# Gravitational Waves:
# I. The Stochastic Background and its Anisotropies
# II. A test for Gravitational Theories

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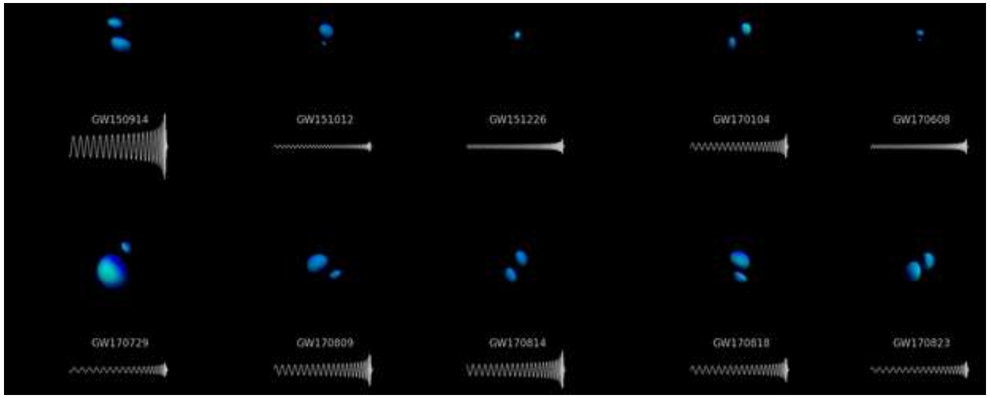
# Outline

- Stochastic gravitational-wave background (SGWB)
- GWs → info about population of compact binaries
- GWs → info about beyond Standard Model
- Anisotropies in the SGWB → info about large-scale-structure (LSS)
- GWs → test general relativity (GR) and modified gravity models
- GWs → test quantum gravity (QG) models

# BBH events from O1 and O2




O1 and O2 BBHs events

LIGO and Virgo have detected 10 GW signals from binary black hole (BBH) mergers and 1 from a binary neutron star (BNS) merger

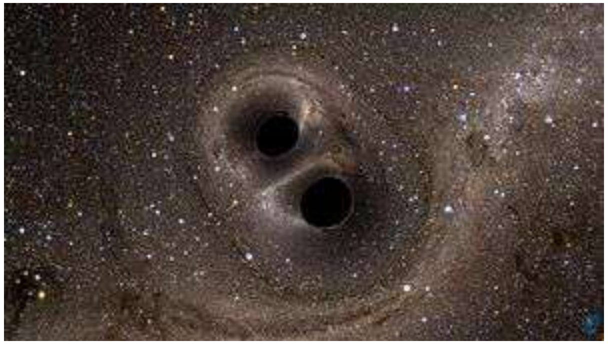
*Abbott et al, Phys. Rev. Lett. 120, 091101 (2018)*

# GW bursts

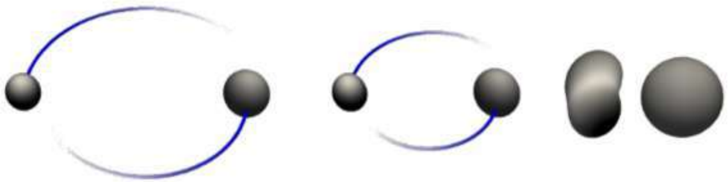
Astrophysical phenomena: supernova explosions or final merging of compact binary objects (NS-NS, BH-BH, BH-NS) can liberate a large amount of energy (up to a few per cent of its total mass) in GWs in a very short time (less than 1 sec, or as small as few milliseconds)

**GW bursts**

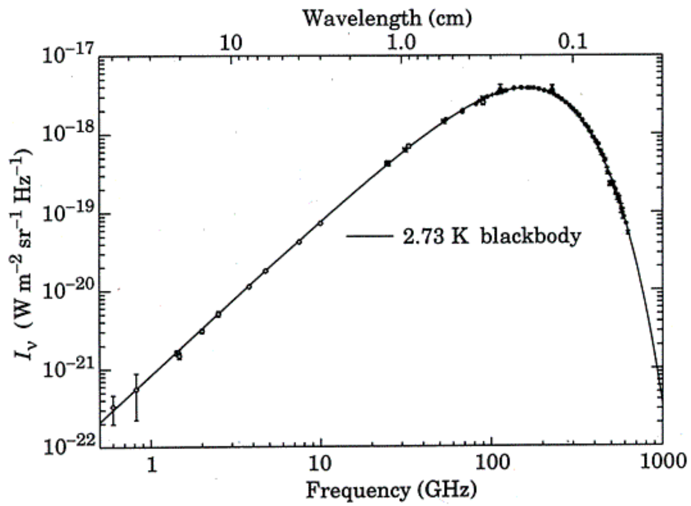
$\tau_{\rm g}$ : duration of GW bursts



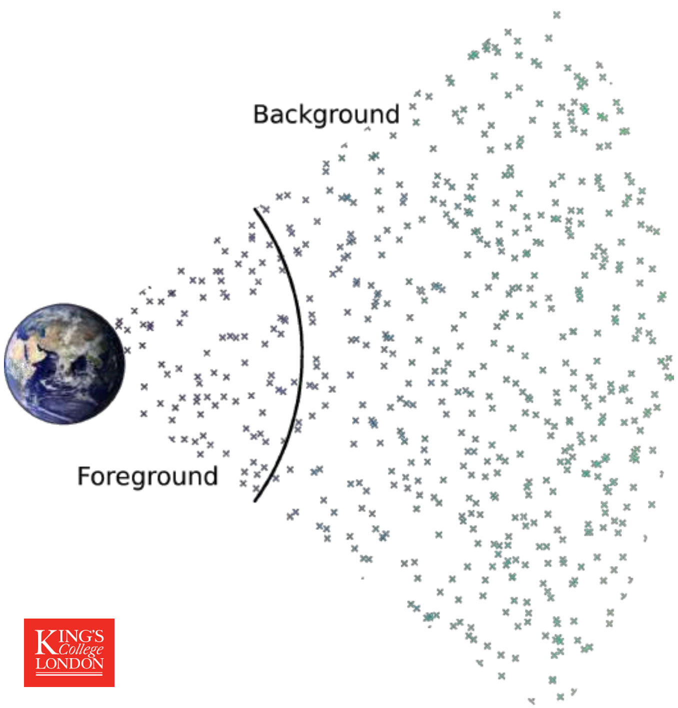
In Fourier space, a GW burst has a continuum spectrum of frequency over a broad range, up to a maximum frequency $f_{\rm max} \sim 1/\tau_{\rm g}$



# Stochastic GW Background (SGWB)


Penzias and Wilson (1965) : Universe is permeated by the CMB electromagnetic radiation




The Universe is permeated also by a SGWB

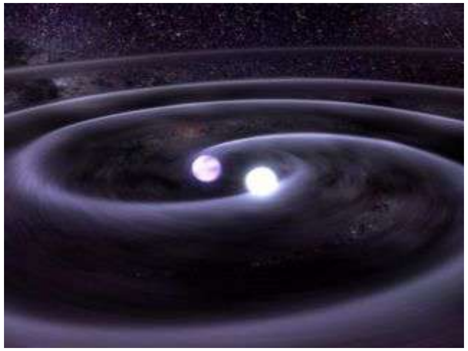
It emerges from the incoherent superposition of a large number of sources, too weak to be detected separately, and such that the number of sources that contribute to each frequency bin is much larger than one

# Stochastic GW Background (SGWB)

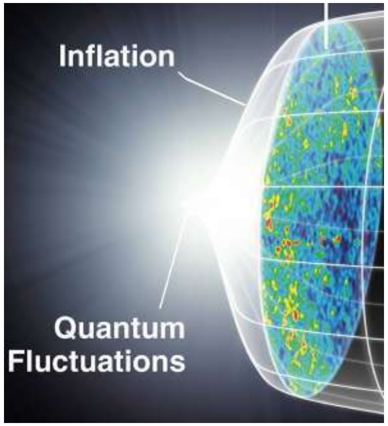
*Produced by a superposition of many weak, independent and unresolved sources of astrophysical or cosmological origin*

Supernovae

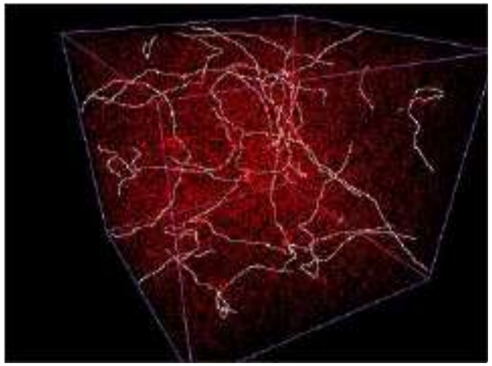
Neutron stars



Binaries



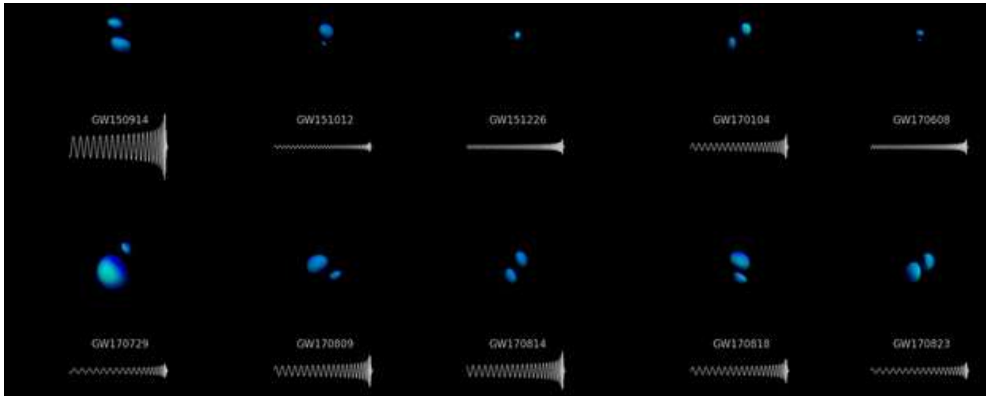

Inflation



Cosmic strings

Cosmological phase transitions

# SGWB from CBCs



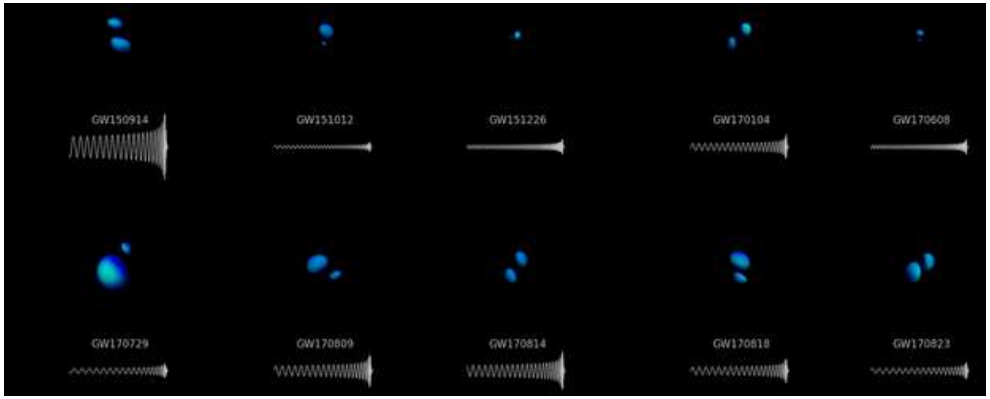

*Abbott et al, Phys. Rev. Lett. 120, 091101 (2018)*

Approximately one **binary neutron star merger** every **13 seconds** and one **binary black hole merger** every **223 seconds**

but

most of these events are too faint to be individually detected

# SGWB from CBCs




$$\Omega_{\mathrm{gw}}(\nu) = \frac{1}{\rho_c} \frac{d\rho_{\mathrm{gw}}(\nu)}{d\ln\nu}$$

*Abbott et al, Phys. Rev. Lett. 120, 091101 (2018)*

$$\nu_{\mathrm{s}} = (1+z)\nu$$

$$\boxed{\Omega_{\mathrm{GW}}(\nu,\theta) = \frac{\nu}{\rho_c H_0} \int_0^{z_{\max}} \mathrm{d}z \frac{R_{\mathrm{m}}(z;\theta) \frac{\mathrm{d}E_{\mathrm{GW}}(\nu_{\mathrm{s}};\theta)}{\mathrm{d}\nu_{\mathrm{s}}}}{(1+z)E(\Omega_{\mathrm{M}},\Omega_{\Lambda},z)}}$$

$$\Omega_M = 1 - \Omega_\Lambda = 0.3065$$

$$E(\Omega_{\mathrm{M}},\Omega_{\Lambda},z) = \sqrt{\Omega_{\mathrm{M}}(1+z)^3 + \Omega_{\Lambda}}$$

High merging rate and large masses of observed systems implies strong SGWB

# Inferring BBH population parameters

input from LIGO/Virgo:

- local rate
- mass distribution

$$p(m_1) \propto m_1^{-\alpha_m}$$

$$p(m_2) = \text{uniform}$$

$$m_{\min} \leq m_2 \leq m_1 \leq m_{\max}$$

$$m_{\min} = 5M_\odot$$

$$m_1 + m_2 \leq \quad 200M_\odot$$

- *Beta distribution for the BH spins*

Wysocki, Lange, O'Shaughnessy (2018)

$$\boxed{p(\chi_i) \propto \chi_i^{\alpha_\chi - 1}(1-\chi_i)^{\beta_\chi - 1}}$$

$$\left.\begin{array}{c} \alpha_m \\ m_{\max} \\ \alpha_\chi, \beta_\chi \end{array}\right\}$$ *infrerred from observed BBHs*

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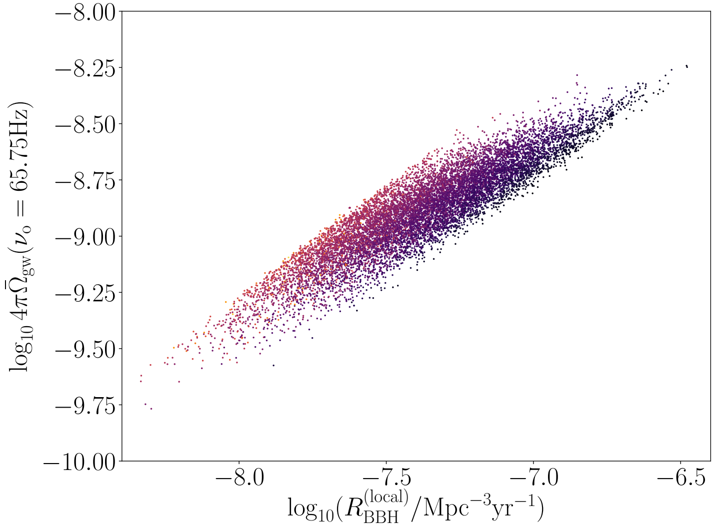



*Wysocki, Lange, O'Shaughnessy (2018)*

The **total energy density varies over nearly two orders of magnitude**

**Monopole: a new probe of population of compact objects**

*Jenkins, O'Shaughnessy, Sakellariadou, Wysocki, PRL 122, 111101 (2019)*

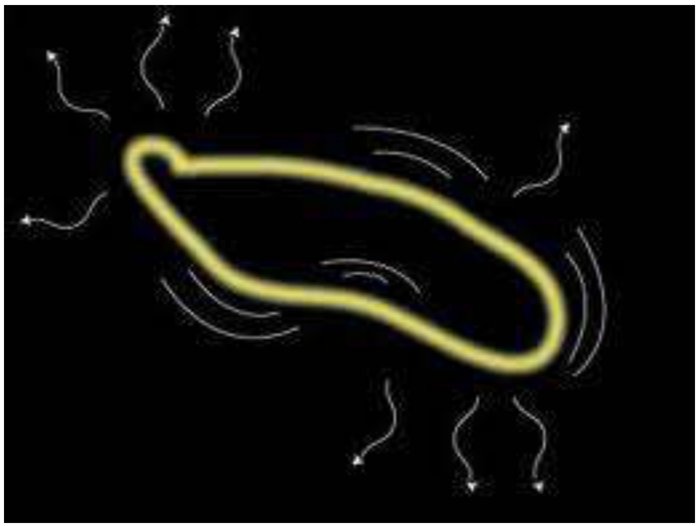
# Info beyond SM physics: SGWB from cosmic strings

1dim topological defects formed in the early universe as a result of a PT followed by SSB, characterised by a vacuum manifold with non-contractible closed curves

*Kibble (1976)*

Generically formed in the context of GUTs

*Jeannerot, Rocher, Sakellariadou, PRD68 (2003) 103514*



$$G\mu \sim \left(\frac{\Lambda_{\mathrm{NP}}}{M_{\mathrm{Pl}}}\right)^2$$

CS loops (length $\ell$ ) oscillate periodically ($T = \ell/2$ ) in time emitting GWs (fundamental frequency $\omega = 4\pi/\ell$ )

$$\tau = \frac{\ell}{\gamma_{\mathrm{d}}} \qquad \gamma_{\mathrm{d}} \equiv \Gamma G\mu \qquad \Gamma \simeq 50$$

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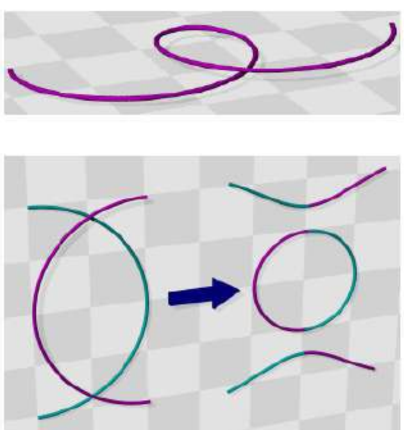
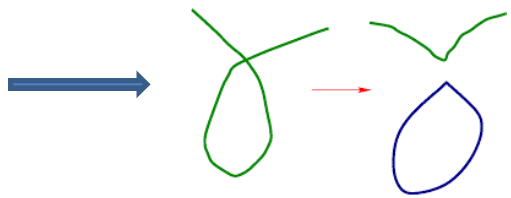
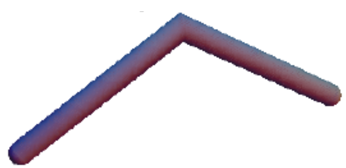
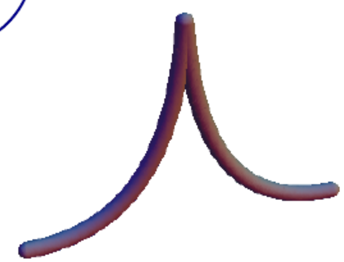


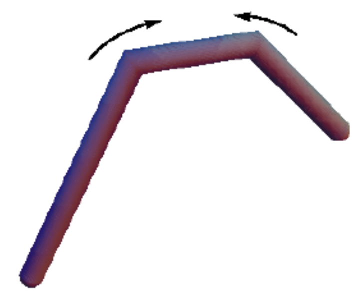




Kink



Cusp



Kink–Kink Collision

GW in a highly concentrated beam

$$\theta_b \approx \left(\frac{4}{\sqrt{3}\nu_s l}\right)^{1/3}$$

GW is isotropic

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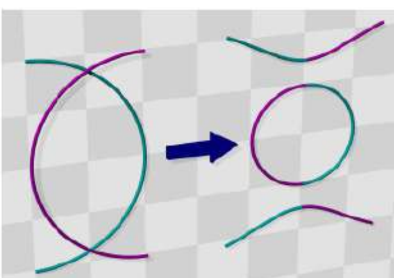

$$\kappa_{\rm c}(\nu_{\rm s},\hat{e}_{\rm s}) \approx \frac{8}{\Gamma^2\left(\frac{1}{3}\right)}\left(\frac{2}{3}\right)^{2/3}\frac{G\mu l^{2/3}}{\nu_{\rm s}^{1/3}}\Theta\left(\nu_{\rm s}-\frac{2}{l}\right)\Theta\left(\theta_{\rm b}-\cos^{-1}\left(\hat{e}_{\rm s}\cdot\hat{e}_{\rm c}\right)\right)$$

$$\kappa_{\rm k}(\nu_{\rm s},\hat{e}_{\rm s}) \approx \frac{2\sqrt{2}}{\pi\Gamma\left(\frac{1}{3}\right)}\left(\frac{2}{3}\right)^{1/3}\frac{G\mu l^{1/3}}{\nu_{\rm s}^{2/3}}\Theta\left(\nu_{\rm s}-\frac{2}{l}\right)\Theta\left(\theta_{\rm b}-\cos^{-1}\left(\hat{e}_{\rm s}\cdot\hat{e}_{\rm k}\right)\right)$$

$$\kappa_{\rm kk}(\nu_{\rm s}) \approx \frac{G\mu}{\pi^2\nu_{\rm s}}\Theta\left(\nu_{\rm s}-\frac{2}{l}\right)$$

*Damour, Vilenkin (2001)*

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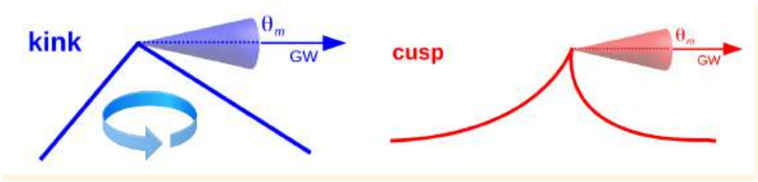


Cusps: GW amplitude scales as $\omega^{-4/3}$

Kinks: GW amplitude scales as $\omega^{-5/3}$

Kink-kink collision: GW amplitude scales as $\omega^{-2}$ $\quad N_{\rm kk} = \frac{N_{\rm k}^2}{4}$

*Damour, Vilenkin (2001)*

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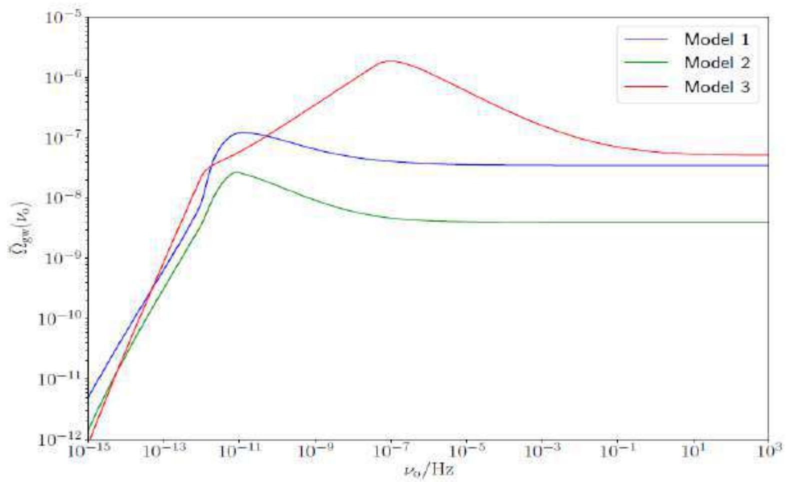
$$\bar{\Omega}_{\mathrm{gw}} = \frac{2(G\mu)^2}{3\pi^2 H_o^2 \nu_o} \int_0^{t_*} \frac{\mathrm{d}t}{t^4} a^5 \int_0^{\gamma_*} \frac{\mathrm{d}\gamma}{\gamma} \bar{\mathcal{F}} \Theta\left(\gamma - \frac{2a}{\nu_o t}\right) \left[N_k^2 + 4AN_k \left(\frac{\nu_o \gamma t}{a}\right)^{1/3} + A^2 N_c \left(\frac{\nu_o \gamma t}{a}\right)^{2/3}\right]$$

$$\gamma \equiv \frac{\ell}{t} \qquad \mathcal{F}(\gamma) \equiv t^4 n(t, \ell)$$

Model 1: *old (obsolete model)*
Model 2: *Blanco-Pillado, Olum, Shlaer, PRD (2014)*
Model 3: *Lorenz, Ringeval, Sakellariadou, JCAP1010 (2010)*
*Ringeval, Sakellariadou, Bouchet, JCAP0702 (2007)*



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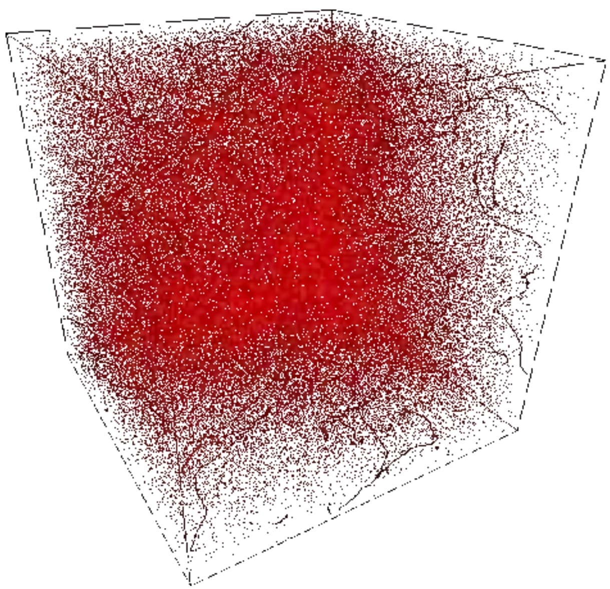
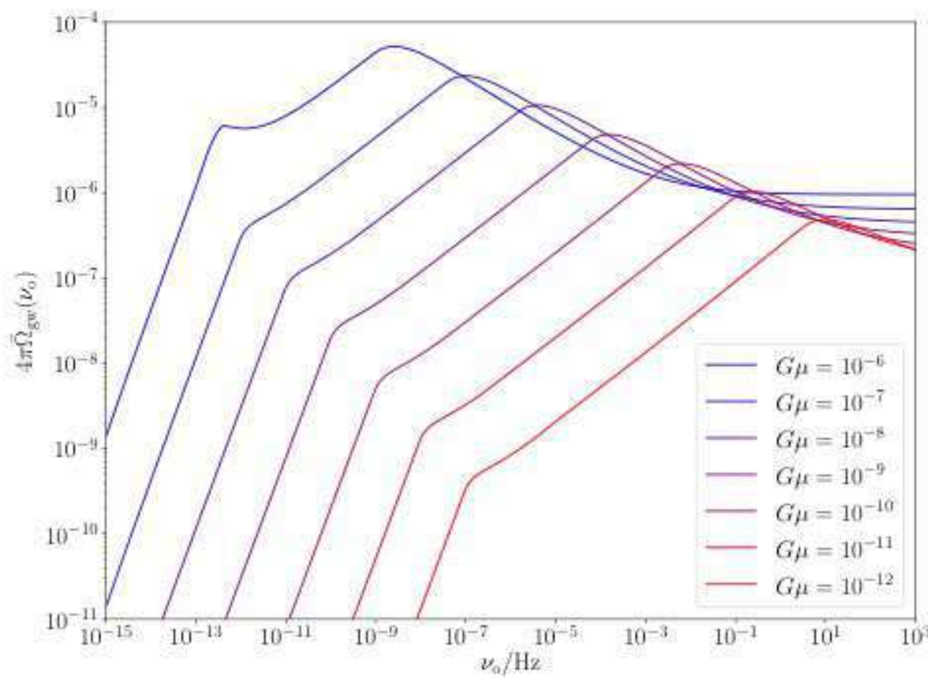


*Lorenz, Ringeval, Sakellariadou, JCAP1010 (2010)*
*Ringeval, Sakellariadou, Bouchet, JCAP0702 (2007)*




*Jenkins, Sakellariadou, PRD 98, 063509 (2018)*

# Detection of a SGWB

To first approximation, the SGWB is assumed to be isotropic (analogous to CMB)

It would appear as noise in a single GW detector

$$\boxed{s(t) = n(t) + h(t)}$$

*Signal from the detector* *Noise* *GW strain*

For a stochastic GW signal:

$$n(t) >> h(t)$$

To detect a SGWB take the correlation between two detector outputs:

$$\begin{aligned}
\langle s_1(t)\ s_2(t)\rangle &= \langle (n_1(t)+h(t))\,(n_2(t)+h(t))\rangle \\
&= \langle n_1(t)\ n_2(t)\rangle + \langle n_1(t)\ h(t)\rangle + \langle h(t)\ n_2(t)\rangle + \langle h(t)\ h(t)\rangle \\
&\approx \langle h(t)\ h(t)\rangle
\end{aligned}$$

# Detection of a SGWB

Correlation methods between two or more interferometric detectors

Root mean square of the strain

$$h^2_{rms} = \left\langle \sum_{i,j} h_{ij} h_{ij} \right\rangle = \int_0^\infty d\nu S_h(\nu)$$

One-sided GW strain power spectral density

$$\sqrt{S_h(\nu)} = 2\nu^{1/2} |\tilde{h}(\nu)|$$

$$\rho_{\rm gw} = \int_0^\infty d\nu S_h(\nu) \frac{\pi c^2 \nu^2}{8G}$$

# Detection of a SGWB

*Stationary, Gaussian, unpolarised, and isotropic stochastic background*

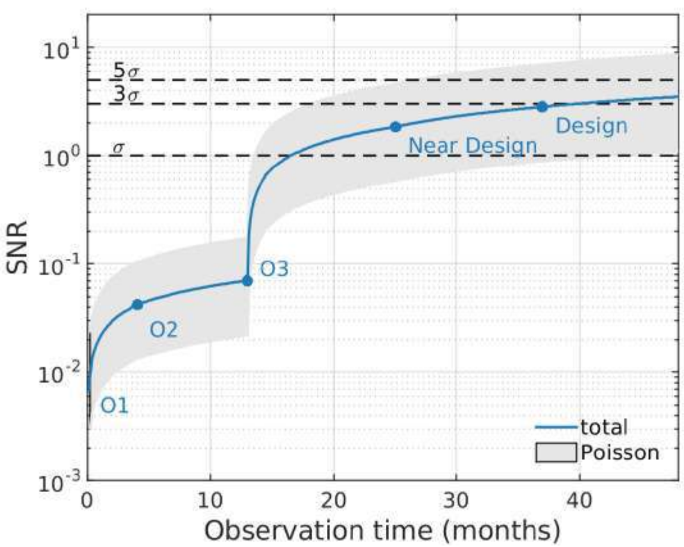
Cross-correlation statistic in every frequency bin

$$\hat{C}(\nu) = \frac{2}{T} \frac{\mathrm{Re}[\tilde{h}_1^\star(\nu)\tilde{h}_2(\nu)]}{\gamma_T(\nu) S_0(\nu)}$$

$$\boxed{\langle \hat{C}(\nu) \rangle = \Omega_{\mathrm{GW}}(\nu)}$$

Spectral shape $S_0(\nu) = \frac{3H_0^2}{10\pi^2\nu^3}$

$$\mathrm{SNR} = \frac{3H_0^2}{10\pi^2}\sqrt{2T}\left[\int_0^\infty \mathrm{d}\nu \sum_{i=1}^{n}\sum_{j>1} \frac{\gamma_{ij}^2(\nu)\Omega_{\mathrm{GW}}^2(\nu)}{\nu^6 S_{n,i}(\nu) S_{n,j}(\nu)}\right]^{1/2}$$




$$\boxed{\Omega_{\mathrm{GW}}(\nu) = \Omega_{\mathrm{ref}} \left(\frac{\nu}{\nu_{\mathrm{ref}}}\right)^\alpha}$$

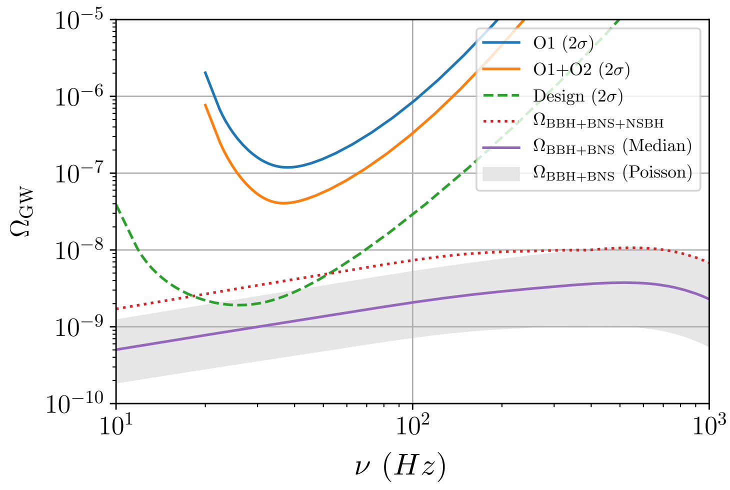
$$\nu_{\mathrm{ref}} = 25\mathrm{Hz}$$

# Current limits on SGWB from CBCs

$$\Omega_{\rm GW}(\nu) = \Omega_{\rm ref}\left(\frac{\nu}{\nu_{\rm ref}}\right)^{\alpha}$$

α=2/3

$$\nu_{\rm ref} = 25{\rm Hz}$$




$$\boxed{\Omega_{\rm GW} < 4.8\times 10^{-8} \quad {\rm at}\ 25\ {\rm Hz}}$$

*LVC, arXiv:1903.02886*

# Current limits on SGWB from Cosmic Strings

$$\Omega_{\rm GW}(\nu) = \Omega_{\rm ref}\left(\frac{\nu}{\nu_{\rm ref}}\right)^{\alpha}$$ α=0

$\nu_{\rm ref} = 25{\rm Hz}$

$\Omega < 7.9 \times 10^{-9}$ at 25 Hz

$G\mu/c^2 \leq 1.1 \times 10^{-6}$ For the CS model of *Blanco-Pillado, Olum, Shlaer (2014)*

$G\mu/c^2 \leq 1.6 \times 10^{-11}$ Pulsar timing limit *Lasky et al (2016)*

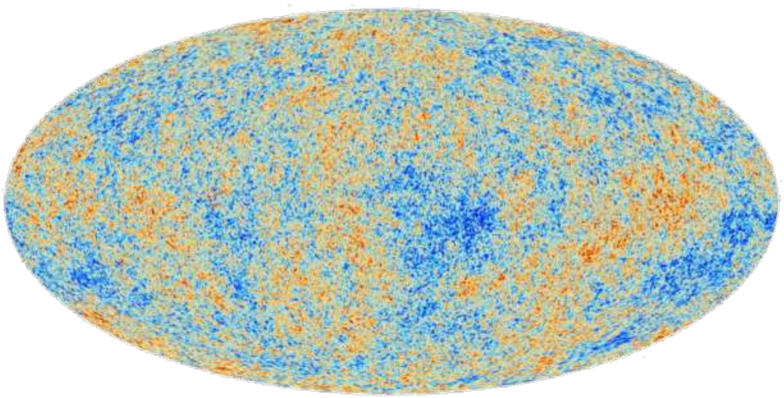
$G\mu/c^2 \leq 2.1 \times 10^{-14}$ For the CS model of *Lorenz, Ringeval, Sakellariadou, JCAP 1010 (2010) 003*
*Ringeval, Sakellariadou, Bouchet, JCAP 1712 (2007) 027*

$G\mu/c^2 \leq 6.2 \times 10^{-12}$ Pulsar timing limit

*LVC, arXiv:1903.02886*

# Anisotropies in the Stochastic GW Background

To a first approximation, the SGWB is assumed to be isotropic (analogous to the CMB)



*The afterglow radiation left over from the Hot Big Bang*

- its temperature is extremely uniform all over the sky
- **tiny temperature fluctuations** (one part 100,000)

$$C_\ell = \int \mathrm{d}^2\hat{\boldsymbol{n}} P_\ell(\cos\theta) \, \langle \delta T_\gamma \delta T_\gamma \rangle$$

Similar to the CMB, there are signal searches that attempt to measure an anisotropic SGWB

$$C_\ell = \int \mathrm{d}^2\hat{\boldsymbol{n}} P_\ell(\cos\theta) \, \langle \delta \Omega_{\mathrm{gw}} \delta \Omega_{\mathrm{gw}} \rangle$$

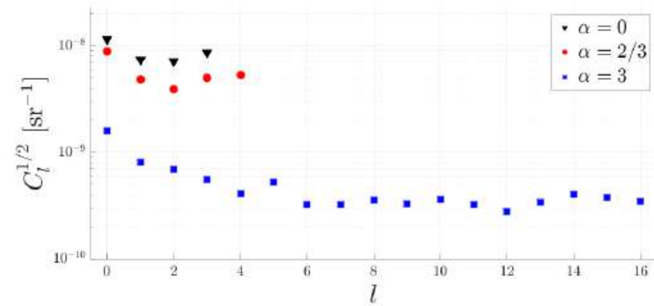
An anisotropic SGWB was not observed with the aLIGO O1/O2 data; upper limits were set

*Abbott et al, arXiv:1903.08844*

# Anisotropies in the Stochastic GW Background

Gravitational wave sources with an anisotropic spatial distribution lead to a SGWB characterised by preferred directions, and hence anisotropies

## Search for anisotropies




- for extended sources: *spherical harmonic decomposition*

$$C_\ell = \int d^2\hat{\boldsymbol{n}} P_\ell(\cos\theta) \langle \delta\Omega_{\rm gw} \delta\Omega_{\rm gw} \rangle$$

- for point sources: broadband radiometer analysis

$$\Omega_\alpha(\Theta) < (0.19 - 2.89) \times 10^{-8}\ {\rm sr}^{-1}$$

- in the direction of interesting objects in the sky (galactic centre, Scorpius X-1, SN 1987A): narrowband radiometer search

$$h_0 < (3.6 - 4.7) \times 10^{-25}$$

An anisotropic stochastic background was not observed with the Advanced LIGO O1/O2 data, but important upper limits were set

*Abbott et al, arXiv:1903.08844*

# Anisotropies in the SGWB

$$\Omega_{\mathrm{gw}} = \frac{\pi\nu_{\mathrm{o}}^3}{3H_{\mathrm{o}}^2}\int_0^{\eta_*}\mathrm{d}\eta\, a^2\int\mathrm{d}\zeta\,\bar{n}R(1+\delta_n+\hat{\mathbf{e}}_{\mathrm{o}}\cdot\mathbf{v}_{\mathrm{o}})\int_{S^2}\mathrm{d}^2\sigma_{\mathrm{s}}\,r_{\mathrm{s}}^2\tilde{h}^2$$

$$\Lambda_* = \frac{4\pi}{\nu_{\mathrm{o}}}\int\mathrm{d}\zeta\int_{\eta_*}^{\eta_{\mathrm{o}}}\mathrm{d}\eta\, a^3(\eta_{\mathrm{o}}-\eta)^2 f_{\mathrm{o}}\bar{n}R$$

$\Lambda$<<1 : foreground
$\Lambda$>>1 : SWGB

*Duty cycle: the average number of overlapping signals at experienced by the observer*

Jenkins, Sakellariadou, PRD 98, 063509 (2018)

# Anisotropies in the SGWB

$$\Omega_{\mathrm{gw}} = \frac{\pi\nu_{\mathrm{o}}^3}{3H_{\mathrm{o}}^2}\int_0^{\eta_*}\mathrm{d}\eta\, a^2 \int \mathrm{d}\zeta\, \bar{n} R(1+\delta_n+\hat{\mathbf{e}}_{\mathrm{o}}\cdot\mathbf{v}_{\mathrm{o}})\int_{S^2}\mathrm{d}^2\sigma_{\mathrm{s}}\, r_{\mathrm{s}}^2 \tilde{h}^2$$

Anisotropy due to source density contrast $\delta_n \equiv \frac{n-\bar{n}}{\bar{n}}$

Intensity of SGWB: $$\Omega_{\mathrm{gw}}(\nu_{\mathrm{o}}, \hat{e}_{\mathrm{o}}) \equiv \bar{\Omega}_{\mathrm{gw}}(1+\delta_{\mathrm{gw}})$$

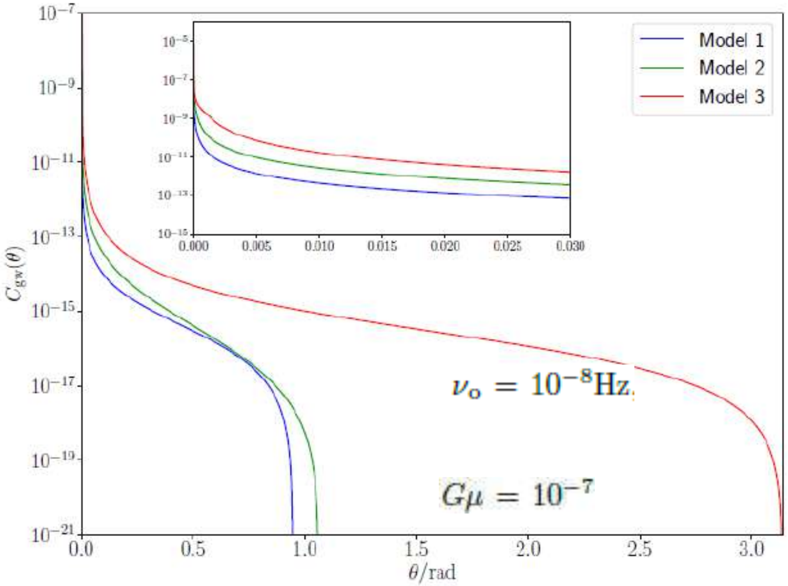
$$\delta_{\mathrm{gw}} = \delta_{\mathrm{gw}}^{(\mathrm{s})} + \mathcal{D}\,\hat{e}_{\mathrm{o}}\cdot\hat{v}_{\mathrm{o}}$$

2PCF : $$C_{\mathrm{gw}}(\theta_{\mathrm{o}}, \nu_{\mathrm{o}}) \equiv \left\langle \delta_{\mathrm{gw}}^{(\mathrm{s})}(\nu_{\mathrm{o}}, \hat{e}_{\mathrm{o}})\delta_{\mathrm{gw}}^{(\mathrm{s})}(\nu_{\mathrm{o}}, \hat{e}'_{\mathrm{o}})\right\rangle$$

$$C_{\mathrm{gw}}(\theta_{\mathrm{o}}, \nu_{\mathrm{o}}) = \sum_{l=0}^{\infty}\frac{2l+1}{4\pi}C_l(\nu_{\mathrm{o}})P_l(\cos\theta_{\mathrm{o}}) \qquad \theta_{\mathrm{o}} \equiv \cos^{-1}(\hat{e}_{\mathrm{o}}\cdot\hat{e}'_{\mathrm{o}})$$

*Jenkins, Sakellariadou, PRD 98, 063509 (2018)*

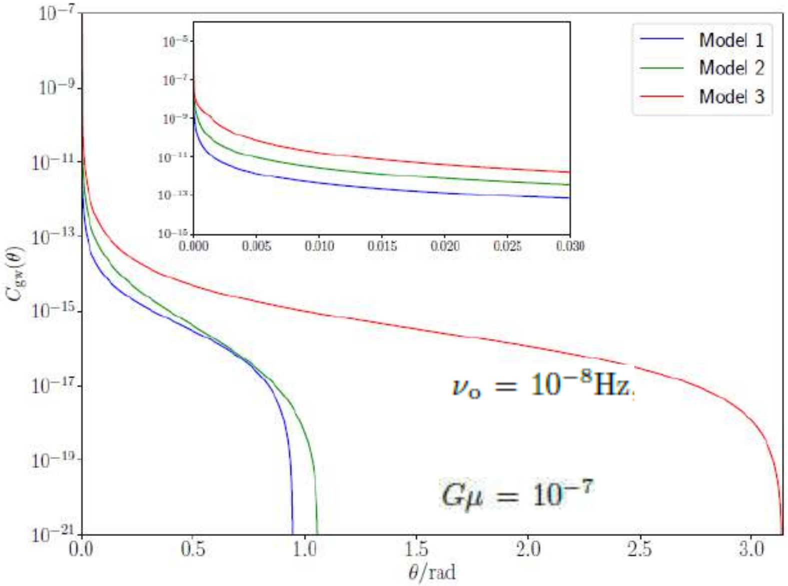
# Anisotropies in the SGWB from cosmic strings

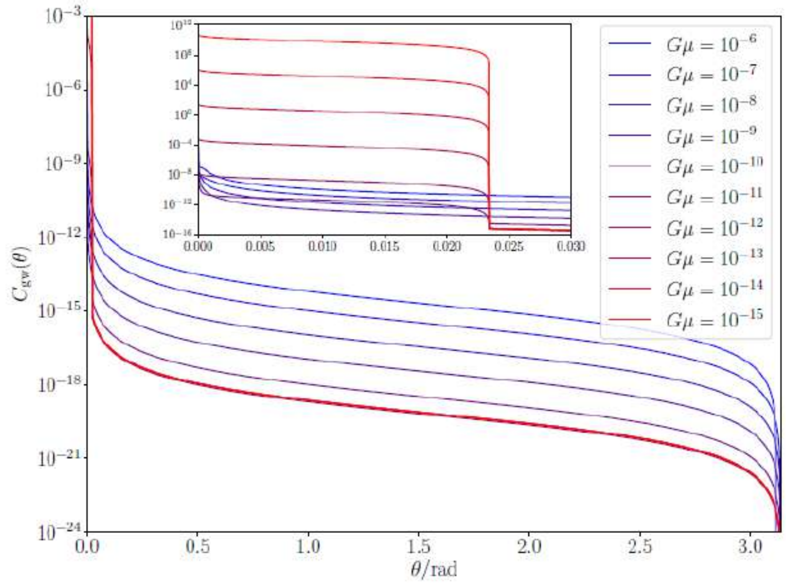


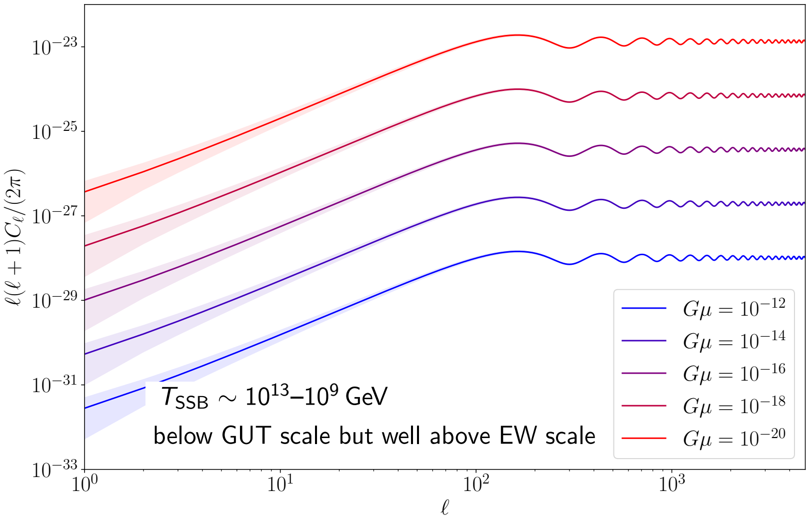

$$C_1^{1/2} \approx 10^{-10}\ \mathrm{sr}^{-1}$$

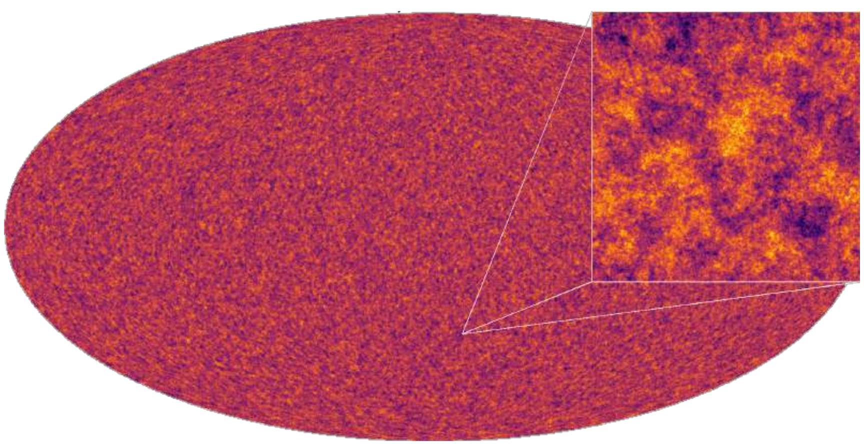
*Jenkins, Sakellariadou, PRD 98, 063509 (2018)*

# Anisotropies in the SGWB from cosmic strings



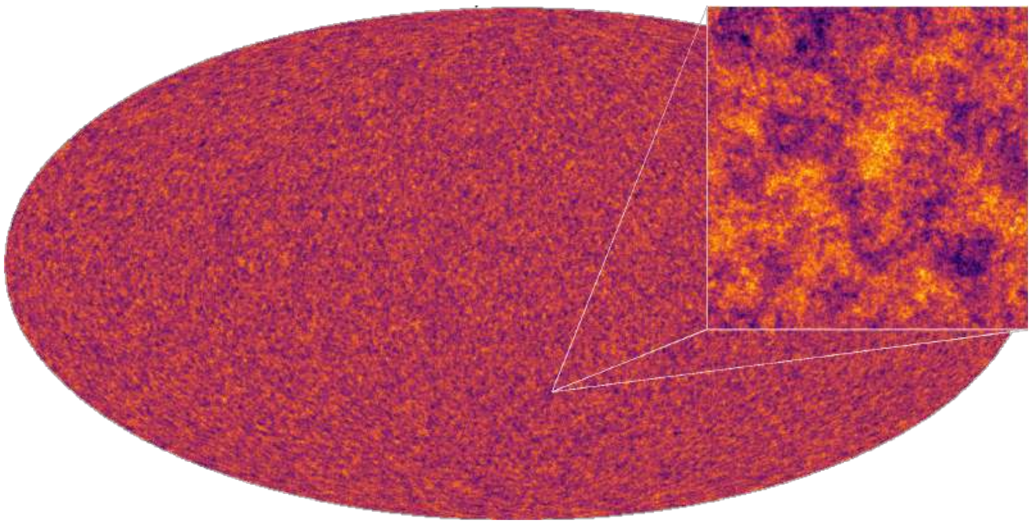



Jenkins, Sakellariadou, PRD 98, 063509 (2018)

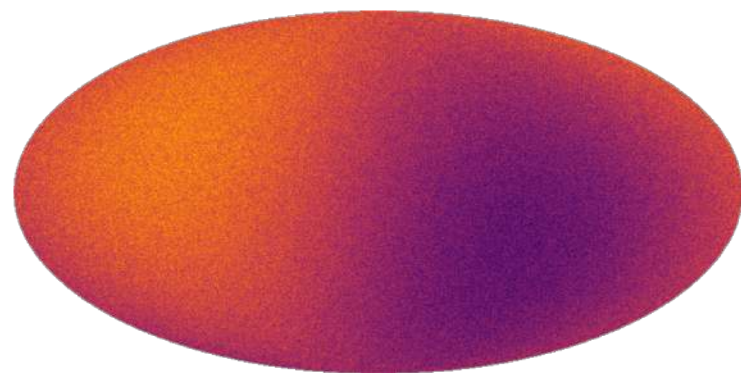
*Mairi Sakellariadou*

# Random realisations of SGWB created from $C_l$ coefficients (up to $\ell = 5000$ )

Magnified $10^\circ \times 10^\circ$ regions



Angular resolution of about 50 arcseconds



The observer's motion relative to the cosmic rest frame induces a kinematic dipole

*Jenkins, Sakellariadou, PRD 98, 063509 (2018)*

# Anisotropies in the Astrophysical Stochastic GW Background (ASGWB)

Consider an FLRW spacetime and neglect cosmological perturbations, keeping only anisotropy due to the source density contrast and the one induced by the peculiar motion of the observer

Star formation rate (SFR) of galaxies $\longrightarrow$ population of CBOs $\longrightarrow$ rate of mergers

Metallicity of galaxies *The formation of massive black holes from stars is inhibited by stellar winds in high-metallicity environments*

Masses $m_1, m_2$ & spin angular momentum $S_1$, $S_2$ of two binaries

Mergers: BHBH, NSNS, BHNS

$$\chi_1 \equiv \frac{S_1}{m_1^2}, \qquad \chi_2 \equiv \frac{S_2}{m_2^2}, \qquad \chi_1, \chi_2 \in [-1, +1],$$

$$p_{\rm BNS} \propto \delta(\chi_1)\delta(\chi_2), \qquad 1M_\odot \le m_1 \le 2M_\odot, \qquad 1M_\odot \le m_2 \le 2M_\odot,$$

$$p_{\rm BBH} \propto m_1^{-2.35}/(m_1 - 5M_\odot), \qquad 5M_\odot \le m_2 \le m_1 \le 95M_\odot, \qquad m_1 + m_2 \le 100M_\odot,$$

$$p_{\rm BHNS} \propto m_1^{-2.35}\delta(\chi_2), \qquad 5M_\odot \le m_1 \le 95M_\odot, \qquad 1M_\odot \le m_2 \le 2M_\odot,$$

*The fiducial LVC astrophysical model*

# Anisotropies in the Astrophysical Stochastic GW Background (ASGWB)

*Jenkins, Regimbau, Sakellariadou, Slezak, PRD 98, 063501 (2018)*

- analytic estimates:

Use simple analytical functions for the galaxy density $\bar{n}$ and the galaxy-galaxy 2PCF $\langle \delta_n \delta_n \rangle$

$$\boxed{\langle \delta_n \delta_n \rangle \approx \left( \frac{d}{d_1} \right)^{-\gamma} \delta(z - z'),}$$

$$d_1 = (4.29 \pm 0.19) h^{-1} \mathrm{Mpc}$$
$$\gamma = 1.63 \pm 0.04$$

$d(z, \hat{e}_o, \hat{e}'_o)$ : comoving distance

*Marulli, et al (2013)*

- using mock galaxy catalogues *Millenium mock galaxy catalogue*

- N-body simulation of LSS formation through DM clustering

*Springel, et al (2005) ; Blaizot, et al (2005) ; Lemson, et al (2006)*

- Galaxies added to DM haloes with sophisticated semi-analytic models

*De Lucia, Blaizot (2007)*

- Light-cone constructed to mimic real galaxy catalog z < 0.78 (cut-off in apparent magnitude)

# Anisotropies in the Astrophysical Stochastic GW Background (ASGWB)

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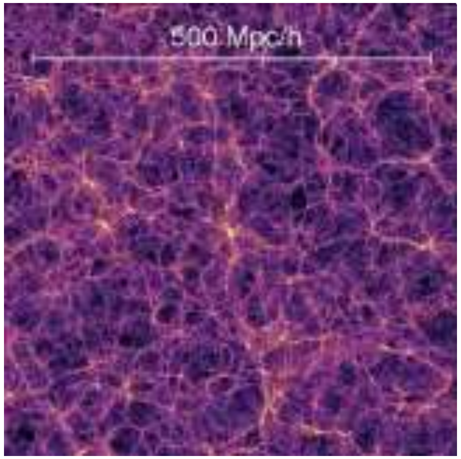
*Marulli, et al (2013)*

- using mock galaxy catalogues

*Millenium mock galaxy catalogue*

- get galaxies from simulation
- calculate the rate of mergers for each galaxy
- superimpose in order to get a SGWB map



# Anisotropies in the Astrophysical Stochastic GW Background (ASGWB)

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$d(z, \hat{e}_o, \hat{e}'_o)$ : comoving distance

*Marulli, et al (2013)*

- using mock galaxy catalogues *Millenium mock galaxy catalogue*

Now we have an explicit expression for $\Omega_{gw}$ as a function of sky location

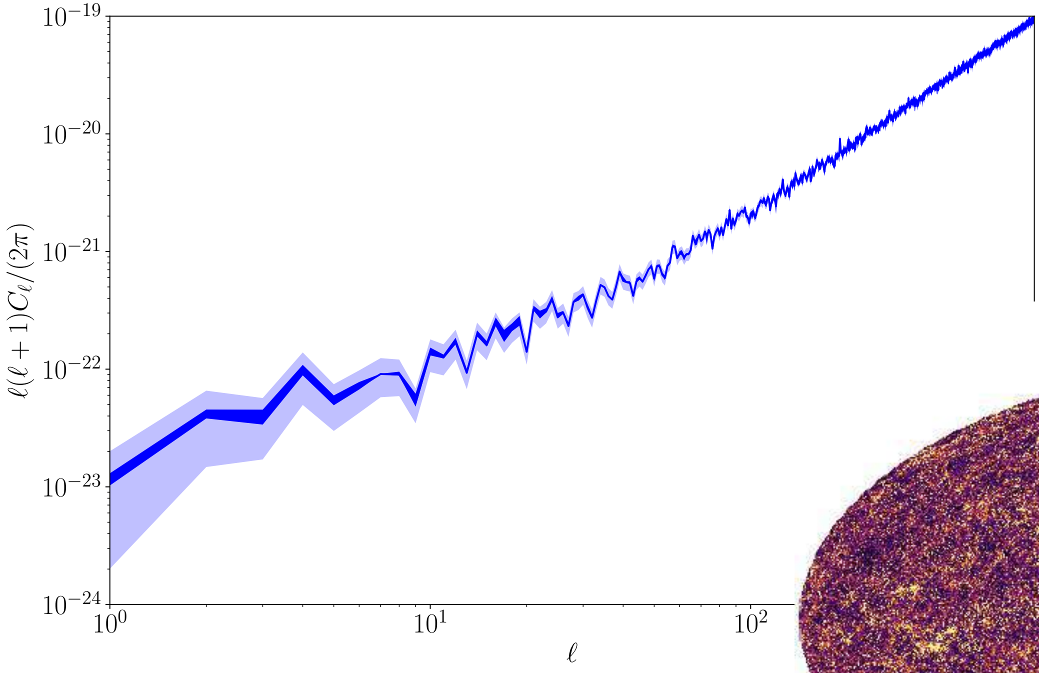
$$\langle \Omega_{gw} \Omega_{gw} \rangle \longrightarrow C_{gw}(\theta_o, \nu_o) = \left\langle \delta_{gw}^{(s)} \delta_{gw}^{(s)} \right\rangle$$

$$\delta_{gw}^{(s)}(\nu_o, \hat{e}_o) \equiv \left. \frac{\Omega_{gw} - \bar{\Omega}_{gw}}{\bar{\Omega}_{gw}} \right|_{v_o = 0}$$

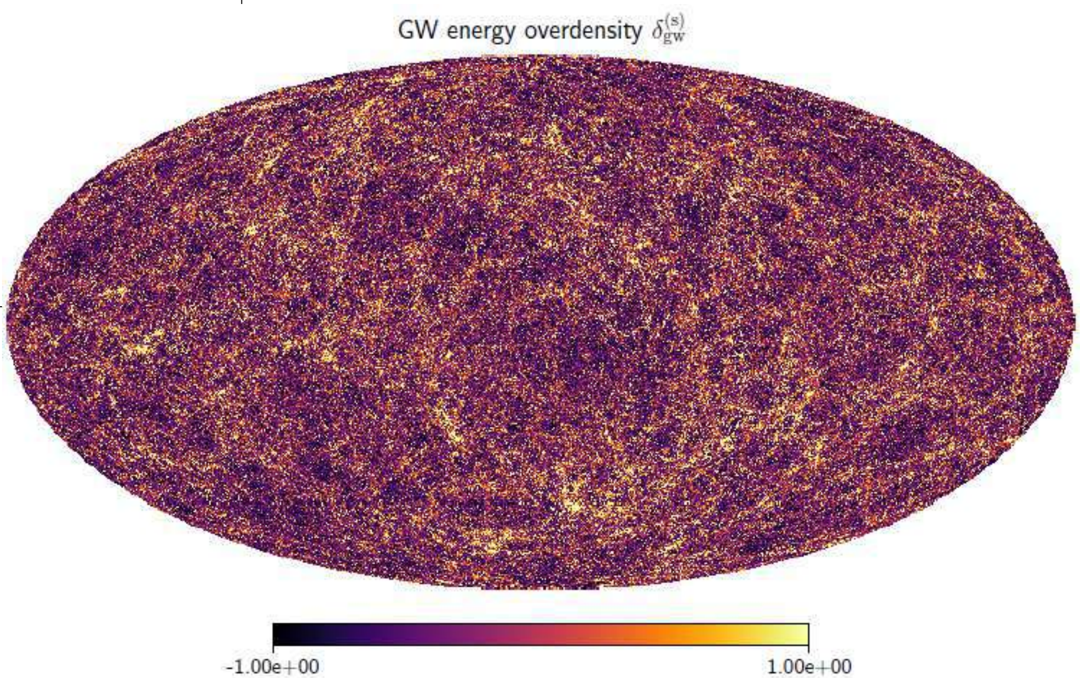
$$\boxed{C_l(\nu_o) = 2\pi \int_{-1}^{+1} d(\cos\theta_o)\, P_l(\cos\theta_o) C_{gw}}$$

***maps*** $\xleftarrow{\textit{Healpix}}$

# Anisotropies in the Astrophysical Stochastic GW Background (ASGWB)




$$C_l^{1/2} \approx 3 \times 10^{-11}\ \mathrm{sr}^{-1}\ \text{for}\ 1 \leq l \leq 4$$




Angular resolution: 13.7 arcminutes ---- 7.3 galaxies per pixel

*Jenkins, Regimbau, Sakellariadou, Slezak, PRD 98, 063501 (2018)*

# Inferring BBH population parameters

Most important quantities describing each BBH are the masses and spins of each component BH

Use Bayesian techniques to infer them from GW observations

*Truncated power-law BH mass distribution:*

$$\boxed{p(m_1, m_2) \propto \begin{cases} \frac{m_1^{-\alpha_m}}{m_1 - m_{\min}}, & m_{\min} \le m_2 \le m_1 \le m_{\max} \\ & m_1 + m_2 \le M_{\max} \\ 0, & \text{otherwise} \end{cases}}$$

$$m_{\min} = 5M_{\odot}$$

$$M_{\max} = 200M_{\odot}$$

*Beta distribution for the BH spins:*

$$\boxed{p(\chi_i) \propto \chi_i^{\alpha_\chi - 1}(1 - \chi_i)^{\beta_\chi - 1}}$$

$$\left.\begin{array}{c} \alpha_m \\ m_{\max} \\ \alpha_\chi, \beta_\chi \end{array}\right\}$$

*infrerred from observed BBHs*

*Wysocki, Lange, O'Shaughnessy (2018)*

# Inferring BBH population parameters

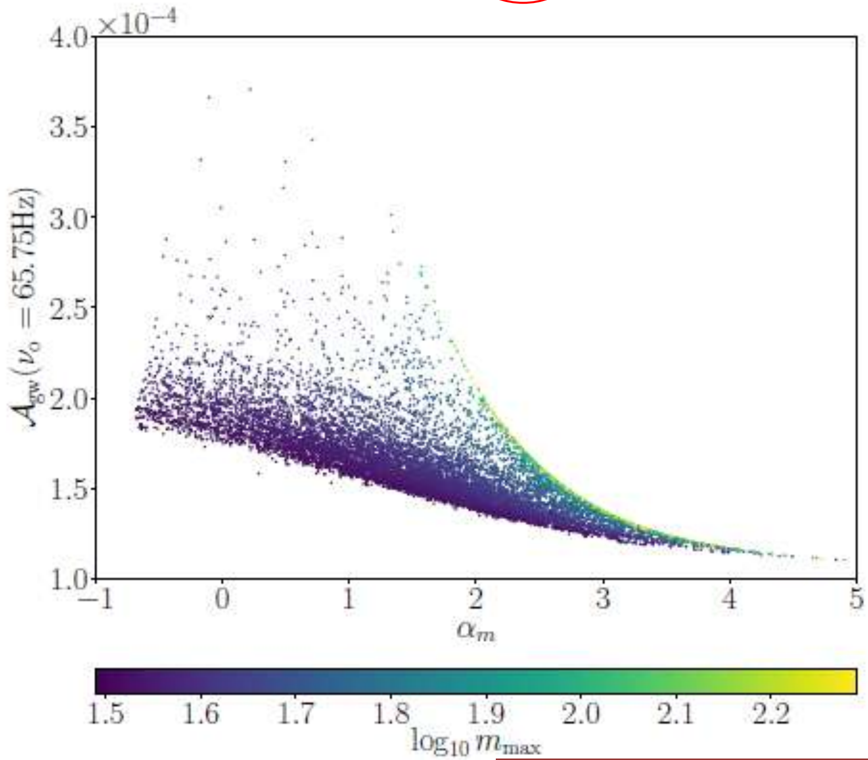
$$p(m_1, m_2) \propto \begin{cases} \frac{m_1^{-\alpha_m}}{m_1 - m_{\min}}, & m_{\min} \leq m_2 \leq m_1 \leq m_{\max} \\ & m_1 + m_2 \leq M_{\max} \\ 0, & \text{otherwise} \end{cases}$$

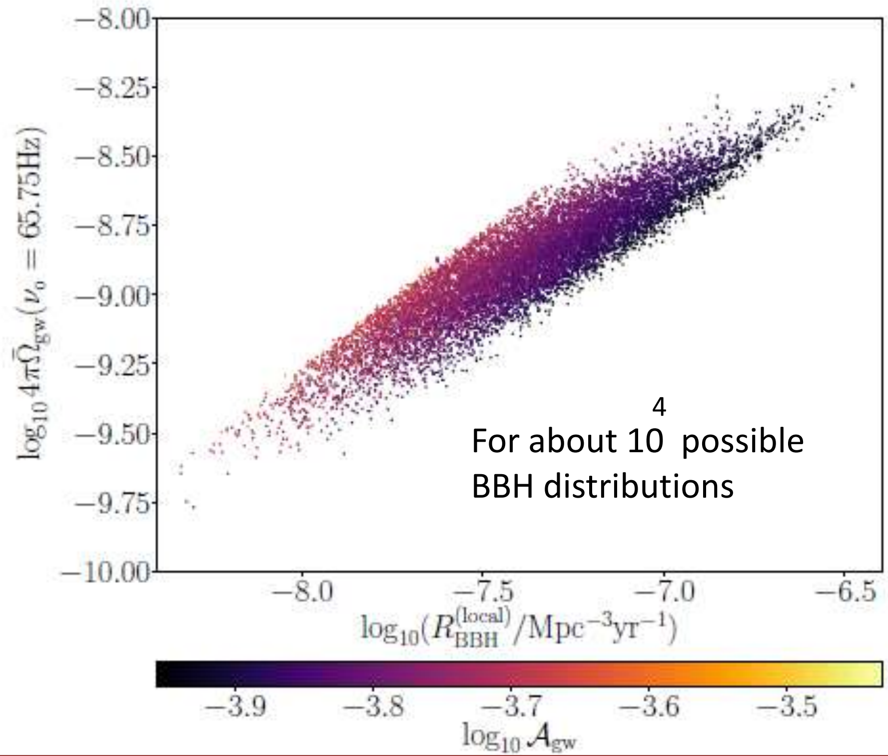
$$m_{\min} = 5M_\odot$$

$$M_{\max} = 200M_\odot$$

$$C_\ell(\nu_o) = 4\pi \mathcal{A}_{gw}(\nu_o) \frac{{}_3F_2(-\ell, \ell+1, 1-\frac{\gamma}{2}; 1, 2; 1)}{\text{sinc}(\pi\gamma/2)}$$

$$\nu_o = 65.75 \text{ Hz}$$




*Jenkins, O'Shaughnessy, Sakellariadou, Wysocki, PRL 122, 111101 (2019)*

# Inferring BBH population parameters

$$p(m_1, m_2) \propto \begin{cases} \frac{m_1^{-\alpha_m}}{m_1 - m_{\min}}, & m_{\min} \le m_2 \le m_1 \le m_{\max} \\ & m_1 + m_2 \le M_{\max} \\ 0, & \text{otherwise} \end{cases}$$

$$m_{\min} = 5M_\odot$$

$$M_{\max} = 200M_\odot$$

- The anisotropies are **insensitive to the details of the BBH population;** the ***anisotropy parameter varies by O(1) factor between all the BBH distributions***

- The astrophysical GWB anisotropies: a new probe of LSS of the Universe

*Jenkins, O'Shaughnessy, Sakellariadou, Wysocki, PRL 122, 111101 (2019)*

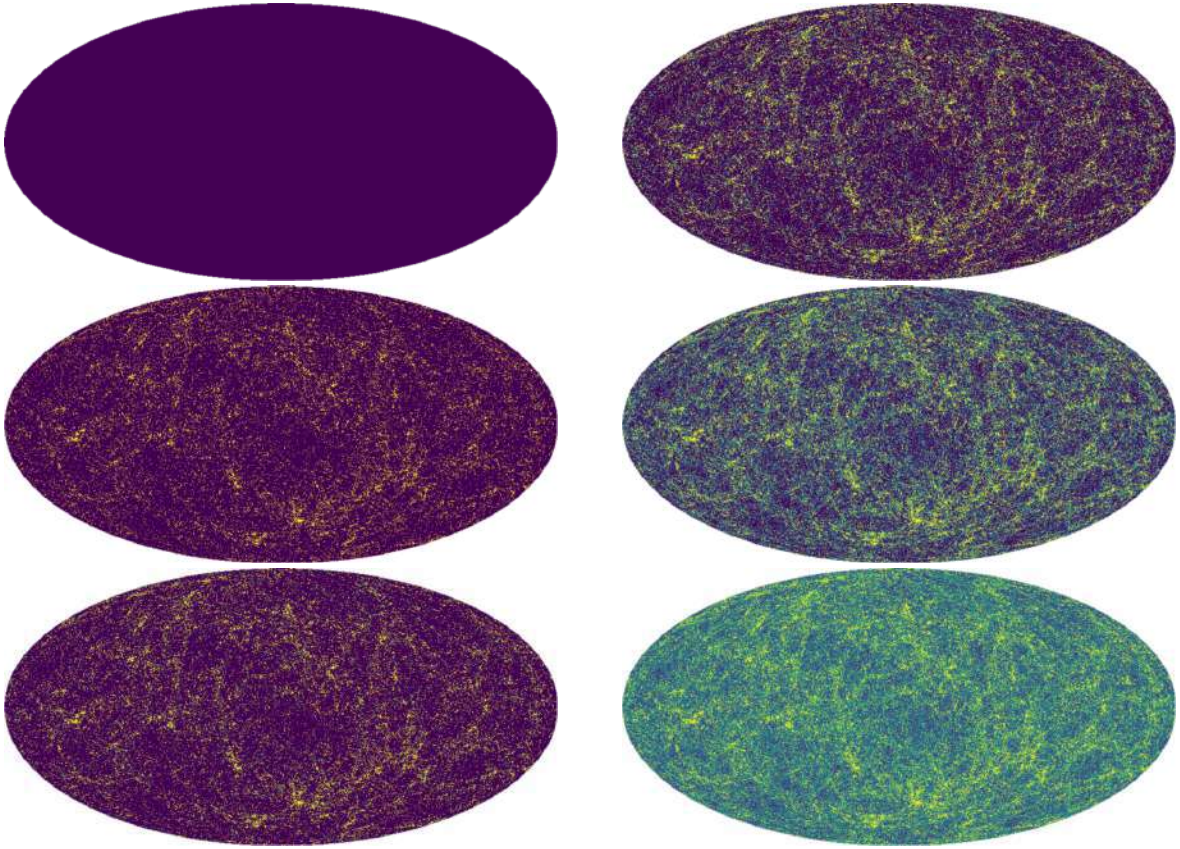
# AGWB including all effects

Gauge invariant formalism to compute the astrophysical GW spectrum, taking into account all effects intervening between the source and the observer

- events with short emission (merging binaries, SN explosions)
- inspiraling binaries which have not merged during a Hubble time

*Bertaca, Ricciardone, Bellomo, Jenkins, Matarese, Raccanelli, Regimbau, Sakellariadou (in progress)*

# Can we probe LSS with astrophysical SGWB anisotropies?



# Can we probe LSS with astrophysical SGWB anisotropies?

Finite number of CBC's per observational time

→ *temporal* **shot noise** (scale-invariant bias term)

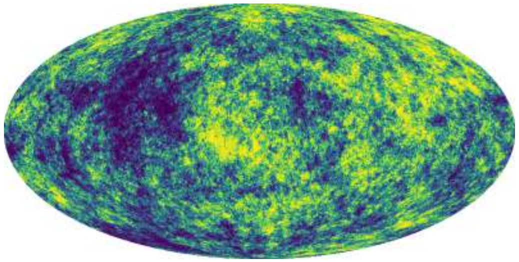
$$\boxed{C_\ell \to C_\ell + \mathcal{W}}$$

$$\mathcal{W} \gg C_\ell$$

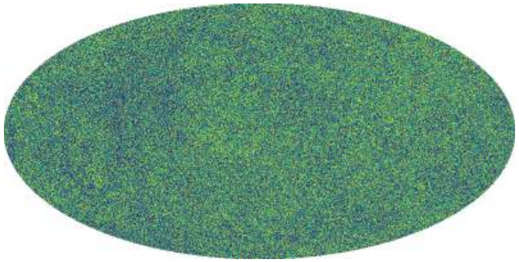
$$\mathcal{W} \propto \frac{1}{T_{\rm obs}}$$

Finite number of CBCs and very short time within LIGO/Virgo frequency band

→ angular power spectrum dominated by shot noise



without shot noise



with shot noise

$\mathcal{W} = 10^{-3}\bar{\Omega}^2$

+ finite number of galaxies (*spatial shot noise*)
+ cosmic variance

*Jenkins, Sakellariadou, PRD (2019)*

# Can we probe LSS with astrophysical SGWB anisotropies?

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Finite number of CBCs and very short time within LIGO/Virgo frequency band

→ angular power spectrum dominated by shot noise

Exploit statistical independence of different shot noise realisations at different times

Cross-correlate different time segments to build a (new) minimum-variance unbiased estimator

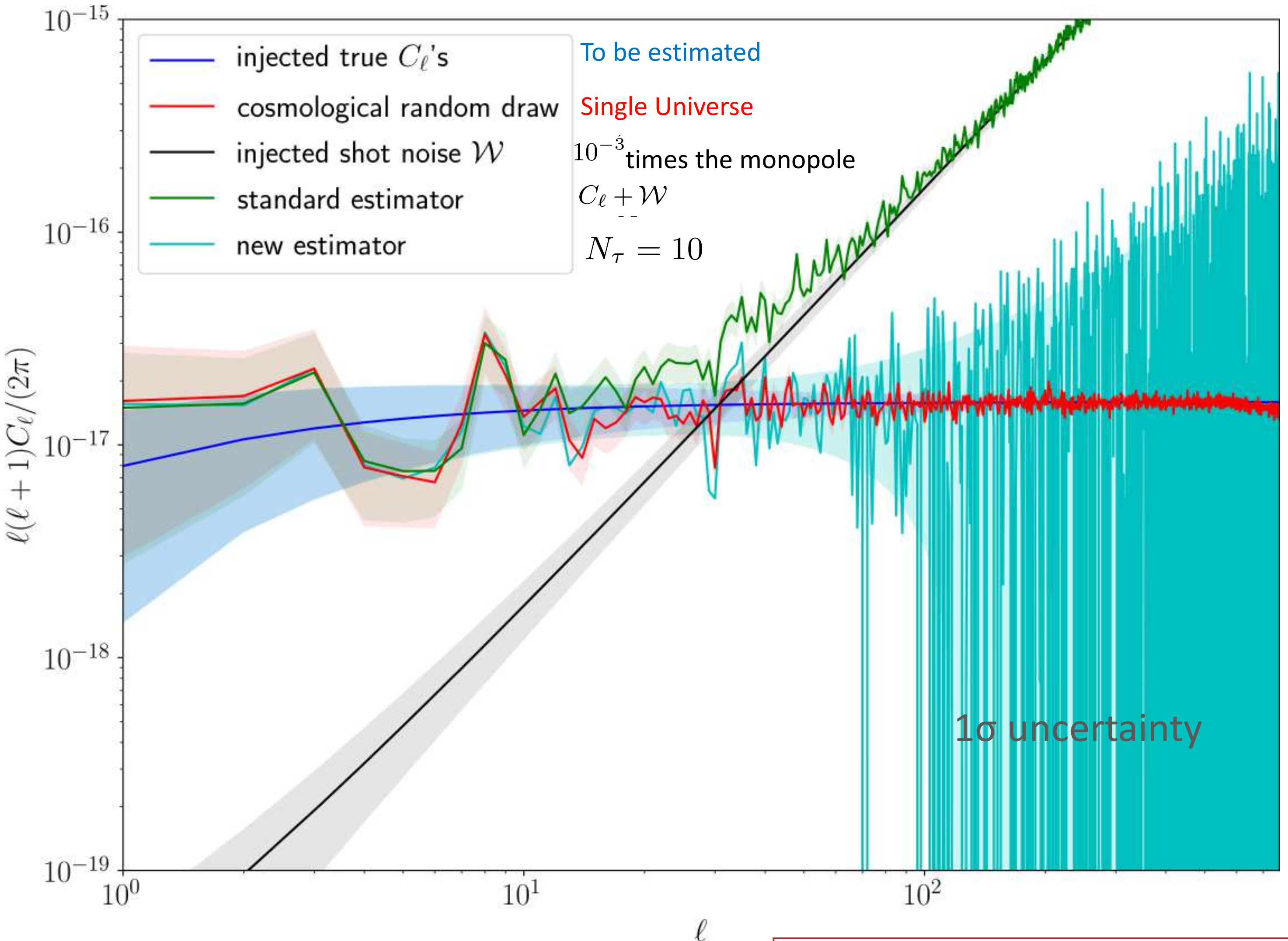
$$\boxed{\hat{C}_\ell^{\rm new} \equiv \frac{1}{N_{\rm pairs}} \sum_{\mu\neq\nu}^{N_{\rm pairs}} \frac{1}{2\ell+1} \sum_{m=-\ell}^{+\ell} \Omega^{\mu}_{\ell m} \Omega^{\nu *}_{\ell m}}$$

$$\boxed{\langle \hat{C}_\ell^{\rm new} \rangle = C_\ell}$$

$$\boxed{\mathrm{Var}[\hat{C}_\ell^{\rm new}] = \frac{2}{2\ell+1}(C_\ell + \mathcal{W})^2}$$

*Jenkins, Romano, Sakellariadou, arXiv:1907.06642*

# Can we probe LSS with ASGWB anisotropies?

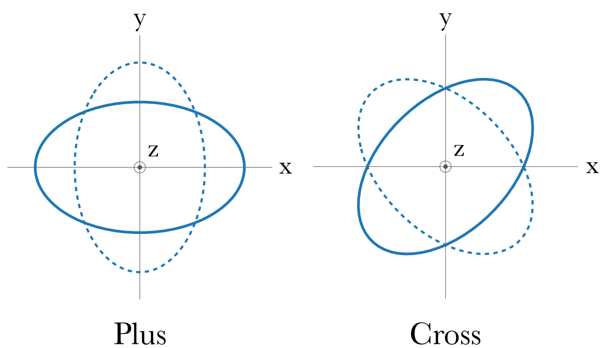



*Jenkins, Romano, Sakellariadou, arXiv:1907.06642*

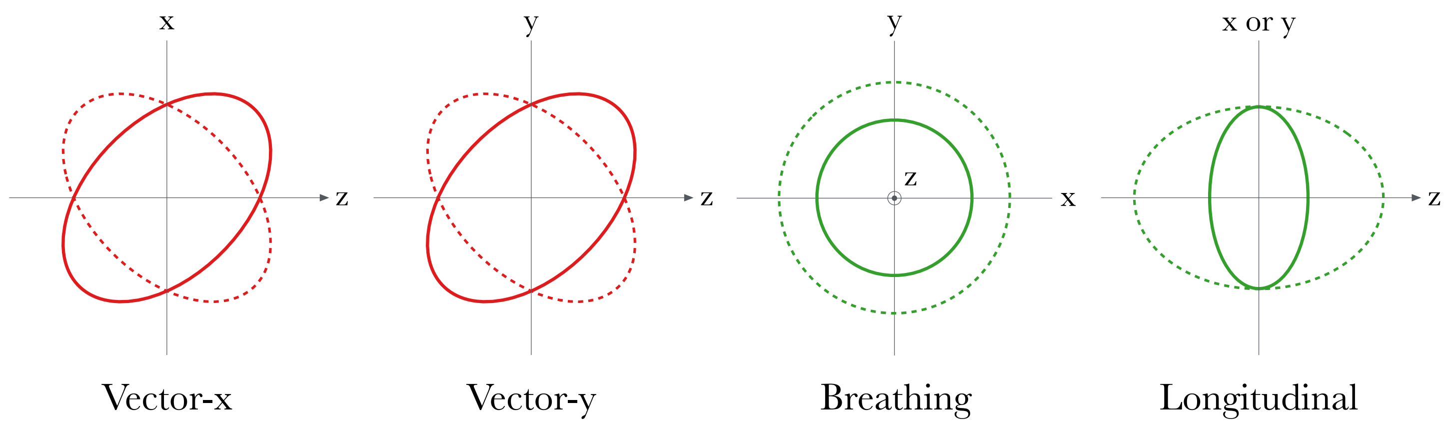
# Testing GR: **polarization modes**

Deformation of a ring of freely-falling test particles under the influence of GW in z-direction

GR




Alternate gravity theories allow for extra polarizations (2 vector and/or 2 scalar ones)




They correspond to the to the independent electric-type components of the Riemann curvature tensor $R_{0i0j}$

# Testing GR: **polarization modes**

The three-detector Advanced LIGO-Virgo network is generally unable to distinguish the polarization of transient GW signals, like those from BBHs



- Two LIGO detectors are nearly **co-oriented**, leaving Advanced LIGO largely sensitive to only a single polarization mode

- Even if the LIGO detectors were more favourably-oriented, a network of **at least six detectors** is generically required to uniquely determine the polarization content of a GW transient

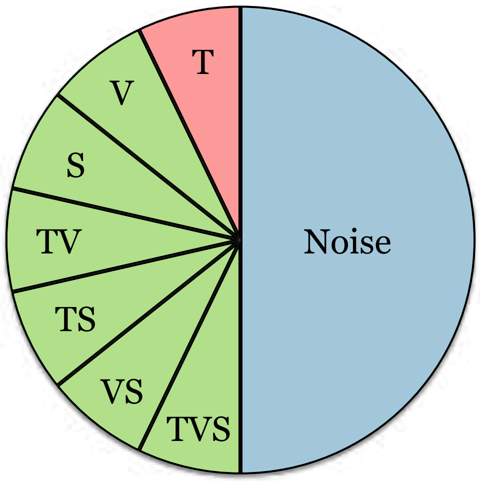
Problem of disentangling modes: **time-series of 6 polarizations + 2 direction angles** that affect the projection of the modes on the detector --- but only six observables $R_{0i0j}$

# Testing GR: **polarization modes**

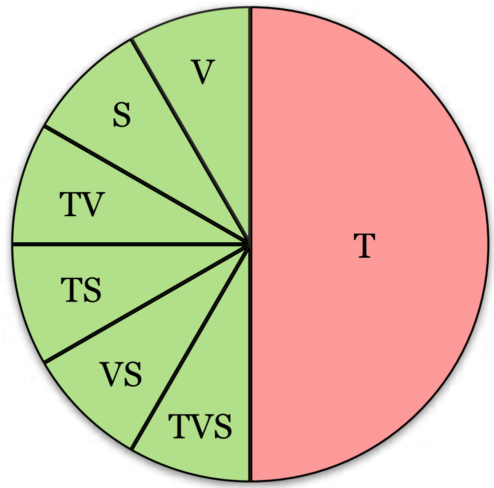
Bayesian search

$$\Omega_{\mathrm{TVS}}(\nu) = \Omega_0^{\mathrm{T}} \left(\frac{\nu}{\nu_0}\right)^{\alpha_{\mathrm{T}}} \boxed{+ \Omega_0^{\mathrm{V}} \left(\frac{\nu}{\nu_0}\right)^{\alpha_{\mathrm{V}}} + \Omega_0^{\mathrm{S}} \left(\frac{\nu}{\nu_0}\right)^{\alpha_{\mathrm{S}}}}$$

7 hypotheses: TVS, TV, TS, VS, T, V, S




Signal vs. Noise




GR vs. Non-GR

Equal prior probability to noise and signal models, as well as equal prior probability to the seven signal sub-hypotheses

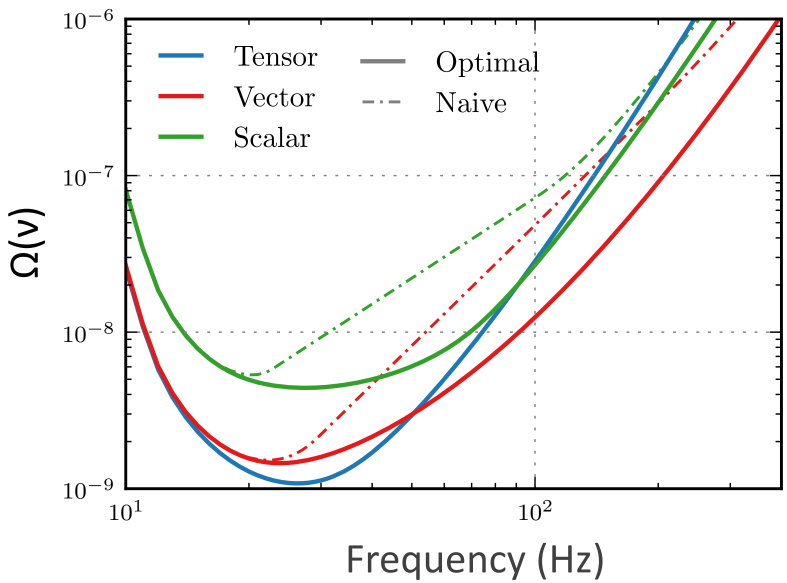
Equal prior probability to the non-GR and GR models and identically weight the six non-GR sub-hypotheses

*Callister, …, Sakellariadou, …, PRX7 (2017) 041058*

# Testing GR: **polarization modes**

$$\langle \hat{C}(\nu) \rangle_{\mathrm{TVS}} = \beta_{\mathrm{T}}(\nu)\Omega^{\mathrm{T}}_{\mathrm{ref}} \left(\frac{\nu}{\nu_{\mathrm{ref}}}\right)^{\alpha_{\mathrm{T}}} + \beta_{\mathrm{V}}(\nu)\Omega^{\mathrm{V}}_{\mathrm{ref}} \left(\frac{\nu}{\nu_{\mathrm{ref}}}\right)^{\alpha_{\mathrm{V}}} + \beta_{\mathrm{S}}(\nu)\Omega^{\mathrm{S}}_{\mathrm{ref}} \left(\frac{\nu}{\nu_{\mathrm{ref}}}\right)^{\alpha_{\mathrm{S}}}$$

$$\beta_{\mathrm{A}}(\nu) \equiv \frac{\gamma_{\mathrm{A}}(\nu)}{\gamma_{\mathrm{T}}(\nu)} \quad , \quad \mathrm{A} = \{\mathrm{T}, \mathrm{V}, \mathrm{S}\}$$




PI curves showing sensitivity of aLIGO to SGWB of T, V, S polarizations

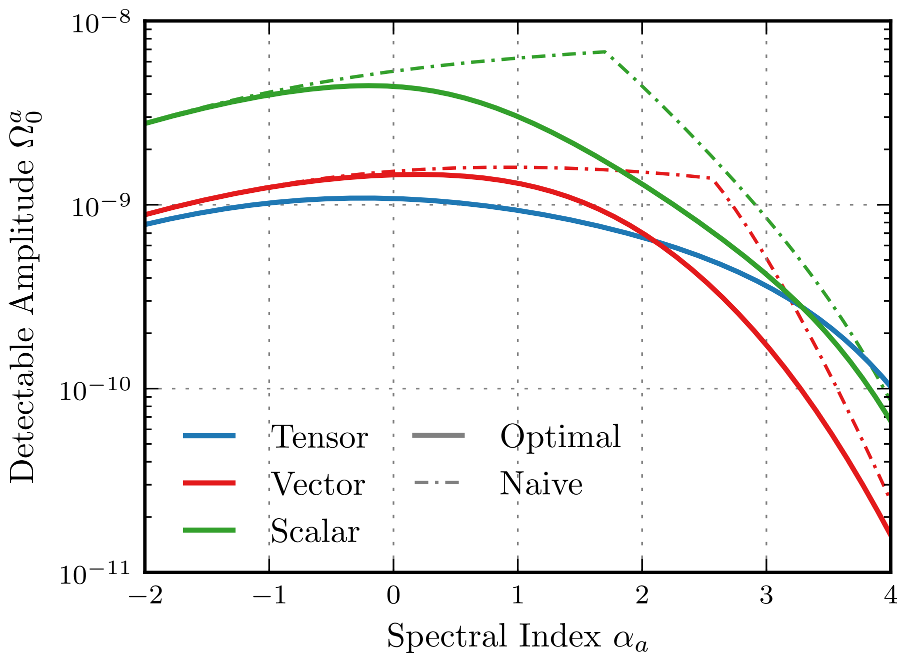
Power-law energy density spectra tangent to the PI curves have SNR=3 after 3 years of observation at design sensibility

*Callister, …, Sakellariadou, …, PRX7 (2017) 041058*

# Testing GR: **polarization modes**

$$\langle \hat{C}(\nu) \rangle_{\mathrm{TVS}} = \boxed{\beta_{\mathrm{T}}(\nu)} \Omega^{\mathrm{T}}_{\mathrm{ref}} \left( \frac{\nu}{\nu_{\mathrm{ref}}} \right)^{\alpha_{\mathrm{T}}} + \boxed{\beta_{\mathrm{V}}(\nu) \Omega^{\mathrm{V}}_{\mathrm{ref}} \left( \frac{\nu}{\nu_{\mathrm{ref}}} \right)^{\alpha_{\mathrm{V}}} + \beta_{\mathrm{S}}(\nu) \Omega^{\mathrm{S}}_{\mathrm{ref}} \left( \frac{\nu}{\nu_{\mathrm{ref}}} \right)^{\alpha_{\mathrm{S}}}}$$

$$\beta_{\mathrm{A}}(\nu) \equiv \frac{\gamma_{\mathrm{A}}(\nu)}{\gamma_{\mathrm{T}}(\nu)} \quad , \quad \mathrm{A} = \{\mathrm{T}, \mathrm{V}, \mathrm{S}\}$$




Minimum detectable background amplitudes (<SNR>=3 after 3 years of observation at design sensitivity) as a function of spectral index α

*Callister, …, Sakellariadou, …, PRX7 (2017) 041058*

# Testing GR: **polarization modes**

- Given the non-detection of any generic SGWB, we put Upper limits assuming all three modes potentially present, marginalizing over amplitudes and spectral indices for all but one mode

| Polarization | Uniform prior | Log-uniform prior |
|---|---|---|
| Tensor | $8.2 \times 10^{-8}$ | $3.2 \times 10^{-8}$ |
| Vector | $1.2 \times 10^{-7}$ | $2.9 \times 10^{-8}$ |
| Scalar | $4.2 \times 10^{-7}$ | $6.1 \times 10^{-8}$ |

- log Bayes factors consistent with Gaussian noise and GR-polarization modes

*Abbott, et al arXiv:1903.02886*

# Parametrized tests of GW propagation

Possible frequency dependence of speed of GWs

*Purely phenomenological model*

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

$$\alpha = 0, 0.5, 1, 1.5, 2.5, 3, 3.5, 4$$

*Lorentz-violating dispersion relation*

$A_0 > 0$ : massive graviton with $m_g = A_0^{1/2}/c^2$

$\alpha = 2.5$ : multi-fractal spacetime

$\alpha = 3$ : doubly special relativity

$\alpha = 4$ : Horava-Lifshitz and extra dimensional theories

*Abbott, et al arXiv:1903.04667*

# Parametrized tests of GW propagation

Possible frequency dependence of speed of GWs

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

$$\alpha = 0, \underbrace{0.5, 1, 1.5, 2.5, 3, 3.5, 4}_{\textit{Lorentz-violating dispersion relation}}$$

$$v_g/c = (dE/dp)/c = 1 + (\alpha - 1)A_\alpha E^{\alpha-2}/2 + O(A_\alpha^2).$$

Scale of modifications to the Newtonian potential associated with this dispersion relation

$$\boxed{\lambda_A := hc|A_\alpha|^{1/(\alpha-2)}}$$

*Abbott, et al arXiv:1903.04667*

# Parametrized tests of GW propagation

Possible frequency dependence of speed of GWs

$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

$$\tilde{h}(\nu) = A(\nu)e^{i\Phi(\nu)}$$

$$\tilde{h}(\nu) = A(\nu)e^{i(\Phi(\nu)+\delta\Phi_\alpha(\nu))}$$

depends on binary's **luminosity distance**, binary's **detector–frame chirp mass**, binary's **redshift** and a **distance parameter** (where cosmological parameters will also enter)

*Abbott, et al arXiv:1903.04667*

# Parametrized tests of GW propagation

Possible frequency dependence of speed of GWs

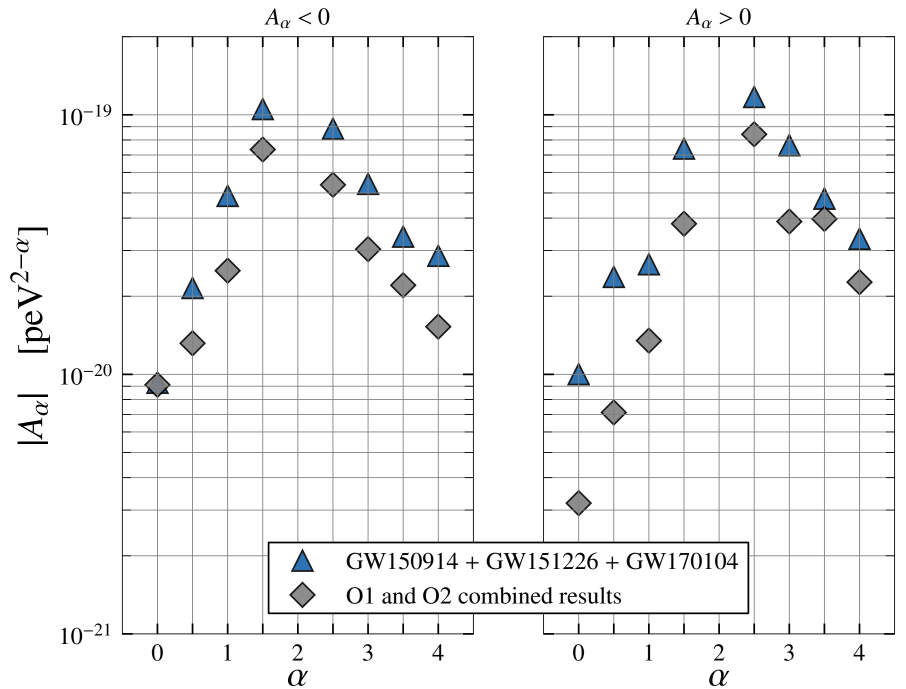
$$E^2 = p^2c^2 + A_\alpha p^\alpha c^\alpha$$

*90% credible upper bounds on the absolute value of the modified dispersion relation parameter* $A_\alpha$

$$1\ \text{peV} \simeq h \times 250\ \text{Hz}$$

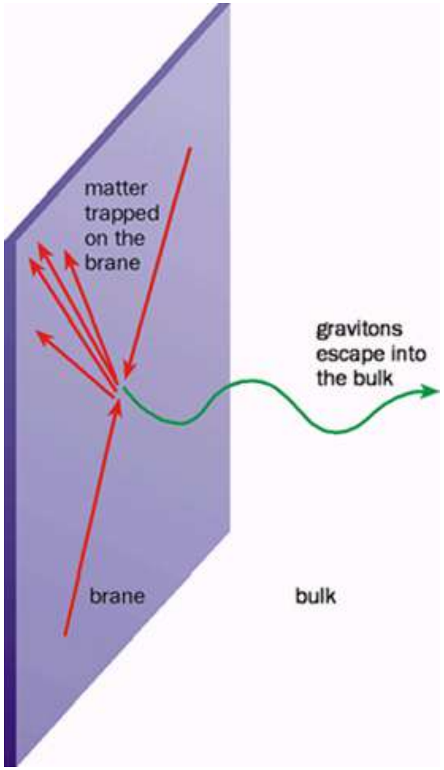
$$\boxed{m_g \le 5.0 \times 10^{-23}\ \text{eV}/c^2}$$

at 90% credible limit




*Abbott, et al arXiv:1903.04667*

# Constraints on the number of spacetime dimensions




Damping of the waveform due to gravitational leakage into extra dim

GR: $h_{\rm GR} \propto d_L^{-1}$

$$d_L^{\rm EM} \simeq \frac{z(1+z)}{H_0} \overset{z \ll 1}{\simeq} \frac{z}{H_0}$$

Deviation depends on the number of dimensions D and would result to a systematic **overestimation of the source** $d_L^{\rm EM}$ **inferred from GW data**

Extra dim models: assume that light and matter propagate in 4 ST dim

$$\boxed{h \propto \frac{1}{d_L^{\rm GW}} = \frac{1}{d_L^{\rm EM}}\left[1+\left(\frac{d_L^{\rm EM}}{R_c}\right)^n\right]^{-(D-4)/(2n)}}$$

The **strain** measured in a GW interferometer ⟷ The **luminosity distance** measured for the optical counterpart of the standard siren

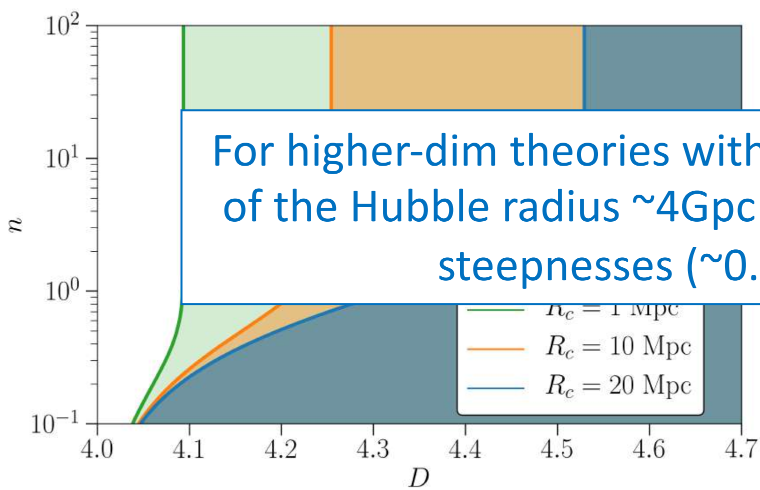
LVC, arXiv:1811.00364

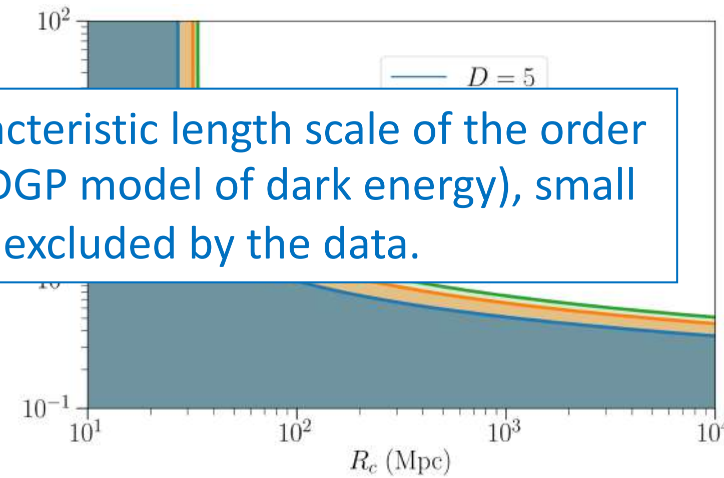
# Constraints on the number of spacetime dimensions

Joint posterior probability for $D, d_L^{\mathrm{GW}}$ and $d_L^{\mathrm{EM}}$ given the two statistically independent measurements of EM data and GW data

$$p(D|x_{\mathrm{GW}}, x_{\mathrm{EM}}) = \int p(d_L^{\mathrm{GW}}|x_{\mathrm{GW}})p(d_L^{\mathrm{EM}}|x_{\mathrm{EM}})\delta(D - D(d_L^{\mathrm{GW}}, d_L^{\mathrm{EM}}, R_c, n))\, \mathrm{d}d_L^{\mathrm{GW}} \mathrm{d}d_L^{\mathrm{EM}}$$

GW170817




For higher-dim theories with characteristic length scale of the order of the Hubble radius ~4Gpc (e.g. DGP model of dark energy), small steepnesses (~0.1) are excluded by the data.

*90% upper bounds on # of spacetime dim assuming fixed steepness and distance scale*

*10% lower limits on distance scale assuming fixed transition steepness and # of spacetime dim*

*Abbott, et al arXiv:1811.00364*

# Tests of QG with GWs: gravitational wave luminosity distance

*Can Quantum Gravity (QG) theories leave a signature in GWs?*

- **NO**: QG corrections will be suppressed by the Planck scale
  Leading-order perturbative quantum corrections to the Einstein-Hilbert action
  In FLRW there are only 2 scales for building dimensionless quantities

  *quantum corrections are of the form* $(\ell_{\rm Pl} H)^n$ *where* $n = 2, 3, \ldots.$

  but today are too small: $(\ell_{\rm Pl} H_0)^n \sim 10^{-60n}$
  and any late-time QG imprint is Planck-suppressed and undetectable

- **Nonperturbative effects beyond the simple dimensional argument**

  If there is a third scale $L \gg \ell_{\rm Pl}$ quantum corrections may become
  $\sim \ell_{\rm Pl}^a H^b L^c$ with $a - b + c = 0$ and NOT all these exponents are small

*Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, arXiv:1904.00384*
*Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, arXiv:1907:02489*

# Tests of QG with GWs: gravitational wave luminosity distance

Long-range nonperturbative mechanism found in most QG candidates:
***Dimensional flow*** (change of spacetime dimensionality)

$$S = \frac{1}{2\ell_*^{2\Gamma}} \int d\varrho \sqrt{-g^{(0)}} \left[ h_{\mu\nu} \mathcal{K} h^{\mu\nu} + O(h_{\mu\nu}^2) + \mathcal{J}^{\mu\nu} h_{\mu\nu} \right]$$

*ST distorted by QG effects characterized by ST measure and kinetic term*

*characteristic scale of geometry*

*generic source term*

*scaling parameter*

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Scaling parameter

$$\boxed{\Gamma(\ell) := \frac{d_{\rm H}(\ell)}{2} - \frac{d_{\rm H}^k(\ell)}{d_{\rm S}(\ell)}}$$

| | $\Gamma_{\rm UV}$ | $\Gamma_{\rm meso} \gtrsim 1$ |
|---|---|---|
| GFT/SF/LQG | $[-3, 0)$ | yes |
| Causal dynamical triangulation | $-2/3$ | |
| $\kappa$-Minkowski (other) | $[-1/2, 1]$ | |
| Stelle gravity | 0 | |
| String theory (low-energy limit) | 0 | |
| Asymptotic safety | 0 | |
| Hořava–Lifshitz gravity | 0 | |
| $\kappa$-Minkowski bicross-product $\nabla^2$ | $3/2$ | yes |
| $\kappa$-Minkowski relative-locality $\nabla^2$ | 2 | yes |
| Padmanabhan nonlocal model | 2 | yes |

$$d_{\rm H}(\ell) := \frac{d\ln \mathcal{V}(\ell)}{d\ln \ell}$$

Hausdorff dimension

*how volumes scale with their linear size*

$$d_{\rm H}^k(\ell) := \frac{d\ln \tilde{\mathcal{V}}(k)}{d\ln k}\bigg|_{k=1/\ell}$$

Hausdorff dim in momentum space

$$d_{\rm S} := -\frac{d\ln \mathcal{P}(\ell)}{d\ln \ell}$$

Spectral dimension

*governed by type of kinetic term in the action; depends on dispersion relation and on measure in momentum ST*

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QG corrections are important

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Hausdorff dim in momentum space

$$d_{\rm S} := \cdot$$

Spec

Contributions to GR small but non-negligible

*governed by type of kinetic term in the action; depends on dispersion relation and on measure in momentum ST*

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# Tests of QG with GWs: gravitational wave luminosity distance

The **strain** measured in a GW interferometer

The **luminosity distance** measured for the optical counterpart of the standard siren

$$h \propto \frac{1}{d_L^{\rm GW}}\,, \qquad d_L^{\rm GW} = d_L^{\rm EM}\left[1+\varepsilon\left(\frac{d_L^{\rm EM}}{\ell_*}\right)^{\gamma-1}\right], \qquad \gamma \neq 0\,,$$

Constraint the parameters $\ell_*\,,\gamma$ by constraining the ratio $d_L^{\rm GW}(z)/d_L^{\rm EM}(z)$ as a function of z

Standard sirens: -- NS merger GW170817 (LIGO/Virgo & Fermi)
-- simulated z=2 supermassive BH merger within Lisa detectability

**Only GFT, SF or LQG *could* generate a signal detectable with standard sirens**

*Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, arXiv:1904.00384*
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# Testing modified gravity to explain DE

Phenomenological proposal

$$\boxed{\frac{d_L^{\rm gw}(a)}{d_L^{\rm em}(a)} = \Xi_0 + a^n(1-\Xi_0)}$$

$\Xi_0 = 1$ corresponds to GR

| Model | $\Xi_0 - 1$ | $n$ |
|---|---|---|
| HS $f(R)$ gravity | $\frac{1}{2} f_{R0}$ | $\frac{3(\tilde{n}+1)\Omega_m}{4-3\Omega_m}$ |
| Designer $f(R)$ gravity | $-0.24\Omega_m^{0.76} B_0$ | $3.1\Omega_m^{0.24}$ |
| Jordan–Brans–Dicke | $\frac{1}{2}\delta\phi_0$ | $\frac{3(\tilde{n}+1)\Omega_m}{4-3\Omega_m}$ |
| Galileon cosmology | $\frac{\beta\phi_0}{2M_{\rm Pl}}$ | $\frac{\dot{\phi}_0}{H_0\phi}$ |
| $\alpha_M = \alpha_{M0} a^{\tilde{n}}$ | $\frac{\alpha_{M0}}{2\tilde{n}}$ | $\tilde{n}$ |
| $\alpha_M = \alpha_{M0}\frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$ | $-\frac{\alpha_{M0}}{6\Omega_\Lambda}\ln\Omega_m$ | $-\frac{3\Omega_\Lambda}{\ln\Omega_m}$ |
| $\Omega = 1 + \Omega_+ a^{\tilde{n}}$ | $\frac{1}{2}\Omega_+$ | $\tilde{n}$ |
| Minimal self-acceleration | $\lambda\left(\ln a_{acc} + \frac{C}{2}\chi_{acc}\right)$ | $\frac{C/H_0-2}{\ln a_{acc}^2 - C\chi_{acc}}$ |

Study prospects of observing modified GW propagation using supermassive binaries as standard sirens with LISA:
construct simulated catalogues of LISA massive BH binaries with EM counterparts

$\Xi_0$ can be measured to an accuracy between 4.4% and 1.1%

*Belgacem,… Sakellariadou, JCAP 1907 (2019) 024*

# Conclusions

**GWs offer a new powerful window into the Universe and the laws governing it**

- **astrophysical models**
- **physics beyond the Standard Model**
- **large scale structure**
- **dark matter candidates (PBHs, axions, …)**
- **GR and modified gravity models**
- **quantum gravity**