Title: Gravitational Waves: the theorist's swiss knife

Speakers: Mairi Sakellariadou

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Abstract: After a short introduction to the stochastic GW background I will highlight how one uses currently available LIGO/Virgo/Kagra data not only to learn about compact binaries and the large-scale-structure of our universe, but also to constrain particle physics models beyond the Standard Model, modified gravity proposals, and even quantum gravity theories.

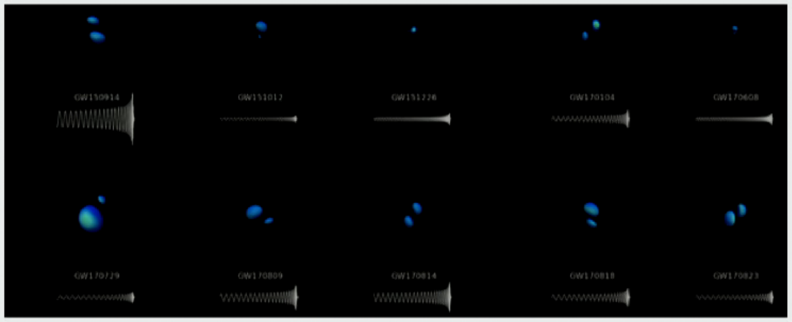
# Gravitational waves: the theorist's swiss knife

*Mairi Sakellariadou*

# Outline


Mairi Sakellariadou

# Introduction



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

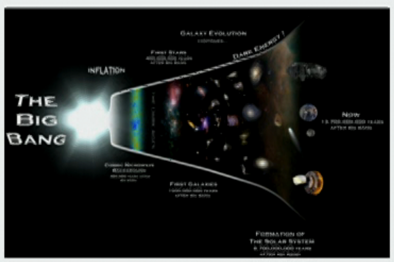
O1 and O2 BBHs events

- LIGO and Virgo have detected 10 GW signals from binary black hole (BBH) mergers and 1 from a binary neutron star (BNS) merger
- The BBH observations have told us that BH masses can be larger than previously expected
- Besides the detection of loud individual sources at close distances, we expect to see the background formed by all the sources from the whole Universe

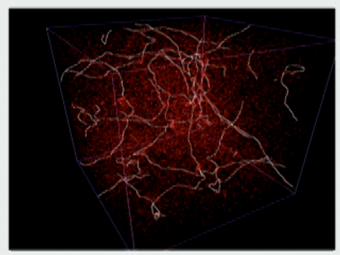
# Stochastic GW Background (SGWB)

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

Binaries, Supernovae, Neutron stars



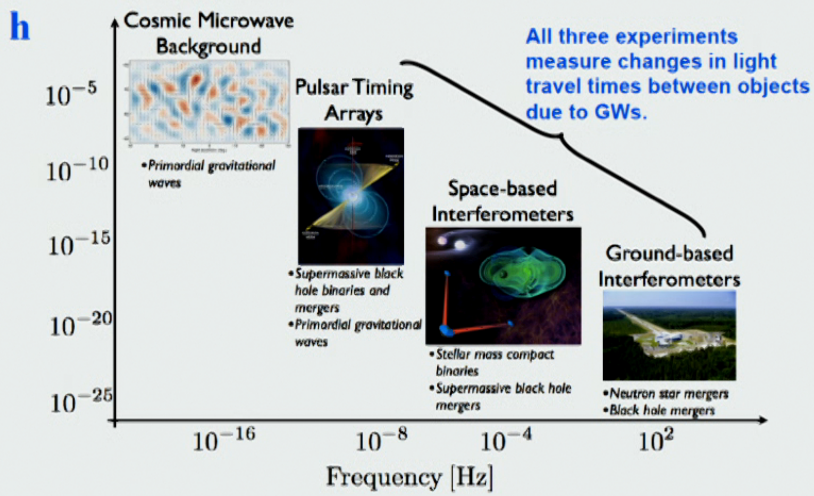

Inflation

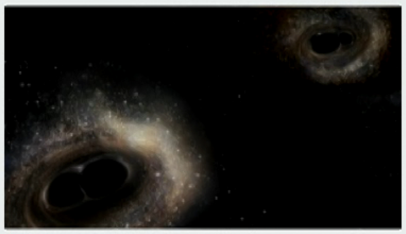


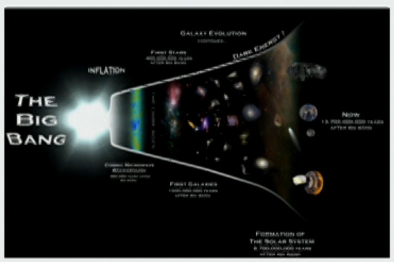
Cosmic strings

Cosmological phase transitions

# Stochastic GW Background (SGWB)



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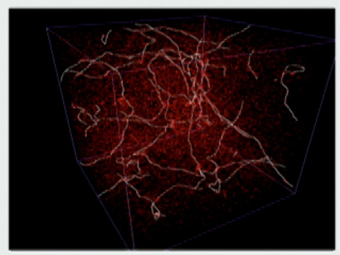

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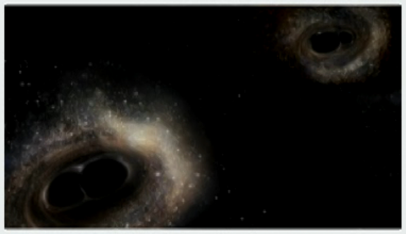
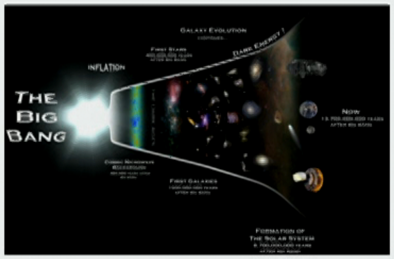
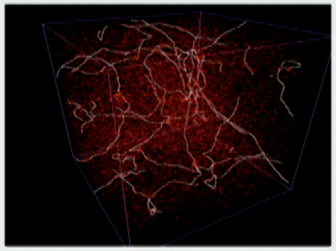
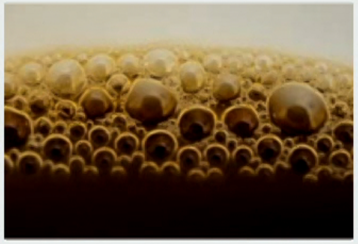


Binaries, Supernovae, Neutron stars





Inflation

Cosmic strings

Cosmological phase transitions

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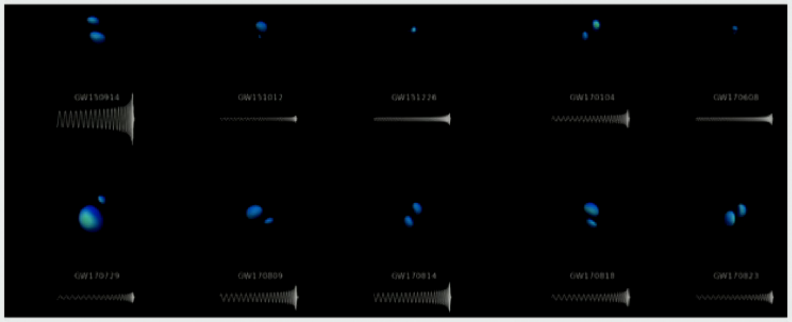
# SGWB from CBC: info about Compact Binary Objects (CBOs)




*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

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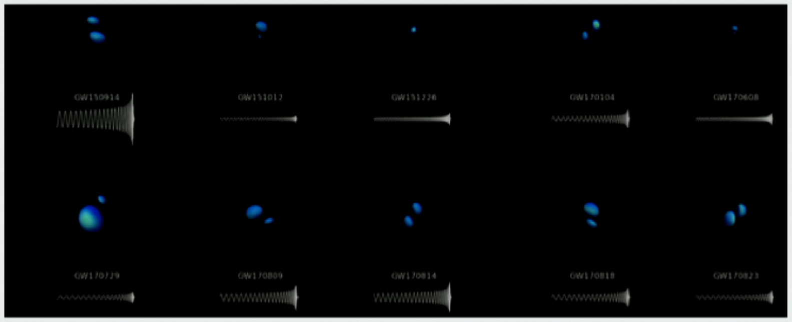
## SGWB from CBC: info about Compact Binary Objects (CBOs)



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

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

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

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

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

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

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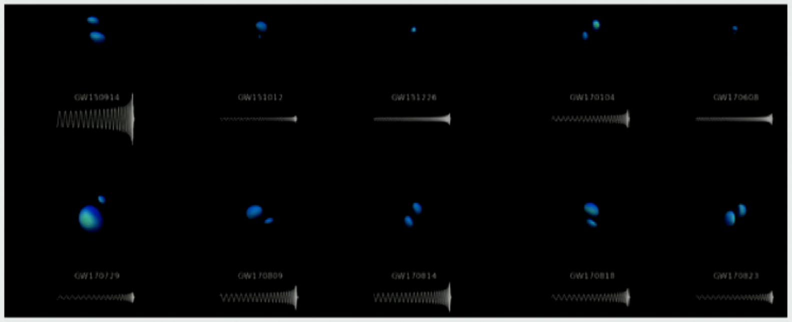
## SGWB from CBC: info about Compact Binary Objects (CBOs)



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## SGWB from CBC: info about Compact Binary Objects (CBOs)

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:*

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

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

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

*Beta distribution for the BH spins:*

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

$\alpha_m$, $m_{\max}$, $\alpha_\chi, \beta_\chi$ — *infrerred from observed BBHs*

*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)*

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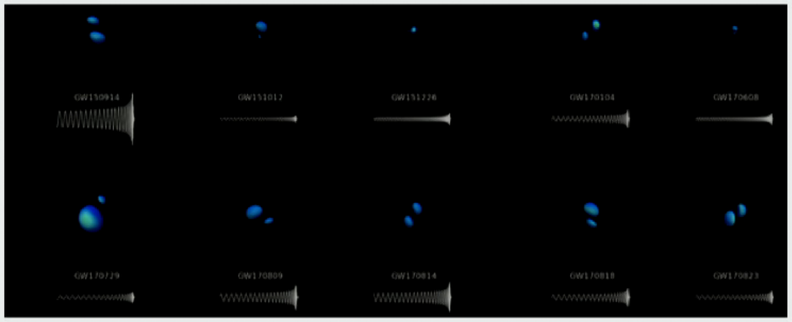

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## SGWB from cosmic strings: info about physics Beyond the Standard Model (BSM)

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

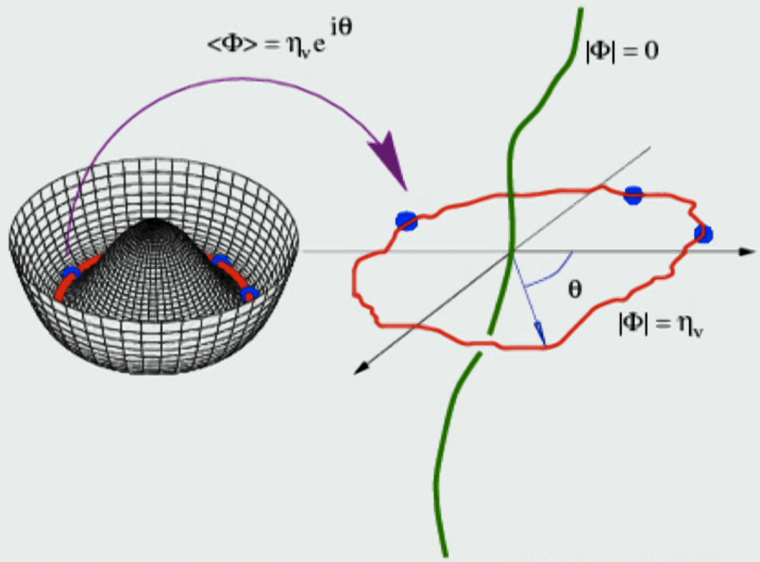
*Kibble (1976)*

Generically formed in the context of GUTs

$G \rightarrow \cdots \rightarrow G_{SM}$

$\pi_1(\mathcal{M}) \neq 0$

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




$$\mathcal{L} = (D_\mu\phi)^*(D^\mu\phi) - \frac{1}{4e^2}F_{\mu\nu}F^{\mu\nu} - \frac{\lambda}{4}(|\phi|^2 - \eta^2)^2$$

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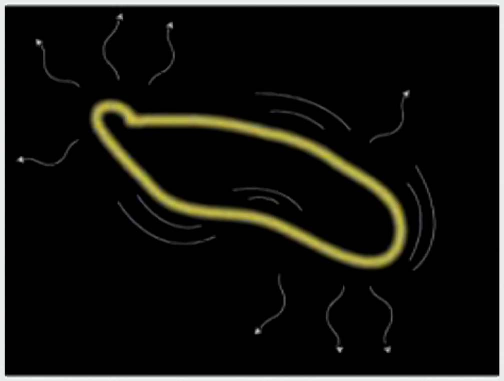
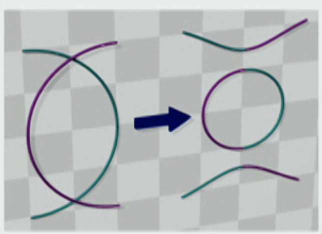


$$G\mu \sim \left(\frac{\text{new physics scale}}{\text{Planck scale}}\right)^2$$

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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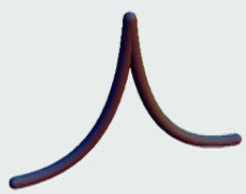
Kink



Cusp

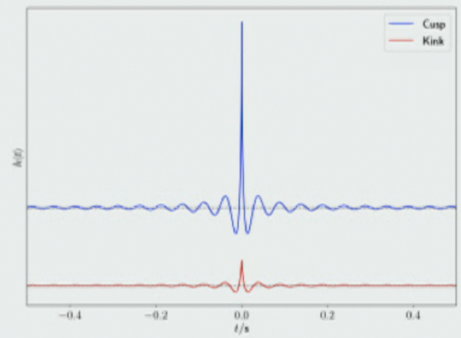
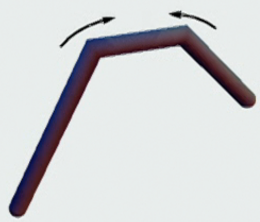



*Image credit: Alex Jenkins*

GW in a highly concentrated beam



Kink–Kink Collision

GW is isotropic

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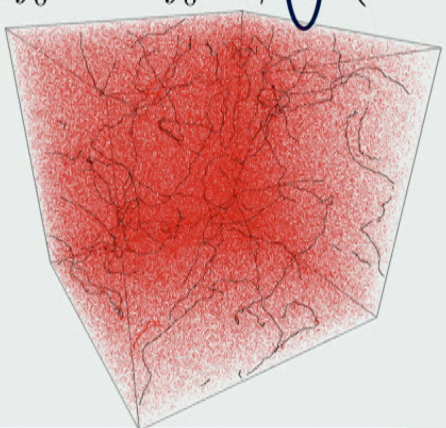
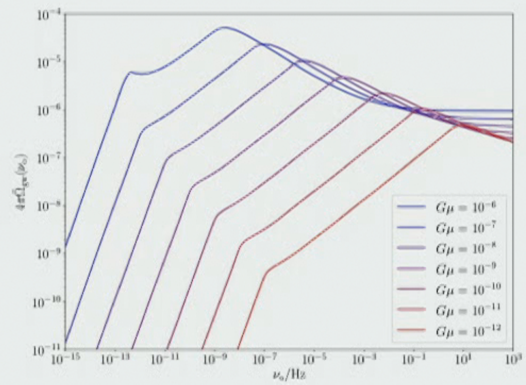
$$\bar{\Omega}_{\rm gw} = \frac{2(G\mu)^2}{3\pi^2 H_{\rm o}^2 \nu_{\rm o}} \int_0^{t_*} \frac{{\rm d}t}{t^4} a^5 \int_0^{\gamma_*} \frac{{\rm d}\gamma}{\gamma} \mathcal{F} \Theta\left(\gamma - \frac{2a}{\nu_{\rm o} t}\right) \left[ N_{\rm k}^2 + 4 A N_{\rm k} \left(\frac{\nu_{\rm o}\gamma t}{a}\right)^{1/3} + A^2 N_{\rm c} \left(\frac{\nu_{\rm o}\gamma t}{a}\right)^{2/3} \right]$$

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






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

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

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# 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

$$s(t) = n(t) + h(t)$$

*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:

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

# SGWB from CBC: info about Compact Binary Objects (CBOs)

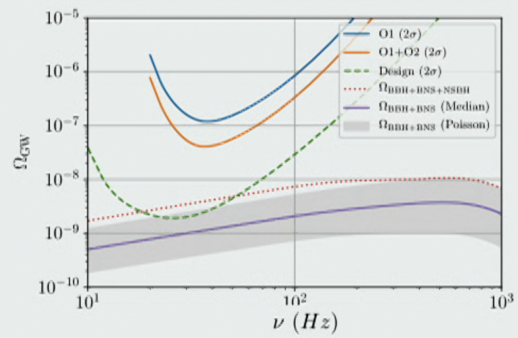
$$\frac{dE_{\rm GW}}{d\nu} = \frac{(G\pi)^{2/3}}{3} \frac{m_1 m_2}{(m_1+m_2)^{1/3}} \nu^{-1/3}$$

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

α=2/3

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

Scales as $\sim 1/\sqrt{\text{obs. time}}$




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

*LVC (PRD) arXiv:1903.02886*

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## SGWB from cosmic strings: info about physics Beyond the Standard Model (BSM)

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

α=0

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

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

*LVC (PRD) arXiv:1903.02886*

$$G\mu/c^2 \le 2.1 \times 10^{-14}$$

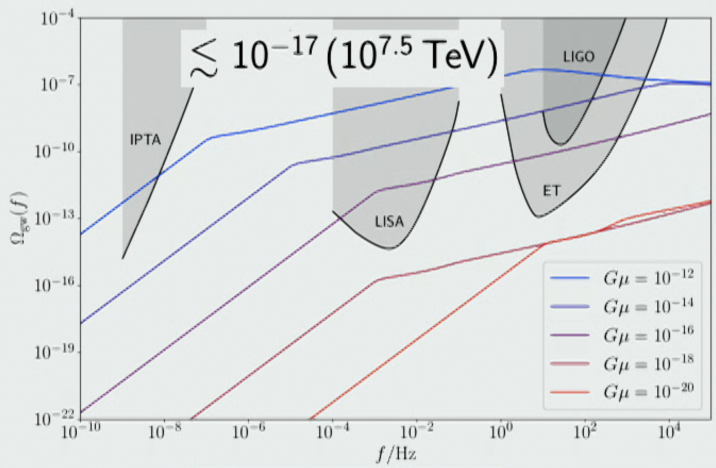
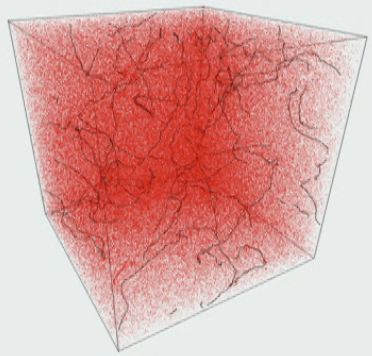



*Image credit: Alex Jenkins*



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α=0

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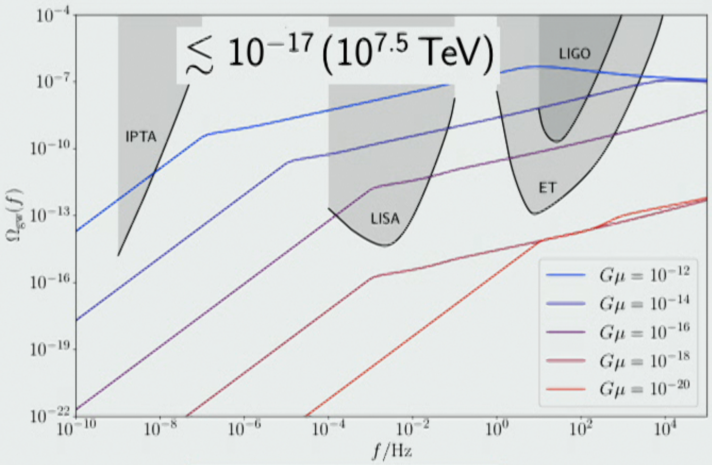


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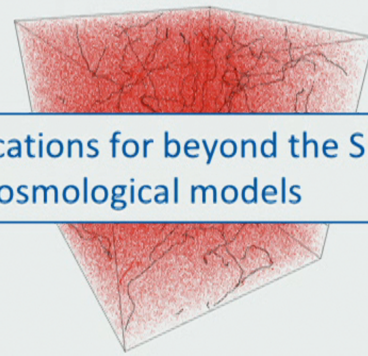

Implications for beyond the SM physics and cosmological models

*Lorenz, Ringeval, Sakellariadou, JCAP1010 (2010)*
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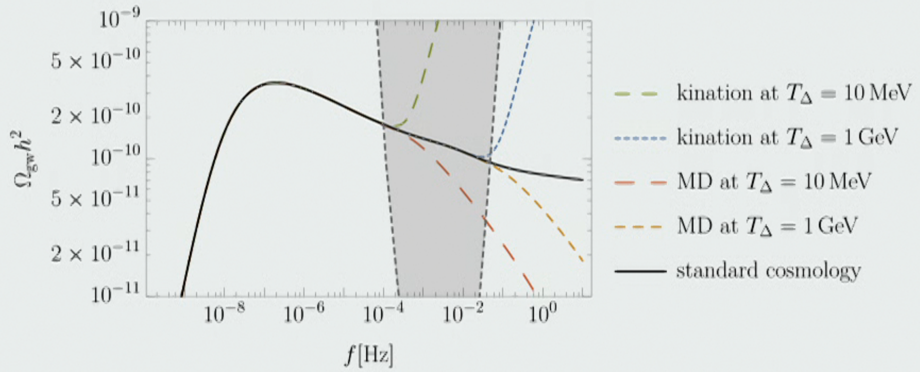
# SGWB from cosmic strings: info about cosmology beyond ΛCDM

## SGWB depends on thermal history

$G\mu = 10^{-11}$




*Auclair, ..., Sakellariadou,... arXiv:1909.00819*

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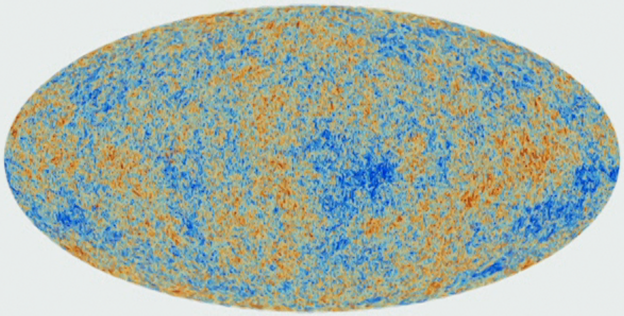
## Anisotropies in the Stochastic GW Background

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)

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

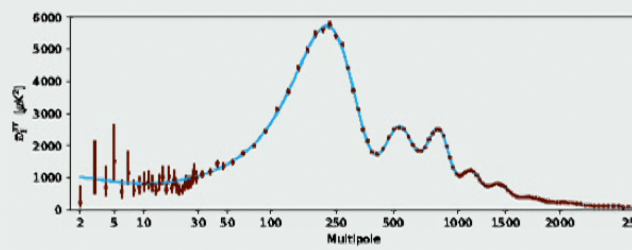



*Image credit: Planck collaboration*

SGWB

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

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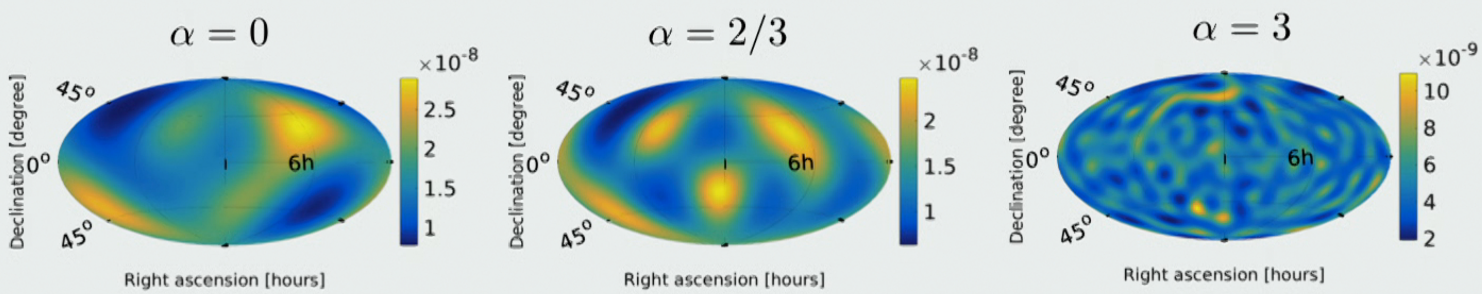
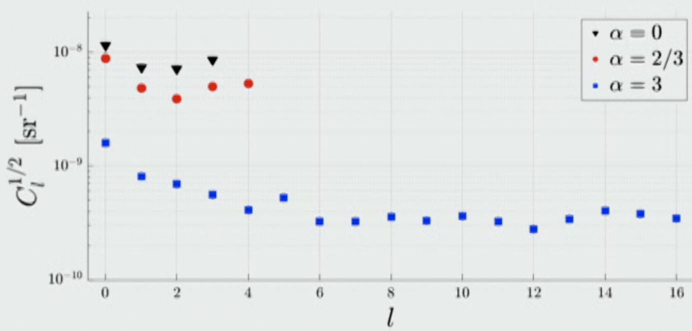
## Anisotropies in the Stochastic GW Background

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




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

*LVC (PRD) arXiv:1903.08844*

## Anisotropies in the Stochastic GW Background

Focus on anisotropy due to source density contrast & neglect most of cosmological perturbations
Include peculiar motion of observer as this introduces a kinematic dipole that interferes with the anisotropy statistics

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

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

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

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

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

*Density contrast due to the source distribution alone, with the kinematic dipole subtracted*

$$C_{\rm gw}(\theta_{\rm o}, \nu_{\rm o}) = \sum_{l=0}^{\infty}\frac{2l+1}{4\pi} C_l(\nu_{\rm o}) P_l(\cos\theta_{\rm o})$$

$\theta_{\rm o} \equiv \cos^{-1}(\hat{e}_{\rm o}\cdot\hat{e}'_{\rm o})$

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

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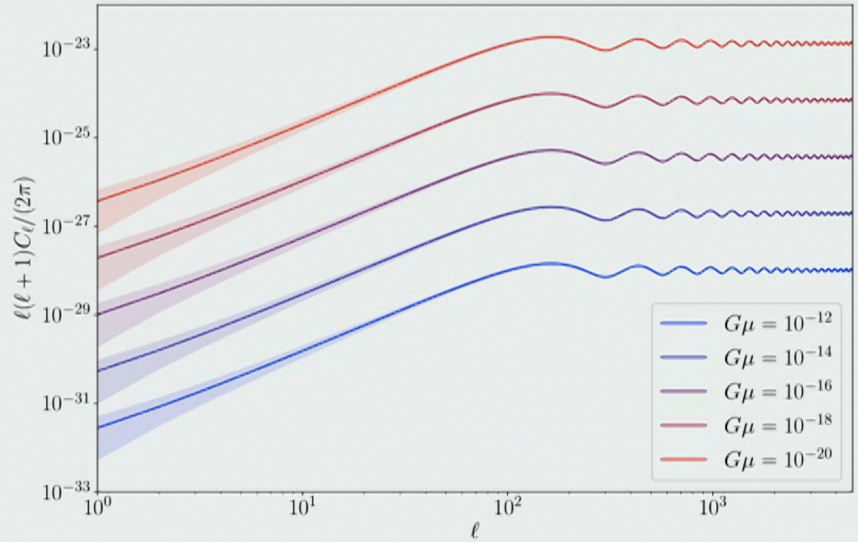
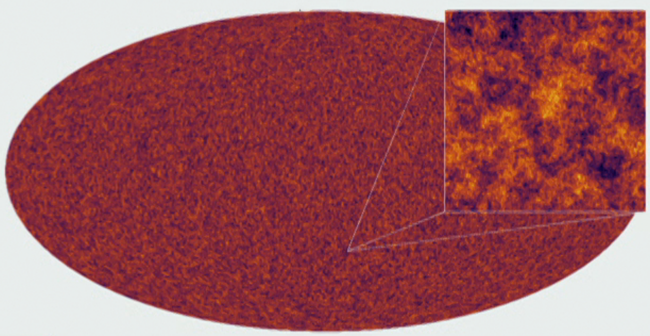
# SGWB from cosmic strings: info about physics Beyond the Standard Model (BSM)

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

Stronger for smaller string tension




$T_{\rm SSB} \sim 10^{13}$–$10^9$ GeV

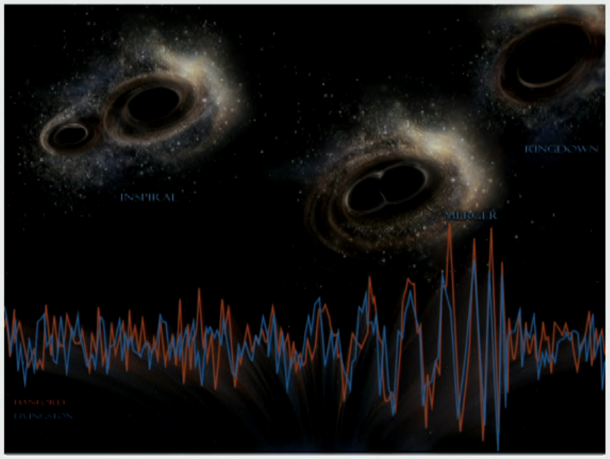


*Jenkins, Sakellariadou, PRD 98, 063509 (2018)*

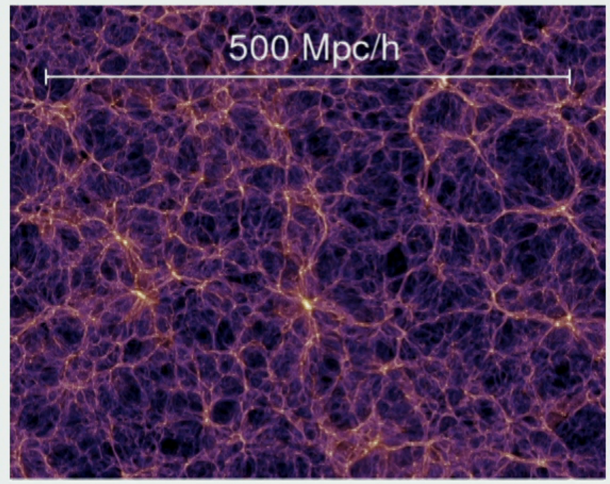
*Mairi Sakellariadou*

# SGWB from CBC: info about Large Scale Structure (LSS)

CBCs are the loudest component of the SGWB



*Millenium mock galaxy catalogue (N-body simulation)*




*Spingel et al (Nature), arXiv:0504097*

BBH / BNS / BHNS are within galaxies → LSS

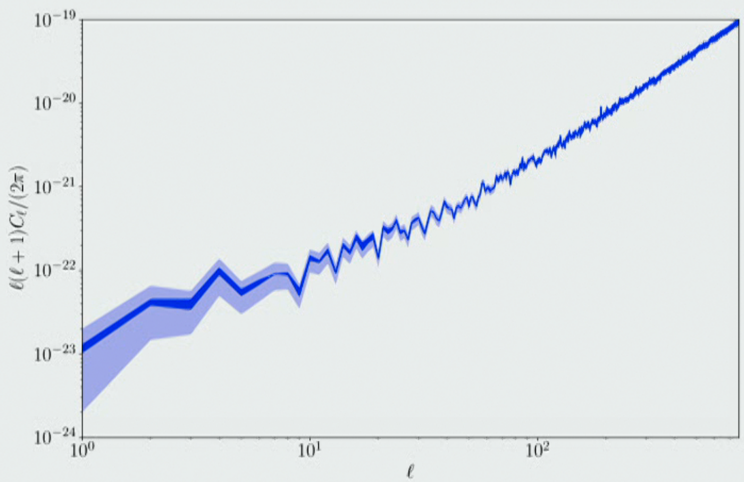
*Mairi Sakellariadou*

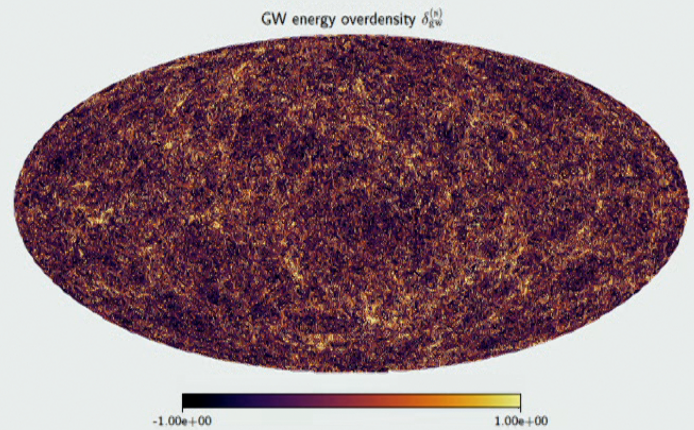
# SGWB from CBC: info about Large Scale Structure (LSS)

*Get galaxies from the Millenium catalogue –> compute merger rate for each galaxy –> superimpose to get a SGWB map*

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

$$\langle \Omega_{\rm gw} \Omega_{\rm gw} \rangle \Longrightarrow C_{\rm gw}(\theta_{\rm o}, \nu_{\rm o}) = \left\langle \delta^{(\rm s)}_{\rm gw} \delta^{(\rm s)}_{\rm gw} \right\rangle \Longrightarrow C_l(\nu_{\rm o}) = 2\pi \int_{-1}^{+1} \mathrm{d}(\cos\theta_{\rm o})\, P_l(\cos\theta_{\rm o}) C_{\rm gw}$$




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

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

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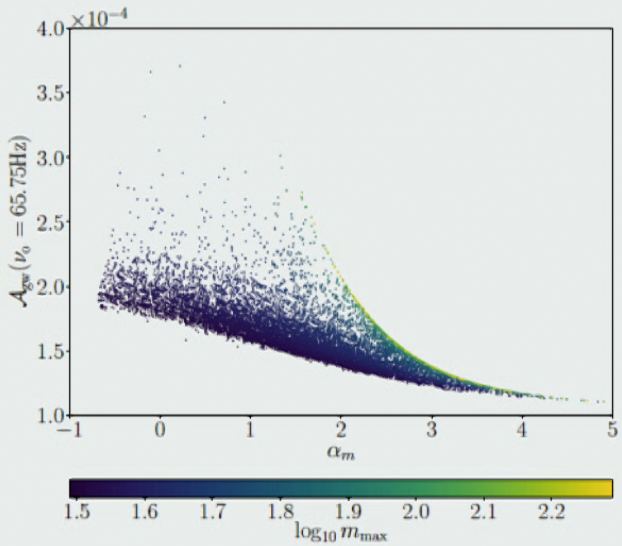
## SGWB from CBC: info about Large Scale Structure (LSS)

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

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

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

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




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

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

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# SGWB from CBC: info about Large Scale Structure (LSS)

## Probing LSS with LVK (LIGO/Virgo/Kagra)

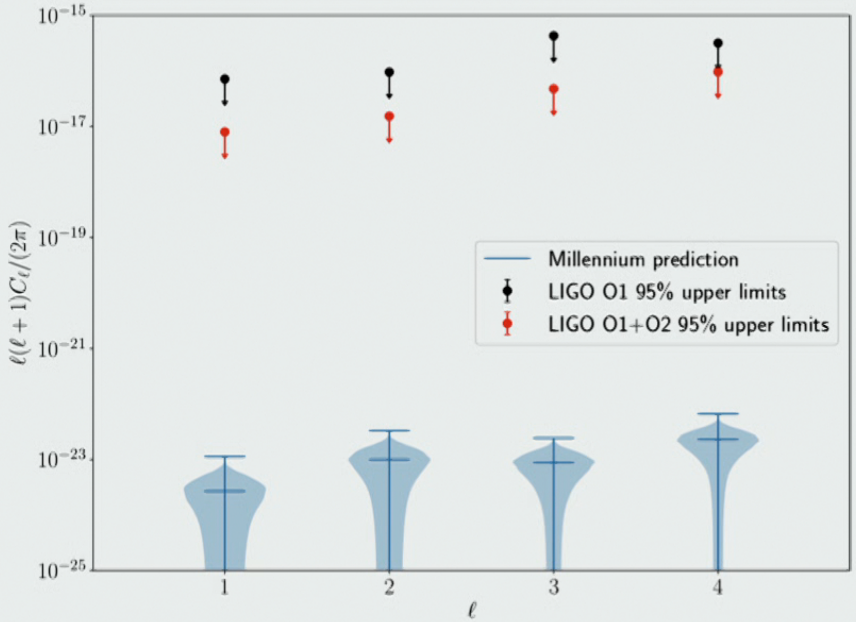



*Image credit: Alex Jenkins*

## Cross correlations with galaxy surveys?

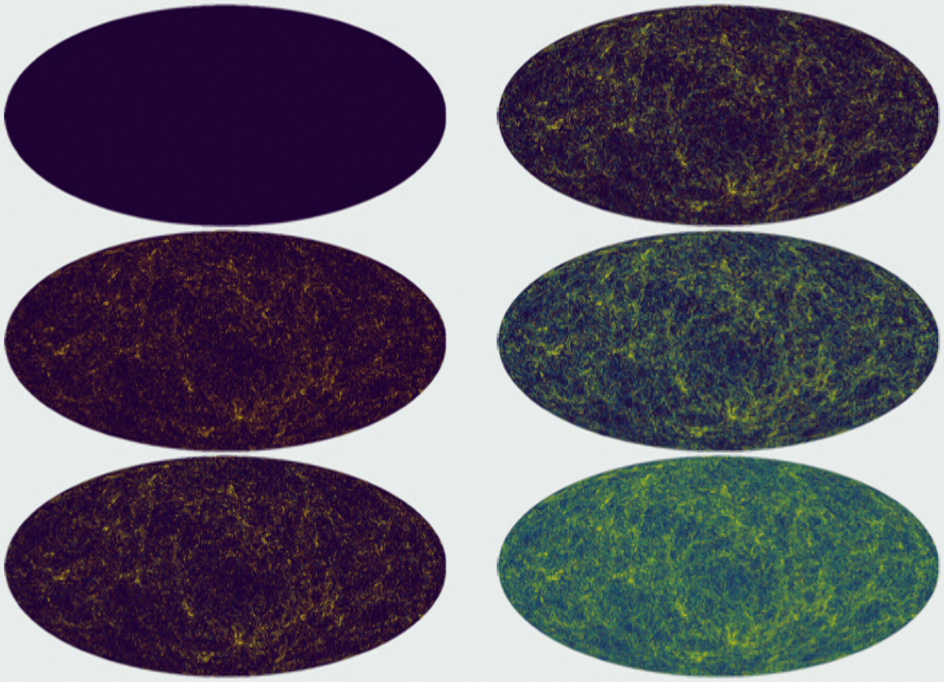
*Canas-Herrea, Contigiani, Vardanyan, arXiv:1910.08353*
*Canas-Herrea, Contigiani, Jenkins, Sakellariadou, Vardanyan (in progress)*

*Mairi Sakellariadou*

## SGWB from CBC: info about Large Scale Structure (LSS)

Finite number of CBC's per observational time

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



## SGWB from CBC: info about Large Scale Structure (LSS)

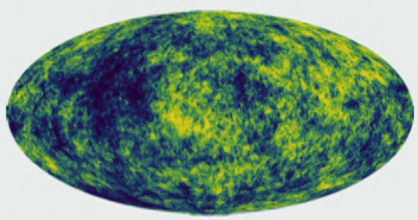
Finite number of CBC's per observational time

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

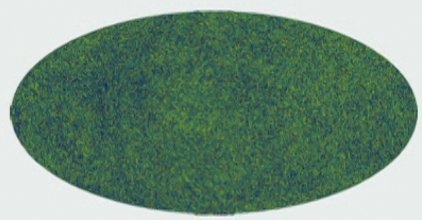
$$C_\ell \to C_\ell + \mathcal{W} \qquad \mathcal{W} \gg C_\ell \qquad \mathcal{W} \propto \frac{1}{T_{\rm obs}}$$

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

*Jenkins, Sakellariadou, PRD100 (2019) 063508*

\+ finite number of galaxies (*spatial shot noise*)

\+ cosmic variance

# SGWB from CBC: info about Large Scale Structure (LSS)

Finite number of CBC's per observational time

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

$$C_\ell \to C_\ell + \mathcal{W} \qquad \mathcal{W} \gg C_\ell \qquad \mathcal{W} \propto \frac{1}{T_{\rm obs}}$$

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

→ angular power spectrum dominated by shot noise

Exploit statistical independence of different shot noise realisations at different times

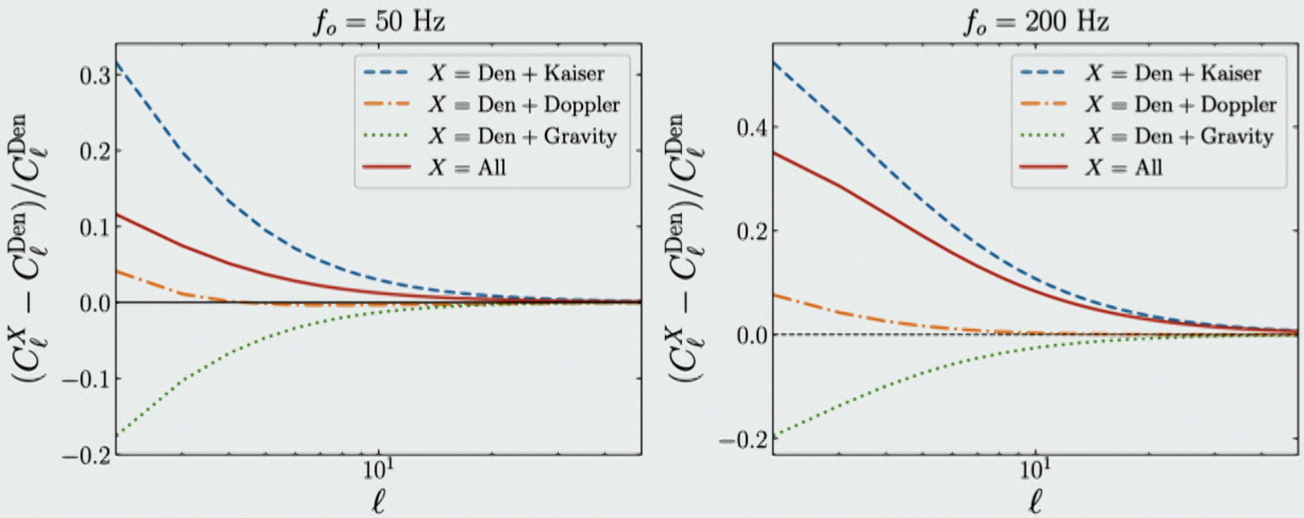
Cross-correlate different time segments to build a (new) minimum-variance unbiased estimator

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

*Jenkins, Romano, Sakellariadou, PRD100 (2019) 083501*

# SGWB from CBC: info about Large Scale Structure (LSS)

## Projection effects:




- Contribution of different effects is larger at lowest angular multipoles and depends on frequency of the signal
- All effects of same order with Kaiser term the most important at all scales
  At largest scales, Kaiser, Doppler, gravitational potentials contribute up to a few tens of percent to the total amplitude

*Bertacca, Ricciardone, Bellomo, Jenkins, Raccanelli, Regimbau, Sakellariadou, arXiv:1909.11627*
*Bellomo, Bertacca, Jenkins, Raccanelli, Regimbau, Ricciardone, Sakellariadou (in progress)*

*Mairi Sakellariadou*

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## GWs: info about Modified Gravity (MG)

### Parametrised tests of GW propagation

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

$A_0 > 0$

*massive graviton* $m_g = A_0^{1/2}/c^2$

*doubly special relativity*

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

*multi-fractal ST*

*Horava-Lifshitz & extra dim*

*Frequency dependence of speed of GWs*

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

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

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)

*LVC (PRD) arXiv:1903.04667*

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## GWs: info about Modified Gravity (MG)

### Parametrised tests of GW propagation

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

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

**GW150914**
GW151012
**GW151226**

**GW170104**
**GW170608**
GW170729
**GW170809**
**GW170814**
GW170818
**GW170823**

$m_g \leq 5.0 \times 10^{-23}\ \mathrm{eV}/c^2$ at 90% credible limit

*LVC (PRD) arXiv:1903.04667*

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## GWs: info about Modified Gravity (MG)

GR: $$h''_A + 2\mathcal{H}\, h'_A + k^2 h_A = \Pi_A$$

$A = +, \times$

To explain the current acceleration of the Universe

Modified gravity:

$$h''_A + 2\left[1 - \delta(\eta)\right]\mathcal{H}\, h'_A + \left[c_T^2(\eta)\, k^2 + m_T^2(\eta)\right] h_A = \Pi_A$$

- Hordenski
  Brans-Dicke, f(R), covariant Galileon,...
- Degenerate higher order scalar-tensor
  (up to cubic order to second derivatives of scalar field and divided in 41 classes)

This function modifies the friction term and affects the luminosity distance extracted from observation of GWs from CBC

*Mairi Sakellariadou*

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## GWs: info about Modified Gravity (MG)

Phenomenological proposal

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

$\Xi_0 = 1$ corresponds to GR

*Belgacem et al (2018)*

- Construct simulated catalogues of LISA massive BH binaries with EM counterparts
- Use these mock catalogues to constrain modified gravity theories

$\Xi_0$ can be measured to an accuracy that reaches 1.1% and even in the worst scenario still is 4.4%

To explain the current acceleration of the Universe

- Hordenski
  Brans-Dicke, f(R), covariant Galileon,...
- Degenerate higher order scalar-tensor
  (up to cubic order to second derivatives of scalar field and divided in 41 classes)

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

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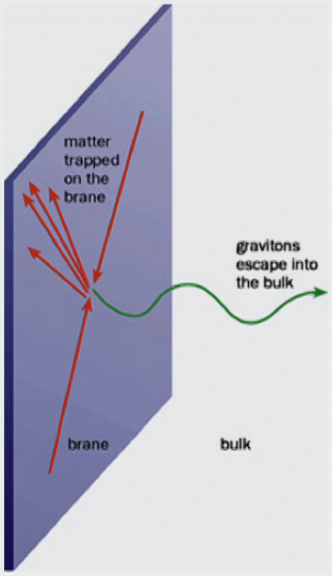
# GWs: info about QG (brane/string theory)

## Constraints on the number of spacetime dimensions




Damping of the waveform due to gravitational leakage into extra dim

GR: $h_{\rm GR} \propto d_L^{-1}$ $\qquad d_L^{\rm EM} \simeq \frac{z(1+z)}{H_0} \overset{z \ll 1}{\simeq} \frac{z}{H_0}$

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

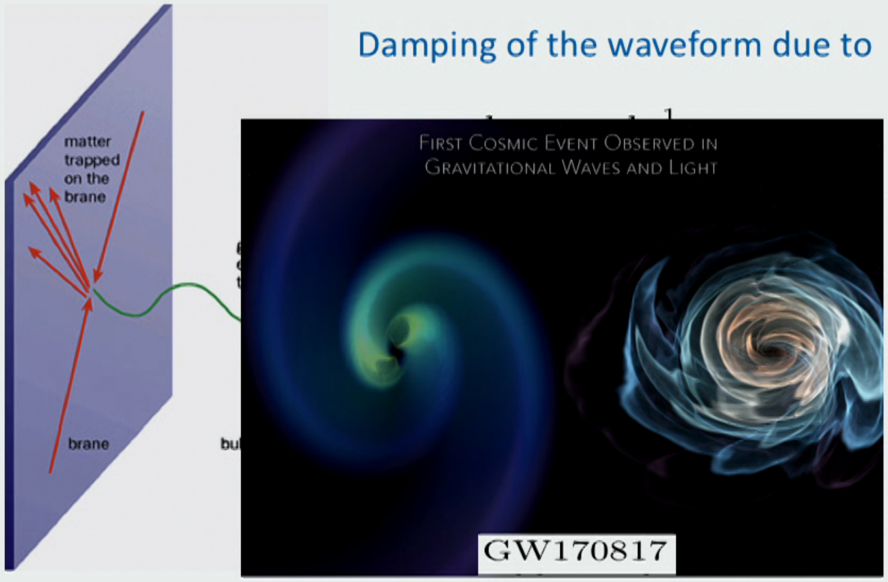
$$h \propto \frac{1}{d_L^{\rm GW}} = \frac{1}{d_L^{\rm EM}} \left[1 + \left(\frac{d_L^{\rm EM}}{R_c}\right)^n\right]^{-(D-4)/(2n)}$$

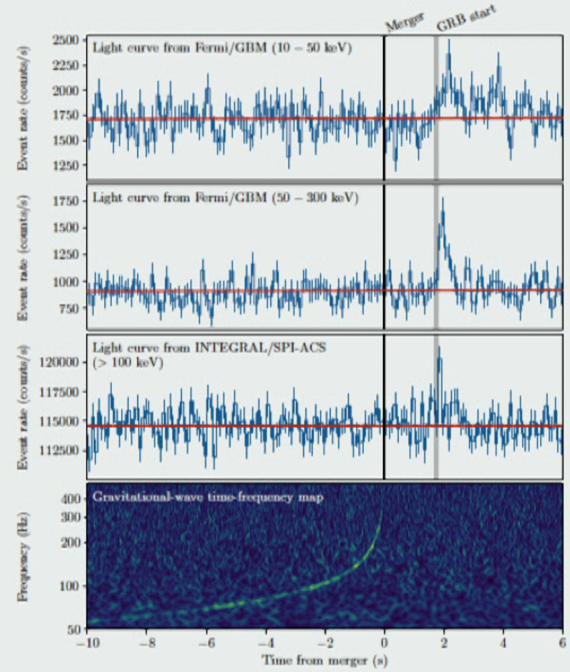
The **strain** measured in a GW interferometer ⟷ The **luminosity distance** measured for the optical counterpart of the standard siren

# GWs: info about QG (brane/string theory)

## Constraints on the number of spacetime dimensions

Damping of the waveform due to



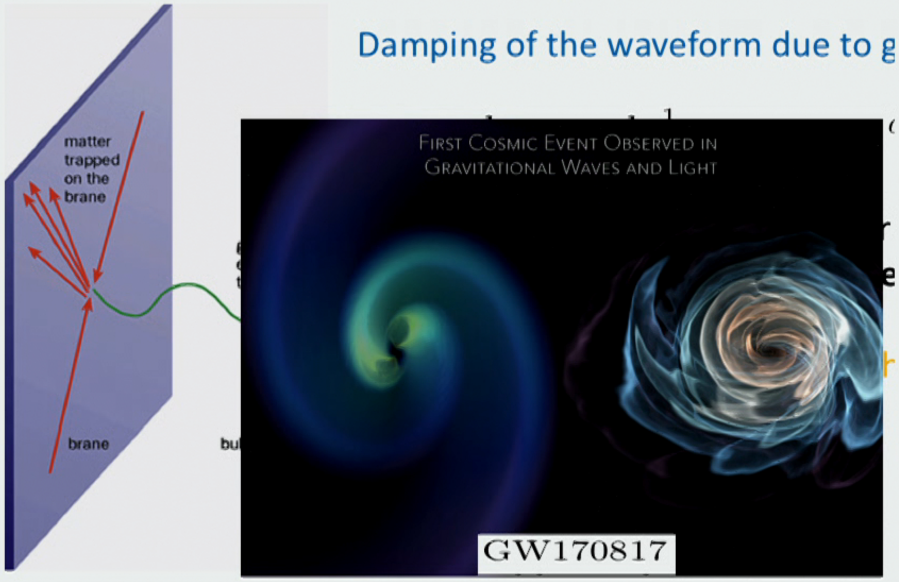

LVC (PRD) arXiv:1811.00364

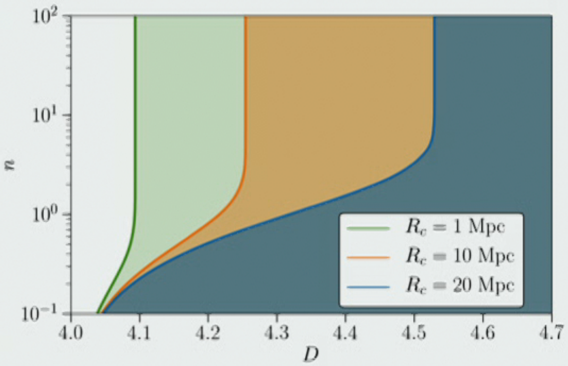
*Mairi Sakellariadou*

## GWs: info about QG (brane/string theory)

### Constraints on the number of spacetime dimensions

Damping of the waveform due to g




- Consistency with GR in D=4 dim
- Some models (e.g. the Dvali-Gabadadze-Porrati (DGP) model) are ruled out

LVC (PRD) arXiv:1811.00364

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## Tests of QG with GWs: gravitational wave luminosity distance

*Can QG theories leave a signature in GWs?*

- **NO**: QG corrections will be suppressed by the Planck scale

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

  but today are too small: $(\ell_{\rm Pl} H_0)^n \sim 10^{-60n}$

- **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

# GWs: info about Quantum Gravity (QG)

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 (how volume scales) and kinetic term (modified dispersion relations)*

$$h \propto \int d\varrho\, \mathcal{J}\, G$$

*characteristic scale of geometry*

*generic source term*

$$G(t,r) \sim f_G(t,r)\, r^{-\Gamma}, \text{ where } f_G \text{ is dimensionless.}$$

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

*scaling parameter*

⇒

$$h(t,r) \sim f_h(t,r)\, (\ell_*/r)^{\Gamma}$$

*In radial coordinates, and in the local wave zone*

*Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, Phys.Lett. B798 (2019) 135000*
*Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, JCAP 1910 (2019) no.10, 012*

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# GWs: info about Quantum Gravity (QG)

GWs propagating over cosmological distances:

The **strain** measured in a GW interferometer

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

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

$$\varepsilon = \pm(\gamma - 1)$$

If there is only one fundamental scale, $\ell_* = \mathcal{O}(\ell_{\mathrm{Pl}})$, the above equation is exact and $\gamma = \Gamma_{\mathrm{UV}}$

If $\ell_*$ is a mesoscopic scale, then the above equation is valid only near the IR regime and $\gamma = \Gamma_{\mathrm{meso}} \approx 1$

*Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, Phys.Lett. B798 (2019) 135000*
*Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, JCAP 1910 (2019) no.10, 012*

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

$$\varepsilon = \pm(\gamma - 1)$$

Observations can place constraints on the parameters $\ell_*$ and $\gamma$ in a model-independent way, by constraining the ratio $d_L^{\rm GW}(z)/d_L^{\rm EM}(z)$ as a function of the redshift of the source

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

*Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, Phys.Lett. B798 (2019) 135000*
*Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, JCAP 1910 (2019) no.10, 012*

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# GWs: info about Quantum Gravity (QG)

When $\gamma = \Gamma_{\rm UV}$ we cannot constrain the deep UV limit of QG, since $\ell_* = \mathcal{O}(\ell_{\rm Pl})$.
(*deviations from classical geometry occur at microscopic scales unobservable in astrophysics*)

The only theories that can be constrained in this way are those with $\Gamma_{\rm meso} > 1 > \Gamma_{\rm UV}$

$$0 < \Gamma_{\rm meso} - 1 < 0.02$$

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

Look for realistic quantum states of geometry giving rise to such a signal

*Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, Phys.Lett. B798 (2019) 135000*
*Calcagni, Kuroyanagi, Marsat, Sakellariadou, Tamanini, Tasinato, JCAP 1910 (2019) no.10, 012*

## Conclusions

GWs offer a novel and powerful way to test:

- astrophysical models
- beyond ΛCDM cosmological model
- physics beyond the Standard Model of particle physics
- *dark matter candidates (PBHS, axions, ...)*
- modified gravity models
- quantum gravity theories

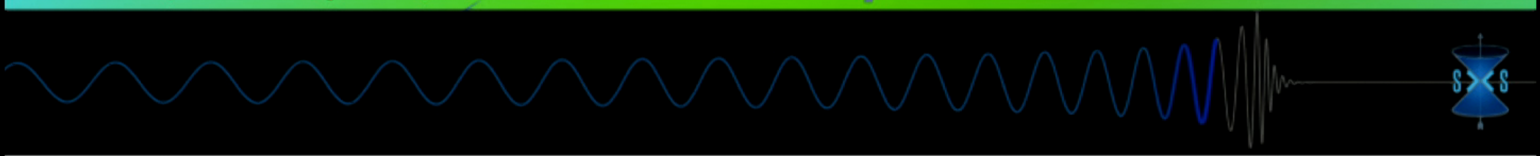

*Image credit: SXS/LIGO*

*Mairi Sakellariadou*

# Conclusions

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Thank you

*Image credit: SXS/LIGO*