Gravitational-Wave Astrophysics using LIGO

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for the LIGO Scientific Collaboration

05/02/09
LIGO-G0900423-v2

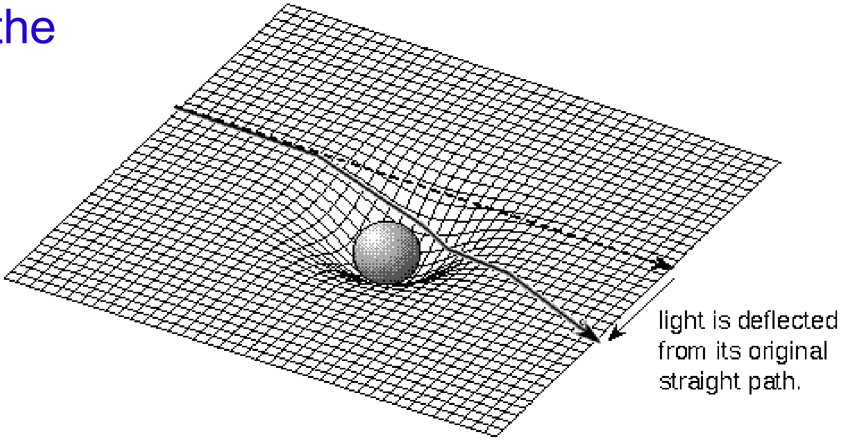
Outline

- Brief overview:
  - » Gravitational waves
  - » Sources of gravitational waves
  - » LIGO - Laser Interferometer Gravitational-wave Observatory:
- Recent results highlights
- Outlook for the future:
  - » Enhanced and Advanced LIGO
  - » Underground interferometers?

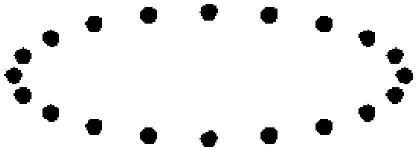
Gravitational Waves

- General Relativity: Presence of mass distorts the fabric of space-time.
- Accelerating quadrupole moment of mass distribution produces waves:
- Einstein's field equations reduce to the wave equation:

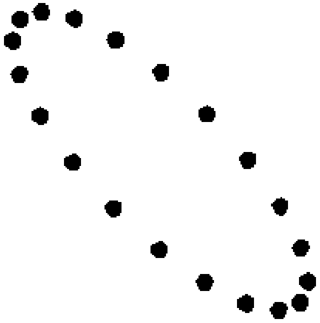
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad \left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h_{\mu\nu} = 0$$



- General Relativity: the "signal" travels at the speed of light.
- Two polarizations:



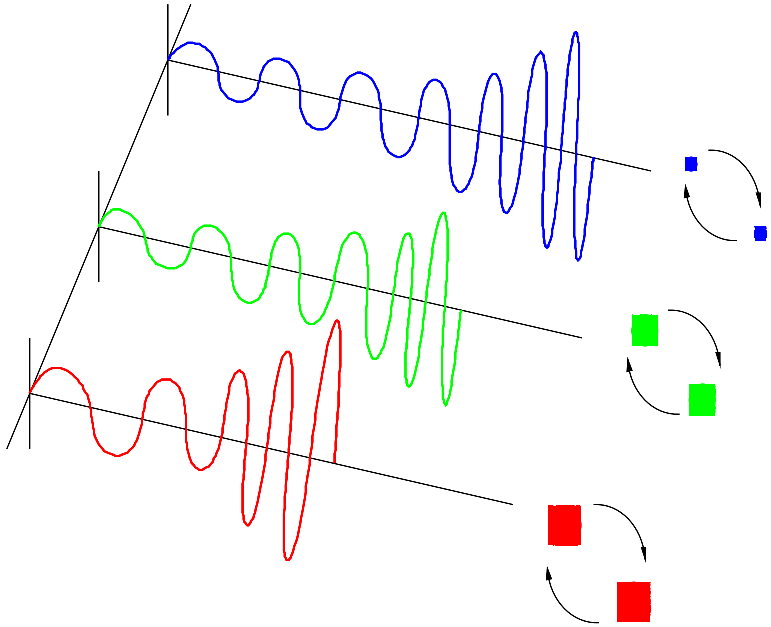
"+" Polarization



"x" Polarization

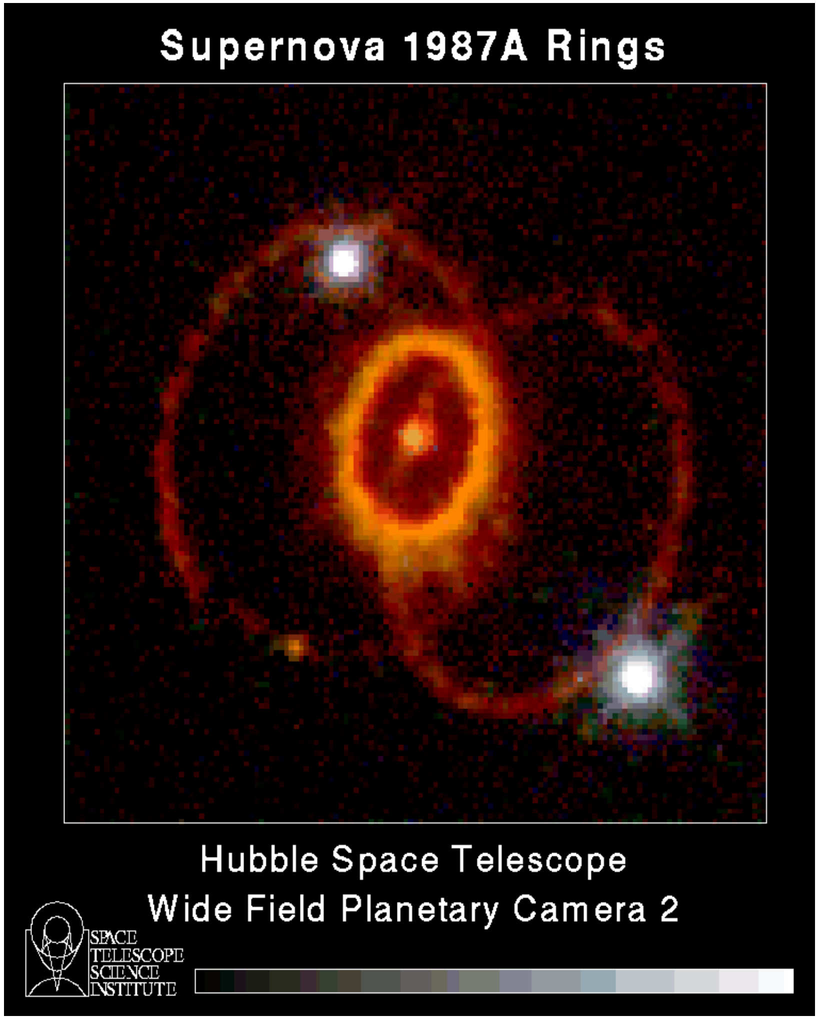
Sources: Binary Coalescence

- Compact binary objects:
  - » Two neutron stars, ~1.4 Solar Masses each.
  - » Two black holes, large mass ranges.
  - » Neutron star and a black hole.
- Inspiral toward each other.
  - » Emit gravitational waves as they inspiral.
- Amplitude and frequency of the waves increases over time, until the merger.
- Waveform relatively well understood.



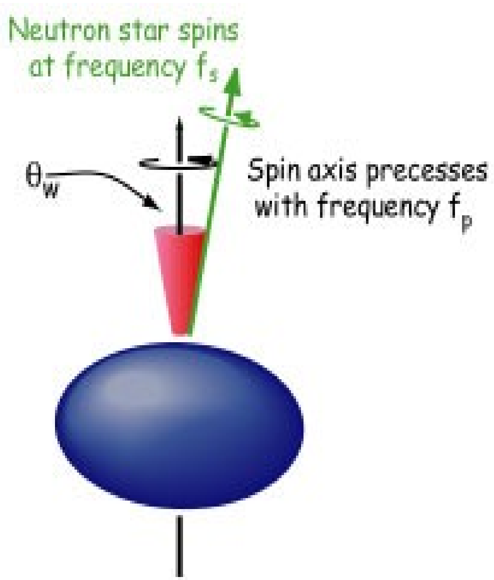
Sources: Bursts

- Various other transients exist:
  - » Supernova explosions: e.g. collapse of massive stars.
  - » Gamma Ray Bursts: collapse of rapidly rotating massive stars or neutron star mergers.
  - » Pulsar glitches: acretion.
- Physics not entirely understood.
- Waveform not known – search for power excess in the data.



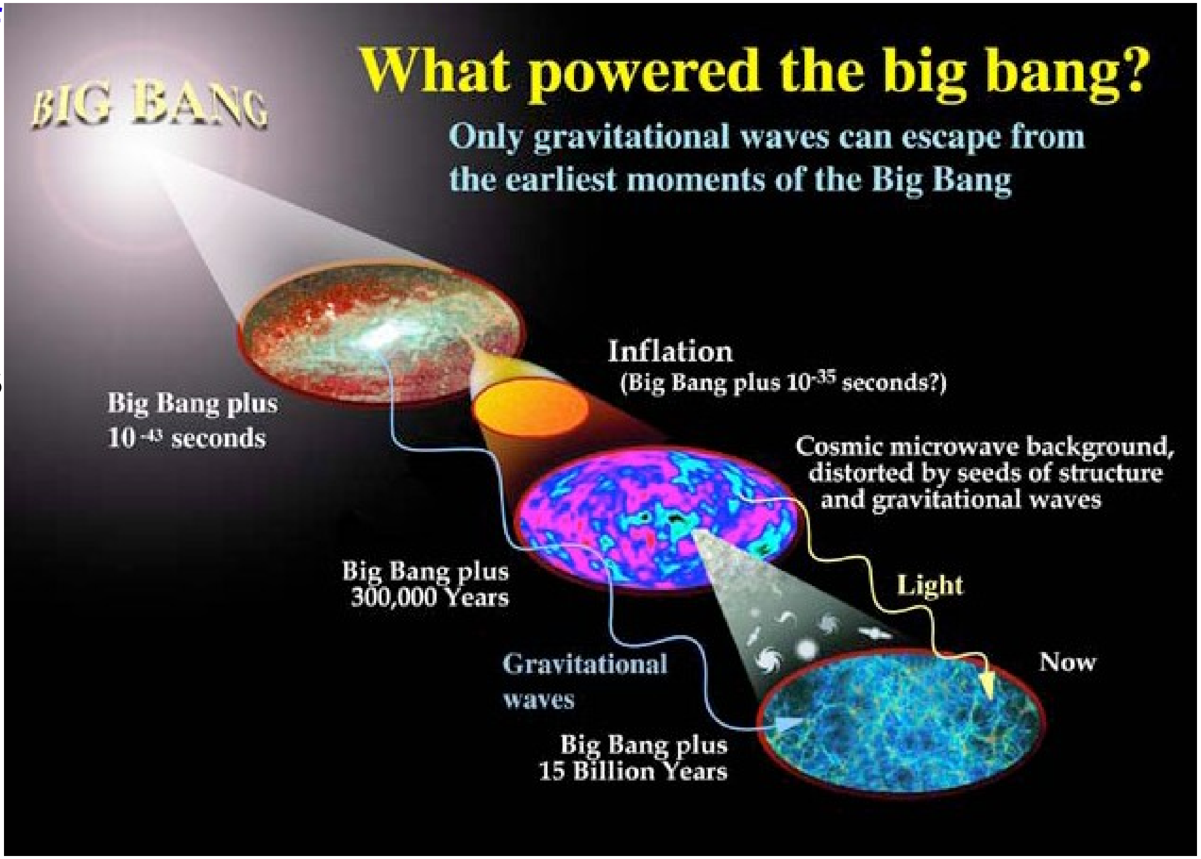
Sources: Periodic

- Pulsars with mass non-uniformity:
  - » Small “mountains”.
  - » Density non-uniformity.
  - » Dynamic processes inside neutron star.
- Produce gravitational-waves at twice the rotational frequency.
- Waveform well understood:
  - » Sinusoidal, but Doppler-modulated.
- Continuous source!



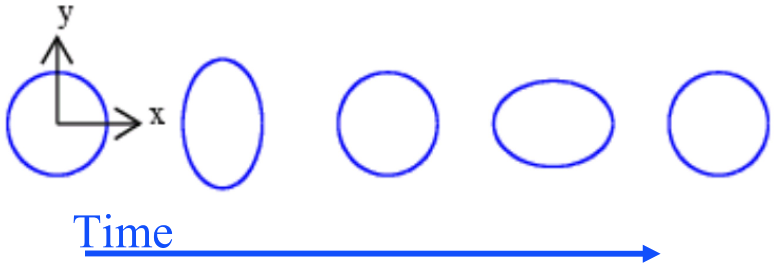
Sources: Stochastic Background

- Incoherent superposition of many unresolved sources.
- Cosmological:
  - » Inflationary epoch
  - » Cosmic strings
  - » Alternative cosmologies
- Astrophysical:
  - » Supernovae
  - » Magnetars
- Potentially could probe physics of the very-early Universe.



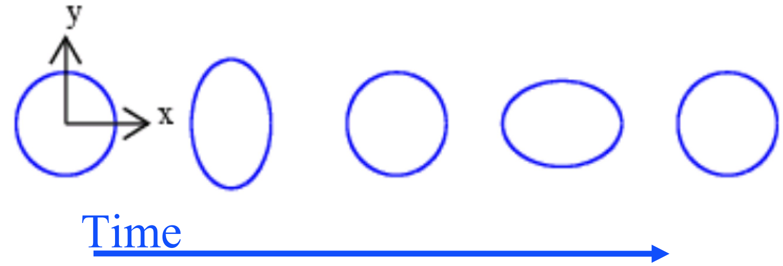
Interferometers as Gravitational Wave Detectors

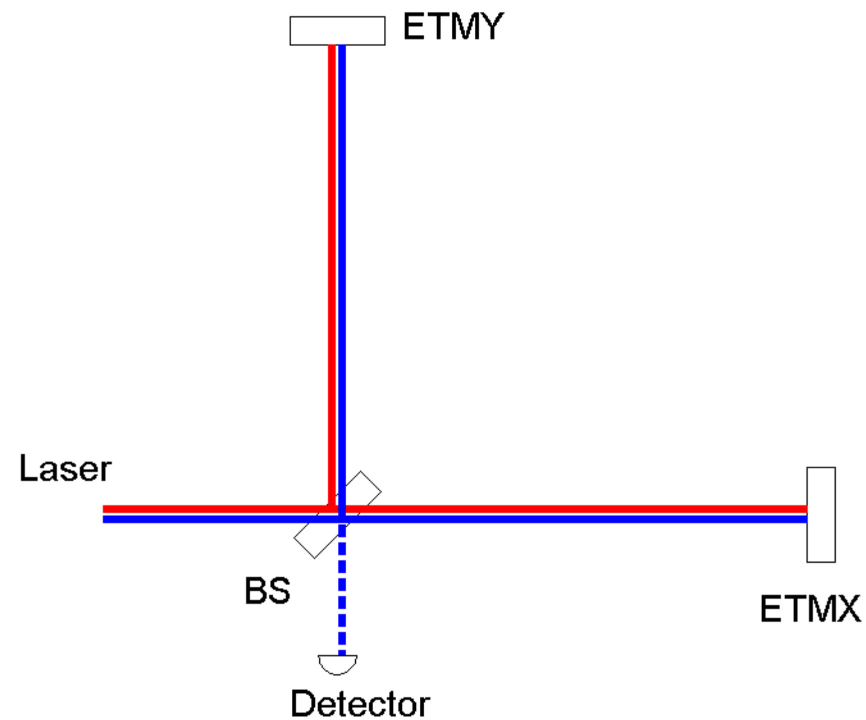
- Gravitational wave effectively stretches one arm while compressing the other.



Interferometers as Gravitational Wave Detectors

- Gravitational wave effectively stretches one arm while compressing the other.
- Interferometer measures the arm-length difference.
  - » Suspended mirrors act as “freely-falling”.
  - » Dark fringe at the detector.





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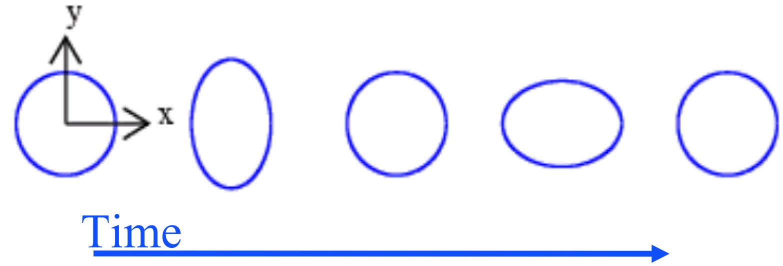
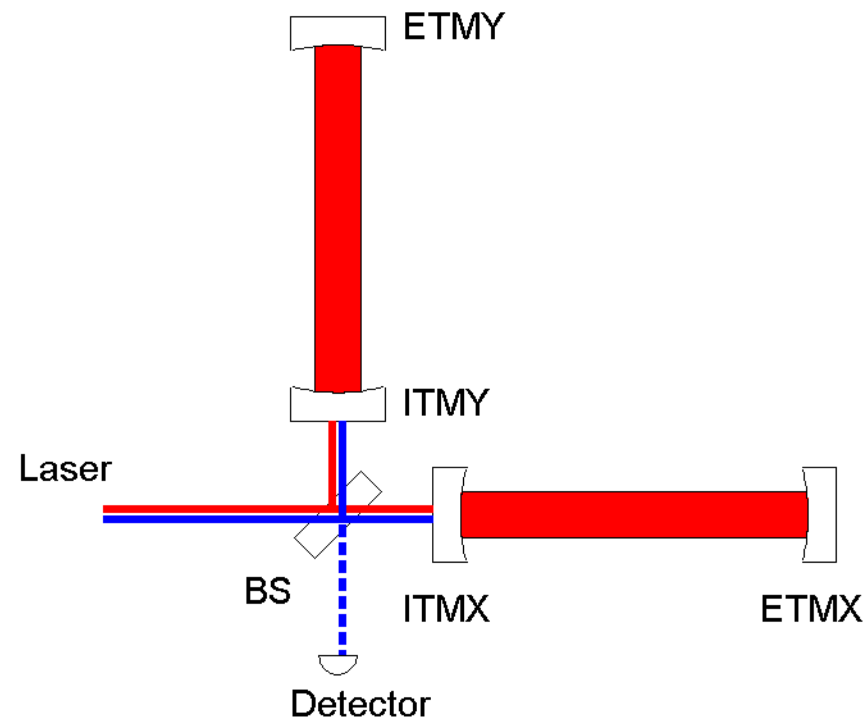
- Fabry-Perot cavities in the arms
  - » Effectively increase arm length ~100 times.





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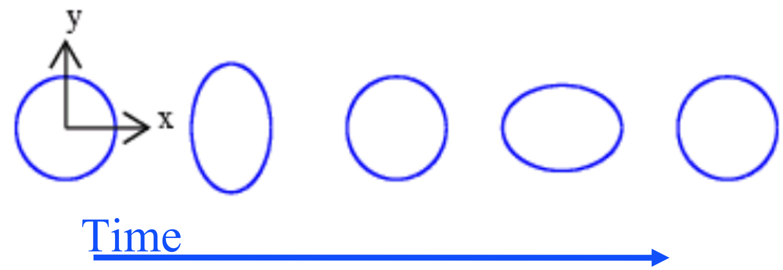
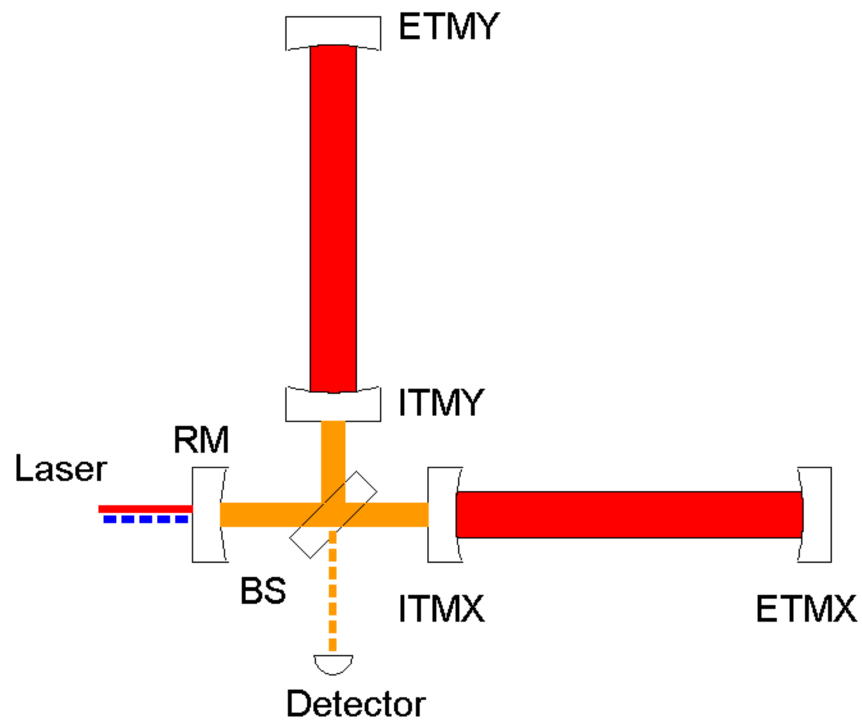
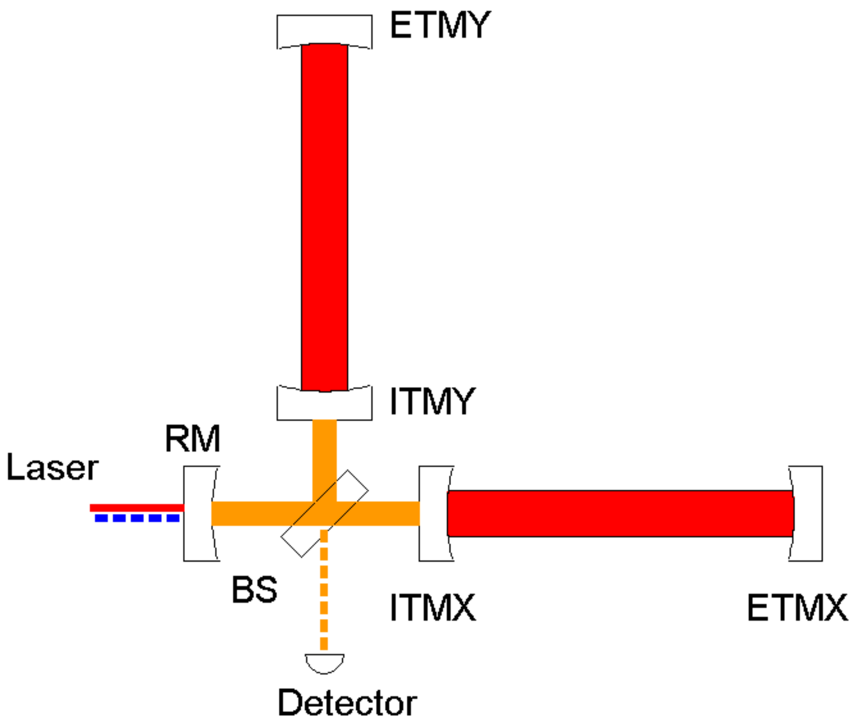
- Power-recycling mirror
  - » Another factor of ~40 in power.





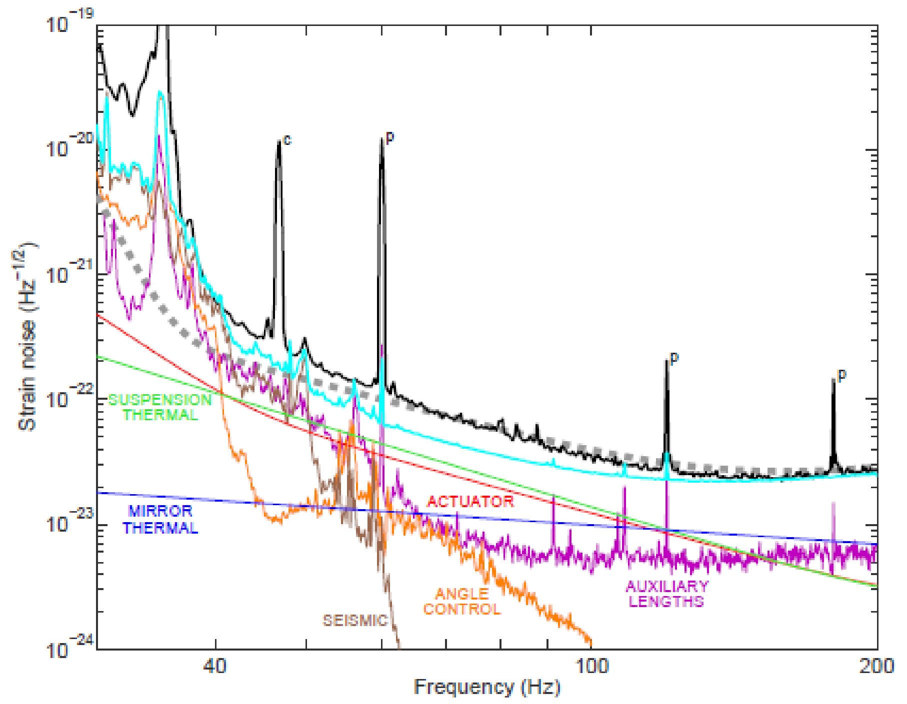
LIGO Sensitivity

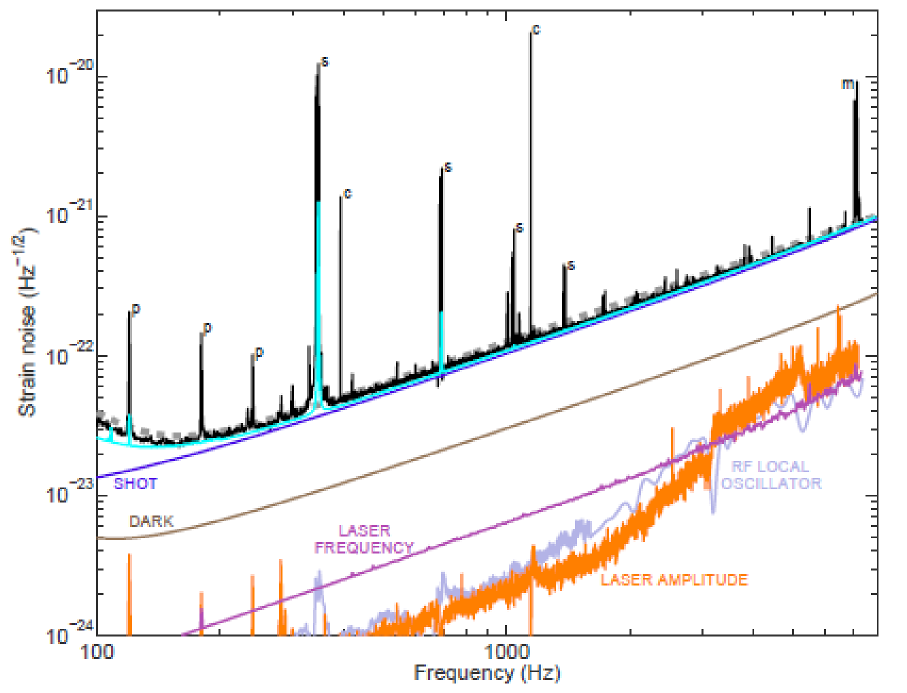
- Rough sensitivity estimate
  » Input laser power: ~5 Watt
- Sensitivity (ΔL) ~ λ (~ 10^{-6} m)
  / Number of Bounces in Arm (~100)
  / Sqrt(Number of Photons (~10^{21}))
  ~ 3×10^{-19} m
- Strain Sensitivity:
  » $h = \Delta L / L \sim 10^{-22}$
  » L = 4 km



LIGO Noise Budget

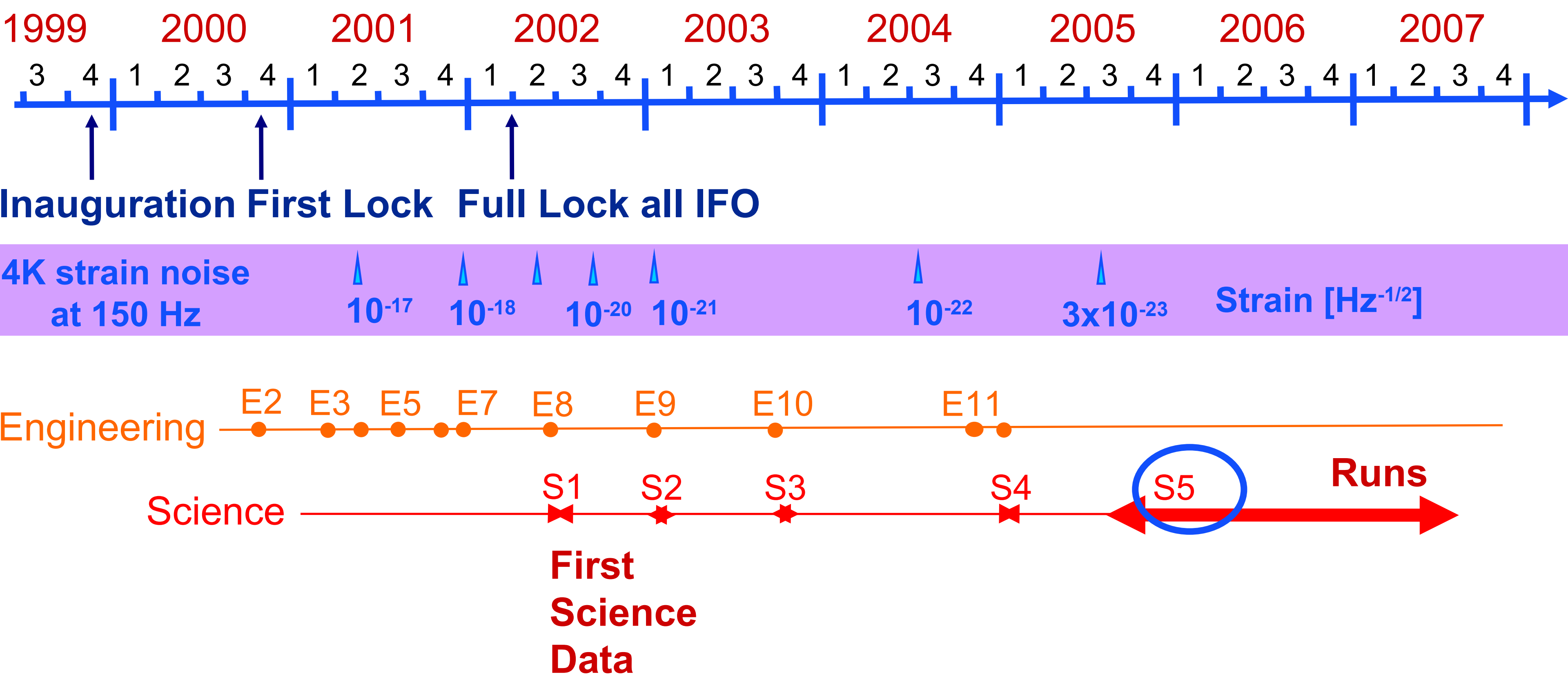
- Fundamental noise sources:
  - » Seismic noise, <40 Hz
  - » Thermal noise, 40-150 Hz
  - » Laser-power shot noise, >150 Hz
- Many technical noise sources:
  - » Electronics, 60 Hz harmonics
  - » Angle-to-length couplings
  - » Auxiliary length degrees of freedom
  - » Laser frequency noise
  - » Laser intensity noise
  - » Oscillator phase noise





LIGO Observatories

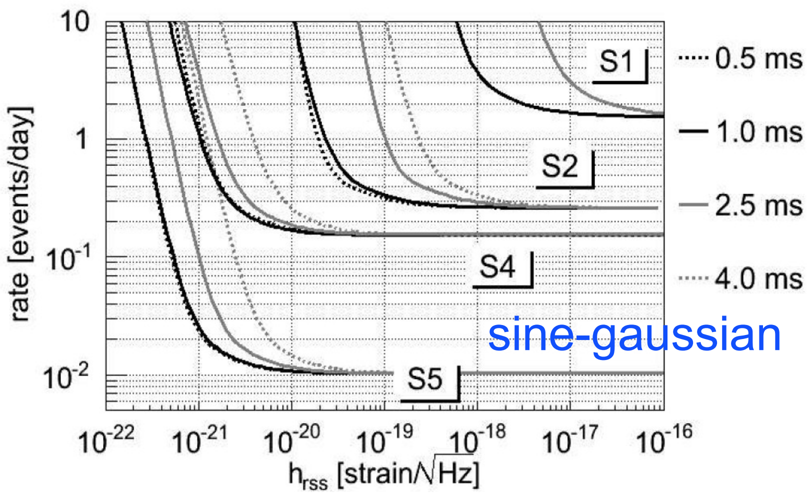
Brief History of LIGO

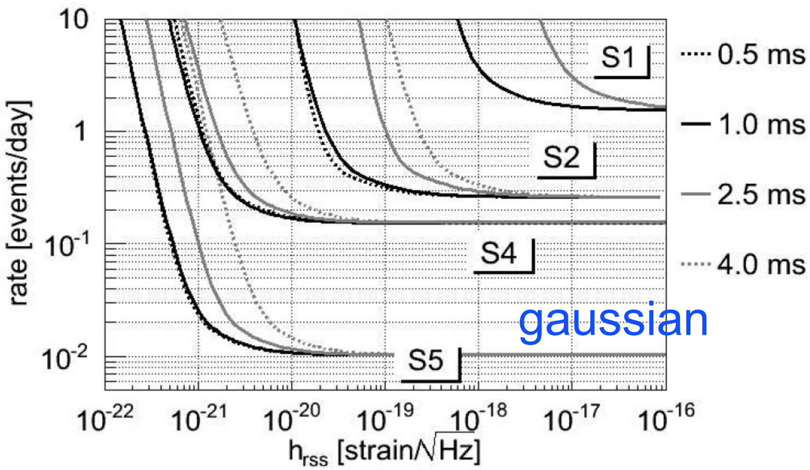


Transient Searches: Bursts (1)

- Search for power excess in data, <1s long.
- Several algorithms deployed:
  - » Different time-frequency decompositions, different methods of estimating excess power and coherence between detectors.
- Frequency bands:
  - » 64-2000 Hz
  - » 1-6 kHz
- First year of S5.
- Data quality evaluation:
  - » Data quality flags
  - » Veto conditions (auxiliary channels etc)
- Background estimation using time-slides.
- Efficiency estimation using software simulations of signals.

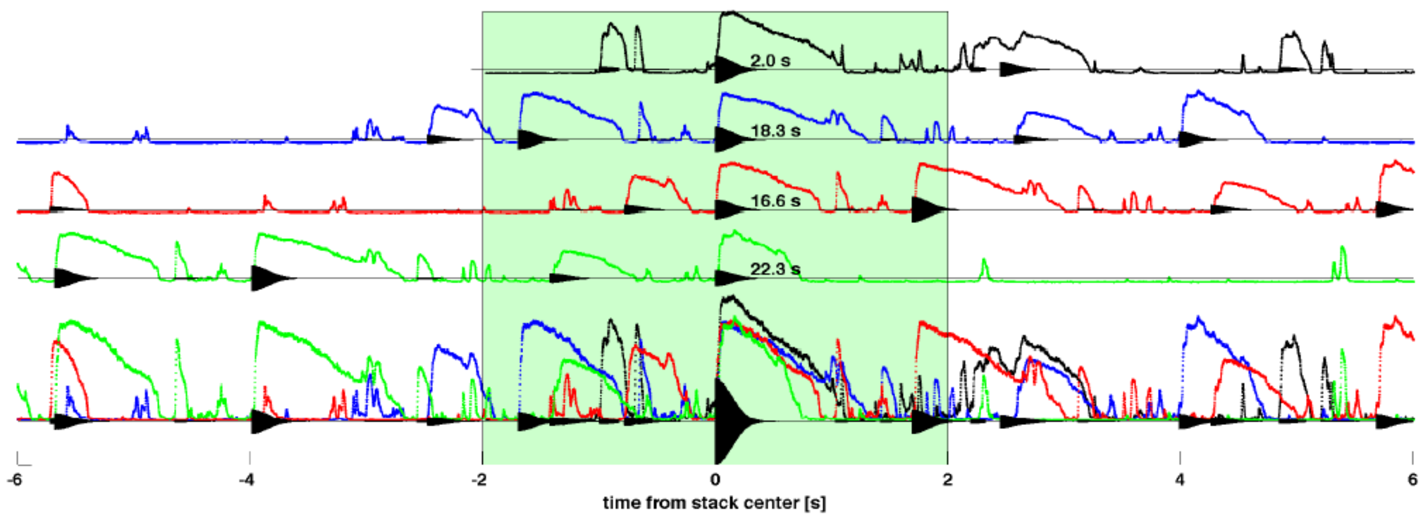
90% Confidence Rate Limits





Transient Searches: Bursts (2)

- Soft Gamma Repeaters (SGR): brief (~0.1sec) bursts of gamma rays.
  - » Magnetar model: Galactic neutron star in a strong magnetic field.
- "Storm": SGR 1900+14, March 29, 2006, about 30-sec long.
- Timing information from Swift.
- Stacking technique: time-align the GW data to overlap individual bursts.
- Consider several example waveforms: ringdowns at different frequencies, frequency band-limited or white-noise bursts.
- No signal observed: 90% UL on energy emitted at 10 kpc between 2×10^{45} erg and 6×10^{50} erg, depending on the waveform type.



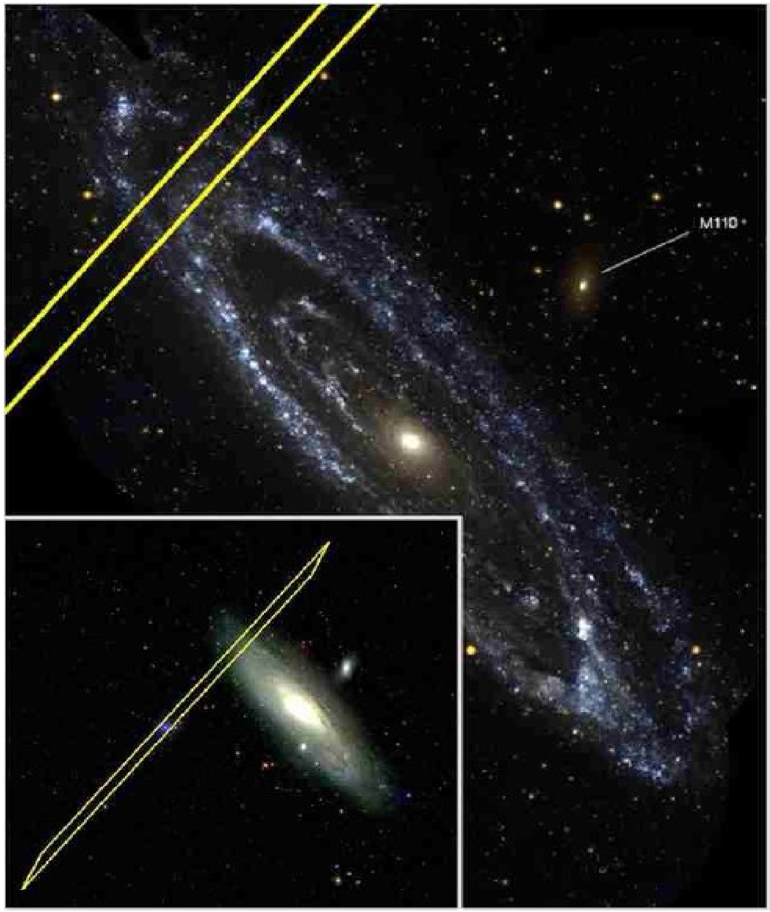
Transient Searches: CBC

- CBC: Compact Binary Coalescences:
  - » Infall of 2 neutron stars, 2 black holes, or a neutron star and a black hole toward each other.
  - » Ends with a merger (outside of the sensitive band).
- Using most of S5 data.
  - » 2-35 $M_\odot$ binaries, minimum component mass 1 $M_\odot$.
  - » Matched-template search.
  - » Require coincidence in 2 or more detectors (mass and time)
  - » Apply vetoes (environmental, instrumental)
- No candidates, place 90% rate upper limits:
  - » In units: $(L_{10}yr)^{-1}$ where L_{10} is$10^{10}\times$ the blue solar luminosity.

Type	90% UL	Realistic Expected	Optimistic Expected
BNS	1.4×10^{-2}	5×10^{-5}	5×10^{-4}
BBH	7.3×10^{-4}	4×10^{-7}	6×10^{-5}
NSBH	3.6×10^{-3}	2×10^{-6}	6×10^{-5}

Transient Searches: Burst + CBC

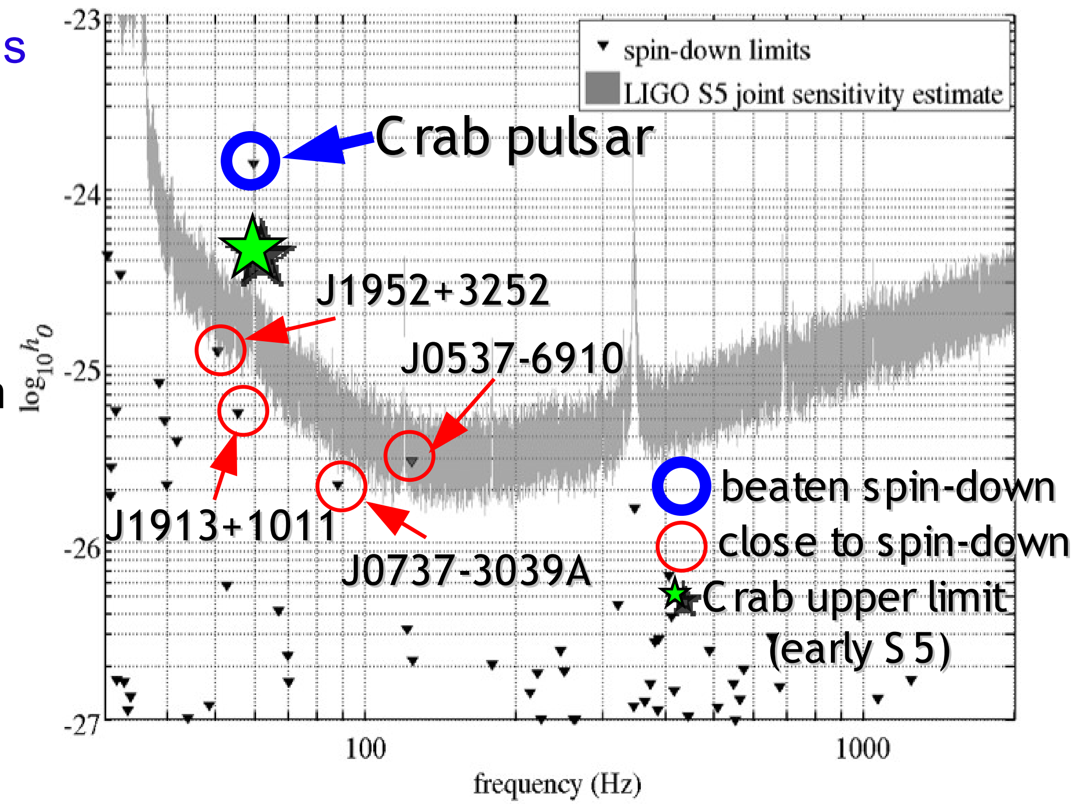
- Short Gamma Ray Bursts (GRBs): intense flashes of gamma rays, lasting <2s.
  - » Nearby: soft gamma-ray repeaters (SGRs).
  - » Distant: neutron star and/or black hole merger.
- GRB 070201 was observed in the direction of Andromeda galaxy (M31) by several spacecraft (Konus-*Wind,* Integral, Messenger, Swift).
- H1 and H2 operational at the time.
  - » Search -120/+60 sec around the GRB time.
  - » No gravitational-wave candidate was found (Astrop. J. 681, 1419 (2008)).
- Inspiral search for compact binary merger ($M_\odot < m_1 < 3M_\odot$, $M_\odot < m_2 < 40M_\odot$):
  - » In M31 (770 kpc) excluded at 99% confidence.
  - » Excluded at 90% confidence out to 3.5 Mpc.
- Un-modeled burst: SGR in M31 not excluded.



IPN3 error box overlaps with M31

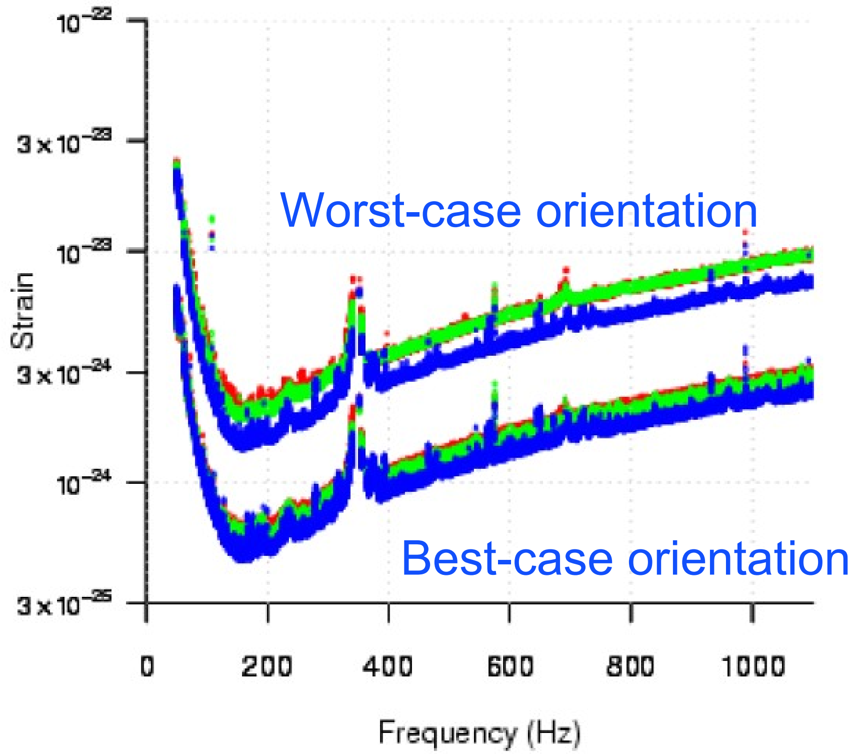
Continuous Waves (1)

- Search for known pulsars:
  - 113 known ms-pulsars >20 Hz.
  - Known positions, spin evolutions from radio (JBO, Green Bank, Parkes) and X-ray (RXTE) observations.
  - Assume GWs phase locked to EM signal.
- Neutron star ellipticity can constrain its equation of state.
- Crab pulsar:
  - Spin-down of 3.7×10^{-10} Hz/s implies maximum strain of 1.4×10^{-24}.
- Major Milestone: Beating the Crab spin-down limit!
  - Based on first 10 months of S5.
  - Ap. J. Lett. 683, 45 (2008)



Continuous Waves (2)

- All-sky search:
  - » First 8 months of S5.
  - » Frequency: 50-1100 Hz.
  - » Spin-down: -5×10^{-9} – 0 Hz/s.
  - » Isotropic sky-position grid.
  - » 5 polarizations.
  - » 30-min segments, 0.5 mHz resolution.
- H1 and L1 analyzed.
  - » 6 candidates found with SNR>6.25 in both H1 and L1.
  - » "Coincidence" requirements met.
  - » But not of constant amplitude/spin-down.
  - » Reject all candidates.

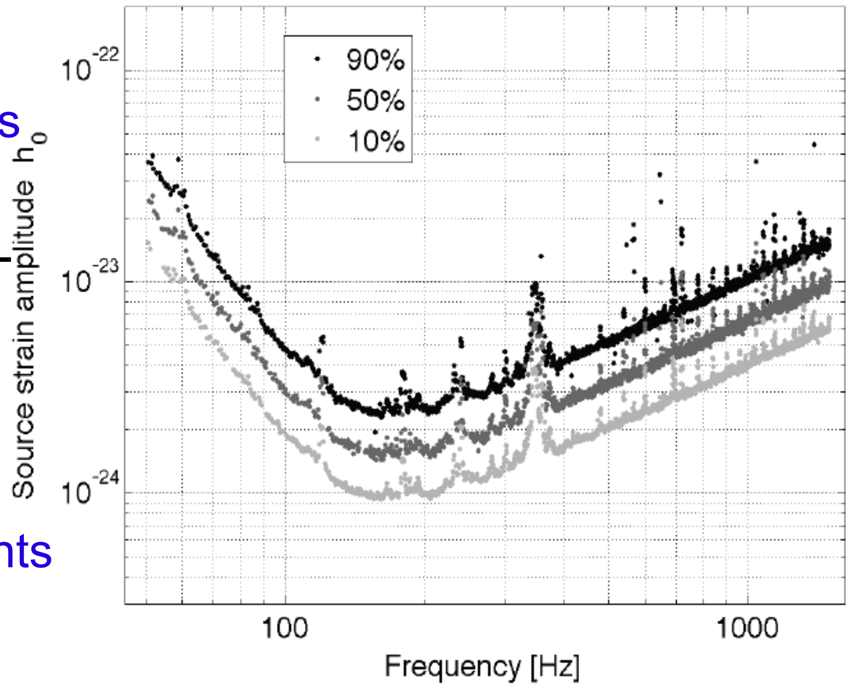


Blue: Polar
Red: Equatorial
Green: intermediate

Continuous Waves (3)

- Einstein@Home:
  - » Analysis performed by 100,000 computers volunteered by general public.
  - » Spans 66 days of S5, in 28 30-hr segments.
  - » Frequency band: 50 – 1500 Hz.
  - » Frequency resolution: 3-6 μHz
  - » Spin-down resolution: $(1.6\text{-}4.0) \times 10^{-10}$ Hz/s
  - » Sky-position grid.
- Less data, but much finer frequency and spin-down grids – similar sensitivity to the all-sky search.
- Require 20 (out of 28) segments to agree for detection.
  - » Background level: <10 (out of 28) segments in coincidence.
  - » No candidate found!

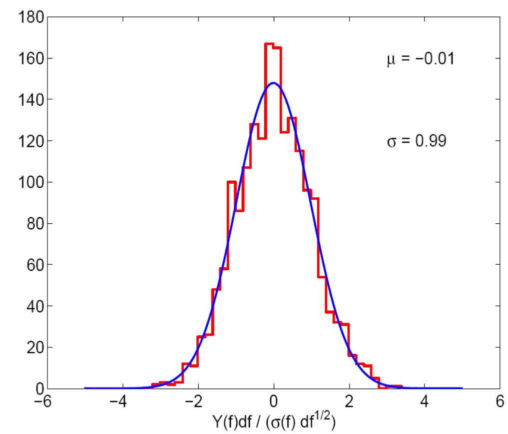
Strain amplitude at which 10%,50%, and 90% of simulated pulsars are detected by Einstein@Home



Stochastic Background (1)

- Search for GW energy density by cross-correlating L1 and H1.

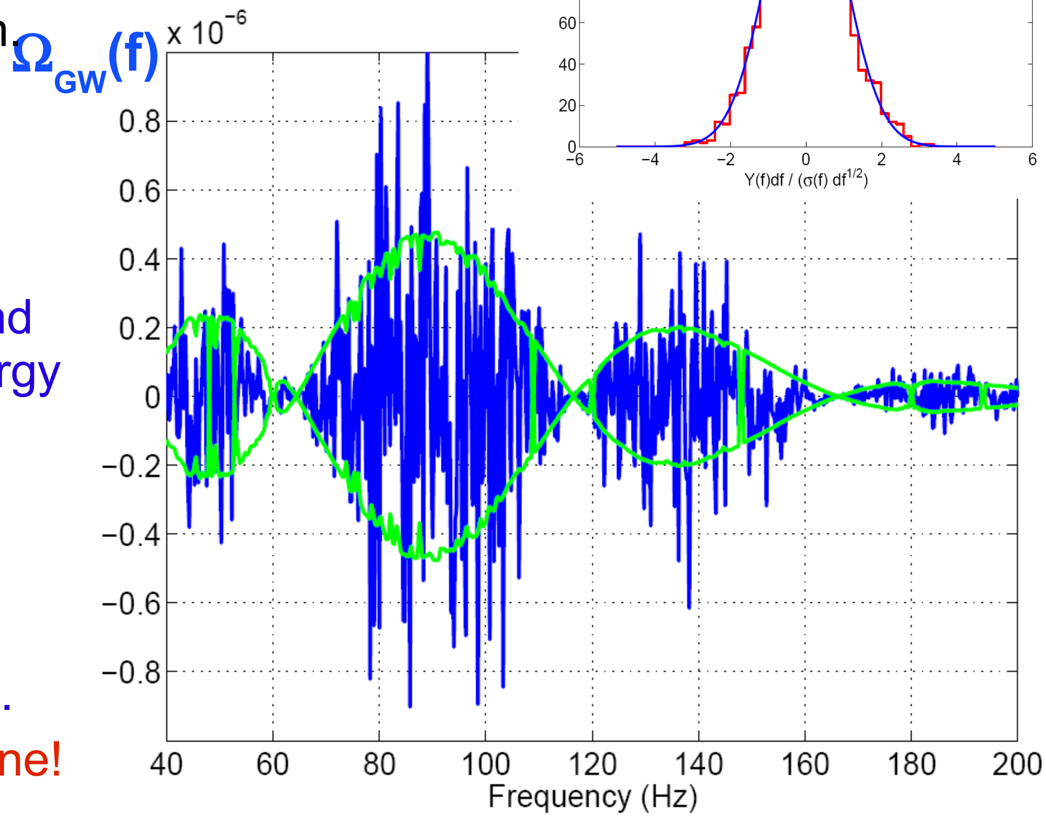
$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d\ln f}$$



- Use S5 data up to Jan 22, 2007:
  - Frequency band: 41-178 Hz.
  - Frequency-independent spectrum.
- Preliminary S5 H1L1 result:
  - » $\Omega \pm \sigma_\Omega = (1.0 \pm 5.2) \times 10^{-6}$
- Bayesian 90% UL: **9.0×10^{-6}**
- Big-Bang Nucleosynthesis model and observations constrain the total energy at the time of BBN:

$$\int \Omega_{\mathrm{GW}}(f) h_{100}^2 d(\ln f) < 6.3 \times 10^{-6}$$

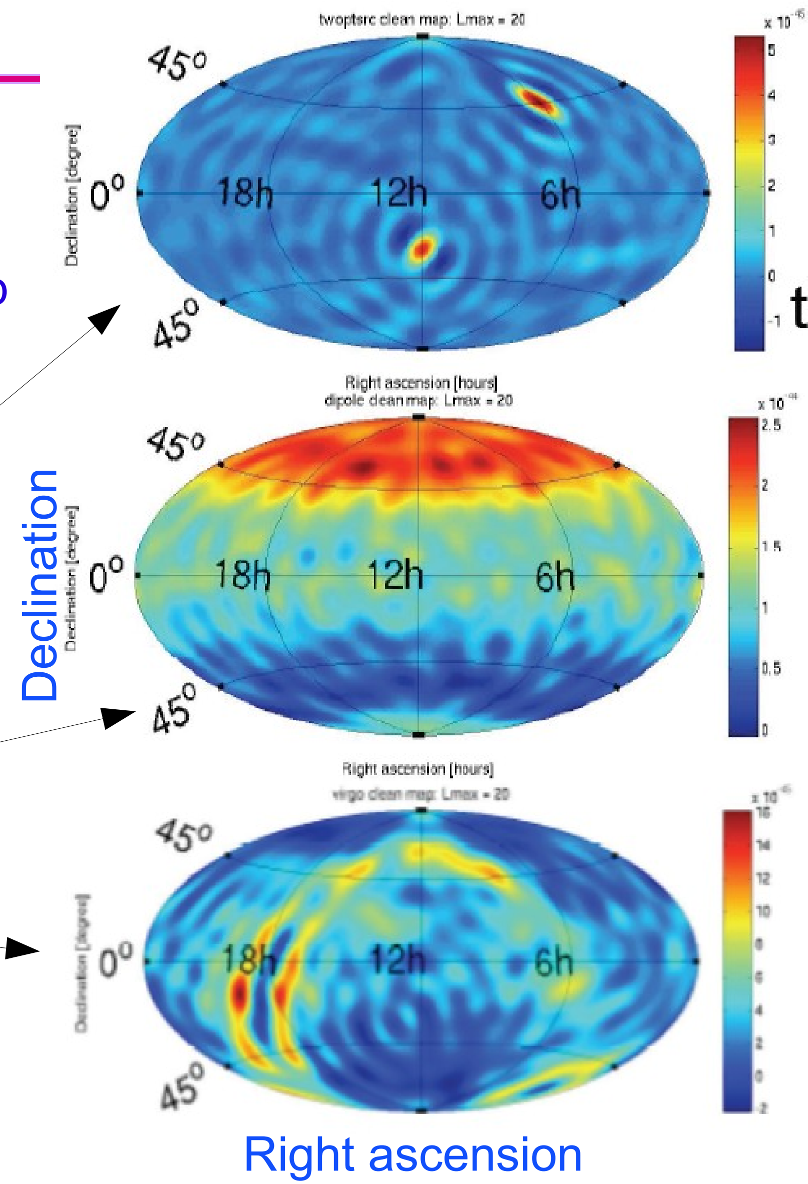
- BBN in LIGO band: $\Omega_0 < 1.0 \times 10^{-5}$
- We have surpassed the BBN bound.
  - » Another important LIGO milestone!



Stochastic Background (2)

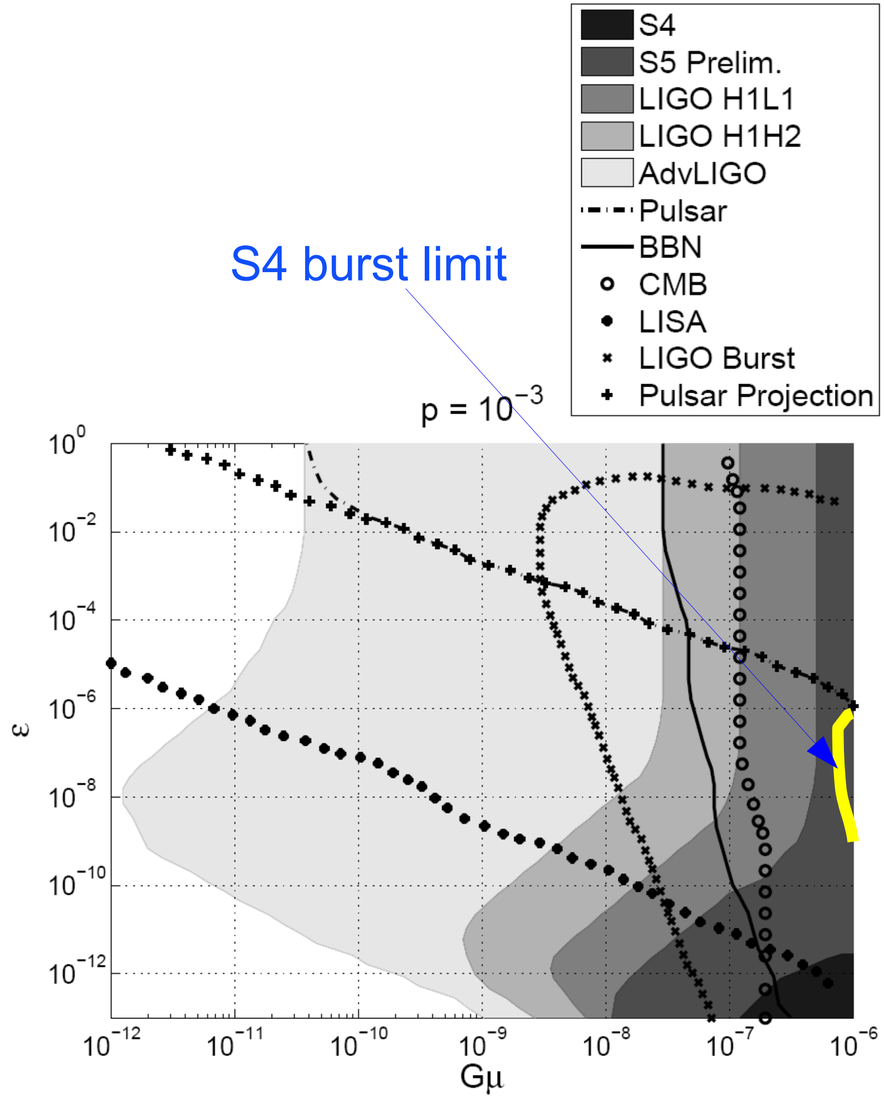
- Directional searches:
  - » Search for point-sources (S4 run).
  - » Generated stochastic GW upper-limit map (analogous to CMB maps).
    - Phys. Rev. D 76, 082003 (2007).

- Spherical Harmonic Decomposition
  - » Complex GW power sky-distributions.
  - » In progress with S5 data.
  - » Recovering simulated signals:
    - 2 point sources.
    - Dipole moment.
    - Galactic distribution.

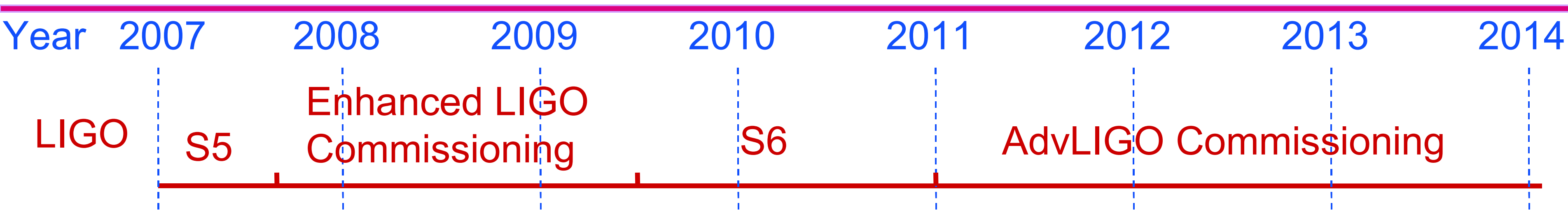


Cosmic (Super)Strings: Burst and Stochastic

- Cosmic Strings:
  - » Topological defects from phase transitions in early universe.
  - » Fundamental strings.
- Cosmic string cusps, Lorentz boosted toward Earth produce bursts of GWs.
- Integrating over the whole network gives a stochastic background.
- Model parameters (small loop scenario)
  - » Loop-size parametrized by: $10^{-13} < \varepsilon < 1$
  - » String tension: $10^{-12} < G\mu < 10^{-6}$
  - » Reconnection probability: $10^{-3} < p < 1$
- Preliminary S5 stochastic result and S4 burst result probe this parameter space.



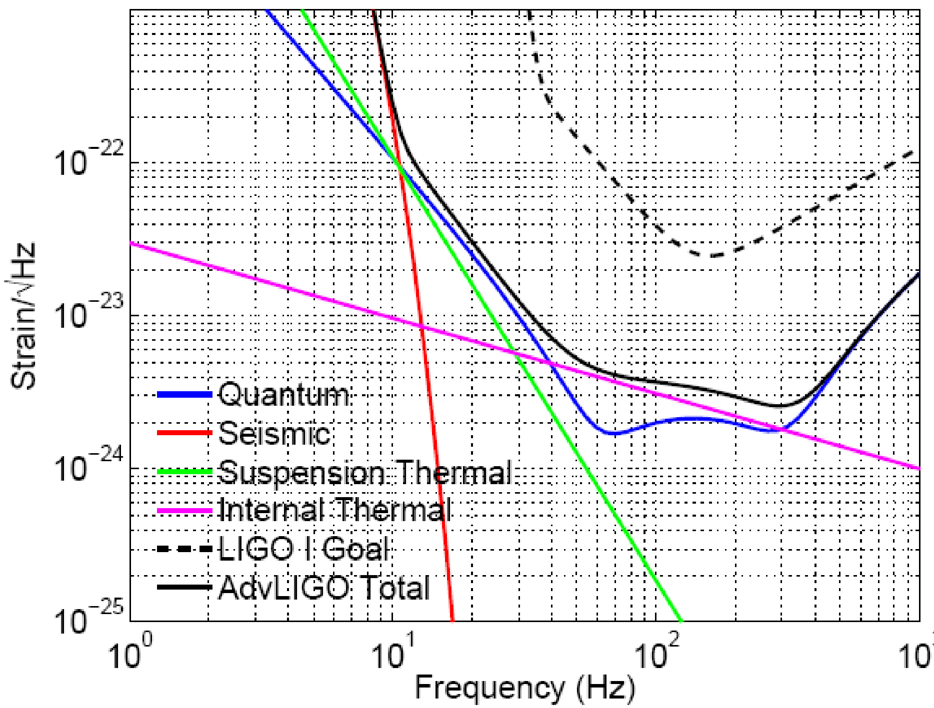
Expected Future Timeline



- Enhanced LIGO
  - » Relatively small upgrade over the Initial LIGO.
  - » Improve strain sensitivity of 4-km interferometers ~2 times.
  - » Test some of the Advanced LIGO concepts.
  - » NSF support: $150M over 2009-2013 for LIGO Lab operation!
- Advanced LIGO
  - » Major upgrade: essentially every aspect of the experiment will be significantly improved.
  - » Improve strain sensitivity of all interferometers >10 times.
  - » Widen the sensitive band down to 10 Hz.
  - » Substantial increase in the number of expected accessible sources.
  - » NSF support: $205M over 2008-2015 for ALIGO construction!

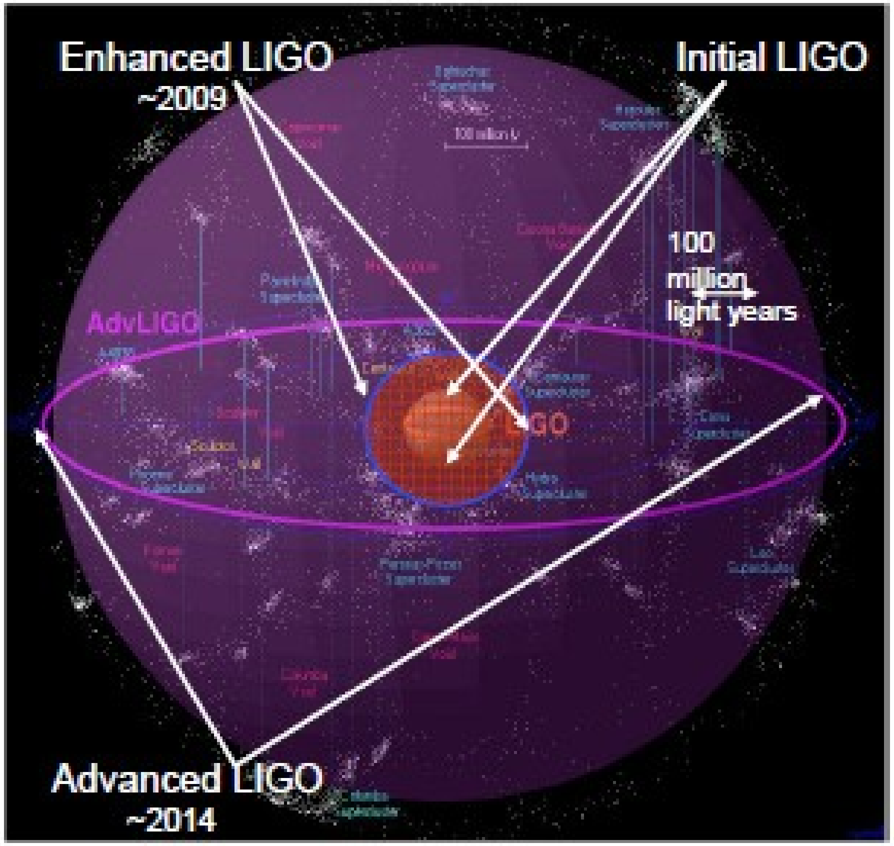
Advanced LIGO

- Keep the same facilities, but redesign all subsystems.
  - » Improve sensitivity over the whole frequency range.
- Increase laser power in arms.
- Better seismic isolation.
  - » Quadruple pendula for each mass
- Larger mirrors to suppress thermal noise.
- Silica wires to suppress suspension thermal noise.
- "New" noise source due to increased laser power: radiation pressure noise.
- Signal recycling mirror
  - » Allows tuning sensitivity for a particular frequency range.



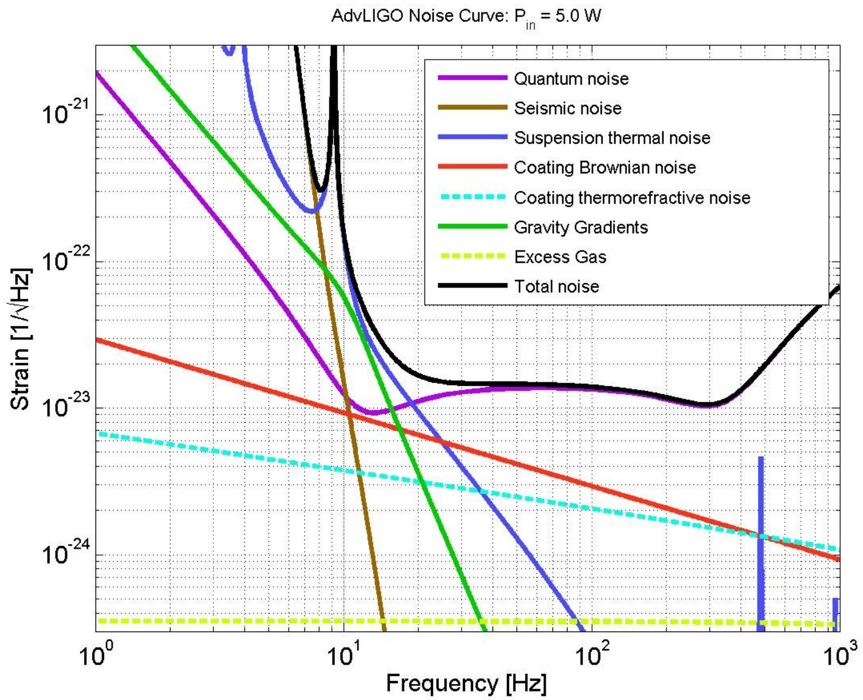
Advanced LIGO

- Three 4km interferometers.
  - » Two at Hanford, one at Livingston.
- Significantly larger expected number of GW sources.
- Project started in April 2008.
- Presently finalizing designs, placing orders.
  - » Preliminary tests of various subsystems.
  - » Some of the hardware and concepts to be tested by Enhanced LIGO.
- Installation expected to start in 2011.
  - » First results: ~2014.



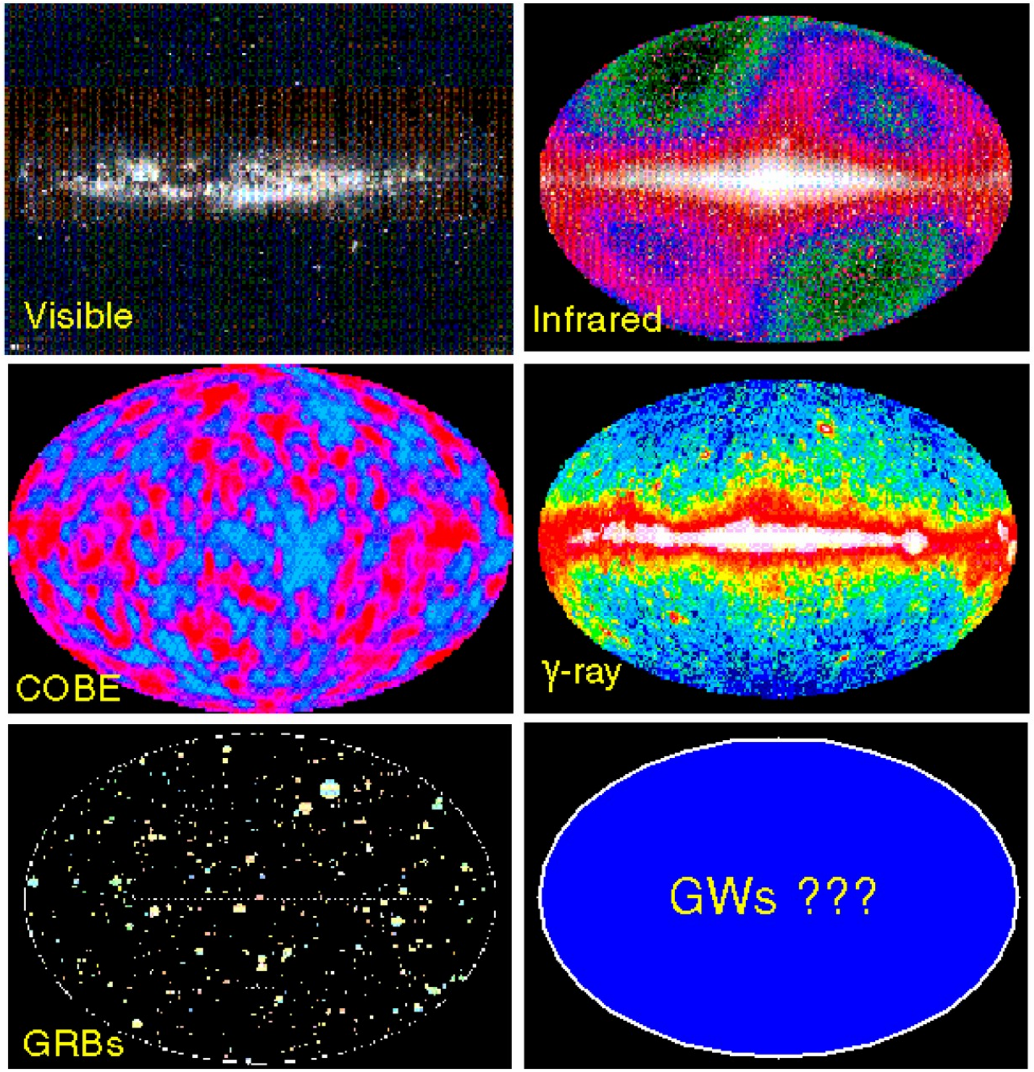
Beyond Advanced LIGO: Probing ~1 Hz

- Scientific Motivation for probing 1Hz GWs is very strong.
  - » Stochastic: $$S(f) = \frac{3H_0^2}{10\pi^2} \frac{\Omega_{GW}(f)}{f^3}$$
  - » Periodic: Most known pulsars are in the 0.1-10 Hz band.
  - » Inspirals: larger total mass (IMBH), longer observations.
- Technology challenge:
  - » Quantum (shot + rad. pressure)
  - » Thermal
  - » Seismic + gravity gradient
- Underground interferometers?
  - » Ongoing project at Homestake mine characterizing seismic and gravity gradient noise 1.5-2 km underground.



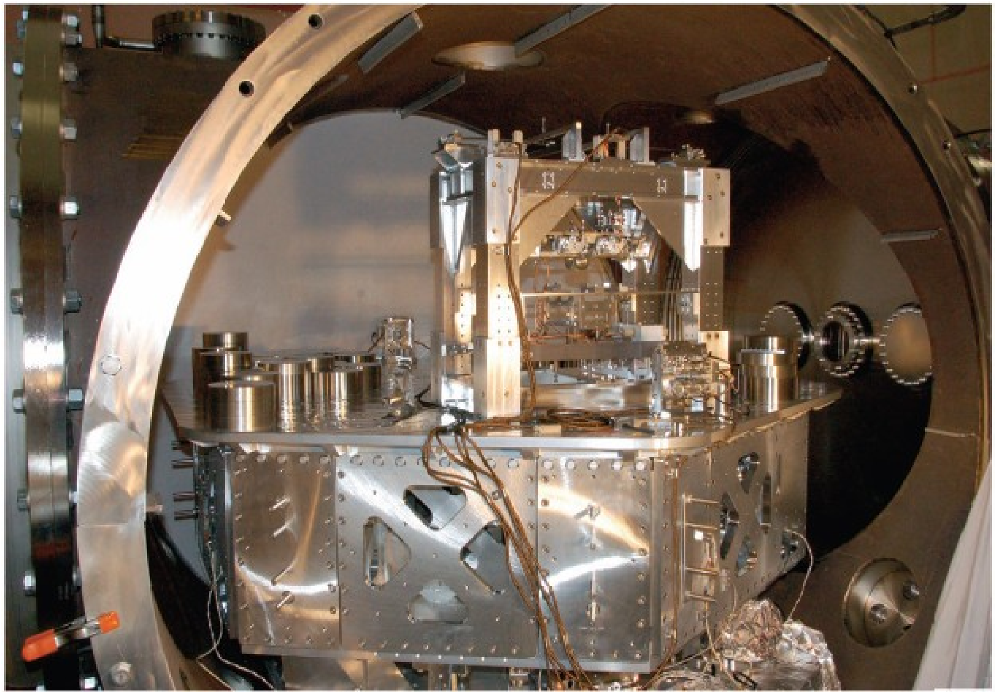
Conclusion

- LIGO achieved design sensitivity and completed a year-long science run.
- Many searches for GW sources completed, many still in the pipeline
  - » Beginning to have astrophysical implications.
- Significant improvements expected in the coming years:
  - » Enhanced LIGO to start in the summer, ~2x better strain sensitivity.
  - » Advanced LIGO construction under way.
  - » Already thinking about third generation.
- Stay tuned...



Enhanced LIGO

- Modifications only planned for 4-km interferometers: H1 and L1.
- Hardware installation nearly complete.
- More powerful laser (35 W instead of 6 W), with upgraded input optics.
- New, active seismic isolation platform in the output port.
- Output mode cleaner, suspended, in vacuum.
- New locking scheme.
- New earthquake stops (SiO_2) to suppress charging of the mirrors.
- New magnets (SmCo instead of NdFeB) to minimize non-linear, up-conversion effects.



LIGO Sensitivity

- Seismic Noise (<40 Hz)
  - Active and passive isolation
  - Suspensions
  - Effective "Seismic Wall" at 40 Hz
- Thermal Noise (40-150 Hz)
  - Suspension wires
  - Internal mirror modes
  - Mirror coatings modes
- Shot noise (>150 Hz)