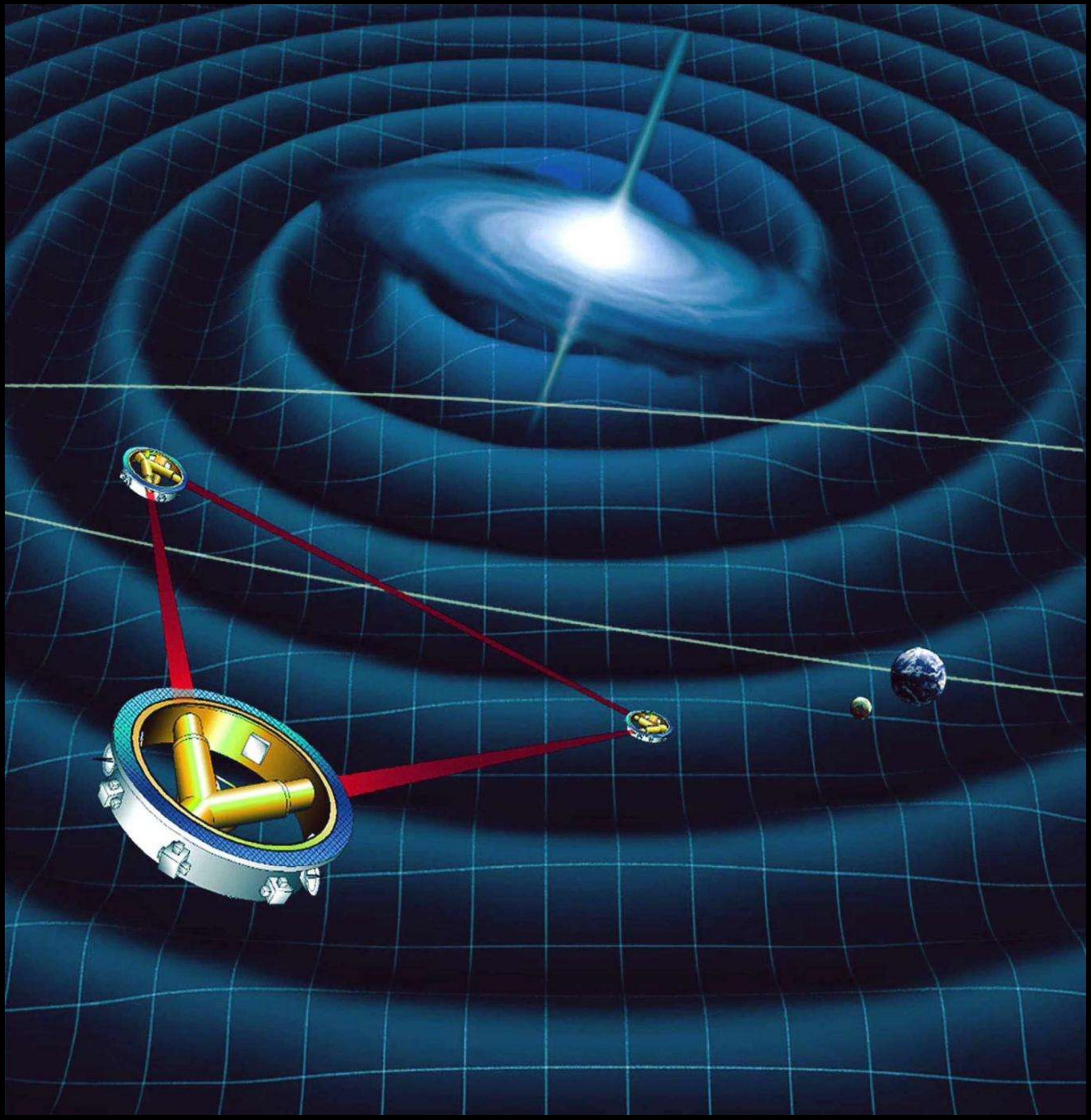
Duke Physics 55 Spring 2005

Lecture #31:

Experimental Tests of General Relativity



ADMINISTRATIVE STUFF

- Friday: Quiz 6, 15 minutes at beginning of class

Material: → BDSV Ch. 22,S2,S3 (focus on lecture WUN2K)
→ Homeworks 11, 12
→ Astronomy Place tutorials for above
(Dark Matter in Galaxies, Black Holes)

- Partial solar eclipse on Friday, about 5:45 pm!
I will arrange a viewing (if weather permits)

OUTLINE

BDSV Chapter S3, 18.4

- Experimental Tests of General Relativity
  - precession of Mercury
  - bending of light; gravitational lensing
  - gravitational time shift and redshift
  - gravitational waves
- More on Black Holes
- Some Speculations
  - wormholes and warp drives

PRS Question

Which of the following best describes the relation between Newton's theory of gravity and general relativity?

a. General relativity applies at the subatomic level, but Newton's does not.

b. Newton's theory and general relativity give the same answers, but the former tells us to think of gravity as a force, and the latter tells us think of it as curvature of spacetime.

c. Newton's theory of gravity is an approximation to general relativity that works when gravity is relatively weak, but breaks down when gravity is strong.

d. Newton's theory is now know to be false, and we were previously misled by measurement errors.

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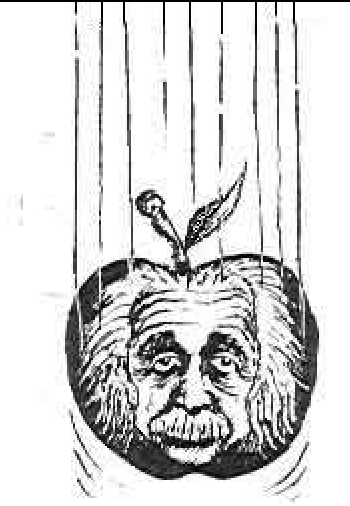

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Review PRS Question

According to general relativity, why does the Earth orbit the Sun?

a. Earth is following the straightest path possible through spacetime, but this path happens to go around the Sun.

b. Because a mysterious force that we call gravity holds the Earth in orbit.

c. Because the Earth and Sun are connected by a 'rope-like' set of invisible, subatomic particles.

d. Earth orbits the Sun because a spacetime diagram shows the Sun to be a bowl-shaped dip in a rubber sheet.

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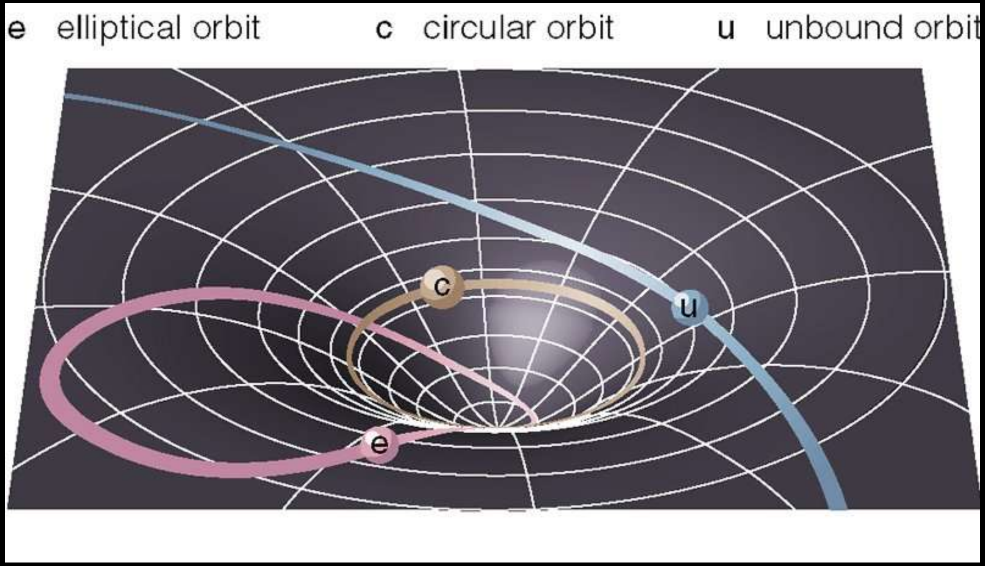
Basic Ideas of General Relativity

An object floating freely
has a worldline
that follows the straightest
possible path through
spacetime. If you feel weight,
then you are not on the
straightest possible path

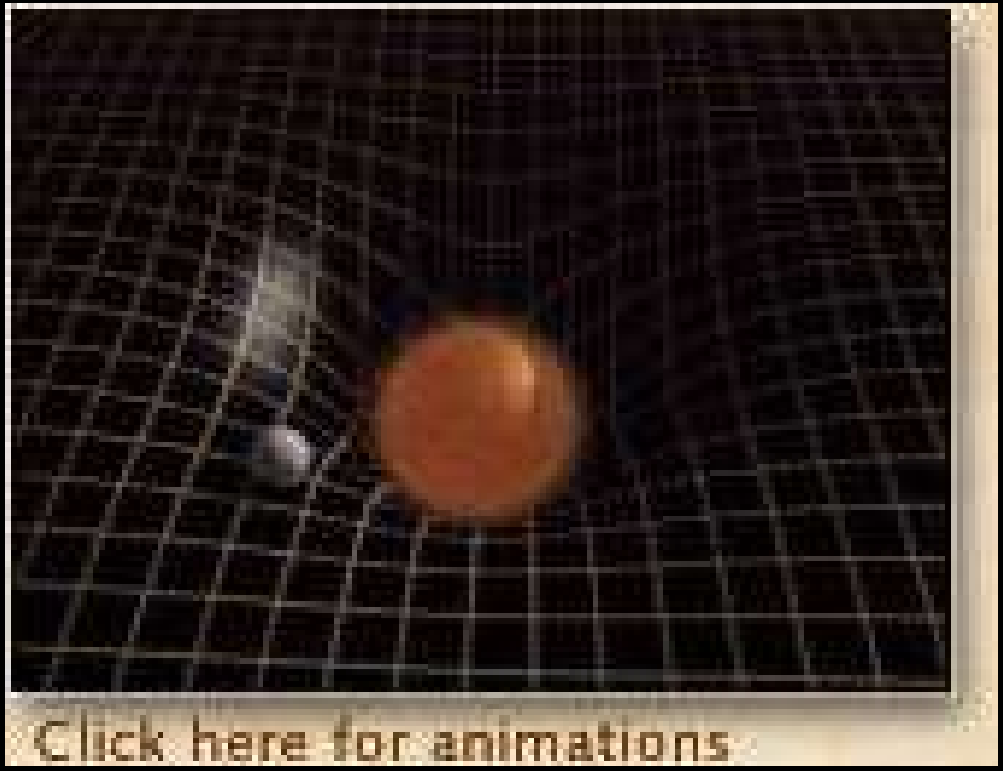


What we feel as gravity arises
from the curvature of spacetime.
Mass causes spacetime to curve,
and the curvature determines
the paths of freely moving masses.

'Matter tells space how to curve;
space tells matter how to move'

Spacetime and gravity movie

www.pbs.org/wgbh/nova/einstein/relativity/animations.html

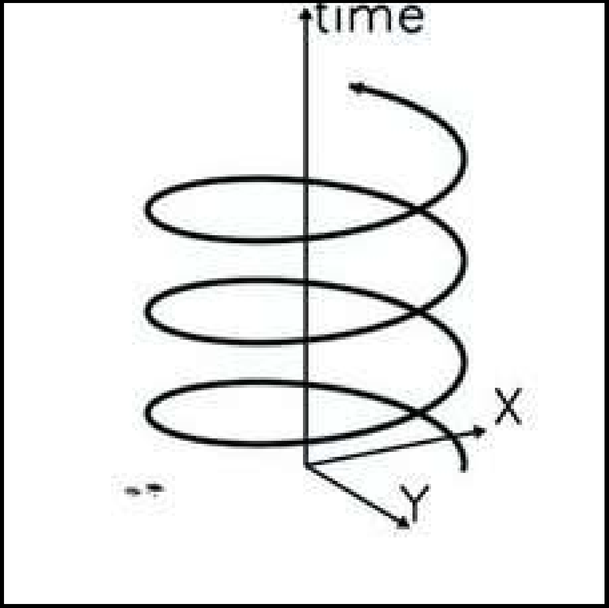


Caveats for rubber sheet analogy

- masses are really *part of* the universe, not on top of it

- we can only see orbits in 2D; for instance orbits at the same radius can be in different planes

- time part of spacetime not shown... for instance Earth never returns to the same point in spacetime

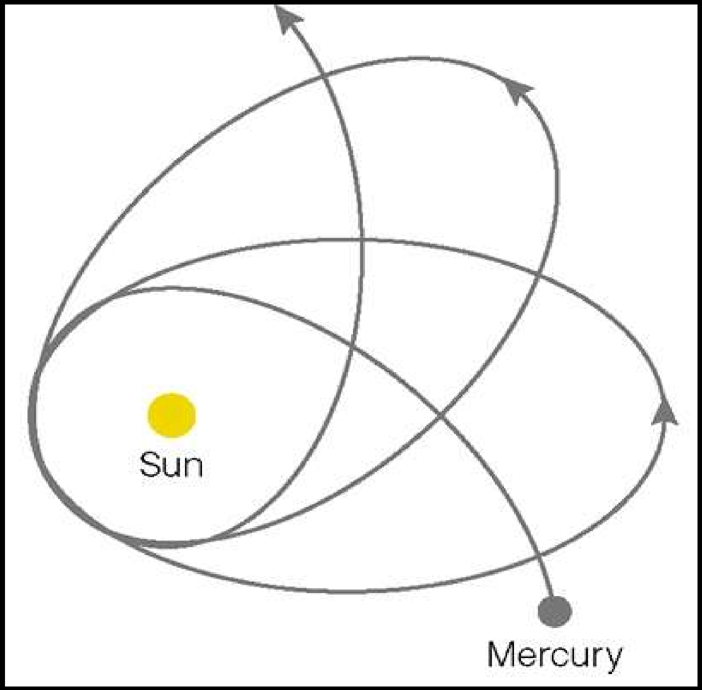


Nevertheless, it's extremely helpful for visualization

What evidence do we have that these ideas are valid?

Precession of Mercury's orbit

Newton's theory predicts that Mercury's orbit will precess, due to the influence of the other planets (one cycle per 20,000 yr)



(exaggerated precession)

Einstein's theory predicts a small discrepancy, because space is more curved near the Sun time runs slower at perihelion:

this is *measured* (observed before Einstein!)

PRS Question

Suppose Mercury's orbit were more elliptical than it is... the discrepancy with Newtonian gravity would be

a. greater
b. smaller
c. the same
d. impossible to tell

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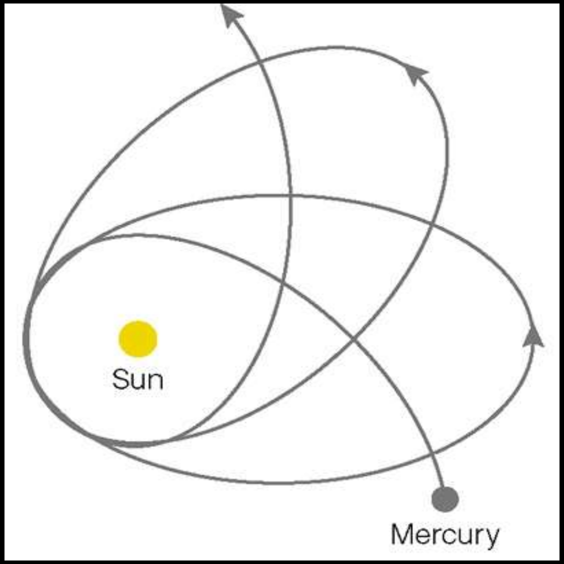
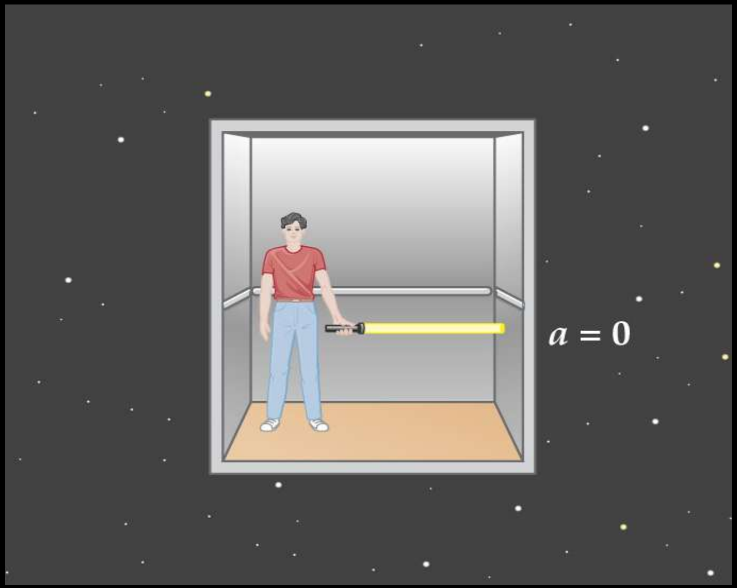


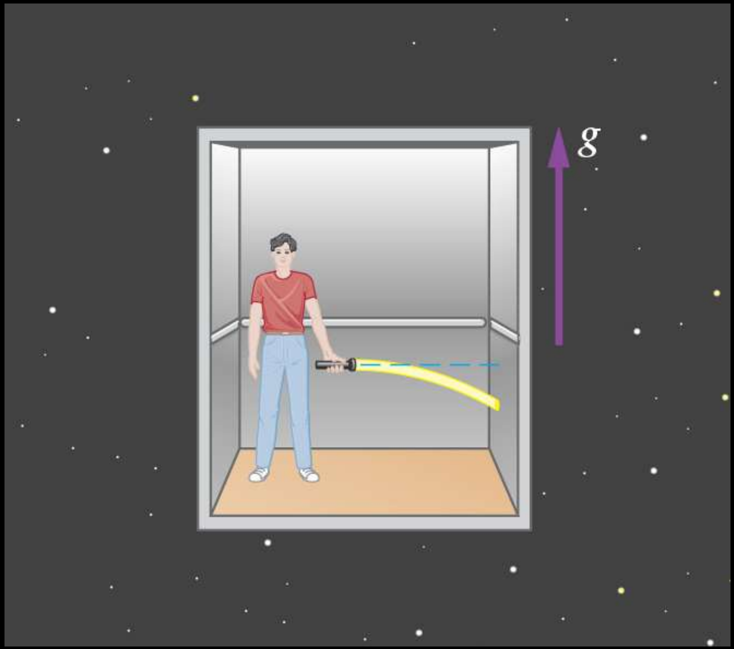
Greater difference
in perihelion and aphelion
means greater difference in clock rate
from gravitational time dilation

Another prediction of GR: gravity *bends light*

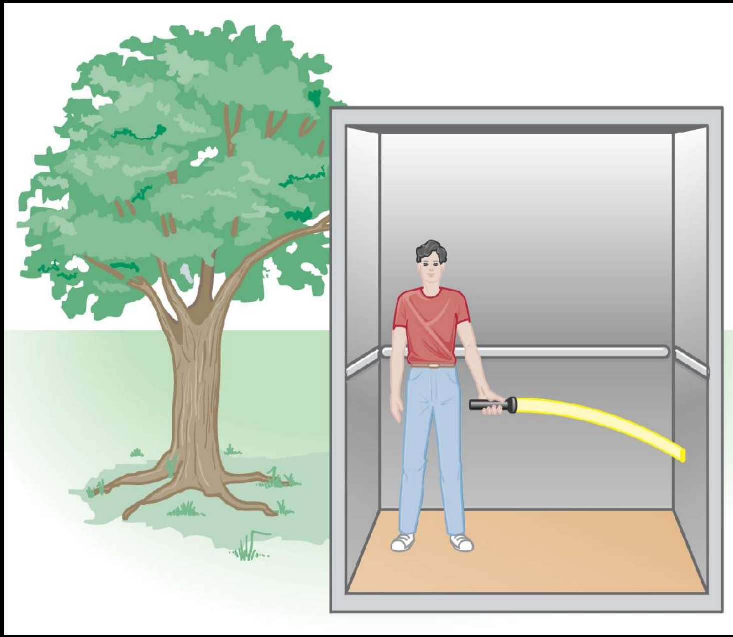
Light always travels along the straightest possible path in spacetime

Inertial reference frame

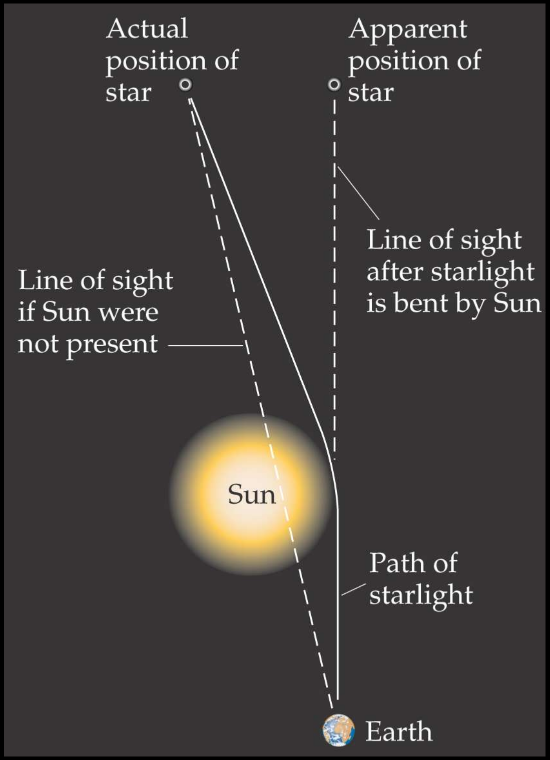


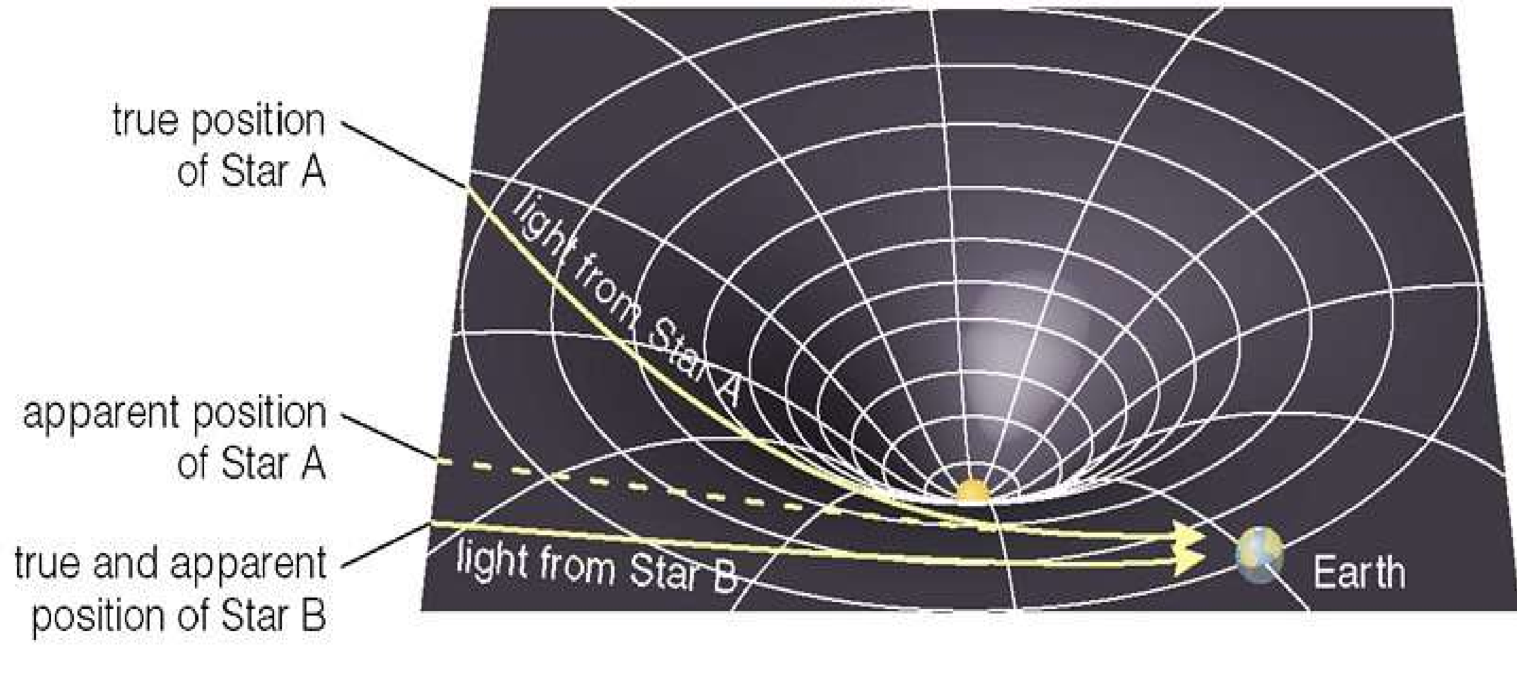


equivalent to



When the light passes through the curved spacetime from a strong gravitational field, it follows a curved path





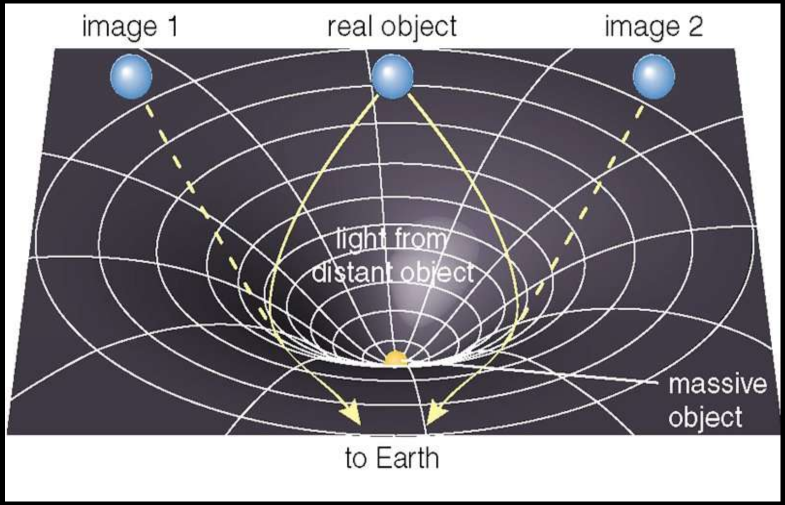
The apparent position of a object may shift due to the curved path of light

This is observed!

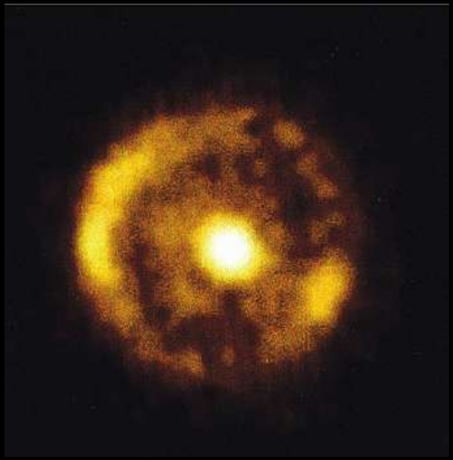
First observation of this effect: Eddington observed the Hyades near the Sun during the eclipse of 1919

Multiple images of the same star are possible

Gravitational lensing (strong lensing)



Einstein cross

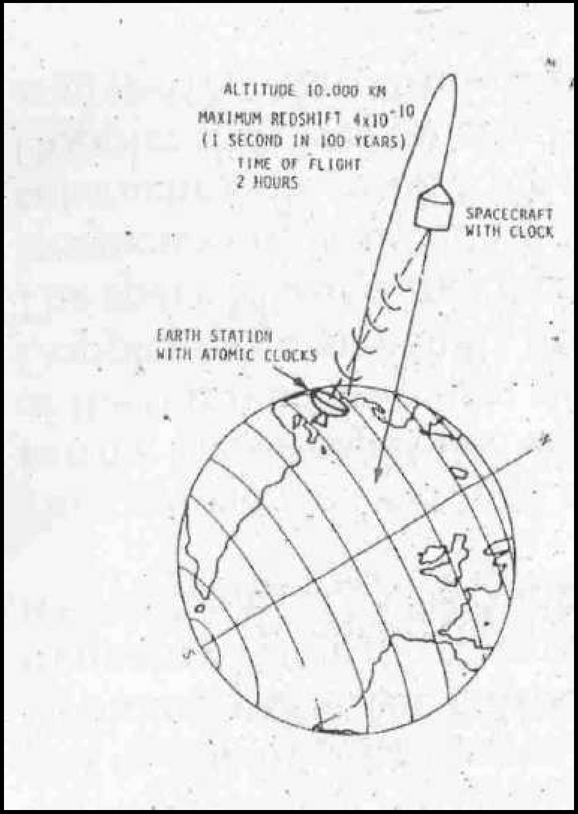


Einstein ring

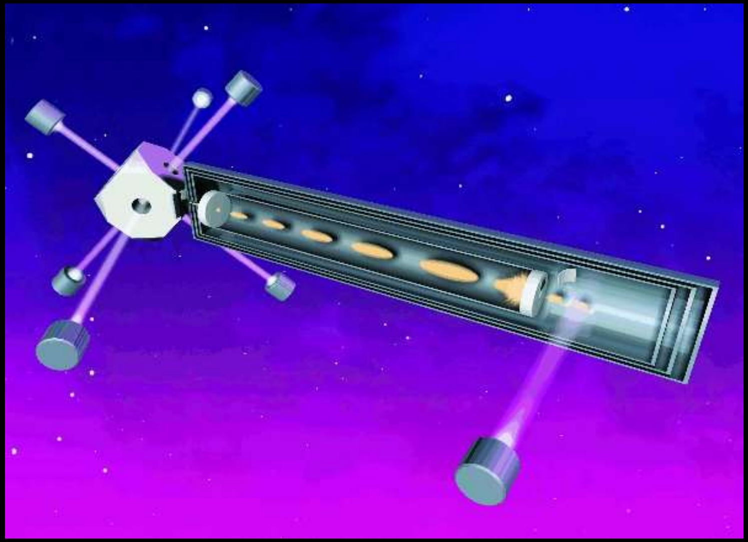
Another test: check gravitational time dilation with precise clocks

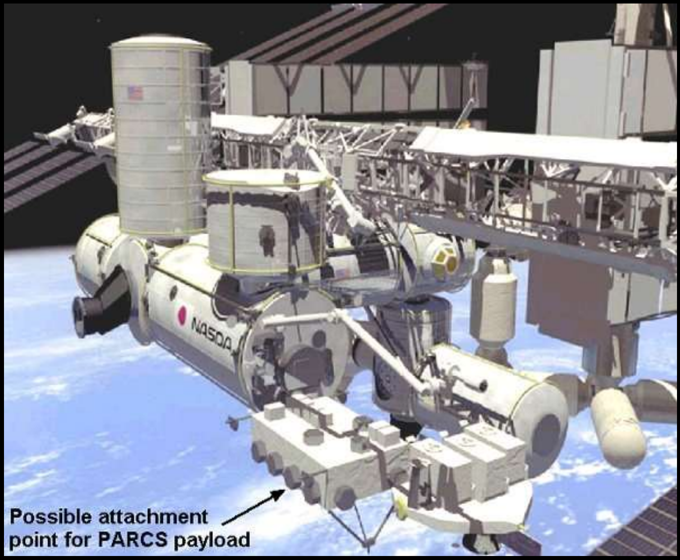
Measurements with clocks on spacecraft: do clocks slow as the gravitational field increases, as predicted by GR?

So far, no deviations from predictions found



Gravity Probe A, 1976

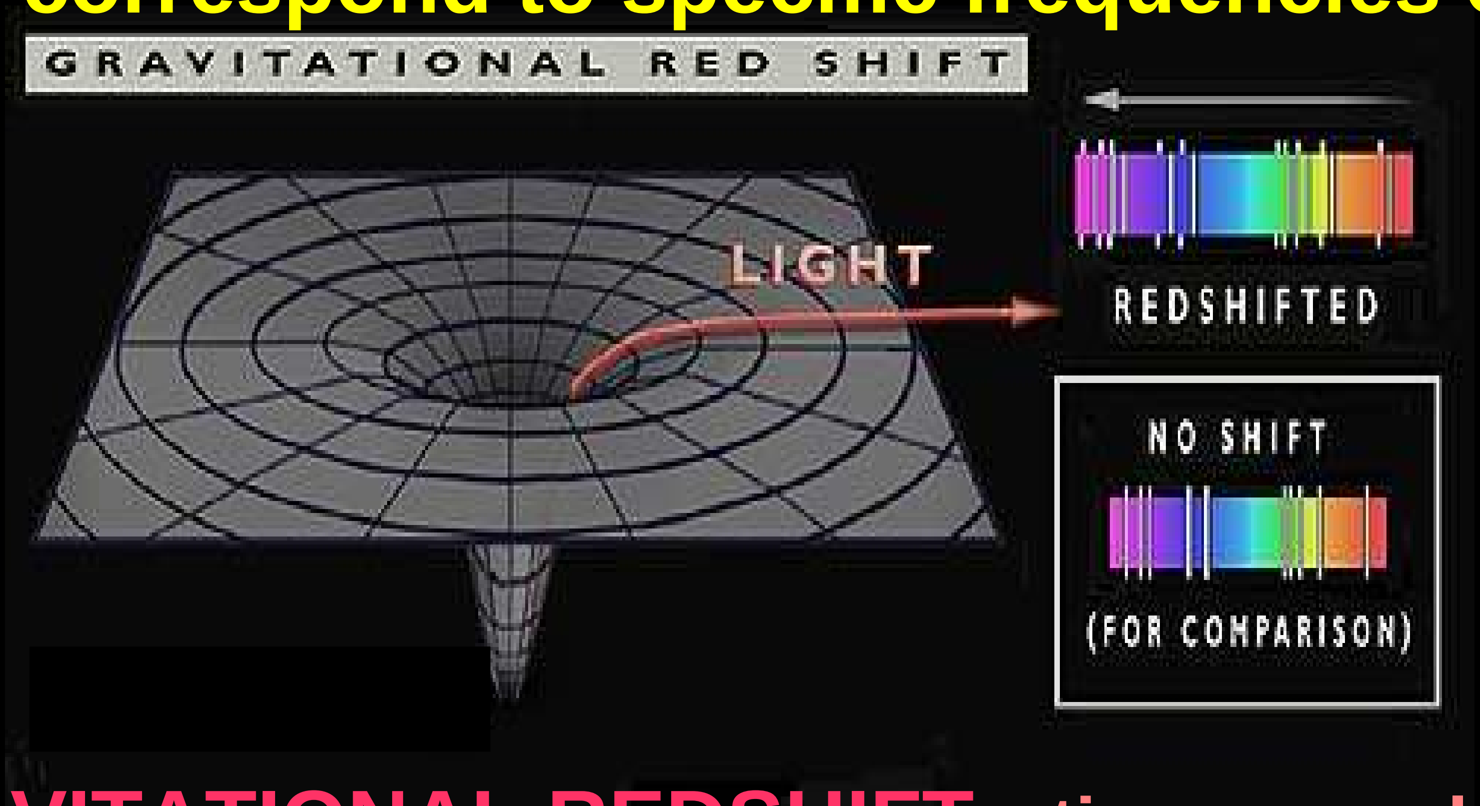




Primary Atomic Reference Clock in Space for International Space Station

Can use *spectral lines* as clocks:

they correspond to specific frequencies of light

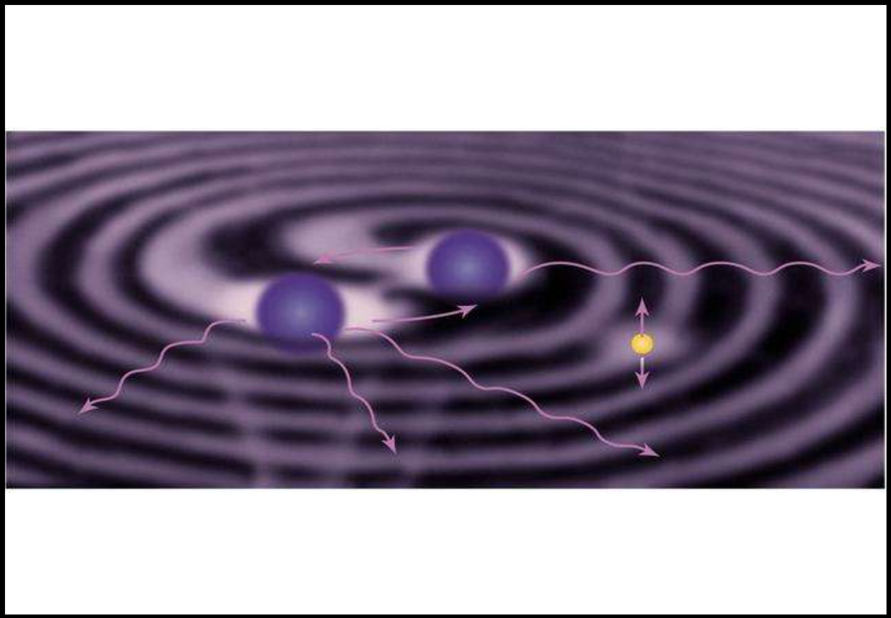


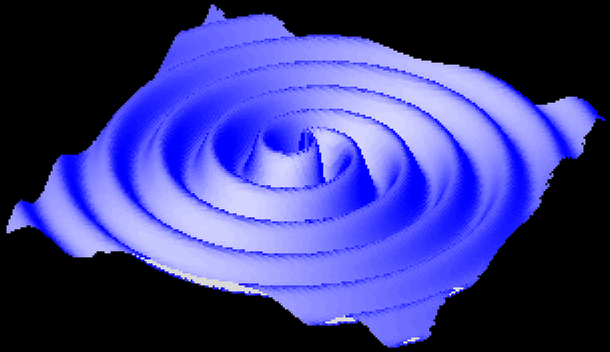
GRAVITATIONAL REDSHIFT: time runs slow near a strong gravitational field, so lines emitted near large objects will be redshifted (not same as Doppler shift)

This is observed, and results agree with GR predictions

Gravitational Waves

Ripples in spacetime caused by a disturbance

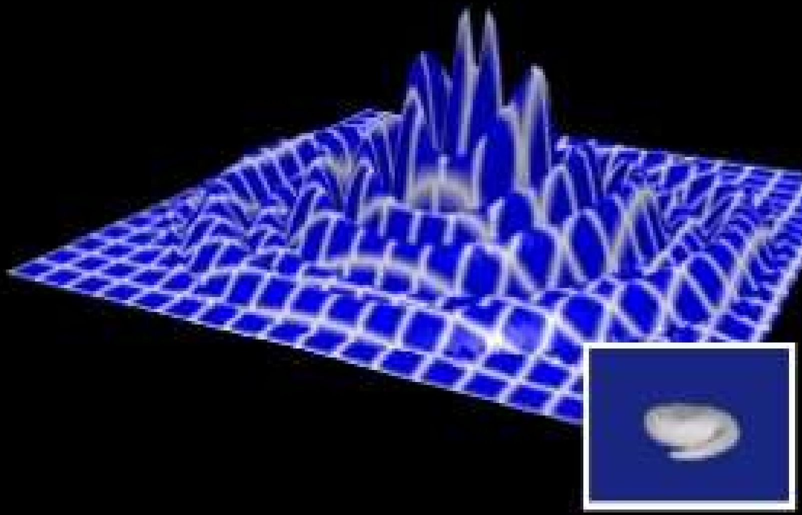


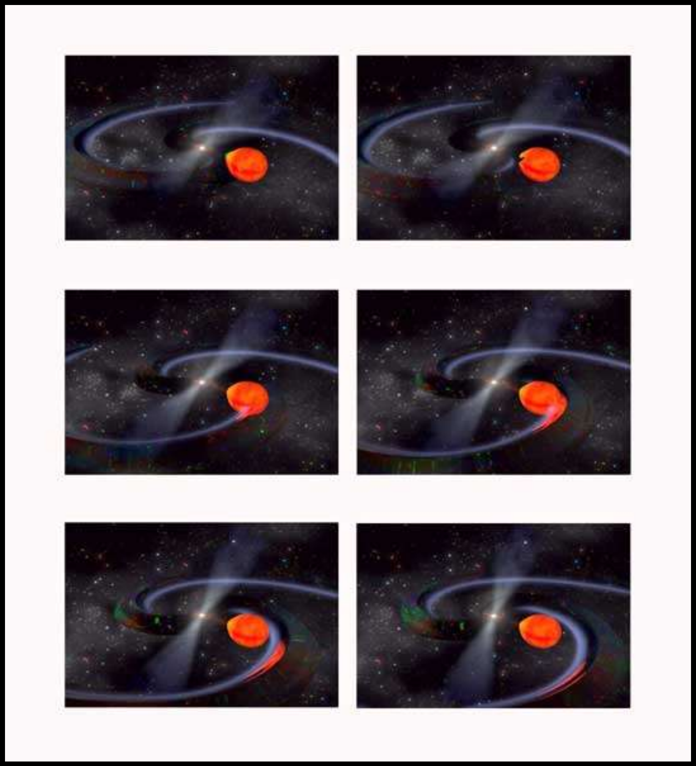


The waves carry energy; they compress and expand objects as they pass

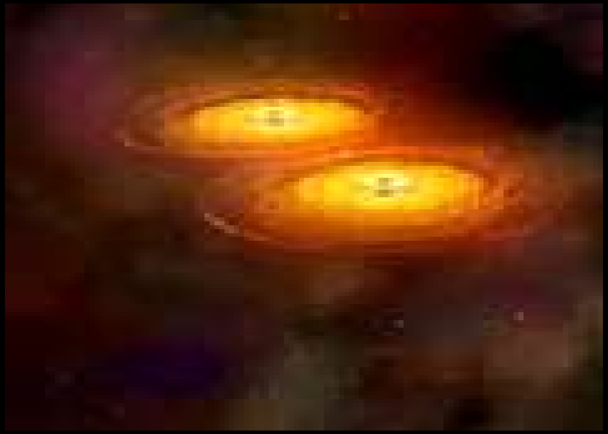
Gravitational Wave animations

rotating asymmetric object



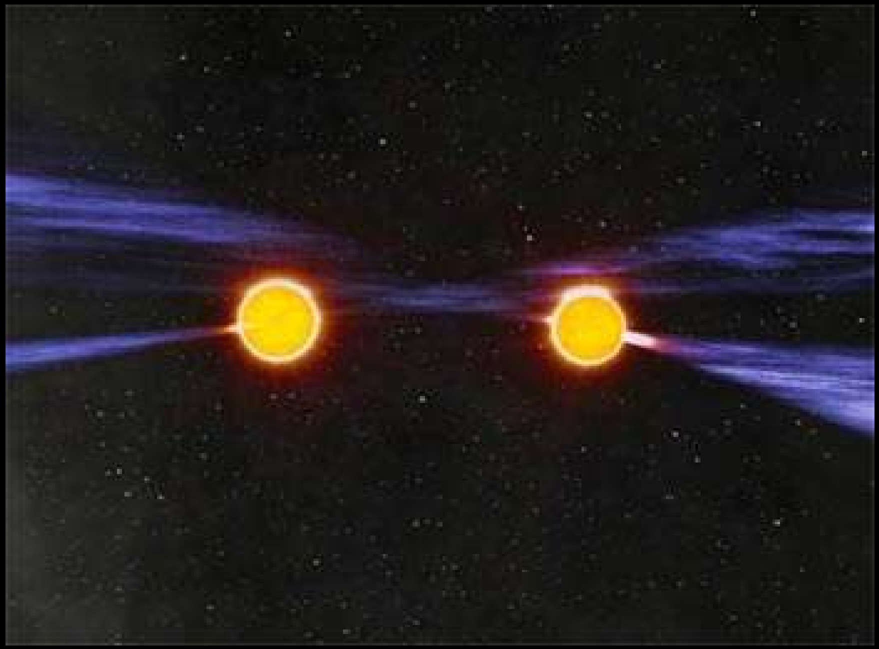


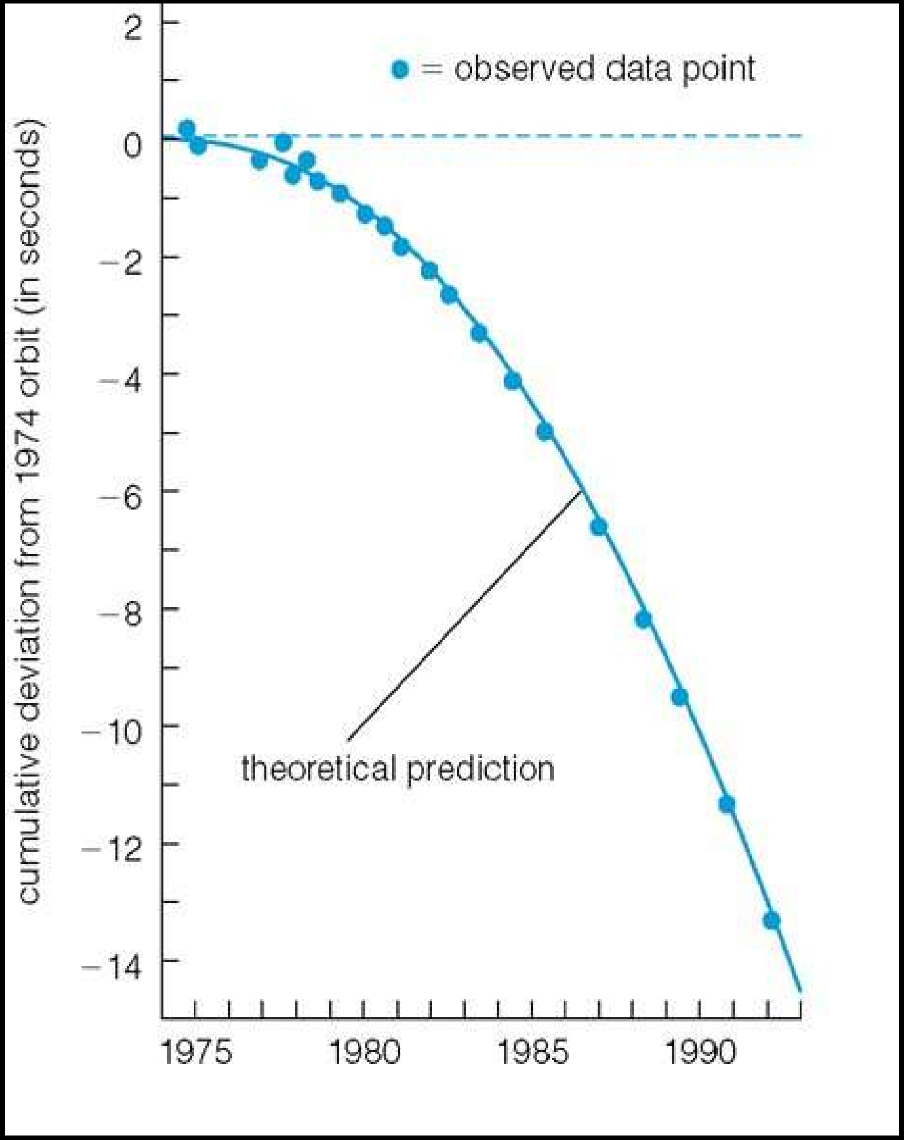
rapidly rotating pulsar



black hole merger from galaxy collision

Gravitational waves have so far been observed only INDIRECTLY





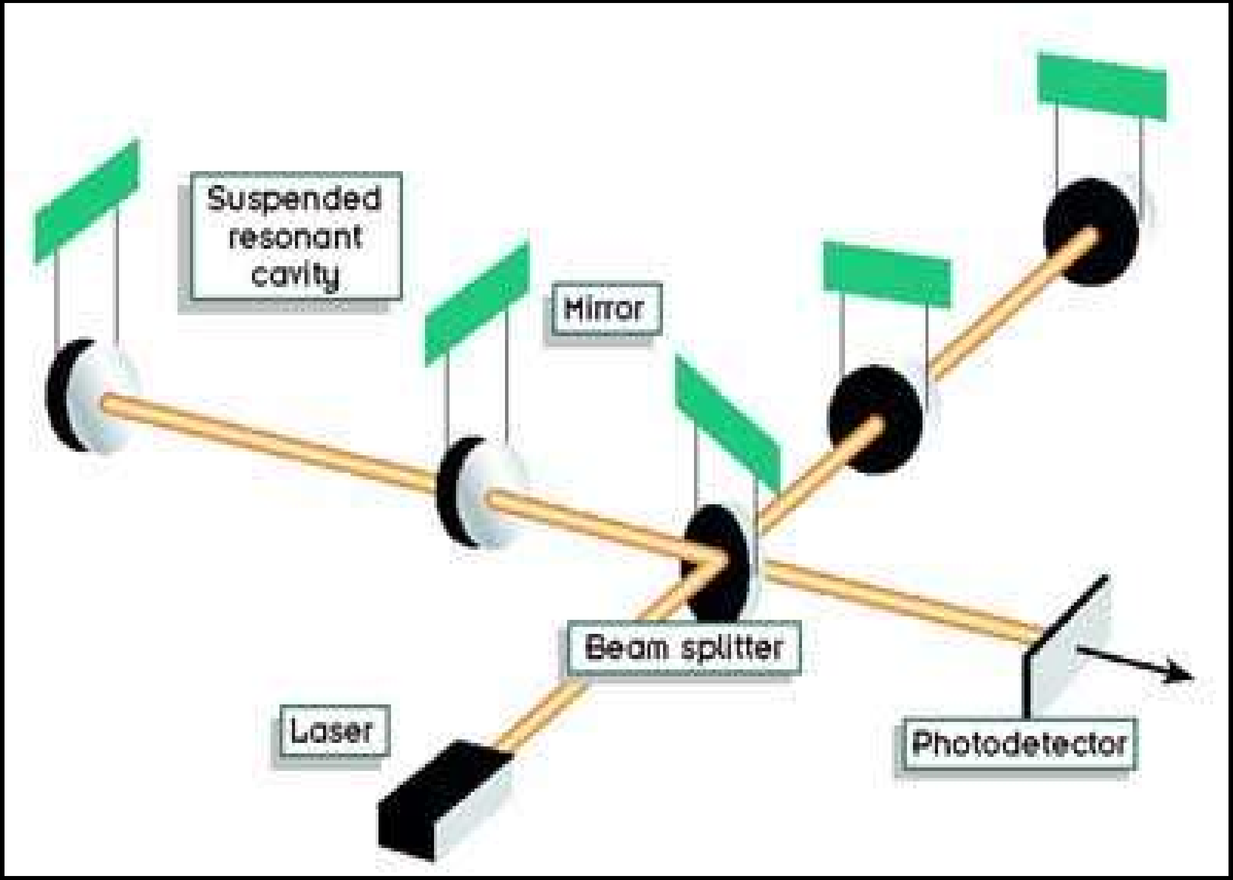
Hulse-Taylor binary pulsar, 1974

Energy lost to gravitational waves causes the orbits to decay

... observed!

Ongoing search to observe gravitational waves *directly*

LASER INTERFEROMETER



Passing wave causes tiny displacements of masses ~km apart, as spacetime is stretched and squashed...

this is detected by laser beam interference

LIGO: Laser Interferometer Gravitational Wave Observatory

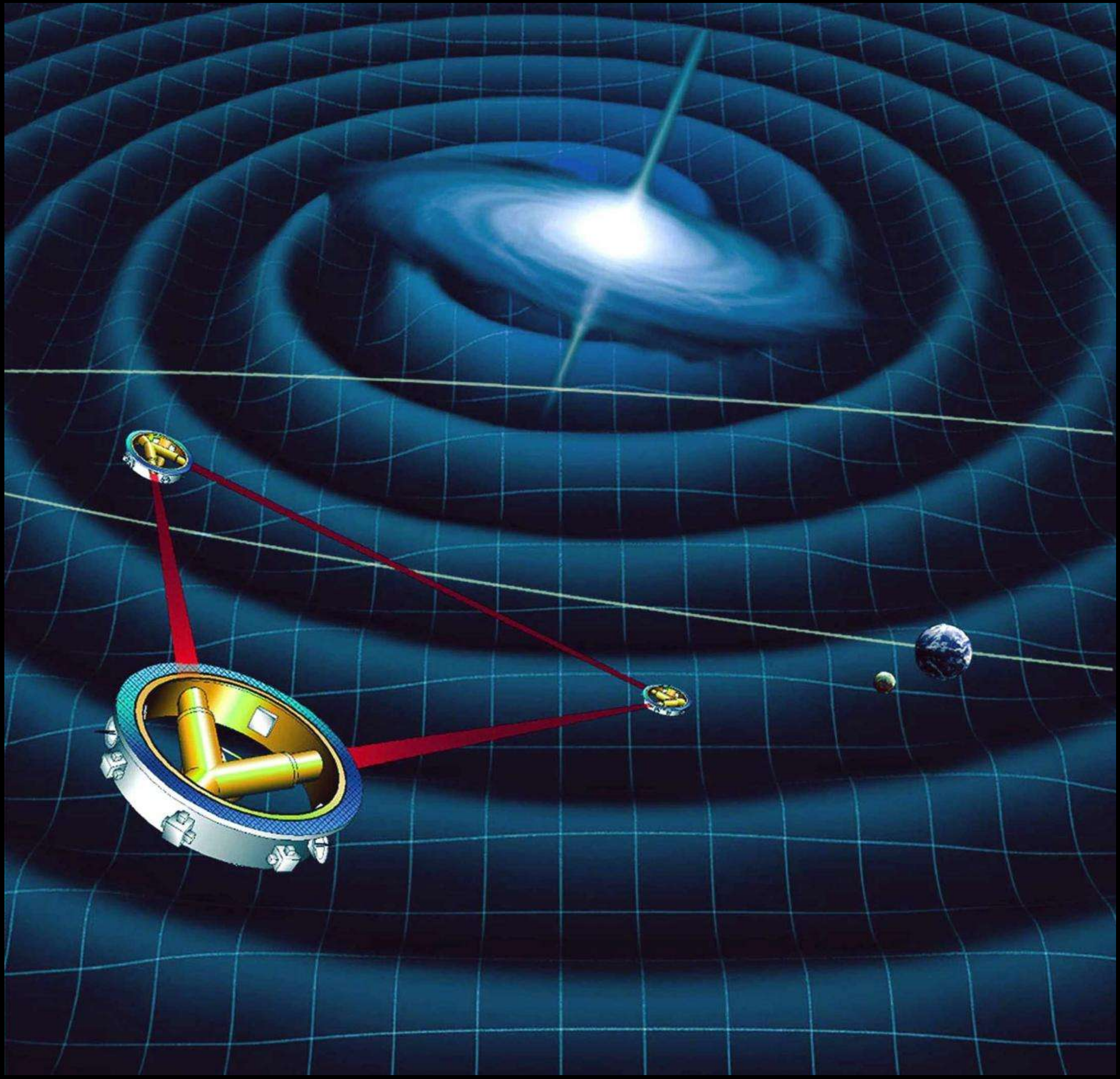
currently searching for gravitational waves
(requires tremendously good noise reduction)

Hanford, Washington

Livingston, Louisiana

Several similar projects around the world are also searching... none yet found, but prospects are good

Possible future project: LISA



laser interferometer in space

Let's revisit black holes in the context of general relativity...

We saw black holes as compressed stars: collapse as neutron degeneracy pressure can no longer counteract gravity

Escape velocity

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

If r is really small, v_e gets really big

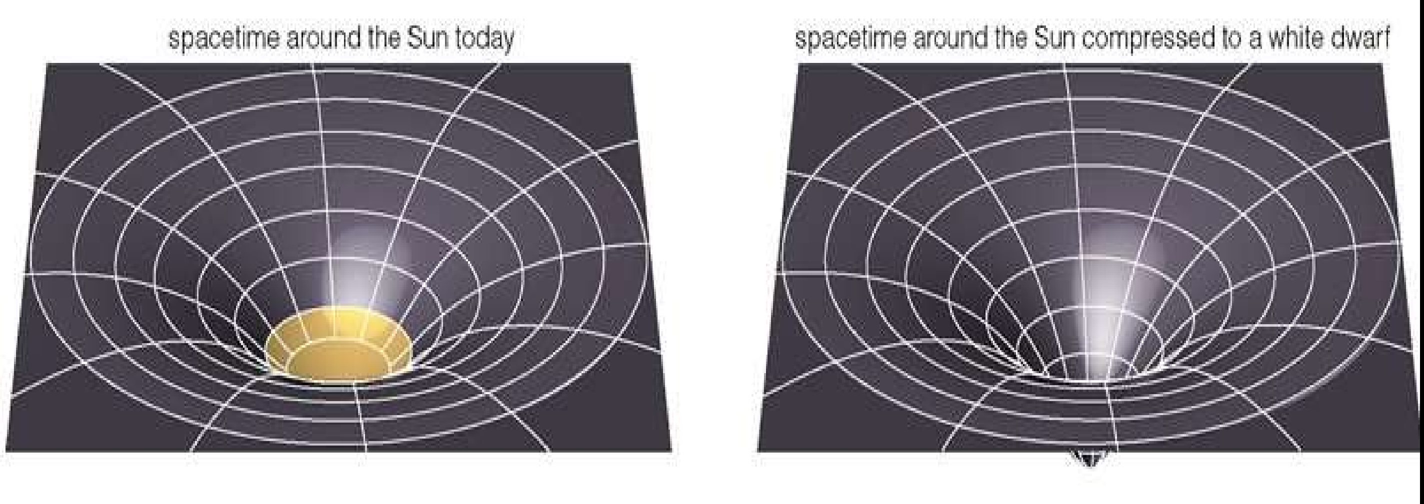
Inside the EVENT HORIZON nothing can ever get out, not even light!

Schwarzschild radius

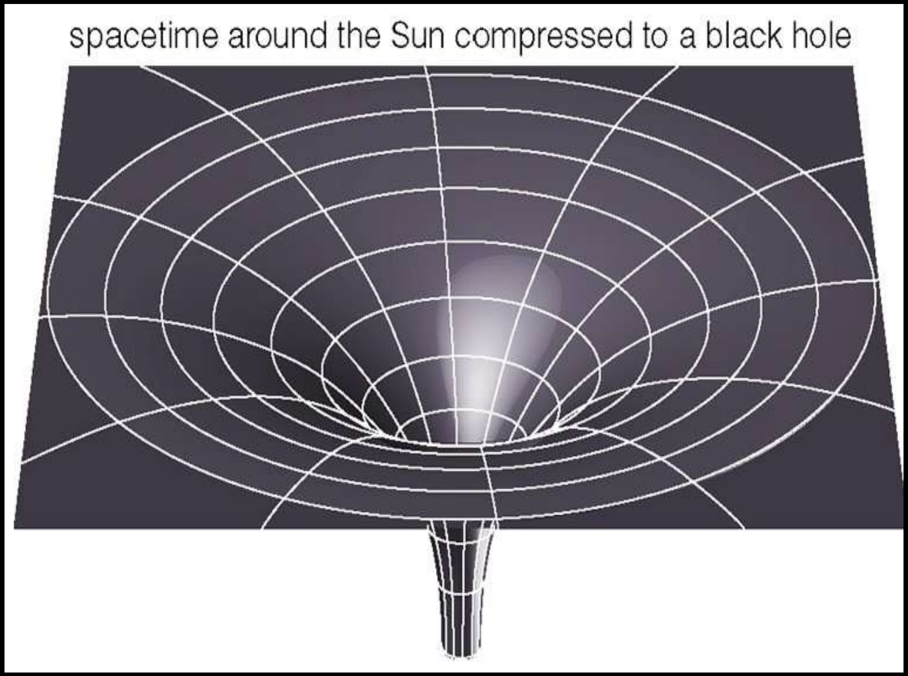
$$R_s = \frac{2GM}{c^2}$$

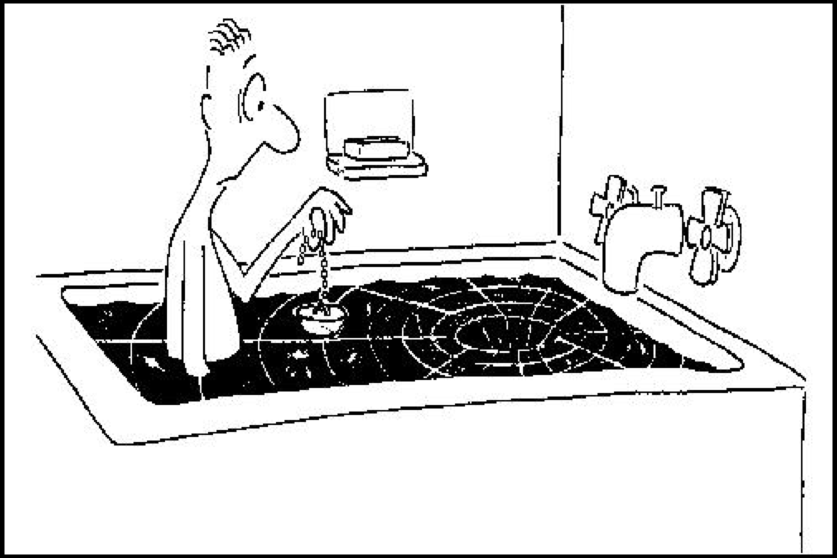
When objects compress, the curvature increases nearby them

(no change outside)

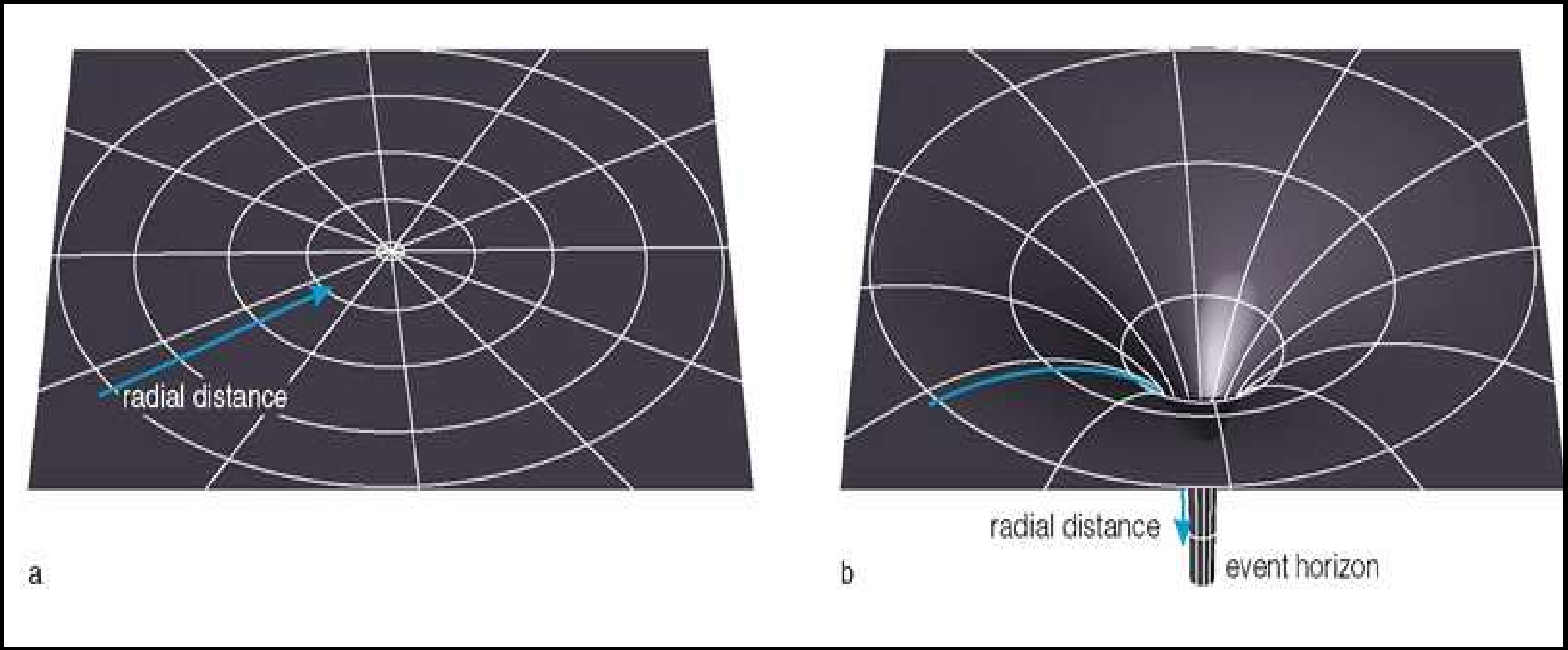


In our rubber sheet analogy, a black hole really is a 'hole in the universe'





Meaning of the event horizon in this picture:



Light always takes the straightest possible path:

inside the event horizon, the path is curved such that light can never exit

Schwarzschild radius:

radius the event horizon would have if spacetime were flat

PRS Question

Suppose you drop a clock toward a black hole. As you look at the clock from a high orbit, what will you notice?

a. The clock will fall faster and faster, reaching the speed of light as it crosses the event horizon.

b. The clock will fall toward the black hole at a steady rate, so that you'll see it plunge through the event horizon within minutes.

c. Time on the clock will run faster as it approaches the black hole, and light from the clock will be increasingly blueshifted.

d. Time on the clock will run slower as it approaches the black hole, and light from the clock will be increasingly redshifted.

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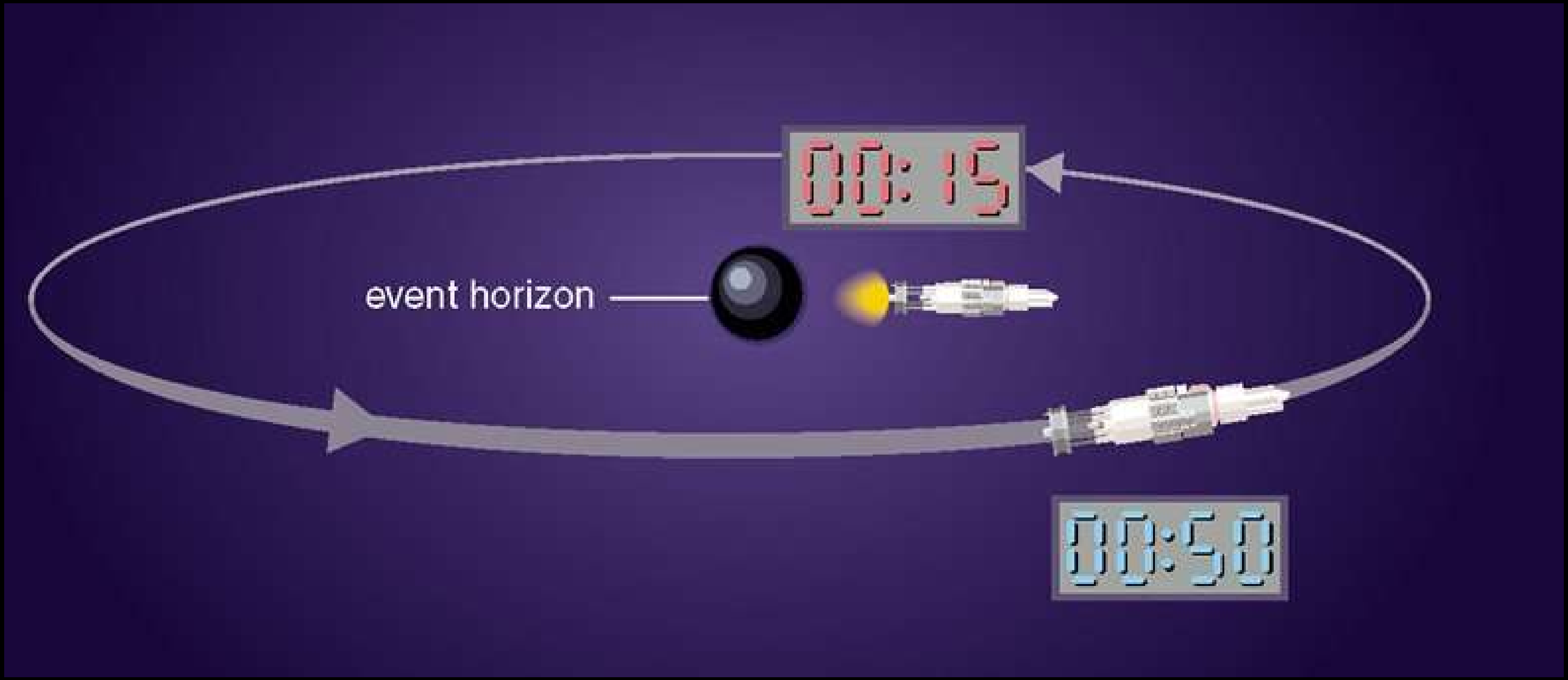
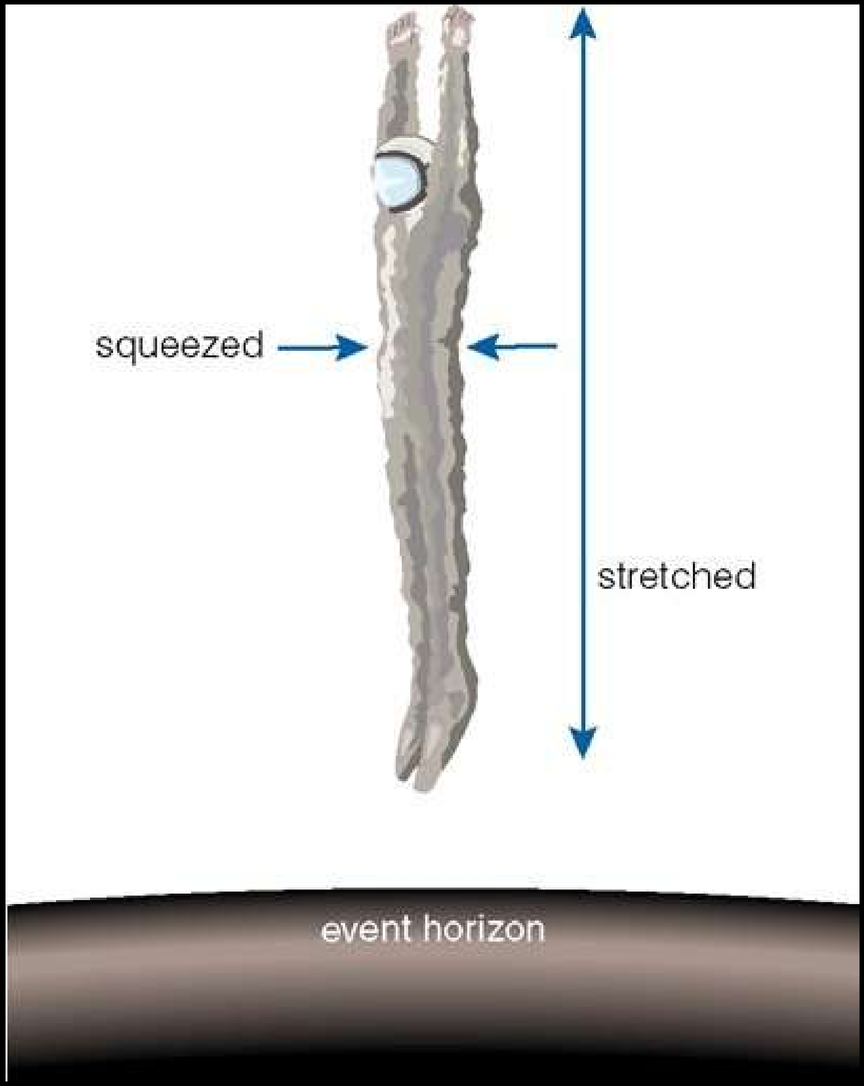
Due to gravitational redshift/time dilation, time *runs slower the closer you get* to a black hole



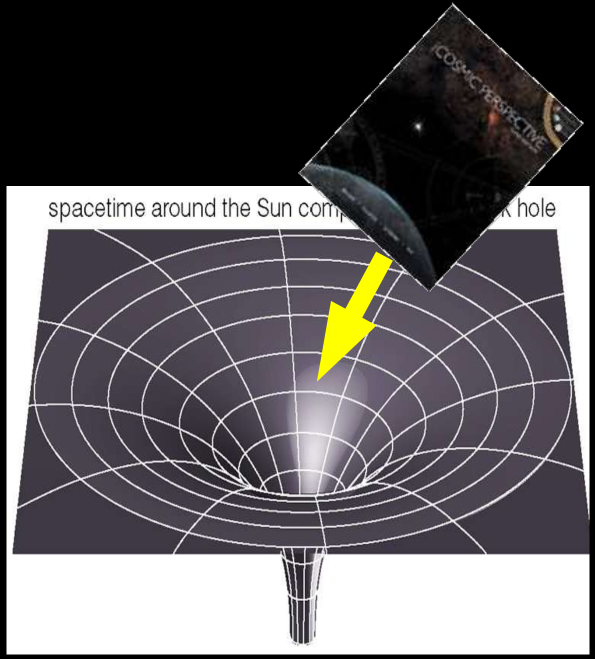
If your friend Jackie dives towards the black hole, you will see her clock come to a stop... it takes an infinite time for her to cross from your point of view!

(she sees *your* time running fast!)

But in fact, Jackie may get squished before she crosses, due to the gravitational force pulling her feet harder than her head!



What's inside the black hole?



An infinitely dense point?
A SINGULARITY

We do not know what happens there: information cannot get out!

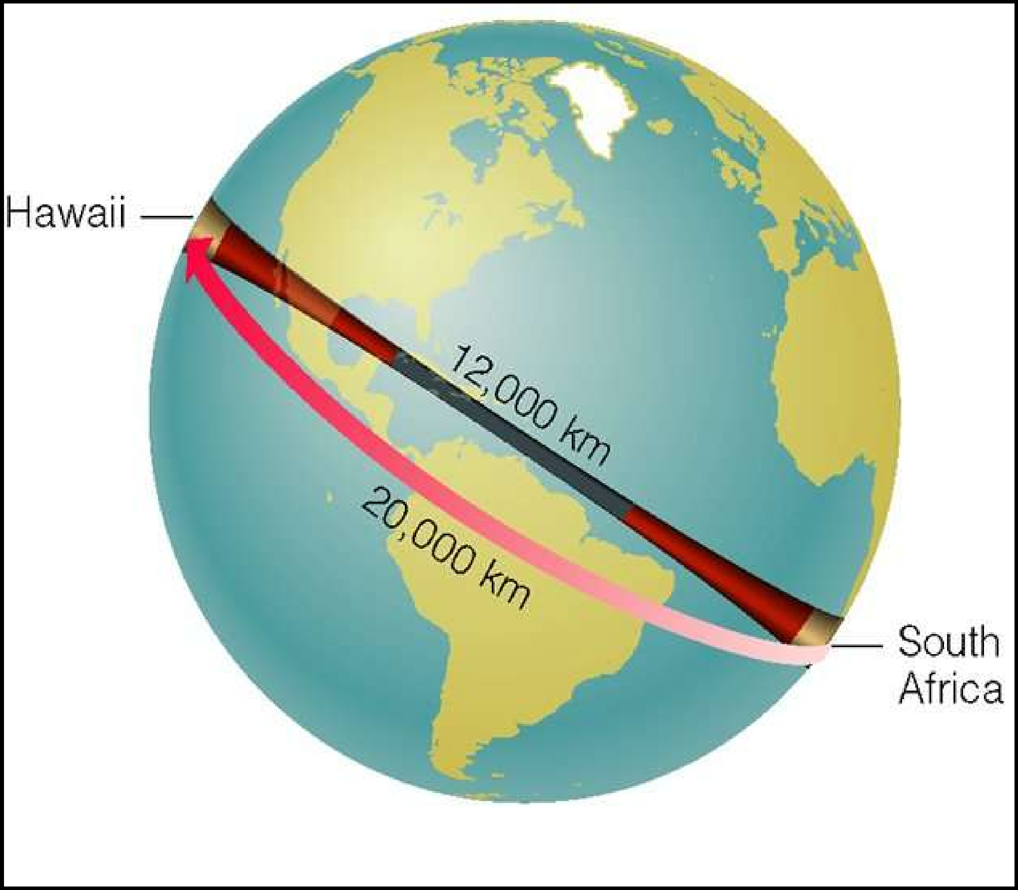
- **GR predicts infinite curvature**
- **Quantum physics predicts fluctuations**

Is *information* really *lost* from the universe?

Stephen Hawking thought yes...
now has changed his mind...

Some speculations:

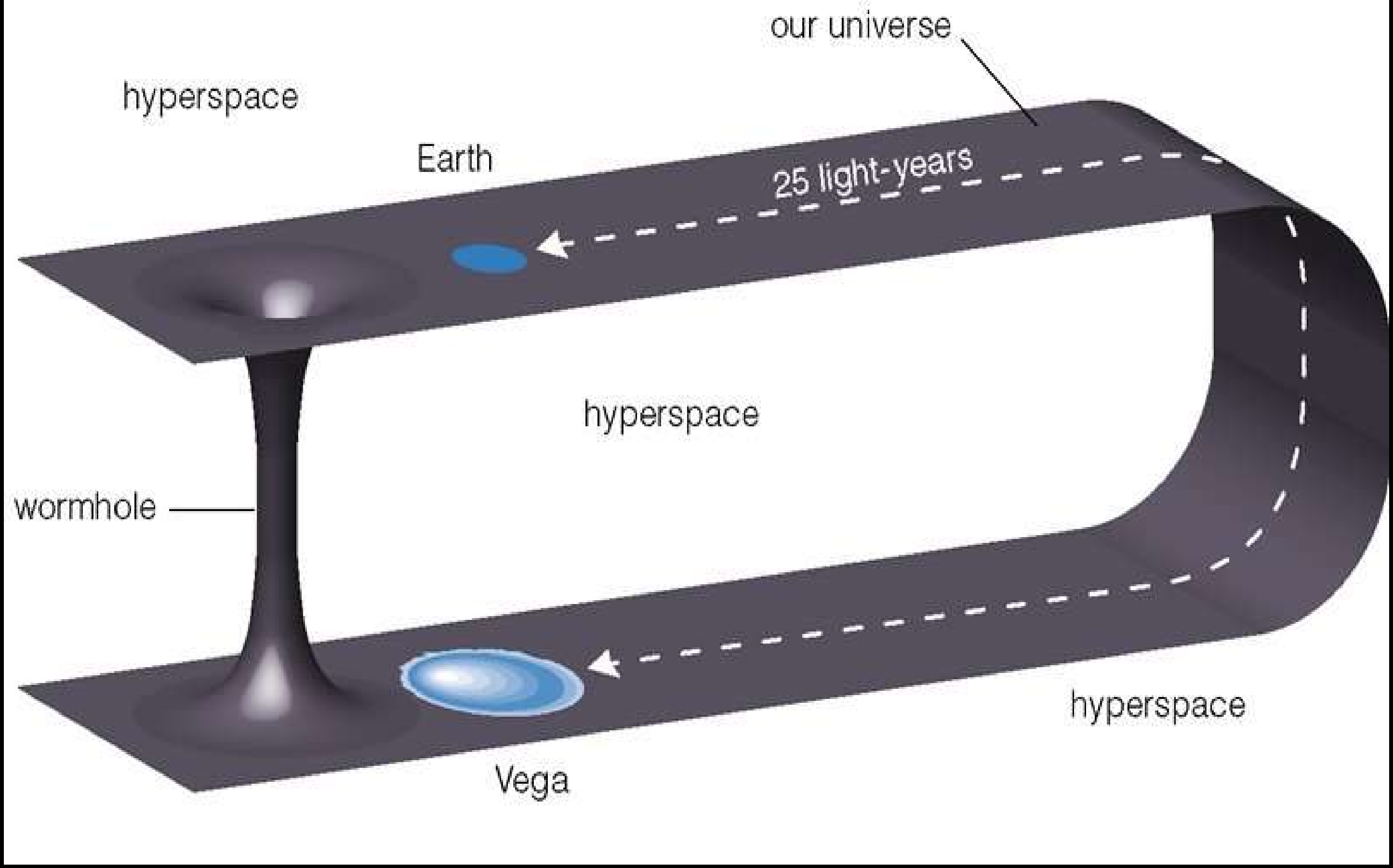
Take a short cut through spacetime with a WORMHOLE??



3D analogy: it takes less time to travel *through* the Earth than across the 2D surface if you tunnel through

What if you could tunnel through hyperspace?

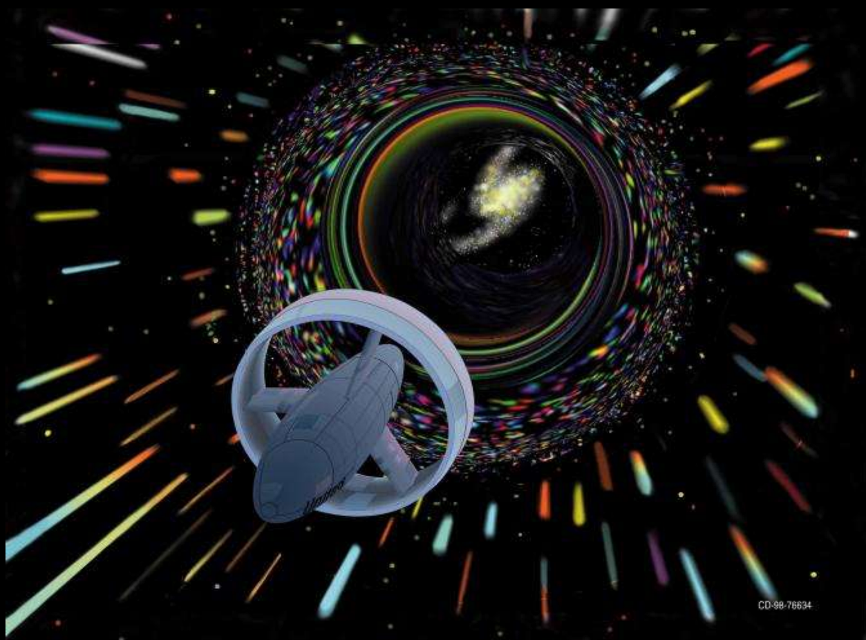
You could travel at a speed effectively greater than c



This would work if space is conveniently curved...

Or, might we curve space ourselves with **WARP DRIVE?**

We have no evidence this would work...
but it's also apparently not strictly prohibited

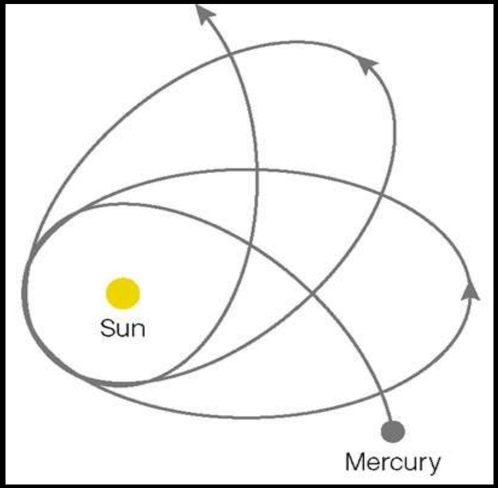


But this allows travel in *time*, too

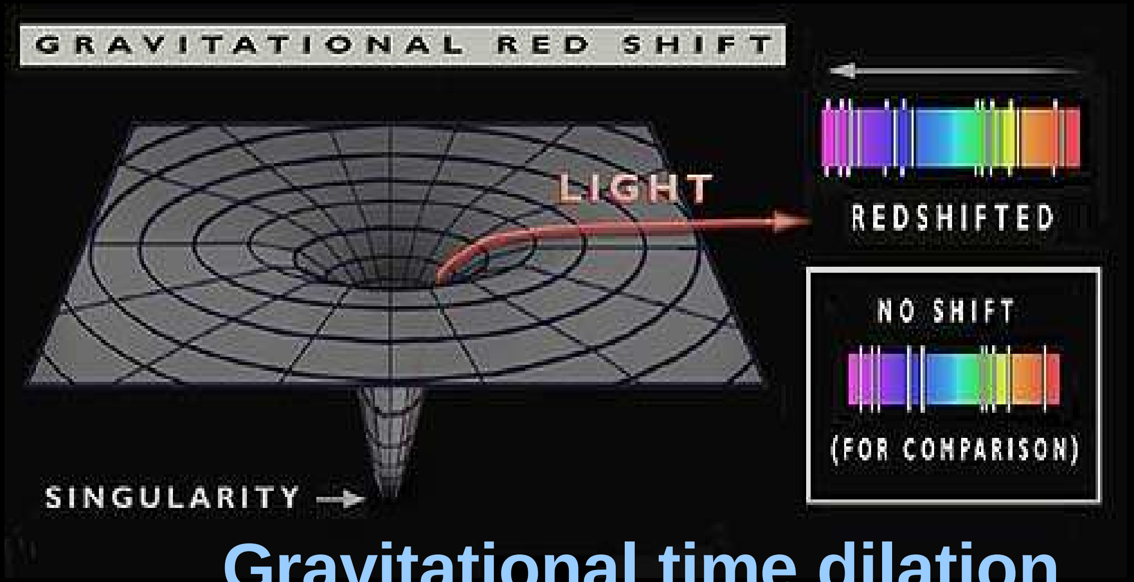
Problem: violate causality?
Well explored in science fiction...

WUN2K

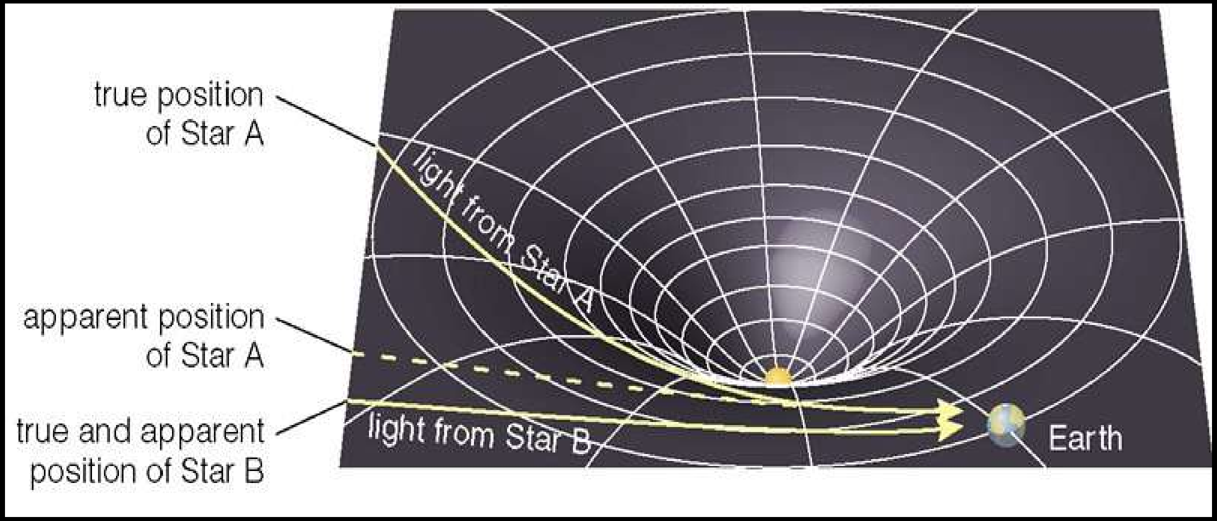
General relativity has so far passed *all* experimental tests



Precession of Mercury



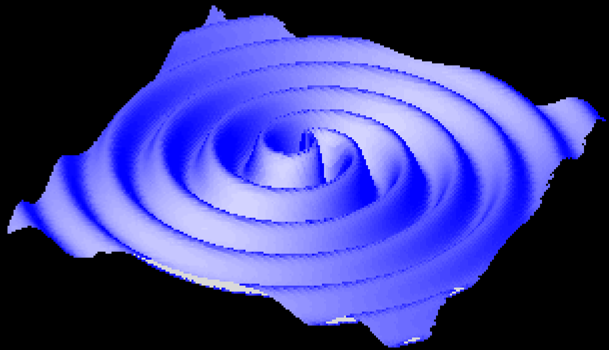
Gravitational time dilation and redshift



Bending of light; gravitational lensing

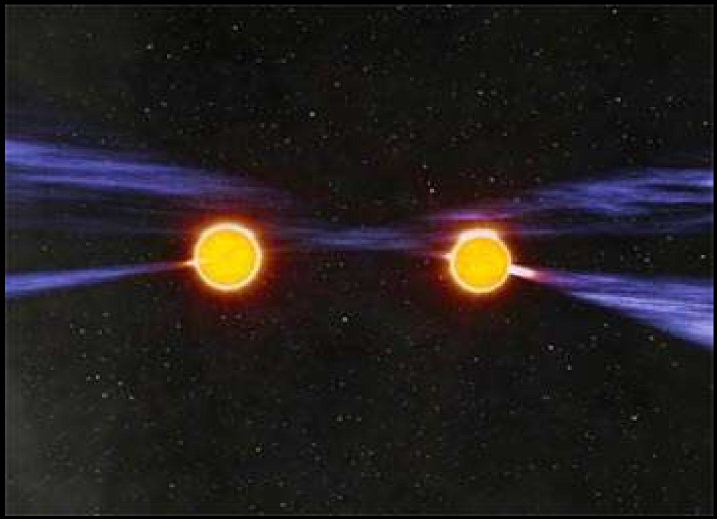
WUN2K

GR is still under test! (Does it break down somewhere?)



Gravitational Waves:

ripples in spacetime caused by a disturbance



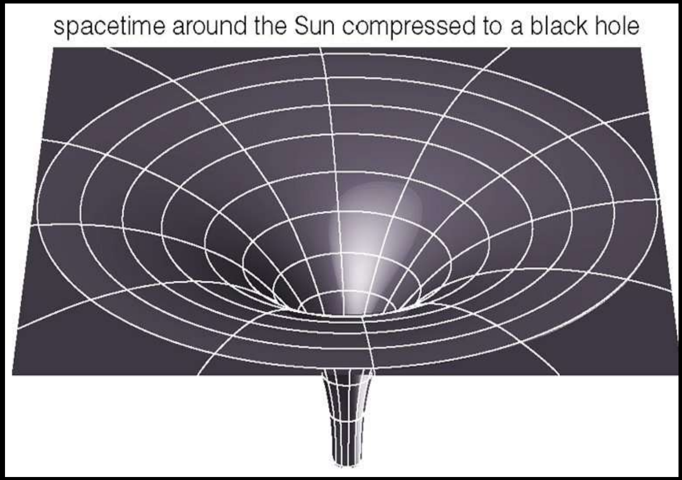
GW observed *indirectly* from orbital decay of binary pulsars

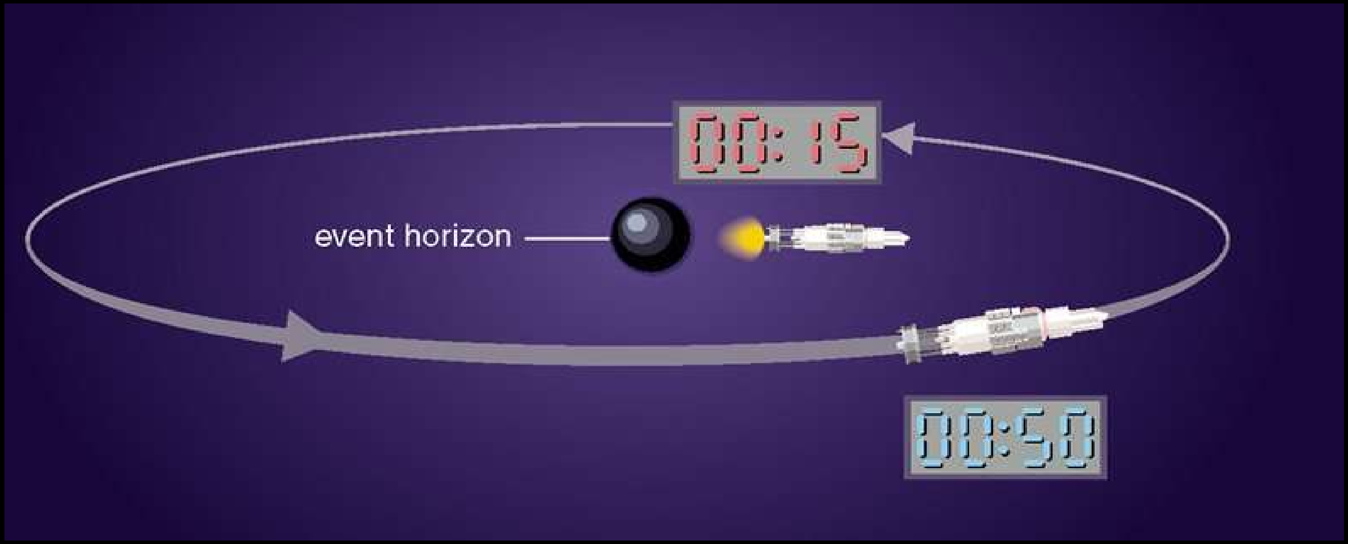
Current attempts to observe GW *directly* using giant laser interferometers

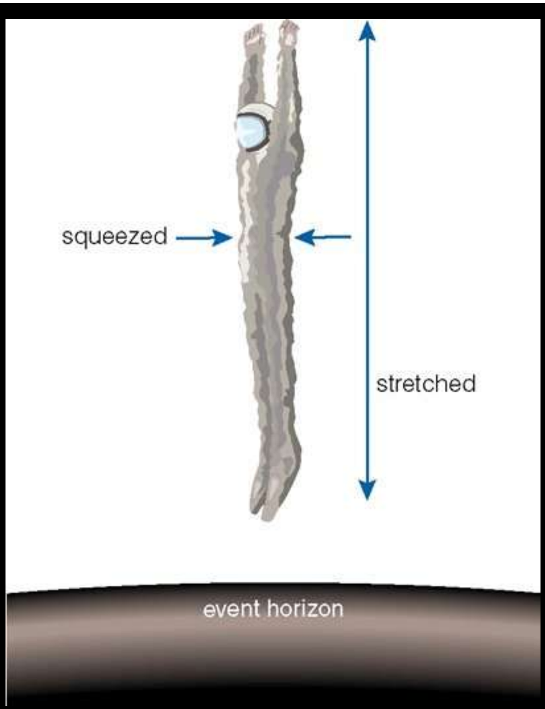
WUN2K

Black holes revisited

Region of infinite curvature? (singularity)





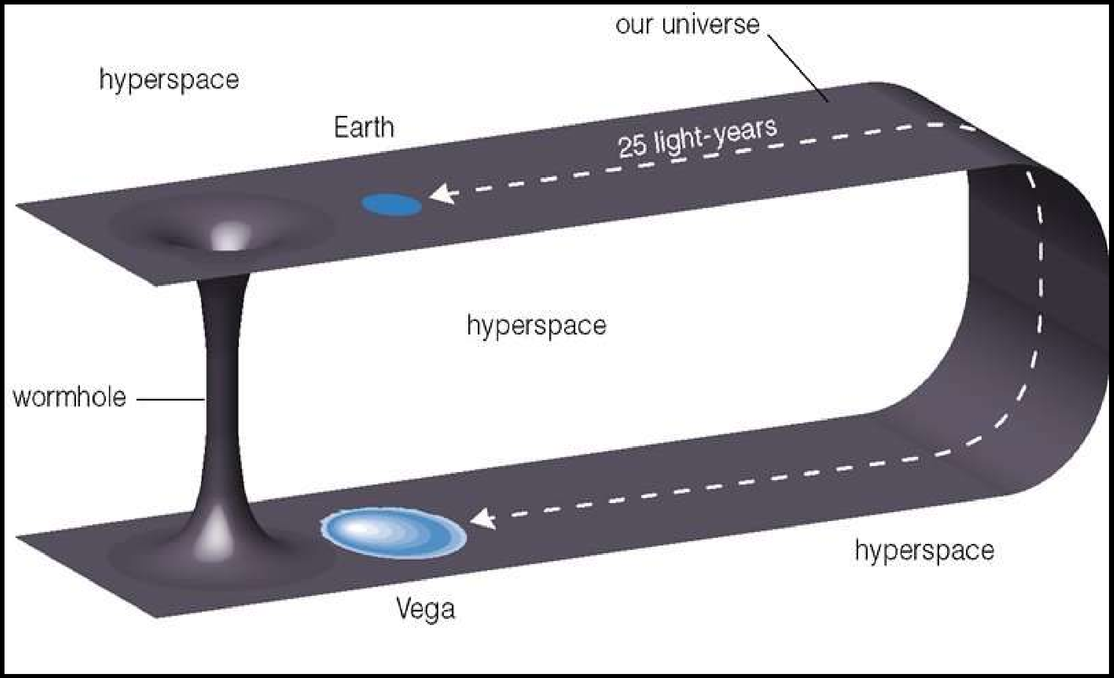


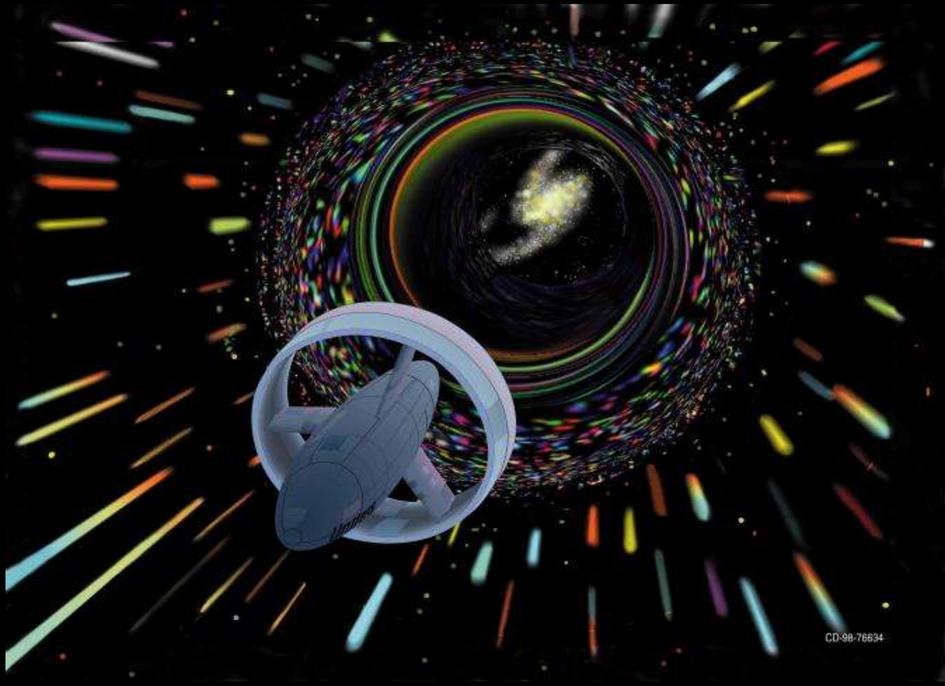
Time slows to a stop at the event horizon; objects squeezed by tidal forces

WUN2K

Speculative ideas

(not known if they work, but not strictly forbidden)





Wormhole: shortcut through hyperspace;
travel at speeds effectively >c

Warp drive: curving spacetime at will?

Minute Questionnaire

Please take a minute to fill it out.

I will answer try to answer all (well-posed) questions on the web as soon as I can

Please use this to give me feedback