GENERAL RELATIVITY

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

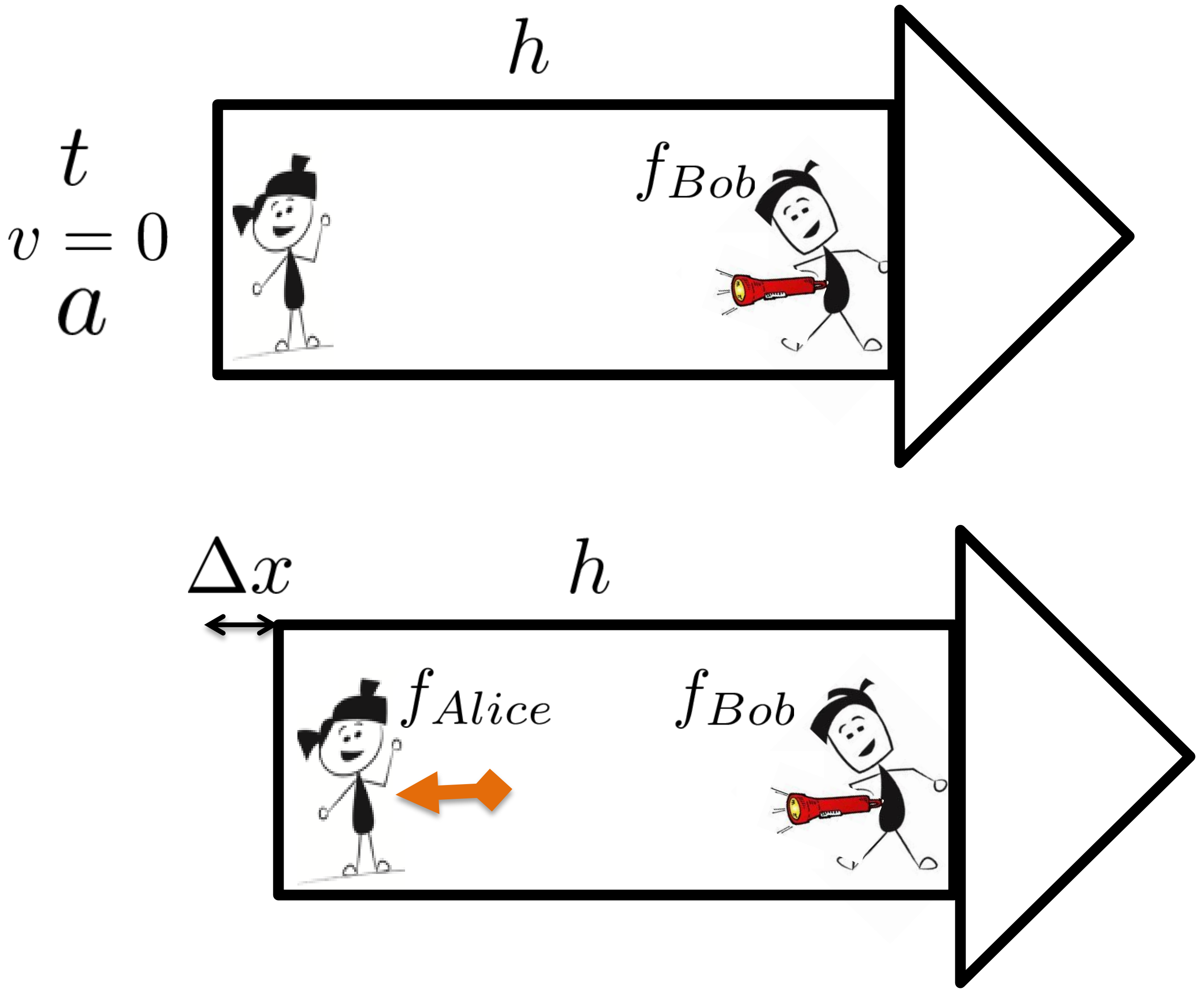
What is Gravity?

Gravity is the curvature (a.k.a. warping) of spacetime.

The Earth does not exert a force on objects...it curves spacetime so that the ground is *accelerating* up without *moving* up.

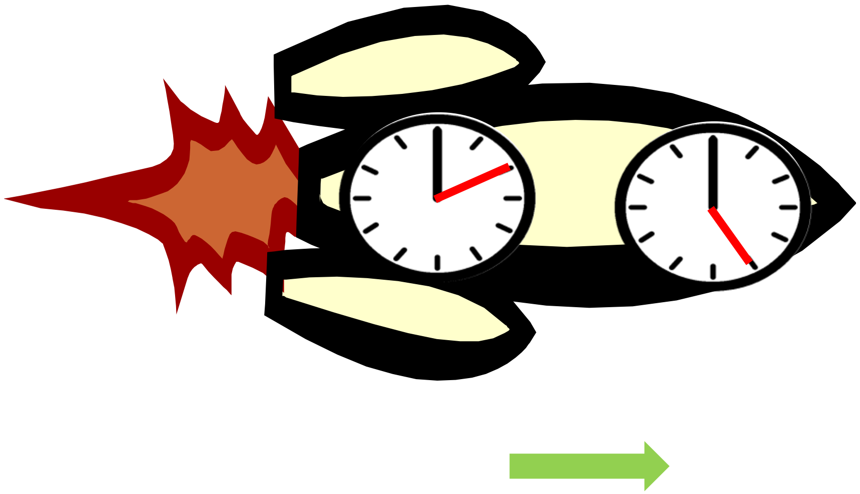
We experience this acceleration through weight, freefall, etc.

Light Pulse in an Accelerated Rocket



Acceleration Affects Time

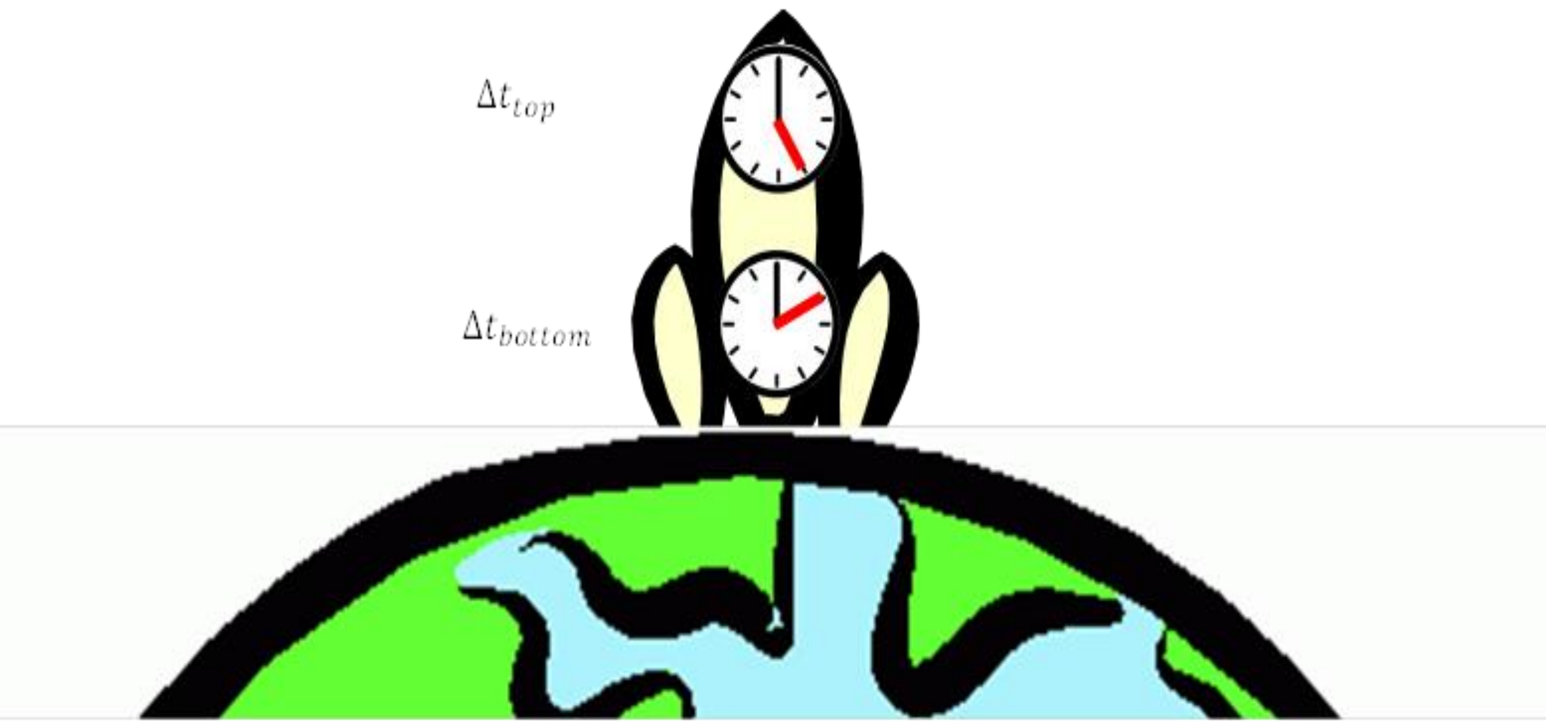
Observers at the front have clocks that tick faster!



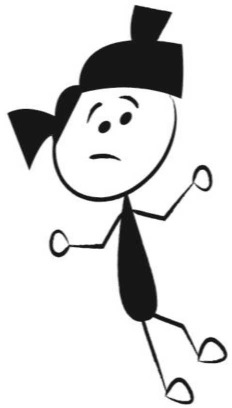
$$\Delta t_{back} = (1 - \frac{ah}{c^2})\Delta t_{front}$$

Mass Affects Time

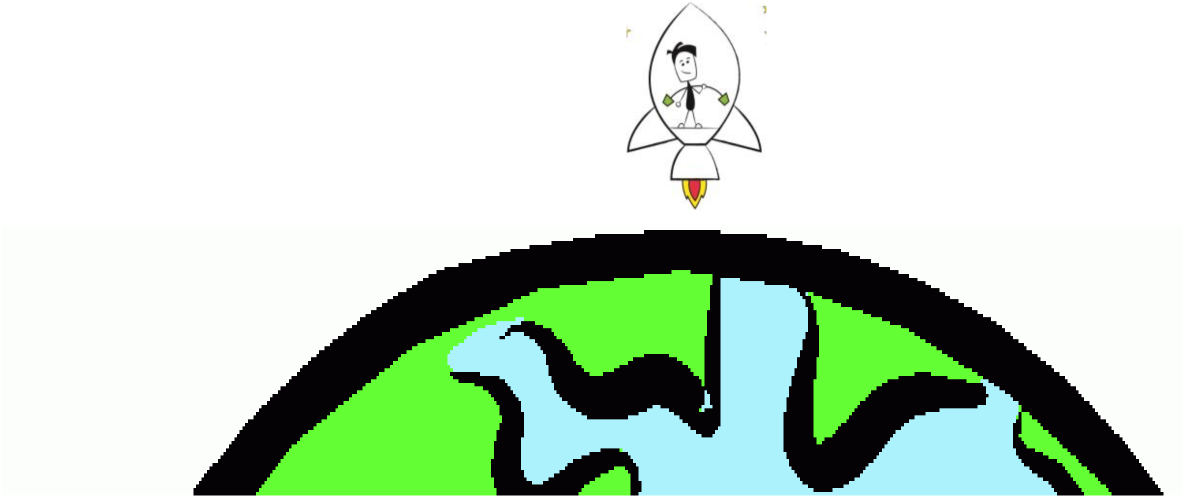
$$\Delta t_{bottom} = (1 - gh/c^2)\Delta t_{top}$$



Imagine Alice in free-fall towards the Earth.



What is her velocity right before she hits the Earth?



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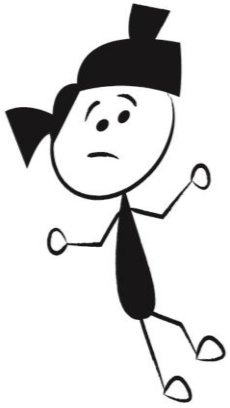
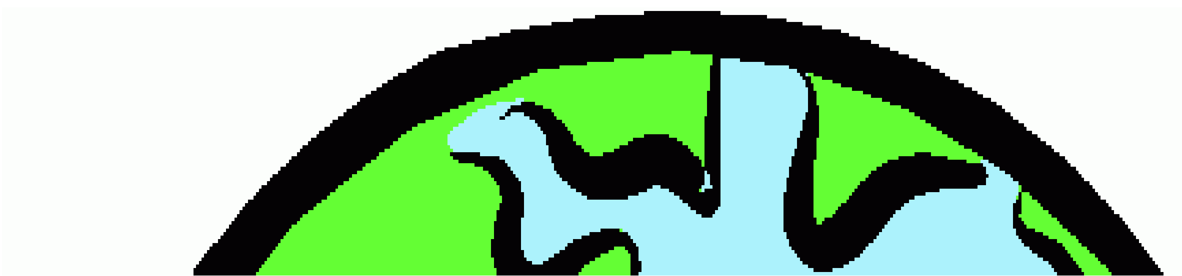


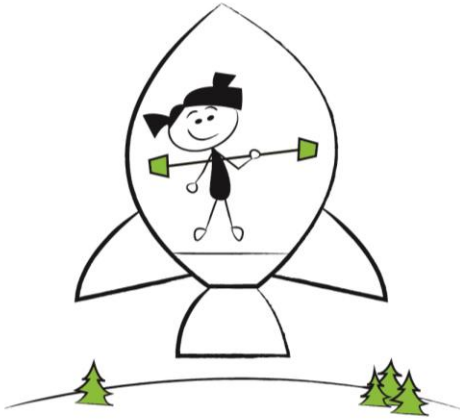
What is her velocity right before she hits the Earth?

$$KE_i + PE_i = KE_f + PE_f$$

$$0 + 0 = \frac{1}{2}mv^2 - \frac{GMm}{r}$$

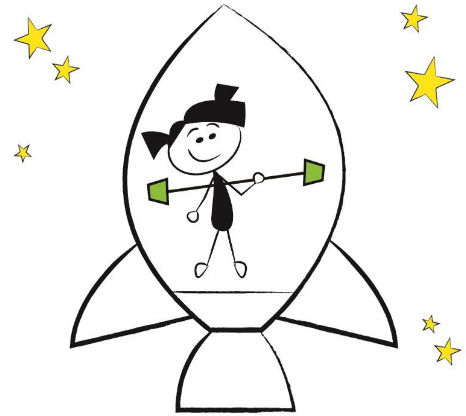
$$v_e = \sqrt{\frac{2GM}{r}}$$





Falling

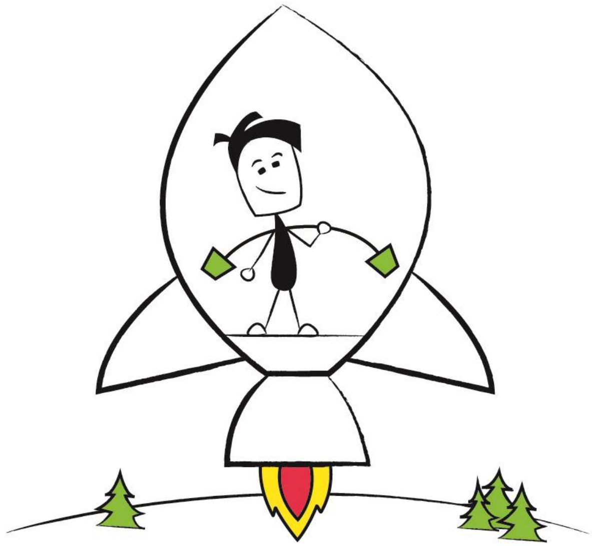
=



Floating

Alice is free-falling. She does not accelerate!

She moves on a **straight path** through curved spacetime!



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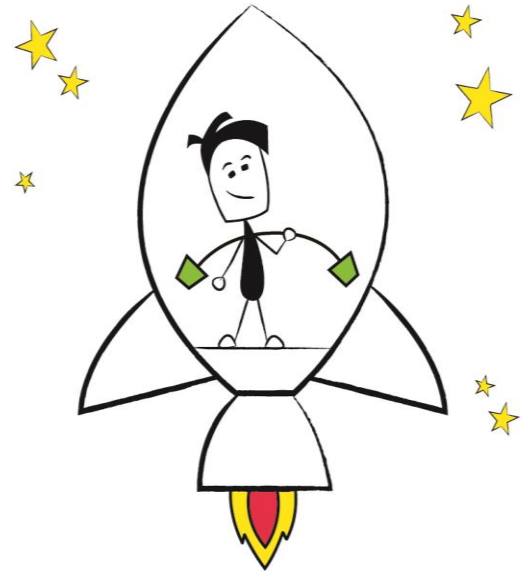
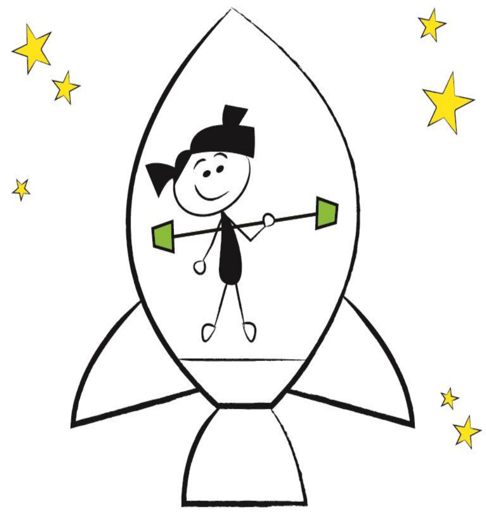


Hovering

Accelerating

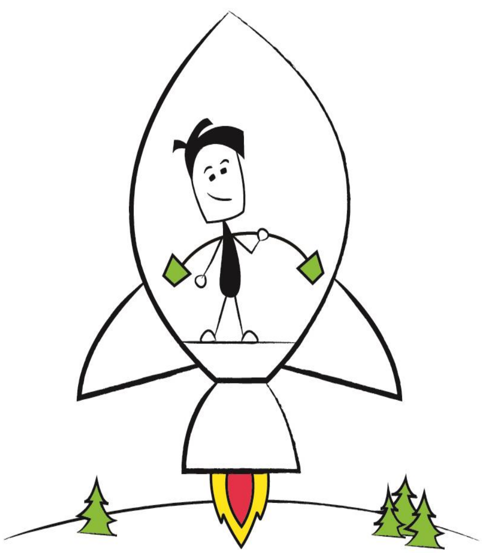
Bob is accelerating upward. He feels a force pushing him up!

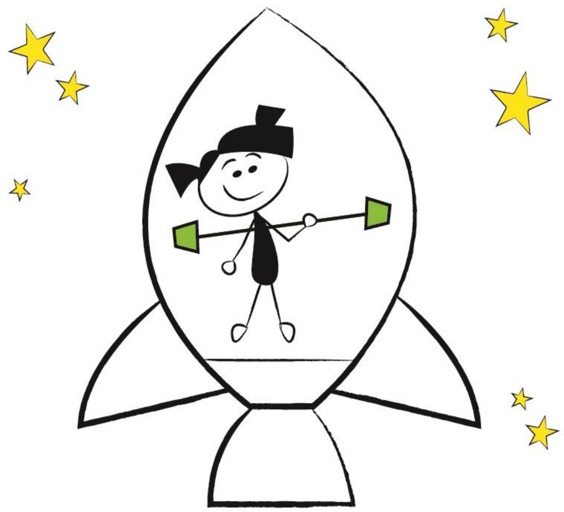
He moves on a **curved** path in spacetime!



The situation is equivalent to:

- Alice floating at rest
- Bob accelerating at a constant rate





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- Alice floating at rest
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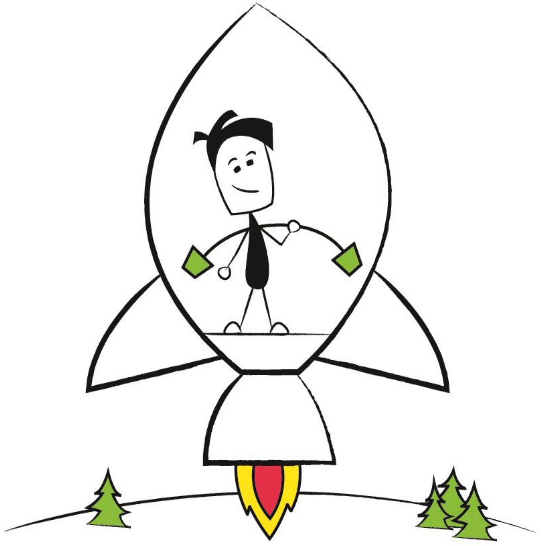
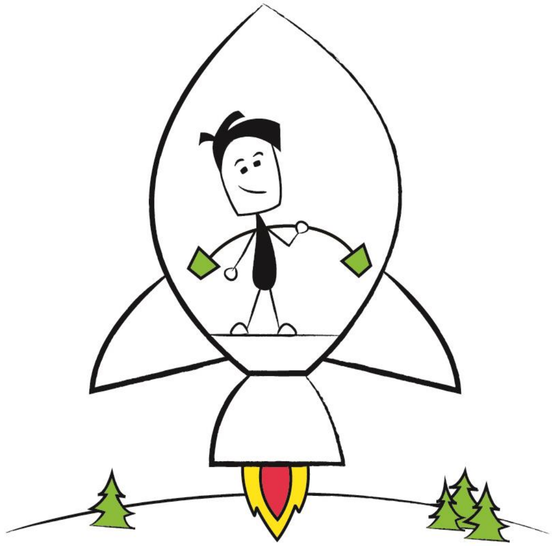
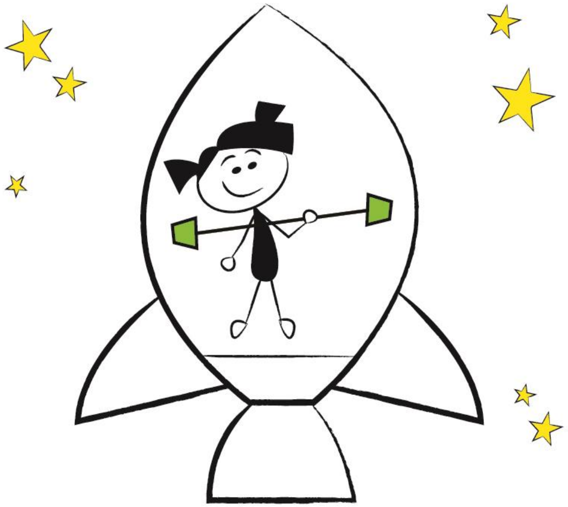


- When Bob reaches Alice he whizzes past with velocity v_{escape}





As he passes, Alice looks in and sees Bob's clock running slow!

By what factor?

$$\Delta t_{r,Bob} = \sqrt{1 - \frac{v^2}{c^2}} \Delta t_{\infty,Alice} \quad = \sqrt{1 - \frac{2GM}{c^2 r}} \Delta t_{\infty,Alice}$$

Exercise to Try!

$$\Delta t_{r,Bob} = \sqrt{1 - \frac{2GM}{c^2 r}}\,\Delta t_{\infty,Alice}$$

Use the binomial approximation to derive the gravitational time dilation factor for the Earth.

$$\Delta t_{bottom} = (1 - gh/c^2)\Delta t_{top}$$

What are the dimensions of the factor $\frac{2GM}{c^2 r}$?

What happens as $\frac{2GM}{c^2 r}$ increases?

$\frac{2GM}{c^2 r}$ is a measure of how "relativistic" the situation is

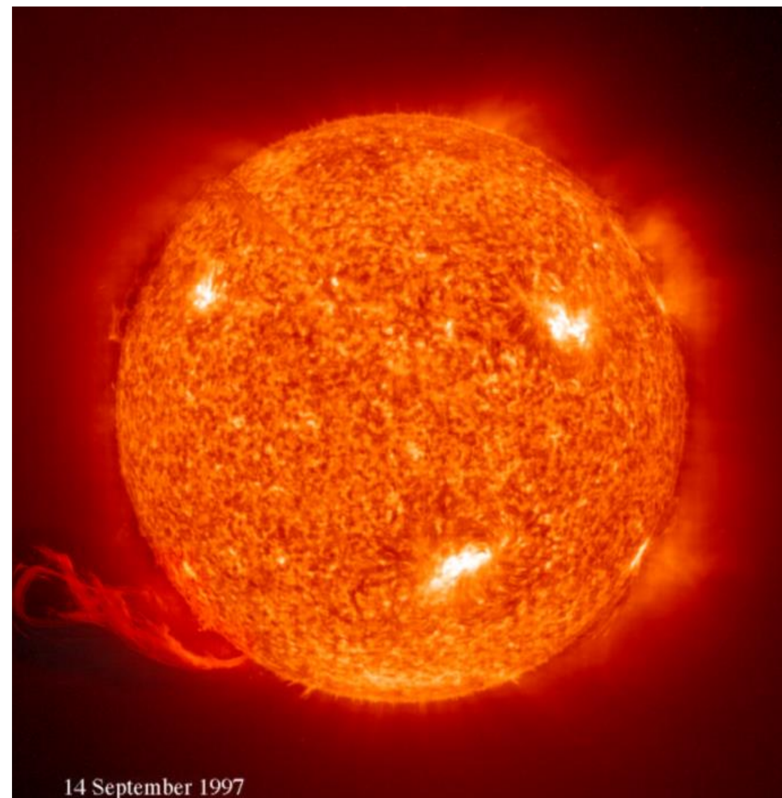
$$\Delta t_{r,Bob} = \sqrt{1 - \frac{2GM}{c^2 r}}\, \Delta t_{\infty,Alice}$$

The most massive body in the solar system is the sun.

What is $\frac{2GM}{c^2 r}$ for the sun?

$M_{sun} = 2 \times 10^{30}\text{kg}$

$r_{sun} = 7 \times 10^{5}$ km



Global Positioning System

What are the GPS SR + GR time dilation factors?

What is the time difference for one day?

$$v = 4\ \mathrm{km/s}$$

$$h = 20000\ \mathrm{km}$$

Global Positioning System – Special Relativity

$$v = 4 \text{ km/s}$$

$$\Delta t_{GPS} = \sqrt{1-\beta^2}\Delta t_E$$

$$\frac{\Delta t_E - \Delta t_{GPS}}{\Delta t_E} = \frac{\Delta t_E - \sqrt{1-\beta^2}}{\Delta t_E}$$

$$\frac{\Delta t_E - \Delta t_{GPS}}{\Delta t_E} = 1 - \sqrt{1-\beta^2} = -9 \times 10^{-11}$$

Global Positioning System – Special Relativity

$$\frac{\Delta t_E - \Delta t_{GPS}}{\Delta t_E} = -9 \times 10^{-11}$$

One day has 86 400 s.

GPS clocks tick ***slower*** by 7.7 μs per day.

Global Positioning System – General Relativity

$$M = 6 \times 10^{24}\ \text{kg} \qquad G = 6.67 \times 10^{-11}\text{m}^3\text{kg}^{-1}\text{s}^{-2}$$

$$r_E = 6378\ \text{km}$$

$$\Delta t_E = \sqrt{1 - \frac{2GM}{c^2 r}}\Delta t_{GPS}$$

$$\frac{\Delta t_E - \Delta t_{GPS}}{\Delta t_E} = \frac{\Delta t_E - \Delta t_E \frac{1}{\sqrt{1-\frac{2GM}{c^2 r}}}}{\Delta t_E}$$

$$= 1 - \frac{1}{\sqrt{1 - \frac{2GM}{c^2 r}}} = 7 \times 10^{-10}$$

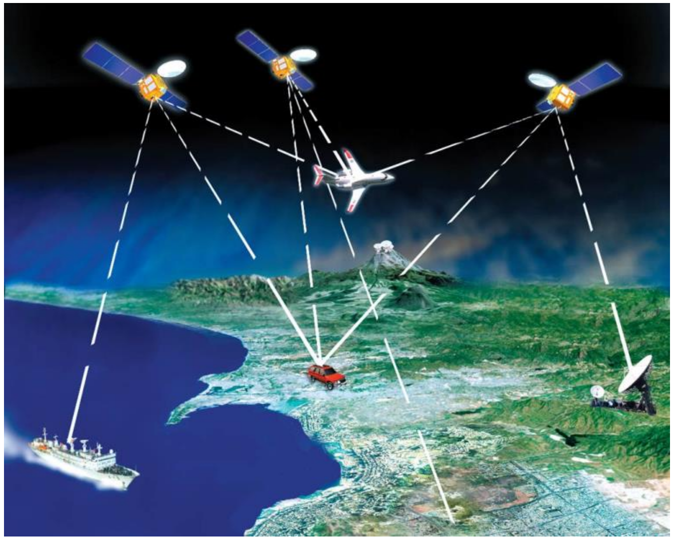
Global Positioning System – General Relativity

$$\frac{\Delta t_E - \Delta t_{GPS}}{\Delta t_E} = 7 \times 10^{-10}$$

One day has 86 400 s.

GPS clocks tick ***faster*** by 60 μs per day.

Global Positioning System

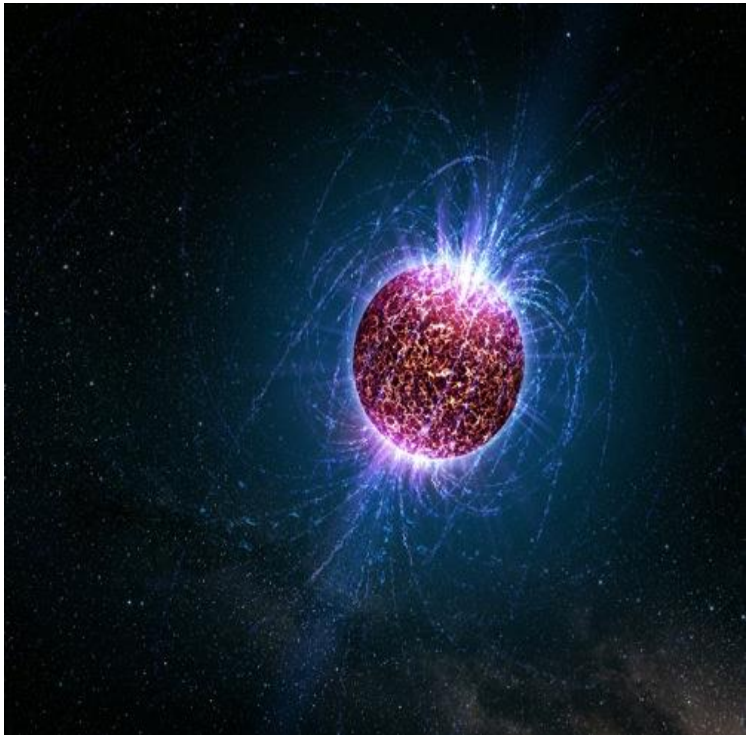


GPS clocks appear to tick ***slower*** due to **SR**.

GPS clocks appear to tick ***faster*** due to **GR.**

$$\Delta t_{r,Bob} = \sqrt{1 - \frac{2GM}{c^2 r}} \Delta t_{\infty,Alice}$$

What is $\frac{2GM}{c^2 r}$ for a neutron star?



$M_{neutron,*} = 2 \times 10^{30}$kg

$r_{neutron,*} = 13$ km

Suppose we are on a star of with mass M and radius R

$$\frac{2GM}{c^2 r} \ll 1$$

Squeeze the mass of the star into a smaller radius.

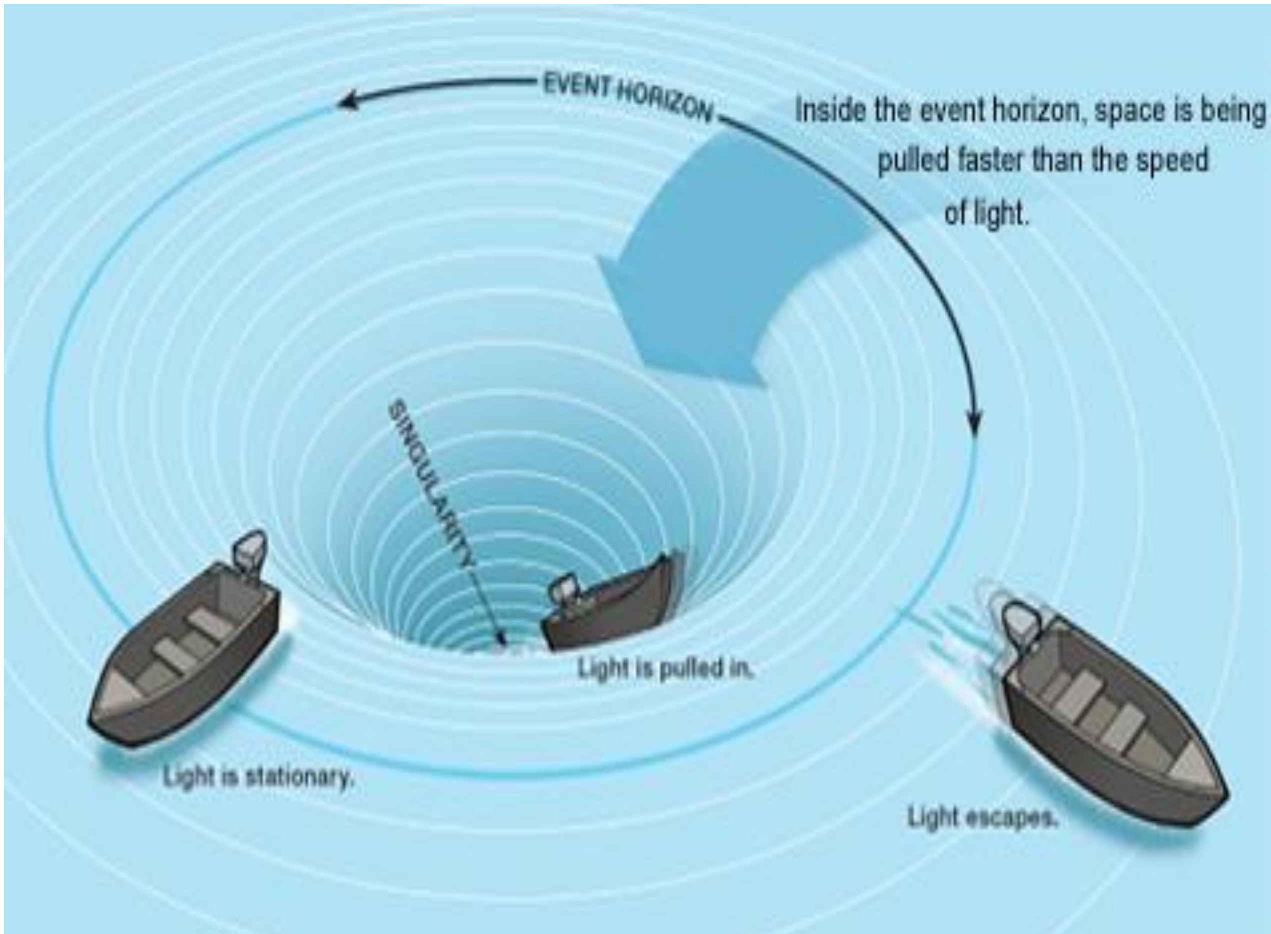
At what radius does something interesting happen?

What happens?

Schwarzschild Radius – Event Horizon

$$r_s = \frac{2GM}{c^2}$$

Escape speed = c

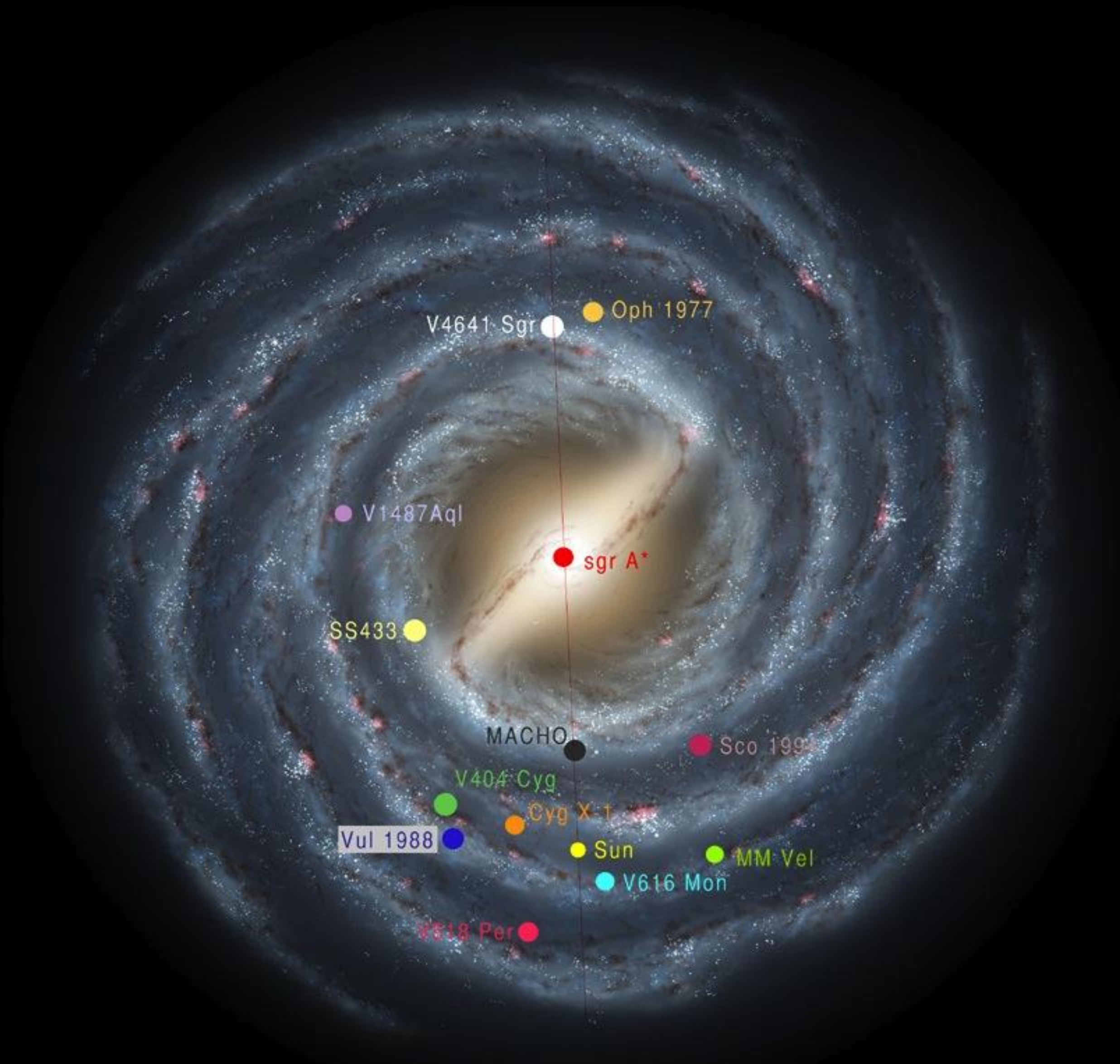


Schwarzschild Radius

Every mass as a Schwarzschild radius!

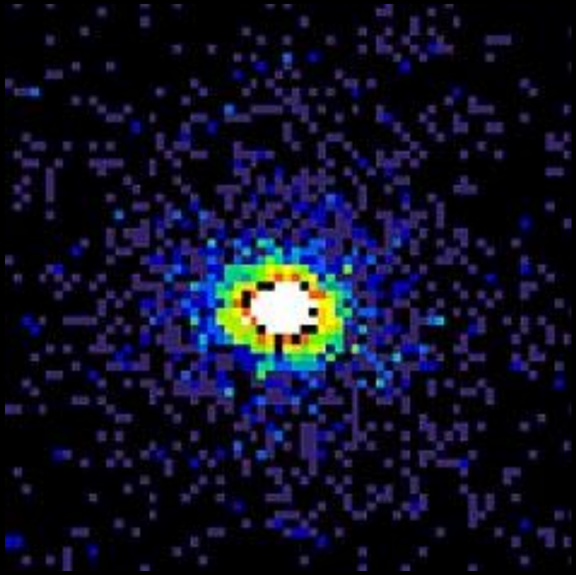
What is yours?

$$r_s = \frac{2GM}{c^2}$$



Oph 1977
V4641 Sgr
V1487Aql
sgr A*
SS433
MACHO
Sco 199
V404 Cyg
Cyg X-1
Vul 1988
Sun
MM Vel
V616 Mon
V518 Per

Cygnus X-1



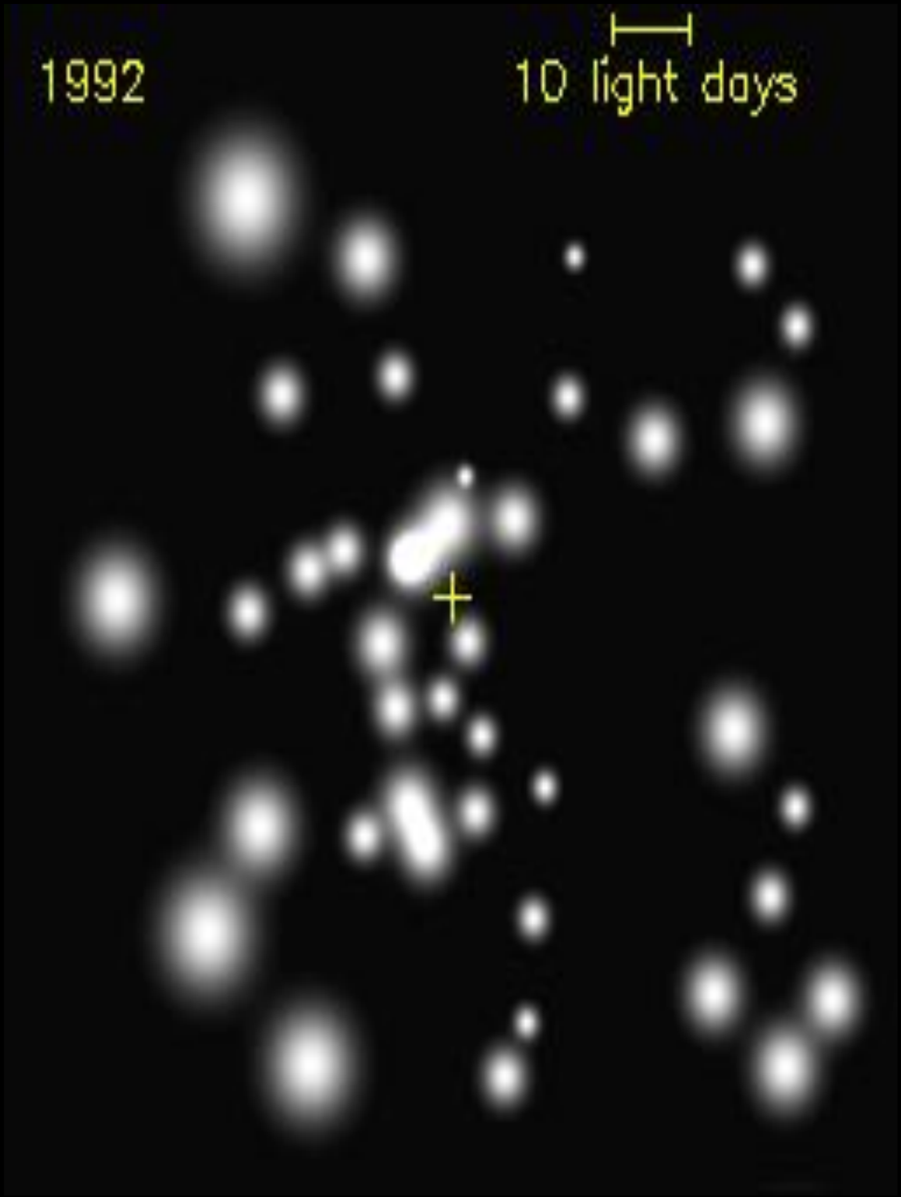
Thorne – Hawking Black Hole Bet

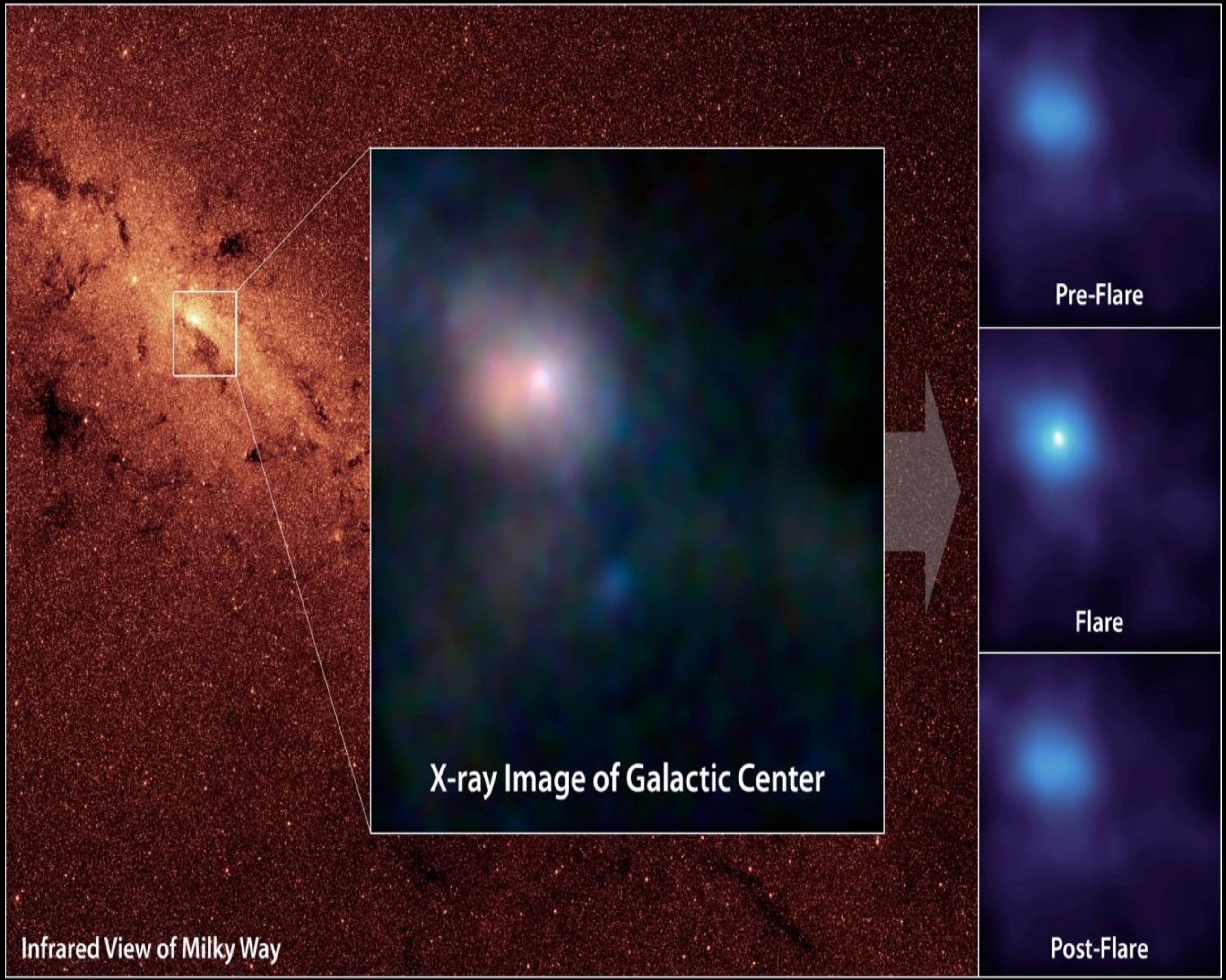
SMBH at the heart of the Milky Way

What is the schwarzschild radius of the black hole?

$M_{SMBH} = 4 \times 10^{6}\, M_{sun} = 8 \times 10^{36}\mathrm{kg}$

$$r_s = \frac{2GM}{c^2}$$


1992
10 light days


Infrared View of Milky Way
X-ray Image of Galactic Center
Pre-Flare
Flare
Post-Flare

Gravity = Warping of Spacetime

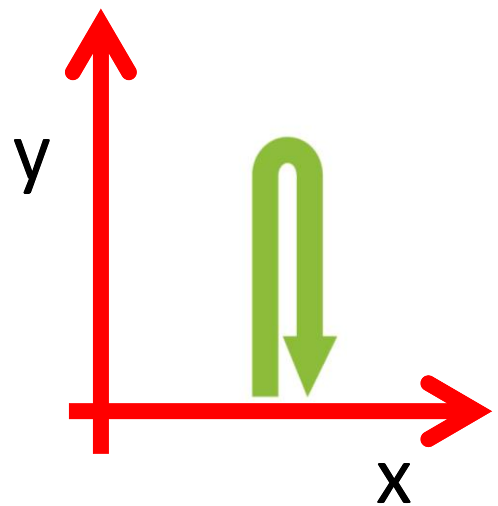
- How does **time warping** explain gravity?

- How does **space warping** explain gravity?

Gravity – Warped Time

Draw the space-space diagram for a ball being tossed straight up.

If the ball starts with a speed of 10 m/s and reaches a maximum height of 5m how long is it in the air?



$$v = v_o - gt$$

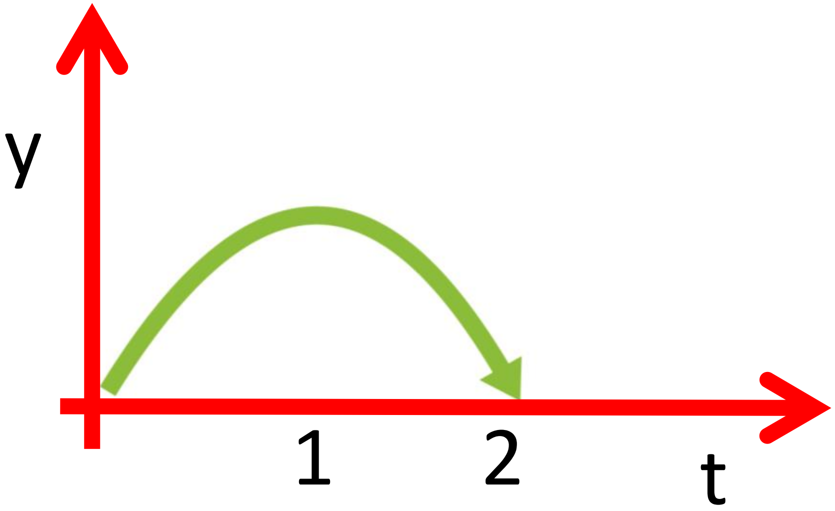
$$t_{top} = \frac{v_o}{g} = 1 \text{ sec}$$

$$t_{air} = 2 \text{ sec}$$

Gravity – Warped Time

Draw the spacetime diagram (t and y) for a ball being tossed straight up.

Gravity – Warped Time



Gravity – Warped Time

SR Time Dilation at t=0 and t=2

$$\sqrt{1-\frac{v^2}{c^2}} \approx 1 - 5 \times 10^{-16}$$

MOVING CLOCKS RUN SLOWER

GR Time Dilation at t=1

$$1+\frac{gh}{c^2} \approx 1 + 5 \times 10^{-16}$$

HIGHER CLOCKS RUN FASTER

Gravity – Warped Time

SR Time Dilation

Moving clocks run slow $\sim 10^{-16}$

GR Time Dilation

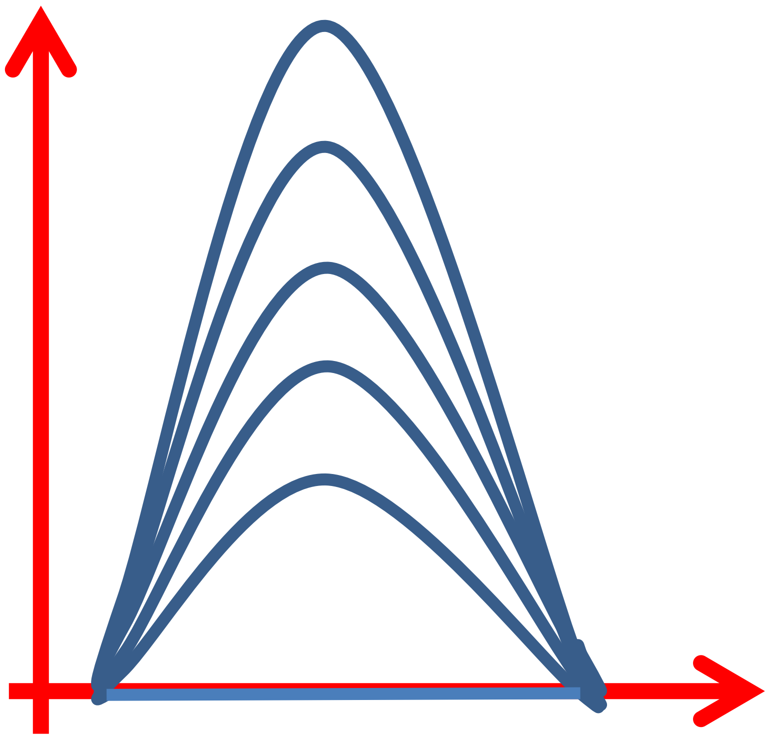
Higher clocks run fast $\sim 10^{-16}$

Gravity – Warped Time

Sketch many ball paths through the same two endpoints starting with a path that moves straight and then through increasing heights.

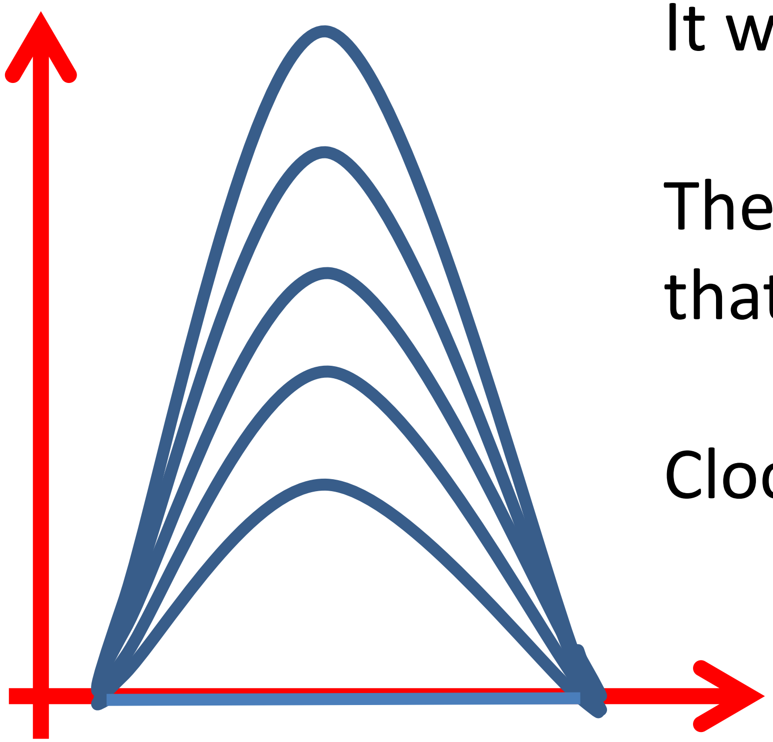
Gravity – Warped Time

Sketch many ball paths through the same two endpoints starting with a path that moves straight and then through increasing heights.



Gravity – Warped Time

What effect will GR time dilation have on the elapsed time for a clock strapped to the ball?



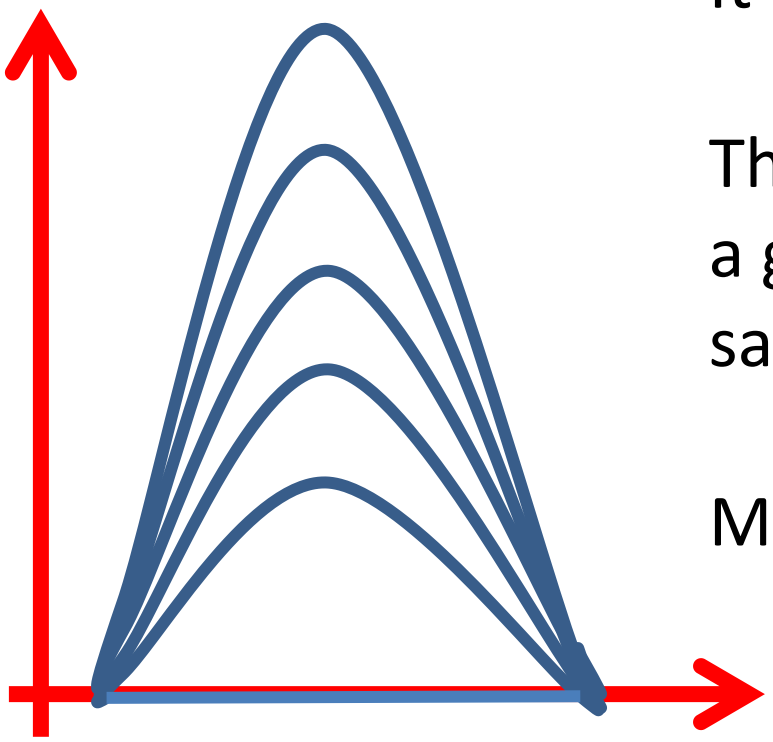
It will **increase** the elapsed time

The ball is moving through a space that is higher up

Clocks tick fast higher up

Gravity – Warped Time

What effect will SR time dilation have on the elapsed time for a clock strapped to the ball?

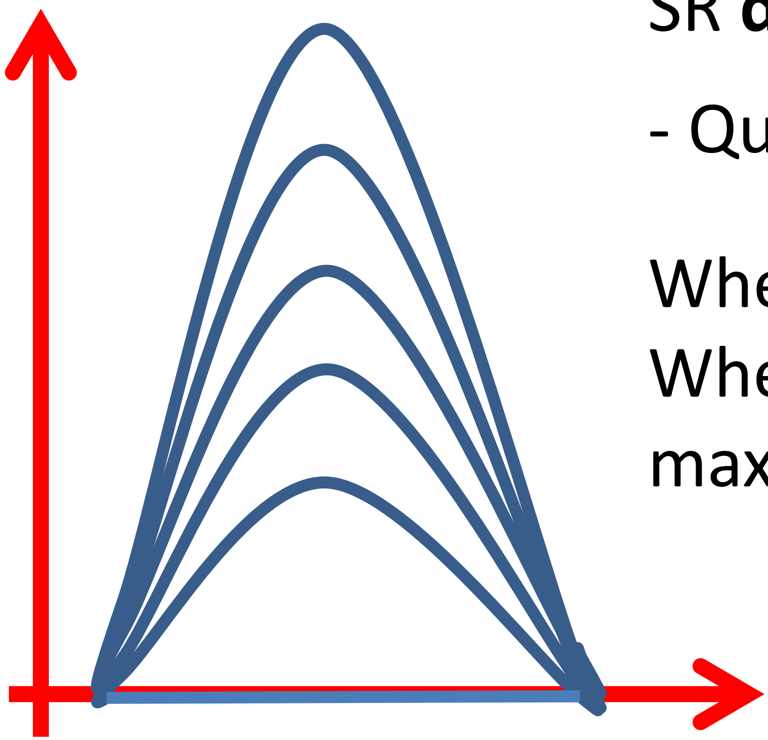


It will **decrease** the elapsed time

The ball must move faster to go to a greater height and back in the same time

Moving clocks run slow

Gravity – Warped Time



GR **increases** elapsed time!

- Linear -> $\frac{gh}{c^2}$

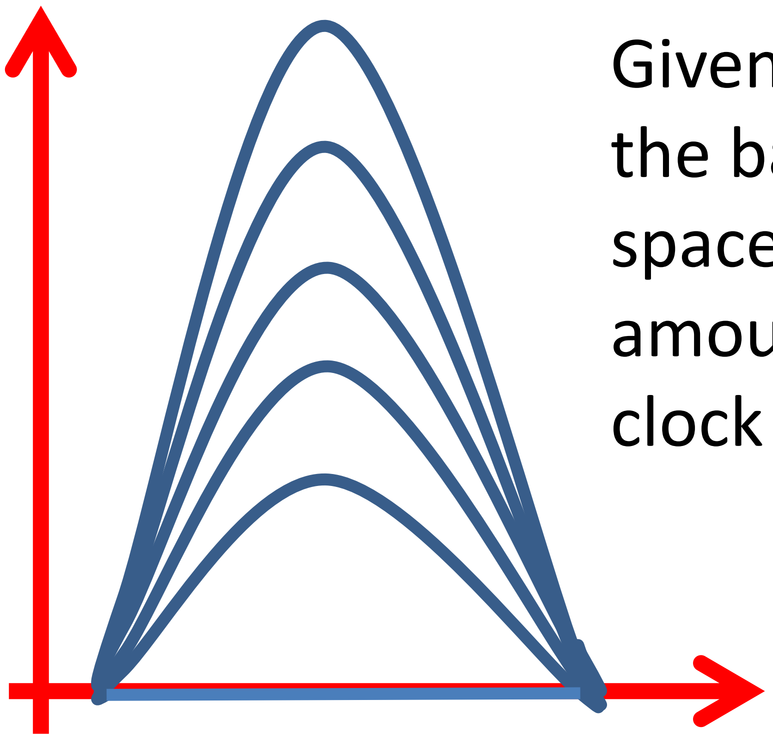
SR **decreases** elapsed time!

- Quadratic -> $\frac{v^2}{c^2}$

Where is the sweet-spot?
Where is the elapsed time is a maximum?

Gravity – Warped Time

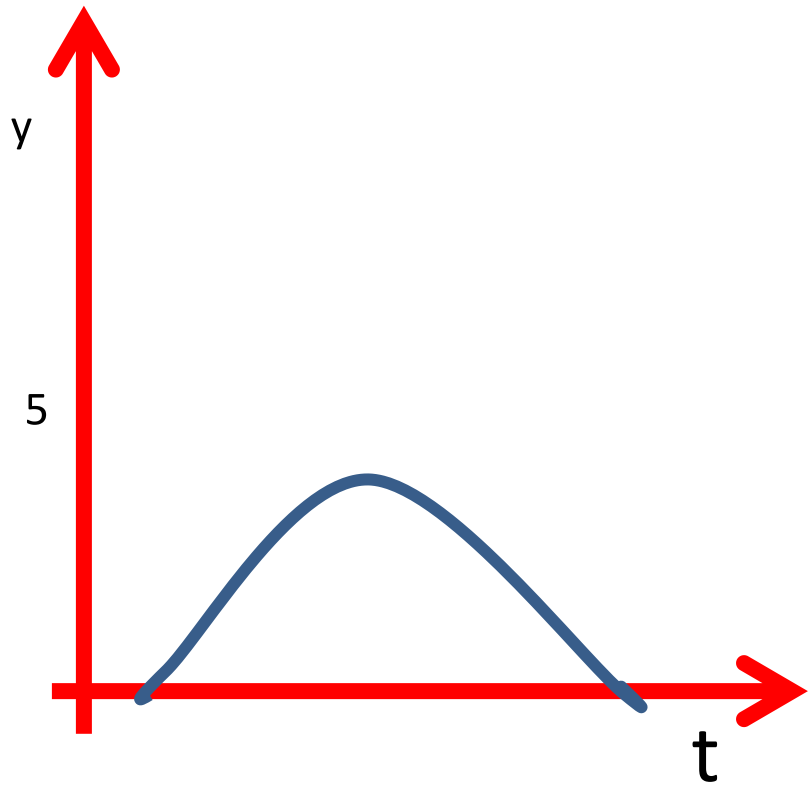
Max. Time = Straight path in curved spacetime

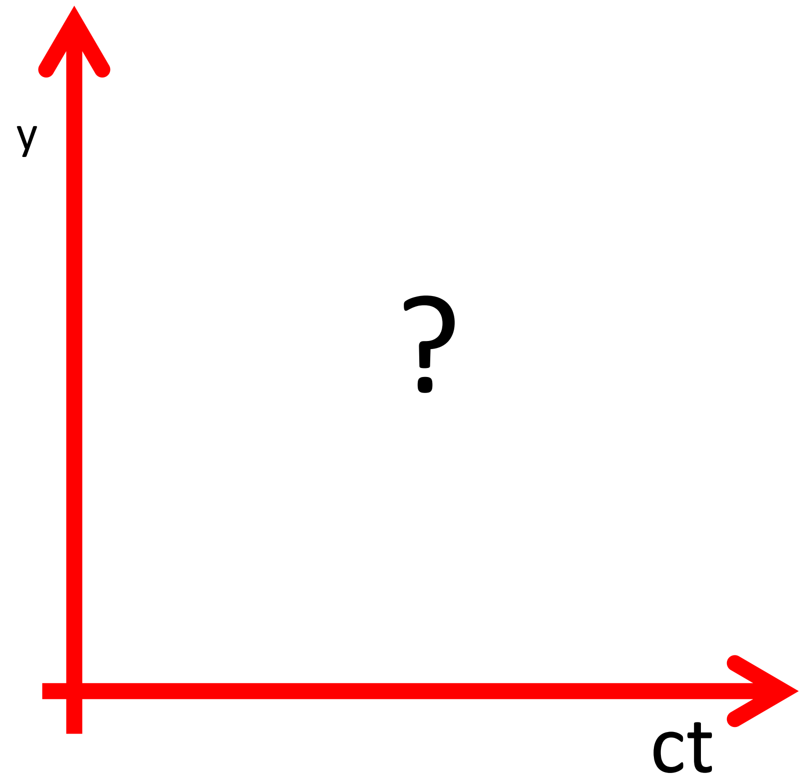


Given two endpoints in spacetime, the ball moves on a path through spacetime for which the **maximum** amount of time will elapse for a clock strapped to the ball.

How curved is the spacetime of the Earth?

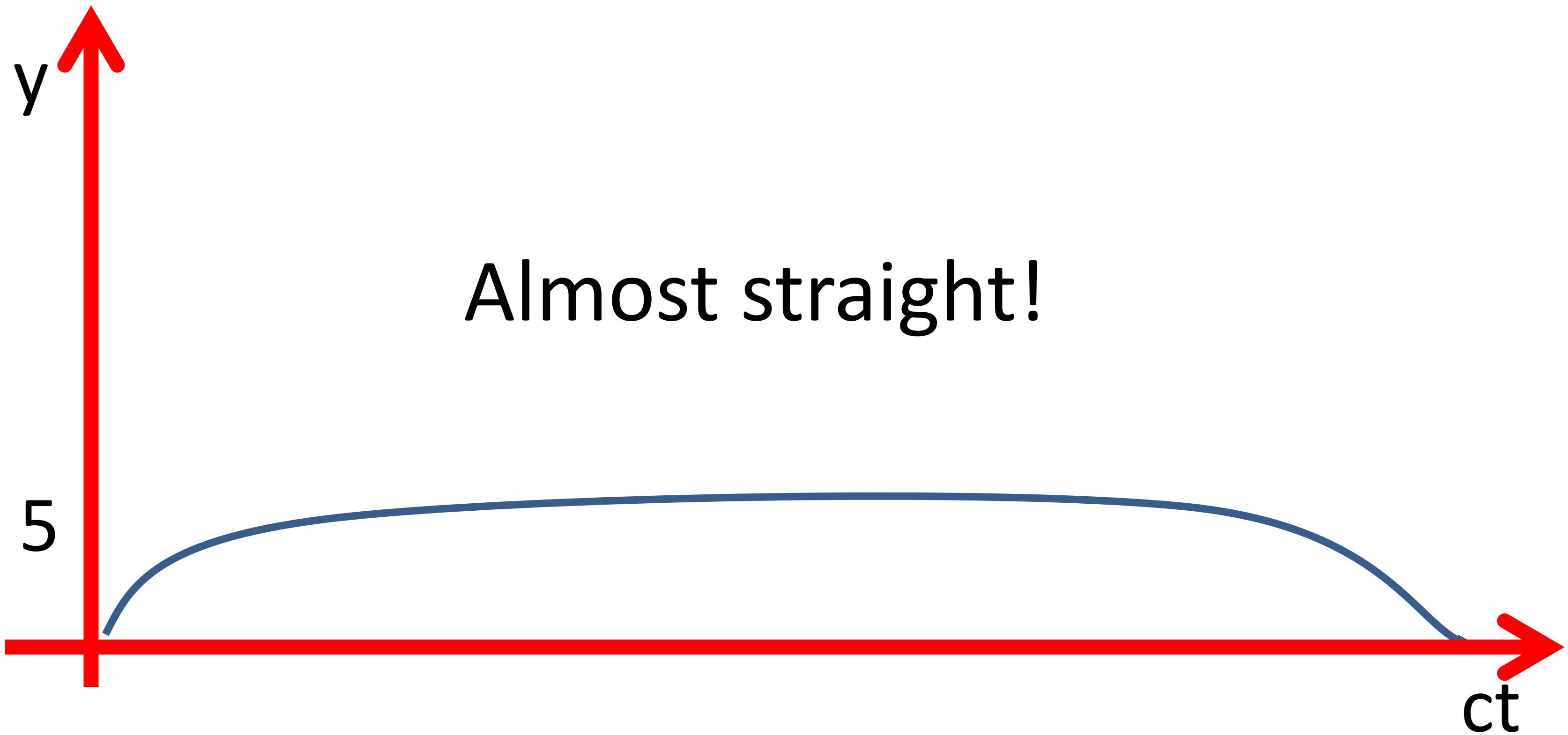
Draw the original path of the ball putting space and time on the same footing!





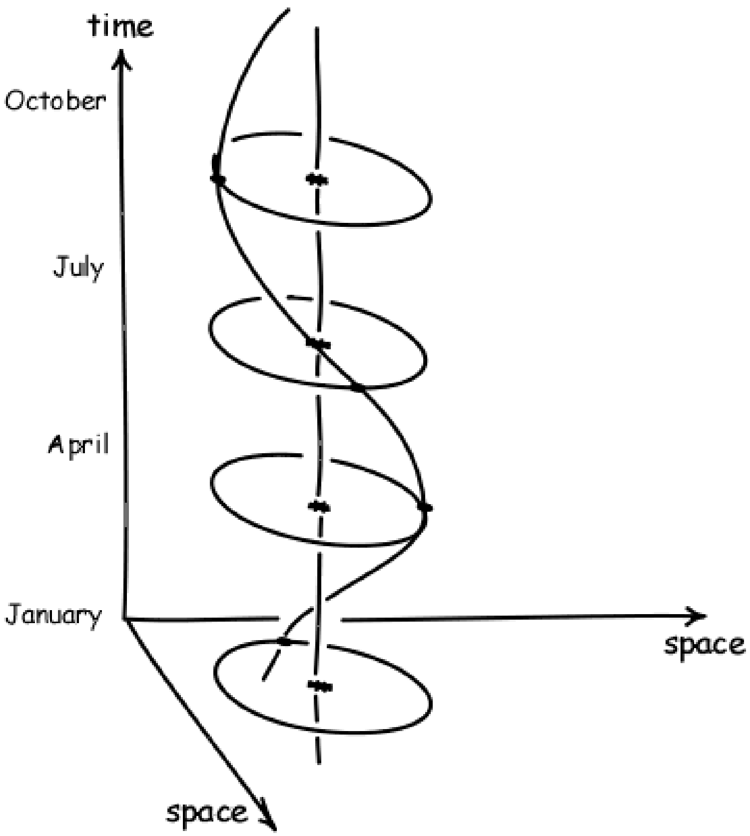
How curved is the spacetime of the Earth?

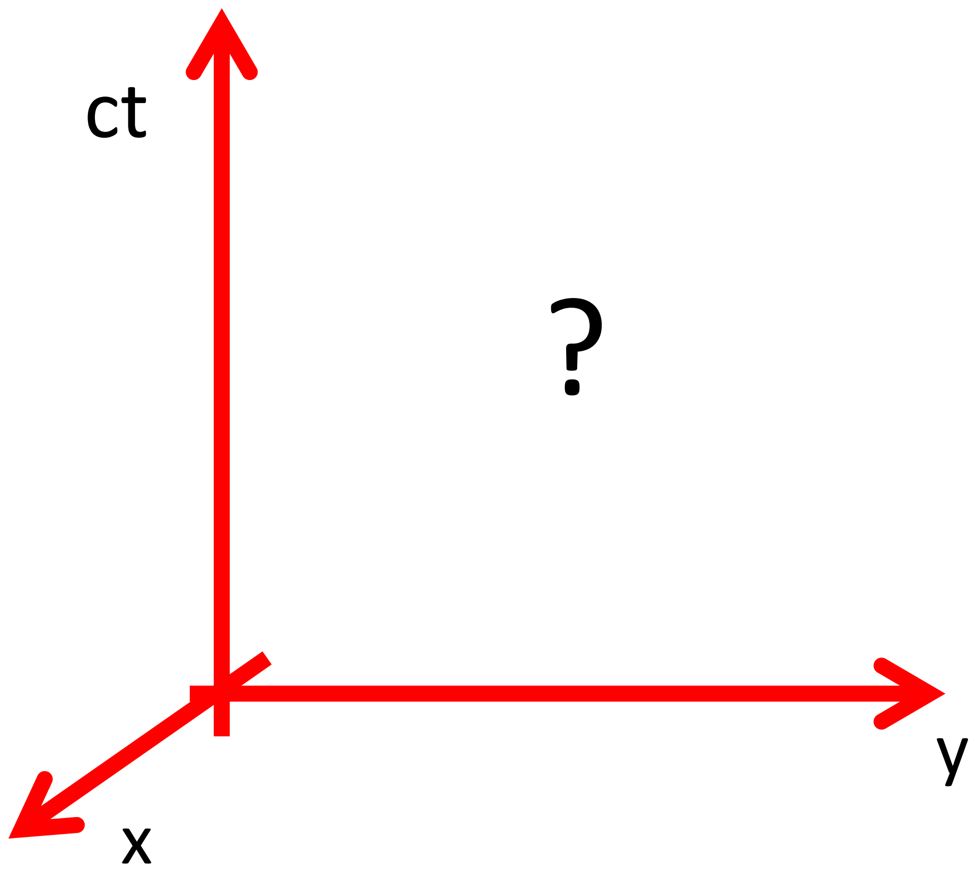
Spacetime is “stiff”. The mass of the Earth hardly warps it!



Can we explain Earth's orbit?

Re-draw Earth's orbit putting space and time on the same footing!





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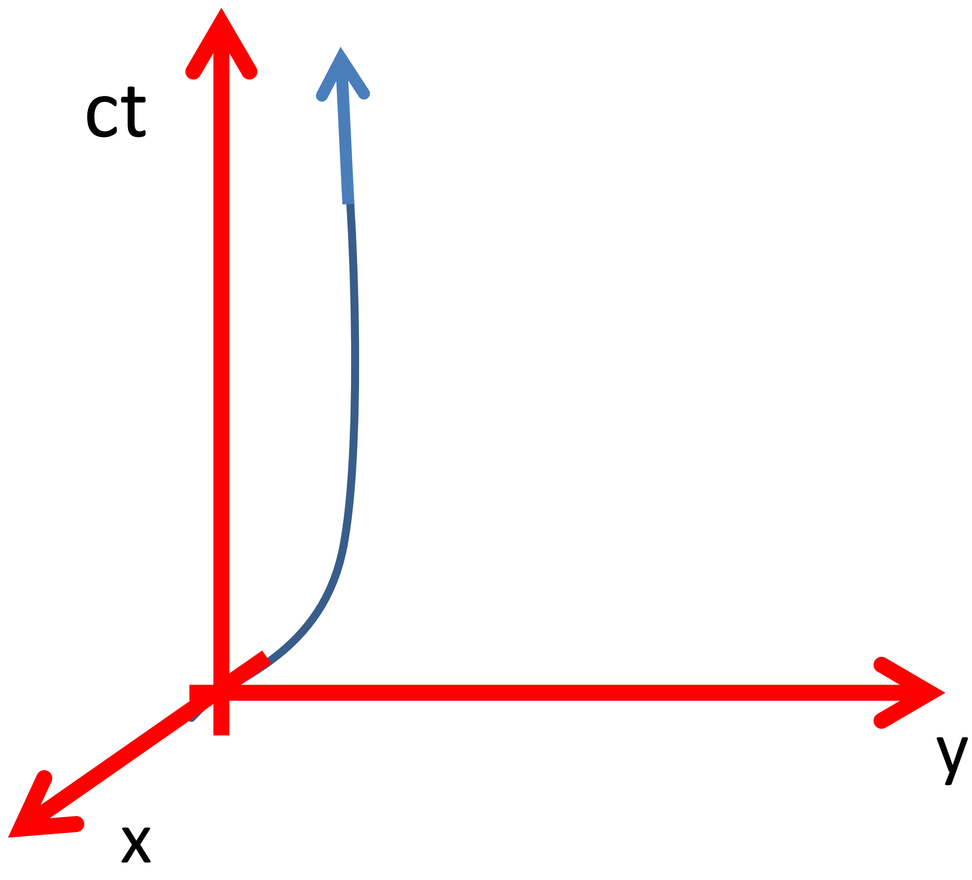
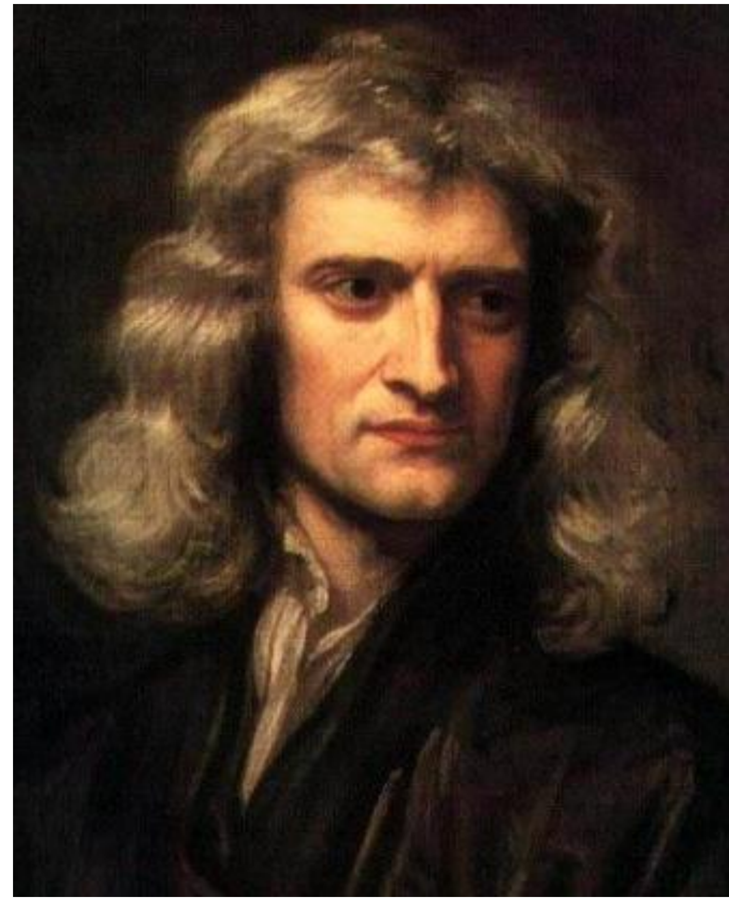


Newton

- Gravity is a force
- Something to put on LHS of F=ma

- This law determines acceleration and motion of the planets

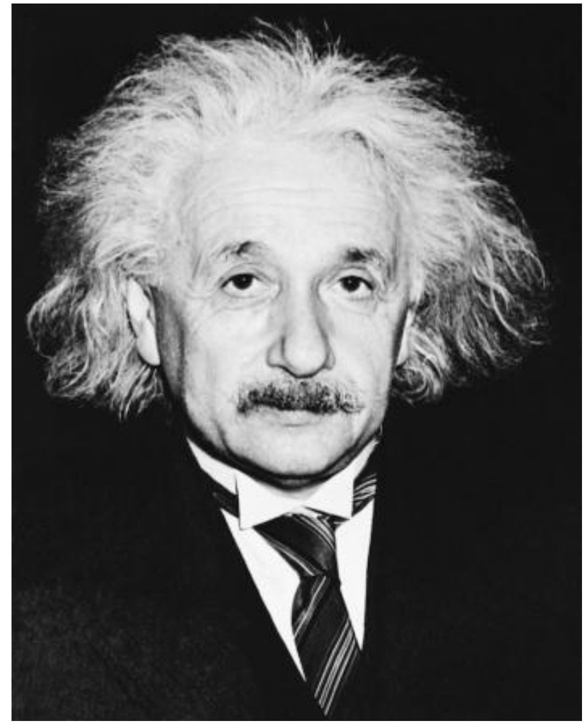


Einstein

- Gravity is not a force
- Doesn't belong in F=ma

- Gravity is part of the first law

- Bodies not acted on by any forces move on straight lines in spacetime

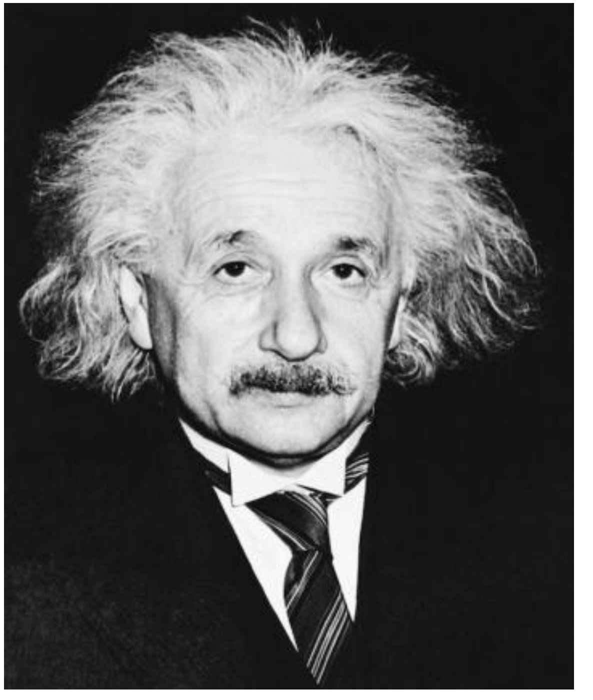


Einstein

1. Replace Newton's absolute space and time with flat spacetime (Minkowski Space)

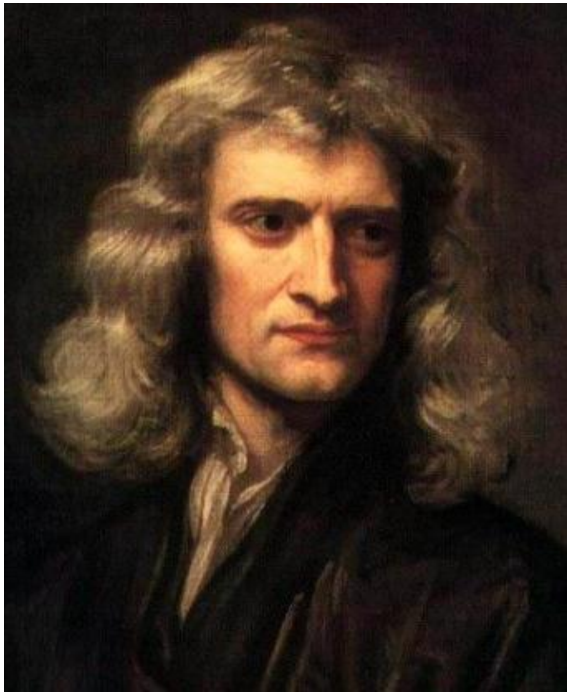
2. Allow spacetime to be curved by the matter it contains.

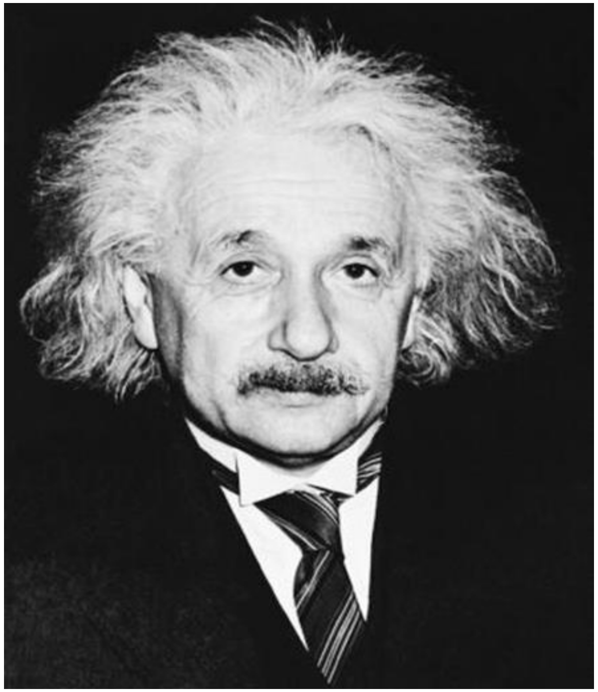
3. Bodies in free-fall move on straight paths in this curved spacetime!



Gravity is not something that happens in spacetime – it is spacetime!

Newton vs. Einstein



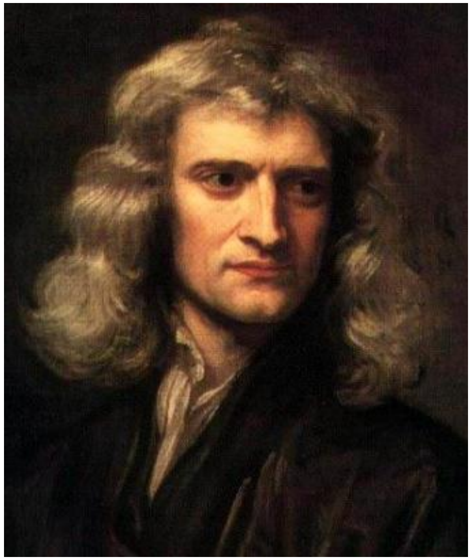


Einstein’s model also predicts that space is warped as well!
Let’s see if we can set Einstein’s model apart!

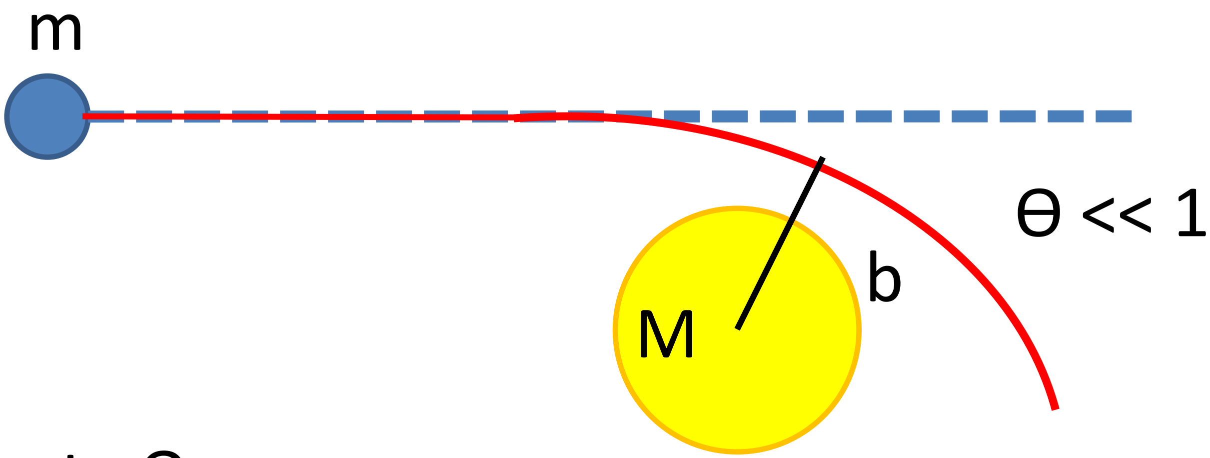
Gravity = Warping of Spacetime

- How does **time warping** explain gravity?
- How does **space warping** explain gravity?

Newton's Deflection



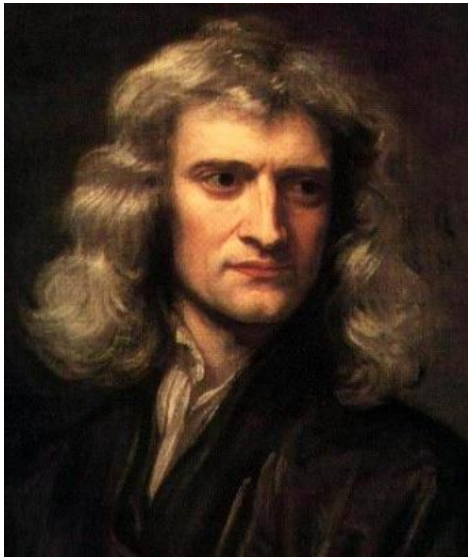
Throw a rock past a star! It will deflect!



Estimate Θ

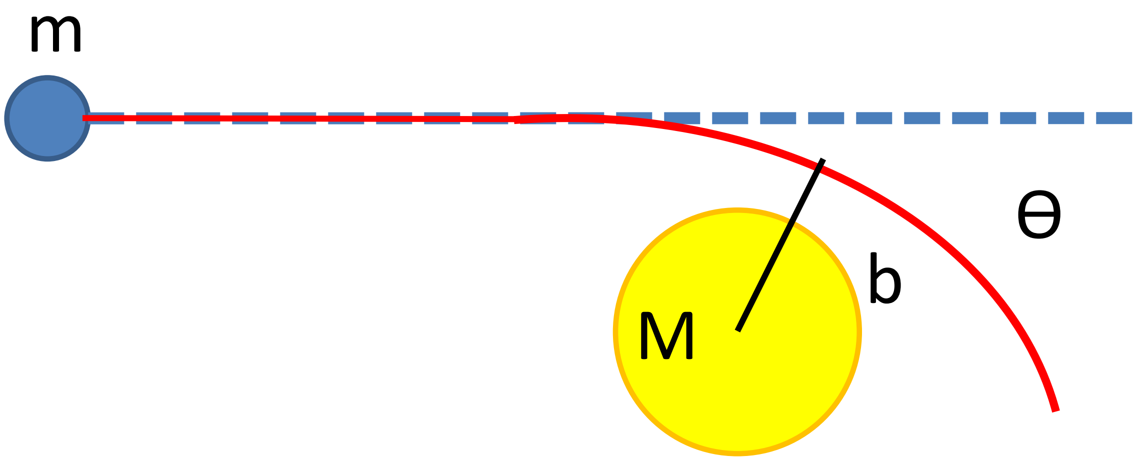
Will it depend on m? Why or why not?

Newton's Deflection



What does θ depend on?

- G (strength of gravity)
- M (mass of star)
- V (speed of rock)
- b (impact parameter)



Use dimensional analysis to find θ

Dimensional Analysis

G $[\frac{L^3}{MT^2}]$

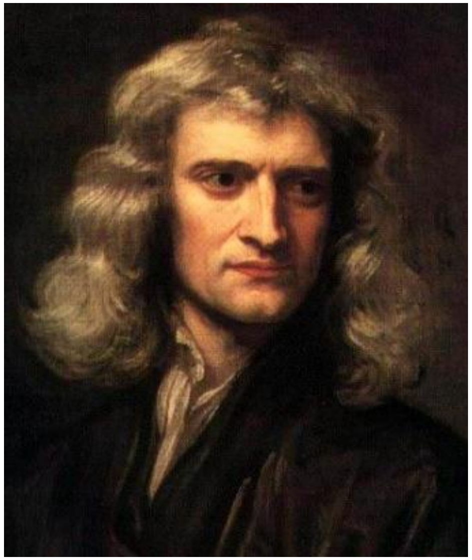
M $[M]$

v $[\frac{L}{T}]$

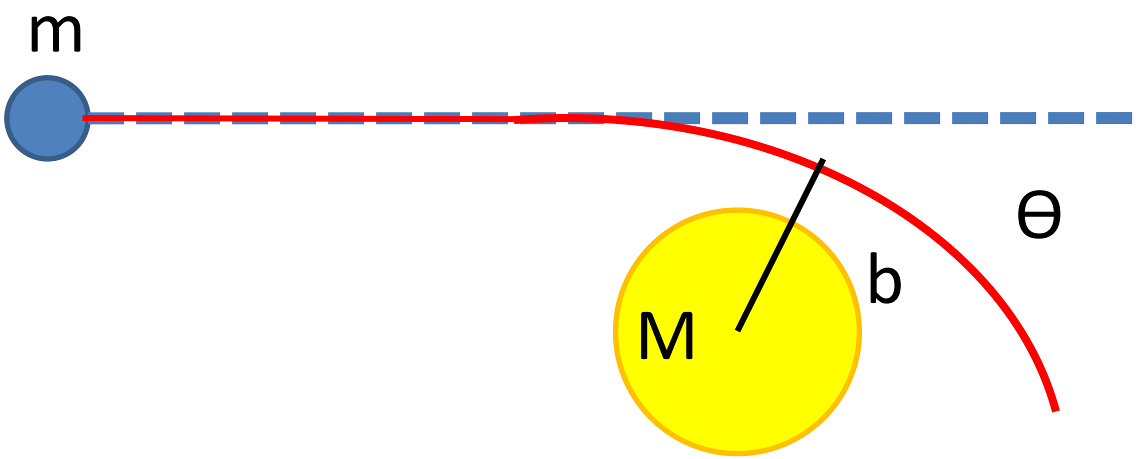
b $[L]$

$$\frac{GM}{bv^2}$$

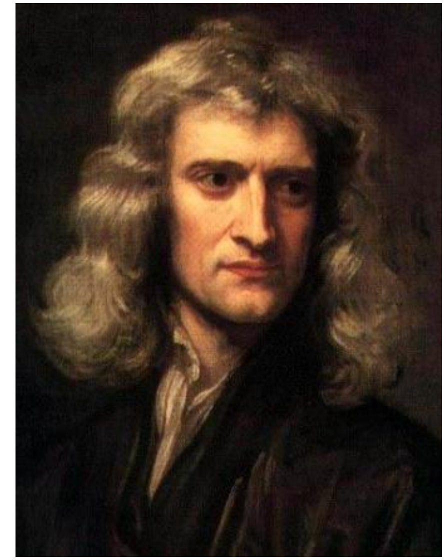
Newton's Deflection



$$\theta_{Newton} = \frac{2GM}{bc^2}$$

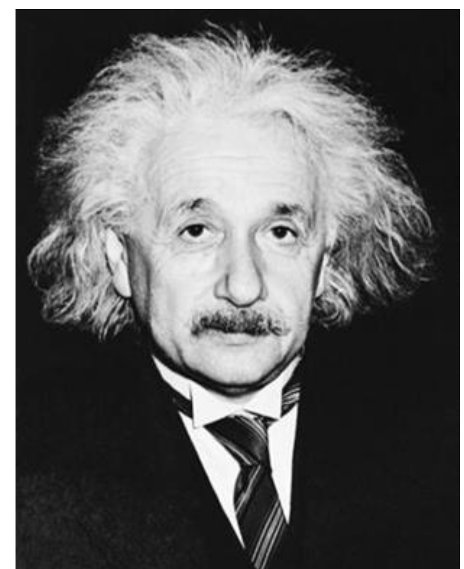


Newton – Bending of Light



$$\theta_{Newton} = \frac{2GM}{bc^2}$$

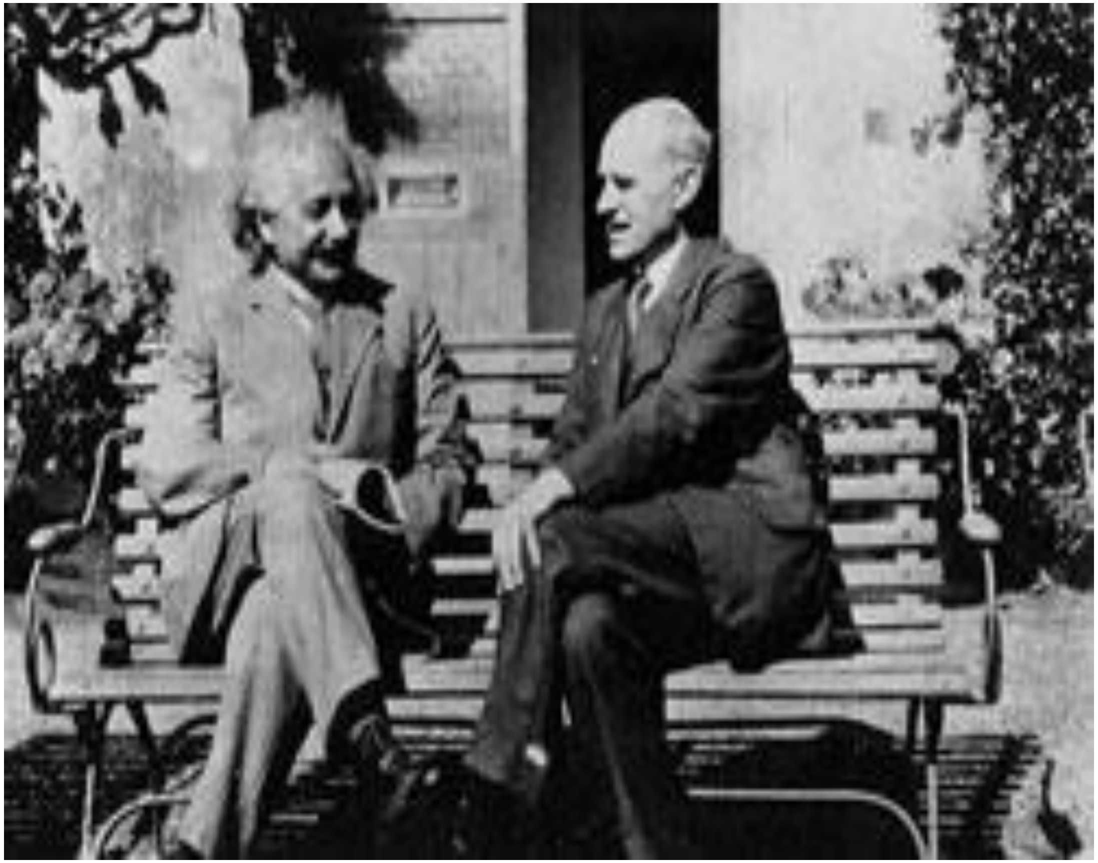
Einstein – Bending of Light

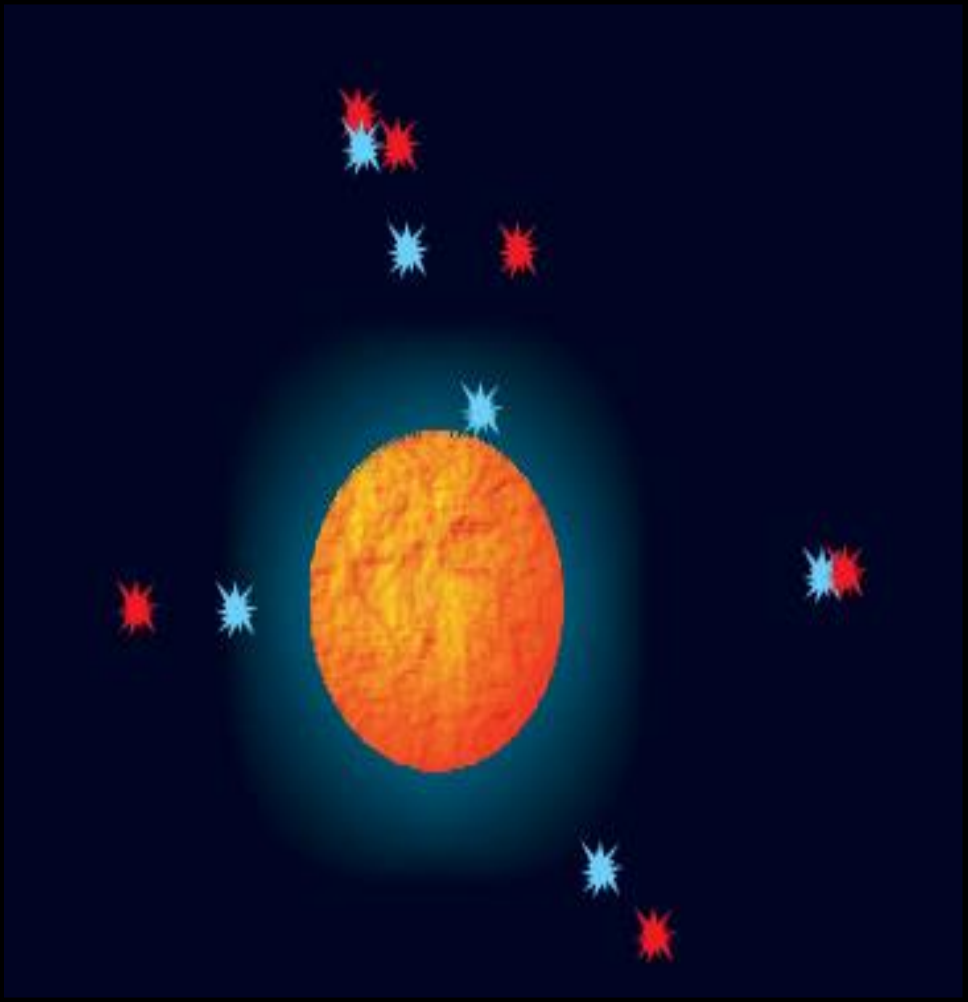


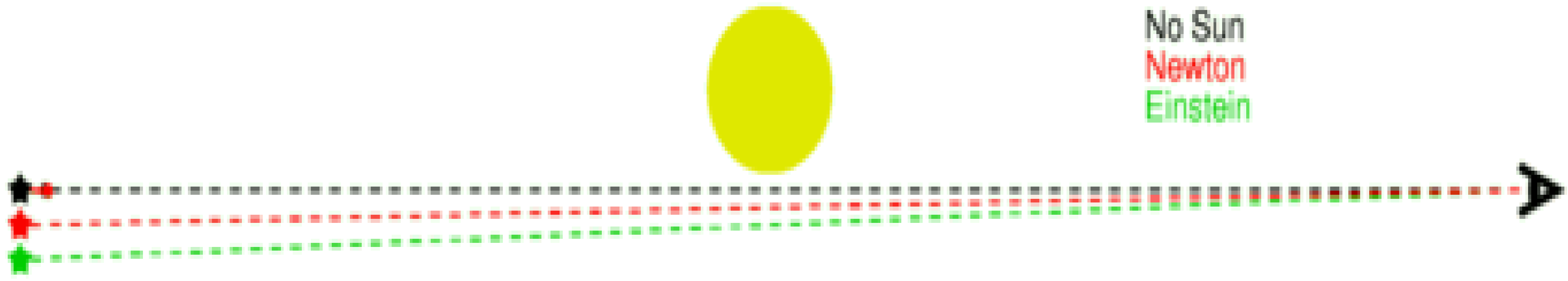
$$\theta_{Einstein} = \frac{4GM}{bc^2} = 2 \times \theta_{Newton}$$

Eddington – Eclipse of 1919

$$\theta_{Einstein} = \frac{4GM}{Rc^2}$$






No Sun
Newton
Einstein

By how much is the star's light deflected?

$$R_{sun} = 7 \times 10^5 \text{ km} \qquad M_{sun} = 2 \times 10^{30} \text{ kg}$$

$$\theta = \frac{4GM_{sun}}{c^2 R_{sun}} = 8.5 \times 10^{-6} \text{ radians}$$

$$= 1.75 \text{ arcsec}$$

$$1 \text{ arcsec} = 4.8 \times 10^{-6} \text{ radians}$$

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

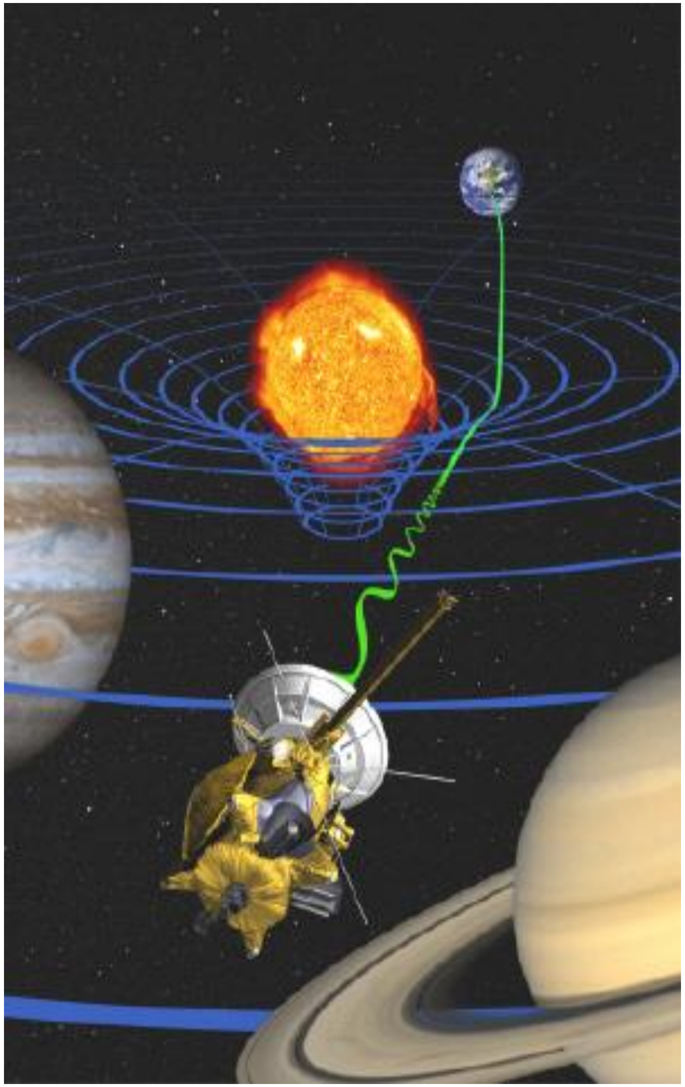
No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Special Cable to THE NEW YORK TIMES.

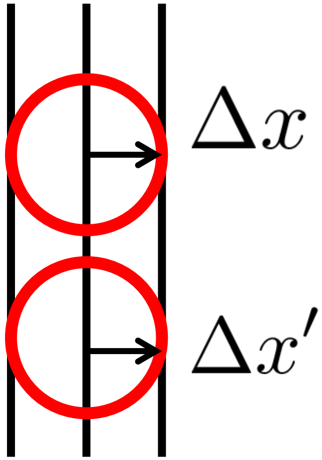
LONDON, Nov. 9.—Efforts made to put in words intelligible to the non-scientific public the Einstein theory of light proved by the eclipse expedition so far have not been very successful. The new theory was discussed at a recent meeting of the Royal Society and Royal Astronomical Society. Sir Joseph Thomson, President of the Royal Society, declares it is not possible to put Einstein's theory into really intelligible words, yet at the same time Thomson adds:

"The results of the eclipse expedition demonstrating that the rays of light from the stars are bent or deflected from their normal course by other aerial bodies acting upon them and consequently the inference that light has weight form a most important contribution to the laws of gravity given us since Newton laid down his principles."

Cassini



Ned Wright



$$\frac{\Delta x}{\Delta t} = c$$

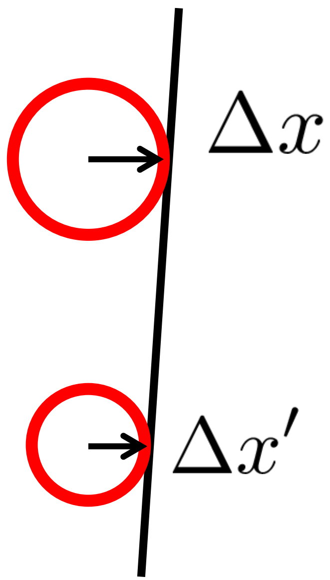
$$\Delta t' = \Delta t$$

No time warp!

$$\Delta x' = \Delta x$$

$$\frac{\Delta x'}{\Delta t'} = c$$

Ray doesn't bend!



$$\frac{\Delta x}{\Delta t} = c$$

$$\Delta t' < \Delta t$$

time warp!

$$\frac{\Delta x'}{\Delta t'} = c$$

But we still need speed c!
There is a space warp!

Ray bends! There is a double tilt!

"One had to be a Newton to notice that the moon is falling when everyone sees that it doesn’t fall.”

- Paul Valery

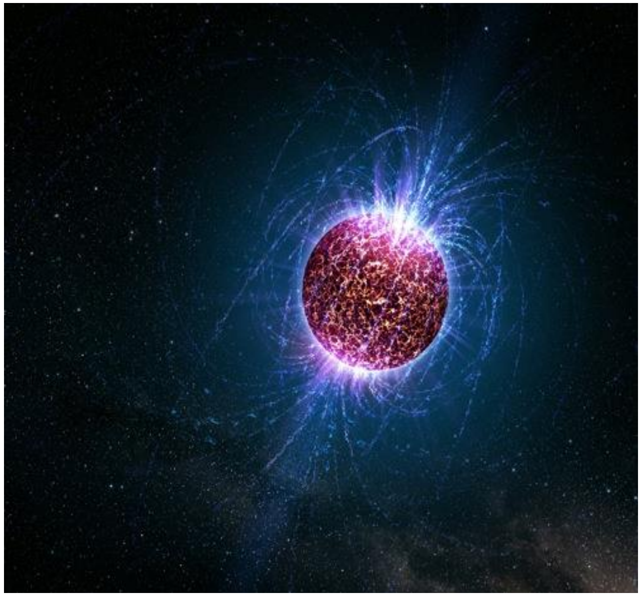
"In the spirit of the epigraph, we can say that it took the genius of Einstein to see that the Moon is moving in a straight line, when everyone sees that it doesn't.”

- W. Burke

What is $\theta_E = \frac{4GM}{c^2 r}$ for a neutron star?

$M_{neutron,*} = 2 \times 10^{30}\text{kg}$

$r_{neutron,*} = 13\text{ km}$



What is $\theta_E = \frac{4GM}{c^2 r}$ for a neutron star?

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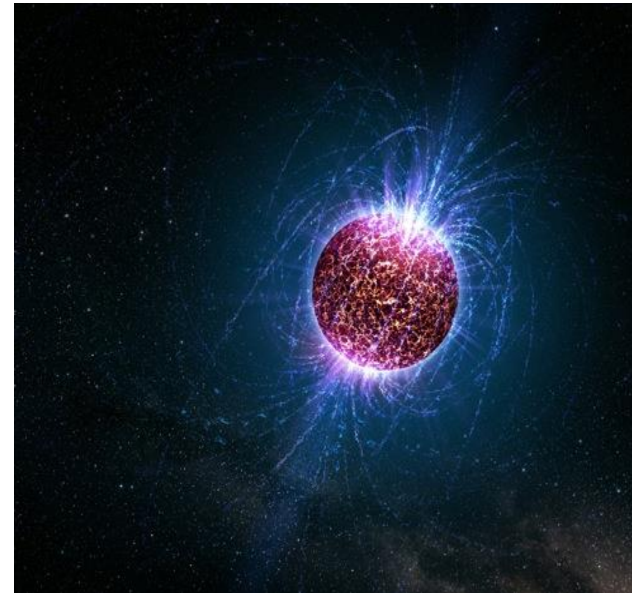
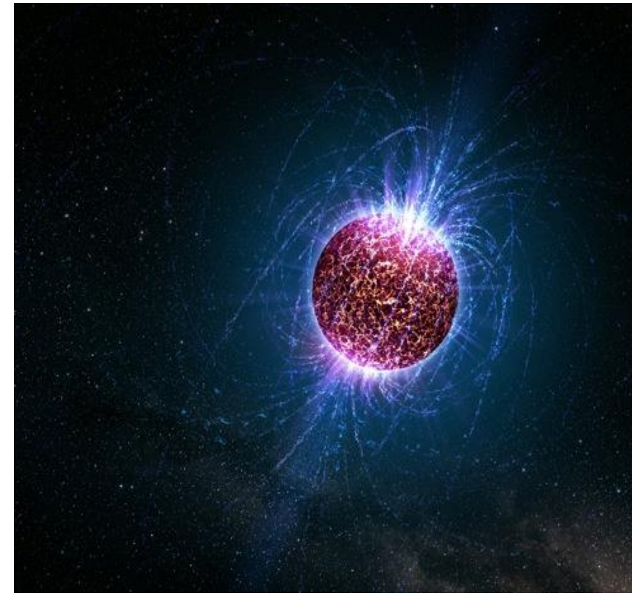


$$\theta_E = \frac{4GM}{c^2 r} = 0.46 \text{ rad} = 26^\circ$$

What is the acceleration due to gravity?

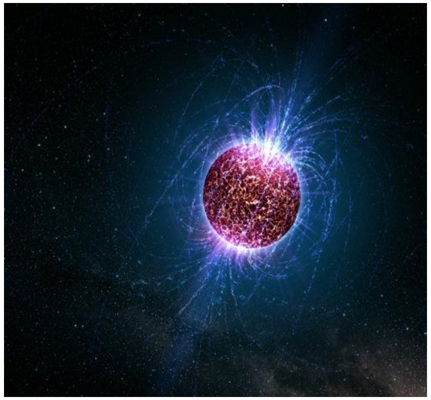
$M_{neutron,*} = 2 \times 10^{30}$kg

$r_{neutron,*} = 13$ km



$$a = \frac{GM_{neutron}}{r^2} = 8 \times 10^{11} \text{ m/s}^2$$

If we shine a light 1 m off the surface, how far would light travel before it is bent down so much it hits the surface?



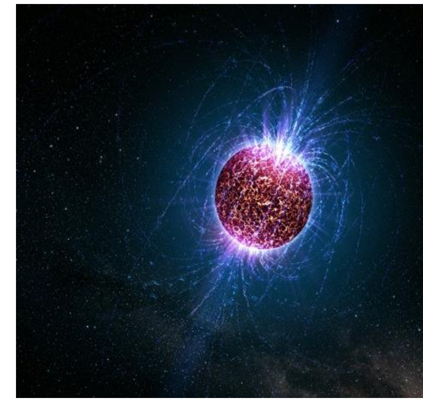
$$a = \frac{GM_{neutron}}{r^2} = 8 \times 10^{11}\ \mathrm{m/s}^2$$

$$v_i t + \frac{1}{2} a t^2$$ **Newtonian**

$$h \approx 2 \times \left(\frac{1}{2} a t^2\right) \approx a \left(\frac{d}{c}\right)^2$$

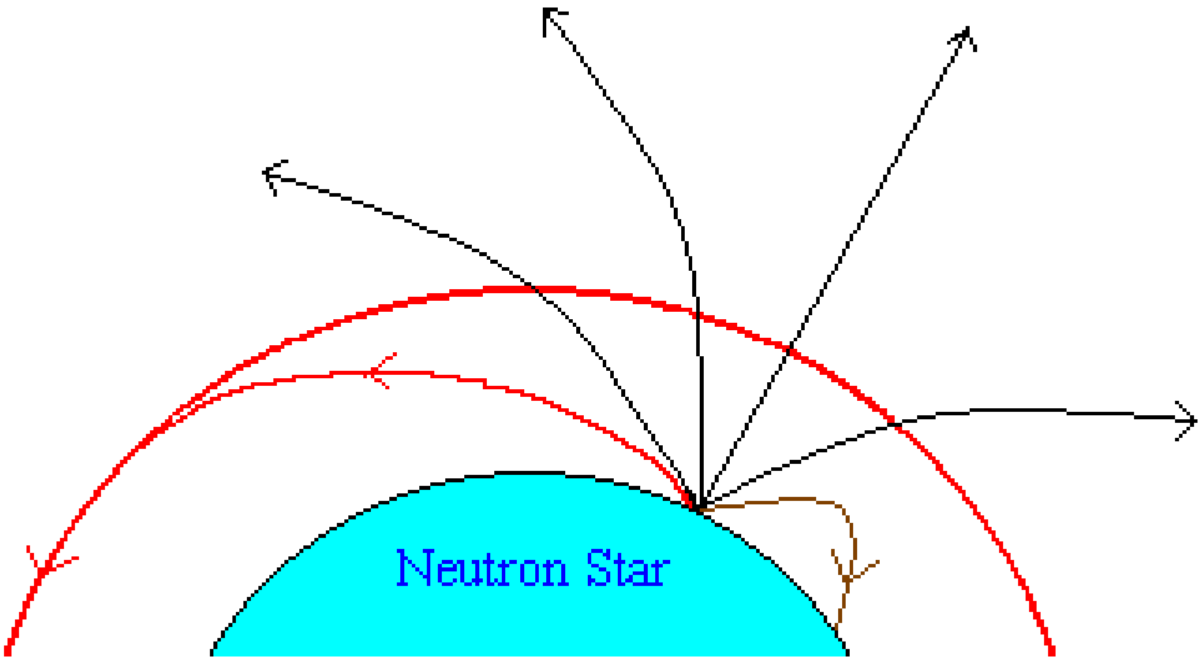
Double the Newtonian Effect

If we shine a light 1 m off the surface, how far would light travel before it is bent down so much it hits the surface?



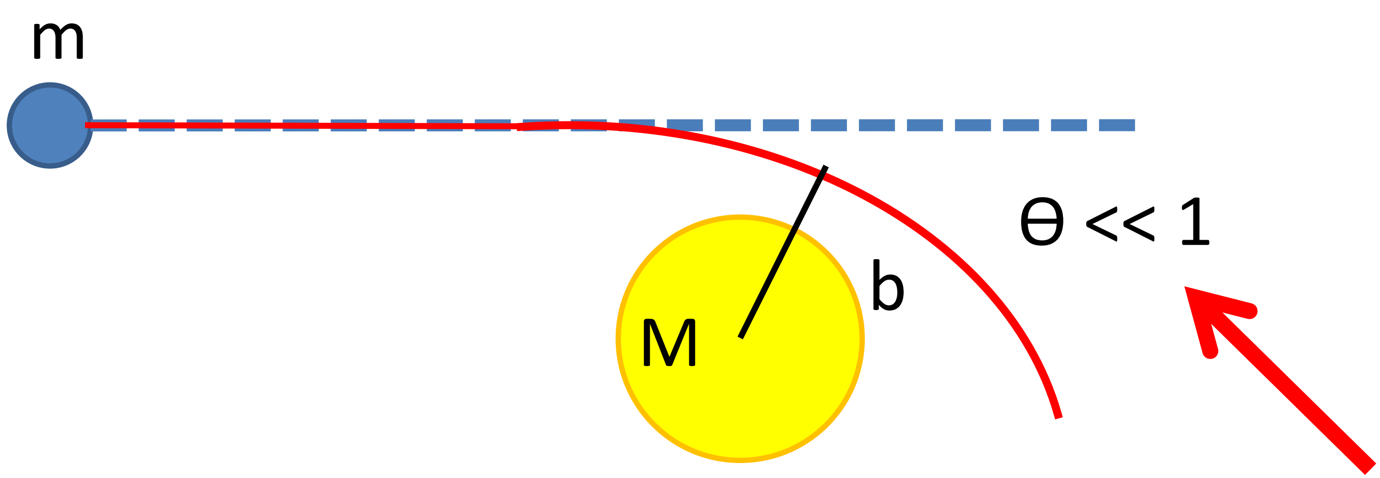
$$d = \sqrt{\frac{h}{a}}c$$

You would be able to see light bending!



Black Holes

What prediction does Einstein's formula make when the impact parameter approaches R_s ?

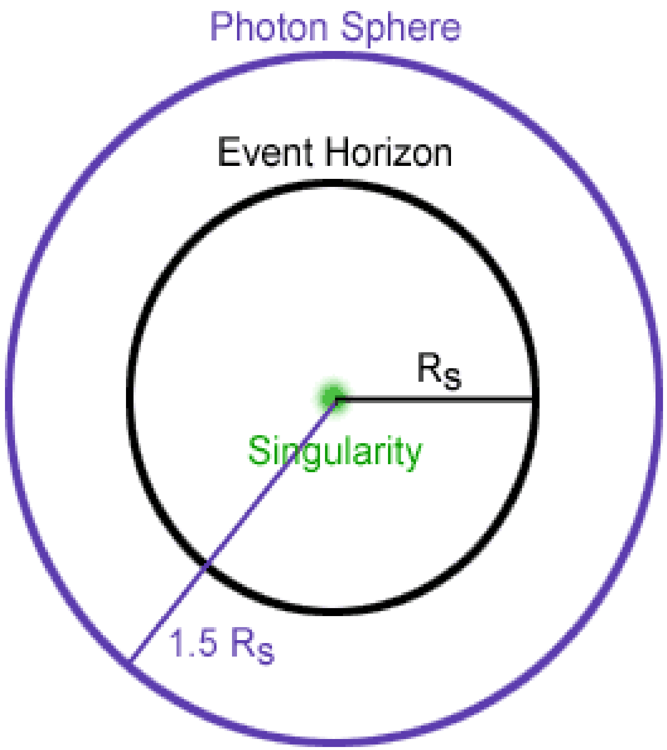


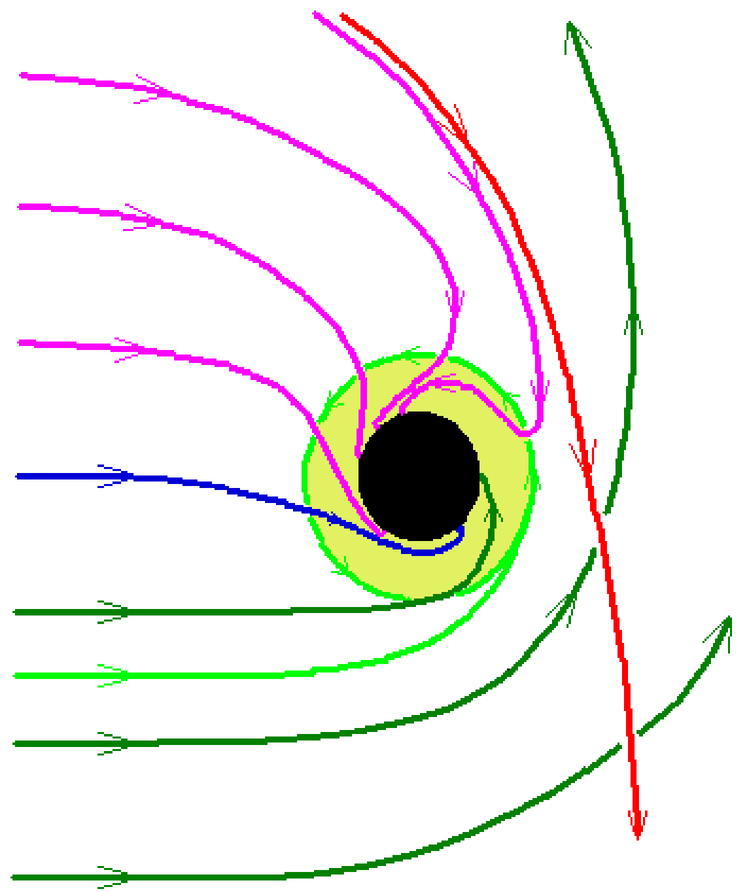
Should we trust this prediction?

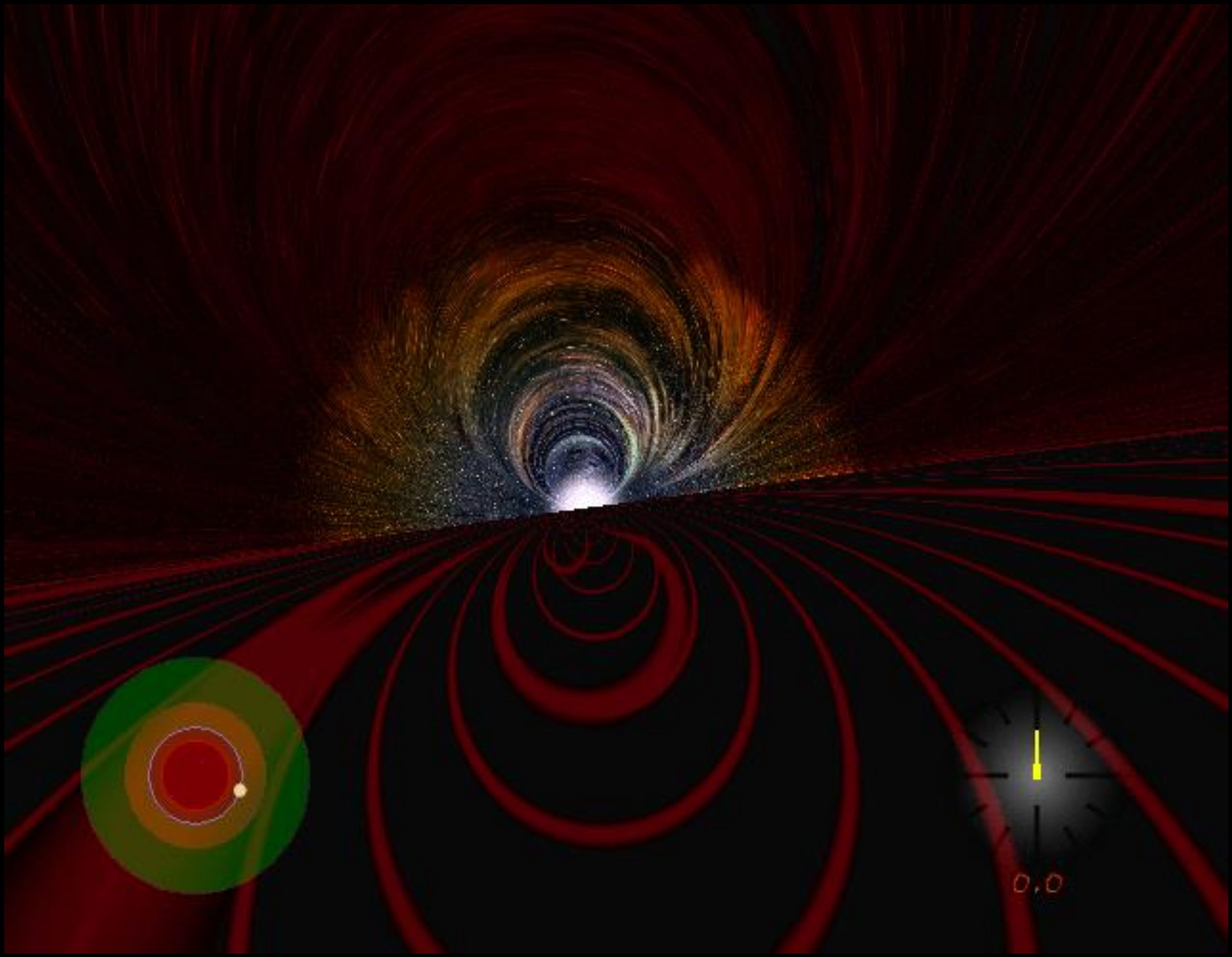
$$\theta_E = \frac{4GM}{c^2 b}$$

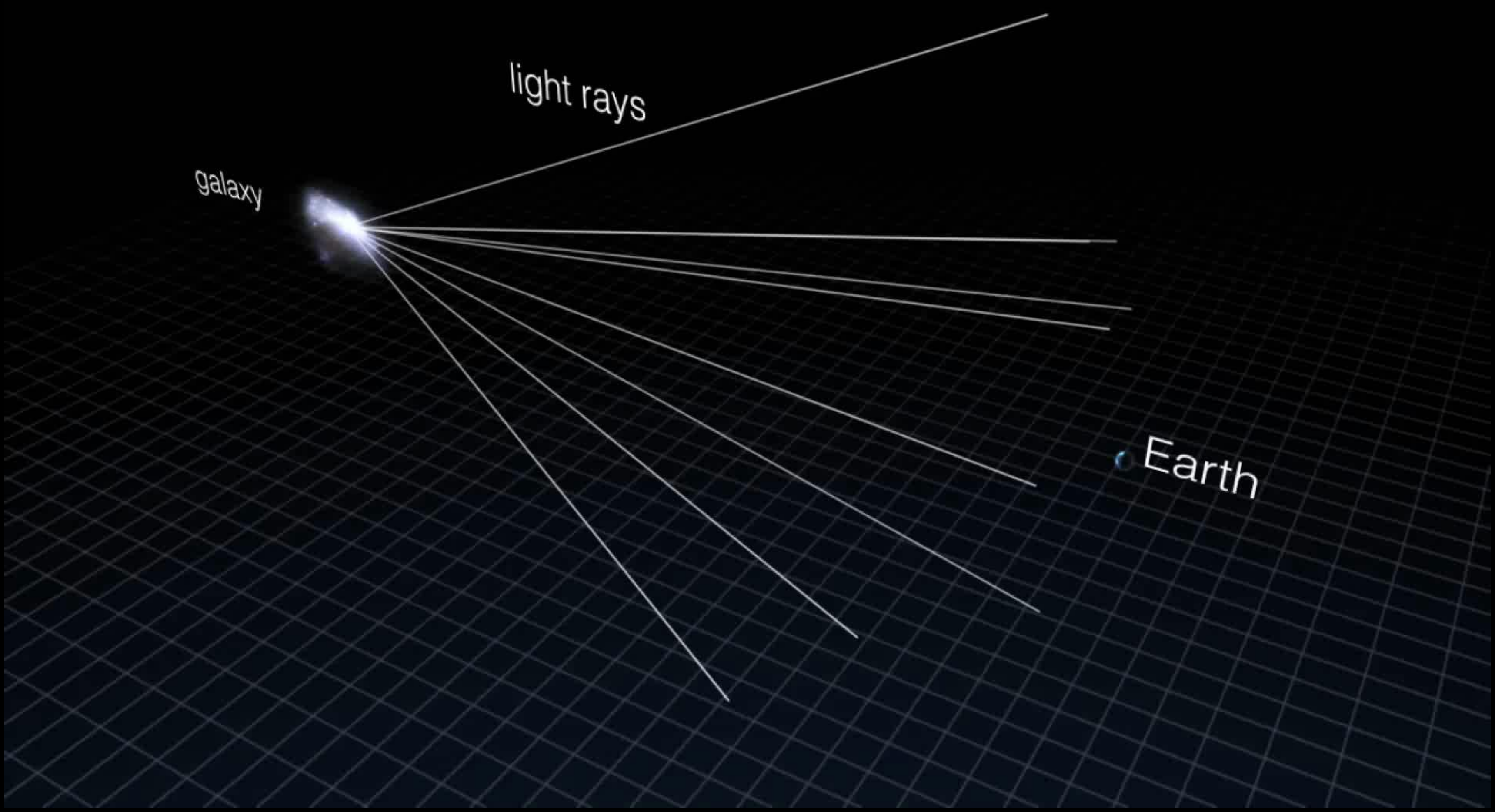
Black Holes

A full GR calculation reveals that for b= 1.5 R_s, a ray of light will be so bent it will orbit the black hole.

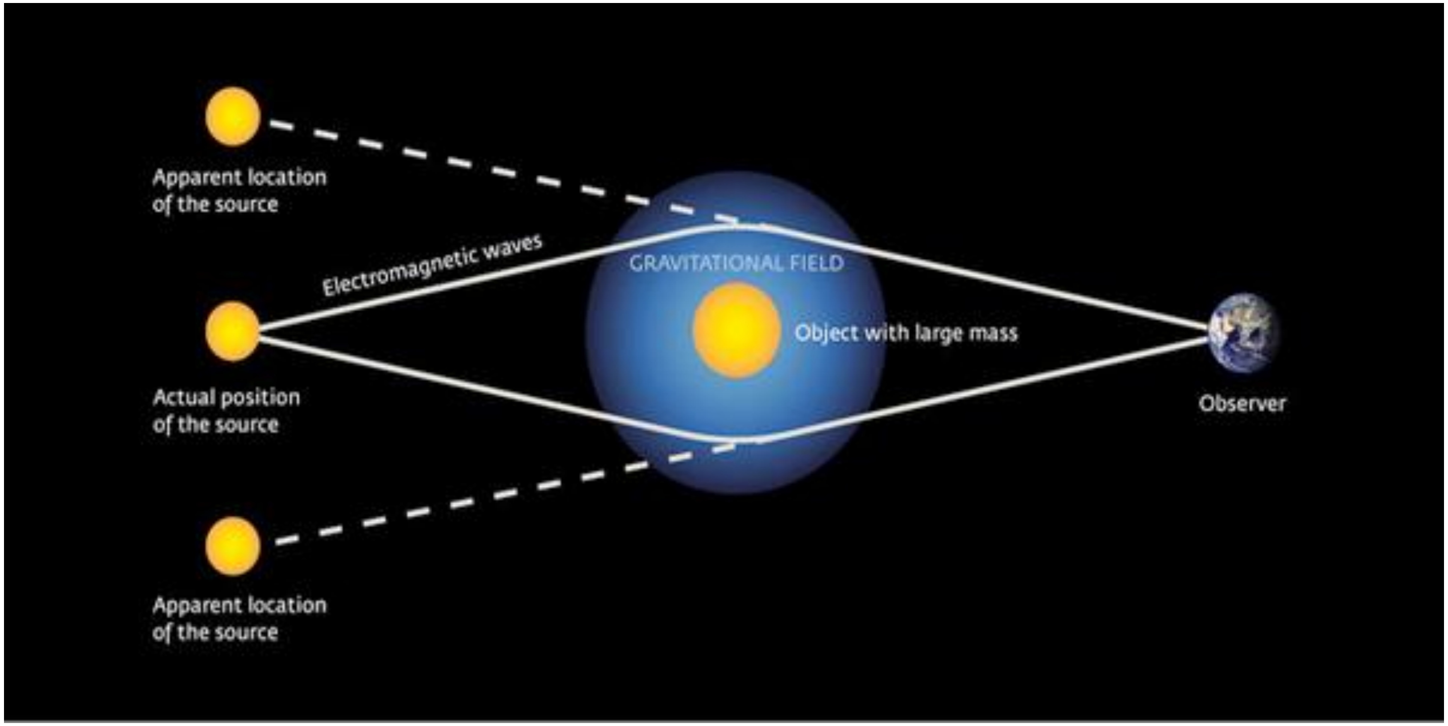





0.0

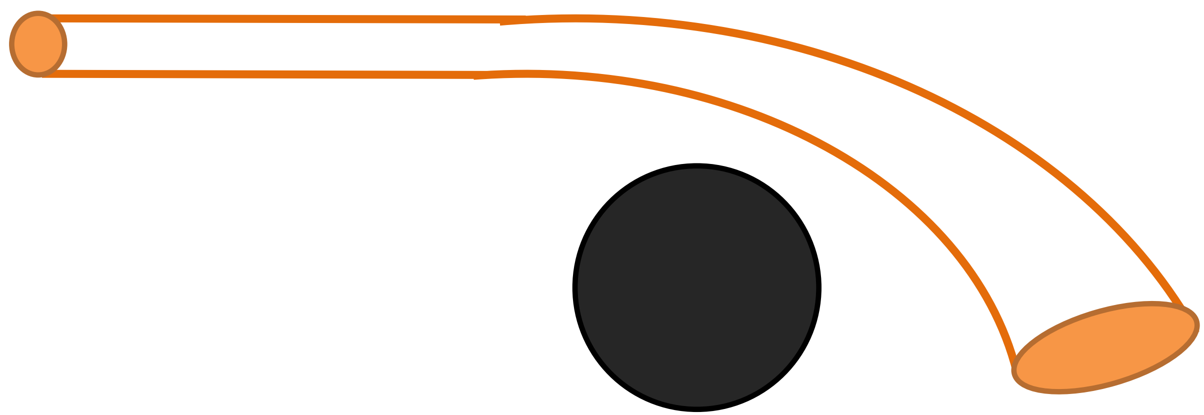

light rays
galaxy
Earth

Gravitational Lensing

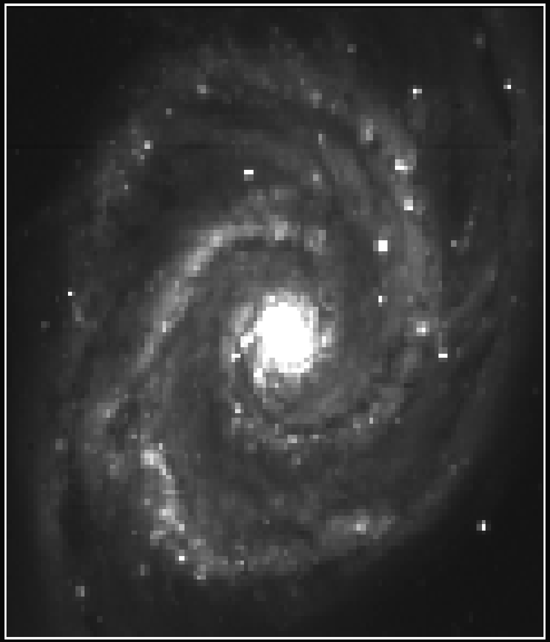


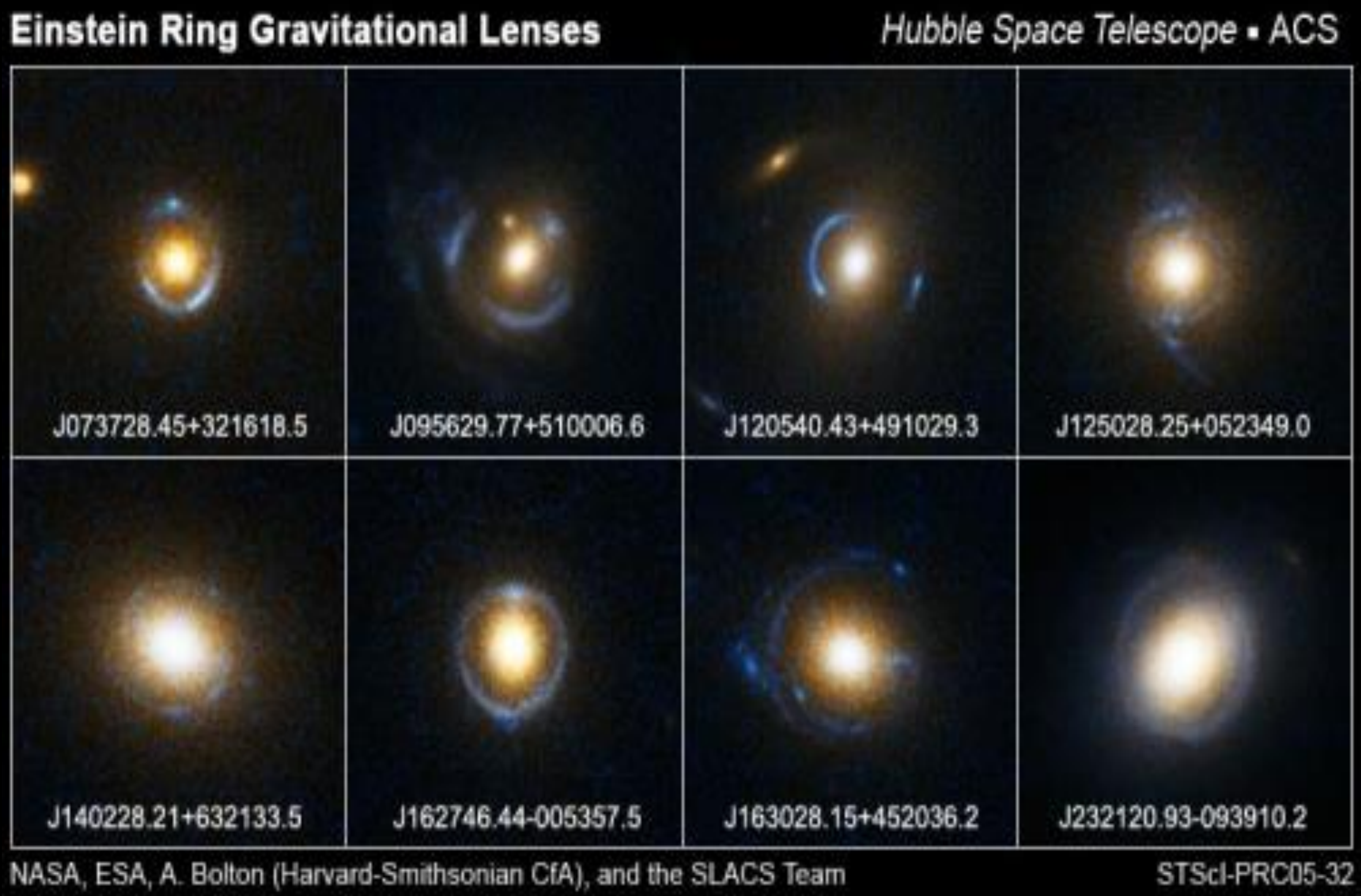
Gravitational Lensing

An extended object like a galaxy is stretched!
The surface brightness stays the same but area increases so the total luminosity becomes brighter.



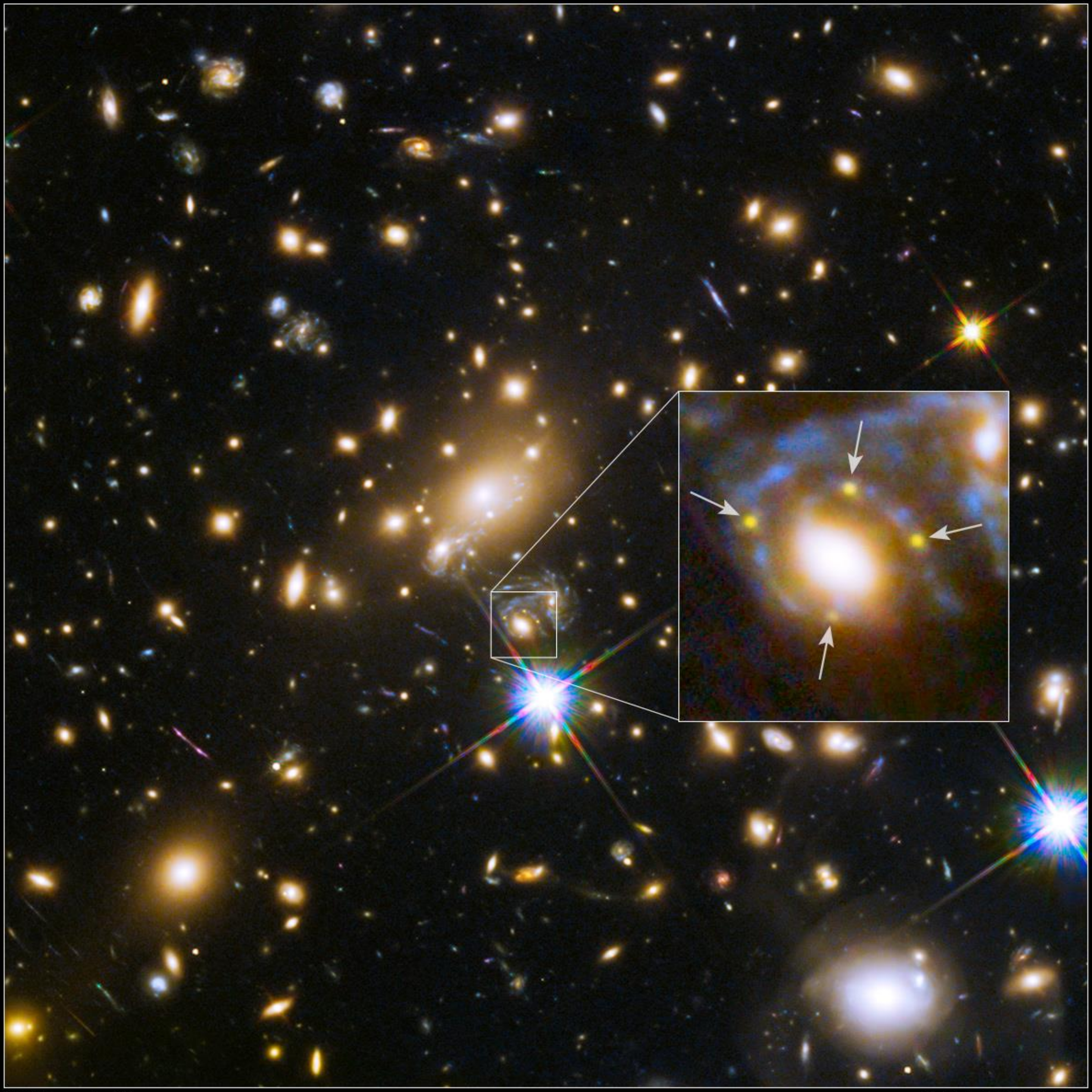
Lensing Galaxy




Einstein Ring Gravitational Lenses
Hubble Space Telescope ▪ ACS
J073728.45+321618.5
J095629.77+510006.6
J120540.43+491029.3
J125028.25+052349.0
J140228.21+632133.5
J162746.44-005357.5
J163028.15+452036.2
J232120.93-093910.2
NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team
STScI-PRC05-32

Supernova Refsdal
Galaxy Cluster MACS J1149.6+2223

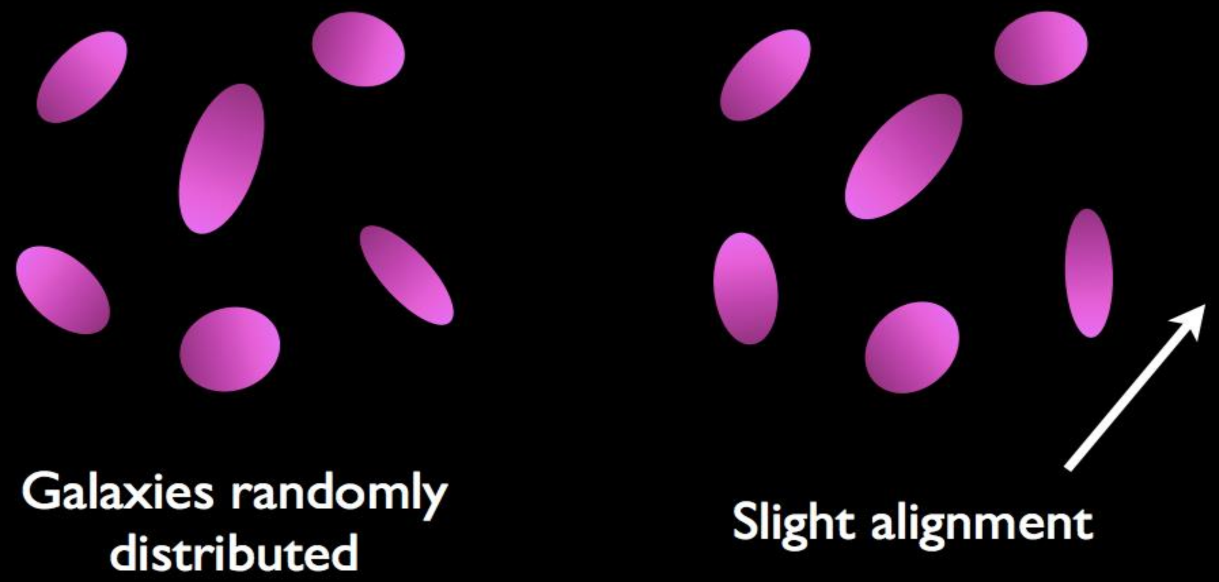
Hubble Space Telescope
ACS/WFC ▪ WFC3/IR

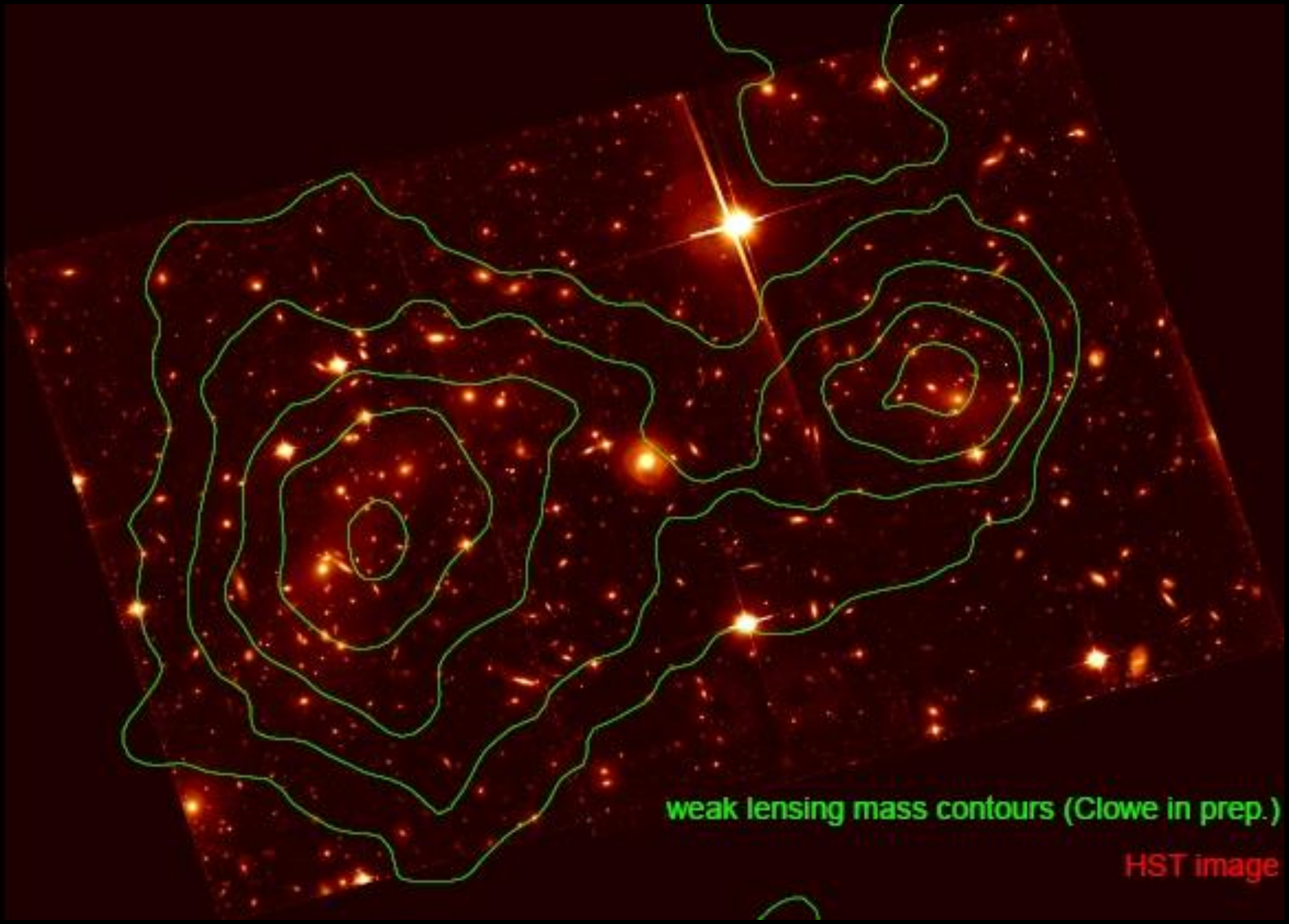


NASA and ESA

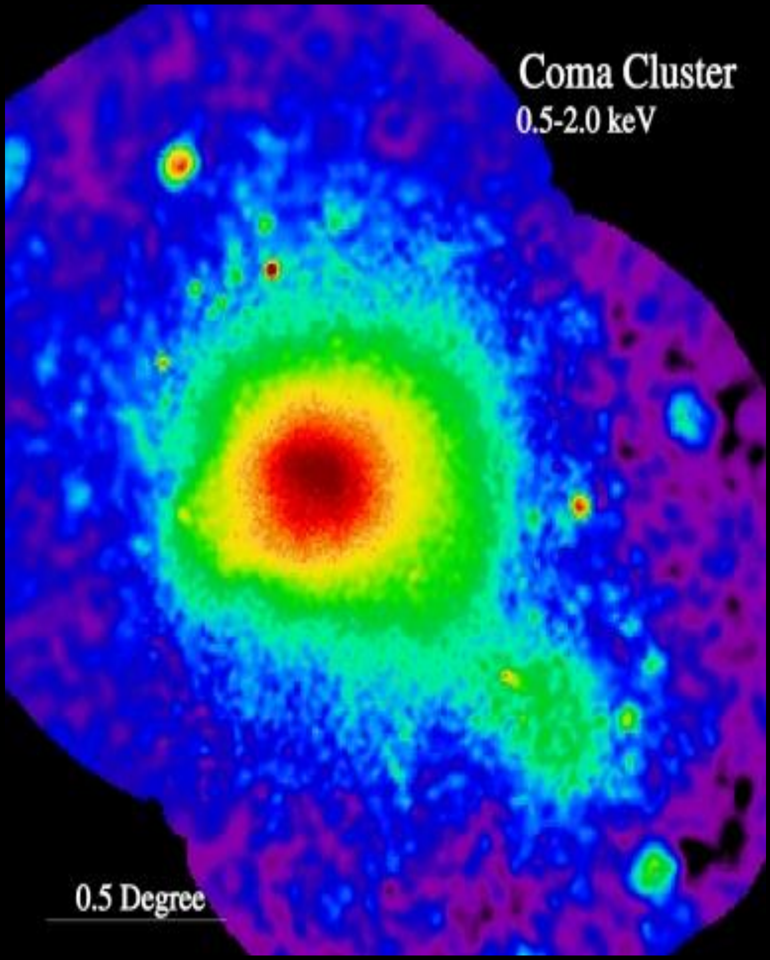
STScI-PRC15-08a

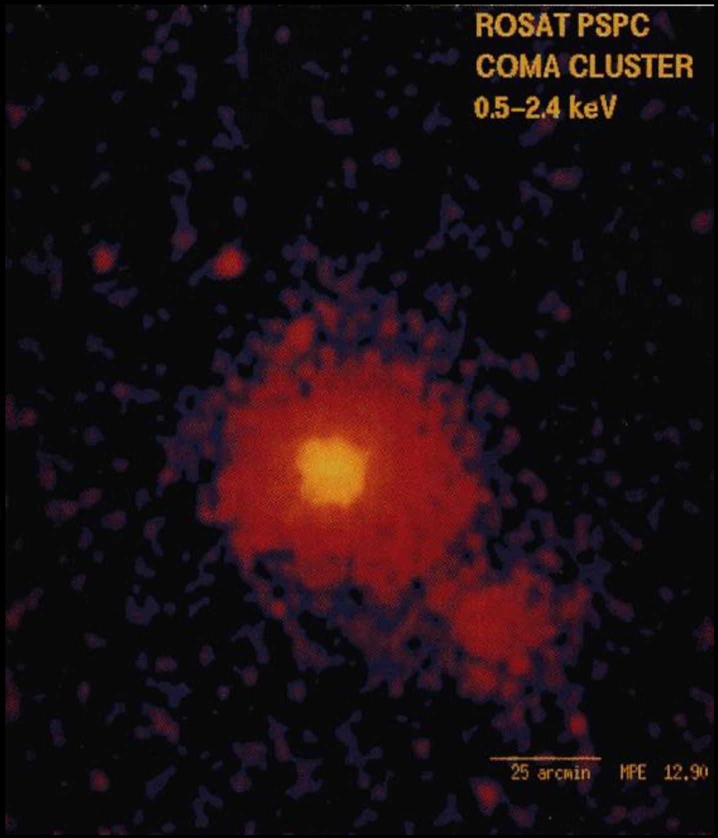
Weak Lensing



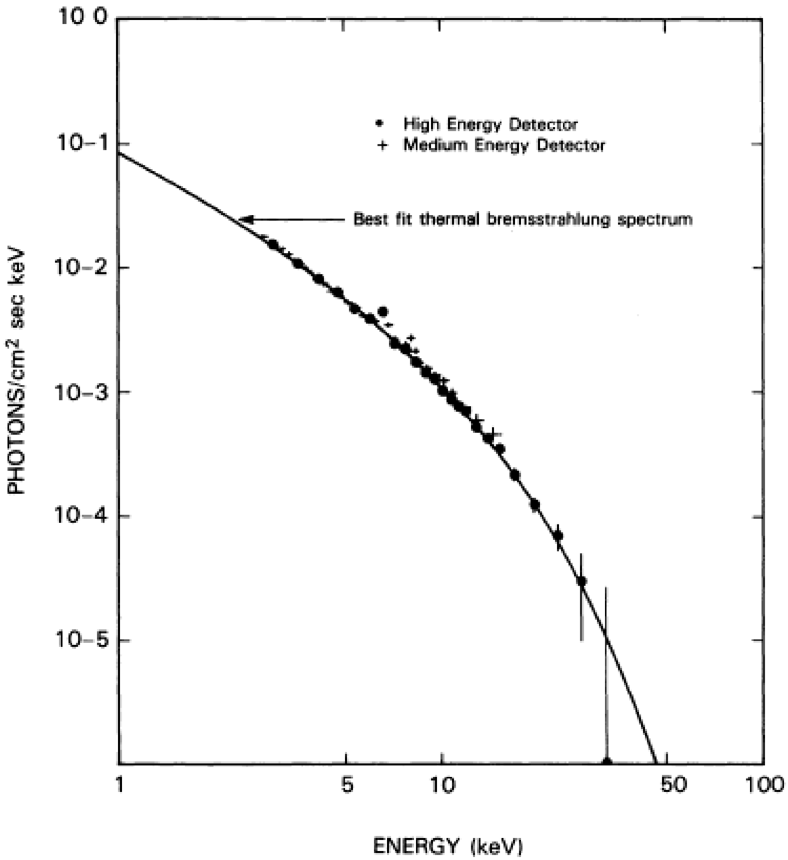

weak lensing mass contours (Clowe in prep.)
HST image

Hot Intracluster Gas

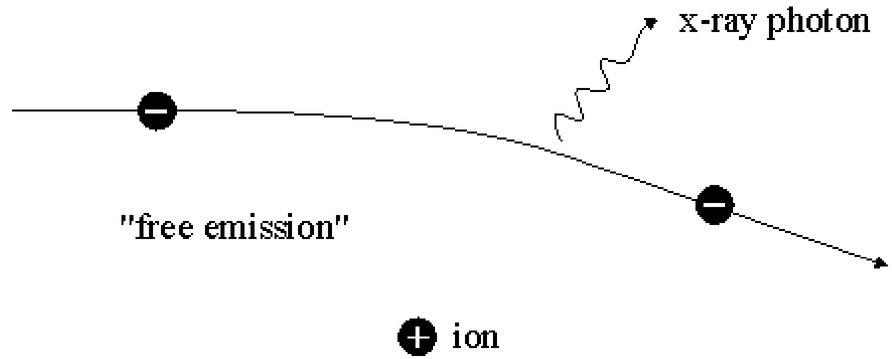




Hot Ionized – 10^7-10^8 K



Henriksen and Mushotzky (1986) ApJ 302, 287



X-rays produce by Thermal Bremsstrahlung Radiation

Mass is ~ 10^{14} M_{sun}

More intracluster gas than luminous matter!

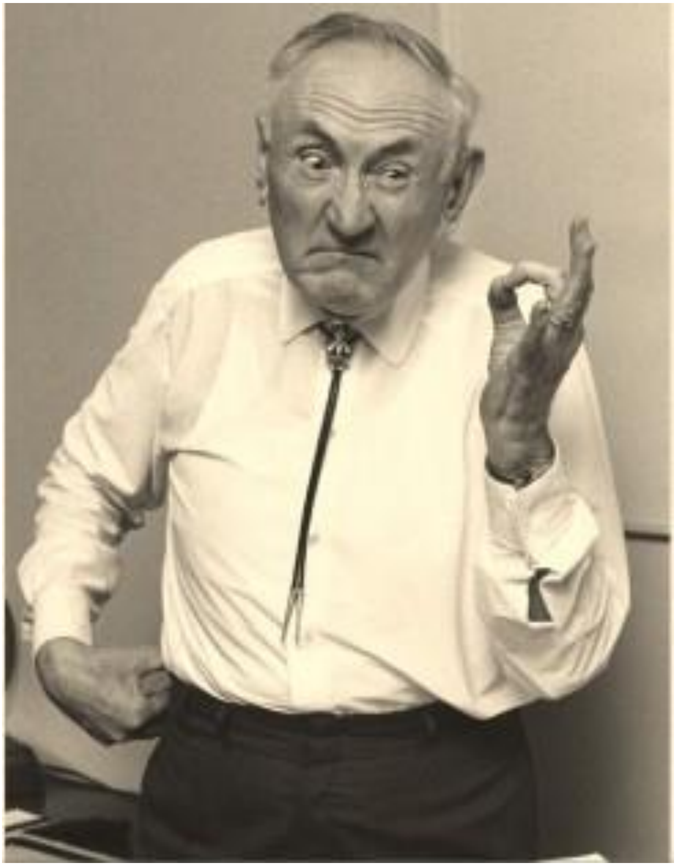
Gas Mass

$$M \approx 10^{14}\ \mathrm{M}_{\odot}$$

Luminous Mass

$$M = 10^{13}\ \mathrm{L}_{\odot}(3\ \mathrm{M}_{\odot}/\ \mathrm{L}_{\odot}) = 3 \times 10^{13}\ \mathrm{M}_{\odot}$$

Zwicky & Dark Matter



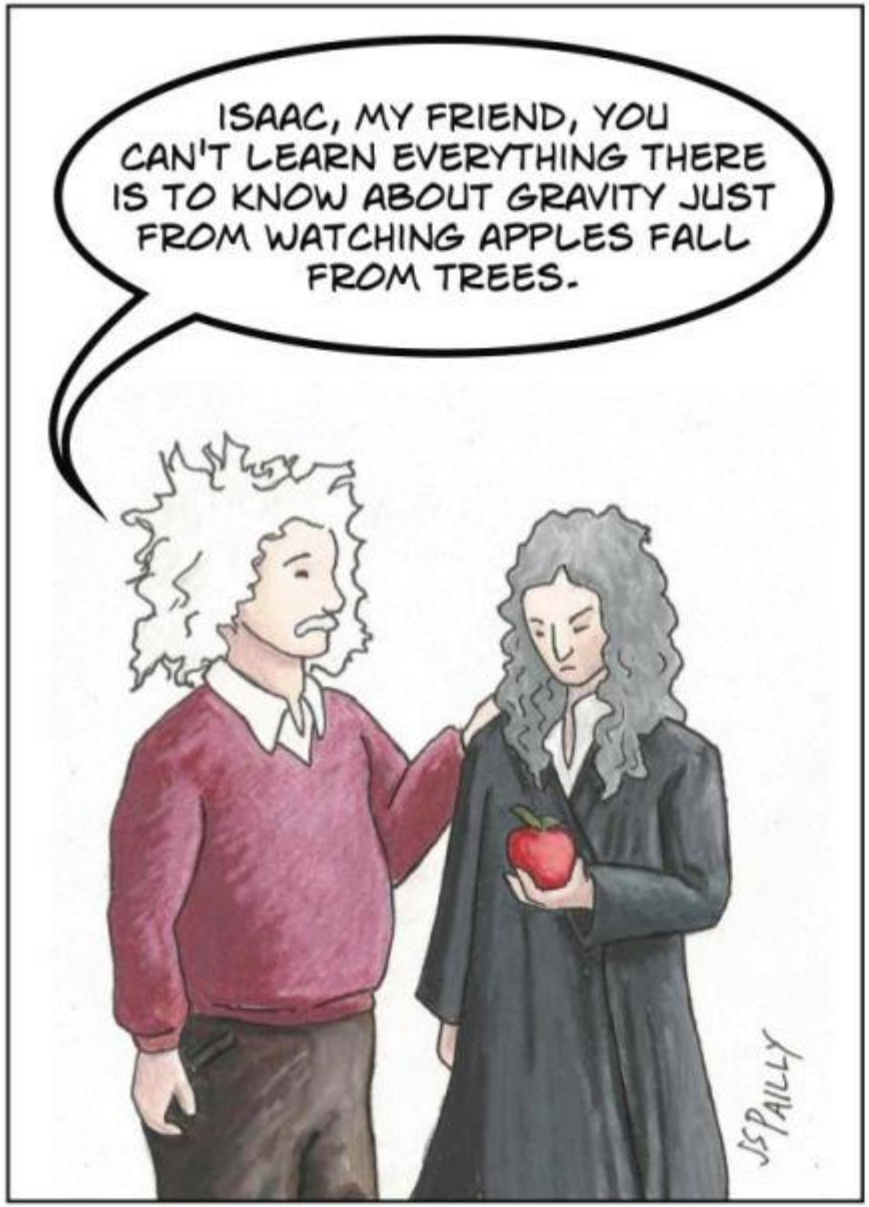
First to use the label “dark matter”

Gravity = Warping of Spacetime

- **Time warping** explains gravity

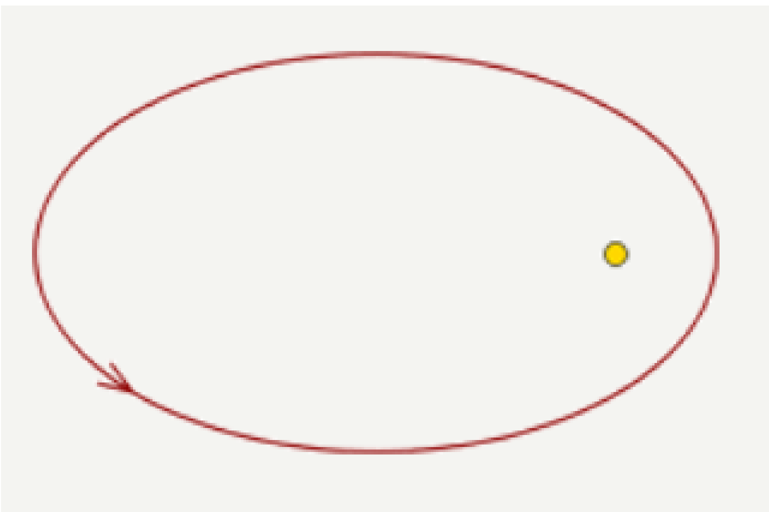
- **Space warping** explains gravity

Newton's Gravity = Einstein's with time warp only



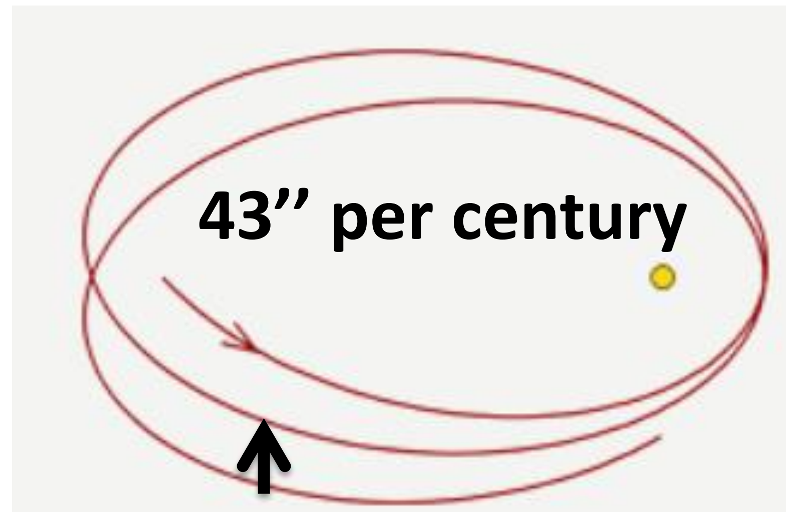
Newton's Gravity = Einstein's with time warp only

Newton



Mercury has a closed elliptical orbit.

Einstein



Including space warp leads to a different prediction – rosette!

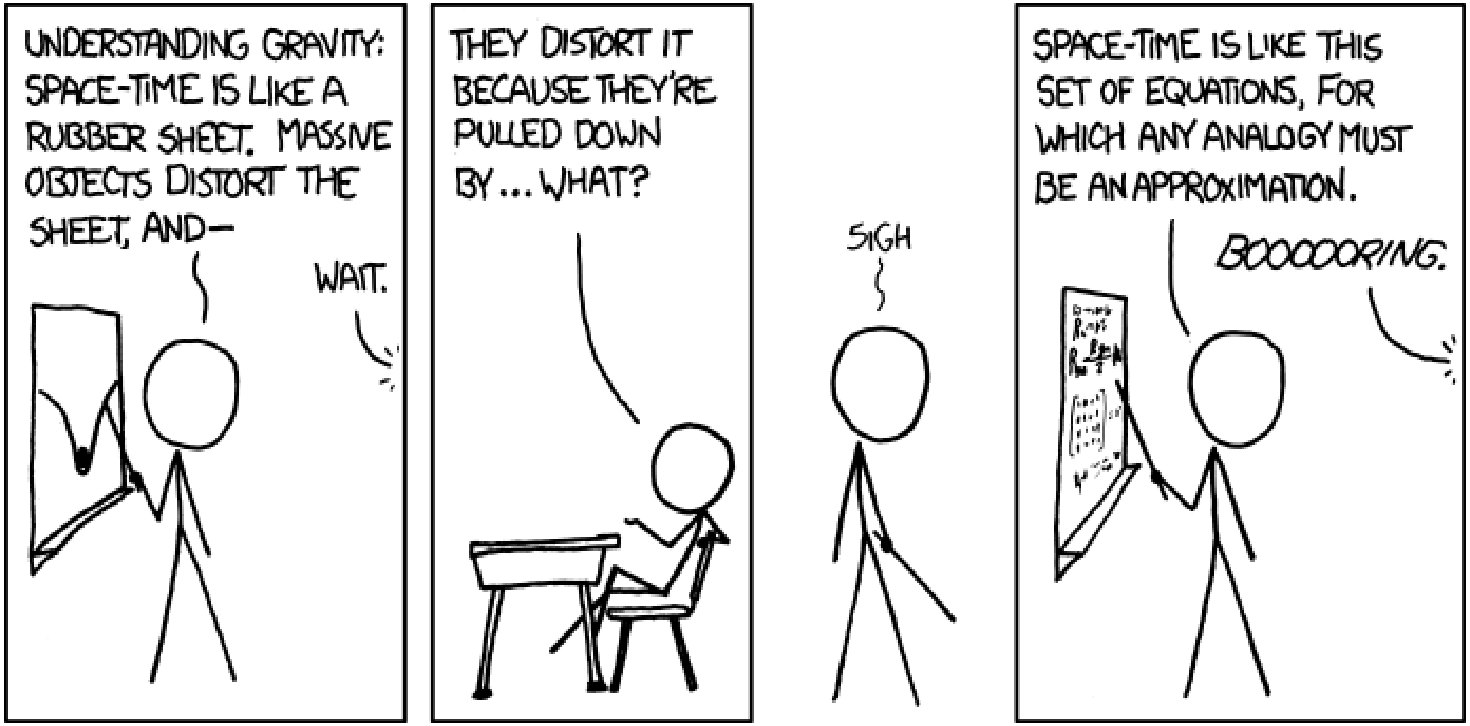
GR Calculation

$$\theta_{\text{per orbit}}$$

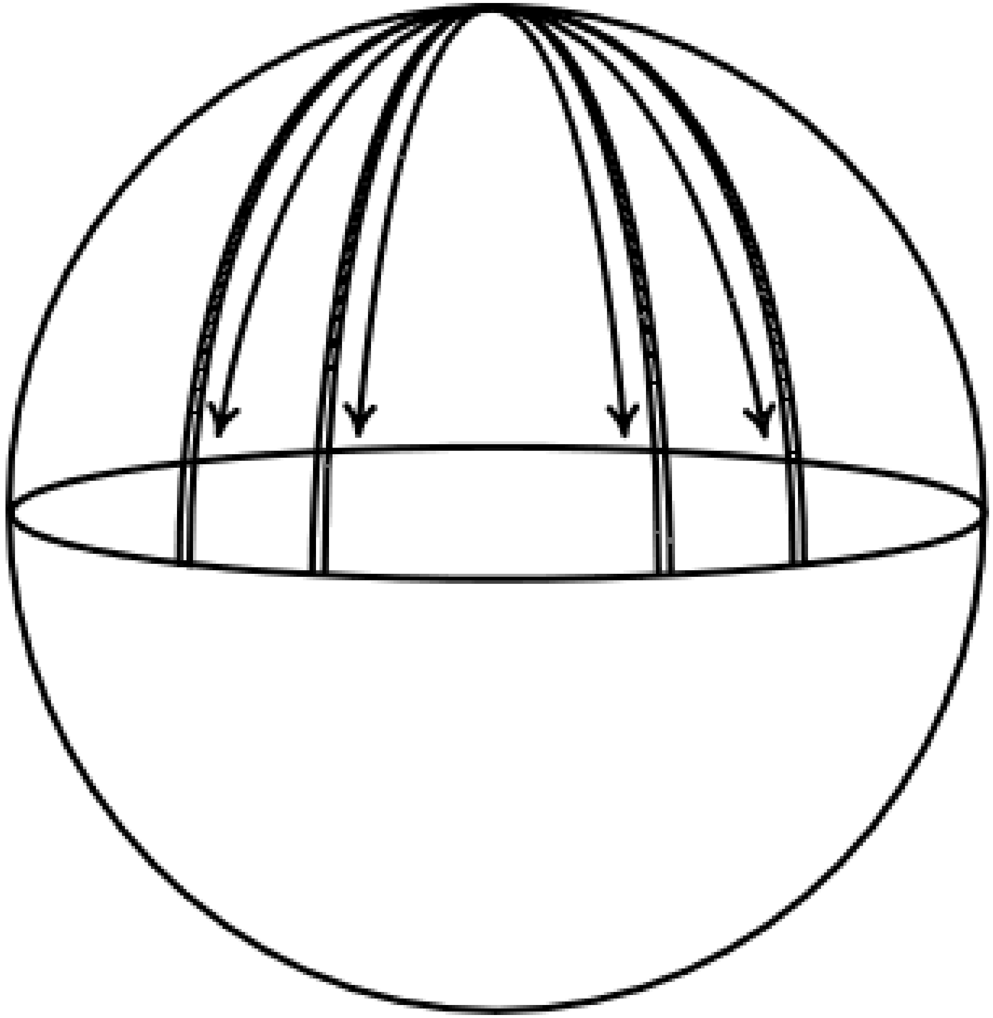
$$P_{\text{Mercury}} = 88 \text{ days} \Rrightarrow 415 \text{ orbits per century}$$

$$\theta_{\text{per century}} = 415 \times \theta_{\text{per orbit}}$$

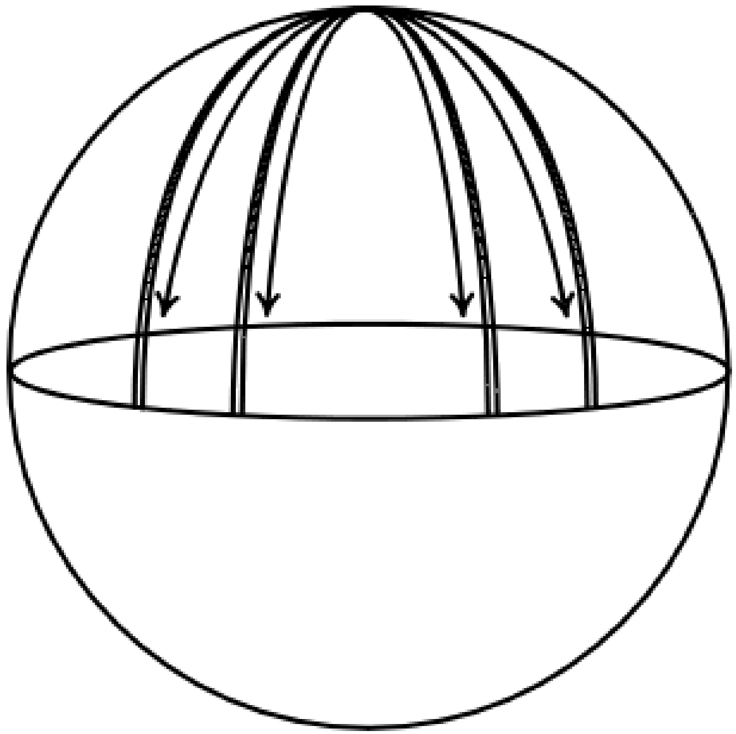
How can we describe curvature?

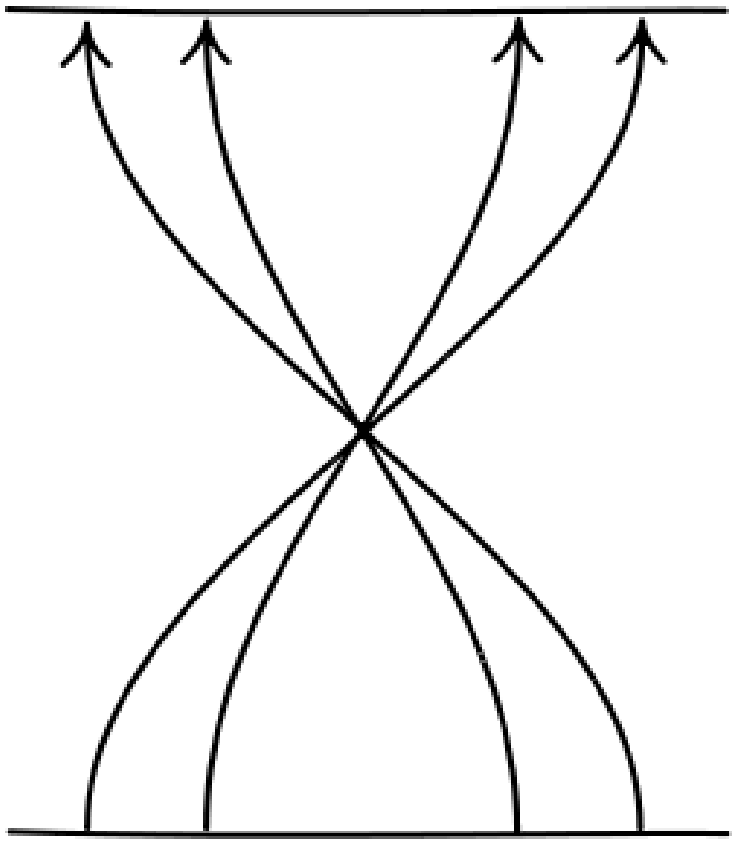


Curvature of Space

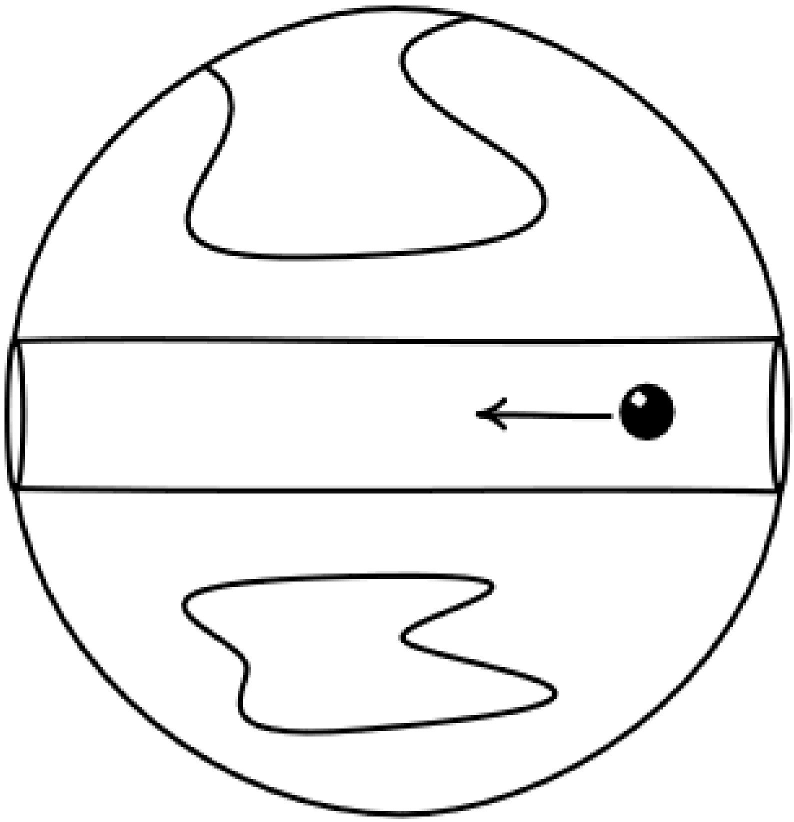


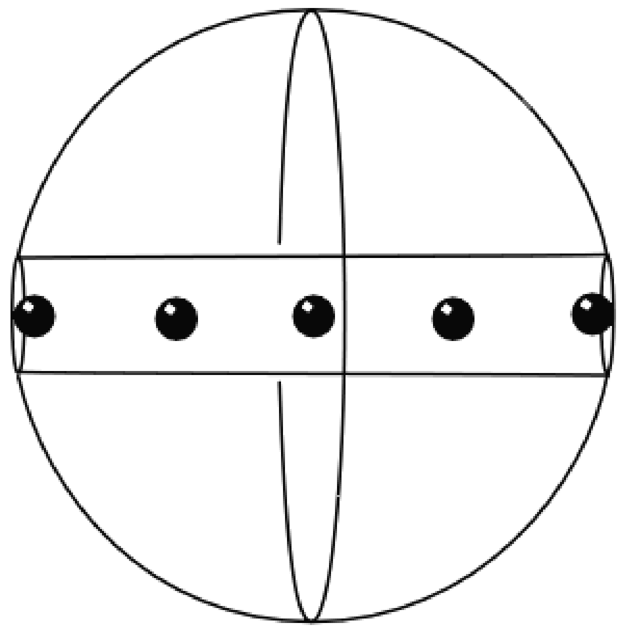
Curvature of Space



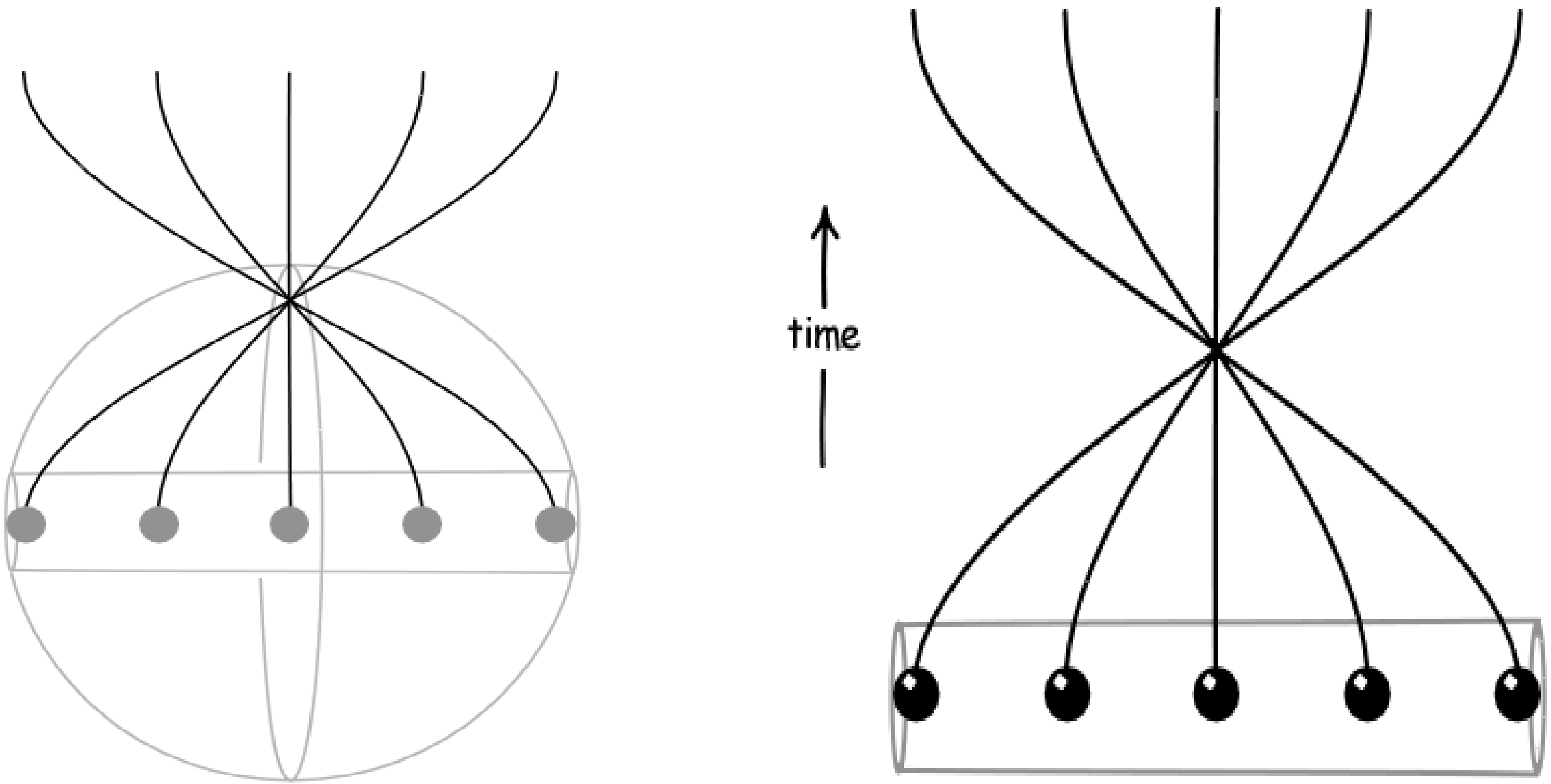


What about Spacetime?





Spacetime Curvature



$$\text{Curvature in Spacetime Sheet in Earth} \propto \text{ Matter Density of Earth}$$

Key Concepts

Space and space-time are not rigid.

Matter and energy tell spacetime how to curve.

Objects travel along the straightest possible lines in curved spacetime.

Metrics

- Euclidean Space

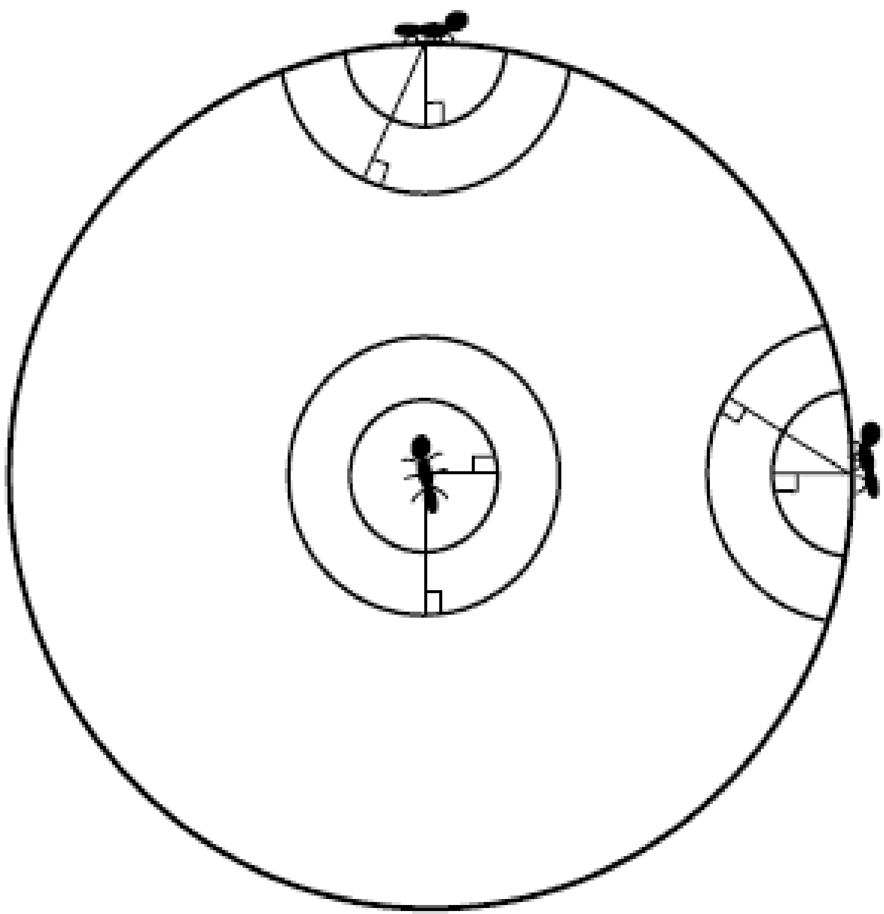
$$(dr)^2 = (dx)^2 + (dy)^2 + (dz)^2$$

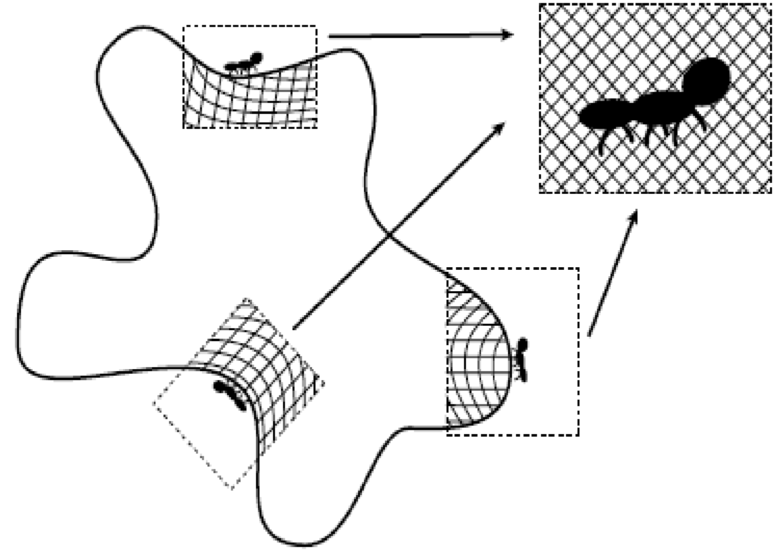
- Minkowski Metric

$$(ds)^2 = (cdt)^2 - (dr)^2$$

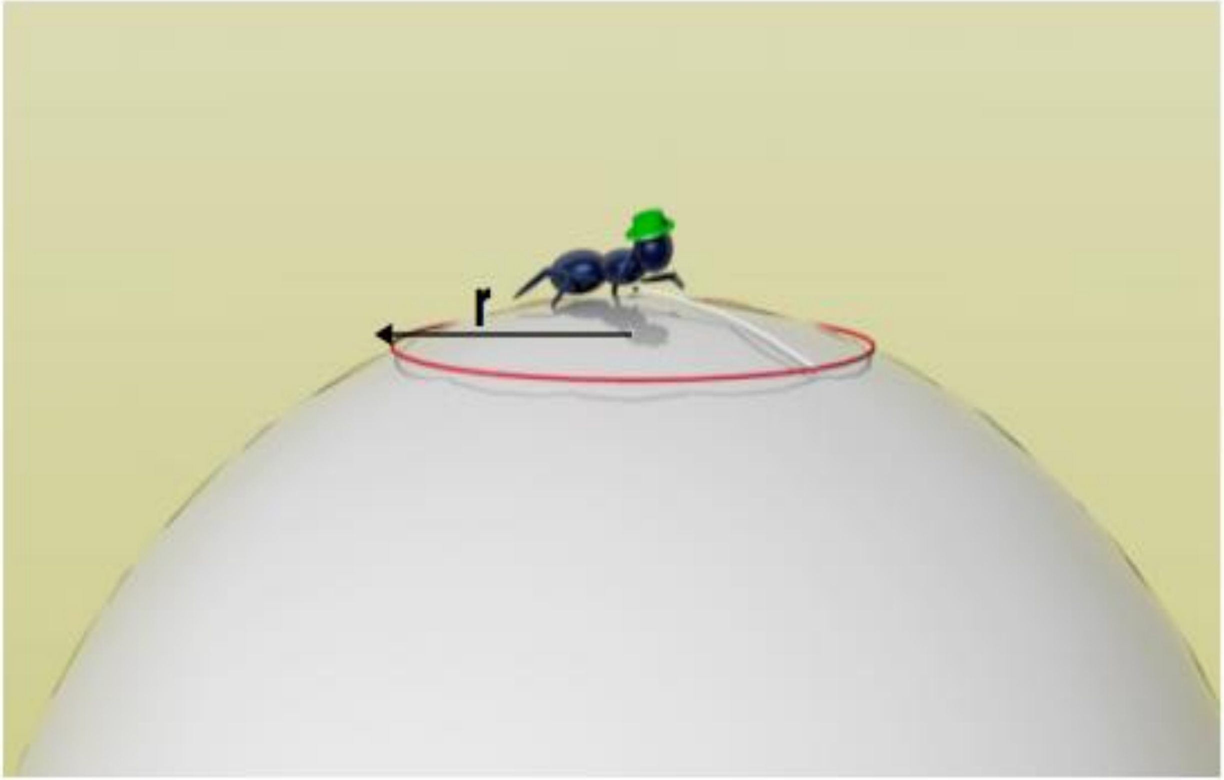
A metric defines the separation of two nearby points (or events, if we include time).

Curvature – taught by ants



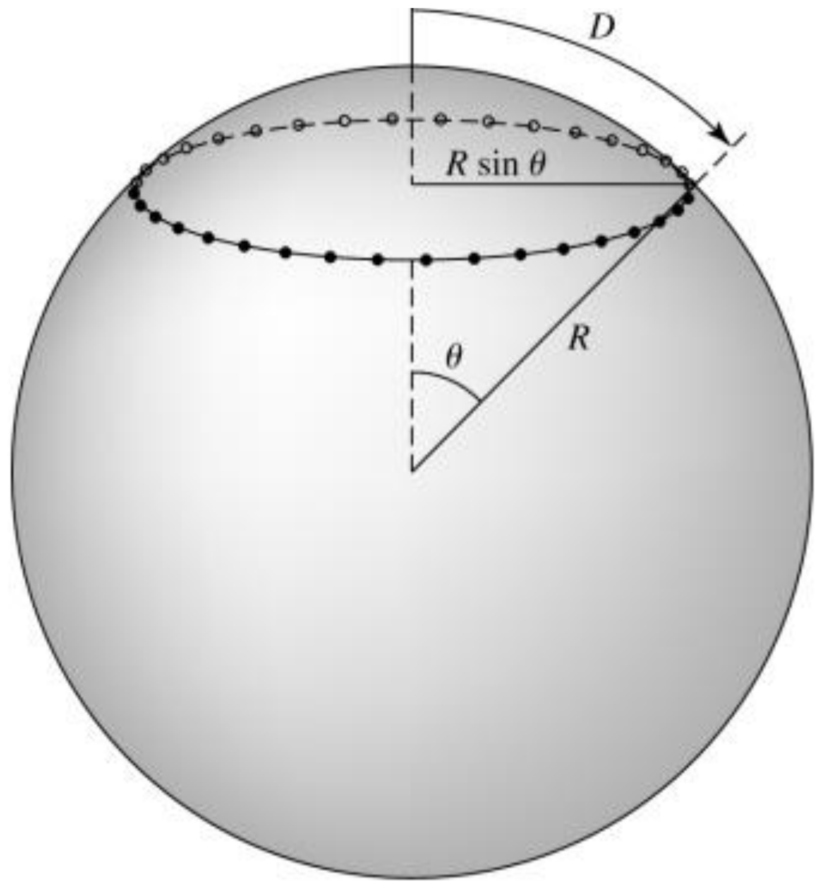


Ant Measurements



$$C_{\mathrm{walk}} = 2\pi R \sin\theta$$

$$C_{\mathrm{rope}} = 2\pi D = 2\pi R\theta$$



Curvature

Curvature, K is defined as:

$$K = 6\pi \frac{C_{rope} - C_{walk}}{C_{rope} A_{rope}} = \frac{1}{R^2} + O^2 + \ldots$$

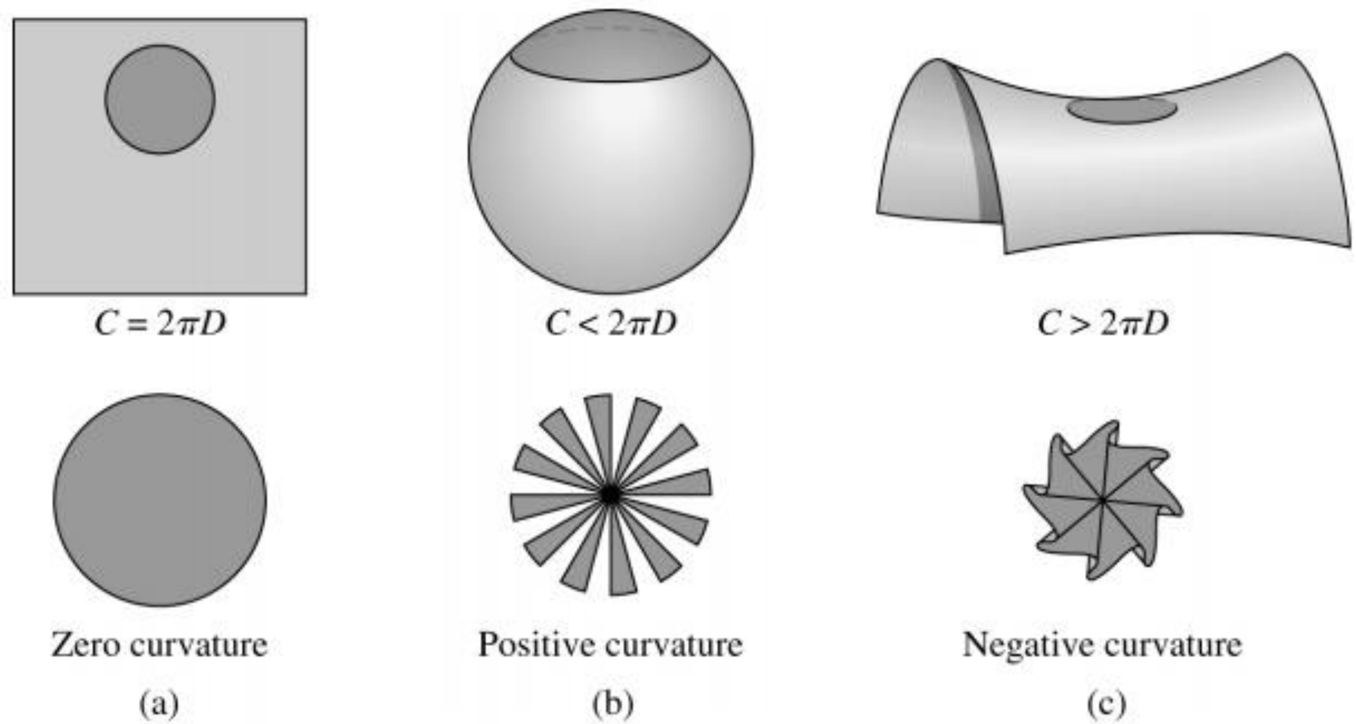
Radius of sphere

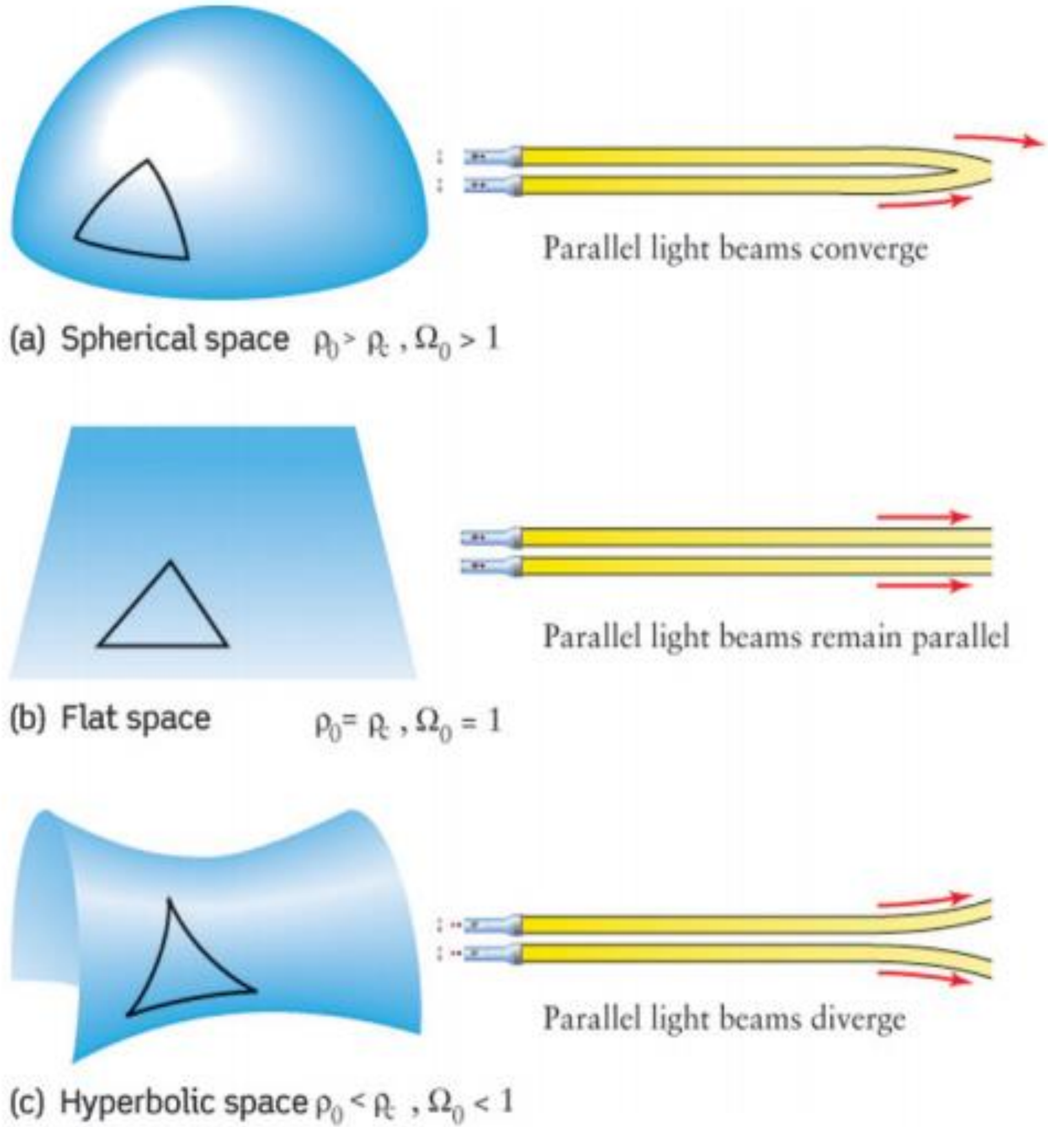
The curvature *K* proportional to R^{-2}, ie large sphere appears locally flat.

k=0: flat

k<0: negative curvature

k>0: positive curvature




Parallel light beams converge
(a) Spherical space $\rho_0 > \rho_c$, $\Omega_0 > 1$
Parallel light beams remain parallel
(b) Flat space $\rho_0 = \rho_c$, $\Omega_0 = 1$
Parallel light beams diverge
(c) Hyperbolic space $\rho_0 < \rho_c$, $\Omega_0 < 1$

Metrics

- Euclidean Space

$$(dr)^2 = (dx)^2 + (dy)^2 + (dz)^2$$

- Minkowski Metric

$$(ds)^2 = (cdt)^2 - (dr)^2$$

A metric defines the separation of two nearby points (or events, if we include time).

Robertson-Walker Metric

$$\boxed{(ds)^2 = (cdt)^2 - R^2(t)\left[\left(\frac{d\bar{\omega}}{\sqrt{1-K\bar{\omega}^2}}\right)^2 + (\bar{\omega}d\theta)^2 + (\bar{\omega}\sin\theta d\phi)^2\right]}$$

- ds is just the interval between two spacetime events
- K is the present day curvature
- R(t) is the expansion rate (or scale factor)
- w is the comoving radial coordinate

Einstein's Field Equations

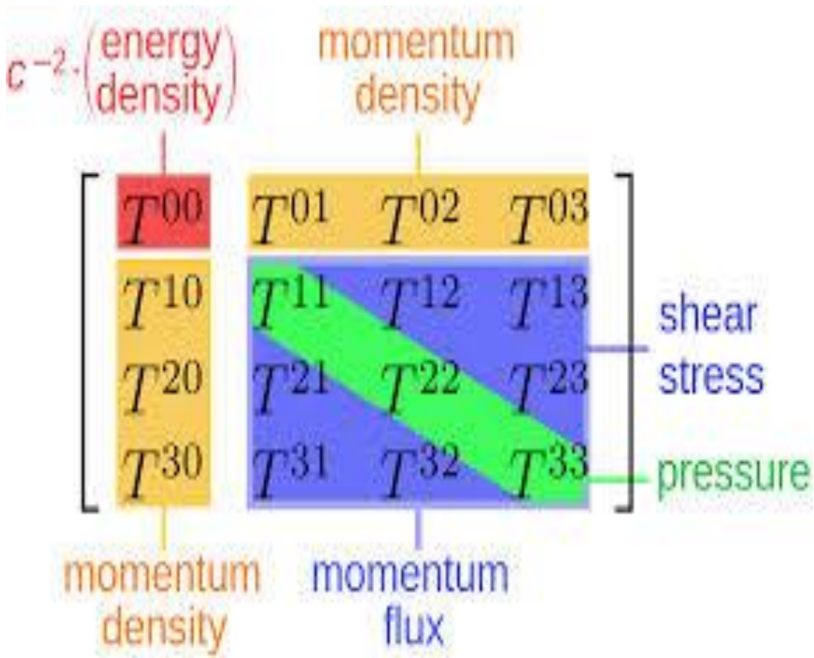
$$G_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu}$$

Spacetime Geometry **Mass-energy & Momentum**

- Solving this equation for spacetimes with matter inside yields a curved spacetime.

- A set of 10 equations which say which Universes are "allowed" according to Einstein's theory.
- "allowed" = Spacetimes whose curvature is correctly related to matter density

Stress-Energy Tensor



Energy, momentum, pressure and shear all contribute to the twisting and warping of spacetime!

Minkowski Metric in Cartesian 4D Spacetime

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}_{\mu\nu}$$

GR + RW Metric = Friedmann

$$H^2 = \overbrace{\frac{8\pi G}{3}\rho}^{\text{matter density}} - \overbrace{\frac{kc^2}{R^2}}^{\text{curvature}}$$

H = Hubble's constant

c = speed of light

G = gravitational constant

ρ = matter density of the Universe

k = curvature of the Universe

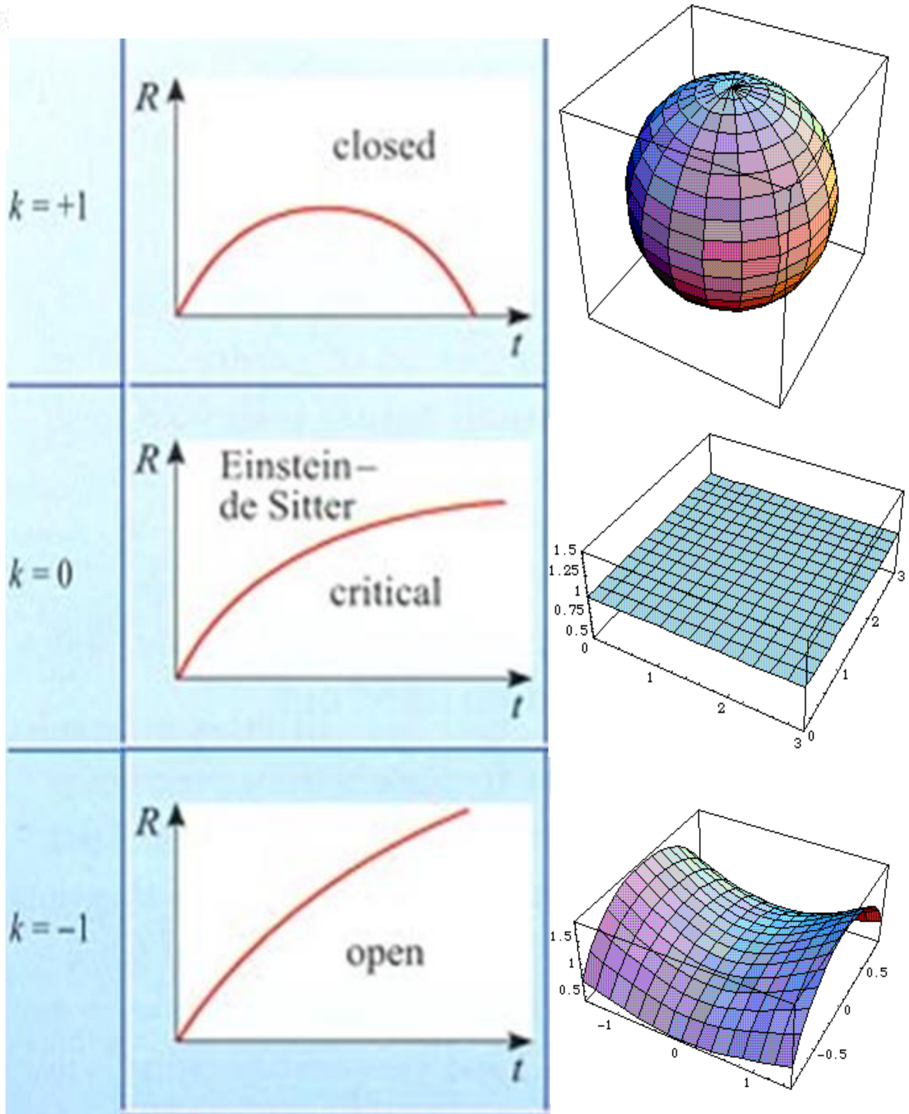
ıstant

R = radius of the Universe

If we measure the matter density of the Universe, we can solve for the curvature and determine the fate of the Universe.

$$H^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{R^2}$$

$$\rho_c = \frac{3H^2}{8\pi G}$$



Cosmological Constant

- At the time (1917), Hubble had not yet discovered that the Universe was expanding.

- Einstein adhered to the idea that the universe was **static**, i.e. **not** expanding or contracting

- Since the equations could not produce a static universe, he introduced a constant.

GR + RW Metric = Friedman

$$H^2 = \overbrace{\frac{8\pi G}{3}\rho}^{\text{matter density}} - \overbrace{\frac{kc^2}{R^2}}^{\text{curvature}} + \overbrace{\frac{\Lambda}{3}}^{\text{dark energy}}$$

H = Hubble's constant

c = speed of light

G = gravitational constant

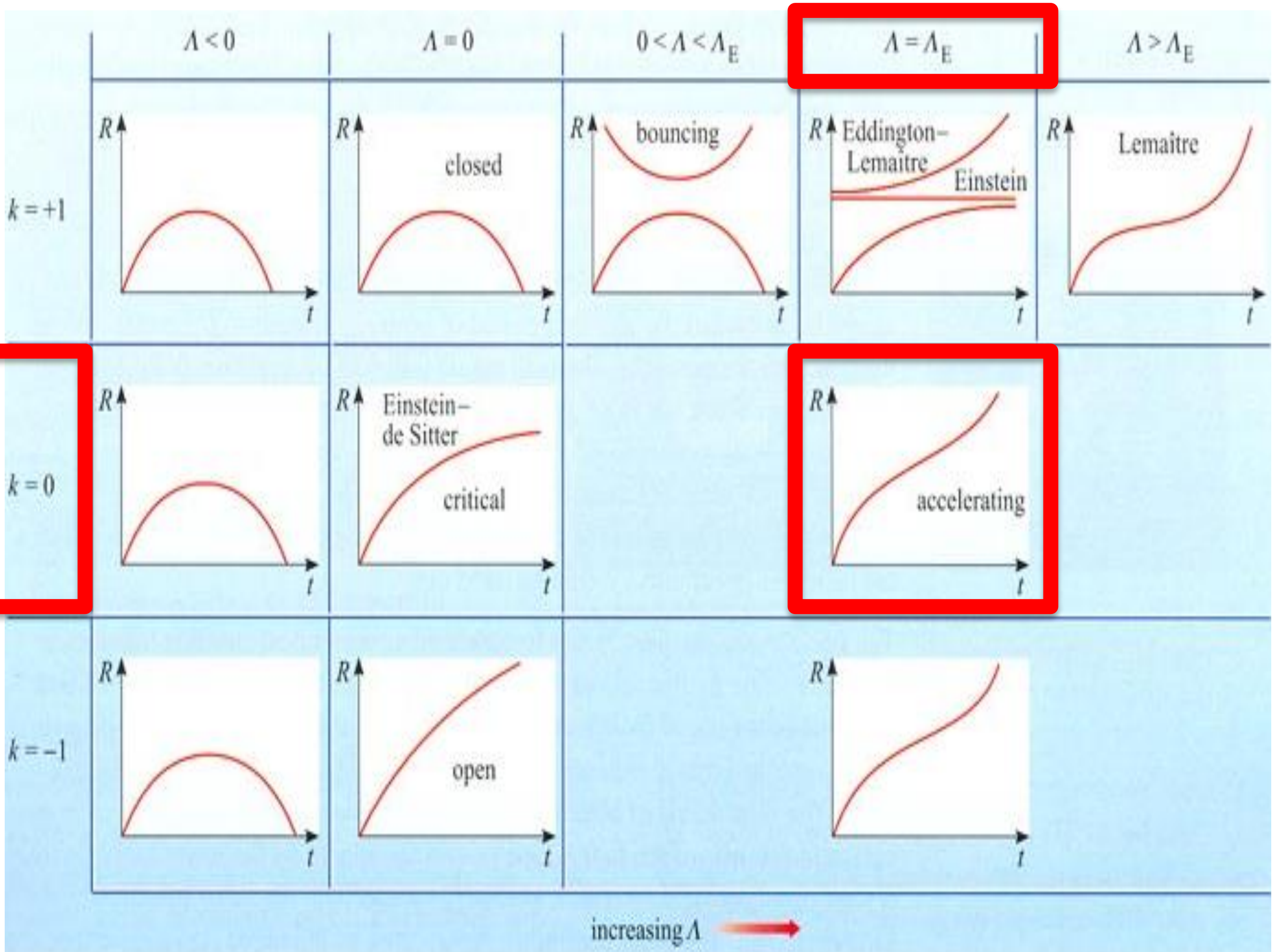
ρ = matter density of the Universe

k = curvature of the Universe

Λ = cosmological constant

R = radius of the Universe

If we measure the matter density of the Universe, we can solve for the curvature and determine the fate of the Universe.



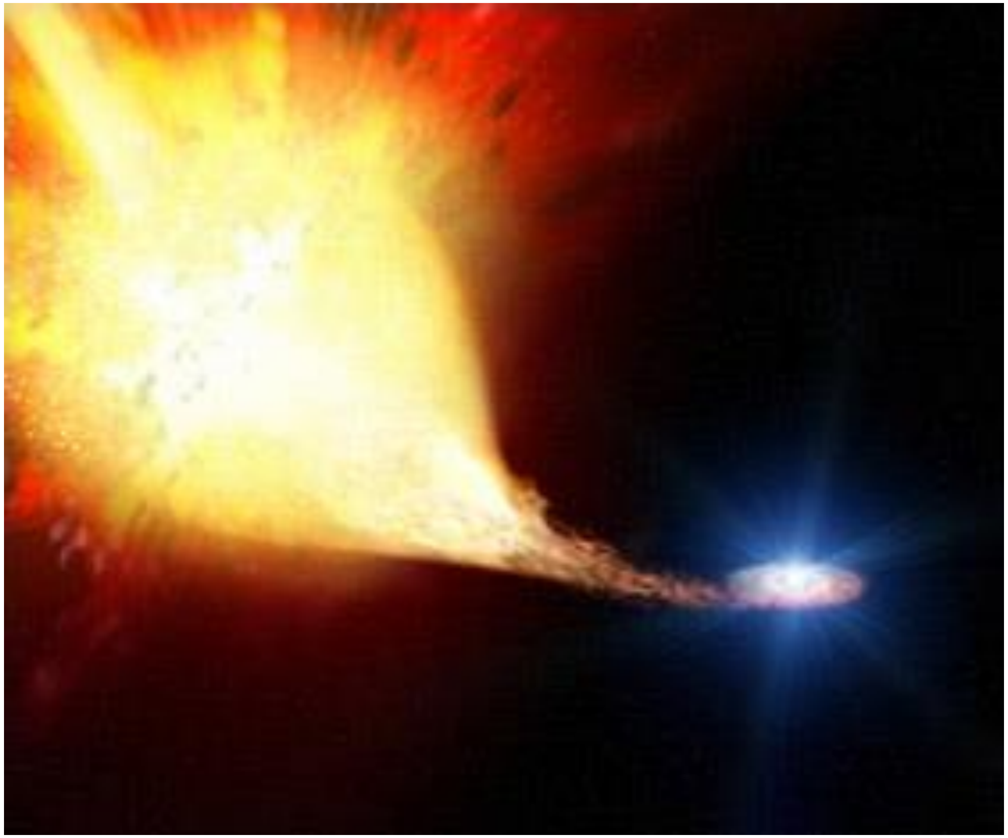
Be careful: The presence of the cosmological constant means that the geometry does not necessarily determine the fate of the universe!

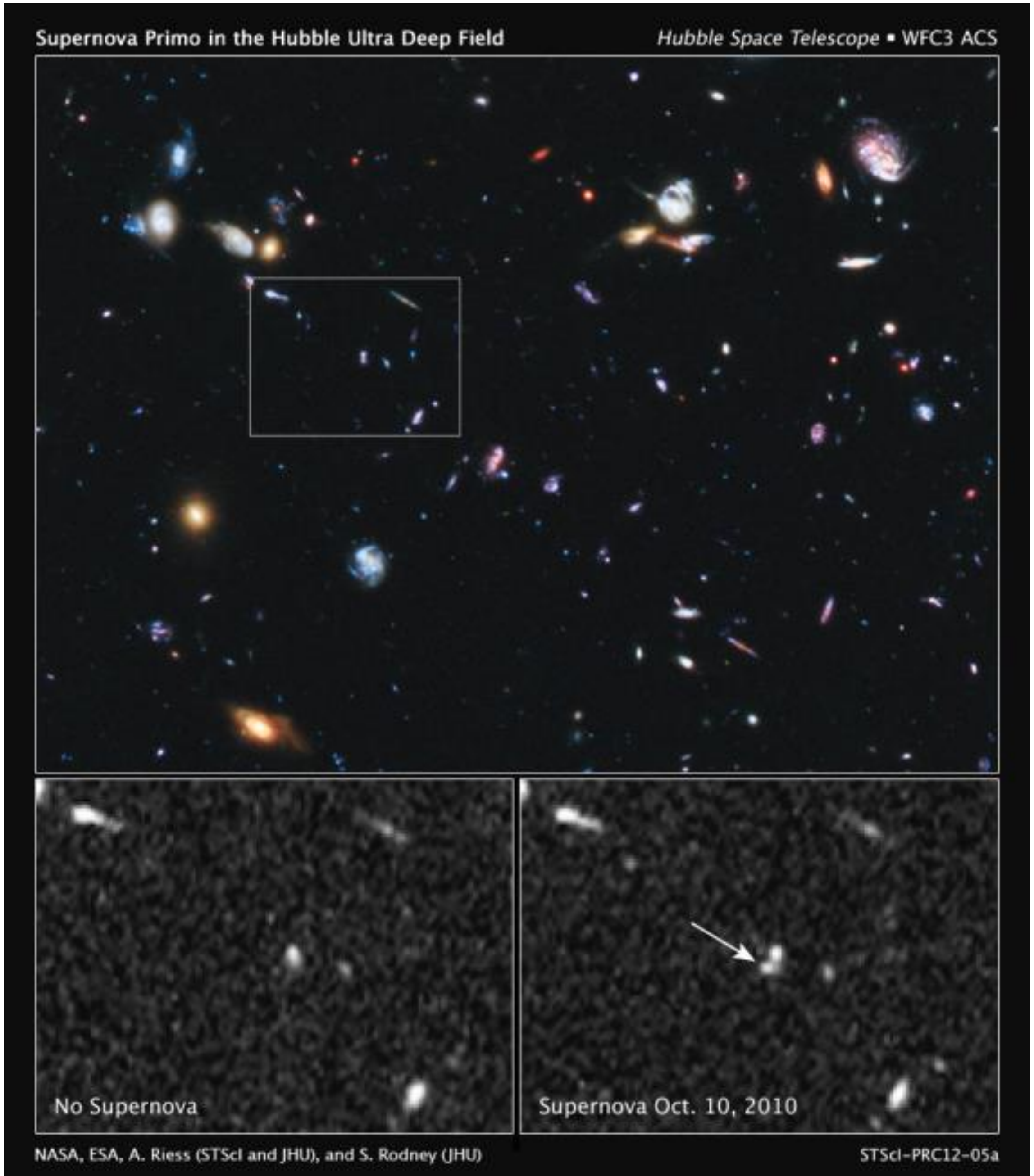
Dark Energy

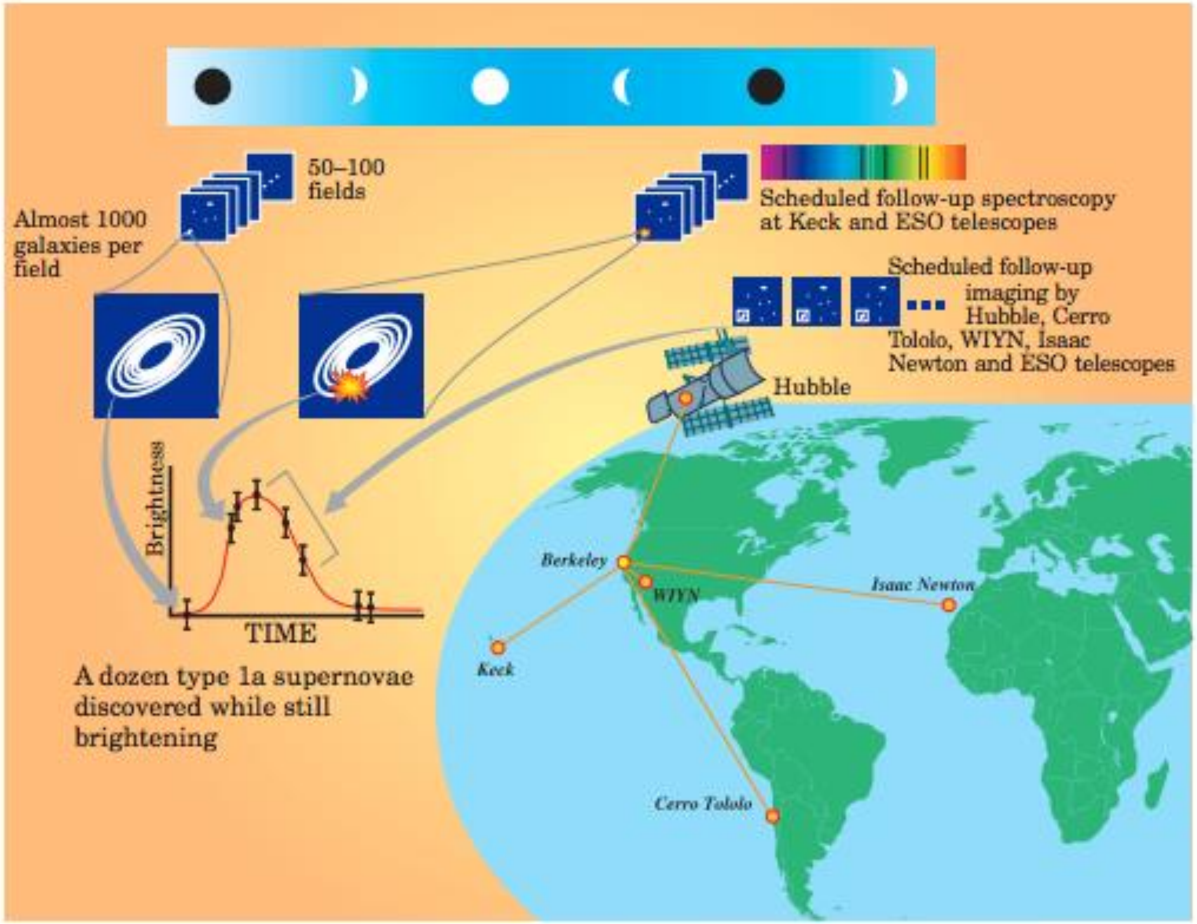
What if we look really far away?

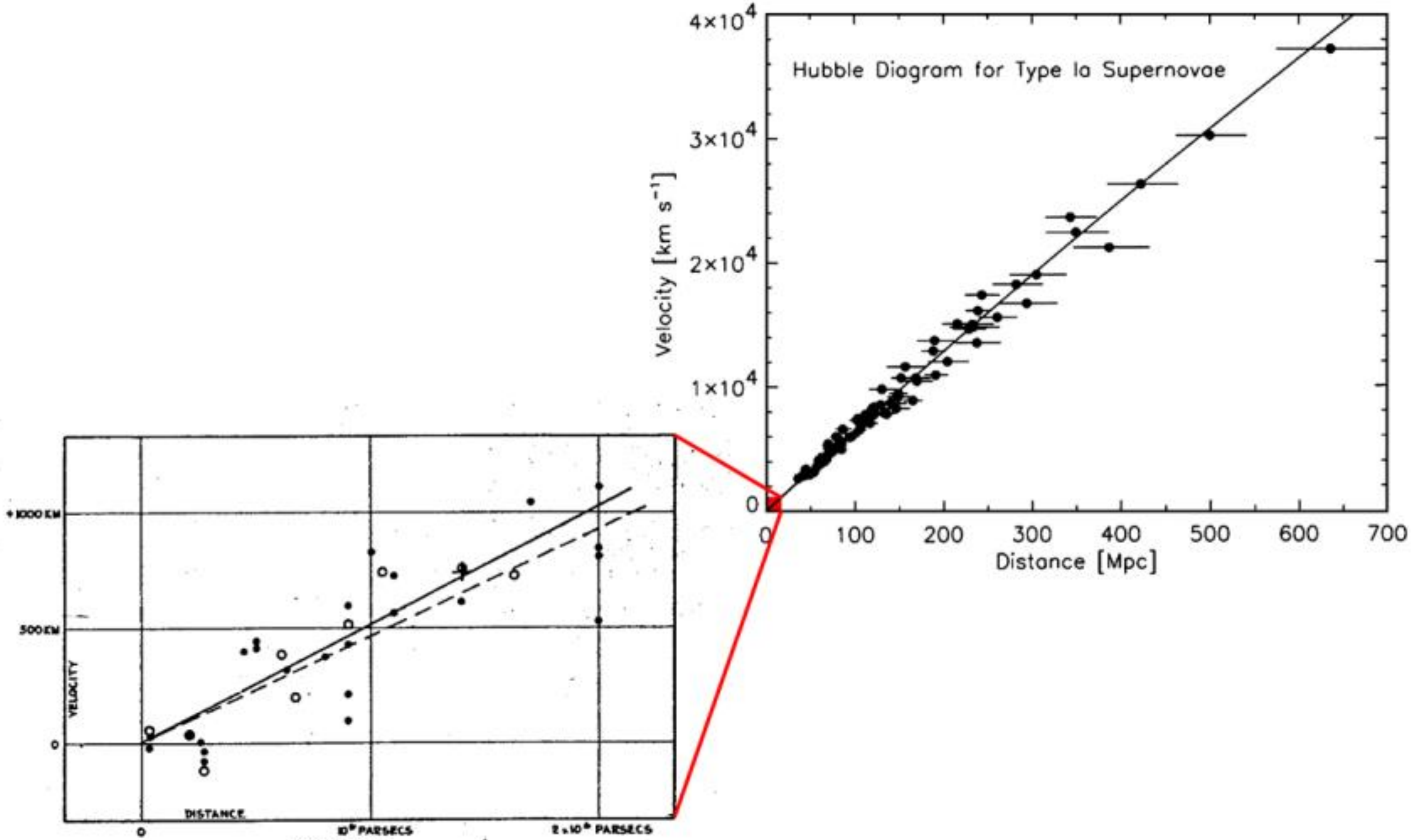
We need a new Standard Candle

Type 1a Supernova



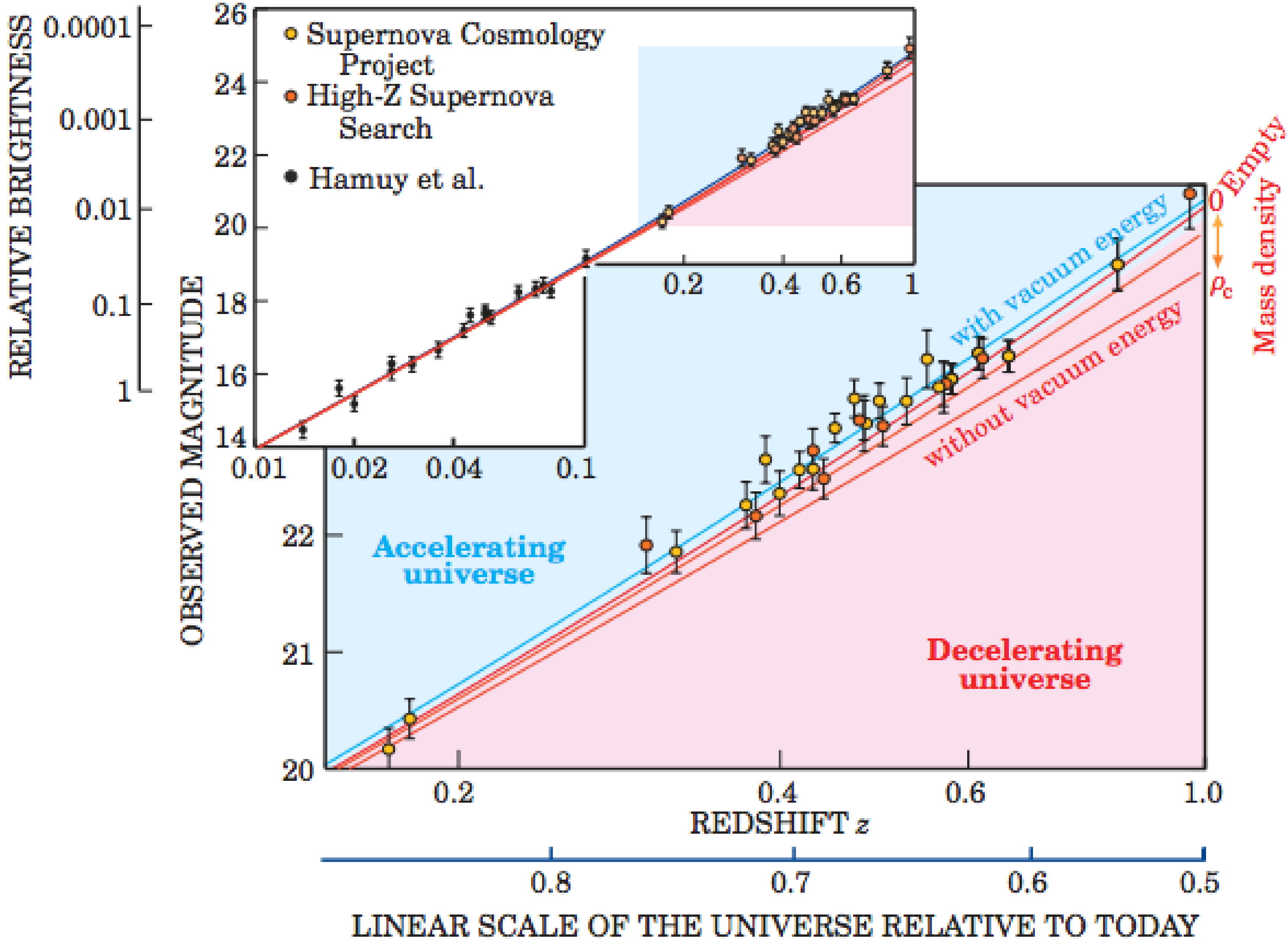

Supernova Primo in the Hubble Ultra Deep Field
Hubble Space Telescope ▪ WFC3 ACS
No Supernova
Supernova Oct. 10, 2010
NASA, ESA, A. Riess (STScI and JHU), and S. Rodney (JHU)
STScI-PRC12-05a


50–100 fields
Almost 1000 galaxies per field
Scheduled follow-up spectroscopy at Keck and ESO telescopes
Scheduled follow-up imaging by Hubble, Cerro Tololo, WIYN, Isaac Newton and ESO telescopes
Hubble
Brightness
TIME
A dozen type 1a supernovae discovered while still brightening
Berkeley
WIYN
Isaac Newton
Keck
Cerro Tololo



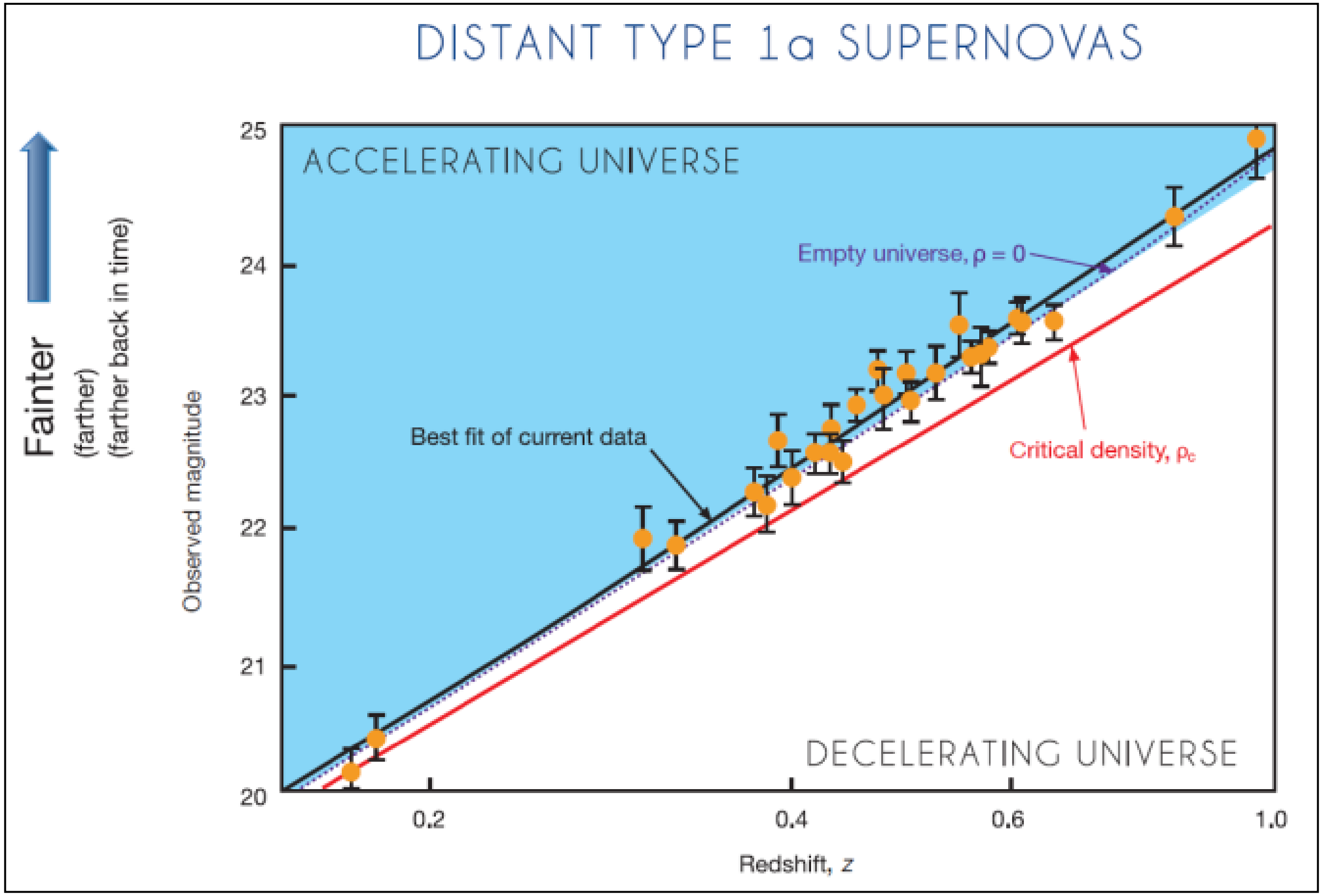
Hubble Diagram for Type Ia Supernovae
Velocity [km s⁻¹]
Distance [Mpc]
0
1×10⁴
2×10⁴
3×10⁴
4×10⁴
0
100
200
300
400
500
600
700
+1000 KM
500 KM
0
VELOCITY
DISTANCE
0
10⁶ PARSECS
2×10⁶ PARSECS

FIGURE 1



Supernova Cosmology Project
High-Z Supernova Search
Hamuy et al.
RELATIVE BRIGHTNESS
0.0001
0.001
0.01
0.1
1
OBSERVED MAGNITUDE
26
24
22
20
18
16
14
0.01
0.02
0.04
0.1
0.2
0.4
0.6
1
22
21
20
0.2
0.4
0.6
1.0
REDSHIFT z
Accelerating universe
Decelerating universe
with vacuum energy
without vacuum energy
0 Empty
Mass density
ρ_c
0.8
0.7
0.6
0.5
LINEAR SCALE OF THE UNIVERSE RELATIVE TO TODAY

Dark Energy


DISTANT TYPE 1a SUPERNOVAS
Fainter
(farther)
(farther back in time)
Observed magnitude
25
24
23
22
21
20
ACCELERATING UNIVERSE
Empty universe, ρ = 0
Best fit of current data
Critical density, ρc
DECELERATING UNIVERSE
0.2
0.4
0.6
1.0
Redshift, z

Whose Universe is accelerating faster?

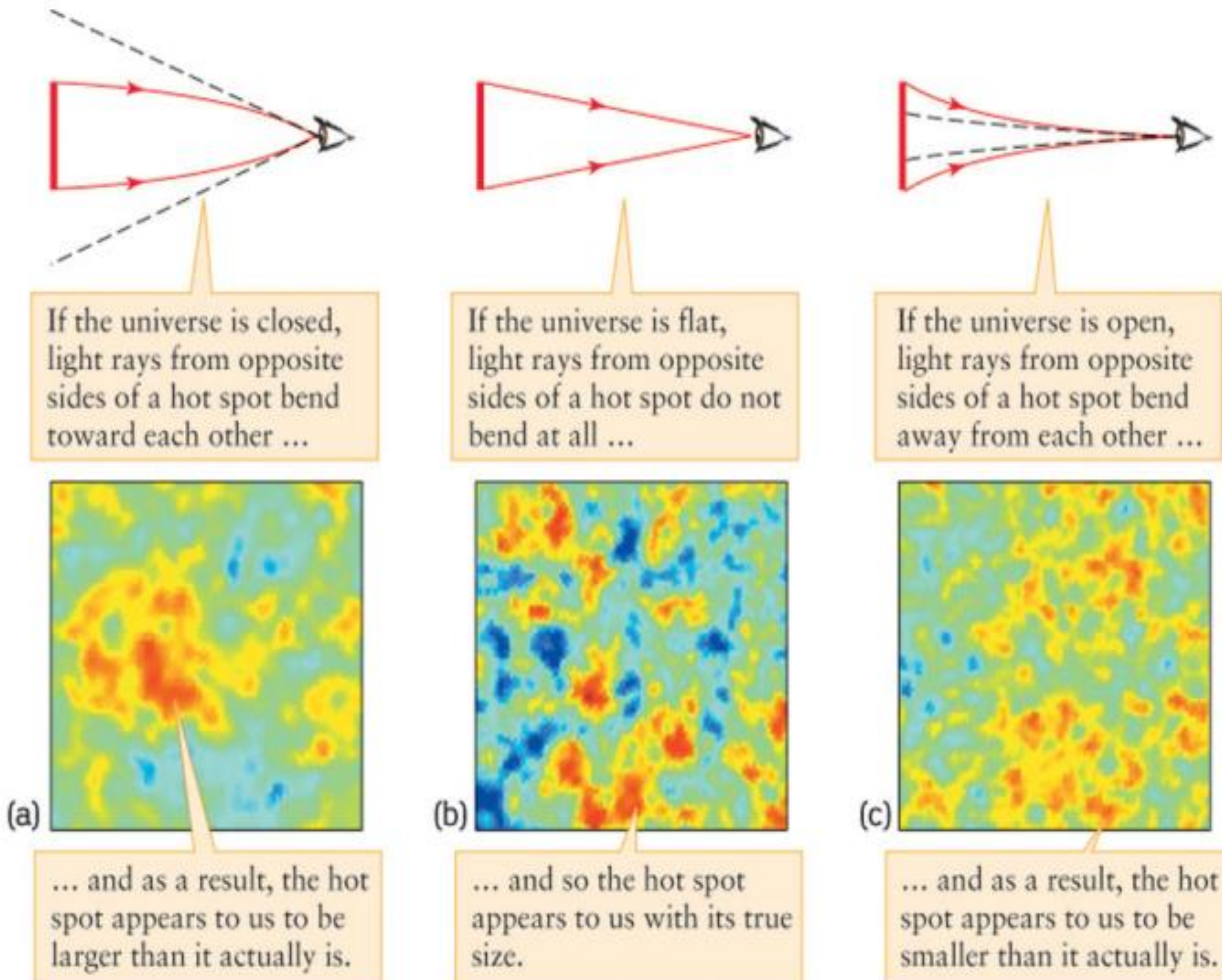
Schmidt & Perlmutter - eventually share with Riess the 2011 Nobel Prize.

Dark Energy

What does it mean that the line of best fit is steeper than an empty universe?

There must be energy in the vacuum!

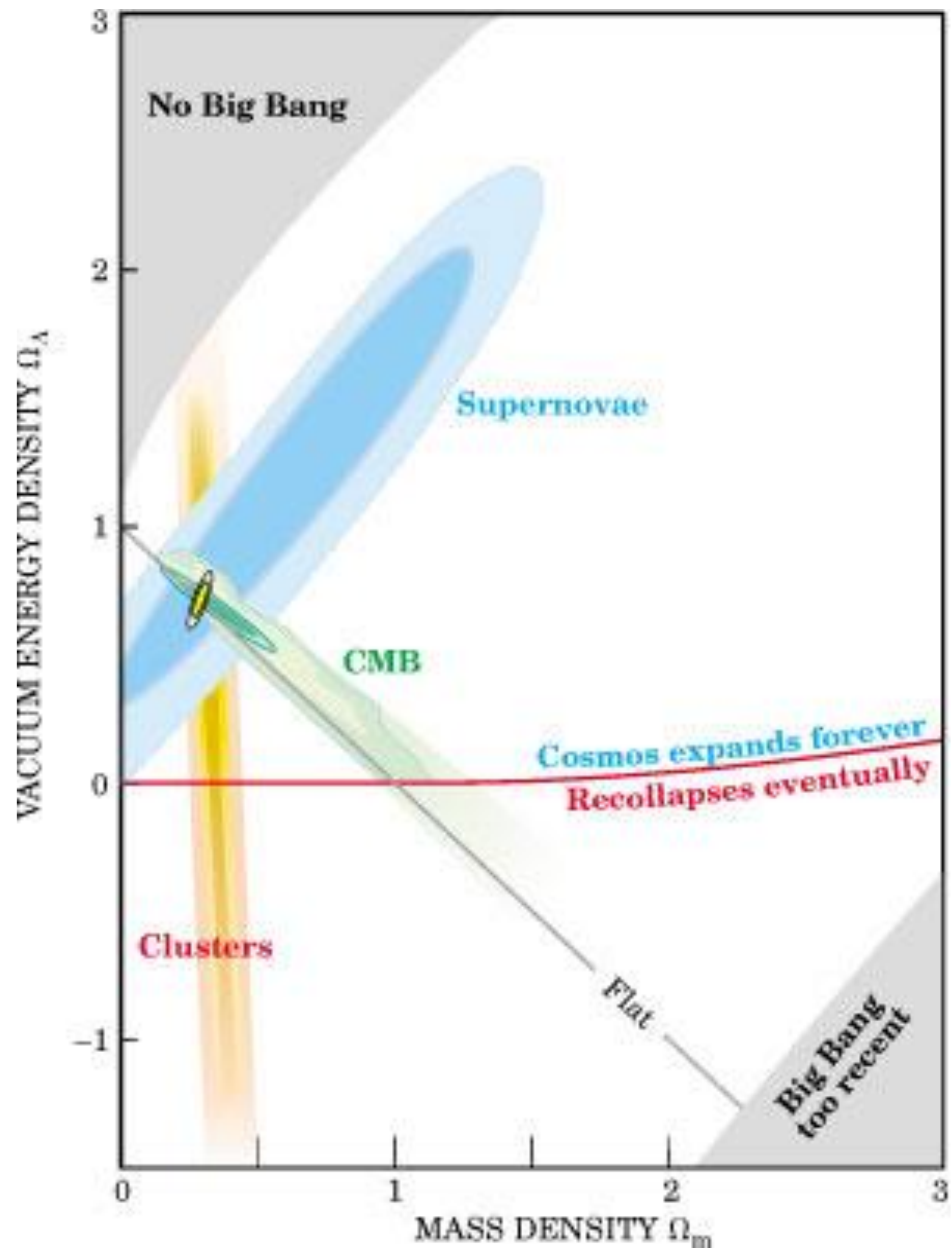
The Curvature of our Universe



The size of the CMB fluctuations is consistent with a flat universe!

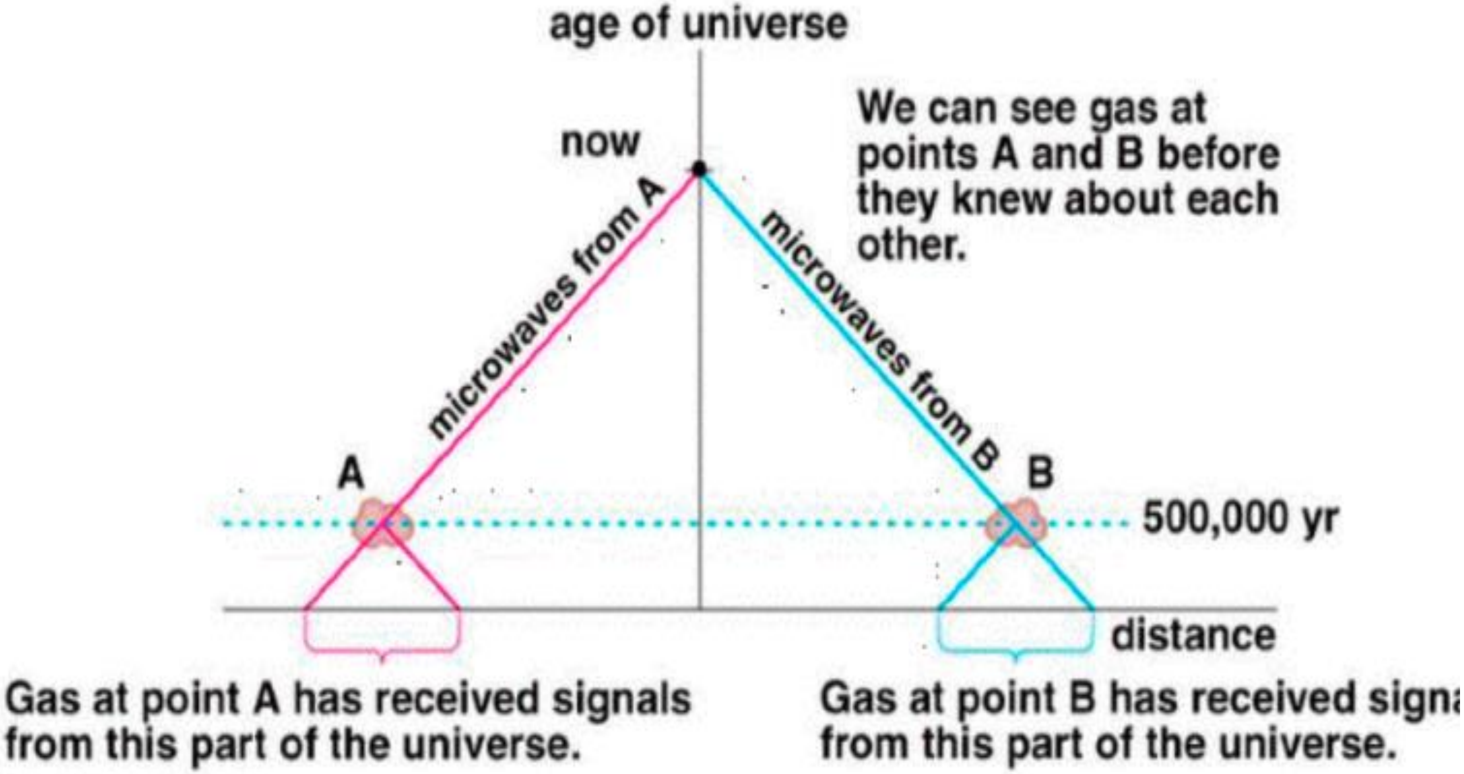
Flatness Problem

Why is the Universe so finely tuned?

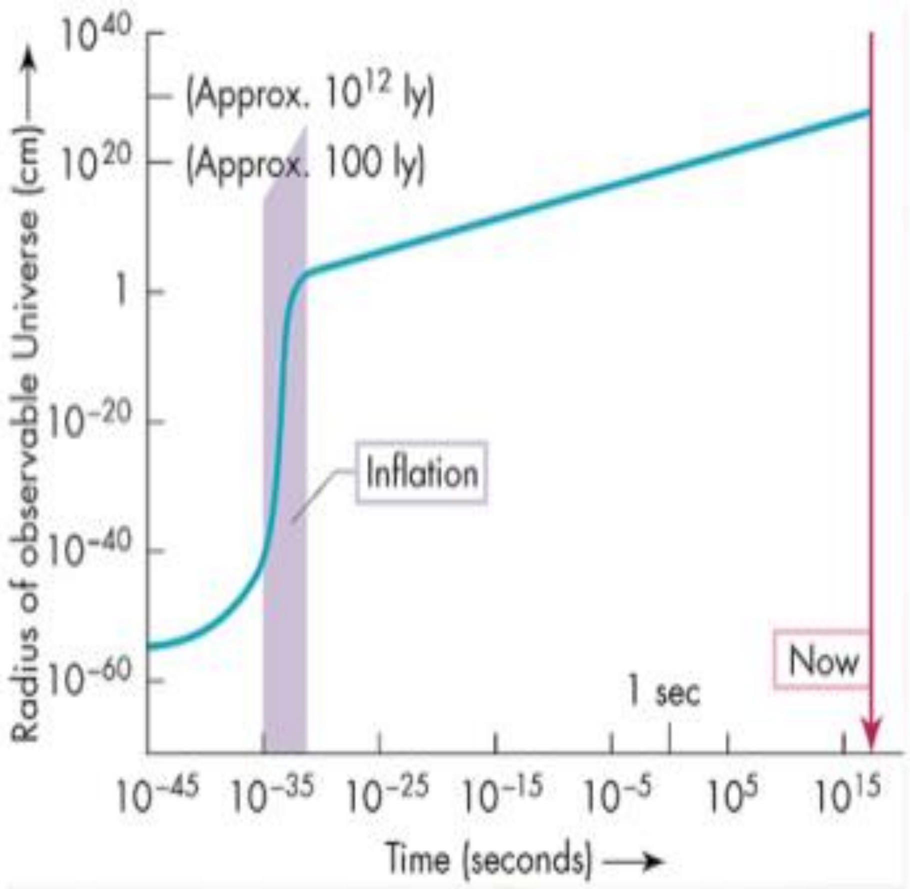


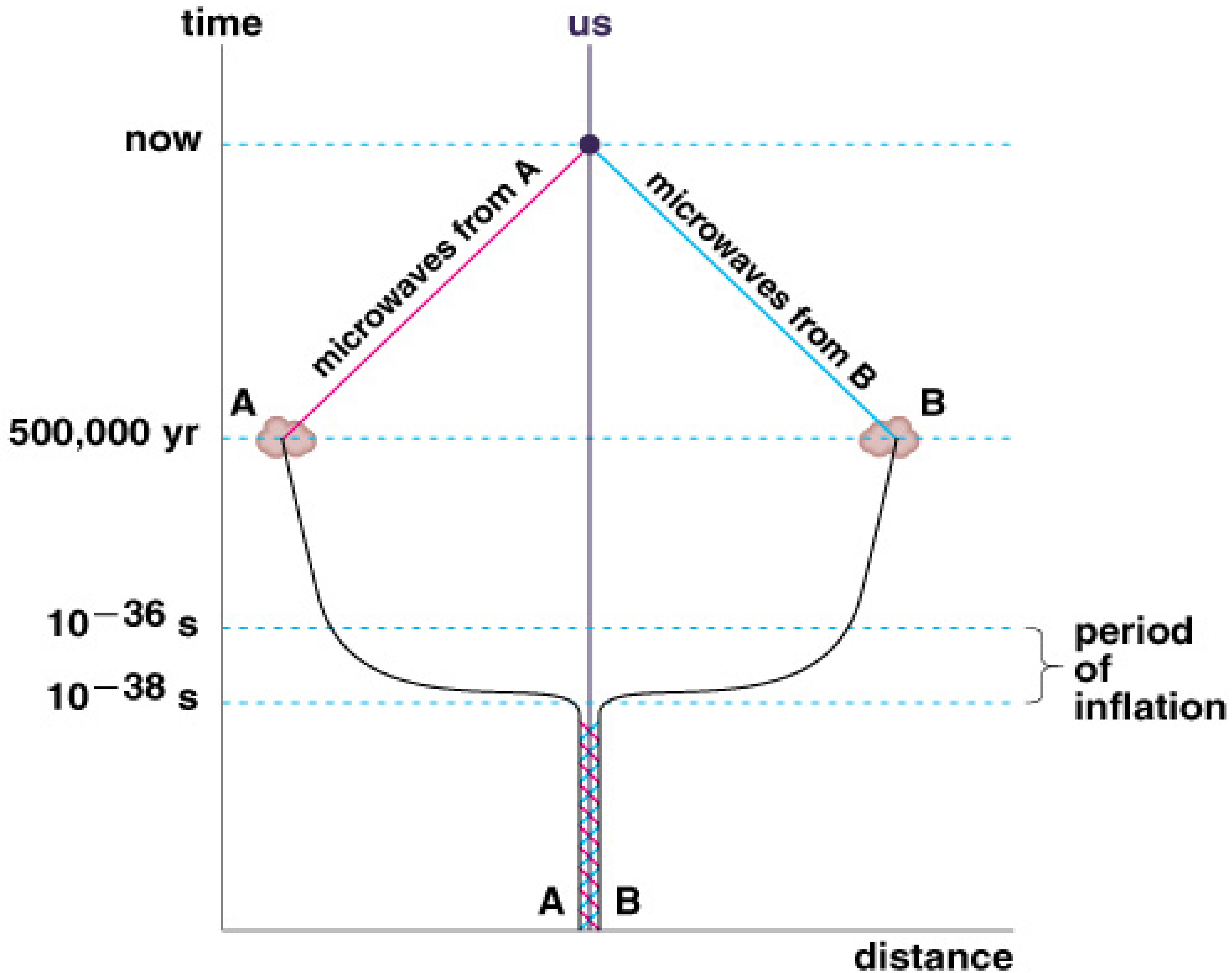
Horizon Problem

Why is the CMB so smooth?

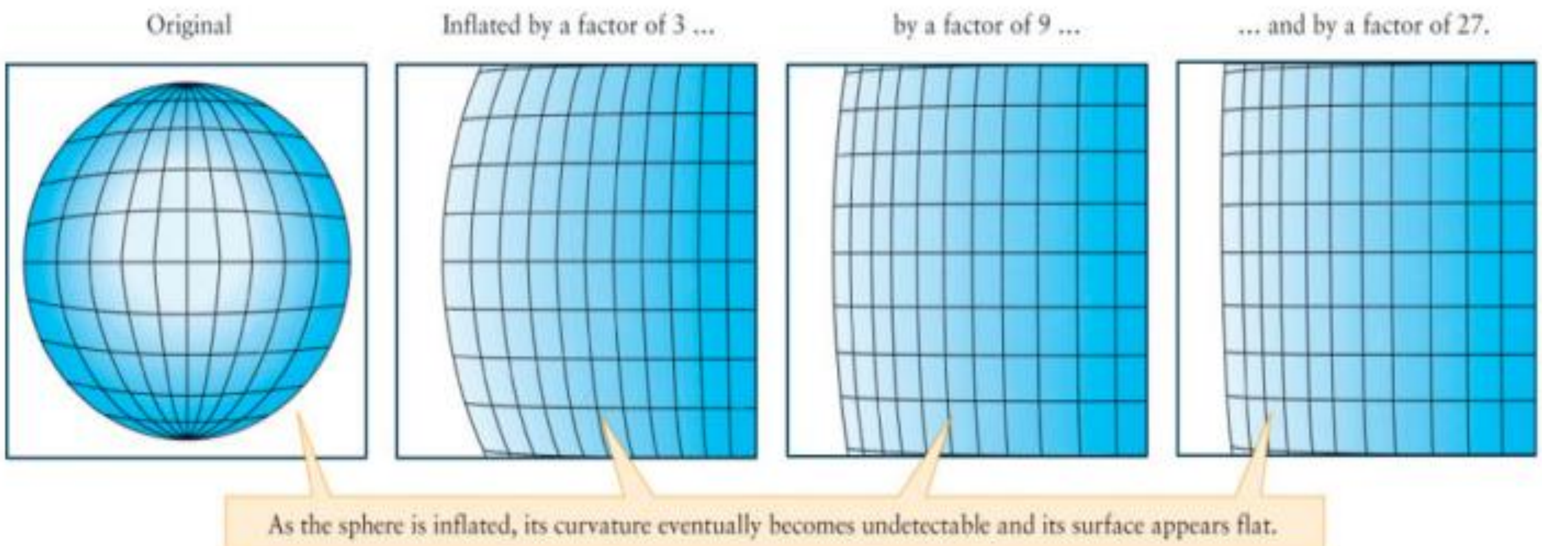


Solution? Inflation





time
us
now
microwaves from A
microwaves from B
A
B
500,000 yr
10−36 s
10−38 s
period
of
inflation
A
B
distance


Original
Inflated by a factor of 3 ...
by a factor of 9 ...
... and by a factor of 27.
As the sphere is inflated, its curvature eventually becomes undetectable and its surface appears flat.

Inflation

Does such a rapid expansion violate relativity?

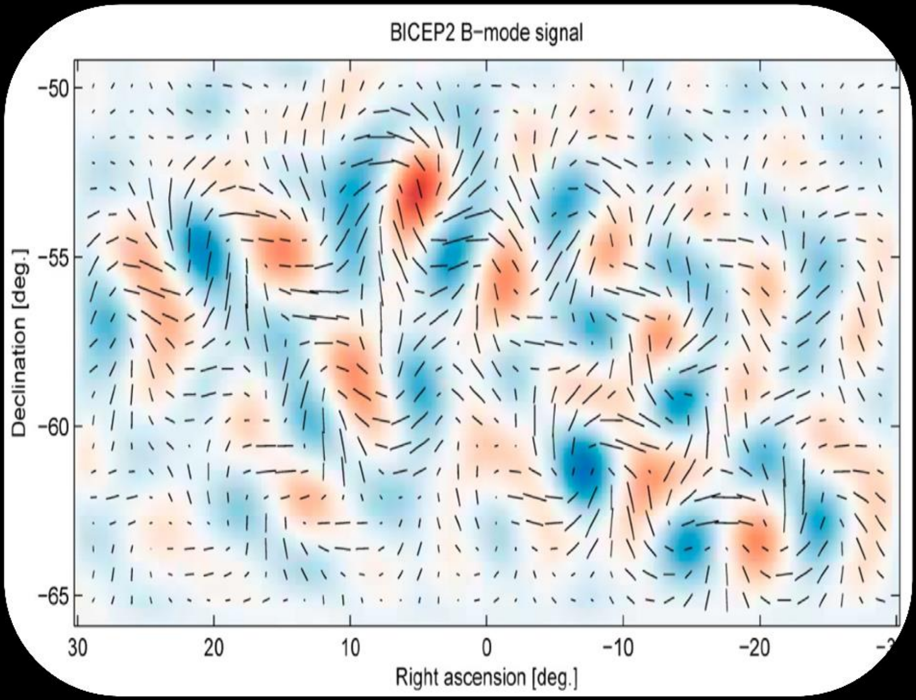
- No, because it is space itself that is expanding rather than material particles flying away at high speeds!

What's New in Physics?

Gravitational Waves

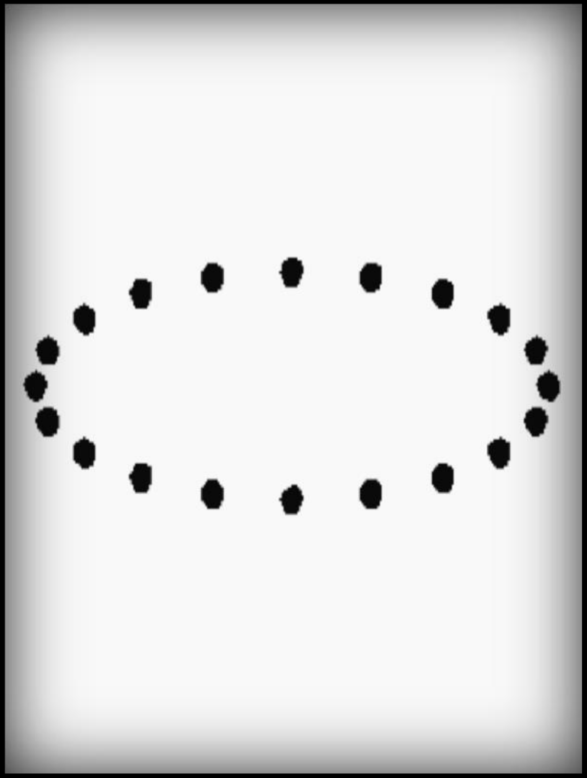
First maybe…then maybe not

Is science 'working'?

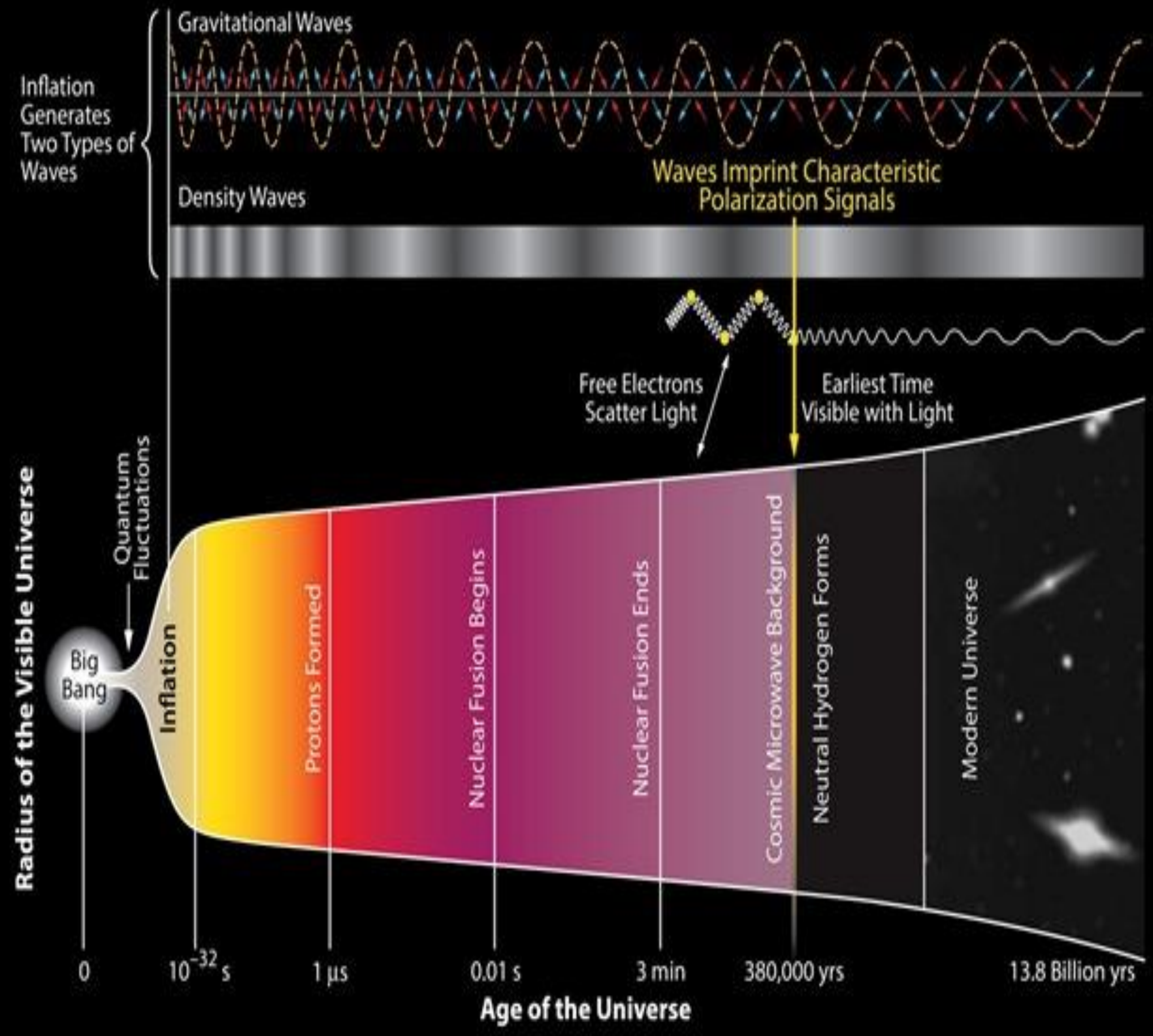


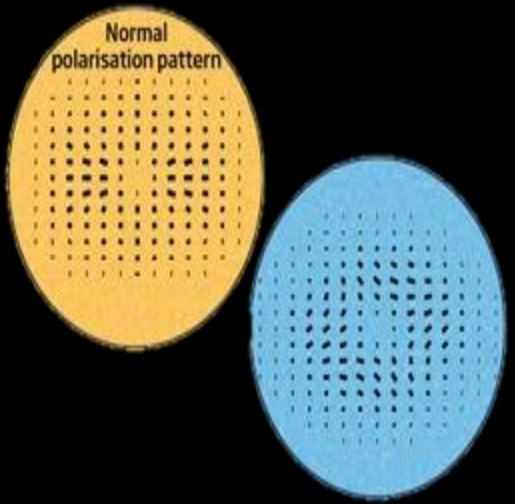
Gravitational Waves

What is Waving?

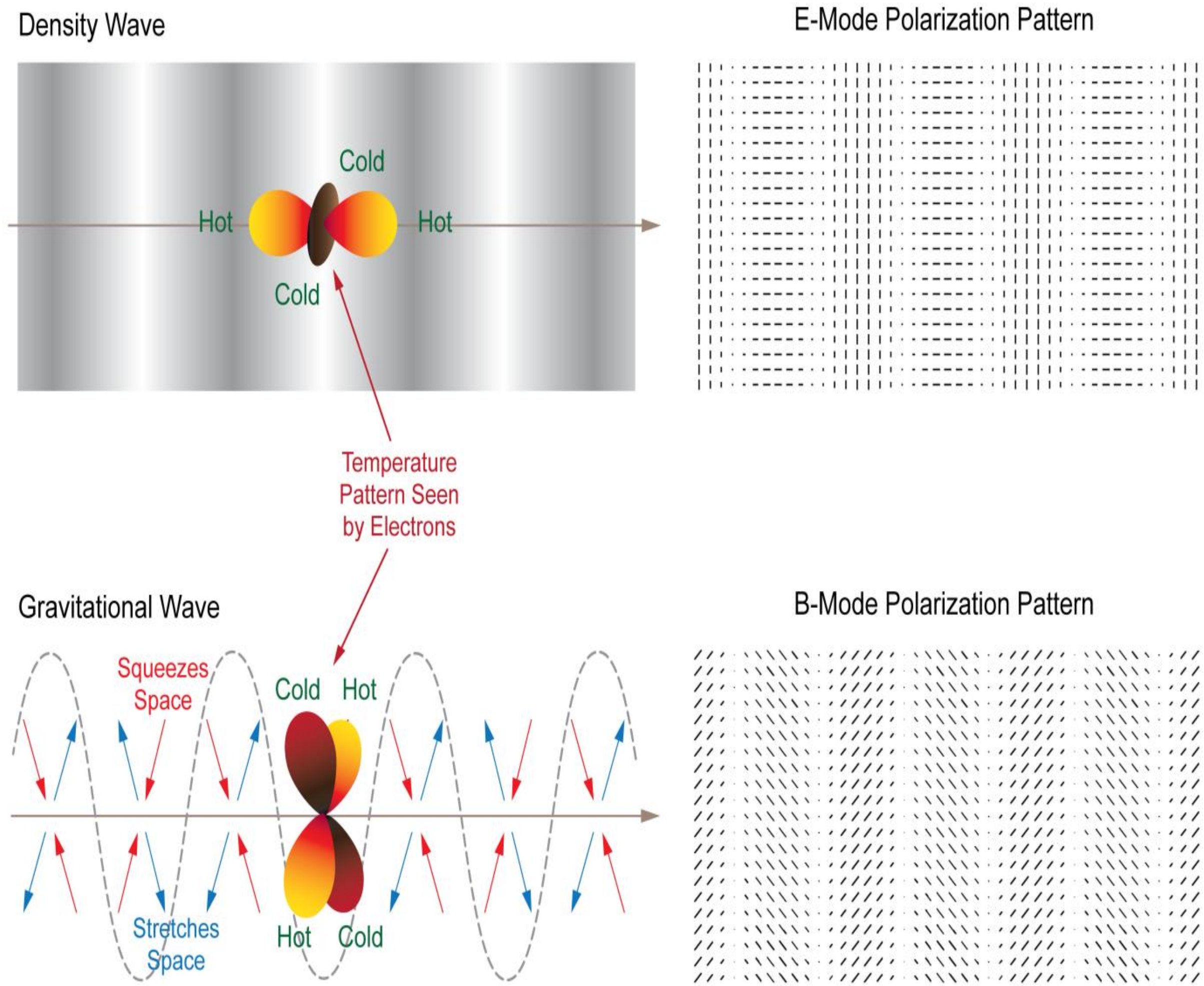


History of the Universe



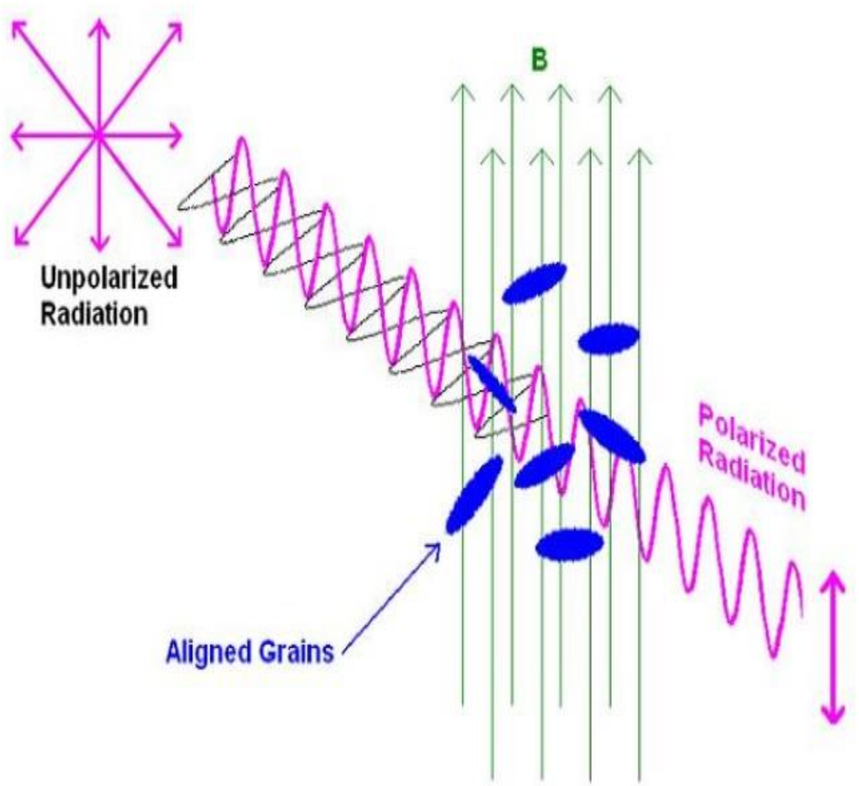


First Tremors of the Big Bang



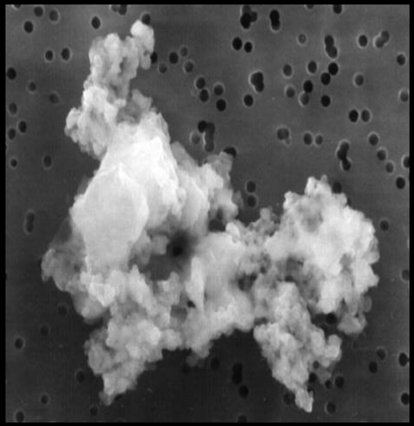
Density Wave
E-Mode Polarization Pattern
Cold
Hot
Hot
Cold
Temperature
Pattern Seen
by Electrons
Gravitational Wave
B-Mode Polarization Pattern
Squeezes
Space
Cold
Hot
Stretches
Space
Hot
Cold

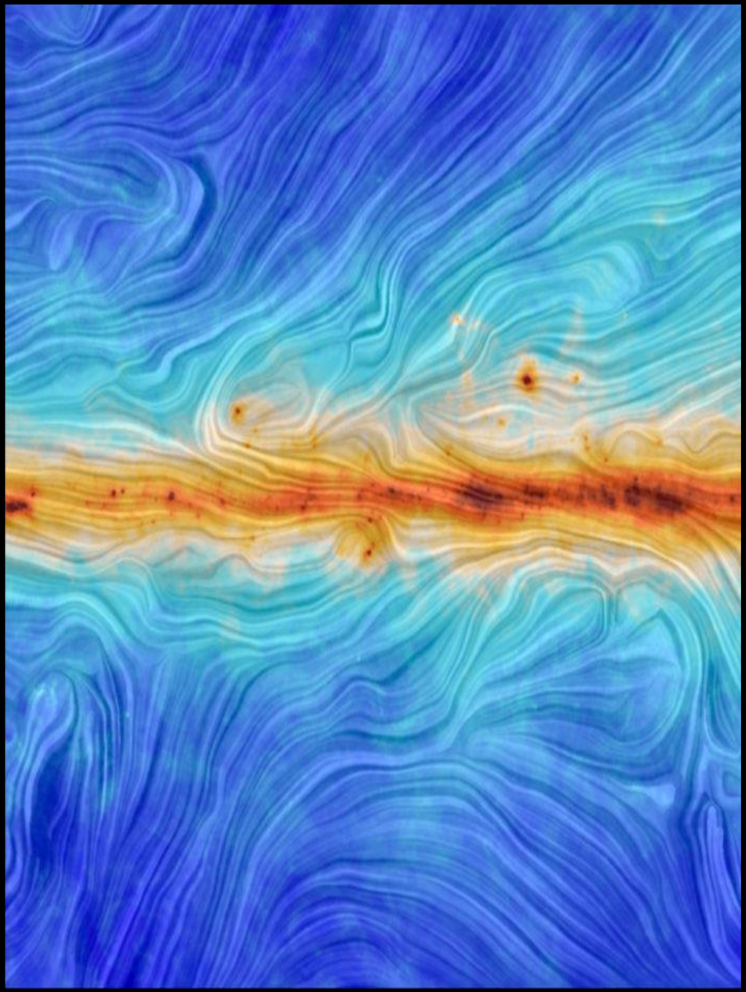
Dust Polarizes Light

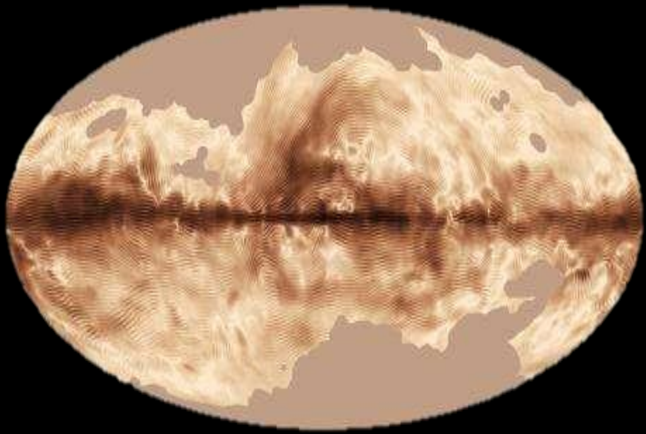


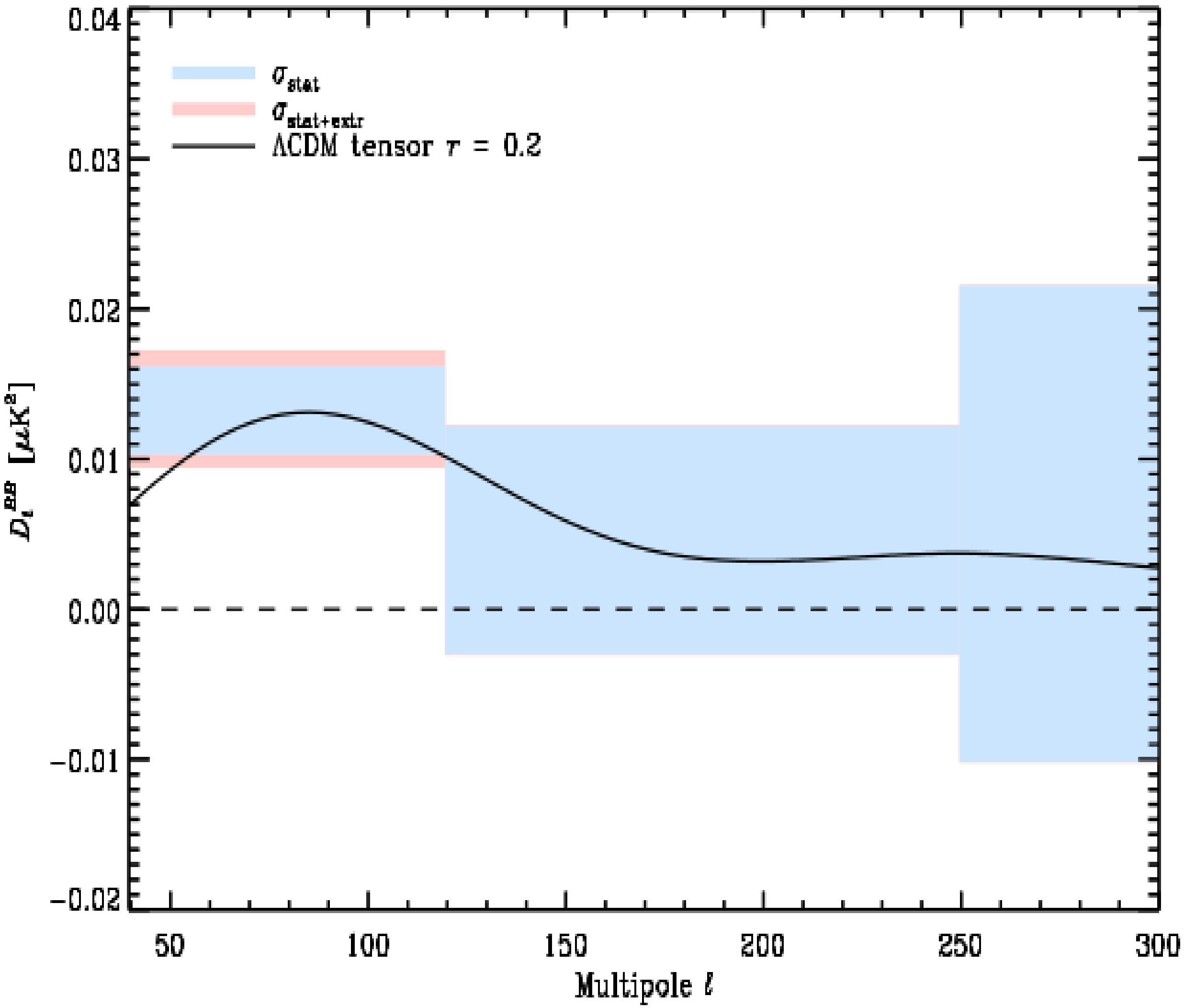
Milky Way's Magnetic Fingerprint

Planck Satellite









σ_{stat}
$\sigma_{stat+extr}$
ΛCDM tensor r = 0.2
0.04
0.03
0.02
0.01
0.00
−0.01
−0.02
$\mathcal{D}_\ell^{BB}$ [μK^2]
50
100
150
200
250
300
Multipole ℓ