The search for gravitational waves

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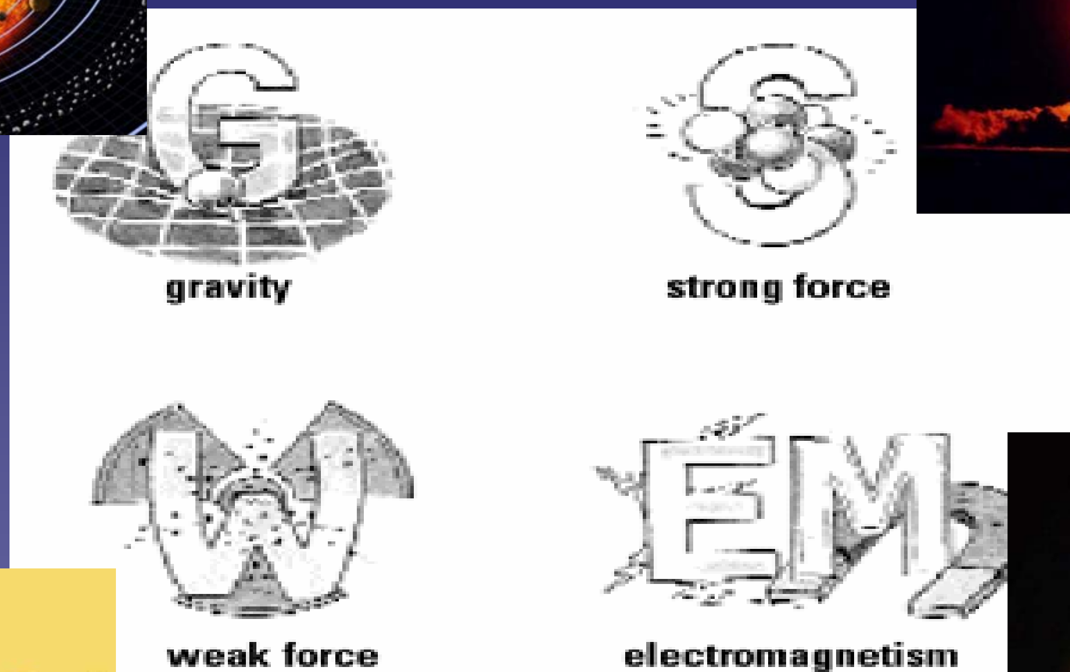
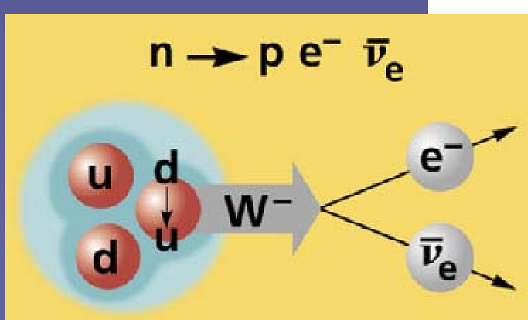
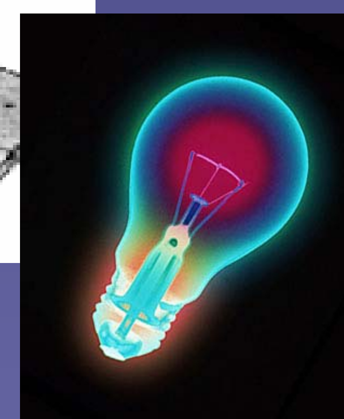
Overview

- **What are gravitational waves?**
- **Detecting gravitational waves.**
- **Astrophysical sources of and searches for gravitational waves.**
- **The future of gravitational wave astronomy.**

Fundamental Forces







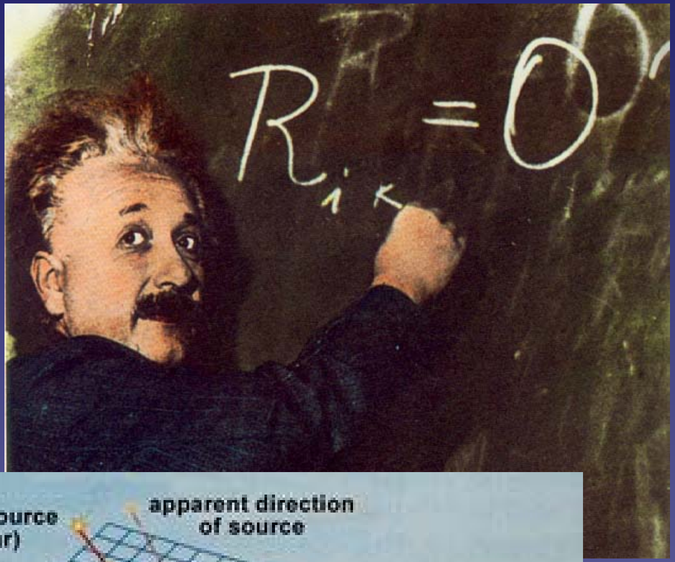
Gravity

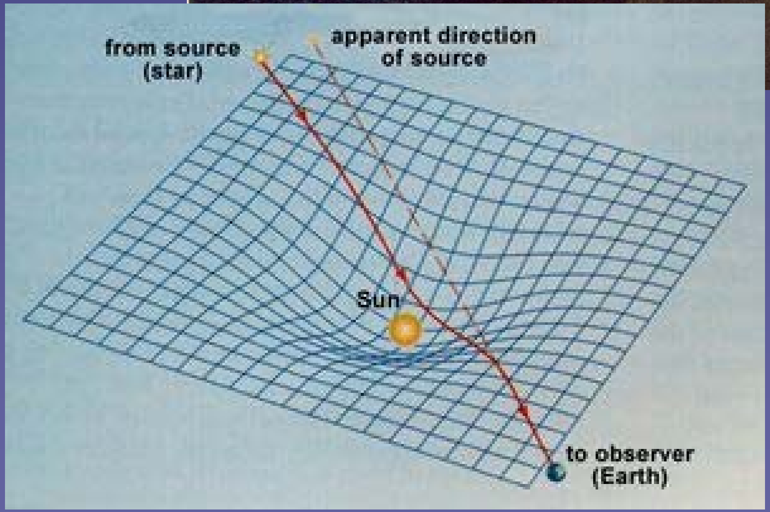
- Sir Isaac Newton published a theory of gravity in 1686 (*Principia Mathematica*).
- Massive objects exert a force on other massive objects.
- Force acted instantaneously.

$$F = \frac{G m_{Earth} m_{apple}}{d^2}.$$

Gravity

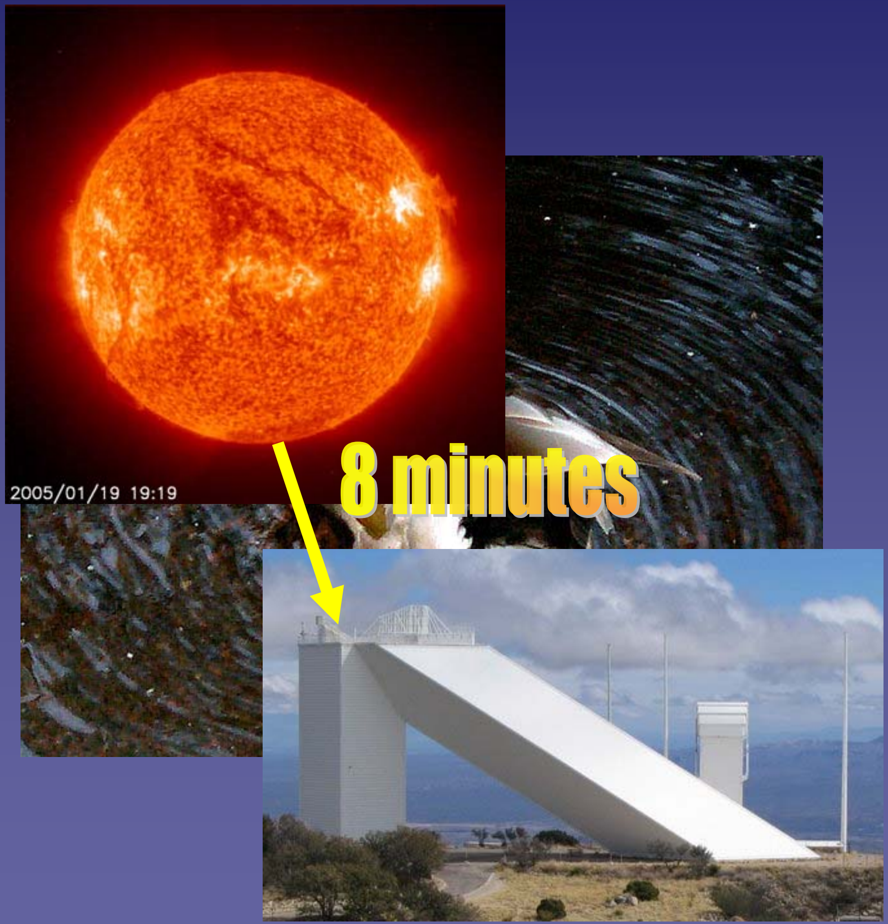
- Einstein's General Theory of Relativity (1915) – called GR
- Gravity is product of curvature/geometry of space-time, caused by mass and energy.





Gravity

- Equations of GR show gravity does not act instantaneously.
- Gravity propagates from its source at a finite speed, just like electromagnetic waves (e.g. light waves), sound waves or ripples on a pond.

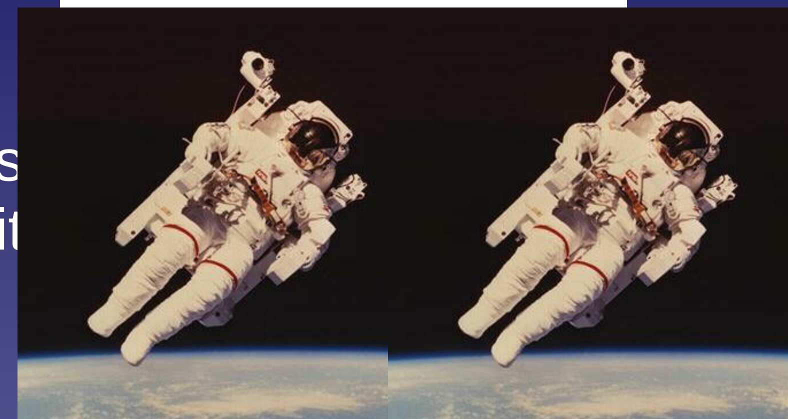


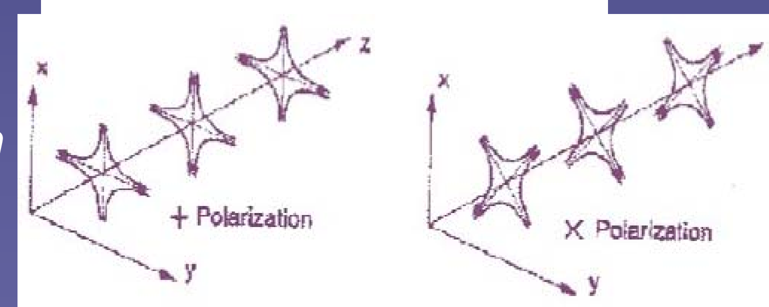
Gravitational waves

- Gravitational waves (GW) are ripples in space-time and are a direct prediction of GR.
- Accelerating masses (time varying mass quadrupoles) produce changing curvature that cause these ripples.
- Ripples propagate away from the source at the speed of light generally unaffected by matter.

Gravitational waves

- GWs stretch and squeeze space (push and pull freely falling objects apart) as they propagate through it
  - *transverse to the direction of propagation*
  - *equal and opposite in orthogonal directions (traceless)*
- *Two polarisations called 'plus' + and 'cross' x rotated at 45^o to each other*



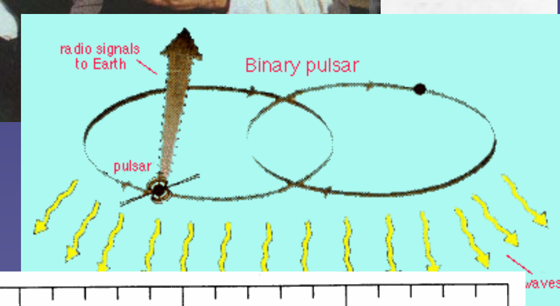


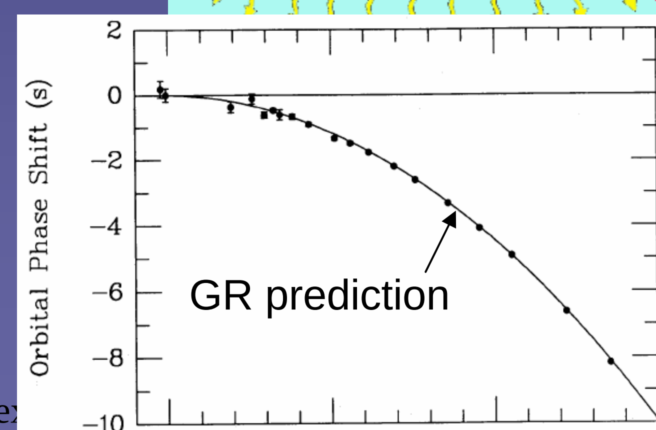
Gravitational waves

- Gravity is a very weak force (only very large masses produce noticeable forces, e.g. the Earth and the Sun).
- Space-time is very stiff
- GWs only cause very small distortions in space, e.g 10^{-16} cm even for the strongest sources!
- Therefore they are *very* hard to detect.

Evidence for gravitational waves

- Direct prediction of GR – has correctly predicted observed effects:
  - Perihelion advance of Mercury
  - Gravitational lensing
  - Shapiro delay
- Binary neutron star systems seen to lose energy at exactly the rate predicted by loss through GWs
  - Hulse & Taylor got 1993 Nobel prize for this observation



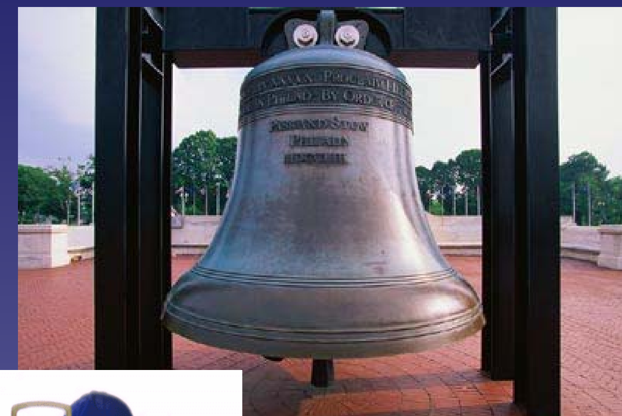


Detecting gravitational waves

- Joseph Weber pioneered the first efforts to detect GWs in the 1960s.
- Needed to design and build extremely sensitive equipment for the job.

Detecting gravitational waves

- The basic principle of a detector is that it detects the displacement of two masses caused by the passing GW.
- Two main types of detector have been used:
  - Resonant mass or bar detectors
  - Laser interferometer detectors

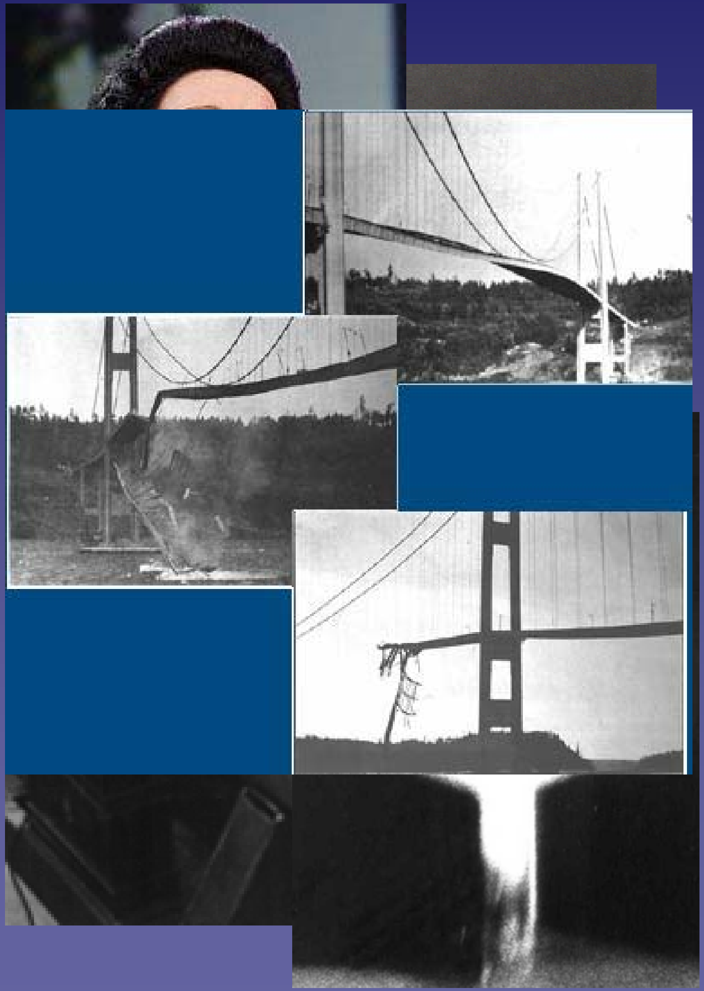


Detecting gravitational waves

- For detectors there are many noise sources which need to be overcome, which are otherwise far larger than any GW signal.
- These include seismic, thermal, gravity gradient and photon shot noise.

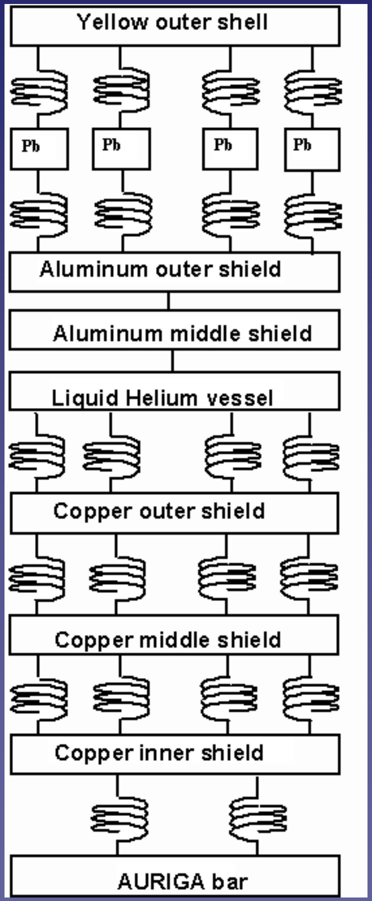
Bar detectors

- These were the first type of detector used by Weber in 1960s.
- Consist of a large cylindrical bar (generally aluminium) with transducer around its middle.
- Bar will vibrate if passing GW is near its resonant frequency (inherently narrow band detectors).
- Narrow-band – 1-10s of Hz around the resonant frequency



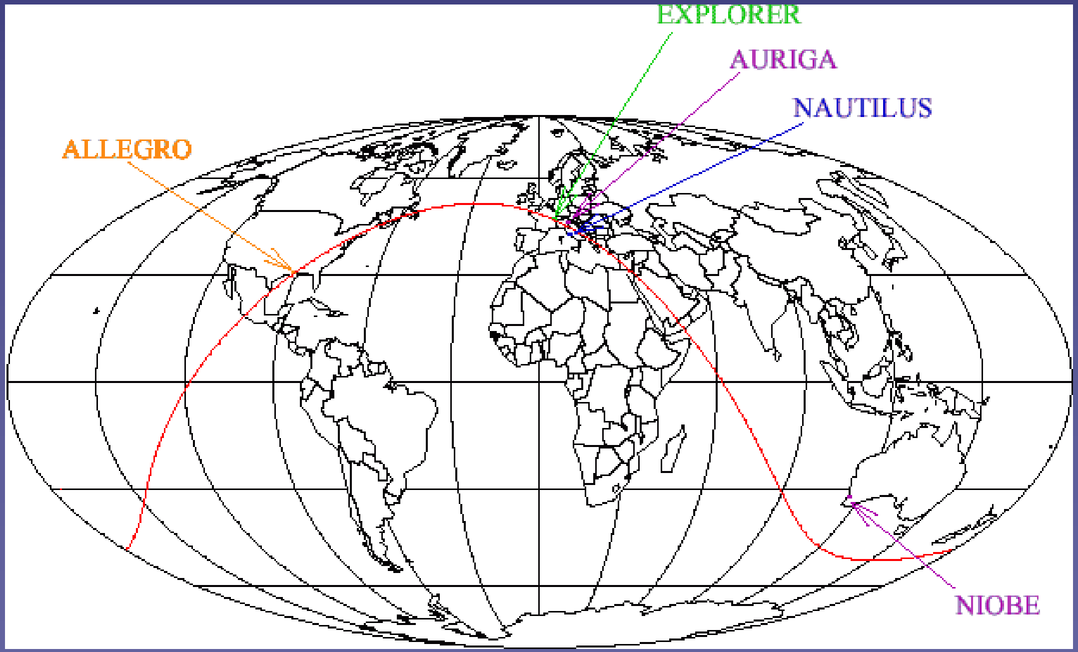
Bar detectors

- Main noise sources for bars are seismic noise and thermal noise.
- Seismic noise is reduced by isolating the bar with suspensions and springs.
- Thermal noise (thermally induced vibrations of the bar) is reduced in several ways:
  - Bar can be cooled using cryostat to temperatures of few K – mK.
  - Bars are heavy (> 1000kg).
  - Bars are kept in vacuum chambers.
- Can only reduce noise – never entirely get rid of it.

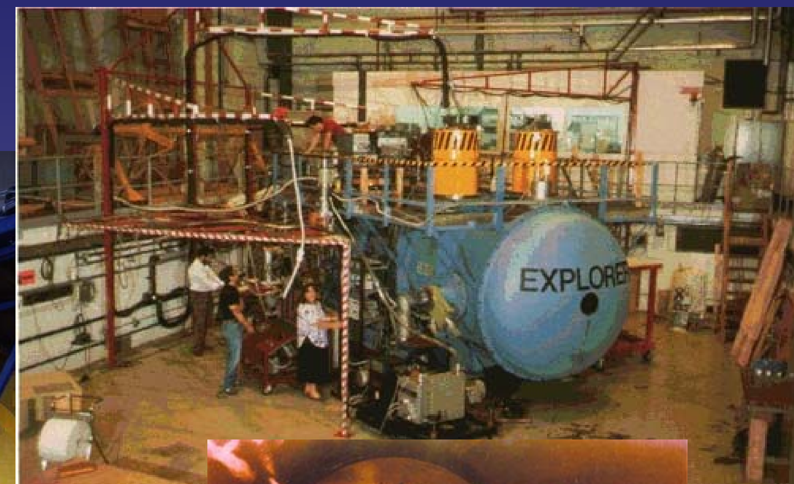


Bar detectors

- There are several bar detectors operating around the world.

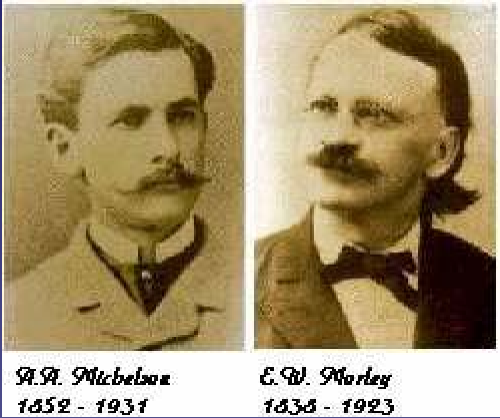


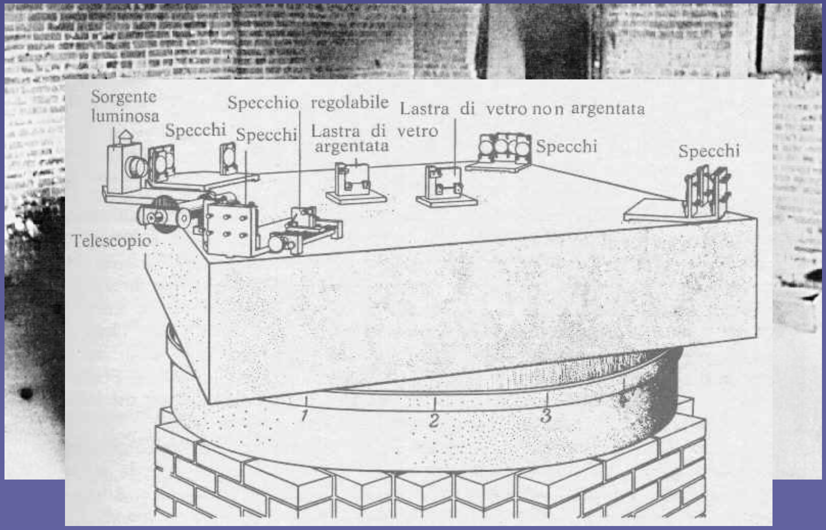
Bar detectors



Interferometers

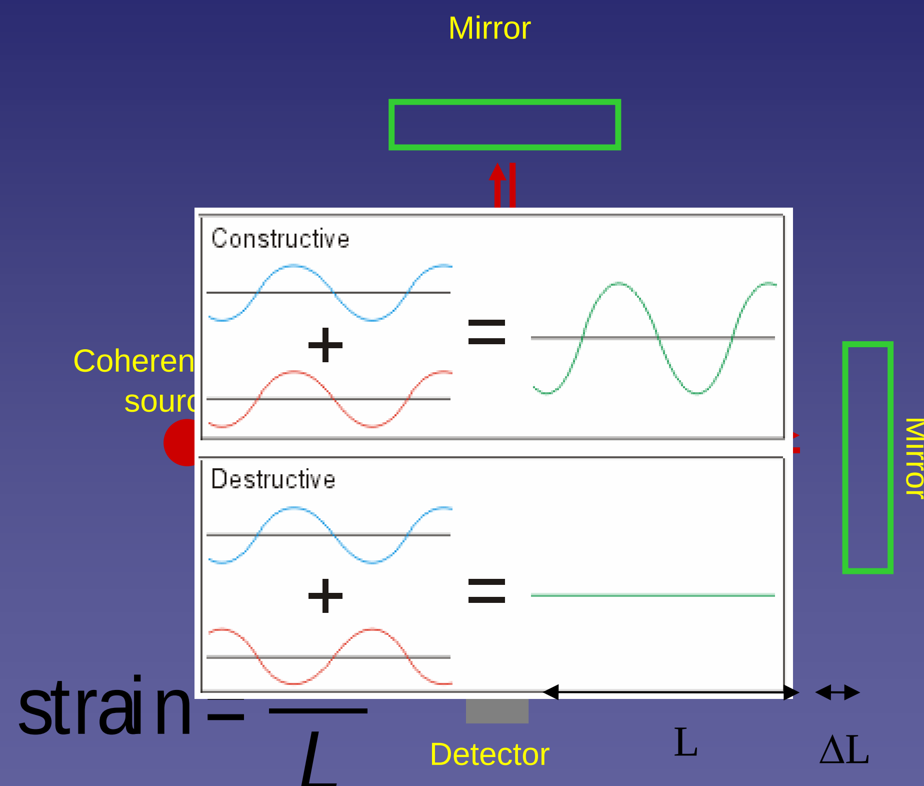
- Michelson and Morley attempted to detect presence of aether in 1887
- They used an interferometer to try to measure changes in the speed of light
- Null result provided insight into Einstein's Special Relativity – speed of light is constant in all frames





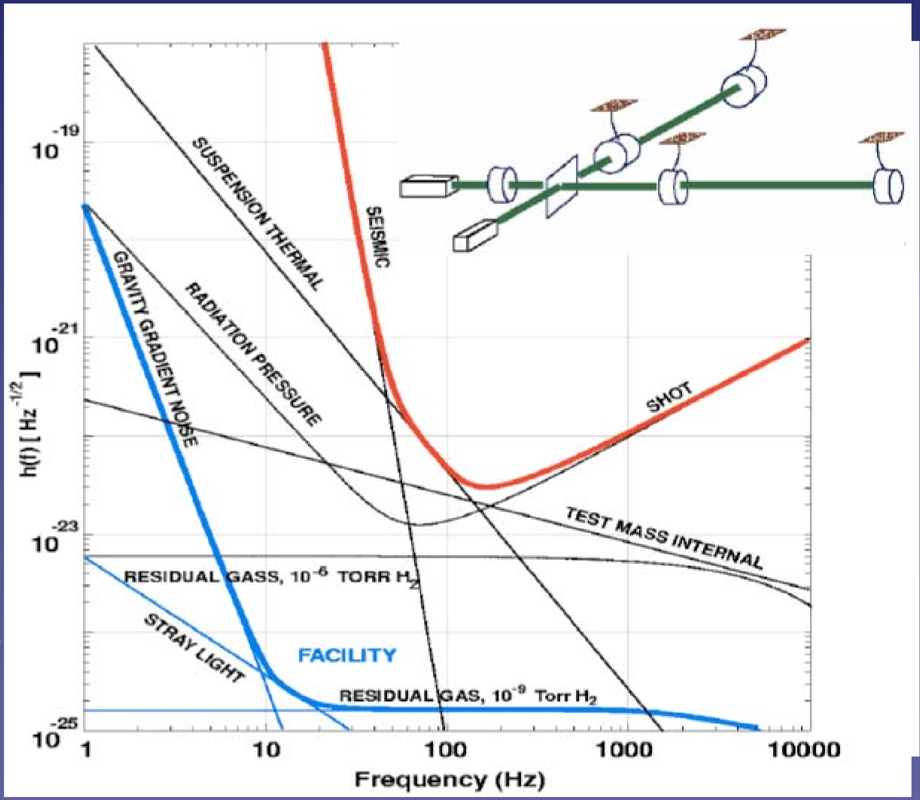
Interferometers

- Basic set-up for gravitational wave detectors is the Michelson interferometer
- Can use laser to measure the displacement of test end mirrors – or difference in speed of light down the arms.
- Split the light down the two paths and recombine it
- Differences between the two paths will show up as changes in the interference pattern at the output



Interferometers

- Passing GW causes changes in the interferometer arm lengths.
- Causes output laser interference pattern to change.
- Interferometers are broadband – can see a wide range of GW frequencies
- Again we have a range of noise sources which limit our sensitivity

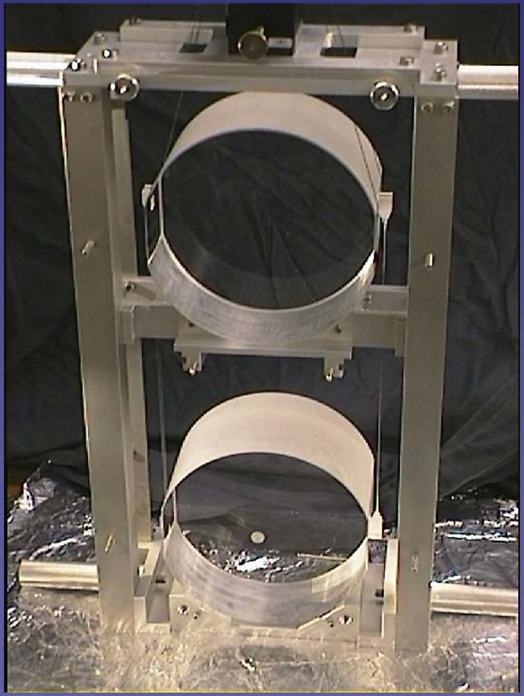


Interferometers

- Seismic noise is the dominant source of noise in low frequencies (Hz – 10s Hz).
  - Isolate test masses by suspension
  - Have interferometers with long arms (> km).

Interferometers

- Thermal noise dominates at mid-frequencies (10s – 100s Hz)
  - Choose test mass / mirror coating materials for good thermal properties e.g. silica (glass).
  - Have large masses (10's kg).
  - House interferometer in vacuum chamber.



Interferometers

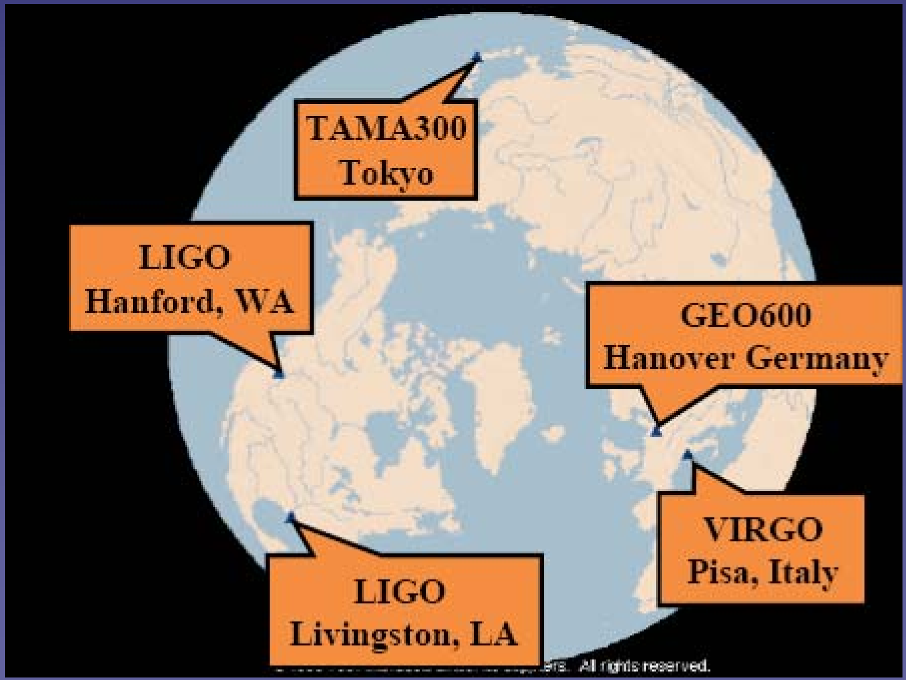
- Photon shot noise dominates at high frequencies (100s – 1000 Hz).
- QM nature of light means number of photons hitting test masses varies.
  - Use high power lasers ~ 10W (cf 5 mW for CD player).
  - Increase laser power in interferometer arms using power recycling (~10 kW).

Interferometers

- Gravity gradient noise is overall limiting factor at low frequencies for earth based interferometers.
- Human activity, nature, atmospheric changes cause local gravity field to change (e.g. 0.1 kg bird flying 50 m from 10kg test mass causes it to move ~ 10^{-13} cm over 1 sec cf. 10^{-16} cm for GW) – low frequency (<1 Hz)
- Solution – go into space!

Interferometers

- Several interferometers in operation / under commissioning around the world.



Interferometers

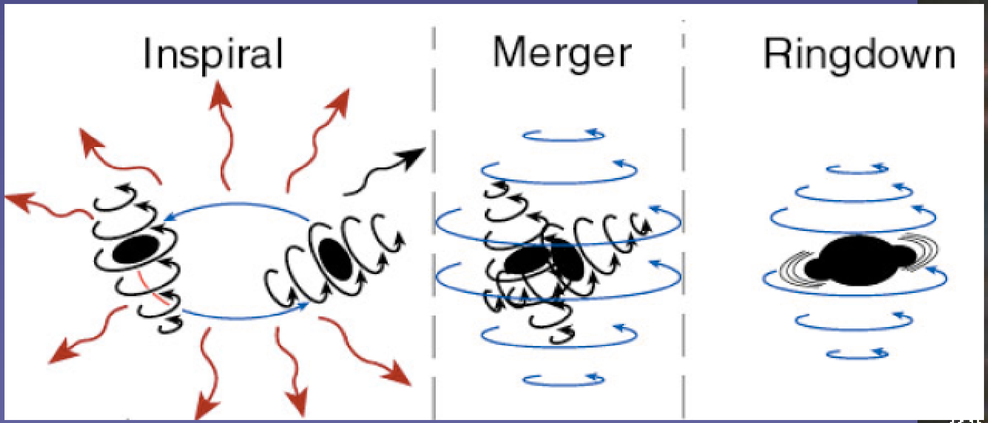
LIGO

GEO600

VIRGO

Sources

- Because GWs are so weak, detectable sources have to be the most violent and energetic objects / events in the universe
- Must have very large amounts of mass accelerating extremely fast

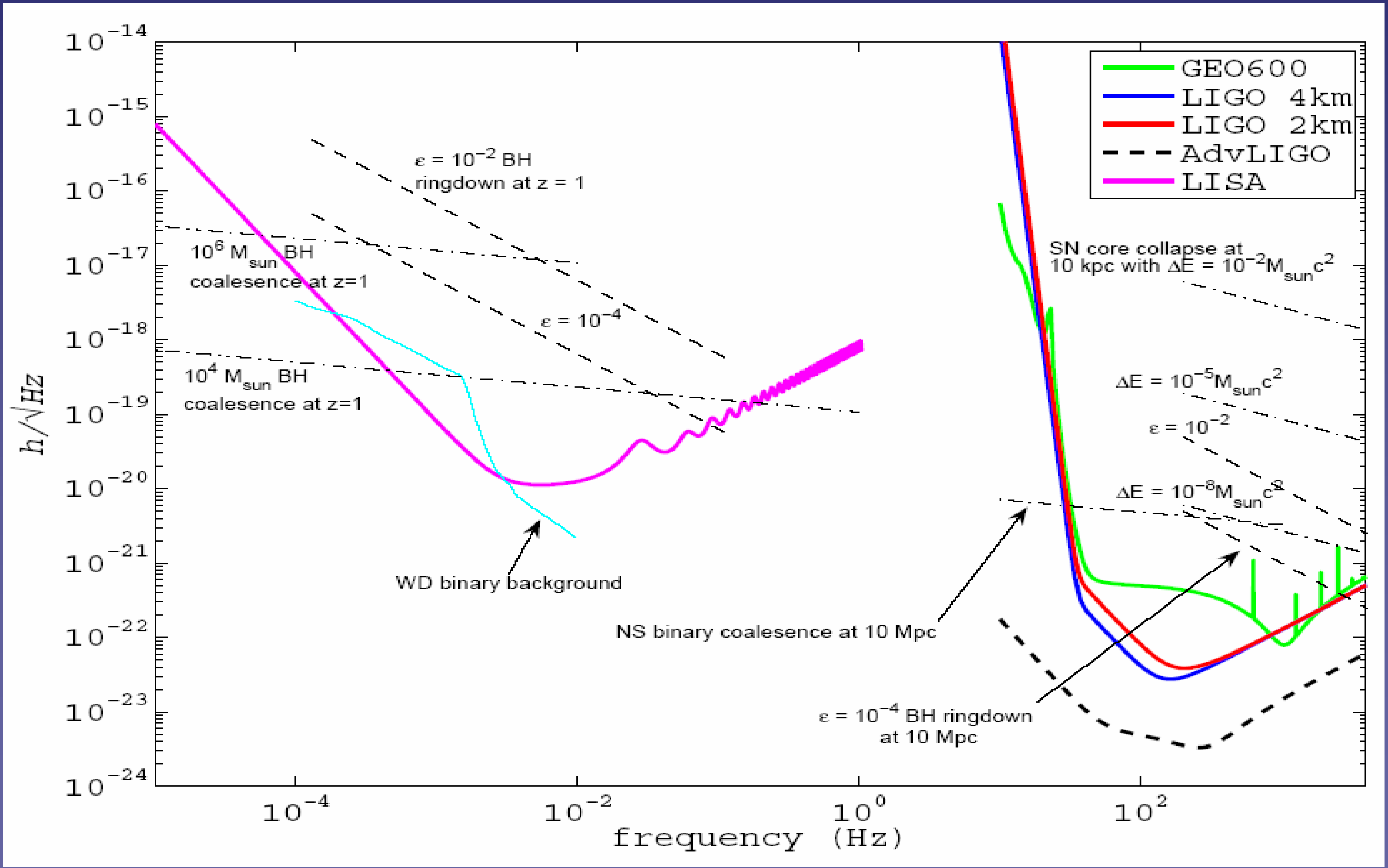


Sources

- Sources are grouped into 4 main catagories according to the form of GWs emitted:
  - Bursts
  - Periodic / continuous waves
  - Inspirals
  - Stochastic

Sources

- Different sources cover variety of frequency ranges and strengths



Burst sources

- Burst sources are those that emit a short burst of GWs:
  - Supernova
  - GRBs
  - Binary inspirals
  - Stars falling into supermassive black hole
  - Neutron star glitches
  - Other?

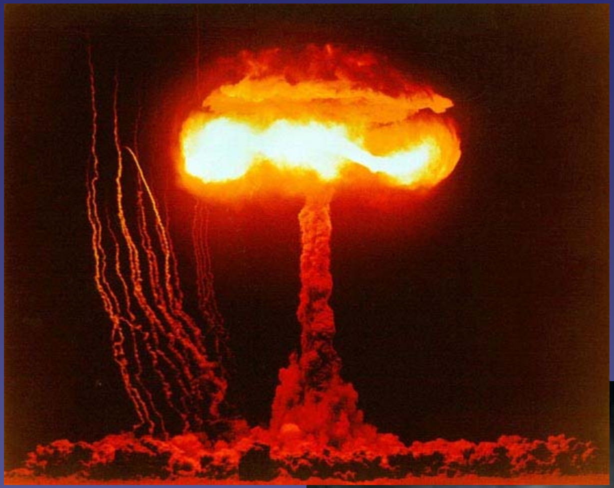
Bursts – supernova

- Death of a massive star (10s of solar masses).
- Core collapses into a neutron star or black hole.
- Non-symmetric collapse cause burst of GWs.
- Outer layers of star blown away.
- See local supernova with LIGO

SN1987A

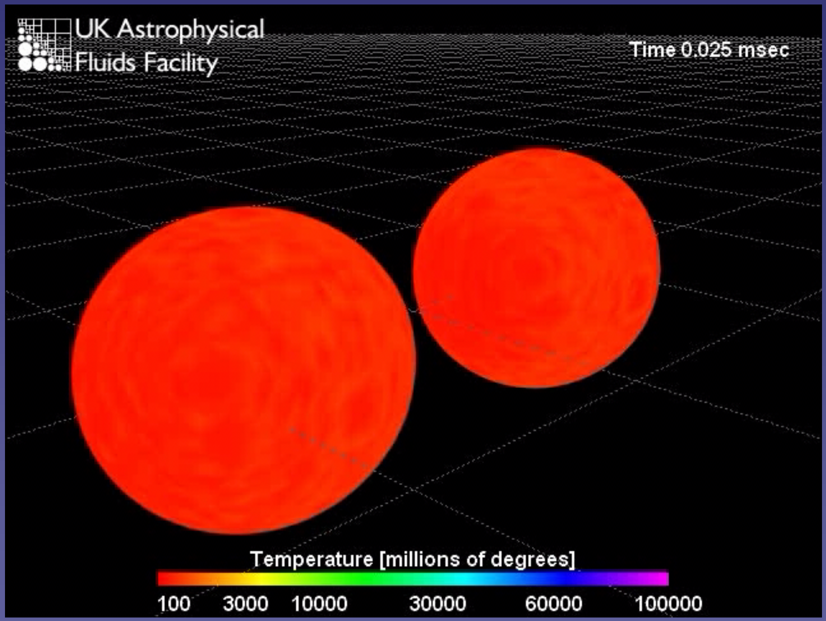
Bursts – GRBs

- GRBs are short bursts of gamma rays (very high energy photons) mainly originating from extremely distant sources.
- First discovered by American spy satellites looking for evidence of Russian nuclear testing.
- Probable explanation now thought to be hypernovae and binary mergers.



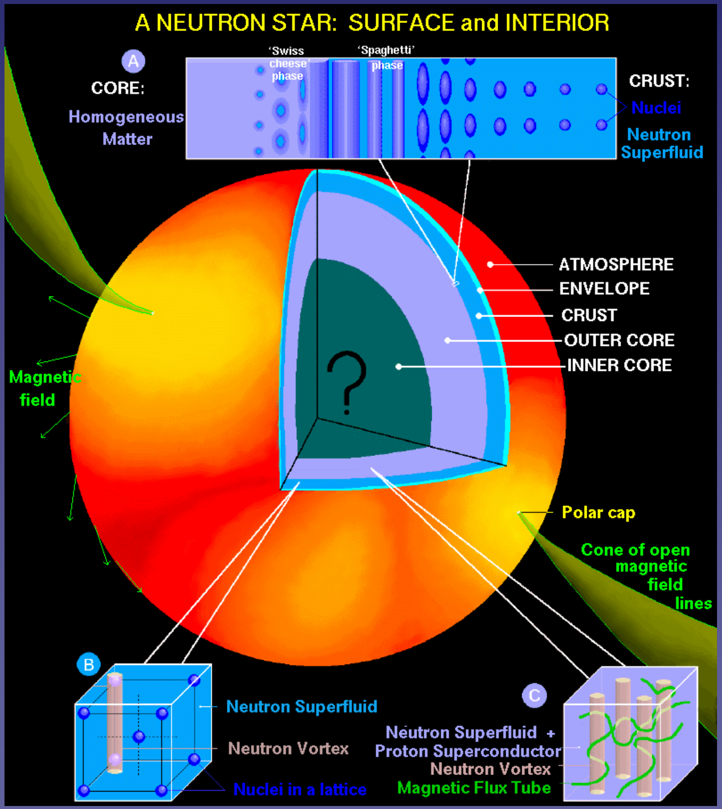
Bursts – binary inspirals

- Large numbers of stars are in binary systems.
- Population of black hole – black hole, neutron star – neutron star binaries (Hulse and Taylor).
- Orbits of these decay through emission of GWs.
  - Well modelled until stars get pulled apart by strong field
- Final stages of system strong GWs are emitted – can be seen out to many Mpc



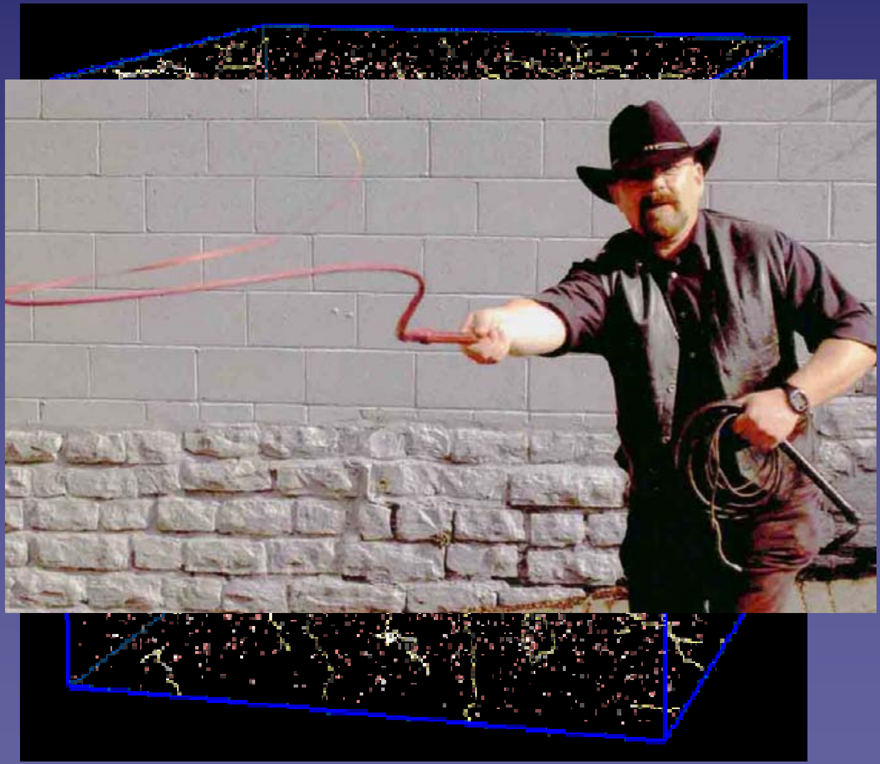
Bursts - glitches

- Neutron stars, the extremely stellar dense remnants left after supernova, can be spinning very rapidly.
- The spin frequency can occasionally jump suddenly – called a glitch.
- The mechanism for this is unknown, but it could cause the star to ring like a bell emitting a burst of gravitational waves
  - only see local sources within the galaxy
- This allows us to perform astroseismology i.e. probe the interior of the star.



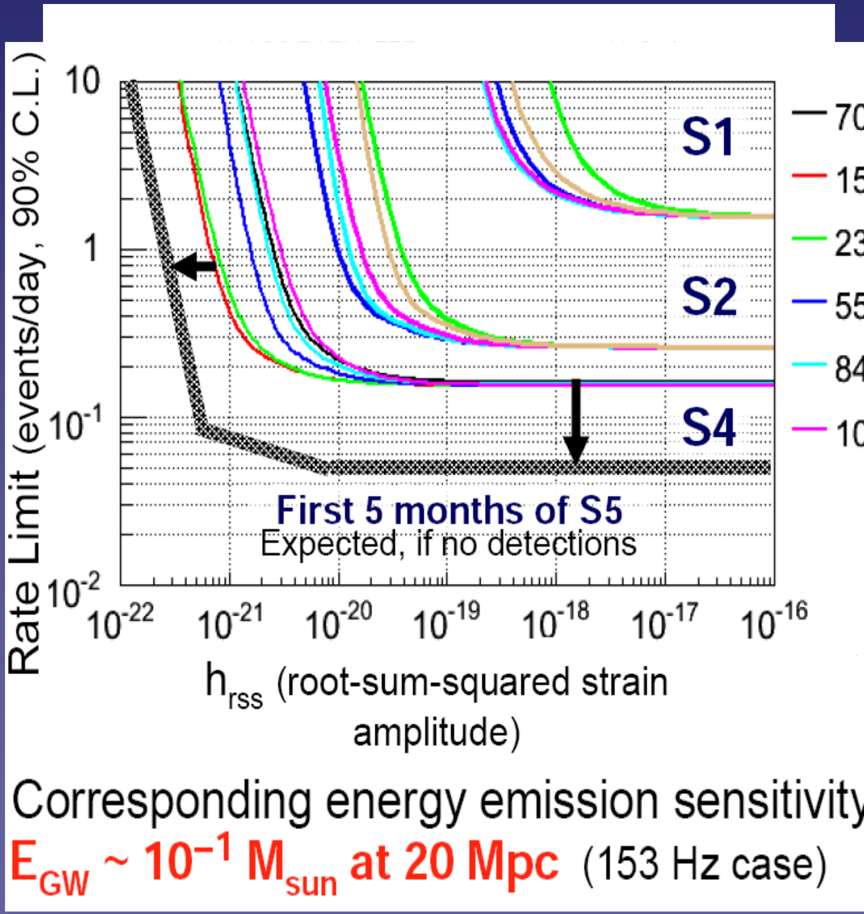
Cosmic strings

- Cosmic strings are potential relics from fractions of seconds after the big bang
- Extremely thin and long line like objects with very high densities (10^{20} kg/m)
- Strings can contain kinks or crack like a whip giving rise to an intense gravitational wave burst
- GWs possibly one of the only ways to detect strings



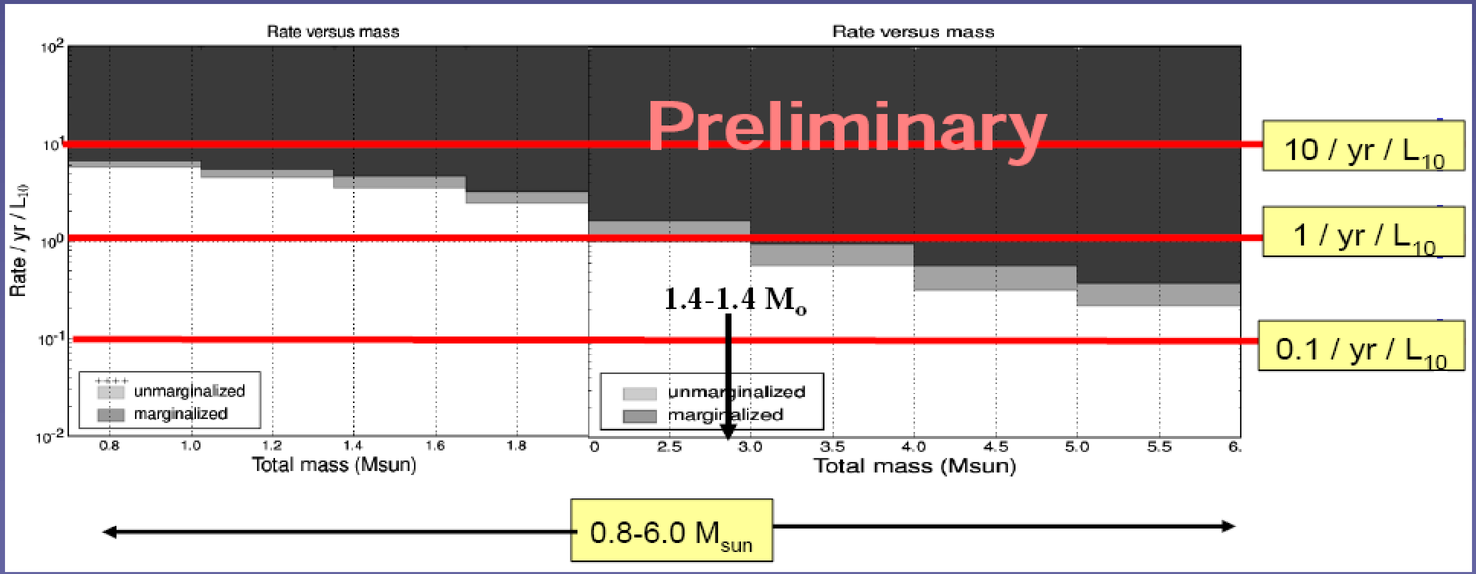
Burst searches

- Unmodelled sources e.g. supernova
  - look for excess power in time-frequency plane
  - wavelet analysis, data statistics change point analysis, coherent multi-detector analysis
- No detection over LIGO science runs



Inspiral searches

- Use a template of the signal (well modelled) to cross-correlate with the data – matched filtering.
- Searches for NS-NS binaries, NS-BH binaries and BH-BH binaries
  - reach to ~15 Mpc for NS-NS, ~100 Mpc for BH-BH

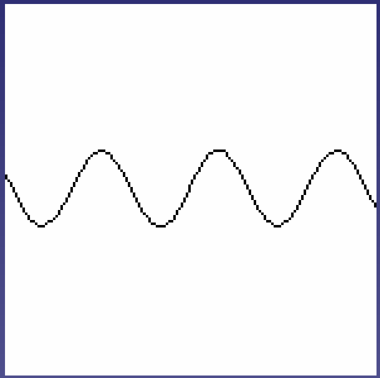


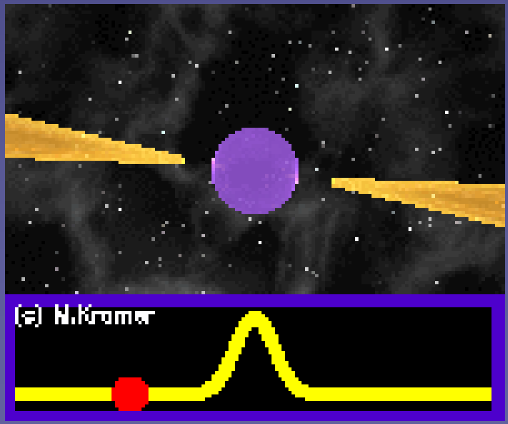
Burst sources

- What can study of bursts tell us?
  - Reveal what happens at the heart of supernovae.
  - Reveal dynamics of systems pushing the extremes of GR theory.
  - Give population information of these sorts of systems.
  - Probe neutron star interiors.
  - Possibility to reveal new objects that can't be seen any other way.

Continuous wave sources

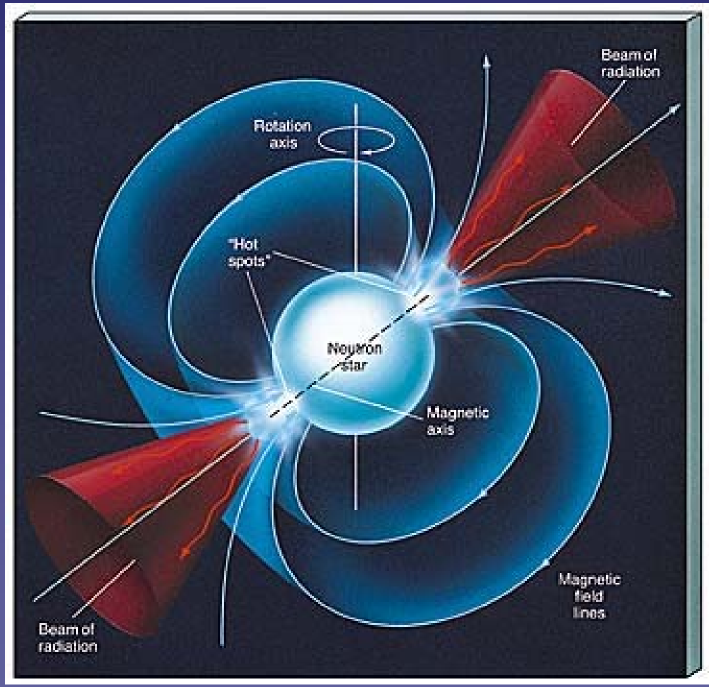
- Main source of continuous (periodic) GWs in frequency band of current interferometers will be neutron stars.
  - Pulsars
  - Low Mass X-ray binaries (LMXBs)
- White dwarf binaries will be low frequency sources – seen with LISA





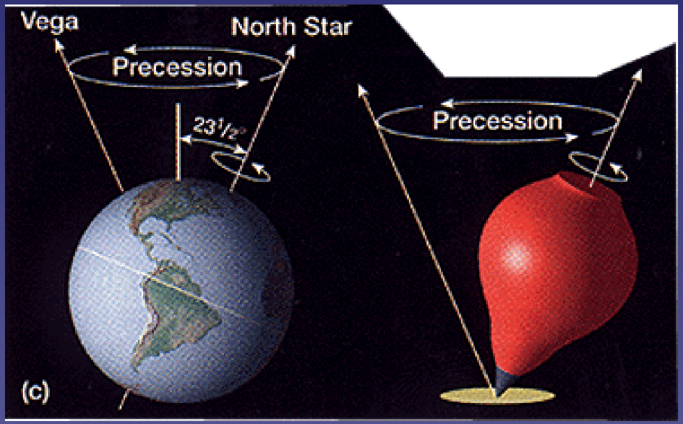
Continuous waves - pulsars

- Pulsars are neutron stars that emit an electromagnetic signal (mainly observed in radio) that appears pulsed from Earth, analogous to a lighthouse.
- Discovered in 1967 by Hewish and Bell.



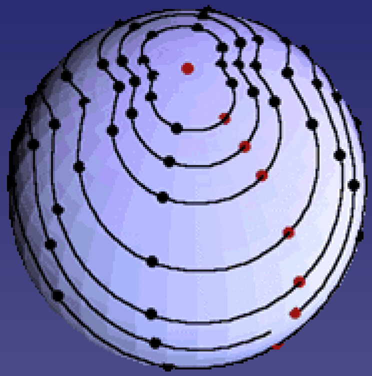
Continuous waves - pulsars

- Isolated pulsars with bumps or mountains (~< 1 mm), or that precess would emit GWs.
- Bumps could be caused by crustal deformations.
- Probably only a weak source of GWs



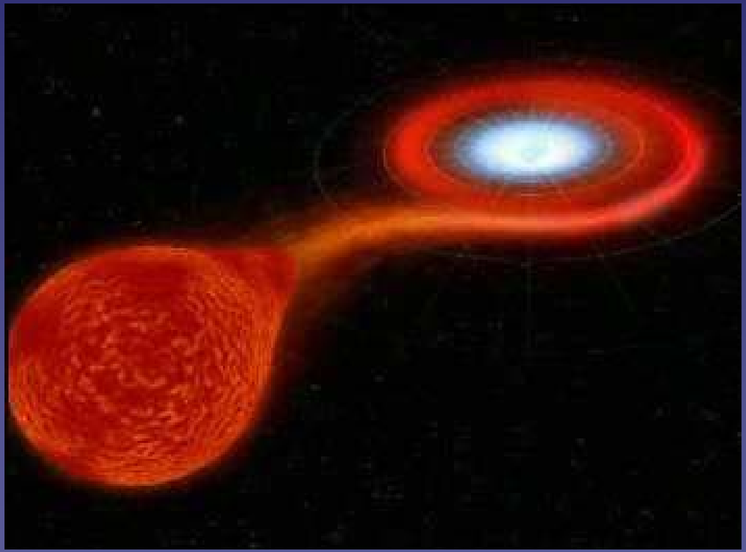
Continuous waves - pulsars

- Newborn pulsars are more promising source of GWs.
- Emission could be due to r-modes (like waves on the sea) in the surface of the pulsar.
- Of known pulsars Crab pulsar is most promising source, also possible pulsar in SN1987A remnant.



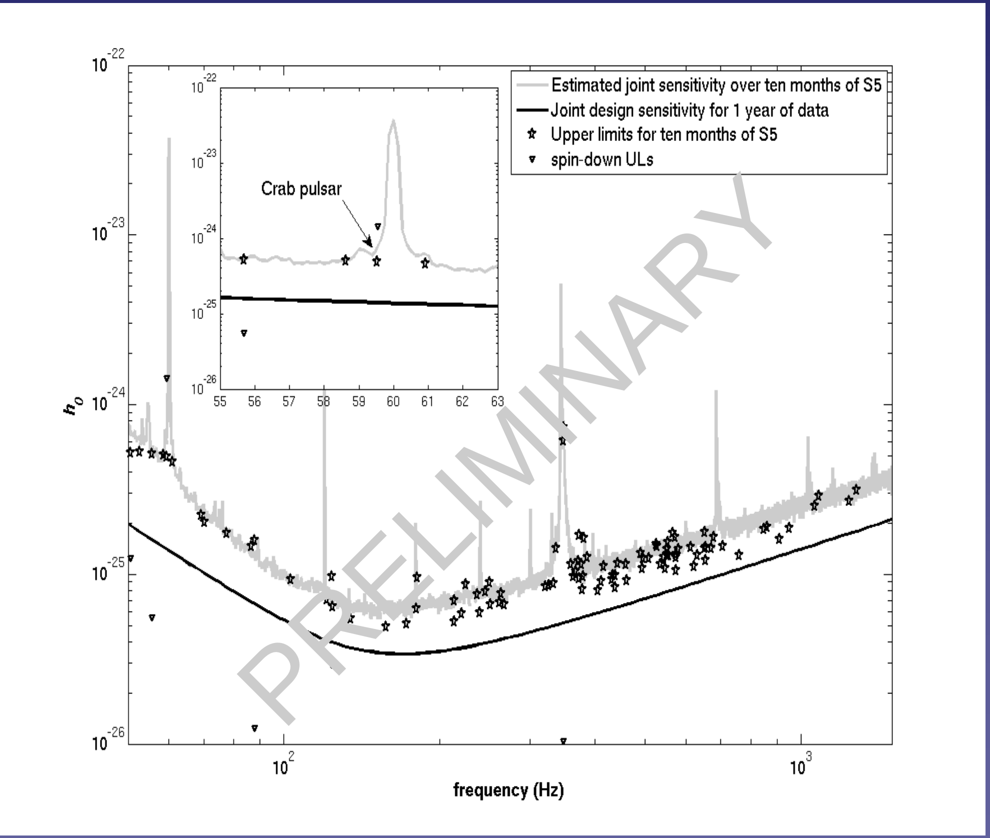
Continuous waves - LMXBs

- LMXBs are neutron stars/pulsars in binary systems with low mass stars.
- Neutron star accretes material emitting X-rays.
- Accretion spins-up neutron star.
- Neutron stars lose energy by emitting GWs from r-modes otherwise would spin-up until they broke up.
- Of known LMXBs Sco-X1 thought to be most promising source.



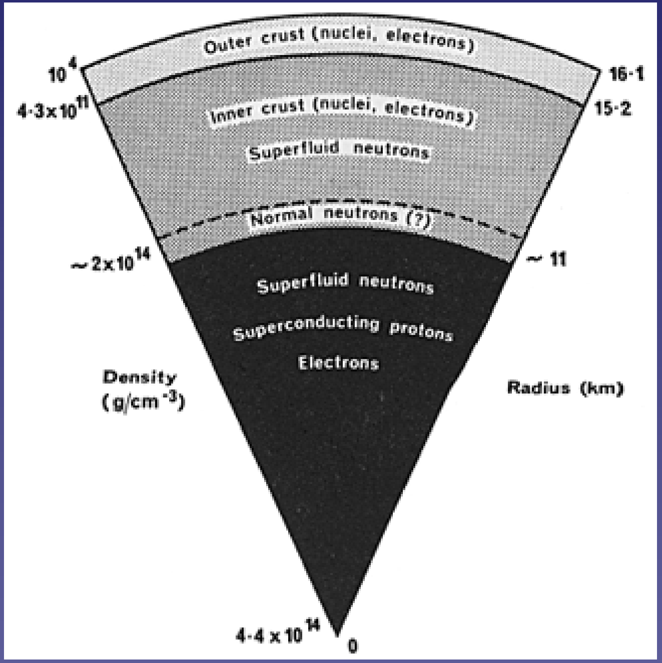
Known pulsar searches

- Search for periodic signals
  - frequecy domain (FFTs)
  - time domain – heterodyne with known phase
- Set upper limits on gravitational waves amplitude from known pulsars
  - can constrain star's equatorial ellipticity



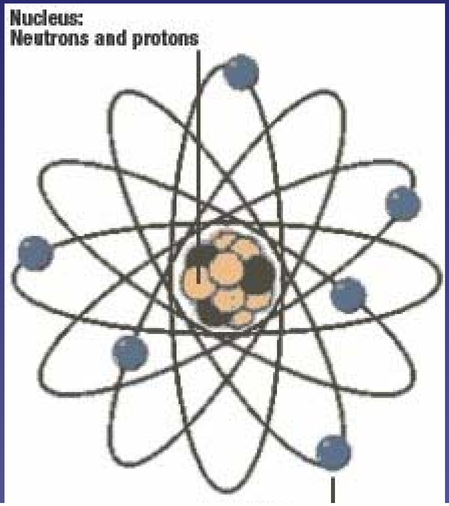
Continuous waves

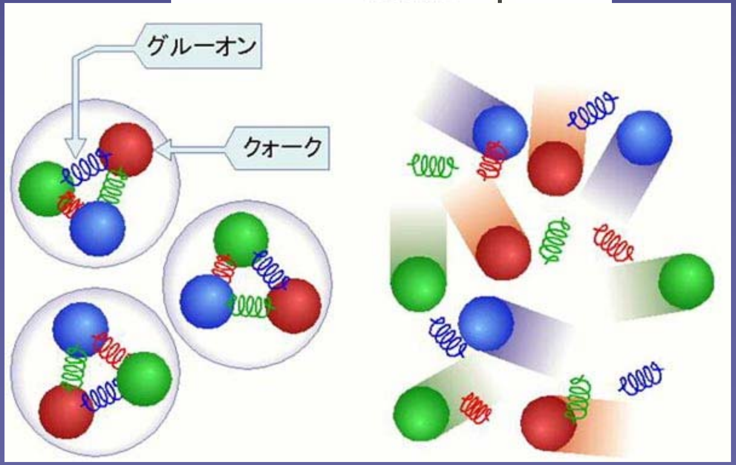
- Detecting GWs from pulsars would tell us lots about neutron stars that cannot be obtained in any other way.
- The GW emission mechanism (bumpy neutron star or r-modes) can constrain the models of neutron stars.
- This can tell us about the internal structure of neutron stars
  - Tells us about nuclear materials at extreme densities



Neutron star structure

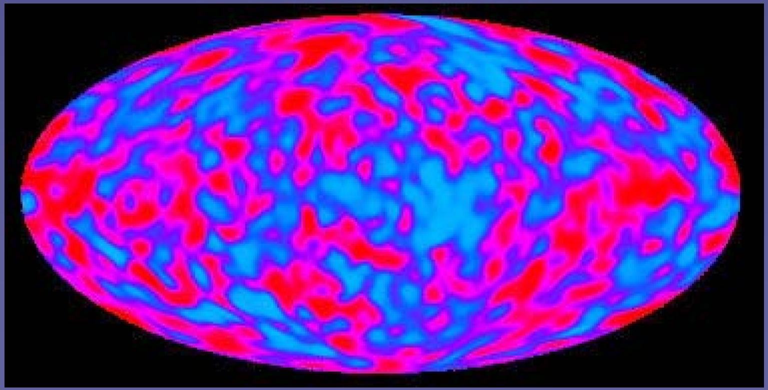
- We cannot reproduce the conditions (density, pressure and gravitational field) inside a neutron star on Earth
- We know conditions similar to in an atomic nucleus – protons and electrons – densities 10^{18} kg/m^3 ~ 25 billion tonnes in a teaspoon!
  - Neutron superfluid
  - Quark-gluon plasma
  - Solid quark star
- Can use gravitational wave observations to calculate mass and radius of star
  - Allows us to constrain models of the neutron star interior





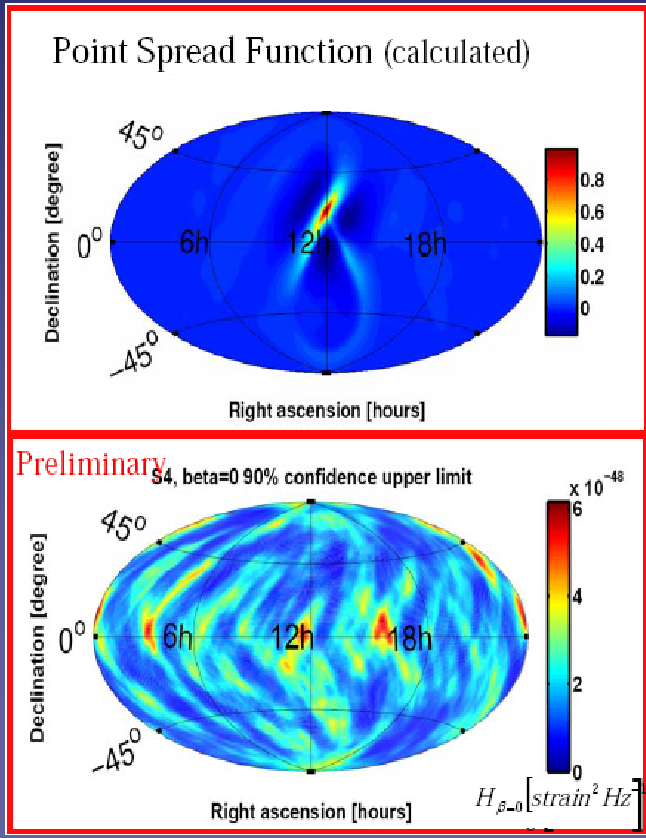
Stochastic sources

- There is a cosmic microwave background (CMBR).
- Could also be cosmic background of GWs:
  - Primordial (from big bang)
  - Combined GWs from other sources could produce a background of GWs.



Stochastic searches

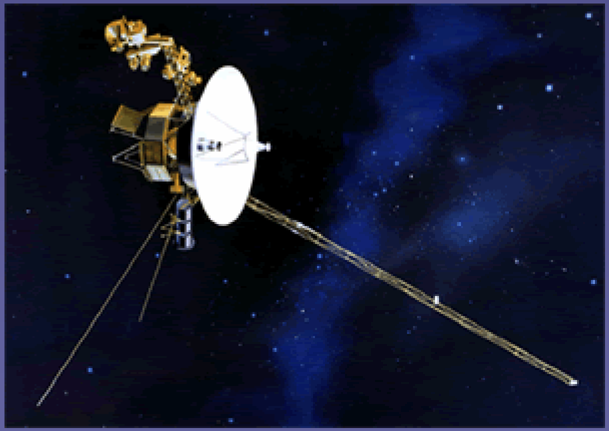
- Cross correlate output of two or more detector i.e. use one data set as a filter for the other
- Set limits on stochastic background in terms of closure density of the universe Ω_{gw}
- S4 upper limit Ω_{gw} **< 6.5x10^{-5}**
- **1 year of S5 data expect Ω_{gw}~4x10^{-6} – big bang nucleosynthesis limit is 10^{-5}!**
- **Can also create upper limit map by making use of the detector antenna patterns**



Stochastic sources

QUEST

- There are a variety of ways being used to look for such primordial sources sources:
  - studying the polarisation of microwaves in the CMBR
  - Doppler tracking of spacecraft
  - pulsar timing
  - Correlations between detectors
- Could be the only way to probe the very early universe fractions of a second after the big bang.



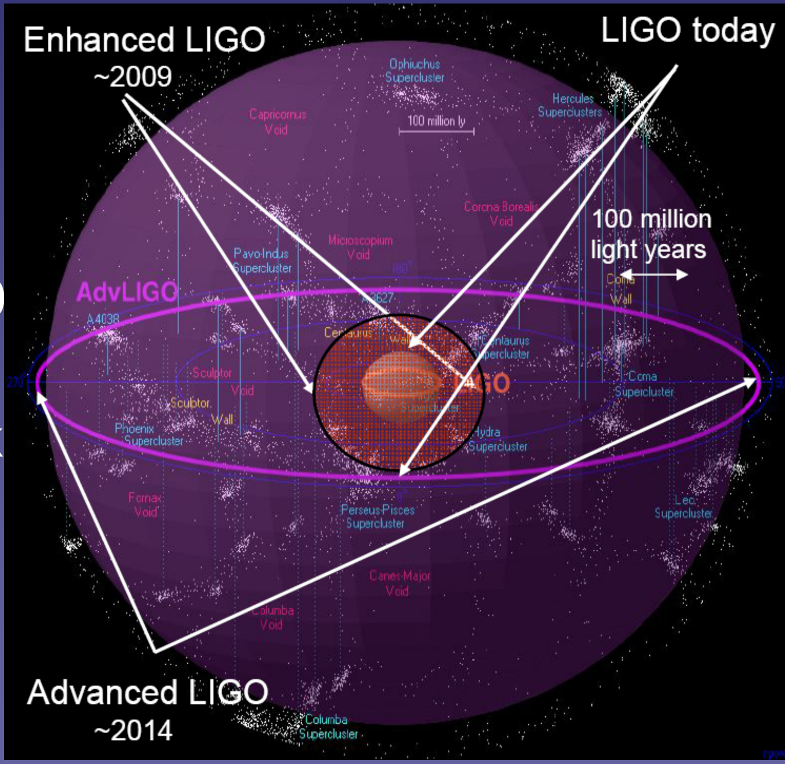
Voyager

Present status of GW searches

- LIGO operating at design sensitivity.
- Have undertaken observation runs in the last four years, with the current run having been observing for over a year.
- VIRGO will joining data taking soon.
- Several bar detectors also running and being upgraded.

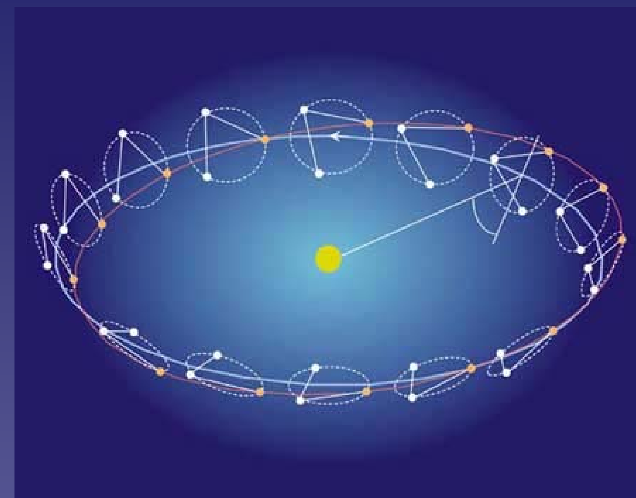
Future - interferometers

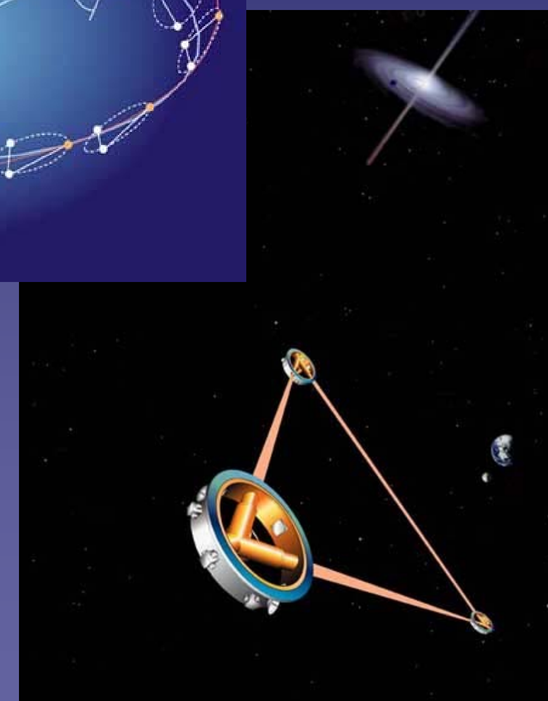
- In ~2007/8 LIGO will be upgraded (Enhanced LIGO), and again in 2013 to Advanced LIGO with new technologies (pioneered in GEO600) to improve sensitivity.
  - factor of 10 sensitivity improvement equals factor of 1000 in volume seen
  - expect to see few events per week
- European (EGO, GEOHF), Japanese (LCGT) and Australian (ACIGA) collaborations are also looking into future detectors covering a range of frequencies.



Future – space based detector

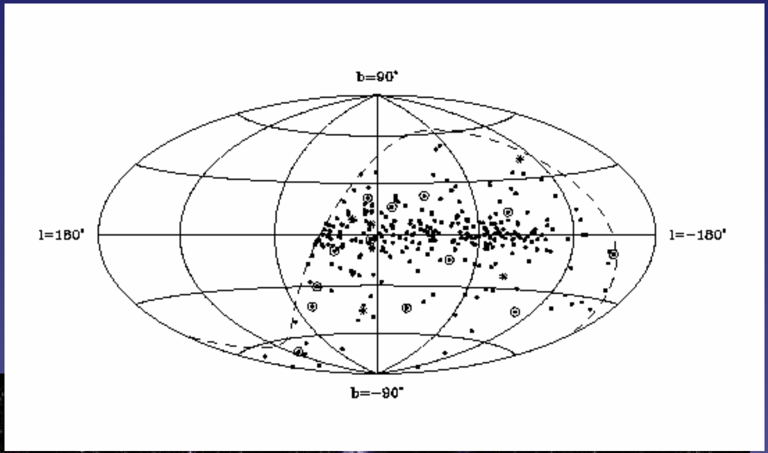
- Laser interferometer space antenna (LISA) is a joint NASA/ESA project for a space based GW detector planned for a 2015 launch.
- LISA has 5 million km arms.
- Will be able to look at low freqs > mHz – not limited by gravity gradient noise

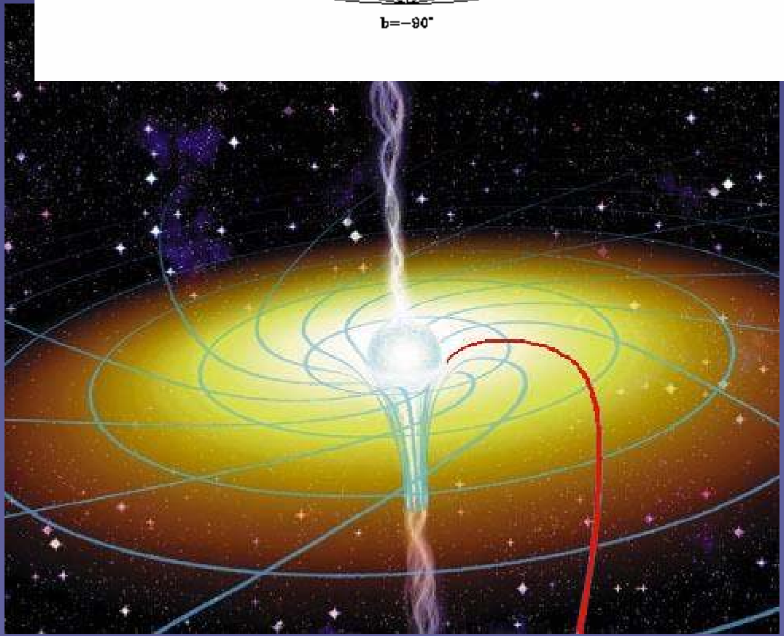




LISA sources

- Sources it will see will be:
  - compact object binary systems – gives us a census of these types of system
  - infall into supermassive black holes – enables us to map space-time in very strong gravity regimes
  - Black hole mergers





Conclusions

- Currently have near continuous operation of LIGO
  - Produced upper limits from many sources
- Good chance of detecting something – even you can help!
- Detector upgrades and LISA should give opportunity to start GW astronomy for real.
- Exciting times for GW astronomy!

Can I help?

- Yes! This year is World Year of Physics or Einstein Year.
- Einstein@home (a SETI@home like screensaver) has been developed for the general public to contribute to searching for gravitational waves from neutron stars using actual data from LIGO and GEO

Visit `http://einstein.phys.uwm.edu`