Measuring the stochastic gravitational-wave background with LIGO-Virgo

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Overview

- Recent stochastic results from LIGO-Virgo
- Prospects for future stochastic studies

LIGO-Virgo S5 isotropic stochastic result

- Data from LIGO's S5 science run: Nov 05-Sep 07.
- Approximately one year of coincident science time.
- Cross-correlate h(t) from Hanford detectors (H1,H2) with Livingston detector (L1) with optimal filter, Q(f):

overlap reduction function

model spectral shape (flat)

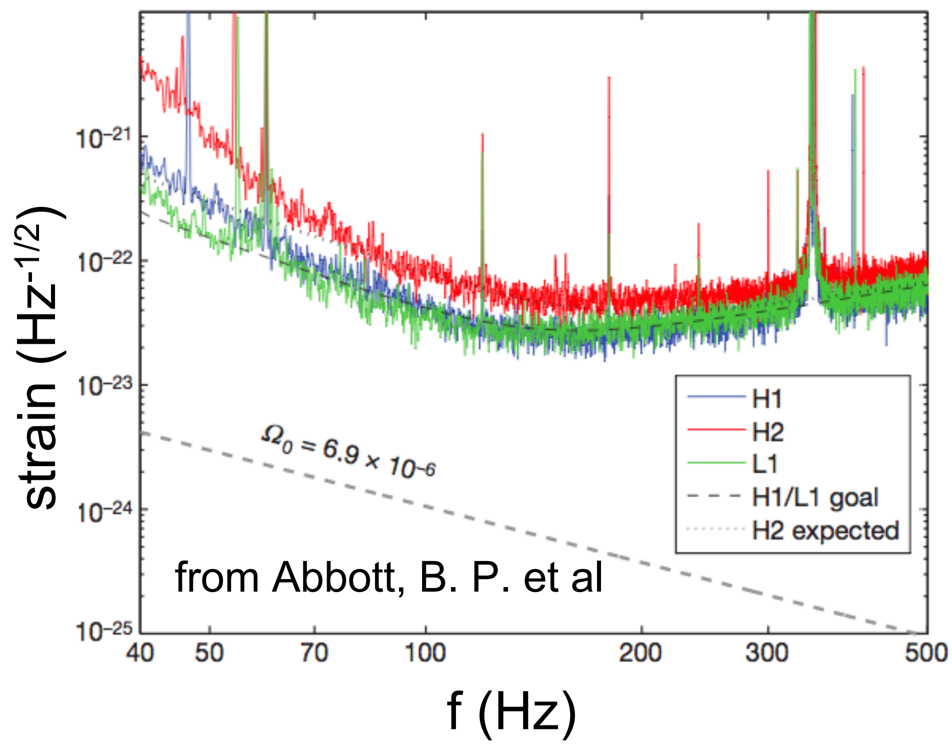
$$\tilde{Q}(f) = N \frac{\gamma(f)\Omega_{GW}(f)H_0^2}{f^3 P_1(f) P_2(f)}$$

power spectral densities (PSDs)

Stochastic S5 isotropic result

- By integrating over a year of data we can constrain Ω_{GW} at values far below the LIGO PSD's.
- Upper limit at 95% CL between 40-169 Hz:

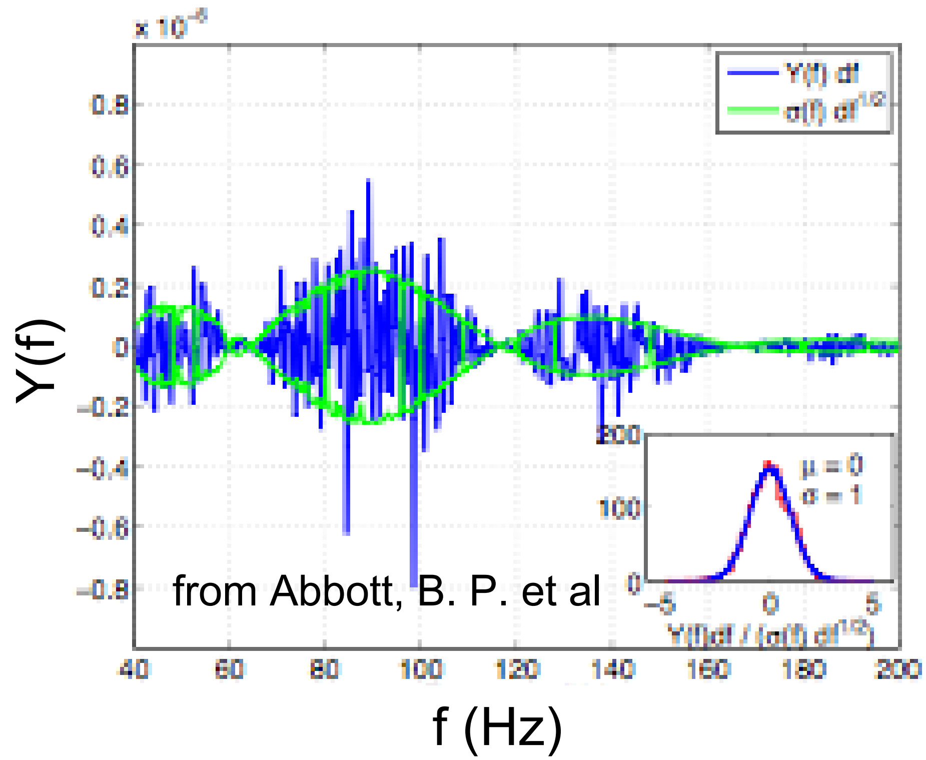
$\Omega_{GW} = 6.9\text{x}10^{-6}$



Abbott, B. P. et al, Nature **460**, 990-994 (2009)

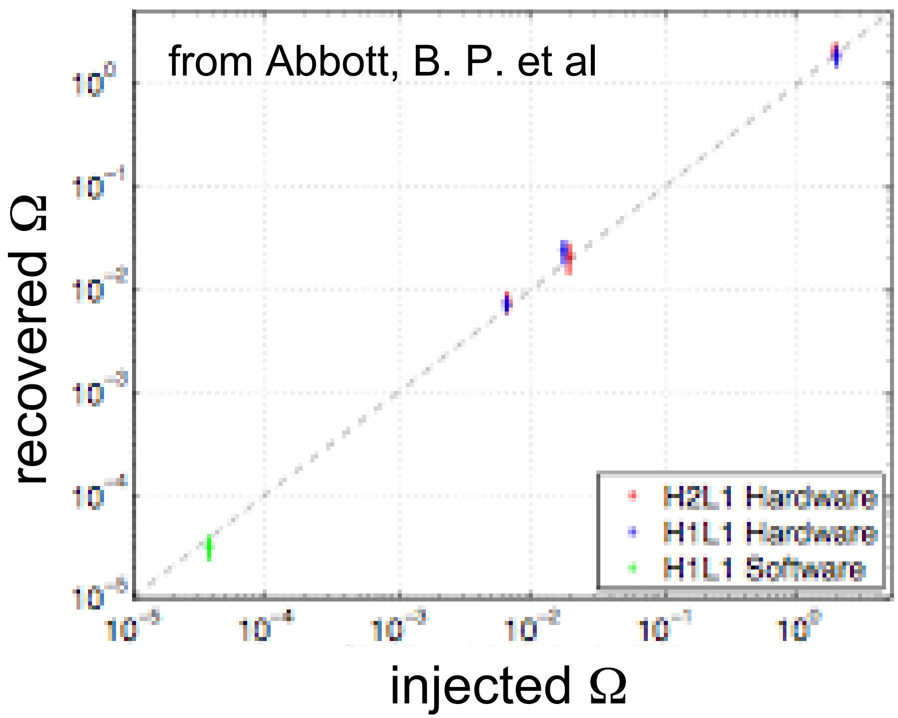
Spectra and sensitivity integrand

- Right: point estimate, Y(f), and σ(f) for H1L1+H2L1 data.
- Inset: SNR(f) = Y(f)/ σ(f)/δ$f^{1/2}$ has mean=0 and standard deviation=1.



Injection recovery

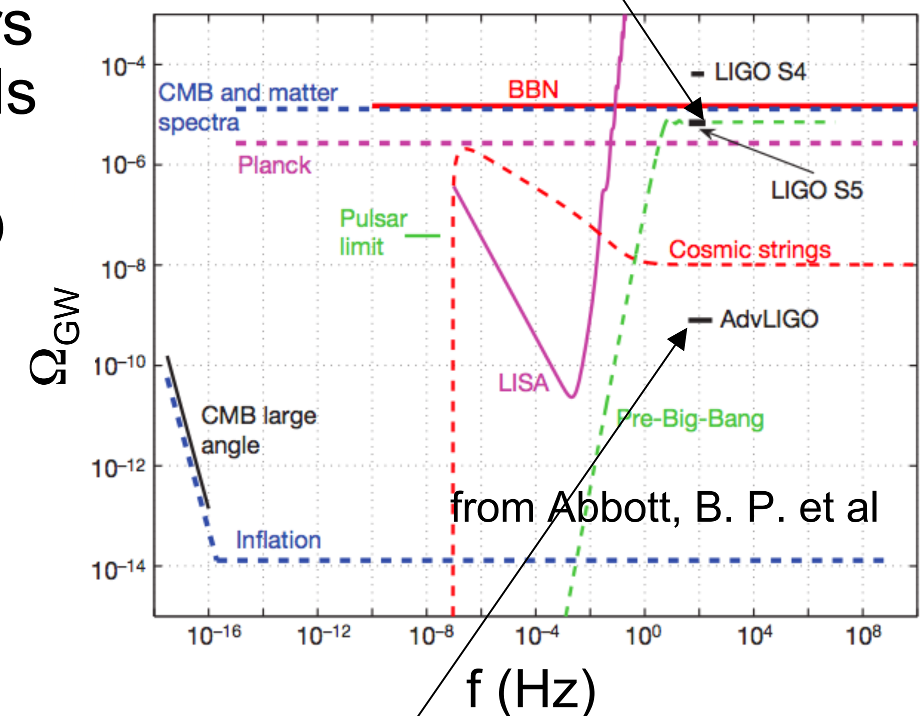
- We performed hardware injections (by shaking one of the end test masses).
- The recovered amplitude was found to be consistent with the injected amplitude.



A milestone for LIGO-Virgo

- For the first time a network of interferometers surpassed indirect bounds inferred from BBN and CMB spectra in the LIGO band: 40-169 Hz.
- A new era: interferometers can meaningfully constrain astrophysical and cosmological models of the SGWB…

LIGO S5 limit



projected AdvLIGO limit

Evolution of the early universe

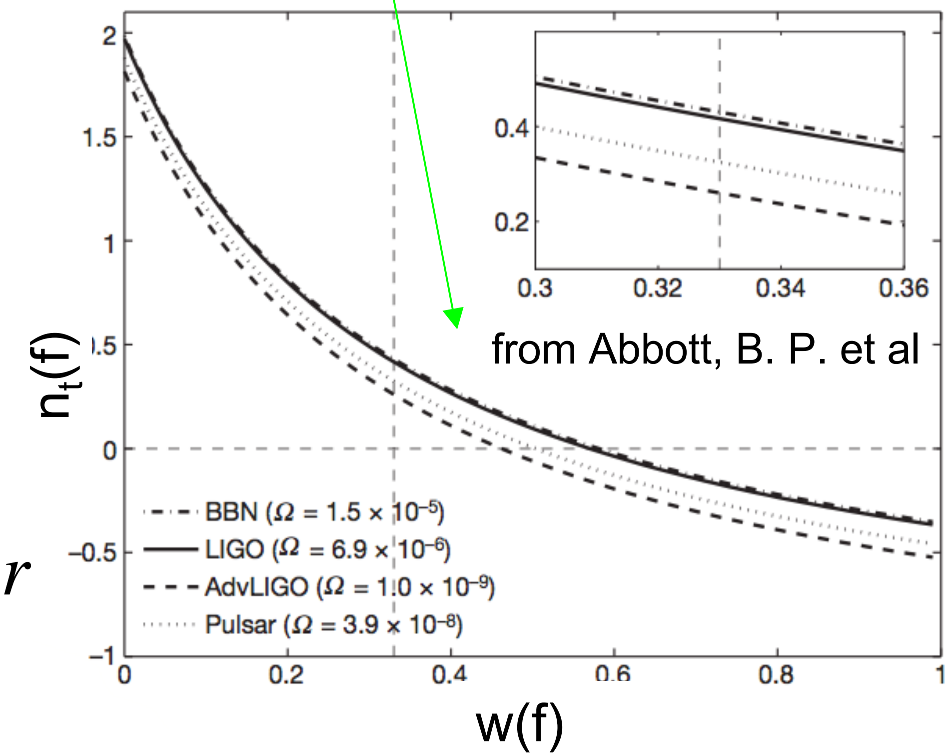
- Early-universe spectrum parameterized in terms of:
  - r≤0.14: ratio of tensor to scalar perturbations
  - n_t: average tensor tilt
  - w: equation of state parameter

$$\Omega_{GW}(f) = A f^{\hat{\alpha}(f)} f^{\hat{n}(f)} r$$

- Right: w-n_t exclusion region for r=0.1.

$$\hat{\alpha}(f) = 2\frac{3\hat{w}(f)-1}{3\hat{w}(f)+1}$$

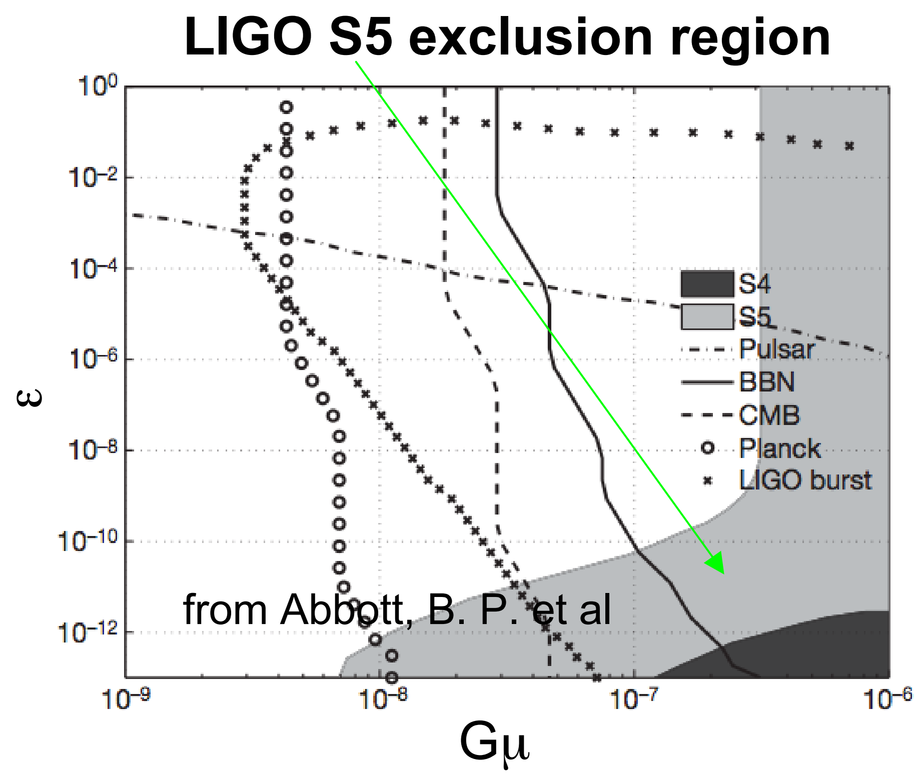
LIGO S5 exclusion region



from Abbott, B. P. et al

Cosmic string models

- Can be parameterized in terms of
  - μ: string tension
  - ε: loop size parameter
  - p: recombination probability
- Right: μ-ε allowed region for p=0.1.



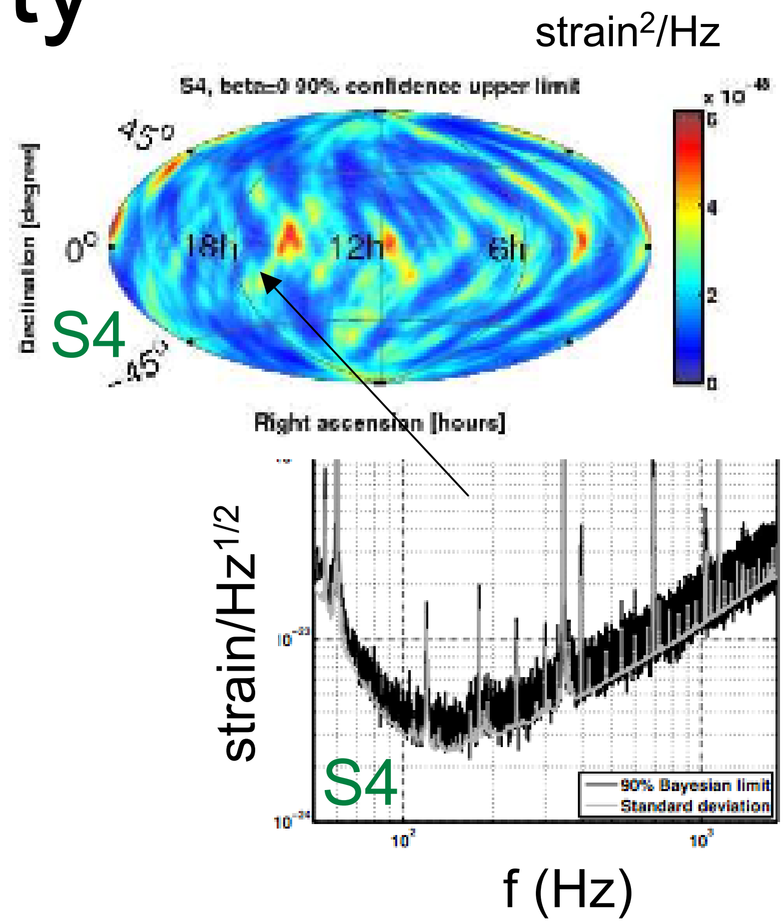
Prospects for future stochastic studies

Directional analyses

- In order to study possibly anisotropic astrophysical/cosmological stochastic gravitational-wave backgrounds/foregrounds.
- Two complementary methods developed:
  - radiometer: optimized for points sources
    - See, e.g., LIGO S4 radiometer paper: (Abbott, B. et al, 2007)
  - spherical-harmonic decomposition: allows for arbitrary angular distributions, but suboptimal for point sources (Thrane 2009)
    - Tool to disentangle different sources of SGWB.

Projected S5 radiometer sensitivity

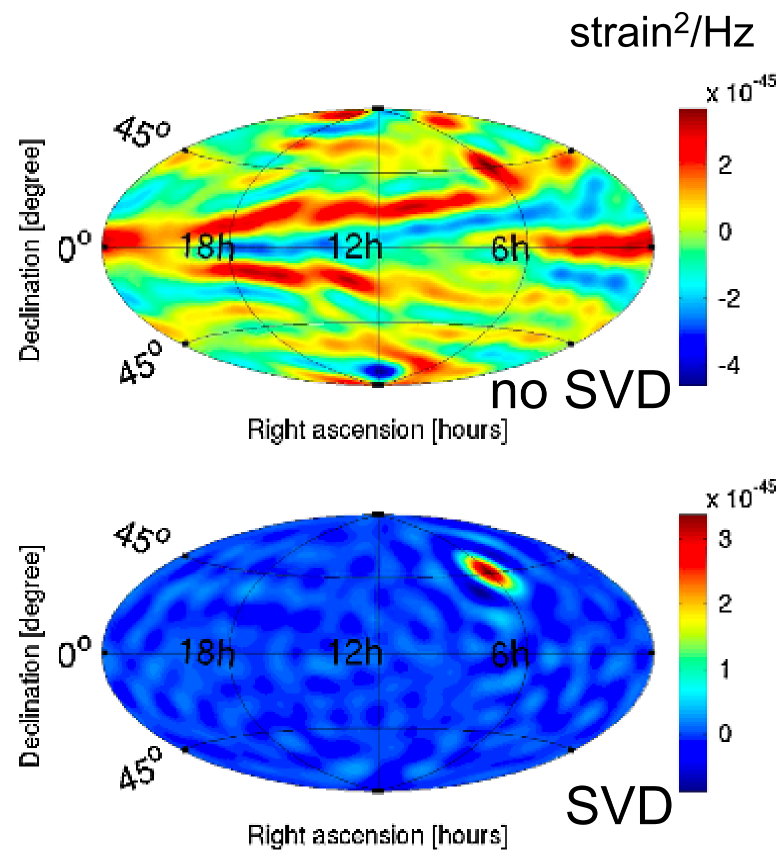
- S4 radiometer analysis produced sky map of upper limits for point source GW power (top) and upper limits on strain from Sco-X1 pulsar (bottom).
- Based on the strain curves presented in S5 isotropic result, analogous S5 limits could improve by factors of ~25 and ~5 respectively.



From (Abbott, B. et al, 2007)

Spherical-harmonic decomposition algorithm

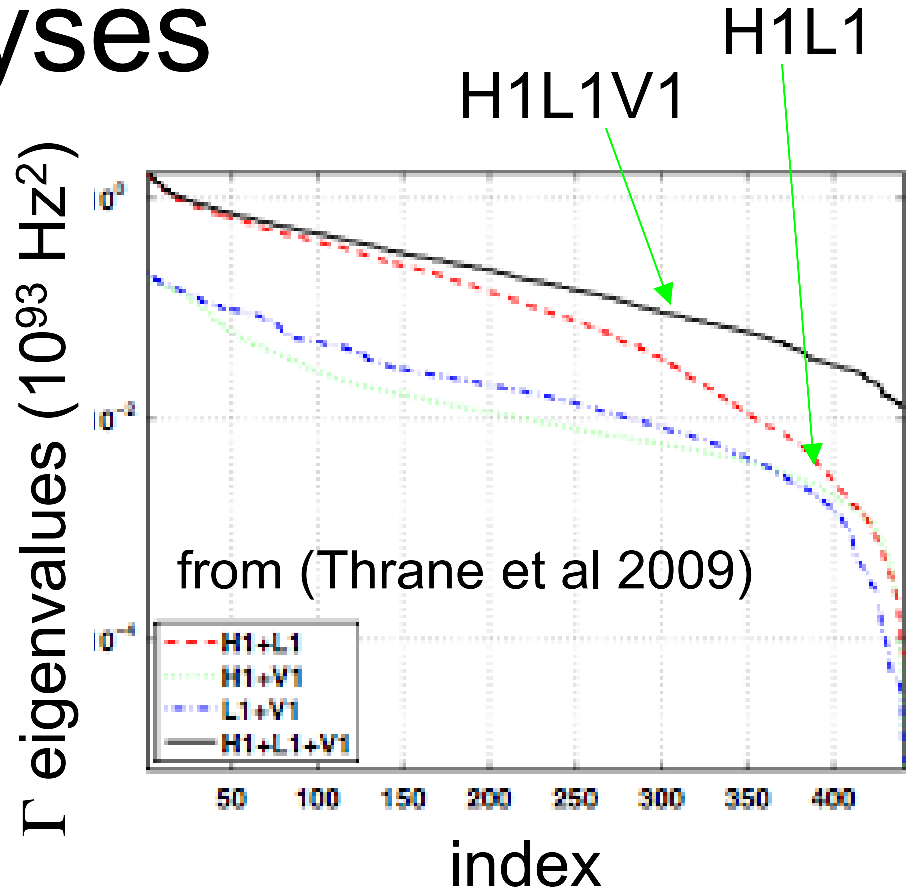
- Decompose sky using Y_{lm}'s up to l_{max} (Thrane et al 2009).
- Demonstrates features of new algorithm:
  - Reproduces isotropic analysis using lmax=0 and radiometer analysis by setting lmax→∞.
  - Regularization to deconvolve beam pattern matrix.
  - Effective regularization from ≥3 interferometers…



Point source regularization (Thrane 2009).

≥3 Detector directional analyses

- Singularities in two-detector Fisher matrix reflect poor sensitivity to some modes.
- Adding a third detector significantly improves sensitivity to these modes.



LSC LIGO Scientific Collaboration

VIRGO

An illustration…

strain^2/Hz

strain^2/Hz

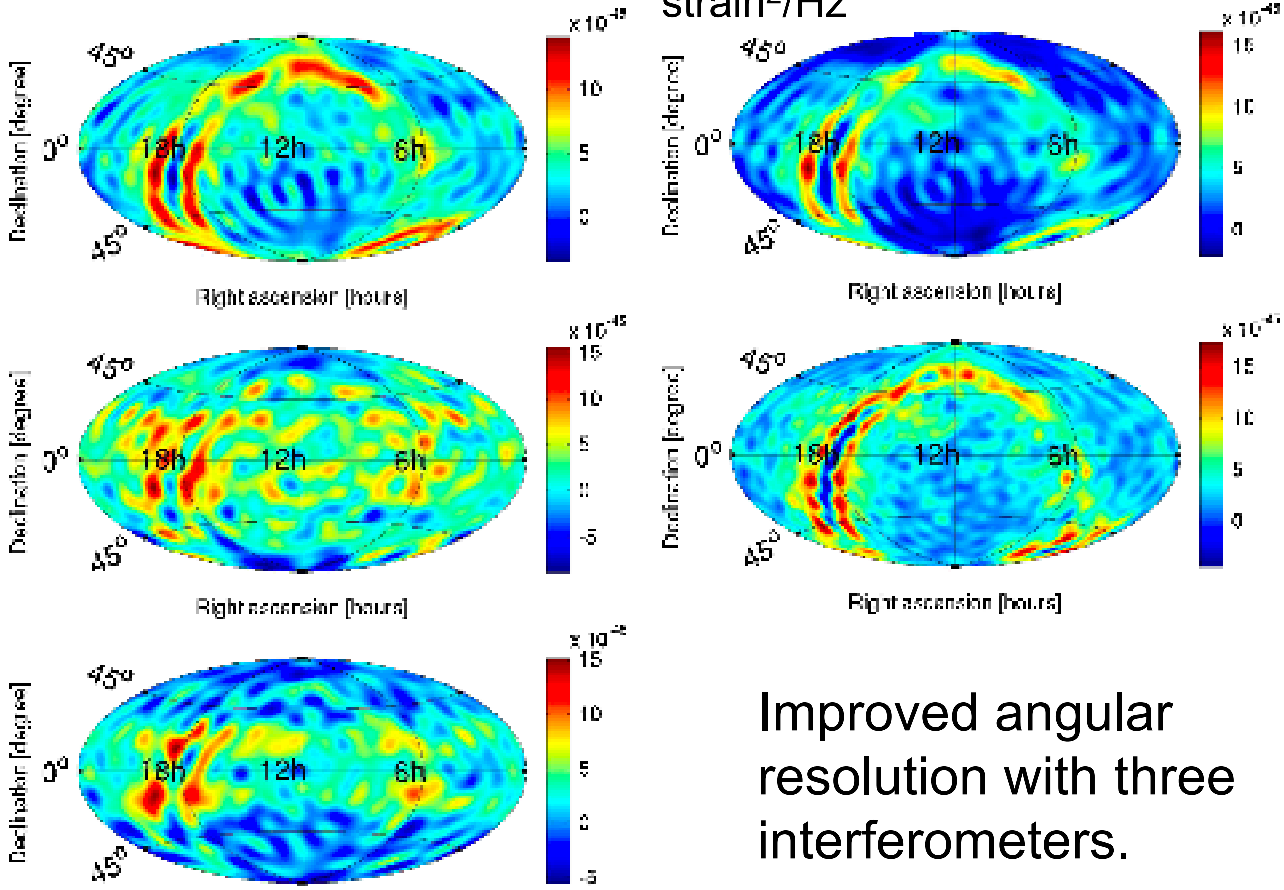
H1L1

H1L1V1

H1V1

source

L1V1

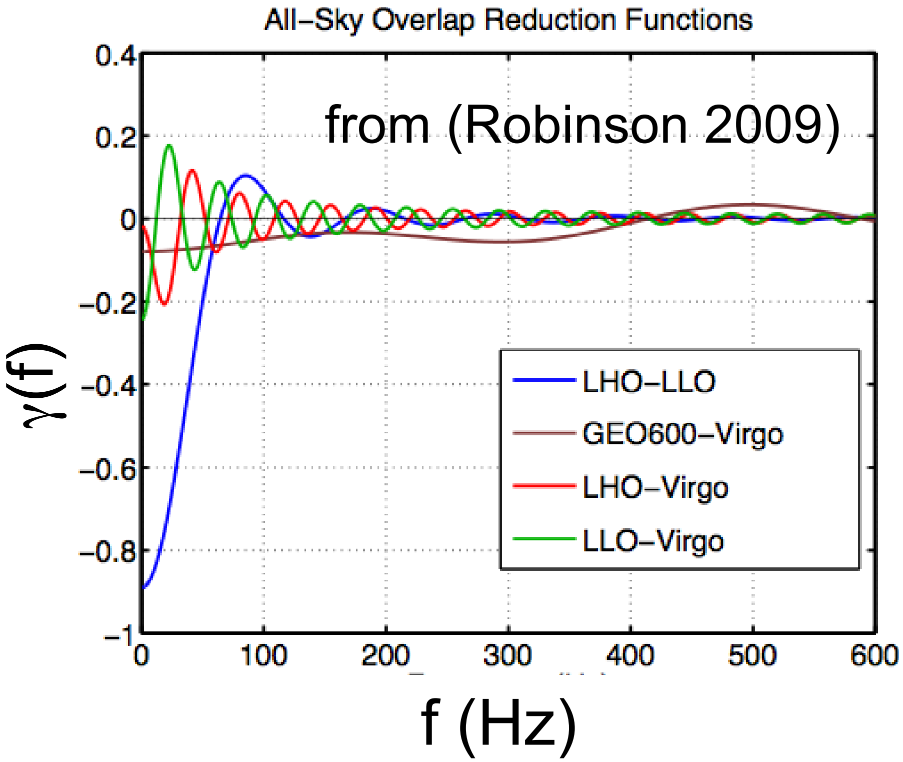


Improved angular resolution with three interferometers.

from (Thrane et al 2009)

≥3 Detector networks

- For isotropic analyses, LIGO+Virgo becomes most useful at high frequencies where LHO-LLO overlap reduction function is small.
- Significant enhancement for analysis of astrophysical sources with the assumption that H(f)~const.



Analyses with co-located interferometers

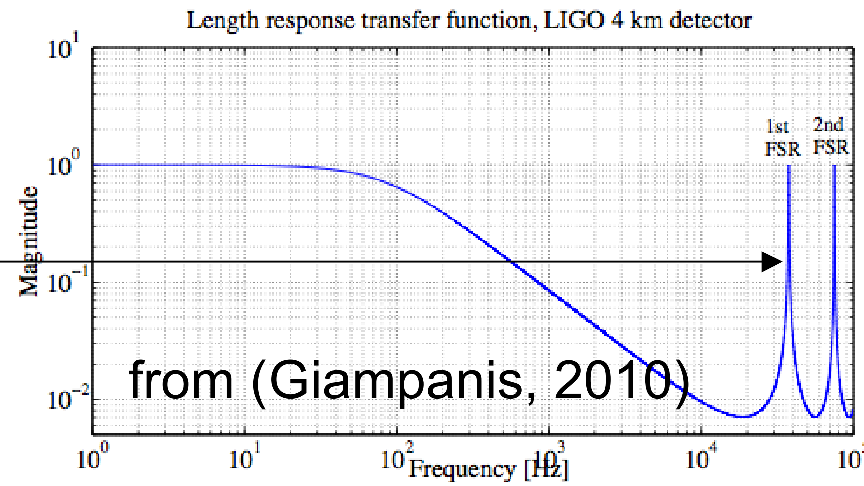
- Two co-located interferometers H1,H2 at LHO.
- Co-located interferometers have $\gamma=1$ at relevant frequencies: ~10x gain in sensitivity.
- However, correlated noise complicates analysis: what if broadband correlated noise mimics (or cancels) SGWB signal?
  - Bayesian model selection scheme (Fotopoulos et al, 2010).
- Noise reduction…

Subtraction of environmental noise

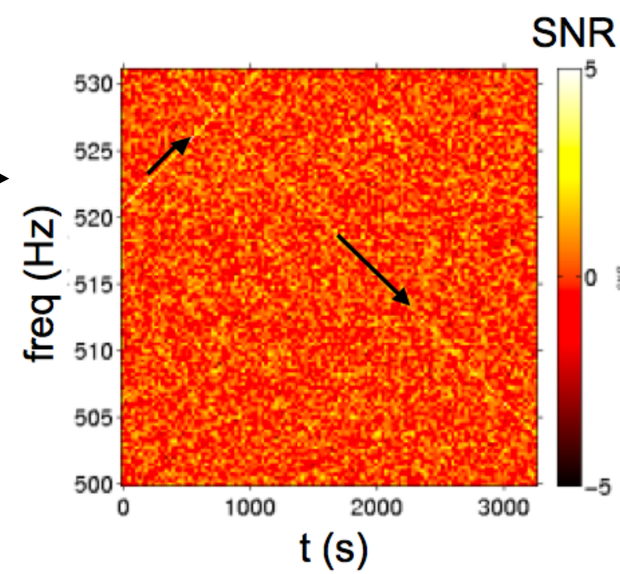
- (Fotopoulos 2006) presents a method for subtraction of noise coherent with environmental sensors (not-sensitive to GWs).
- May be used to remove correlated noise that can be identified with environmental.

Other directions…

- Very-high frequency search at free-spectral range for exotic physics.



- Intermediate-duration transients using stochastic data (see poster).



Non-Gaussian (popcorn) analyses

- Many events, time between events long compared to duration of an event.
- Possible popcorn sources include cosmic strings (Damour & Vilenkin 2001) and supernovae (Marassi et al 2009).
- Maximum likelihood statistic developed by (Drasco & Flanagan 2003) can enhance sensitivity by up to x10.

Conclusions

- LIGO-Virgo S5 stochastic result surpasses indirect bounds in 40-169 Hz band.
- Stochastic analyses from advanced detector era will probe new astrophysics and cosmology (e.g., observe / rule out cosmic strings).
- Many interesting analyses possible with existing interferometers and data.

Literature Cited

Abbott, B. P. et al, Nature **460**, 990-994 (2009)

Abbott, B. et al, PRD, **76** 082003 (2007)

Damour, T. & Vilenkin, A., PRD **64** 064008 (2001)

Drasco, S. & Flanagan, É., PRD **67** 082003 (2003)

Marassi, Schneider, R. & Ferrari, V., MNRAS **398**, 293, 2009

Fotopoulos, N., et al, CQG, **23** S693-S704 (2006)

Fotopoulos, N., et al, in preparation (2010)

Robinson, E., talk at GWDAW-13, Puerto Rico (2003)

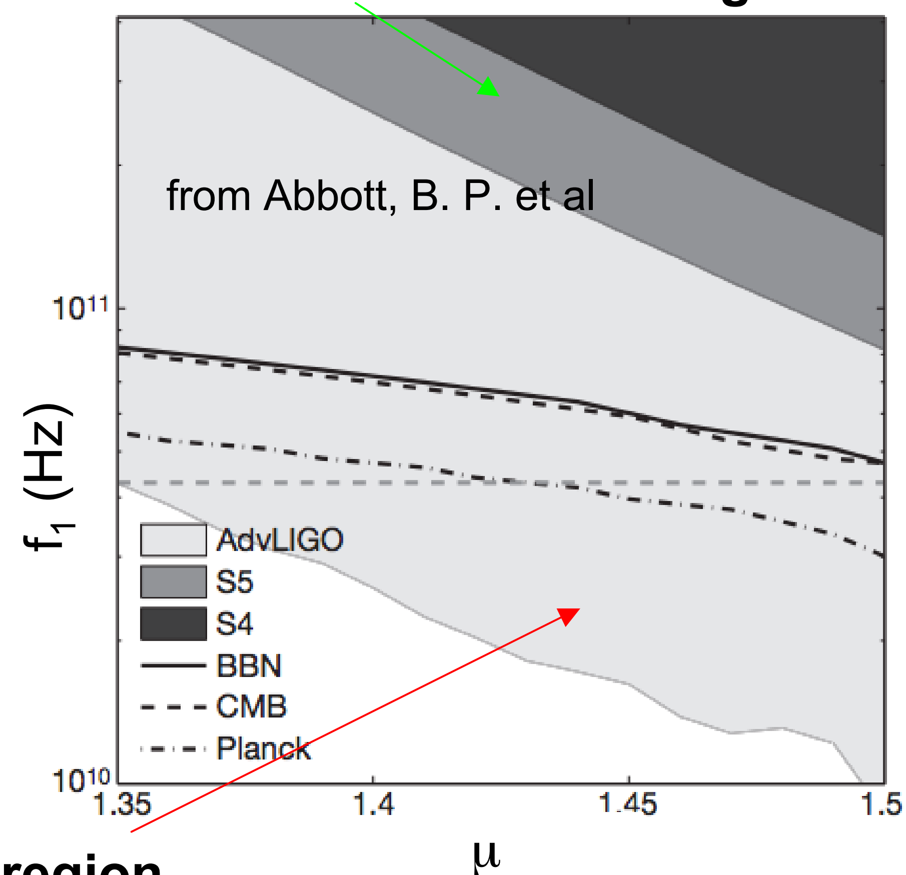
Thrane, E., et al, PRD **80** 122002, 2009

Extra slides

Pre-Big-Bang Models

- Spectrum parameterized in terms of cutoff frequency f_1 and spectral index m such that $\Omega_{GW} \sim f^{3-2\mu}$ above some turnover frequency f_s.
- Right: μ-f_1 exclusion region for f_s=30 Hz.

LIGO S5 exclusion region



predicted AdvLIGO exclusion region