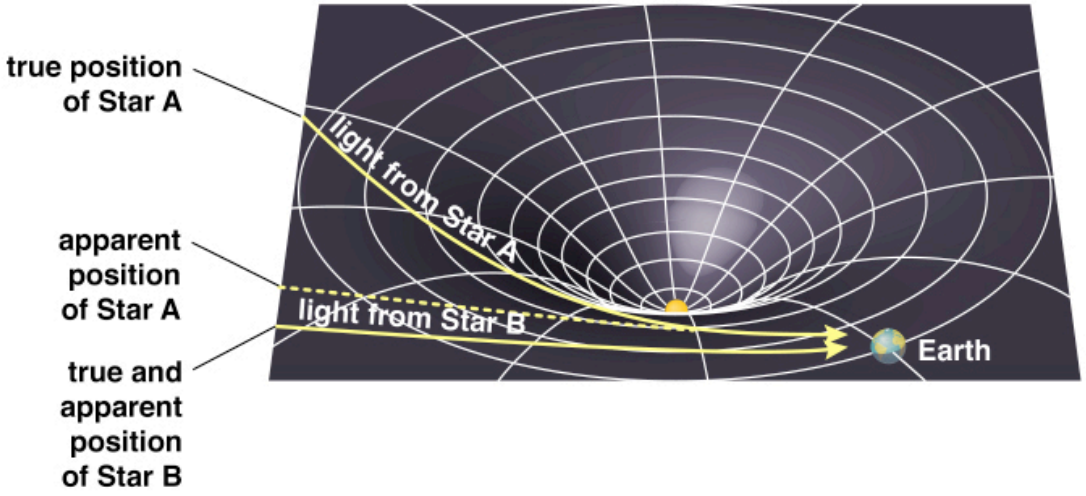
Recap: Eddington's observation was the first (of very few) piece(s) of (new) evidence for GR



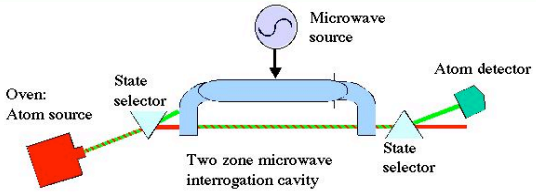
Recall: How do you define the second?

Some physical process.

The Earth's revolution around the Sun isn't as constant as you think. A pendulum is pretty good -- but how do you know the one in Paris and the one in Berlin are exactly the same? And can you really measure it to 10 or 20 digit accuracy?

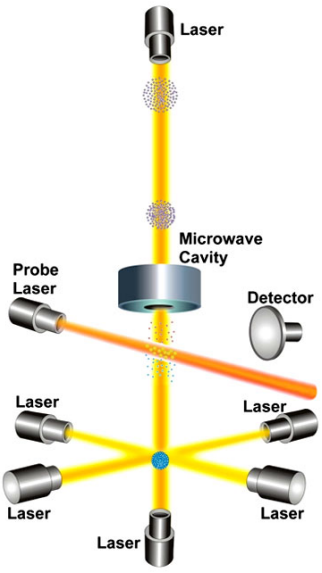
Beam clocks

Atomic clocks:
every atom of Cesium behaves
exactly the same way, so use



- Fast beam interacts with microwaves twice
  - Time between interactions of 10's of ms
- Flux into atom detector gives error signal

How do you *define* the second?



How do you *define* the second?

But gravity is the same as acceleration, which dilates space and time (recall Sue seeing Lou age while she accelerates), and NIST – in Colorado, a mile above sea level – feels *slightly* weaker gravity than Ottawa

During the 1970s it was realized that gravitational time dilation caused the second produced by each atomic clock to differ depending on its altitude. A uniform second was produced by correcting the output of each atomic clock to mean sea level (the rotating geoid), lengthening the second by about $1 \cdot 10^{-10}$. This correction was applied at the beginning of 1977 and formalized in 1980. In relativistic terms, the SI second is defined as the proper time on the rotating geoid.[21]

Gravity Waves

There is *energy* stored in the "stress" of curved spacetime.

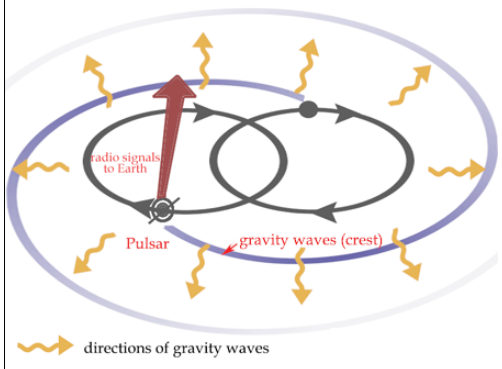
(Remember gravitational potential energy?)

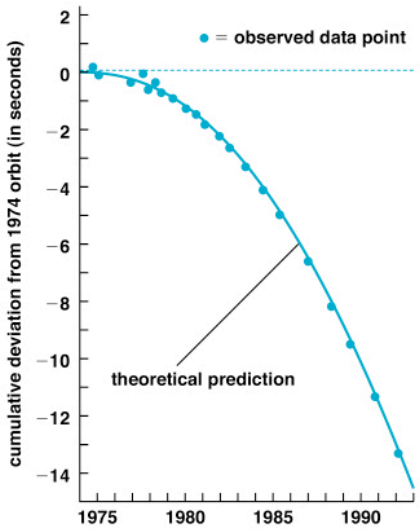
But if an object shakes around on a sheet, won't ripples start propagating in the sheet?

Einstein's equations predict exactly the same thing: *waves of pure gravity*.

Hulse & Taylor 1993 Nobel Prize

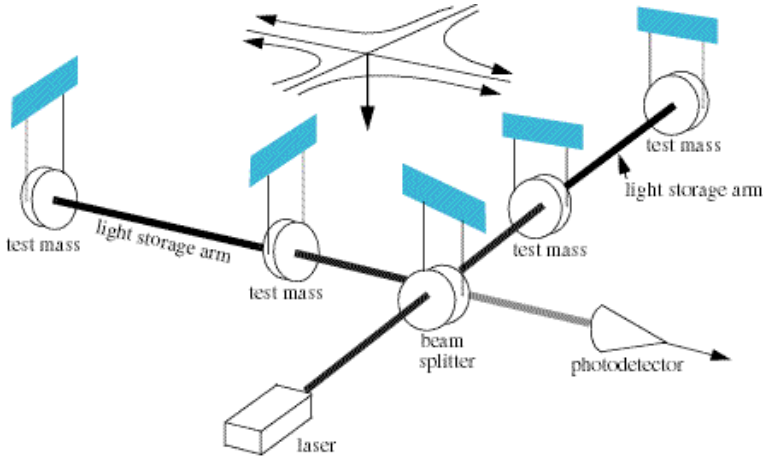
(none to Eddington... and none to Einstein for GR!)





But where are the waves???

LIGO

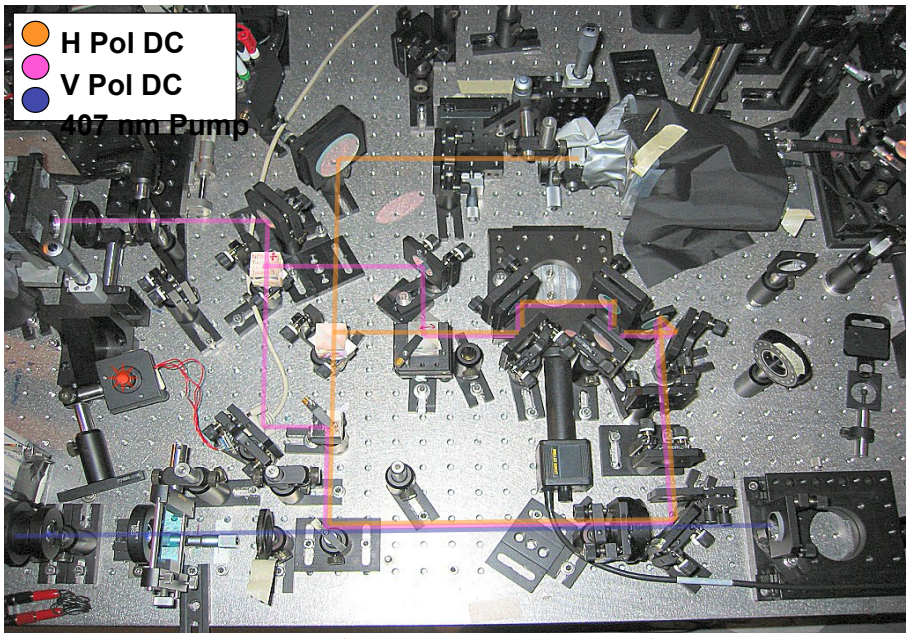


How to achieve a sensitivity of one part in 10^{21} (ten billion times ten billion, times ten for good measure)??

Ten billion would be one millimetre out of the diameter of the Earth, or about one single atom out of one metre.

10^{21} would be one single atom out of the *distance to the Sun*.

An interferometer



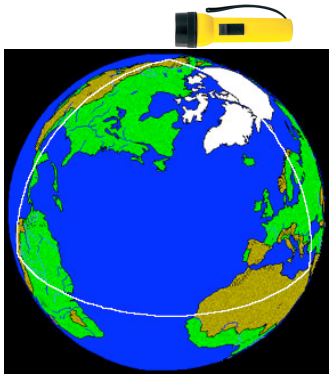
30 cm

LIGO

The arms are empty vacuum - all that matters is the motion of the mirrors on the end. They are suspended like little pendulums, to be immune as much as possible from earthquakes, logging, trucks,...

Geodesics

Question: what path does light follow on the surface of the earth?

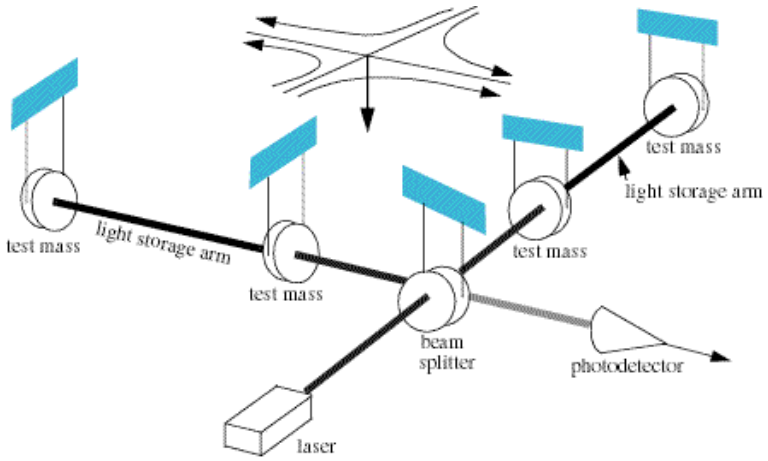


Geodesics...

what path will light follow around the Earth?

If they'd ordered a "straight road," the light would have missed the mirror by nearly a metre!

What makes the mirrors move?



Nothing. The mirrors *don't move*.
Spacetime itself changes, so that the *distance* between the mirrors oscillates -- even while both mirrors sit perfectly still.

Cosmology

Einstein could now write down the equation for the whole universe. Except, he found that it would necessarily suck itself together due to gravity and collapse.

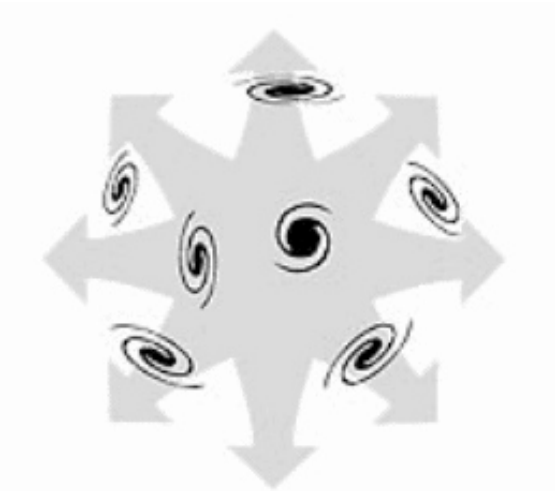
So, he found a place where his equations left some freedom, and added a number -- the "cosmological constant" -- to stop this.

In 1929, Edwin Hubble discovered something:

everything in the universe is moving away from us, and things which are twice as far away move twice as fast!

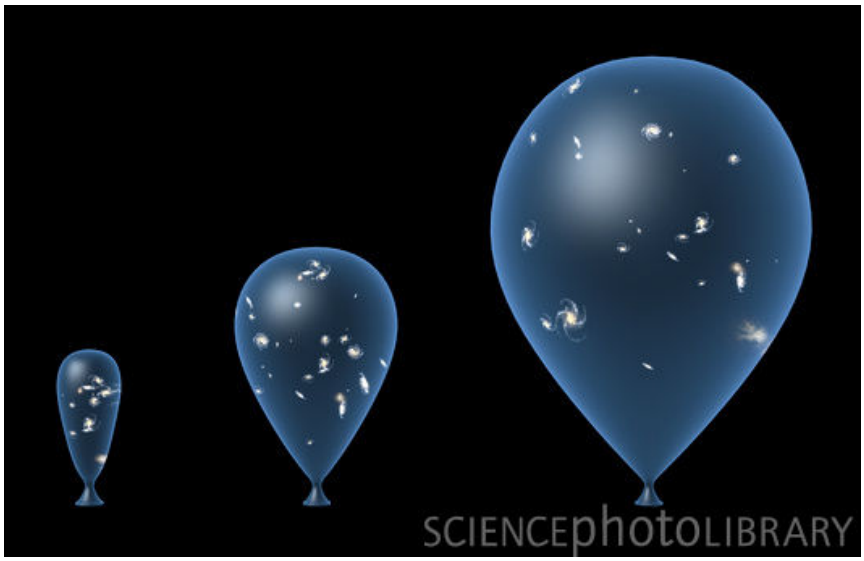
Einstein: "my greatest blunder."

Why are they all moving away from *us*?



They're not – remember dimensional analysis.
If every distance I measure gets twice as big, what happens to my prediction for distances other people measure?
Every one thinks he/she's at the centre, and it doesn't matter...

They're not.



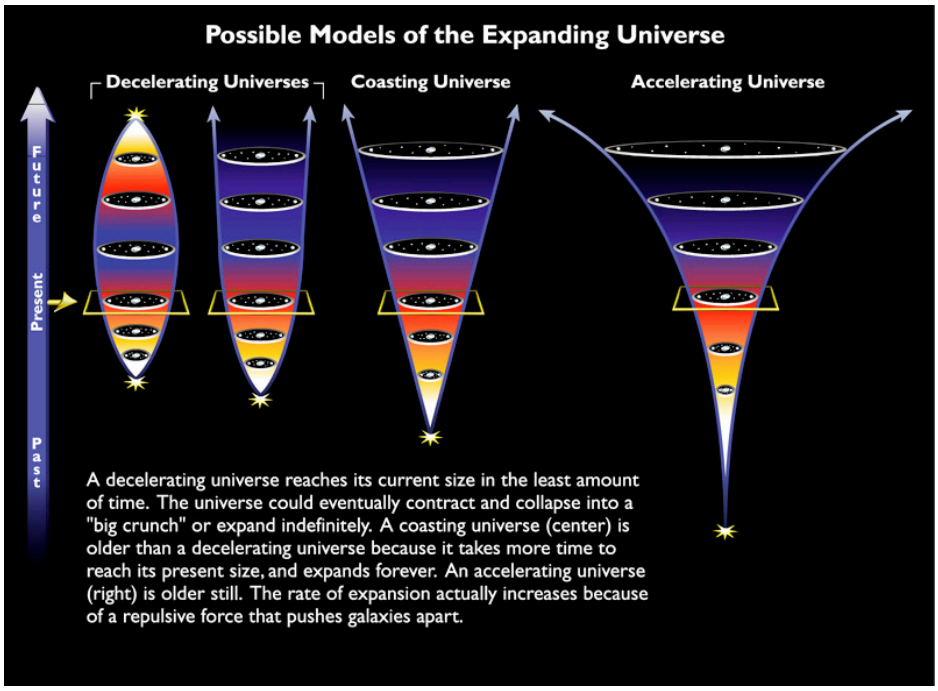
Just like LIGO's mirrors, every galaxy is sitting (mostly) still, and yet the distance just gets bigger and bigger underneath us.

Q: Why, then, is the Sun no further away than it used to be? Why is there still not enough parking in New York City?

I awoke on Friday and because the universe is expanding it took me longer than usual to find my robe. This made me late leaving for work, and because the concept of up and down is relative the elevator I got into went to the roof, where it was very difficult to hail a taxi. Please keep in mind that a man on a rocket ship approaching the speed of light would have seemed on time for work—or perhaps even a little early and certainly better dressed. When I finally got to the office and approached my employer Mr. Muchnick to explain the delay, my mass increased the closer I came to him, which he took as a sign of insubordination. There was some rather bitter talk of docking my pay, which, when measured against the speed of light, is very small anyhow. The

- Woody Allen, "Strung Out" (*New Yorker*, 2003)

"CLOSED, SPHERICAL" "FLAT" "SADDLE-SHAPED"



Except: dark energy

It seems, so far as we can tell, that

(a) the universe *is* flat on the largest length scales

(b) instead of "coasting" or slowing down, it's accelerating *outwards*.

Einstein's "cosmological constant" seems to exist after all-- but no one has any idea what exactly it is.

"Dark energy." There seems to be just enough of it to "flatten out" a universe that would otherwise be too light.

"Inflation"?

Questions

Over time, we see a distant galaxy getting further away from us. How can we tell whether they're moving or whether we are?

When the size of the Universe has increased by 10%, how long will a meterstick be?

When the size of the Universe has increased by 10%, what will the distance from the Earth to the Sun be?

When the size of the Universe has increased by 10%, what will the distance from the Sun to α-Centauri be?