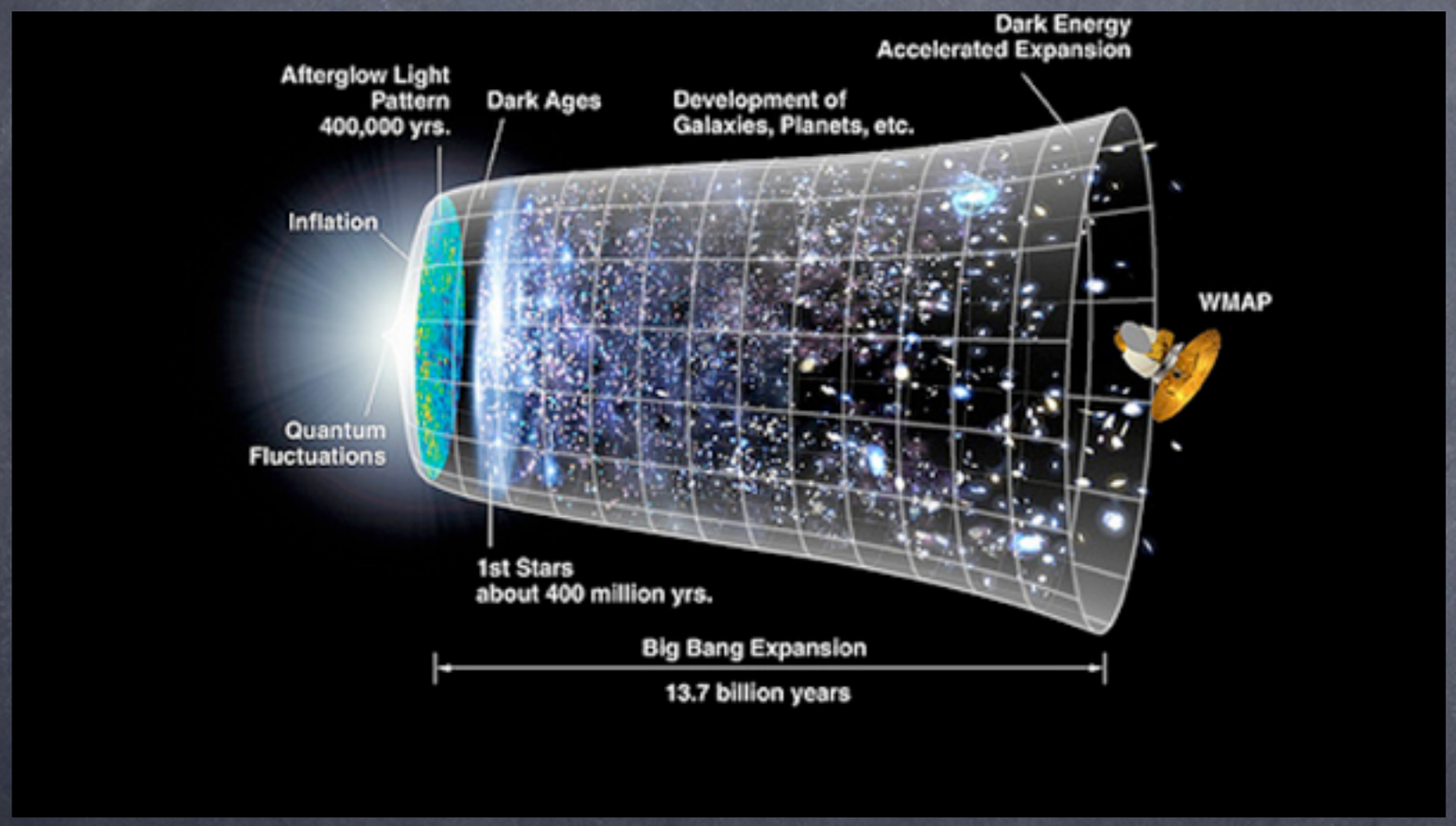
- But the time dilation factor at the event horizon is infinite - so from the point of view of an outside observer, the traveler never gets there!

The Big Bang, Cosmology, & the Expanding Universe

- General Relativity also governs the geometry & time evolution of the entire universe.

- The Big Bang occurred about 13.8 billion years ago.

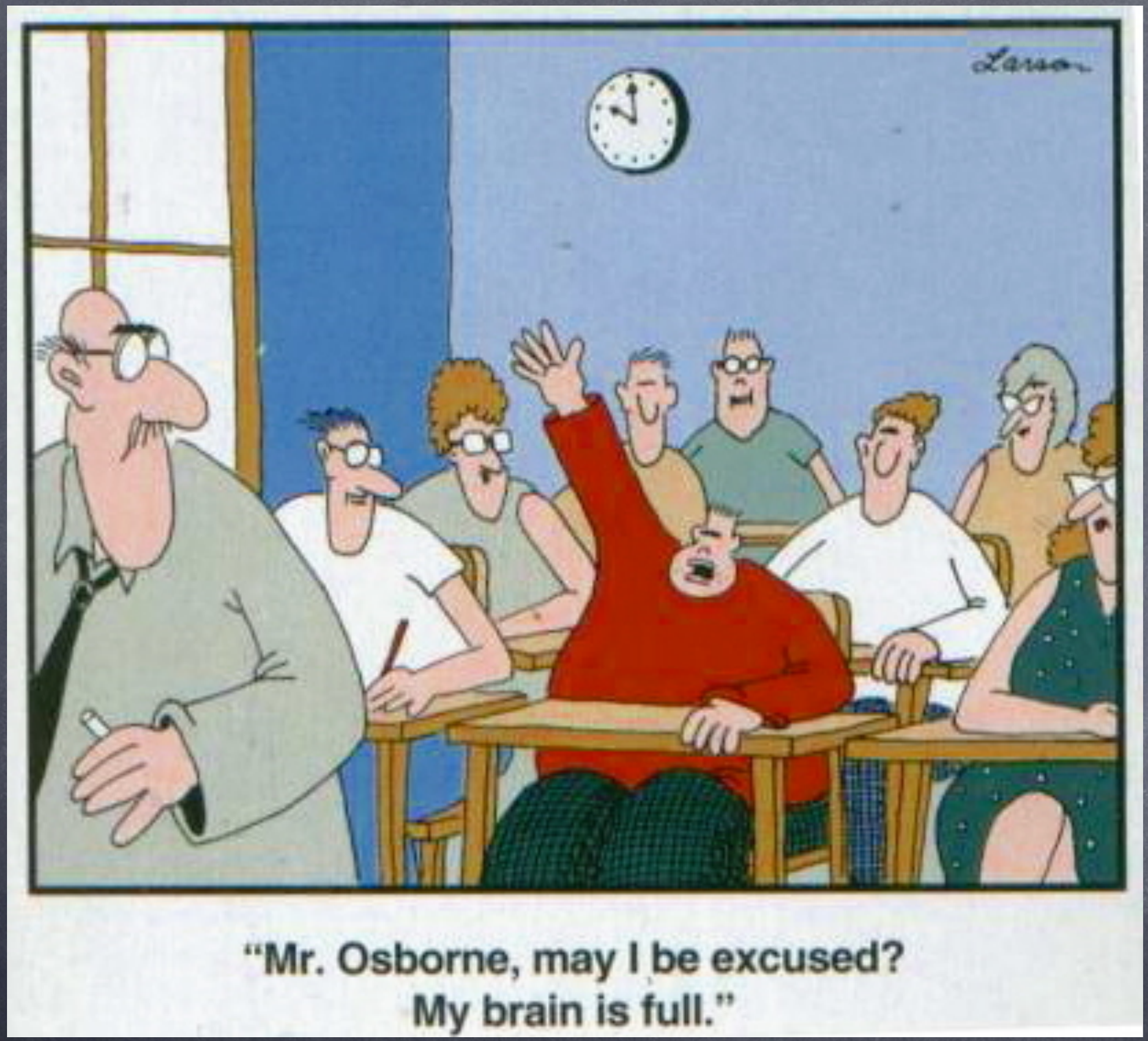




- ...and the expansion of the universe seems to be accelerating. Dark energy?

Relativistic frame-dragging & Mach's Principle

- If all motion is relative, what about a universe consisting only of 2 stars orbiting around each other? If no rotation, they should just fall towards each other.
- In GR, moving masses produce a "gravomagnetic force".
- Local inertial frame determined by large scale distribution of matter.
- Rotating with respect to the rest of the universe should be the same as you standing still & the rest of the universe rotating!

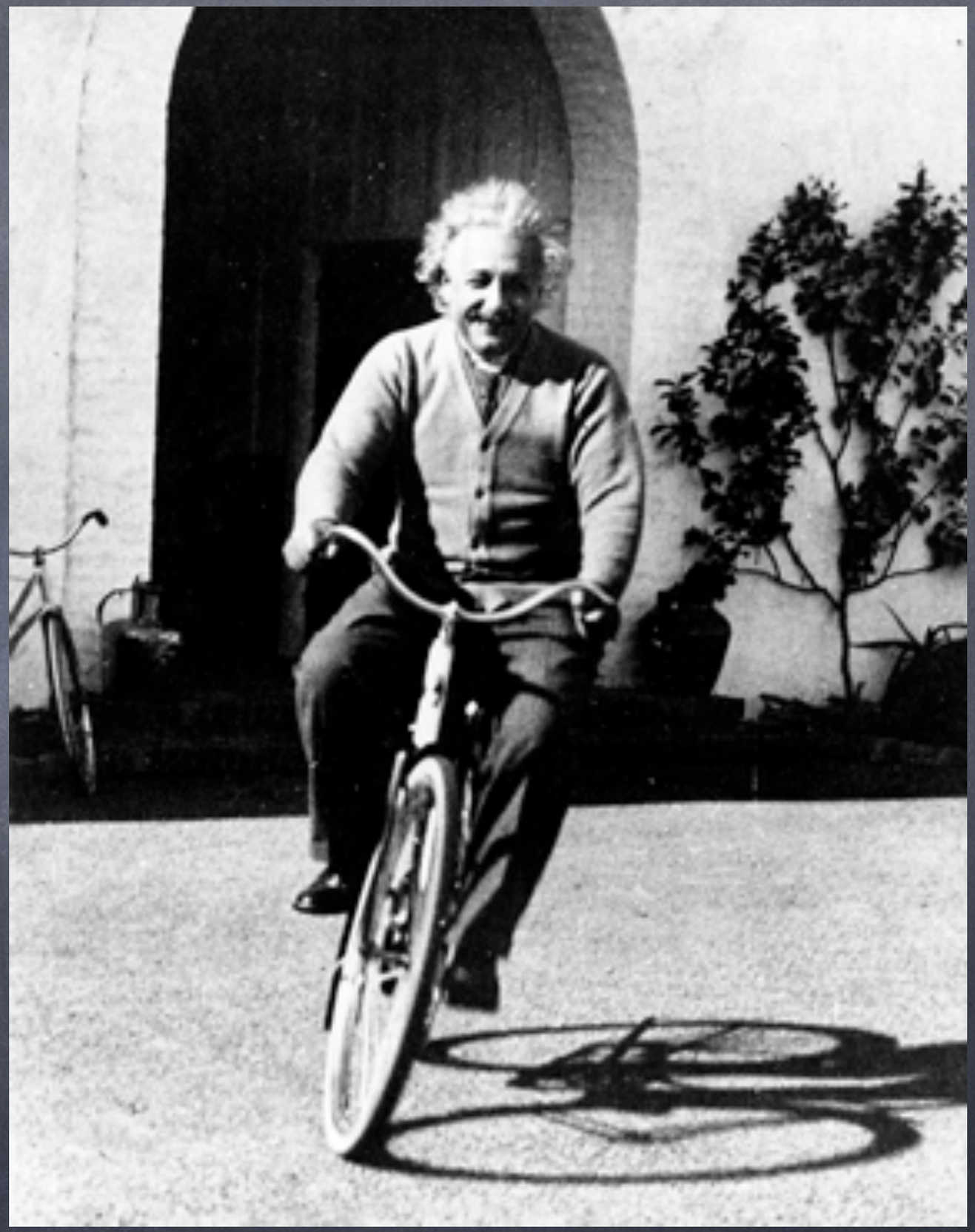


The Far Side

Any questions!

IV. Where did it come from?

- Einstein was really smart.
- His work rested on that of many other people.
- But he was also an extremely creative thinker with a healthy disrespect for authority.
- He had the ability to question basic assumptions, even when the consequences were very weird.

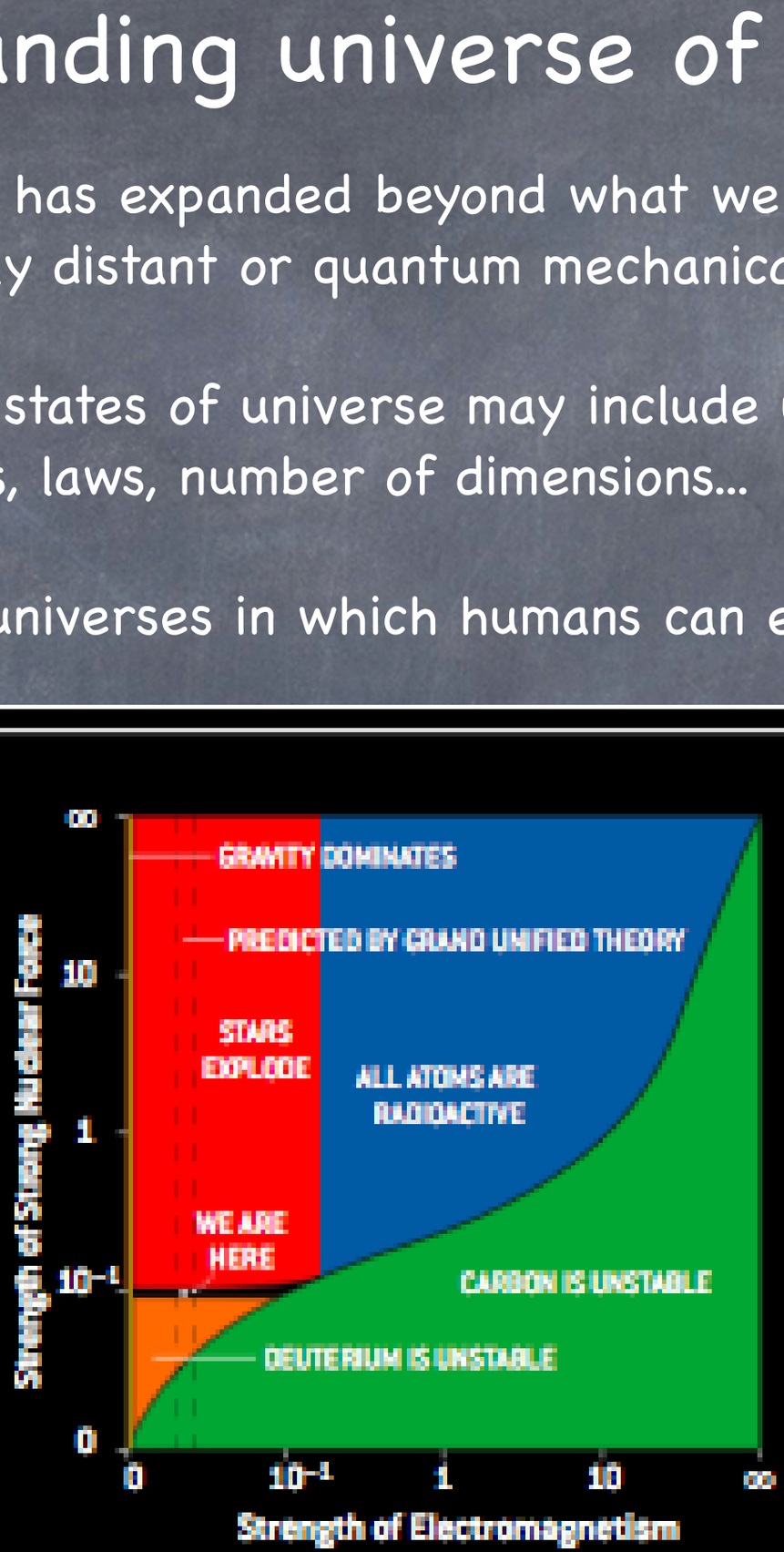


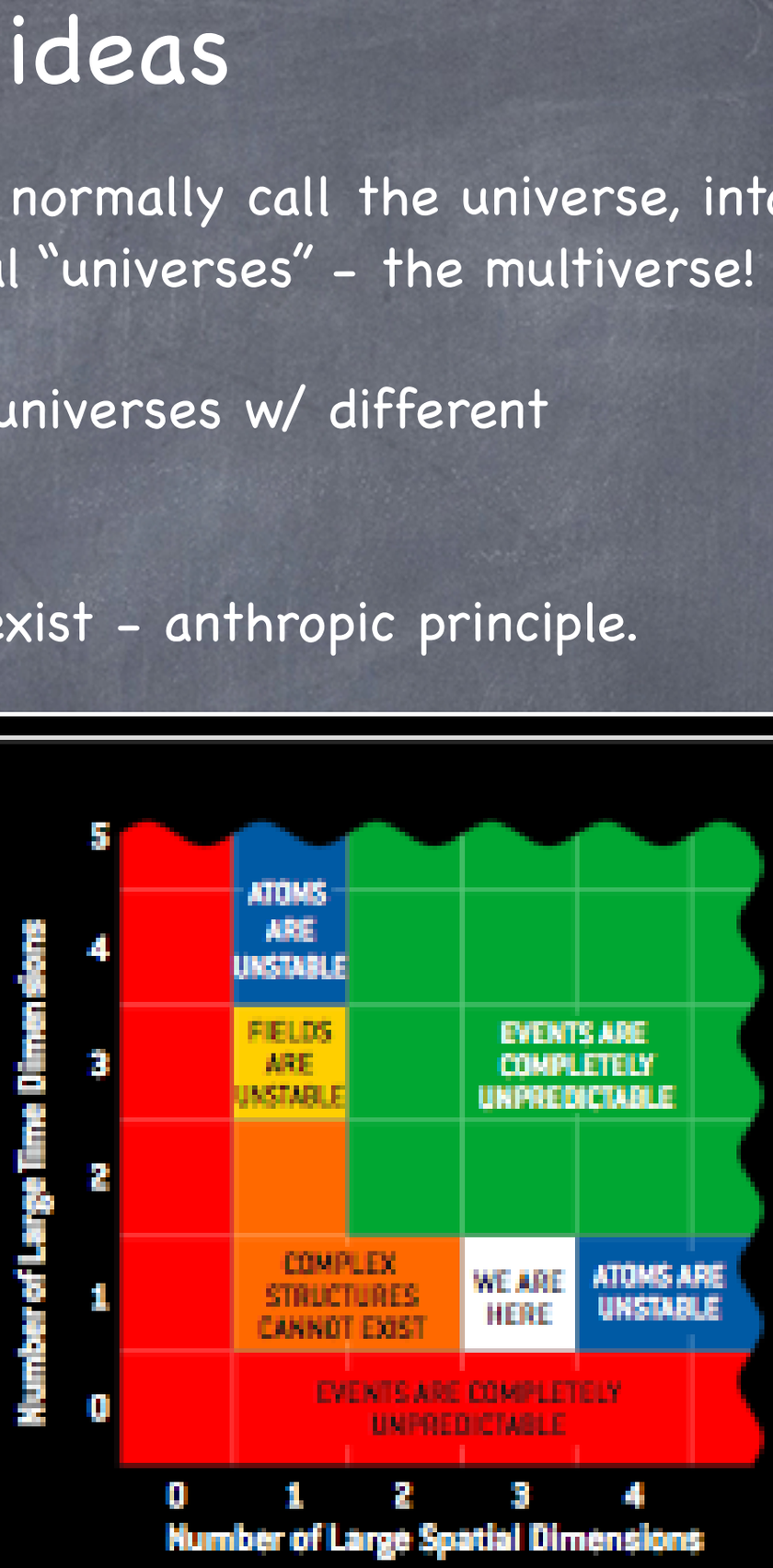
V. The expanding universe of ideas

- Our universe of ideas has expanded beyond what we normally call the universe, into a collection of spatially distant or quantum mechanical "universes" - the multiverse!
- Relativistically, set of states of universe may include universes w/ different fundamental constants, laws, number of dimensions...
- Humans exist only in universes in which humans can exist - anthropic principle.

Evidence

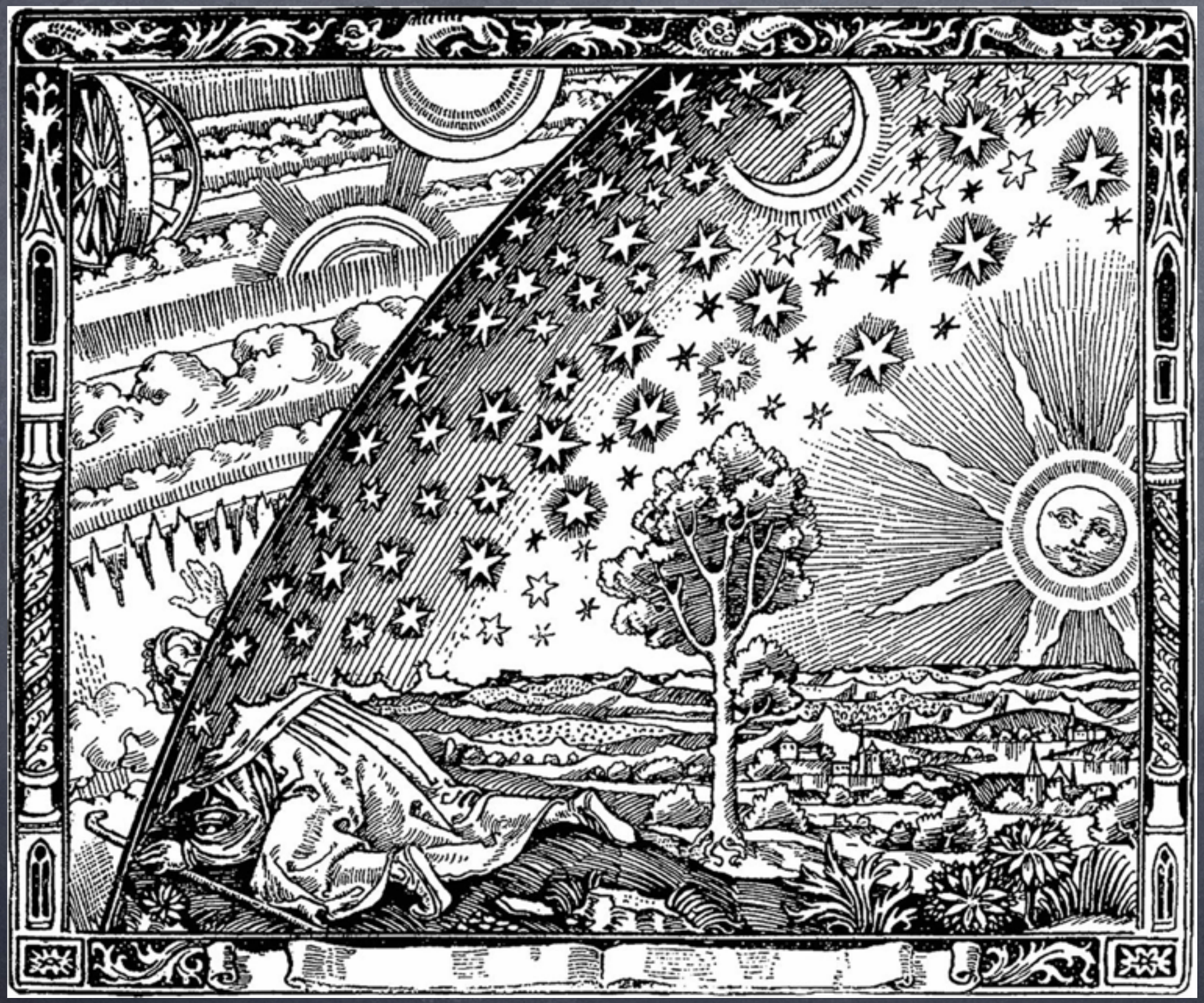
COSMOLOGISTS INFER the presence of Level II parallel universes by scrutinizing the properties of our universe. These properties, including the strength of the forces of nature (*right*) and the number of observable space and time dimensions (*far right*), were established by random processes during the birth of our universe. Yet they have exactly the values that sustain life. That suggests the existence of other universes with other values.





Tegmark 2003

The quest...for knowledge...continues!



Thank you to our symposium organizers, Wafeek Wahby & Steven Daniels!!!

- sources:
  - Hawking, Stephen, A Stubbornly Persistent Illusion: Hawking on Einstein (2007)
  - Einstein, A., The Meaning of Relativity 5th edition (1956)
  - Schwartz, J. & McGuinness, Einstein for Beginners (1979)
  - Pais, A., 'Subtle is the Lord...': The Science & the Life of Albert Einstein (1982)
  - Isaacson, W., Einstein (2007)
  - Wikipedia!

You're still here?

The Einstein-Podolsky-Rosen (EPR) Paradox

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

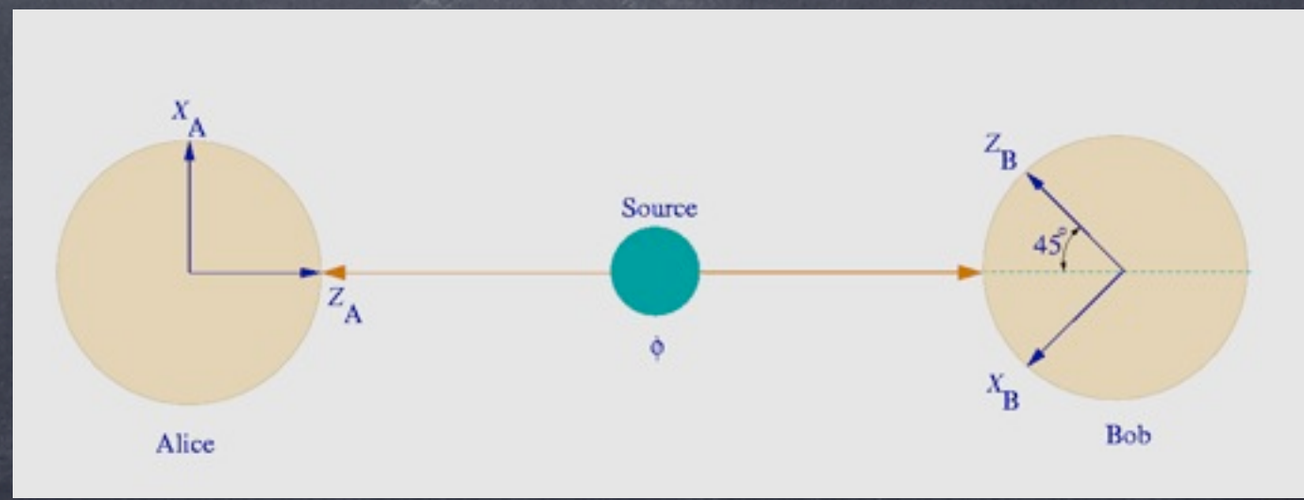
Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*

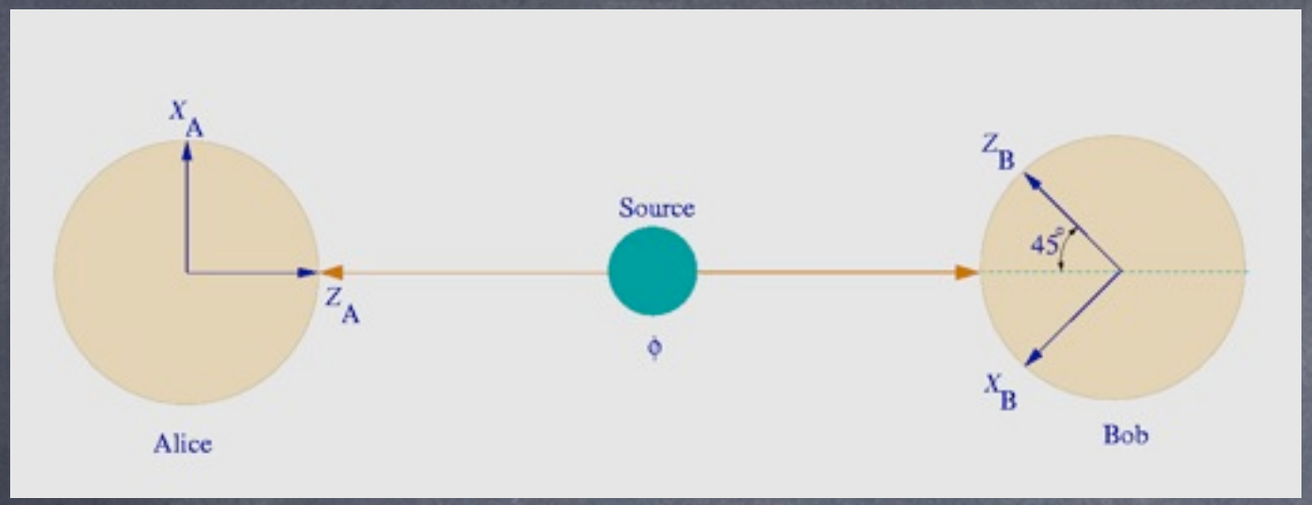
(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

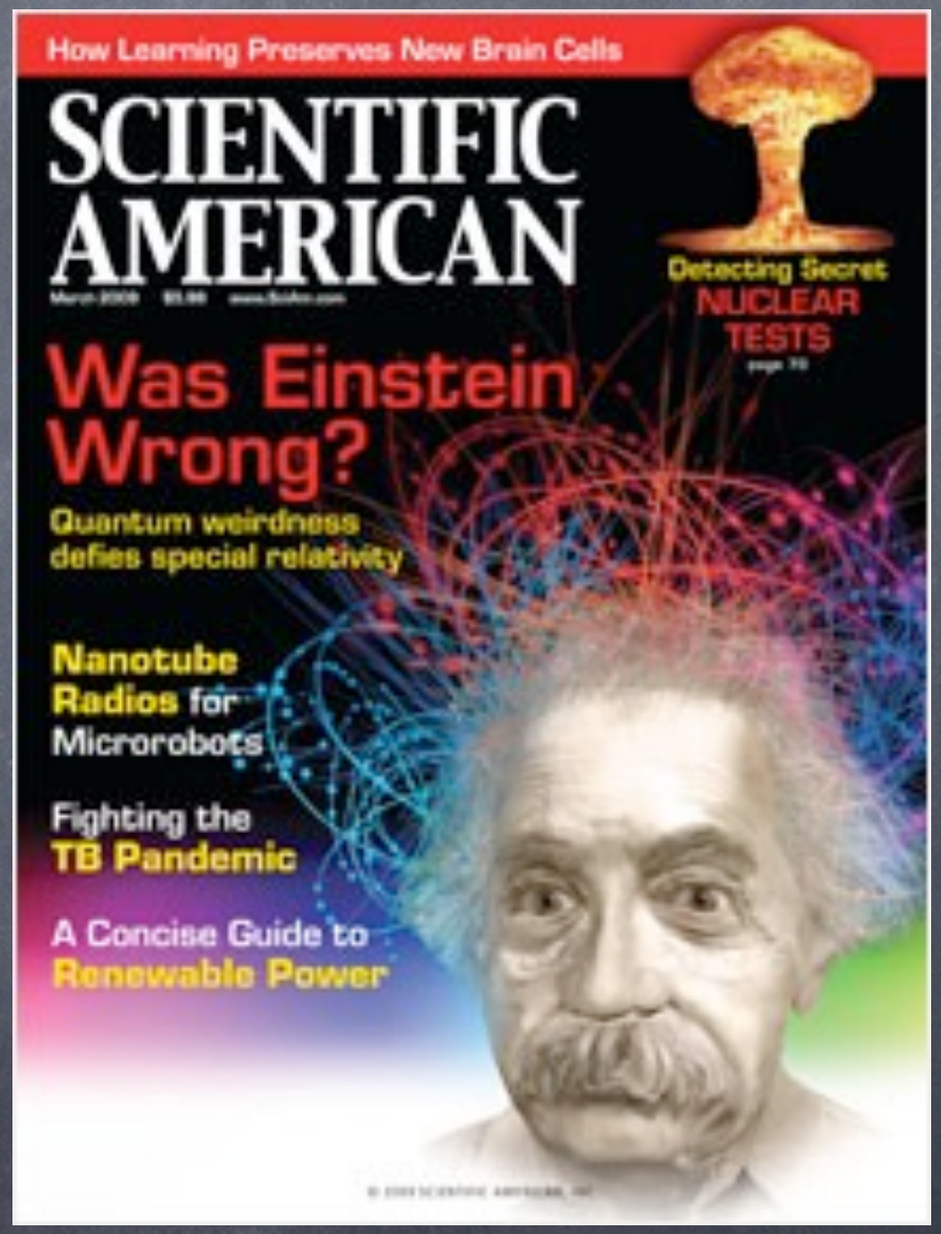
- Famous Einstein quote "God does not play dice".
- Considers a pair of correlated (entangled) particles.
- Measurement of one instantaneously changes state of the other, no matter how far away.
- Einstein: "spooky action at a distance"



The Einstein-Podolsky-Rosen (EPR) Paradox



- Appears to violate Special Relativity.



- MWI explanation: measurement of 1st particle just tells us which branch we're in! No signal needs to propagate faster than c.

- (Sci. Am. 3/09 article by Albert & Galchen says that MWI solves this problem, but is beset by many (unspecified) problems.)