# Astro 13 Galaxies & Cosmology
# LECTURE 8 Thurs 23 April 2009 D. Koo

- 10m I Ask An Astronomer Period
- 25m II Continue with Relativity
- 25m III Black Holes
- 10m IV Break
- 45m V Models of the Universe & Curvature
- NOTE: HW#2 Due; Report Topic is Due;
- Reminder: get HW#3 on web
- Lick Trip: Thursday 28 May still to be confirmed

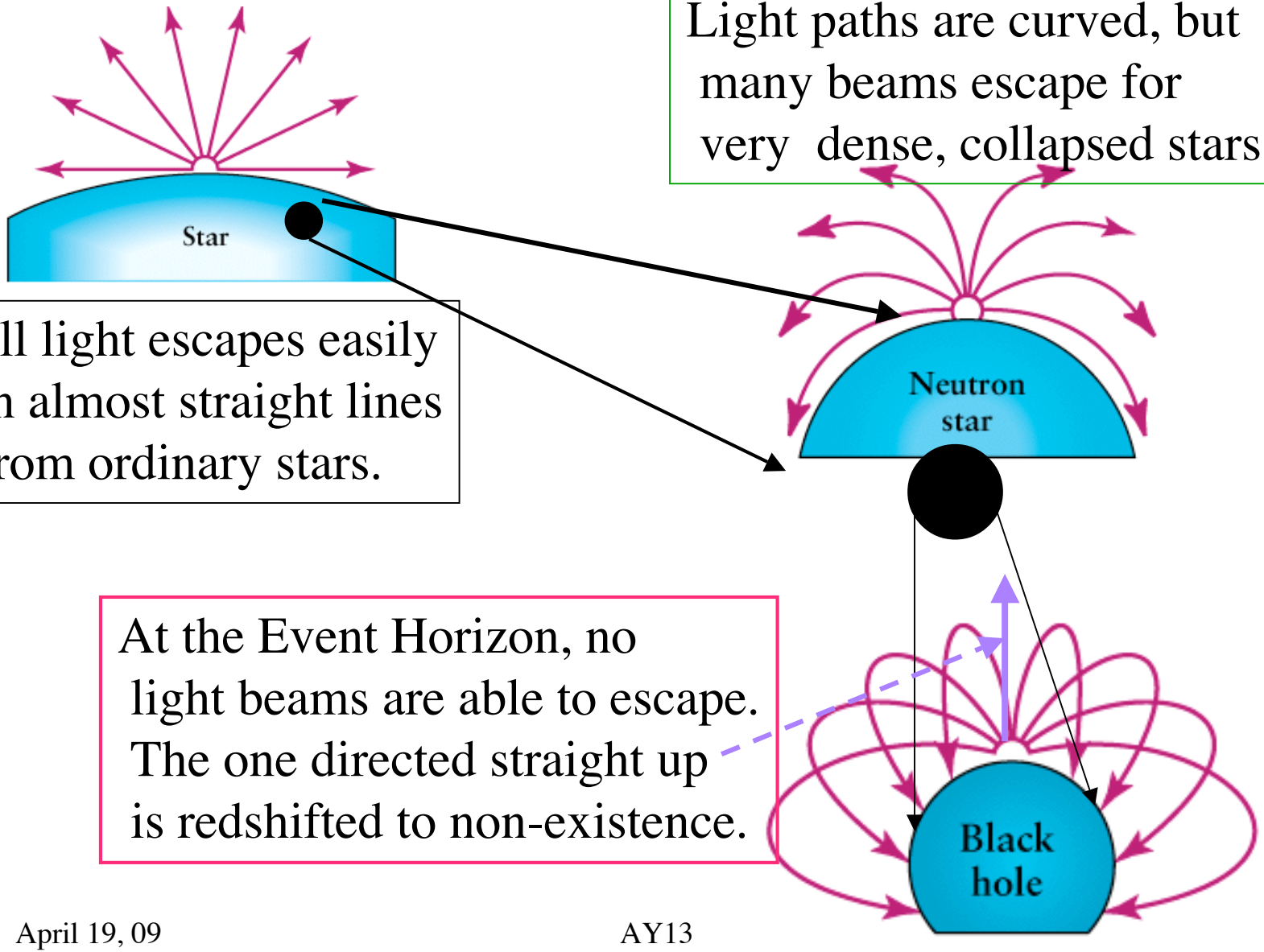
# Black Holes

One of the most profound and intriguing implications of GR is the existence of Black Holes. Such objects are the result of a mass being squeezed so small, that the ESCAPE VELOCITY reaches that of LIGHT c itself…in other words, even light cannot escape and thus the object is "Black".

The mass itself collapses to a single point of zero volume and infinite density called a Singularity. This singularity lies at the center of an imaginary surface called the Event Horizon, where the escape speed matches the speed of light.

Fun web sight with nifty movies of Special Relativity and Black Holes: http://casa.colorado.edu/~ajsh/

# Paths of Light Beams emitted from the Surface



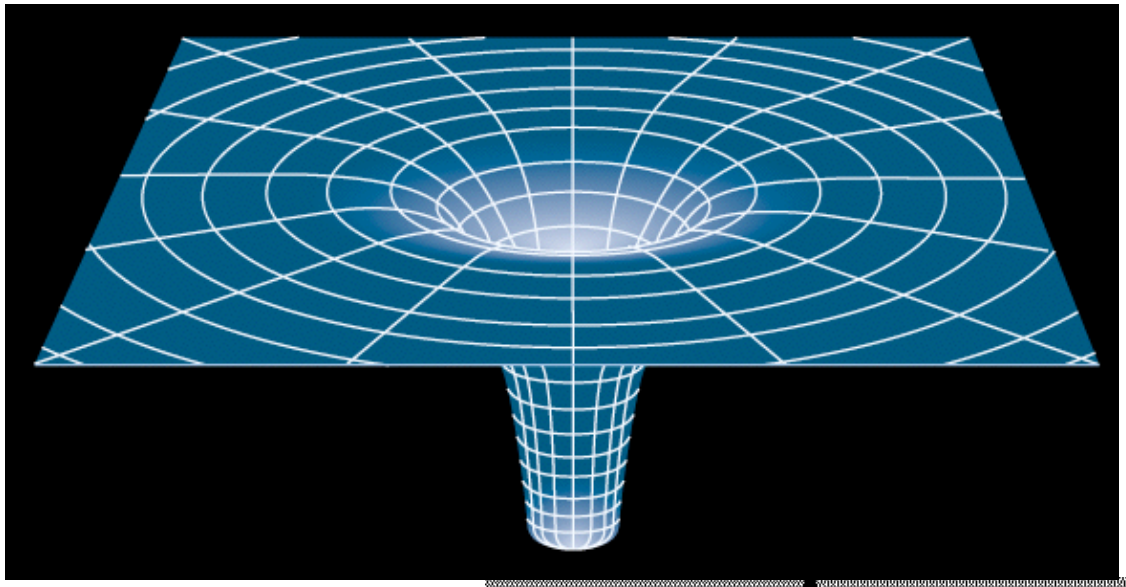

Light paths are curved, but many beams escape for very dense, collapsed stars.

All light escapes easily in almost straight lines from ordinary stars.

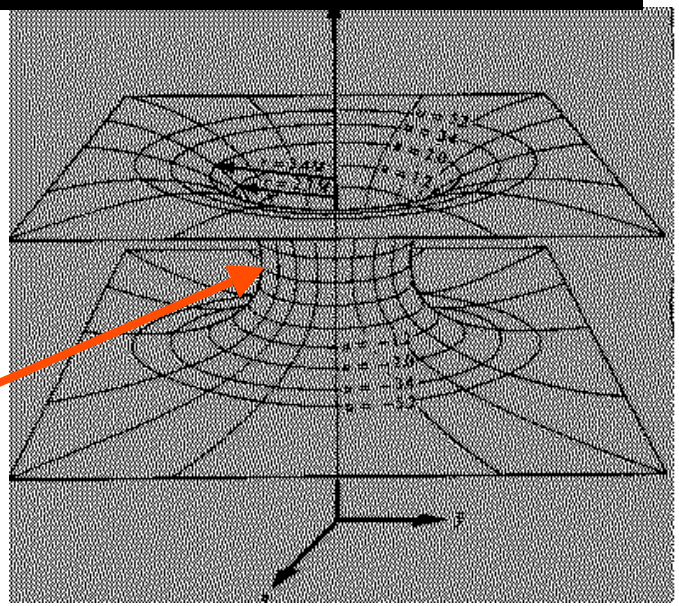
At the Event Horizon, no light beams are able to escape. The one directed straight up is redshifted to non-existence.

# Black Hole Viewed in Space-Time

From afar, the space-time is nearly FLAT since gravitational force is weak. Closer in, space-time is highly curved. The central depth of a Black Hole is infinitely deep.

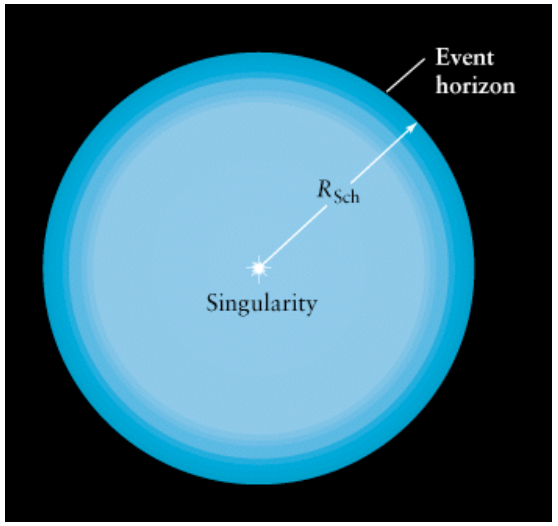


Some scientists have proposed that the Black Hole may connect to other Parallel universes or other parts of space time in our own Universe via wormholes or an Einstein-Rosen Bridge.

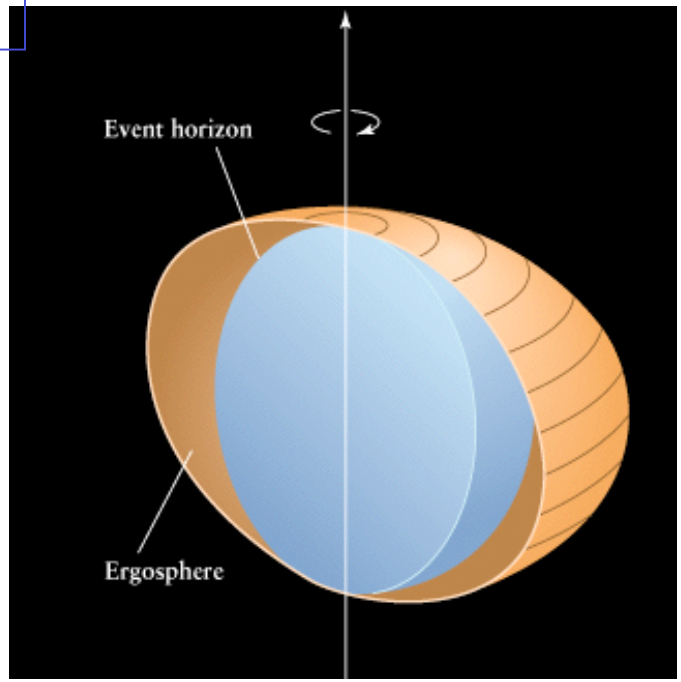


# Structure of a Black Hole

A simple non-rotating BH is described by only its center (Singularity) and a surface ( Event Horizon). The radius of the event horizon is known as the Schwarzschild Radius Rsc(m) = $2GM/c^2$
G=const. gravity = $6.67 \times 10^{-11}$ newton $m^2/kg^2$
c = speed of light  M=mass of BH in kg
For sun, Rsc=3km - smaller than Santa Cruz!




In principle, besides its mass, BH may also have charge and may be rotating ( angular momentum). In the latter case, space-time appears to be dragged around so that objects grazing the ergosphere would be flung back out faster than it went in -- "FREE" KICK of ENERGY!

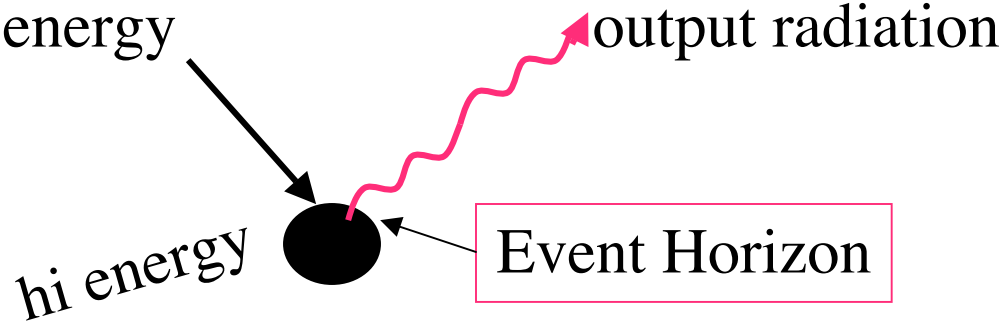


# Properties of Black Holes

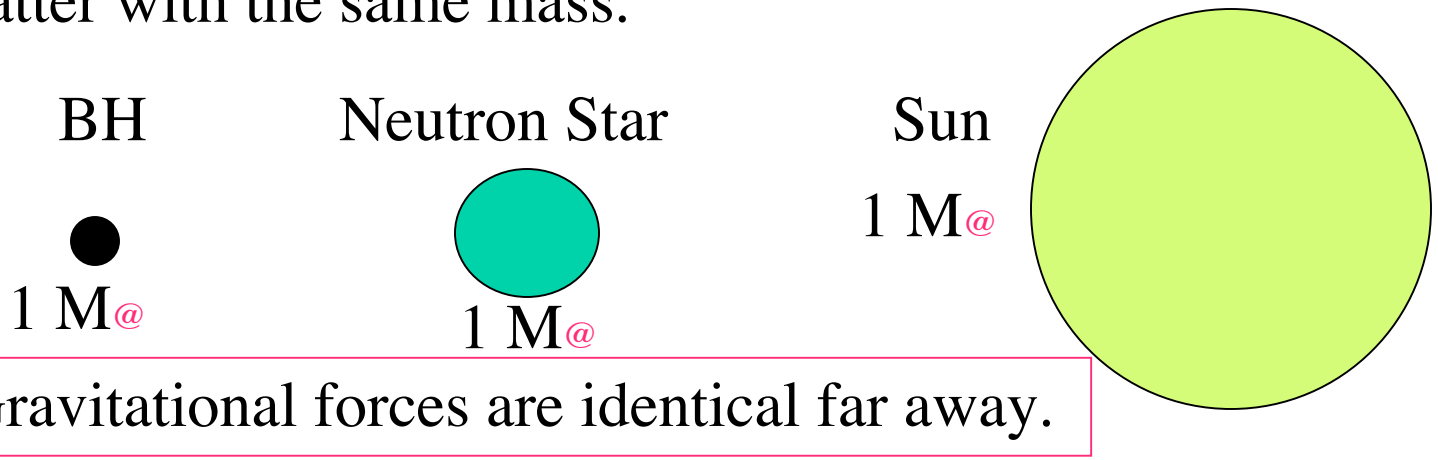
* True in general, but to lesser degree

1) Light cannot escape within Event Horizon (closer than Schwarzschild radius) -- reason for name sake of BLACK

2*) Matter falling into the BH gains enormous kinetic energy, so regions outside the event horizon may give off enormous amounts of radiation and energy.

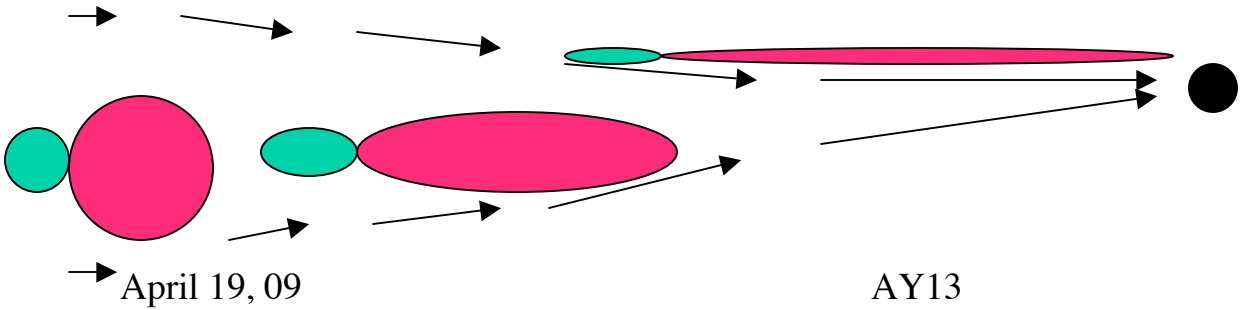


3*) BH do NOT act like vacuum cleaners sucking up their surroundings. They act no differently than a much larger chunk of matter with the same mass.




Gravitational forces are identical far away.

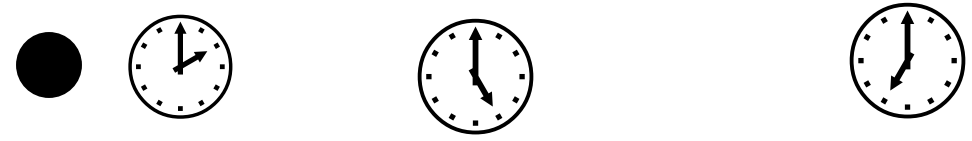
4*) Objects falling into a BH would get stretched and squeezed to very high temperatures, and eventually split apart, even on the atomic level (from hot spagetti to subatomic soup to nothing).



5*) Light from objects closer to a BH appear redshifted to a far away observer -- Gravitational Redshift:

Due to energy loss leaving the gravitational pull of the BH, similar to slowing down of a ball thrown up above the earth.

6*) Similarly, just as light frequency drops (wavelength increases) due to drop in energy, clocks appear to tick more slowly -- Time Dilation

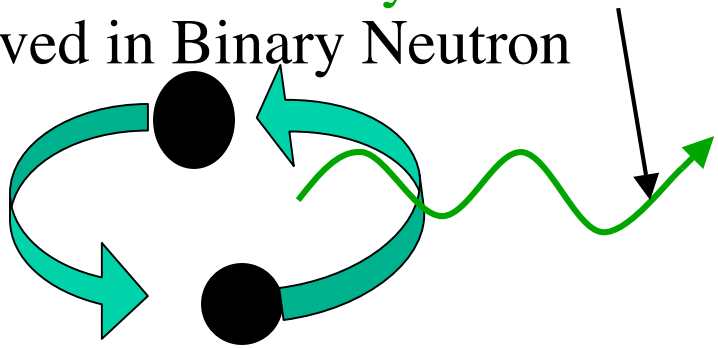



7) As observed object approaches the event horizon, light redshifts to infinity and clocks appear to stop to the to the outside world, but infalling object continues to the Singularity without noting any such peculiarities.

8) As stuff falls into a BH, outside world can only know:
MASS (independent of material -- rocks, iron, water or even light)
CHARGE (electric charge of + or -)]
SPIN (angular momentum)

9*) Like E&M radiation, changing the mass distribution generates
GRAVITY WAVES

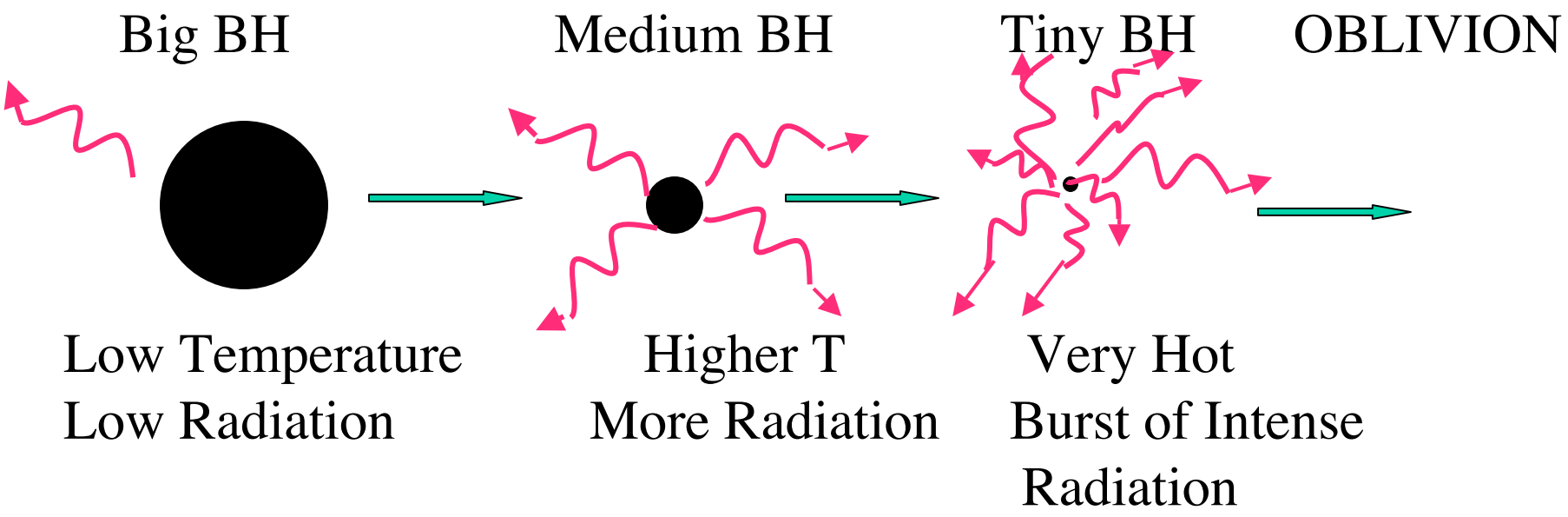
Prediction of Gravity Waves -
- observed in Binary Neutron stars



Note objects can be BH or more ordinary objects like stars.

10) SURPRISE!! Stephen Hawking has predicted that UNFED Black Holes glow like blackbodies, lose mass, and eventually explode with high temperature gamma radiation into oblivion.

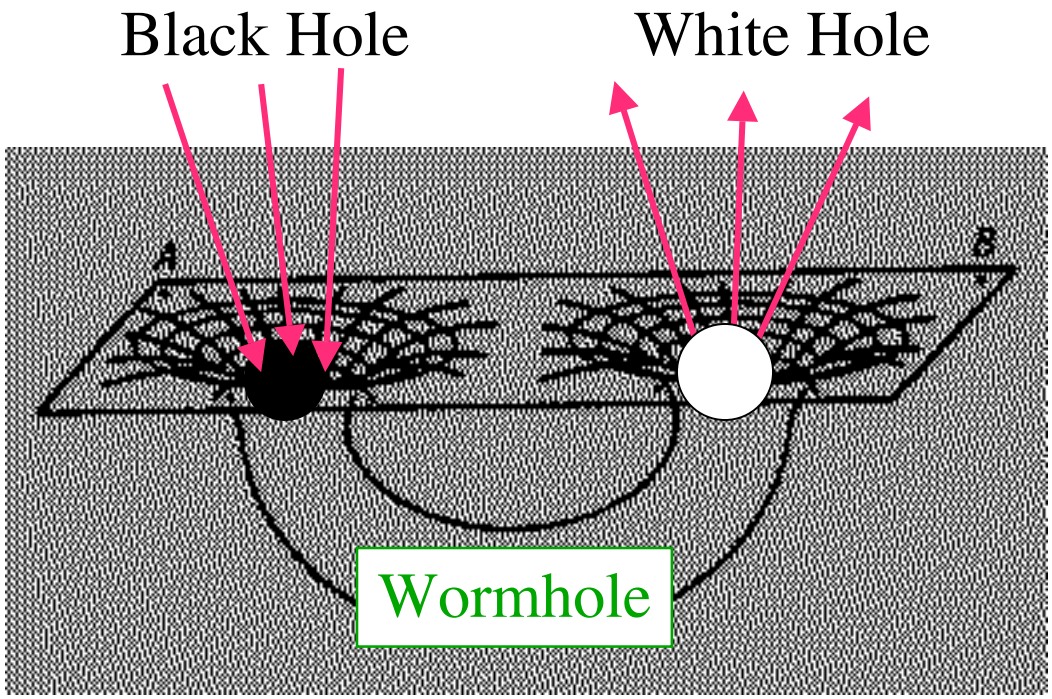
HAWKING RADIATION



# What Happens as One Enters within BH's Event Horizon into Singularity?

Physicists are unsure, since current physical laws do not apply.
Some unproven and unobserved proposals include:

1) BH connect through WORMHOLES into ours or other U or even White Holes, which spew out matter and energy (QSO)?

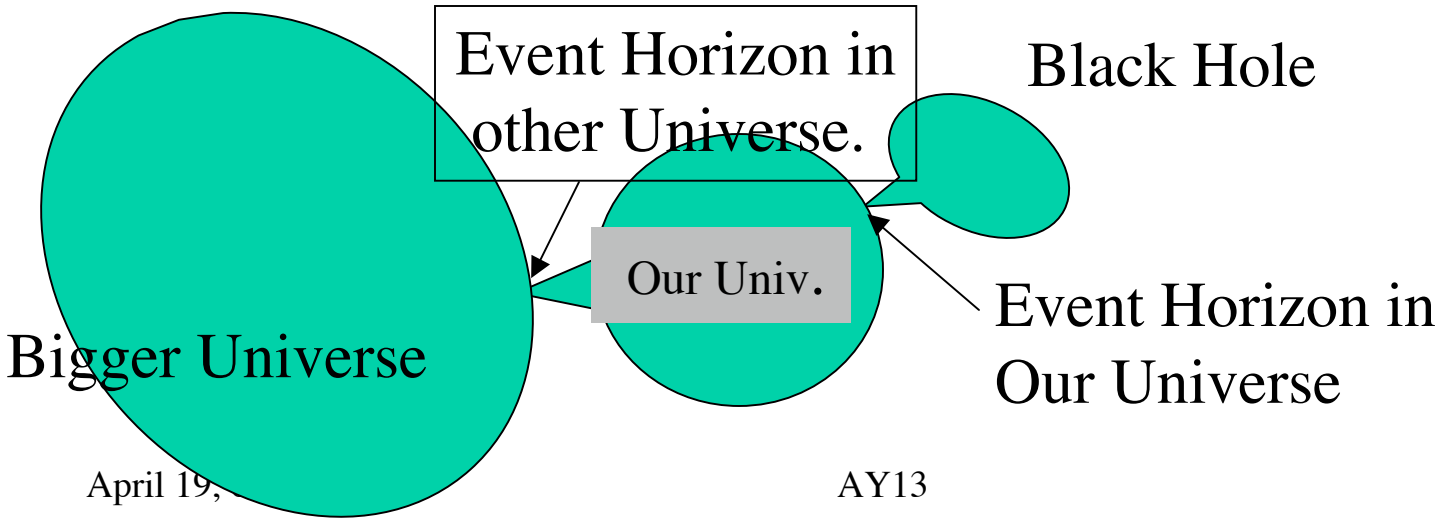


2) Creation of new states of matter.

3) Time travel within our U via Einstein-Rosen bridges, but then causality, meaning cause should occur before the effect, might breakdown.

Some have proposed the new PRINCIPLE of Cosmic Censorship, so that TIME TRAVEL is not possible.

4) But maybe we live in a huge Black Hole -- the U itself. A BH is viewed as sealing itself from our U, but maybe we are sealed from an even larger U.



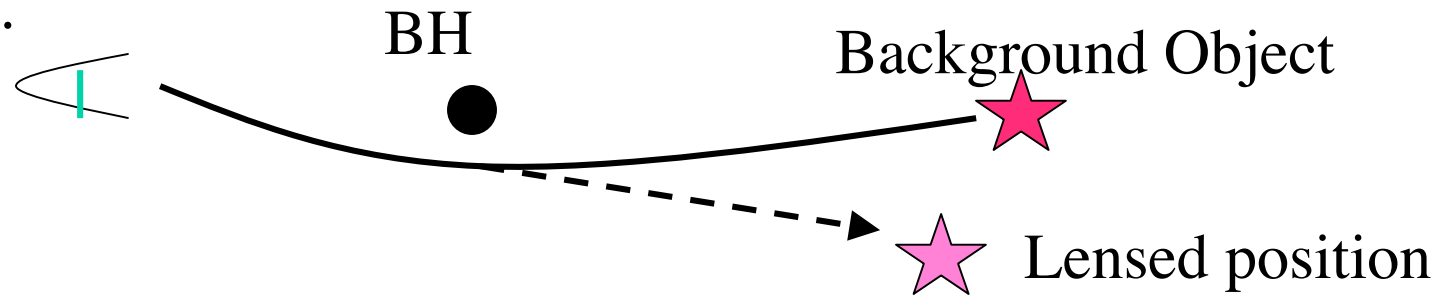
# How can a Black Hole be Created?

Simple Answer: squeeze a chunk of material to very small sizes: that is to the size of the Schwarzschild Radius.

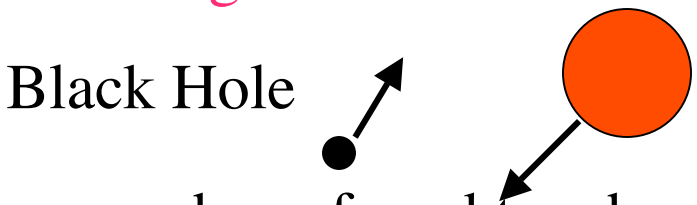
Humans have not been able to do this in a laboratory, but exploding stars may squeeze their cores so much as to produce a BH. Theory predicts that if this core is more than 1.5-3.0 Mo, it will collapse into a blackhole. After the formation of a "seed" Black Hole, it can continue to grow by addition of mass from infalling gas and stars or perhaps other Black Holes.

# How Can one Find a BH in Space?

1) See the effect of a BH via bending of light. E. g., if the Sun were a BH, we would see stars near it appear to move. But it is difficult to know where to look. So far, no candidates via this method.

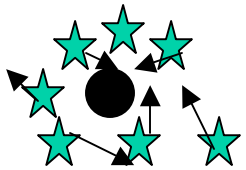



2) See its gravitational effects on nearby companion stars.




Astronomers have found two handfuls of good candidates, but for many, we cannot exclude other "Dark" objects, such as neutron stars.

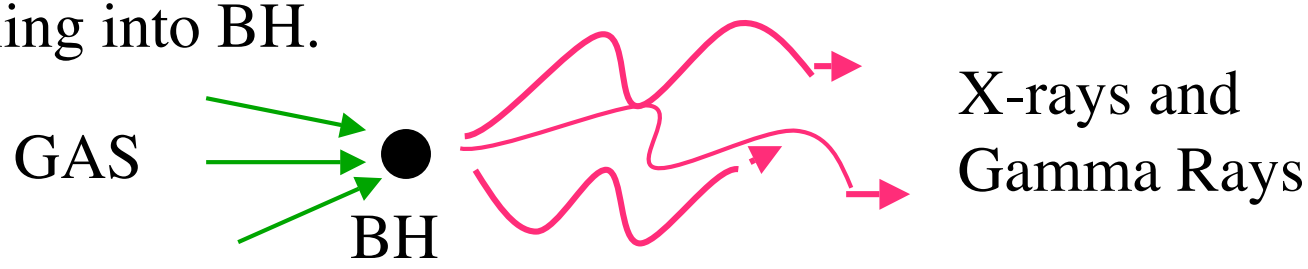
3) Measure a very large mass in a small volume that is darker than expected.



Use the motions of surrounding stars to estimate masses.

Using this method with Hubble Space Telescope, astronomers find the centers of many Galaxies to be massive and yet very small and darker than if made of ordinary stars.

4) find very high energies from tiny regions of space due to matter falling into BH.




5) Bursts of Gamma Rays from evaporating BH - Hawking Radiation.

# Models of the Universe

Many possibilities exist, but we will focus on those which:
- Satisfy the Cosmological Principles
- Satisfy Einstein's Theory of General Relativity
- Satisfy simple geometries (curved spaces) - there are 3 basic types

We will also consider INFLATION, a process that occurred just after the Big Bang and is important in solving 3 major Cosmological Mysteries:

- 1. Horizon Problem
- 2. Flatness Problem
- 3. Monopole Problem

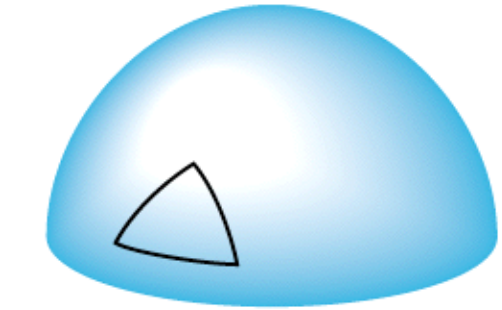
# Curvature of Space

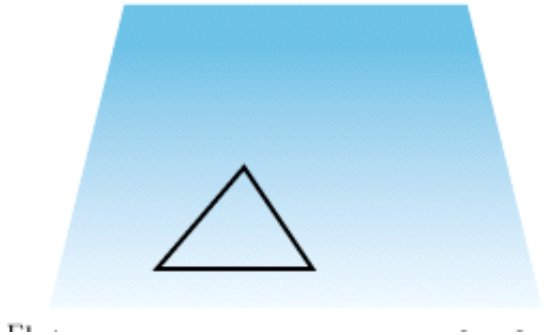
There exists three basic curvatures:

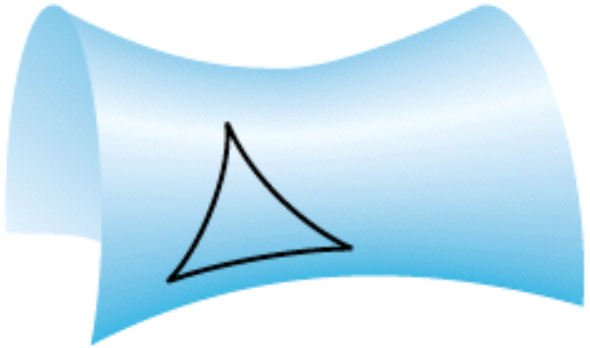
POSITIVE ZERO NEGATIVE

with 2-Dimensional equivalents that resemble the SURFACES:

SPHERE FLAT HYPERBOLIC (SADDLE)





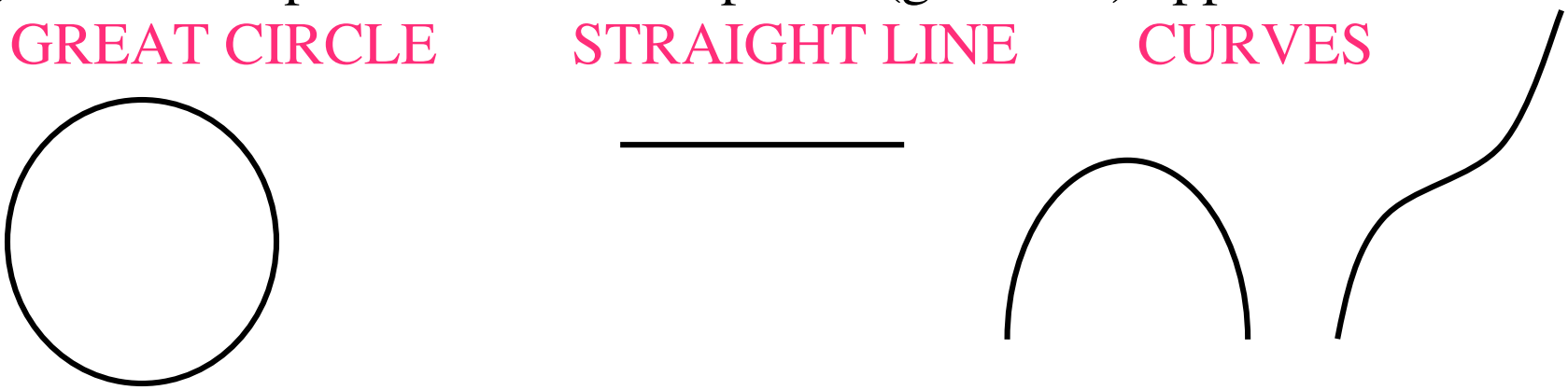


# Observable (Measurable) Properties of Curvature

1) Locally Flat (Euclidian) such that Special Relativity applies

2) Minimum path between two points (geodesic) appear as:

GREAT CIRCLE STRAIGHT LINE CURVES



# Observable (Measurable) Properties of Curvature

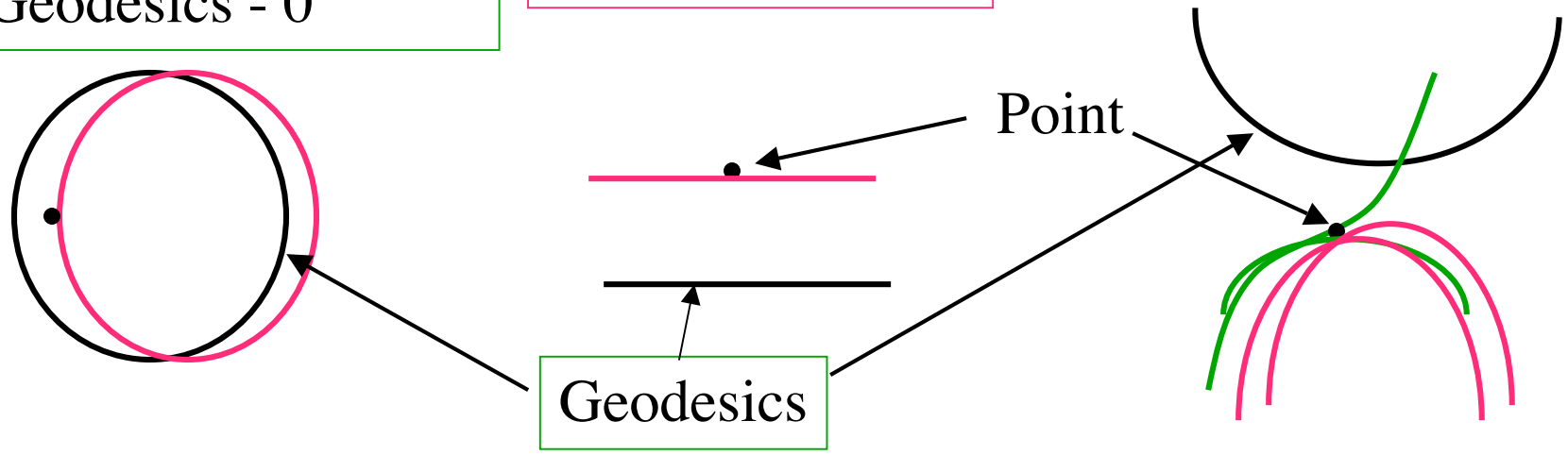
3) Number of Parallel Lines through a point away from a

Geodesic:

All Geodesics cross, So no parallel Geodesics - 0

If geodesics are Parallel, they never cross & vv

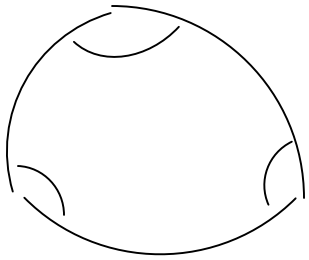
An infinite number of non-intersecting lines are found in Negative curvatures

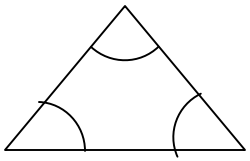


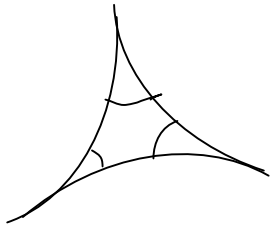
# Observable (Measurable) Properties of Curvature

4) Sum of angles in triangles depend on geometry:

| $> 180^o$ | $= 180^o$ | $<180^o$ |
|---|---|---|







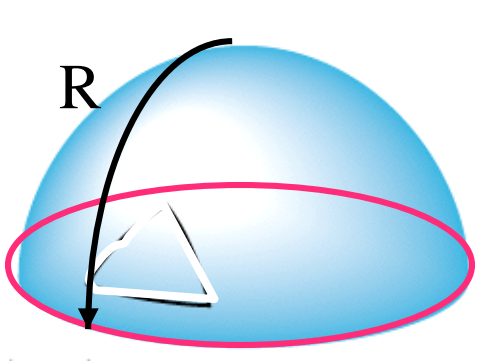
5) Finiteness

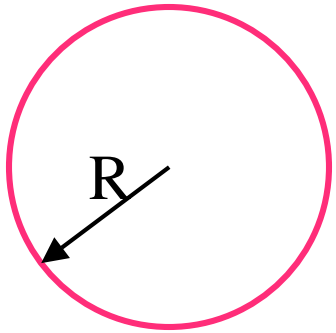
| FINITE | INFINITE | INFINITE |
|---|---|---|
| "CLOSED" | "FLAT" | "OPEN" |

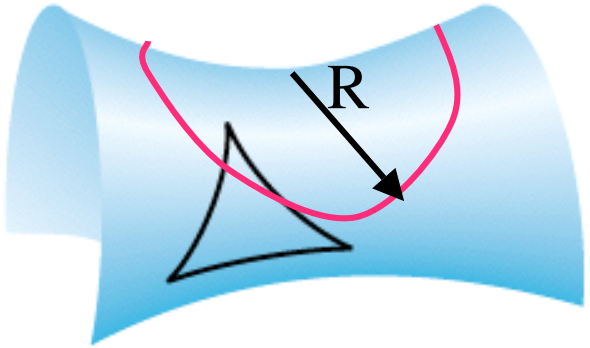
# Observable (Measurable) Properties of Curvature

6. Circumference of a Circle (equivalent to surface area in 3-D)

| $< 2\pi R$ | $=2\pi R$ | $>2\pi R$ |
|---|---|---|
| Pole to Equator | Normal Circle | |



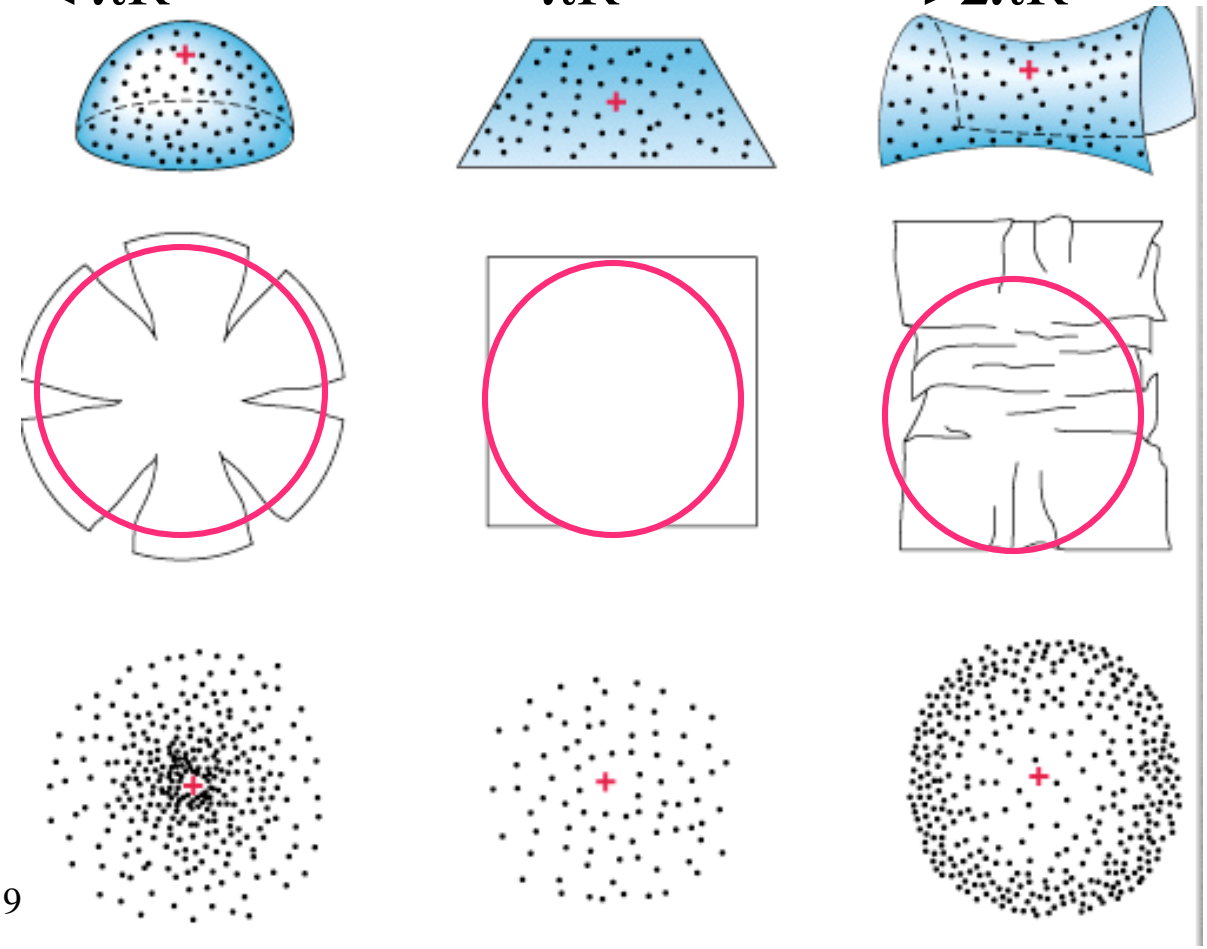



# Observable (Measurable) Properties of Curvature

7. Area of a Circle (equivalent to Volume in 3-D)

| $< \pi R^2$ | $= \pi R^2$ | $> 2\pi R^2$ |
|---|---|---|



# Curvature & Density of the Universe

Einstein's Theory of General Relativity plus adopting the Cosmological Principles of homogeneity and isotropy results in a variety of behaviors for the evolution of the Universe. By evolution, we mean how the SCALING SIZE of the universe, R, is changing with time, R(t).

The key physical parameter that controls this evolution (assuming no Cosmological Constant or Dark or Vacuum Energy) is the average density of the Universe and how it compares to the CRITICAL DENSITY ($D_{crit}$).

Density is the Mass/Volume ($kg/m^3$)

## CRITICAL DENSITY $D_{crit}$

This is the density of the Universe just enough to barely halt the expansion of the U after an infinite time and is directly equivalent to the idea of Escape Velocity Vesc $\propto \sqrt{\frac{Mass}{Radius}}$

A) Mass is just $\propto$ Density(D) x Volume but Volume $\propto$ Radius$(R)^3$ and so Mass $\propto$ $DxR^3$ and so since $V^2esc \propto$ Mass/Radius this means that $V^2esc \propto D_{crit}xR^2$ or $D_{crit} \propto V^2/R^2$

B) But recall that Velocity = Ho x Distance(R) or V/R = Ho so we end up with $D_{crit} \propto Ho^2$ with actual value: $D_{crit} = \frac{3H_o^2}{8\pi G}$ where G is the Gravition constant.

C) For G = $6.7x10^{-11}$ N-$m^2/kg^2$ and Ho = 70 km/s/Mpc
$D_{crit} = 1.0\ x10^{-26}$ $kg/m^3$ which is about 1 proton/$m^3$ vs $10^{30}$ for water