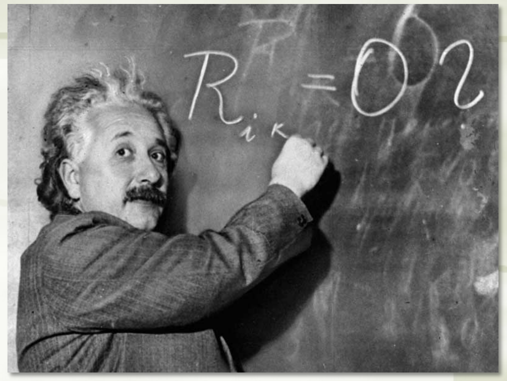


General Relativity

Classical tests

Gravitational lensing

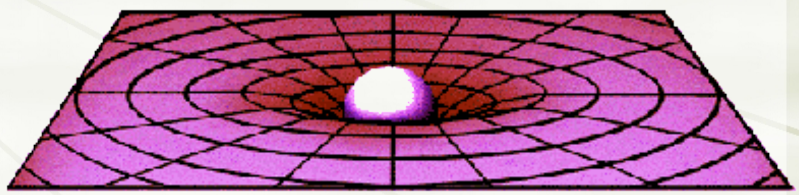
Gravitational waves

General Relativity II

- The General Theory of Relativity
  - Einstein's equations
- Consequences of GR
  - Orbit of Mercury
  - Gravitational lensing
  - Gravitational waves

How does matter "warp" space?

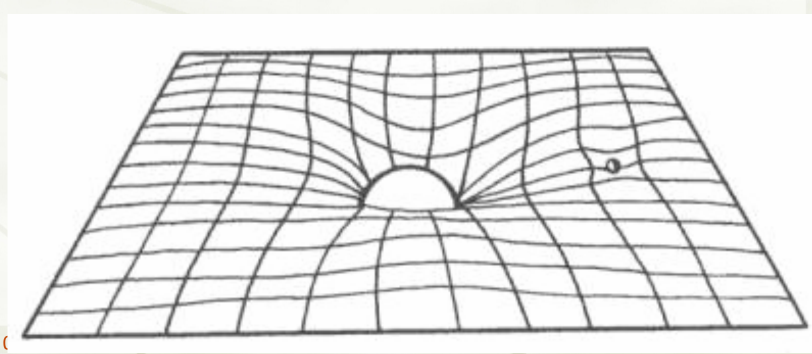
- Use two-dimensional space as an analogy: think of how rubber sheet is affected by weights
- Any weight causes sheet to sag locally
- Amount that sheet sags depends on how heavy weight is



From web site of UCSD

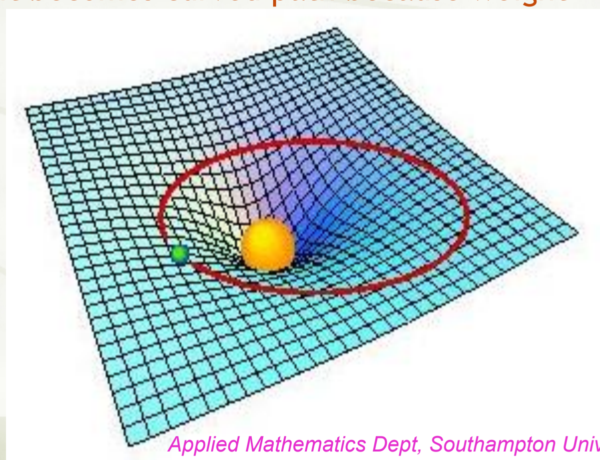
Effect of matter on coordinates

- Lines that would be straight become curved (*to external observer*) when sheet is "weighted"



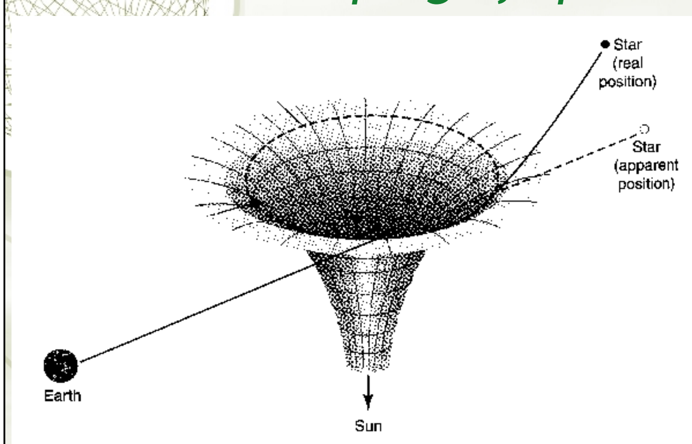
How are orbits affected?

- Marble would follow straight line if weight were not there
- Marble's orbit becomes curved path because weight warps space



Applied Mathematics Dept, Southampton University

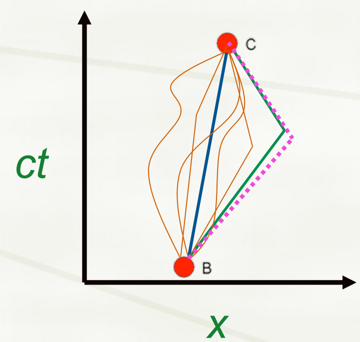
Warping of space by Sun's gravity



- Light rays follow geodesics in warped space

Particle's trajectories and geodesics

- **Particles travel paths that maximize their proper time!!**
- In a non-expanding flat space-time (inertial frame): Considering all possible world lines joining two points in a space-time diagram, the one with the **longest proper time** (=invariant interval) is always the **straight world line that connects the two points**
- In a curved space-time a geodesic is the path that maximize the proper time!



THE GENERAL THEORY OF RELATIVITY

- Within a free-falling frame, the Special Theory of Relativity applies.
- Free-falling particles/observers move on geodesics through curved space-time
- The distribution of matter and energy determines how space-time is curved.

"Space-time curvature tells matter/energy how to move. Matter/energy tells space-time how to curve."

Mathematical description of GR

$$\underline{\underline{\mathbf{G}}} = \frac{8\pi G}{c^4}\underline{\underline{\mathbf{T}}}$$

- The Einstein curvature tensor "$\underline{\underline{\mathbf{G}}}$" is mathematical object describing curvature of 4-D space-time.
- The Stress-Energy tensor "$\underline{\underline{\mathbf{T}}}$" is mathematical object describing distribution of mass/energy.
- Both $\underline{\underline{\mathbf{G}}}$ **and** $\underline{\underline{\mathbf{T}}}$ can be written in terms of components, similar to a matrix.
- Newton's constant of gravitation "G" and the speed of light "c" appear as fundamental constants in this equation.
- This is actually a horrendous set of 10 coupled non-linear partial differential equations!!
- For weak gravitational fields, this reduces to Newton's law of gravitation, to an excellent approximation

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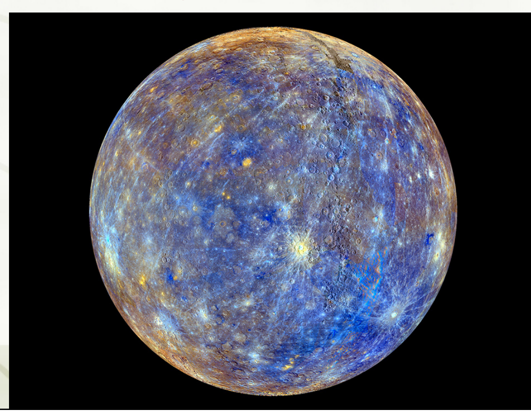
GR EFFECTS IN THE SOLAR SYSTEM

- Already discussed bending of star light by the Sun (detected by Eddington).
- **Orbit of Mercury:**



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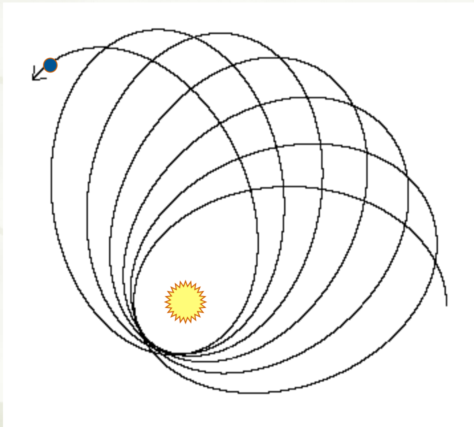
Precession of the perihelion

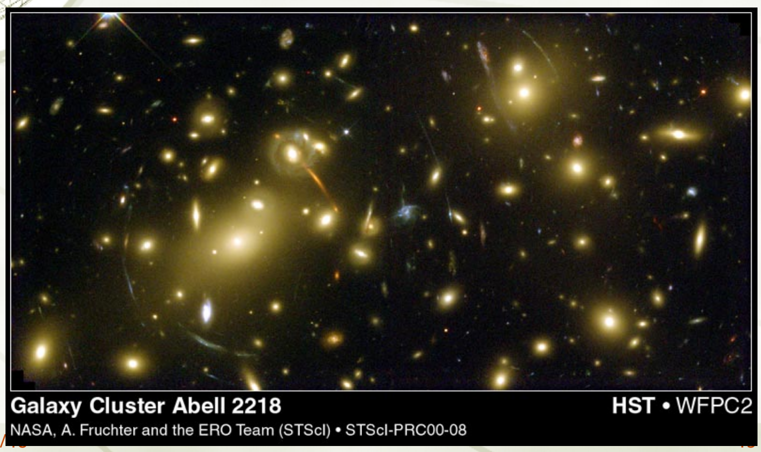
- Effect called "precession of perihelion"



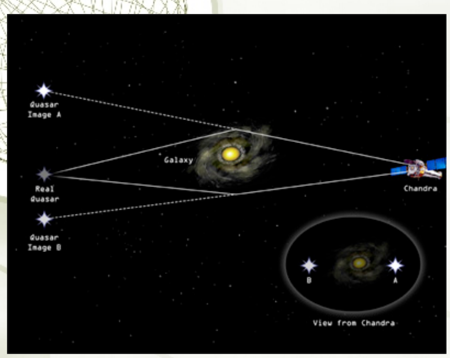
Precession of Mercury's perihelion

- This happens to all planets, but Mercury is closest to the Sun (a place with unusually bendy space-time in the Solar system)
- Effect is small - orbit twists by 5600 arc-seconds (1.56 degrees) per century
  - With Newtonian gravity, we can explain 5557 arc-seconds/century as due to
    - Changes in Earth's frame (equinox precession): 5025.6 arcsecs
    - Gravitational effect of other planets: 531.4 arcsec
    - Deformation of the Sun: 0.025 arcsec
  - But this still leaves 43 arc-seconds per century unexplained… (Vulcan?)
- Using GR, Einstein predicted (with no fiddling!) that Mercury's orbit should precess exactly 43 extra arcseconds per century!

THE BENDING OF LIGHT (GRAVITATIONAL LENSING)

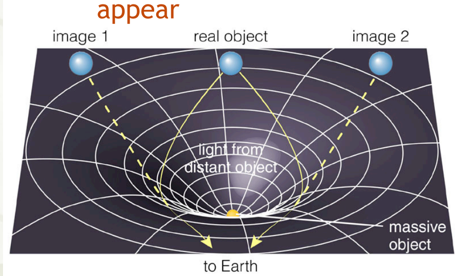


Actual and apparent light paths with gravitational lens



From Chandra telescope web page

- Massive galaxy or cluster is foreground 'lens'
- Light rays from distant quasar or galaxy bend around foreground object
- Two or more images appear



From University of Georgia web page

"The Einstein Cross"

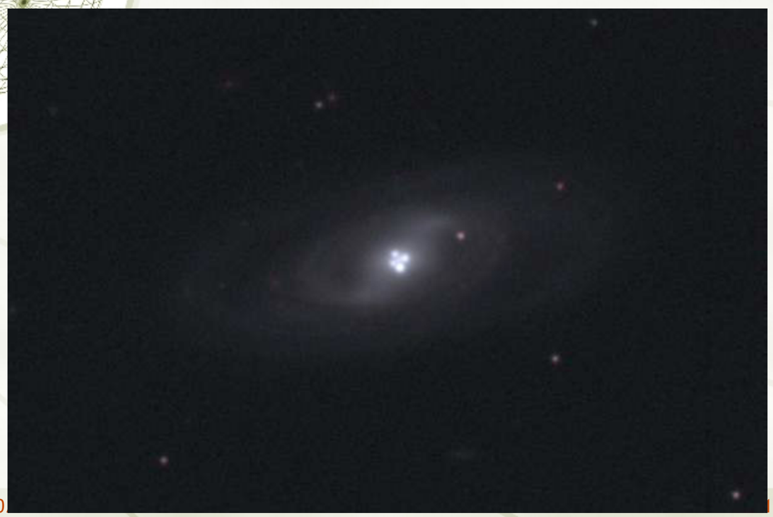
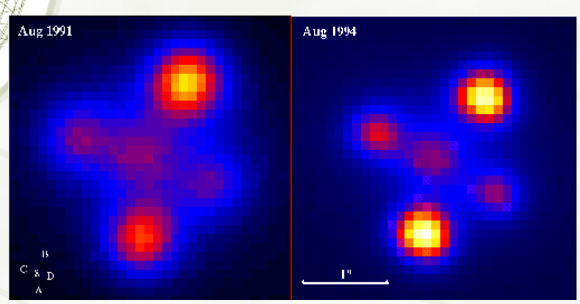
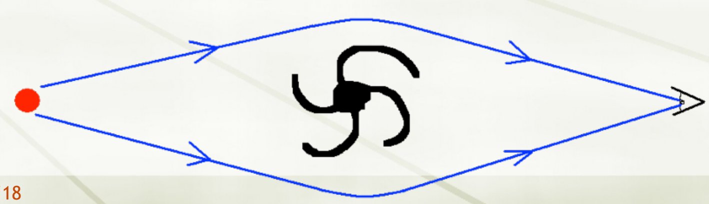


Image brightnesses vary as source & lens move



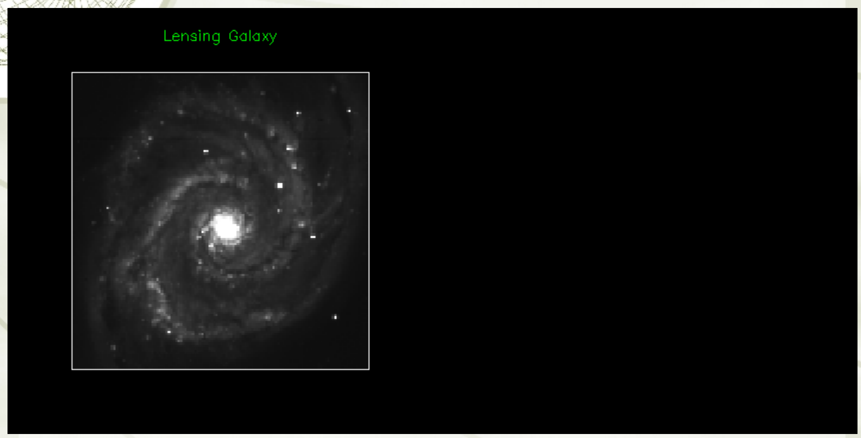


Smithsonian Castle

Smithsonian with black hole

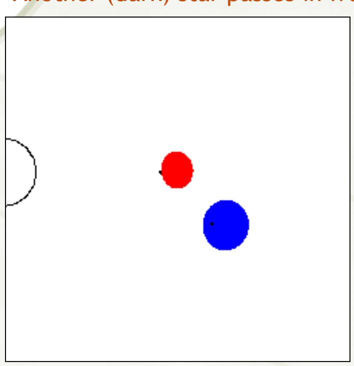
E. Falco CASTLES survey, black hole of Saturn's mass in the middle of the mall

Simulated galaxy lensing



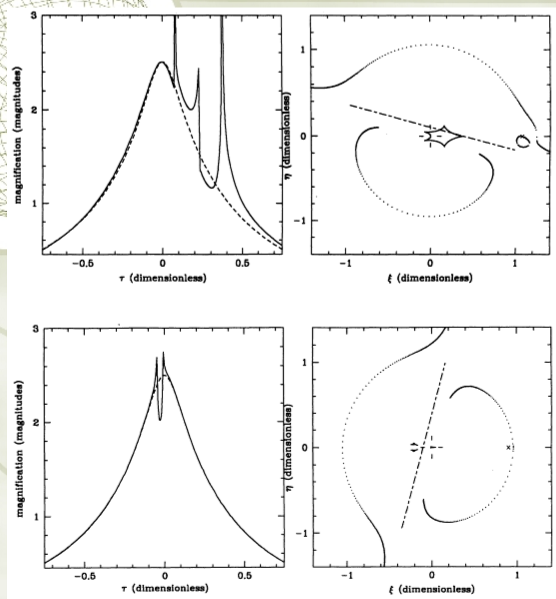
Gravitational micro-lensing

- Individual stars can also make a gravitational lens… **microlensing.**
- Suppose we…
  - Look at a distant star in our galaxy
  - Another (dark) star passes in front…



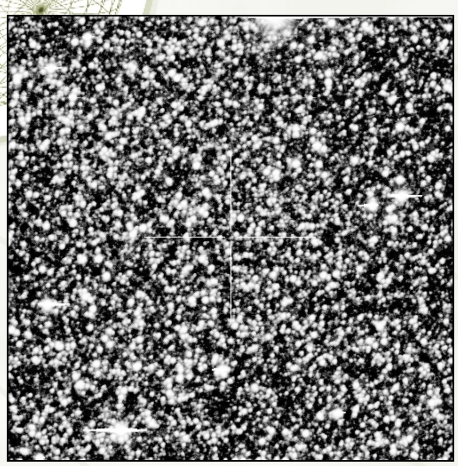
Binary microlens, from web site of Ned Wright (UCLA)

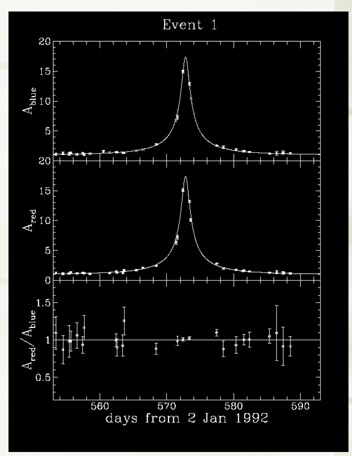
  - Causes temporary increases in observed brightness of stellar images



- Images for binary lenses with high mass ratio (i.e., a star and a planet, analogous to the Sun and Jupiter; Bolatto & Falco 1994)

So many stars…makes this really hard to do!

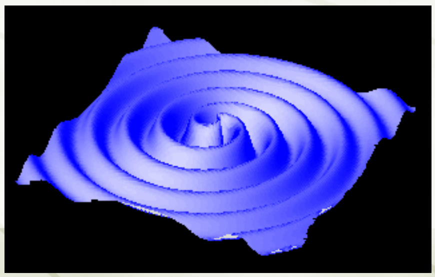




MACHO Project

GRAVITATIONAL WAVES

- Accelerating masses produce continual changes in space geometry
- Periodically-moving bodies (e.g. orbiting stars) create ripples in space-time curvature
- Ripples travel at speed of light through space (how do we know this if we've never found one?)
- These are called **gravitational waves.**



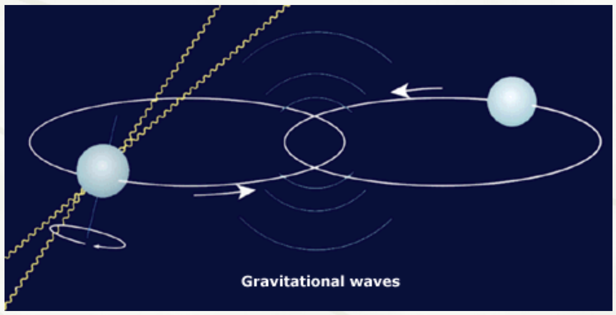
From LISA2 movie

Gravitational waves

- Features of gravitational waves…
  - Usually extremely weak!
  - Only become strong when massive objects are orbiting close to each other.
  - Gravitational waves carry energy away from orbiting objects… this causes objects to spiral toward each other
  - The grand challenge – to compute the spiralling together of two black holes.
- How do we know that these waves exist?

The binary pulsar (PSR1913+16)

- Russell Hulse & Joseph Taylor (1974)
  - Discovered remarkable double star system
  - Nobel prize in 1993



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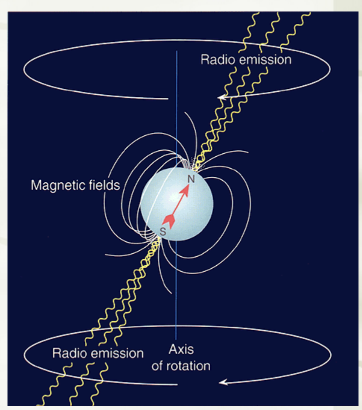
Hulse-Taylor system

- Two neutron stars orbiting each other
- One neutron star is a pulsar –
  - Neutron star is spinning on its axis (period of 59ms)
  - Emits pulse of radio towards Earth with each revolution
  - Acts as a very accurate clock!
- Interesting place to study GR
  - Orbit precesses by 4 degree per year!
  - Orbit is shrinking due to gravitational waves



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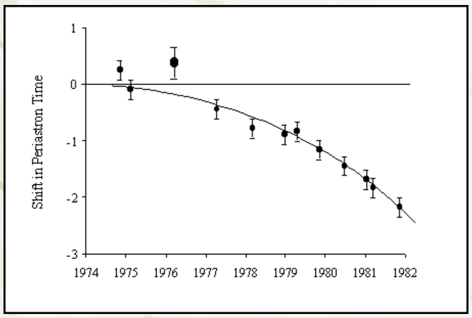
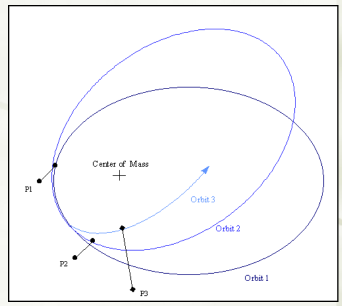
Precise test of certain aspects of GR

- When pulsar is approaching Earth, pulse frequency increases (Doppler shift); when pulsar is receding, pulse frequency decreases -- orbit of pulsar can therefore be "mapped"
- Orbit is observed to be precessing and shrinking at exactly the rate predicted by Einstein's theory





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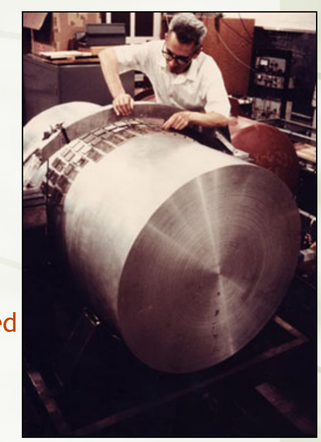
Direct detection of gravitational waves

- How do you search for gravitational waves?
- Look for tidal forces as gravitational wave passes: local compression or expansion of space
- Pioneered by Joseph Weber (UMD Professor)
  - Estimated wave frequency (10000Hz)
  - Looked for "ringing" in a metal bar caused by passage of gravitational wave
  - Insufficient technology in the 1970's for detection



AIP archives

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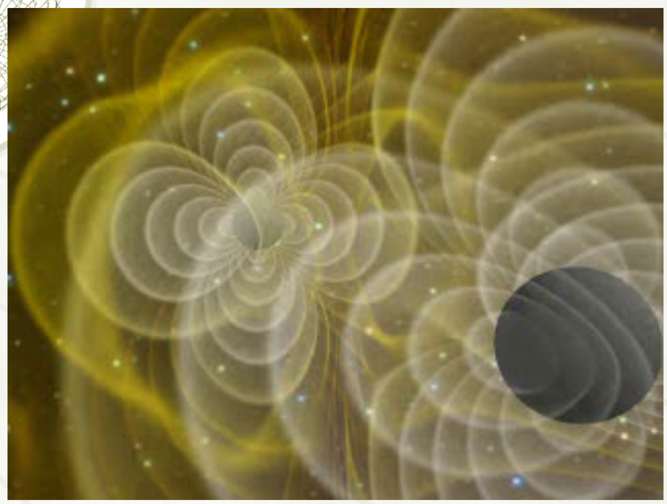
Binary black hole merger



Movie: NASA GSFC

Modern experiments : LIGO

- **L**aser **I**nterferometer **G**ravitational Wave **O**bservatory
- Two L-shaped 4km components: Hanford, Washington, & Livington, Louisiana
- Can detect gravitational waves with frequencies of about 10-1000Hz.
- Operating since mid 2015 with advanced detectors
- VERY sensitive… need to account for
  - Earthquakes and Geological movement
  - Traffic and people!
- What will it detect?
  - Stellar mass black holes spiraling together
  - Neutron stars spiraling together

LIGO announcement: 11 February 2016

- LIGO collaboration announced the first observation of gravitational waves, from a signal detected at 09:50:45 GMT on 14 September 2015[84]
    - Two black holes with masses of 29 and 36 solar masses merging about 1.3 billion light-years away.
- On 16 October 2017: first ever detection of gravitational waves originating from the coalescence of a binary neutron star system. Followed up by all telescopes and observed from gamma rays to radio wavelengths.

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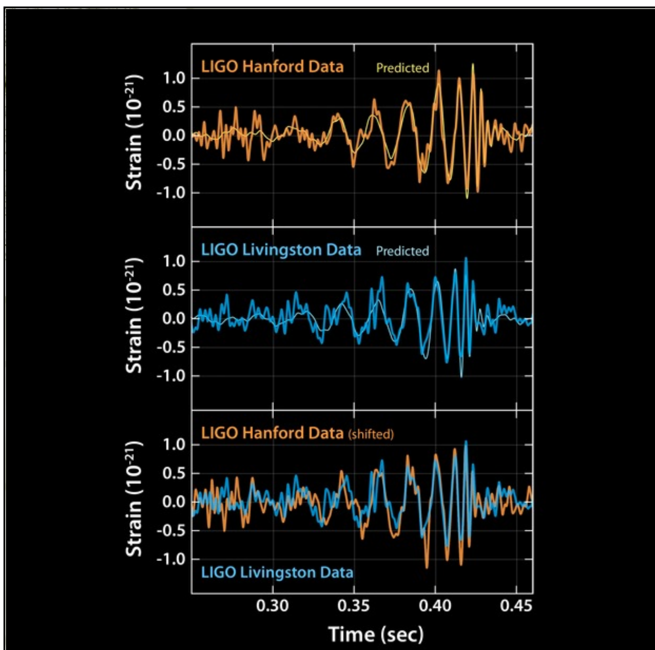

Binary black hole merger

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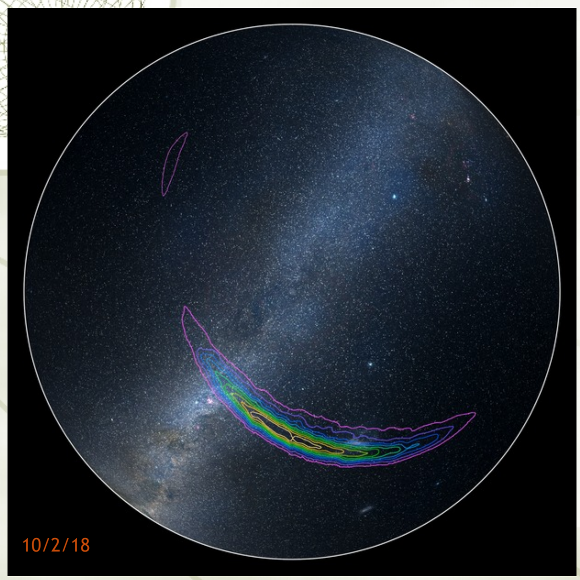
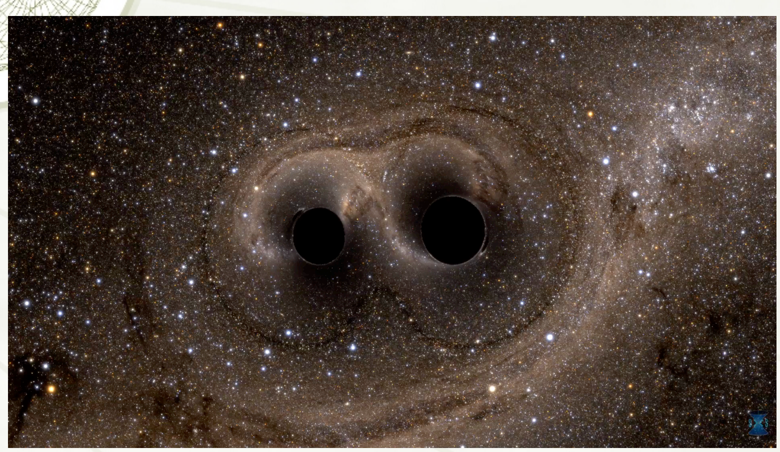
Where did the merger happen?

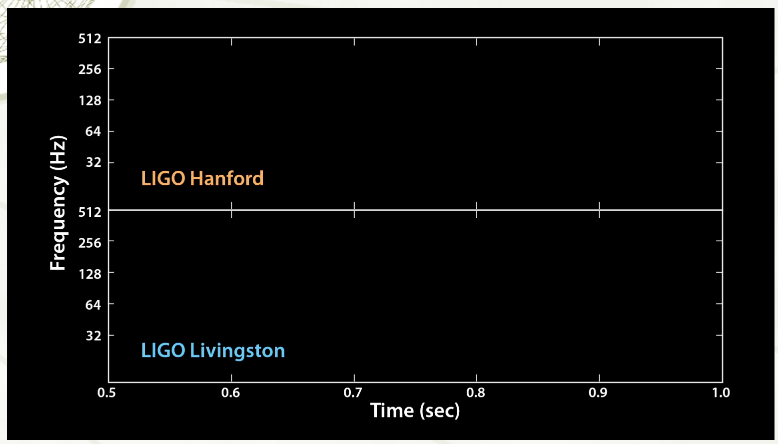


aLIGO detected a merger between a 29 and a 36 Solar Masses black holes that occurred 1.3 billion years ago. LIGO cannot pinpoint it with precision, but it is in the Southern sky.

BH merging for LIGO event



The “sound” of BH merging



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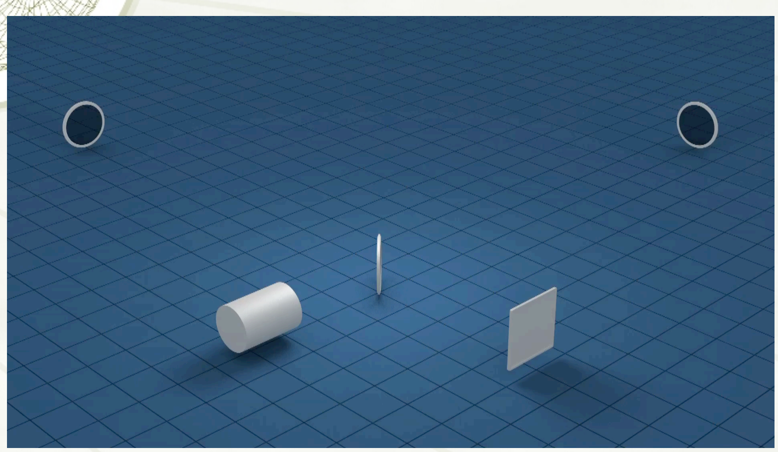
How to detect them



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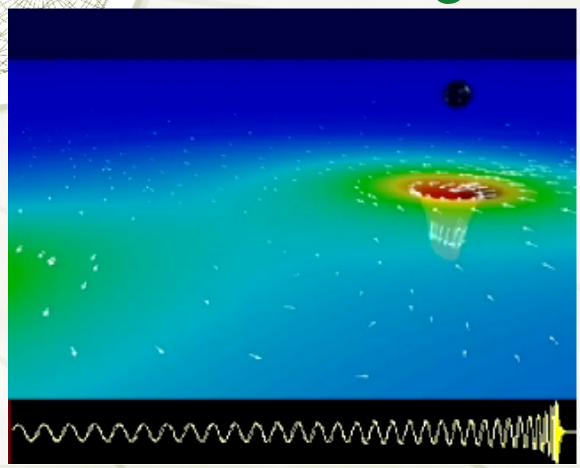
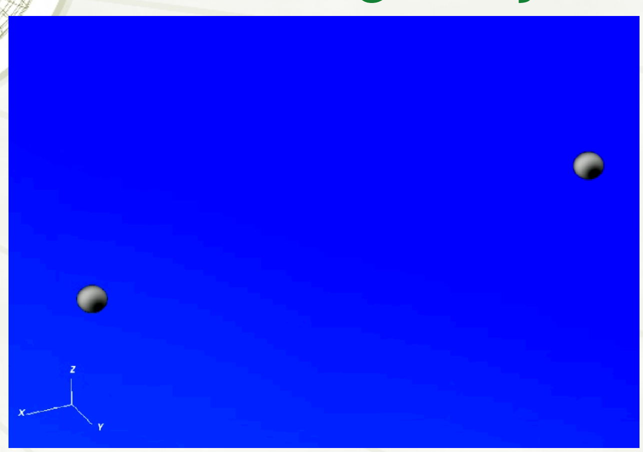
Black holes merging and gravity waves



Caltech-Cornell numerical GR group, http://www.black-holes.org

Black holes merging and gravity waves



Caltech-Cornell numerical GR group, http://www.black-holes.org

LISA

- **L**aser **I**nterferometer **S**pace **A**ntenna "pathfinder"
- Space-based version of LIGO (planned launch date November 2015, used to be 2011)
- Sensitive to lower-frequency waves (0.0001 – 0.1Hz)
- Will be able to see
  - Normal binary stars in the Galaxy
  - Stars spiraling into large black holes in the nearby Universe.
  - Massive black holes spiraling together anywhere in the universe!