Hunting for the stochastic gravitational-wave background: implications for astrophysical and high energy physics models

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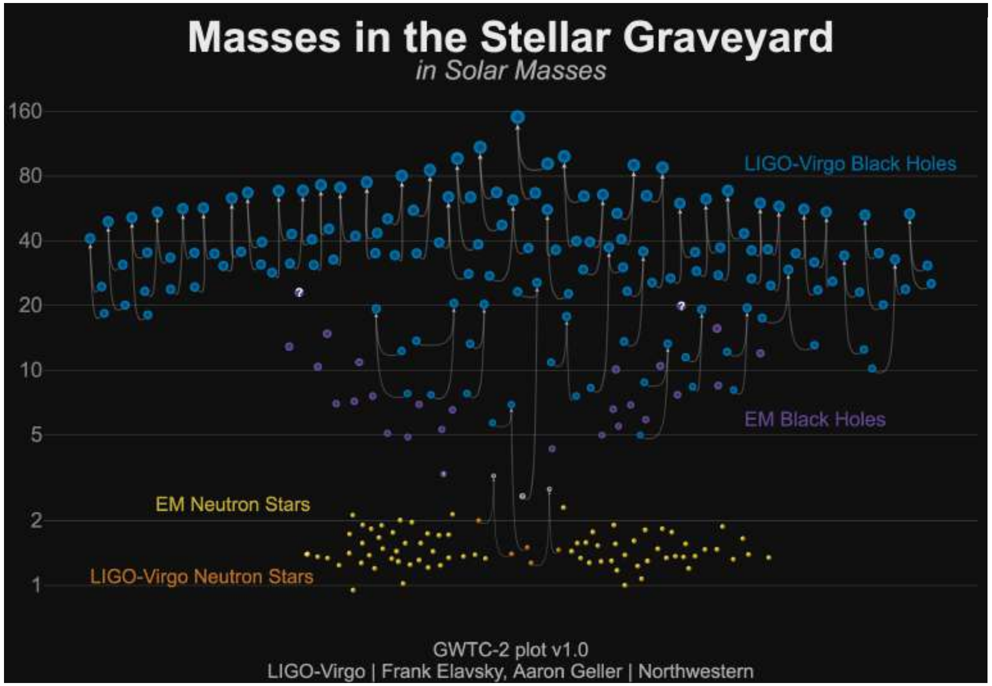
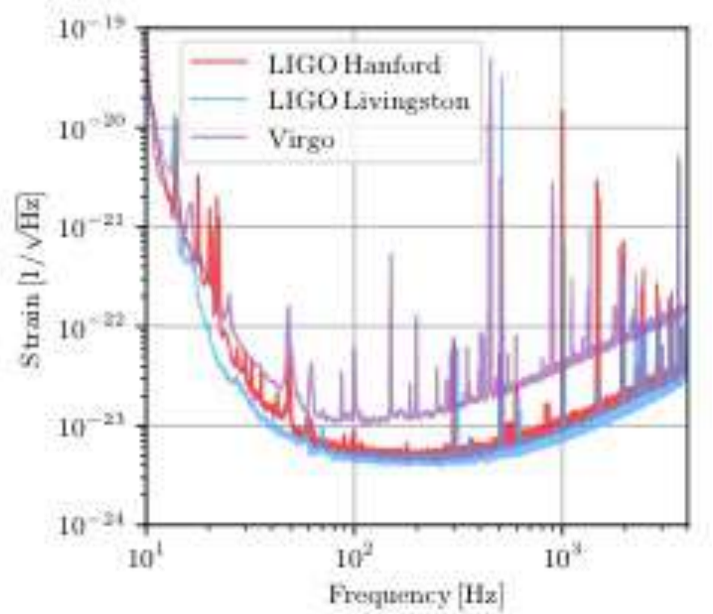
Outline

- Introduction to the SGWB
- Detection method
- Detecting SGWB in the presence of correlated magnetic noise
- SGWB from compact binary coalescences: info about astrophysical models
- SGWB from cosmic strings: info beyond standard model particle physics
- Simultaneous estimation of astrophysical and cosmological SGWB
- Introduction to anisotropies in the SGWB
- Anisotropies from cosmic strings
- Anisotropies from CBCs: info about large-scale-structure
- The issue of shot noise and a new statistics

GWs detected from aLIGO/aVIRGO





O3a: 1st April 2019 - 1st October 2019

39 candidate events in ~26 weeks of data (~1.5 per week)

BBH, BNS, NSBH

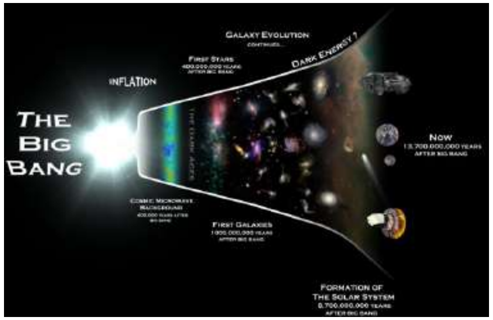
LVC, arXiv:2010.14527

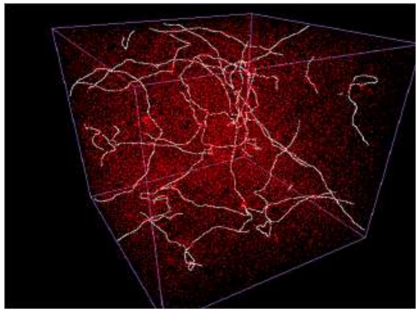
Stochastic GW Background (SGWB)

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

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

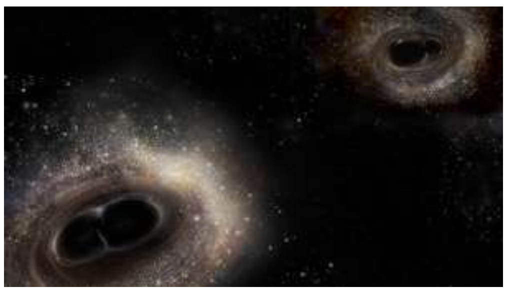
Binaries, Supernovae, Neutron stars

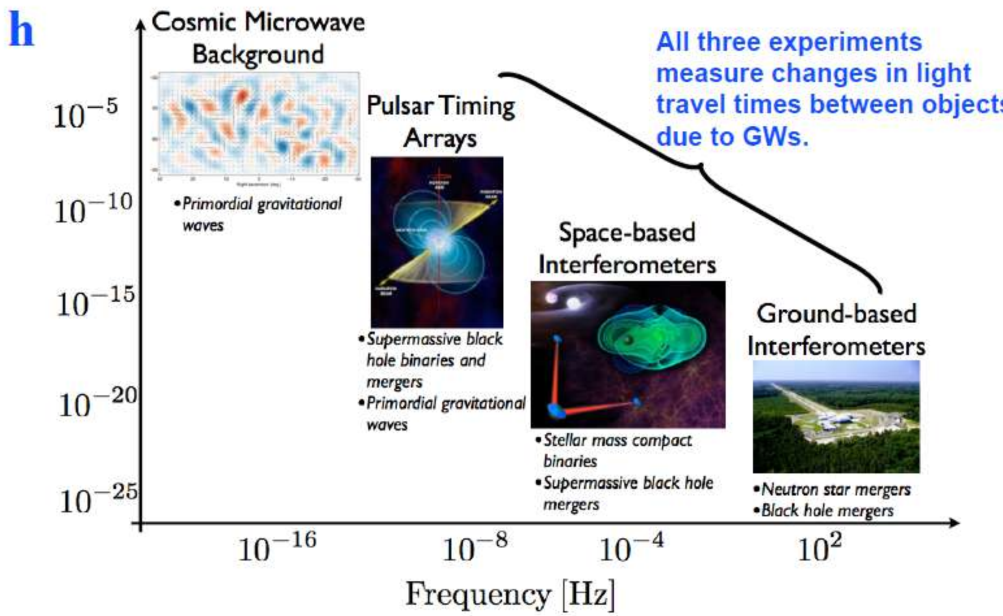


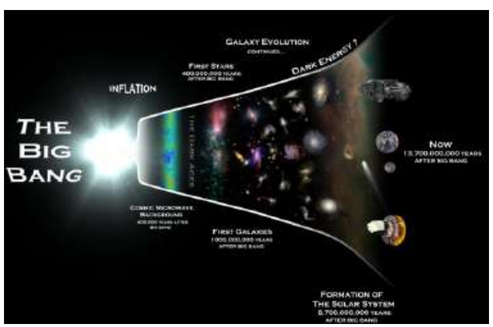


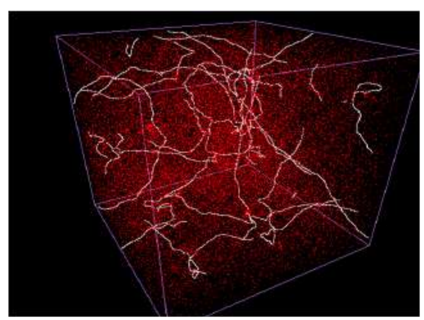
Inflation | Cosmic strings | Cosmological phase transitions

Stochastic GW Background (SGWB)









Inflation

Cosmic strings

Cosmological phase transitions

Stochastic GW Background (SGWB)

Assuming the SGWB to be isotropic, Gaussian, stationary and unpolarised:

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

$$\Omega_{\rm gw}(f) = \Omega_\alpha \left(\frac{f}{f_{\rm ref}}\right)^\alpha$$

$$f_{\rm ref} = 25 \text{ Hz}$$

Unresolved CBCs give a background spectrum with $\alpha = 2/3$

Inflation and cosmic strings give $\alpha = 0$

Also common to consider spectrum flat in GW power $\alpha = 3$ to mimic signals from PT and SN

How de we detect a SGWB ?

A detection of the SGWB from unresolved compact binary coalescences could be made by Advanced LIGO and Advanced Virgo at their design sensitivities

It would appear as noise in a single GW detector

$$\tilde{s}_i(f) = \tilde{h}_i(f) + \tilde{n}_i(f)$$

For a stochastic GW signal:
noise >> strain

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

$$\langle \tilde{s}_i^*(f)\tilde{s}_j(f')\rangle = \langle \tilde{h}_i^*(f)\tilde{h}_j(f')\rangle + \langle \tilde{h}_i^*(f)\tilde{n}_j(f')\rangle + \langle \tilde{n}_i^*(f)\tilde{h}_j(f')\rangle + \langle \tilde{n}_i^*(f)\tilde{n}_j(f')\rangle$$

How de we detect a SGWB ?

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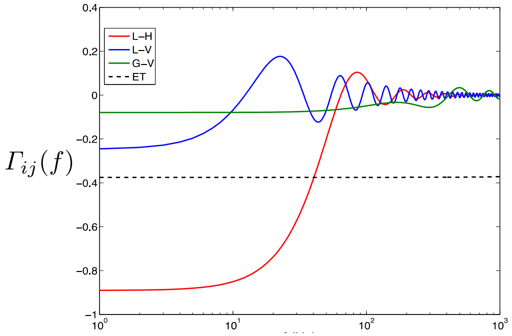

$$\hat{C}_{ij}(f;t) = \frac{2}{T}\frac{\mathrm{Re}[\tilde{s}_i^*(f;t)\tilde{s}_j(f;t)]}{\Gamma_{ij}(f)S_0(f)}$$

$$S_0(f) = 3H_0^2/(10\pi^2 f^3)$$

$$\langle \tilde{h}_i^*(f)\tilde{h}_j(f')\rangle = \frac{1}{2}\delta_T(f-f')\Gamma_{ij}(f)S_{\mathrm{gw}}(f)$$

Single power spectral density (PSD)

$$S_{\mathrm{gw}}(f) = \frac{3H_0^2}{10\pi^2}\frac{\Omega_{\mathrm{gw}}(f)}{f^3}$$

$$\Omega_{\mathrm{gw}}(f) = \Omega_\alpha\left(\frac{f}{f_{\mathrm{ref}}}\right)^\alpha$$

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

Assuming the GW signal and the intrinsic noise are uncorrelated $\langle \tilde{h}_i^*(f)\tilde{n}_j(f')\rangle = 0$ and that the noise in each frequency bin is independent

$$\langle \hat{C}_{ij}(f;t)\rangle = \Omega_{\mathrm{gw}}(f) + 2\,\mathrm{Re}\left[\frac{\langle \tilde{n}_i^*(f;t)\tilde{n}_j(f;t)\rangle}{T\Gamma_{ij}(f)S_0(f)}\right]$$

In the absence of correlated noise: $\langle \tilde{n}_i^*(f)\tilde{n}_j(f)\rangle = 0,$

⇒ $\langle \hat{C}_{ij}(f)\rangle$ is an estimator for $\Omega_{\mathrm{gw}}(f)$

How de we detect a SGWB ?

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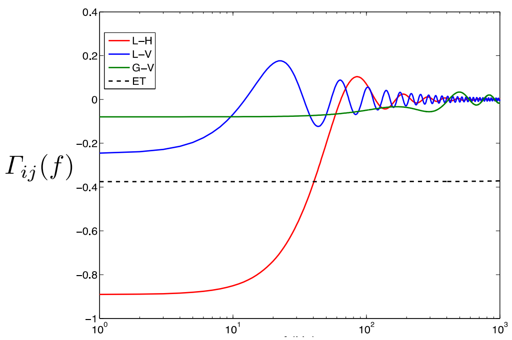

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In the absence of correlated noise: $\langle \tilde{n}_i^*(f)\tilde{n}_j(f)\rangle = 0,$

what if:

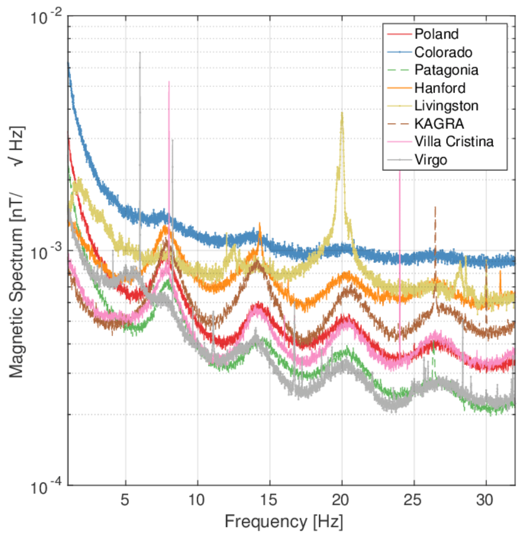
$$\langle \tilde{n}_i^*(f)\tilde{n}_j(f)\rangle \neq 0$$

⇒ $\langle \hat{C}_{ij}(f)\rangle$ is an estimator for $\Omega_{\rm gw}(f)$

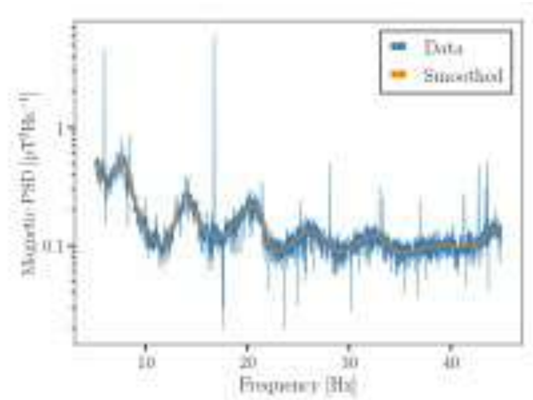
How are we sure that there is a real SGWB detection?

Schumann Resonances

- Resonances in the global electromagnetic field of Earth
- **Correlated** magnetic noise contamination



Median power spectral density of magnetometers. [1802.00885]



Power spectral density of magnetometer data near aVIRGO

$$\langle \hat{C}_{ij}(f) \rangle = \Omega_{\rm gw}(f) + \Omega_{{\rm M},ij}(f),$$

magnetic contribution

Meyers, Martinovic, Christensen, Sakellariadou, PRD (2020)

How are we sure that there is a real SGWB detection?

- Use magnetometers on-site to measure the cross spectral density $\langle \tilde{m}_i^*(f)\tilde{m}_j(f')\rangle$

$$\langle \tilde{m}_i^*(f)\tilde{m}_j(f')\rangle = \frac{1}{2}\delta_T(f-f')\gamma_{ij}^M(f)M(f)$$

magnetic analogue to the GW ORF — *correlated power spectral density*

measured from local magnetometers on site

- Magnetic fields can induce correlated noise in GW detectors: $\tilde{n}(f) = T(f)\tilde{m}(f)$

transfer function (power law)

- Parameter estimation using correlated noise model and power-law model for the SGWB

$$\Omega_{M,ij}(f) = \kappa_i\kappa_j\left(\frac{f}{10\ \mathrm{Hz}}\right)^{-\beta_i-\beta_j}\hat{M}_{ij}(f)\times 10^{-22}$$

$$\hat{M}_{ij}(f) = \frac{\sum_k \hat{M}_{ij,k}(f)\sigma_{ij,k}^{-2}(f)}{\sum_k \sigma_{ij,k}^{-2}(f)}. \qquad \hat{M}_{ij,k}(f) = \frac{2}{T}\frac{\mathrm{Re}\left[\tilde{m}_i^*(f;t_k)\tilde{m}_j(f;t_k)\right]}{\Gamma_{ij}(f)S_0(f)}$$

$$\Omega_{gw}(f) = \Omega_\alpha\left(\frac{f}{f_{\mathrm{ref}}}\right)^{\alpha}$$

The coupling functions (values of κ, β) differ in both shape and amplitude at each site

Simulate correlated data in $\tilde{m}_H(f), \tilde{m}_L(f), \tilde{m}_V(f)$ using same scheme as we do for SGWB and project onto detector using transfer functions

Meyers, Martinovic, Christensen, Sakellariadou, PRD (2020)

How are we sure that there is a real SGWB detection?

Assume a Gaussian likelihood for $\hat{C}_{ij}(f)$:

$$\ln p(\hat{C}_{ij}(f)|\boldsymbol{\theta}_{\rm gw}, \boldsymbol{\theta}_{\rm M}) = -\frac{1}{2}\sum_f \left\{ \frac{\left[\hat{C}_{ij}(f) - \Omega_{\rm gw}(f, \boldsymbol{\theta}_{\rm gw}) - \Omega_{{\rm M},ij}(f, \boldsymbol{\theta}_{\rm M})\right]^2}{\sigma_{ij}^2(f)} + \ln\left(2\pi\sigma_{ij}^2(f)\right) \right\}$$

$$\boldsymbol{\theta}_{\rm gw} = \Omega_{2/3} \text{ and } \alpha = 2/3 \text{ fixed} \qquad \boldsymbol{\theta}_{\rm M} = (\kappa_i, \kappa_j, \beta_i, \beta_j)$$

Multi-baseline likelihood:

$$p(\{\hat{C}_{ij}(f)\}_{ij\in{\rm pairs}}|\boldsymbol{\theta}_{\rm gw}, \boldsymbol{\theta}_{\rm M}) = \prod_{ij\in{\rm pairs}} p(\hat{C}_{ij}(f)|\boldsymbol{\theta}_{\rm gw}, \boldsymbol{\theta}_{\rm M}).$$

Estimate posterior distribution of the parameters

Meyers, Martinovic, Christensen, Sakellariadou, PRD (2020)

How are we sure that there is a real SGWB detection?

Compare different models for the data using Bayesian model selection

1. **NOISE:** $\Omega_{\rm M}(f) = \Omega_{\rm gw}(f) = 0,$
2. **GW:** $\Omega_{\rm M}(f) = 0,\ \Omega_{\rm gw}(f) \neq 0,$
3. **SCHU:** $\Omega_{\rm M}(f) \neq 0,\ \Omega_{\rm gw}(f) = 0,$
4. **GW+SCHU:** $\Omega_{\rm M}(f) \neq 0,\ \Omega_{\rm gw}(f) \neq 0$

Compare models using Bayes factors

Example:

$$\mathcal{B}^{\rm GW}_{\rm NOISE} = \frac{\int {\rm d}\boldsymbol{\theta}_{\rm gw} p(\hat{C}_{ij}(f)|\boldsymbol{\theta}_{\rm gw}) \underbrace{p(\boldsymbol{\theta}_{\rm gw})}_{\text{prior}}}{\mathcal{N}}$$

Parameter	Prior
$\Omega_{2/3}$	$\mathrm{LogUniform}(10^{-12},\ 10^{-7})$
κ_H	$\mathrm{Uniform}(0,\ 10)$
κ_L	$\mathrm{Uniform}(0,\ 10)$
κ_V	$\mathrm{Uniform}(0,\ 10)$
β_H	$\mathrm{Uniform}(0,\ 10)$
β_L	$\mathrm{Uniform}(0,\ 10)$
β_V	$\mathrm{Uniform}(0,\ 10)$

$\mathcal{B}^{\rm GW}_{\rm NOISE} > 1$: there is support for the GW model compared to the noise model

Using realistic simulations, we have shown that this method prevents a false SGWB detection due to correlated magnetic noise.

It can also be used for a detection of SGWB in the presence of strong correlated magnetic noise

Meyers, Martinovic, Christensen, Sakellariadou (2020)

SGWB from compact binary coalescence (CBC)

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

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

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

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

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

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:

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

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

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

Beta distribution for the BH spins:

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

α_m

$m_{\max}$

α_χ, β_χ

infrerred from observed BBHs

Wysocki, Lange, O'Shaughnessy (2018)

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

→ **a new probe of population of compact objects**

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

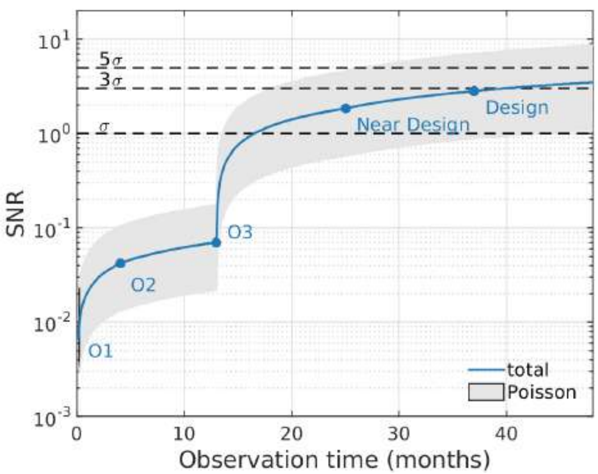
SGWB from compact binary coalescence (CBC)

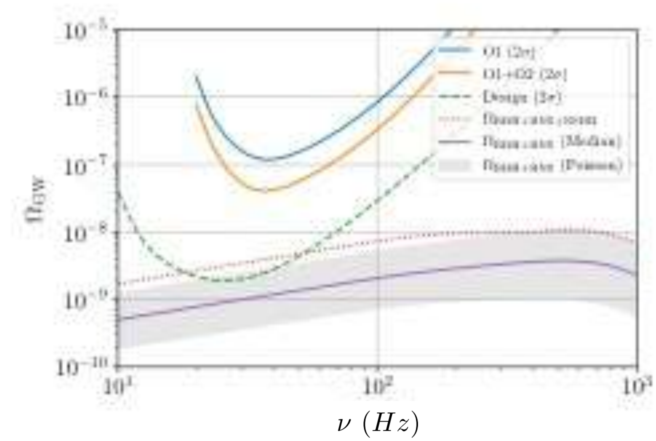
$$\frac{dE_{\rm GW}}{d\nu} = \frac{(G\pi)^{2/3}}{3}\frac{m_1 m_2}{(m_1+m_2)^{1/3}}\nu^{-1/3}$$

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

α=2/3

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





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

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

LVC (PRD) arXiv:1903.02886

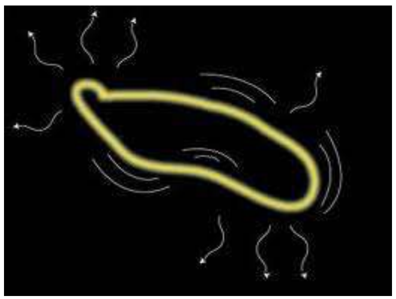
SGWB from cosmic strings

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)

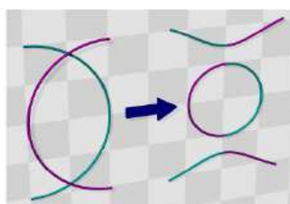
Generically formed in the context of GUTs

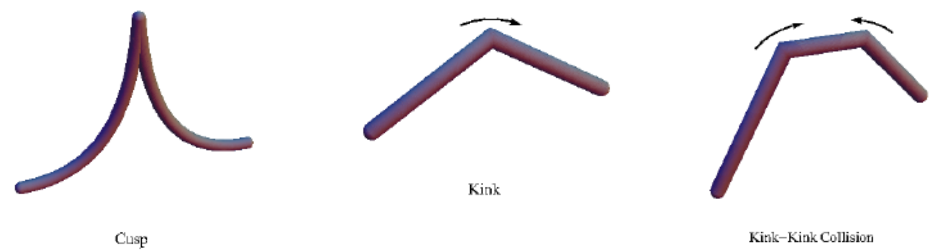
Jeannerot, Rocher, Sakellariadou, PRD68 (2003) 103514



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

$$\tau \sim \frac{\ell}{G\mu}$$





GW in a highly concentrated beam

GW is isotropic

Oscillating loops of cosmic strings generate a SGWB that is strongly non-Gaussian, and includes occasional sharp bursts due to cusps and kinks

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

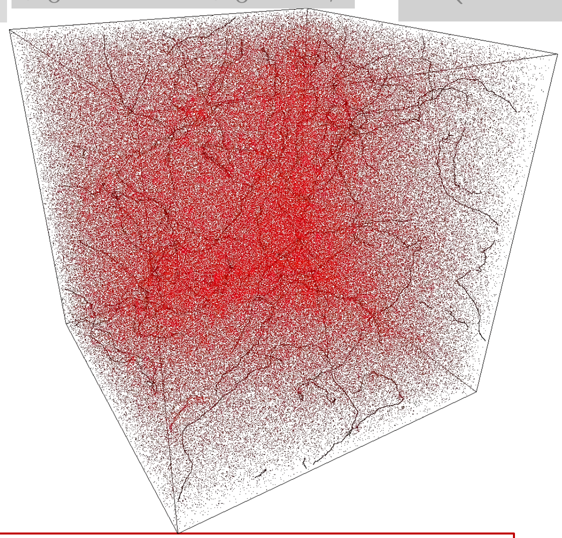
Kibble (1976)

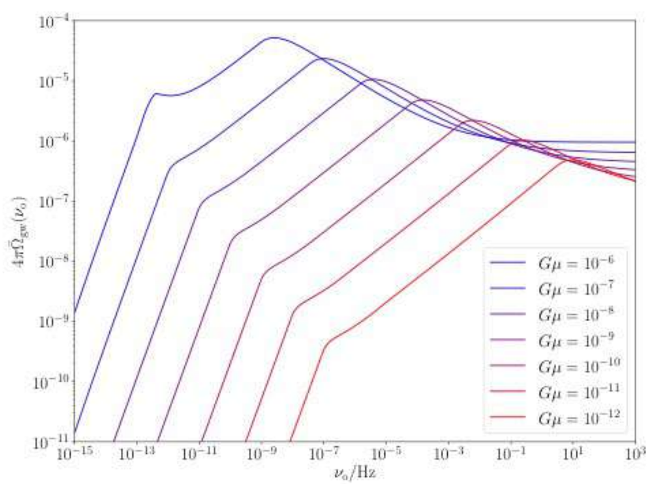
Generically formed in the context of GUTs

Jeannerot, Rocher, Sakellariadou, PRD68 (2003) 103514

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

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





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

Jenkins, Sakellariadou, PRD 98, 063509 (2018)

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

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

α=0

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

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

LVC (PRD) arXiv:1903.02886

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

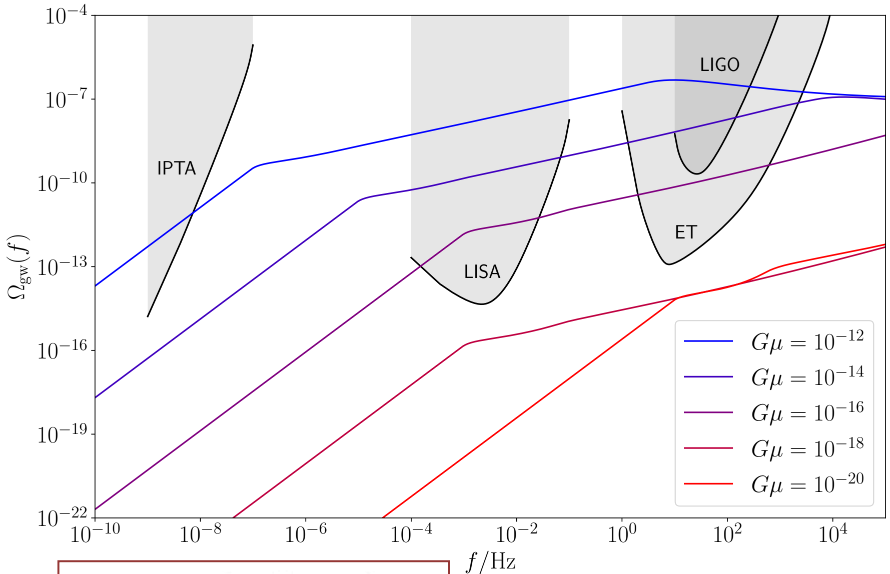
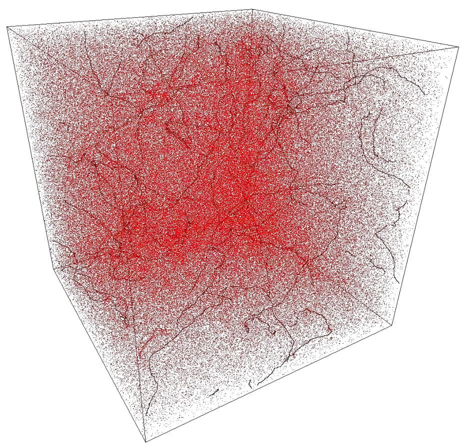


Image credit: Alex Jenkins



Lorenz, Ringeval, Sakellariadou, JCAP1010 (2010)
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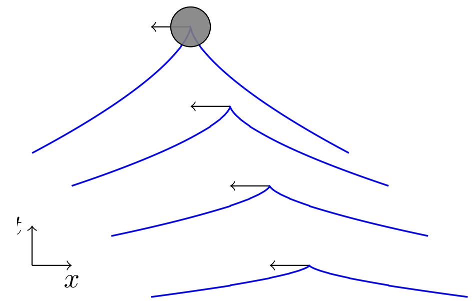
SGWB from cosmic strings: info Beyond the Standard Model (BSM)

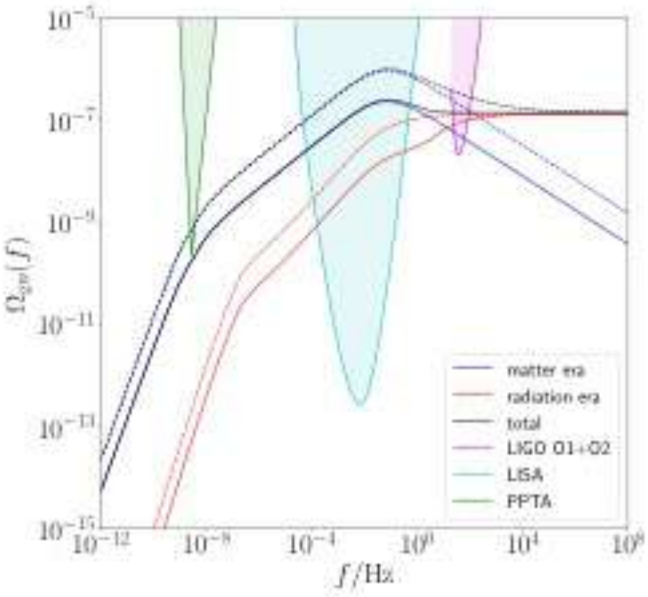
- Cusps on CS collapse to form PBHs
- Many more PBHs than previously thought

collapse of circular loops due to string tension – very few loops circular enough, so very few PBHs

- Subsolar-mass PBHs with large (but non-extremal) spin



The cusp-collapse spectrum is smaller than that of a non-collapsing cusp by a factor ¼ at low f, has a strong peak at very high f due to QNM ringing of the PBH, and then decays like 1/f



$G\mu = 3 \times 10^{-11}$

New constraints from PBH evaporation independent of model $G\mu \lesssim 10^{-11}$

SGWB constraints on string tension relaxes slightly (dependent on the model)

Jenkins, Sakellariadou, (2020)

Can we distinguish between astrophysical vs cosmological sources?

GW models:

- CBC background

$$\Omega_{\rm CBC}(f) = \Omega_{2/3}\left(\frac{f}{25\,{\rm Hz}}\right)^{2/3}$$

- CS background (flat)

$$\Omega_{\rm CS}(f) = {\rm const.}$$

- PT background (smooth broken power law (BPL))

$$\Omega_{\rm BPL} = \Omega_*\left(\frac{f}{f_*}\right)^{\alpha_1}\left[1+\left(\frac{f}{f_*}\right)^{\Delta}\right]^{(\alpha_2-\alpha_1)/\Delta}$$

we fix $\alpha_1 = 3, \alpha_2 = -4, \Delta = 2$ to approximates sound waves contribution

Meyers, Martinovic, Sakellariadou, Christensen, (2020)

Multi-baseline likelihood

The log-likelihood for a single detector pair is given by:

$$\log p(\hat{C}_{ij}(f)|\boldsymbol{\theta}_{\rm GW}) = -\frac{1}{2}\sum_f \frac{\left[\hat{C}_{ij}(f) - \Omega_{\rm GW}(f, \boldsymbol{\theta}_{\rm GW})\right]^2}{\sigma_{ij}^2(f)} - \frac{1}{2}\sum_f \log\left[2\pi\sigma_{ij}^2(f)\right]$$

The set of GW parameters in the posterior depends on the type of search we perform. We focus on

- CBC Power Law: $\boldsymbol{\theta} = (\Omega_{2/3})$,
- CBC + CS: $\boldsymbol{\theta} = (\Omega_{2/3}, \Omega_{\rm CS})$.
- CBC + BPL: $\boldsymbol{\theta} = (\Omega_{2/3}, \Omega_*, f_*)$.

The multi-baseline likelihood is a simple generalization

$$\log p(\{\hat{C}_{IJ}(f)\}_{IJ\in{\rm pairs}}|\boldsymbol{\theta}) = \sum_{IJ\in{\rm pairs}} \log p(\hat{C}_{IJ}(f)|\boldsymbol{\theta}),$$

where "pairs" simply refers to the set of available detector pairs (e.g. HL, HV, LV).

Meyers, Martinovic, Sakellariadou, Christensen, (2020)

Can we distinguish between astrophysical vs cosmological sources?

Model selection   To compare two models we use Bayes factors

$$\mathcal{B}^{\mathcal{M}_1}_{\mathcal{M}_2} = \frac{\int \mathrm{d}\boldsymbol{\theta}\ p(\hat{C}_{ij}(f)|\boldsymbol{\theta}, \mathcal{M}_1) p(\boldsymbol{\theta}|\mathcal{M}_1)}{\int \mathrm{d}\boldsymbol{\theta}\ p(\hat{C}_{ij}(f)|\boldsymbol{\theta}, \mathcal{M}_2) p(\boldsymbol{\theta}|\mathcal{M}_2)}$$

$p(\boldsymbol{\theta}|\cdot)$ *: prior probability of parameters given a choice of model*

Detector networks

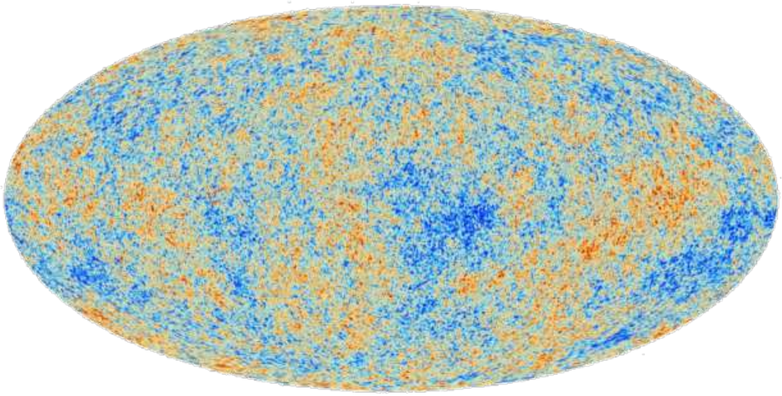
- Hanford, Livinston, Virgo, O4 sensitivity, 1 year of run time
- Cosmic Explorers (CE) at Hanford and Livingston locations, Einstein Telescope (ET) at Virgo, 1 year of run time

- Current GW detectors are unable to separate astrophysical from cosmological sources
- Future GW detectors (CE, ET) can dig out cosmological signals, provided one can subtract the *loud* astrophysical foreground

Meyers, Martinovic, Sakellariadou, Christensen, (2020)

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)

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

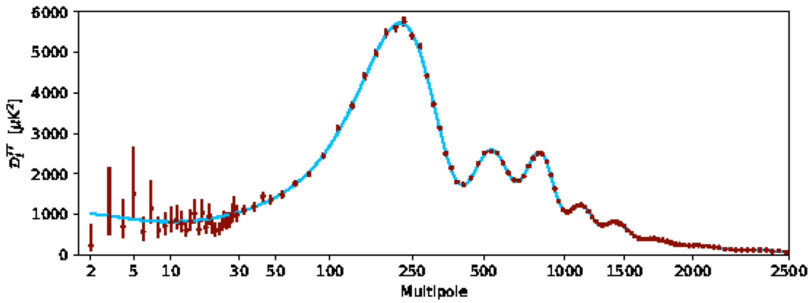
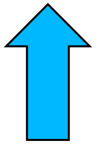


Image credit: Planck collaboration

LSS

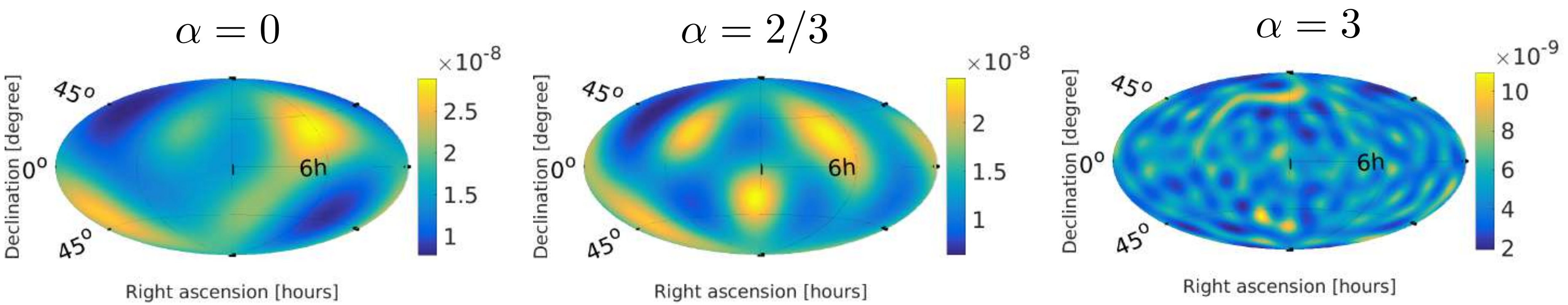


SGWB

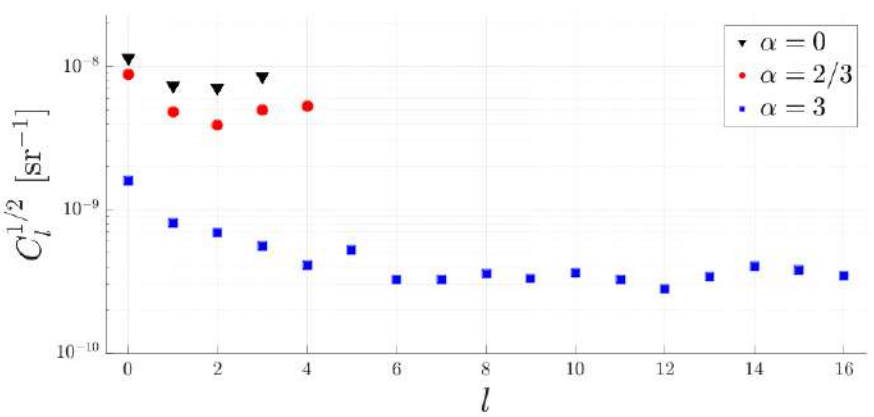
$$C_\ell = \int d^2\hat{\boldsymbol{n}} P_\ell(\cos\theta) \langle \delta\Omega_{GW} \delta\Omega_{GW} \rangle_\theta$$

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



Upper limits at 95% confidence on the energy density of the SGWB Ω_α [sr^{-1}]



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

LVC (PRD) (2019)

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

$$\Omega_{\rm gw} = \frac{\pi \nu_o^3}{3H_o^2}\int_0^{\eta_*} \mathrm{d}\eta\, a^2 \int \mathrm{d}\zeta\, \bar{n} R(1+\delta_n + \hat{\mathbf{e}}_o \cdot \mathbf{v}_o) \int_{S^2} \mathrm{d}^2\sigma_s\, r_s^2 \tilde{h}^2$$

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

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

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

2PCF : $$C_{\rm gw}(\theta_o, \nu_o) \equiv \left\langle \delta_{\rm gw}^{(s)}(\nu_o, \hat{e}_o)\delta_{\rm gw}^{(s)}(\nu_o, \hat{e}'_o)\right\rangle$$

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

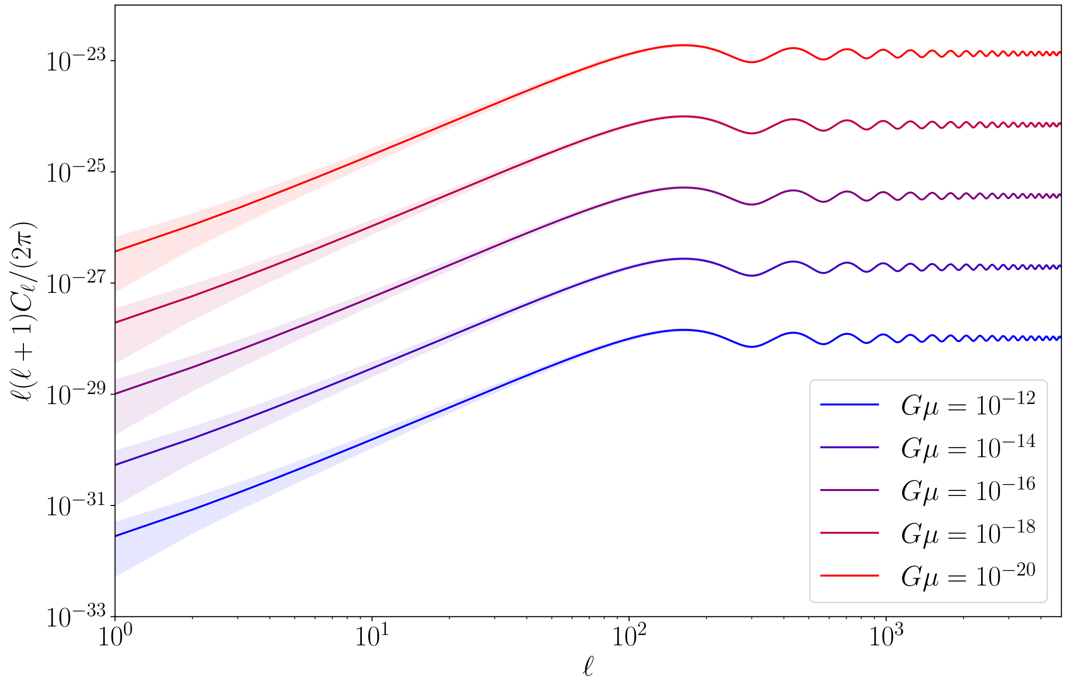
$$C_{\rm gw}(\theta_o, \nu_o) = \sum_{l=0}^{\infty} \frac{2l+1}{4\pi} C_l(\nu_o) P_l(\cos\theta_o)$$

$$\theta_o \equiv \cos^{-1}(\hat{e}_o \cdot \hat{e}'_o)$$

Jenkins, Sakellariadou, PRD 98, 063509 (2018)

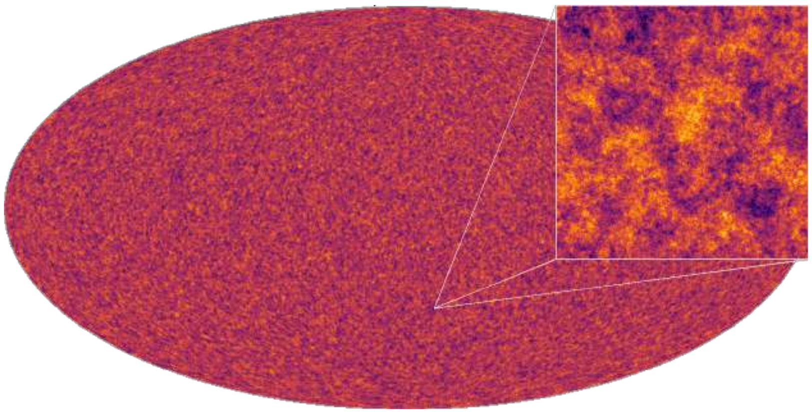
SGWB from cosmic strings: info about physics Beyond the Standard Model (BSM)

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



Stronger fo smaller string tension

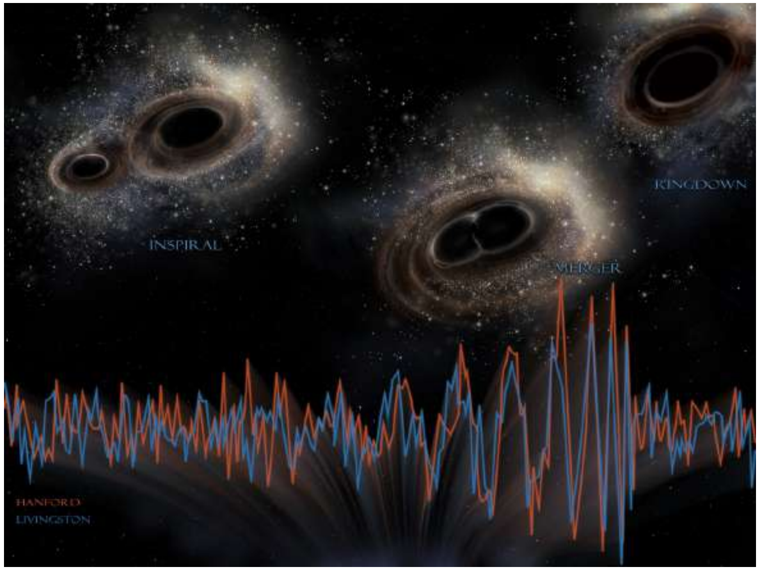
$T_{\rm SSB} \sim 10^{13}$–10^9 GeV



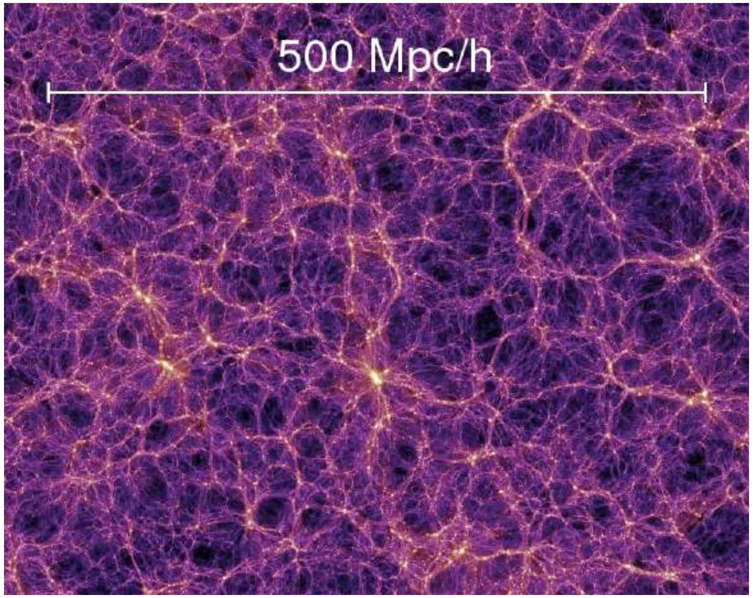
Jenkins, Sakellariadou, PRD 98, 063509 (2018)

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

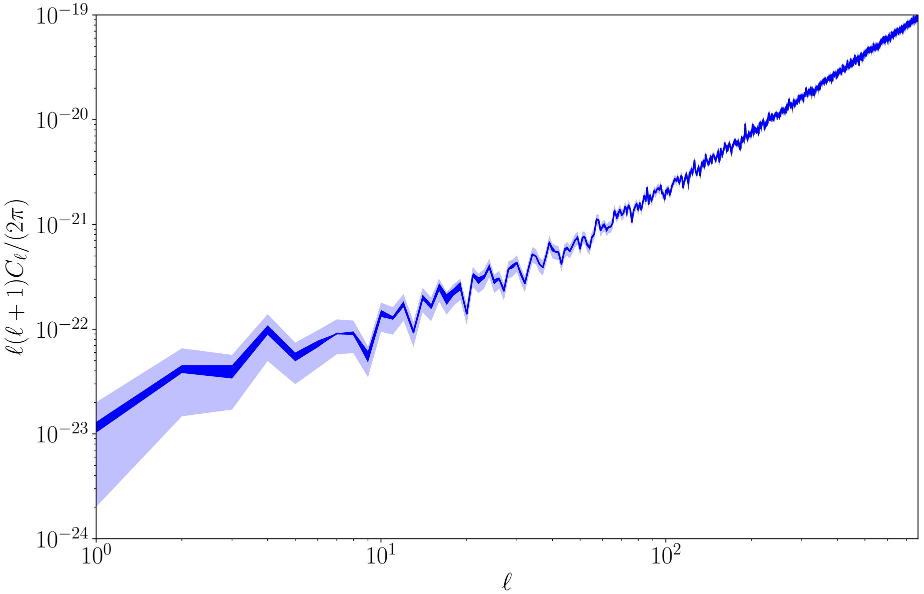
BBH / BNS / BHNS are within galaxies → LSS

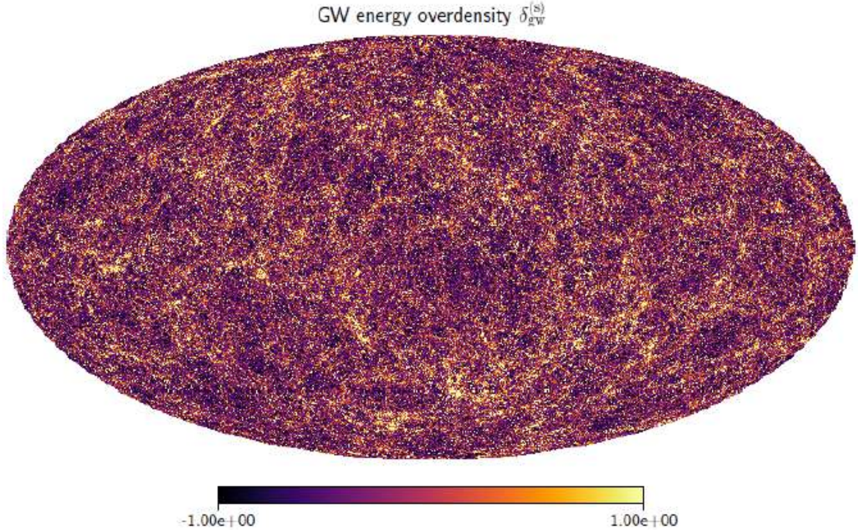
SGWB from CBC: info about Large Scale Structure (LSS)

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

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





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

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

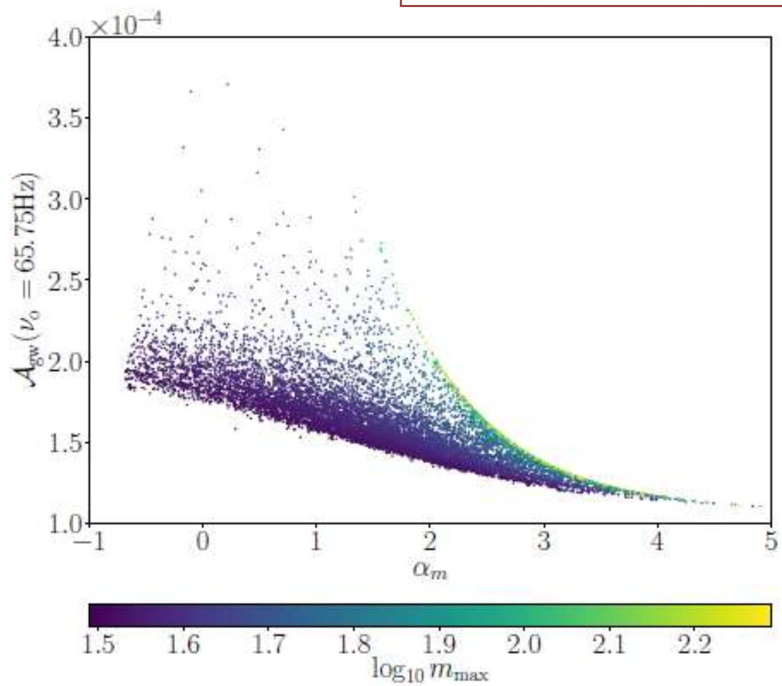
SGWB from CBC: info about Large Scale Structure (LSS)

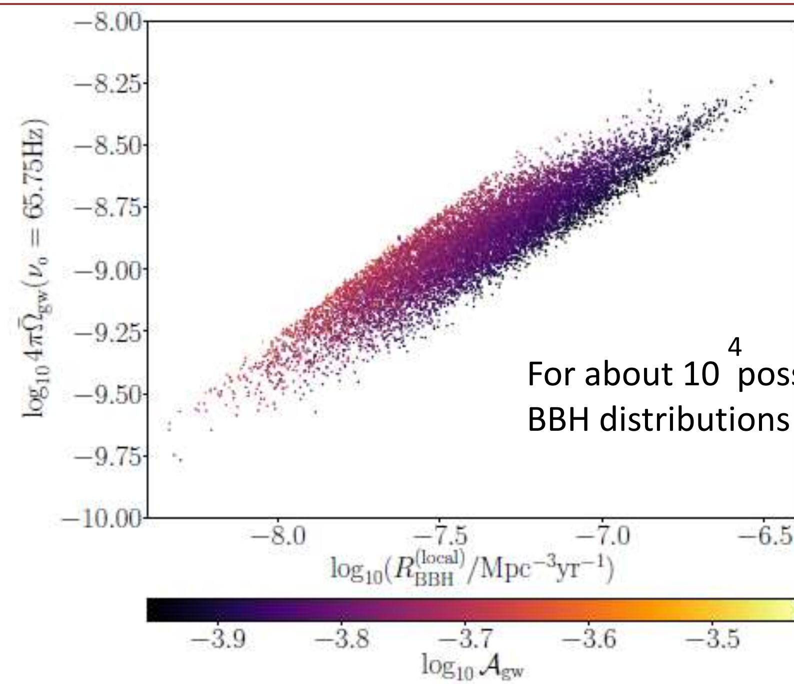
$$p(m_1, m_2) \propto \begin{cases} \frac{m_1^{-\alpha_m}}{m_1 - m_{\min}}, & m_{\min} \le m_2 \le m_1 \le m_{\max} \\ & m_1 + m_2 \le M_{\max} \\ 0, & \text{otherwise} \end{cases}$$

$$m_{\min} = 5 M_\odot \qquad M_{\max} = 200 M_\odot$$

$$C_\ell(\nu_o) = 4\pi \mathcal{A}_{gw}(\nu_o) \frac{{}_3F_2(-\ell, \ell+1, 1-\frac{\gamma}{2}; 1, 2; 1)}{\mathrm{sinc}(\pi\gamma/2)} \qquad \nu_o = 65.75 \text{ Hz}$$

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



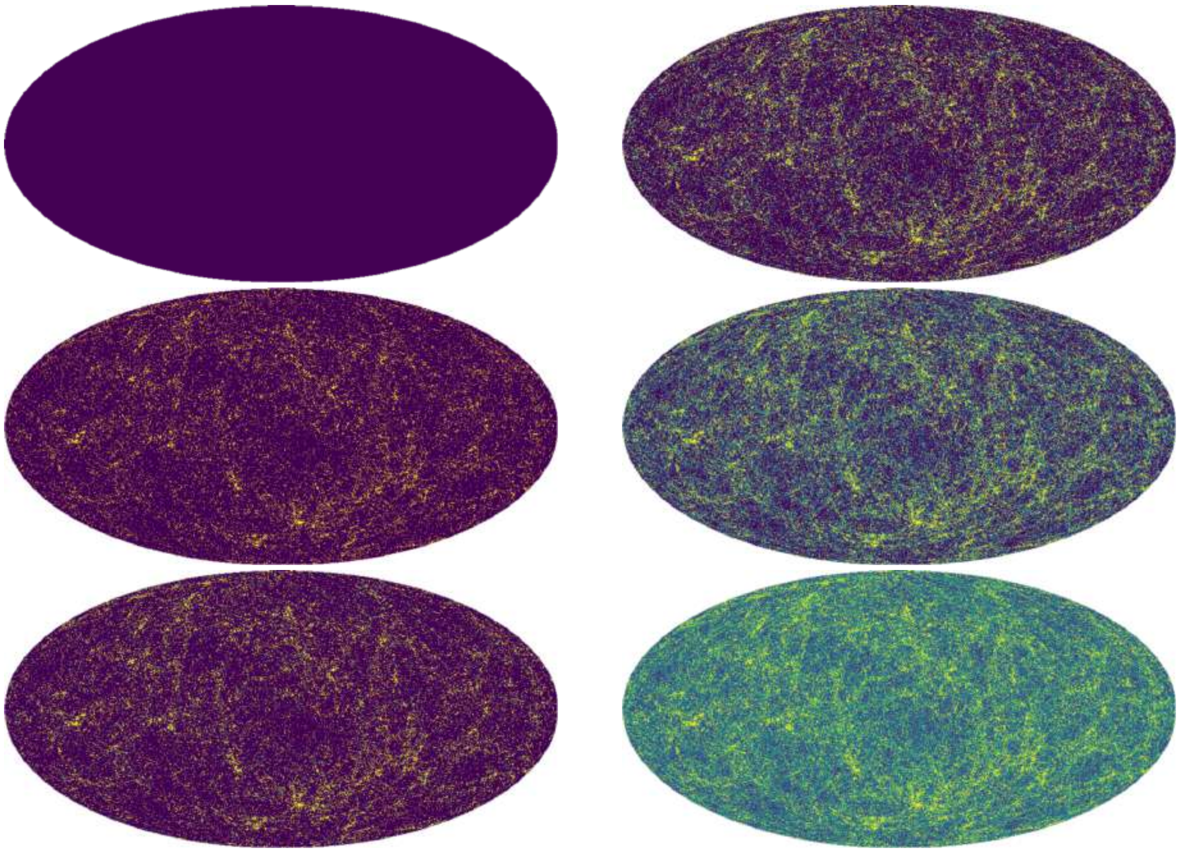


For about 10^4 possible BBH distributions

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)

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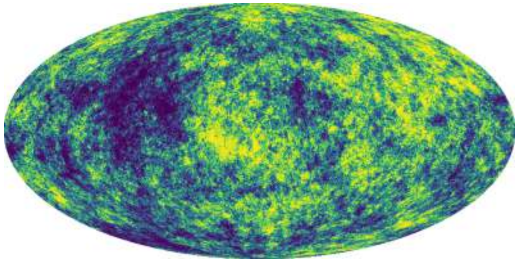
→ *temporal* **shot noise** (scale-invariant bias term)

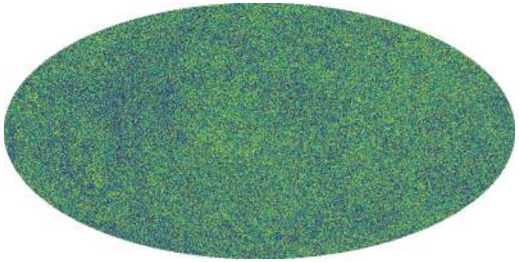
$$C_\ell \to C_\ell + \mathcal{W} \qquad \mathcal{W} \gg C_\ell \qquad \mathcal{W} \propto \frac{1}{T_{\rm obs}}$$

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)

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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

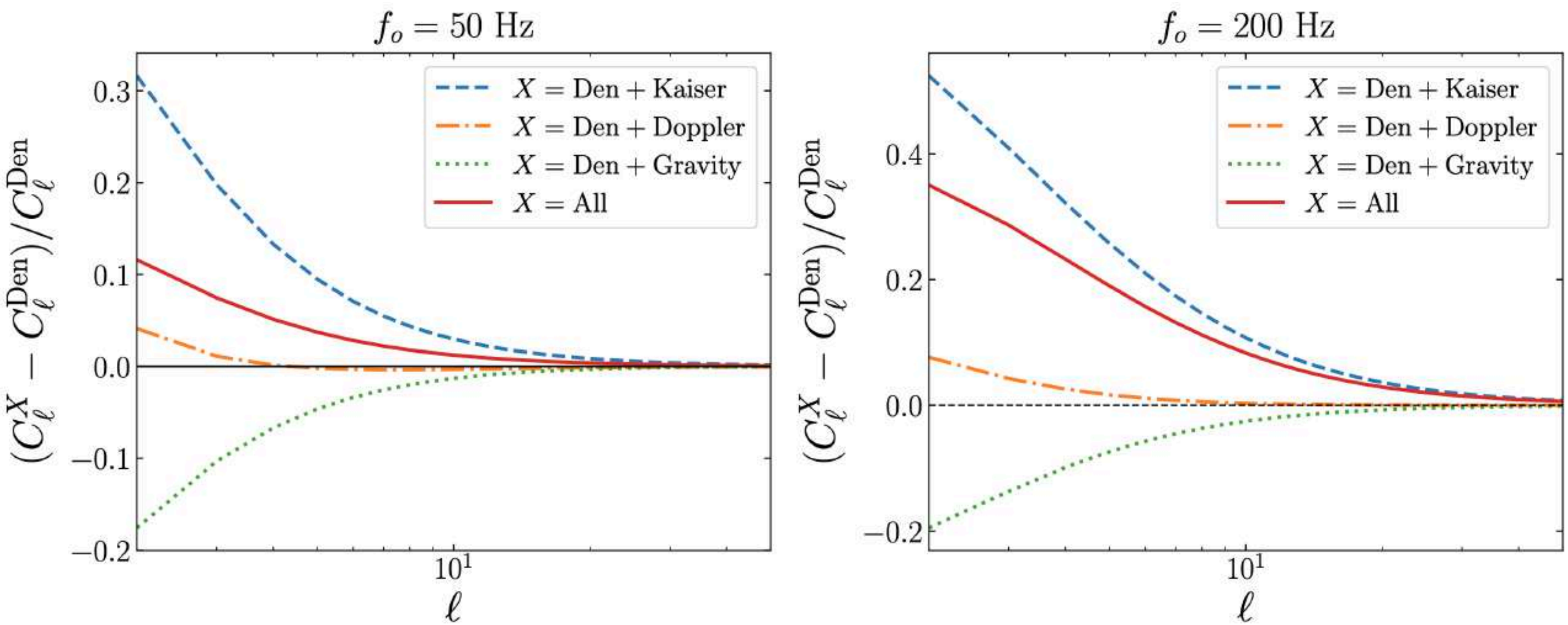
Cross-correlate different time segments to build a (new) minimum-variance unbiased estimator

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

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, JCAP (2020)

Conclusions

A detection of the SGWB from unresolved compact binary coalescences could be made by Advanced LIGO and Advanced Virgo at their design sensitivities

- Detecting a SGWB in the presence of correlated magnetic noise

- Simultaneous estimation of astrophysical and cosmological GW backgrounds with terrestrial interferometers

- SGWB will give us information about astrophysical models (compact binaries), beyond the standard model particle physics (cosmic strings, phase transitions), large-scale-structure of our Universe

- Isotropic and directional searches are an ongoing effort of the LIGO/Virgo/KAGRA Collaboration

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Thank you