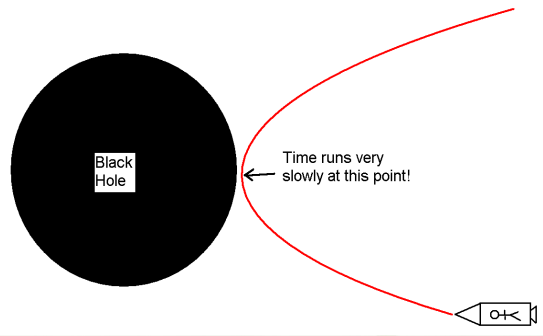
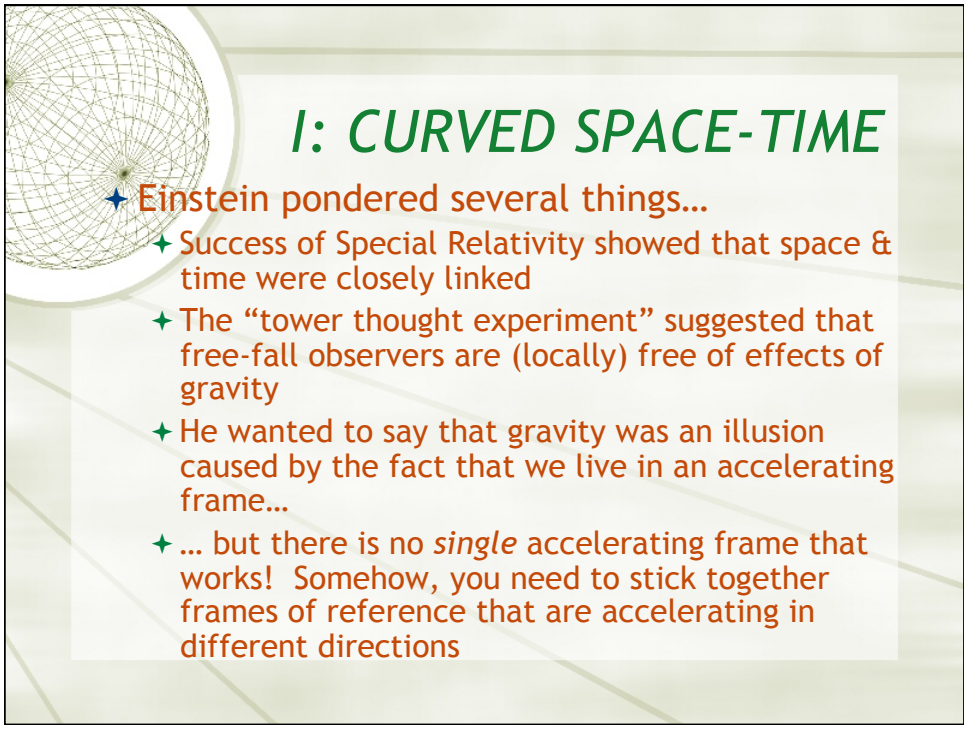
Lecture 12: General Relativity II

- Recap : gravitational redshift
- Curved spacetime and geodesics
- The General Theory of Relativity
- Gravitational Lensing

How to live for a 1000 years!

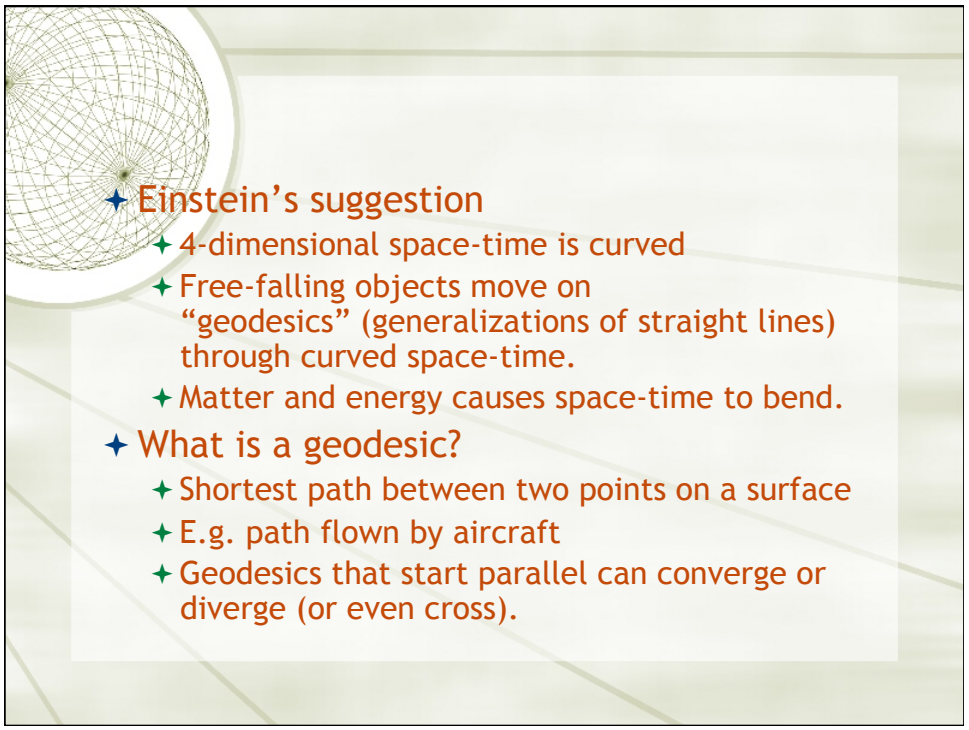


- Go where gravity is very strong!
- Observer on Earth would see astronaut's clock running **very** slowly when close to black hole – astronaut would age very slowly.
- (In fact, there are other discomforts from of being near a black hole!)

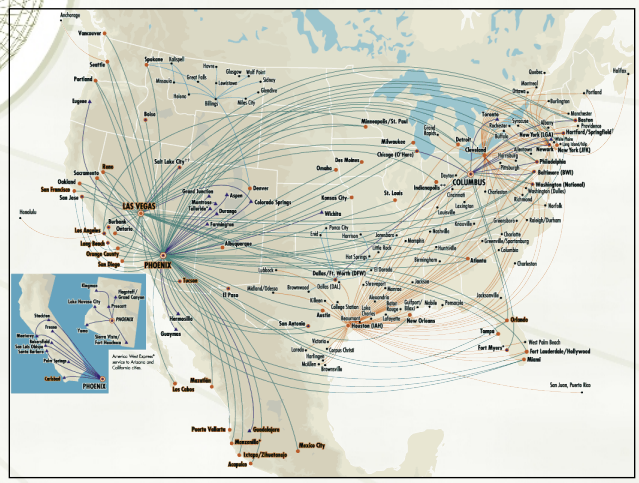


I: CURVED SPACE-TIME

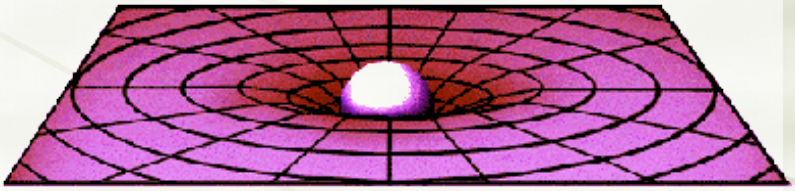
- Einstein pondered several things…
  - Success of Special Relativity showed that space & time were closely linked
  - The "tower thought experiment" suggested that free-fall observers are (locally) free of effects of gravity
  - He wanted to say that gravity was an illusion caused by the fact that we live in an accelerating frame…
  - … but there is no *single* accelerating frame that works! Somehow, you need to stick together frames of reference that are accelerating in different directions



- Einstein's suggestion
  - 4-dimensional space-time is curved
  - Free-falling objects move on "geodesics" (generalizations of straight lines) through curved space-time.
  - Matter and energy causes space-time to bend.
- What is a geodesic?
  - Shortest path between two points on a surface
  - E.g. path flown by aircraft
  - Geodesics that start parallel can converge or diverge (or even cross).



- Curved space around the Earth looks something like this…



From web site of UCSD

II: THE GENERAL THEORY OF RELATIVITY

- Within a free-falling frame, the Special Theory of Relativity applies.
- Free-falling particles/observers move on geodesics through curved space-time
- The distribution of matter and energy determines how space-time is curved.

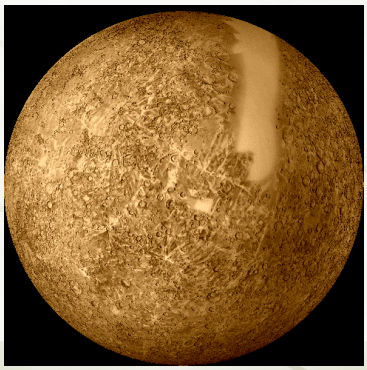
"Space-time curvature tells matter/energy how to move. Matter/energy tells space-time how to curve."

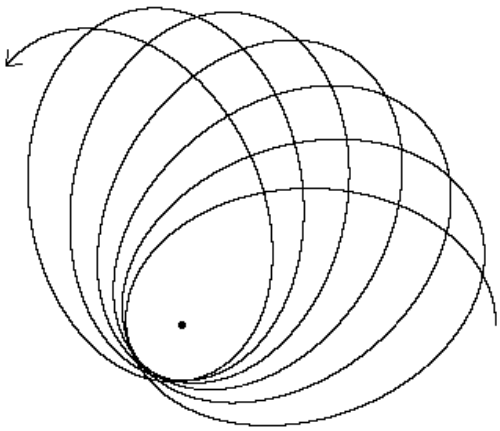
$$\underline{\underline{\mathbf{G}}} = \frac{8\pi G}{c^4}\underline{\underline{\mathbf{T}}}$$

- Notes:
  - The Einstein curvature tensor "G" is mathematical object describing curvature of 4-D space-time.
  - The Stress-Energy tensor "T" is mathematical object describing distribution of mass/energy.
  - Newton's constant of gravitation "G" and the speed of light "c" appear as fundamental constants in this equation.
  - This is actually a horrendous set of 10 coupled non-linear partial differential equations!!
- For weak gravitational fields, this gives Newton's law of gravitation.

III: GR EFFECTS IN THE SOLAR SYSTEM

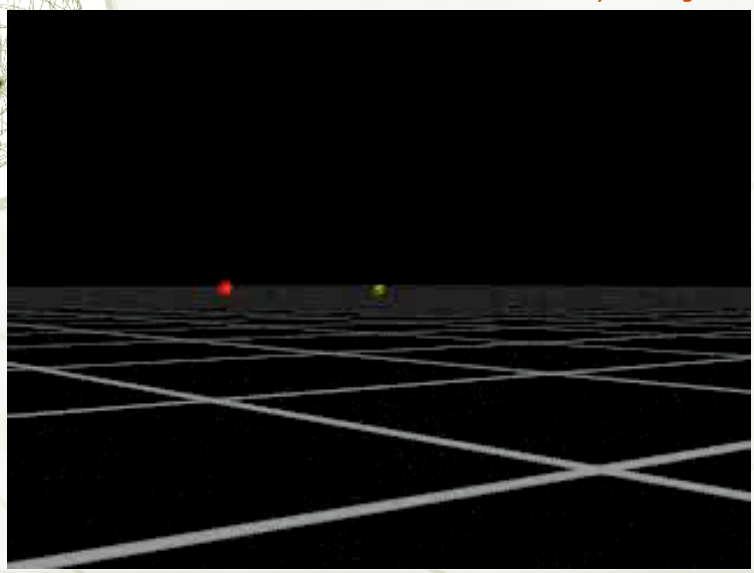
- Have already heard about bending of star light by the Sun (detected by Eddington).
- **Orbit of Mercury:**



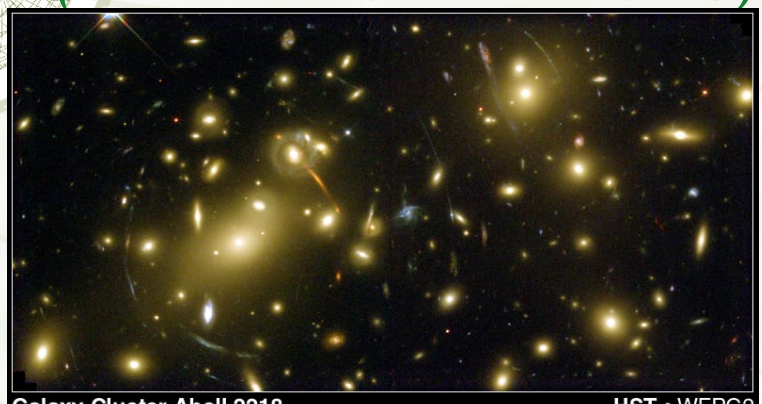


- Effect called “precession of perihelion”.
- Effect small - orbit twists by 5600 arc-seconds (1.56 degrees) per century
  - With Newtonian gravity, can explain 5557 arc-seconds/ century as due to
    - Gravitational effect of other planets,
    - deformation of the Sun,
    - non-inertial nature of Earth’s frame
  - But still leaves 43 arc-seconds per century unexplained…
- Using GR, Einstein predicted (with no fiddling!) that Mercury should precess 43 arcseconds per century!

From the web site of
The University of Oregon

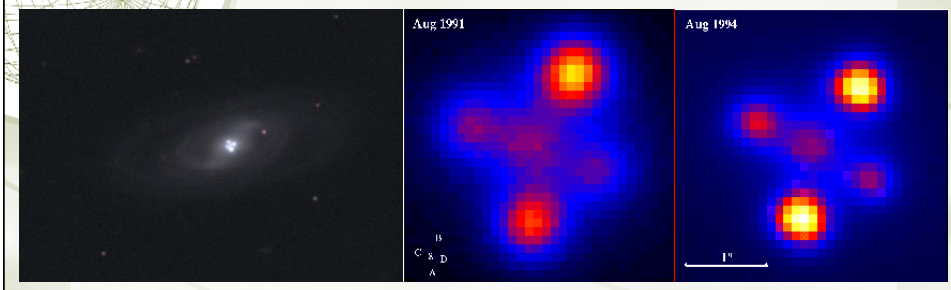


IV : THE BENDING OF LIGHT (GRAVITATIONAL LENSING)



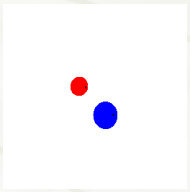
Galaxy Cluster Abell 2218 **HST** • WFPC2
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

"The Einstein Cross"



Gravitational micro-lensing

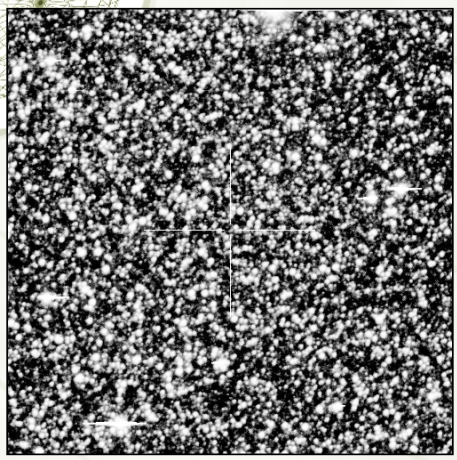
- Individual stars can also make a gravitational lens… **microlensing**.
- Suppose we…
  - Look at a distant star in our galaxy
  - Another massive (but dark) star passes in front…

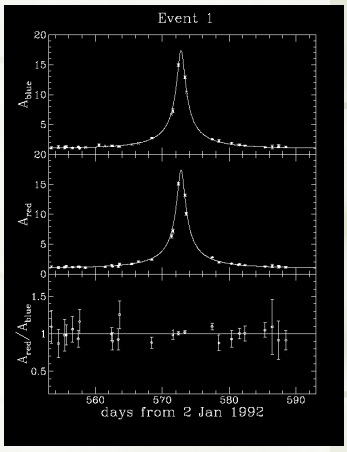


From web site of
Ned Wright (UCLA)

- Causes apparent increases in brightness of stellar image

Really hard to do!





MACHO Project