LIGO

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Search for Stochastic Gravitational Waves with LIGO

XLII^nd Rencontres de Moriond

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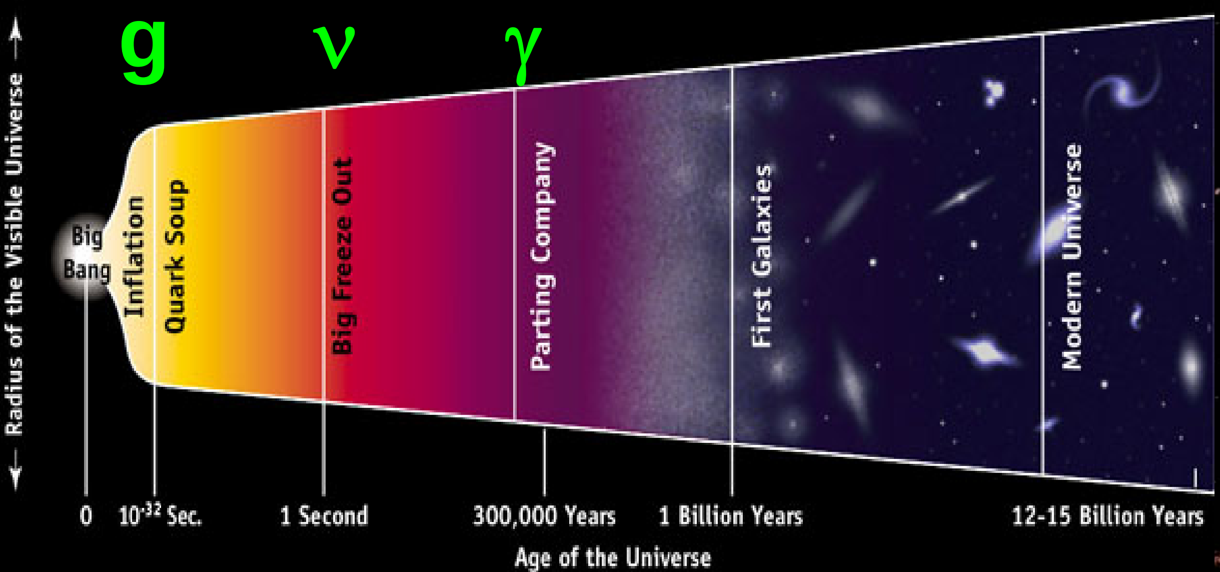
NASA/WMAP Science Team

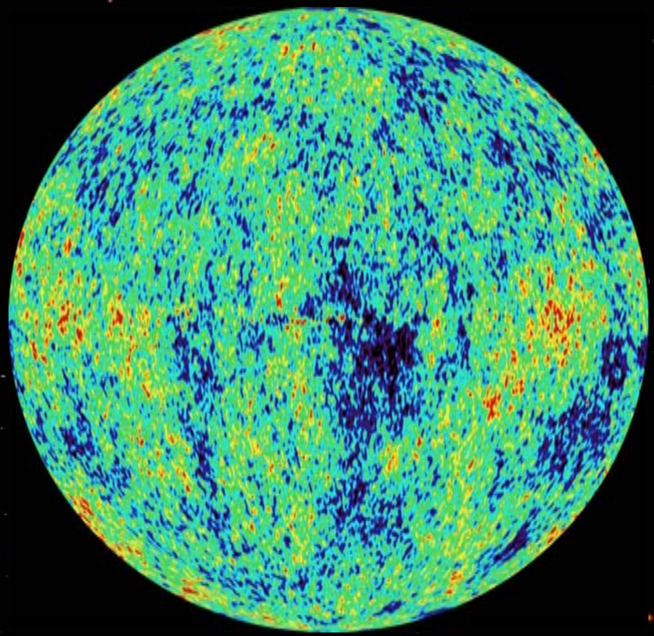
Outline

- Stochastic gravitational waves
  - Sources
  - Characterization of strain
- Search techniques
  - All-sky averaged search
  - Spatially resolved map
- Recent observational results
- Prospects

Stochastic gravitational wave background

- GWs are the able to probe the very early universe





Analog from cosmic microwave background -- WMAP 2003

- Search for a GW background by cross-correlating interferometer outputs in pairs
  - US-LIGO : Hanford, Livingston
  - Europe: GEO600, Virgo
  - Japan: TAMA
- Good sensitivity requires:
  - $\lambda_{GW} \geq 2D$ (detector baseline)
  - $f \leq 40$ Hz for LIGO pair over 3000 km baseline
  - Good low-f sensitivity and short baselines

Stochastic signals

Cosmological processes

- Inflation -- flat spectrum (Turner)
- Phase transitions -- peaked at phase transition energy scale (Kamionkowski)
- Cosmic strings -- gradually decreasing spectrum (Damour & Vilenkin)
- Pre big-bang cosmology -- rising strength with f (Buonanno et al.)

Astrophysical Foregrounds

- Incoherent superposition of many signals from various signal classes (Ferrari, Regimbau)
  - Coalescing binaries
  - Supernovae
  - Pulsars
  - Low Mass X-Ray Binaries (LMXBs)
  - Newly born neutrons stars
    - Normal modes - R modes
  - Binary black holes
  - Black hole ringdowns
- Gaussian -> non-Gaussian ("popcorn" noise) depending on rates

  Drasco & Flannigan, Phys.Rev. D67 (2003)
- Spectra follow from characteristics of individual sources -- e.g., spatial anisotropy for nearby (foreground) contributors

Characterization of a Stochastic Gravitational Wave Background

- **GW energy density given by time derivative of strain**

$$\rho_{gw} = \frac{1}{32\pi G}\overline{\dot{h}_{ij}(t)\dot{h}_{ij}(t)}$$

- **Assuming SGWB is isotropic, stationary and Gaussian, the strength is fully specified by the energy density in GWs**

$$\frac{\rho_{gw}}{\rho_c} = \int_0^{\infty} \Omega_{gw}(f) d\ln f$$

- ***Ω(f)* in terms of a *measurable* strain power spectrum, $S_{gw}(f)$:**

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

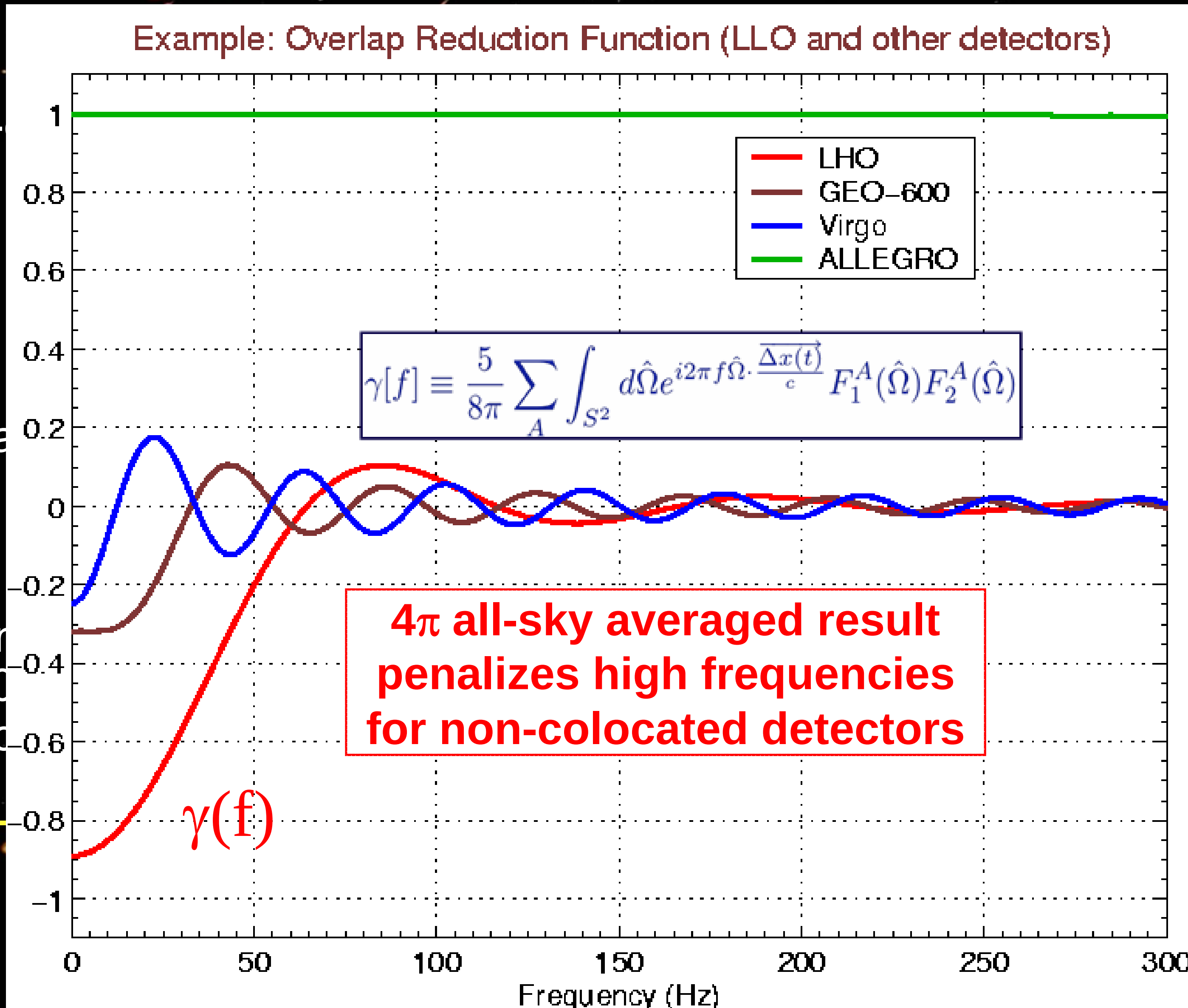
- **Strain amplitude scale:**

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

Allen & Romano, *Phys.Rev. D59 (1999)*

Technique -- Sky-averaged search
Time-independent Detection Strategy

- Cross-



df

$(f)|^2$

- Optima

$\frac{(f)}{(f)}$

- Make r
(T = 60
variatio

$Y_i = \Omega_i T$ … $1/\sigma_i^2$

Sensitivities of LIGO interferometers during S4

22 February - 23 March 2005

H1 - L1: 353.9 hr
H2 - L1: 332.7 hr.

Scheduled for publication March 2007 : ApJ 658 (2007)

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

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improves sensitivity reach over
individual noise floors.

Run Averaged Coherences: A measure of intrinsic sensitivity

$$\Gamma(f) \equiv \frac{|P_{12}(f)|^2}{P_1(f)P_2(f)}$$

H1 - L1

1 Hz comb due to GPS timing pulse

Distribution of coherence follows expected exponential PDF

1/N noise floor

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TIFF (LZW) deco decompressor
are needed to see thee this picture.

H2 - L1

16 Hz Data Acq. + injected lines

Histogram of normalized measurement residuals

- **Make a measurement every 192s**
- **Look at statistics of measurements to determine whether they are Gaussian**

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T_{obs} = 353.9 hr
N_{seg} = 12637
(after cuts)

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

All-sky averaged results for S4

LIGO

H1 - L1

Evolution of measurement over time

Optimally combined spectrum: H1 - L1 & H2 - L1

H1 - L1: 353.9 hr; N_{seg} = 12,637
H2 - L1: 332.7 hr; N_{seg} = 11,849

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Standard deviation of measurement

Modulation of envelope due to $\gamma(f)$

- Scheduled for publication in ApJ 658 (March 2007)

90% Bayesian upper limit vs. spectral index, α

$$\Omega(f) \equiv \Omega_\alpha \left(\frac{f}{100\text{Hz}}\right)^\alpha$$

S4 result: $\Omega_0 < 6.5 \times 10^{-5}$ (90% U.L.)

$$\Omega_{expt,S4} = \int Y(f)df = -8 \times 10^{-6}$$

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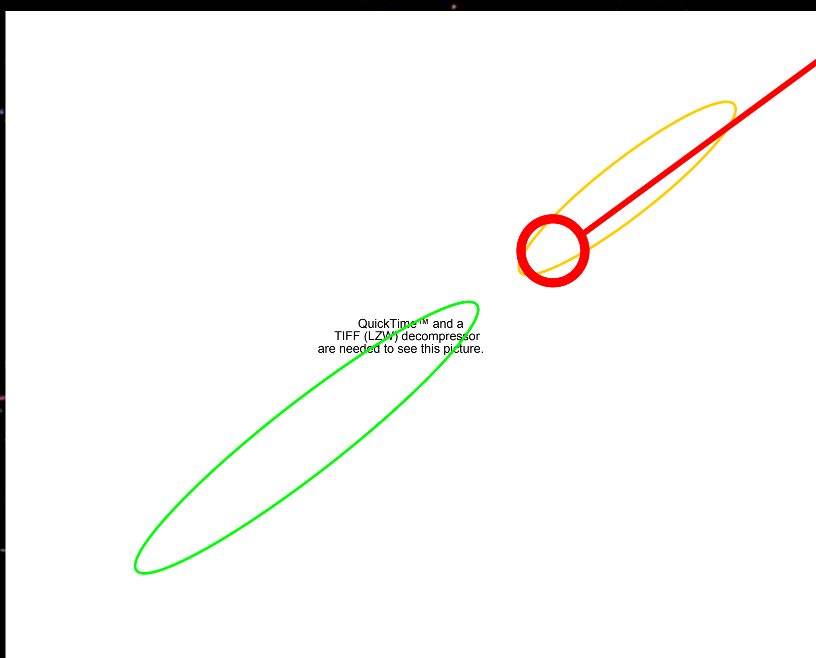
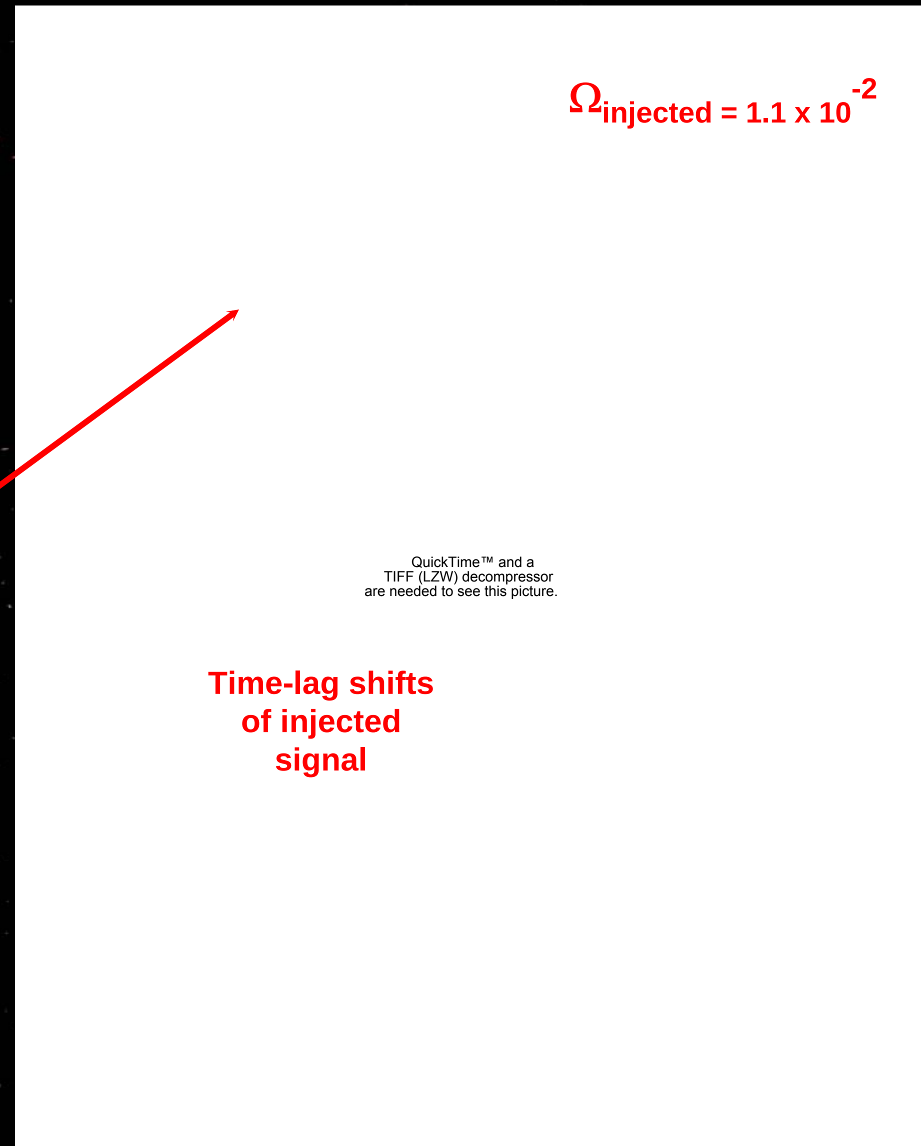
$$\sigma_{expt,S4} = \sqrt{\int sigma_Y^2(f)df} = 4.3 \times 10^{-5}$$

Tests with signal injections Hardware & Software

- HW: Introduce coherent excitation of test masses (WA - LA) with a spectrum simulation a constant $\Omega_{GW}(f)$ background with different strengths
- SW: Simulated signal added to strain signal





The Stochastic GW Landscape

H_0 = 72 km/s/Mpc

Armstrong,
ApJ 599 (2003) 806

Smith et al.,
PRL 97 (2006) 021301

Kolb & Turner,
The Early Universe (1990)

Jenet et al.,
ApJ 653 (2006) 1571

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Allen&Koranda,
PRD 50 (1994) 3713

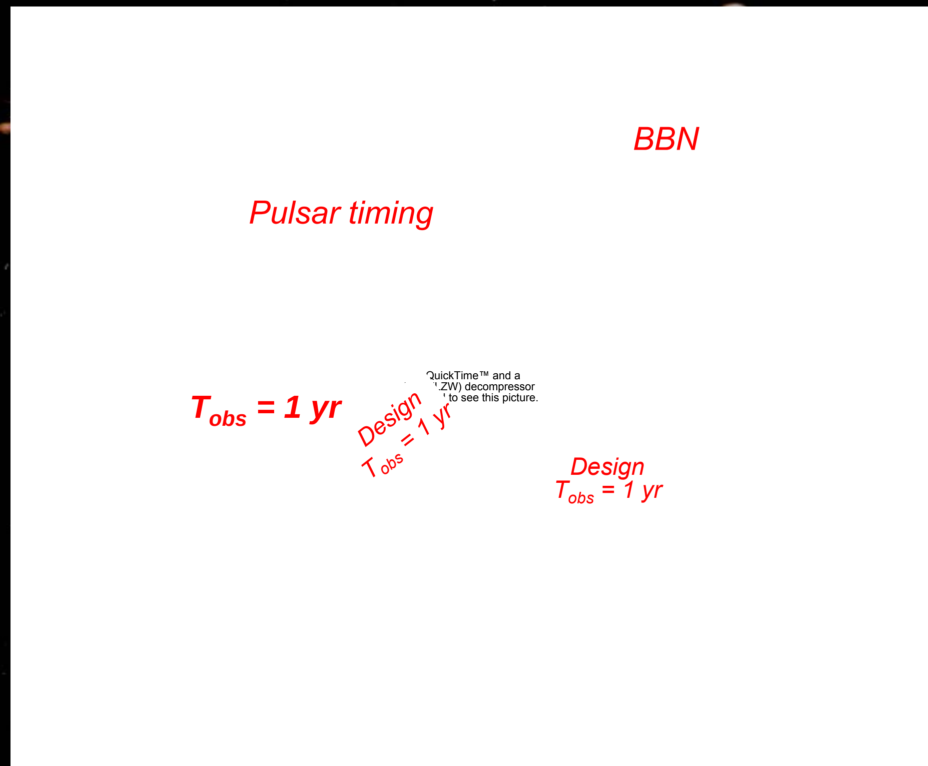
Damour & Vilenkin
PRD 71 (2005) 063510

Buonanno et al.,
PRD 55 (1997) 3330

Gasperini & Veneziano,
Phys. Rep. 373 (2003) 1

Turner,PRD 55 (1997) 435

S4 all-sky observations
Implications for Cosmic strings



- Model of Damour & Vilenkin
- p: probability for reconnection
- Gμ: string tension - regime accessible by LIGO
- ε: loop size - regime accessible by LIGO

Spatially-resolved search
Time-dependent Detection Strategy

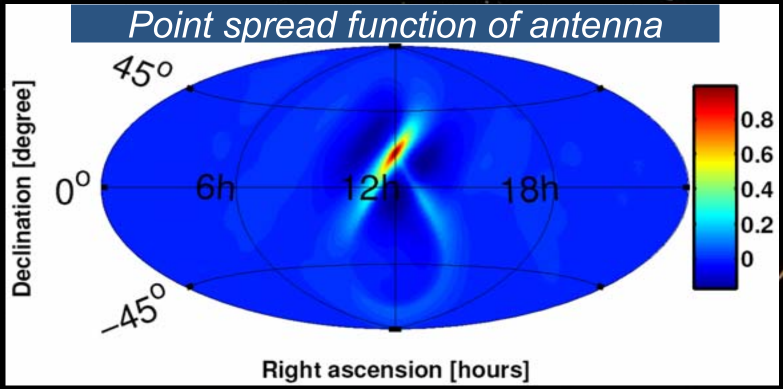
- Time-dependent overlap reduction function tracks a point in the sky over the sidereal day:

$$\gamma_{point}(f,t:\widehat{\Omega}) = \frac{1}{2}\sum_A e^{i2\pi f\hat{\Omega}\cdot\frac{\Delta\vec{x}}{c}} F_1^A(\hat{\Omega})F_2^A(\hat{\Omega})$$

- Time dependent optimal filter enables spatially resolved measurement:

$$\widetilde{Q}(f,t:\widehat{\Omega}) = \frac{\gamma(f,t:\widehat{\Omega})\Omega_{gw}^{model}(f)}{f^3P_1(f)P_2(f)}$$

- Characteristic size of point spread function:
  - λ/D
  - ~ 11^o @ 500 Hz for D = 3000 km
  - Diffraction-limited GW astronomy



Spatially resolved search with S4
Simulations & Validation

Detection of an injected hardware pulsar simulation

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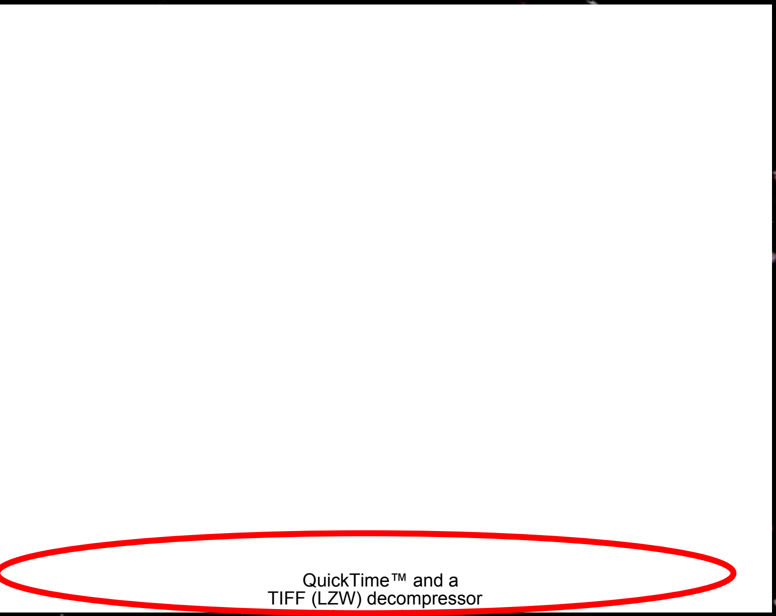
Pulsars Hardware Injection			
Parameter	Pulsar3	Pulsar4	Pulsar8
Freq. during S4	108.86 Hz	1402.20 Hz	193.94 Hz
Estimate Hdf on source	1.74×10^{-46}	4.05×10^{-44}	1.79×10^{-46}
Error bar	1.89×10^{-47}	6.04×10^{-46}	1.73×10^{-47}
SNR	9.2	67.1	10.3
inj. Hdf	1.74×10^{-46}	4.28×10^{-44}	1.54×10^{-46}

Upper limit sky maps

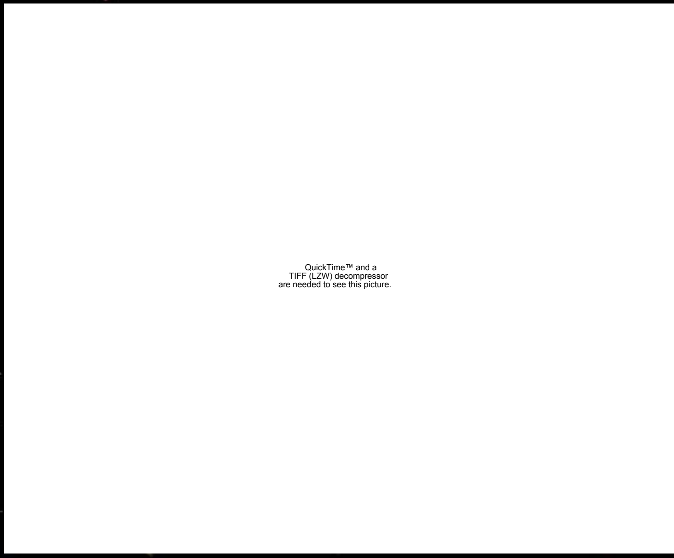
No detection of signal at S4 sensitivity

Submitted to PRD; arXiv:astro-ph/0701877v1



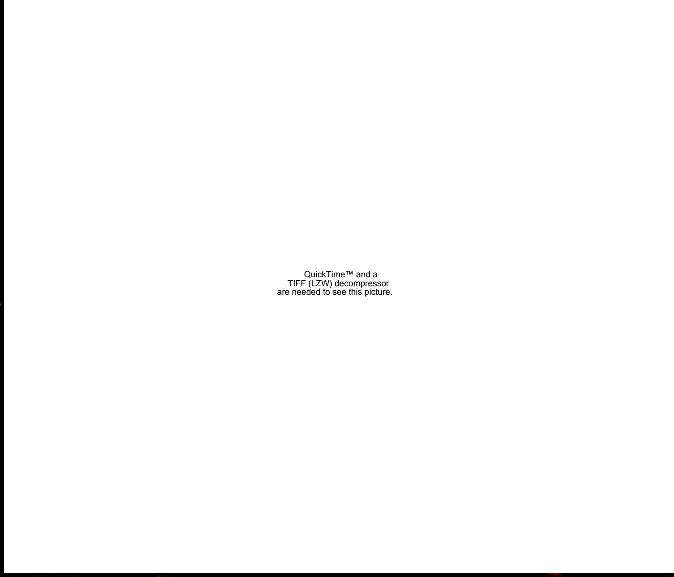
$\Omega_{GW}(f)$ ~ const Results

- Integration over sky yields sky-averaged result that is consistent with the all-sky technique within measurement errors
- Distribution of signal consistent with Gaussian PDF with 100 DOFs (# of independent sky patches)
- ***90% Bayesian UL:*** *$\Omega_{GW} < 1.02 \times 10^{-4}$*



$\Omega_{GW}(f)$ ~ f^3 Results

- Distribution of signal consistent with Gaussian PDF with 400 DOFs (# of indpendent sky patches)
- ***90% Bayesian UL:*** *$\Omega_{GW}(f) < 5.1 \times 10^{-5} (f/100Hz)^3$*



Use spatially resolved stochastic search technique to look for periodic emissions of unknown f: Sco-X1

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Template-less search: use signal in one detector as the “template”

QuickTime™ and a
TIFF (LZW) decompressor
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Summary - S4 results

- All-sky measurement: $\Omega_0 h_{72}^2 < 6.5 \times 10^{-5}$
  - 13X improvement over previous (S3) result
  - Still weaker than existing BBN limit
  - S4 (and previous S3) are starting to explore, restrict parameter space of some stochastic models, such as cosmic strings and pre-big bang
  - The S5 data analysis is in progress -- should beat the BBN limits for models in which signal is concentrated in the LIGO band

- Spatially resolved measurements:
  - New technique that exploits phased-array nature of the LIGO site pairs to steer beam and to track sky positions
  - All-sky result follows as a subset of the measurements
  - Approach can be used look for a number of astrophysical foregrounds, by changing the optimal filter to match the source properties
  - Work ongoing to (i) implement deconvolution of antenna point spread function from raw maps; (ii) decompose map into spherical harmonics basis functions, analogous to CMB maps.

- Expected sensitivities with one year of data from LLO-LHO:
  - Initial LIGO $\Omega_0 h^2 < 2 \times 10^{-6}$
  - Advanced LIGO $\Omega_0 h^2 < 7 \times 10^{-10}$

FINIS

I□□rinsic Sensitivity: σ_Y Trend for Entire Run

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

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