Gravitational-Waves Detectors and Seismic Noise

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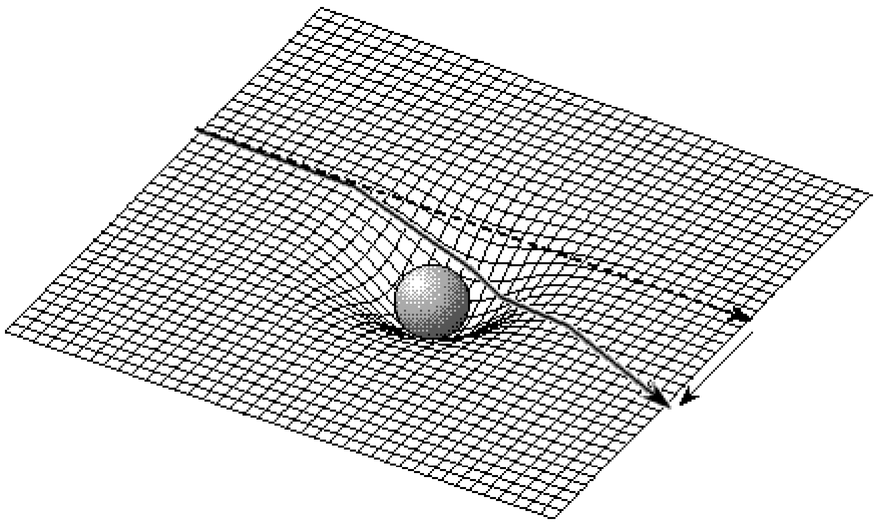
10/23/15

General Relativity

- Einstein's General Relativity:
  - » Mass/Energy and Space-Time are related.
- Presence of mass distorts the fabric of space-time.
  - » Straight lines not always shortest distances.
- Gravity is an effect of curved space-time.

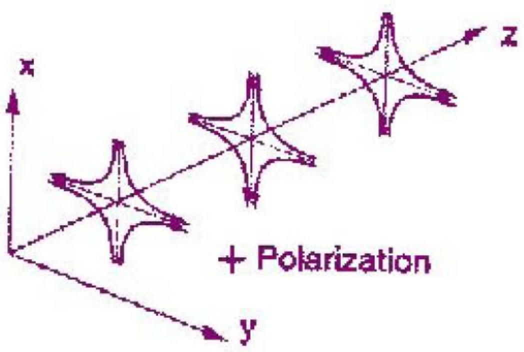


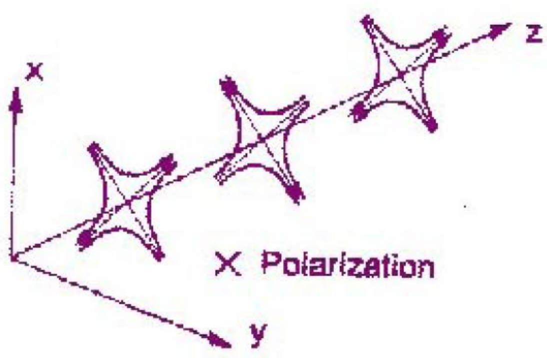
Gravitational Waves

- Newtonian gravity: instantaneous action at a distance.
- General Relativity: the “signal” travels at the speed of light.
- Weak field limit: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
- Einstein’s field equations reduce to the wave equation:

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

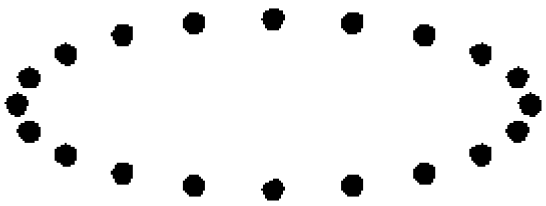
- Two polarizations: $h = a h_+ + b h_\times$ *a,b ~ f(ωt - **k·x**)*

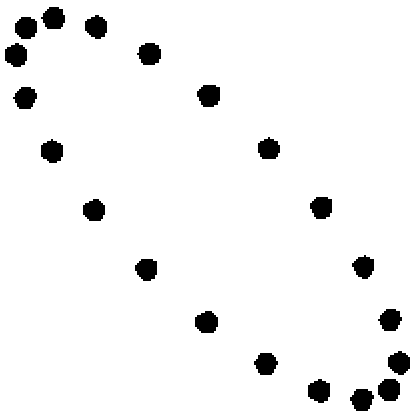




Gravitational Waves

Two Polarizations:





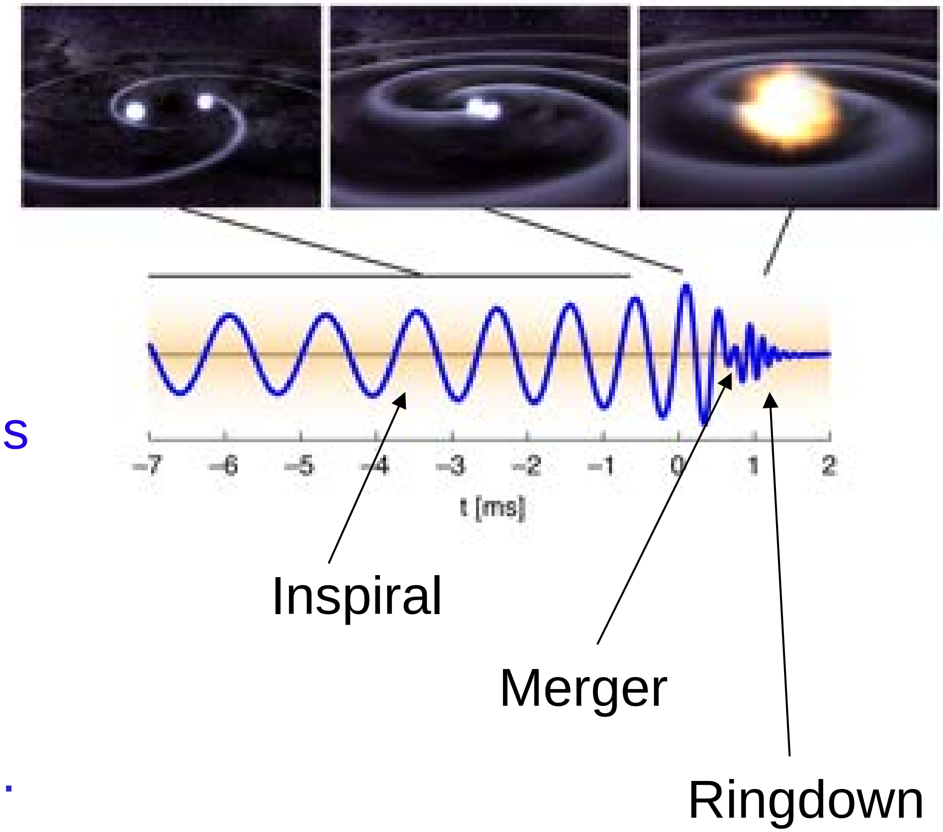
"+" Polarization

"x" Polarization

Compact Binary Coalescences

- Compact binary objects:
  - » Two neutron stars and/or black holes.
- 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, matched template searches.
- Science:
  - » Strong field GR (BH-BH mergers).
  - » Equation of state in NS.
  - » Standard “sirens” - probe cosmology.

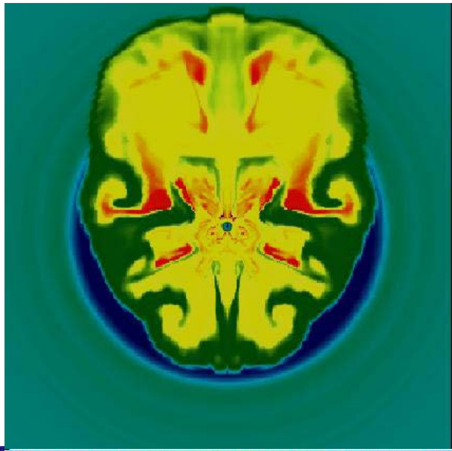
R. Spero

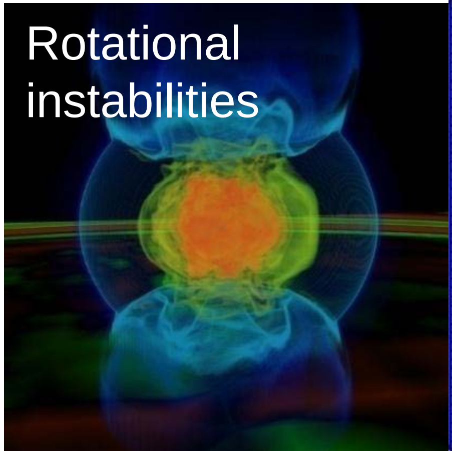


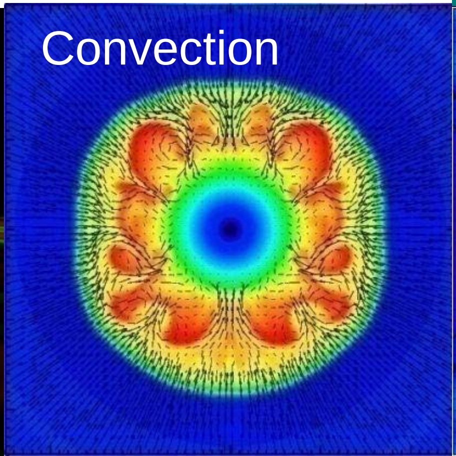
Bursts

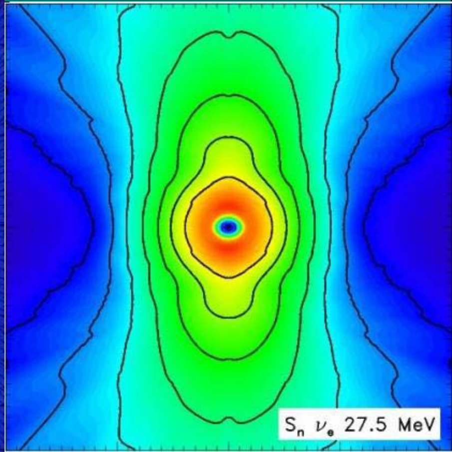
- Many potential transient sources:
  - » Supernovae: probe the explosion mechanisms.
  - » Gamma Ray Bursts: collapse of rapidly rotating massive stars or neutron star mergers.
  - » Pulsar glitches: accretion.
  - » Cosmic strings cusps.
- Models are ok, but not essential:
  - » Search for power excess in the data.
  - » Search for any short signal with measurable strain signal.

Aspherical outflows





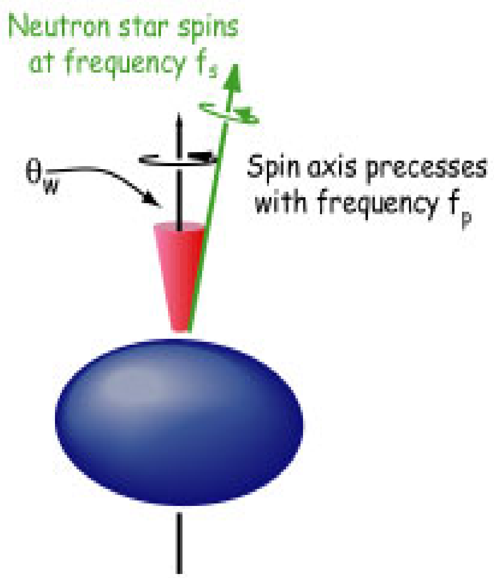




C. Ott

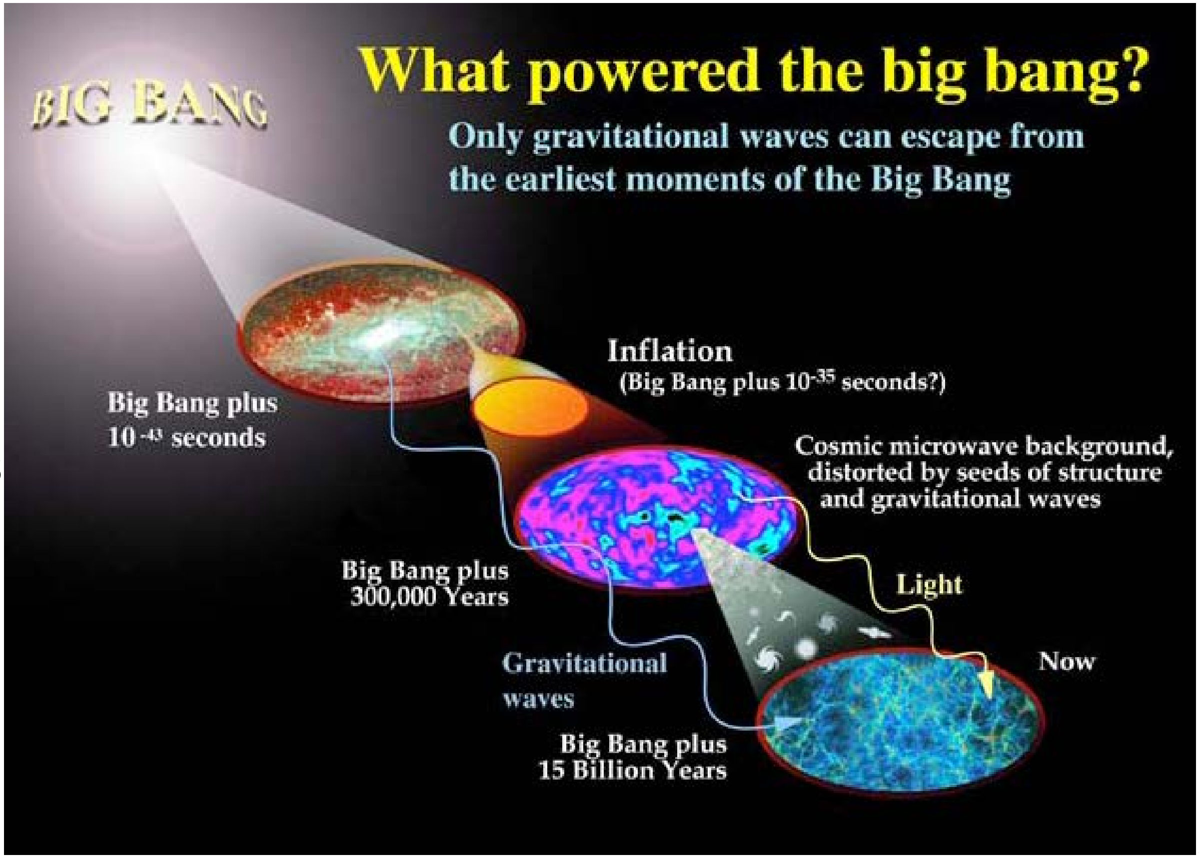
Sources: Periodic

- Pulsars with mass non-uniformity:
  - » Small "mountain".
  - » Density non-uniformity.
  - » Dynamic processes inside neutron star, leading to various instabilities.
- Produce gravitational-waves, often at twice the rotational frequency.
- Waveform well understood:
  - » Sinusoidal, but Doppler-modulated.
- Continuous source!



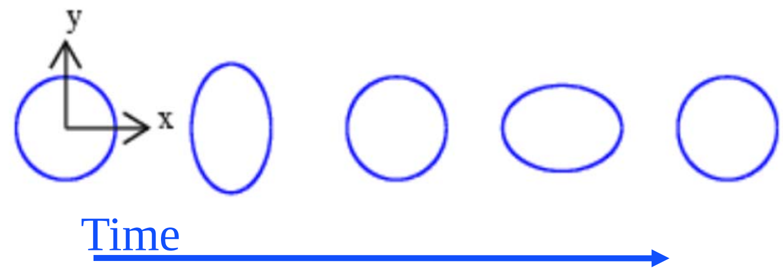
Sources: Stochastic Background

- Incoherent superposition of many unresolved sources.
- Cosmological:
  - » Inflationary epoch, preheating, reheating
  - » Phase transitions
  - » Cosmic strings
  - » Alternative cosmologies
- Astrophysical:
  - » Supernovae
  - » Magnetars
  - » Double neutron stars
- Potentially could probe physics of the very-early Universe.



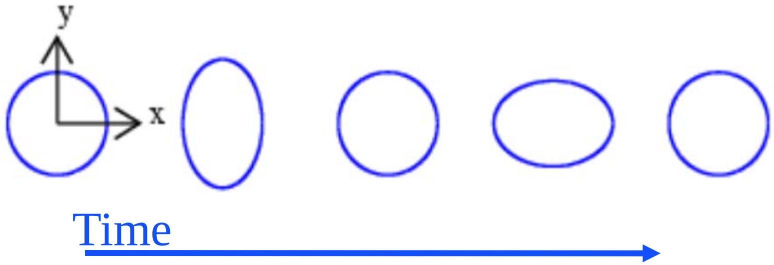
Interferometers as Gravitational Wave Detectors

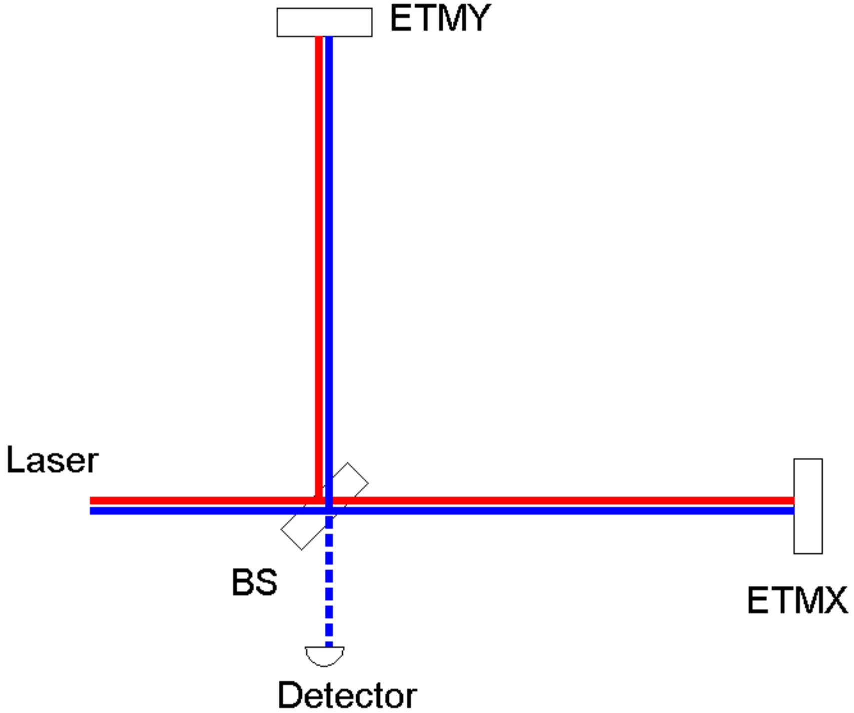
- Gravitational wave effectively stretches one arm while compressing the other.



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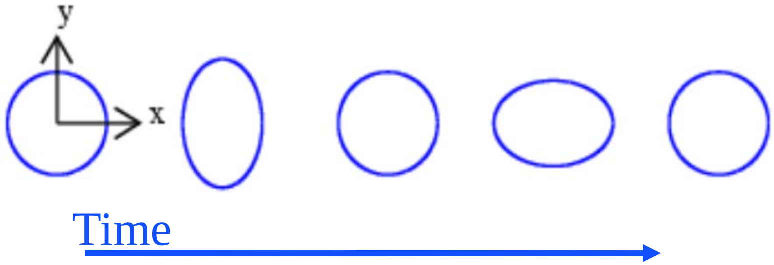
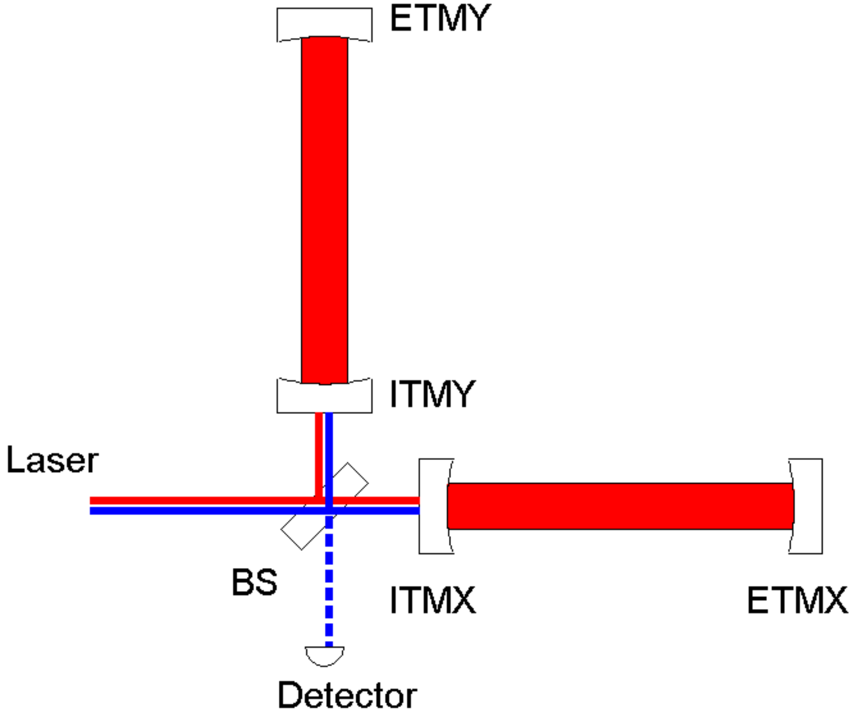
- Fabry-Perot cavities in the arms
  - » Effectively increase arm length ~100 times.





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  - » Suspended mirrors act as “freely-falling”.
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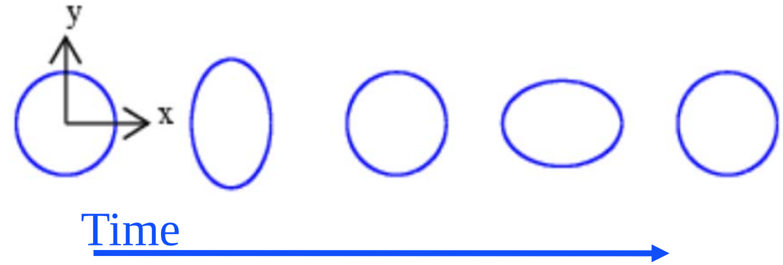
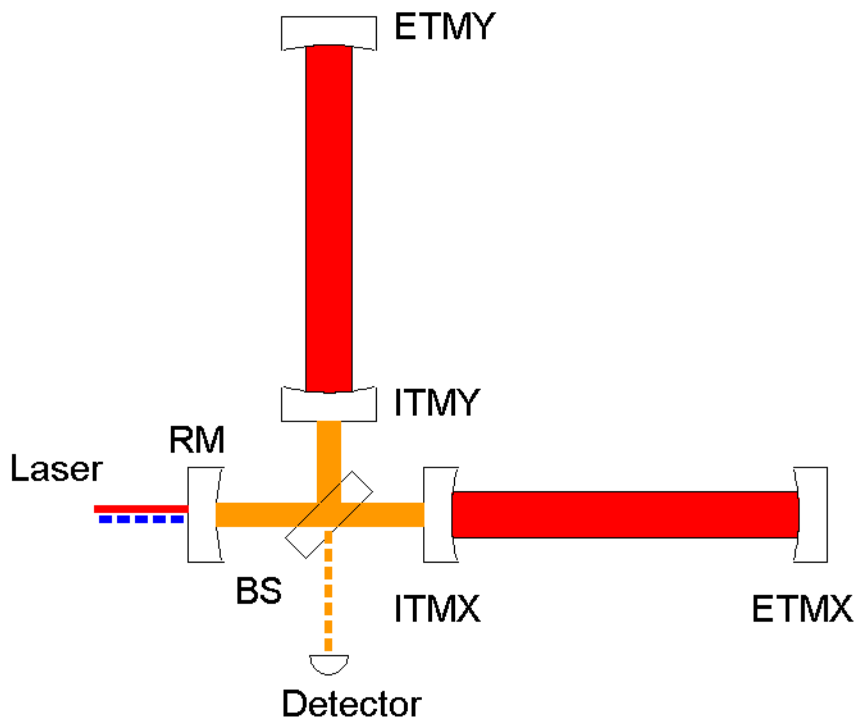
- Fabry-Perot cavities in the arms
  - » Effectively increase arm length ~100 times.
- Power-recycling mirror
  - » Another factor of ~40 in power.





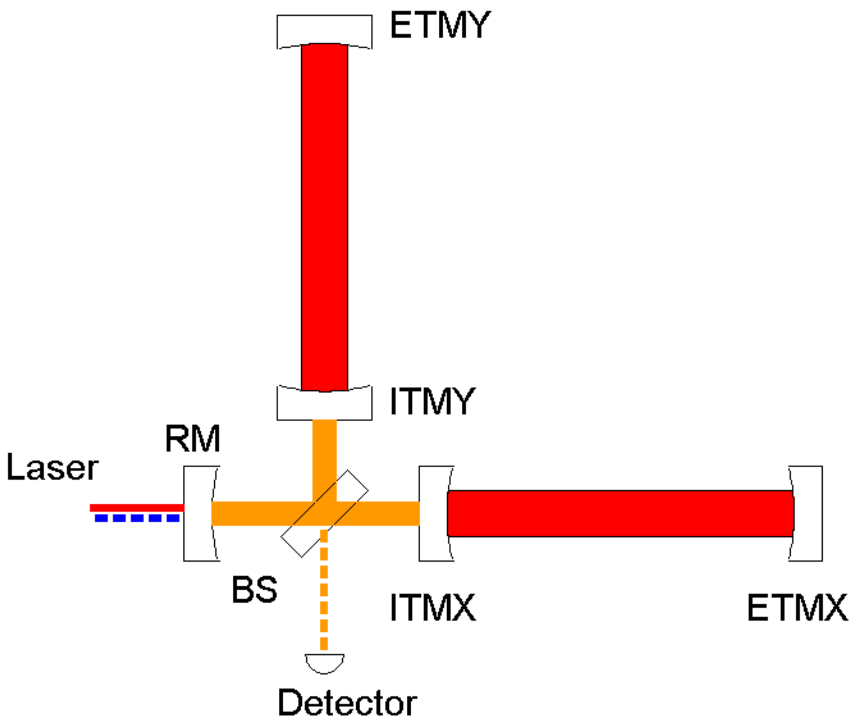
LIGO Sensitivity

- 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}))

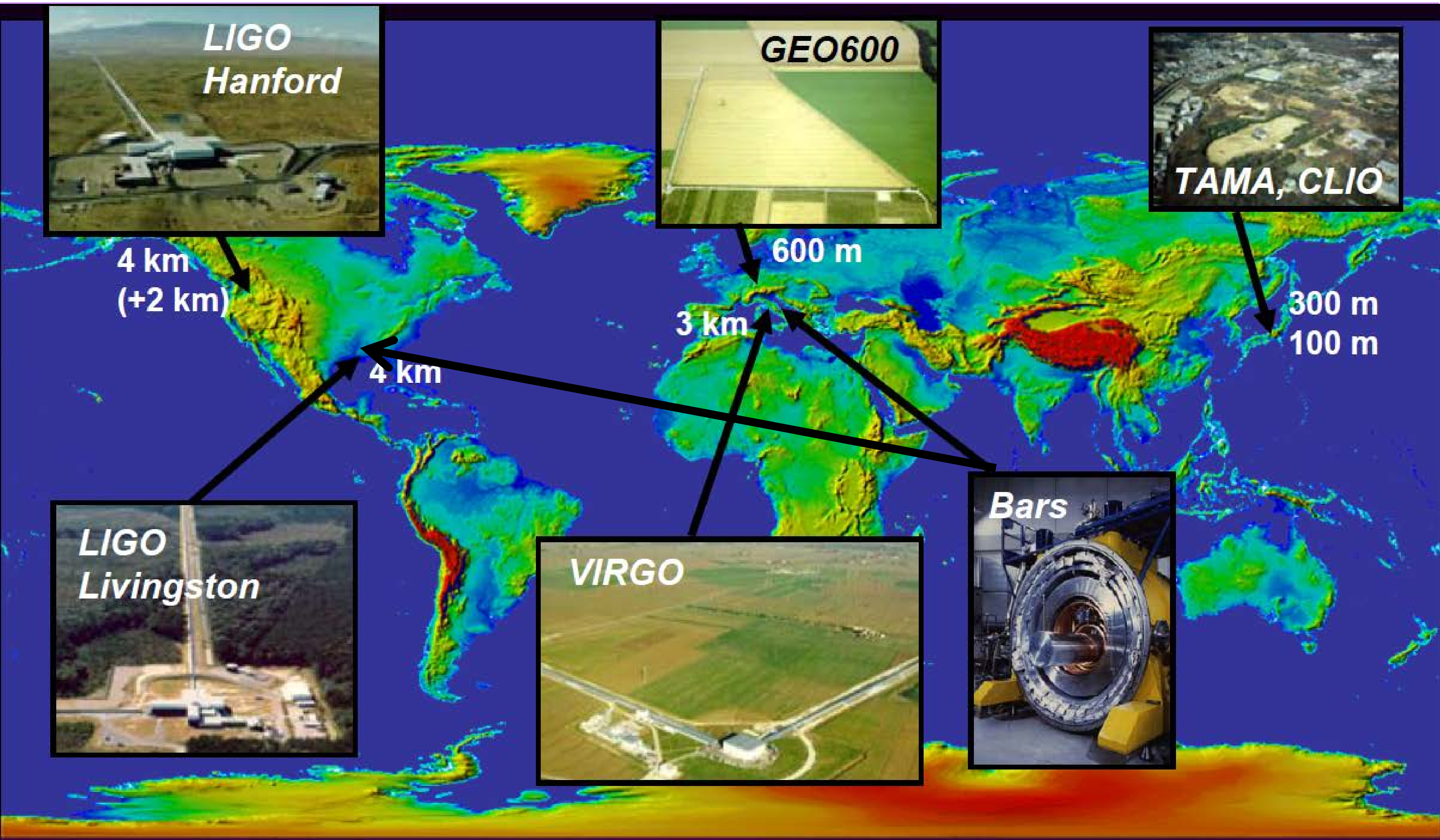
  ~ 3×10^{-19} m
- Strain Sensitivity:
  - » $h = \Delta L / L \sim 10^{-22}$
  - » L = 4 km



LIGO

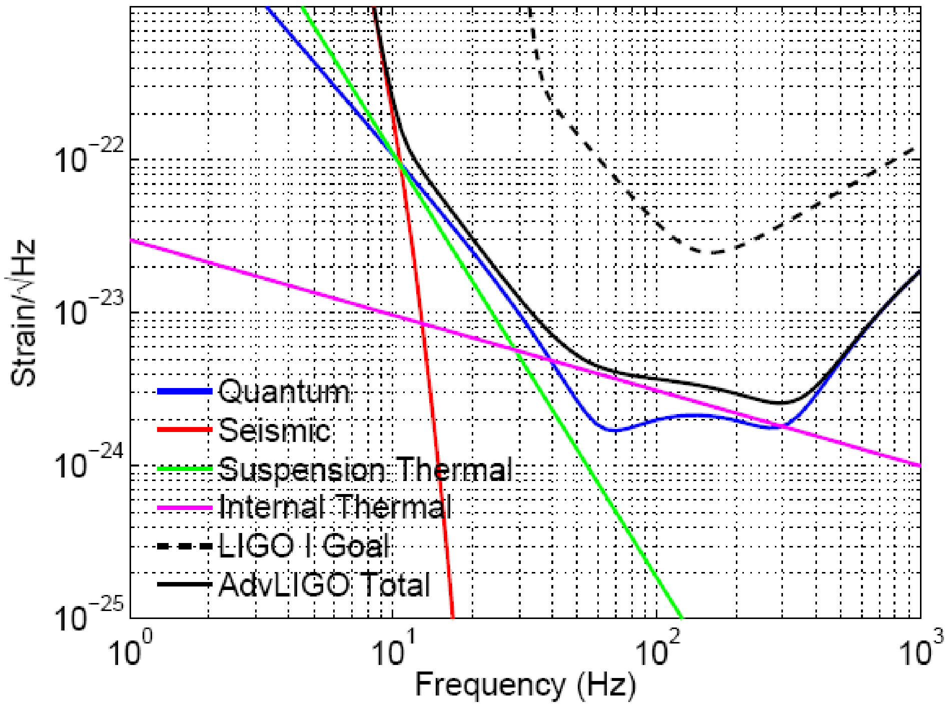
- Laser Interferometer Gravitational-wave Observatory.

Network of Gravitational-Wave Detectors: 2005-2010



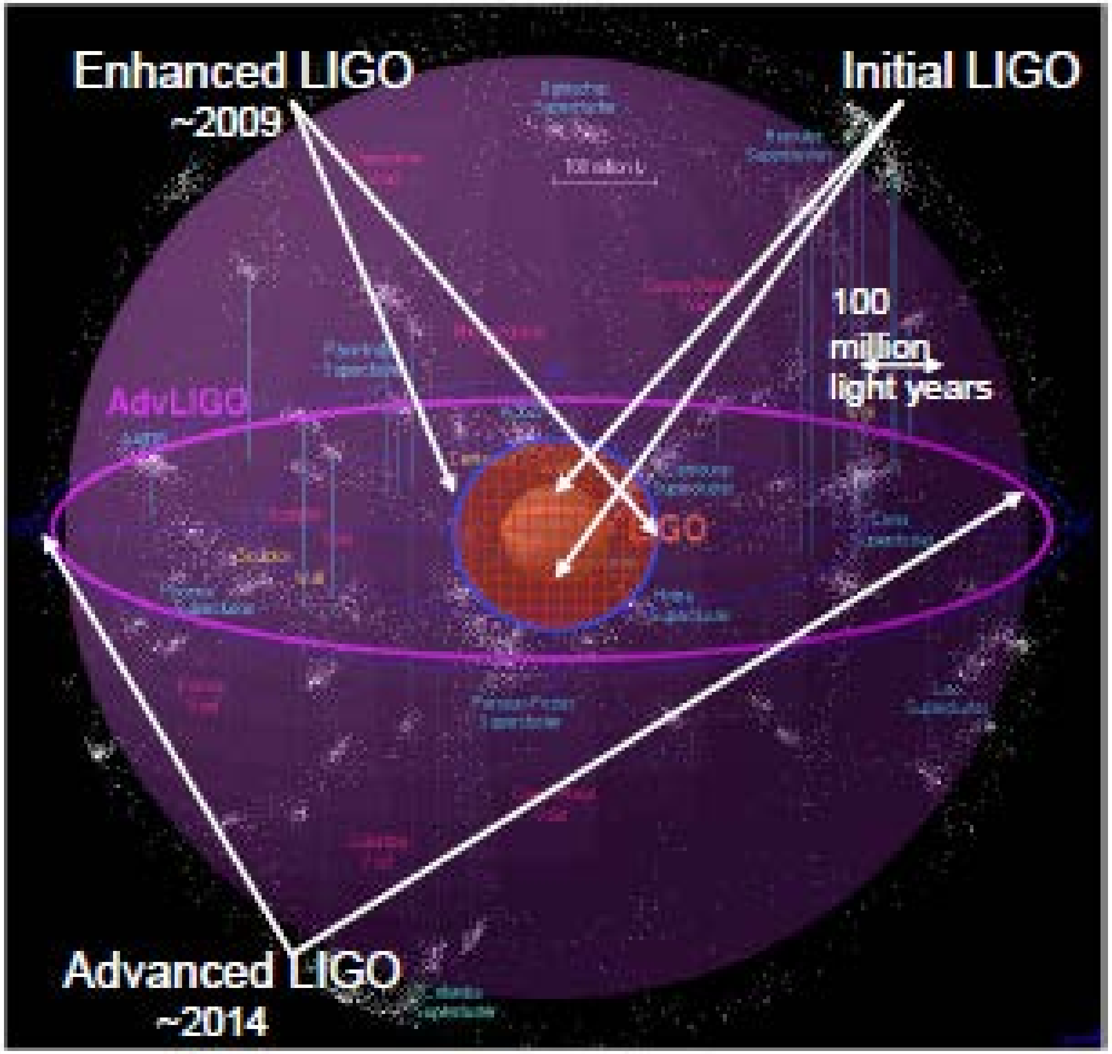
Advanced LIGO

- Major improvements relative to the Initial LIGO (2005-2010).
- Keep the same facilities, but redesign all subsystems.
  - » Improving sensitivity over the whole frequency range.
- Increased 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.



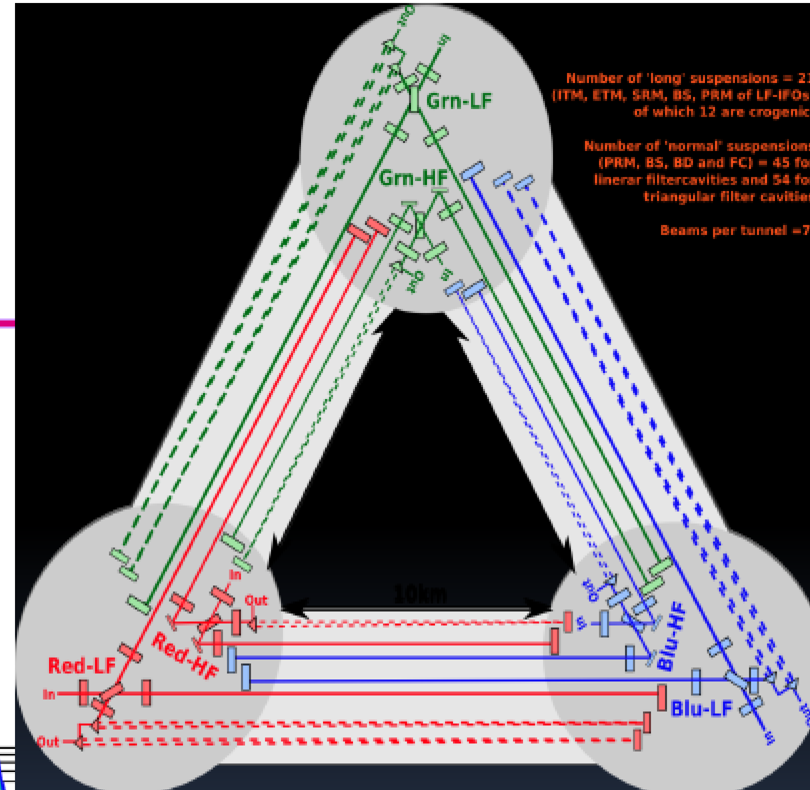
Advanced LIGO

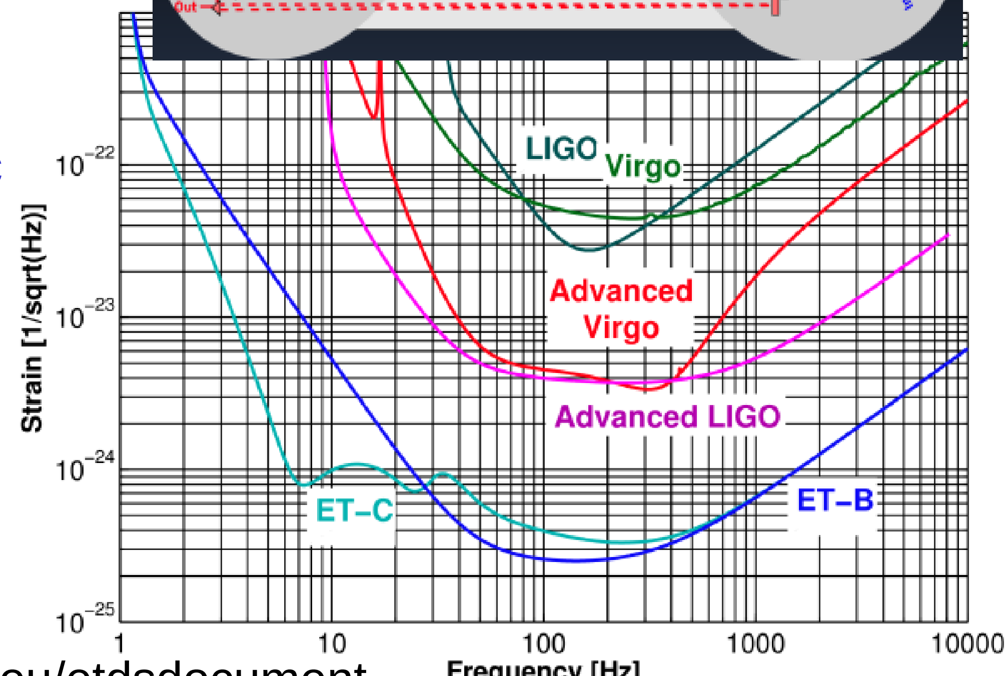
- Significant (10x) improvements in sensitivity.
- Can observe 10x further.
- ~1000x larger accessible volume, ~1000x more possible sources.
- Already running, data rolling in!



Einstein Telescope

- EU funded a design study to define the scientific scope and conceptual design of a third-generation detector.
- Xylophone concept: several detectors, focusing on different frequency bands.
- 10km arms, triangle configuration.
- Underground to improve on seismic and Newtonian noise.
- Novel optical configurations, squeezing, more powerful laser (500W).
- Cryogenic mirrors, novel coatings, larger beams to reduce thermal noise.

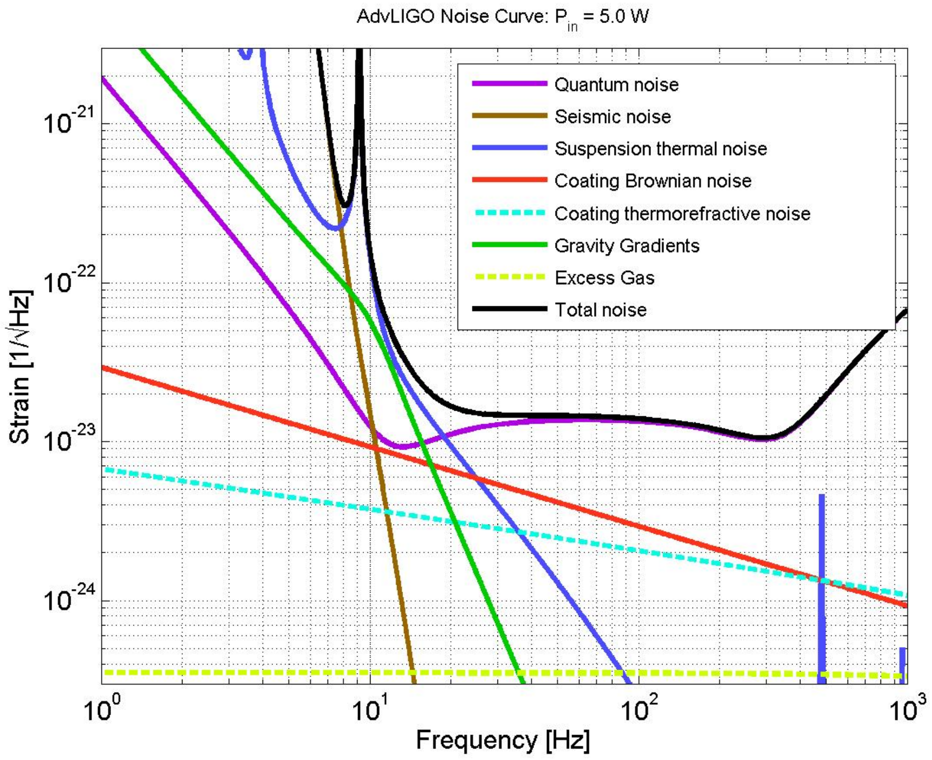




http://www.et-gw.eu/etdsdocument

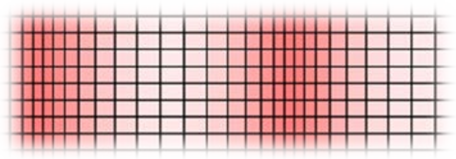
Beyond Advanced LIGO

- Newtonian noise limits sensitivity below 10 Hz.
  - » Fluctuations in the local gravity.
- Underground may be better:
  - » Seismic motion is smaller.
  - » No atmospheric fluctuations, very stable environment.
  - » No people.
- This has never been quantified!

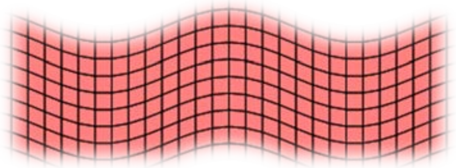


Newtonian Noise due to Seismic Noise

- Seismic noise generates fluctuations in the local gravitational field, via two main mechanisms.



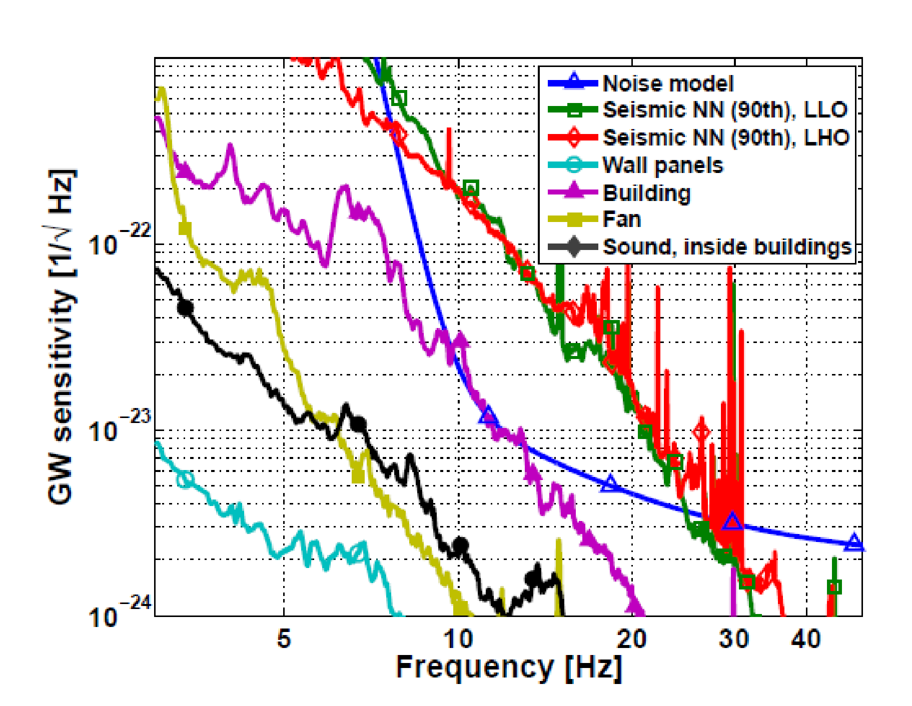
- Density perturbations:
  - Caused by body pressure waves.
  - Caused by P-component of surface waves (suppressed with depth).



- Dragging effects, produced at interfaces:
  - Surface and body waves at the surface (suppressed with depth).
  - P and S body waves at the cavity surface.

Newtonian Noise due to Seismic Noise

- Need better understanding of the seismic wave field.
- Array measurements done at LIGO sites to get better estimates.
  - Assuming the entire wave field dominated by Rayleigh surface waves.
  - Do we need underground seismometers?
- Underground:
  - Modal content and directionality matters even more.
  - How large should the seismic array be? What configuration?



Driggers, Harms, Adhikari, Phys. Rev. D 86, 102001 (2012)

Measure the seismic field better. Develop simulations of NN for the given seismic field.

Data Analysis Directions

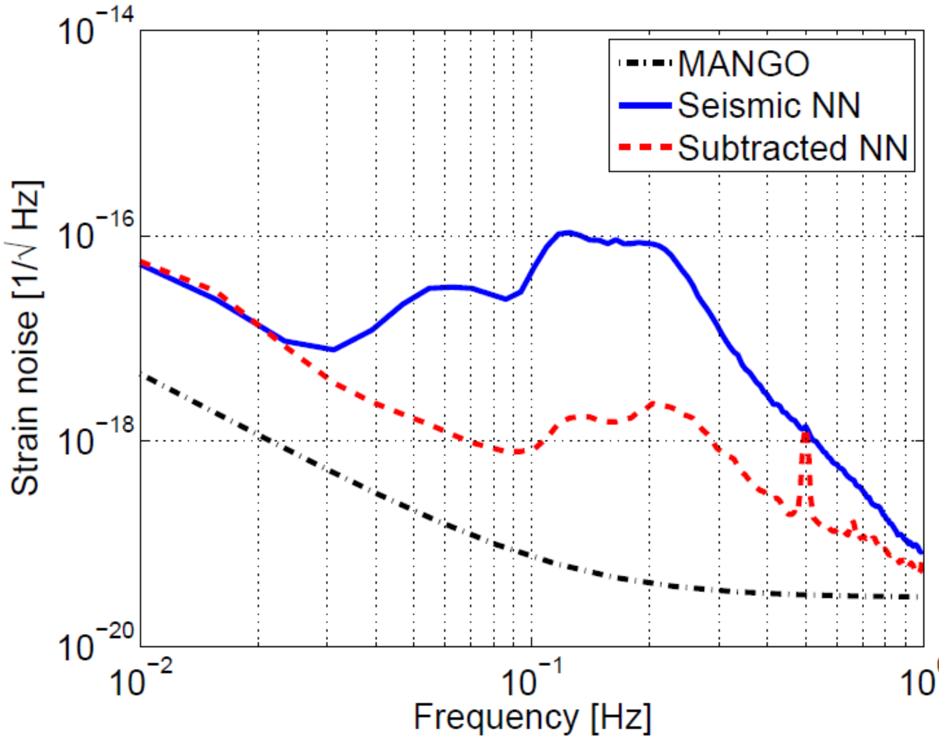
- Two main directions we would like to pursue.

- Wiener filtering:
  - » Don't need to understand the seismic wave field composition/model, but try to measure it sufficiently well.
  - » Then you can directly subtract "seismic" contributions to the GW channels.
  - » Can do this already for aLIGO.

- Estimate the seismic wave field composition.
  - » Combine with a model to estimate the corresponding Newtonian Noise.
  - » Use this to inform the design of future detectors.

Wiener Filtering

- Use two seismometers to predict (and subtract) the seismic signal at the third seismometer.
- ~50x suppression across the microseismic peak.
- Relatively robust:
  - » Different time-scales
  - » Different depths
- Plan to repeat the study with the larger array.
  - » Will hear from Michael and Jan about this on Sunday.



M. Coughlin et al, CQG 31, 2014, 215003.

Estimating Seismic Field Composition

- In general, the seismic wave field is complex.
- Pressure (P) waves are longitudinal and fastest.
- Shear (S) waves are transverse, a bit slower, and have two polarizations.
- Surface waves are a complicated composition of P- and S-waves, whose amplitude exponentially decays with depth.
- Scattering and reflection leads to mixing of different modes.

$$
\begin{aligned}
\vec{s}(\vec{x},t) &= \sum_A \int df\, d\hat{\Omega}\; S_A(f,\hat{\Omega})\; \vec{e}_A(\hat{\Omega})\; e^{2\pi i f(t-\hat{\Omega}\cdot\vec{x}/v_s)} \\
\vec{p}(\vec{x},t) &= \int df\, d\hat{\Omega}\; P(f,\hat{\Omega})\; \hat{\Omega}\; e^{2\pi i f(t-\hat{\Omega}\cdot\vec{x}/v_p)} \\
\vec{r}(\vec{x},t) &= \int df\, d\hat{\Omega}\; e^{-z/\alpha}\; R(f,\hat{\Omega})\; e^{2\pi i f(t-\hat{\Omega}\cdot\vec{x}/v_r)} \left(\hat{\Omega} + \epsilon \hat{z} e^{i\pi/2}\right)
\end{aligned}
$$

Estimating Seismic Field Composition

- Adapting the radiometer algorithm from the gravitational-wave field.
- Use cross correlations between different seismometers/channels to optimally estimate directional content.

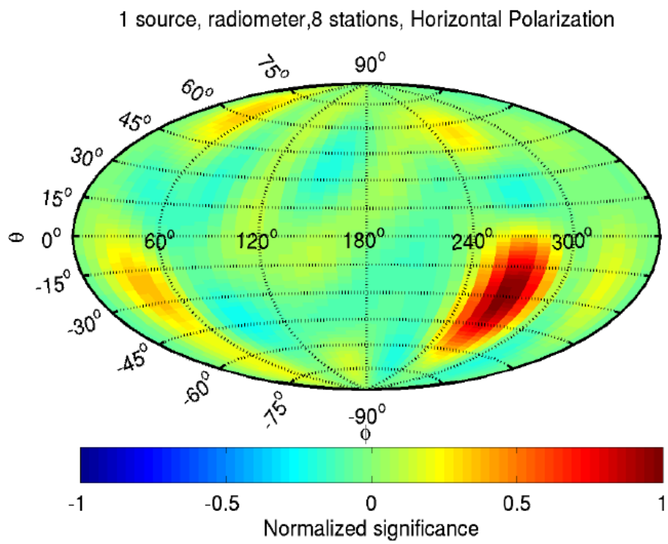
$$H(\hat{\Omega}) = \sum_d S_d Q_d(\hat{\Omega})$$

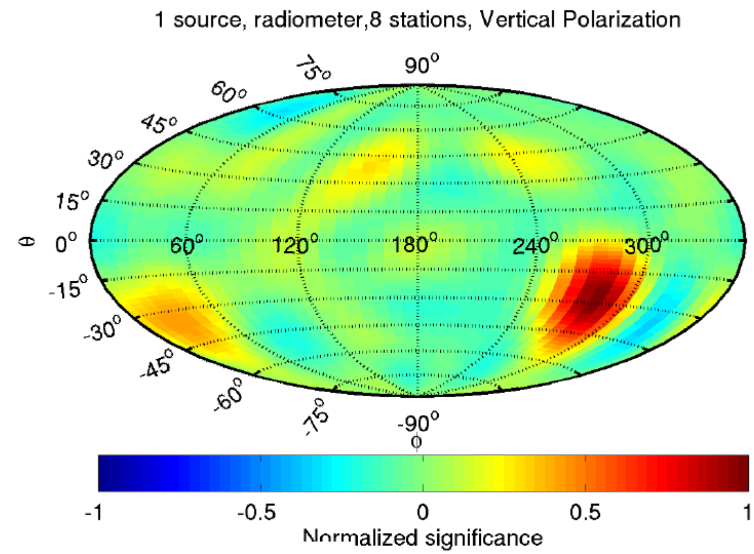
$$\langle Y_{aibj} \rangle = \sum_d S_d \gamma_d$$

$$\begin{aligned}
\gamma_{S1a} &= \int d\hat{\Omega}\; Q_a(\hat{\Omega}) e_{1,\alpha}(\hat{\Omega}) e_{1,\beta}(\hat{\Omega}) e^{2\pi i f \hat{\Omega}\cdot\Delta\vec{x}/v_s} \\
\gamma_{S2a} &= \int d\hat{\Omega}\; Q_a(\hat{\Omega}) e_{2,\alpha}(\hat{\Omega}) e_{2,\beta}(\hat{\Omega}) e^{2\pi i f \hat{\Omega}\cdot\Delta\vec{x}/v_s} \\
\gamma_{Pa} &= \int d\hat{\Omega}\; Q_a(\hat{\Omega}) \Omega_\alpha \Omega_\beta e^{2\pi i f \hat{\Omega}\cdot\Delta\vec{x}/v_p}
\end{aligned}$$

$$\vec{S} = (\gamma^{T*}\gamma)^{-1}\gamma^{*}\vec{Y}$$

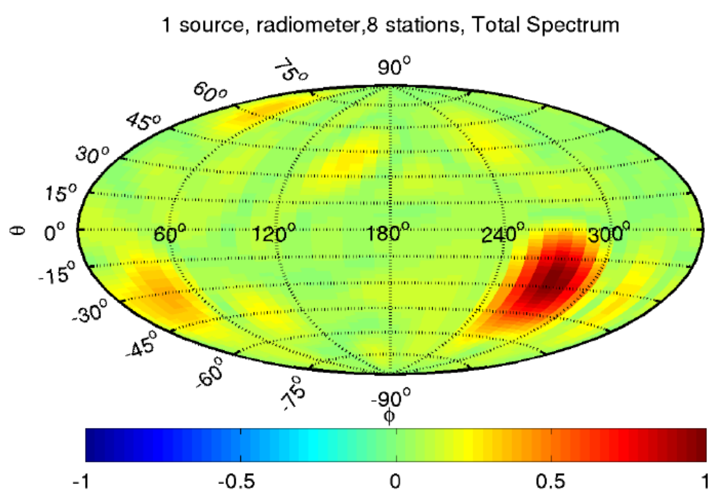
Seismic Radiometer Simulations





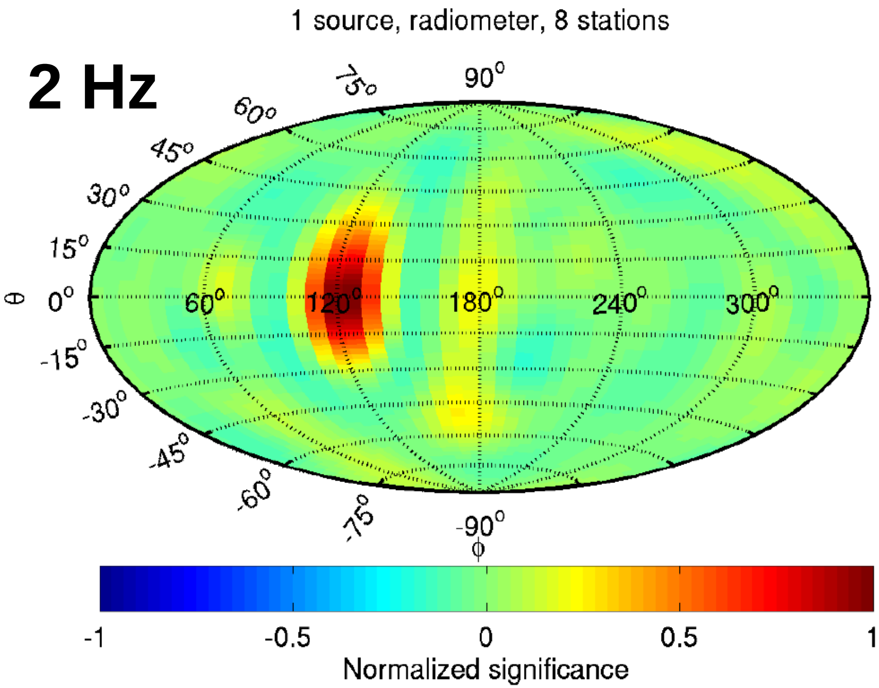
S-wave recovery:

- 2 Hz wave
- 45 degree polarization
- 8 detectors
- Randomly spaced in a cubic kilometer.



Seismic Radiometer Simulations

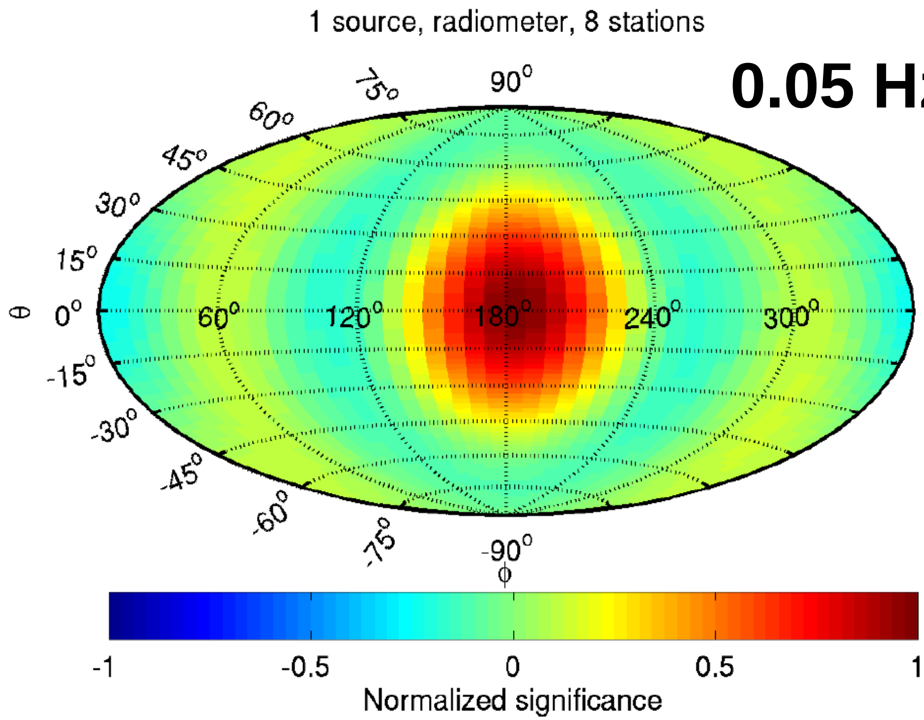
2 Hz



Simulated surface wave recovery:

- Assuming 500m decay length.
- 8 detectors spanning cubic kilometer.

0.05 Hz



Interesting dependence on:

- Frequency.
- P- vs S- content.
- Decay length.
- Seismometer array configuration.

What do we hope to get from the workshop?

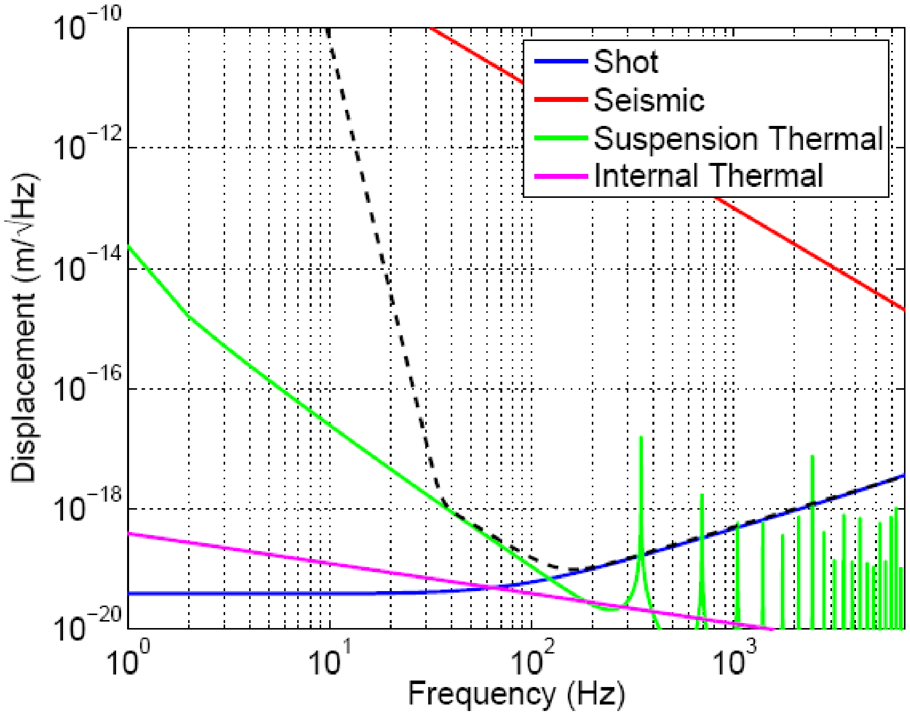
- Better understanding of the seismic waves:
  - » Speed for different modes
  - » Speed anisotropy
  - » What is the appropriate model for the Rayleigh field?
  - » Depth dependence of the Rayleigh waves
  - » P and S "content" of the Rayleigh waves

- Would like to develop/test the radiometer algorithm.
  - » Potentially something new we could give to the geophysics

- Compare radiometer with existing techniques.
  - » What are the best techniques to use?
  - » Compare limitations and performance in different situations…

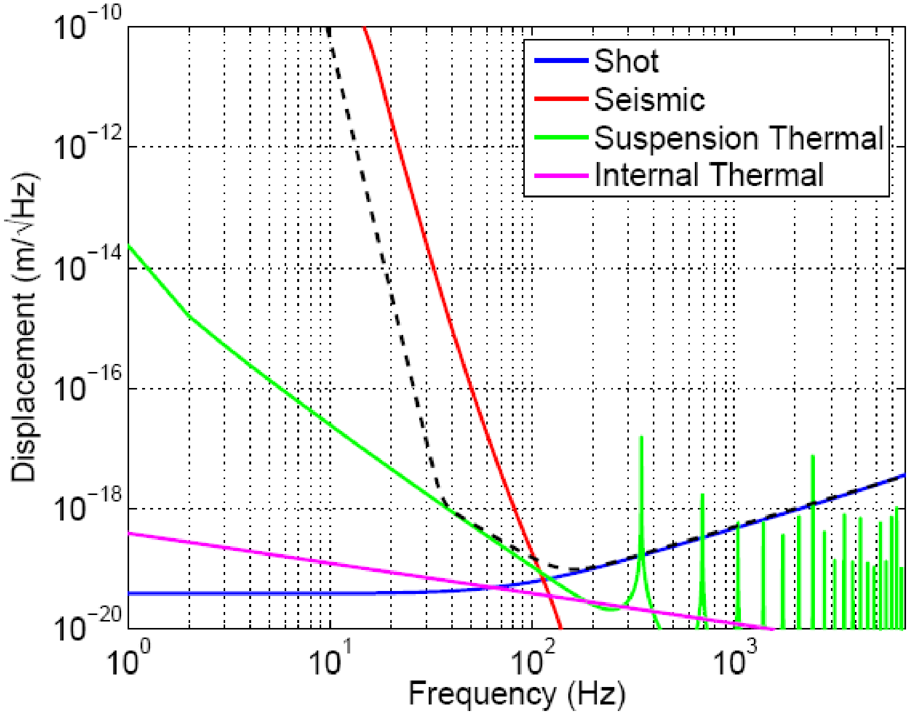
LIGO Sensitivity

- Seismic Noise



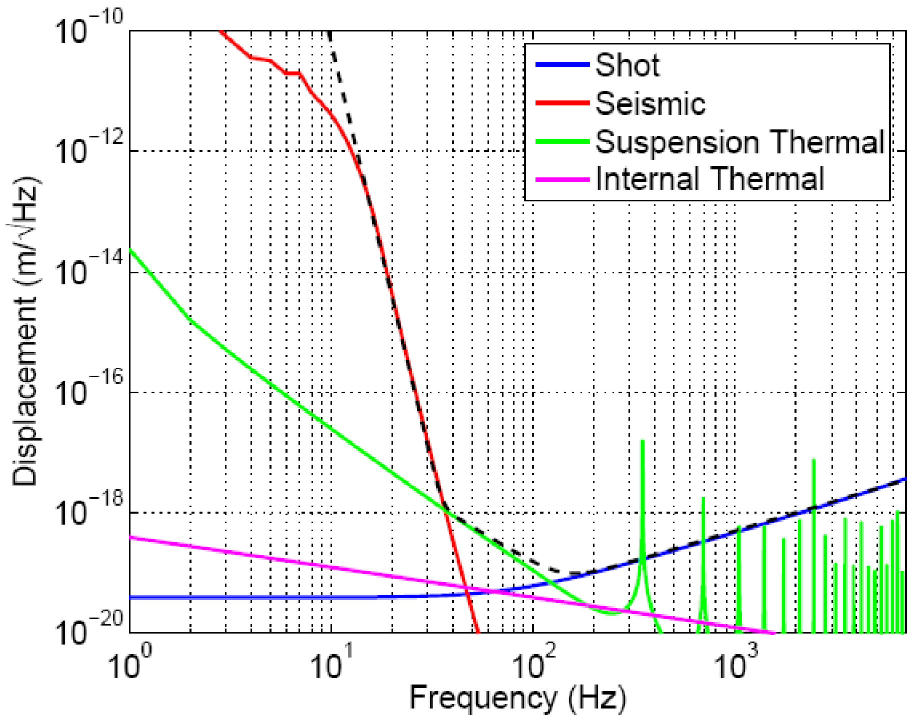
LIGO Sensitivity

- Seismic Noise
  - » Active and passive isolation



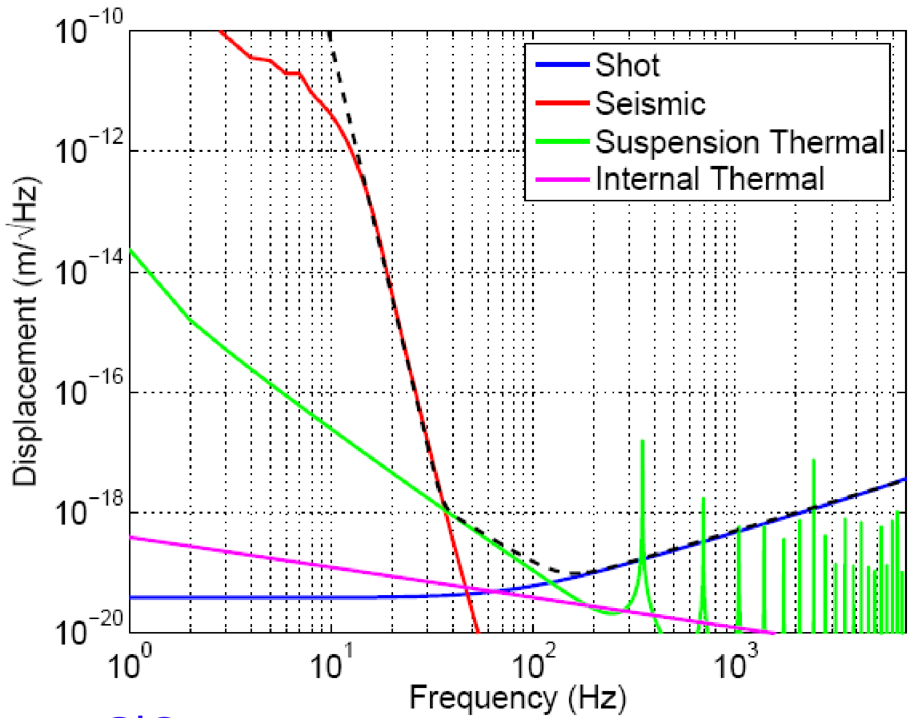
LIGO Sensitivity

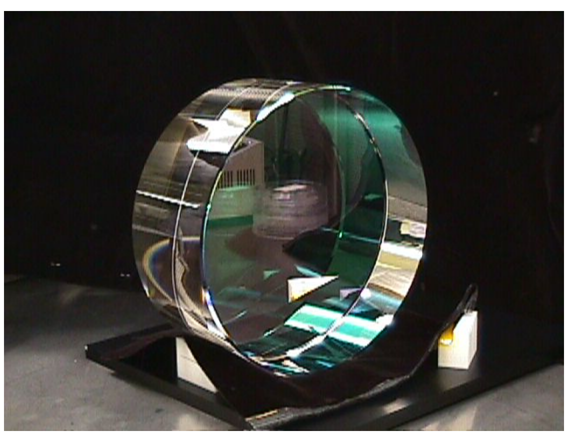
- Seismic Noise
  - » Active and passive isolation
  - » Suspensions
  - » Effective "Seismic Wall" at 40 Hz



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
- Shot noise (>150 Hz)





- Substrates: SiO_2
  - » 25 cm Diameter, 10 cm thick
  - » Internal mode Q's > 2 x 10^6
- Polishing
  - » Surface uniformity < 1 nm rms (λ / 1000)