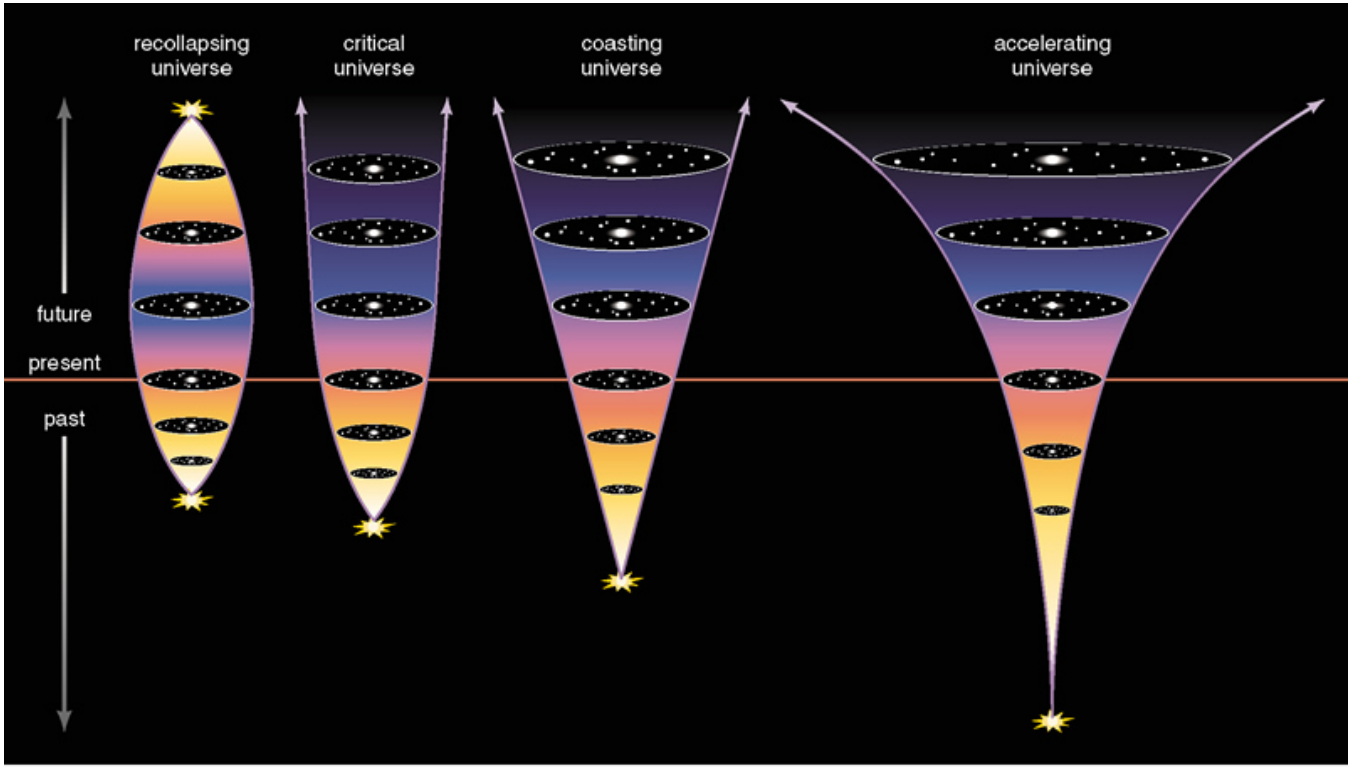
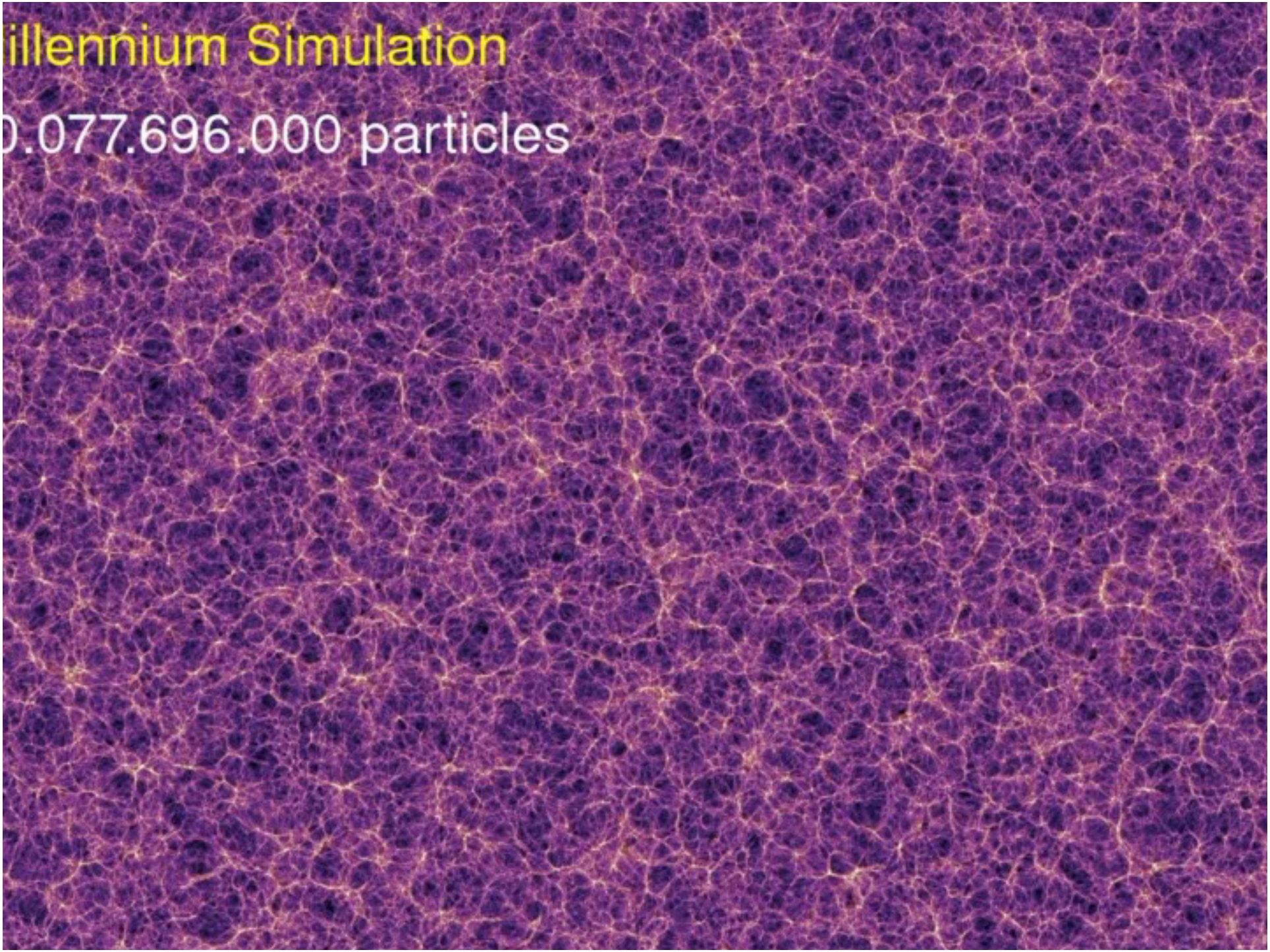
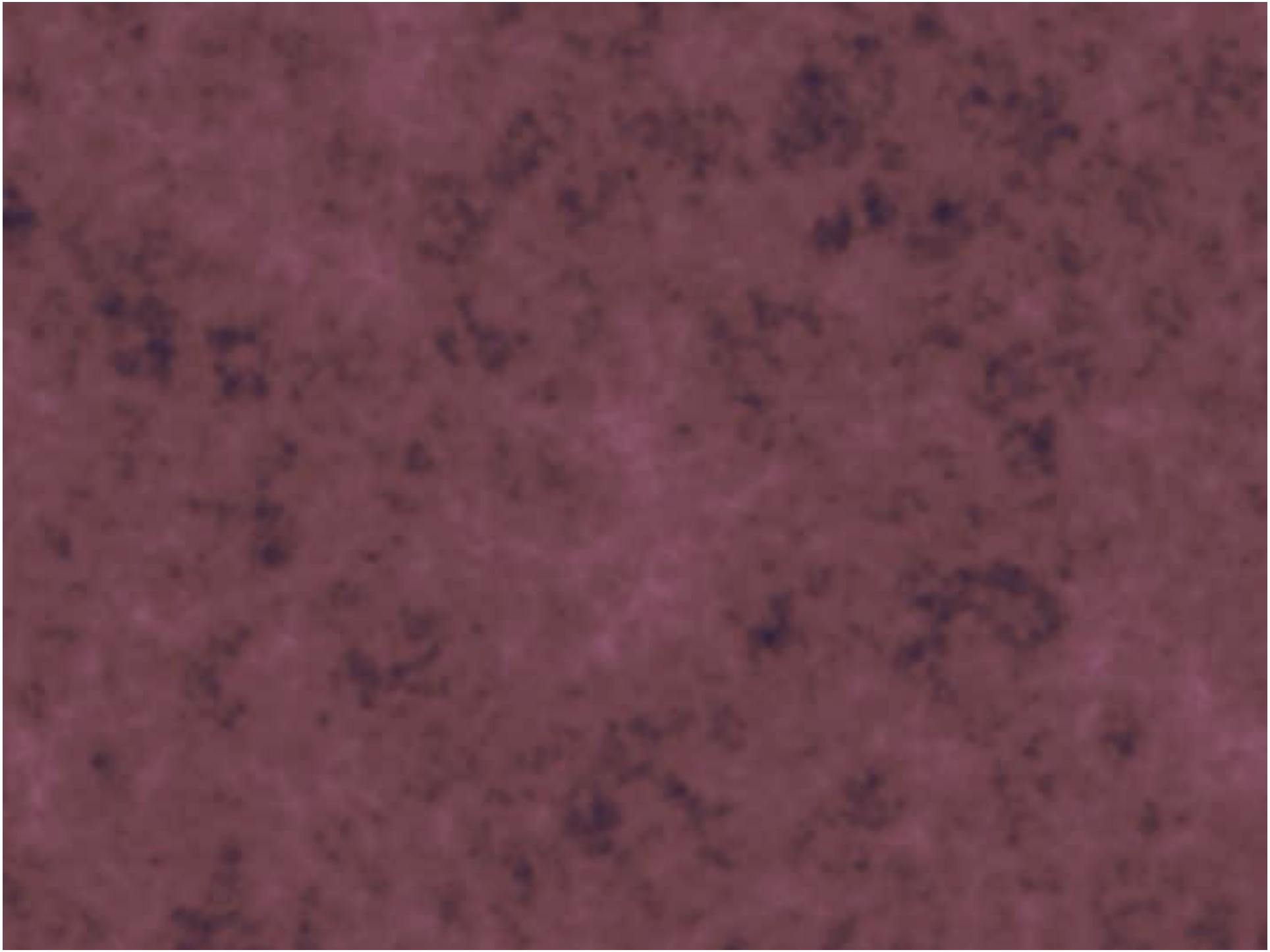
Four Models for the Future of the Universe

1. Recollapsing Universe: the expansion will someday halt and reverse
2. Critical Universe: will not collapse, but will expand more slowly with time
3. Coasting Universe: will expand forever with little slowdown
4. Accelerating Universe*: the expansion will accelerate with time

*currently favored




illennium Simulation
.077.696.000 particles



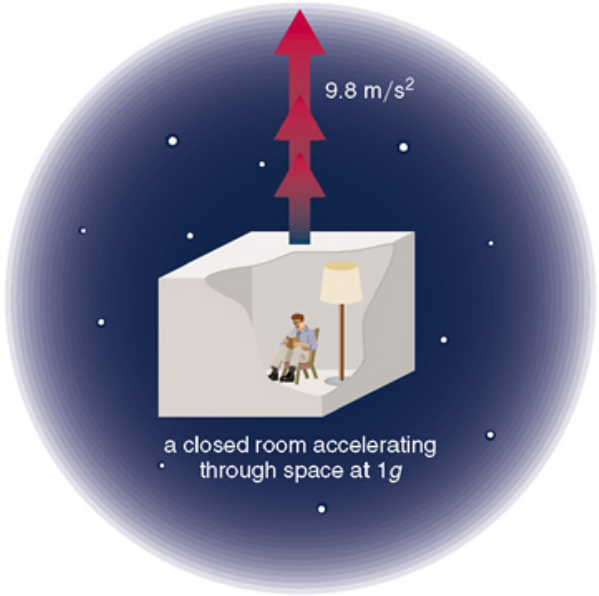
The Topic is Gravity

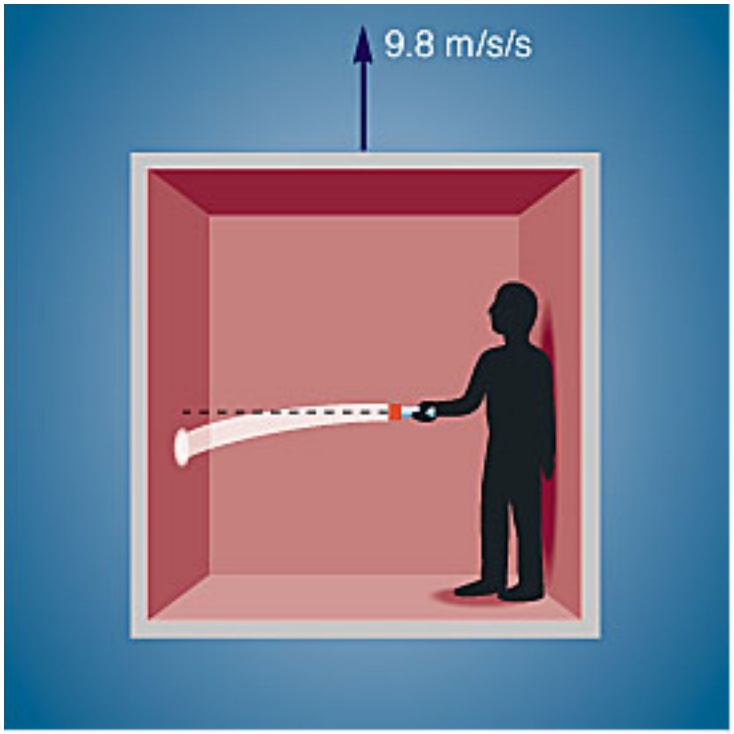
- Albert Einstein stunned the scientific world again in 1915…
  - with publication of his **general theory of relativity**
  - it is primarily a theory of *gravity*
- Isaac Newton saw gravity as a mysterious "force."
  - he could explain its actions, but not how it was transmitted through space
  - Einstein theorized that the "force" of gravity arises from distortions of space (or **spacetime**) itself!
- spacetime…the 4-dimensional combination of space & time that forms the very fabric of the Universe
- matter shapes and distorts spacetime
  - space(time) itself can be curved
  - you may think you are traveling a straight line
  - but your motion is actually curved

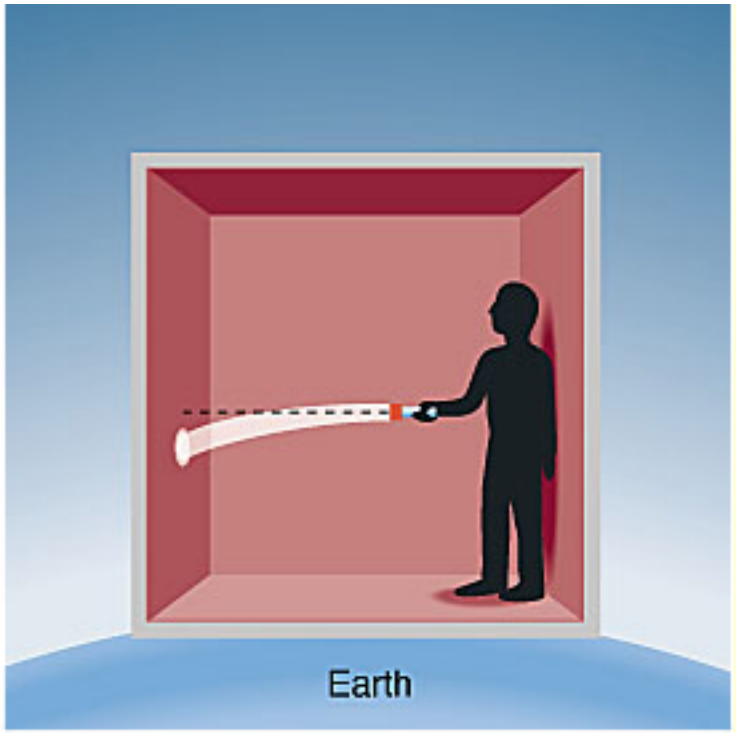
The Equivalence Principle

- If you are sitting in a closed room, there is no experiment you can do to tell whether the room is accelerating upward, or gravitational field is applied.

a closed room on Earth





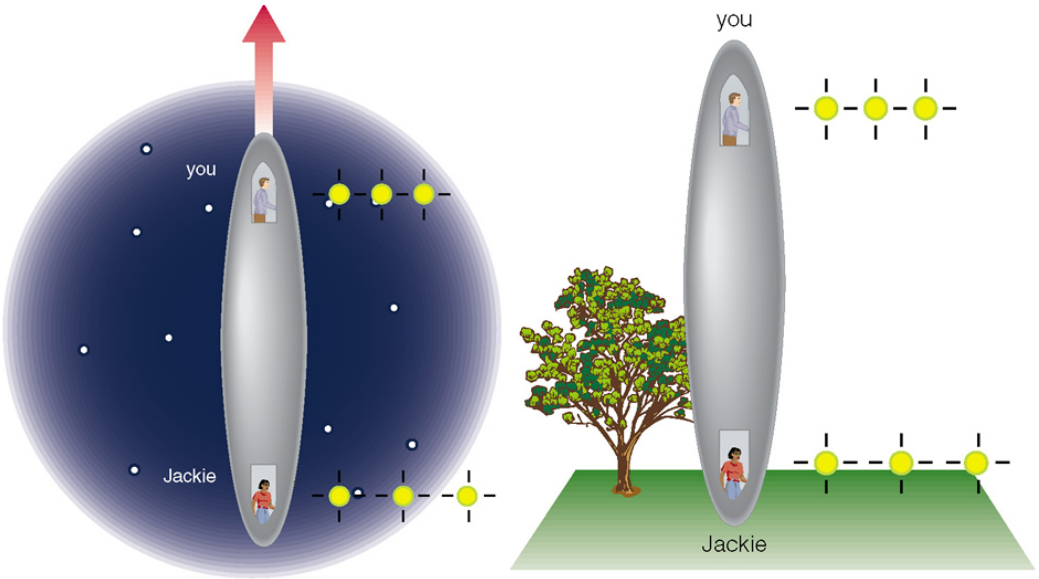


Since the light bends in accelerated elevator, it MUST bend in ANY gravitational field!!

----the equivalence principal has real power---

This is why we see gravitational lenses in space!!

Gravitational Time Dilation

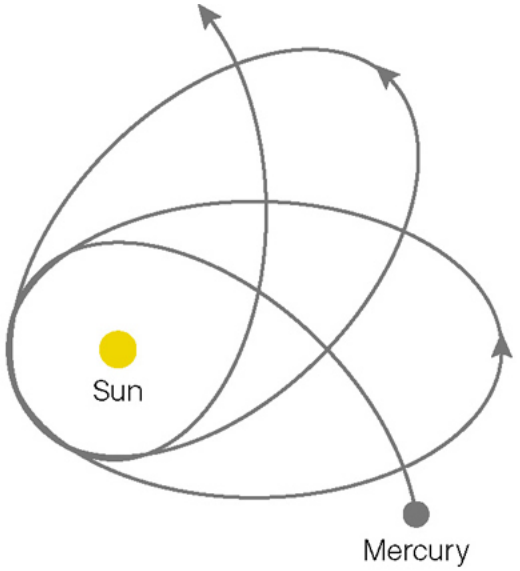


- We use the equivalence principle to study the effect of gravity on time.
- You & Jackie in the ship have synchronized watches
  - the ship accelerates
  - the watches flash

- Moving away from Jackie, you see larger time intervals between her flashes.
  - time appears to be moving slower for her
- Moving towards you, Jackie sees shorter time intervals between your flashes.
  - time appears to be moving faster for you
  - you both agree
- So, in the equivalent gravitational field…
  - time moves more slowly where the gravity is stronger *(where is that?)*
  - Time goes more slowly on 1st floor relative to top floor of a building!

Precession of Mercury's Orbit

- Newton's law predicted that the orbit of Mercury should precess.
  - due to gravitational influence of the planets
  - this precession was measured in the 1800s
  - **but** Newton's law could not account for the exact precession period which was observed
  - the discrepancy between observation and theoretical prediction was real



Note: The amount of precession with each orbit is highly exaggerated in this picture.

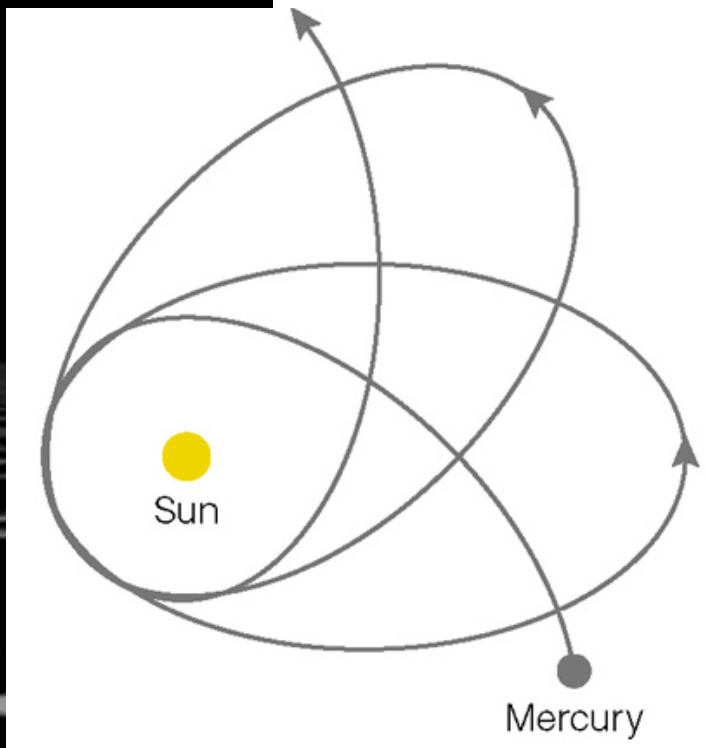
- Einstein knew of this discrepancy and used general relativity to explain it.
  - Newton's law assumed that time was absolute & space was flat
  - but when Mercury is closest to the Sun, time runs more slowly & space is more curved
- Predictions of general relativity matched the observations exactly!

Precession of perihelion of Mercury

~43 sec/century was known "excess" of perihelon, not explainable by motion of planets.

Einstein, out of the blue, calculates effect in solar system, and it matches!

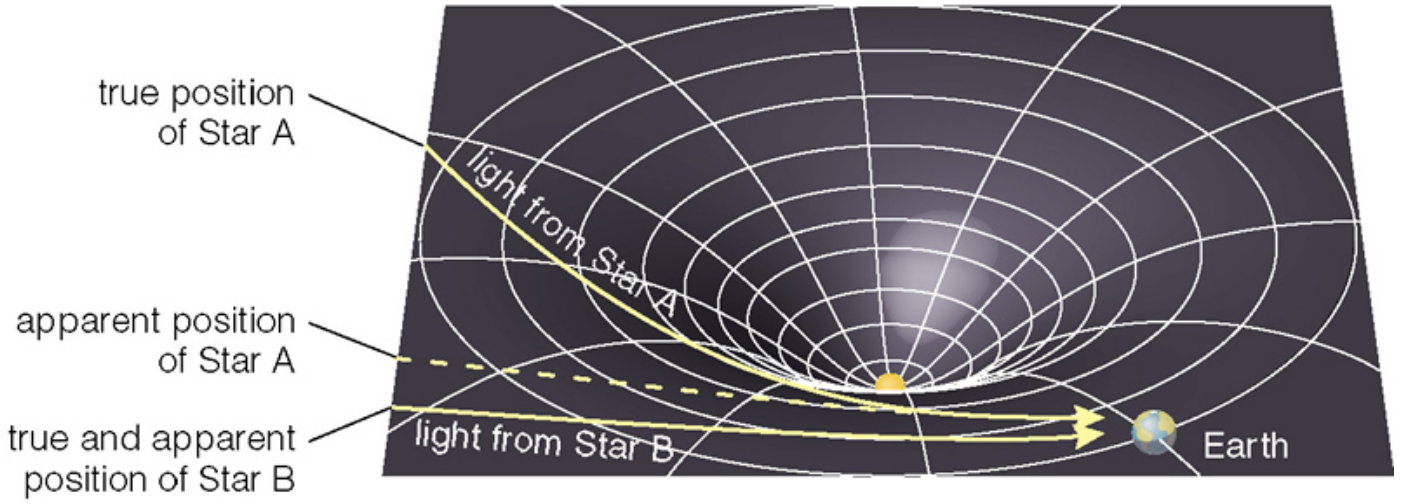
This makes scientists into believers!



Note: The amount of precession with each orbit is highly exaggerated in this picture.

Gravitational Lensing

- Light will always travel at a constant velocity.
  - therefore, it will follow the straightest possible path through spacetime
  - if spacetime is curved near a massive object, so will the trajectory of light

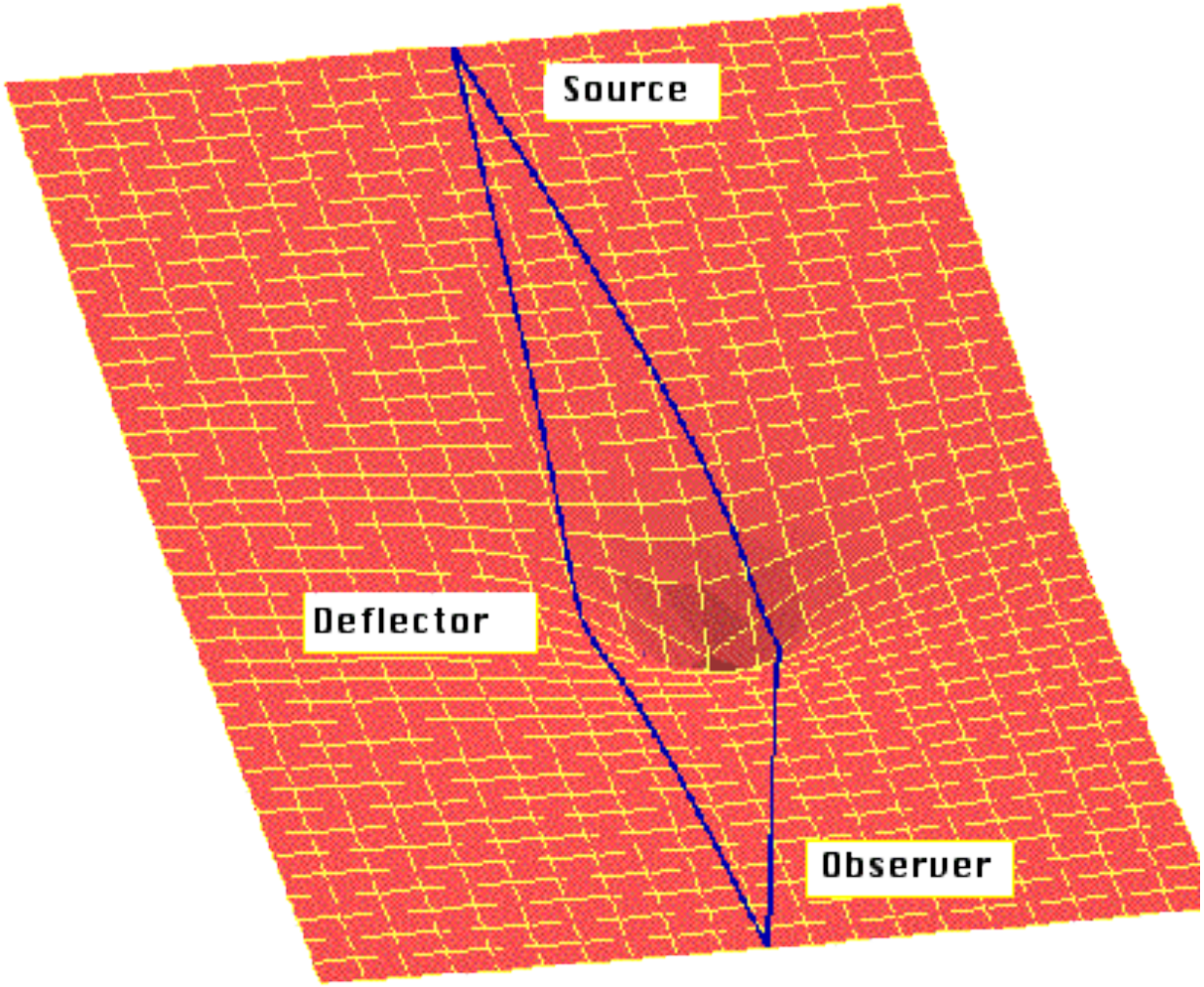


- During a Solar eclipse in 1919, two stars near the Sun…
  - were observed to have a larger angular separation than is usually measured for them at night at other times of the year
- This observation verified Einstein's theory…
  - making him a celebrity

Gravitational Lensing

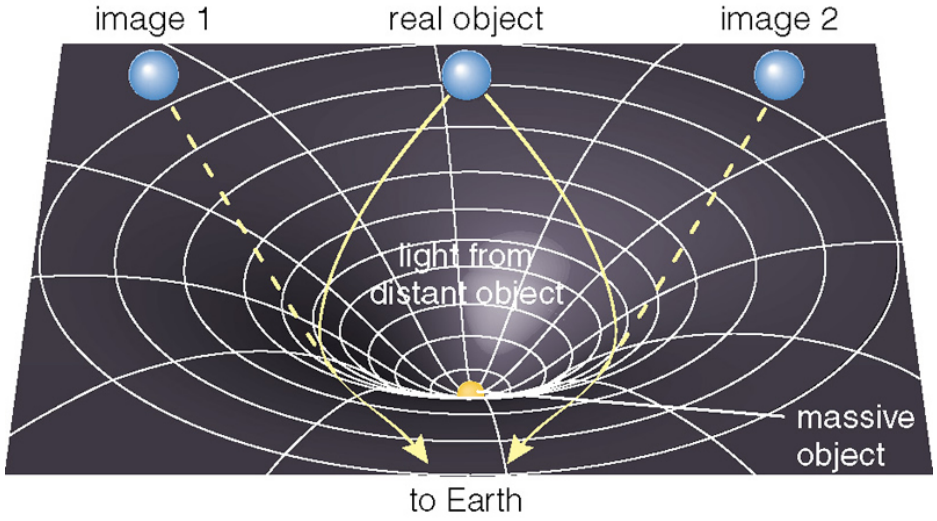
Radiation Emitted by Source in all directions

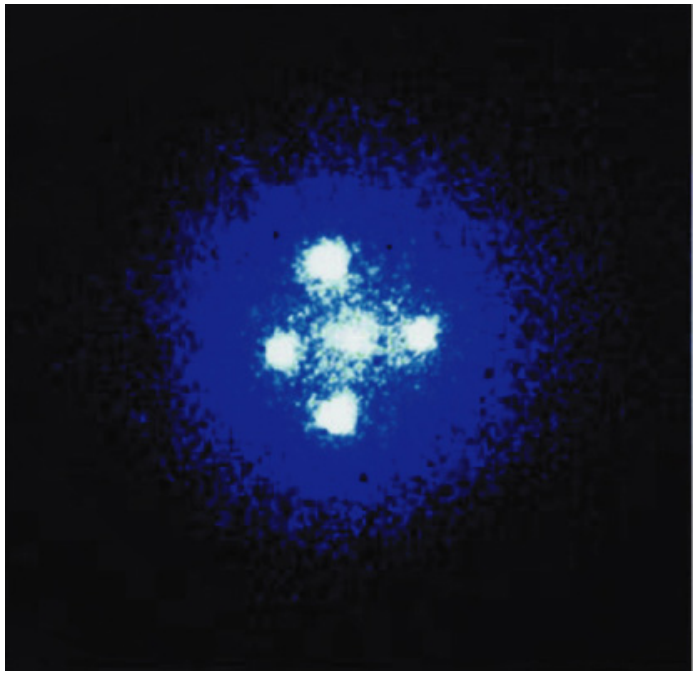
Each path is a shortest line from source to observer



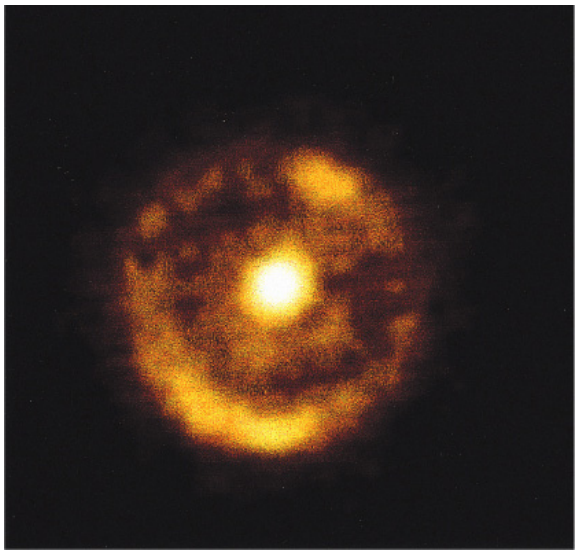
Gravitational Lensing

- Since that time, more examples of **gravitational lensing** have been seen.
- They usually involve light paths from quasars & galaxies being bent by intervening galaxies & clusters.





Einstein's Cross



an Einstein ring
galaxy directly behind a galaxy

Gravitatio

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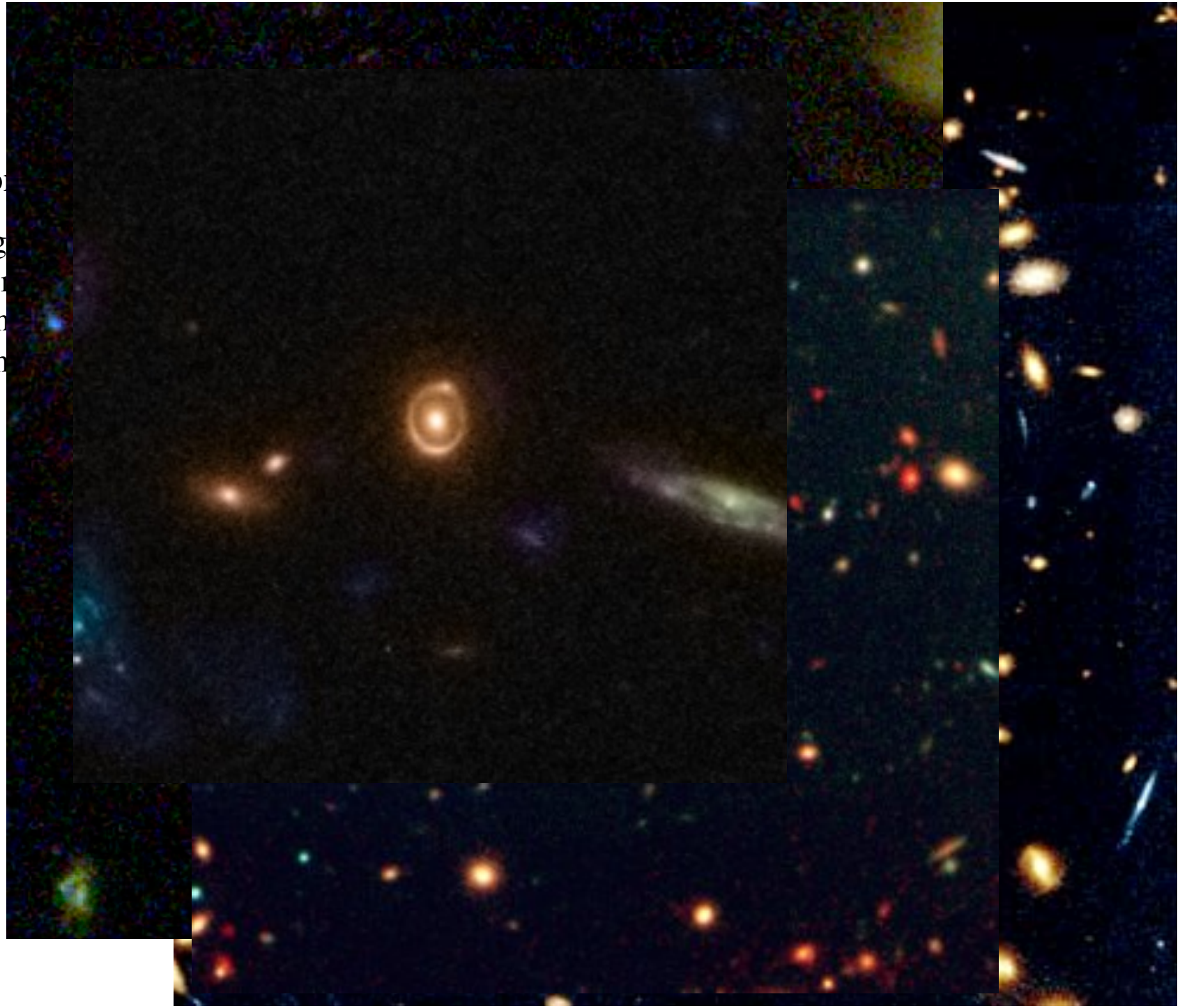
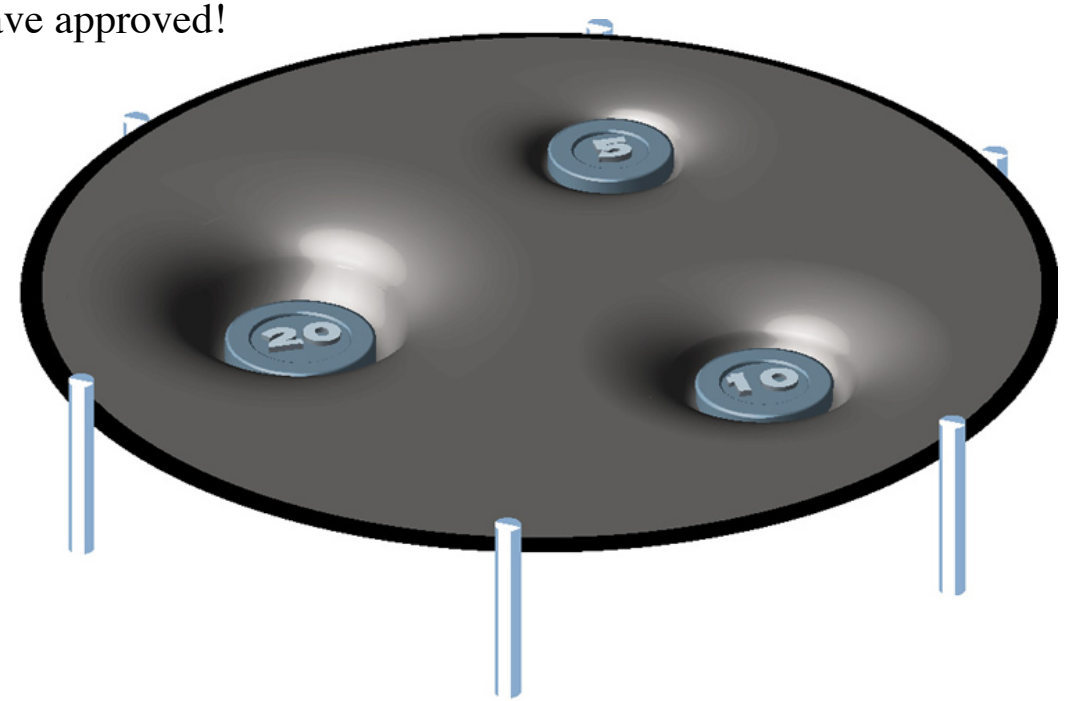


Einstein's spreading fame

- In May 1919, a team led by the British astronomer Arthur Eddington claimed to have confirmed Einstein's prediction of gravitational deflection of starlight by the Sun while photographing a solar eclipse with dual expeditions in Brazil and a West African island.
- British newspaper the *Times* printed a banner headline that read: "Revolution in Science – New Theory of the Universe – Newtonian Ideas Overthrown"
- Nobel laureate Max Born praised general relativity as the "greatest feat of human thinking about nature"; fellow laureate Paul Dirac was quoted saying it was "probably the greatest scientific discovery ever made". The international media guaranteed Einstein's global renown.

Mass deflects a tight sheet and its effect is "felt at a distance".

•Newton would have approved!



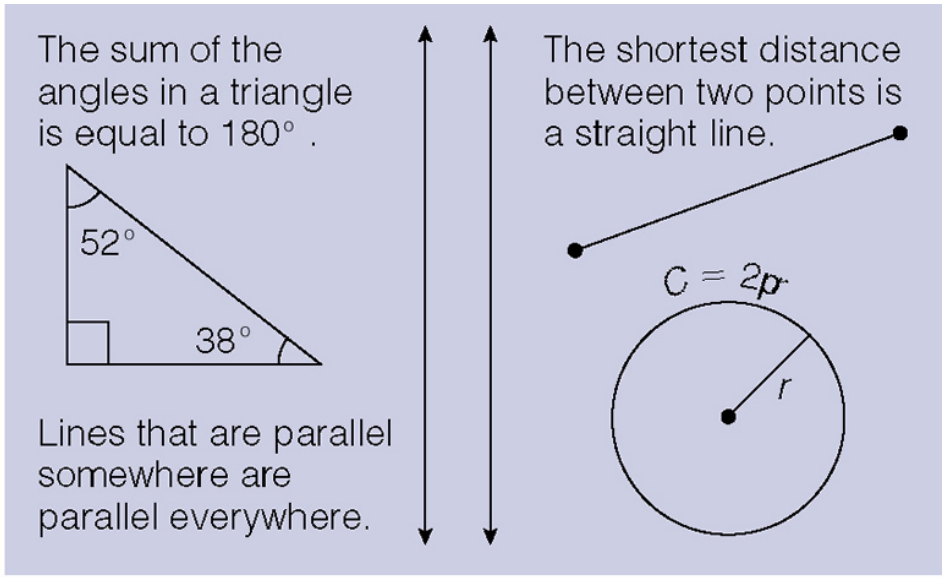
Matter distorts spacetime like weights on a taut rubber sheet. The greater the mass, the greater the distortion of spacetime.

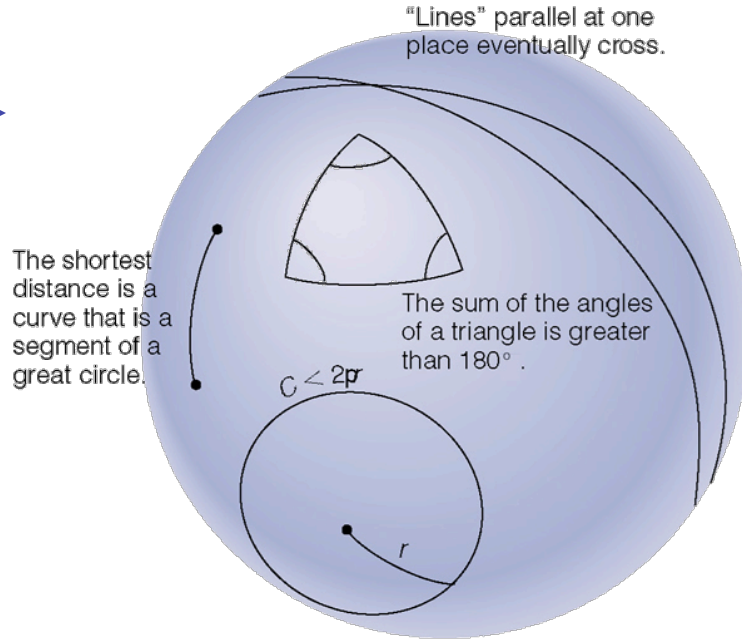
Note that this distortion has used the 3rd dimension to show effect of a bent 2-d surface. The real situation has a curved 3-d surface, and a flat 4-d space to show the curvature. In other words, the picture above is not quite correct.

The Rules of Geometry

- The geometry you know is valid when drawn on a flat surface.
- The rules change if the surface is not flat.

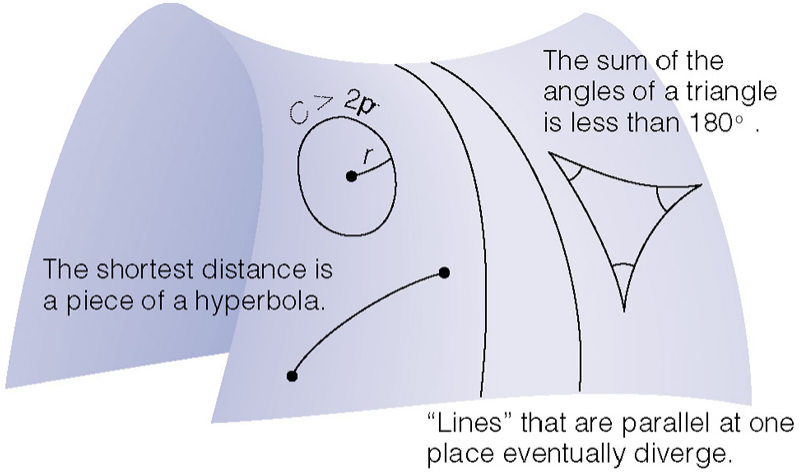
spherical (curved-in) geometry →





flat (Euclidean) geometry

saddle-shaped (curved-out) geometry →

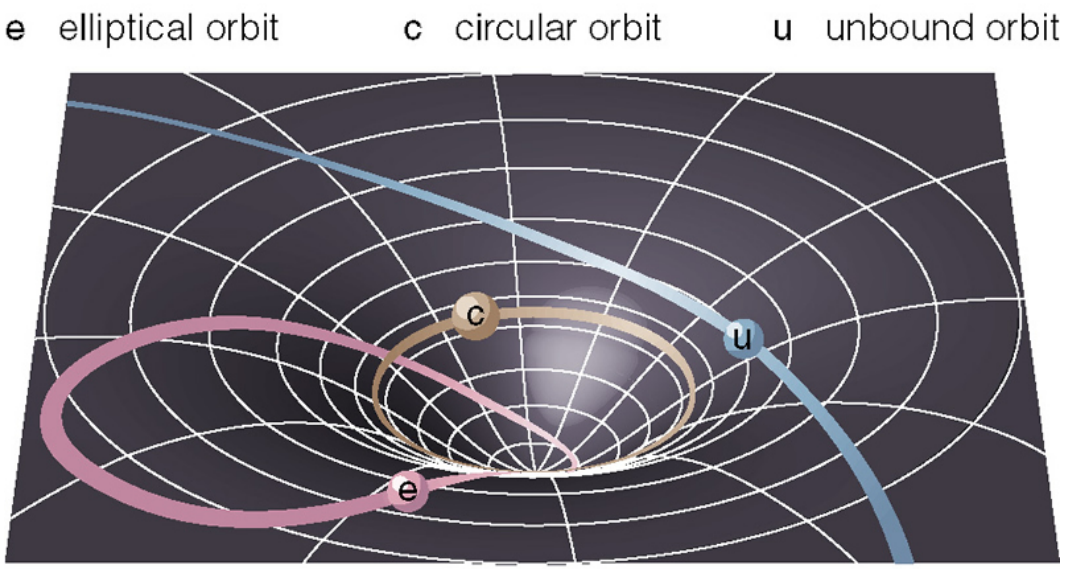


Geometry of Spacetime

- Spacetime can have three possible geometries:
  - flat…the rules of Euclidean geometry apply
  - spherical…parallel lines eventually meet
  - saddle-shaped…parallel lines eventually diverge
- Spacetime may have different geometries in different places.
- If spacetime is curved, then no line can be perfectly straight.
- Since being in "free-fall" is equivalent to traveling at constant velocity (i.e. a straight line)…
  - objects experiencing weightlessness must be traveling along the straightest possible worldline in spacetime
- Objects in orbit are **weightless**.
  - the shapes & speeds of their orbits can reveal the geometry of spacetime
  - these same orbits are determined by *gravity*

Mass and Spacetime

- According to Newton, all bodies with mass exert a gravitational force on each other.
  - even Newton had problems accepting this concept of "action at a distance"
- General relativity removes this concept.
  - mass causes spacetime to curve
  - the greater the mass, the greater the distortion of spacetime
  - curvature of spacetime determines the paths of freely moving objects

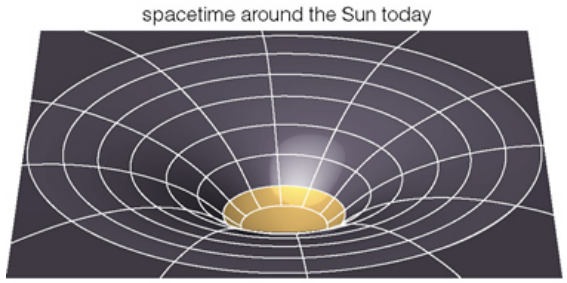


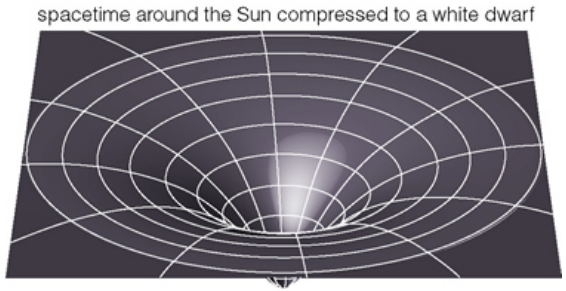
- Orbits can now be explained in a new way.
  - an object will travel on as straight a path as possible through spacetime

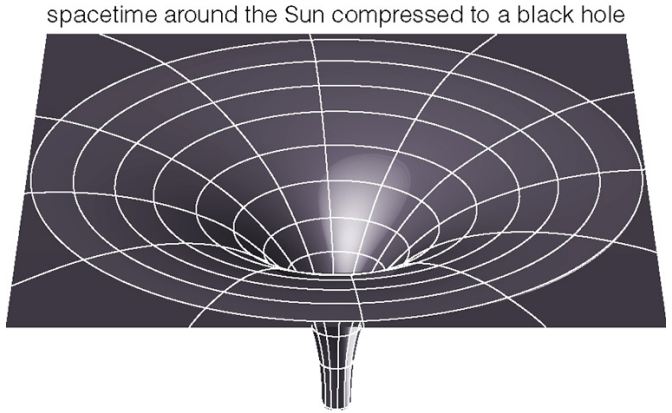
SpacetimeMarsRadOrbit.swf

The Strength of Gravity

- The more that spacetime curves, the stronger gravity becomes.
- Two basic ways to increase gravity/curvature of spacetime:
  - increased mass results in greater curvature at distances away from it
  - curvature is greater near the object's surface for denser objects
    - for objects of a given mass, this implies smaller objects







- All three objects impose the same curvature at a distance.
- White dwarf imposes steeper curvature at Sun's former position.
- Black hole punches a hole in the fabric of spacetime.
- Nothing can escape from within the event horizon.

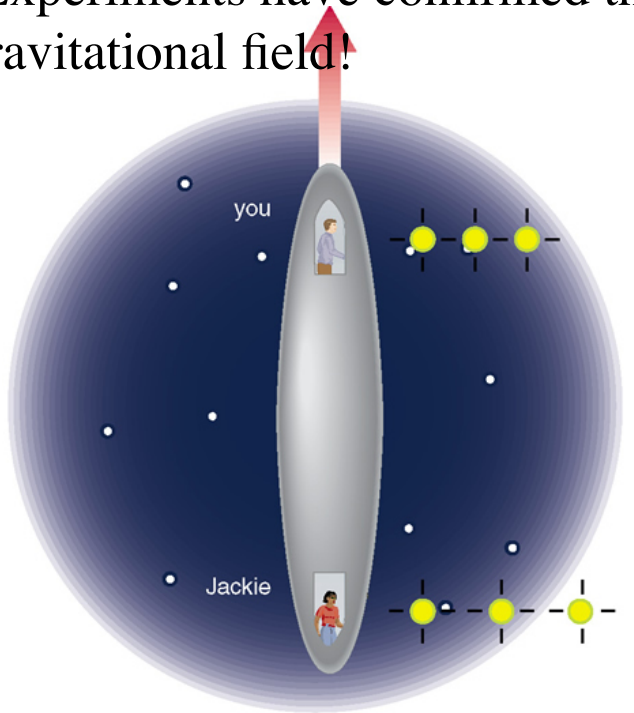
Do clocks run at same speed?

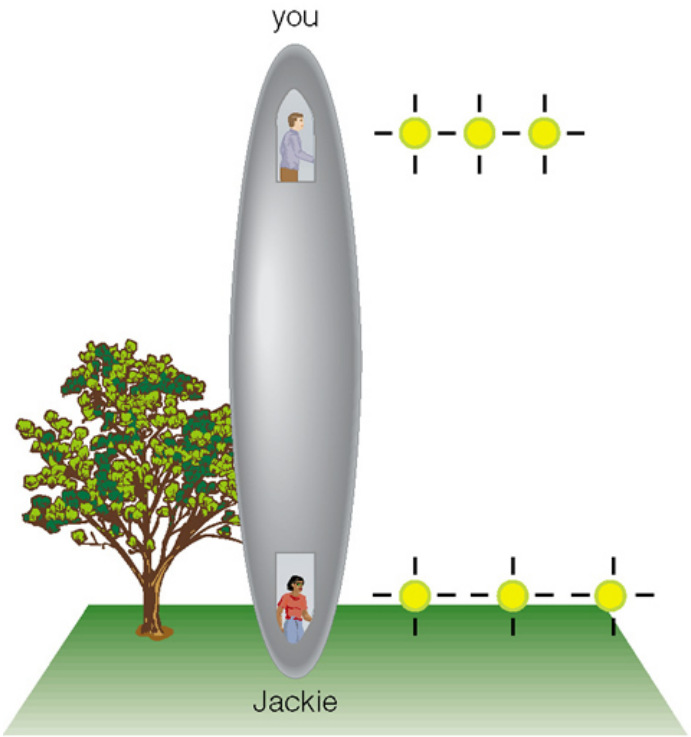
•In rocket ship, you appear to be running away from Jackie, each count is stretched out (redshifted).

•Jackie perceives your pulses to be sped up, (blueshifted)

•Einstein argued, from equivalence proposal, that deep in a potential well the clocks would run **slower**!

•Experiments have confirmed that clocks do run slower when lower in the gravitational field!





Gravitational Redshift

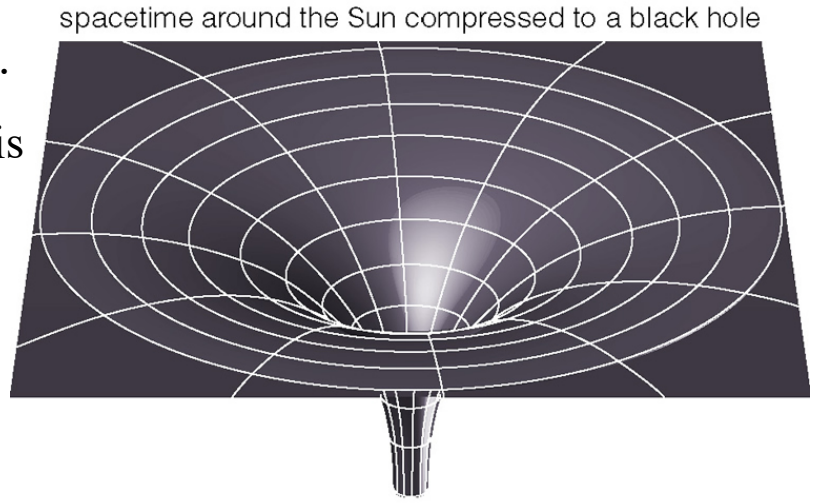
- If time runs more slowly on the surface of stars than on Earth…
  - spectral lines emitted or absorbed on the surfaces of stars
  - will appear at a lower frequency (cycles/s) than measured on Earth
  - the length of 1 second is longer on the star's surface than on Earth
- This **gravitational redshift** has been observed.

•Clock beats slower as one drops in potential.

•It is not possible to synchronize clocks in this space!

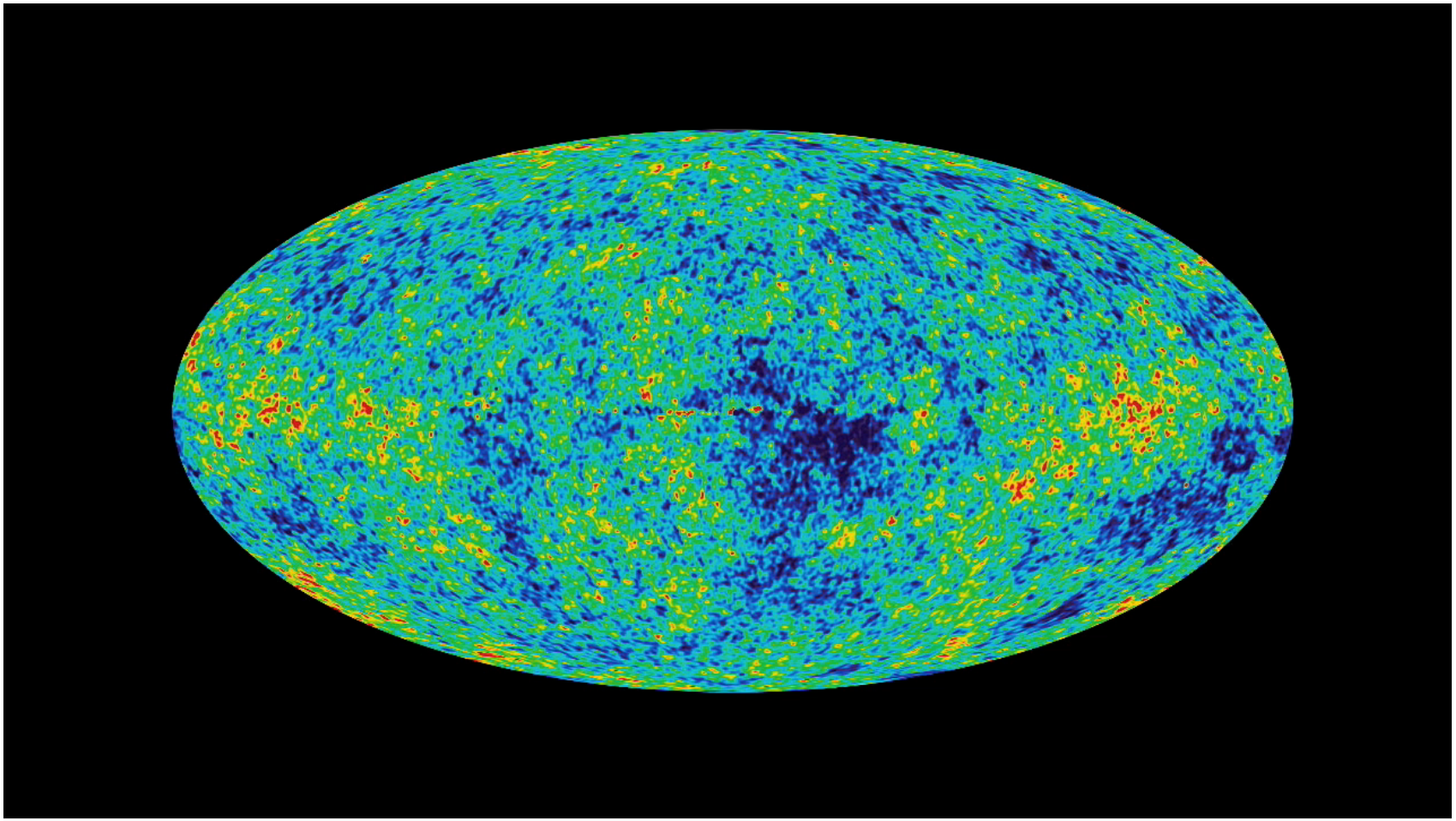
•This is Einstein's 3rd prediction of GR:

- •bending light
- •precession of perihelion of Mercury
- •gravitational redshifts



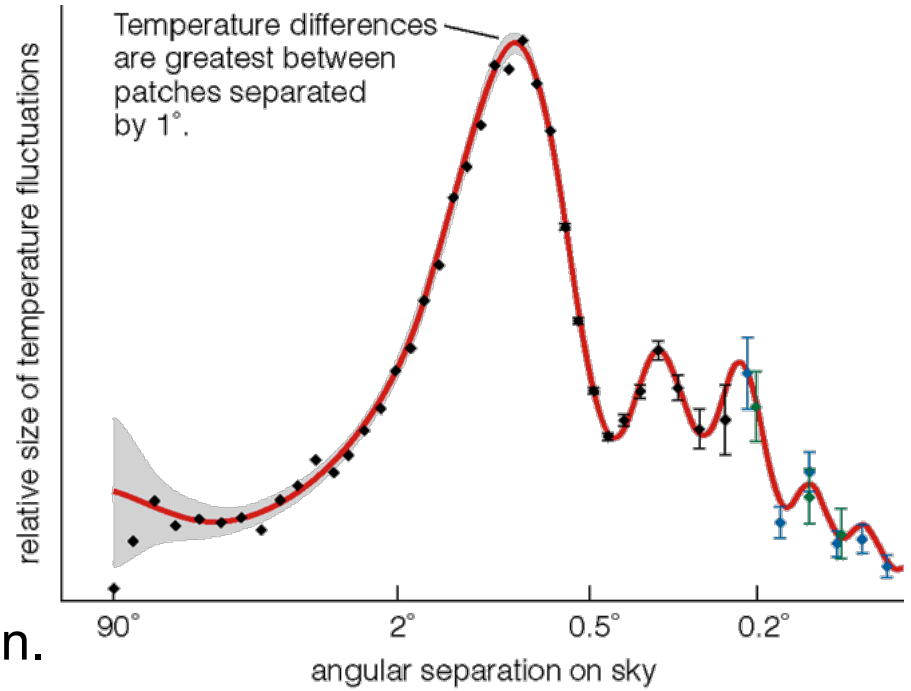
WMAP results

fluctuations are 10^{-5} of CMB intensity



New Evidence for Inflation

- A Big Bang model with inflation was fitted to:
  - temperature variations plotted as angular separation on the sky →



- Spectrum fully consistent with Inflation.
- Overall geometry of the Universe is flat.
- Total matter density is 27% of the critical density.
  - in agreement with M/L in clusters of galaxies
- Density of baryonic (ordinary) matter is 4.4% of critical density.
  - in agreement with observed abundance of Deuterium
- Flat geometry + matter density < critical implies dark energy.
  - in agreement with accelerating expansion from white dwarf supernovae
- Age of the Universe is 13.7 billion years.

Connecting CMBR fluctuations to LSS

- Consider a stereo receiver with knobs for tuning amplitude of different frequencies, bass, midrange, treble, etc. Adjusting these knobs tunes the *spectrum of sound waves.*
- Difference between a viola and a piccolo playing the same note is the higher frequency harmonics and anyone can tell the difference.
- Similarly the spectrum of *inhomogeneous matter waves* in the Universe is tuned by different types of dark matter, different cosmological models.
- Observations of Large Scale structure and CMBR fluctuations seen by COBE and WMAP **are perfectly consistent with cold dark matter models. Current situation is that models are essentially perfect. This was a big triumph!** Pretty amazing!!!

Evolution of a Universe

- Temperature variations in the 380,000 year-old Universe serve as a “genetic code” for the structure of the Universe today!