Gravitational-wave detection and astronomy

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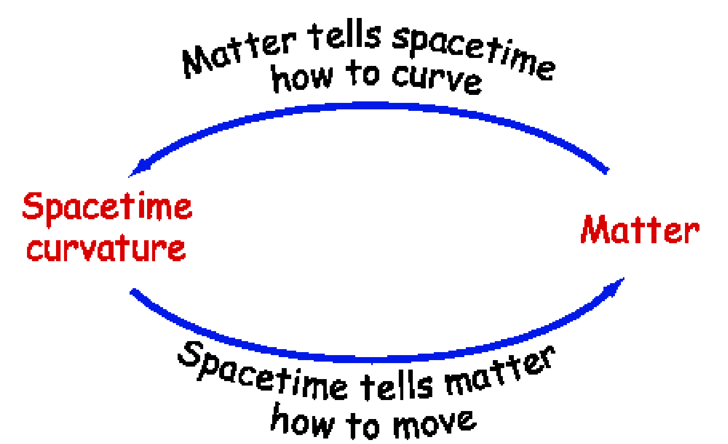
General Relativity

- Einstein's field equations (1915)
  - Relate the curvature of spacetime to the stress-energy of matter

$$R_{ab} - \frac{1}{2} R g_{ab} = 8\pi T_{ab}$$

  - Gravitational force is extremely weak compared to electromagnetic force, difficult to measure small effects

- According to Einstein
  - Test bodies move along geodesics of spacetime
  - Geodesics are determined by the curvature



Einstein on gravitational waves

- *Uber die Gravitationswellen*, Einstein (1918)
  - Shows that his equations reduce to wave equation in weak field
- Spacetime interval can be written

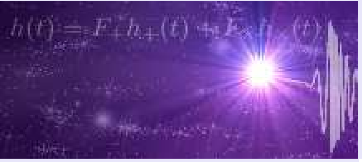
$$ds^2 = (\eta_{\alpha\beta} + h_{\alpha\beta})dx^\alpha dx^\beta$$

where $\eta_{\alpha\beta}$ Minkowski metric, $h_{\alpha\beta}$ is the metric perturbation

- For weak gravitational fields $h \ll 1$

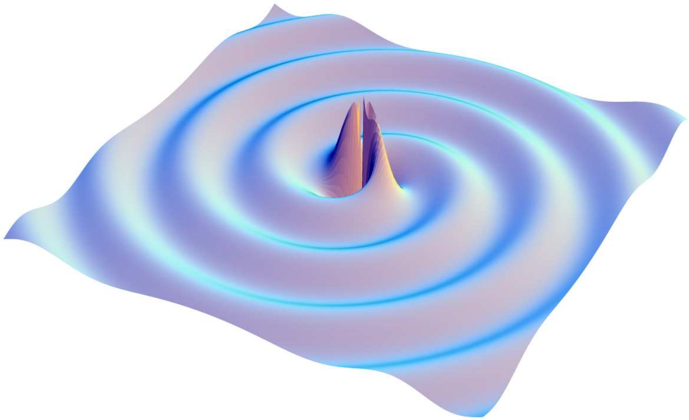
$$\left(-\frac{\partial^2}{\partial t^2} + \nabla^2\right)\overline{h}^{\alpha\beta} = -16\pi T^{\alpha\beta}$$

where $\overline{h}^{\alpha\beta} = h^{\alpha\beta} - \frac{1}{2}\eta^{\alpha\beta}h$



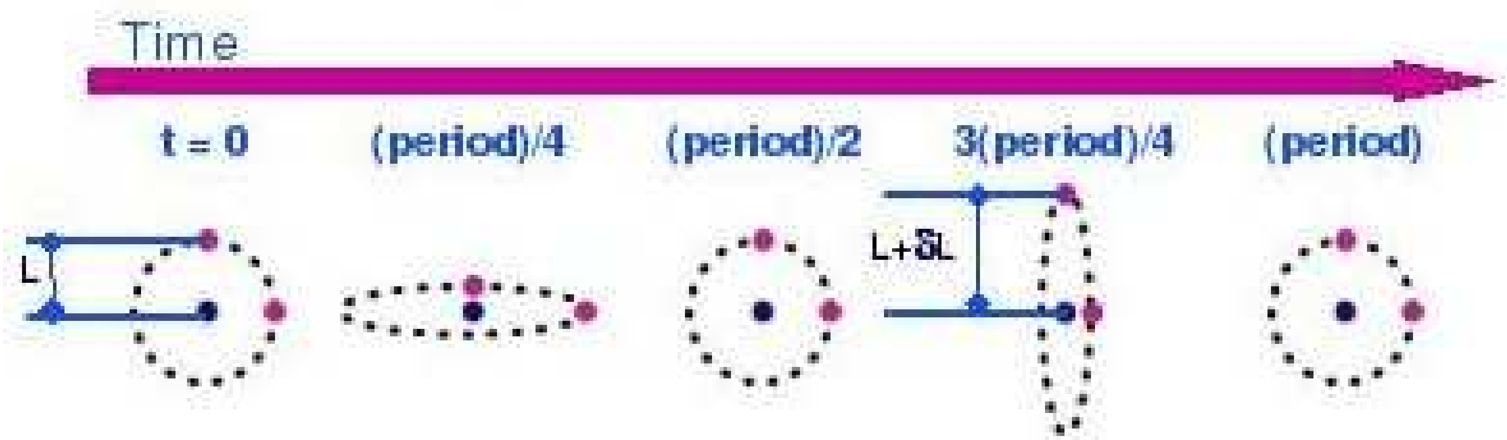
What are gravitational waves?

- Solve the wave equation in vacuum
  - $\bar{h}^{\alpha\beta} = A^{\alpha\beta} \exp(i k_\delta x^\delta)$
  - Metric perturbation is a gravitational wave amplitude that propagates at the speed of light
  - Gravitational waves stretch and squeeze the space they pass through
- Einstein's field equations:
  - When matter moves, or changes configuration, its gravitational field changes
  - This change propagates outward as a ripple in curvature of spacetime – a gravitational wave



Physical effects of the waves

- General relativity predicts
  - Transverse propagation at the speed of light
  - Quadrupole radiation at lowest order
  - Two polarizations ...
- As gravitational waves pass, they change the distance between neighboring bodies, e.g. plus polarization (h_+)



Fractional change in distance is the strain given by $h = \frac{\delta L}{L}$

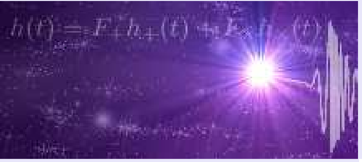
Contrast EM and GW information

Electromagnetic

- Propagate through space-time
- Incoherent superposition from many atoms
- Wavelength small compared to source
- $\sim 10^6$ Hz and up

Gravitational

- Waves in fabric of space-time
- Coherent motion of huge masses
- Wavelength long compared to size of source
- ~ 1 kHz and down



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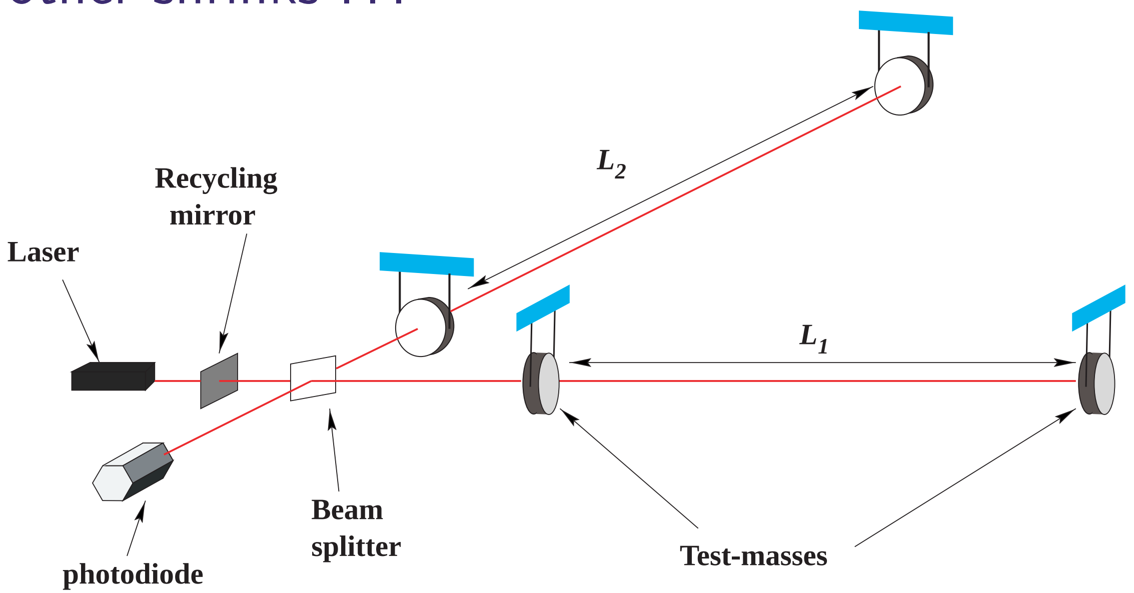
Gravitational waves provide a unique probe of the Universe

Interferometric detectors

- A laser is used to measure the relative lengths of two orthogonal cavities (or arms)
- As a gravitational wave passes, one arm stretches and the other shrinks . . .

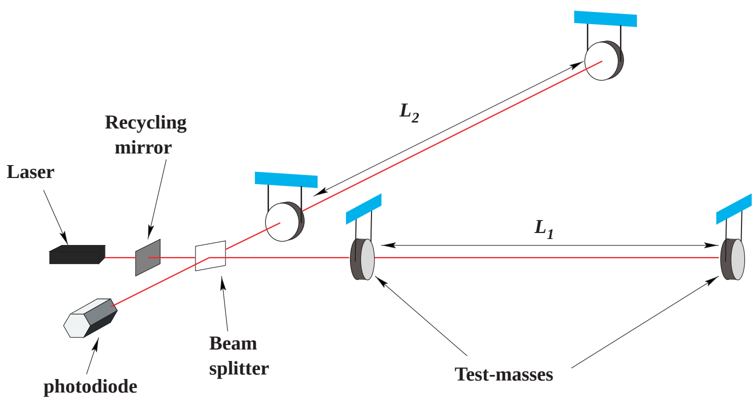


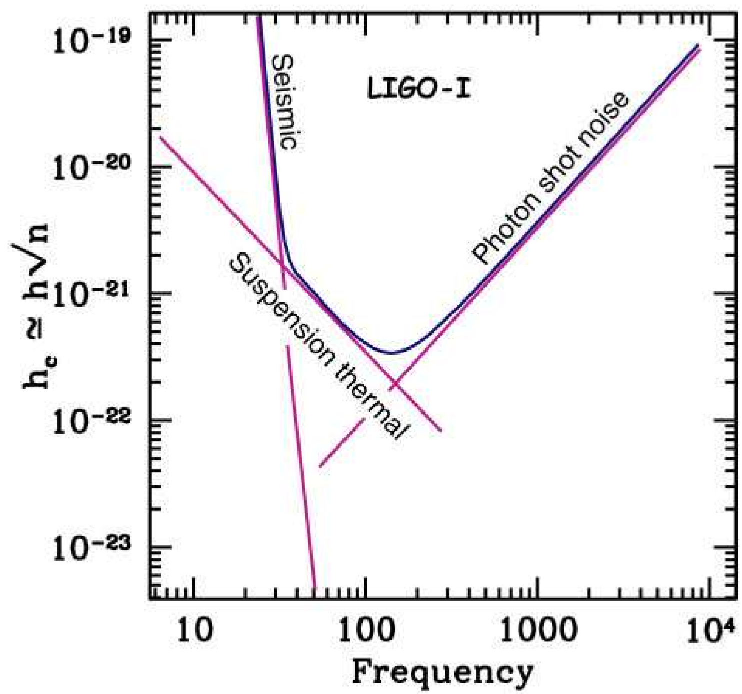
- . . . causing the interference pattern to change at the photodiode

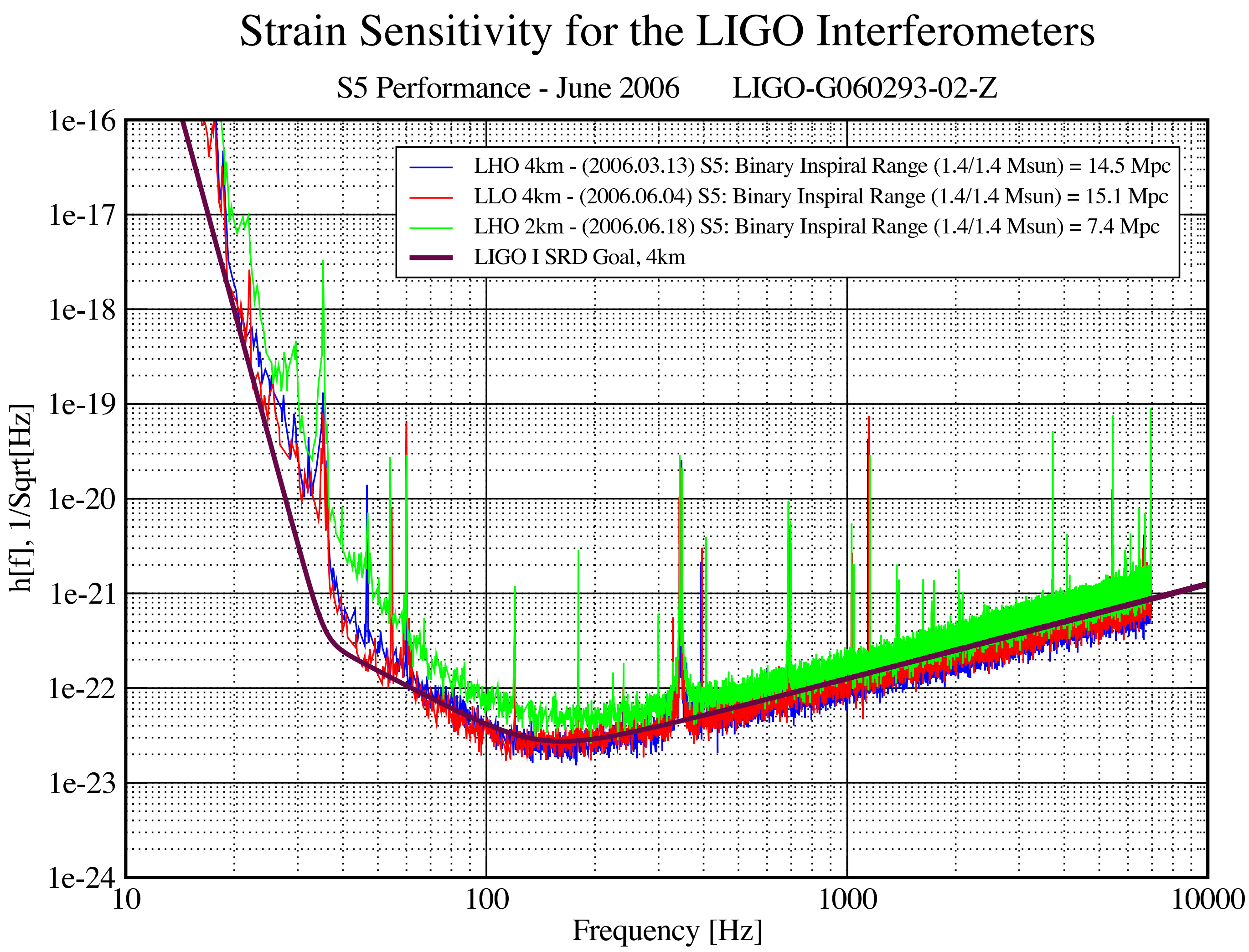
LIGO Sensitivity

- Laser Interferometer Gravitational-wave Observatory (LIGO) is US effort to detect gravitational waves
  - Design goal was to measure fractional change in arm length $h = \delta L / L \sim 10^{-21}$

- The noise in the detectors is dominated by three different processes depending on frequency band

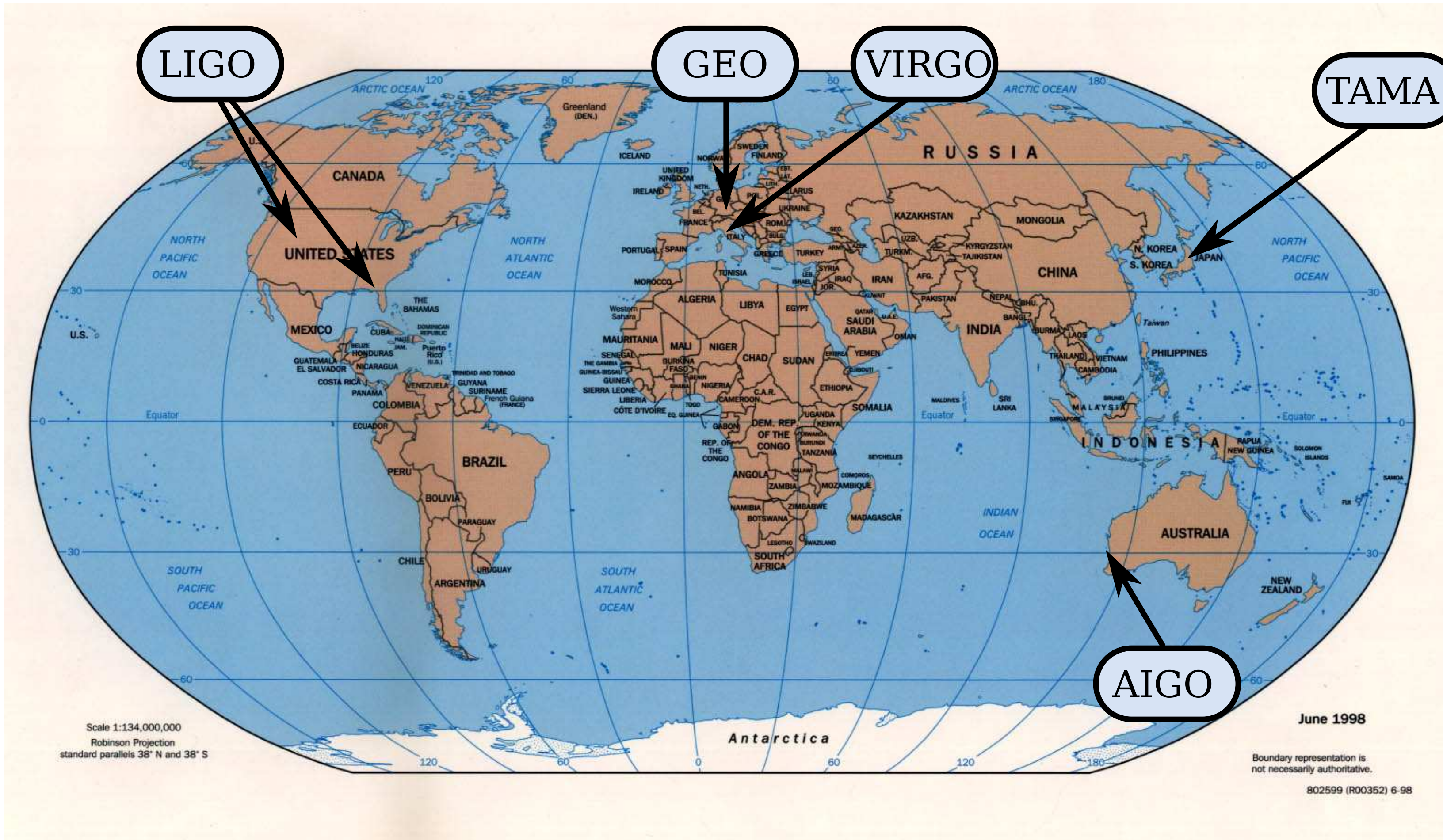




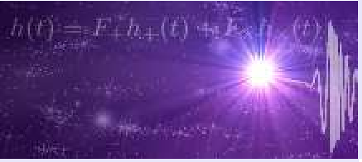


Strain Sensitivity for the LIGO Interferometers
S5 Performance - June 2006 LIGO-G060293-02-Z
LHO 4km - (2006.03.13) S5: Binary Inspiral Range (1.4/1.4 Msun) = 14.5 Mpc
LLO 4km - (2006.06.04) S5: Binary Inspiral Range (1.4/1.4 Msun) = 15.1 Mpc
LHO 2km - (2006.06.18) S5: Binary Inspiral Range (1.4/1.4 Msun) = 7.4 Mpc
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]

An international network of gravitational-wave detectors



- LIGO, GEO and Virgo will operate jointly starting in 2007

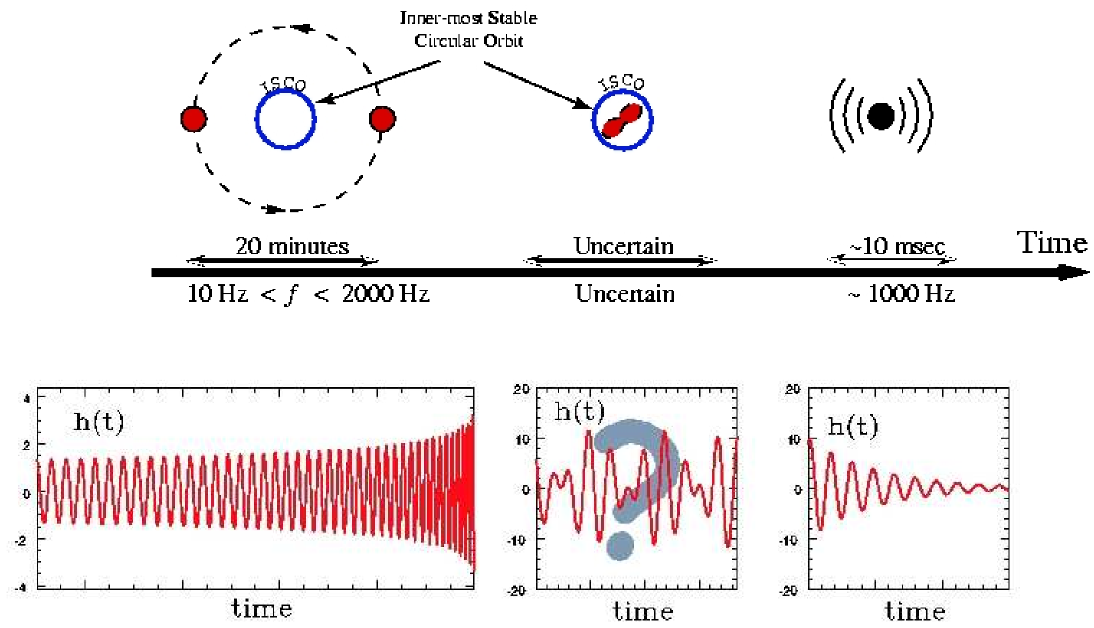


Science with gravitational waves

- Direct verification of two of most dramatic predictions of Einsteins general relativity
  - Existence of gravitational waves
  - Direct observation of black holes
- Physics
  - Detailed tests of gravitational wave properties, e.g. speed, polarization, strength, graviton mass, ...
  - Probe strong field gravity around black holes and in the early universe; probe the neutron star equation of state
- Astronomy
  - By performing routine astronomical observations, understand compact binary populations, rates of supernovae explosions, test gamma-ray burst models

Compact binaries I

- LIGO is sensitive to gravitational waves from binary systems containing neutron stars & stellar mass black holes
  - Last several minutes of inspiral driven by GW emission
  - Clean systems, accurate modeling shows that GWs depend on masses/spins only

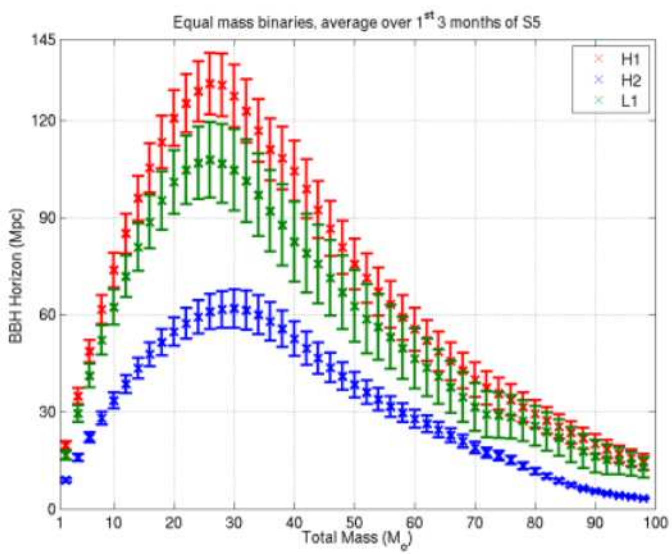


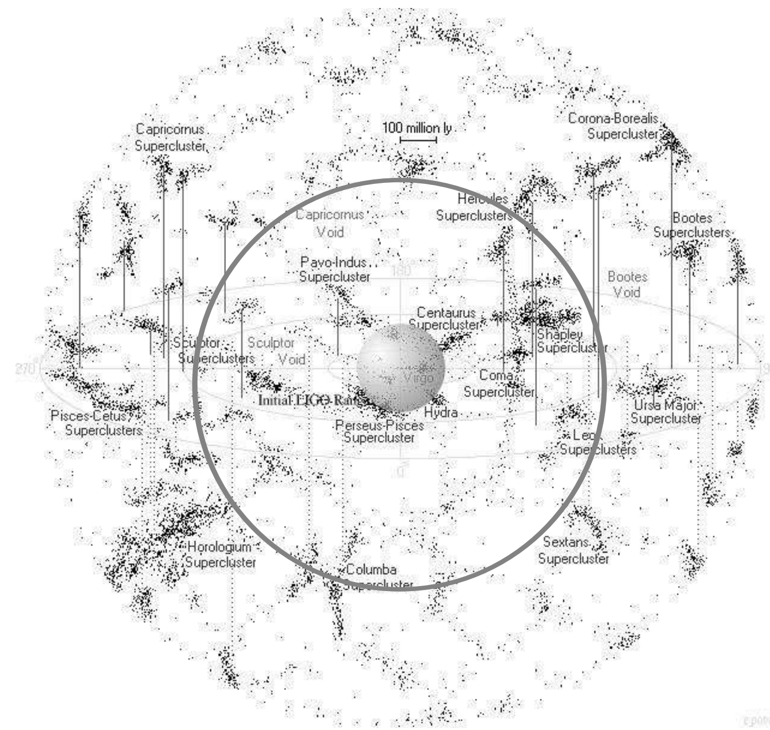
Compact binaries II

- Binary Neutron Star Rates
  - Theoretical upper bound of $\sim 10^{-4}$/yr per Milky Way
  - LIGO S2 search 47/yr per Milky-Way like galaxy [LIGO Scientific Collaboration, Phys.Rev.D.72,082002(2005); Phys.Rev.D.72,082001(2005);]
  - S4 BNS search complete (Under internal review)
  - 0.05 yr of data, ~ 24 Milky-Way like galaxies
- Binary Black Hole Rates
  - Estimated upper bound of $\sim 10^{-6}$/yr per Milky Way
  - LIGO S2 search 38/yr per Milky-Way like galaxy [LIGO Scientific Collaboration, Phys.Rev.D.73,063001(2006)]
  - S4 BBH search complete (Under internal review)
  - 0.05 yr of data, ~ 150 Milky-Way like galaxies for 5+5 $M_\odot$

Compact binaries III

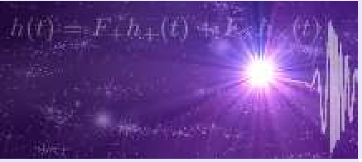
- LIGO S5 Searches
  - Ongoing science run to acquire 1 year of data
  - Compare reach of the search . . .





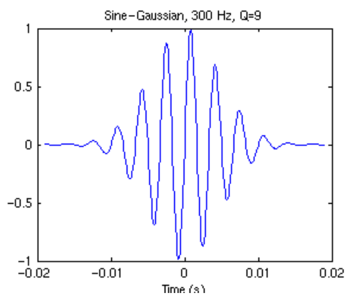
Burst sources I

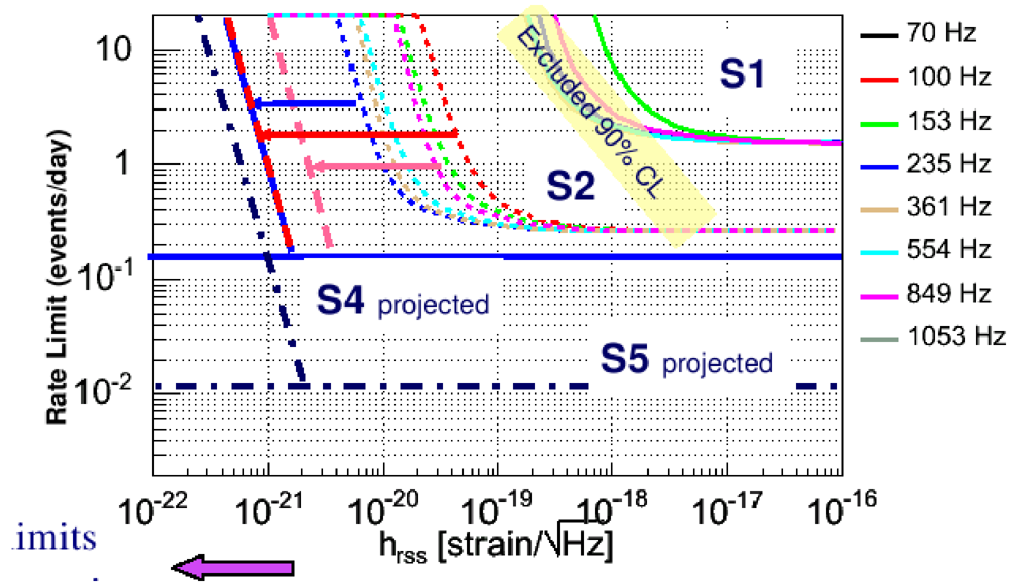
- General Properties
  - Duration $\ll$ observation time
- Promise
  - Unexpected sources and serendipity
  - Search techniques must use minimal information
- Examples
  - Black hole and neutron star merger
  - Supernovae and γ-ray bursters
  - Kinks and cusps on cosmic strings



Burst sources II

Target waveforms



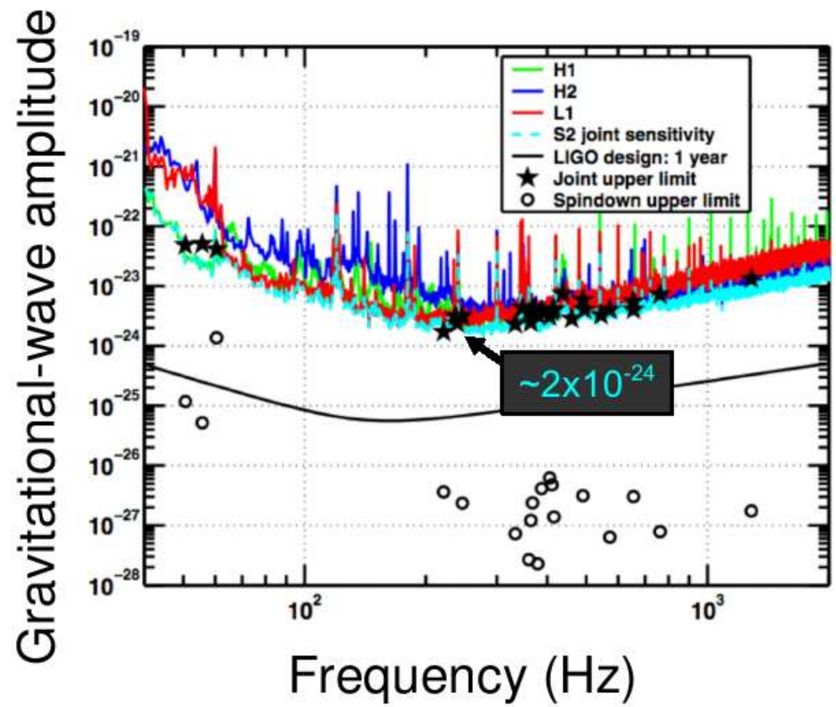


- Astrophysical interpretation: minimum detectable in-band energy in GWs (in S5)
  - $E_{gw} > 1.00 M_\odot$ at $r \sim 75$ Mpc
  - $E_{gw} > 0.05 M_\odot$ at $r \sim 15$ Mpc
- [LIGO Scientific Collaboration,Phys.Rev.D72,042002(2005); Class.Quant.Grav.23,S29S39(2006)]

Continuous waves I

- Known pulsar searches
  - Catalog of known pulsars
  - Heterodyne, narrow bandwidth folding data
  - Coherent frequency domain search using Hough transform
- Wide area search
  - Demodulation is depends sensitively on sky location and spindown for long integration
  - Computationally *very* expensive
  - Hierarchical searches under development
  - See *Einstein@Home* project to participate

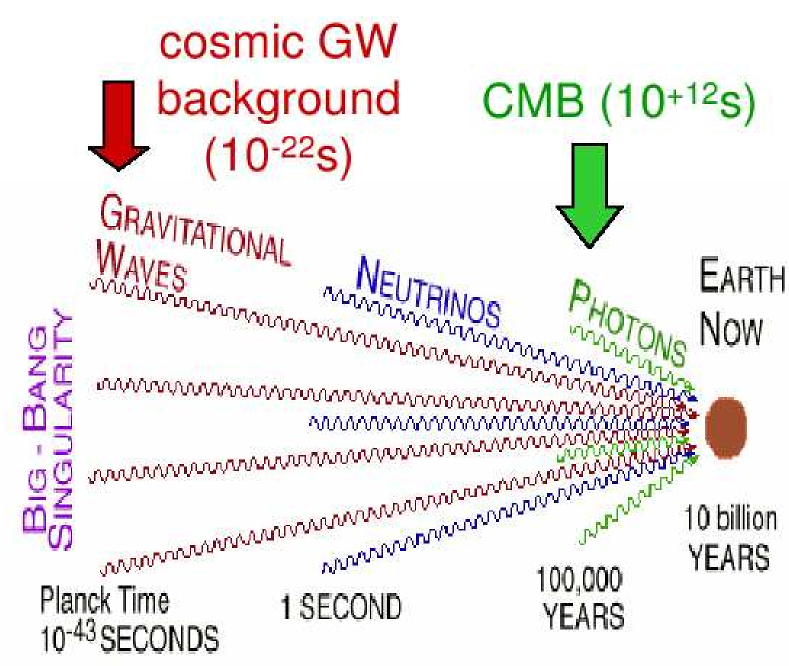
- Pulsars for which the ephemeris is known from EM observations
  - In S2, 28 known isolated pulsars targeted
  - Spindown limit assumes all angular momentum radiated to GW
  - Minimum amplitude sensitivity 2×10^{-24}
- In S5 minimum amplitude sensitivity $\sim 10^{-25}$
- Gravitational ellipticity $\sim 10^{-6}$

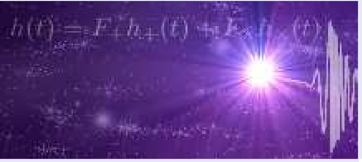


[PhysicalReviewLetters94181103(2005)]

Stochastic background I

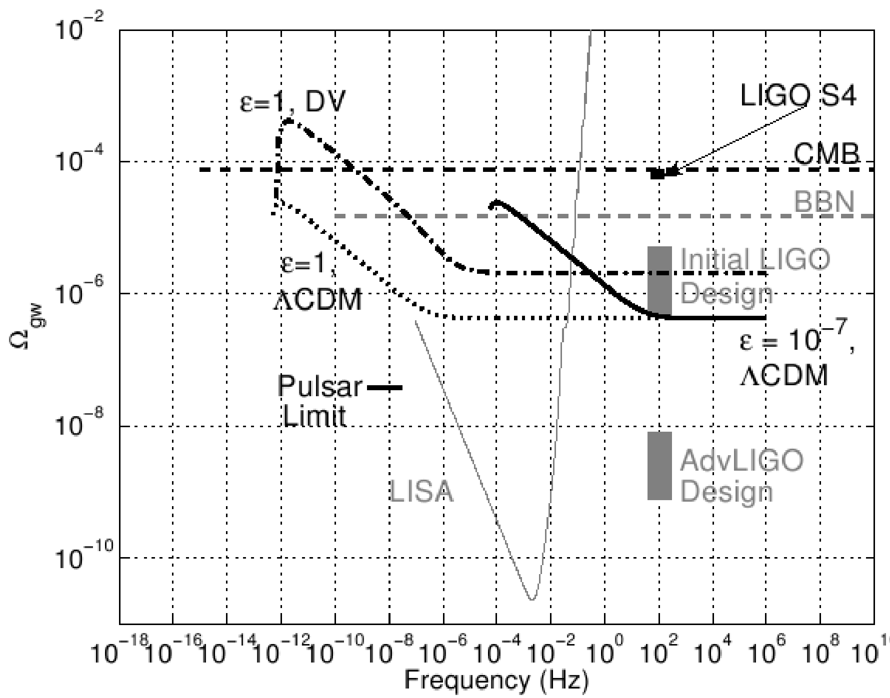
- Cosmological background from the big bang (analagous to CMB)
- Astrophysical backgrounds due to unresolved individual sources
  - Supernovae, compact binary mergers, bursts from cosmic strings





Stochastic background II

- Observational limits on stochastic gravitational-wave background $\Omega_{gw} < 6.5 \times 10^{-5}$ [LIGO Scientific Collaboration, PhysicalReviewLetters95221103(2005); and astro-ph/06080606]



[Siemens, Mandic, and Creighton, *Gravitational-wave stochastic background from cosmic (super)strings*, astro-ph/06080606]

The future

- Current generation of gravitational wave detectors are sensitive enough to make a detection possible, but unlikely
- LIGO plans to upgrade the two 4km detectors to gain a factor of ~ 2 in range on 2009 time frame.
- LIGO and Virgo have plans for advanced instruments. LIGO hopes to commission these advanced detectors in the early part of next decade.
  - These upgrades should bring us into an era of regular detections
- Many other topics: space-based interferometers, bar detectors, coincidence with GRBs . . .
- There are exciting prospects for gravitational-wave astronomy during the next decade