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Exploring a stochastic background of gravitational waves with LIGO

Letizia Sammut

for the LIGO Scientific Collaboration and the Virgo Collaboration

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LIGO
Scientific
Collaboration



Stochastic GW Background

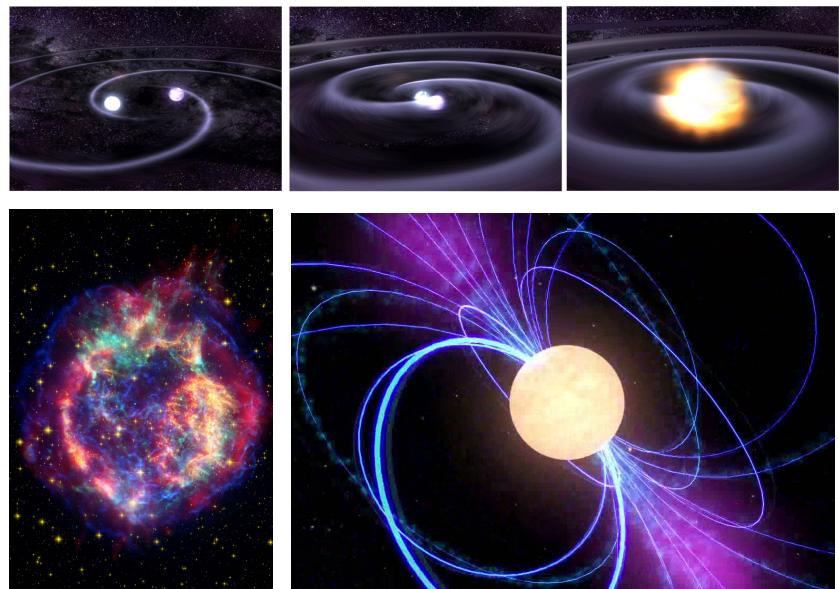
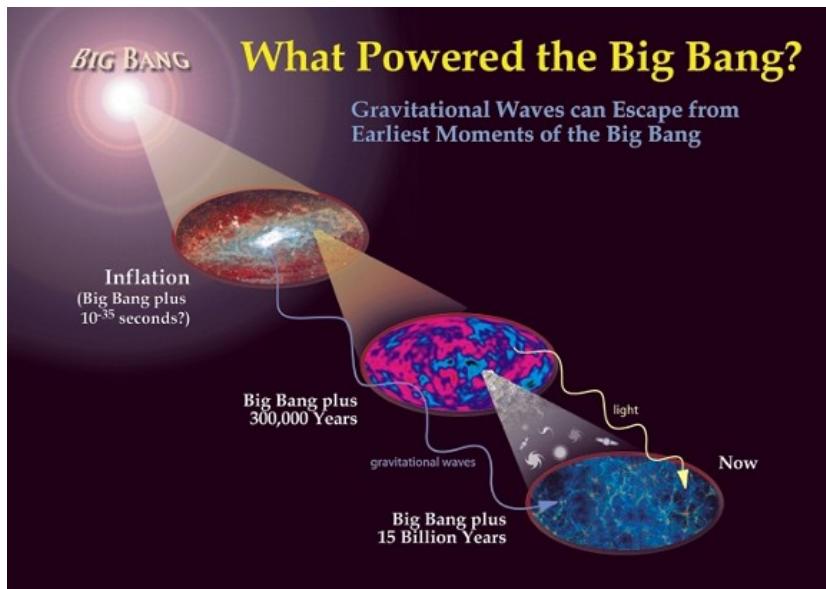
superposition of signals too weak or numerous to be resolved individually

Cosmological:

- *Vacuum fluctuation*
- *inflationary models*
- *phase transitions and cosmic strings*
- *String cosmology*

Astrophysical:

- *compact binary coalescences*
- *core-collapse supernovae*
- *rotating neutron stars*



Energy density spectrum

$$\Omega_{\text{GW}}(f) \equiv \frac{f}{\rho_c} \frac{d\rho_{\text{GW}}}{df}$$

Critical energy density to close the universe $\rho_c = \frac{3c^2H_0^2}{8\pi G}$

GW energy density contained in the frequency range f and $f + df$

Theoretical models of stochastic backgrounds in the LIGO band are characterized by a power-law spectrum. We can therefore assume:

$$\Omega(f, \Phi) = \Omega_\alpha(\Phi) \left(\frac{f}{f_{\text{ref}}} \right)^\alpha, \quad \Omega_\alpha(\Phi) = \frac{2\pi^2}{3H_0^2} f_{\text{ref}}^3 \mathcal{P}(\Phi)$$

Spectral index

- $\alpha = 0$ constant energy density, representative of many cosmological models
- $\alpha = 3$ constant strain, characteristic of many astrophysical models
- $\alpha = 2/3$ background dominated by compact binary (eg BBH) inspirals

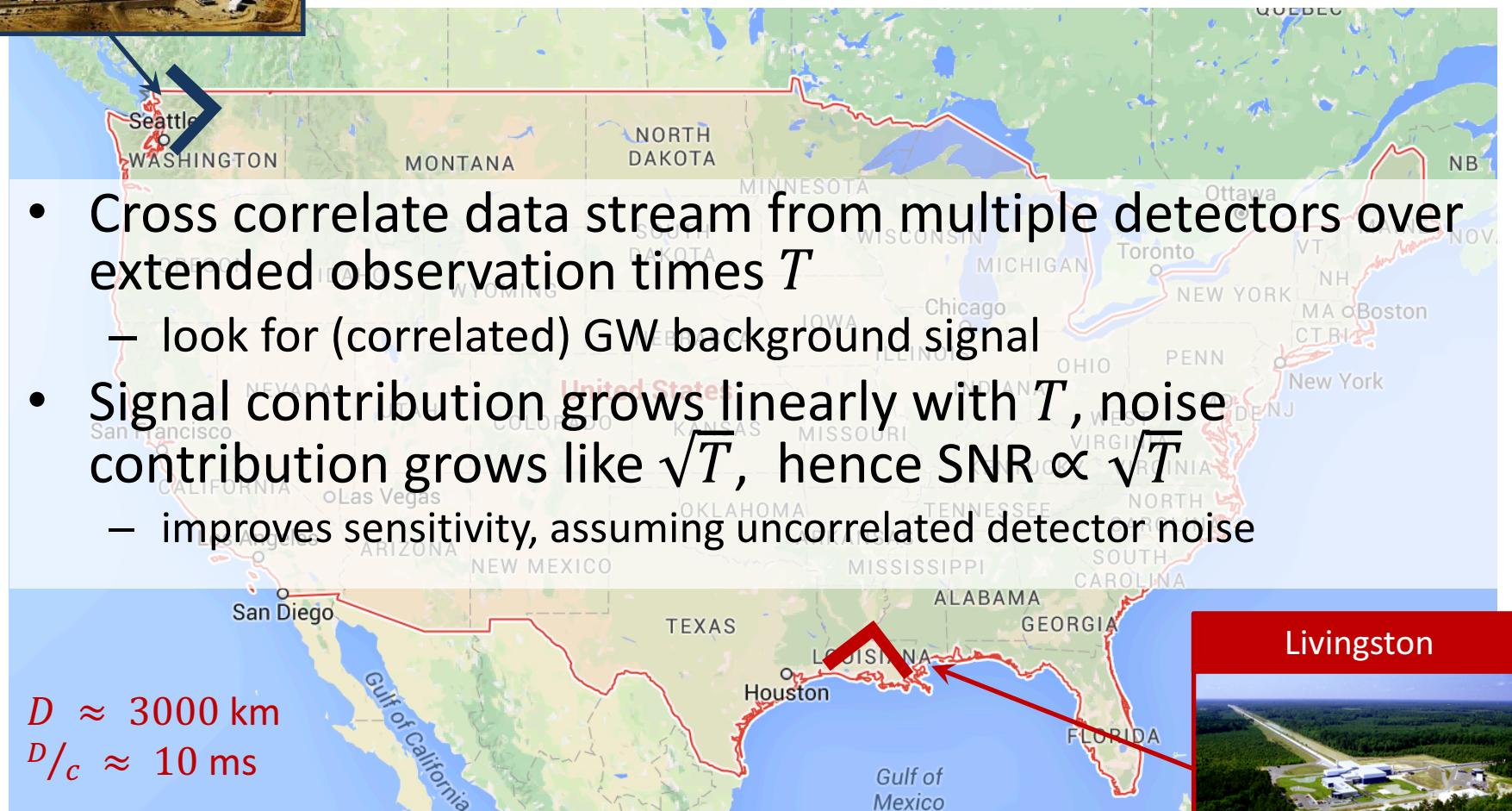
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Detection strategy

- Cross correlate data stream from multiple detectors over extended observation times T
 - look for (correlated) GW background signal
- Signal contribution grows linearly with T , noise contribution grows like \sqrt{T} , hence $\text{SNR} \propto \sqrt{T}$
 - improves sensitivity, assuming uncorrelated detector noise

$$D \approx 3000 \text{ km}$$
$$D/c \approx 10 \text{ ms}$$



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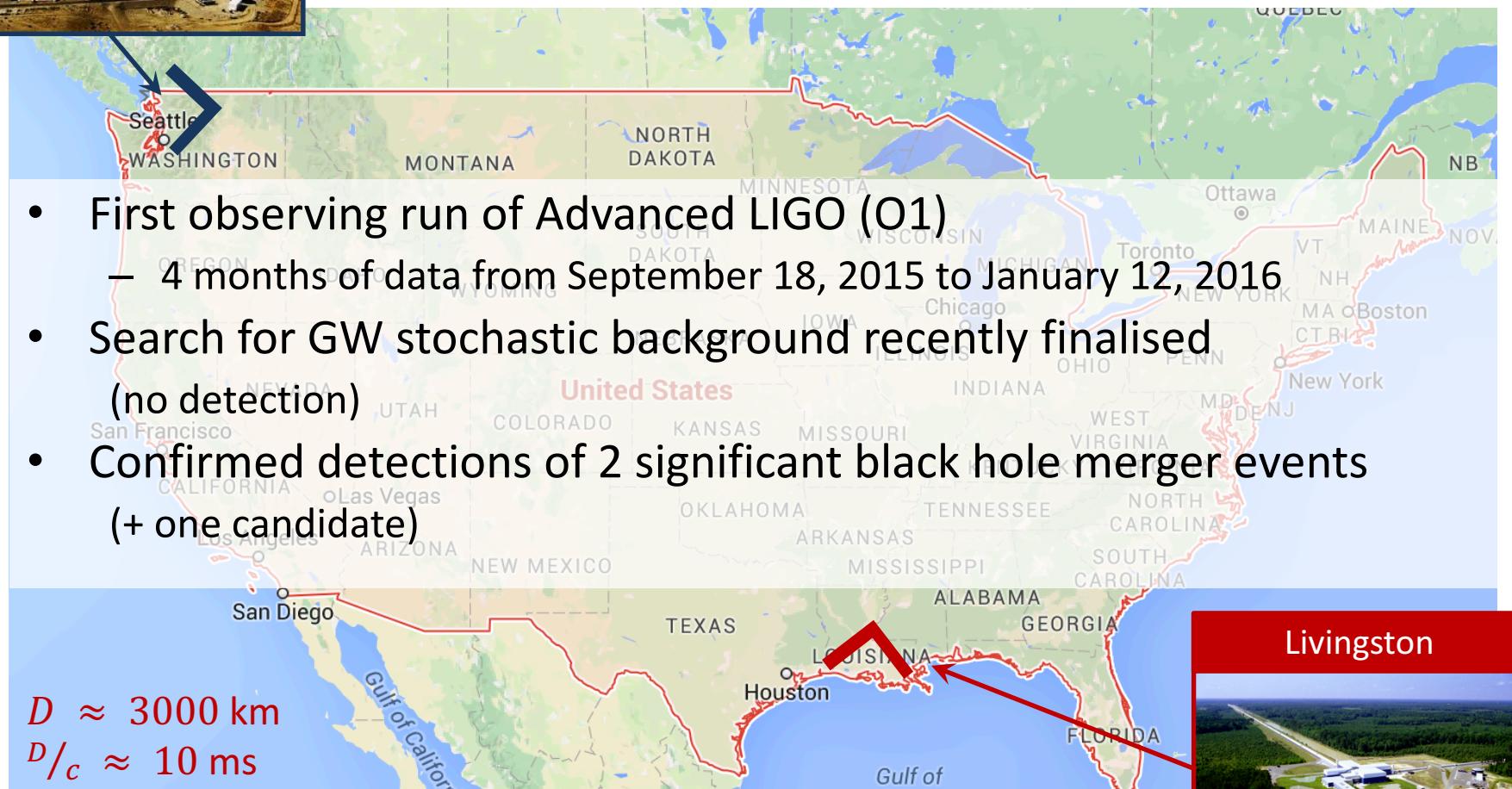


$$\text{SNR} = \frac{3H_0^2}{10\pi^2} \sqrt{2T} \left[\int_0^\infty df \sum_{i=1}^n \sum_{j>i} \frac{\gamma_{ij}^2(f) \Omega_{\text{GW}}^2(f)}{f^6 P_i(f) P_j(f)} \right]^{1/2}$$

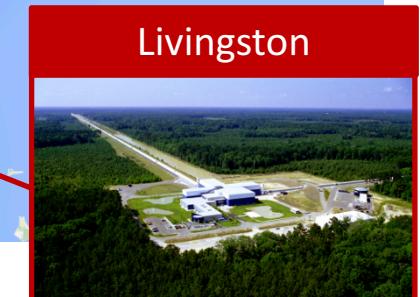
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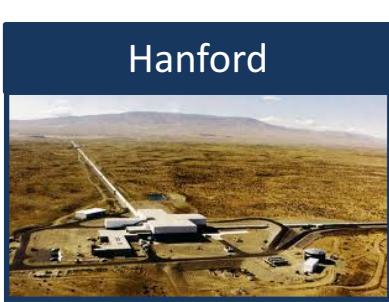
Advanced LIGO



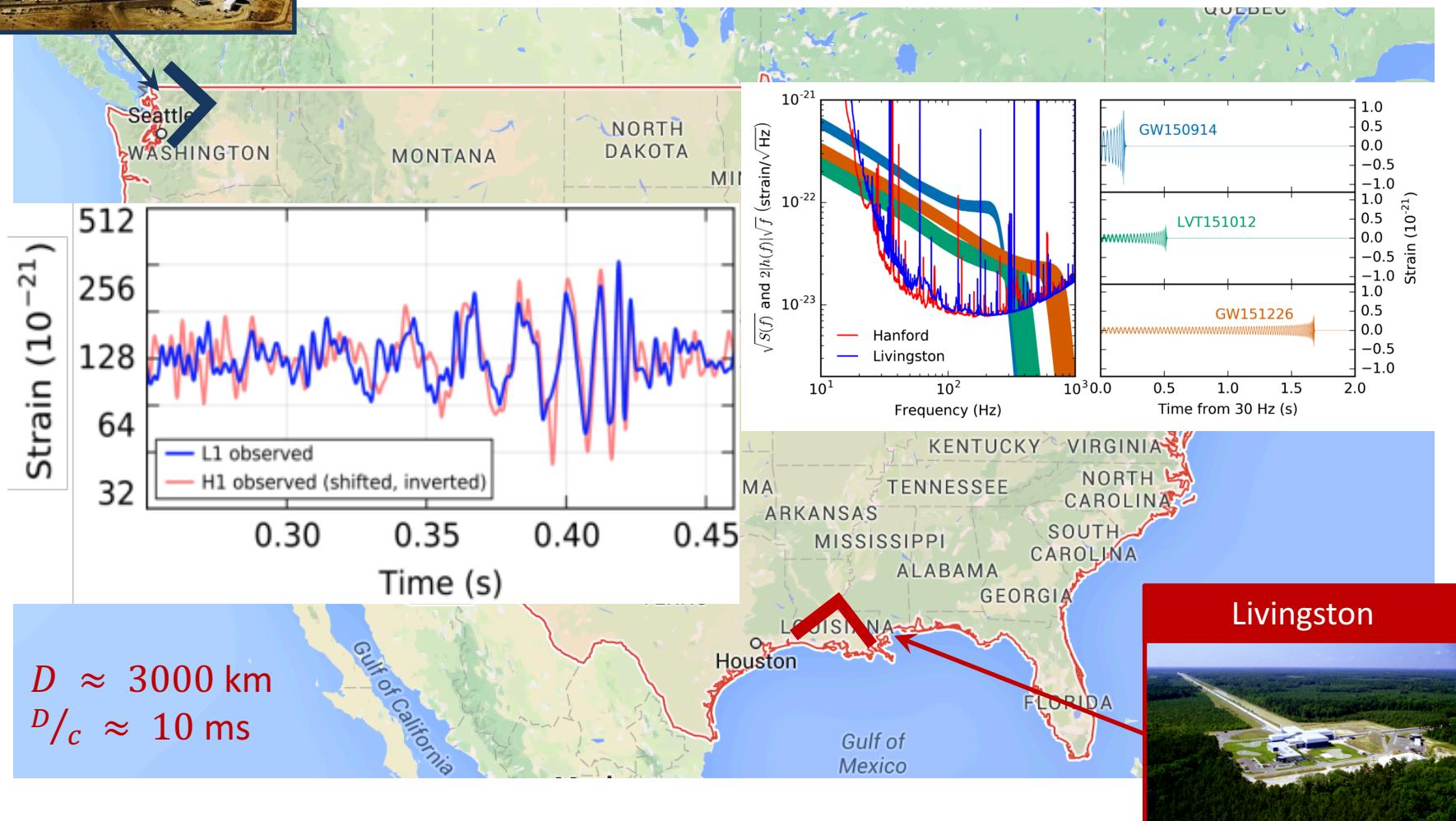
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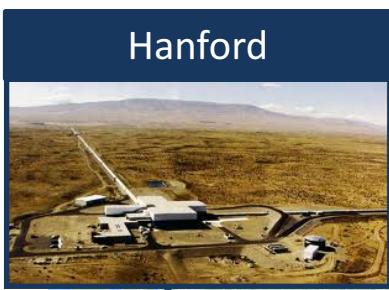
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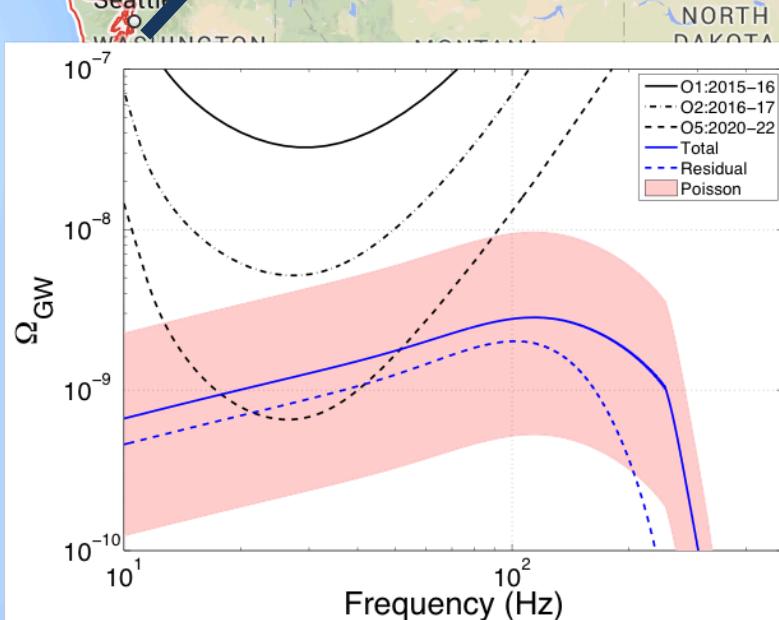
O1 Detections



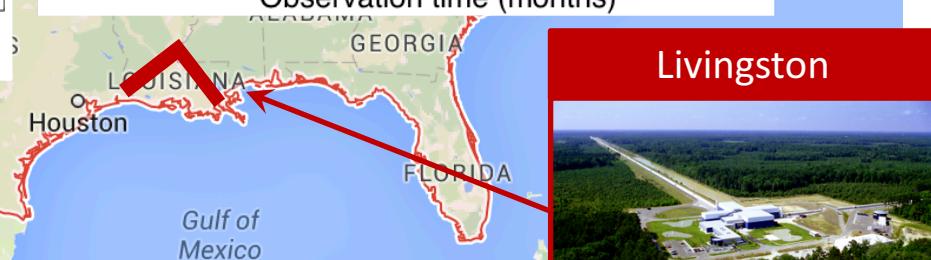
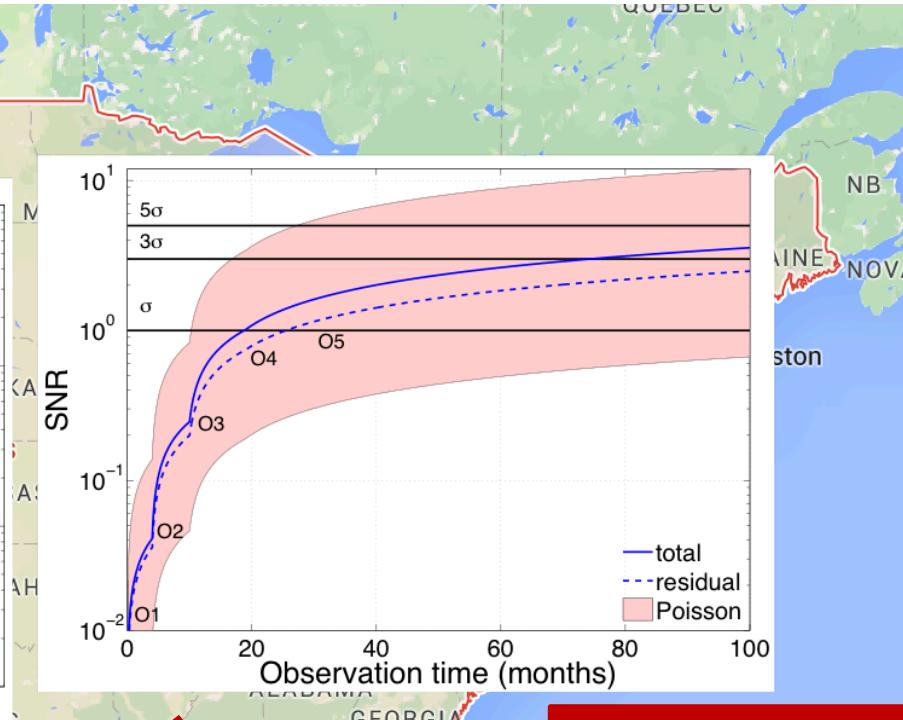
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Implications

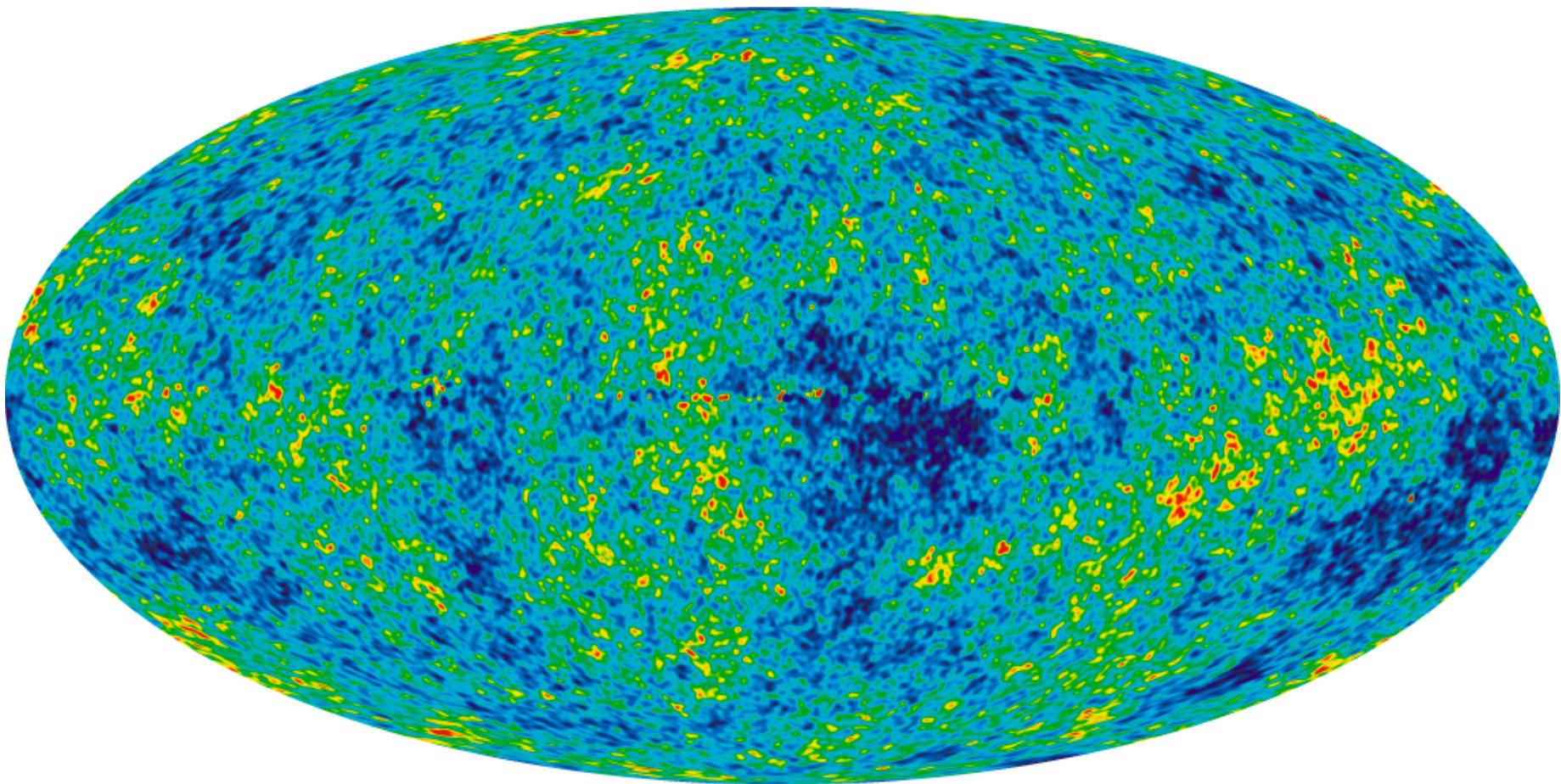


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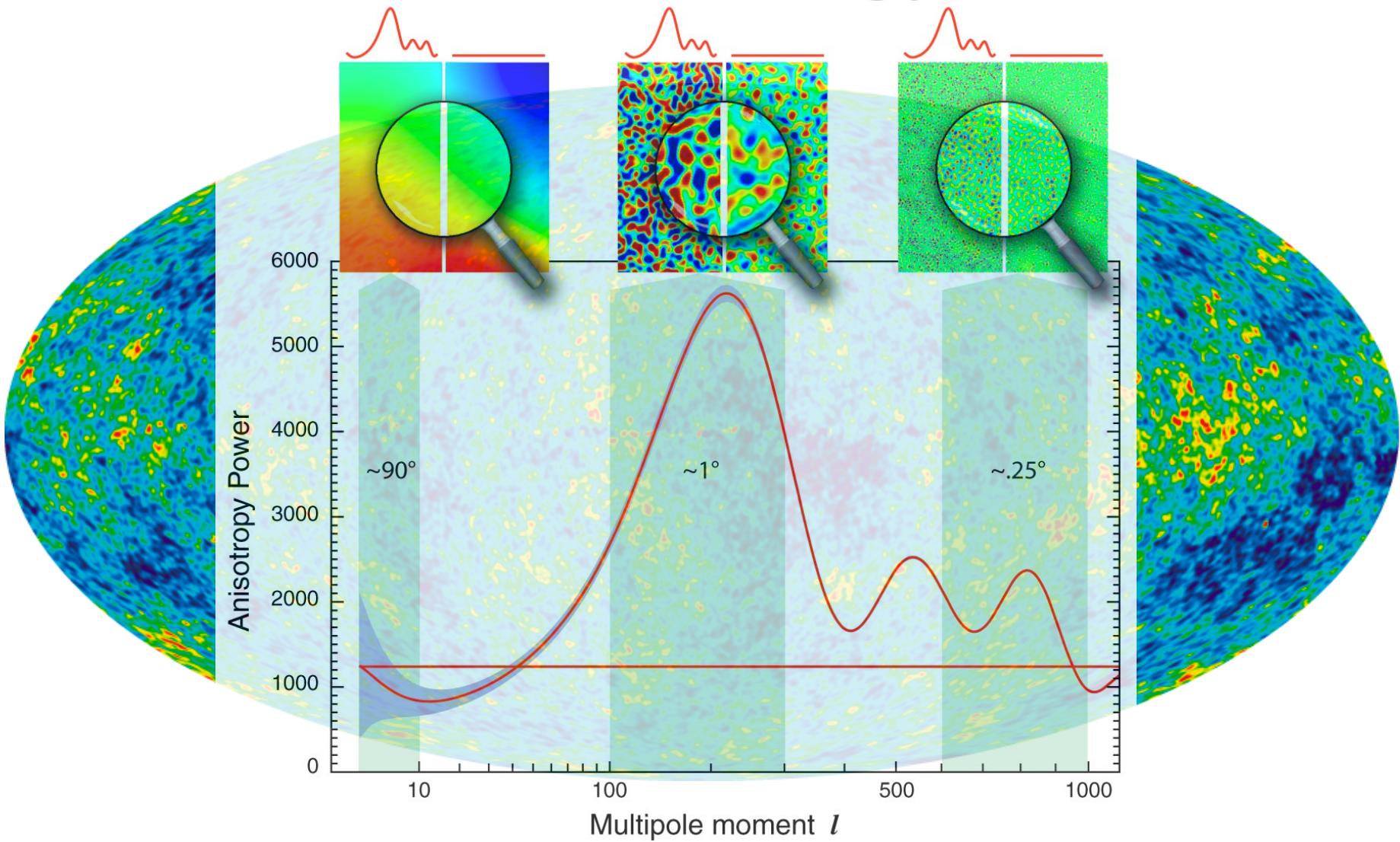
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CMB analogy



<https://map.gsfc.nasa.gov/media/060913/index.html>

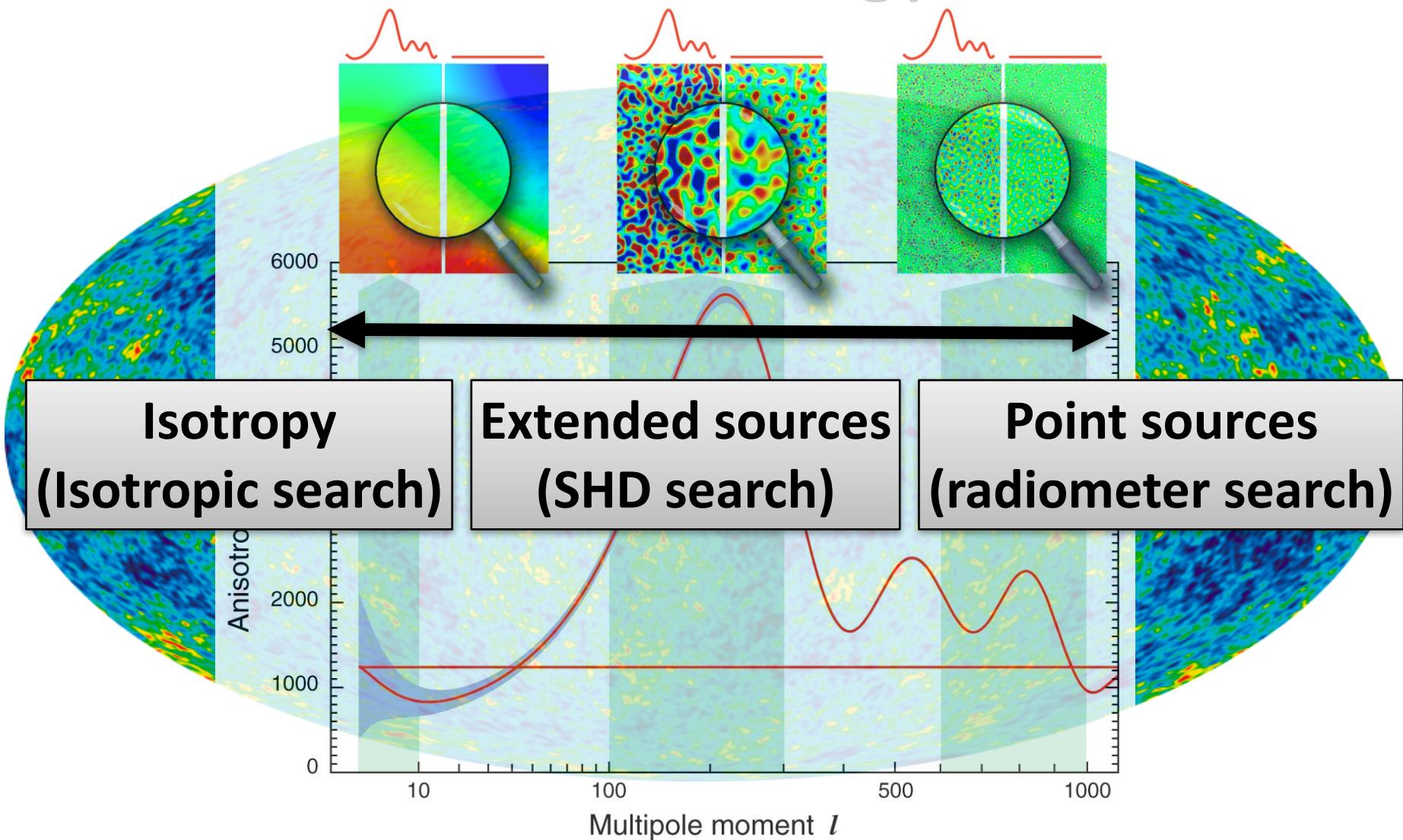
CMB analogy



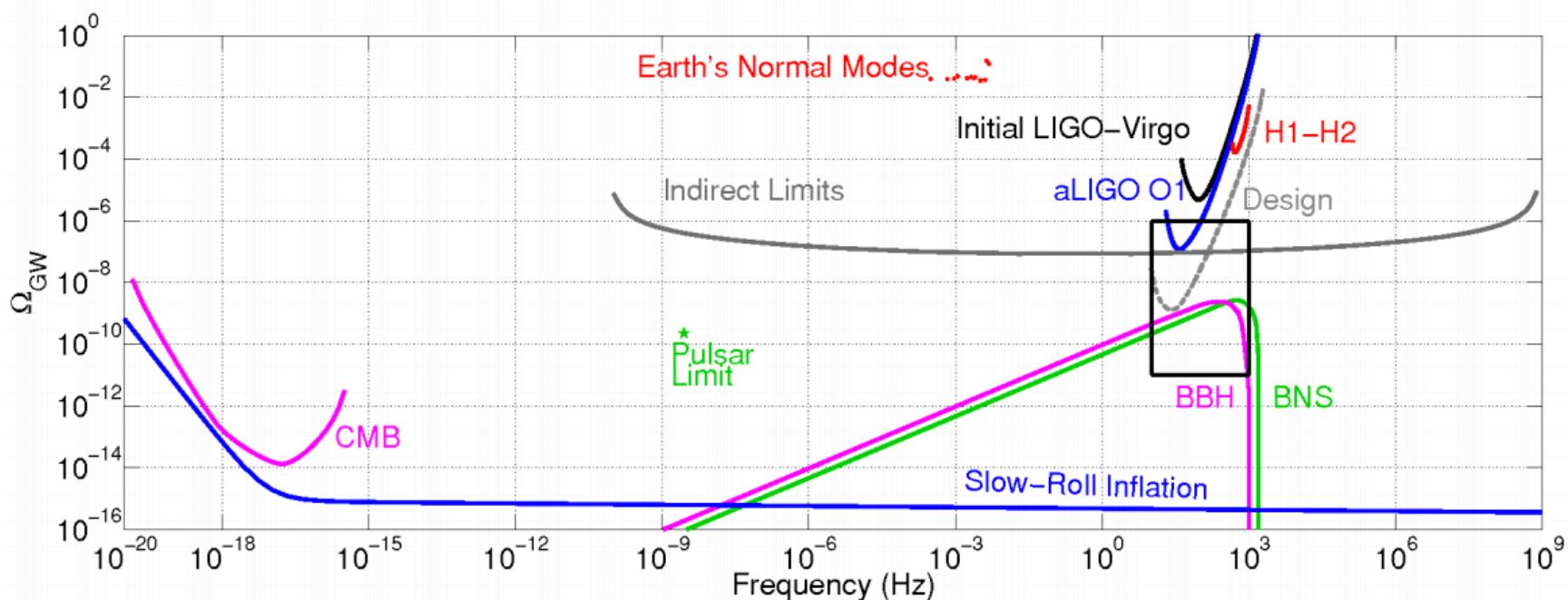
<https://map.gsfc.nasa.gov/media/060913/index.html>

https://map.gsfc.nasa.gov/mission/sgoals_parameters_spect.html

CMB analogy



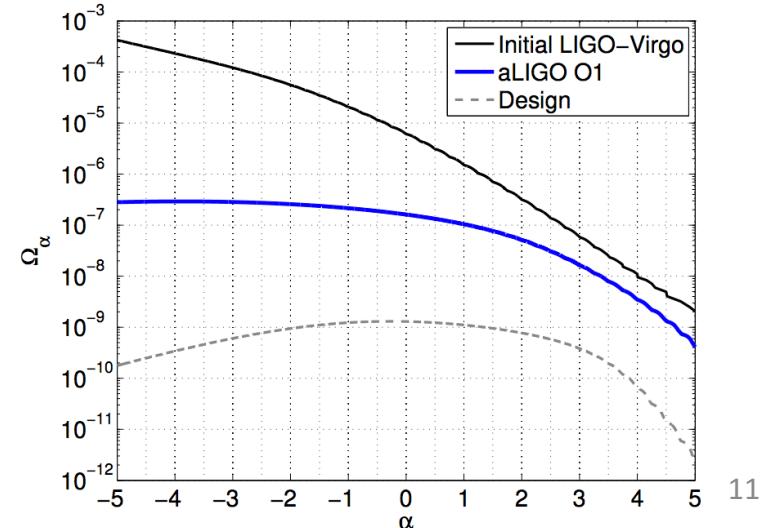
Isotropic Search



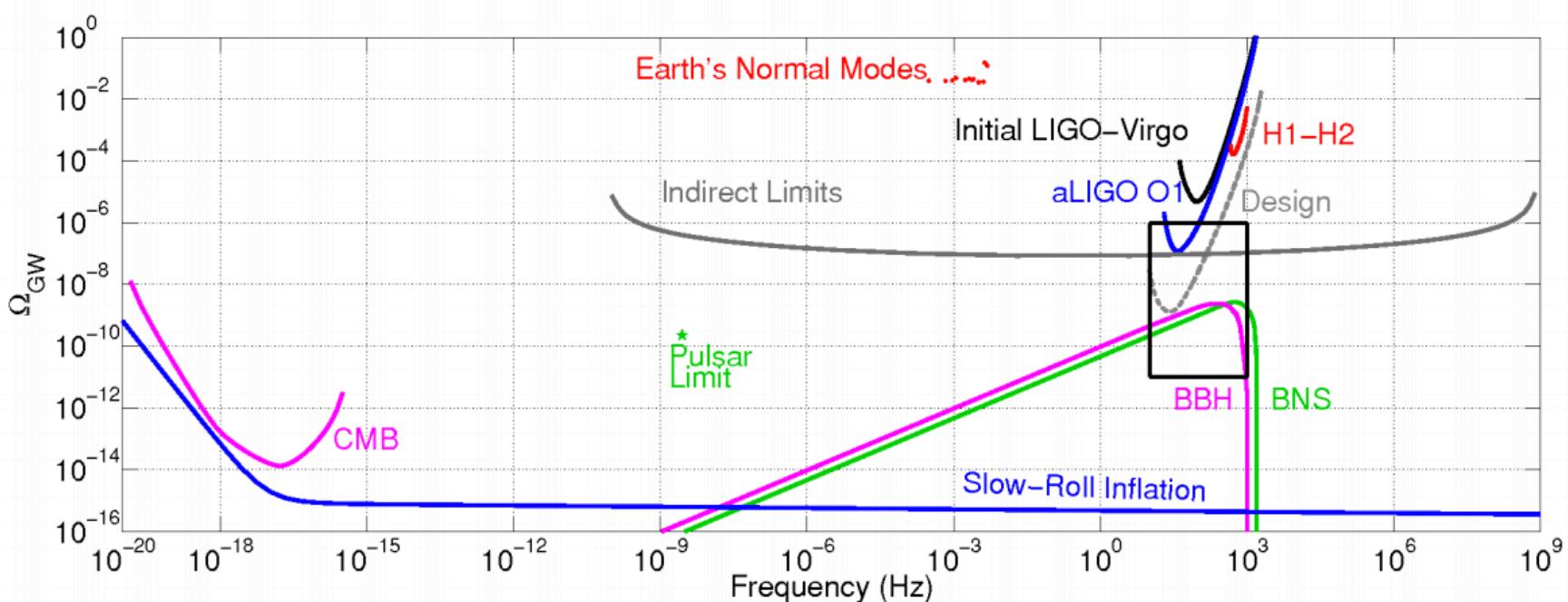
Assumes background is:

- isotropic
- unpolarised
- Stationary
- Gaussian
- and well represented by a power-law

No significant signal detected.



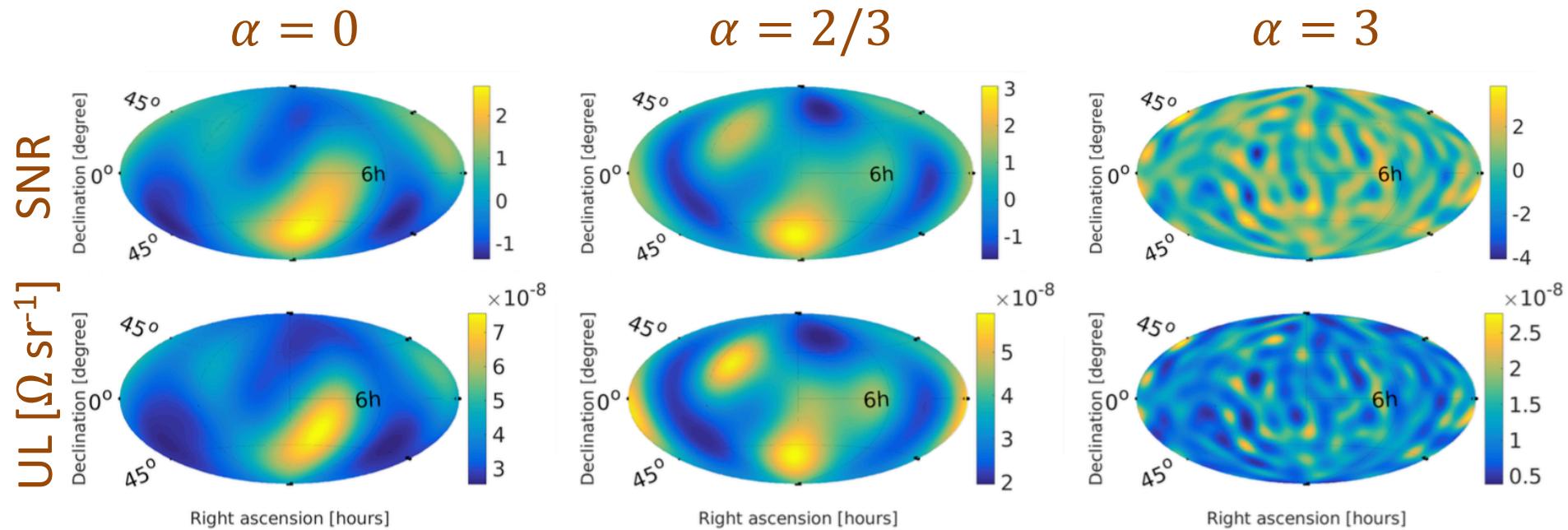
Isotropic Search



Spectral index α	Frequency band with 99% sensitivity	Amplitude Ω_α	95% CL upper limit	Previous limits [33]
0	$20 - 85.8 \text{ Hz}$	$(4.4 \pm 5.9) \times 10^{-8}$	1.7×10^{-7}	5.6×10^{-6}
$2/3$	$20 - 98.2 \text{ Hz}$	$(3.5 \pm 4.4) \times 10^{-8}$	1.3×10^{-7}	—
3	$20 - 305 \text{ Hz}$	$(3.7 \pm 6.5) \times 10^{-9}$	1.7×10^{-8}	7.6×10^{-8}

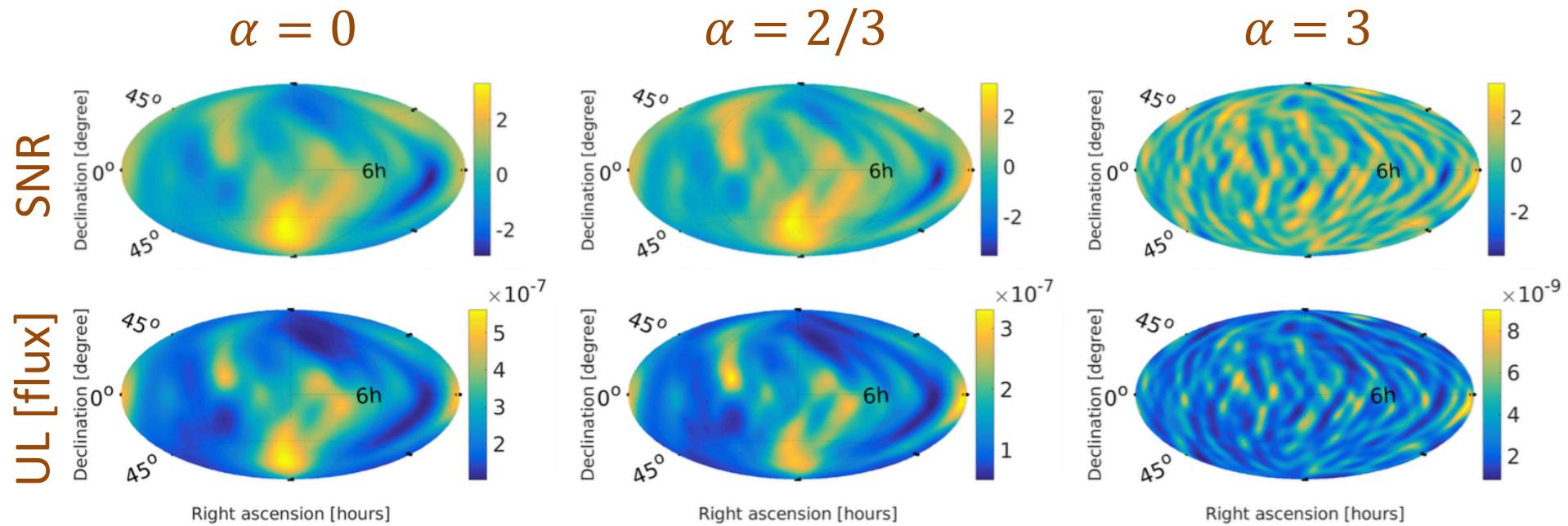
Arbitrary angular distribution

- Spherical harmonic decomposition looks for point sources
- No significant signal detected
- Upper limit maps of fractional energy density per solid angle [$\Omega \text{ sr}^{-1}$]

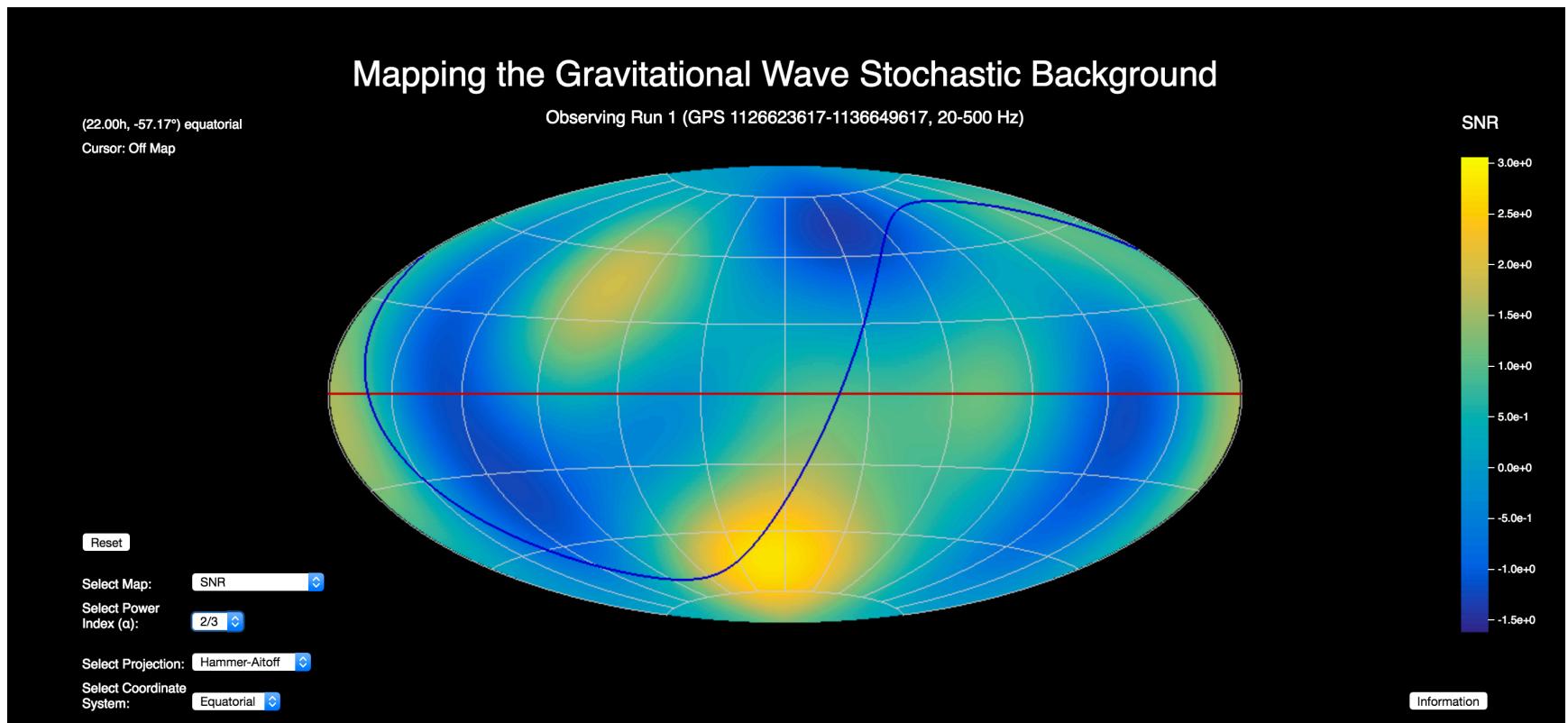


Point sources

- Radiometer search optimised for point sources
- No significant signal detected
- Upper limit maps of energy flux [$\text{erg cm}^2 \text{ s}^{-1} \text{ Hz}^{-1}$]



Interactive maps

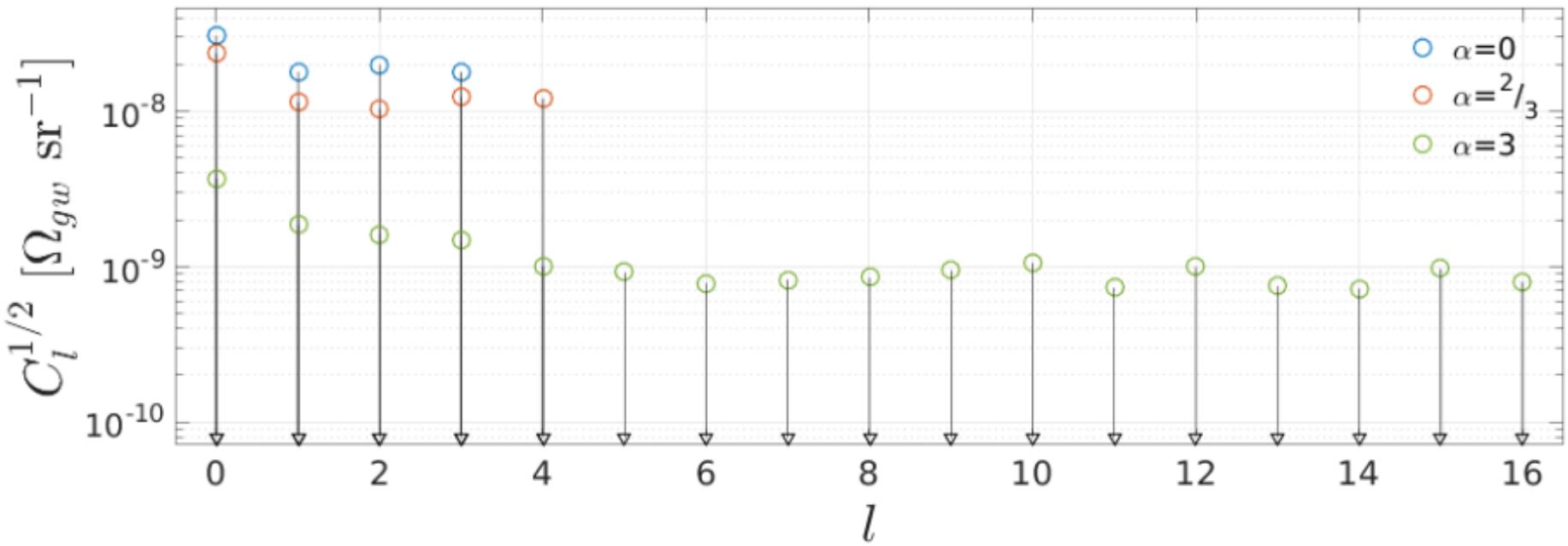


<https://ldas-jobs.ligo.caltech.edu/~will.campbell/>

Angular power spectra (SHD)

- Upper limits on GW background anisotropy

$$\hat{C}_l \equiv \frac{1}{2l+1} \sum_m \left[|\hat{\mathcal{P}}_{lm}|^2 - (\Gamma_R^{-1})_{lm,lm} \right]$$



Conclusions

- SGWB searches can constrain important cosmological and astrophysical background models
 - probe physics at energy scales inaccessible by other means
 - constrain models of conjectural objects such as cosmic strings
- More detectors with better sensitivity will continue to improve the effectiveness of our searches
- Reasonable chance of detecting binary black hole background as advanced detectors reach design sensitivity

THANK YOU