MICHIGAN STATE UNIVERSITY

Today

- Announcements:
  - HW#4 is due by 8:00 am Wednesday February 14th.
  - The second and third extra credit assignments are open and are due in two weeks at 8:00 am on Feb 13th
  - Exam #1 is next week on Thursday, there is an important review lecture on Tuesday
- General Relativity

Something to tell your friends about…

Newton's second law of force tell us that

$$E = mc^2$$

Picture

The following is a picture of a chemical reaction:

Start with some initial mass (kg)

Something happens

End up with some final mass (kg)

Some fraction, f, is converted to energy

f- see the table on the next page

ENERGY (Joules, J)

The amount of energy is $E = m_{converted}\, c^2$

$m_{converted}$ = (Mass to start) x fraction

Fraction of Energy Converted

- In a chemical reaction not all the mass can be converted to energy. Actually only a very small fraction (the exact value of the fraction depends on the chemical reaction).

Reaction	Fraction	Example
Matter-Antimatter Annihilation	1	No common example; happens at particle accelerators
Fusion	0.007	Power source of the Sun
Fission	0.001	Nuclear power plant
Chemical	$1x10^{-10}$	Burning coal
Mechanical	$1x10^{-15}$	Compressing a spring

Some Samples

- A power plant generates 500 MW of electrical power and 700 MW of waste heat (plants always make more waste heat than electrical power). How many Joules of energy does the plant generate in 1 day? Data: 1 Watt = 1 Joule/s

$$\text{Energy (1 day)} = (500\text{MW} + 700\text{MW}) \times \text{seconds in a day}$$

$$= 1200 \times 10^6 \, \frac{\text{J}}{\text{s}} \times \frac{60s}{m} \times \frac{60m}{hr} \times \frac{24hr}{d} \times 1d$$

$$\text{Electrical Energy (produced in 1 day)} = 1.04\text{E}14 \;\; \text{J}$$

More on the power plant

Assume the power plant in the previous problem burns 2.2 kg of oxygen and 1 kg of carbon from coal to make 33 MJ of energy. How many kg of carbon and oxygen will the plant use in a day?

$$\text{mass (kg)} = \frac{\text{total energy produced}}{\left(\text{energy generated}\big/\text{kg}\right)} = \frac{\text{electrical} + \text{waste energy}}{\left(\text{energy generated}\big/\text{kg}\right)}$$

$$\text{mass (kg)} = \frac{1.037\text{E}14\ \text{J}}{\left(33.\text{E}6\ \text{J}\big/(2.2\ \text{kg} + 1.0\ \text{kg})\right)} = 1.01E7\ kg$$

How much of that mass was converted to energy?

$$E = m_{\text{converted}} c^2 \Rightarrow m_{converted} = \frac{E}{c^2}$$

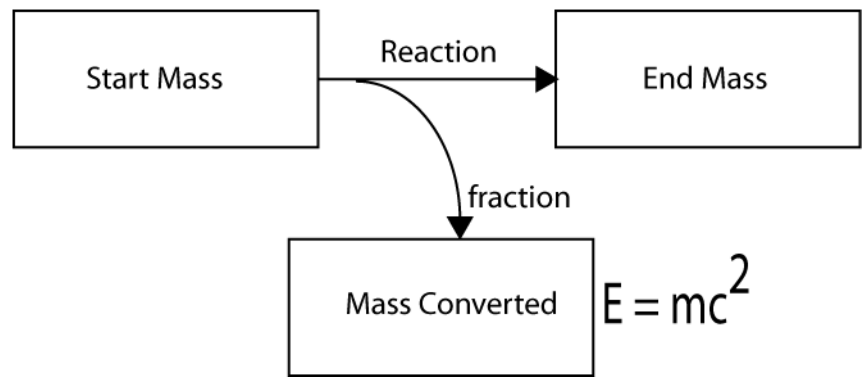
$$m_{converted} = \frac{1.04E14\ J}{\left(3E8\ {}^{m}\!/\!_{s}\right)^2} = 1.16 \times 10^{-3}\ kg$$

But we used more than 10^7 kg (10,000 metric tons), where did it all go?

Hint: The main byproduct of burning coal is $C0_2$.

HW Help: How long will the Sun burn?

The sun generates 3.82E24 W of power by fusion of hydrogen into helium. The fraction of mass converted for fusion is 0.007. How many kg of protons and electrons does the Sun use every second?



$$m_{burned\ each\ s} = \frac{m_{converted}}{f} = \frac{E/c^2}{f} = \frac{3.82E24\ J \big/ \left(3E8\ m/s\right)^2}{0.007} = 6.06E9\ kg$$

Years Sun will last = (Total mass of the core/mass used per second) x (years/s)

Note: 1 year = 3.156E+7 s

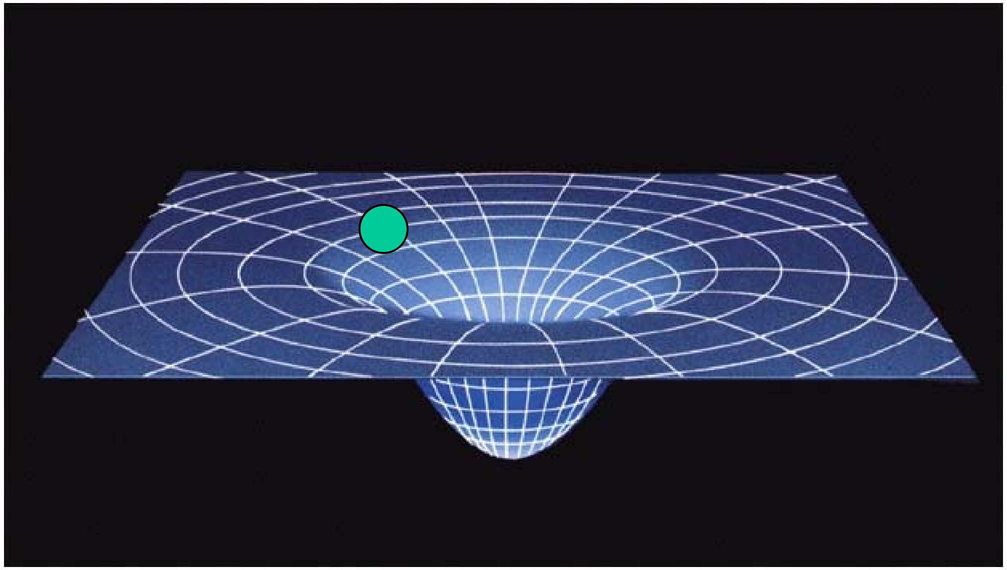
General Relativity

- On the surface of the Earth things accelerate at the same rate, independent of their mass (neglecting air resistance) $F = ma = mg \quad a = g$
- Why is gravitational mass (mg) the same as inertial mass (ma)?
- This is one of the questions that inspired Einstein. His answer is General Relativity.
- Special Relativity was for non-accelerating frames of reference. General Relativity covers both accelerating and non-accelerating.

General Relativity continued

- Main Postulate: Acceleration in one direction is like gravity in the other direction. It is not possible distinguish the two. This is called the principle of equivalence.
- What we perceive as gravity is really acceleration resulting from space stretched by mass
- Mass warps space
- Space and time are combined into a 4-dimensional space-time

Pictorial



Gravity is actually the result of warped space. What we perceive as acceleration (and hence say is due to a force) is really just stretched space.

Department of Physics and Astronomy

MICHIGAN STATE UNIVERSITY

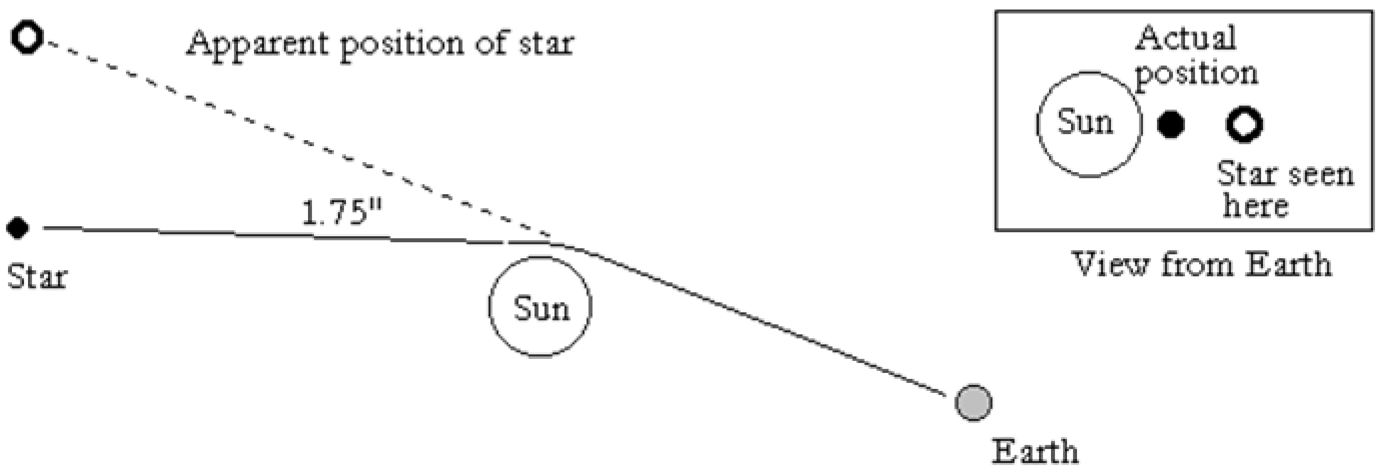
Gravitational Time Dilation

- Mass stretches space, but since space and time are connected (space-time) it also affects time.
- Near a mass, time runs more slowly. On the surface of the Earth this affect is only 10^{-9} s, but near a black hole it could be infinite.
- Why? As you travel through space you travel through time. Where space is stretched, time is stretched.
- Metric equation: $$(\Delta s)^2 = (\Delta x)^2 + (\Delta y)^2 + (\Delta z)^2 - (c\Delta t)^2$$

The (-) is part of what is called the metric of space time. It is contained in the tensor called the *metric of space time*.

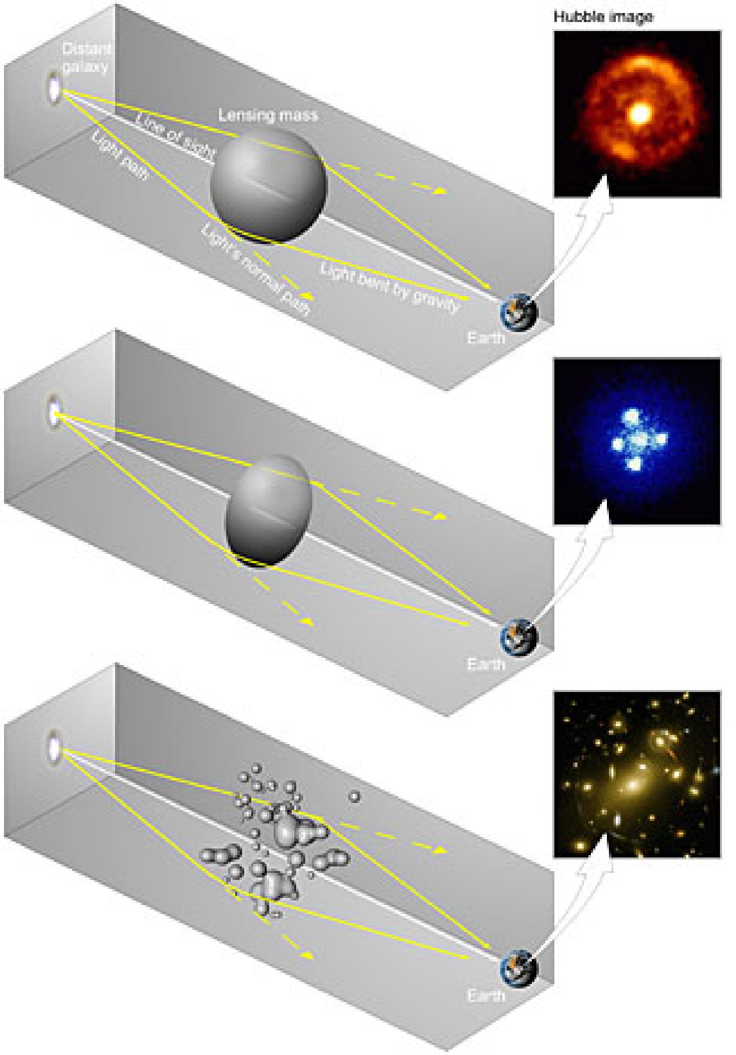
Proof of General Relativity I

- Bending of star light – the gravitational field of the Sun bends star light by 1.75 arcseconds. This was observed by A. Eddington in 1919 during an eclipse.

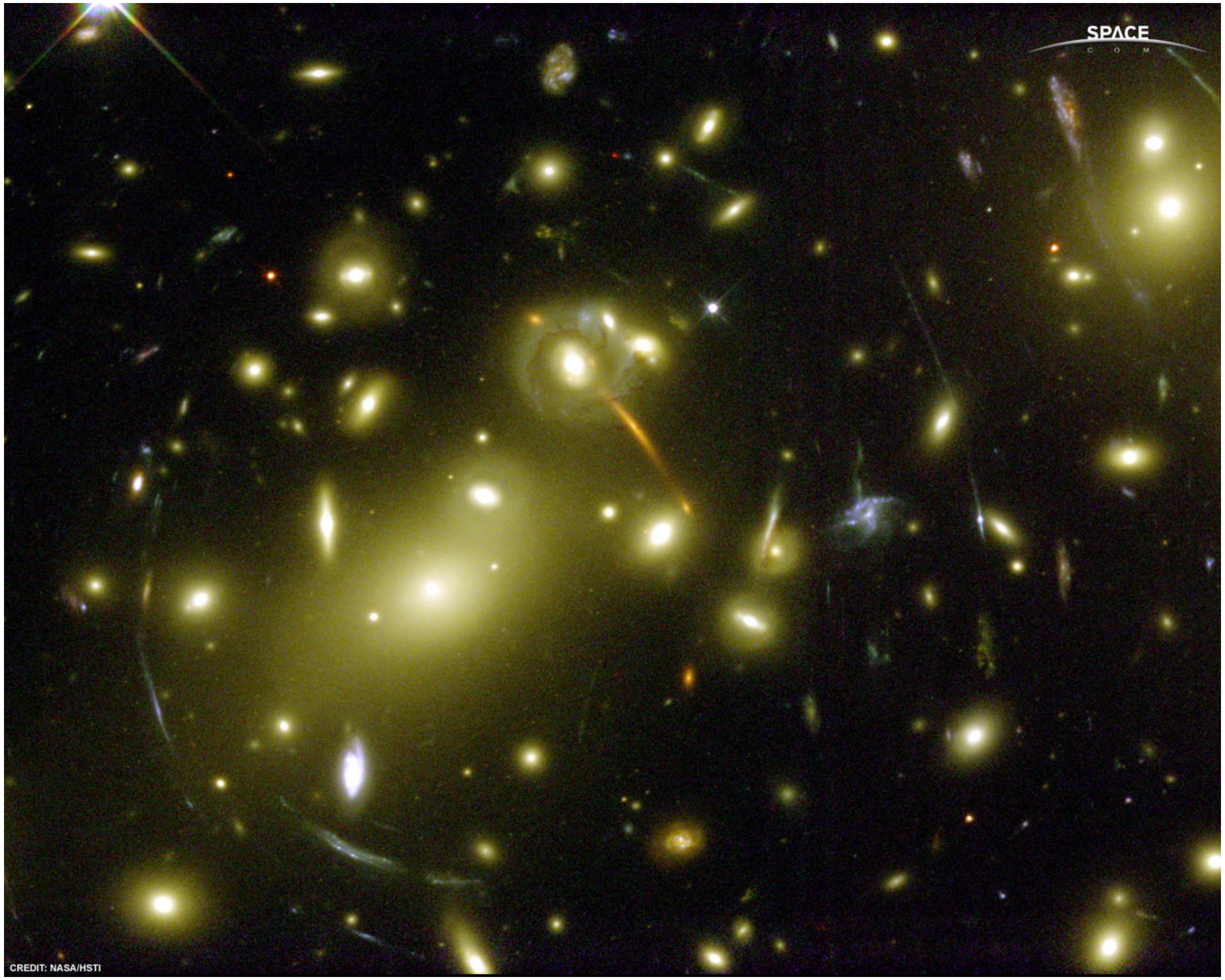


Proof of General Relativity II

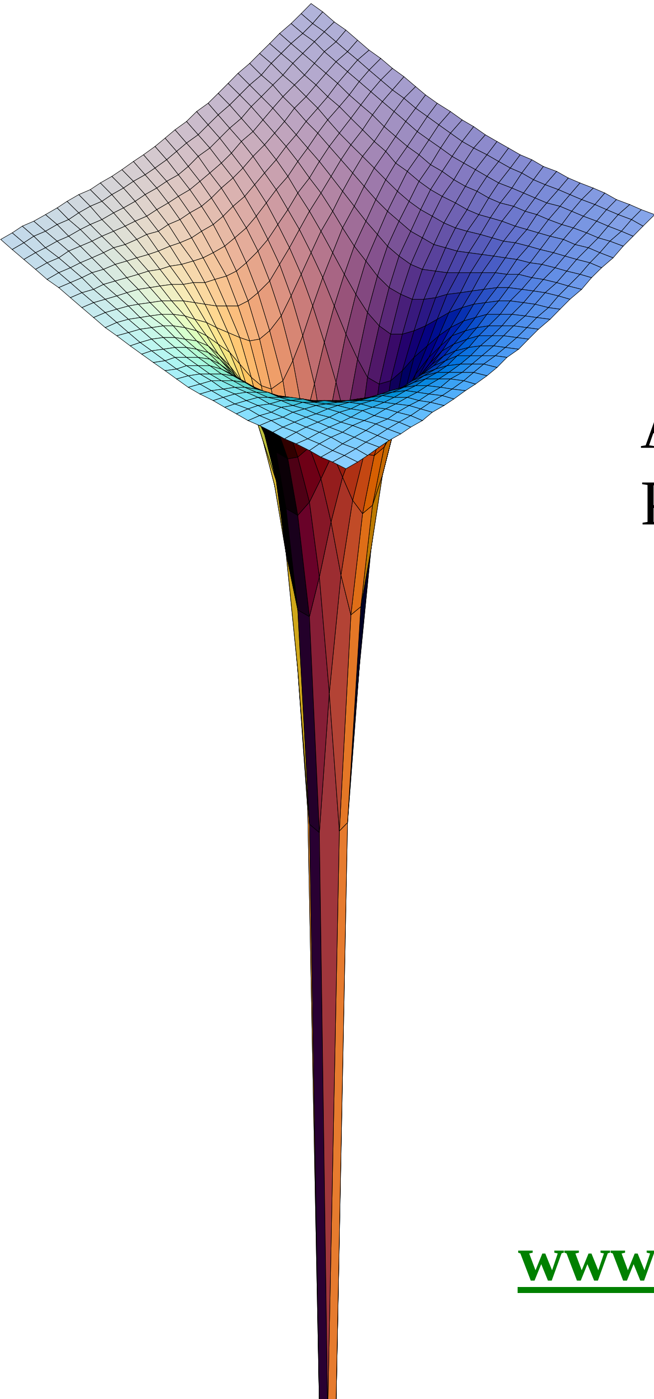
Gravitational Lensing:
Routinely observed and used to measure the mass of distant clusters of galaxies.



Real picture from the Hubble Telescope

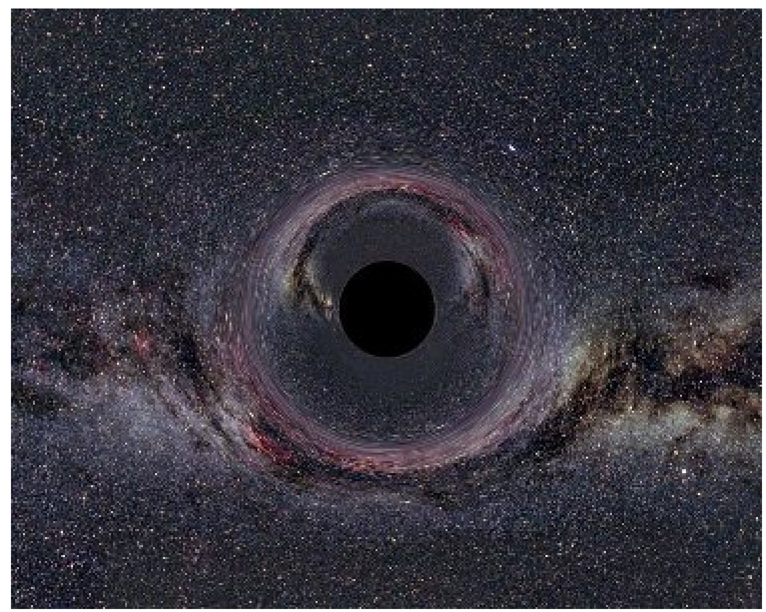


Abel galaxy cluster



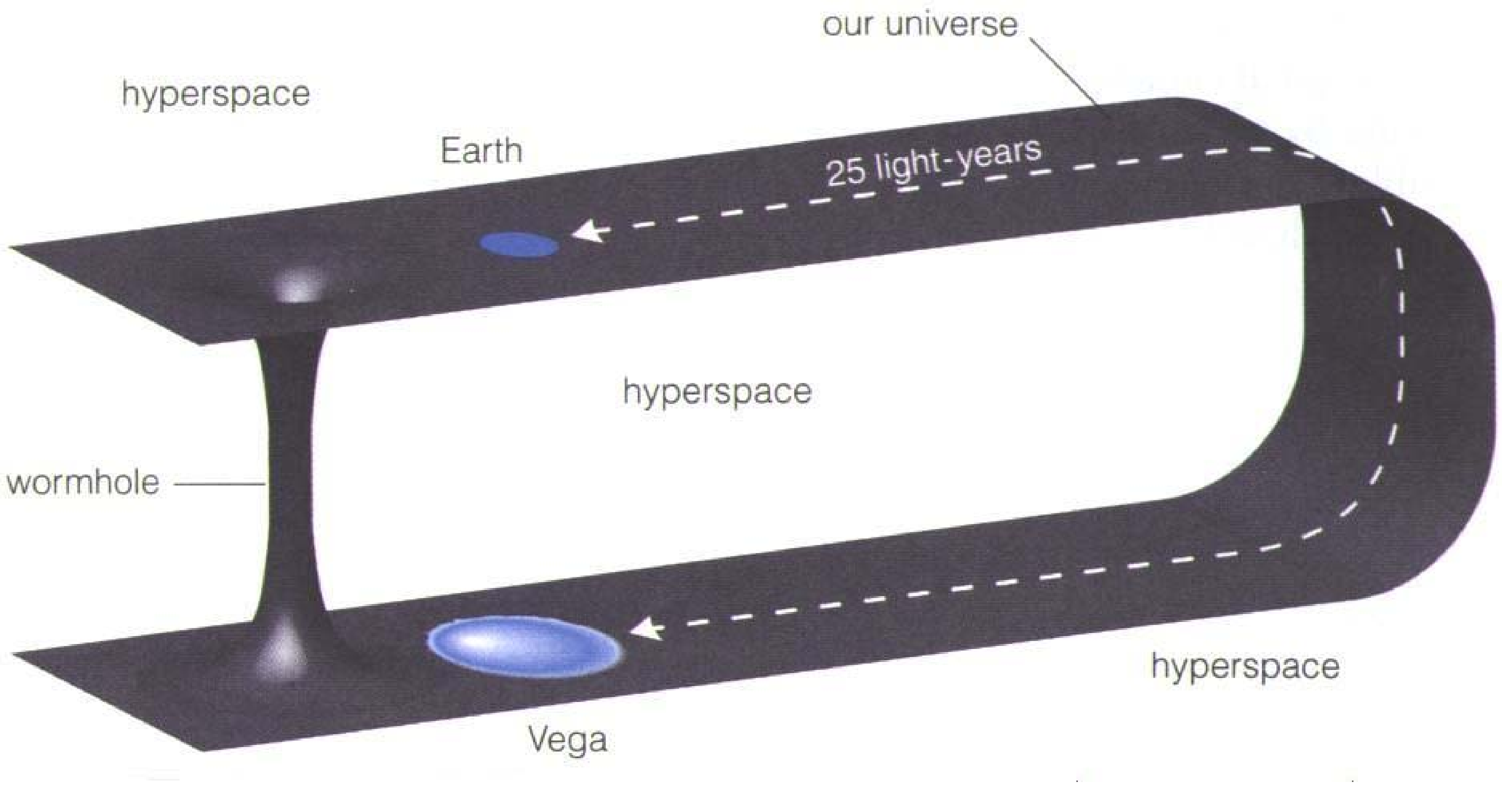
Black holes

A hole so deep that even light can not escape.
Picture of what a black hole would “look” like.



www.ifa.hawaii.edu/~barnes/ast110_06/bhaq.html

Wormholes



This could be the basis for a time machine.

Paradoxes in Time Travel

- If time is a dimension like the other three, can we move back and forth in time?
- If we can travel back in time, it would be possible for us to influence things so that we are not born.
- Three theories to resolve the paradox
  - Travel back in time is not possible
  - There are a very large number of parallel universes
  - Something about nature prevents us from influencing the past

Einstein Equation

$$R_{ij} - \frac{1}{2} R g_{ij} - \lambda g_{ij} = \frac{8\pi G}{c^4} T_{ij}$$

• A tensor equation that describes how space-time is influenced by mass.

• The details of what the symbols mean does not matter. Approximately, the left side is the curvature and motion of space and the right side is the location and motion of mass and energy.

• Rij is the Ricci tensor, g is the metric of space-time, G is the gravitational constant, etc.