Gravitational Radiation

Observing the dark and dense Universe

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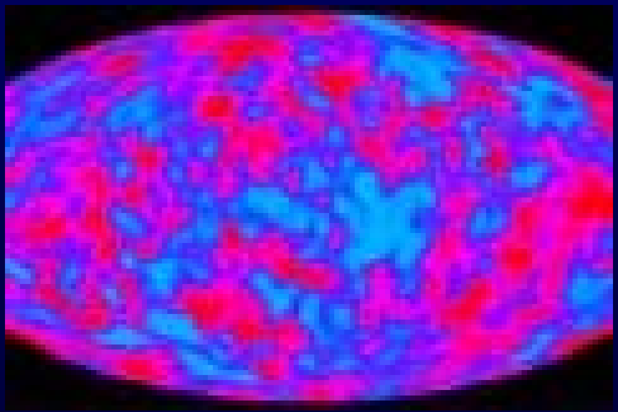
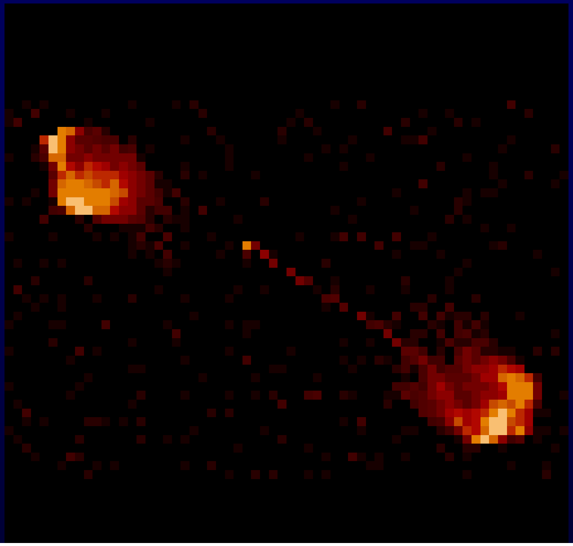
Modern Astronomy

Optical, radio, x- and gamma-ray telescopes have revealed a lot of new objects and phenomena

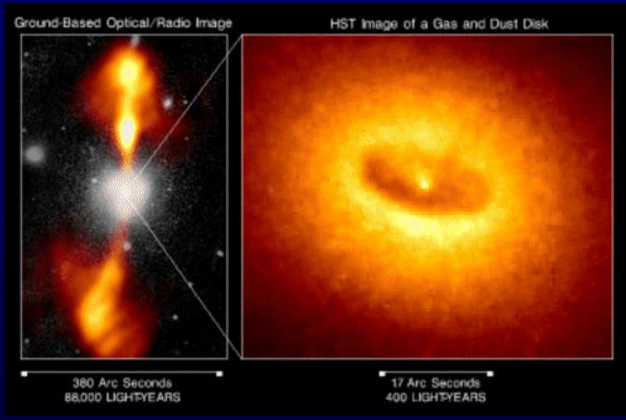
Cosmic micro-wave background and big bang



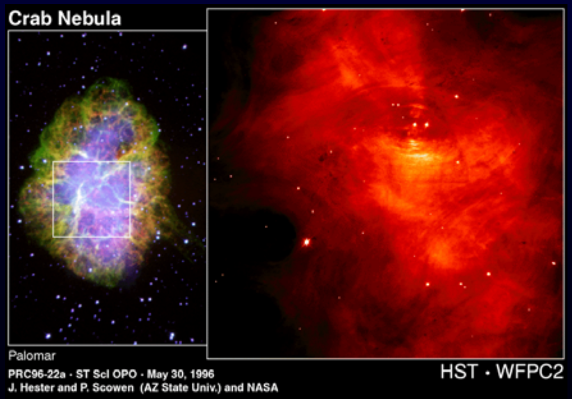
Quasars and Radio galaxies

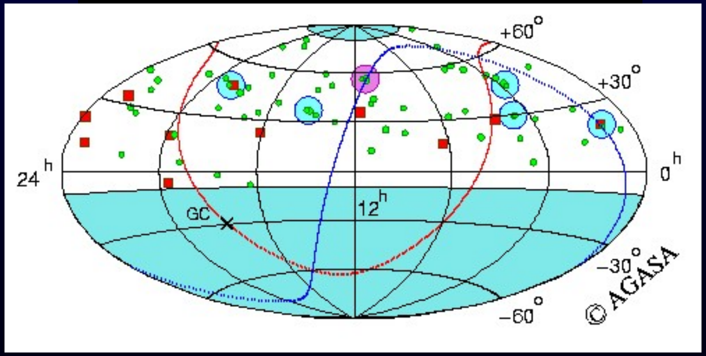


Supermassive Black holes

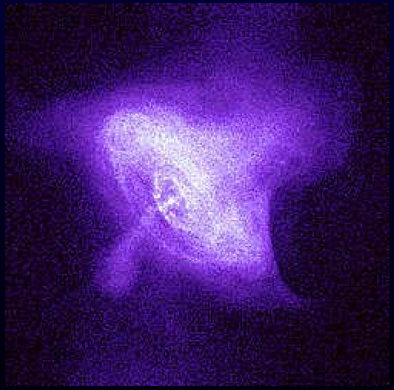


Pulsars





X-ray binaries; gamma-ray emitting sources



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Astronomy has taught us that more than 90% of the Universe is dark

But …

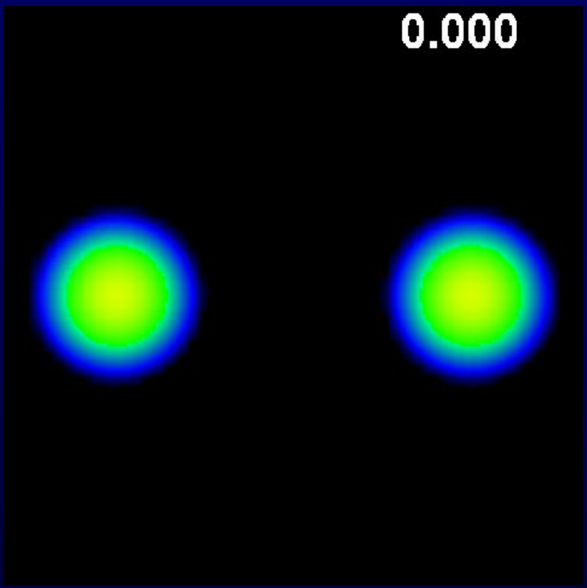
Even this dark matter interacts gravitationally; we should be able to ‘see’ this matter via *gravitational radiation* it might emit

Plan of the talk

- GW theory - a brief overview
- GW detector projects around the world
- Astronomical sources of gravitational waves
  - neutron stars
    - birth, binaries, environment, etc.
  - black holes
    - formation, binaries, super-massive holes and their environs
  - stochastic background
    - primordial, astronomical, white-dwarf, ...
- Gravitational wave data analysis

Gravitational Waves
A simple overview of the theory

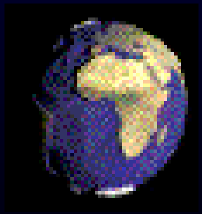
Newton's law of Gravity



- The force of gravity between two masses *m* and *M* separated by a distance *r* is

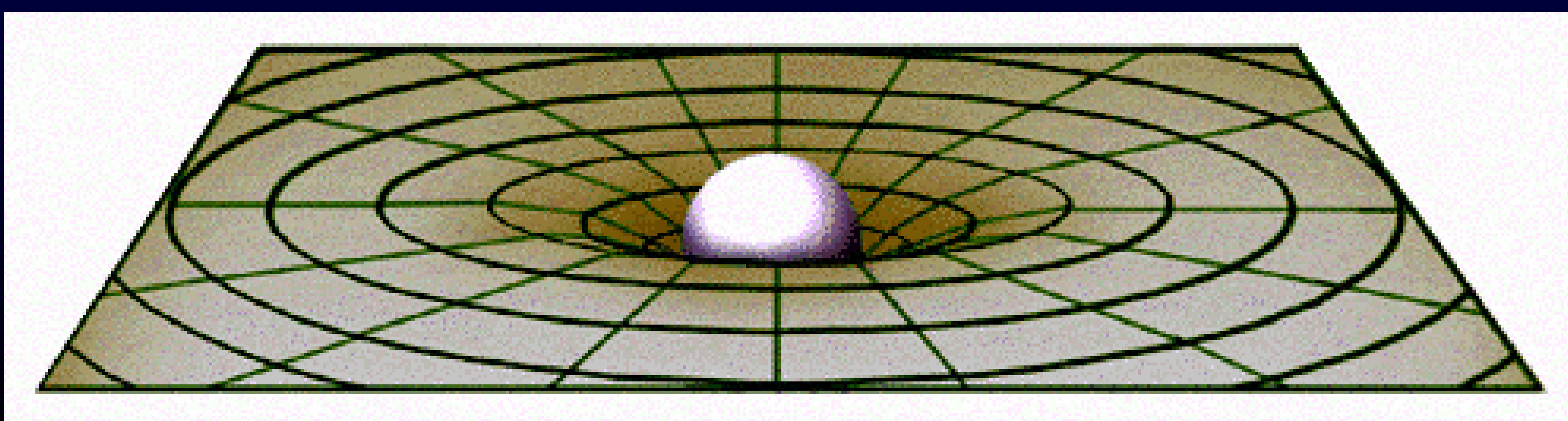
$$^{2}(t) = 4\pi G\, \rho(t)$$

- Newton's law of gravity transmits force instantaneously - if body *M* changes its position it is felt by instantaneously by body *m*
- If Newton's gravity is right we will be able to build a 'gravitational telegraph' which can transmit signals instantaneously - a violation of Einstein's special relativity

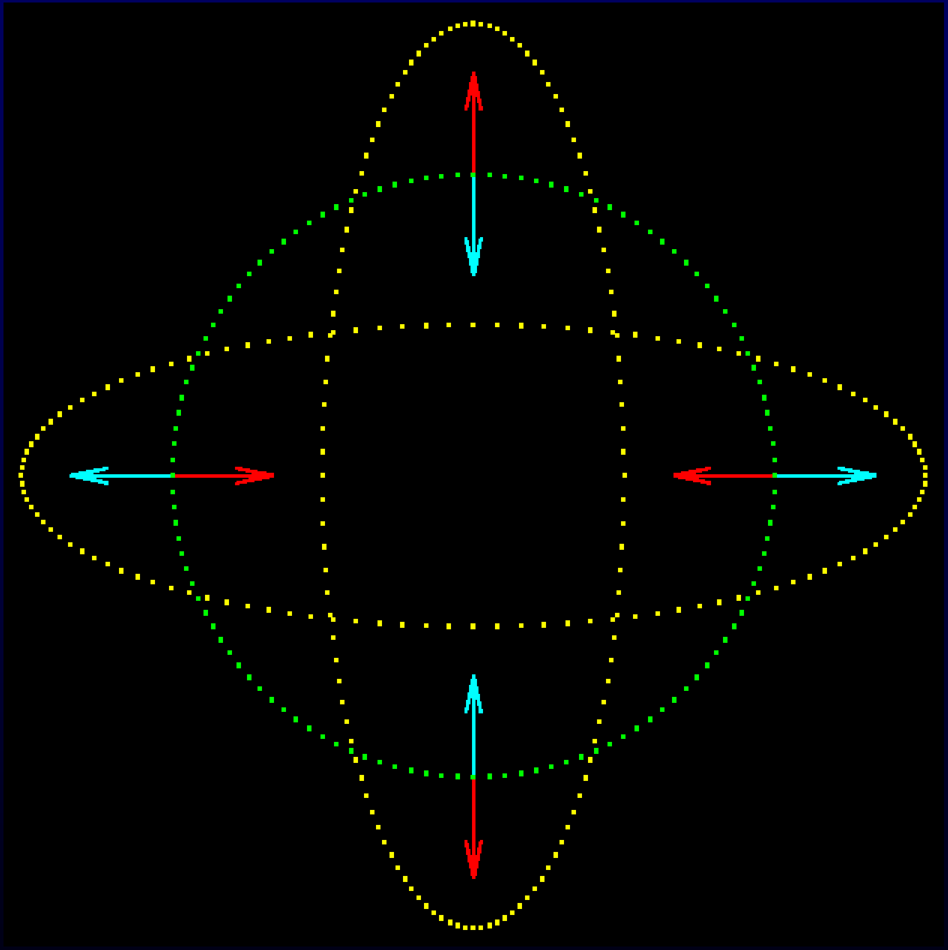


Einstein’s Gravity and Gravitational Waves As Ripples in the Fabric of Spacetime

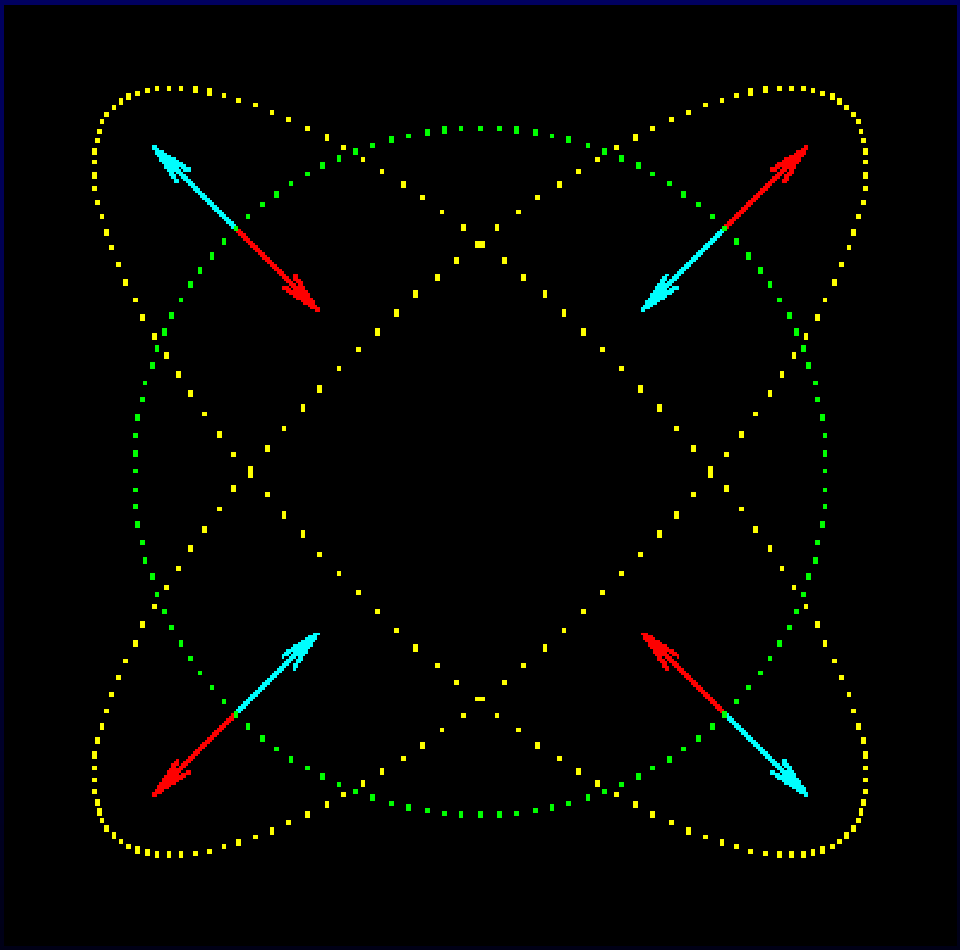
- According to special relativity not even gravitational disturbances should travel at speeds greater than the speed of light
- According to Einstein’s general relativity gravity is not a force but a warping of spacetime
- **Gravitational waves are ripples in the curvature of spacetime that carry information about changing gravitational fields**



Interaction of Gravitational Waves



Plus polarisation



Cross polarisation

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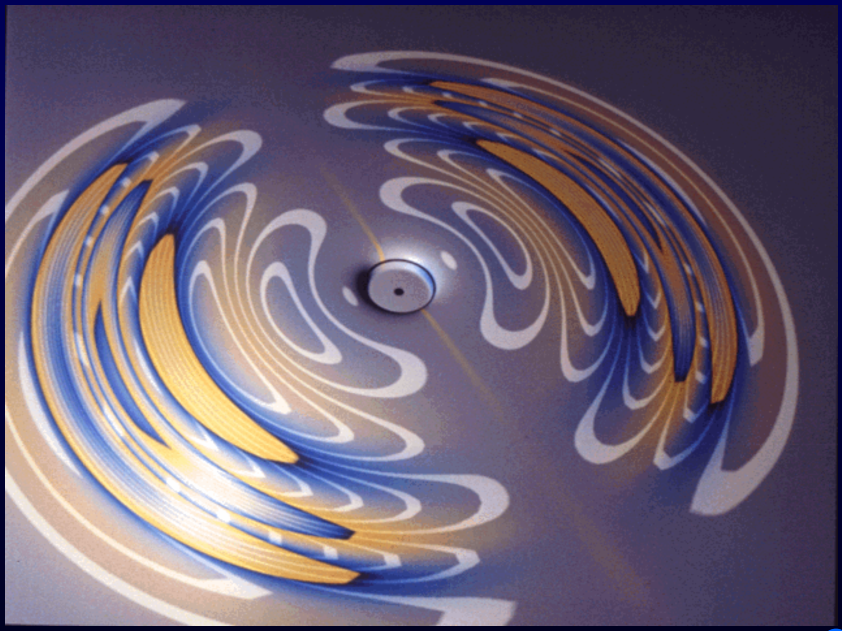
Gravitational Wave Observables

Derived originally by Einstein and confirmed by Landau and Lifschitz

Collision of two black holes at 300 ly can generate detectable amplitudes



- Famous *Quadrupole Formula* - direct consequence of Einstein's equations - gives GW luminosity and amplitude
  - **Luminosity**

    $$L = (\text{Asymmetry})\, M^2 R^2 \omega^6$$

  - **Amplitude**

    $$h = (\text{Asymmetry})\, (M/R)\, (M/r)$$

    The amplitude gives strain caused in space as the wave propagates

  - **Frequency**: Dynamical frequency in the system
- Man made GW are very weak to observe
- For typical astronomical sources $h \sim 10^{-21}$

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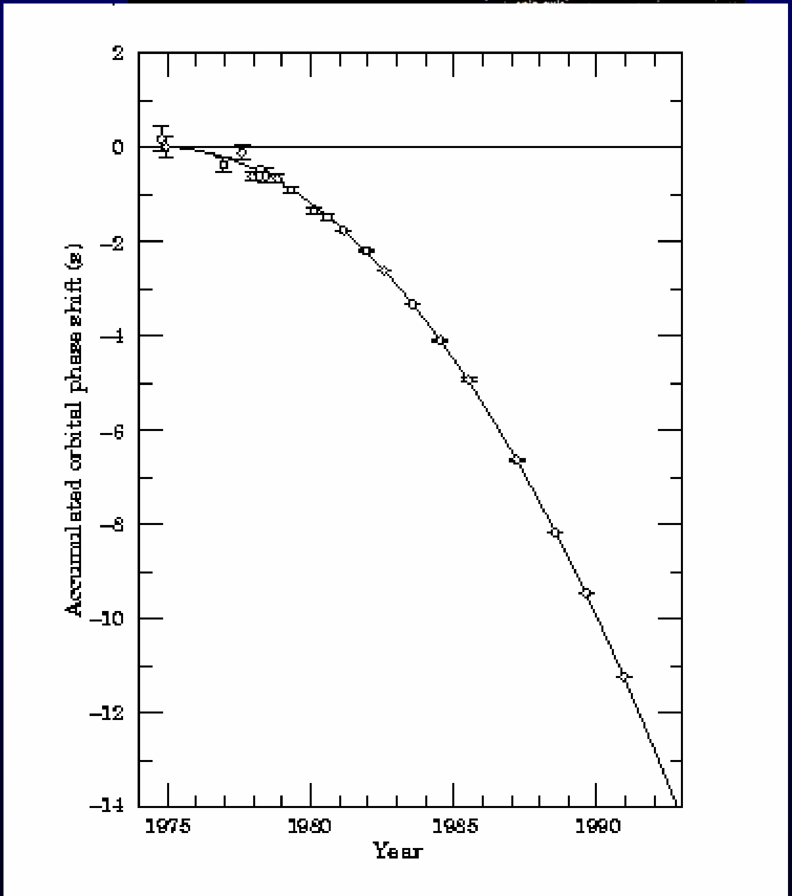
Do Gravitational Waves Exist?

Inspiral in Hulse-Taylor binary pulsar



But that will take a 100 million years

- Double neutron stars; each of mass 1.4 M Orbital period 7.5 Hrs
- Stars whirling around each other at a thousandth the speed of light
- According to Einstein's theory the binary should emit GW
  - GW carry rotational energy from the system which causes the two stars to spiral in towards each other and a decrease in the period
  - Observed period change is about 10 micro seconds per year
- **This decrease in period is *exactly* as predicted by Einstein's theory**

Eventually the binary will coalesce emitting a burst of GW that will be observable using instruments that are currently being built

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Gravitational Wave Detectors

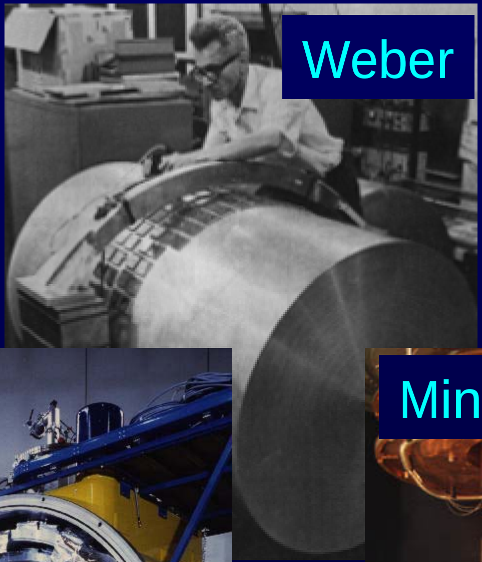
Resonant detectors

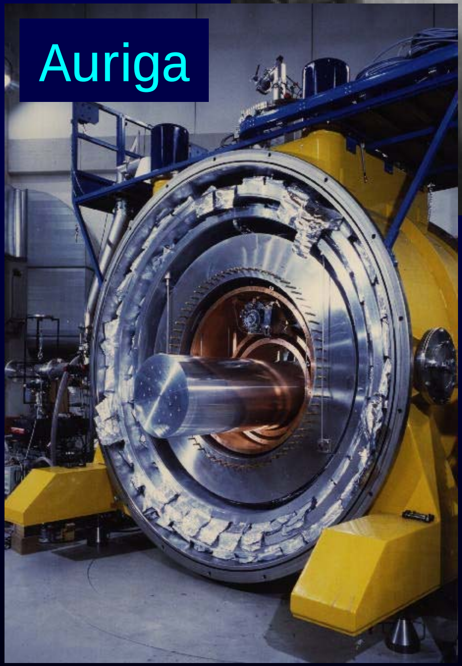
A cryogenic aluminum or niobium bar with a transducer to measure the oscillations induced by the tidal interaction of GW and the bar

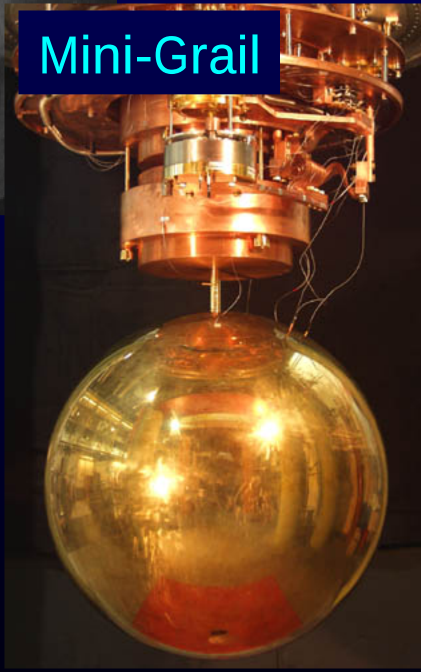
Basically narrow band detectors with sensitivity around the bar's resonant frequency

Several bars are currently in operation (3 in Europe, one in US, one in Australia)

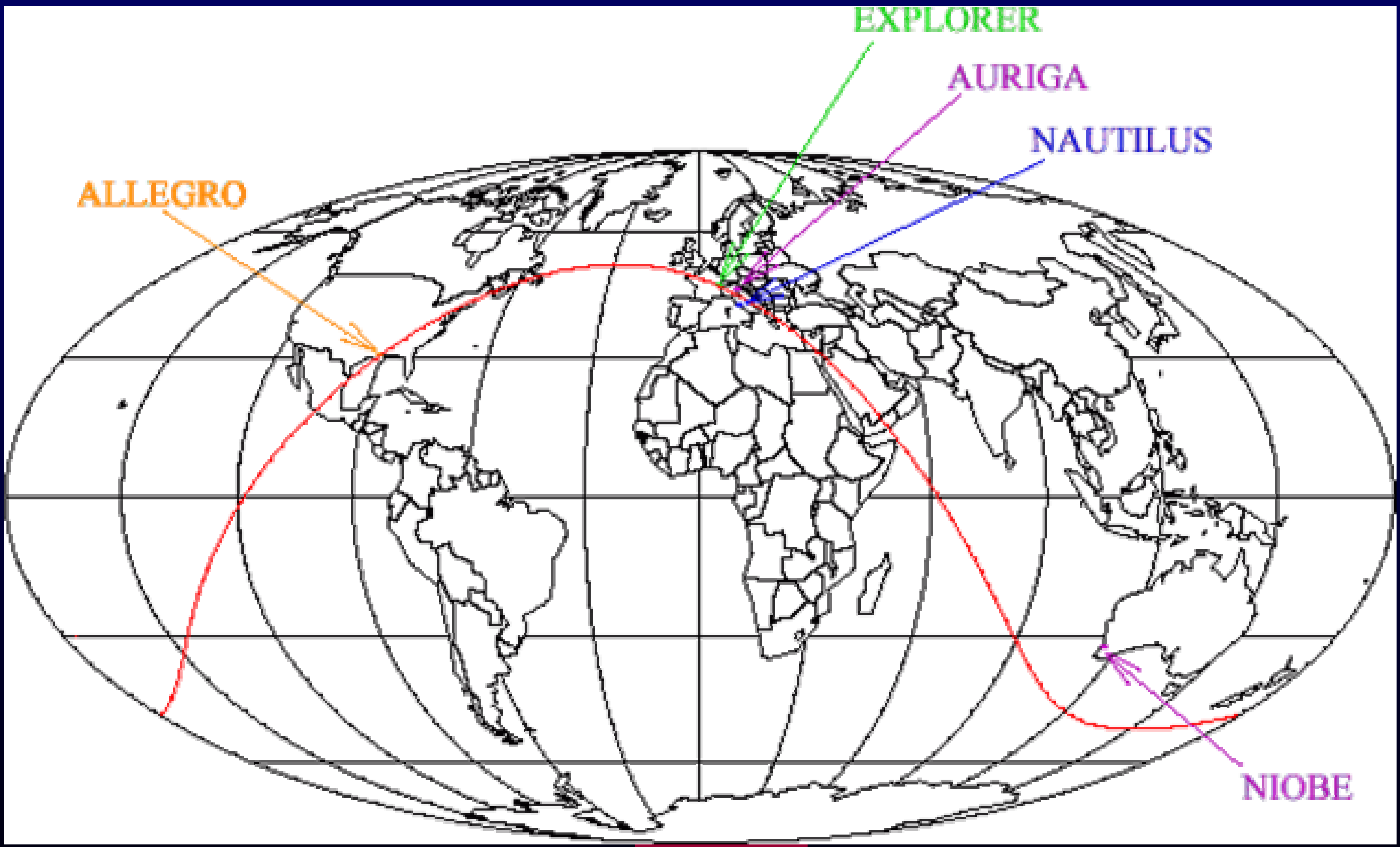
Sensitive to supernovae in our Galaxy - improved versions (spherical detectors) might help in probing neutron stars



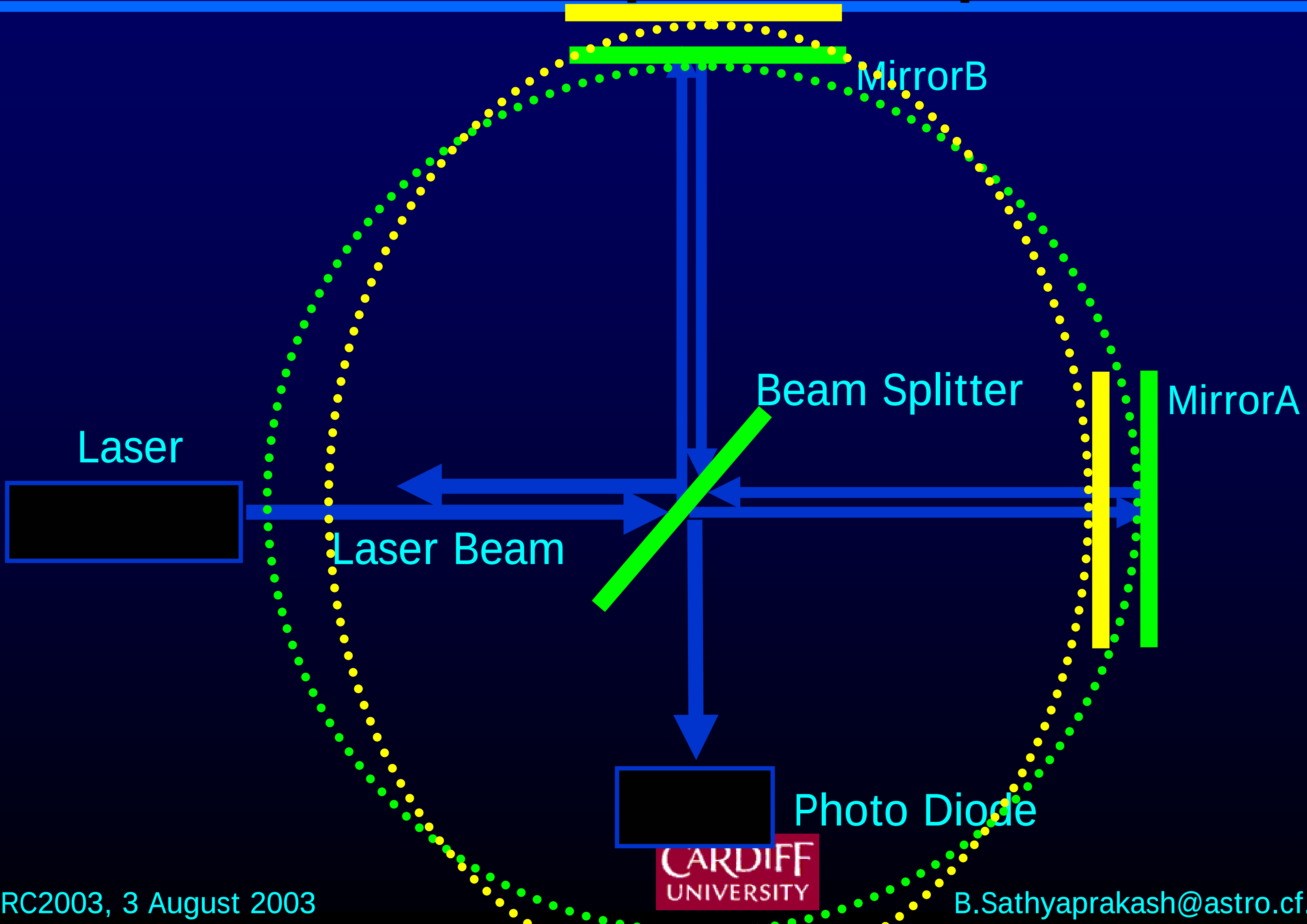




International Gravitational Event Collaboration - IGEC



Laser Interferometric Detectors
Basic Principle of Operation



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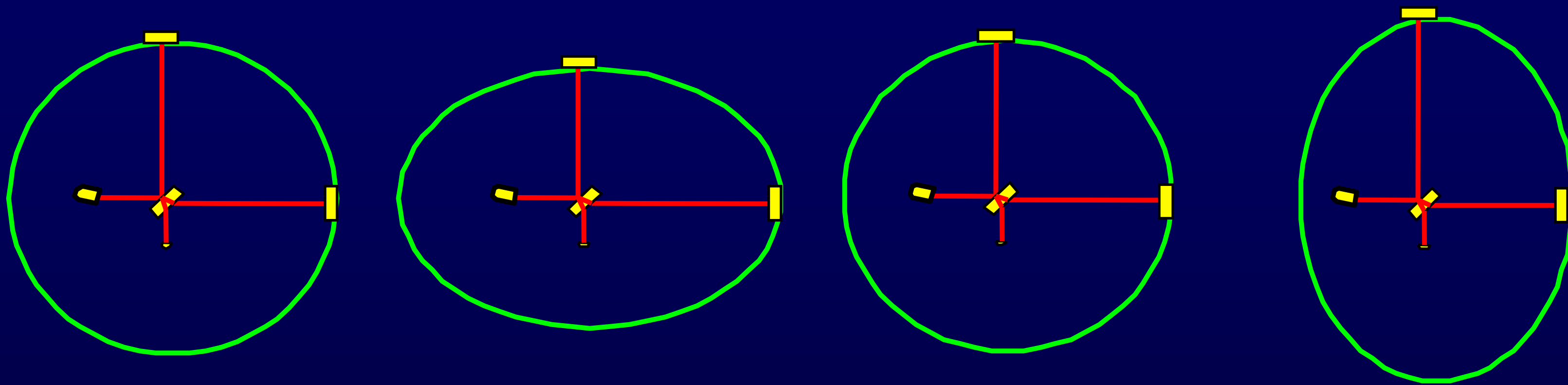
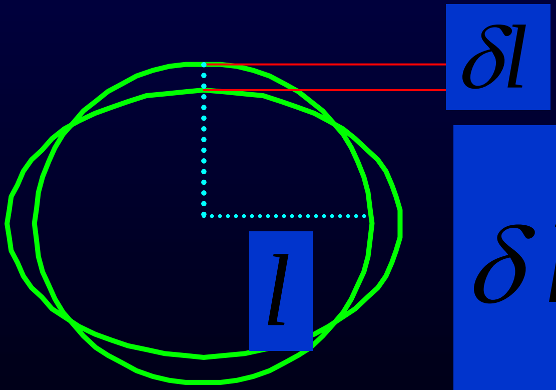
Measuring Gravitational Waves with Interferometers



$t = 0$ $\quad$ $t = \frac{\tau}{4}$ $\quad$ $t = \frac{\tau}{2}$ $\quad$ $t = \frac{3\tau}{4}$



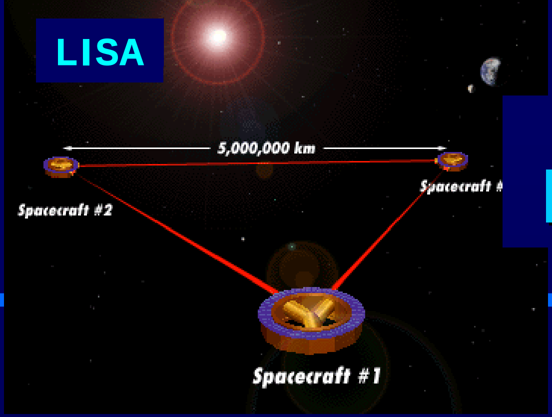
$$\delta l = \frac{h}{2} l$$

For Typical Astronomical sources

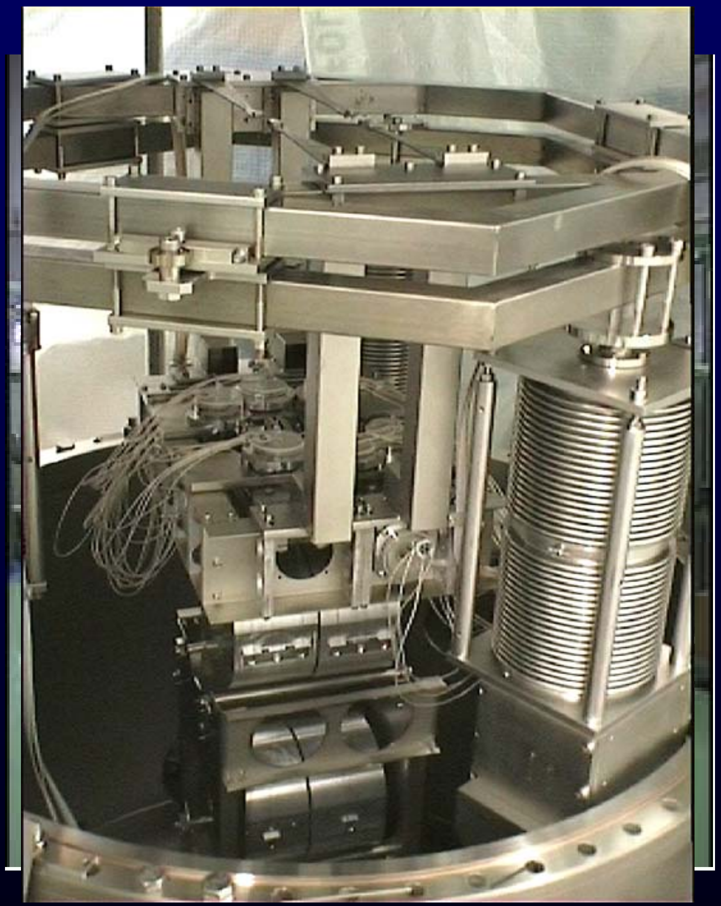
$$h = \frac{2\,\delta\,l}{l} \le 10^{-22}$$

Interferometers

LIGO, GEO and TAMA taking data
VIRGO being installed
AIGO not fully funded yet
LISA is a ESA-NASA project



Technology used in a typical Gravitational Wave Antenna



- All detectors use (or plan to use) the most advanced technology
  - low vacuum (10^{-9} T)
  - high power laser source; signal and power recycling
  - highly reflective mirrors
  - vibration isolation suspension systems
- Sensitive to tiny strains - change in arm lengths to one part in 10^{21}
  - change in length ~ 4 10^{-19} m = 1,000 times smaller than Hydrogen nucleus
  - Equivalent to measuring the distance to the nearest star with an accuracy of the width of human hair

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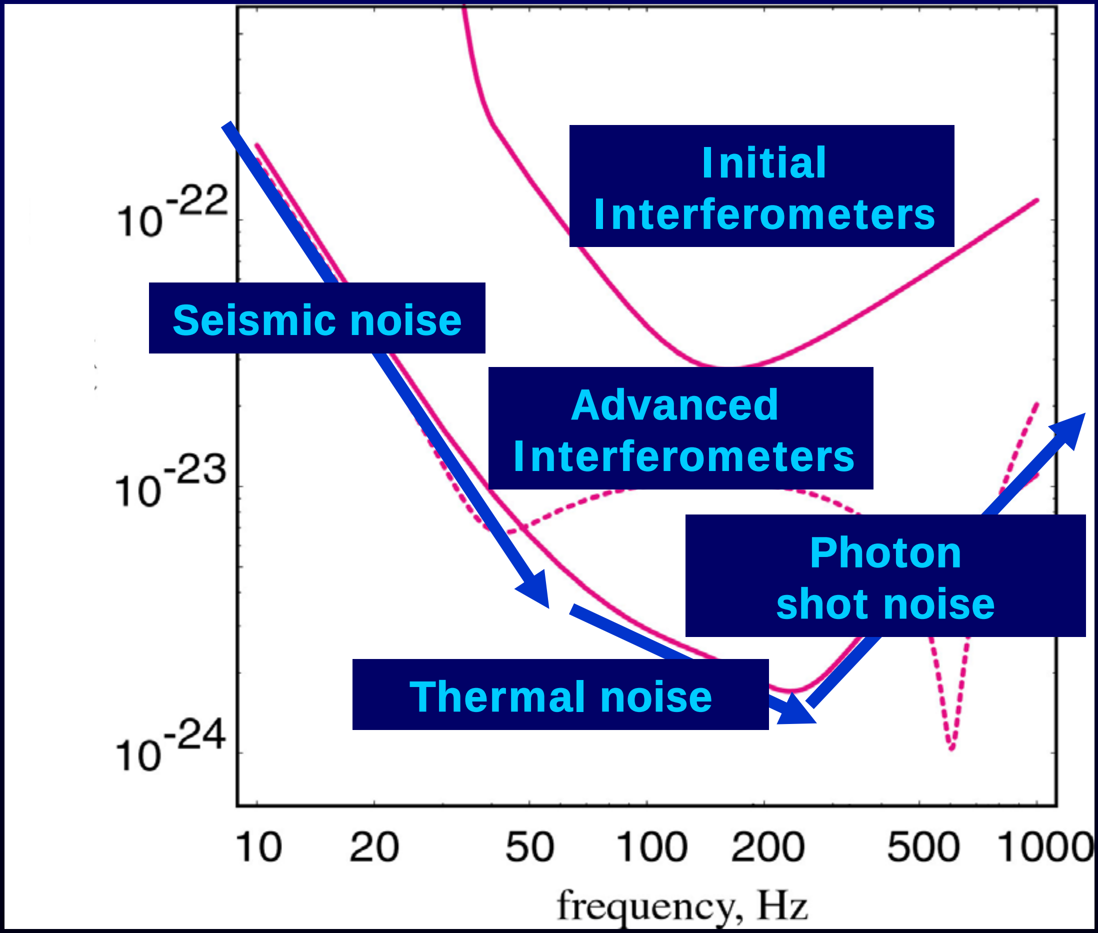
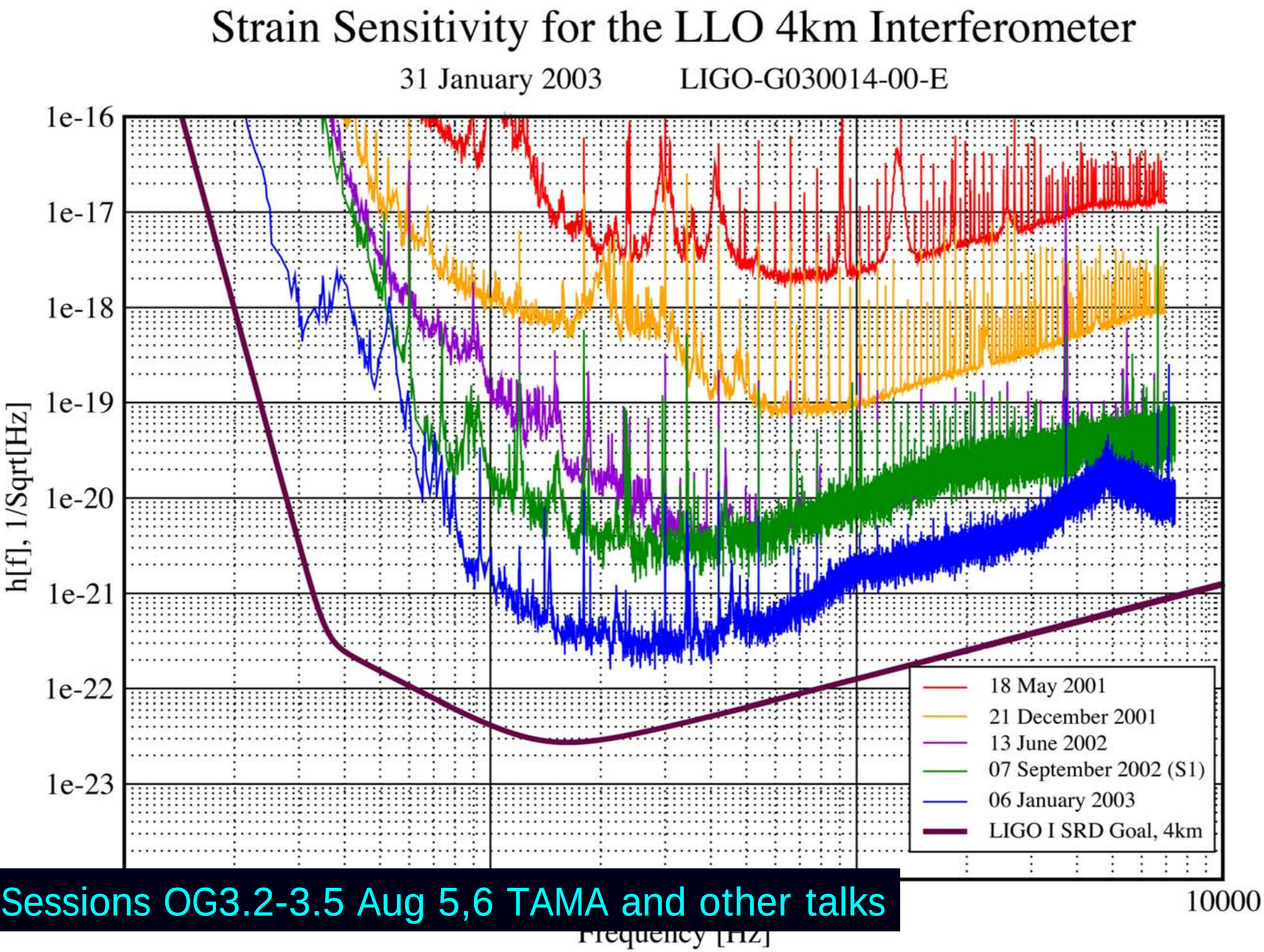
Sensitivity of interferometers and backgrounds limiting their sensitivity

Gravity gradient and quantum uncertainty of mirror positions are the ultimate limiting factors

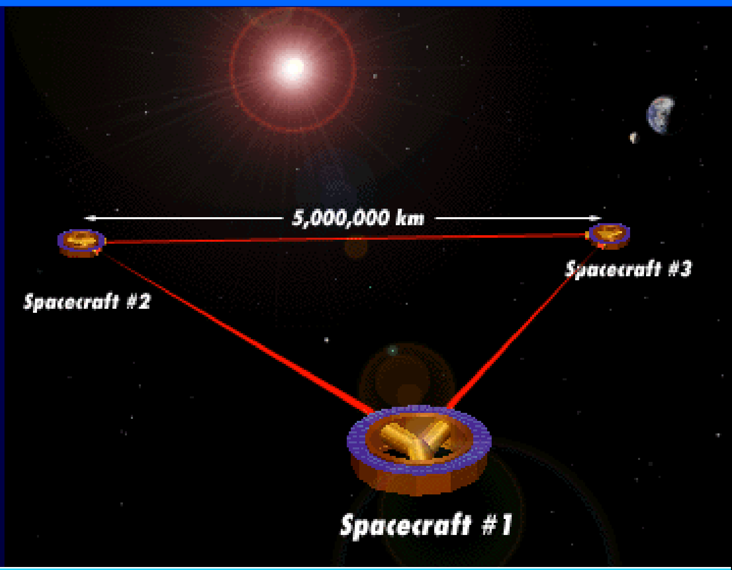


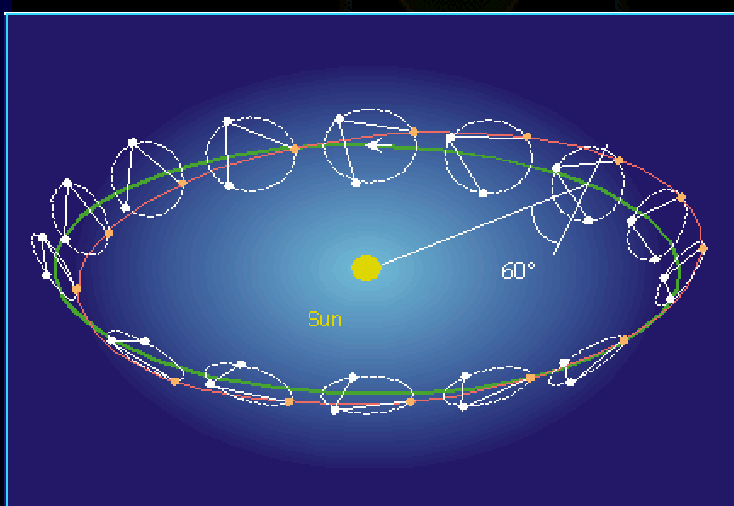


Sessions OG3.2-3.5 Aug 5,6 TAMA and other talks

LIGO Scientific Collaboration

Laser Interferometer Space Antenna



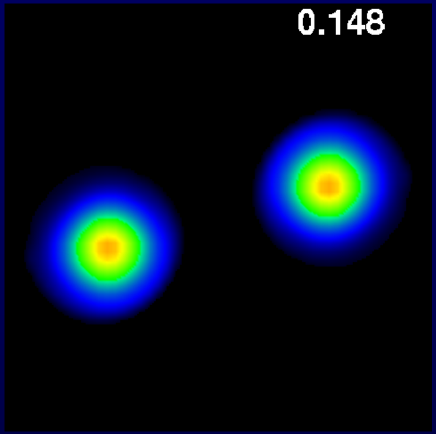


- ESA-NASA collaboration
  - **Intended for launch in 2011**
- 3 space craft, 5 million km apart, in heliocentric orbit
- Test masses are passive mirrors shielded from solar radiation
- Crafts orbit out of the ecliptic always retaining their formation
- Sensitivity limited by:
  - long-term control
  - GW b/g by Galactic sources
  - shot noise …

Session OG3, LCGT LISA and other talks

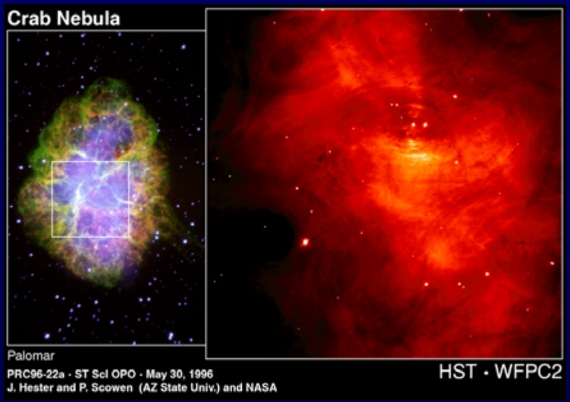
Gravitational Wave Sources

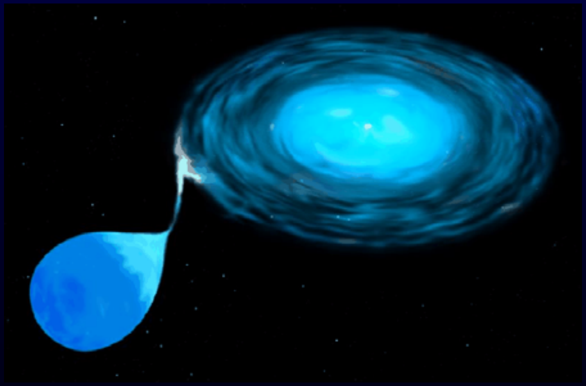
GW sources in ground-based detectors



Binaries of black holes and neutron stars

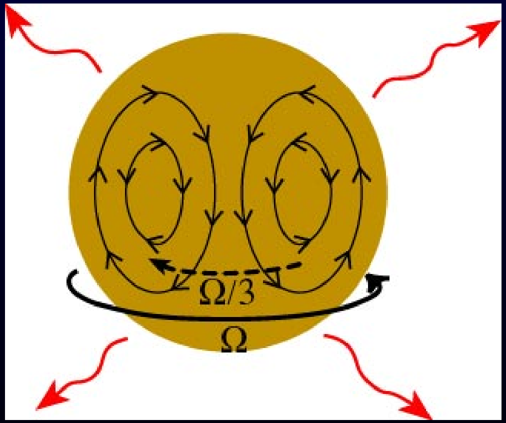
Supernovae and birth of NS and BH





Spinning neutron stars in X-ray binaries

Relativistic Instabilities in young NS



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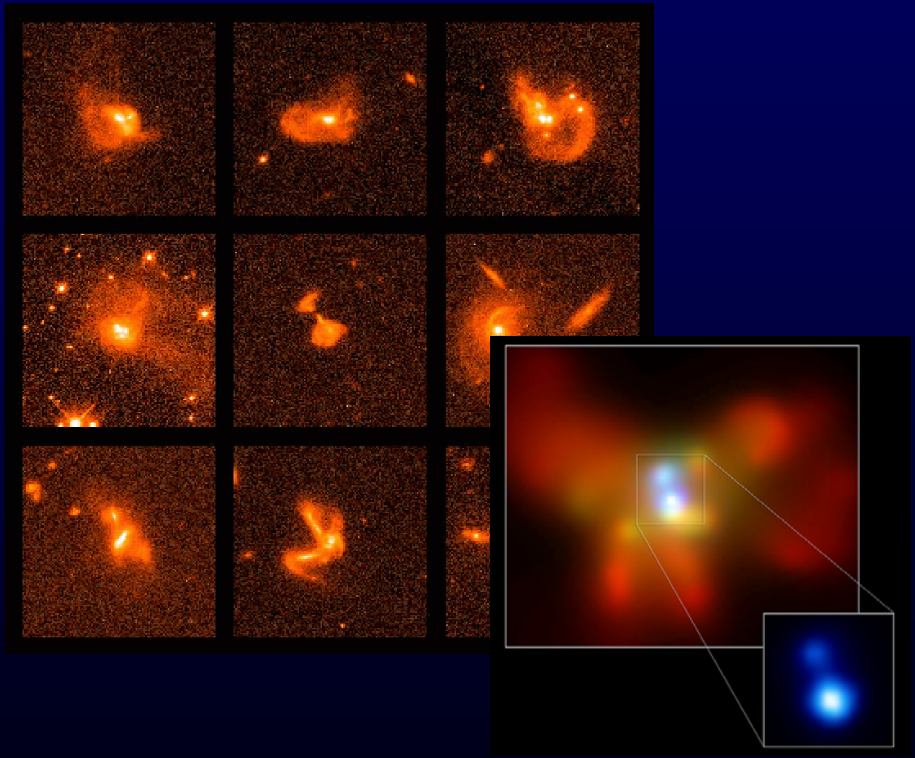
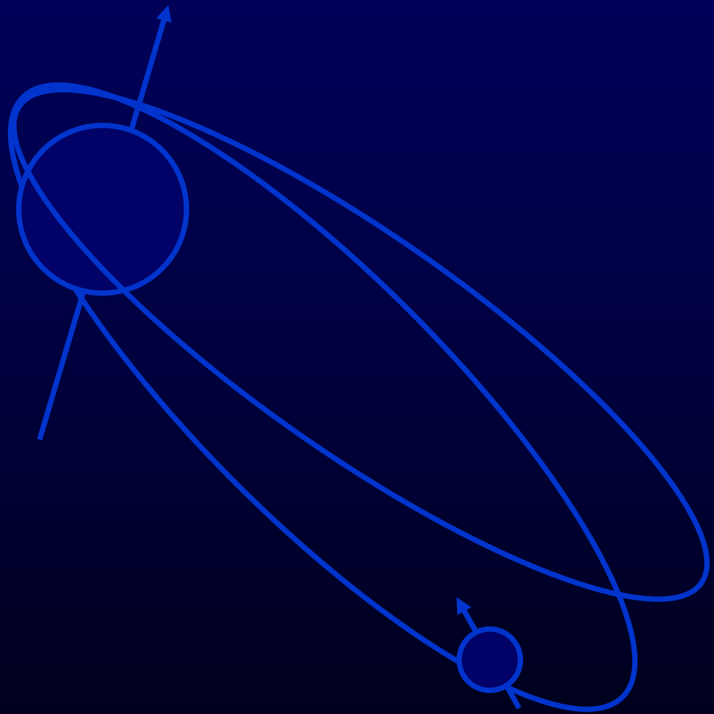
GW Sources in Laser Interferometer Space Antenna

- Merging supermassive black holes (SMBH) in galactic centers



X-ray image of a merging SMBH

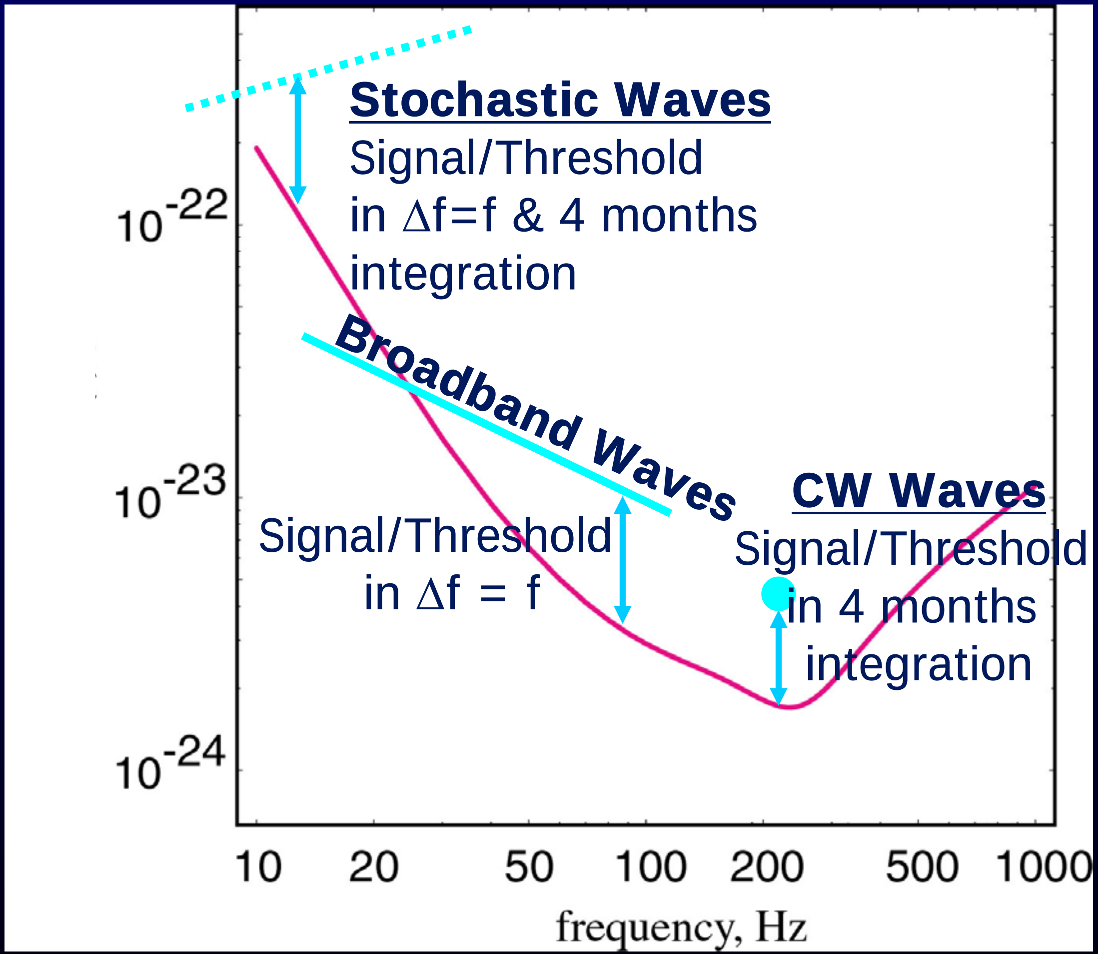
- Signals from gravitational capture of small BHs by SMBHs



Conventions on Source/Sensitivity Plots

- Assume the best search algorithm now known
- Set threshold so that false alarm probability is=1%

$$h_{rms} = h(f)\sqrt{f} \sim 10\, h(f)$$



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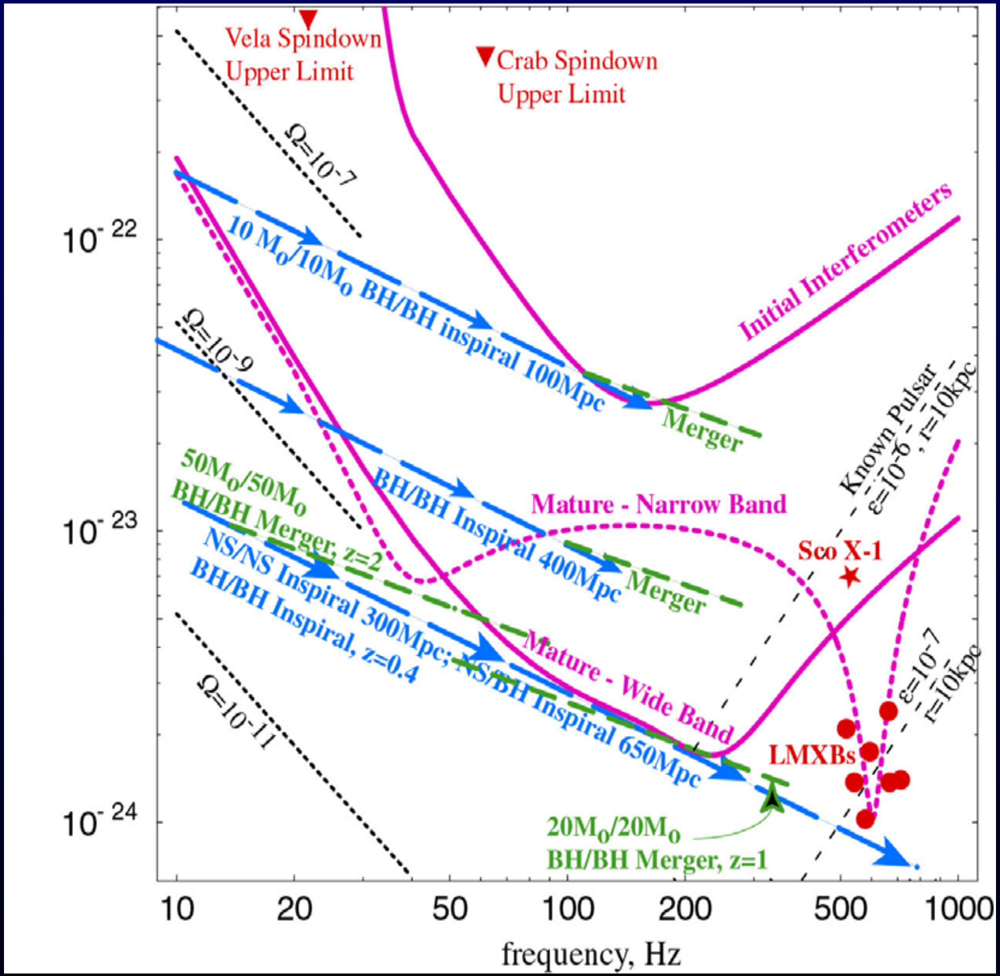
Overview of sources for ground-based detectors

- Neutron Star & Black Hole Binaries
- Spinning NS's
  - LMXBs
  - known pulsars
  - previously unknown
- NS Birth (SN, AIC)
  - tumbling, convection
- Stochastic background
  - big bang, population



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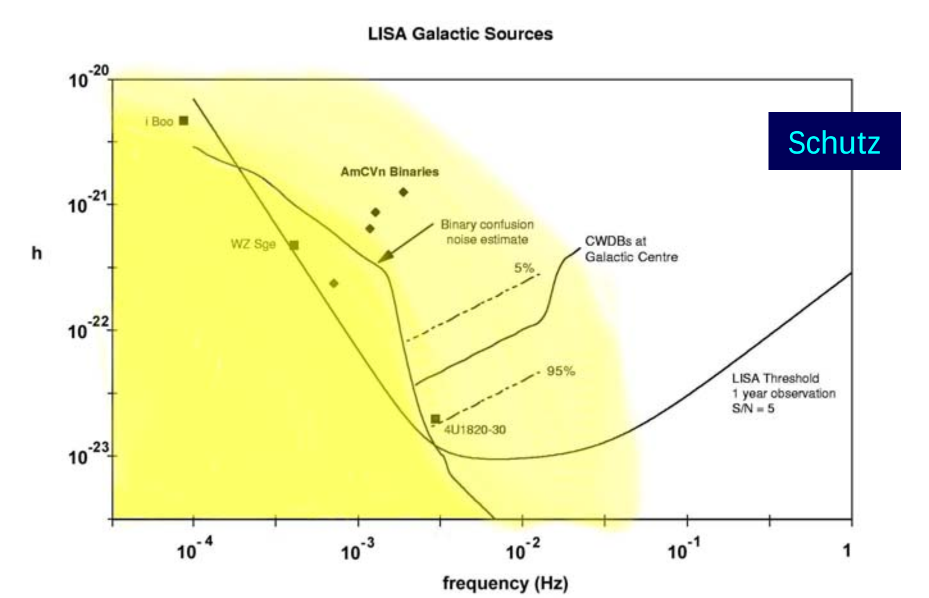
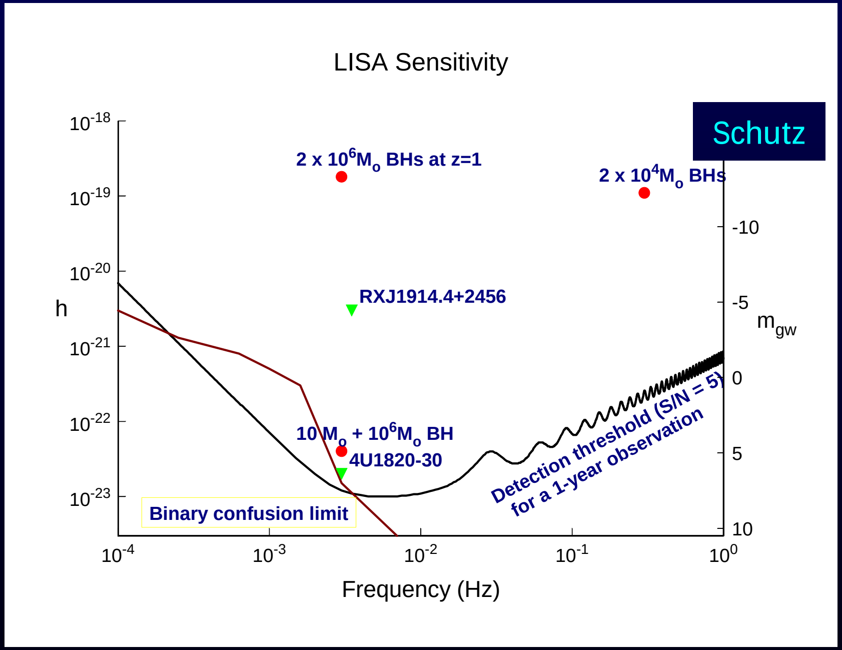
Overview of sources for LISA



LISA will see all the compact white-dwarf and neutron-star binaries in the Galaxy.

LISA will see super-massive black hole collisions wherever they occur in the Universe



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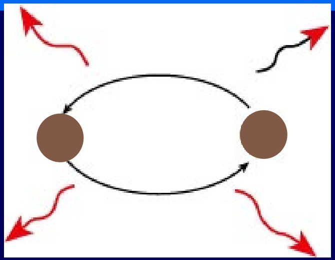
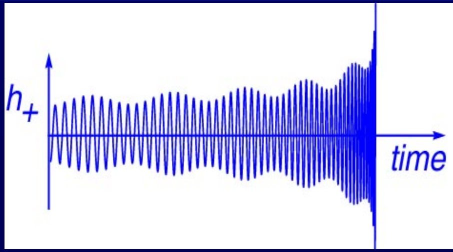
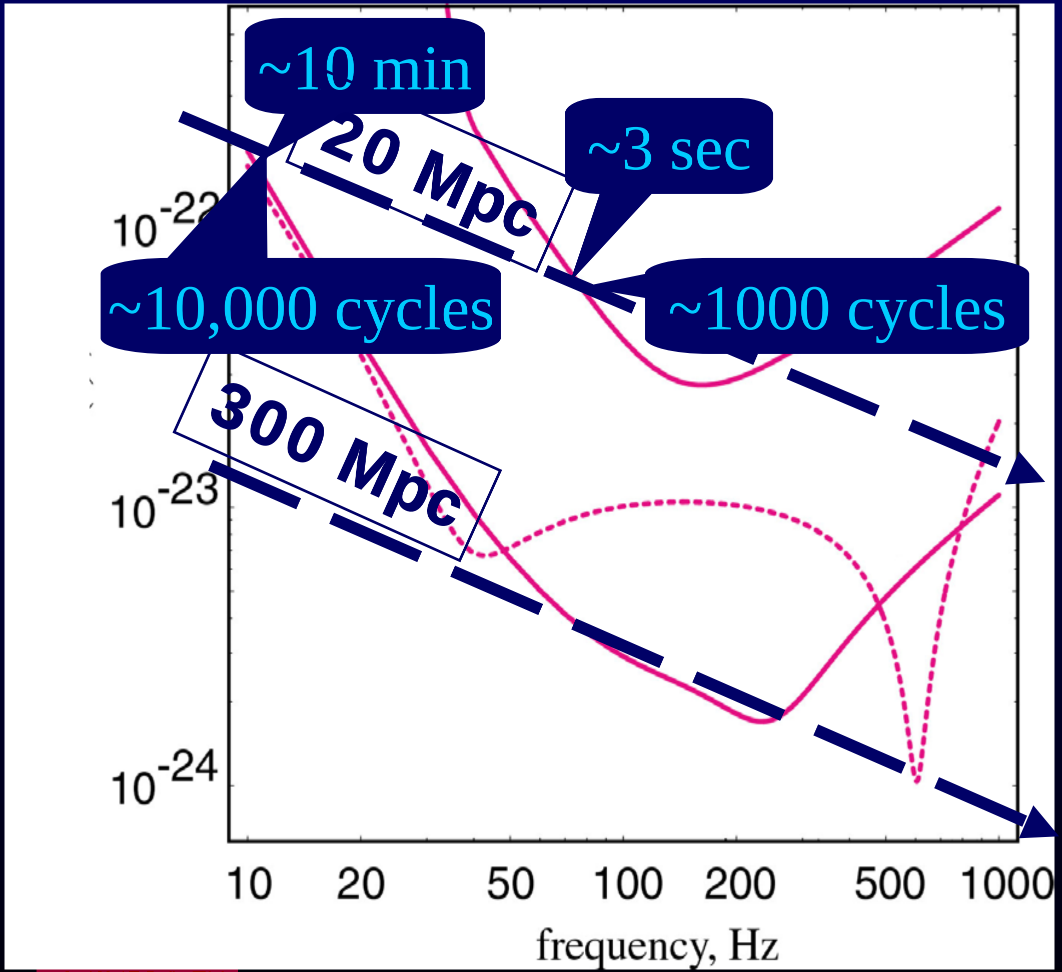
Neutron Star Binary Inspiral

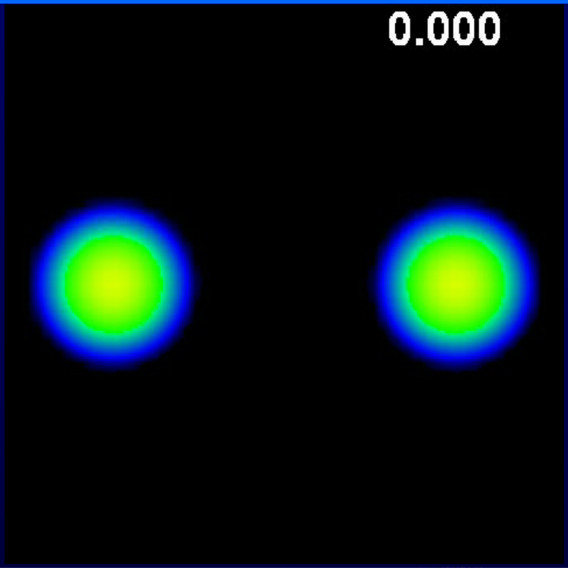




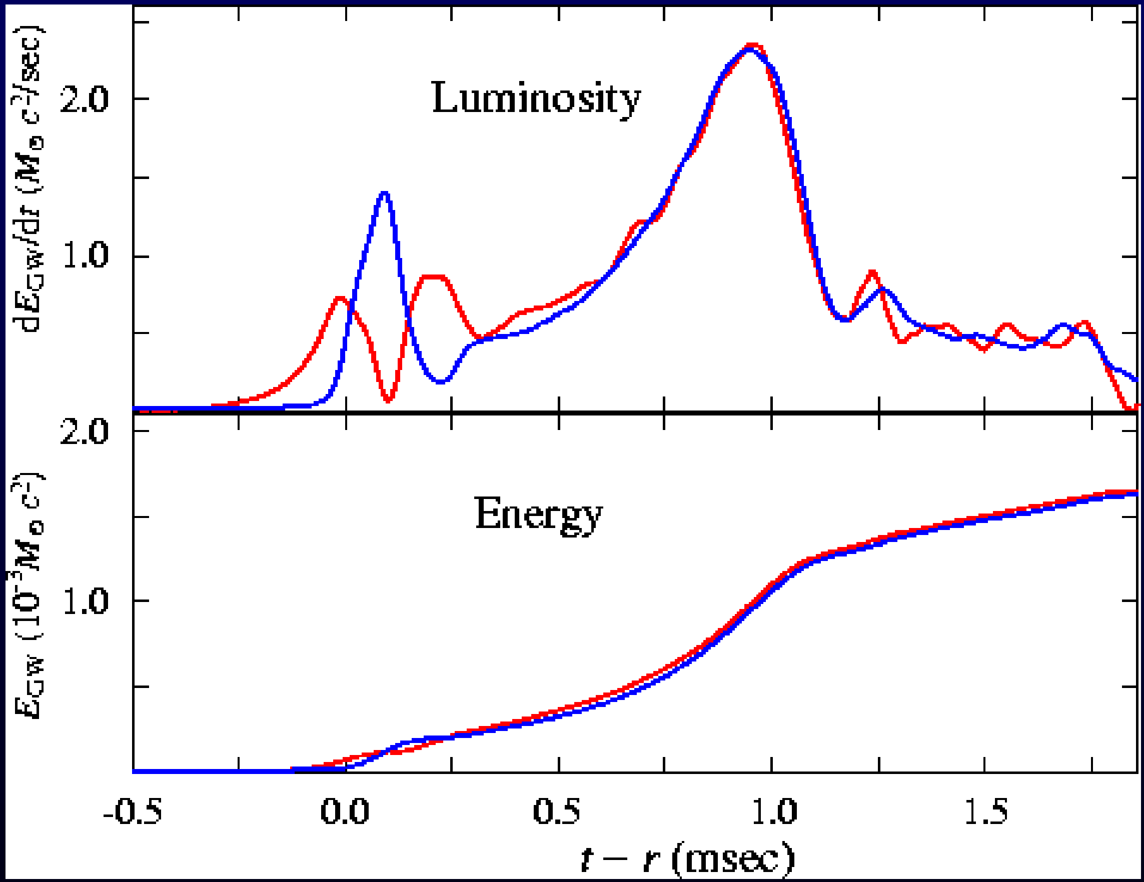
- Event rates
  - Initial IFOs
    - Range: 20 Mpc
    - 1/3000 yrs to 1/3 yrs
  - Advanced IFOs
    - Range: 300Mpc
    - **1/yr to 2/day**

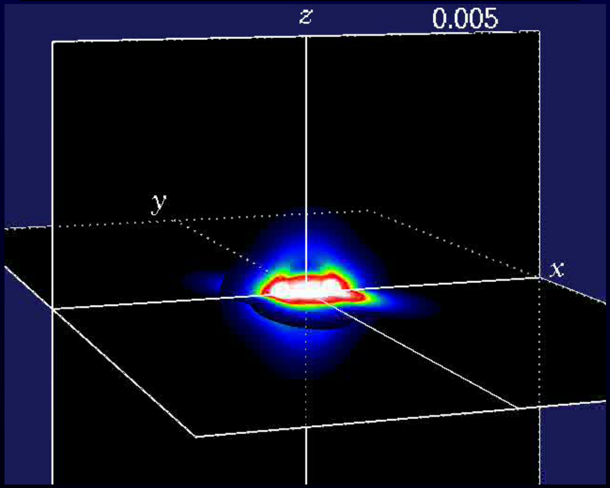


NS-NS Coalescence and bar mode instability

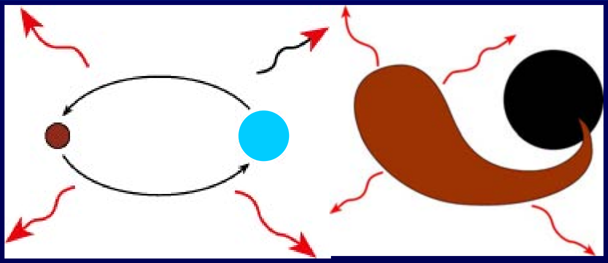


Kawamura, Oohara and Nakamura

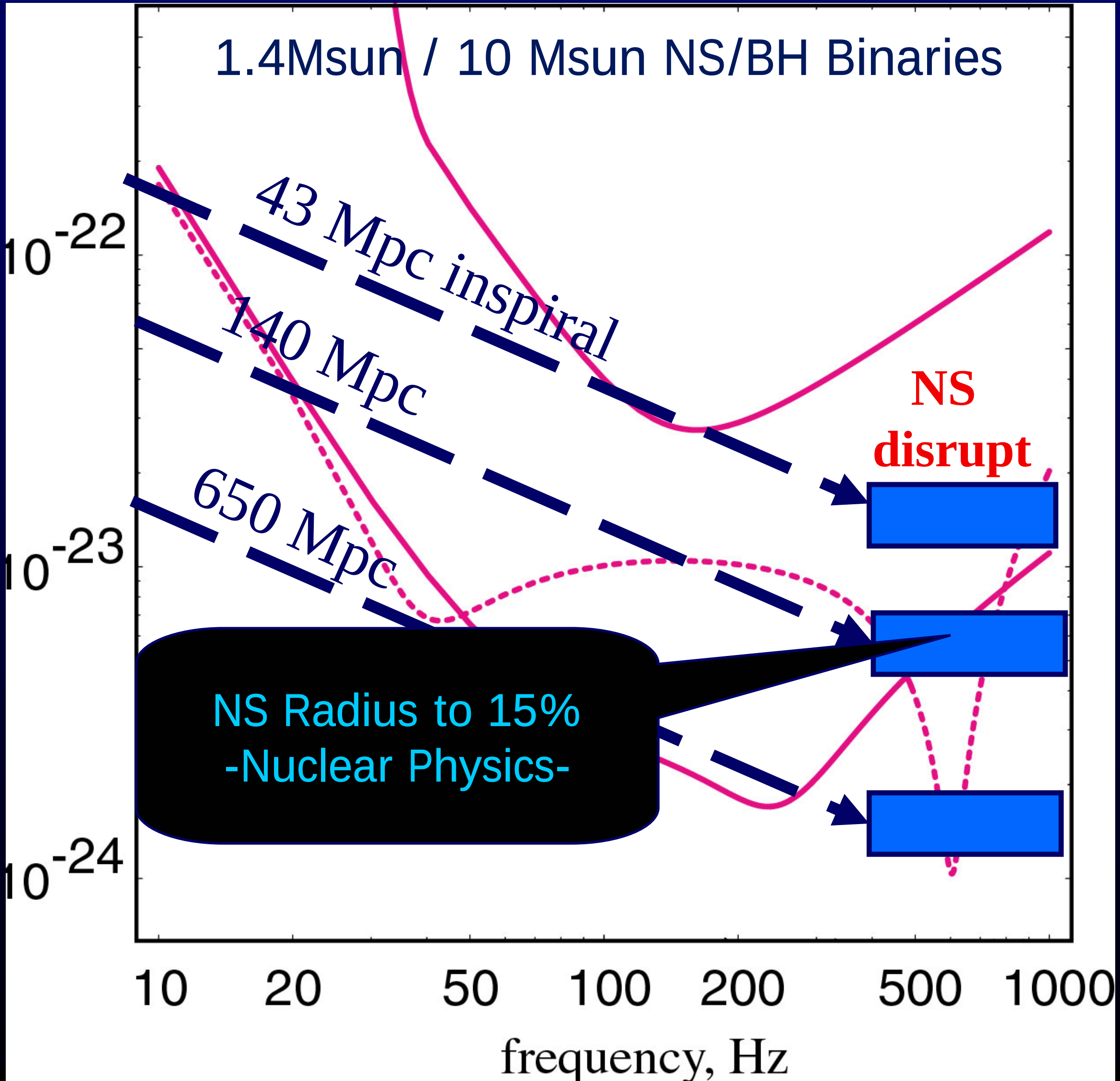




Neutron Star-Black Hole Inspiral and NS Tidal Disruption

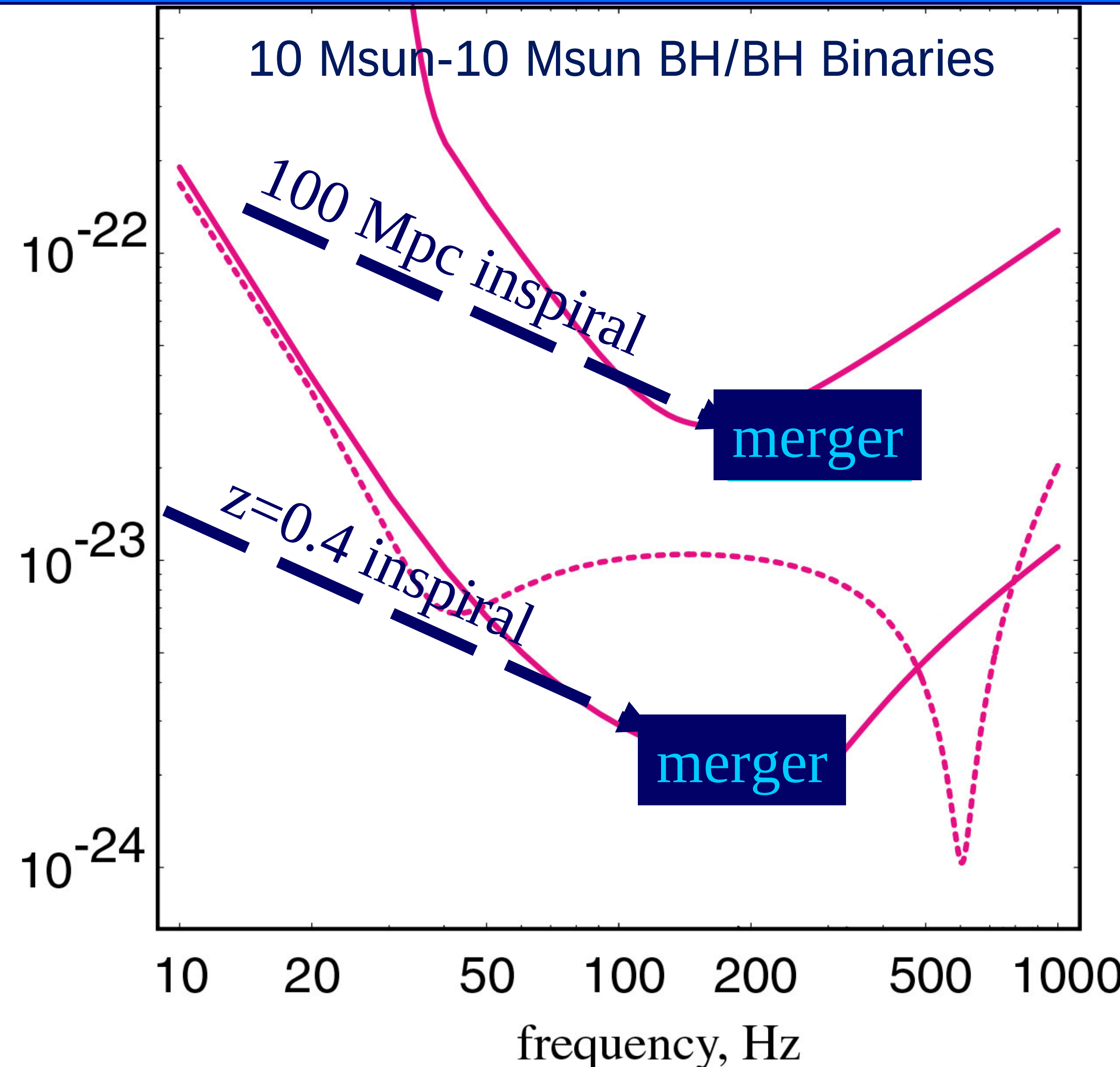


- Event rates
  - *Population Synthesis*
- Initial IFOs
  - Range: 43 Mpc
  - 1/2500 yrs to **1/2yrs**
- Advanced IFOs
  - Range: 650 Mpc
  - **1/yr to 4/day**

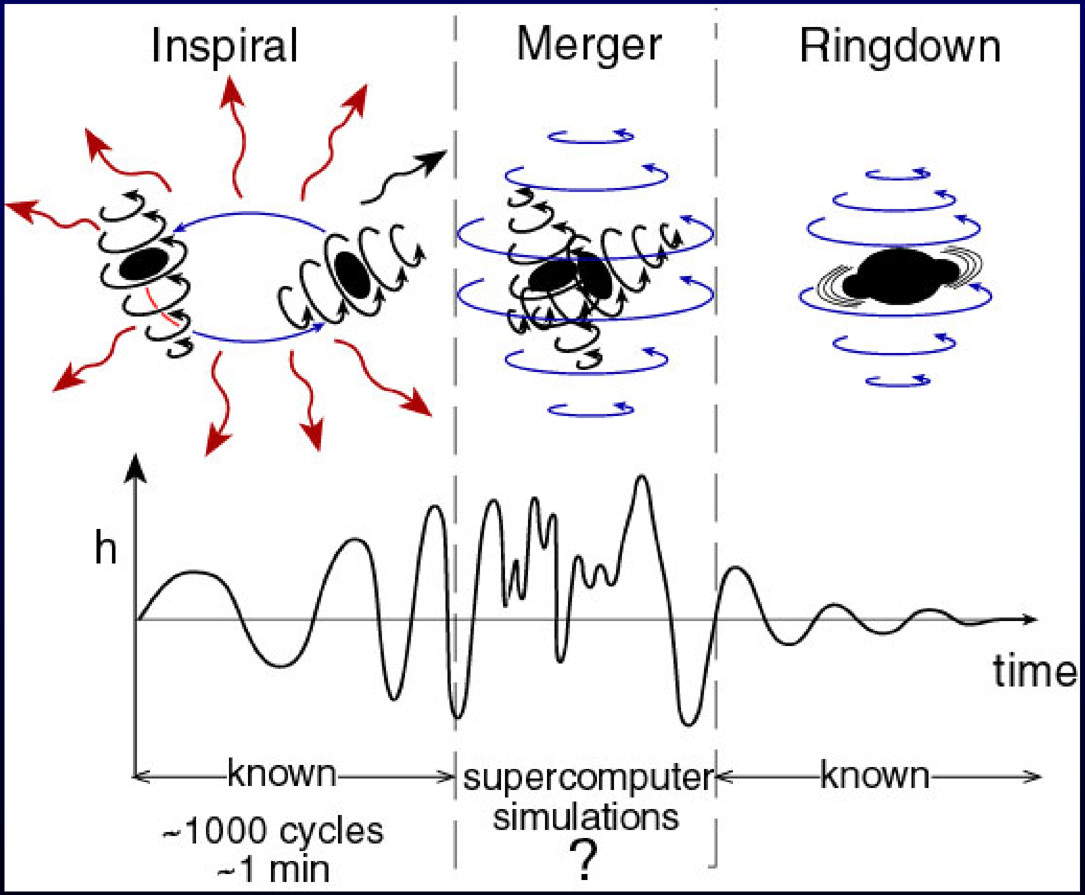


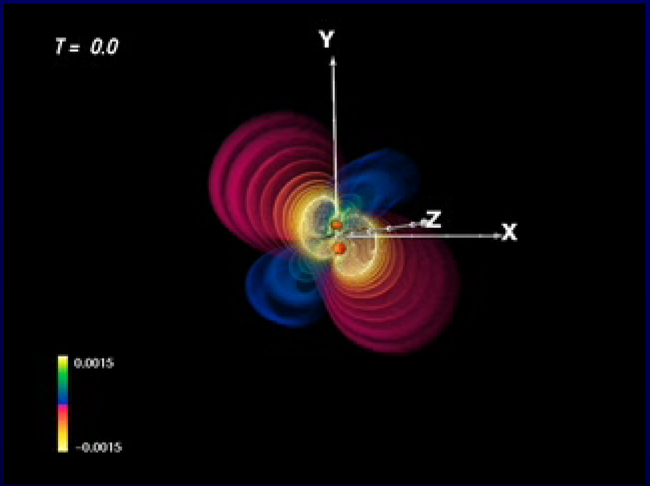
Black Hole-Black Hole Inspiral and Merger

- Event rates are based on population synthesis models normalized to NS-NS rate
- Initial IFO
  - Range: 100 Mpc
  - 1/300yrs to **1/yr**
- Advanced IFO
  - Range: z=0.4
  - **2/mnth to 10/day**
- Note BH-BH rate is larger than NS-NS



BH-BH Mergers: Exploring the Dynamics of Spacetime Warpage





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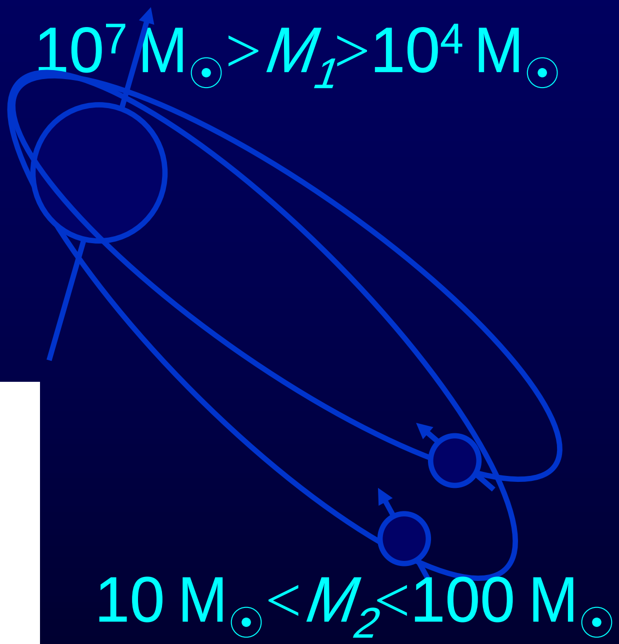
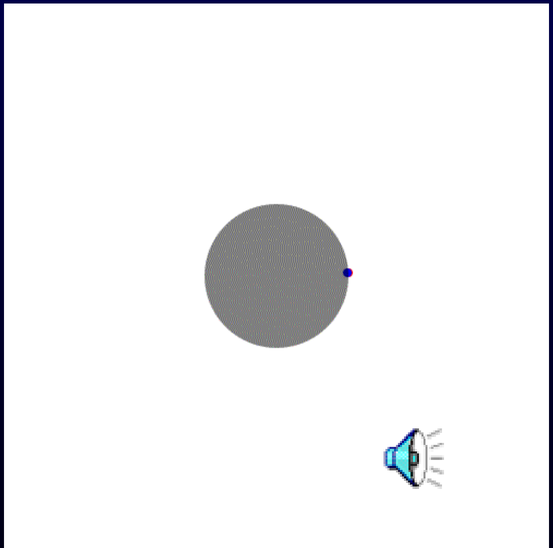
Gravitational capture and testing uniqueness of black hole spacetimes

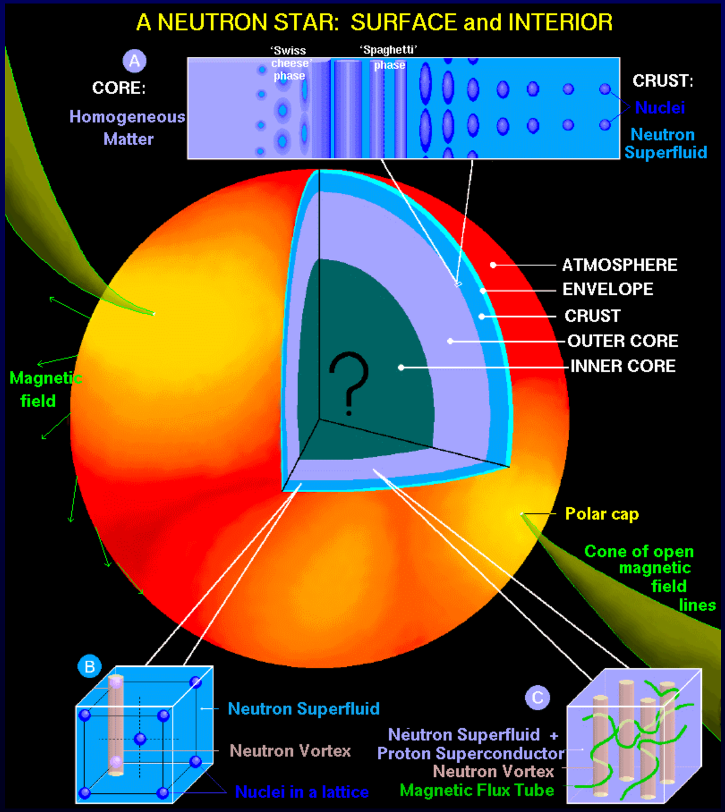
- Modelling gravitational waves emitted when a super-massive BH captures a stellar mass BH
  - large parameter space
  - complicated dynamics
  - spin-orbit and spin-spin couplings
  - eccentric orbit
  - random orientation
  - unknown direction
  - arbitrary initial phase





Neutron Stars Sources

- Continuous-wave (CW) radiation; expect low amplitudes, require long integration times
- Many objects with known frequency and position (pulsars), some more with known positions (X-ray sources)
- Great interest in detecting radiation: physics of such stars is poorly understood.
  - After 35 years we still don't know what makes pulsars pulse.
  - Interior properties not understood: equation of state, superfluidity, superconductivity, solid core, source of magnetic field.
  - May not even be neutron stars: could be made of strange matter!



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Spinning Neutron Stars: Pulsars

- **Crustal asymmetries.**
  - NS Ellipticity based on current understanding of crustal strength and EOS:

    $\varepsilon < 10^{-6} - 10^{-5}$

- **Can explore ellipticities of known pulsars:**

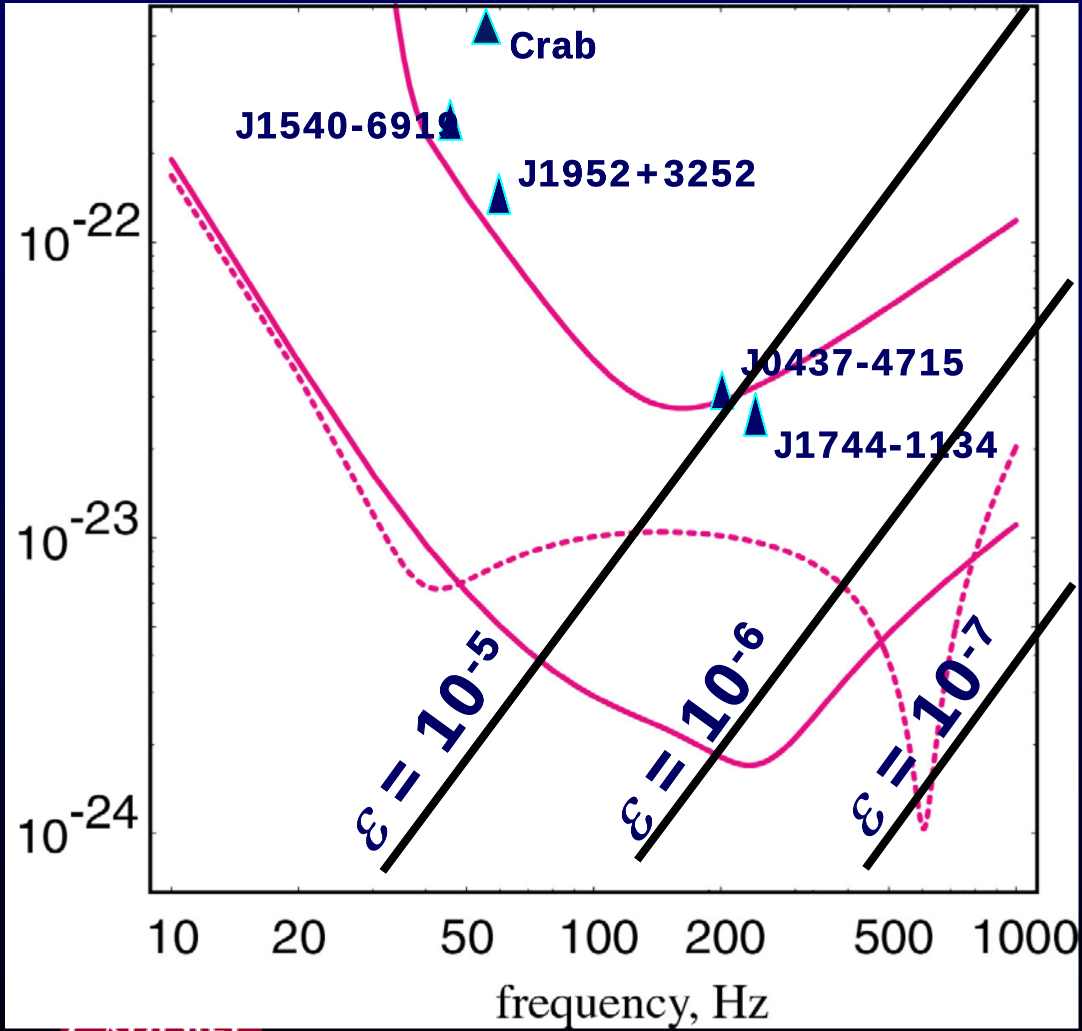
  First IFOs

  $\varepsilon > 3.\ 10^{-6}\ (f_{\mathrm{kHz}})^{-2}\ r_{10\mathrm{kpc}}$

  Adv. Narrowband

  $\varepsilon > 2.\ 10^{-8}\ (f_{\mathrm{kHz}})^{-2}\ r_{10\mathrm{kpc}}$

These are phenomenally small ellipticities



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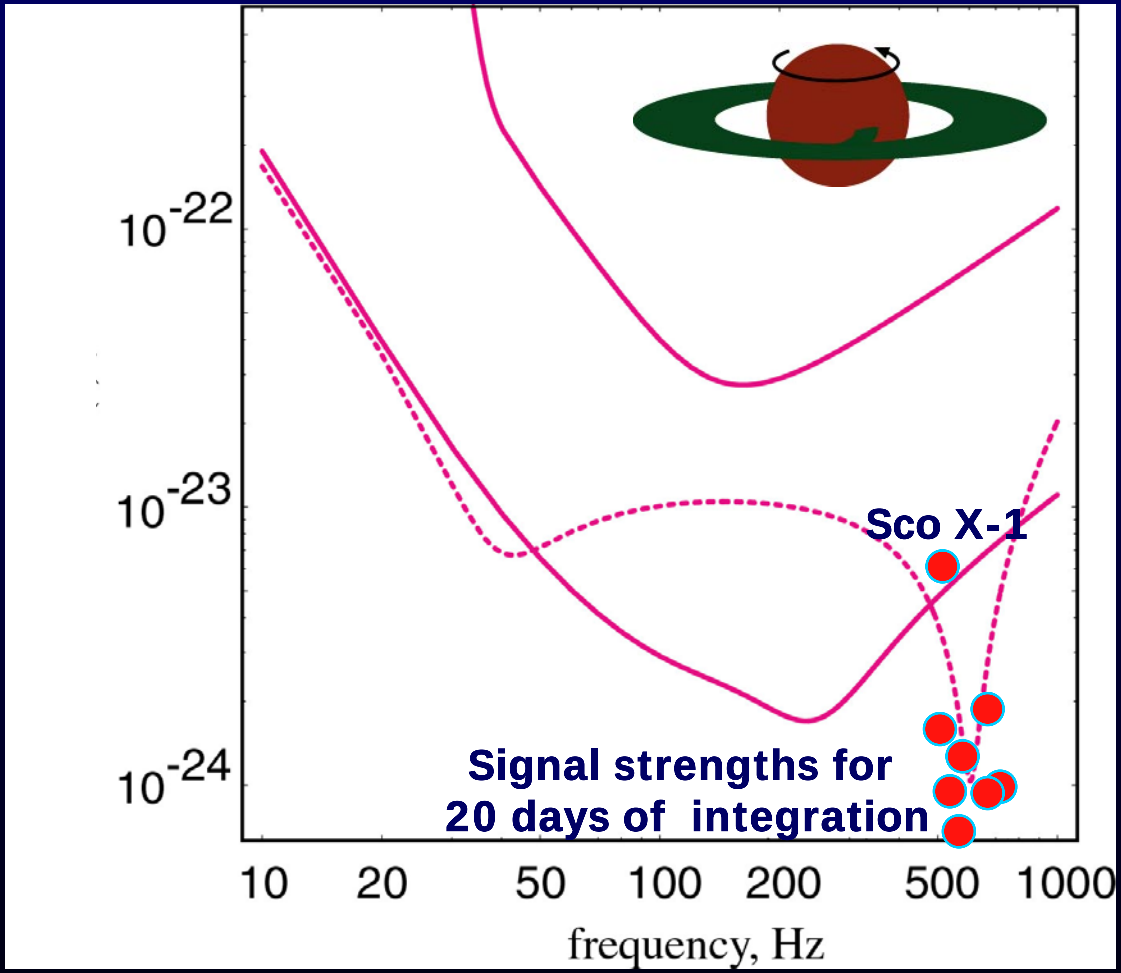
Spinning Neutron Stars in Low-mass X-ray Binaries

- Rotation rates
  - ~250 to 700 rev/sec
  - Why not faster?
    - Spin-up torque balanced by GW emission torque (Bildsten)
- If so and in steady state:
  - X-ray⇒GW strength
  - Combined GW & EM obs's carry information about crust strength and structure, temperature dependence of viscosity, …



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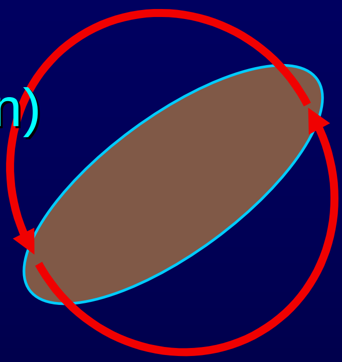
How else do neutron stars radiate?



- Neutron Star Birth
  - Centrifugal hangup, **Tumbling bar** (for a few sec or min)
  - ***With good modeling detectable to:***
    - Initial IFOs: ~5 Mpc (M81 group, ~1 supernova/3yr)
    - Advanced IFOs: ~100 Mpc (~500 supernovae/yr)
- Non-standard stars
  - If stars have solid cores and/or strange-star equations of state, ellipticities can be larger by factors of perhaps 100.
- **New Mechanism**: toroidal B-field flip**.**
  - Pulsar B-fields not understood, but dynamos require toroidal fields B_t. When pulsar is formed, strong differential rotation could wind up poloidal field, creating much stronger toroidal component. This can lead to the star flipping over.

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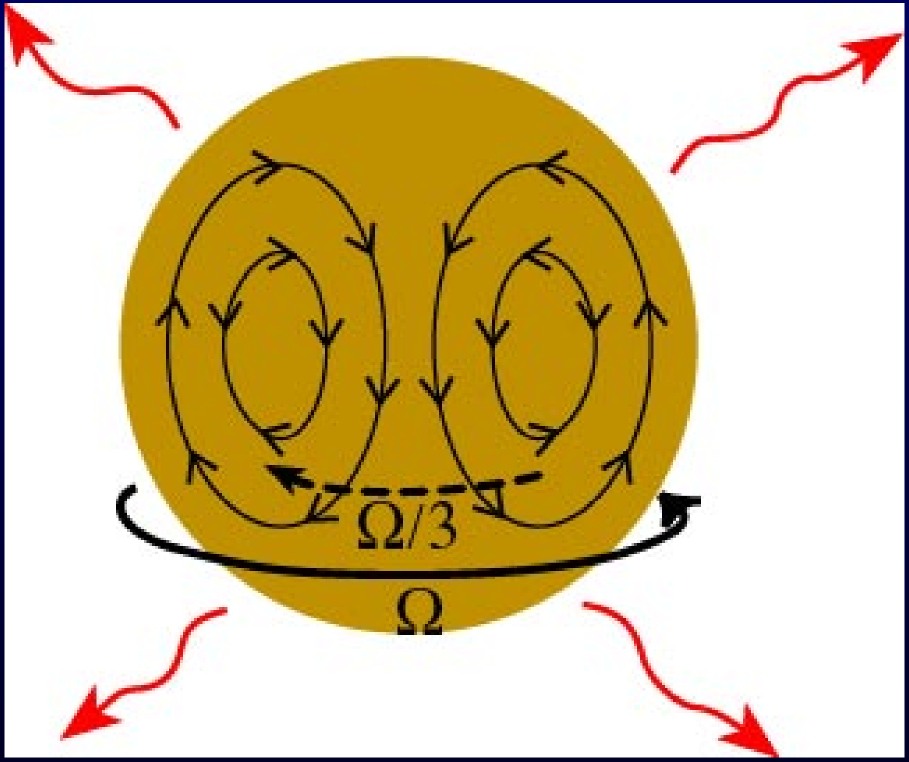
Neutron-Star Births: R-Mode Sloshing in First ~1yr of Life

- NS formed in SN or AIC of a white dwarf.
  - *If* NS born with

    $P_{\mathbf{spin}} < 10$ msec

    then an instability sets in:

    R-Mode instability
  - Gravitational radiation reaction drives sloshing



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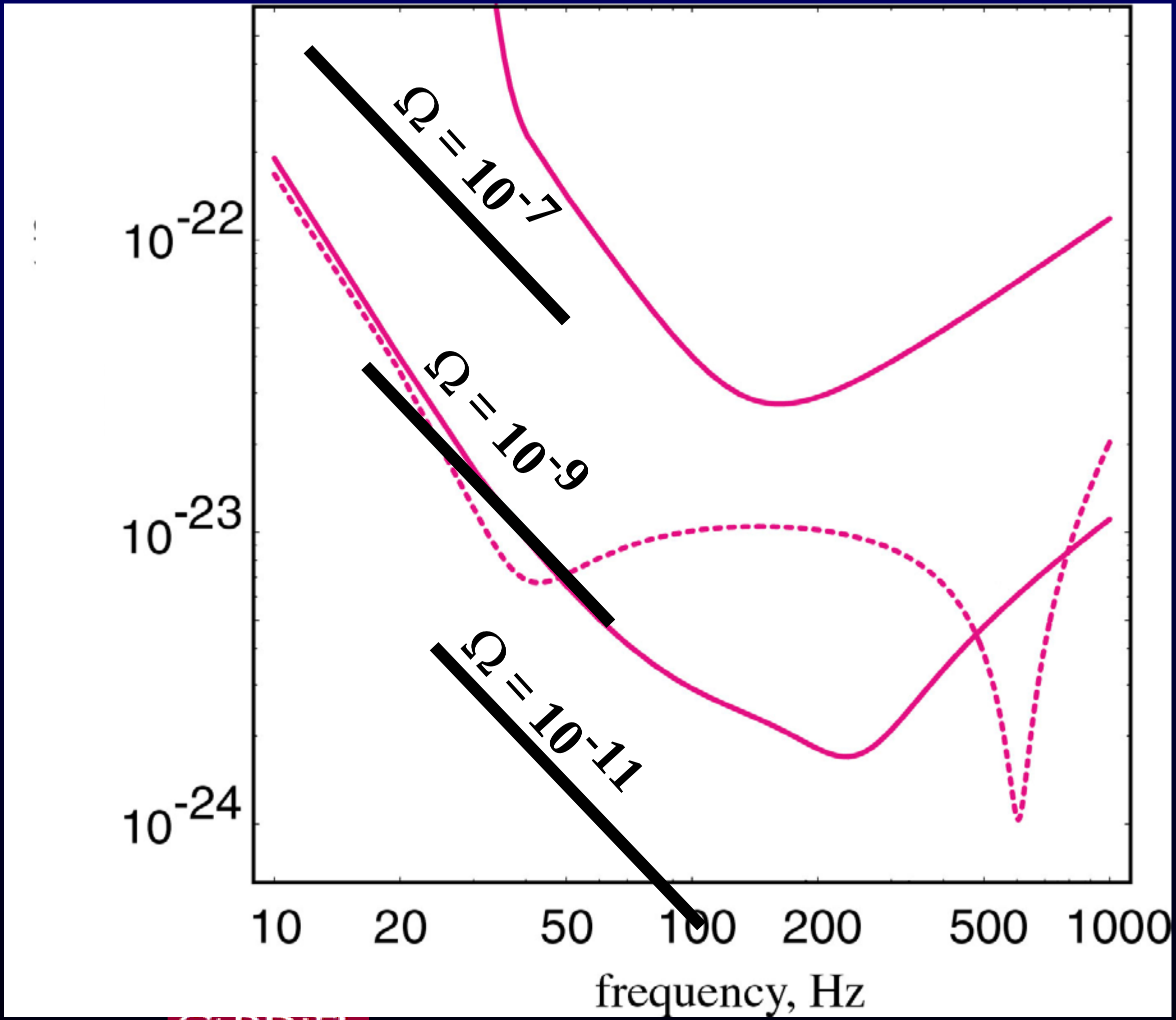
Stochastic Background from Very Early Universe

- Detect by
  - cross correlating output of Hanford & Livingston 4km IFOs
- Good sensitivity requires
  - (GW wavelength) ~ **2x**(det. separation)
  - f ~ 40 Hz
- Initial IFOs
  - detect if Ω **~ 10^{-5}**
- Advanced IFOs:
  - detect if Ω **~5×10^{-9}**



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GW from Very Early Universe

- **Waves from standard inflation: $\Omega \sim 10^{-15}$: too weak**
  - *BUT:* Crude superstring models of big bang suggest waves *might be strong enough* for detection by Advanced LIGO
  - GW bursts from cosmic strings: possibly detectable by Initial IFOs
  - Energetic processes at (universe age) ~ 10^{-25} sec and (universe temperature) ~ 10^{9} Gev $\Rightarrow$ GWs in LIGO band
  - Phase transition at 10^{9} Gev
  - Excitations of our universe as a 3-dimensional “brane” in higher dimensions:
    - Brane forms wrinkled; when wrinkles “come inside the cosmological horizon”, they start to oscillate; oscillation energy goes into GW
    - LIGO probes waves from wrinkles of length ~ 10^{-10} to 10^{-13} mm
    - If wave energy equilibrates: possibly detectable by initial interferometers

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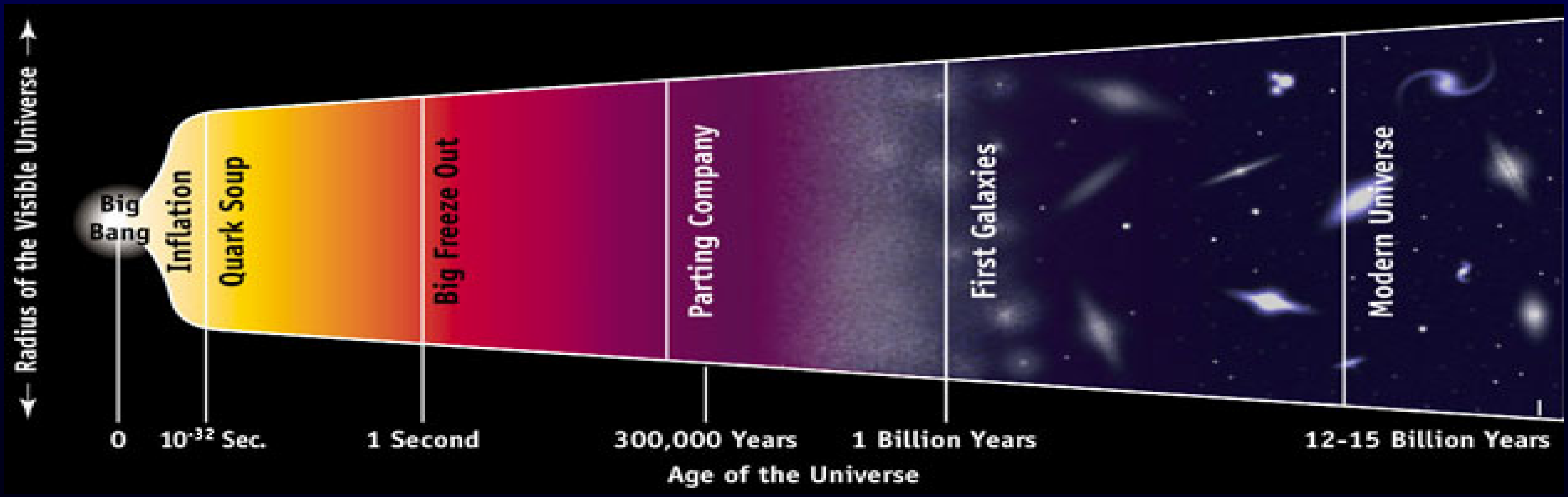
Stochastic Sources in Laser Interferometer Space Antenna

- Survey of all galactic binaries with sufficiently short periods
  - *Population statistics, confusion by large population at lower frequencies, confusion limit on signal extraction, information extraction from observations*
- Backgrounds, astrophysically generated and from the Big Bang
  - *Strength and spectrum of astrophysical backgrounds, production of early-universe radiation, relation to fundamental physics (string theory, branes, ...)*



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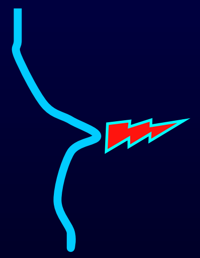
Supernovae and other transients

- Advanced interferometers will have the ability to detect strong transients events without knowing about them ahead of time (GW Astronomy!)
- Cusps of cosmic strings might dissipate energy in the cusp in the form of gravitational waves



... and other unexpected sources

The challenge:
Gravitational Wave Data Analysis

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What are we up against?

Measuring strains that arise from sub-nuclear length changes; almost anything can cause a disturbance

- unknown environmental background
  - seismic disturbances
  - solar flares and magnetic storms, cosmic rays, …
- unknown instrumental noise
  - electronic noise in feedback systems, laser frequency and intensity noise, thermal fluctuations in mirror substrates, thermal vibration of suspension systems, …
- non-Gaussian and non-stationary backgrounds
  - continually changing detector configuration
  - stochastic release of strain energy in suspension systems, electronic feedback, …

Important to understand detectors before any analysis begins - *Detector Characterization* - a huge effort but we shall not talk about that here

Types of gravitational wave signals

- Transients - last for a *short* duration so that detector motion can be neglected
  - Transients with known shape, e.g. black hole binaries
  - Transients with unknown shape, e.g. supernovae
- Stochastic backgrounds
  - population of astronomical sources
  - primordial stochastic gravitational wave signals
- Continuous waves - last for a duration *long enough* so that detector motion cannot be neglected
  - Typically very weak amplitude, signal power a billion times smaller than noise power
  - long integration times needed
  - slowly changing frequency depending on several parameters

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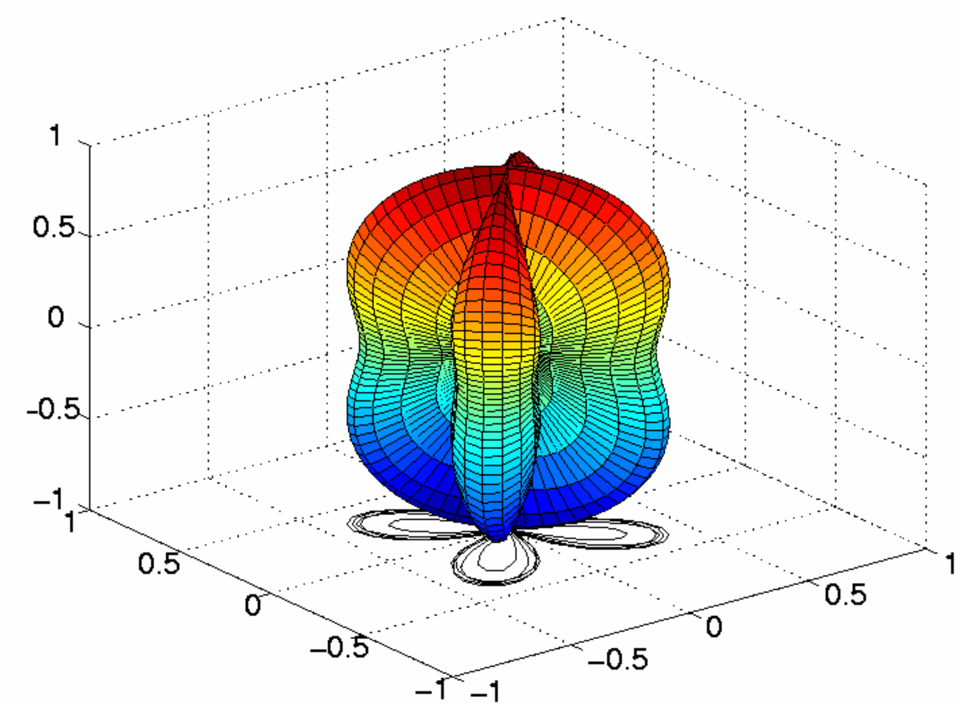
Why GW data analysis challenging?

- All sky sensitivity
  - Quadrupolar antenna pattern
  - multiple detectors to determine direction to source
- Wide band sensitivity
  - 1 kHz BW around 100 Hz
- Low event rates
  - Few per year – few per day
- Large data rates
  - Hundreds of instrumental and environmental channels
  - up to 10 MB per second from each detector x 4 detectors



Gravitational Physics & Astronomy