Searching for Big Bang relicts with LIGO

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For the LSC/VIRGO collaboration
GW2010, University of Minnesota
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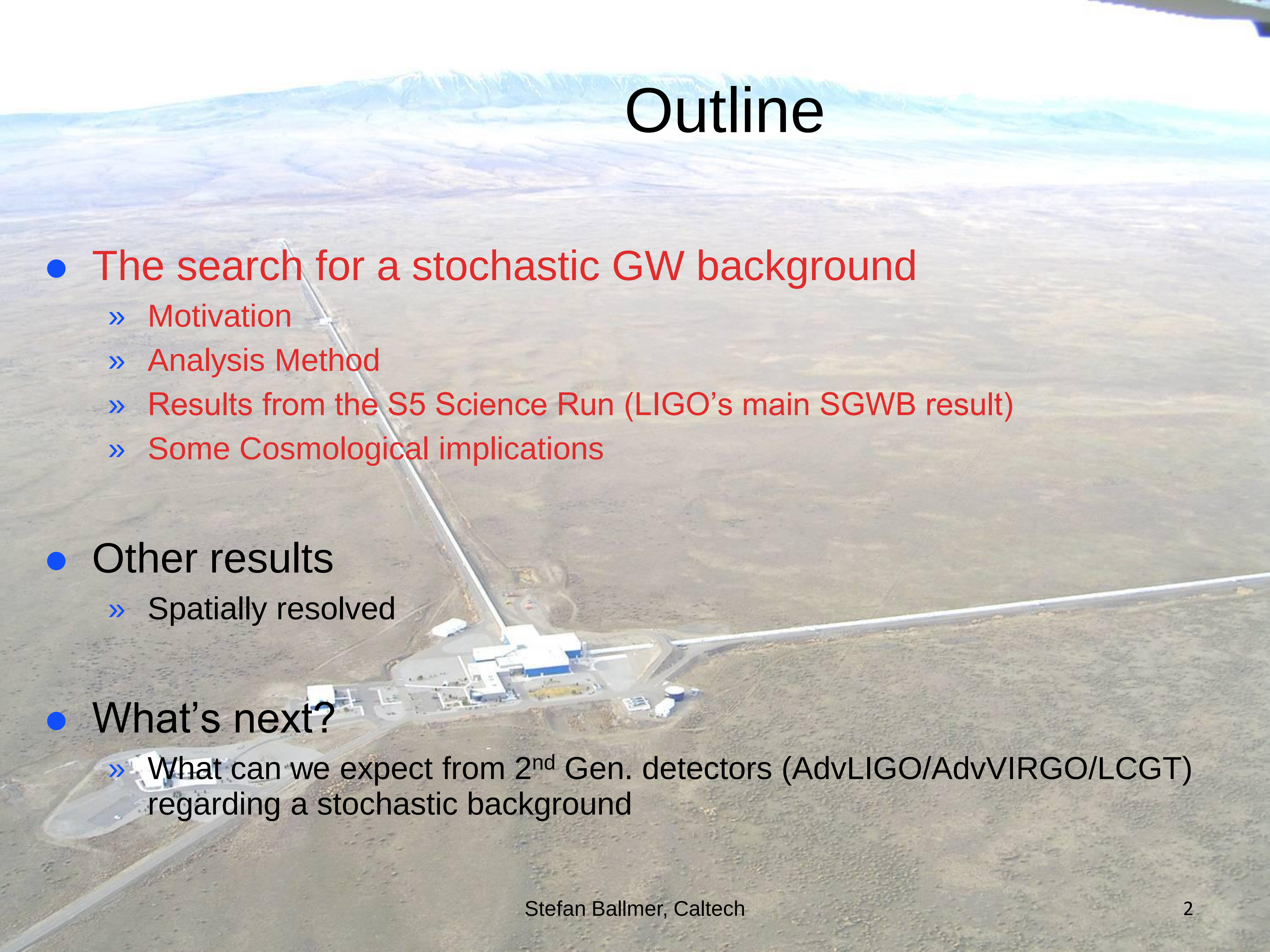
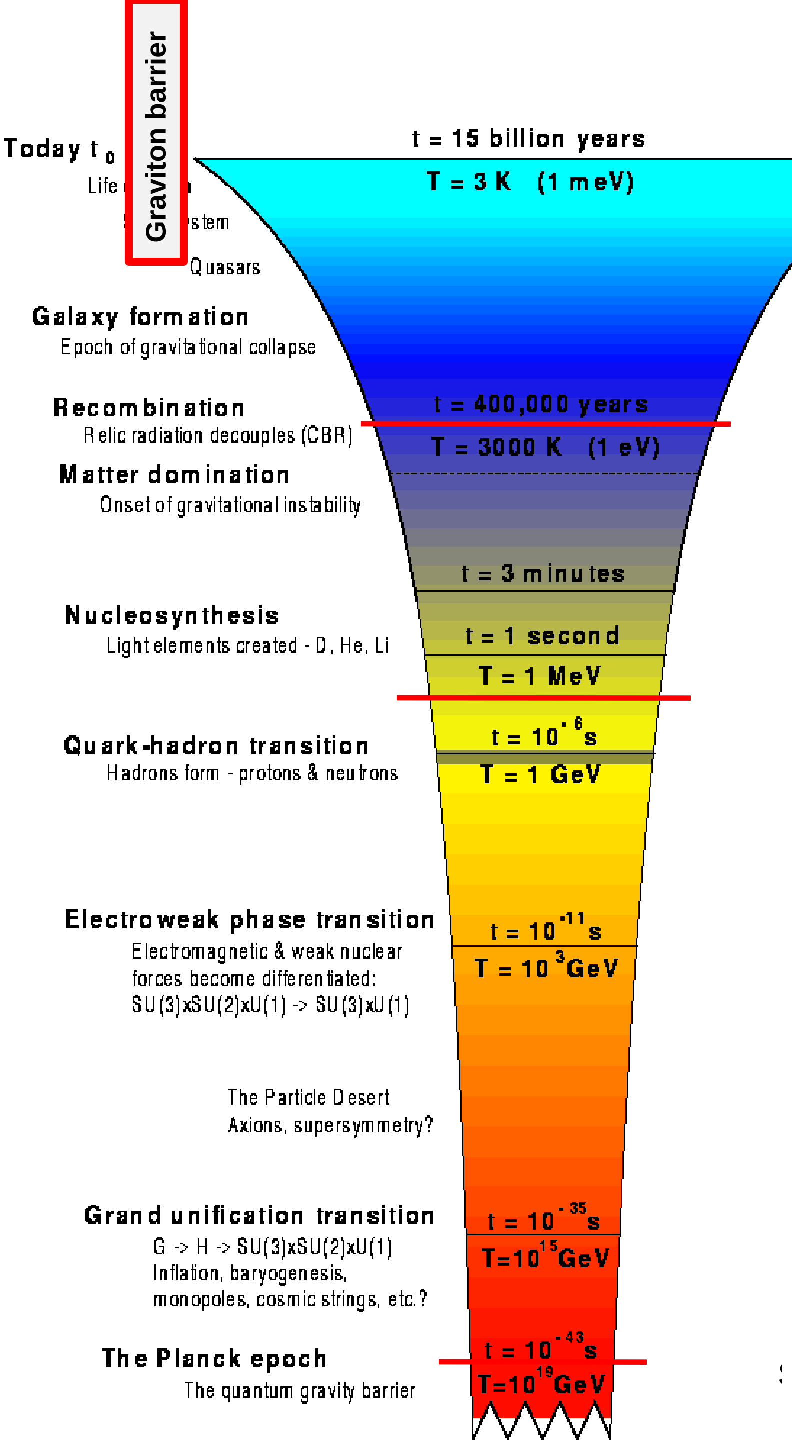
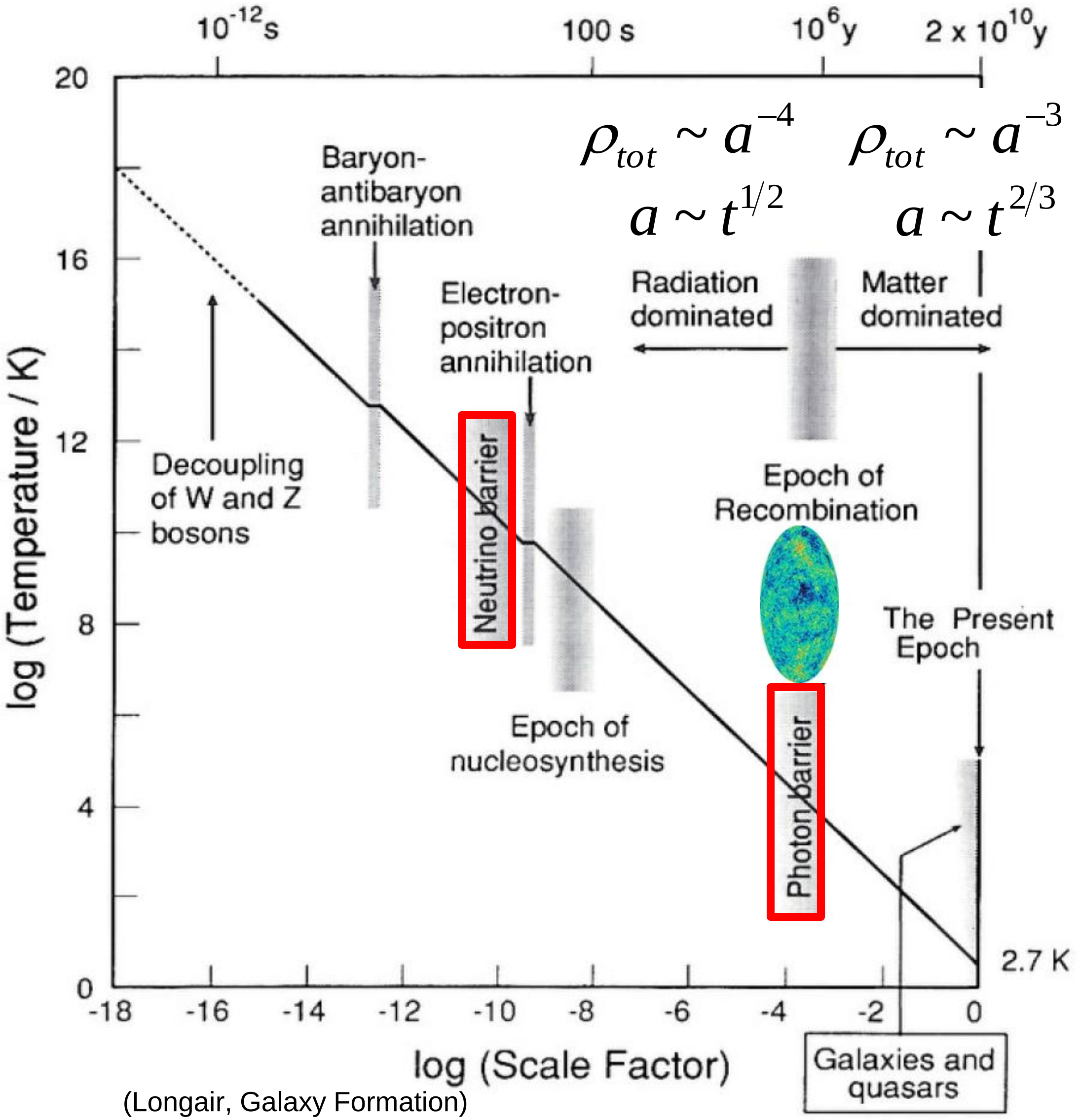


Outline

- The search for a stochastic GW background
  - » Motivation
  - » Analysis Method
  - » Results from the S5 Science Run (LIGO’s main SGWB result)
  - » Some Cosmological implications
- Other results
  - » Spatially resolved
- What’s next?
  - » What can we expect from 2nd Gen. detectors (AdvLIGO/AdvVIRGO/LCGT) regarding a stochastic background

Primordial Background
A brief history…





(Longair, Galaxy Formation)

Stochastic Background of Gravitational Waves

- Energy density:

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

- Characterized by log-frequency spectrum:

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

- Related to the strain power spectrum:

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

- Strain scale:

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

Detection Strategy

- Cross-correlation estimator

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

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

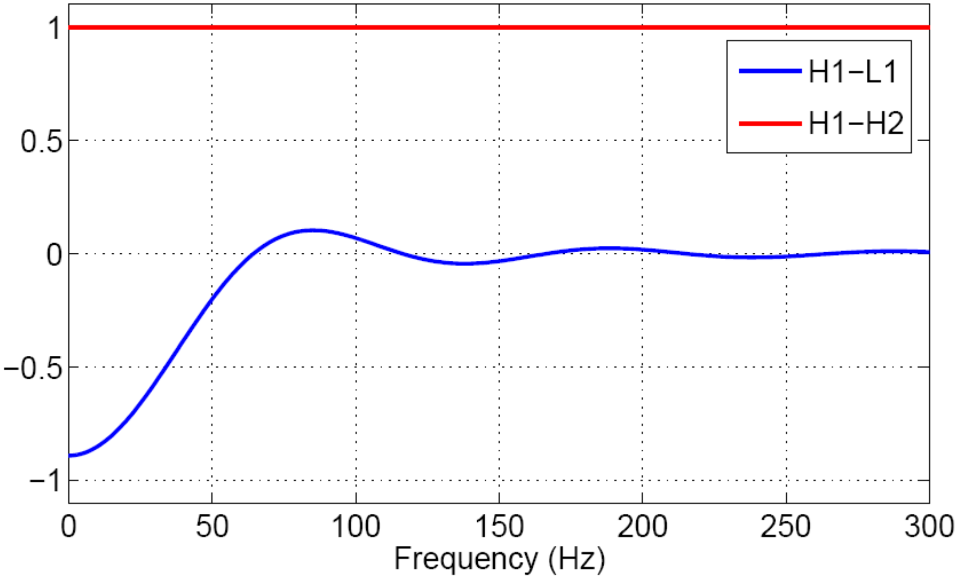
- Theoretical variance

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

- Optimal Filter

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

Overlap Reduction Function



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

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

Analysis Details

- Frequency band (99% of sensitivity):
  - **41.5-169.25 Hz**

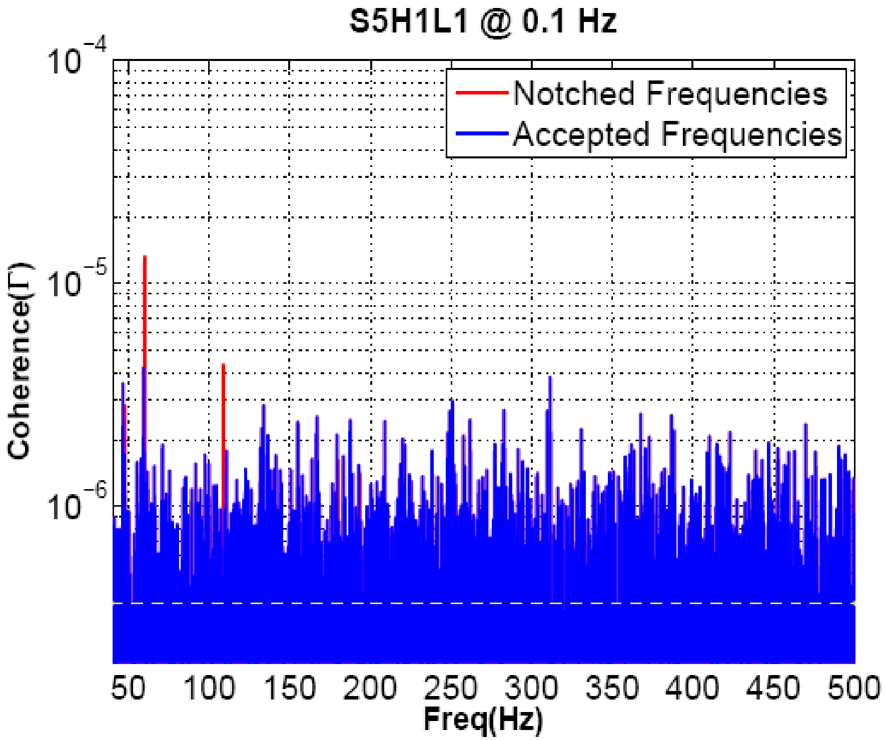
- H1L1 and H2L1 pairs analyzed and combined. (weighted average)

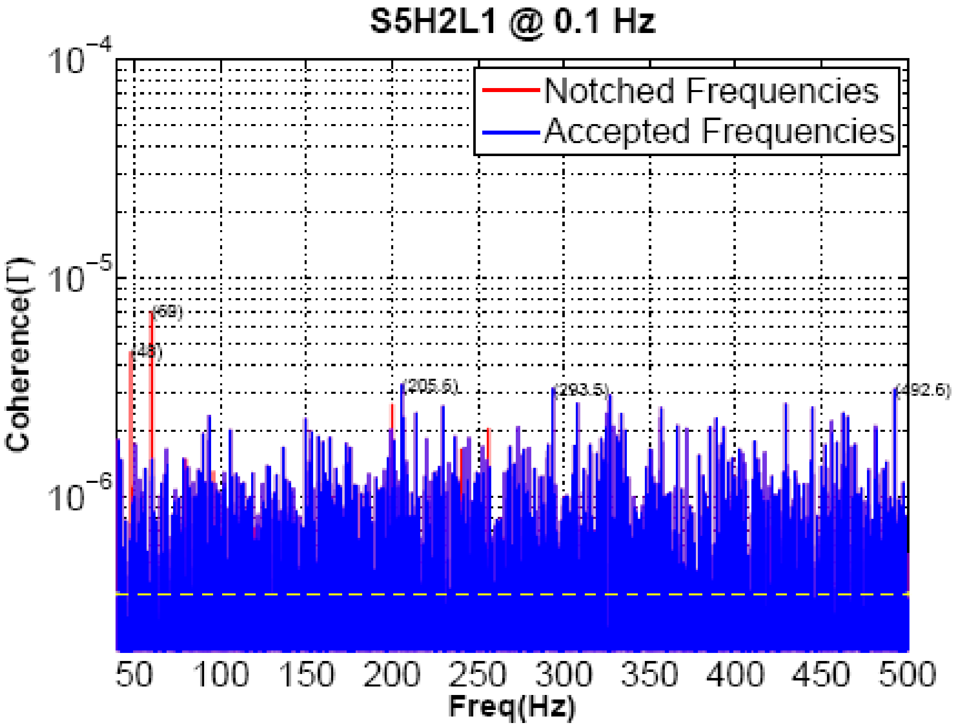
- S5 run effective time:
  - 292 days (H1L1)
  - 294 days (H2L1).

Coherence: 100 mHz

$$\mathrm{Coh} = \mathrm{CSD}^2 / \mathrm{PSD}_1 / \mathrm{PSD}_2$$

- H1L1:
  - » 48 Hz, injected pulsars, 60 Hz harmonics
- H2L1:
  - » 16 Hz harmonics, 100 Hz harmonics, injected pulsars, 60 Hz harmonics





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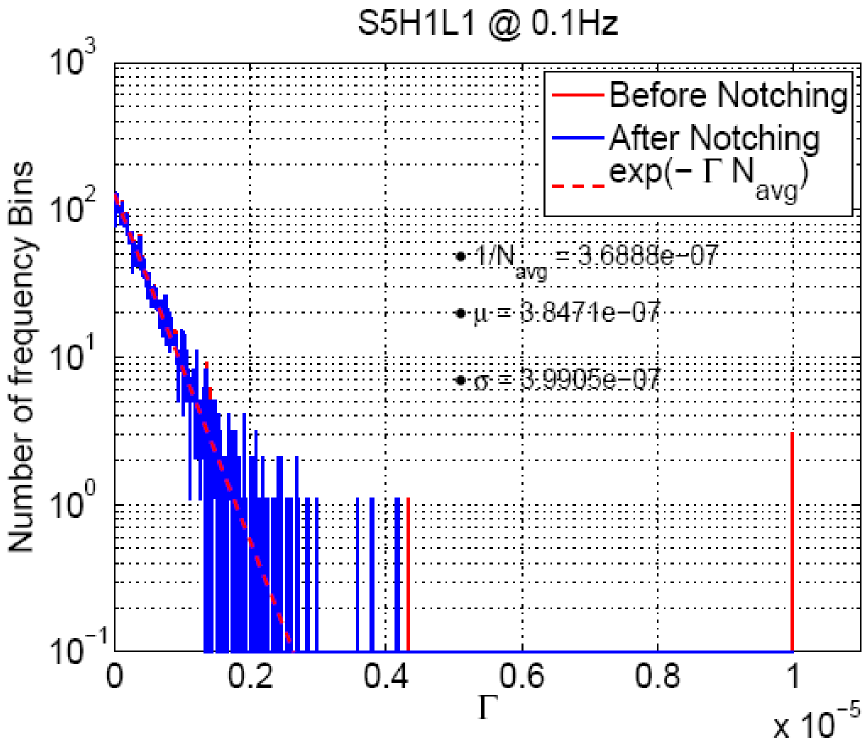

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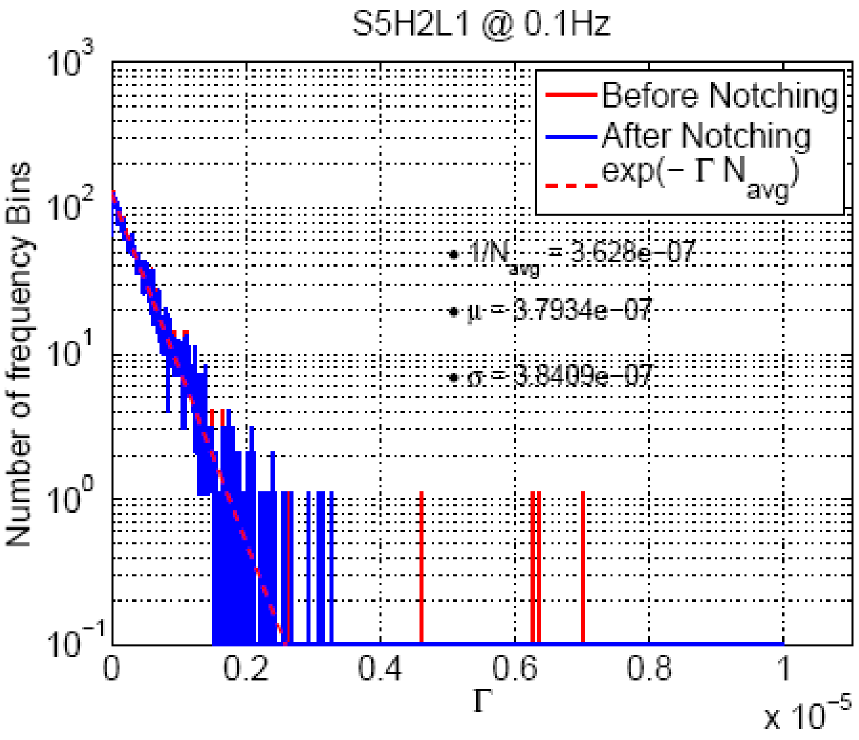

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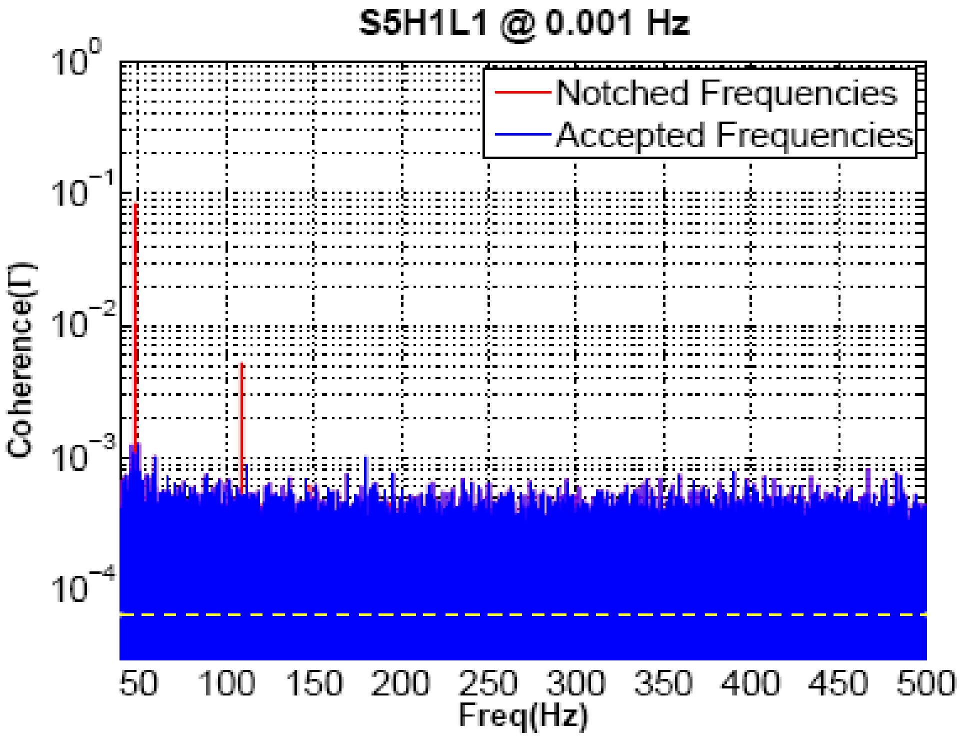

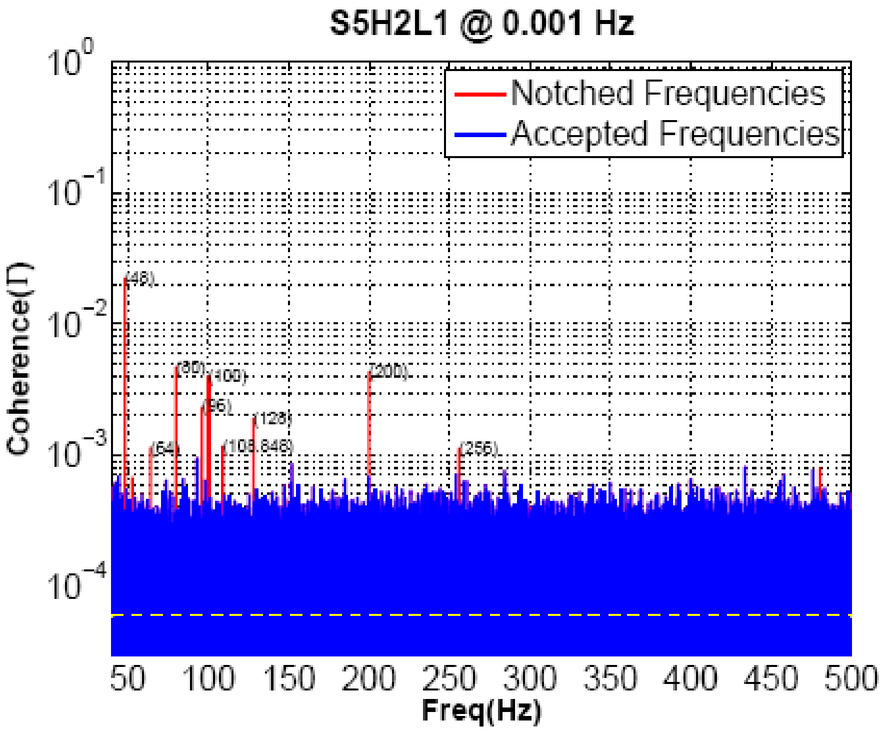

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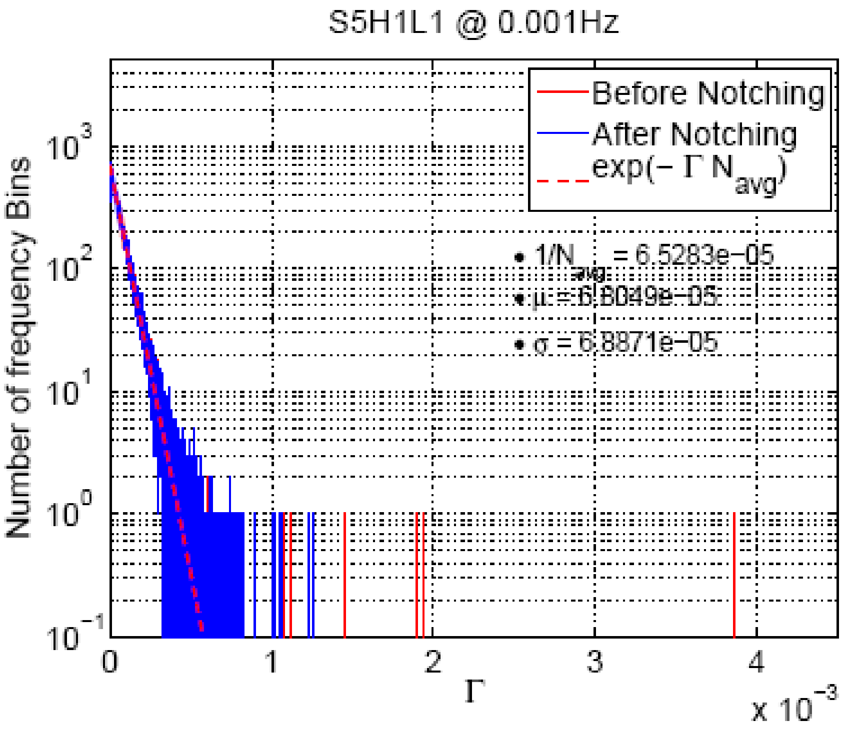
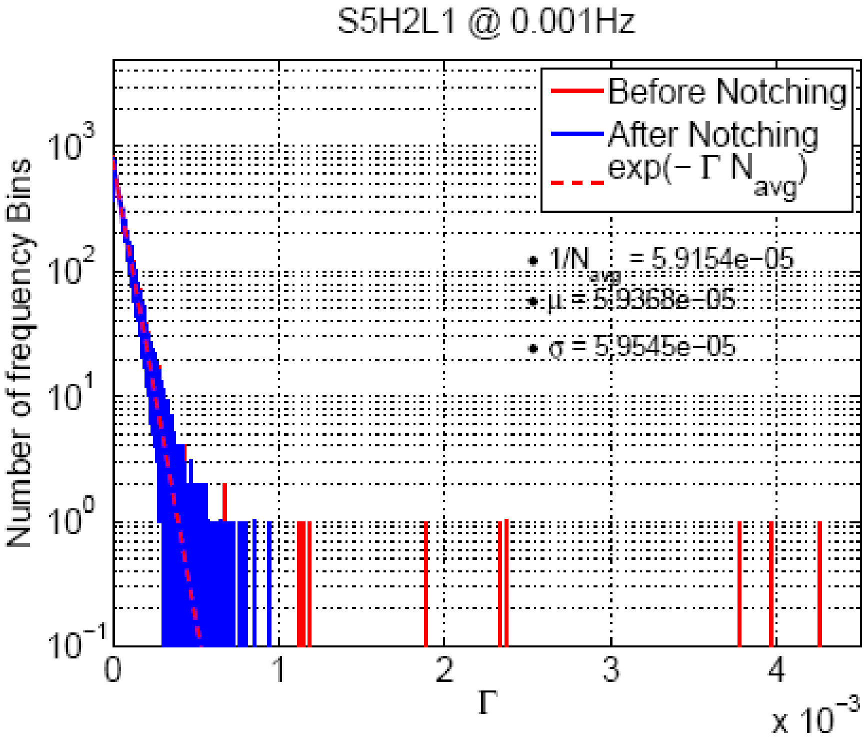
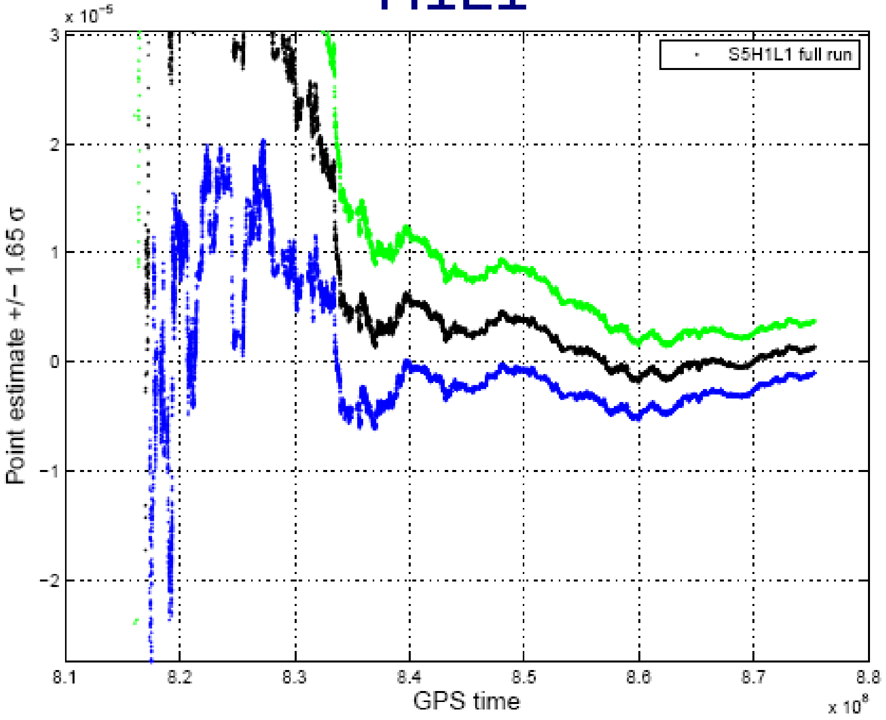


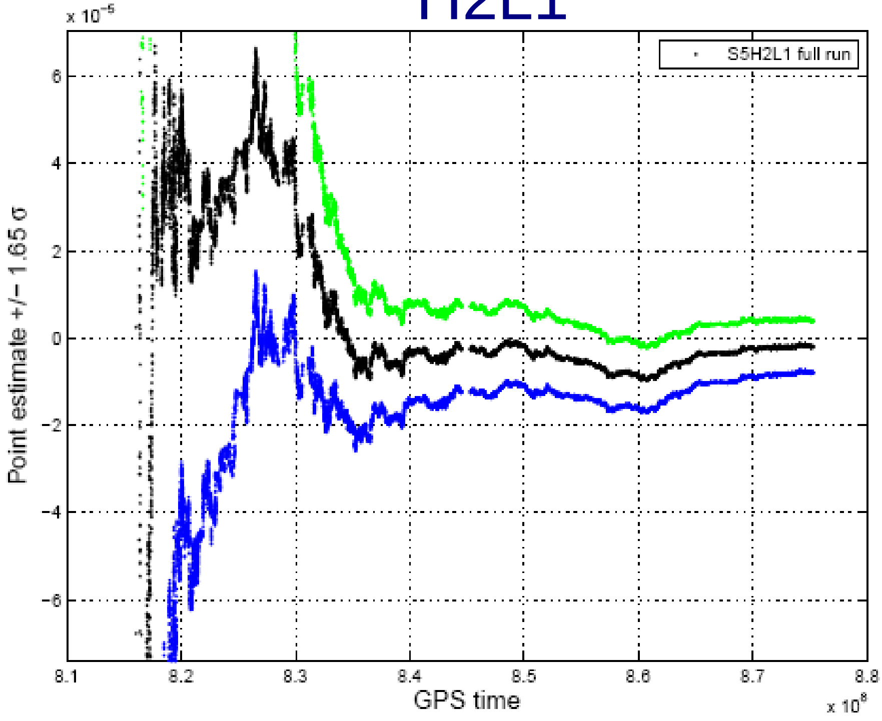


Running Point Estimates

H1L1

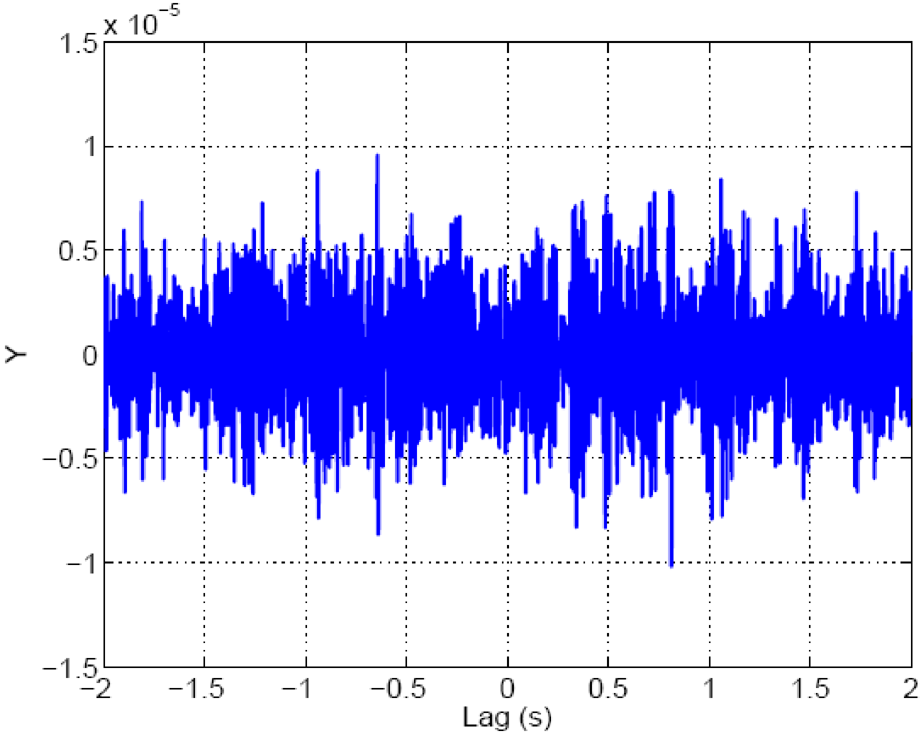


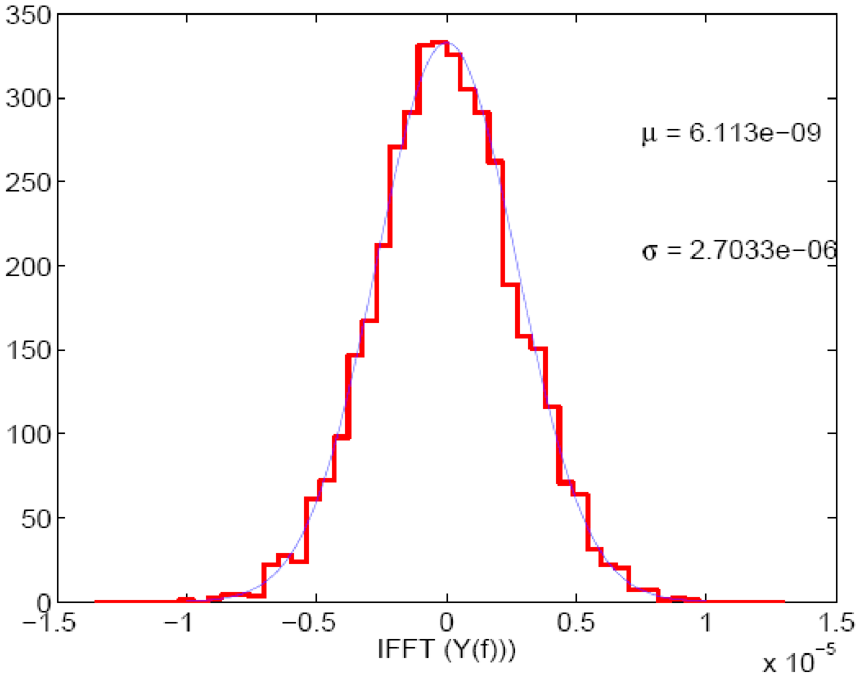
H2L1



IFFT of Y(f)

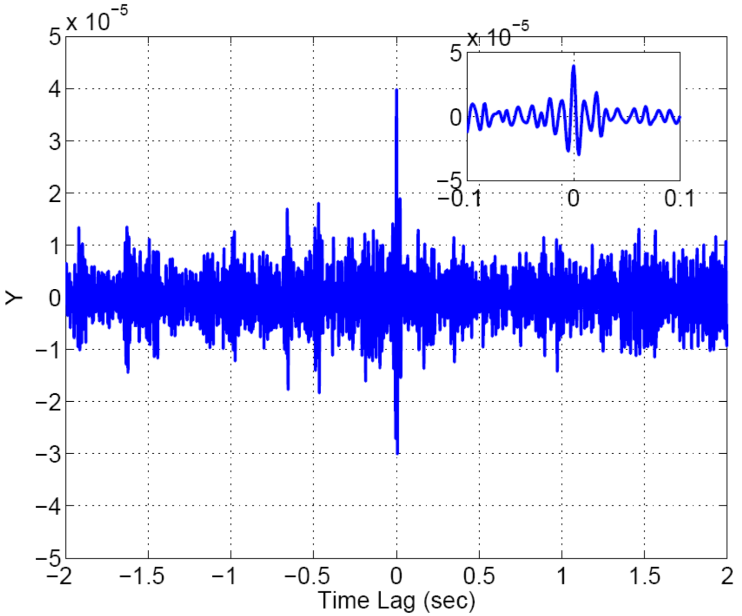
- IFFT of Y(f) provides Y as a function of time-lag between two sites.
- No signal observed at any lag.
- Distribution consistent with the theoretical variance.

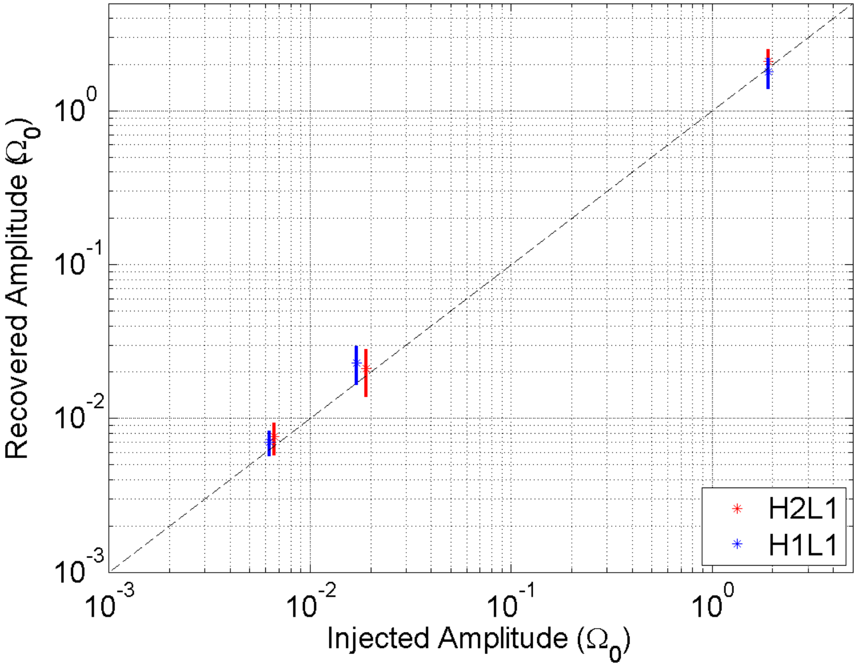




Signal Injections

- Software injections:
  - » Signal added to data in software.
  - » Successfully recovered down to Ω ~ 4 × 10^{-5}.





» Hardware injections:
  - – Physically moving the mirrors.
  - – Successfully performed and recovered three injections (within errors).

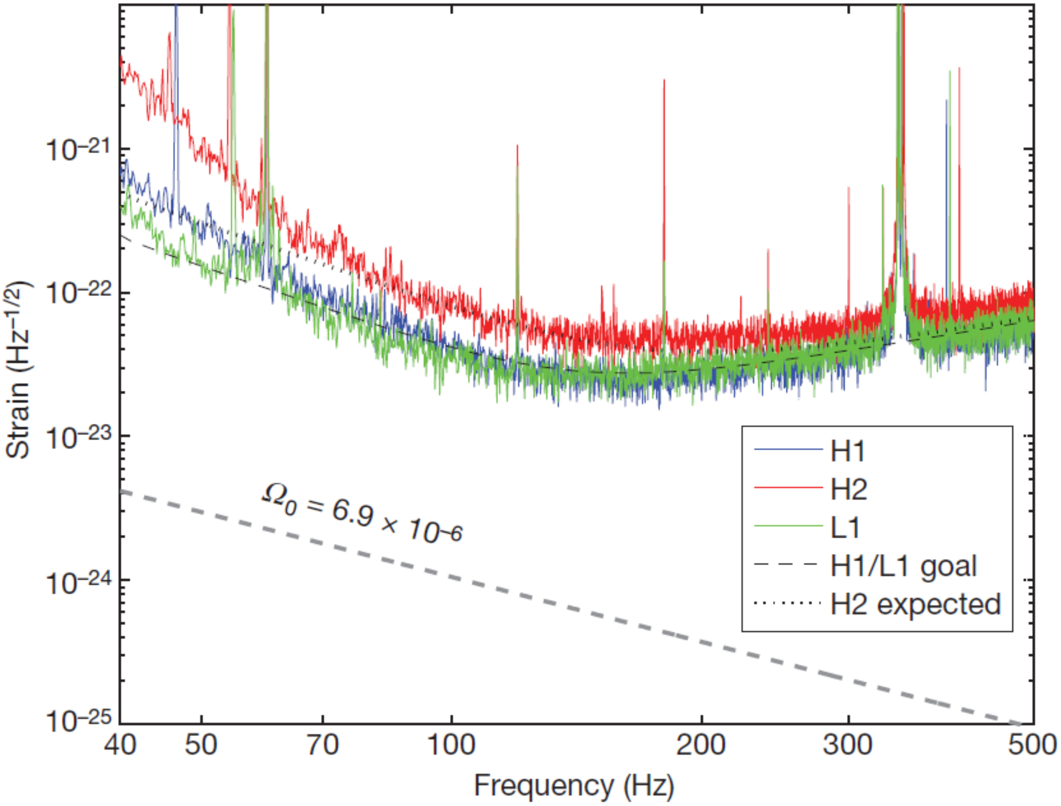
Science Run S5

- Final S5 isotropic result:
  $\Omega \pm \sigma_\Omega = (2.1 \pm 2.7) \times 10^{-6}$

- Bayesian 95% UL:
  - » Prior on Ω: S4 Posterior
  - » Marginalize over calibration uncertainties
    - – 13% for L1
    - – 10% for H1, H2.

- 95% upper limit 6.9×10^{-6}.

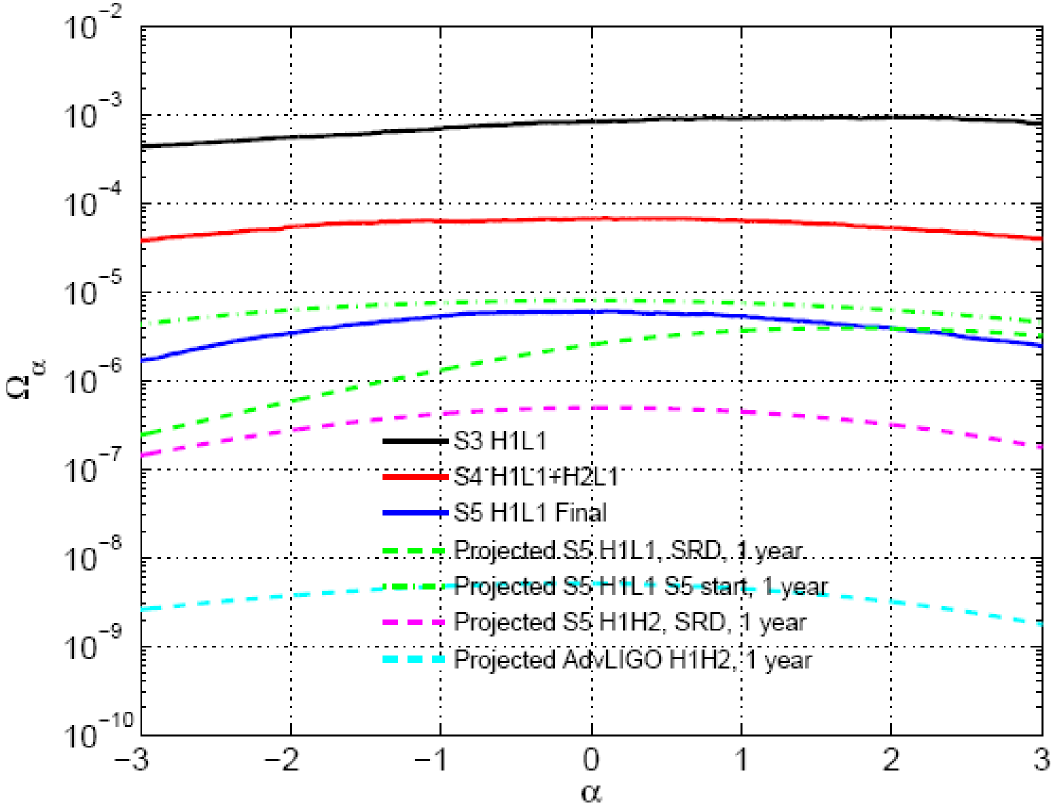
Typical strain sensitivities during S5.



B. Abbott et al., Nature 460, 990 (2009).

Reach as a Function of Spectral Slope

$$\Omega_t(f) = \Omega_\alpha(f/100\ \mathrm{Hz})^\alpha$$



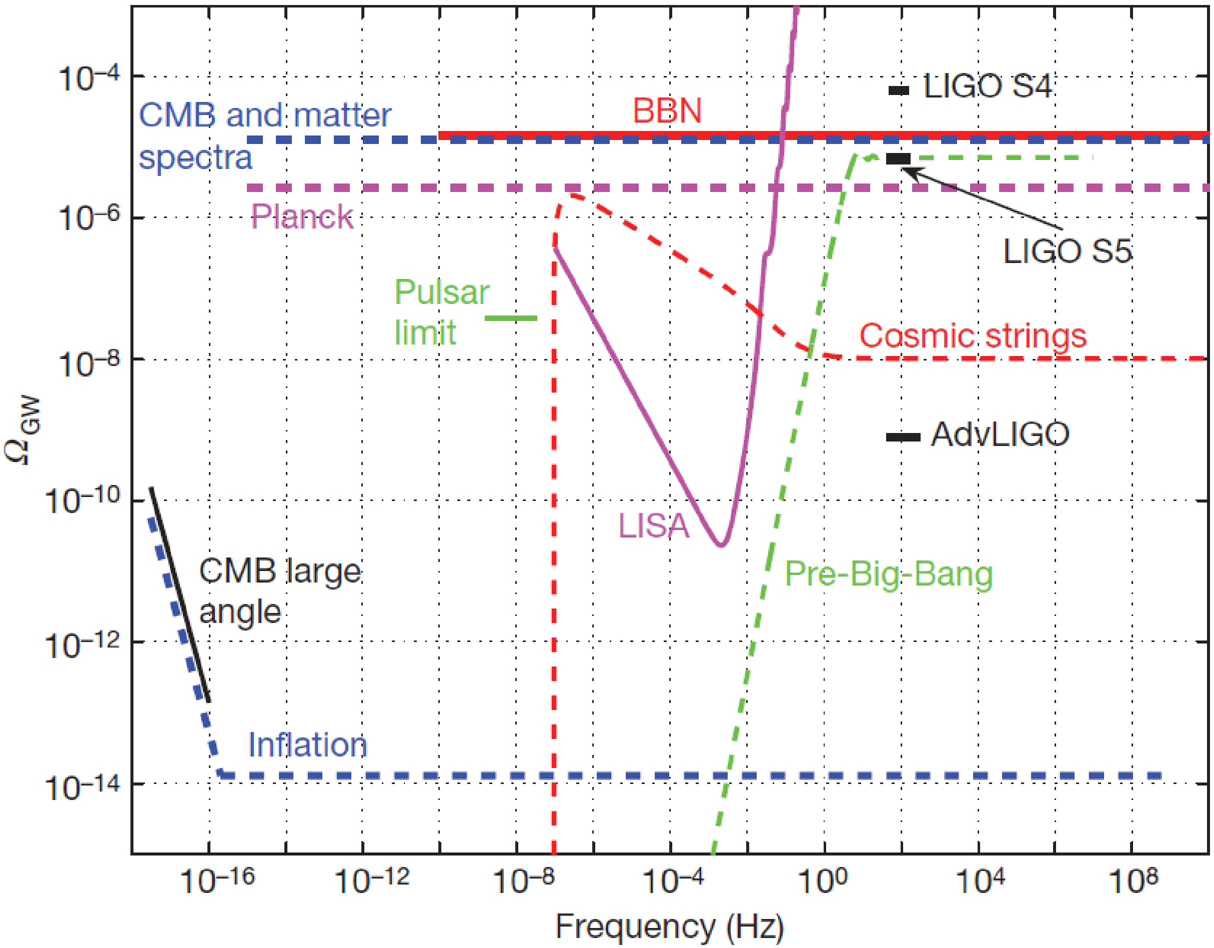
- S3 H1L1: Bayesian 90% UL.
- S4 H1L1+H2L1: Bayesian 90% UL.

- S5 final: Bayesian 90% UL.

- Expected S5: design strain sensitivity and 1 year exposure.

- AdvLIGO: sensitivity optimized for binary neutron star search, and 1 year exposure.

Landscape



-Comparable to Big Bang Nucleosythesis bound

- Beginning to probe models.

BBN Bound

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

$$\boxed{\begin{aligned} \int \Omega_{GW}(f)\, d(\ln f) &< 1.1\times 10^{-5}(N_\nu - 3) \\ &< 1.5\times 10^{-5} \end{aligned}}$$

- IN OUR FREQUENCY BAND, 41.5-169.25 Hz, and assuming frequency independent spectrum, this becomes:
  - $\Omega_0 < 1.1 \times 10^{-5}$
  - This ASSUMES that all energy is in our frequency band…

- Better way to compare: look at specific models…

Observing r and $\Omega^{gw}{}_0$

(L. A. Boyle, A. Buonanno, Phys.Rev.D78:043531,2008)

- Observables at different frequency:
  - CMB tensor to scalar ratio (at 10^{-16}Hz): r
  - Primordial GW background (at 100Hz): $\Omega_0^{\rm gw}(f)$
- Related by

$$\Omega_0^{\rm gw}(f) = \left[A_1 A_2^{\hat{\alpha}(f)} A_3^{\hat{n}_t(f)}\right] r$$

with

- "Effective tensor tilt":

$$\hat{n}_t(f) \equiv \frac{1}{\ln(k/k_{\rm cmb})} \int_{k_{\rm cmb}}^{k} n_t(k') \frac{dk'}{k'}$$

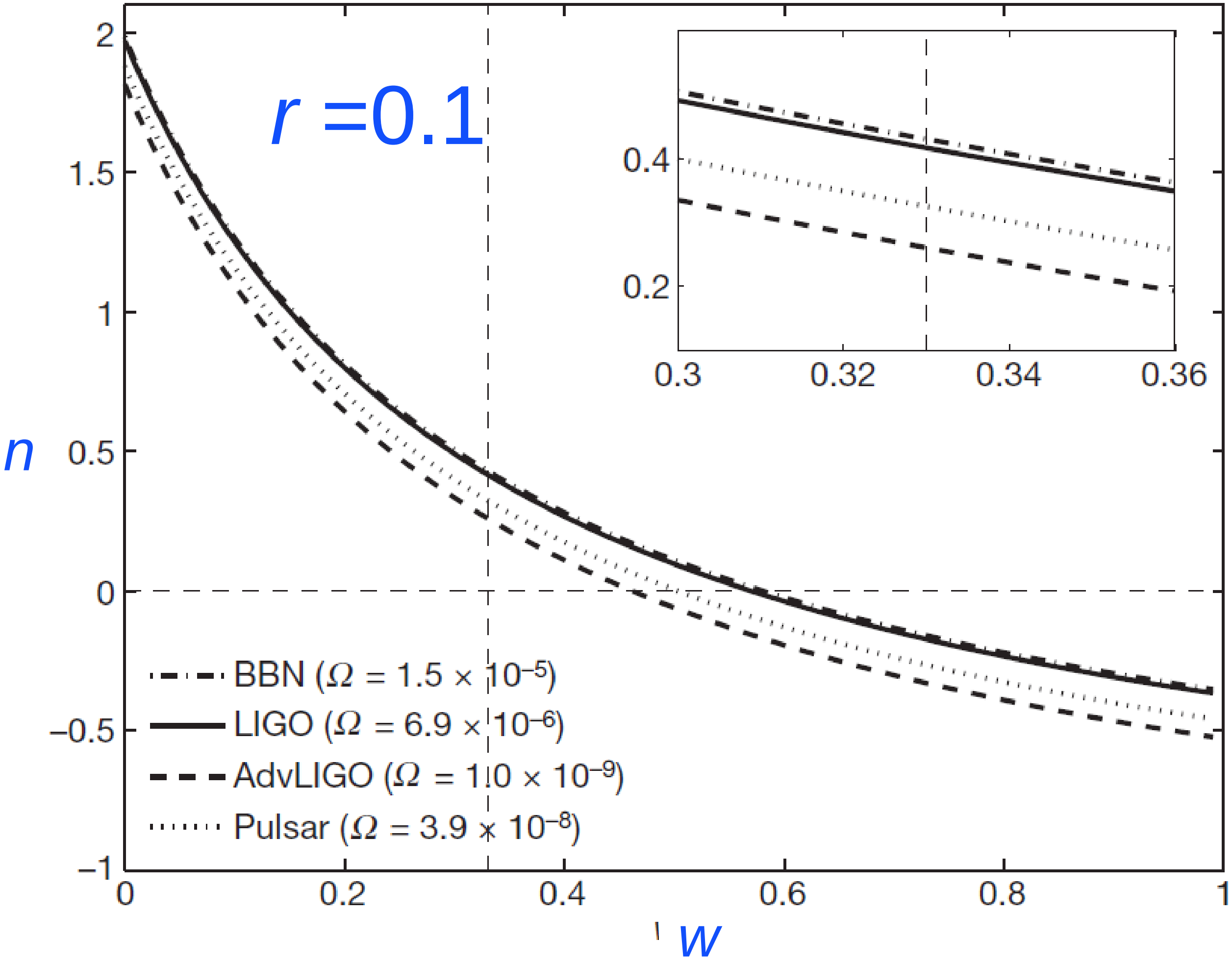
- "Effective eq. of state w":

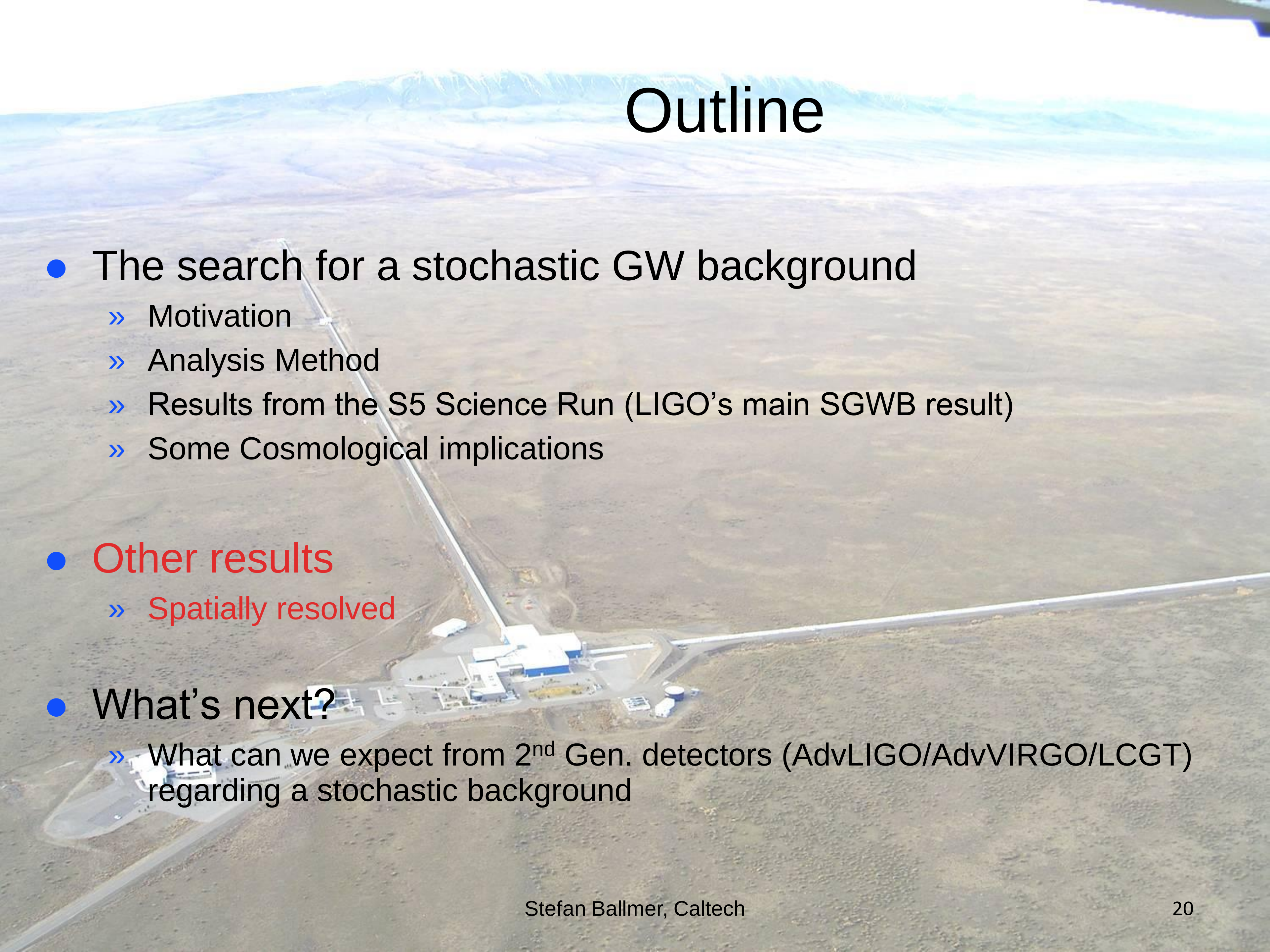
$$\hat{\alpha}(f) \equiv 2\left(\frac{3\hat{w}(f)-1}{3\hat{w}(f)+1}\right) \qquad \hat{w}(f) \equiv \frac{1}{\ln(a_c/a_k)} \int_{a_k}^{a_c} \tilde{w}(a) \frac{da}{a}$$

- A_2, A_3 ~ f

Probing the Early Universe

- Assuming r, one gets a limit on “stiff” (w>1/3) equation of state
- Sensitive to “stiff” equation of state
- Model independent





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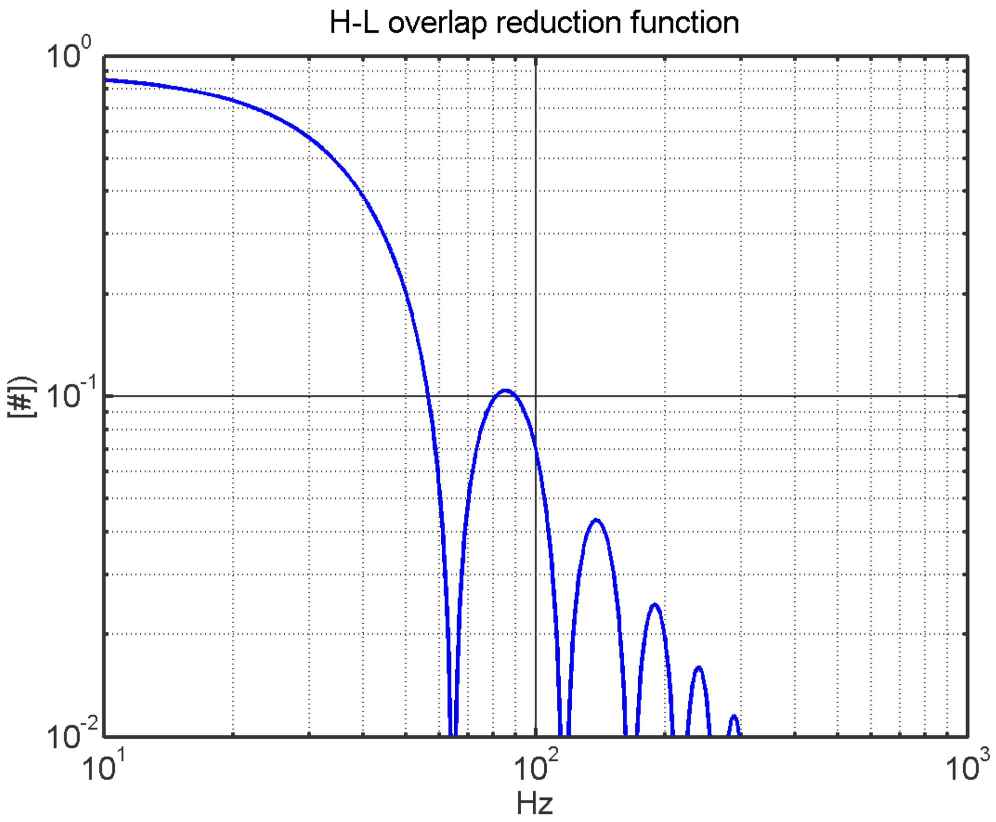
Spatial resolution

- Triangulation and sidereal modulation provide some spatial resolution
  - » No overlap reduction function penalty
- How well can you do experimentally?
  - » Resolution O(100 deg^2)

Overlap Reduction Function



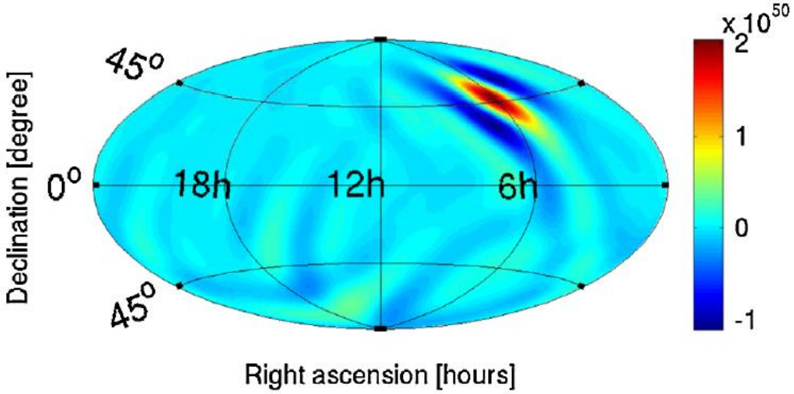
So far:
Looking for Point Sources

- For each pixel:

$$Y_\Omega \propto \sum_t \int df\, \gamma^*_{\Omega,ft} \frac{H_f}{P_{1,f}P_{2,f}} C_{ft}$$

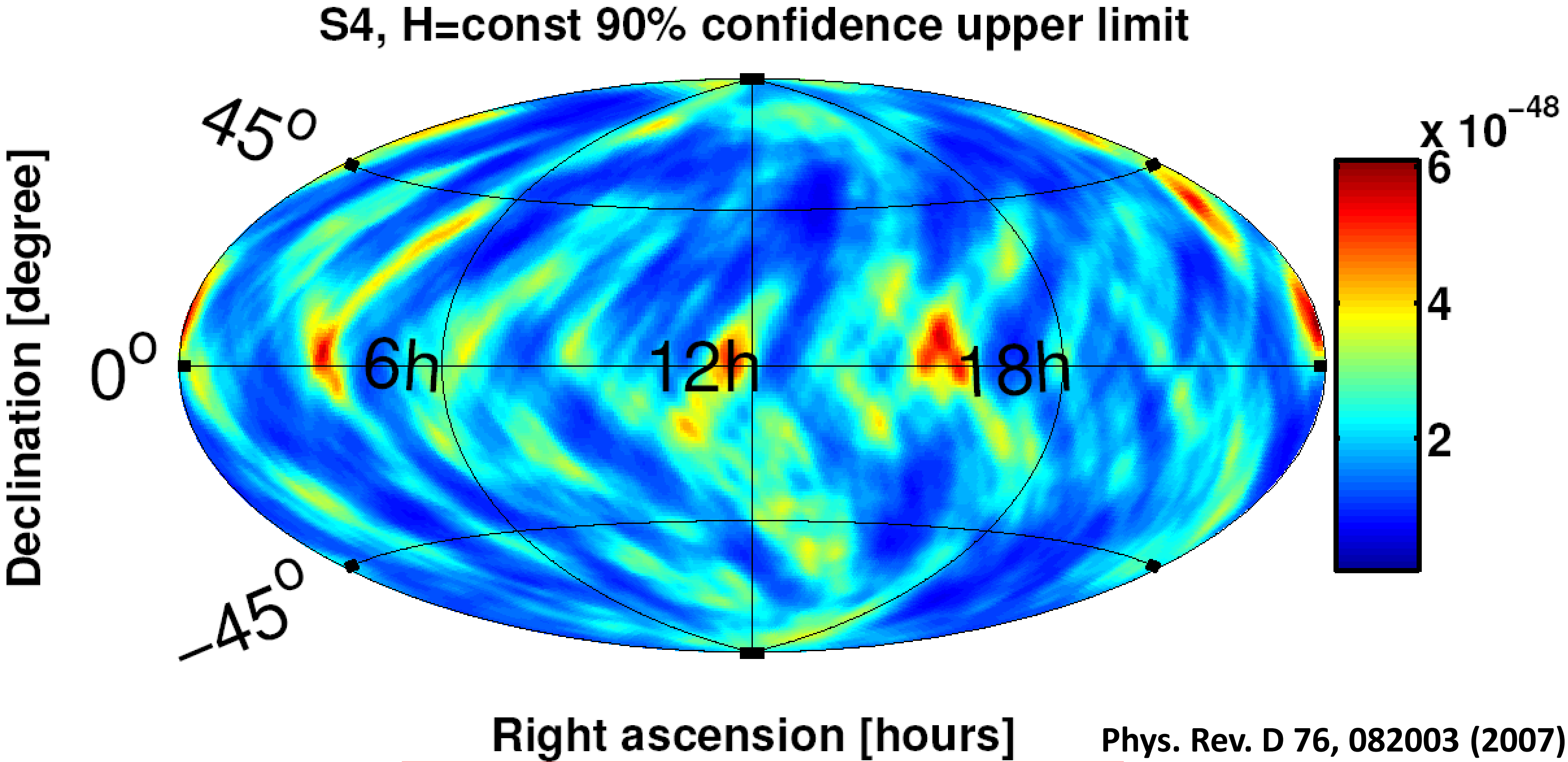
$$\gamma_{t\Omega}(f) = \frac{1}{2}\sum_{A=+,\times} e^{i2\pi f \hat{\Omega}\frac{\Delta\vec{x}(t)}{c}} F_{1,t}^A(\Omega)F_{2,t}^A(\Omega)$$

$$C_{ft} = s_1^*(f,t)s_2(f,t)$$



- Optimal to find isolated Point Sources
- Computationally inexpensive
- Neighboring pixels correlated (“blurred map”)
- S4 result: Phys. Rev. D 76, 082003 (2007)

S4 Result: Limit on Point Source Strain Power Spec.

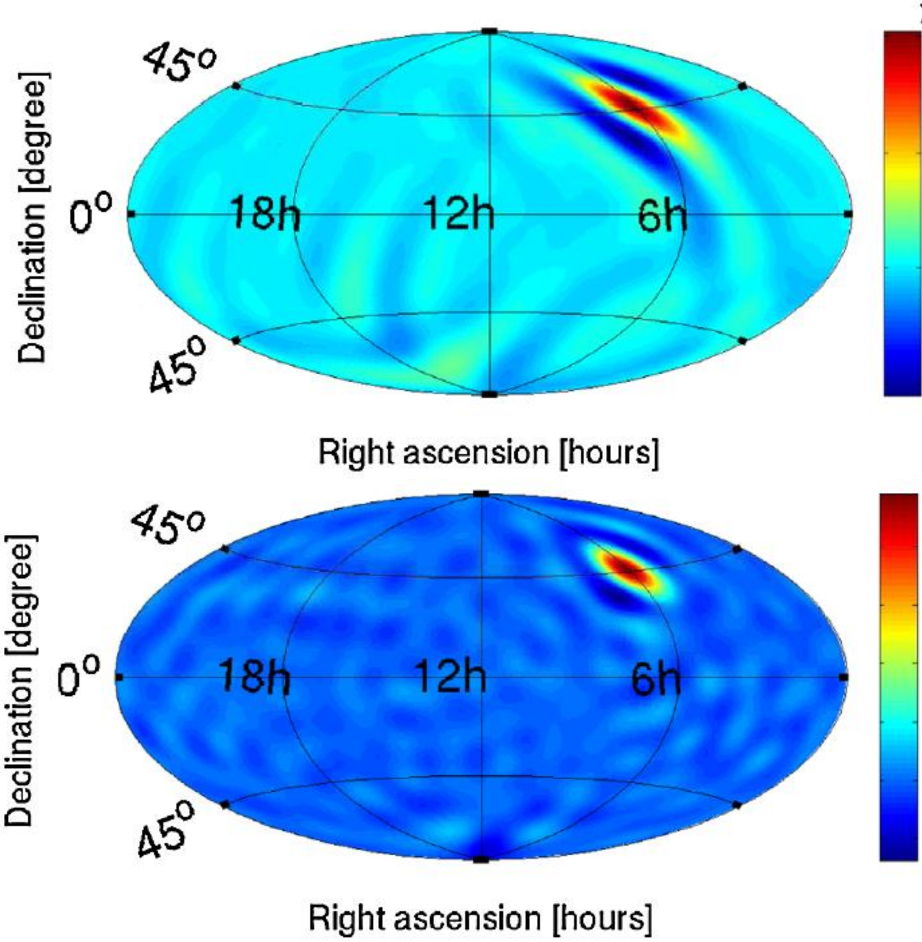


Phys. Rev. D 76, 082003 (2007)

$$H_{90\%} = (0.85 - 6.1) \times 10^{-48} Hz^{-1}$$

Getting rid of the blur

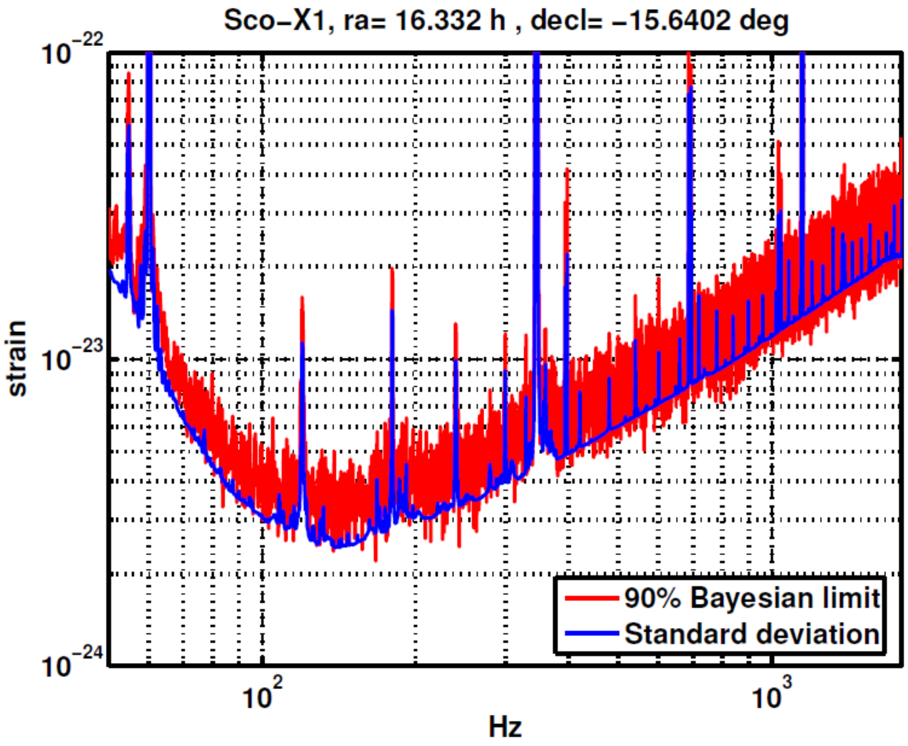
- Blur due to “antenna response of detector pair”
- Described by covariance matrix (known/measured)
  - ➔Max. likelihood de-convolution
- Tricky: some Eigen-vectors poorly measured ➔Regularization required



Thrane et al. PRD 80, 122002 (2009)

Other results / searches

- Narrowband point source search
  - E.g. for poorly modeled (accreting) binaries
- STAMP (Warren's talk)
  - Targeting signal durations from O(1sec) upwards



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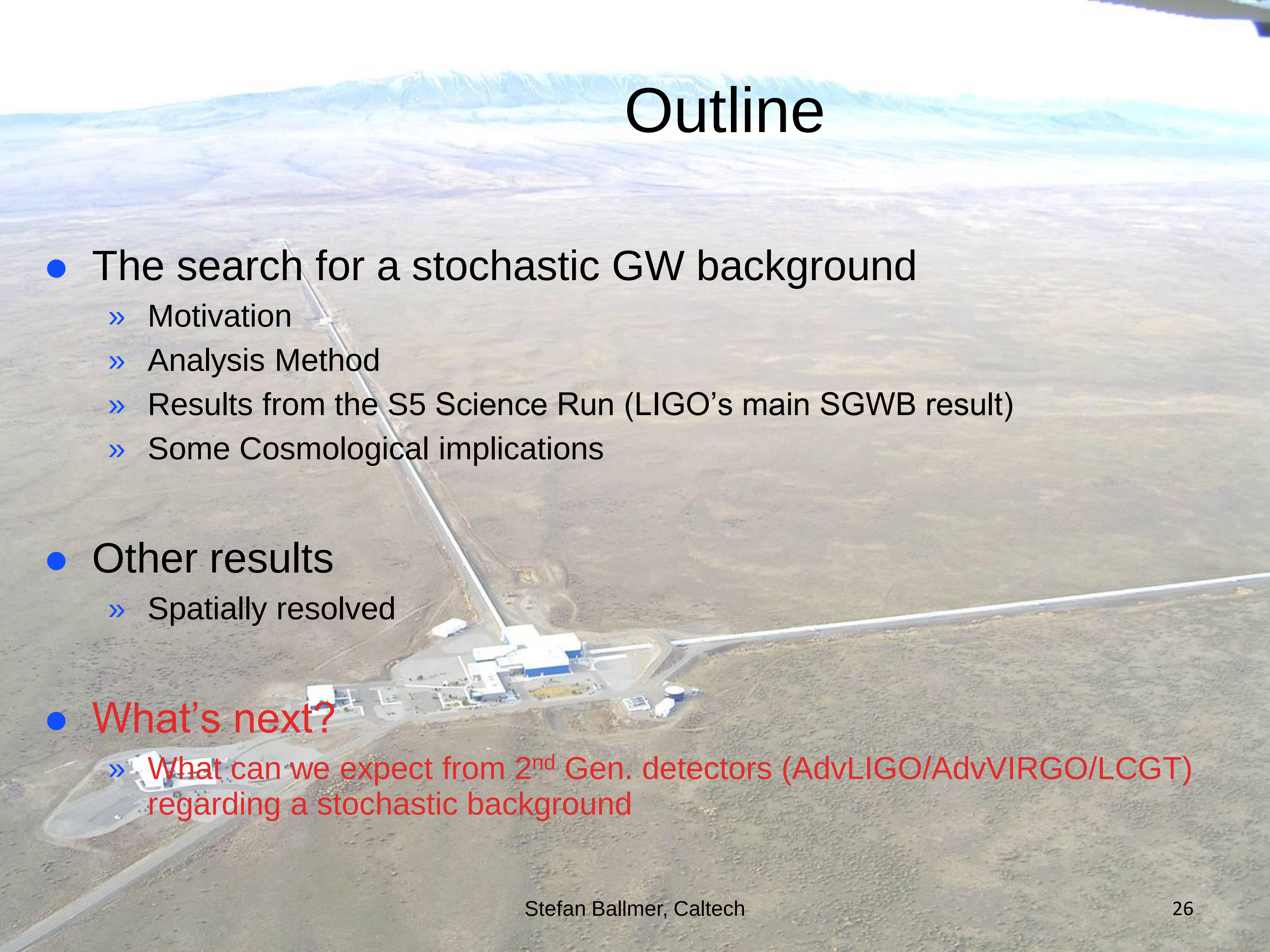

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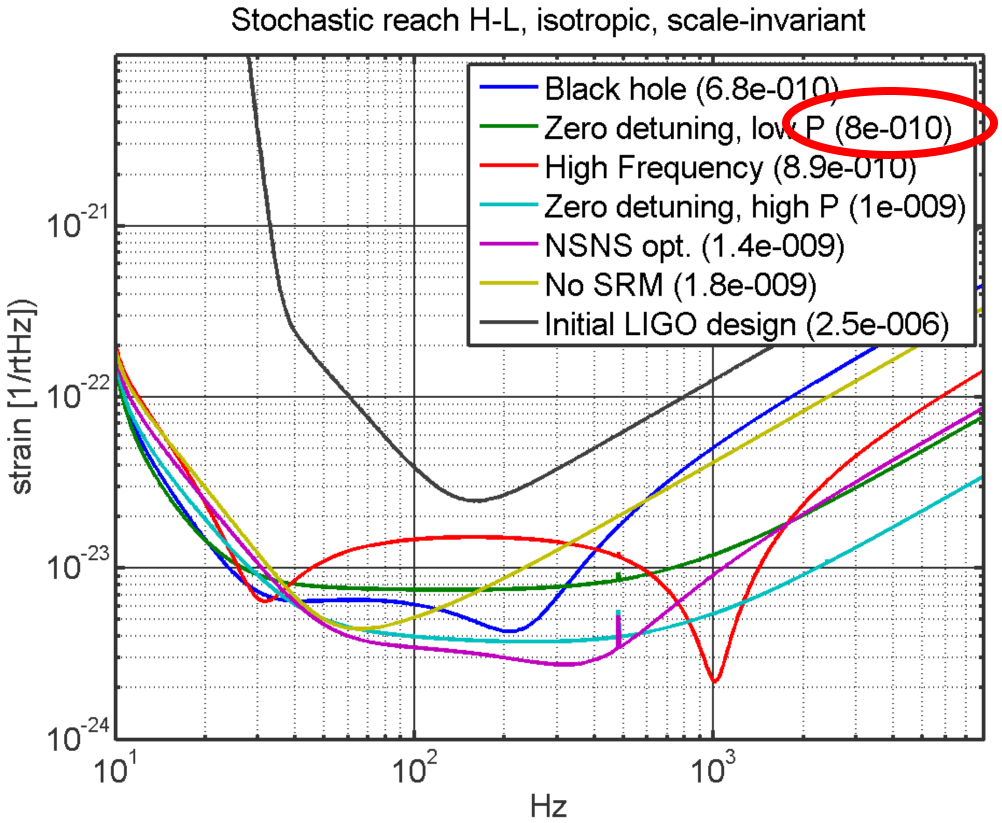
Advanced LIGO Isotropic search

- Isotropic, scale-invariant primordial spectrum
  - » The Overlap reduction function penalty is much smaller
  - » Numbers in (…) are estimated limit on Omega for 1yr



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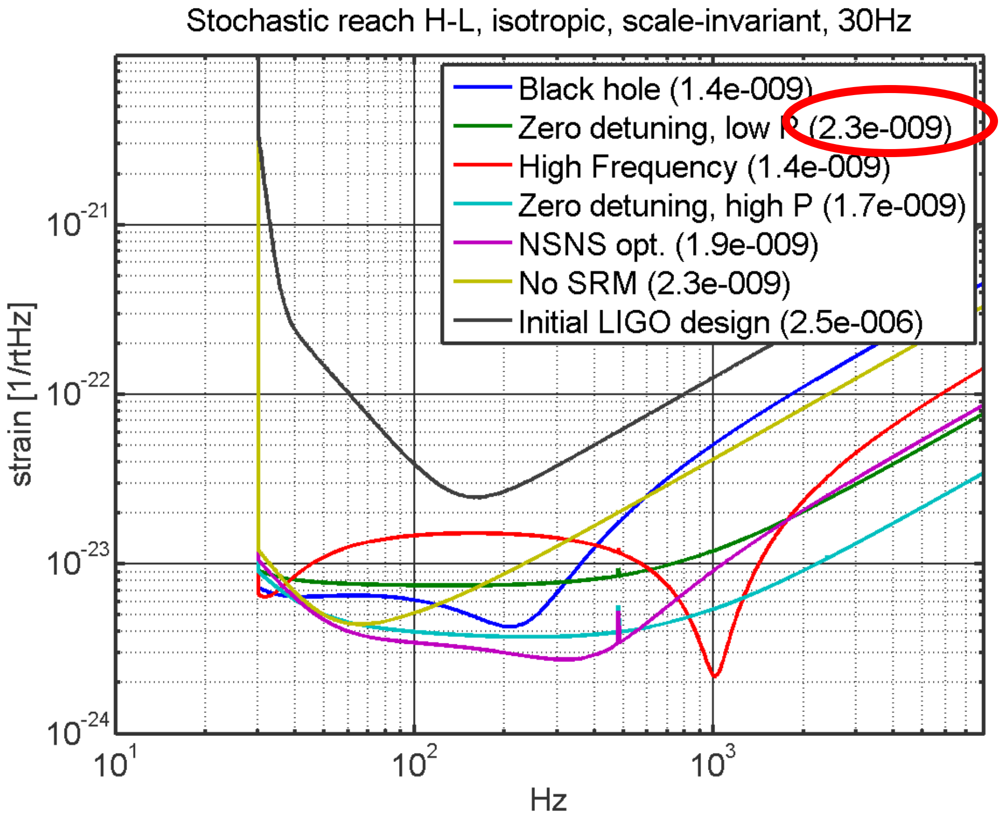
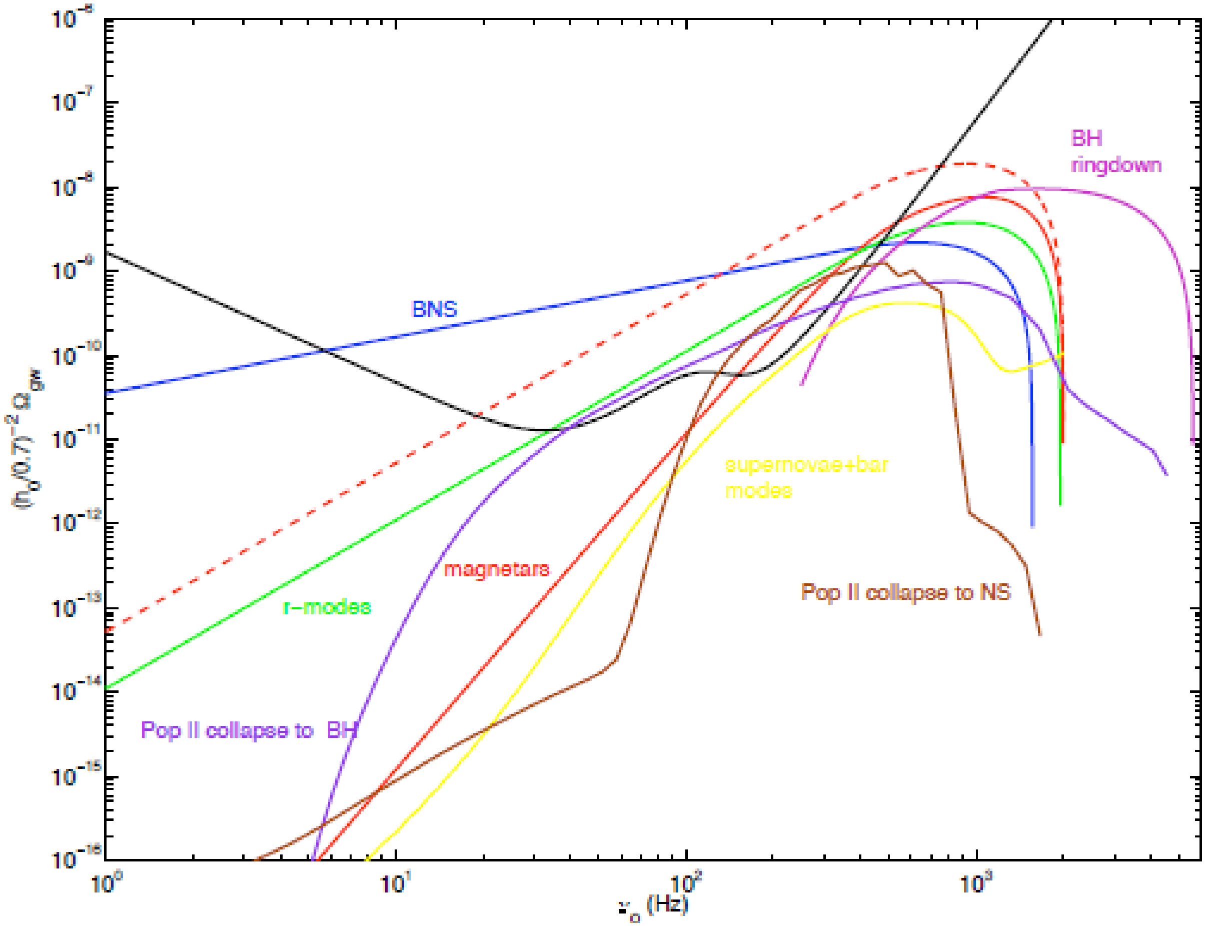


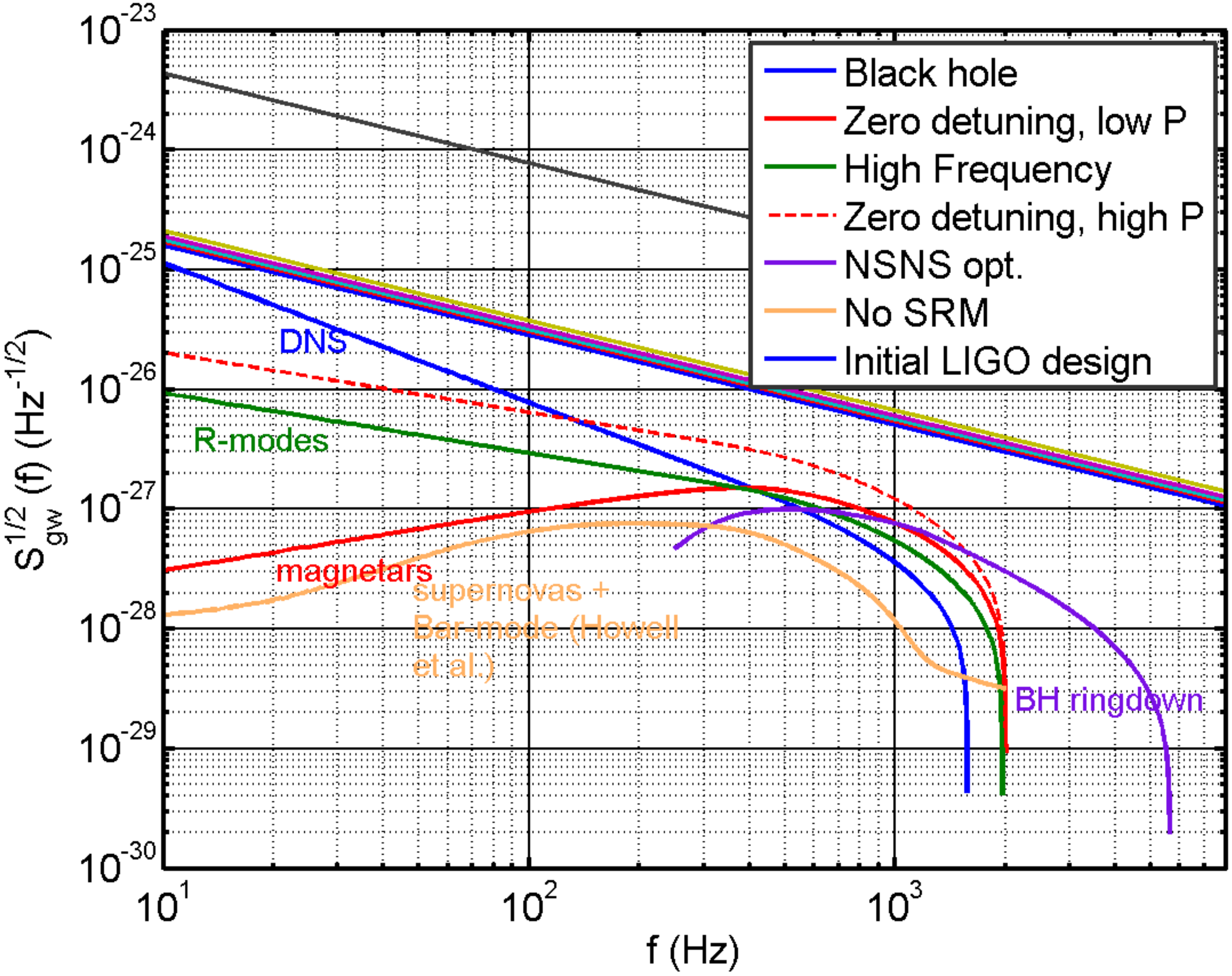
Astrophysical Background



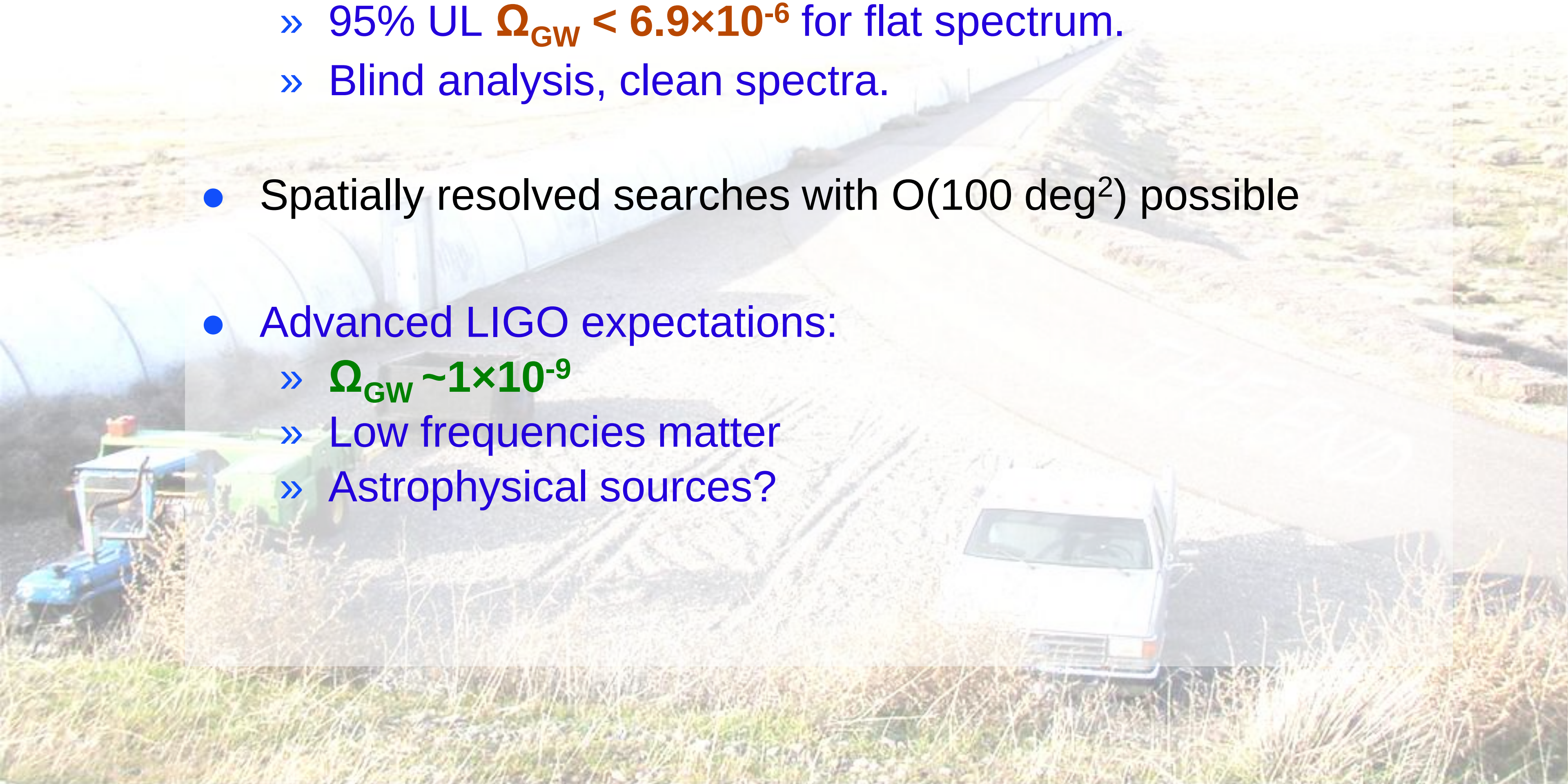
- Background from
  - » Binary NS
  - » Rotating NS
  - » NS instabilities
  - » …

- From Einstein Telescope Design Study: Vision Document, (T. Regimbau)

H-L 1 year reach (alpha=1.5), prelim.

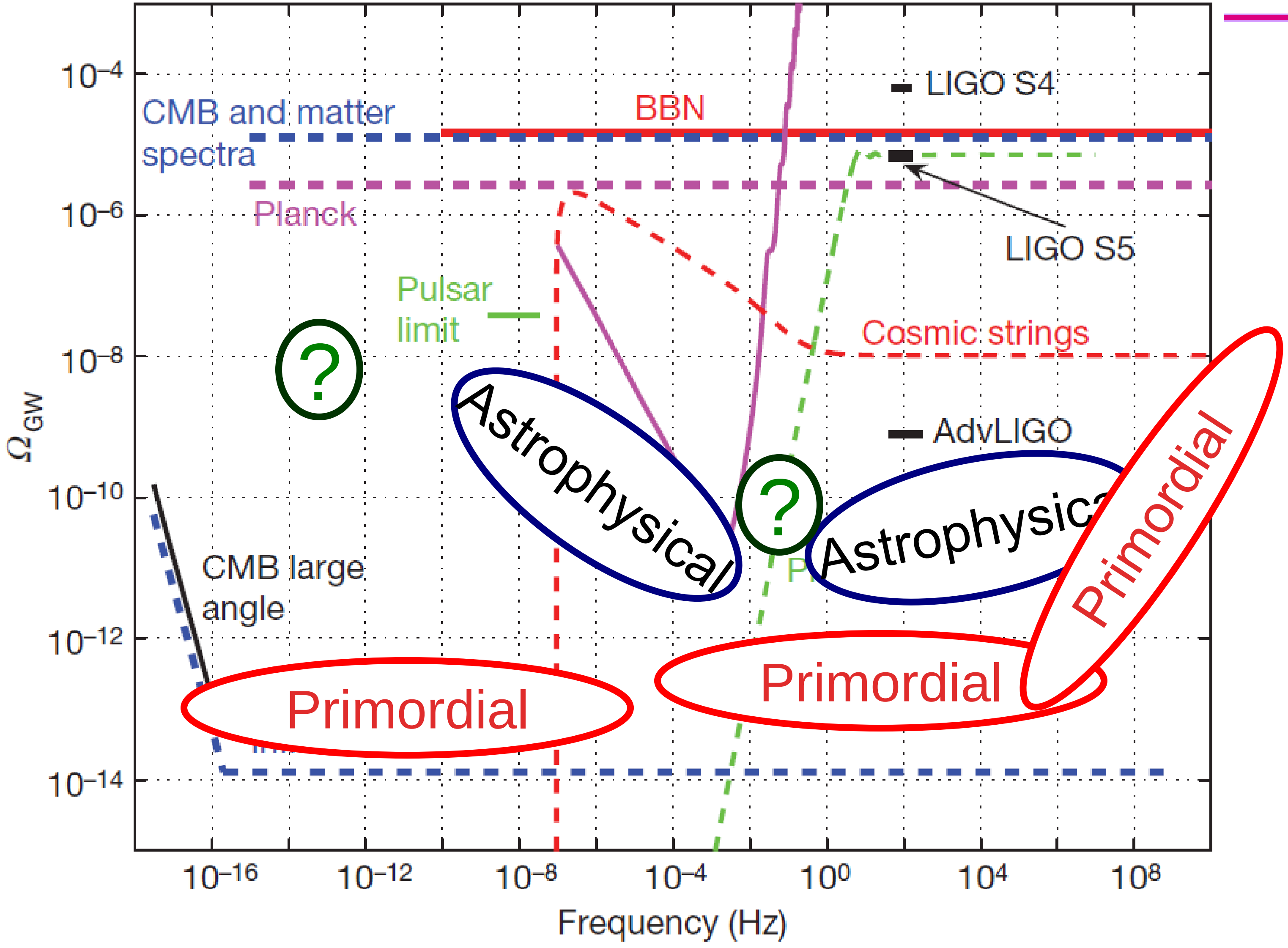


Conclusion



- S5 LHO-LLO limit for an isotropic background :
  - 95% UL **$\Omega_{GW} < 6.9\times10^{-6}$** for flat spectrum.
  - Blind analysis, clean spectra.
- Spatially resolved searches with O(100 deg^2) possible
- Advanced LIGO expectations:
  - **$\Omega_{GW} \sim 1\times10^{-9}$**
  - Low frequencies matter
  - Astrophysical sources?

The GW Landscape



THE END

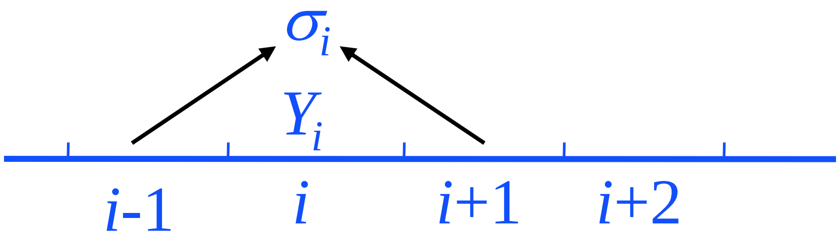
Extra slides

Analysis Details

- Data divided into segments:
  - Y_i and σ_i calculated for each interval *i*.
  - Weighed average performed.
- Sliding Point Estimate:
  - Avoid bias in point estimate
  - Allows stationarity (Δσ) cut
- Data manipulation:
  - Down-sample to 1024 Hz
  - High-pass filter (32 Hz cutoff)
- 50% overlapping Hann windows:
  - Overlap in order to recover the SNR loss due to windowing.

$$Y_{\mathrm{opt}}=\frac{\sum_i \sigma_i^{-2} Y_i}{\sum_i \sigma_i^{-2}}$$

$$\sigma_{\mathrm{opt}}^{-2}=\sum_i \sigma_i^{-2}$$



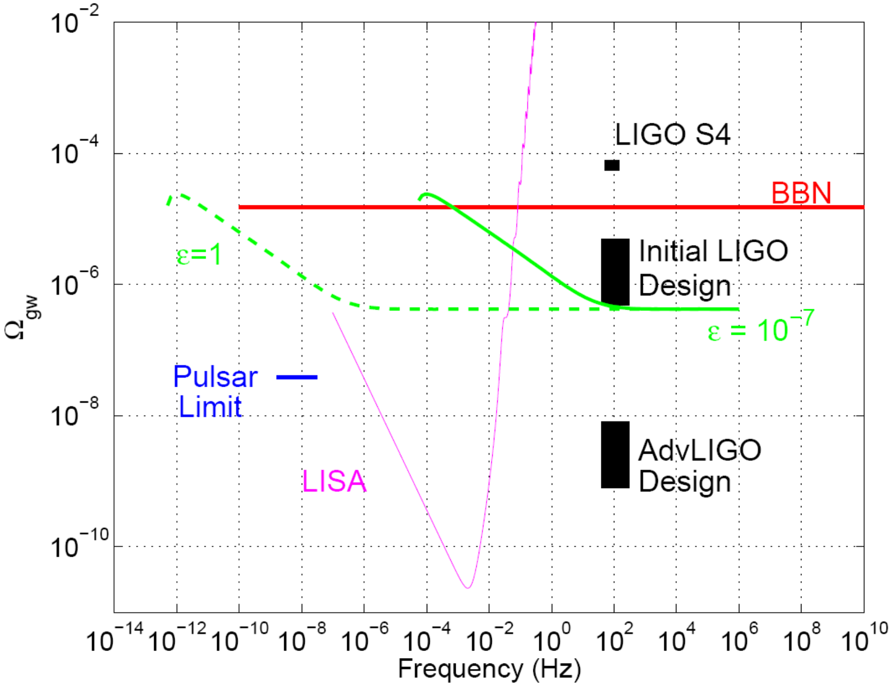
Cosmic Strings: Model

- Topological defects formed during phase transitions in the early Universe.
- Or, fundamental or Dirichlet strings (in string theory).
- Cosmic string cusps, with large Lorentz boosts, can create large GW signals.
- Look for the stochastic background created by superposing cusp signals throughout the Universe.
- Calculation done by Siemens, Mandic & Creighton, PRL98, 111101 (2007).
  - » Update on Damour & Vilenkin, PRD71, 063510 (2005).
  - » There are uncertainties in the calculation.
  - » Some of them can be resolved by improving simulations of cosmic strings networks.

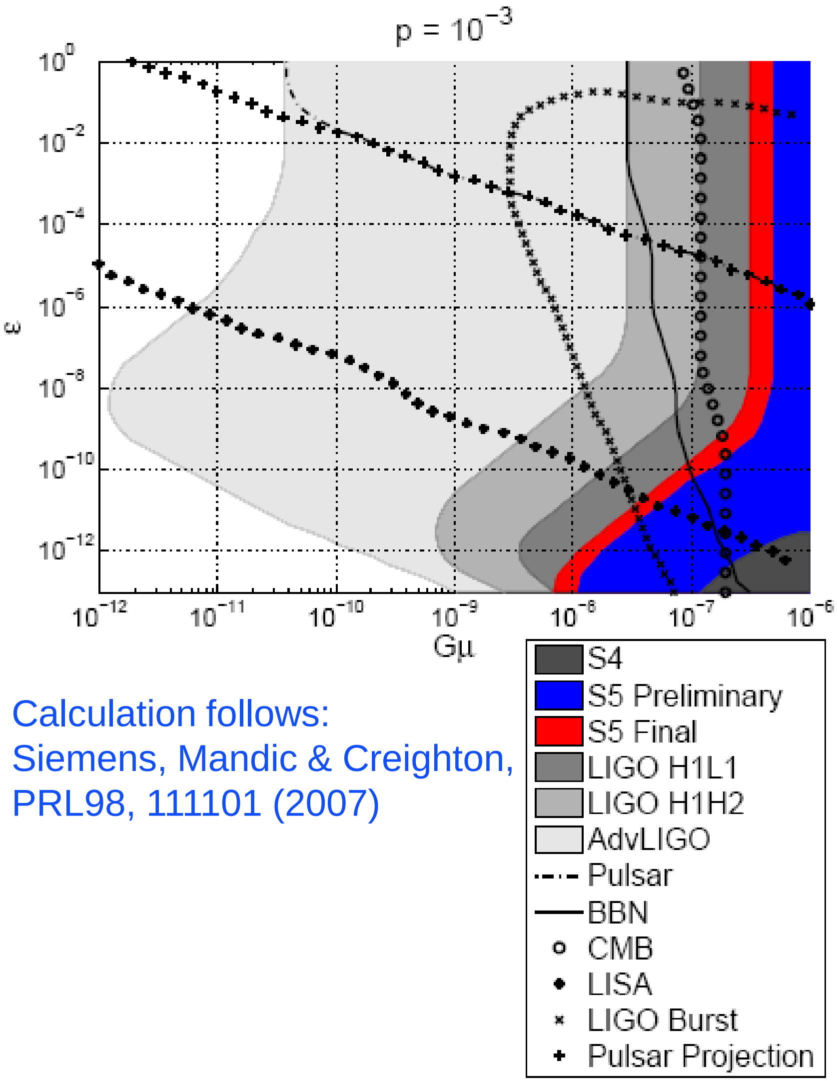
Small-loop Case

$p = 5\times 10^{-3}$

$G\mu = 10^{-7}$



Cosmic Strings: Small Loop Case



Calculation follows:
Siemens, Mandic & Creighton,
PRL98, 111101 (2007)

- If loop-size at formation is determined by gravitational back-reaction, the loops are small and of the same size.
- Parameters:
  - » loop-size parameterized by: $10^{-13} < \varepsilon < 1$
  - » String tension: $10^{-12} < G\mu < 10^{-6}$
    - – Upper bound from CMB observations.
  - » Reconnection probability: $10^{-3} < p < 1$
    - – Determines the density of strings.
- Spectrum has a low-frequency cutoff.
  - » Determined by the string length and the angle at which we observe the cusp.
- Small ε or Gμ push the cutoff to higher frequencies.
- Spectrum amplitude increases with Gμ and with 1/p.

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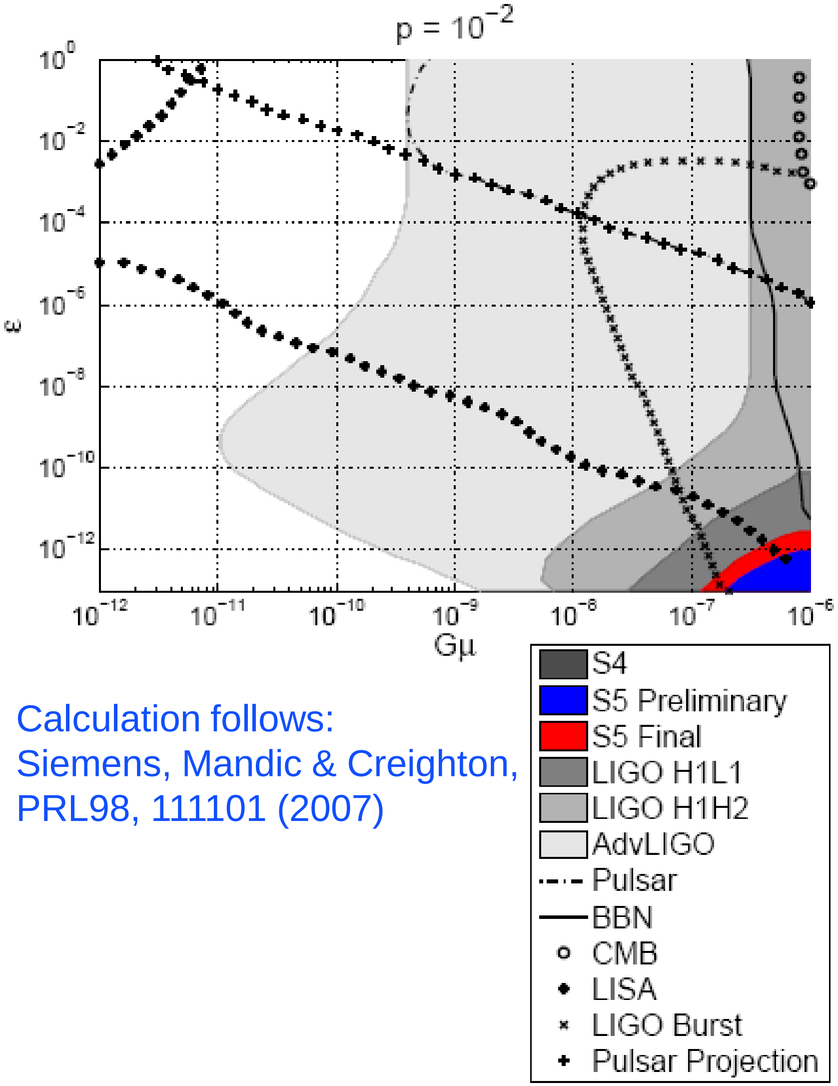

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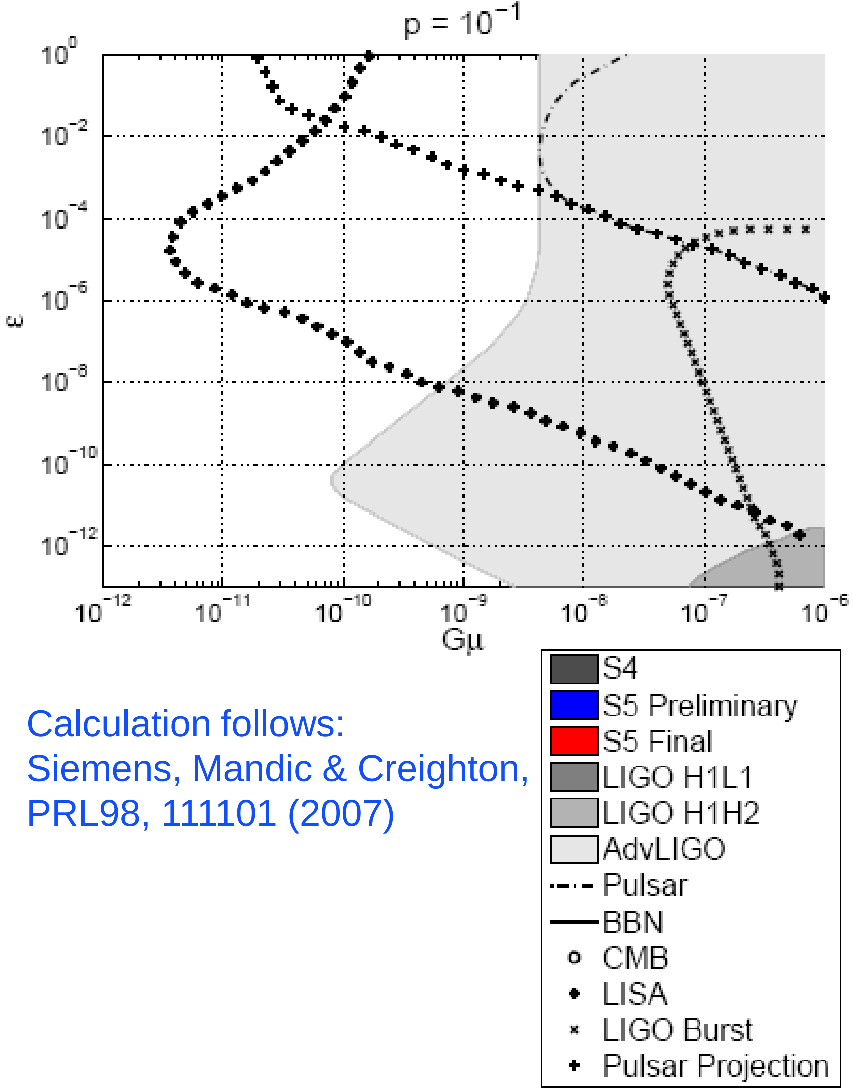
Cosmic Strings: Small Loop Case



Calculation follows:
Siemens, Mandic & Creighton,
PRL98, 111101 (2007)

- If loop-size at formation is determined by gravitational back-reaction, the loops are small and of the same size.
- Parameters:
  - » loop-size parameterized by: $10^{-13} < \varepsilon < 1$
  - » String tension: $10^{-12} < G\mu < 10^{-6}$
    - – Upper bound from CMB observations.
  - » Reconnection probability: $10^{-3} < p < 1$
    - – Determines the density of strings.
- Spectrum has a low-frequency cutoff.
  - » Determined by the string length and the angle at which we observe the cusp.
- Small ε or Gμ push the cutoff to higher frequencies.
- Spectrum amplitude increases with Gμ and with 1/p.

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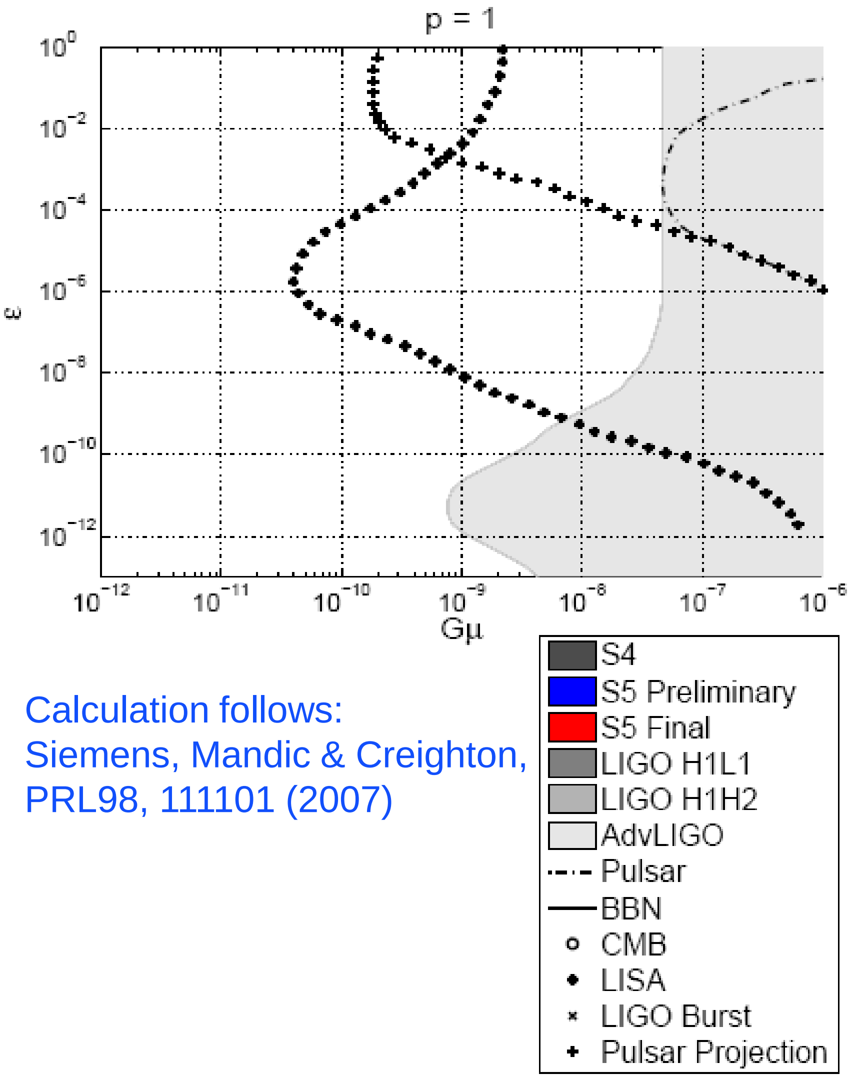

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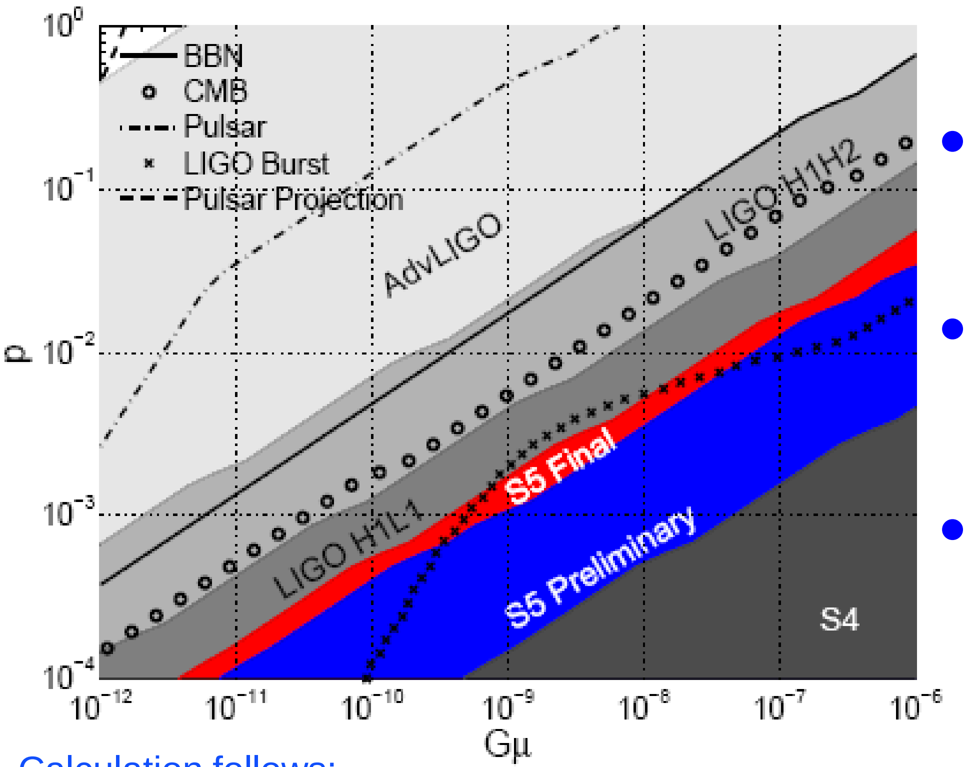
Cosmic Strings: Large Loop Case



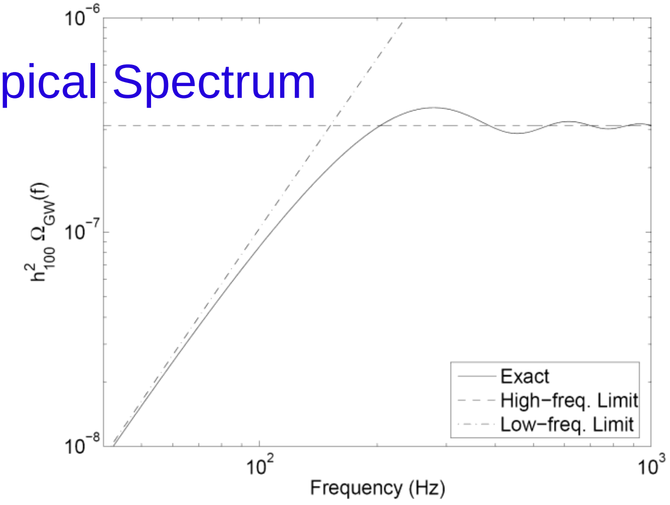
Calculation follows:
Siemens, Mandic & Creighton,
PRL98, 111101 (2007)

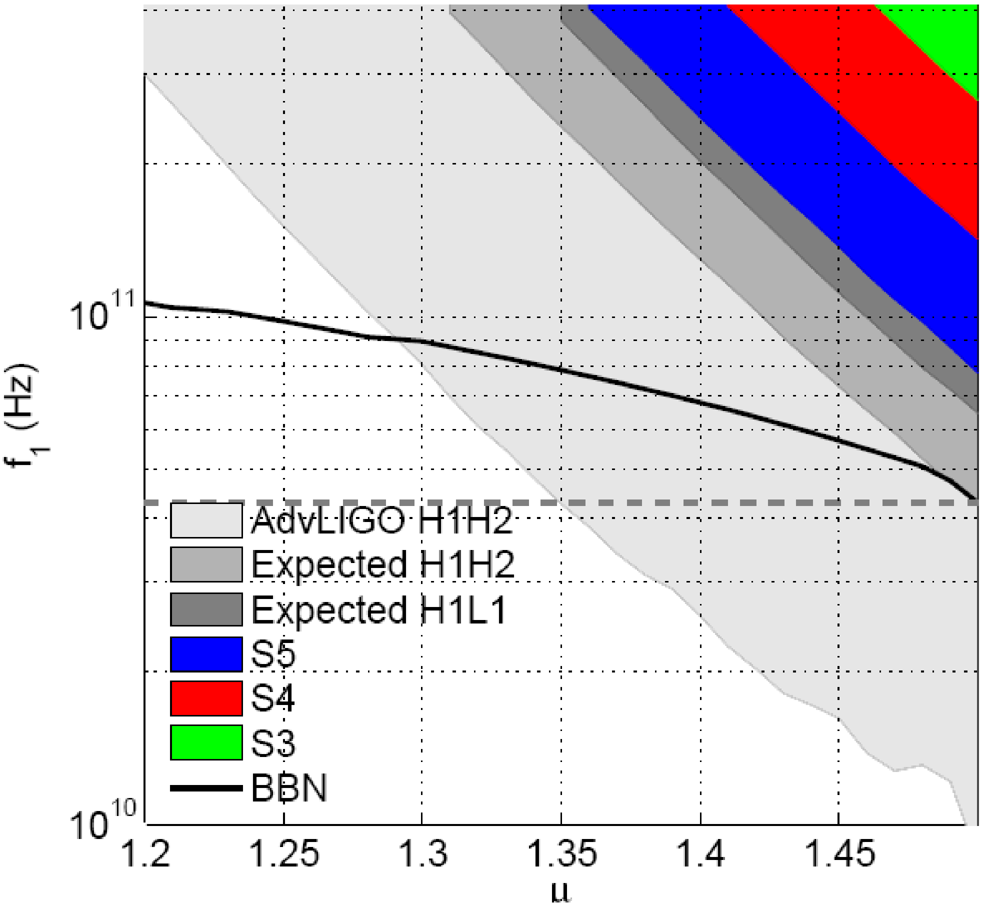
- Recent simulations indicate that loops could be large at formation, and therefore long-lived.
- Loop distribution more complex.
  - » Larger amplitudes of gravitational-wave spectra.
- Free parameters:
  - » String tension: $10^{-12} < G\mu < 10^{-6}$
  - » Reconnection probability: $10^{-4} < p < 1$
- Assuming that loop-size is 10% of the horizon at the formation time.
  - » Some simulations indicate that a more complicated distribution would be more accurate, involving both small and large loops.

Pre-Big-Bang Models

- Scan f_1 - μ plane for f_s=30 Hz.
- For each model, calculate $\Omega_{GW}(f)$ and check if it is within reach of current or future expected LIGO results.
- Beginning to probe the allowed parameter space.
- But, not yet as sensitive as the BBN bound.

Typical Spectrum

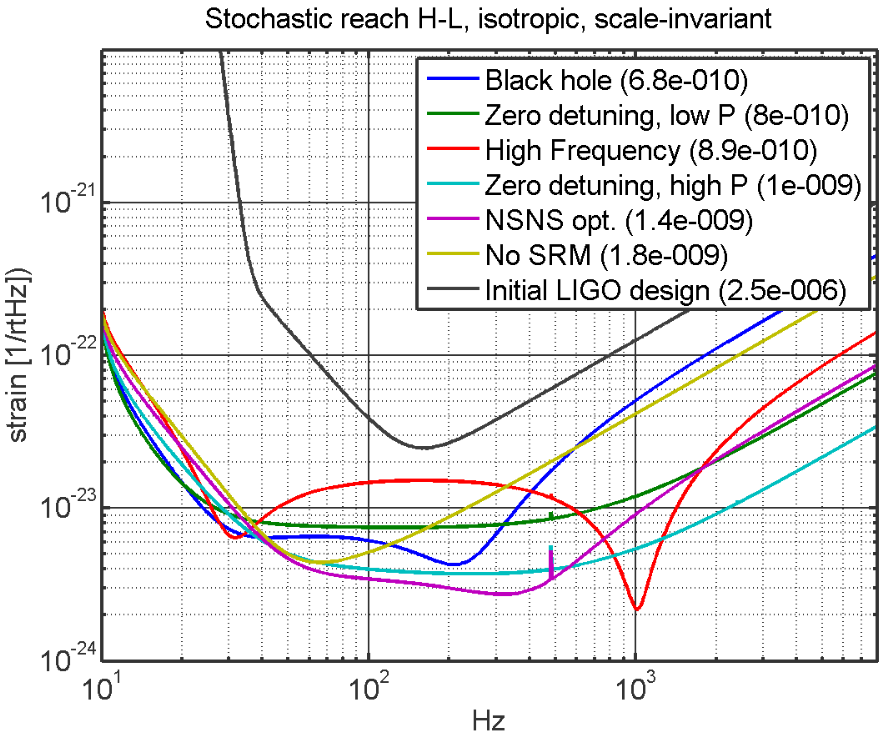




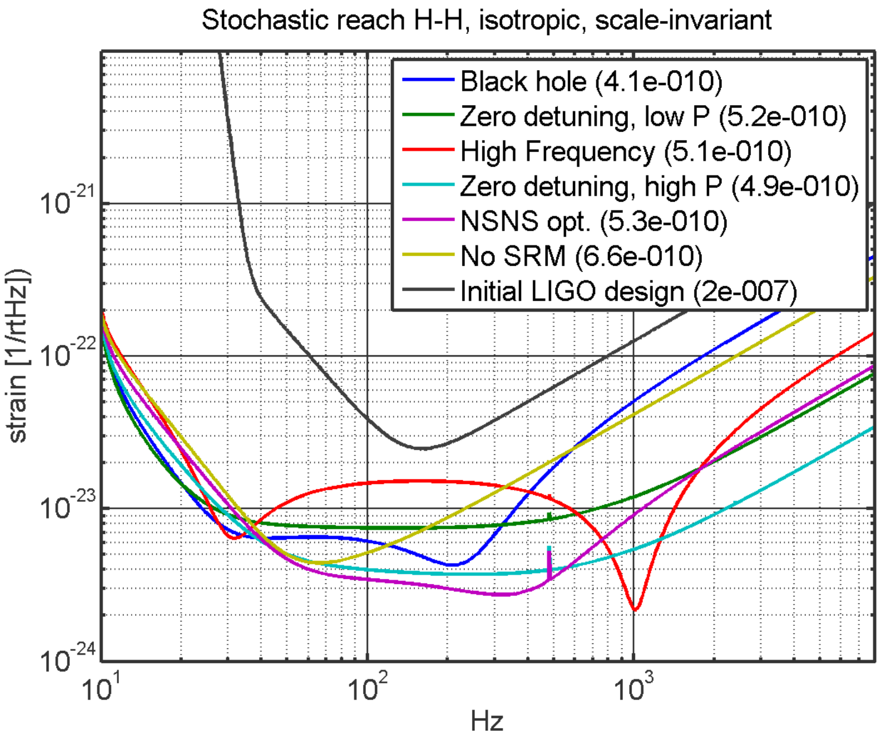
Calculation follows:
Mandic & Buonanno, PRD73, 063008 (2006)

Advanced LIGO Isotropic search

- Isotropic, scale-invariant primordial spectrum
  - » The Overlap reduction function penalty is much smaller
  - » Numbers in (…) are estimated 90% limit on Omega for 1yr



Stochastic reach H-L, isotropic, scale-invariant



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