Searching for Stochastic Gravitational-Wave Background with LIGO

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for the LIGO Scientific Collaboration

Fermilab, 08/06/12

Outline

- Gravitational Waves
  - » Sources
  - » Detectors

- Searches for stochastic background of gravitational waves using LIGO data

- Outlook for the future:
  - » Advanced LIGO

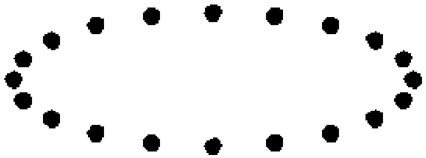
Gravitational Waves

- 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:

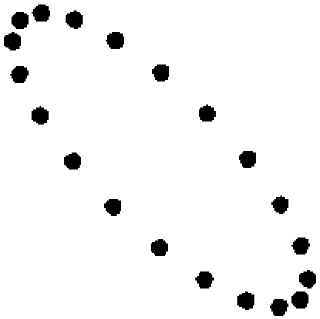
$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)h_{\mu\nu} = 0$$

- Two polarizations: $h = ah_+ + bh_\times$ $a,b \sim f(\omega t - \mathbf{k}\cdot\mathbf{x})$

“+”



“x”



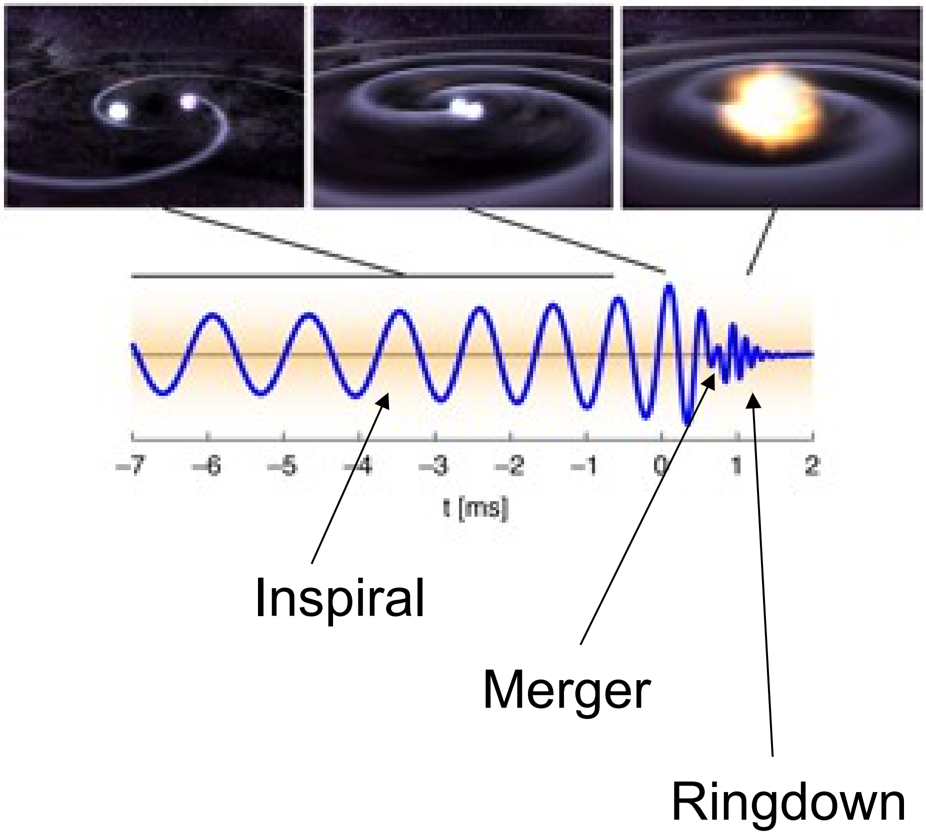
Sources of Gravitational Waves

- Transient sources, typically 1-sec long (or less):
  - » Compact binary coalescences
  - » Bursts: transient emissions during Supernovae, GRBs…
- Continuous sources:
  - » Periodic sources: pulsars
  - » Stochastic sources: cosmological and astrophysical
- New search: long-lasting transients.
  - » Time-scale of minutes, hours, or days
- Unexpected?

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.

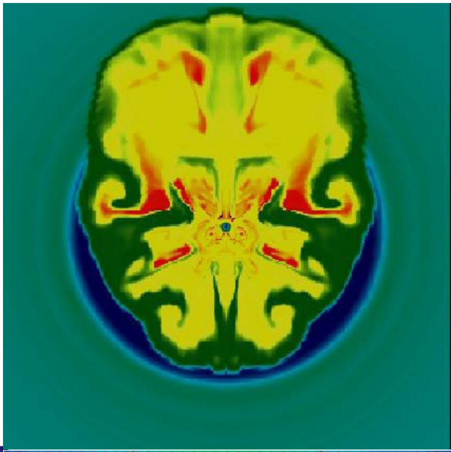
R. Spero

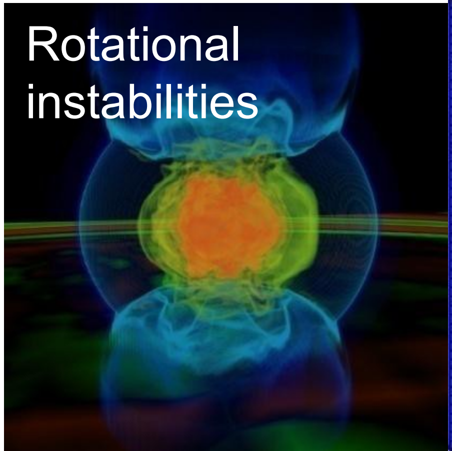


Bursts

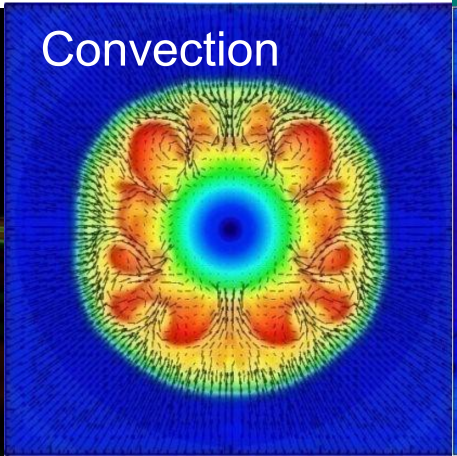
- Many potential transient sources:
  - » Supernovae: probe the explosion mechanisms.
  - » Gamma Ray Bursts: collapse of rapidly rotating massive stars or neutron star mergers.
  - » Pulsar glitches: accretion.
  - » Cosmic strings cusps.
- Models are ok, but not essential:
  - » Search for power excess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

Aspherical outflows

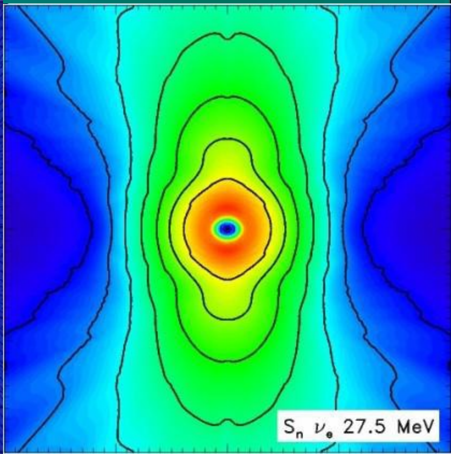




Rotational instabilities



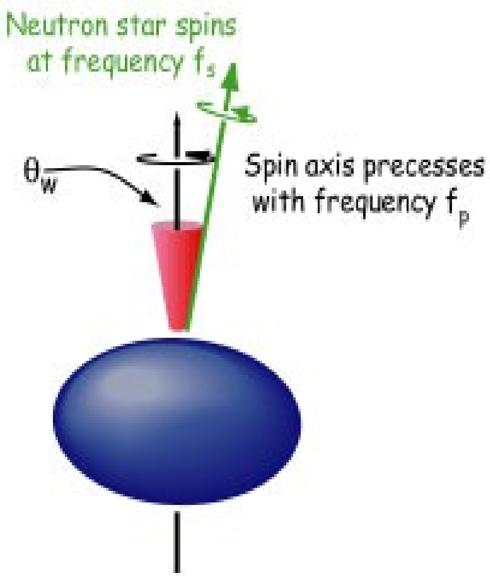
Convection



C. Ott

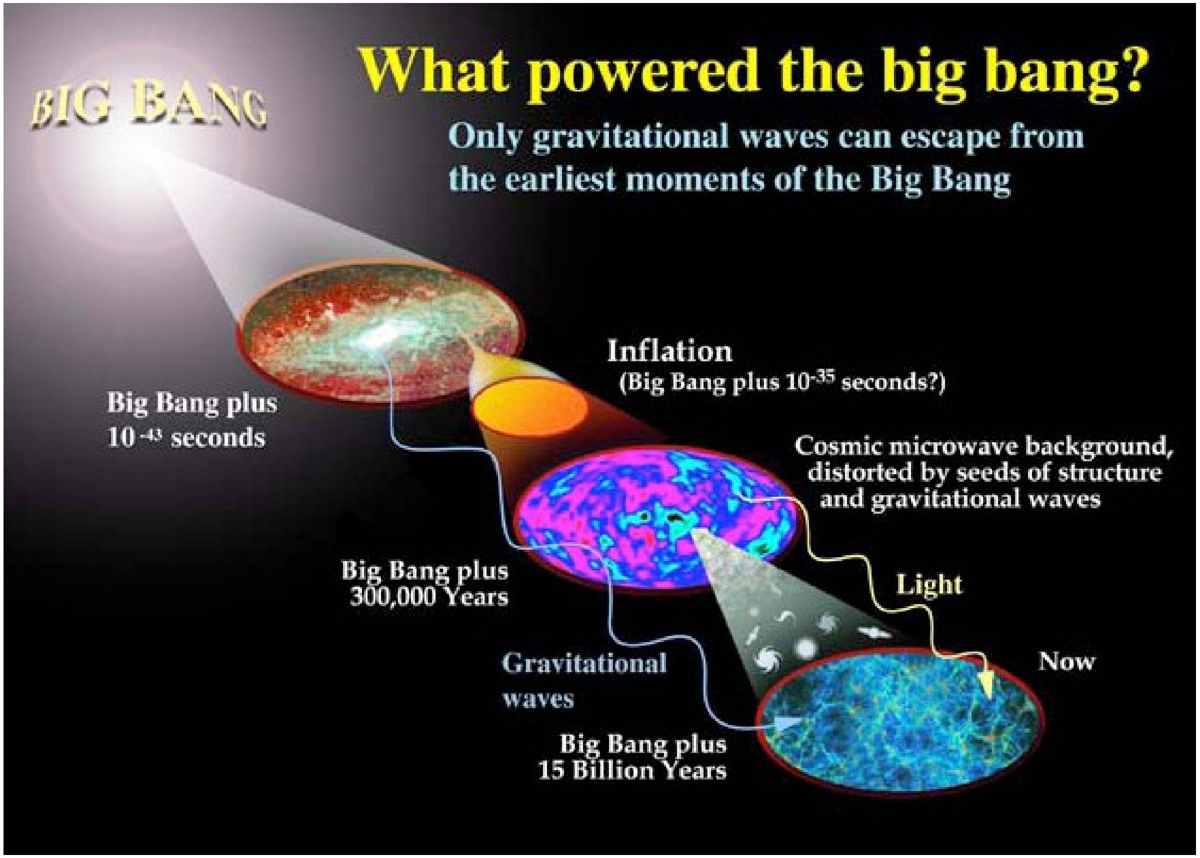
Sources: Periodic

- Pulsars with mass non-uniformity:
  - » Small "mountain".
  - » Density non-uniformity.
  - » Dynamic processes inside neutron star, leading to various instabilities.
- Produce gravitational-waves 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.



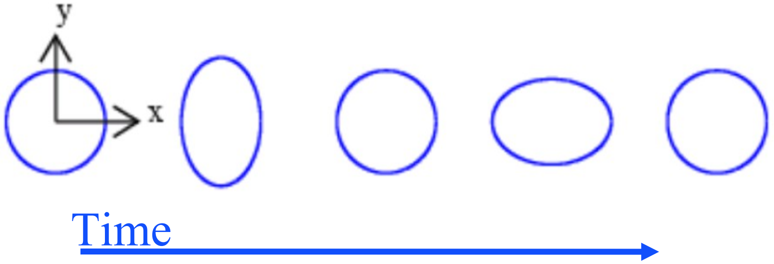
Sources: Long Transients

- New category of sources, received much attention recently.
  - » Tens of seconds or longer.
- Long GRBs (Piro & Pfahl):
  - » In-falling material circularizes and falls into the black hole via an accretion disk.
  - » Strong cooling from helium photodisintegration leads to disk fragmentation, and GWs.
- Magnetars:
  - » ~10% of neutron stars, strong magnetic fields (10^{14} – 10^{16} G).
  - » B-field/accretion can induce tri-axial deformation – GWs.

A. Pyro

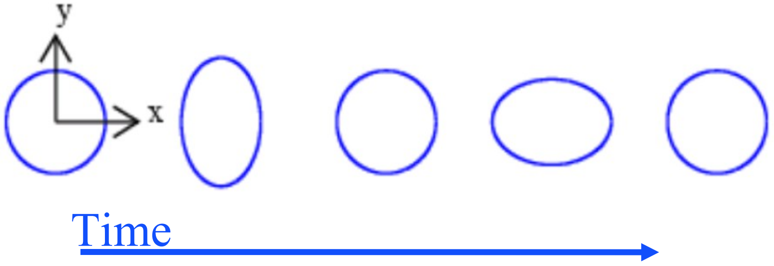
Interferometers as Gravitational Wave Detectors

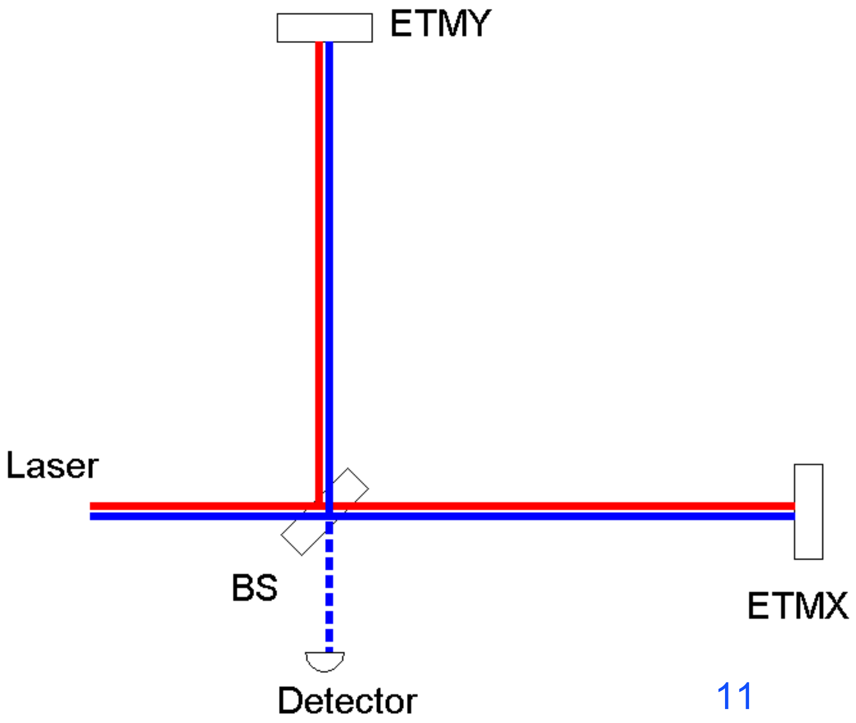
- Gravitational wave effectively stretches one arm while compressing the other.



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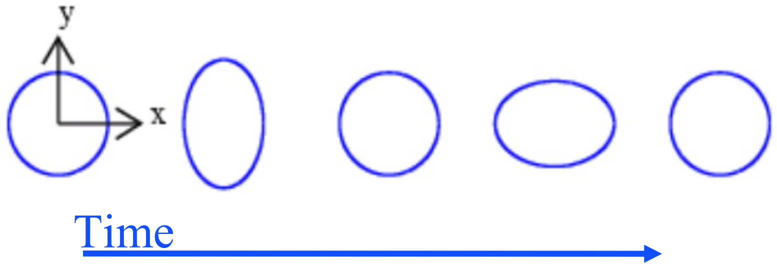
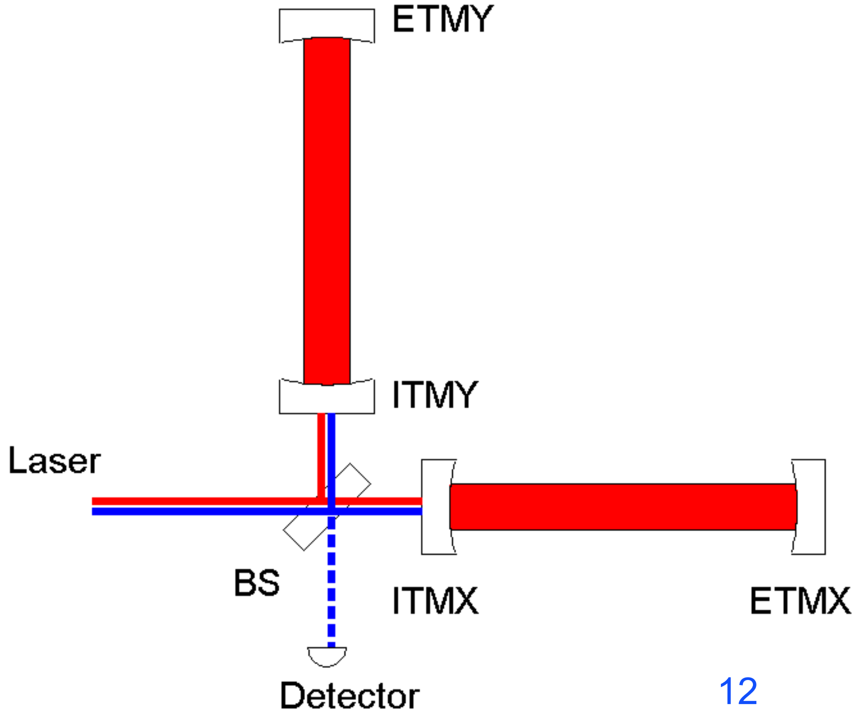
- Fabry-Perot cavities in the arms
  - » Effectively increase arm length ~100 times.





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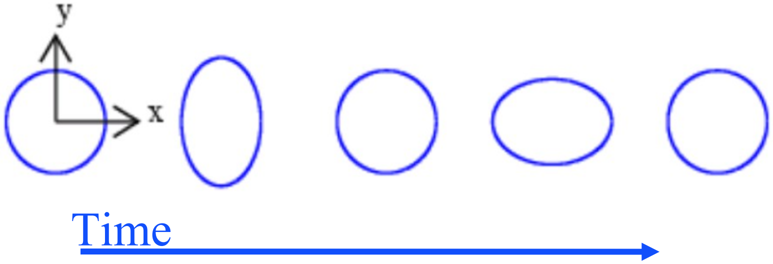
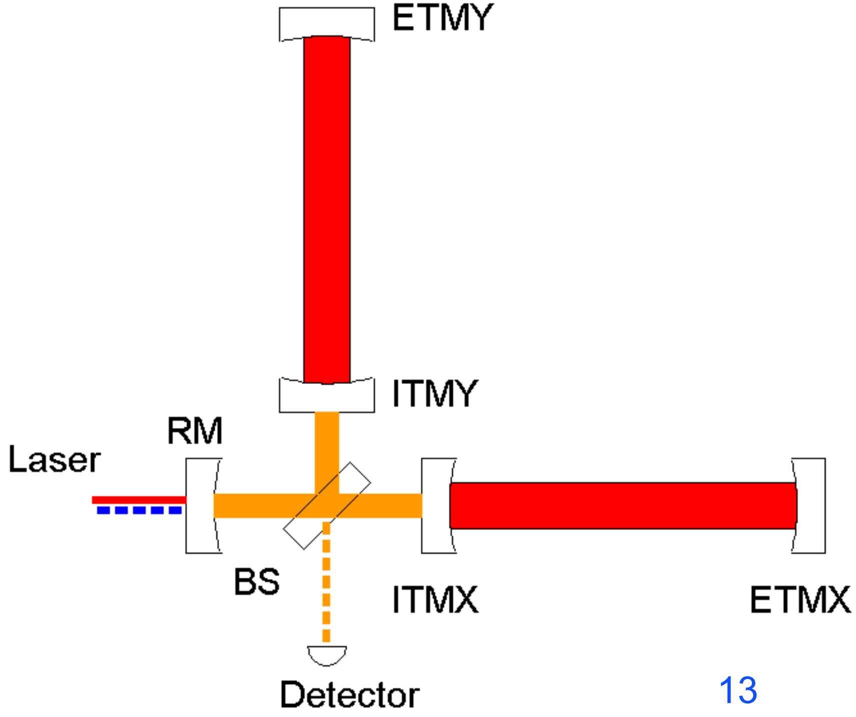
- Fabry-Perot cavities in the arms
  - » Effectively increase arm length ~100 times.
- Power-recycling mirror
  - » Another factor of ~40 in power.





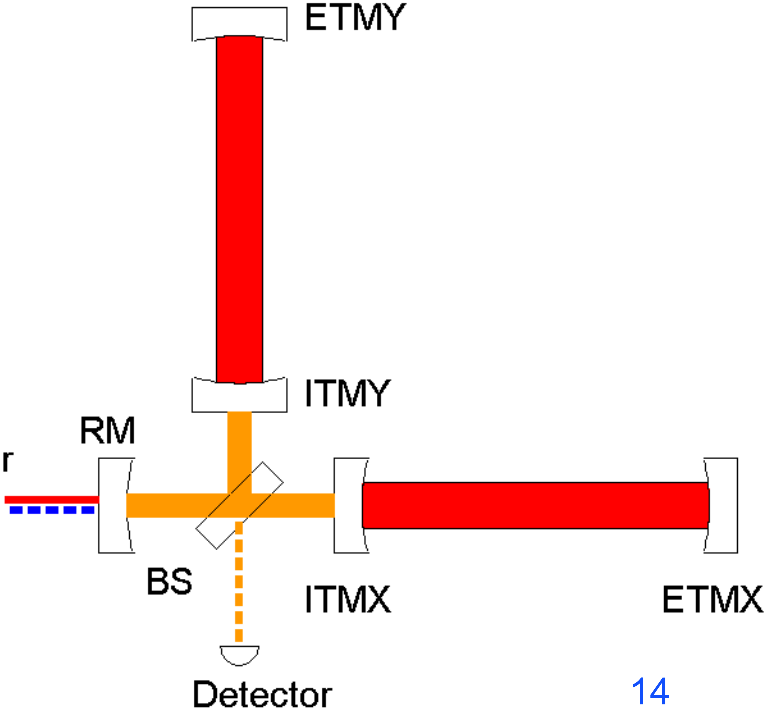
Back-of-the-Envelope Sensitivity

- Rough sensitivity estimate
  - Input laser power: ~5 Watt
- Sensitivity (ΔL) ~ λ (~ 10^{-6} m)

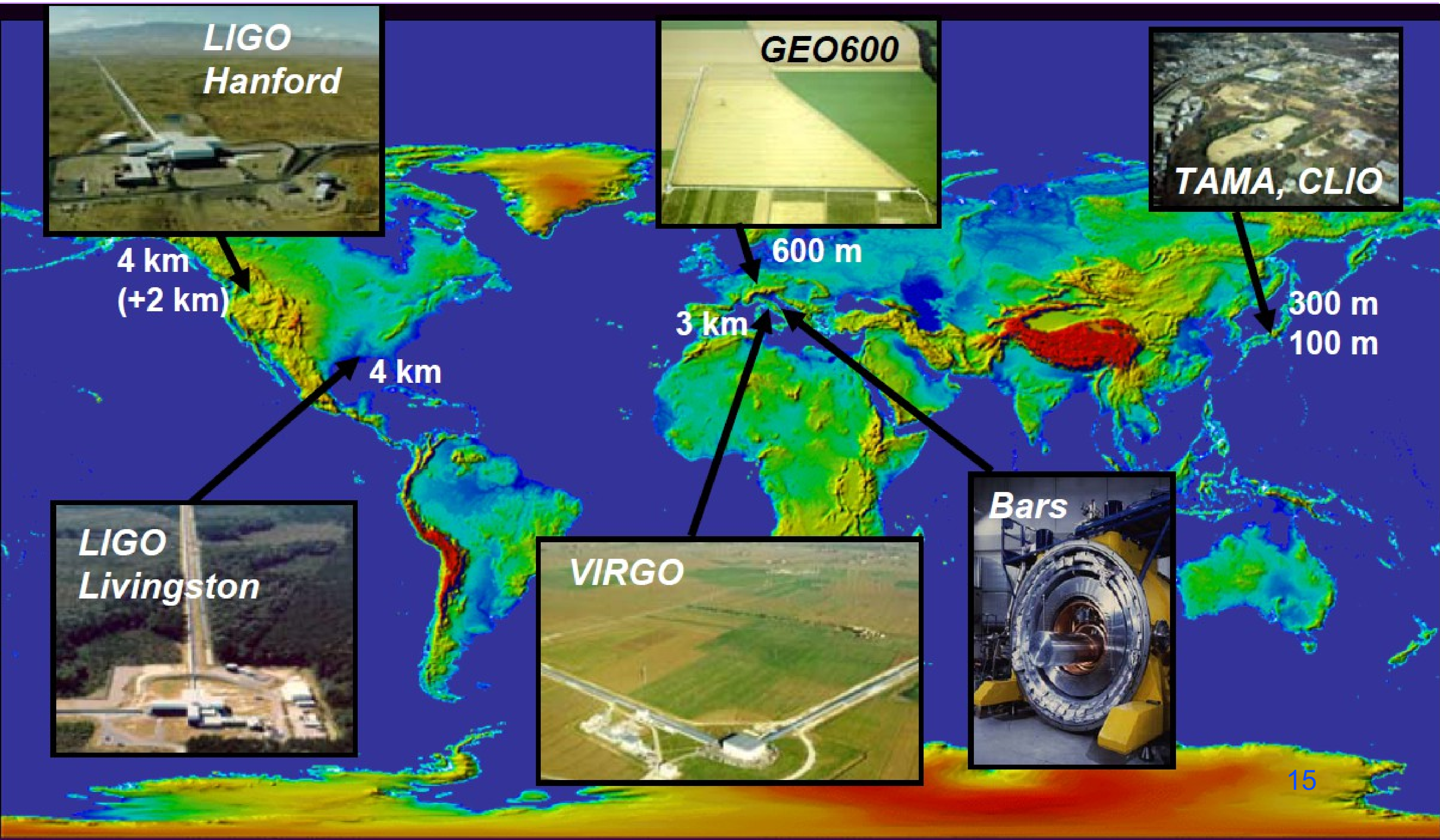
  / Number of Bounces in Arm (~100)

  / Sqrt(Number of Photons (~10^{21}))

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

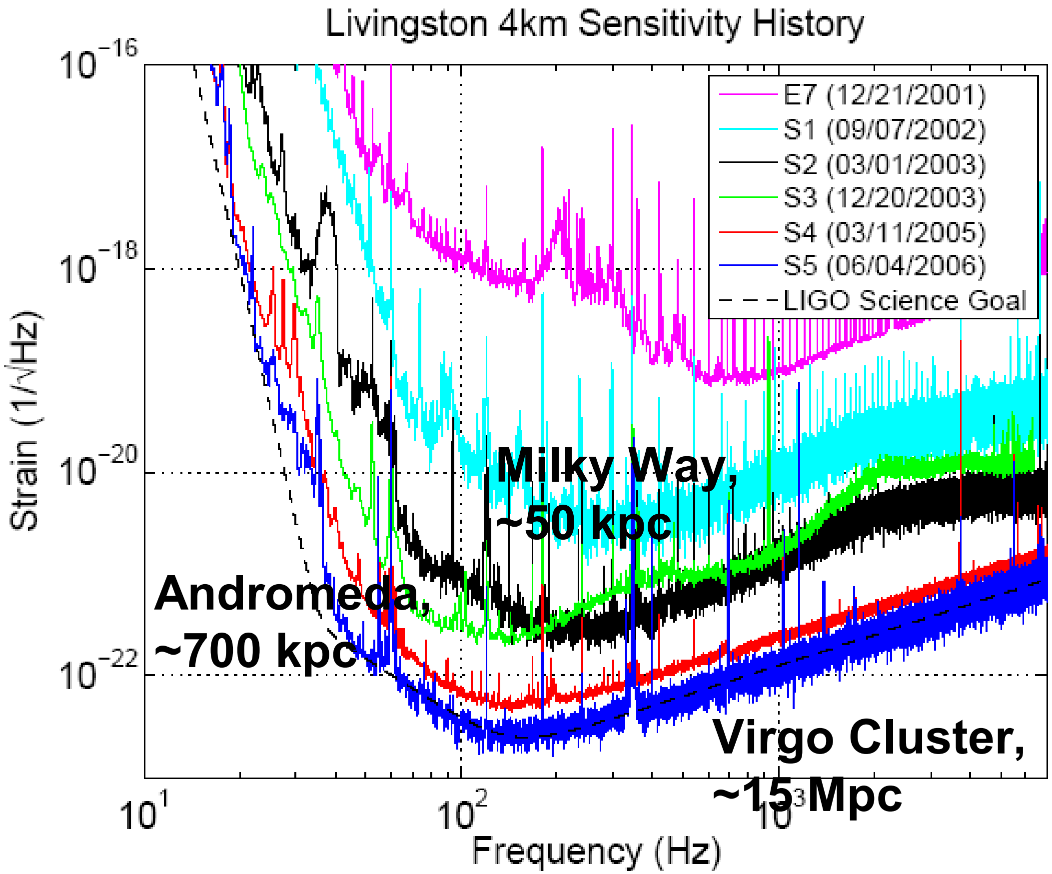


Network of Gravitational-Wave Detectors



Sensitivity History

- Substantial sensitivity improvements:
  - » 5 orders of magnitude in ~5 years.
- LIGO reached its design sensitivity in Nov. 2005.
- Science run at design sensitivity (S5) completed in Oct. 2007.
  - » 1 year of H1-L1-H2 coincident time.
- Data analysis still ongoing.
  - » Several results published.



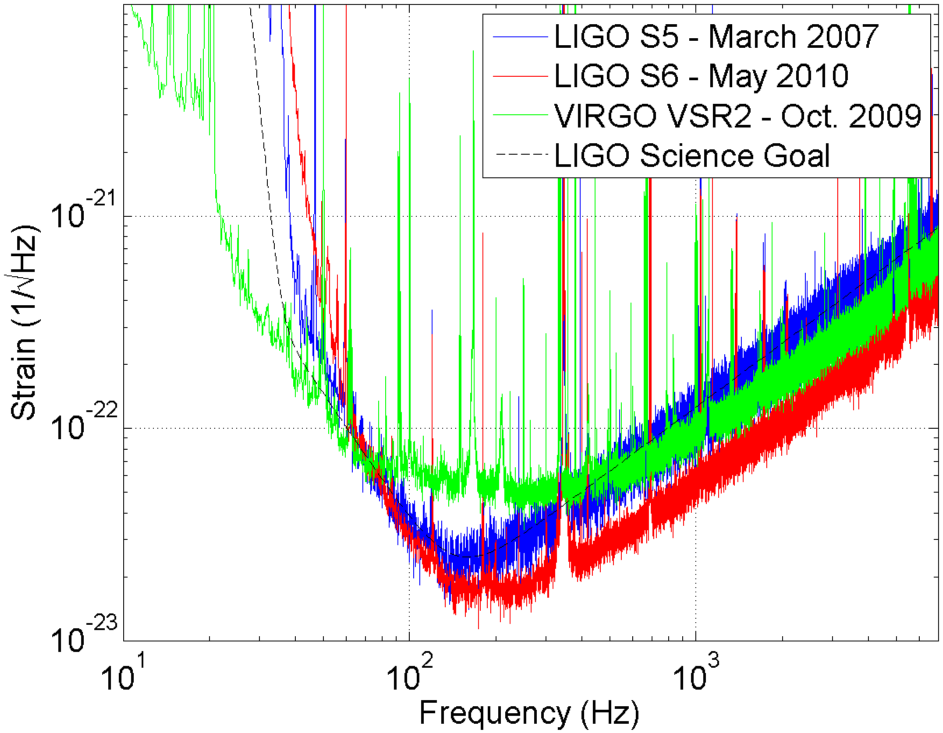
Milky Way, ~50 kpc

Andromeda, ~700 kpc

Virgo Cluster, ~15 Mpc

Enhanced LIGO

- In 2007-2008, upgraded 4km detectors H1 and L1.
  - More powerful laser.
  - Seismically isolated output mode cleaner.
  - New locking scheme.
- In 2009-2010, LIGO performed a new science run (S6) at improved strain sensitivity (Enhanced LIGO).
  - Much of it in coincidence with Virgo and GEO experiments.



Stochastic Background of Gravitational Waves

- Energy density:

$$\rho_{GW} = \frac{c^2}{32\pi G} < \dot{h}_{ab}\, \dot{h}^{ab} >$$

- Characterized by log-frequency spectrum:

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

- Related to the strain power spectrum:

$$S(f) = \frac{3H_0^2}{10\pi^2} \frac{\Omega_{GW}(f)}{f^3}$$

- Strain scale:

$$h(f) = 6.3 \times 10^{-22} \sqrt{\Omega_{GW}(f)} \left(\frac{100\ \mathrm{Hz}}{f}\right)^{3/2} \mathrm{Hz}^{-1/2}$$

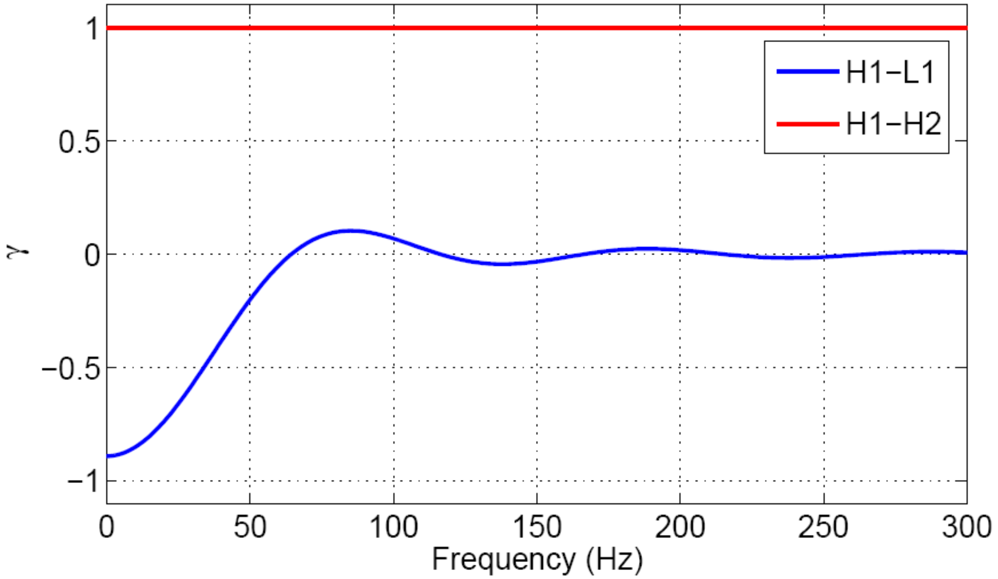
Detection Strategy

- Cross-correlation estimator

$$Y = \int_{-T/2}^{+T/2} dt_1 \int_{-T/2}^{+T/2} dt_2 \; s_1(t_1) \; s_2(t_2) \; Q(t_2 - t_1)$$

$$Y = \int_{-\infty}^{+\infty} df \; \tilde{s}_1^*(f) \; \tilde{s}_2(f) \; \tilde{Q}(f)$$

Overlap Reduction Function



- Theoretical variance

$$\sigma_Y^2 \approx \frac{T}{2} \int_0^{+\infty} df \; P_1(f) \; P_2(f) \; | \; \tilde{Q}(f) \; |^2$$

- Optimal Filter

$$\tilde{Q}(f) = \frac{1}{N} \; \frac{\gamma(f) \; \Omega_t(f)}{f^3 \; P_1(f) \; P_2(f)}$$

For template: $\Omega_t(f) = \Omega_\alpha (f/100 \text{ Hz})^\alpha$

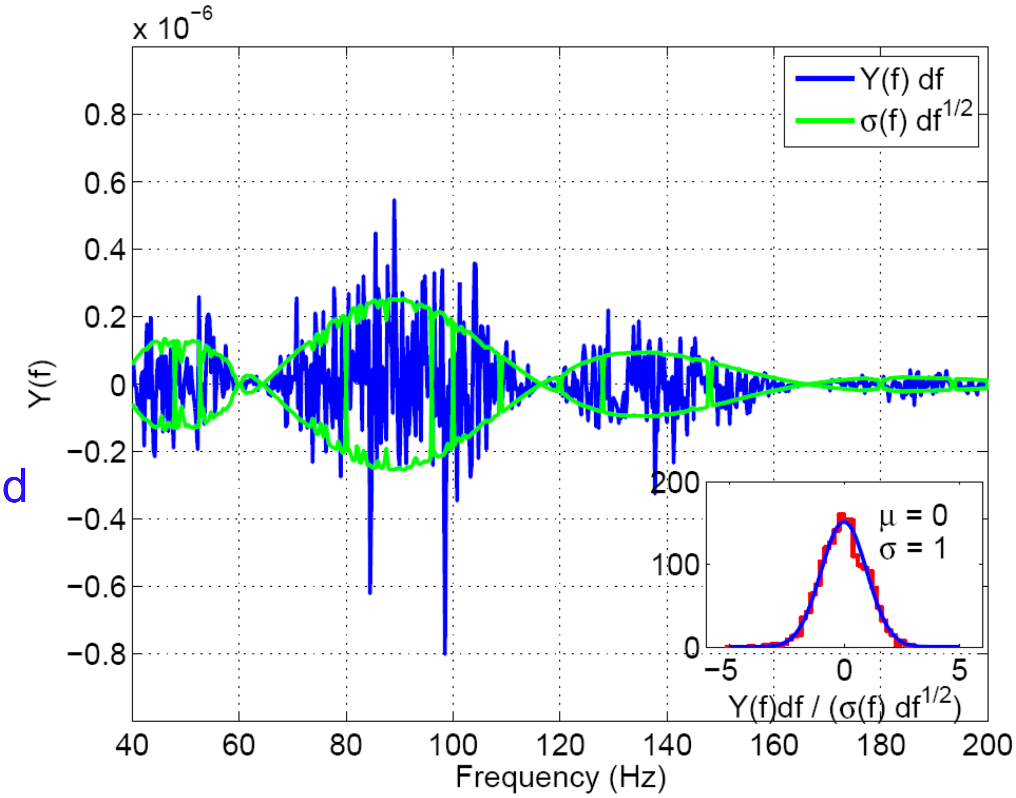
Choose *N* such that: $< Y >= \Omega_\alpha T$

S5 Result

- Use the entire S5 data-set.
  - 292 days of effective observing time.
- S5 LHO-LLO result:

$\Omega_0 \pm \sigma_\Omega = (2.1 \pm 2.7) \times 10^{-6}$

  - H_0 = 72 km/s/Mpc
- The frequency band is selected to include 99% of sensitivity, as measured by the integrand of σ^{-2}.
  - **41.5-169.25 Hz**
- Bayesian 95% UL:
  - Prior on Ω_0: S4 Posterior
  - Marginalize over calibration uncertainties
  - 95% UL: **6.9×10^{-6}**
- Beginning to constrain models of stochastic GW background.



Abbott et al, Nature 460, 990 (2009)

BBN and CMB Indirect Bounds

- Big-Bang Nucleosynthesis model and observations constrain the total energy at the time of BBN:

$$\Omega_{\rm BBN} = \int \Omega_{\rm GW}(f)\, d(\ln f) < 1.1 \times 10^{-5}\, (N_\nu - 3)$$

- Similar bound is derived from CMB observations.
- In the LIGO frequency band, this becomes:
  - » $\Omega_0^{\rm BBN} < 1.0 \times 10^{-5}$
  - » $\Omega_0^{\rm CMB} < 9.5 \times 10^{-6}$
- We have now surpassed these bounds.
  - » Important LIGO milestone!

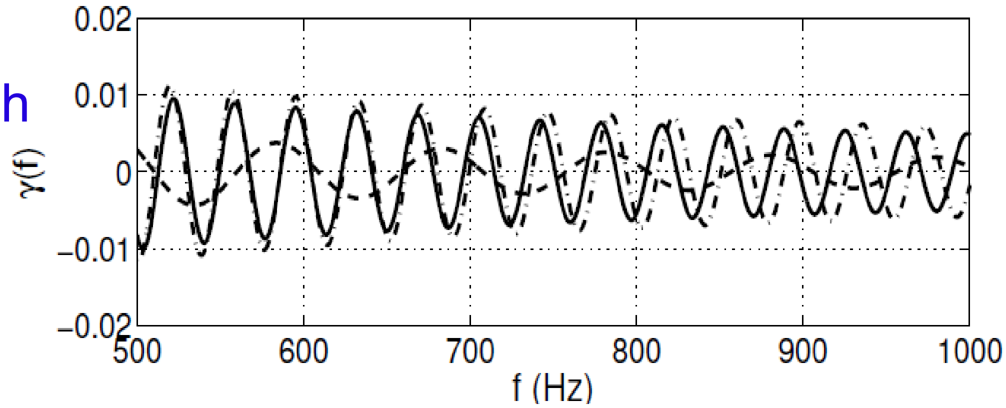
LIGO-Virgo High-Frequency Result

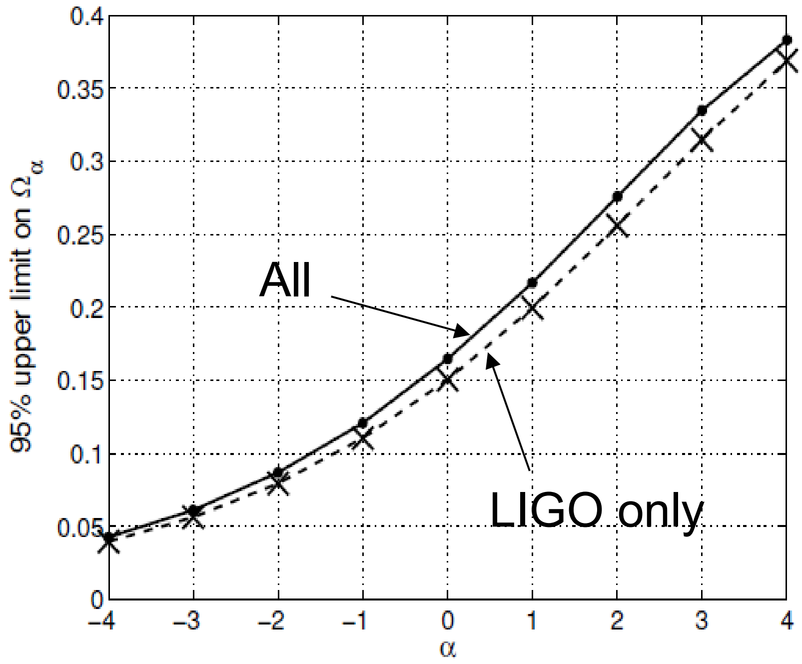
- Repeated a similar analysis at high frequencies: 600-900 Hz.

arXiv:1112.5004, to appear in PRD

- Data from LIGO S5 and Virgo VSR1 runs.
- Using all non-collocated LIGO-Virgo detector pairs.
- Overlap reduction is substantial, but still produced most sensitive measurement in this frequency band.

$\Omega_0 < 0.16$ (H1-H2-L1-V1)





Anisotropic Searches

- Measure from where (on the sky) the signal comes from.
  - » Time-delay between two detectors.
  - » Earth rotation breaks degeneracies for permanent signals.
- Redefine energy density:

$$\Omega_{\rm GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{\rm GW}}{df} = \frac{2\pi^2}{3H_0^2} f^3 \int_{S^2} d\hat{\Omega}\, \mathcal{P}(f,\hat{\Omega})$$

- Point source (radiometer) search: $\mathcal{P}(\hat{\Omega}) \equiv \eta(\hat{\Omega}_0)\, \delta^2(\hat{\Omega},\hat{\Omega}_0)$

- Spherical harmonic decomposition (similar to CMB analyses):

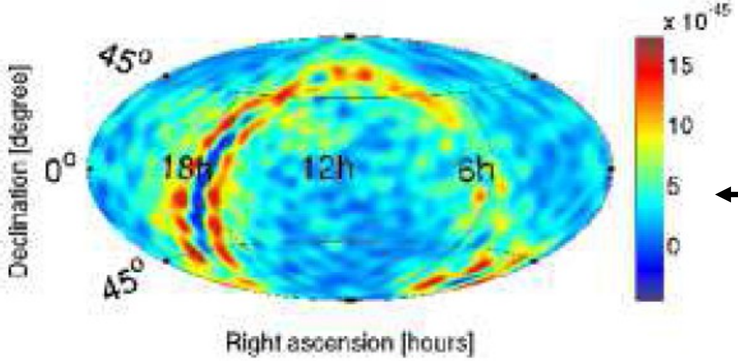
$$\mathcal{P}(\hat{\Omega}) \equiv \sum_{lm} \mathcal{P}_{lm} Y_{lm}(\hat{\Omega})$$

Anisotropic Signal Simulations

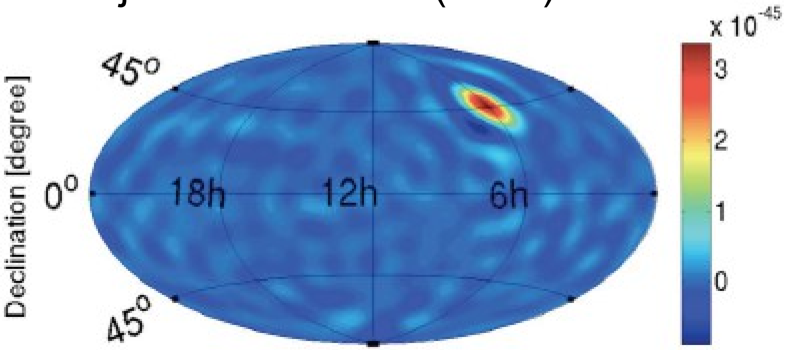
Anisotropic stochastic signal added to the data (in software or hardware) and successfully recovered.

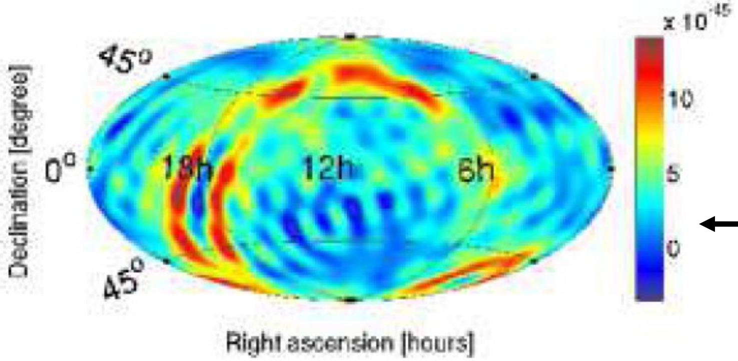
WMAP map added to data in software
E. Thrane et al, Phys. Rev. D 80, 122002 (2009).

Point source simulation in hardware
M. Pihlaja’s M.S. Thesis (2011).

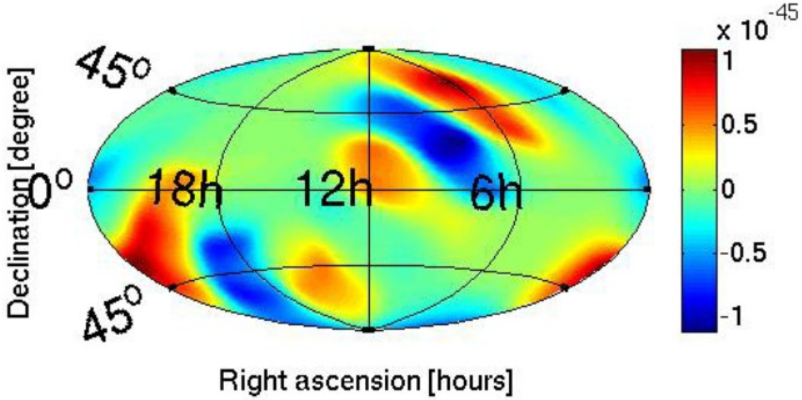


Injected



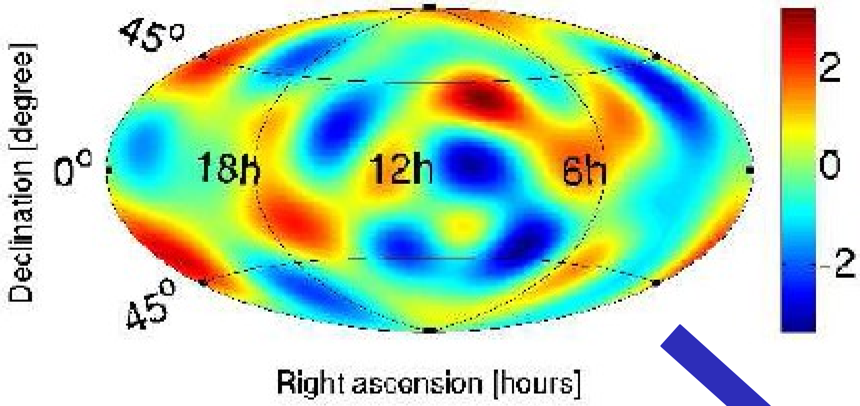


Recovered

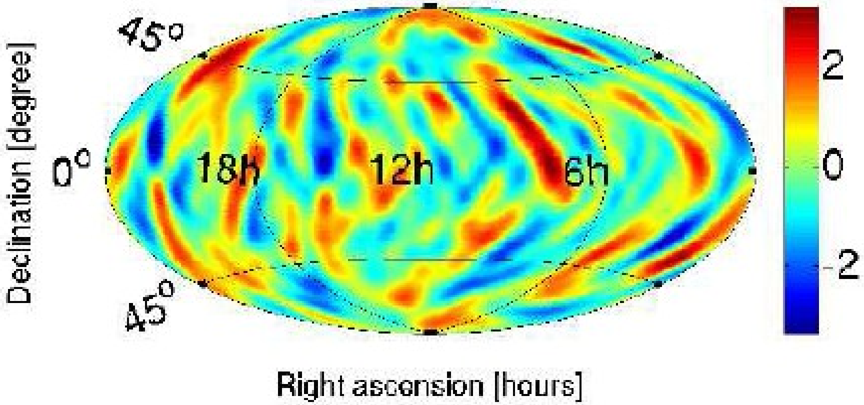


Anisotropic Searches with LIGO S5 Data

SNR Map
Spherical Harmonics Search
Template: Ω_{GW} = const
Maximum SNR significance: 25%

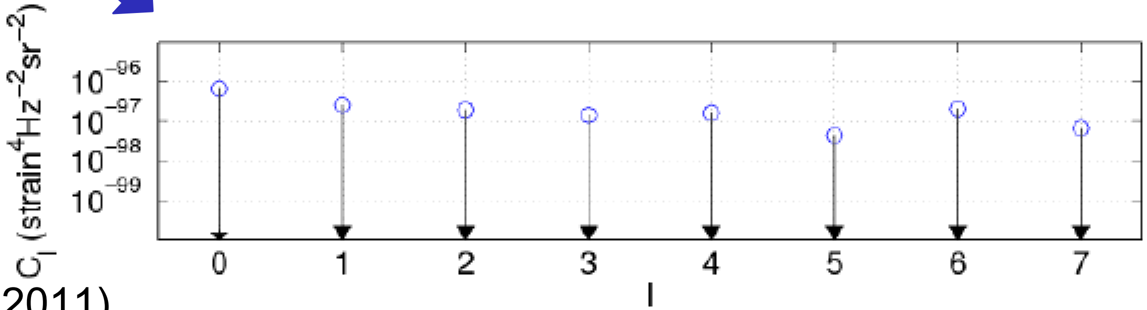


SNR Map
Radiometer Search
Template: strain = const
Maximum SNR significance: 53%



90% CL Upper Limit on C_l

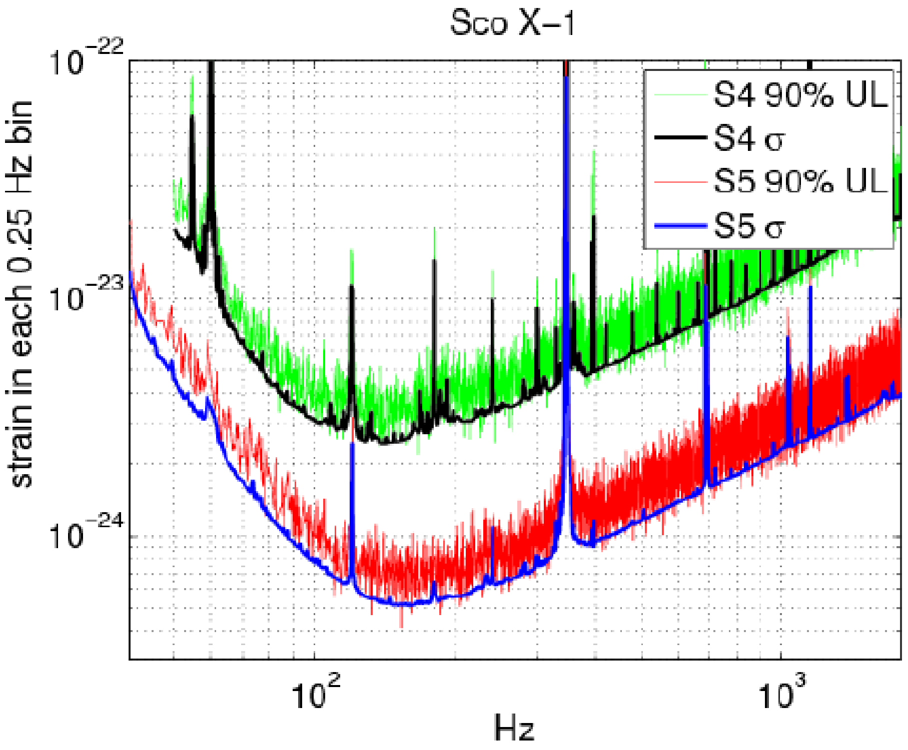
$$C_l \approx \frac{1}{2l+1} \sum_m |\mathcal{P}_{lm}|^2$$

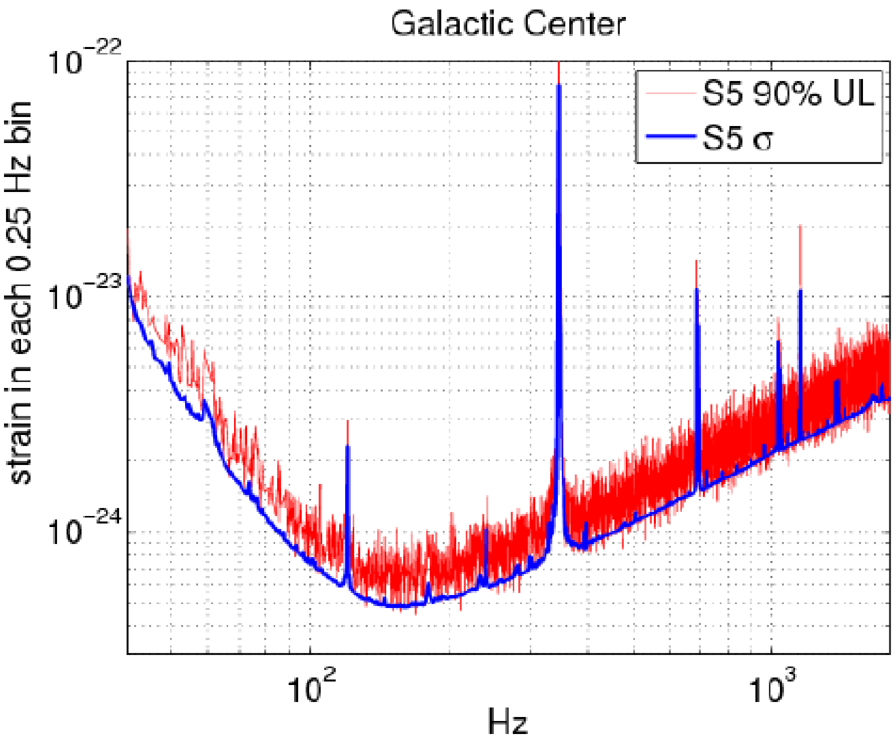


LVC, Phys. Rev. Lett. 107, 271102 (2011).

Point-Source Searches with LIGO S5 Data

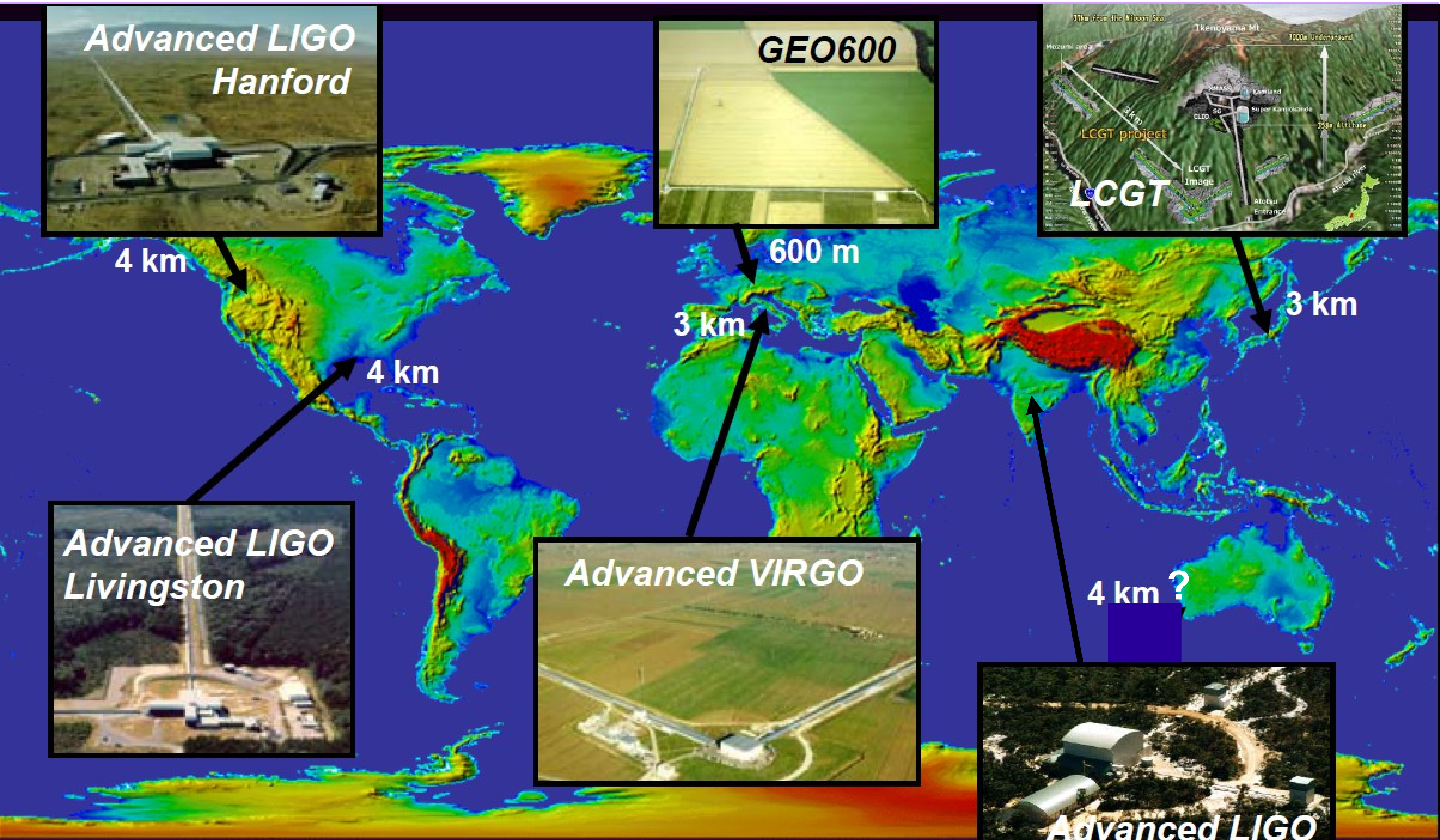
Can also compute 90% CL upper limits on the strain from specific point-sources in the sky.


Sco X−1


Galactic Center

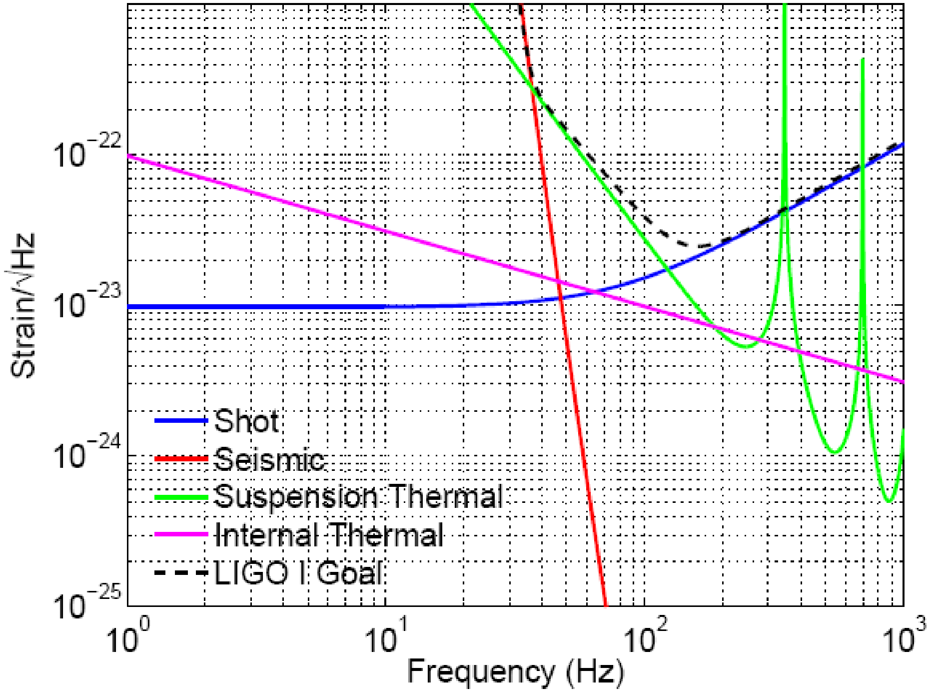
LVC, Phys. Rev. Lett. 107, 271102 (2011).

Advanced Detector Era Network in 2015?



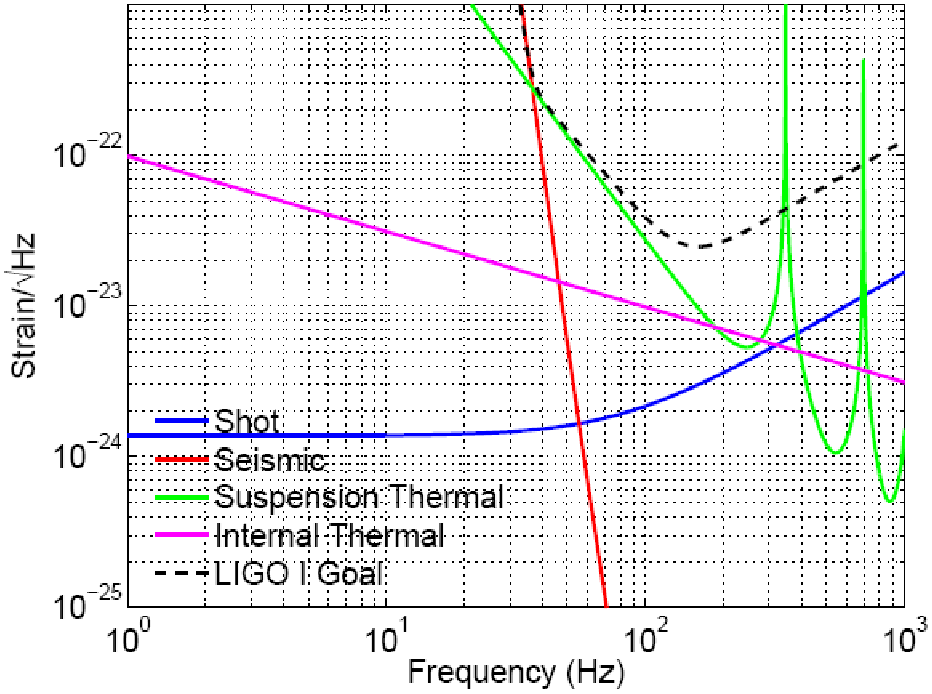
Advanced LIGO

- Keep the same facilities, but redesign all subsystems.
  - Improve sensitivity over the whole frequency range.



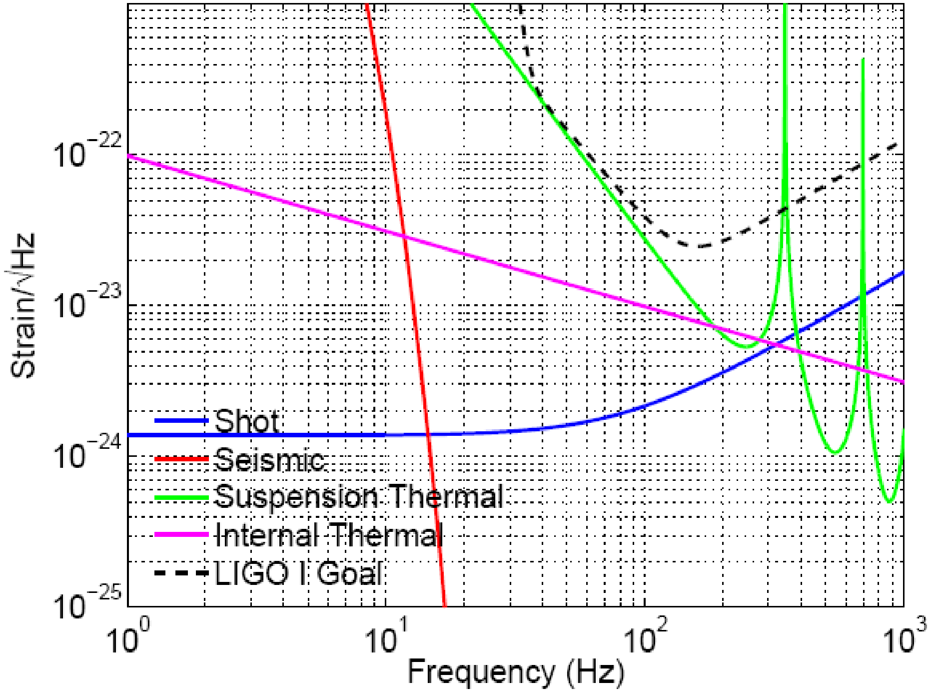
Advanced LIGO

- Keep the same facilities, but redesign all subsystems.
  - » Improve sensitivity over the whole frequency range.
- Increase laser power in arms.



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



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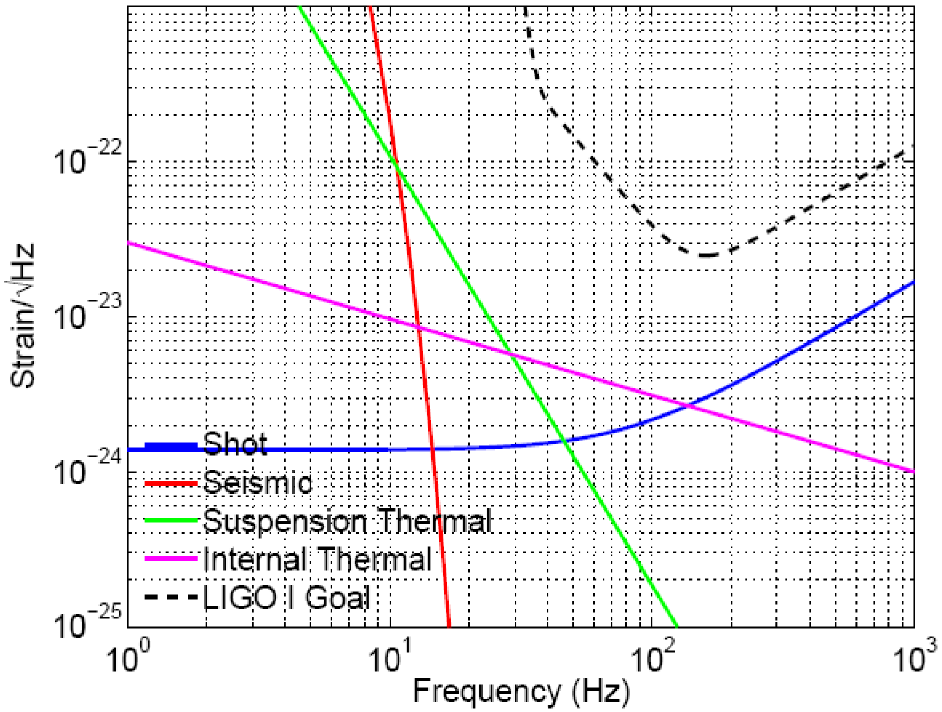
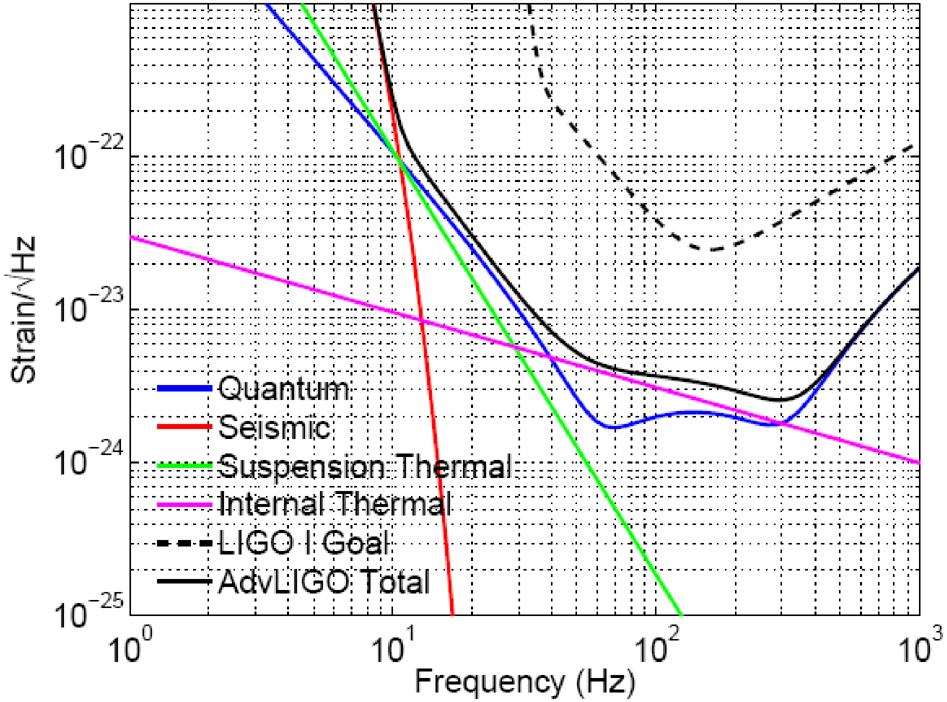
- Larger mirrors to suppress thermal noise.
- Silica wires to suppress suspension thermal noise.



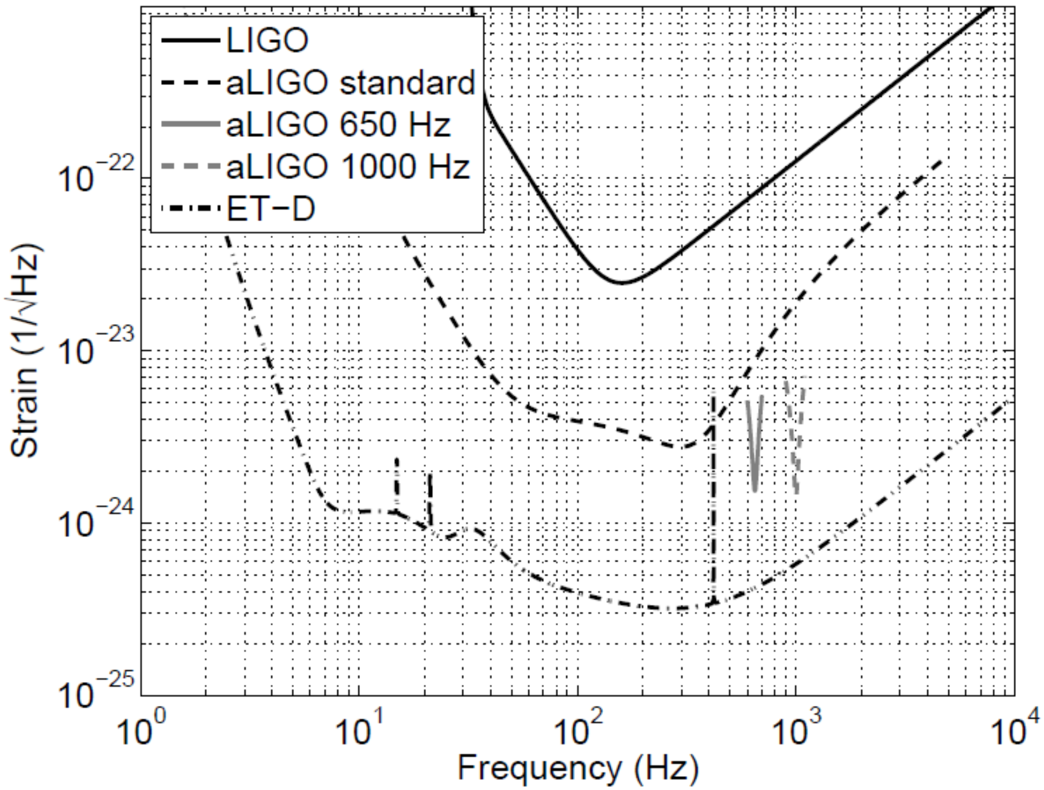
Advanced LIGO

- 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.

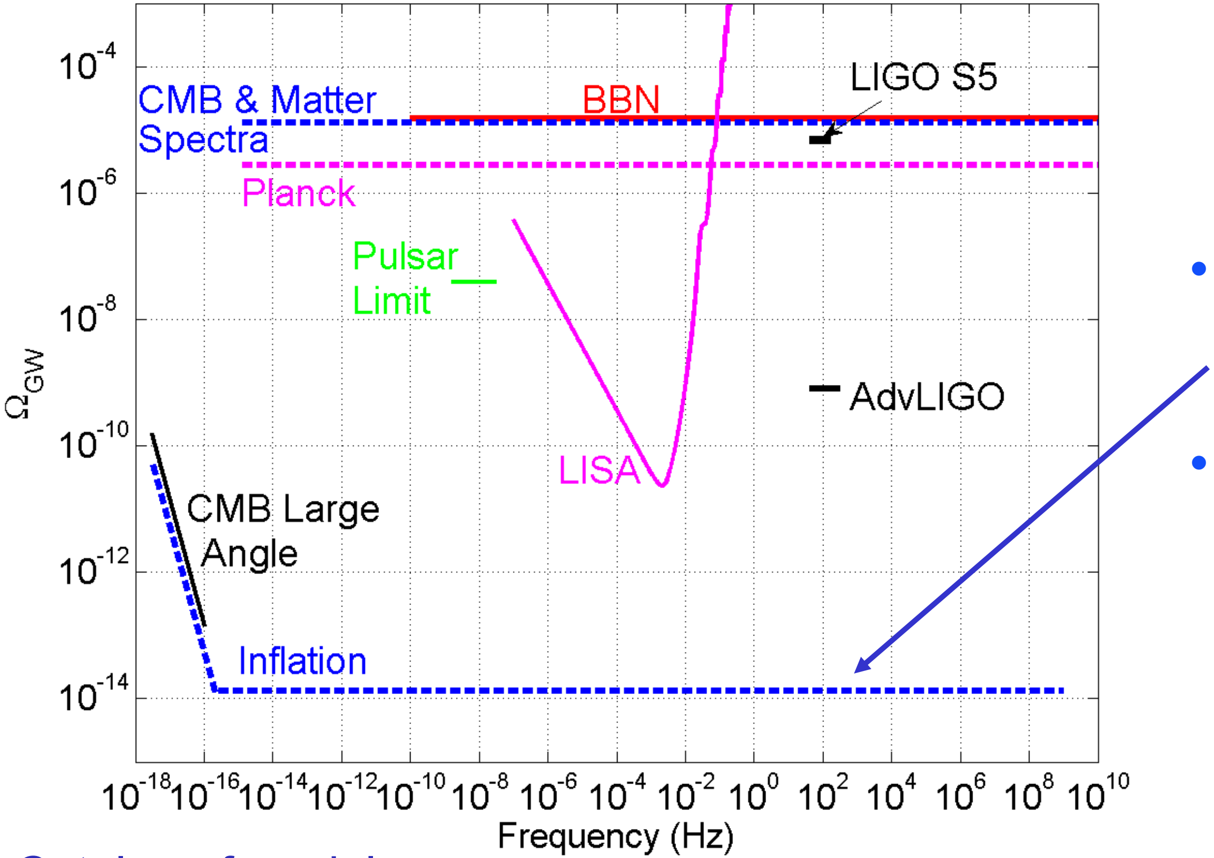


Future of Stochastic Searches

- Second generation:
    - Advanced LIGO/Virgo, GEO-HF, KAGRA.
    - First data: 2014/2015.
    - 10x improvement in strain.
    - Down to 10 Hz.
    - Reaching $\Omega_0 \sim 10^{-9}$.
- Third generation:
    - Einstein Telescope design study.
    - Another 10x improvement in strain, down to few Hz.
    - Reaching $\Omega_0 \sim 10^{-12}$.



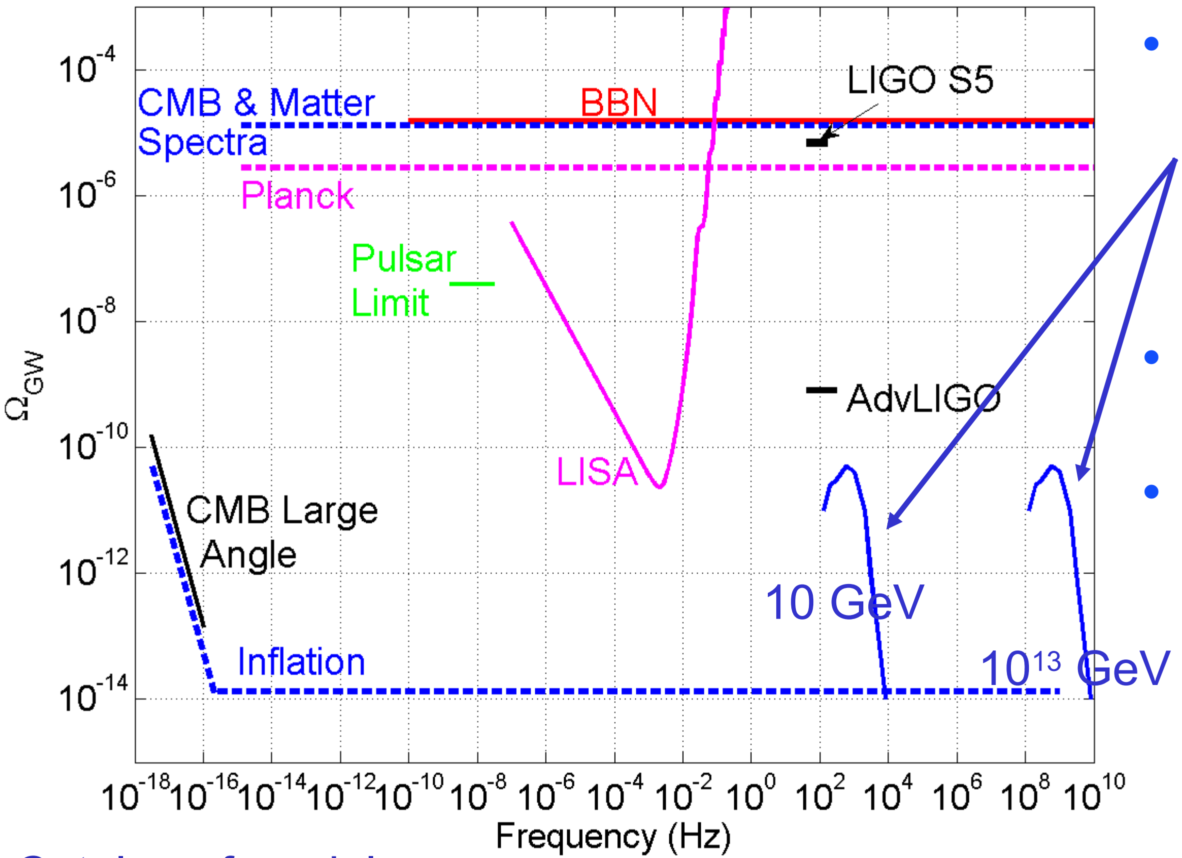
Advanced Detectors and the Stochastic Background



- Standard inflationary models are weakly dependent on frequency.
- Out of reach of advanced detectors by ~5 orders of magnitude

Catalog of models:
http://homepages.spa.umn.edu/~gwplotter/

Advanced Detectors and the Stochastic Background



- If inflation ends with a preheating resonant phase, inflaton energy is efficiently transferred to other particles.
- Can have significant increase in GW background.
- Peak depends on energy scale.
  - Easther & Lim, JCAP 0604, 010 (2006).
  - Easther et al, PRL 99, 221301 (2007).
  - Easther, Nucl. Phys. Proc. Suppl. 194, 33 (2009).

Catalog of models:
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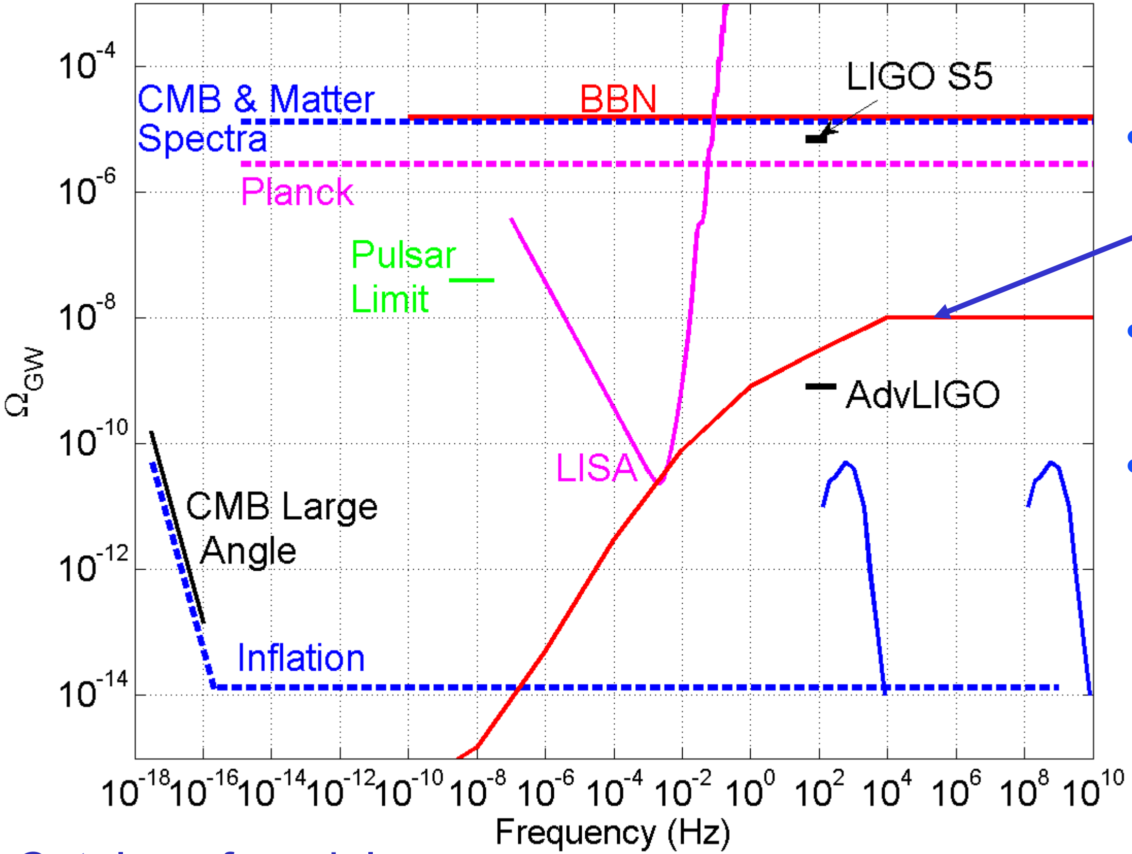

- Axion-based inflation models include axion-gauge couplings.
- Gauge backreaction on the inflaton extends inflation.
- This late inflationary phase increases GW production at high frequencies.
  - Barnaby et al, arXiv:1110.3327.

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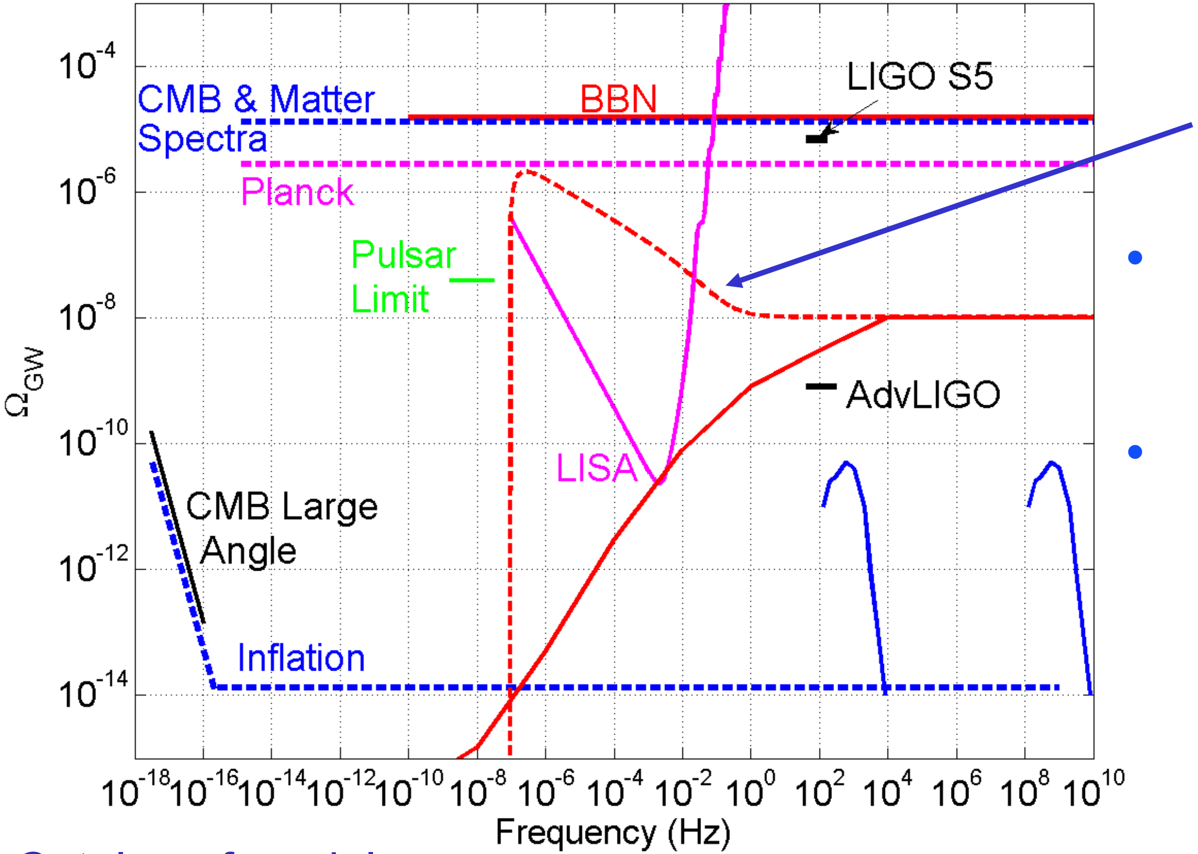

- Cosmic (super)strings models: cusps or kinks moving at relativistic speeds produce bursts of gravitational radiation.
- Integrating over the whole universe leads to a GW background.
- Large parameter space, some of it already probed by initial LIGO.
  - » Damour & Vilenkin, PRL 85, 3761 (2000).
  - » Siemens et al, PRL 98, 111101 (2007).
  - » Olmez et al, PRD 81, 104028 (2010).

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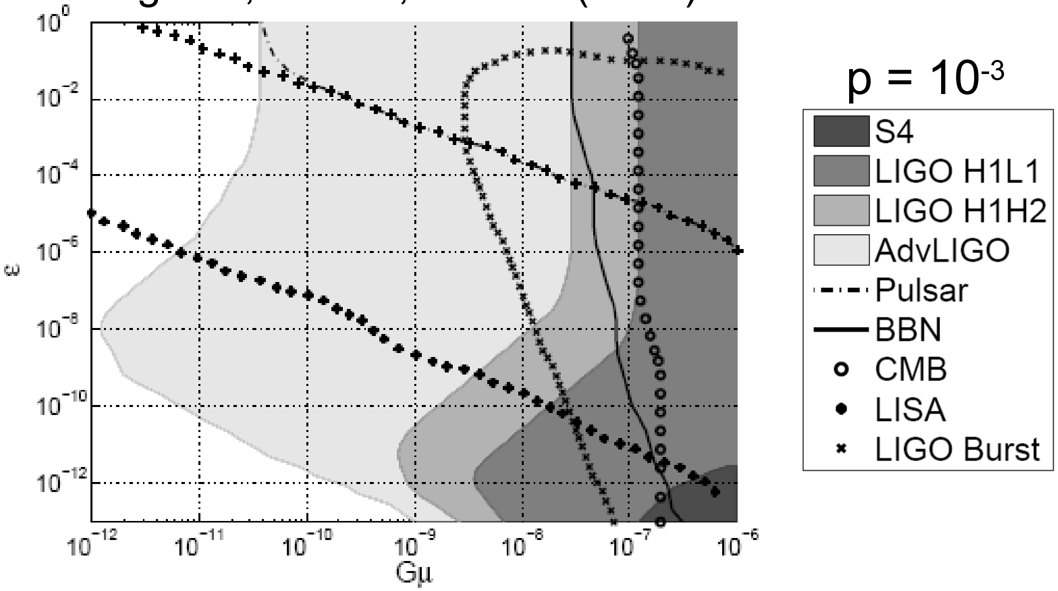
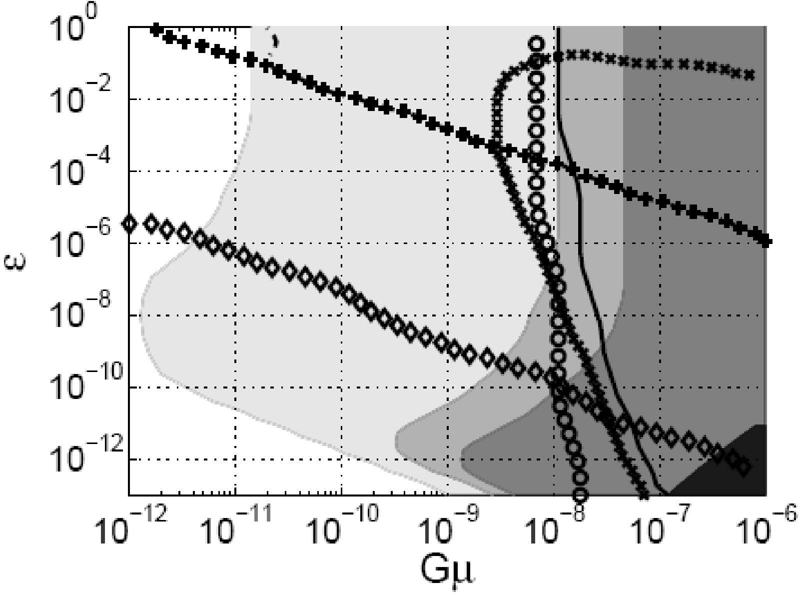
Systematic Study: Cosmic (Super)Strings

- String cusps or links moving at the speed of light produce GW bursts.
- Integrating over the entire universe gives a stochastic background.
- Parameters (small-loop scenario):
  - » loop-size parametrized by: $10^{-13} < \varepsilon < 1$
  - » String tension: $10^{-12} < G\mu < 10^{-6}$
  - » Reconnection probability: $10^{-3} < p < 1$

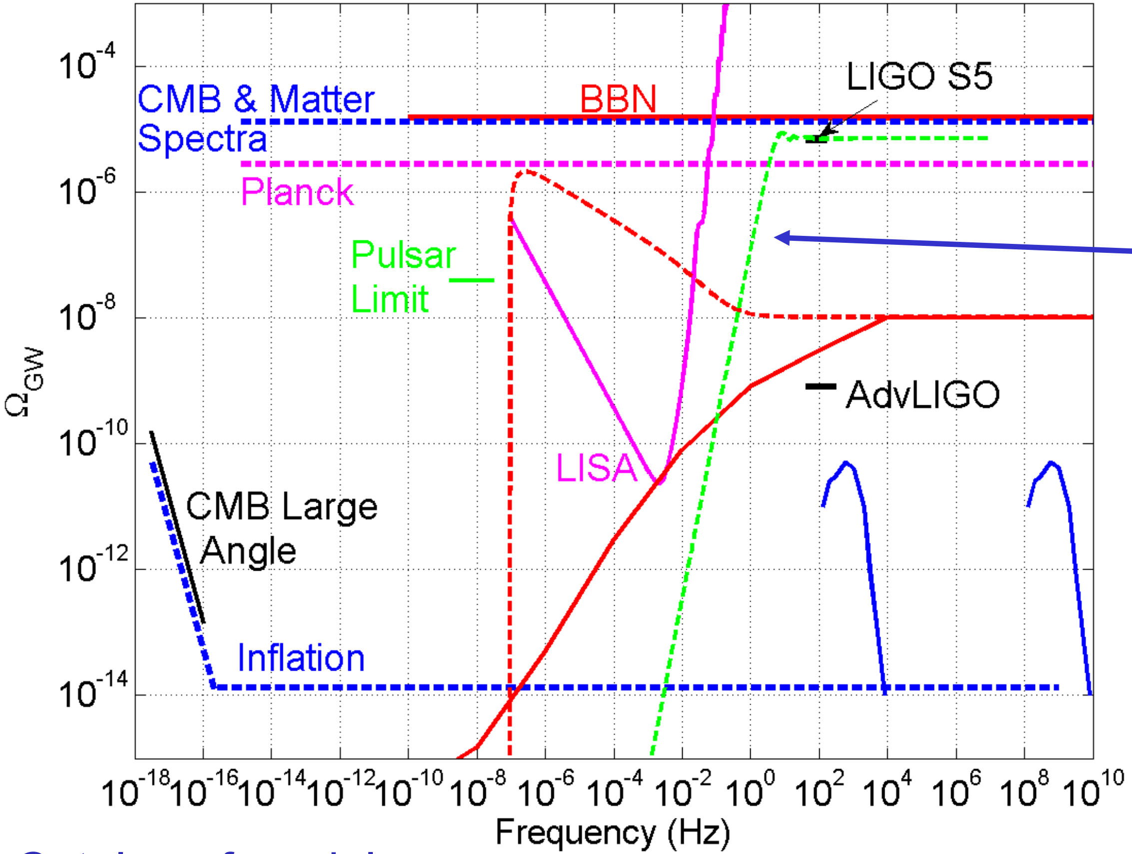
Cusps: X. Siemens, V.M., J. Creighton, PRL98, 111101 (2007).



Kinks: S. Olmez, V.M., X. Siemens, PRD81, 104028 (2010).



Advanced Detectors and the Stochastic Background



- Alternative cosmologies, such as pre-Big-Bang models, can lead to strong GW backgrounds at high frequencies.
  - » Gasperini & Veneziano, Phys. Rep. 373, 1 (2003).
  - » Buonanno et al, PRD 55, 3330 (1997).

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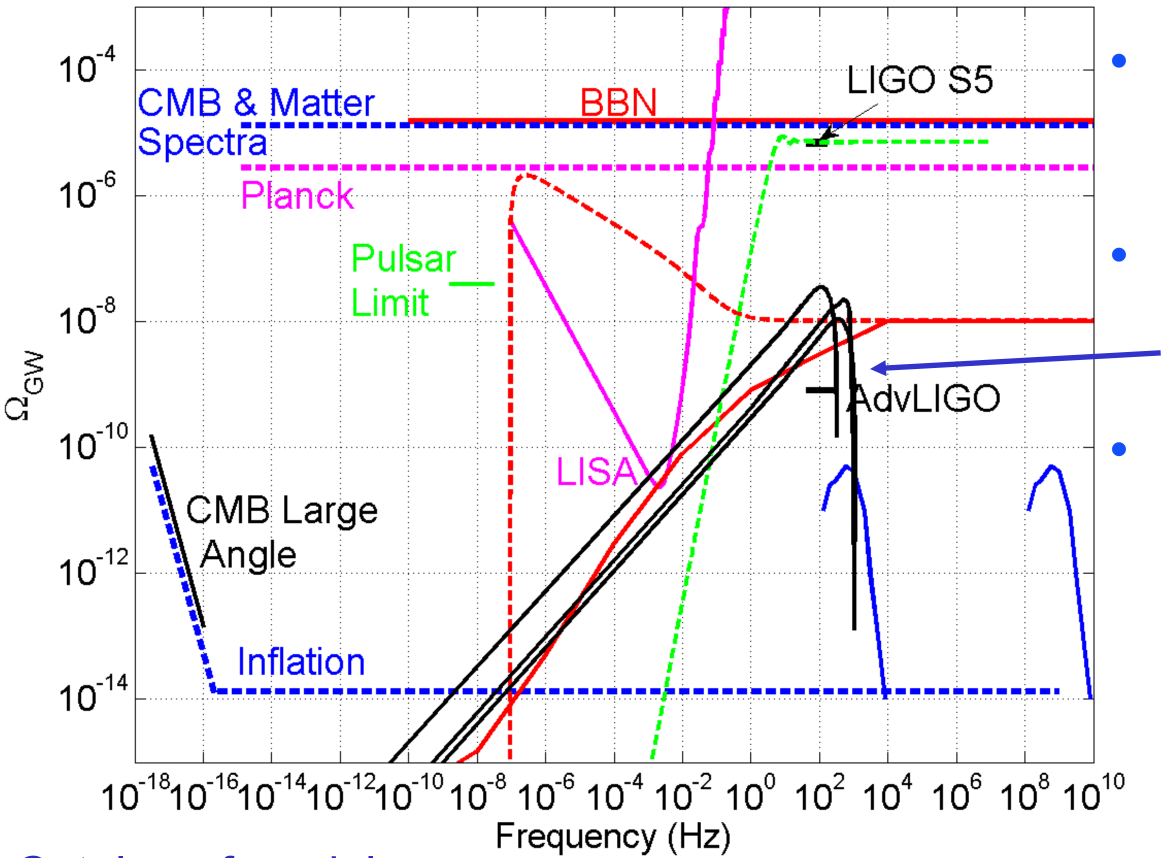

- Individual neutron star and/or black hole pairs generate chirp GW signals.
- Integrating over the whole universe ($z<6$) leads to a GW background.
- Peak in the LIGO band.
  - » Phinney, ApJ 380, L17 (1991).
  - » Ignatiev et al., MNRAS 327, 531 (2001).
  - » Regimbau & de Freitas Pacheco, ApJ 642, 455 (2006).
  - » Wu et al, arXiv:1112.1898.

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Binary Coalescences: Model

Energy Density:

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_c c} \int_{z_{inf}}^{z_{sup}} R_z(z) \frac{1}{4\pi d_L^2(z)} \frac{dE_{\mathrm{GW}}(f)}{df} dz$$

Energy emitted by
a single binary:

$$\frac{dE_{\mathrm{GW}}}{df} = \frac{(G\pi)^{2/3}}{3} (M_c^z)^{5/3} f^{-1/3}$$

Rate of Binaries:

$$R_z(z) = \lambda R_V(z) \frac{dV(z)}{dz}$$

Mass Fraction
Parameter

Cosmology

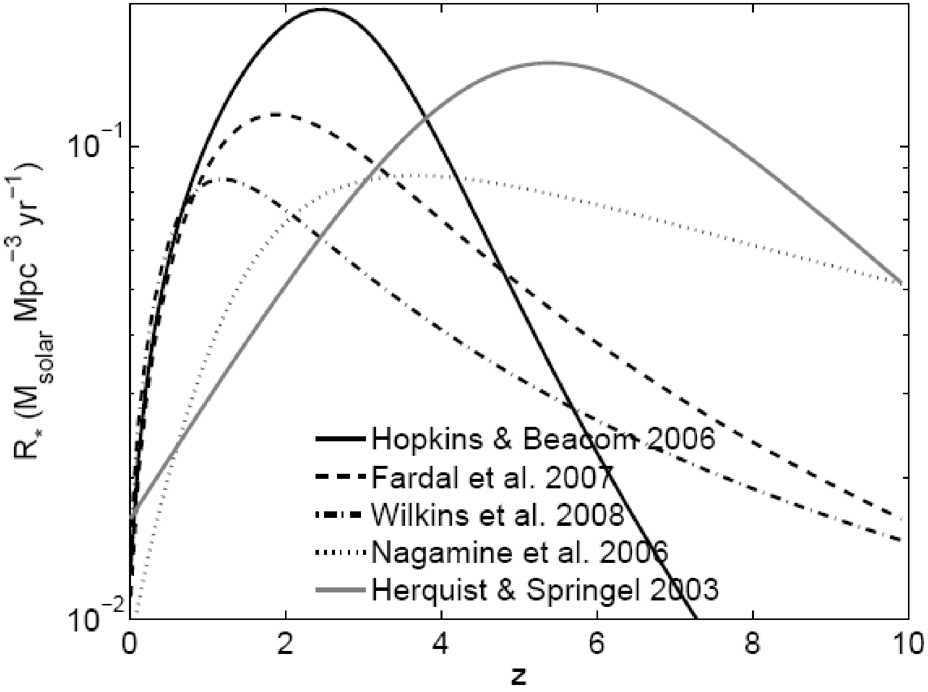
$$R_V(z) = \int \frac{1}{1+z_f} R_*(t_c(z) - t_d) P(t_d) dt_d$$

Time delay between
formation and coalescence

Star Formation Rate

Binary Coalescences: Model

- This model has been around for >20 years:
    - Phinney, ApJ 380, L17 (1991).
- Many papers, multiple authors, different tweaks.
- Wu, Mandic, Regimbau, arXiv:1112.1898, to appear in PRD:
    - Systematic study of the accessibility of the model to Advanced detectors.
    - Scan λ-M_c parameter space.
    - Different star-formation rates.
    - Different time-delays.



Population synthesis: $P(t) \sim t^{\alpha}$, for $t > t_{min}$:

α = -0.5, -1, -1.5

t_{min} = 20, 100 Myr (BNS)

t_{min} =100, 500 Myr (BBH)

Short GRBs: log-normal distribution.

No time-delay.

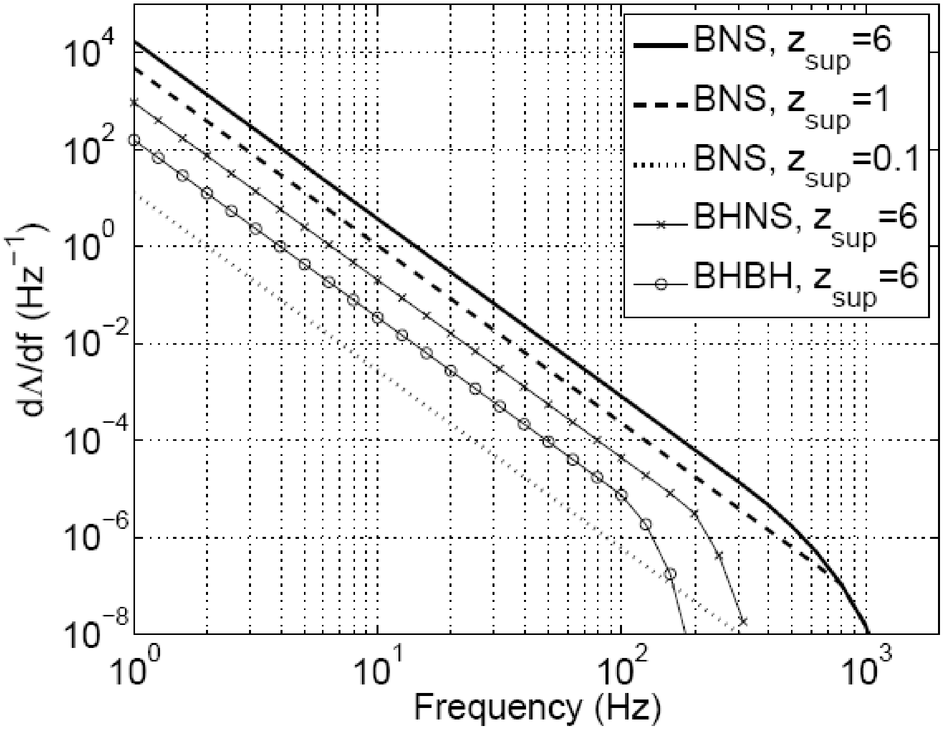
Not a Continuous Background

- …at most frequencies.

Define duty cycle:

$$\frac{d\Lambda}{df} = \int_0^{z_{\rm sup}} R_z(z) \frac{d\tau(z)}{df} dz$$

- Popcorn regime, or individual unidentifiable chirps.



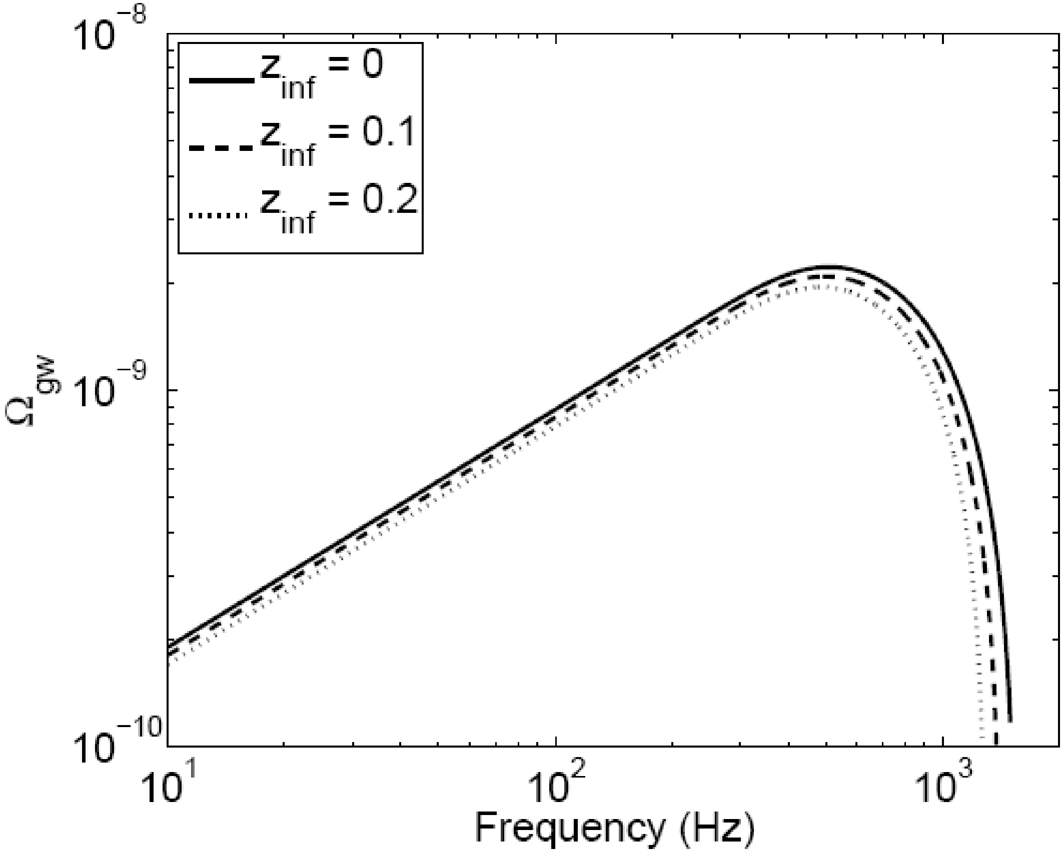
Example Spectra

- Spectrum peaks in the LIGO/Virgo band.

Dominated by the far-away contributions.

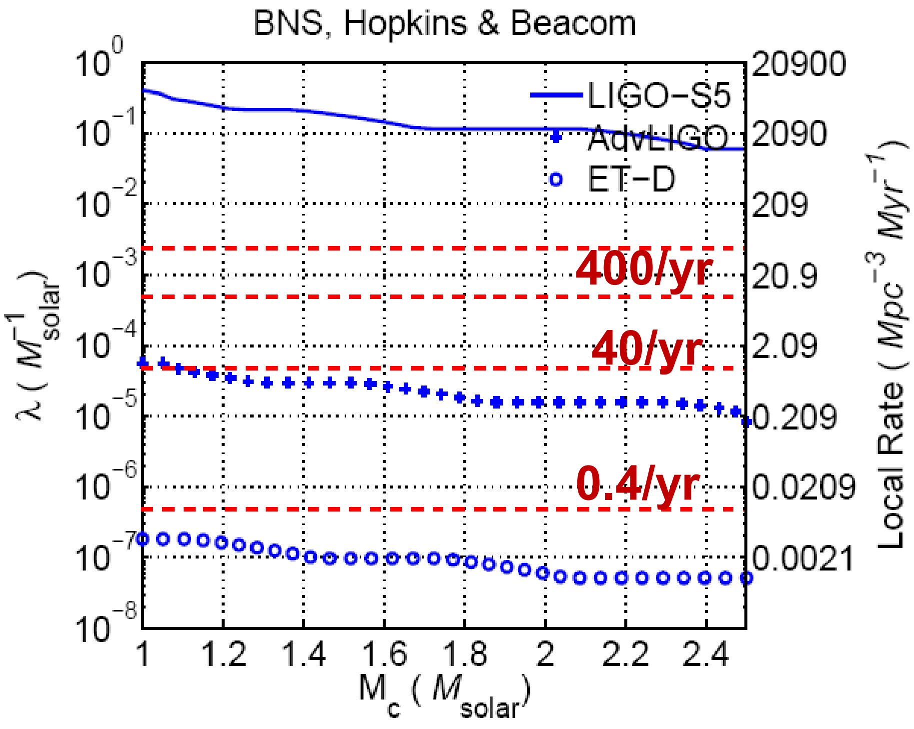
Excluding loudest nearby binaries does not change the spectrum significantly.

- Stochastic search pipeline would possibly reject the loudest CBC transients, but would integrate over all unidentifiable chirps.

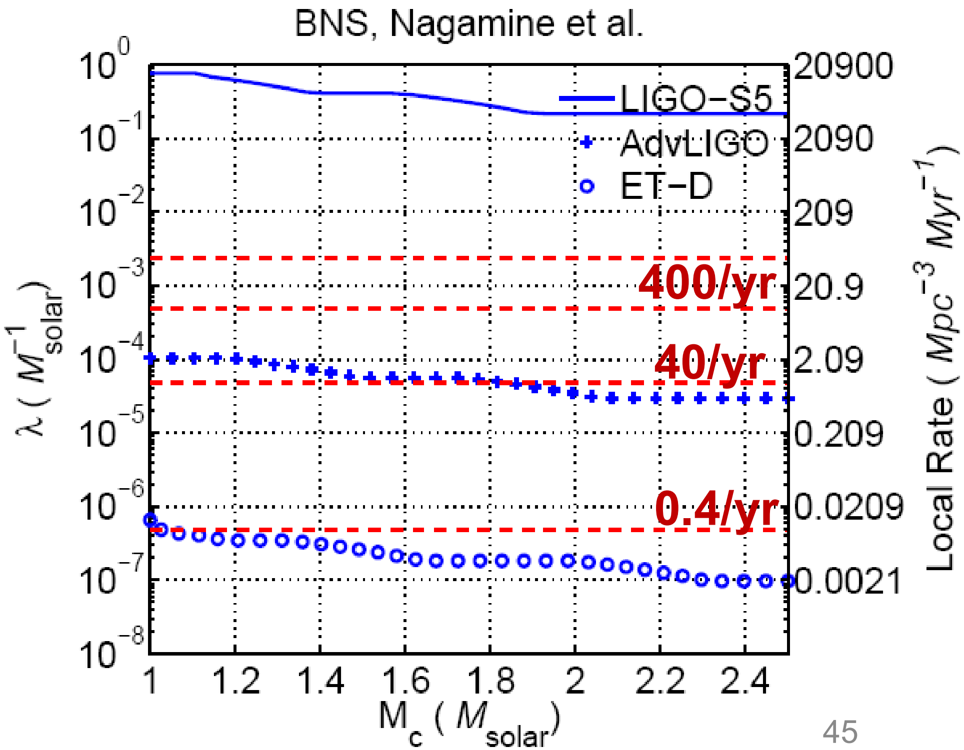


Binary Neutron Stars

1) aLIGO should see GW background corresponding to “realistic” coalescence rates.
2) Third generation detectors will see this as a “foreground”.
3) Star formation rate has little effect.



BNS, Hopkins & Beacom

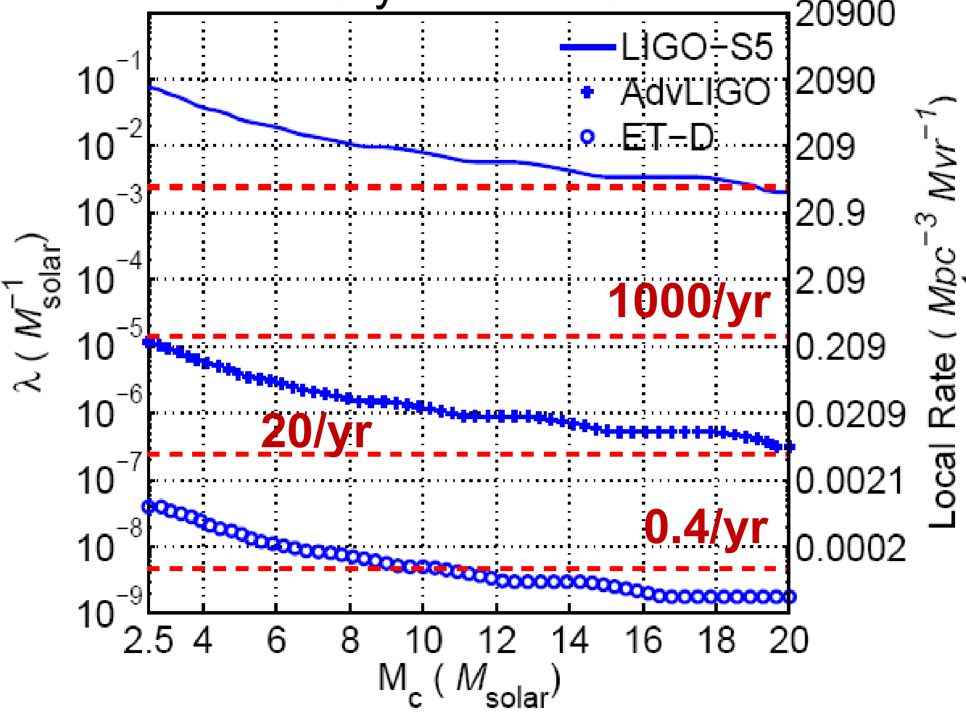


BNS, Nagamine et al.

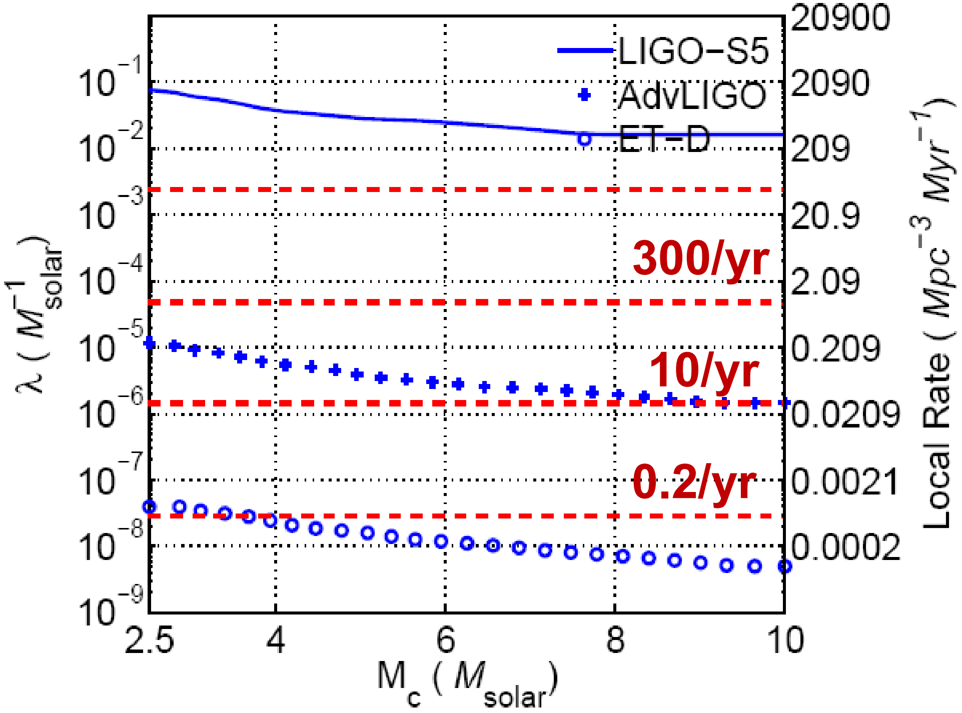
BBH & BHNS

Similar conclusions apply for BBH and BHNS systems.

Binary black holes

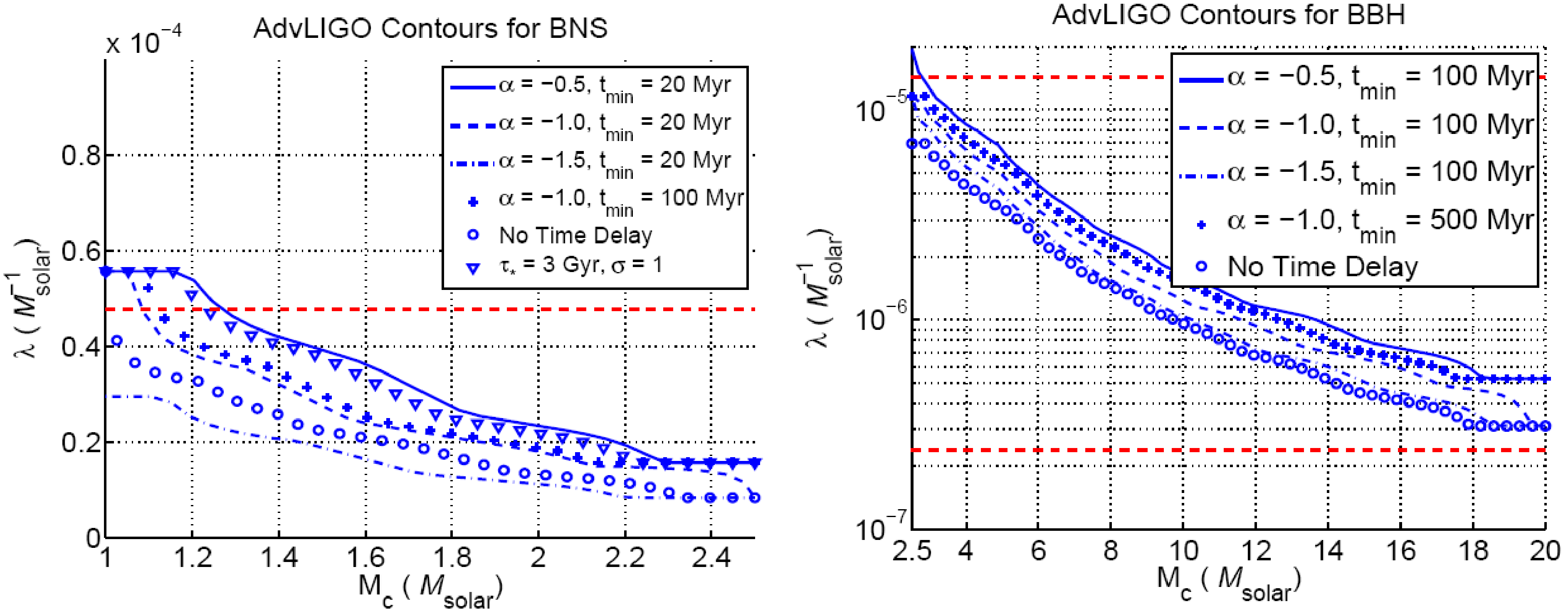


Black Hole – Neutron Star



Time-Delay Distribution

Time-delay distribution (functional form and minimum delay) have no qualitative effect.



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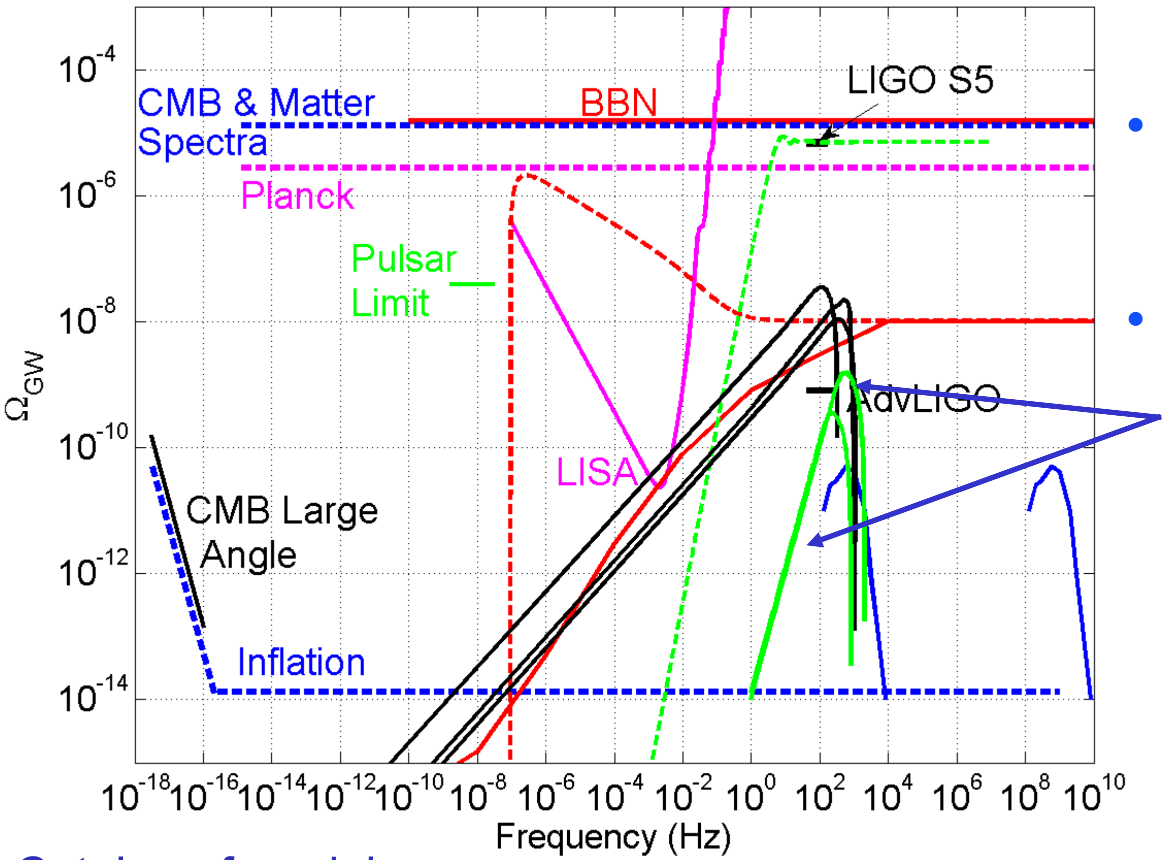

- Neutron stars can have a variety of instabilities: r-modes, bar-modes etc.
- Integrating over the entire universe leads to a GW background.
  - Owen et al, PRD 58, 084020 (1998).
  - Lai & Shapiro, ApJ 442, 259 (1995).
  - Regimbau & de Freitas Pacheco,, A&A 376, 381 (2001).

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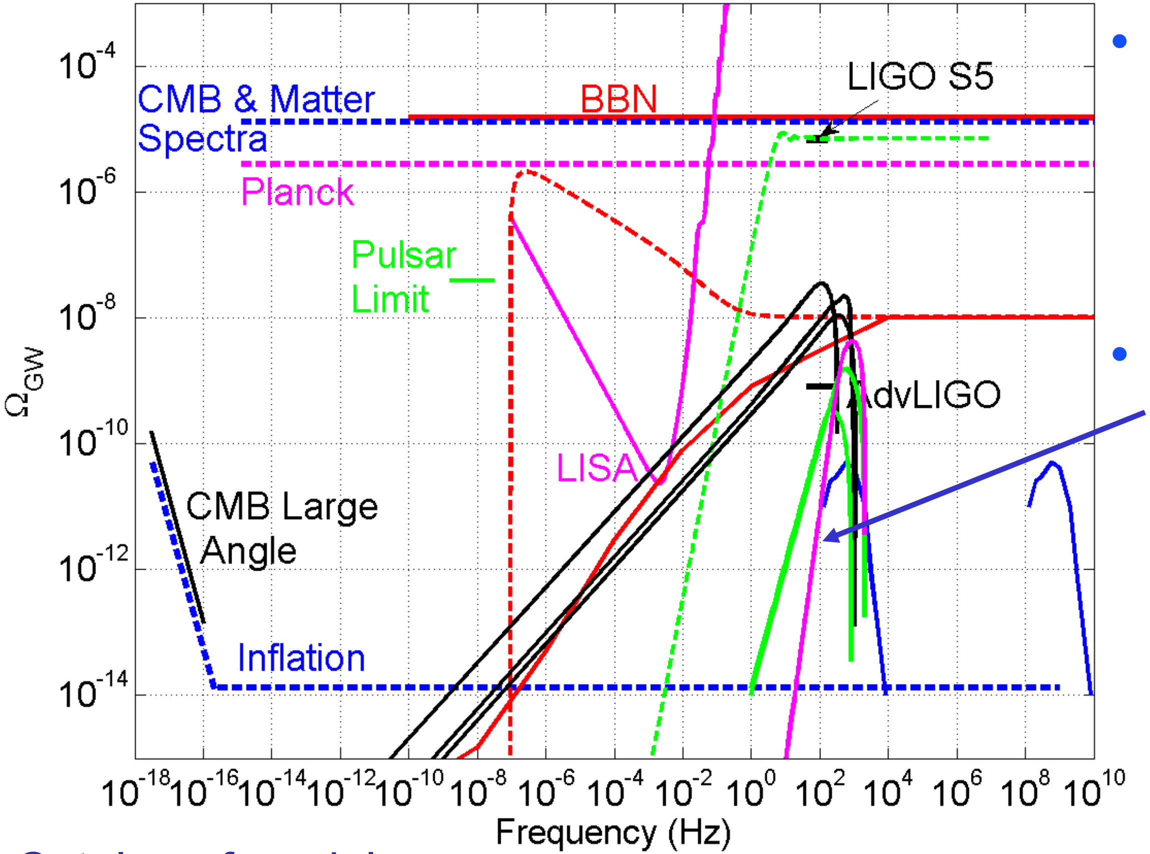

- Magnetar model: protoneutron stars in very strong magnetic fields (10^{16} G) can be distorted (high ellipticity).
- Integrating over the whole universe leads to a GW background.
  - Cutler, PRD 66, 084025 (2002).
  - Regimbau & Mandic, CQG 25, 184018 (2008).
  - Dall'Osso et al, MNRAS 398, 1869 (2009).
  - Marassi et al, MNRAS 411, 2549 (2011).

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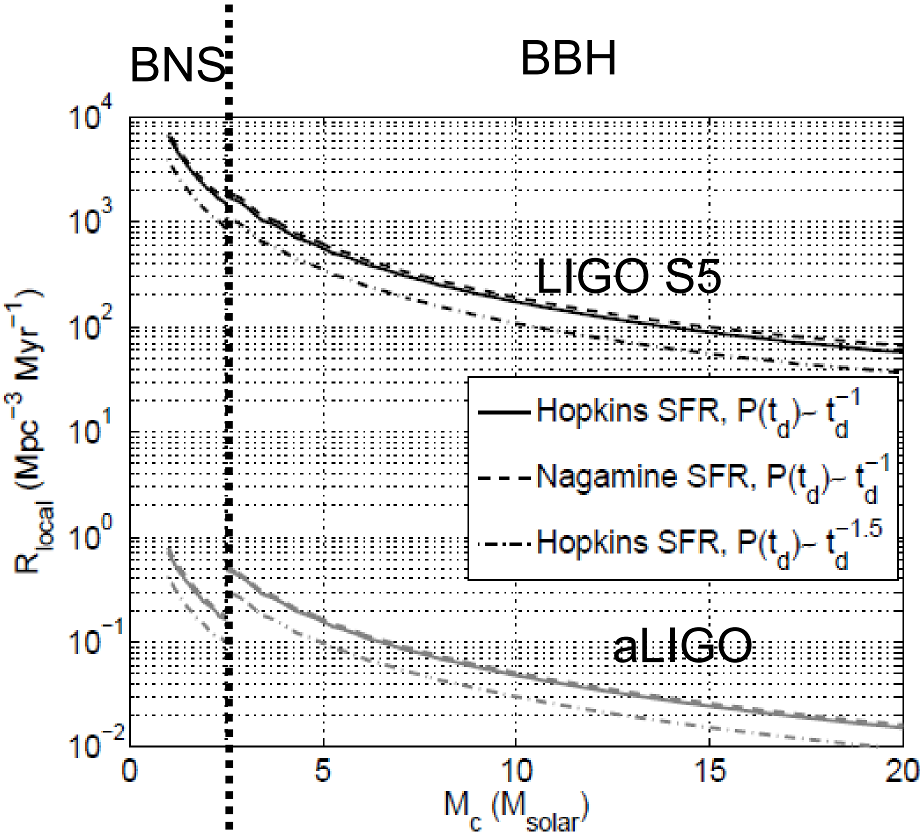
Parameter Estimation

- Perform a likelihood fit of the measured energy spectrum.

$$L(\hat{Y}_i, \sigma_i|\vec{\theta}) \propto \exp\left[-\frac{1}{2}\sum_i \frac{(\hat{Y}_i - \Omega_{\rm M}(f_i;\vec{\theta}))^2}{\sigma_i^2}\right]$$

- Estimate model parameters and constrain the physics of the model.
- Example: constrain the rate of binary coalescences.
- Joint likelihood with the individual CBC observations (and others) to study the energy budget of the GW background.
- Which sources dominate? Are we missing something?



VM, E. Thrane, S. Giampanis, T. Regimbau – in preparation

Conclusion

- GW observations are already yielding interesting astrophysical statements.
- Next-generation detectors are around the corner (2014)!
  - » Expect first direct GW observations in the coming 5 years!
- Follow-up detectors are already being planned to fully exploit the science potential of GW observations.
- Stay tuned...