THE QUEST FOR THE SGWB WITH LIGO/VIRGO

Tania Regimbau

LISA Cosmo Workshop, 11-15/06/2018

Plan of this talk

- Models and implications of the first LIGO/Virgo detections
- Standard detection method in LIGO/Virgo – O1 results
- Searching for anisotropies
- Searching for extra polarizations
- Searching for sub-thresholds BBHs (non Gaussian)
- Prospect for 3G detectors (subtraction of the astrophysical background)

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Sources of SGWB in LIGO/Virgo

A stochastic background of gravitational waves has resulted from the superposition of a large number of independent unresolved sources from different stages in the evolution of the Universe.

- **Astrophysical:** all the sources since the beginning of stellar activity.

Dominated by compact binary coalescences: BBHs, BNSs, BH-NSs.

- **Cosmological:** signature of the early Universe.

Inflation, cosmic strings, no phase transition in LIGO/Virgo, inflation.

Implications of the first LIGO/Virgo detections

- LIGO and Virgo have already observed 5 (+1?) BBHs and 1 BNS. The events we detect now are loud individual sources at close distances ($z \sim 0.07-0.2$ for BBHs and $z \sim 0.01$ for the BNS).

- Many more individual sources at larger distances that contribute to create a stochastic background, which could be the next milestone for LIGO/Virgo.

- Using mass distributions and local rates derived from the first observations, we were able to revise previous predictions of the GW background from BBHs and BNSs.

Stochastic background from BNSs and BBHs

- Energy density in GWs characterized by:

$$\Omega_{GW}(f) = \frac{f}{\rho_c} \sum_{k=1..N} \Omega_{gw}(f,\theta_k)$$

- For a population distributed in the parameter space $\theta_k = (m_1, m_2, \chi_{eff})$:

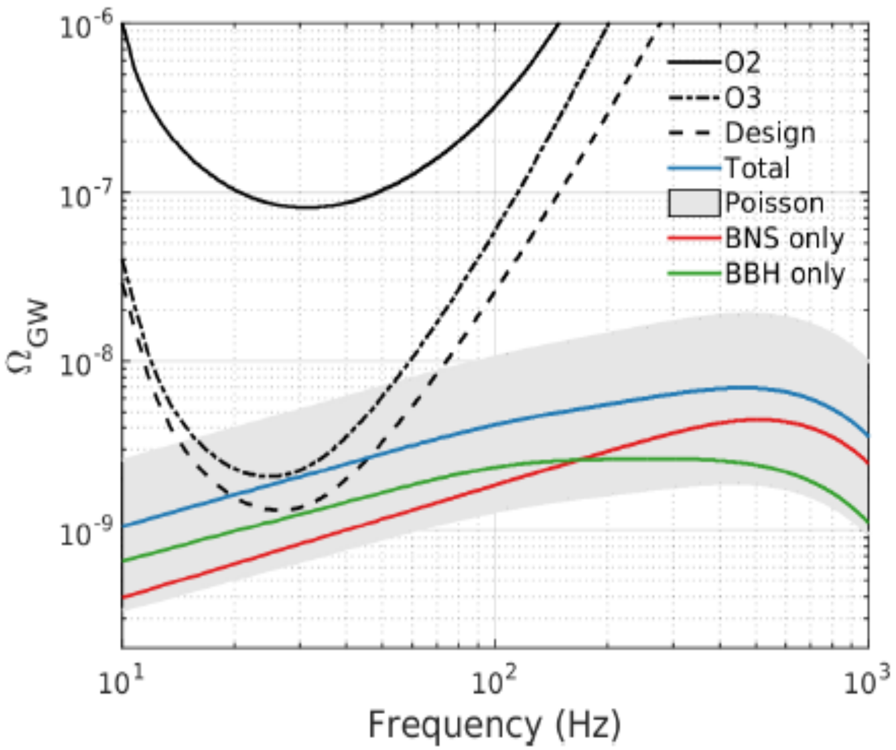
$$\Omega_{GW}(f,\theta_k) = \frac{f}{\rho_c} \int d\theta_k P(\theta_k) \int_0^{10} dz R_m^k(z,\theta_k) \frac{\frac{dE_{gw}}{df}(\theta_k, f(1+z))}{4\pi r^2(z)}$$

with rate:

$$R_m^k(z,\theta_k) = \int_{t_{\min}}^{t_{\max}} R_f(z,\theta_k) P(t_d,\theta_k) dt_d$$

Abbott et al. PRL, 120.091101 (2017)

Estimate from Detected Sources

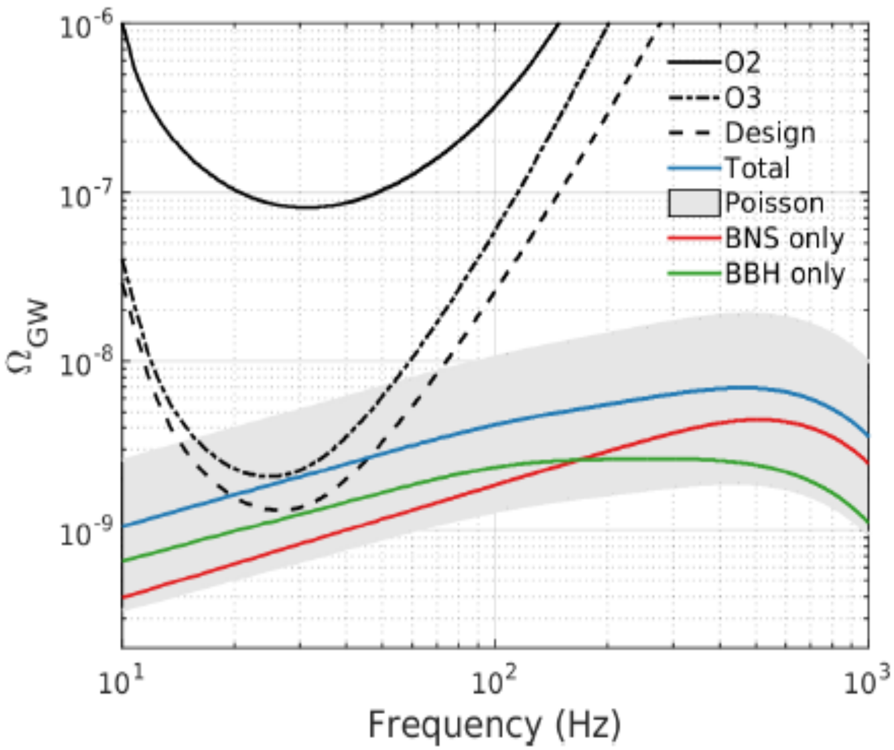


$$\Omega_{GW}^{BBH}(25\text{Hz}) = 1.1^{+1.2}_{-0.7}10^{-9}$$

$$\Omega_{GW}^{BNS}(25\text{Hz}) = 0.7^{+1.5}_{-0.6}10^{-9}$$

Abbott et al. PRL, 120.091101 (2017)

Estimate from Detected Sources



$$\Omega_{GW}^{BBH}(25\text{Hz}) = 1.1_{-0.7}^{+1.2} 10^{-9}$$

From GW150914 only we obtained:

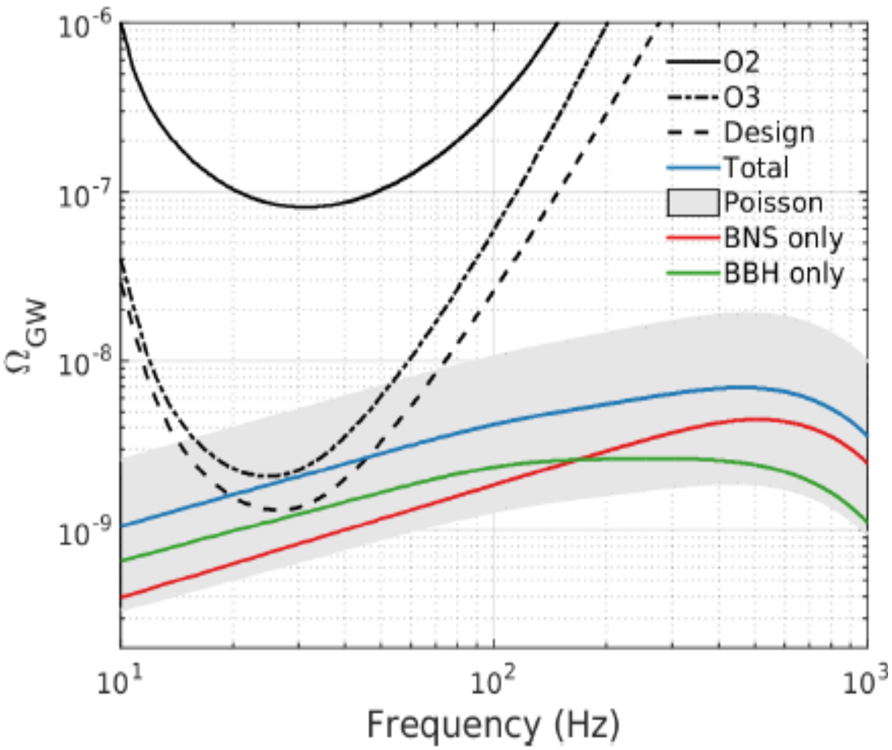
$$\Omega_{GW}^{BBH}(25\text{Hz}) = 1.1_{-0.9}^{+2.7} \times 10^{-9}$$

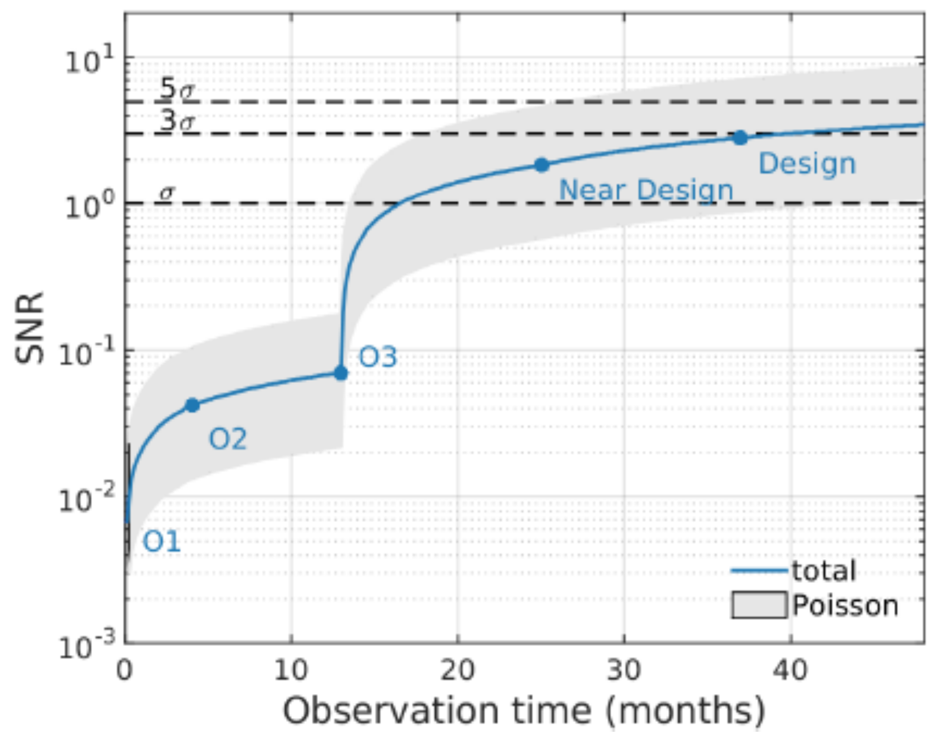
32% of improvement of the error.

Abbott et al. PRL, 120.091101 (2017)

Estimate from Detected Sources

The background could be detected before the detectors reach design sensitivity!





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Data Analysis Principle

- Assume stationary, unpolarized, isotropic and Gaussian stochastic background.
- Cross correlate the output of detector pairs to eliminate the noise:

$$s_i = h_i + n_i$$

$$< s_1 s_2 > = < h_1 h_2 > + \underbrace{< n_1 n_2 >}_{0} + \underbrace{< h_1 n_2 >}_{0} + \underbrace{< n_1 h_2 >}_{0}$$

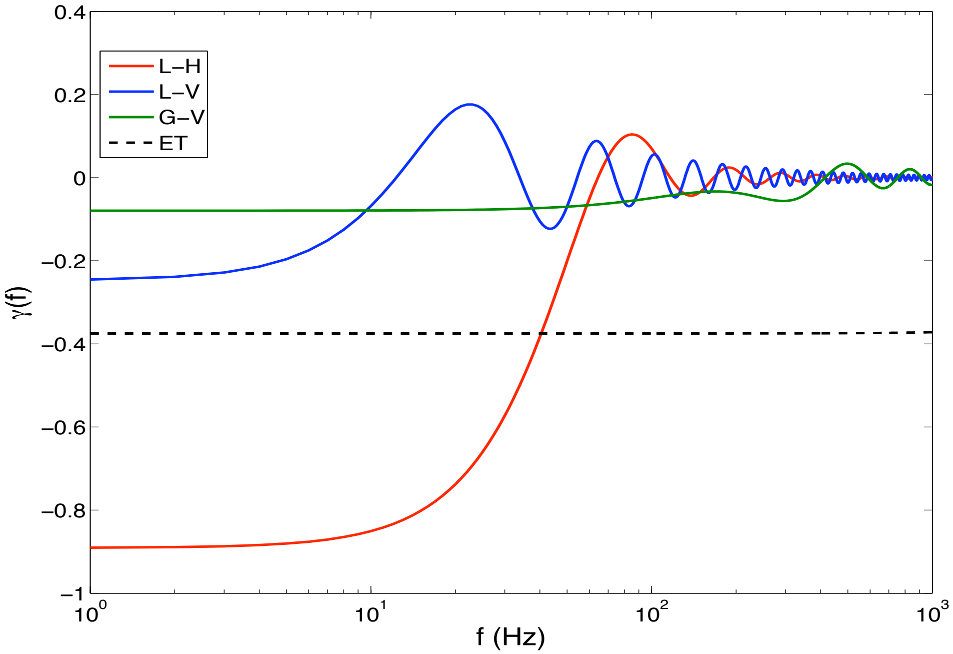
Cross Correlation Statistics

- Standard CC statistics (Allen & Romano, 1999, PRD, 59, 102001)
- Frequency domain cross product: $Y = \int \tilde{s}_1^*(f)\tilde{Q}(f)\tilde{s}_2(f)df$
- optimal filter: $\tilde{Q}(f) \propto \frac{\gamma(f)\Omega_{gw}(f)}{f^3 P_1(f) P_2(f)}$ with $\Omega_{gw}(f) \equiv \Omega_0 f^{\alpha}$
- in the limit noise >> GW signal

$$\text{Mean}(Y) = \Omega_0 T,\ \text{Var}(Y) \equiv \sigma^2 \propto T,\ \text{SNR} \propto \sqrt{T}$$

Overlap Reduction Function

Loss of sensitivity due to the separation and the relative orientation of the detectors.



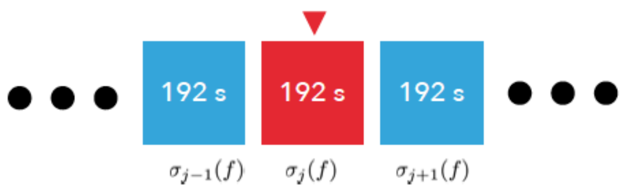
Time delay

$$\gamma(f) = \frac{5}{8\pi} \sum_{A=\{+,\times\}} \int e^{2\pi i f \hat{\Omega}\Delta\vec{x}/c} F_1^A(\hat{\Omega}) F_2^A(\hat{\Omega}) d\Omega$$

Detector response

Pre-analysis: data cut

- data split into half-overlapping 192s segments, downsampled to 1024 Hz, Hann windowed, HPF, Fourier transformed and coarse grained to 0. 03125 Hz.
- remove time segments where the noise is non stationary (35 %).



$$\left|\sigma_j - \frac{\sigma_{j+1}+\sigma_{j-1}}{2}\right| \leq 0.2\sigma_j$$

- remove frequency bins which display coherence with auxiliary chanels (power mains, GPS timing, Schuman resonances).
- assume 4.8-5.4% callibration uncertainty.

Constraints on the GW energy density

- No evidence for a stochastic background (cosmological or astrophysical).

- But set upper limits on the total energy density:

α	99% sens. band	Ω_α	95% UL	S6 UL
0	$20 - 85.8$ Hz	$(4.4 \pm 5.9) \times 10^{-8}$	1.7×10^{-7}	5.6×10^{-6}
$\frac{2}{3}$	$20 - 98.2$ Hz	$(3.5 \pm 4.4) \times 10^{-8}$	1.3×10^{-7}	–
3	$20 - 305$ Hz	$(3.7 \pm 6.5) \times 10^{-9}$	1.7×10^{-8}	3.5×10^{-8}

- For α=0, 33x better than initial LIGO/Virgo.

Abbott et al. arXiv:1712.0116[8]

Constraints on cosmic strings models

- 1D topological defects which can be formed in GUT-scale phase transitions in the early Universe. They can produce large amount of GWs through the production of loops (cusps and kinks).

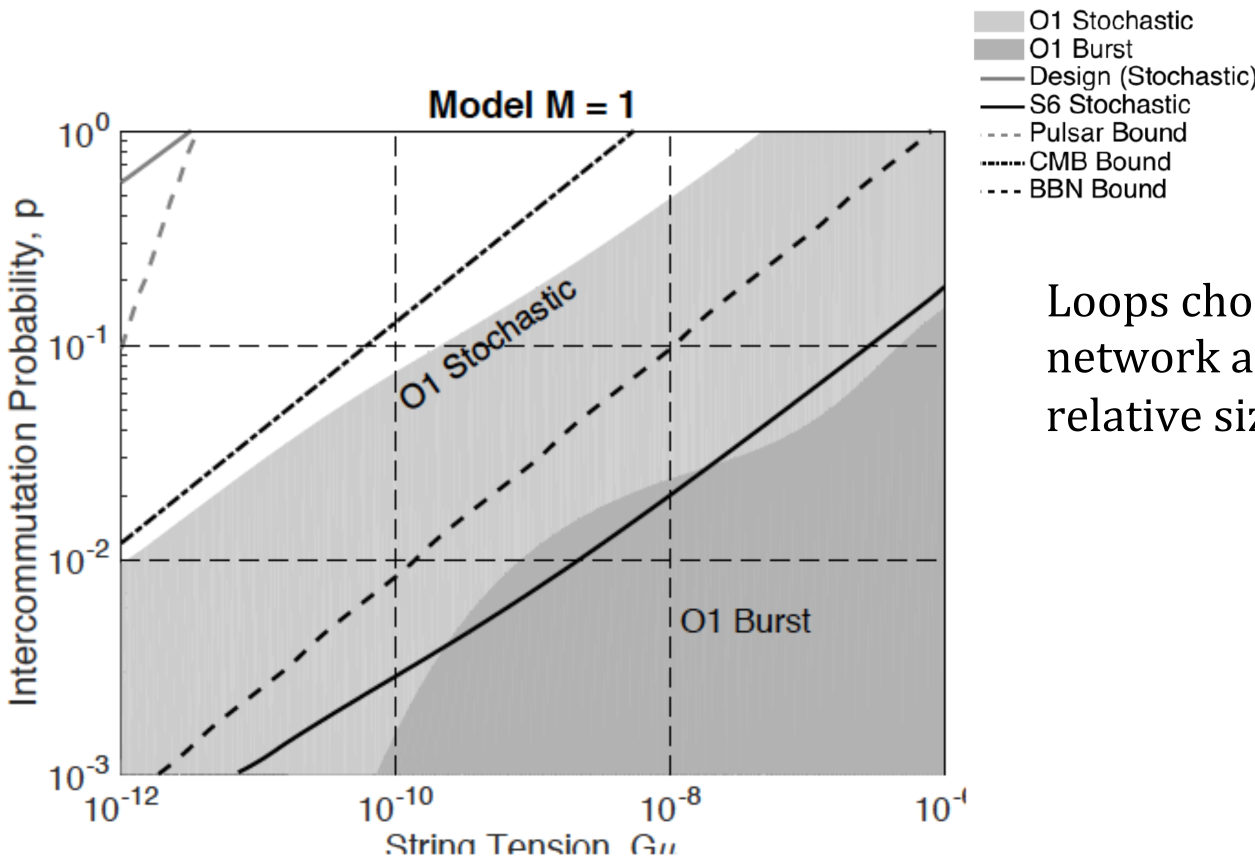
- Strings are charactarized by 2 parameters: tension $G\mu$ and intercommutation probability *p.*

- We consider 3 different models of the number density *n(l,t)* based on Nambu-Goto numerical simulations (*p=1*), and extend to *p<1* assuming:

$$n(l,t,p<1) = n(l,t,p=1)/p$$

Abbott et al. arXiv:1712.0116

Original Large Loop Distribution

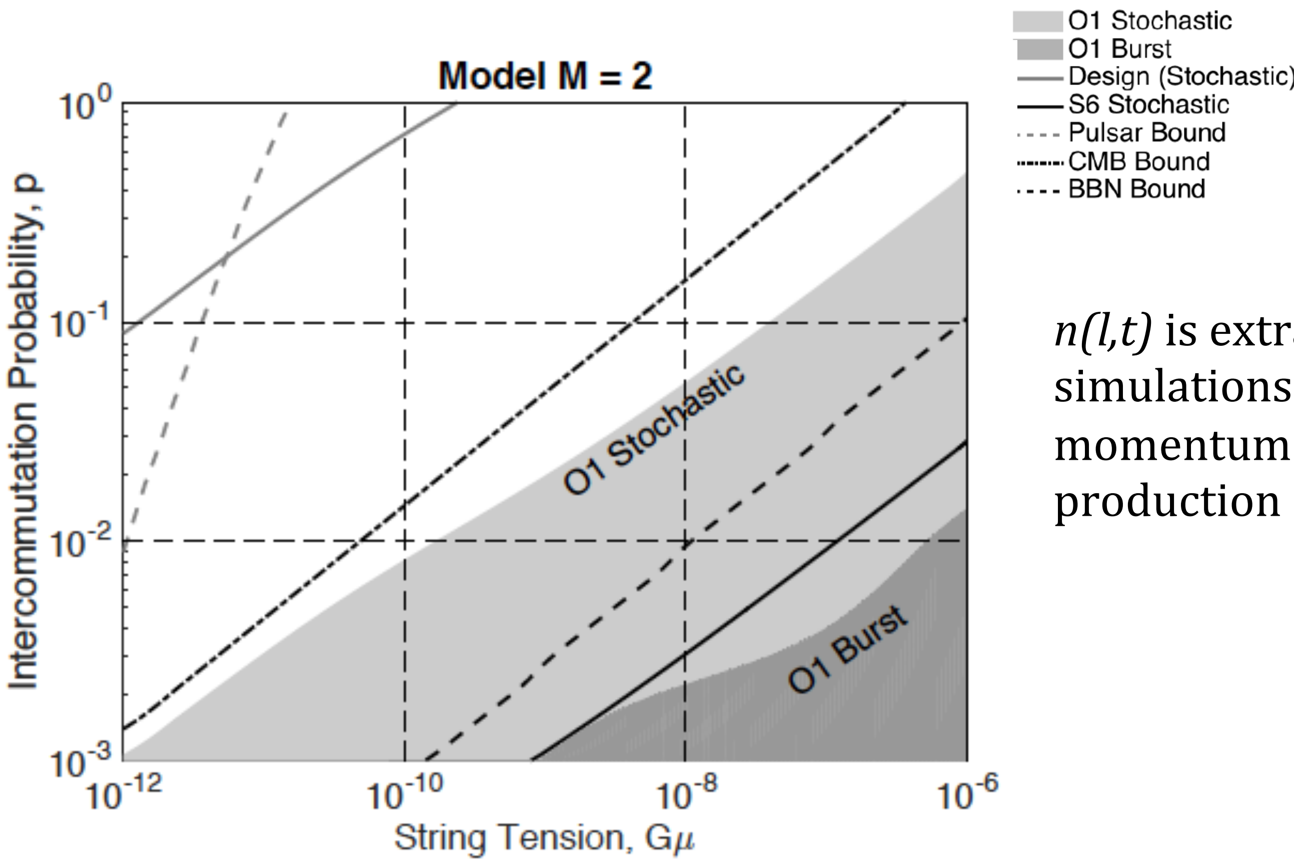


Loops chopped off the infinite string network are formed with the same relative size:

$$l(z) = \alpha t(z)$$

Abbott et al. arXiv:1712.0116[illegible]

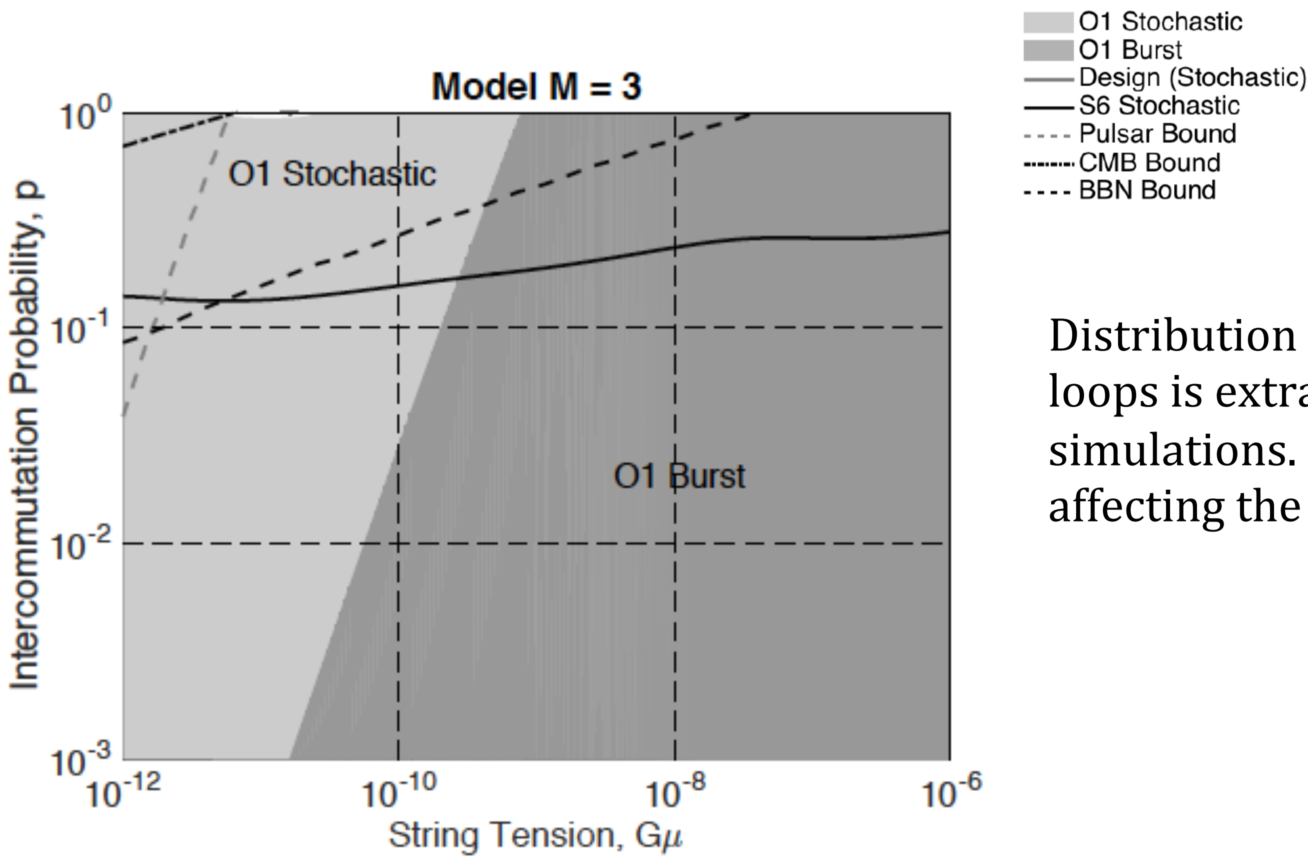
Large loop distribution of Blanco Pillado et al.



n(l,t) is extrapolated from numerical simulations. Assume that the momentum dependence of the loop production function is weak.

Abbott et al. arXiv:1712.01168

Large Loops Distribution of Ringeval et al.



Distribution of non self interacting loops is extrapolated from numerical simulations. Include GW back reaction affecting the production of small loops.

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Directional searches

- relax assumption of isotropy and generalize the search for a stochastic signal to the case of arbitrary angular distribution.

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

$$\mathcal{P}(\hat{\Omega}) = \mathcal{P}_\alpha \mathbf{e}_\alpha(\hat{\Omega})$$

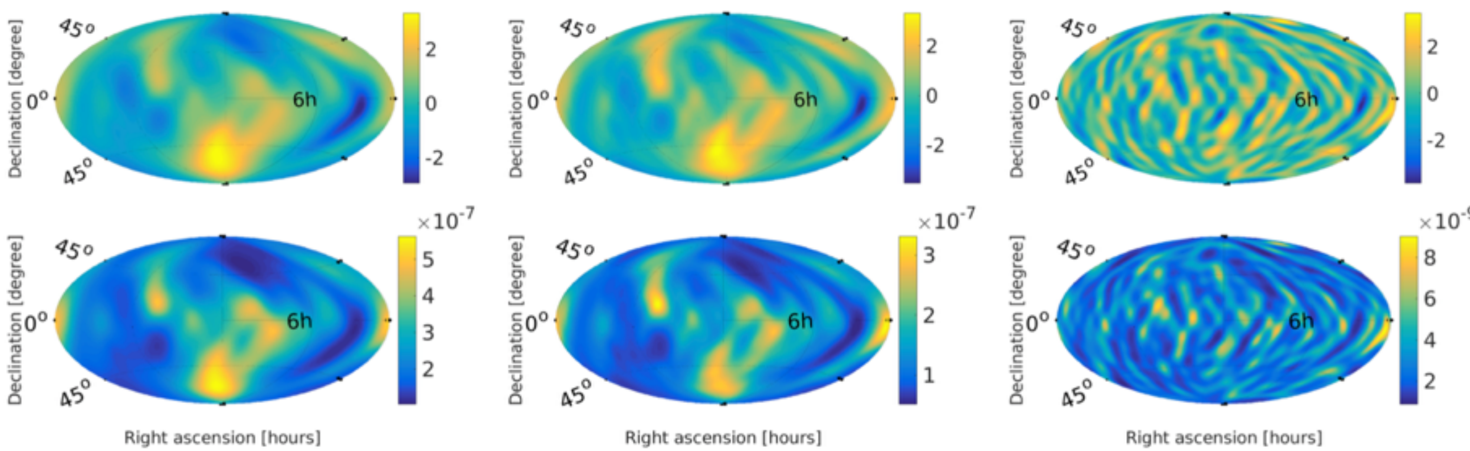
- radiometer analysis for point-like sources: $\mathcal{P}(\hat{\Omega}) \equiv \eta(\hat{\Omega}_0)\delta^2(\hat{\Omega}, \hat{\Omega}_0)$
- spherical harmonic decomposition : $\mathcal{P}(\hat{\Omega}) \equiv \sum_{lm} \mathcal{P}_{lm} Y_{lm}(\hat{\Omega})$

Radiometer: O1 results

						All-sky (broadband) Results			
						Max SNR (% p-value)		Upper limit range	
α	Ω_{gw}	$H(f)$	f_α (Hz)	θ (deg)	l_{max}	BBR	SHD	BBR ($\times 10^{-8}$)	SHD ($\times 10^{-8}$)
0	constant	$\propto f^{-3}$	52.50	55	3	3.32 (7)	2.69 (18)	10 – 56	2.5 – 7.6
2/3	$\propto f^{2/3}$	$\propto f^{-7/3}$	65.75	44	4	3.31 (12)	3.06 (11)	5.1 – 33	2.0 – 5.9
3	$\propto f^{3}$	constant	256.50	11	16	3.43 (47)	3.86 (11)	0.1 – 0.9	0.4 – 2.8

SNR

90% UL



SHD: O1 results

All-sky (broadband) Results

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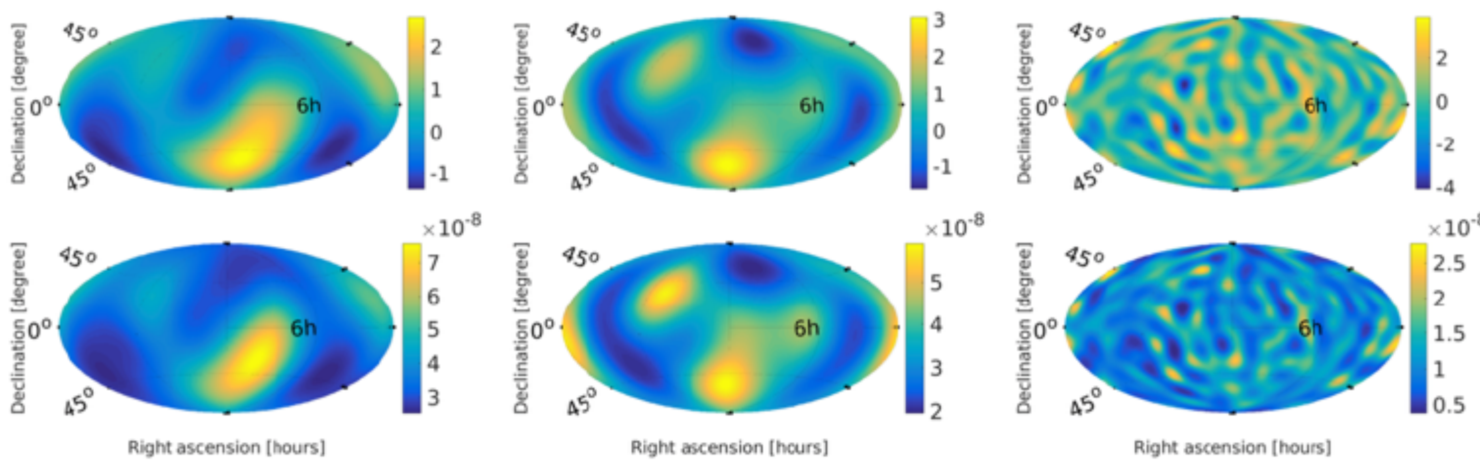


Models of Anisotropies

- We expect anisotropy due to the finitness of the number of sources, the nature of spacetime along the line of sight, and for astrophysical models the local distribution of matter.

- Recent efforts in modeling the anisotropy of the SGWB

Cusin et al., Phys.Rev.D96.103119, arXiv:1711.11345 (formalism), arXiv:1803.03236 (compact binary mergers), Jenkins & Sakellariadou arXiv:1802.06046 (formalism and cosmic strings), Jenkins, Sakellariadou, Regimbau & Slezac arXiv:1806.01718 (compact binary mergers, analytical + galaxy catalog).

- Can be extended to any type of SGWB from cosmological or astrophysical origin.

Anisotropies from Cosmic Strings

- Anisotropy due to source density contrast (neglect cosmological perturbations except peculiar motion of the observer):

$$\Omega_{\mathrm{gw}}(\nu_{\mathrm{o}}, \hat{e}_{\mathrm{o}}) = \frac{\pi}{3}(t_H \nu_{\mathrm{o}})^3 \int_0^{\infty} \mathrm{d}z \, \frac{1+z}{E(z)} \int \mathrm{d}\zeta \, \bar{n} R(1 + \delta_n + \hat{e}_{\mathrm{o}} \cdot v_{\mathrm{o}}) \int_{S^2} \mathrm{d}^2\sigma_{\mathrm{s}} \, r_{\mathrm{s}}^2 \tilde{h}^2$$

$$\Omega_{\mathrm{gw}} \equiv \bar{\Omega}_{\mathrm{gw}}(1 + \delta_{\mathrm{gw}})$$

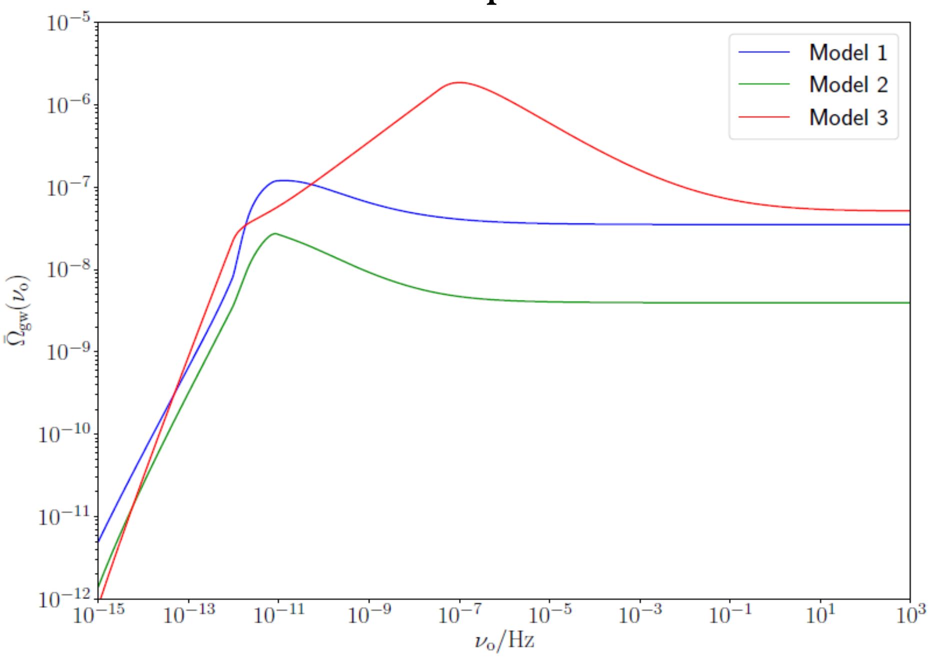
- Use a multiple expansion of the two point correlation function which is the second moment of the density contrast:

$$C_{\mathrm{gw}}(\theta_{\mathrm{o}}, \nu_{\mathrm{o}}) \equiv \left\langle \delta_{\mathrm{gw}}^{(\mathrm{s})}(\nu_{\mathrm{o}}, \hat{e}_{\mathrm{o}}) \delta_{\mathrm{gw}}^{(\mathrm{s})}(\nu_{\mathrm{o}}, \hat{e}'_{\mathrm{o}}) \right\rangle = \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} C_\ell(\nu_{\mathrm{o}}) P_\ell(\cos\theta_{\mathrm{o}})$$

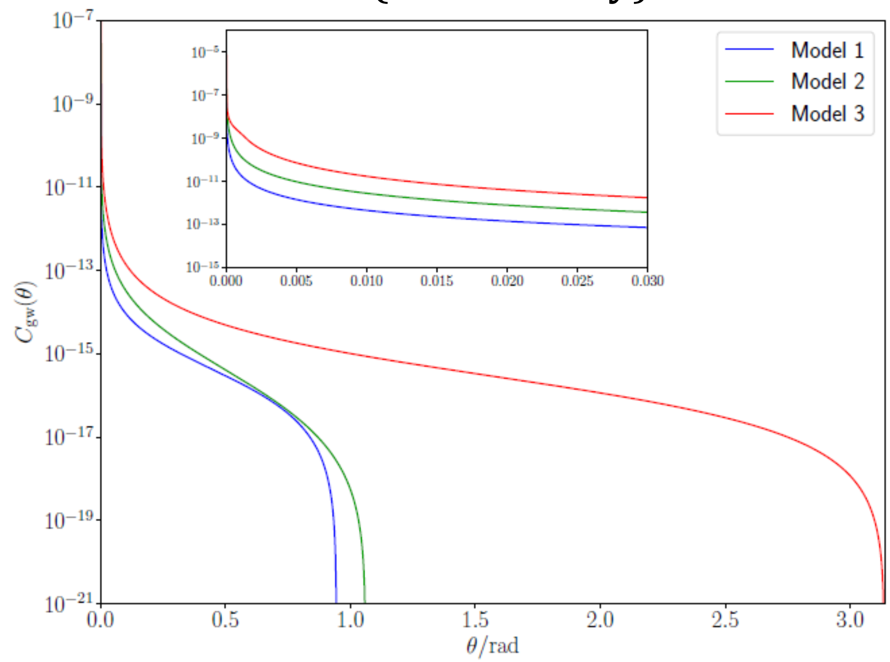
Jenkins & Sakellariadou, arXiv:1802.06046

Anisotropies from Cosmic Strings

Monopole



2PCF (overdensity)

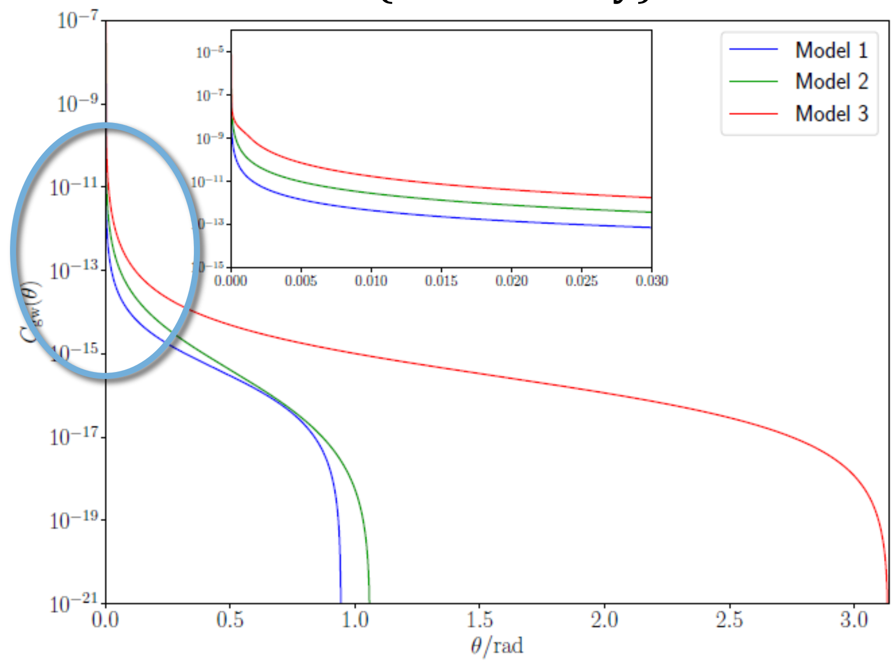


Anisotropies from Cosmic Strings

At smaller angles the angular dependence of the correlation is:

- the dominant one
- almost the same for all 3 models

2PCF (overdensity)

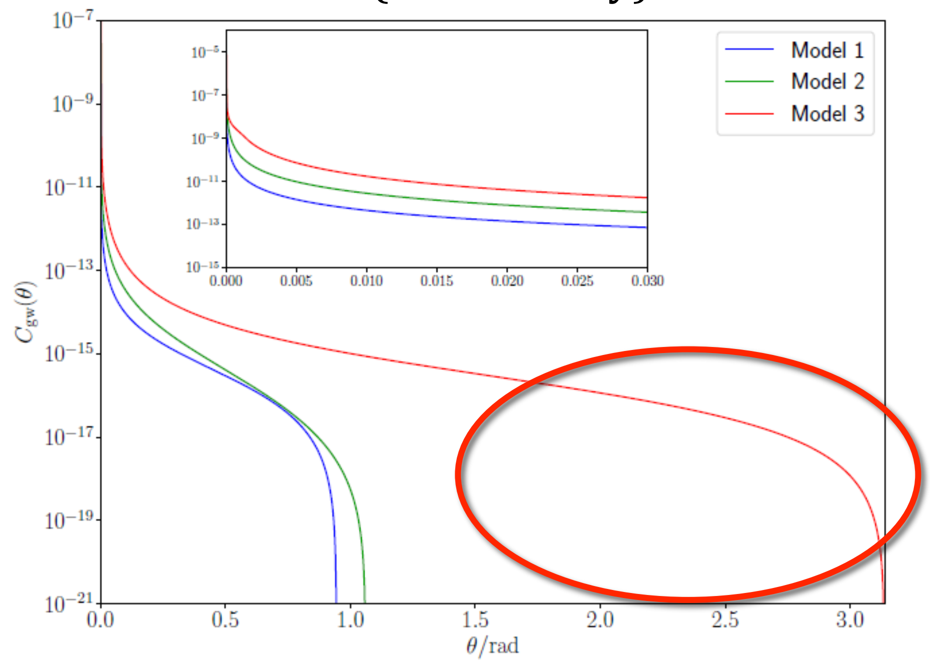


Jenkins & Sakellariadou, arXiv:1802.06046

Anisotropies from Cosmic Strings

At larger angular separation the anisotropy is related to largest loops and M3 allows larger loops

2PCF (overdensity)

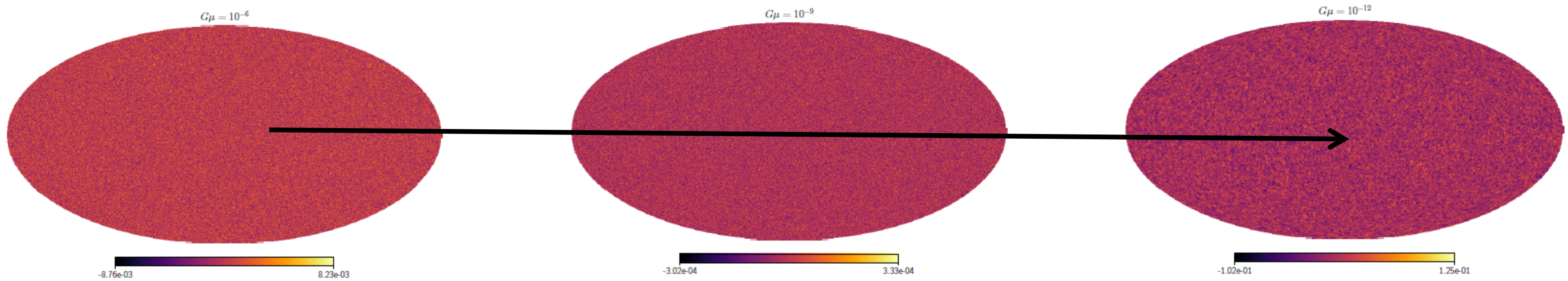


Jenkins & Sakellariadou, arXiv:1802.06046

Anisotropies from Cosmic Strings

$\Omega_{GW} / \bar{\Omega}_{GW}$ up to $l_{\max} = 5000$

$G\mu = 10^{-6}$ $G\mu = 10^{-9}$ $G\mu = 10^{-12}$



when $G\mu \searrow$, Ω_{gw} and then $\bar{\Omega}_{GW} / \Omega_{GW} = 1 + \delta_{GW} \nearrow$

Anisotropies from Compact Binary Mergers

- use simple analytical functions for the galaxy density and the galaxy-galaxy 2PCF (*Cusin et al., arXiv:1803.03236; Jenkins, Sakellariadou, Regimbau & Slezac arXiv:1806.01718)*
- use the Millenium mock galaxy catalogue (Jenkins et al. 2018)

sum over type of binaries

$$\Omega_{\mathrm{gw}} = \sum_i \frac{\pi}{3}(t_H \nu_{\mathrm{o}})^3 \int_0^{z_{\max}} \mathrm{d}z \, \frac{1+z}{E(z)} \int \mathrm{d}\zeta_{\mathrm{g}} \, n(1+\hat{e}_{\mathrm{o}} \cdot \boldsymbol{v}_{\mathrm{o}}) \int \mathrm{d}\zeta_{\mathrm{b}} \, R_i(z, \mathcal{Z}, \zeta_{\mathrm{b}}) \mathcal{S}_i(\nu_{\mathrm{s}}, \zeta_{\mathrm{b}})$$

$$= \sum_k \sum_i \frac{\pi H_{\mathrm{o}}}{3}(t_H \nu_{\mathrm{o}})^3 \frac{1+z_k}{r^2(z_k)}(1+\hat{e}_k \cdot \boldsymbol{v}_{\mathrm{o}}) \int \mathrm{d}\zeta_{\mathrm{b}} \, R_i(z_k, \mathcal{Z}_k, \zeta_{\mathrm{b}}) \mathcal{S}_i(\nu_{\mathrm{s},k}, \zeta_{\mathrm{b}}) \delta^{(2)}(\hat{e}_{\mathrm{o}}, \hat{e}_k)$$

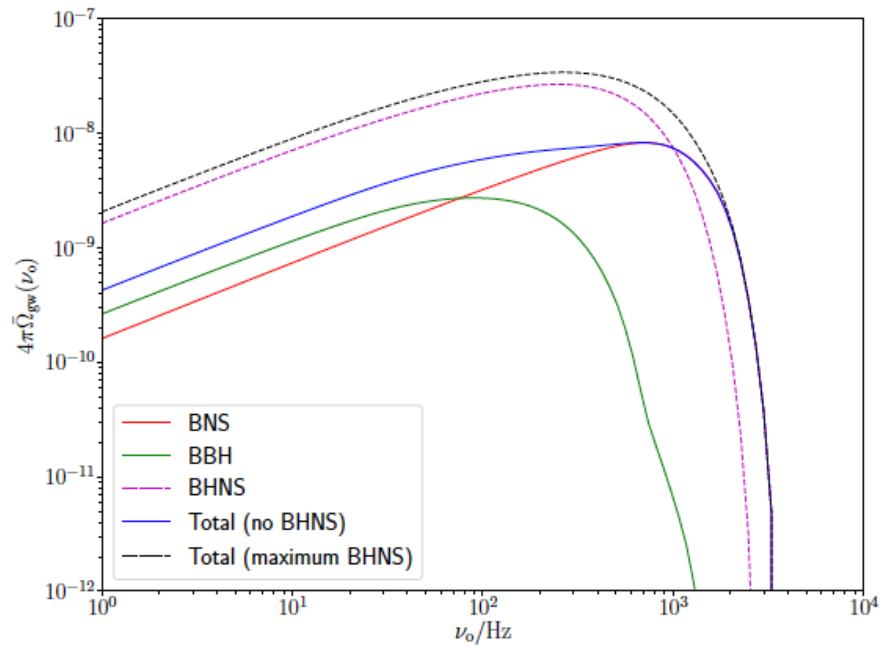
sum over galaxies

Same model as in the LIGO/Virgo stochastic implication papers

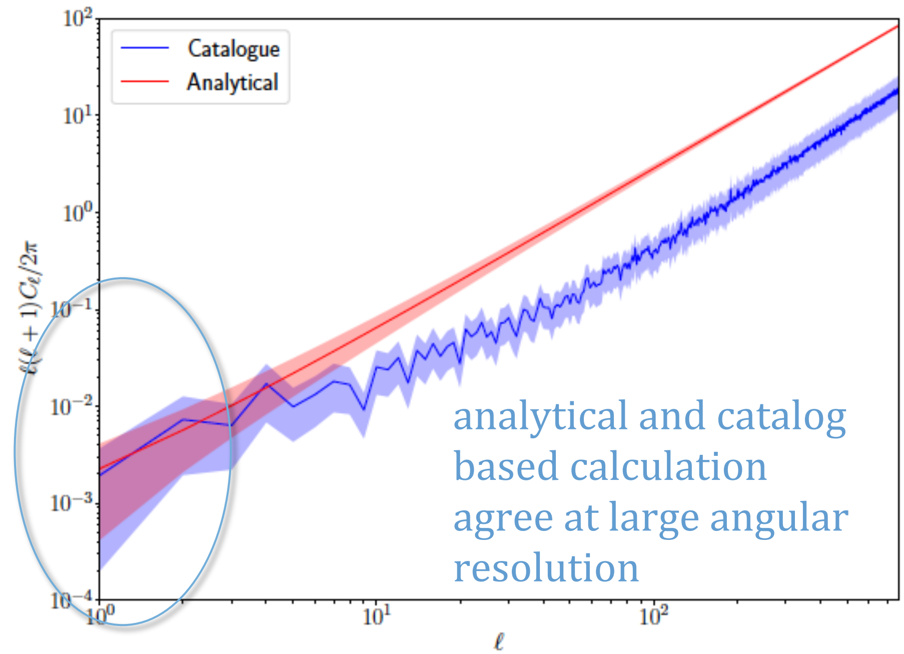
Jenkins & Sakellariadou, arXiv:1802.06046

Anisotropies from Compact Binary Mergers

Monopole



Overdensity



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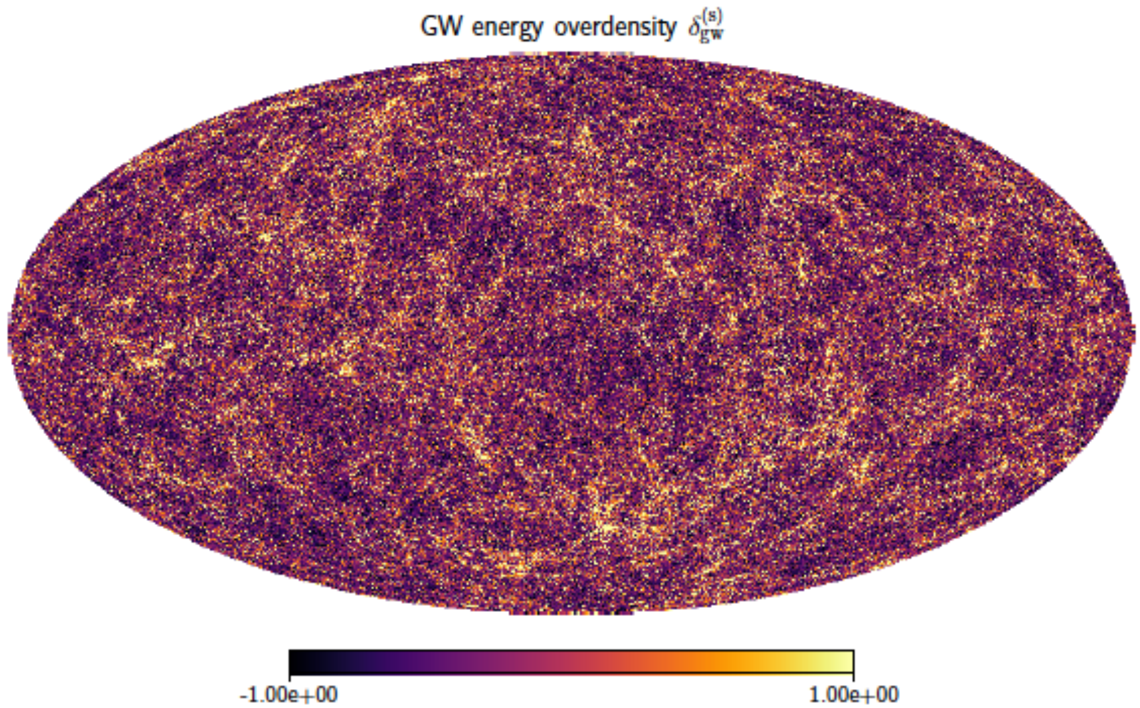

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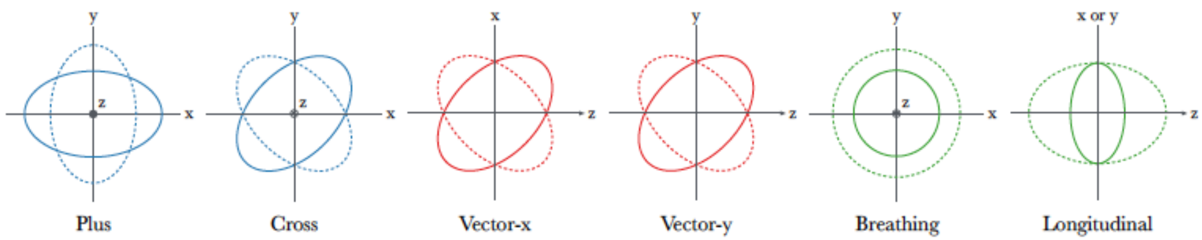
Search for extra polarization

- Most alternative theories of gravity have extra scalar and vector polarization modes and give additional contributions to the energy density of the SGWB.



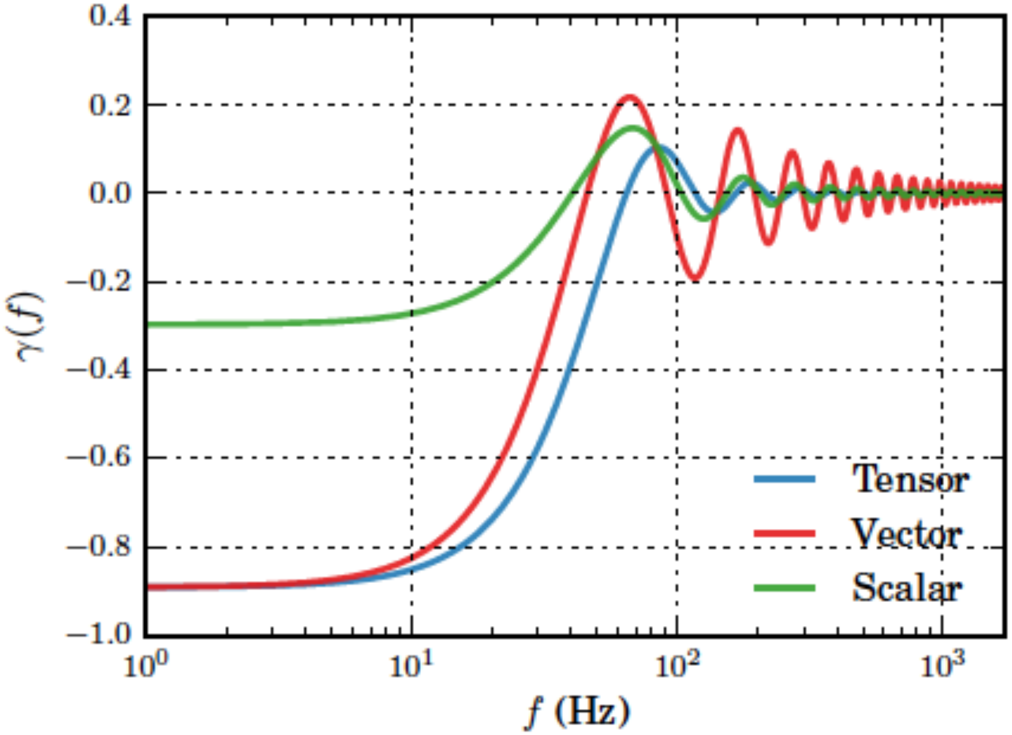
- We assume that the background is Gaussian, isotropic and stationary, uncorrelated between polarization modes and that the tensor and scalar contributions are individually unpolarized.

Overlap reduction functions

$$\langle \tilde{s}_1(f)\tilde{s}_2^*(f')\rangle = \delta(f-f')\sum_A \gamma_A(f)H^A(f)$$

Callister et al., PhysRevX.7.041058

Search for extra polarization



Search for extra polarization

After the cross power spectrum is measured we:

- compute Bayesian evidence for various hypothesis : (N): Gaussian noise only, (SIG): SGWB present of any polarization, (GR): purely tensor-polarized SGWB present, (NGR): SGWB present with tensor and/or scalar polarizations.
- Form two Bayesian odds: O_{N}^{SIG} and O_{GR}^{NGR}
- O1 results

Abbot et al.,

Prior	$\log\Omega_0^T$	$\log\Omega_0^V$	$\log\Omega_0^S$	Ω_0^T	Ω_0^V	Ω_0^S
Log-Uniform	-7.25	-7.20	-6.96	5.6×10^{-8}	6.4×10^{-8}	1.1×10^{-7}
Uniform	-6.70	-6.59	-6.07	2.0×10^{-7}	2.5×10^{-7}	8.4×10^{-7}

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Non Gaussian searches for the BBH SGWB

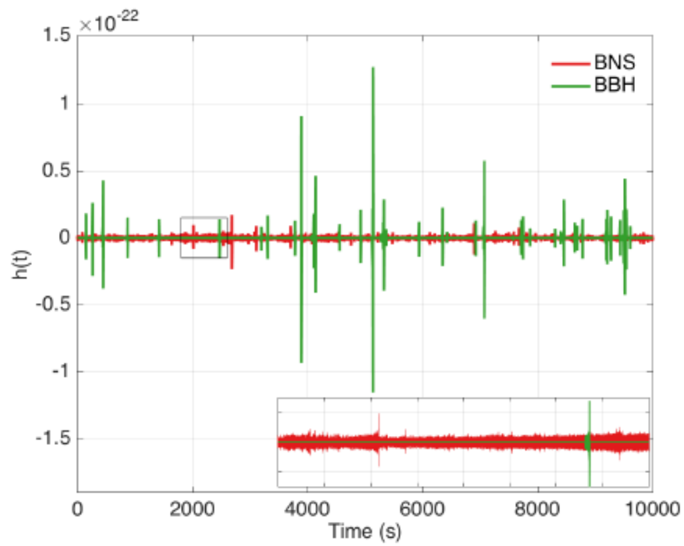
The contibutions from BBHs and BNSs have very different statistical properties.

BNS = continuous and BBH = popcorn like

Duty cycle

	Ω_{GW}(25 Hz)	τ [s]	λ
BNS	$0.7^{+1.5}_{-0.6} \times 10^{-9}$	13^{+49}_{-9}	15^{+30}_{-12}
BBH	$1.1^{+1.2}_{-0.7} \times 10^{-9}$	223^{+352}_{-115}	$0.06^{+0.06}_{-0.04}$
Total	$1.8^{+2.7}_{-1.3} \times 10^{-9}$	12^{44}_{-8}	15^{+31}_{-12}

Abbott et al. PRL, 120.091101 (2017)



Smith & Thrane, PhysRevX.8.021019

Non Gaussian searches for the BBH SGWB

- An idea is to use sub-threshold events detected using match filtering to estimate the SGWB
- Define the likelihood statistic of the signal for segment i:

$$\mathfrak{L}(\vec{s}_i|\theta_i,\xi) = \xi\,\mathcal{L}(\vec{s}_i|\theta_i) + (1-\xi)\,\mathcal{L}(\vec{s}_i|0)$$

signal present

no signal

- Margenalize over source parameters and combine segments.
- Construct Bayes factor: $\mathrm{BF} = \mathcal{Z}_{\mathrm{stoch}}/\mathcal{Z}_0$

where null hypothesis is: $\mathcal{Z}_0 = \mathcal{L}(\{\vec{s}\}|\xi=0)$ and "SGWB evidenc $\mathcal{Z}_{\mathrm{stoch}} = \int d\xi\,\mathcal{L}(\{\vec{s}\}|\xi)\pi(\xi)$

- Preliminary tests demonstrate that the SGWB from loud BBHs can be detected in 1 day rather than 40 months with the stochastic CC search.

Conclusion

- The preliminary goal of the LIGO/Virgo stochastic group is to measure the isotropic SGWB.
- The background from CBCs have a good chance to be detected in the next few years.
- With 3G the goal wil be to subtact it to recover the cosmological background below (Regimbau et al., PhysRevLett.118.151105).
- Many new searches can lead to very interesting results (non-isotropic, non standard polarization, non Gaussian). These searches could be extended to LISA.