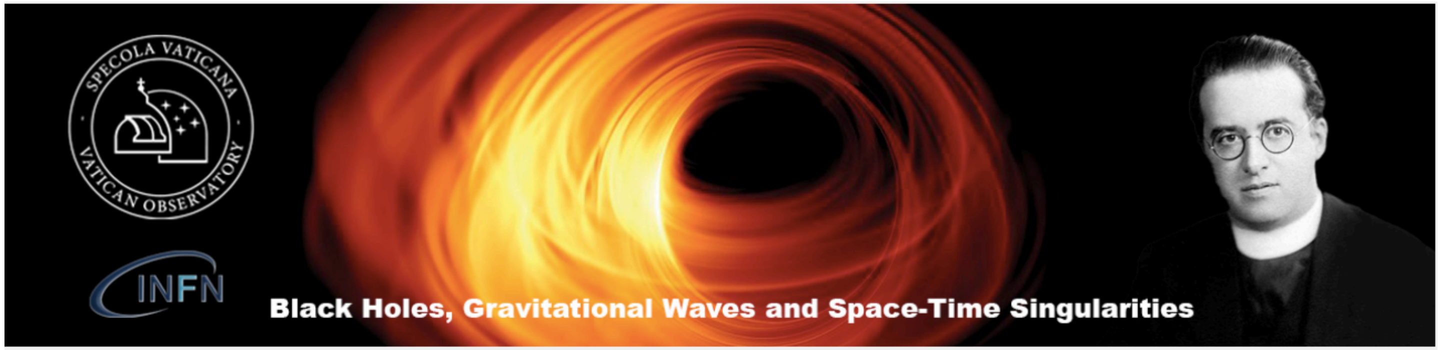
Gravitational Waves: the theorist’s Swiss knife

Mairi Sakellariadou

KING'S College LONDON



Lemaître Conference 2024

Black Holes, Gravitational Waves and Space-Time Singularities

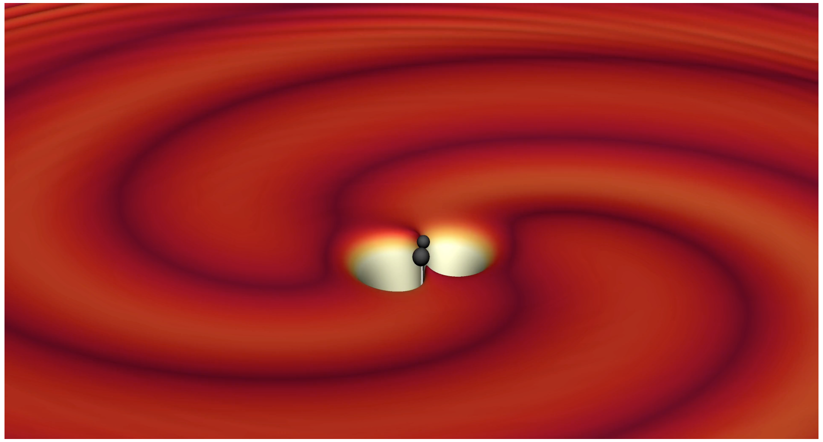
An international workshop to celebrate the legacy of G. Lemaître in the new millennium

Outline

Gravitational Waves

- Introduction: GW signals, GWB
- GWB from compact binary coalescences (BBH): astrophysics
- GWB from first order phase transitions; cosmic strings: beyond standard model
- GWB from 2^{nd} order scalar perturbations; stiff e.o.s: early universe
- Anisotropies in the GWB: large-scale structure
- Transient GWs: dark matter (CDM/IDM; axion-like particles)
- Transient GWs: theories of gravity
- Conclusions

Introduction: GW signals, GWB



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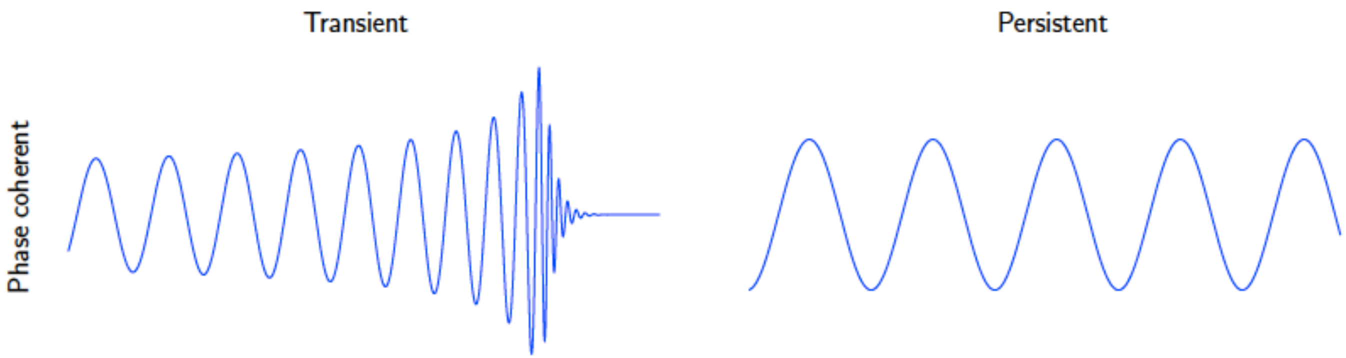
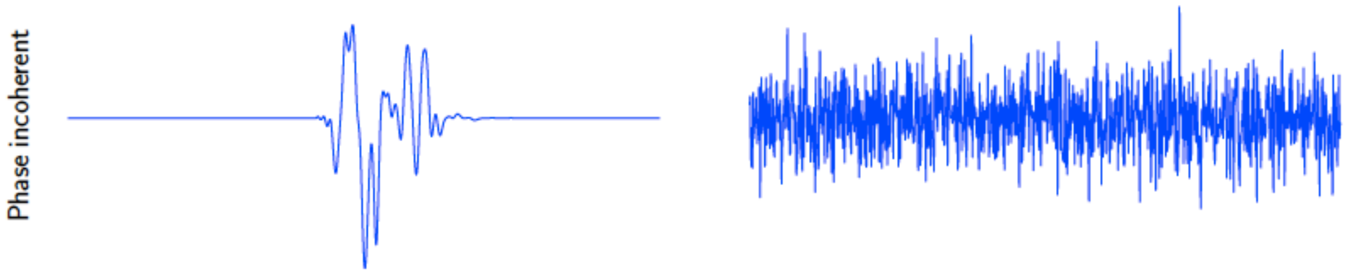
Classification of GW signal morphologies



emitted by compact binaries

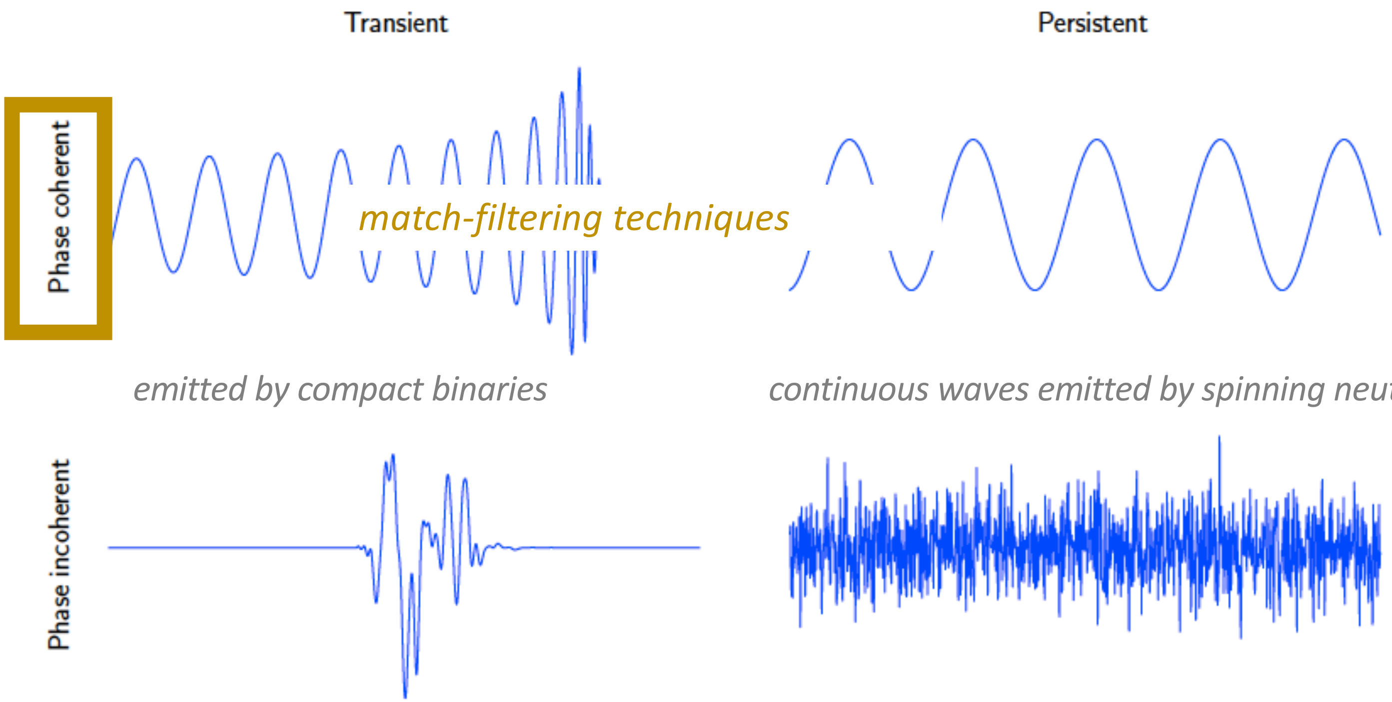
continuous waves emitted by spinning neutron stars



bursts emitted by core-collapse supernova

stochastic GW background

Classification of GW signal morphologies



match-filtering techniques

emitted by compact binaries

continuous waves emitted by spinning neutron stars

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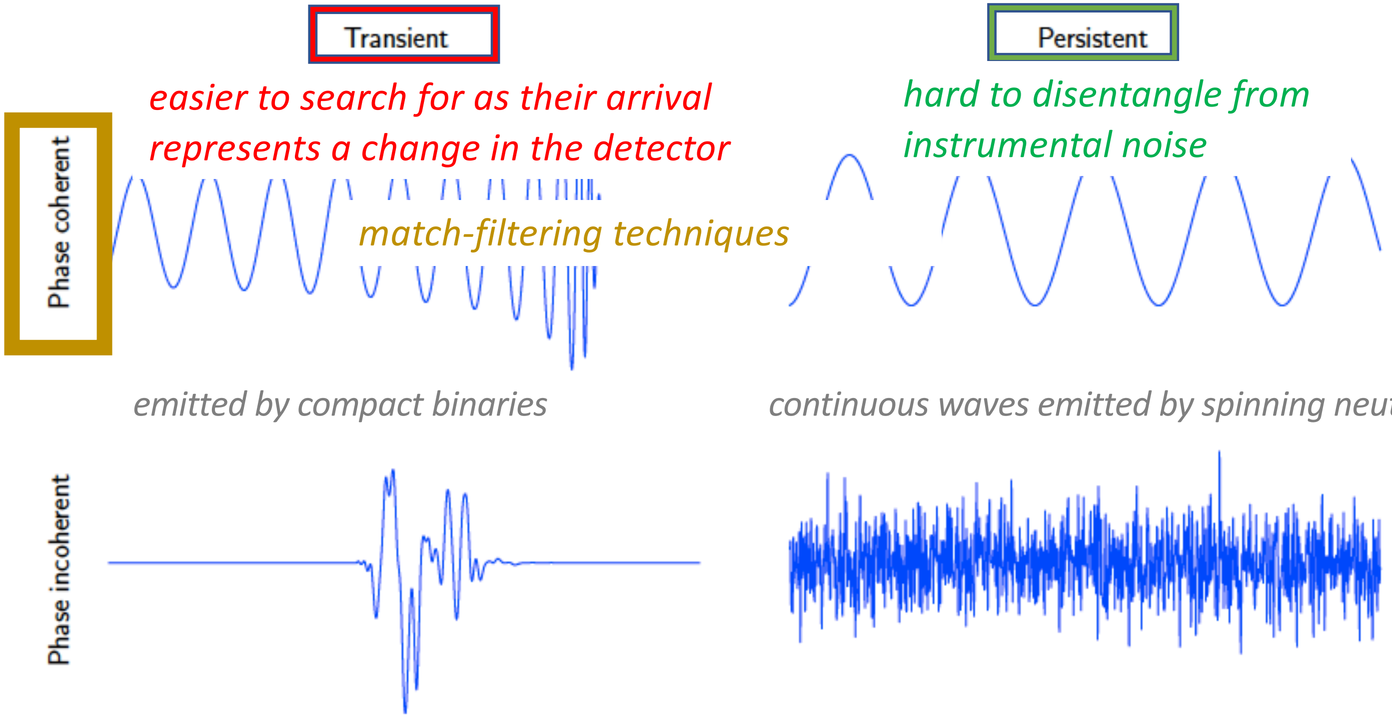
stochastic GW background

Classification of GW signal morphologies



easier to search for as their arrival represents a change in the detector

hard to disentangle from instrumental noise

match-filtering techniques

emitted by compact binaries

continuous waves emitted by spinning neutron stars

bursts emitted by core-collapse supernova

GW background

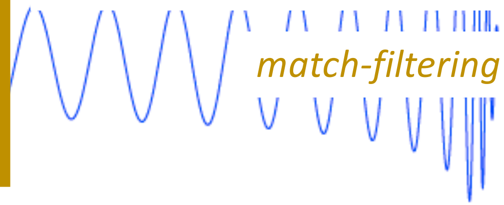
LVK Collaboration, arXiv: 1811.12907
arXiv:2010.14527
arXiv:2108.01045

Classification of GW signal morphologies

Transient

easier to search for as their arrival represents a change in the detector

Phase coherent



match-filtering techniques

emitted by compact binaries

LVK Collaboration, arXiv: 1811.12907
arXiv:2010.14527
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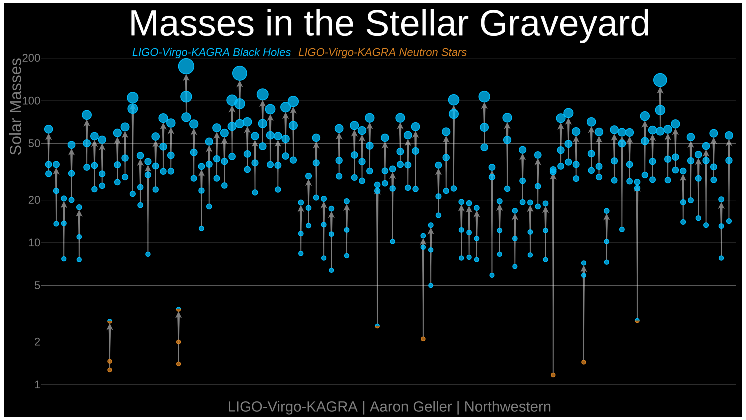
Current GW detection pipelines are based on match-filtering
-- quite successful, with over 100 confident detections

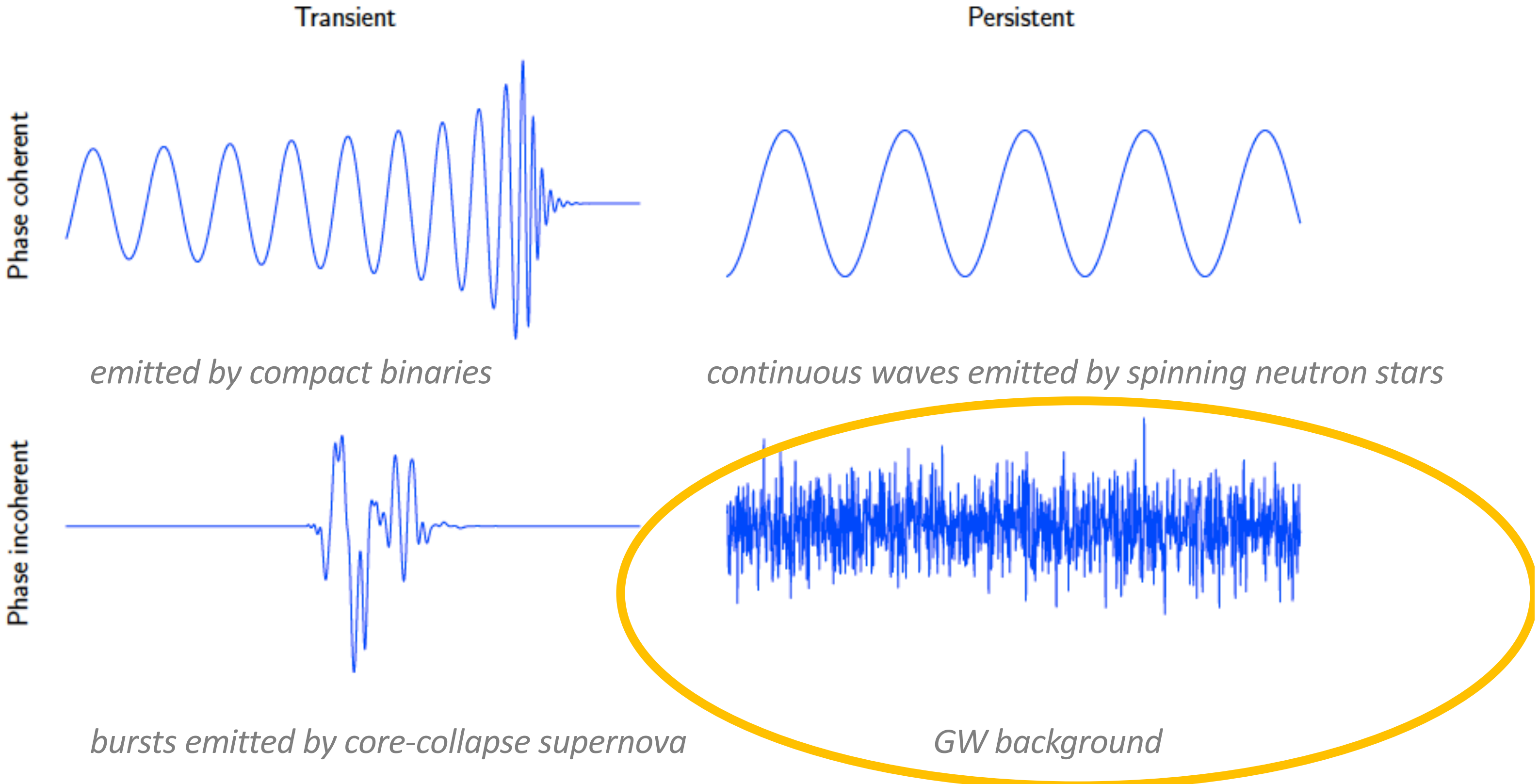


Algorithm to rapidly detect GWs from BBHs using **sparse dictionary coding**

*Badger, Srinivasa, Torres-Forne, Bizouard, Font, **Sakellariadou**, Lamberts, arXiv:2405.17721*

*Badger, Martonovic, Torres-Forne, **Sakellariadou**, Font, PRL 130 (2023) 091401*

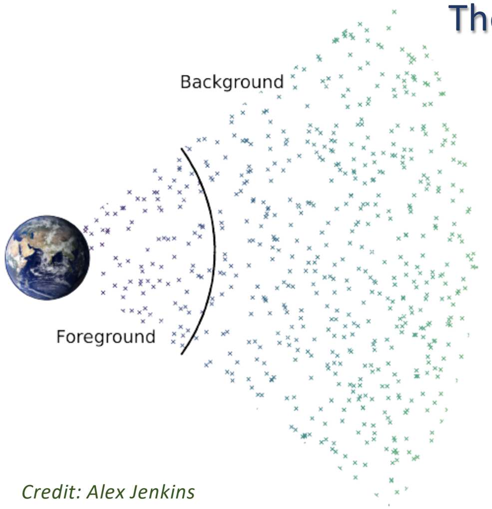
Classification of GW signal morphologies



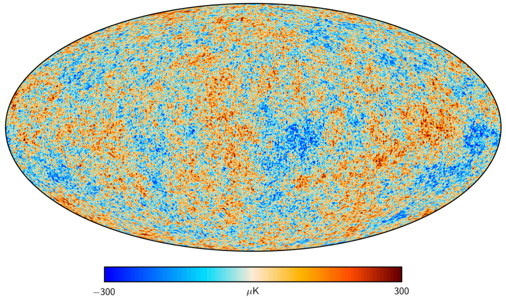
random nondeterministic phase evolution
from a large number of distant sources

Gravitational-Wave Background (GWB)

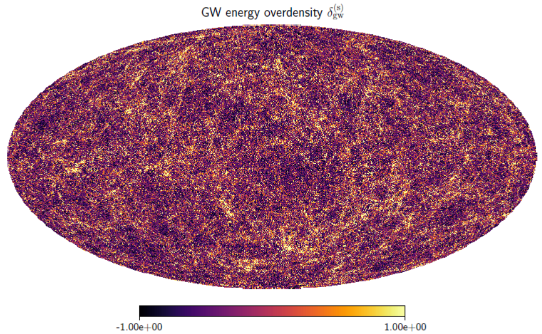
The Universe is permeated by a stochastic GWB generated in the early Universe



Credit: Alex Jenkins



Planck Collaboration



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

$$\Omega_{\rm GW}(f) = \frac{f}{\rho_c}\frac{{\rm d}\rho_{\rm GW}}{{\rm d}f}$$

$$\rho_{\rm GW} \sim \dot{h}^2$$

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

Gravitational-Wave Background (GWB)

Standard assumptions:

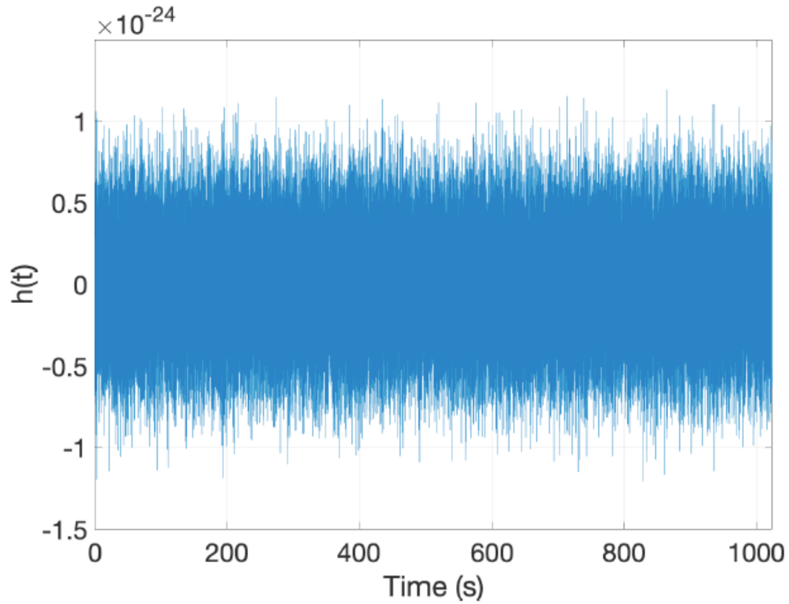
isotropic (no dependence on $\hat{n}$) no phase correlation

$$\langle \tilde{h}_A(f,\hat{n})\tilde{h}^*_{A'}(f',\hat{n}')\rangle = \frac{3H_0^2}{32\pi^3 f^3}\Omega_{GW}(f)\delta_{AA'}\delta(f-f')\delta^2(\hat{n},\hat{n}')$$

($A = +, \times$ are polarisations)

unpolarised stationary

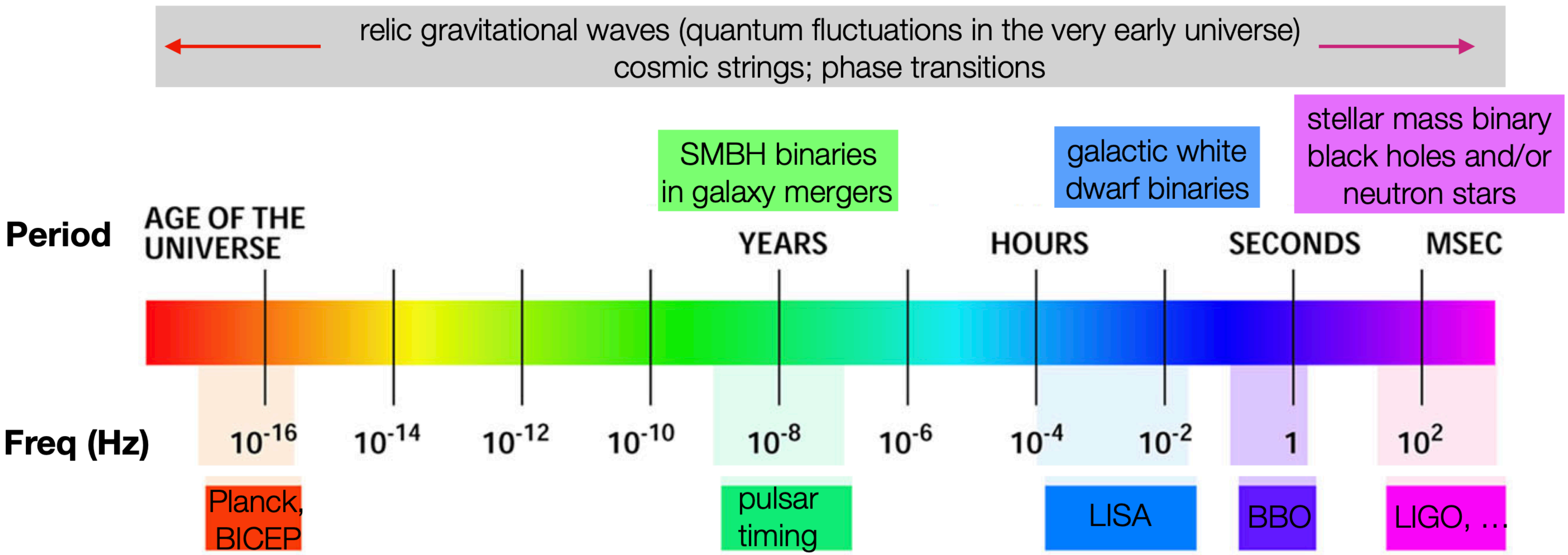
Gaussian (all other moments are trivial)



Time series of the strain amplitude in GWs for a Gaussian and stationary stochastic background

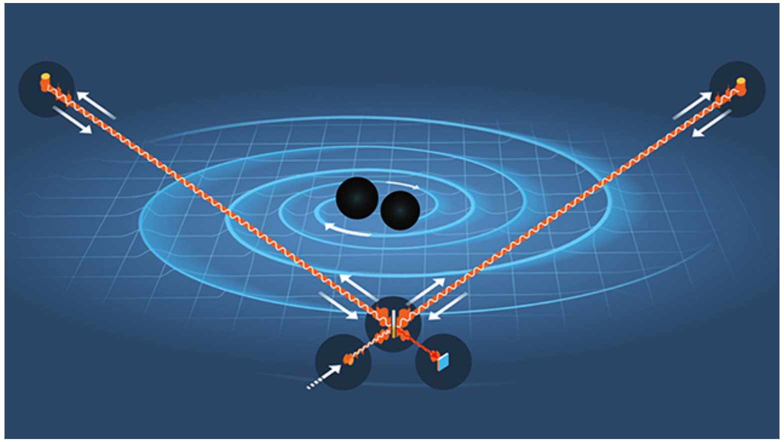
The amplitude at any given time t follows a normal distribution centered in zero and with the same variance

Gravitational-Wave Background (GWB)



Plot of the GW spectrum, with frequencies ranging from a few kHz (for ground-based detectors) to 10^{-17} Hz (corresponding to a period equal to the age of the universe), together with potential sources of GWBs and relevant detectors

GWB: Detection methods

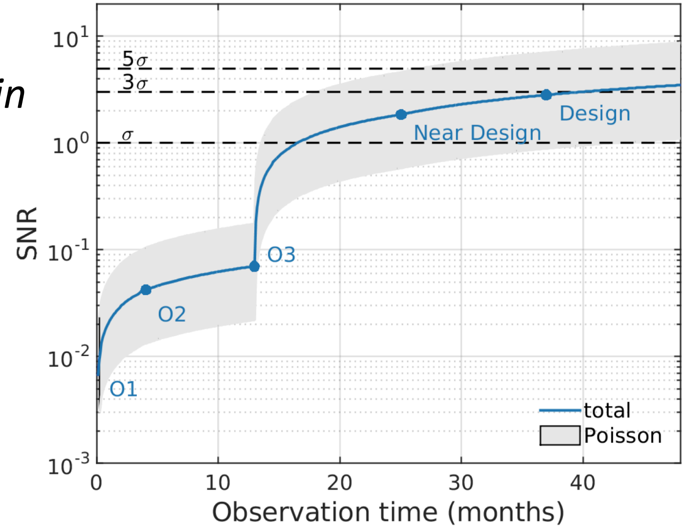


Mairi Sakellariadou

How do we detect a GWB ?

It would appear as noise in a single GW detector

$$\tilde{s}_i(f) = \tilde{h}_i(f) + \tilde{n}_i(f)$$ But *noise* >> *strain*



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

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

SNR grows (slowly) over time:

$$\langle s_1 s_2\rangle \sim \mathrm{Var}[s_1 s_2] \sim T_{\rm obs} \Rightarrow \mathrm{SNR} = \frac{\langle s_1 s_2\rangle}{\sqrt{\mathrm{Var}[s_1 s_2]}} \sim \sqrt{T_{\rm obs}}$$

How do we detect a GWB ?

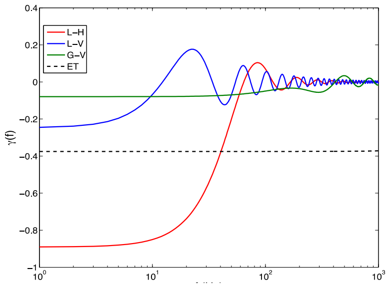
Assuming the GWB to be isotropic, Gaussian, stationary and unpolarised:

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

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

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

$\Gamma_{ij}(f)$



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

Single power spectral density (PSD)

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

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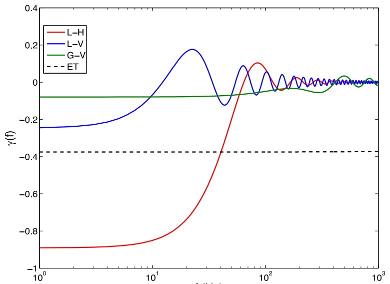

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$$\langle \hat{C}_{ij}(f;t)\rangle = \Omega_{\rm gw}(f) + 2\,\mathrm{Re}\left[\frac{\langle \tilde{n}_i^*(f;t)\tilde{n}_j(f;t)\rangle}{T\Gamma_{ij}(f)S_0(f)}\right]$$

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 $\Omega_{\rm gw}(f)$

How do we detect a GWB ?

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

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

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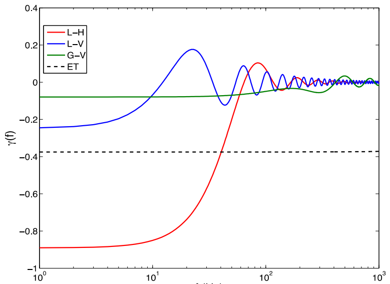
$\Gamma_{ij}(f)$



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

what if:

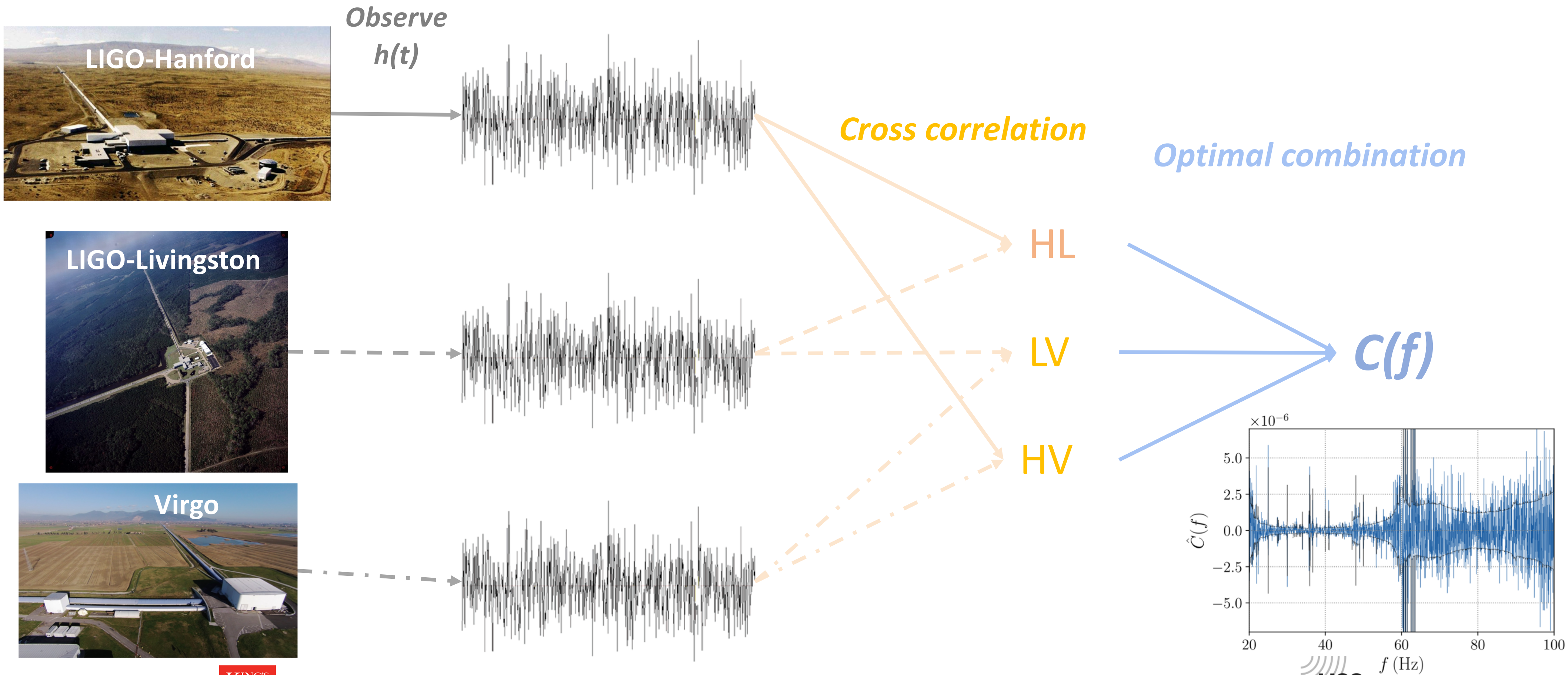
$\langle \tilde{n}_i^*(f)\tilde{n}_j(f)\rangle \neq 0$ ⇒ $\langle \hat{C}_{ij}(f)\rangle = \Omega_{\rm gw}(f) + \Omega_{{\rm M},ij}(f),$

Joint magnetic +GWB fit : a novel approach

*Meyers, Martinovic, Christensen, **Sakellariadou**, PRD 0102 (2020) 102005*

*Janssens, Martinovic, Christensen, Meyers, **Sakellariadou**, PRD 104 (2021) 122006*

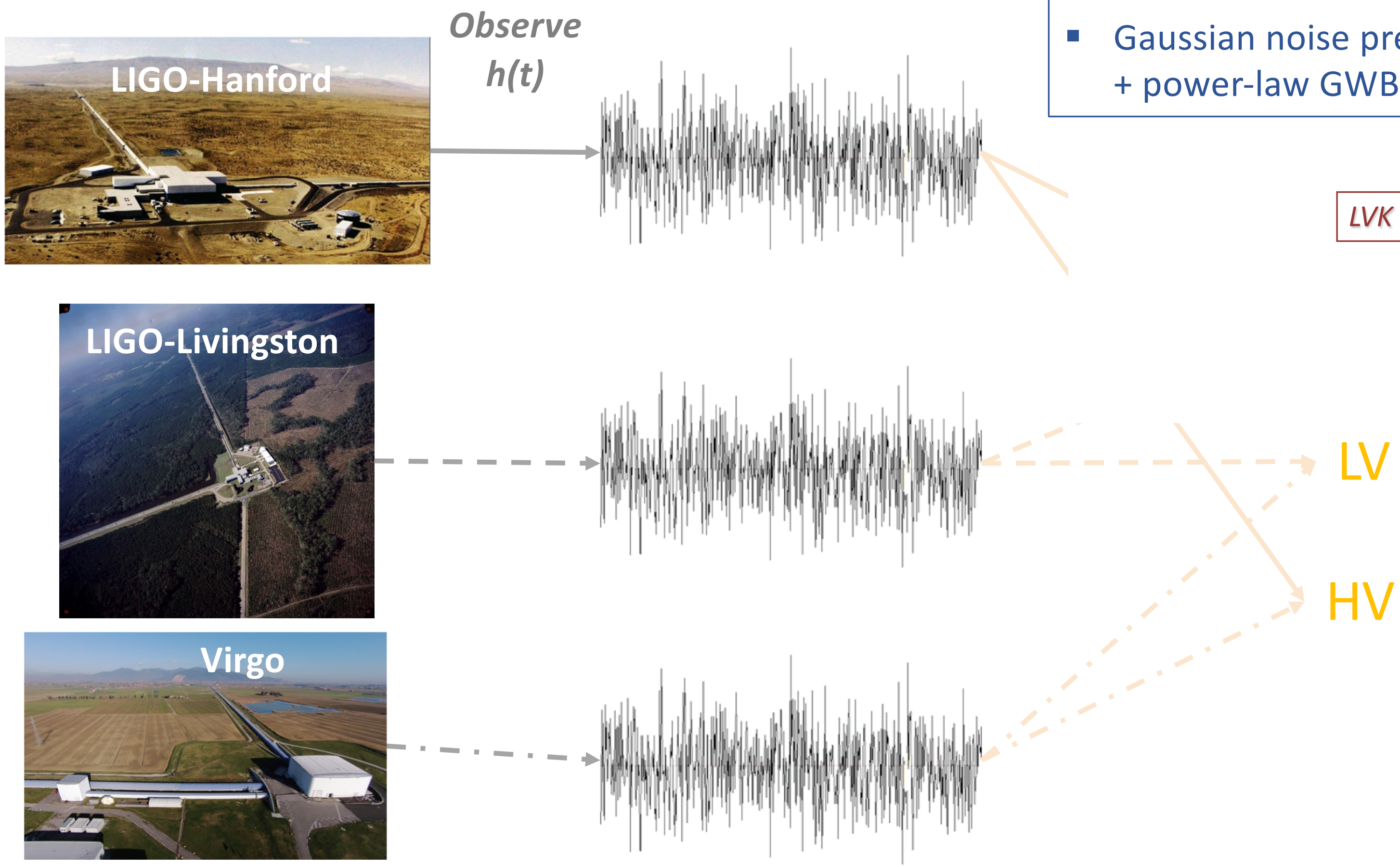
Using the detector network

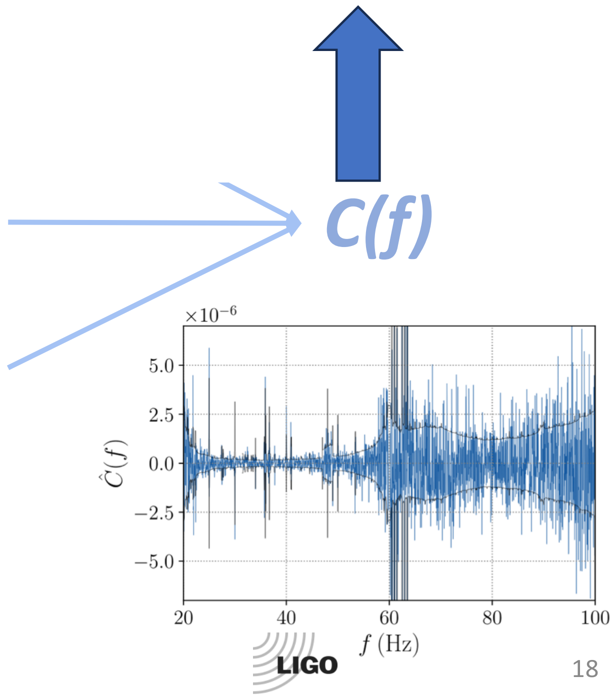


Using the detector network

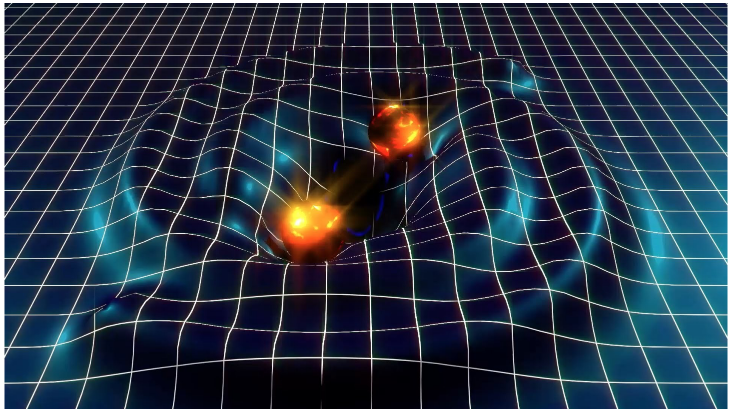
- Gaussian noise preferred over correlated magnetic noise
- Gaussian noise preferred over correlated magnetic noise + power-law GWB

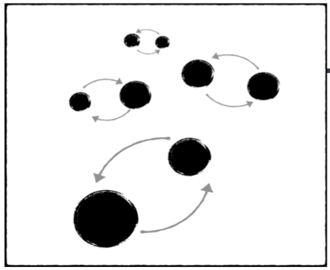
LVK Collaboration, PRD 104 (2021), 2, 022004





GWB : info about astrophysics





Implications for compact binaries: O3 search

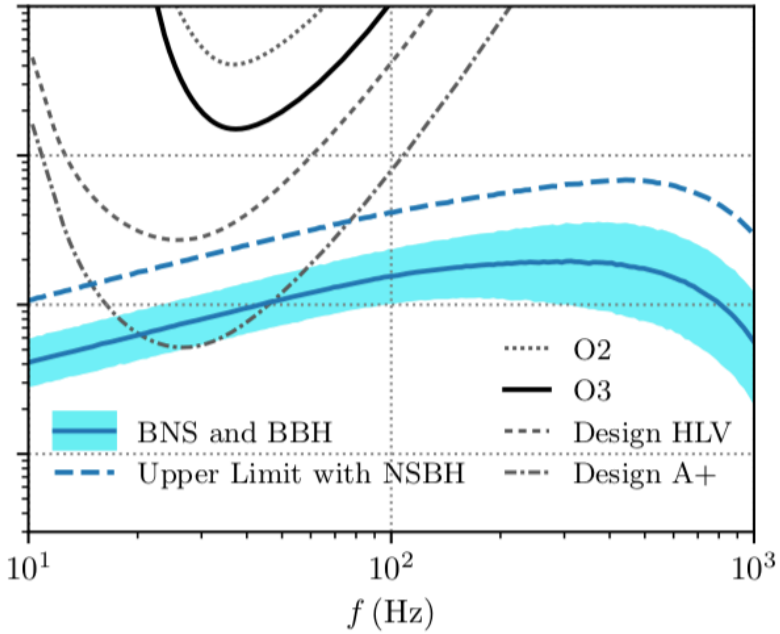
$$\Omega_{\rm GW}(f) = \Omega_{\rm ref}\left(\frac{f}{f_{\rm ref}}\right)^{\alpha}$$

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

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

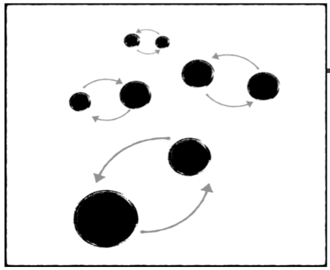
CBC: α=2/3

Compare combined BBH and BNS energy density spectra, and 2σ power-law integrated curves



$$\Omega_{\rm GW}(f) \leq 3.4\times 10^{-9} \quad \text{at } 25 \text{ Hz}$$

LVK Collaboration, PRD 104 (2021), 2, 022004



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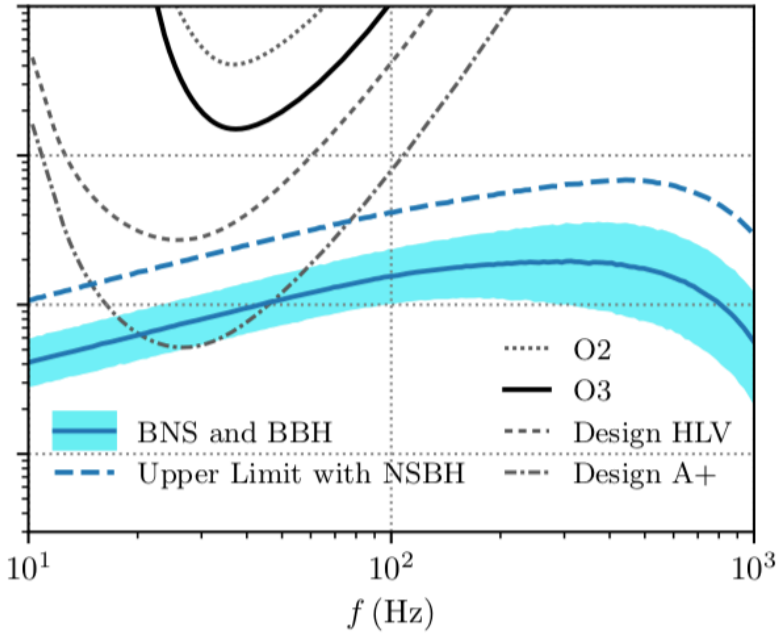
CBC: α=2/3

$$\Omega_{\rm GW} \ll \Omega_{\rm CMB} \approx 10^{-5}$$

So, detection is indeed hard!

Compare combined BBH and BNS energy density spectra, and 2σ power-law integrated curves



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LVK Collaboration, PRD 104 (2021), 2, 022004

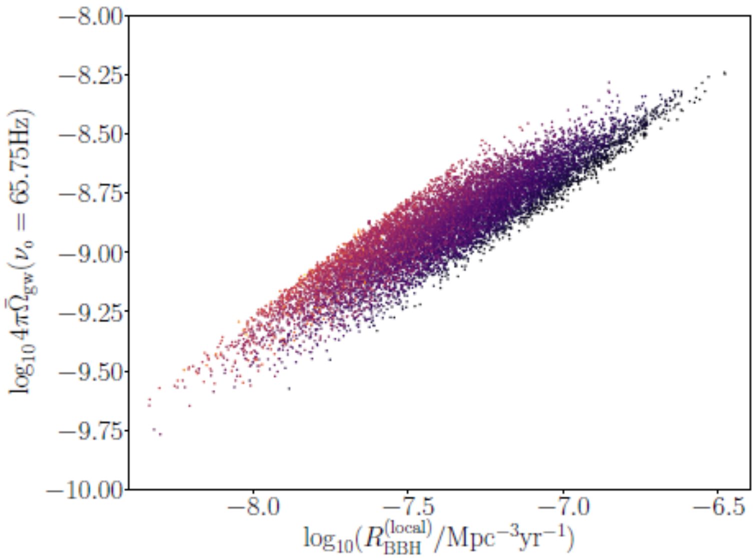
GWB from CBC: info about Compact Binaries

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

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

$$f_{\rm s} = (1+z)f$$

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



- **Star formation rate**
- **Time delays** between star formation and CBC merger

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)*

Implications for compact binaries

Possible complications:

- if there is **population III** that dominates in the residual of 3G detectors: not a 2/3 power spectrum (broken power-law)

*Martinovic, Perigois, Regimbau**, Sakellariadou**, ApJ 940 (2022) 1, 29*
*Kouvatsos**, Sakellariadou**, PRD (2024) (to appear)*

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- GWB from **CBC is expected to be non-Gaussian** in the frequency band of terrestrial detectors

- ratio of average time between events to average duration of an event is **small** (i.e., many events are on at once)
  continuous signal: Gaussian probability distribution

- ratio of average time between events to average duration of an event is small is **large**
  discontinuous or intermittent signal (popcorn): non-Gaussian probability distribution

Thrane, PRD 87 (2013) 043009

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Thrane, PRD 87 (2013) 043009

- GW background will present **anisotropies**

LVK Collaboration, PRD 104 (2021), 2, 022005

$$\Omega_{GW}(f,\hat{\Omega}) = \Omega_{GW}(f)P(\hat{\Omega})$$

$$\int_{S^2} P(\hat{\Omega})d\hat{\Omega} = 1$$

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- if there is **population III** that dominates in the residual of 3G detectors: not a 2/3 power spectrum (broken power-law)

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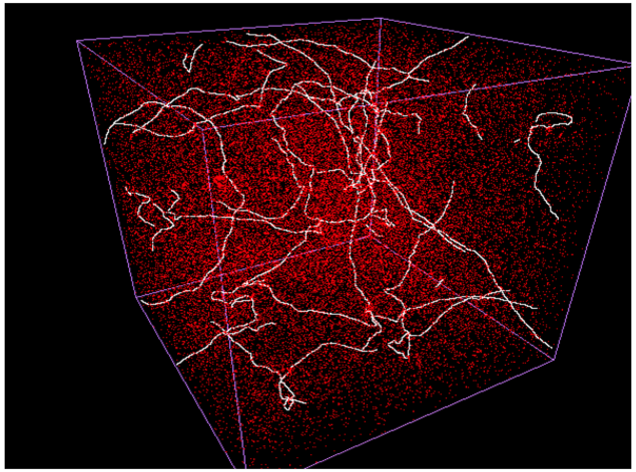
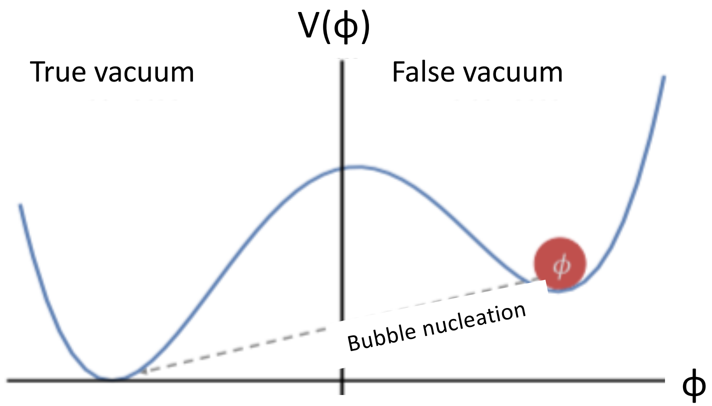
GWB : info about beyond the SM

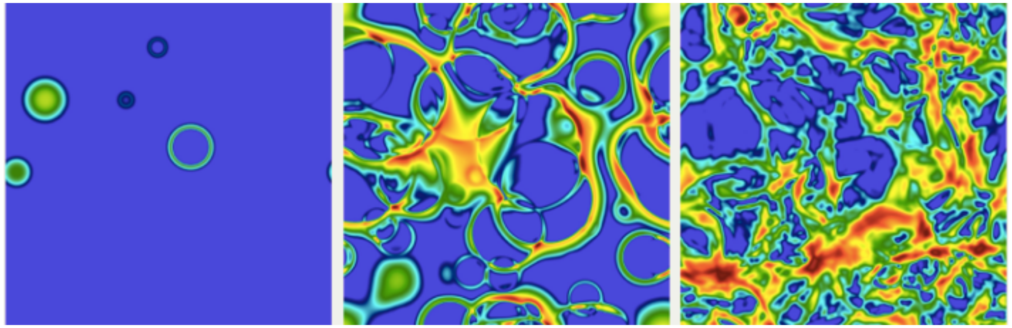


GWB from first order phase transition (FOPT): info Beyond the Standard Model

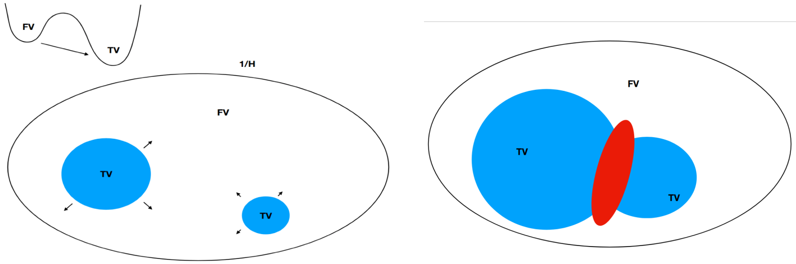
Many compelling extensions of the Standard Model predict strong FOPTs (e.g., GUTs, SUSY, extra dimensions, composite Higgs models, models with extended Higgs sector)



- Bubbles nucleate and grow
- Bubbles expand in the plasma --> reaction front form
- Bubbles + fronts collide
- Sound waves in the plasma
- Endgame: turbulence



GWB from first order phase transition (FOPT): info Beyond the Standard Model

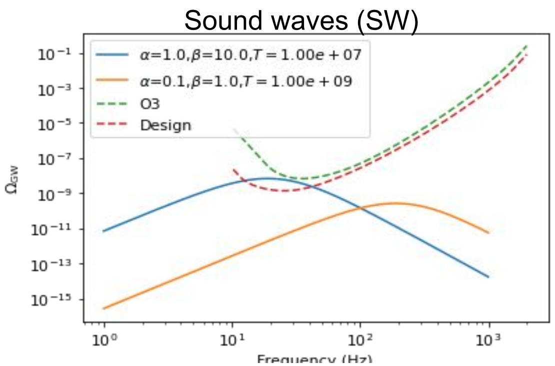


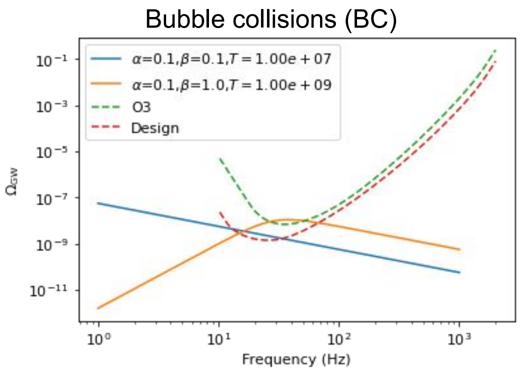
Sources of GWs:

- **Sound waves** (coupling between scalar field and thermal bath)
- **Bubble collisions**
- Magnetohydrodynamic turbulence

GWB: broken power law with peak frequency mainly determined by temperature of FOPT

If $T_{\rm pt} \sim (10^7 - 10^9)$ GeV (not accessible by LHC) : **GWB is within aLIGO/aVIRGO**

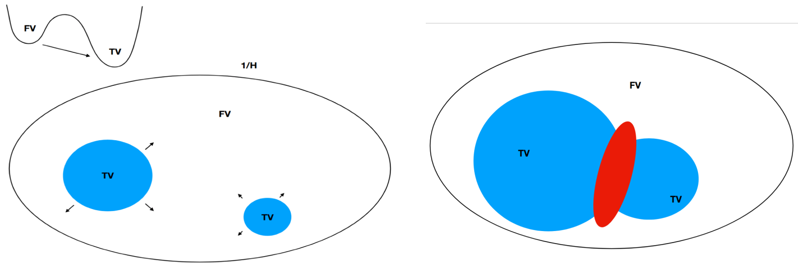




α : strength of FOPT

β : inverse duration of FOPT

GWB from first order phase transition (FOPT): info Beyond the Standard Model



Sources of GWs:

- **Sound waves** (coupling between scalar field and thermal bath)
- **Bubble collisions**
- Magnetohydrodynamic turbulence

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O1+O2+O3: For FOPT above 10^8 GeV

$\Omega_{\rm pt} < 5.8 \times 10^{-9}$ sound waves

$\Omega_{\rm pt} < 5.0 \times 10^{-9}$ bubble collisions

$\Omega_{\rm CBC} < 6.1 \times 10^{-9}$

*Romero, **Sakellariadou**, et al, PRL 126 (2021) 15, 151301*

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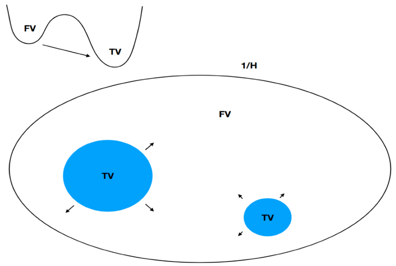

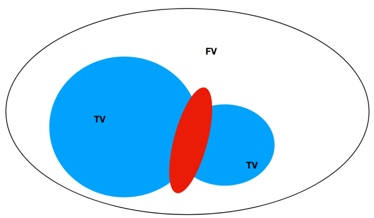

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*Romero, **Sakellariadou**, et al, PRL 126 (2021) 15, 151301*

Constraint parameters of particle physics models using GW data:

Supercooled FOPT

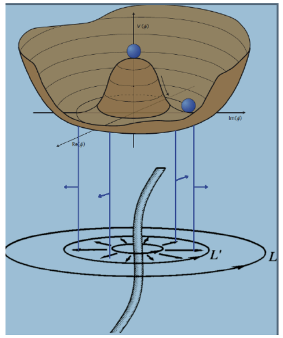
minimal $U(1)_{B-L}$ extension of the SM gauge group

radiatively broken U(1) Peccei-Quinn symmetry

*Badger, **Sakellariadou**, et al, PRD 107 (2022) 023511*

GWB from cosmic strings: info beyond Standard Model

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

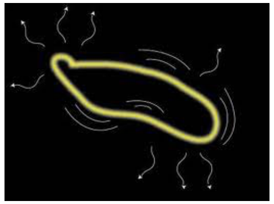


$G \to \cdots \to G_{\mathrm{SM}}$ $\pi_1(\mathcal{M}) \neq 0$

Kibble (1976)

Generically formed in the context of GUTs

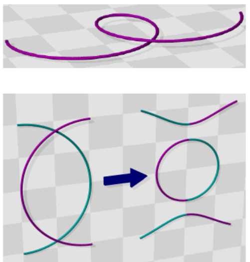
*Jeanneret, Rocher, **Sakellariadou**, PRD68 (2003) 103514*

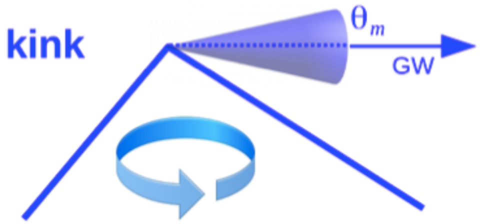


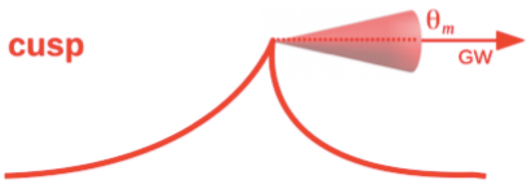
CS loops (length ℓ) oscillate periodically ($T = \ell/2$) in time emitting GWs (fundamental frequency $\omega = 4\pi/\ell$)

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

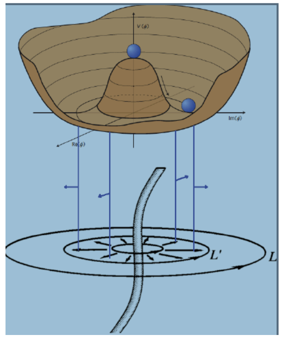
$$G\mu \sim T_{\mathrm{SSB}}^2$$







GWB from cosmic strings: info beyond Standard Model



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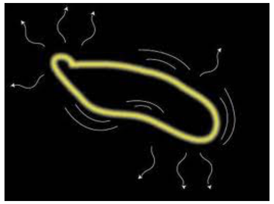

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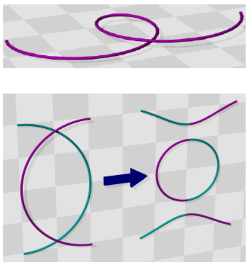
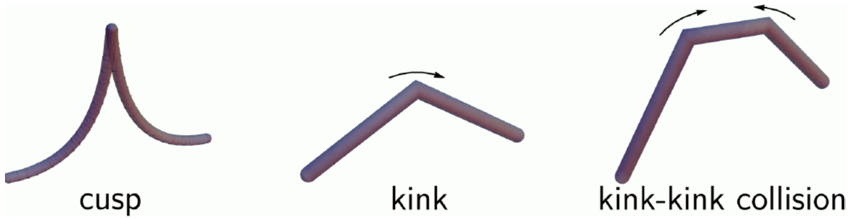




cusp	kink	kink-kink collision
$\tilde{h} \sim f^{-4/3}$	$\tilde{h} \sim f^{-5/3}$	$\tilde{h} \sim f^{-2}$
beamed	beamed	isotropic

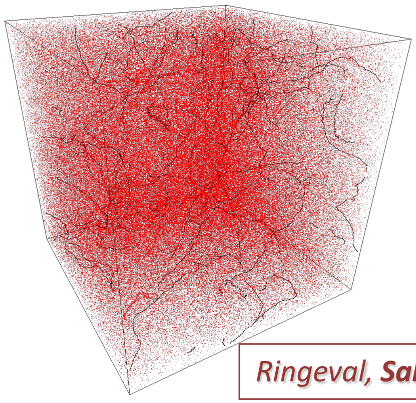
Damour, Vilenkin (2001)

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

At frequency of ground-based detectors, the GWB signal is produced by loops formed during RDE

GWB from cosmic strings: info beyond Standard Model

$$\bar{\Omega}_{\rm gw} = \frac{2(G\mu)^2}{3\pi^2 H_0^2 \nu_o}\int_0^{t_*}\frac{dt}{t^4}a^5\int_0^{\gamma_*}\frac{d\gamma}{\gamma}\bar{\mathcal{F}}\Theta\left(\gamma-\frac{2a}{\nu_o t}\right)\left[N_k^2+4AN_k\left(\frac{\nu_o\gamma t}{a}\right)^{1/3}+A^2N_c\left(\frac{\nu_o\gamma t}{a}\right)^{2/3}\right]$$

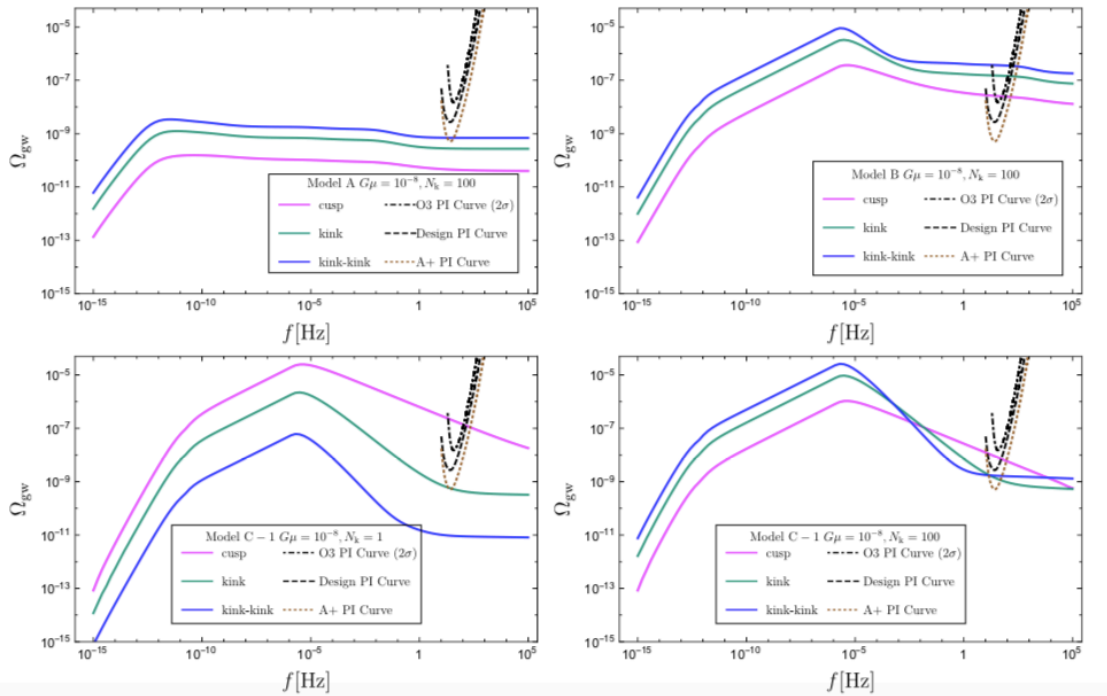


*Ringeval, **Sakellariadou**, Bouchet (2007)*

$$G\mu = \frac{\text{mass}}{\text{length}} \sim \left(\frac{\text{new physics scale}}{\text{Planck scale}}\right)^2 \ll 1$$

$$G\mu \sim T_{\rm SSB}^2$$

Model A: Blanco-Pillado, Olum, Shlaer (2014)
*Model B: Lorenz, Ringeval, **Sakellariadou** (2010)*
*Model C: Auclair, Ringeval, **Sakellariadou**, Steer (2019)*



LVK Collaboration, PRL 126 (2021) 24, 241102

GWB from cosmic strings: info Beyond the Standard Model

Excluded regions:

Model A: $G\mu \gtrsim (9.6 \times 10^{-9} - 10^{-6})$

strongest limit from PTA $G\mu \gtrsim 10^{-10}$

Model B: $G\mu \gtrsim (4.0 - 6.3) \times 10^{-15}$
strongest limit from LVK stochastic

Model C1: $G\mu \gtrsim (2.1 - 4.5) \times 10^{-15}$
strongest limit from LVK stochastic

Model C2: $G\mu \gtrsim (4.2 - 7.0) \times 10^{-15}$
strongest limit from LVK stochastic

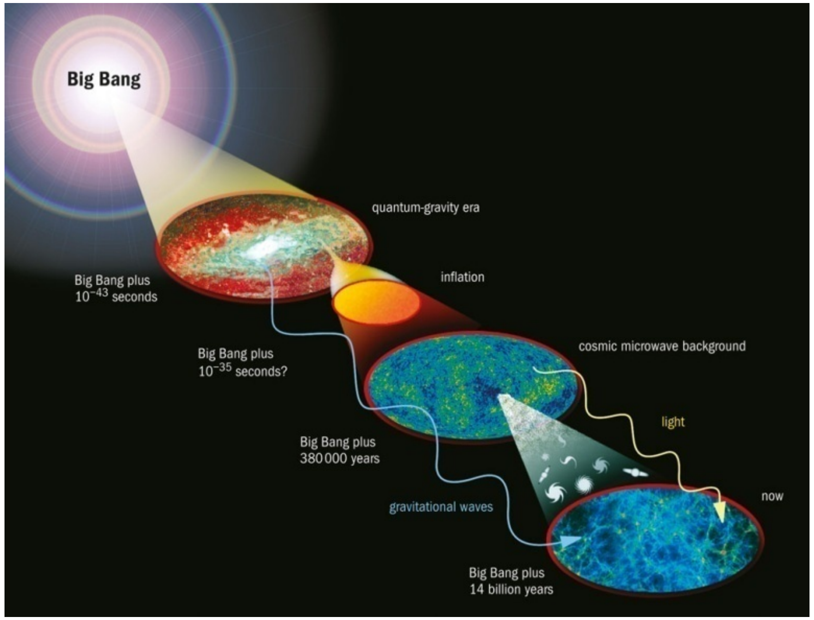
$$\text{Energy scale} \approx \sqrt{\frac{G\mu}{10^{-10}}}10^{14}\text{GeV}$$

Energy scale	Width	Linear density
GUT : 10^{16} GeV	2×10^{-32} m	$G\mu \approx 10^{-6}$
3×10^{10} GeV	5×10^{-27} m	$G\mu \approx 10^{-17}$
10^{8} GeV	2×10^{-24} m	$G\mu \approx 10^{-22}$
EW : 100 GeV	2×10^{-18} m	$G\mu \approx 10^{-34}$

Model A: Blanco-Pillado, Olum, Shlaer (2014)
*Model B: Lorenz, Ringeval, **Sakellariadou** (2010)*
*Model C: Auclair, Ringeval, **Sakellariadou**, Steer (2019)*

LVK Collaboration, PRL 126 (2021) 24, 241102

GWB : info about the EU



GWB from second order scalar perturbations: information about early universe

PBH formation through large curvature perturbations during inflation *Hawking (1971)*

⇒ **Strong GWB generated at 2nd order in perturbation theory from scalar perturbations**

Matarrese, Pantano, Saez (1994)

Spectrum of scalar induced GWs: fixed by curvature power spectrum
CMB: at large scales is $O\,(10^{-9})$ — GWB extremely weak

Planck (2020)

For PBH formation the curvature power spectrum amplitude needs to be O(0.01) at some small scales (assuming PBH formation in RDE) — GWB within reach of GW observatories

Saito, Yokoyama (2009)

Peaks in the curvature power spectrum that reach the amplitude O(0.01) required for PBH formation can be generated by features or turns in the inflaton potential

GWB from second order scalar perturbations: information about early universe

O1+O2+O3: upper limits on the amplitude of power spectrum and fraction of the DM in terms of ultralight PBHs

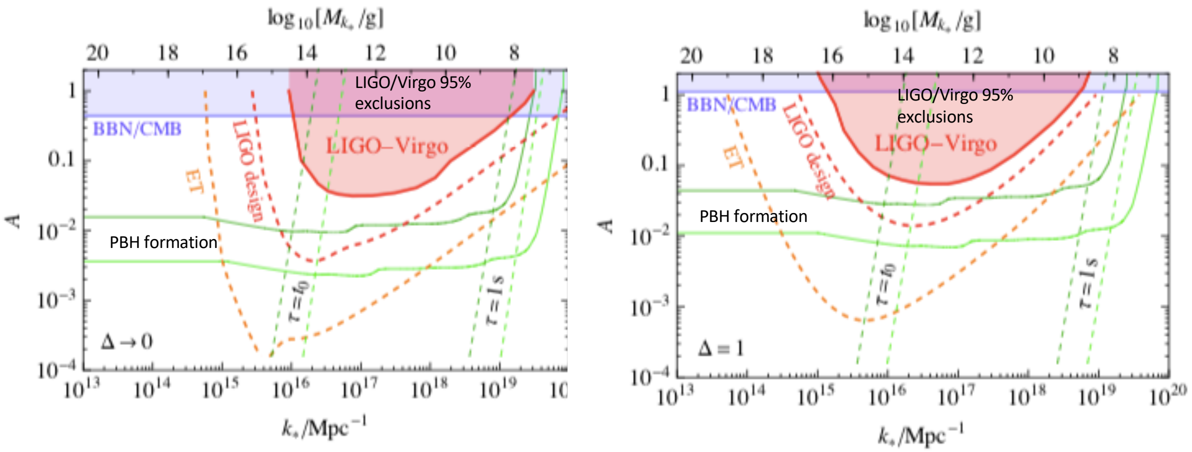
For LIGO/Virgo sensitivity: $M_{\rm PBH} \lesssim 10^{16}\,{\rm g}.$

log-normal shape for the peak in curvature power spectrum

$$\mathcal{P}_\zeta(k) = \frac{A}{\sqrt{2\pi}\Delta}\exp\left[-\frac{\ln^2(k/k_*)}{2\Delta^2}\right]$$

Khori, Terada (2018)

Ω_{GW}

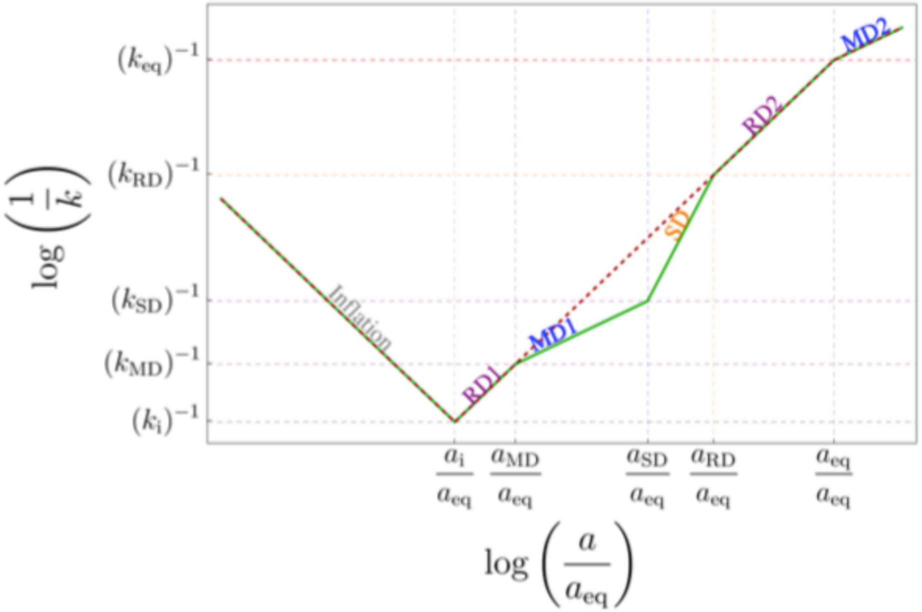


No evidence for such a GWB

95% CL upper limits on integrated power of curvature power spectrum peak down to 0.02 at $10^{17}\,{\rm Mpc}^{-1}$

*Romero-Rodriguez, Martinez, Pujolas, **Sakellariadou**, Vaskonen, PRL 128 (2022) 5, 051301.*

GWB from inflation in an exotic model with a stiff era: information about early universe



$1/3 < w \leq 1$

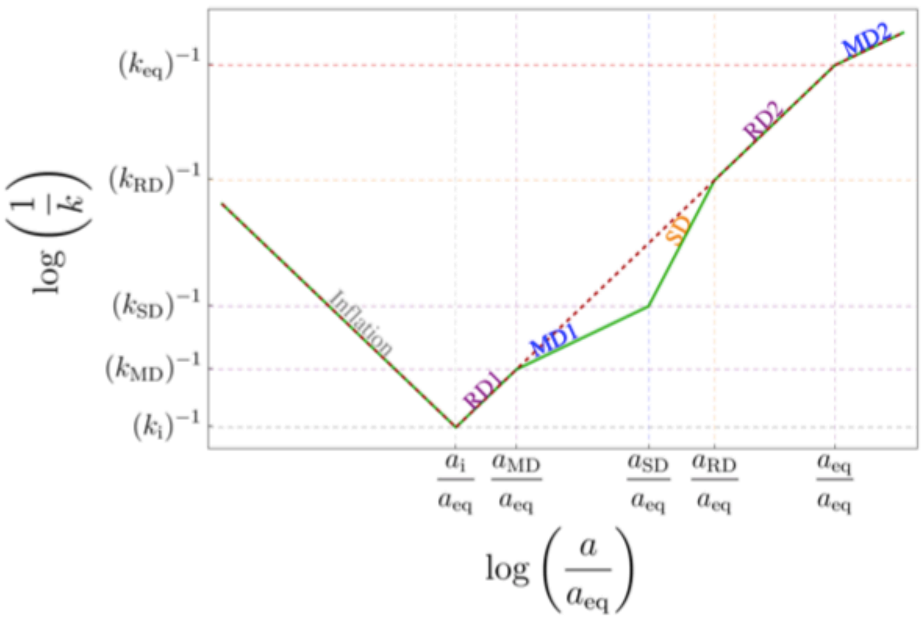
Stiff dominated era: blue-tilted inflationary GWB spectrum at $f>f_{BBN}$

→ potentially detectable GWs

Giovannini (1998)

Duval, Sakellariadou, et al (2024)

GWB from inflation in an exotic model with a stiff era: information about early universe



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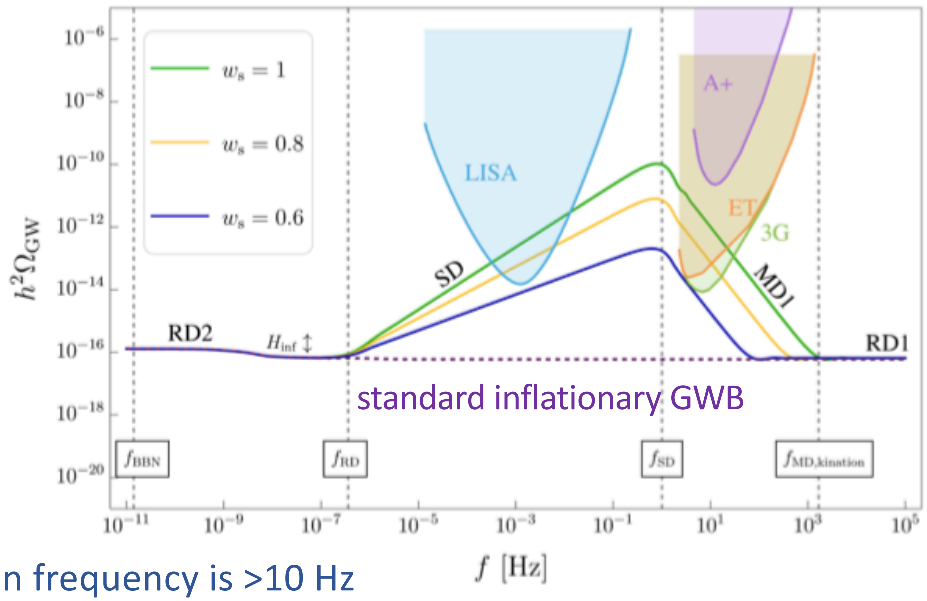
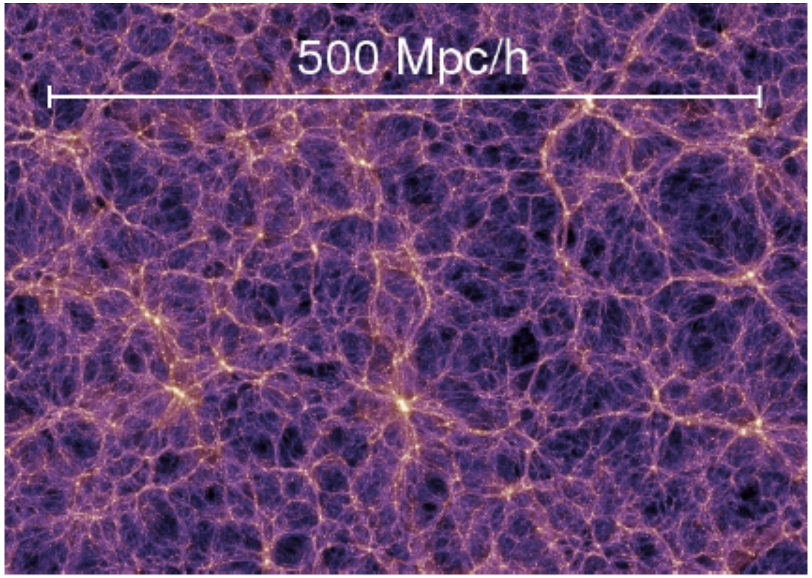


Most promising scenario for GWB detection, **kination**, with $w_s = 1$

O1-O3 LVK data: exclude scenarios where MD1-to-kination transition frequency is >10 Hz and kination-to-radiation transition < 10^{-5} Hz

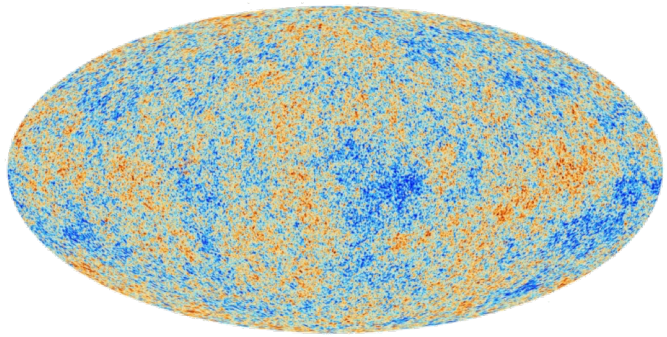
Duval, Sakellariadou, et al (2024)

Anisotropies in the GWB : info about the LSS



Anisotropies in the GW Background: info about large-scale-structure

First approximation: GWB isotropic (analogous to the CMB)



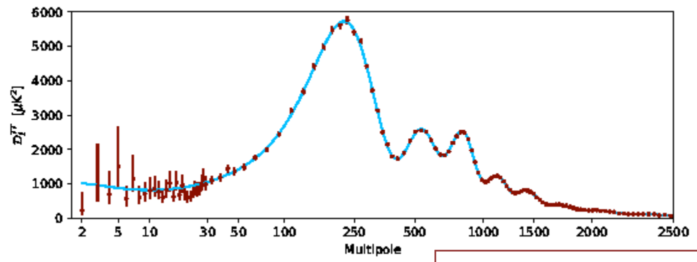


Image credit: Planck collaboration

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

GWB

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

LSS

now a function on the sky

$$\langle \tilde{h}_A(f,\hat{n})\tilde{h}^*_{A'}(f',\hat{n}')\rangle = \frac{3H_0^2}{8\pi^2 f^3}\Omega_{\rm GW}(f,\hat{n})\delta_{AA'}\delta(f-f')\delta^2(\hat{n},\hat{n}')$$

still no phase correlation

Anisotropies in the GW Background: info about large-scale-structure

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

Intensity of GWB: $\Omega_{\rm gw}(f_0, \hat{e}_0) \equiv \bar{\Omega}_{\rm gw}(1 + \delta_{\rm gw})$

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

2PCF : $C_{\rm gw}(\theta_0, f_0) \equiv \langle \delta^{(\rm s)}_{\rm gw}(f_0, \hat{e}_0) \delta^{(\rm s)}_{\rm gw}(f_0, \hat{e}'_0) \rangle$

$$C_{\rm gw}(\theta, f_0) = \sum_{\ell=0}^{\infty} \frac{2\ell+1}{4\pi} C_\ell(f_0) P_\ell(\cos\theta_0)$$

$$\delta_{\rm gw}(\nu_{\rm o}, \hat{\boldsymbol{e}}_{\rm o}) \equiv \frac{\Omega_{\rm gw} - \bar{\Omega}_{\rm gw}}{\bar{\Omega}_{\rm gw}}$$

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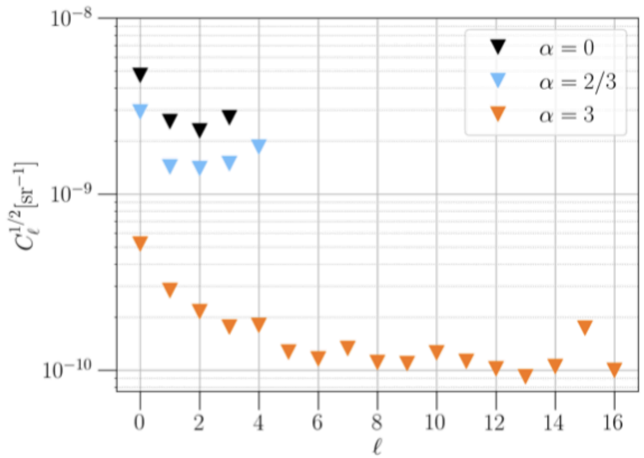

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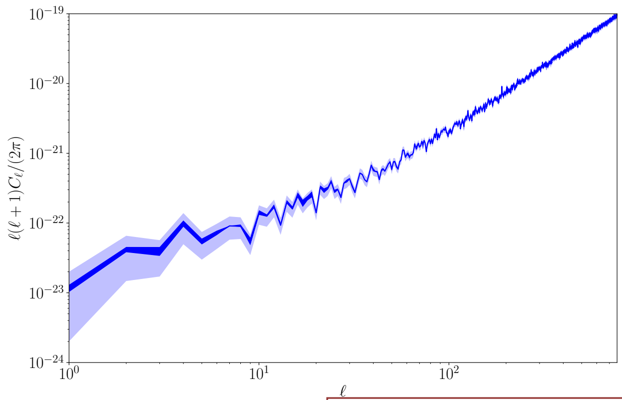
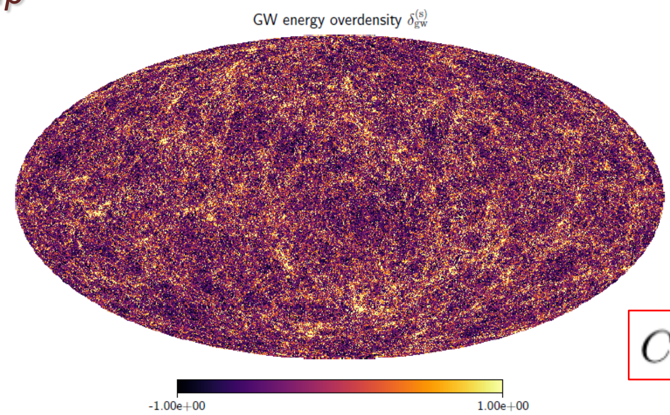
Get galaxies from the Millenium catalogue –> compute merger rate for each galaxy –> superimpose to get a GWB map

LVC PRD 104 (2021), 2, 022005

$$C_\ell^{1/2} < 1.9 \times 10^{-9}\,\mathrm{sr}^{-1},$$





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

$$C_\ell^{1/2} \sim 10^{-12}\,\mathrm{sr}^{-1} \text{ for } 1 \le \ell \le 4,$$

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

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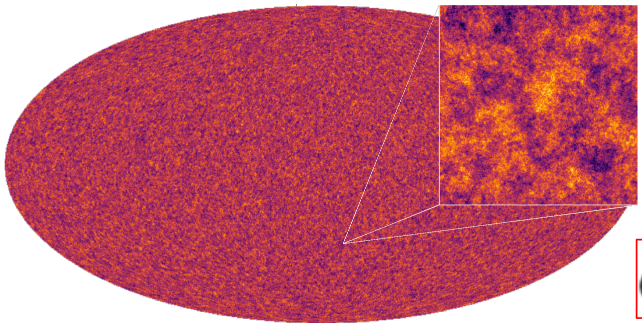

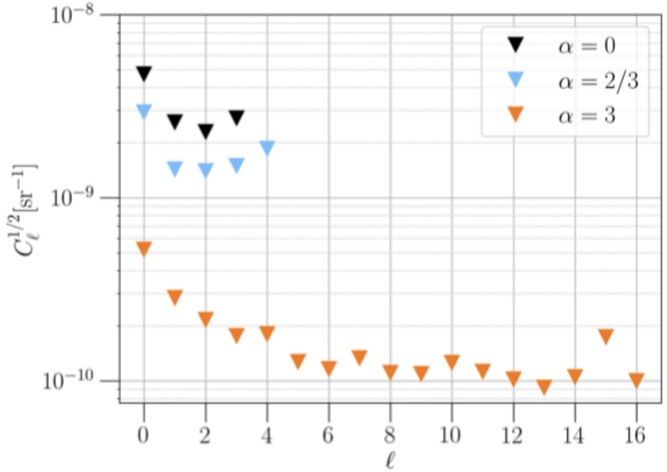

LVC PRD 104 (2021), 2, 022005

$C_1^{1/2} \lesssim 10^{-12}\mathrm{sr}^{-1}$

$C_1^{1/2} < 2.6 \times 10^{-9}\,\mathrm{sr}^{-1}$

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

Anisotropies in the GW Background: info about large-scale-structure

Remarks:

- Propagation effects: Contribution of such effects is larger at lowest angular multipoles and f-dependent

*Bertacca, **Sakellariadou**, et al , PRD 101 (2020) 10, 103513*

*Bellomo, **Sakellariadou**, et al, JCAP 06 (2022) 06, 030*

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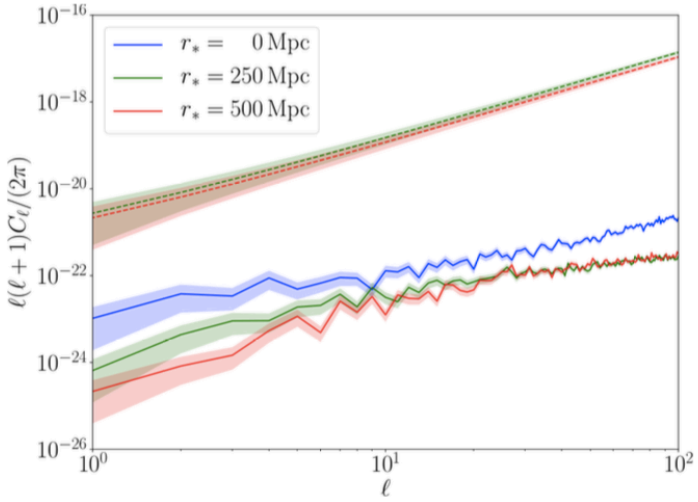
- Finite rate of compact binary mergers ⟶ *temporal shot noise* (scale-invariant bias term) leading to significant bias in measurements of angular power spectrum

*Jenkins, **Sakellariadou,** PRD100 (2019) 063508*



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*Jenkins, **Sakellariadou,** PRD100 (2019) 063508*

- Cross-correlate GW sky maps from different time segments to build a (new) minimum-variance unbiased estimator (*temporal cross-correlation method)*

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

First unbiased anisotropic search pipeline for LIGO-Virgo-KAGRA data

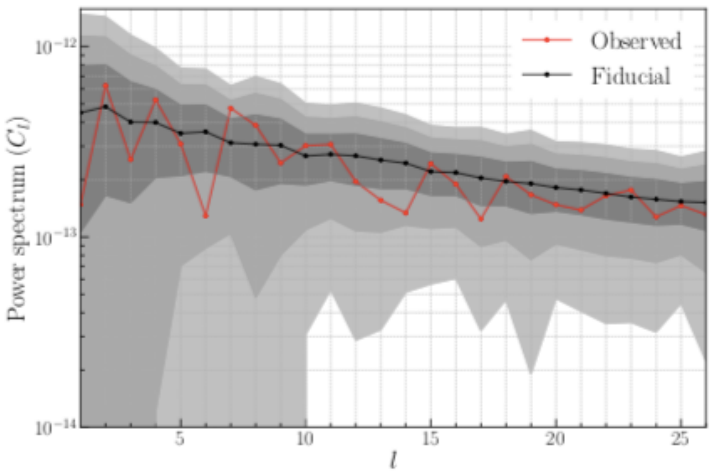
*Kouvatsos, Jenkins, Renzini, Romano, **Sakellariadou**, 2312.09110 (2023)*

Angular power spectrum of GW transient sources as a probe of the LSS

Astrophysical GW background, where the angular power spectrum is derived from the clustering statistics of the BBH host galaxies

New complementary method:
probe the spatial distribution of BBH merger events by computing their **observed angular power spectrum and comparing it to an isotropic distribution**

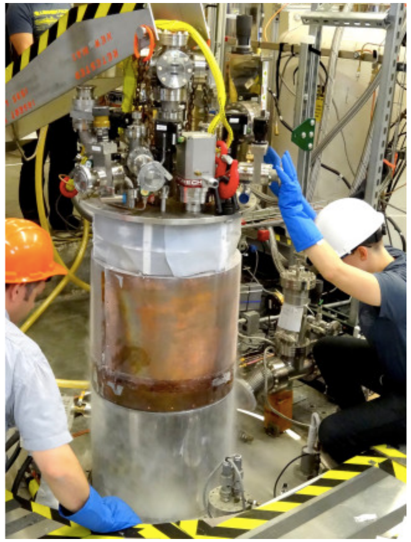
As a first application, we use the BBH mergers observed during the O3 to test the spatial distribution of these sources



No evidence for anisotropy at the 2σ confidence level

Zheng, Kouvatsos, Golomb, Cavaglia, Renzini, ***Sakellariadou*** *, PRL 131 (2023) 17, 171403*

GWs : constraints on dark matter



Mairi Sakellariadou

GWs: constraints on light axions

Inside NS axion potential receives finite density corrections

Phase transition shifting VEV of axion field from 0 to a non-zero value $\pm\pi f_a$ **inside NS**

Radius of NS is about 10 km: PT happens inside the NS for axions with $f_a \lesssim 10^{18}\mathrm{GeV}$

The axion field mediates additional force between two NSs: **attractive** or **repulsive**

If such NSs form binaries, the axion field might also radiate axion waves during binary coalescence

EFT approach: ***first post-Newtonian corrections to the orbital dynamics, radiated power, and gravitational waveform for BNS mergers in the presence of an axion***

aLIGO can potentially exclude axions with $m_a \lesssim 10^{-11}$ eV $f_a \sim (10^{14} - 10^{17})$ GeV

*Huang, Johnson, Sagunski, **Sakellariadou**, Zhang,* Phys. Rev. D 99, 063013 (2019)

GWs: constraints on light axions

$$h(f) \simeq H(f) \exp[i\Psi(f)]$$

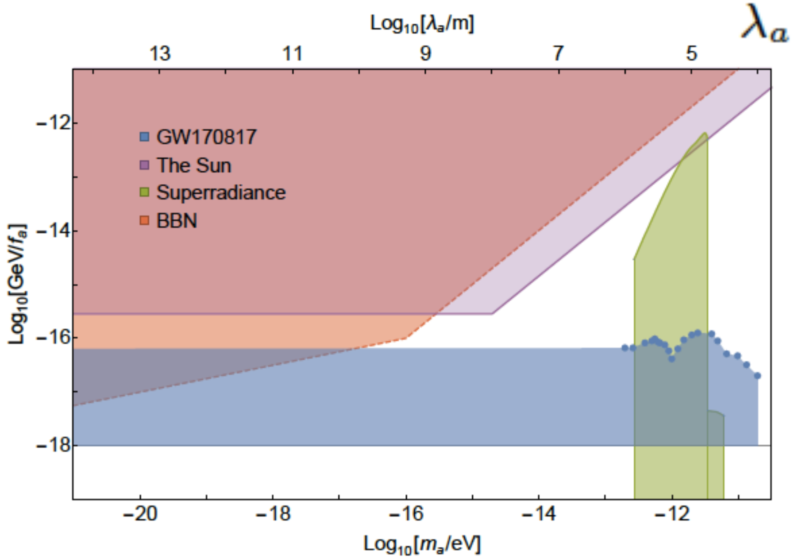
$$\Psi = \Psi_{\rm GR} + \Psi_a + \mathcal{O}(Q_{1,2}^4) + \mathcal{O}(Q_{1,2}^2 v^2)$$

The leading order phase correction by the axion field

counts PN order

Constraints on the axion parameter space

$$\lambda_a \equiv 1/m_a$$



First constraints on nuclear coupling of axionlike particles from the BNS GW event GW170817 taking into account the possible dephasing

Constraints on axions with masses below 10^{-11}eV by excluding the ones with decay constants ranging from 1.6×10^{16}GeV to 10^{18}GeV at 3σ confidence level

Zhang, Lyu, Huang, Johnson, Sagunski, ***Sakellariadou****, Yang,* PRL 127 (2021) 161101

GW event rates as a new probe for DM microphysics

Present observations on **super-galactic scales** are compatible with the hypothesis that the **dark matter is cold**

CDM model: particles do not have significant non-gravitational interactions

However, the key to determining the fundamental nature of DM lies in the **sub-galactic scales, at large redshifts**: **the onset of non-linear structure formation can be very sensitive to the microphysics of the dark matter**

Boehm, Fayet, Schaeffer (2001)

- **Warm Dark Matter**
- **Interacting Dark Matter**
- **Fuzzy Dark Matter**

Predict a cutoff in the linear matter power spectrum at large wave numbers k ("small-scale crisis")

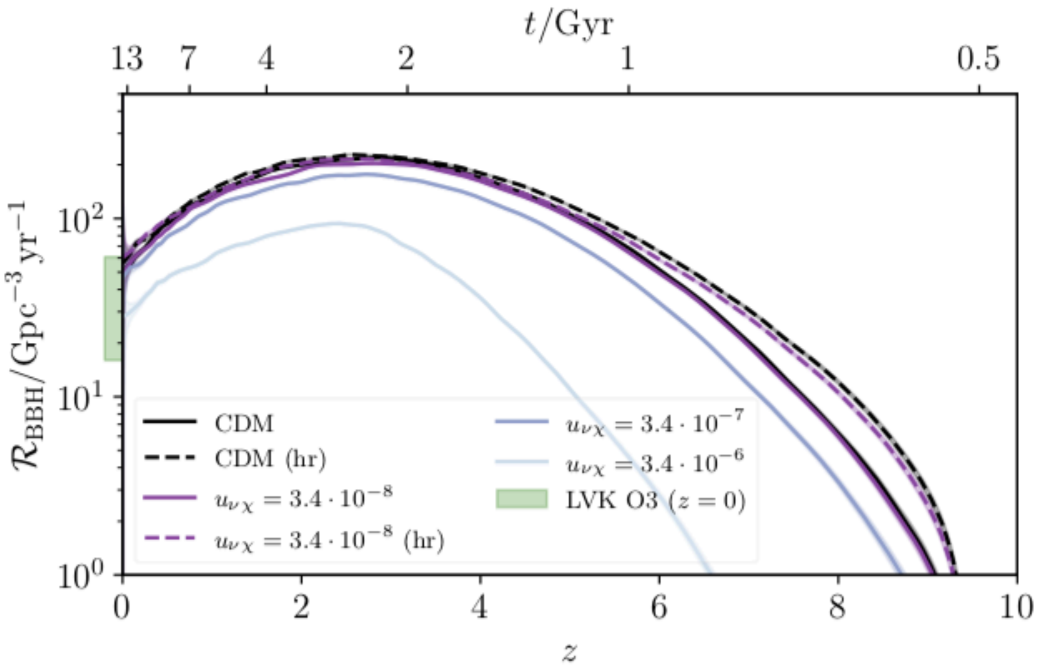
GW event rates as a new probe for DM microphysics

The BBH merger rate is highly sensitive to the suppression of small-scale structure induced by DM microphysics

Example: **DM neutrino interacting model**

$$u_{\nu\chi} \equiv \frac{\sigma_0}{\sigma_{\rm Th}} \left(\frac{m_\chi}{100\,{\rm GeV}/c^2} \right)^{-1}$$ *interaction strength*

*Di Valentino, Boehm, **Shivon, Bouchet (2018)***

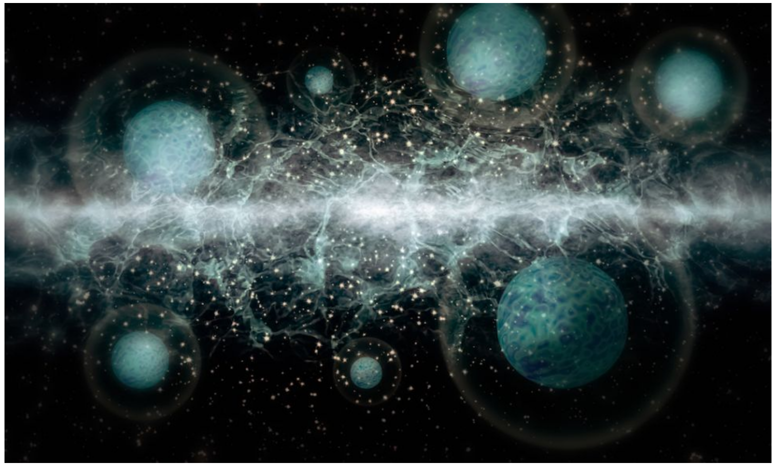


Suppression of small-scale structure
— caused by interacting, warm, or fuzzy DM —
leads to a significant **reduction in the rate of binary black hole mergers at redshifts** z>5

These differences in the high-z BBH merger rate will be detectable with 3g GW detectors

*Mosbech, Jenkins, Bose, Boehm, **Sakellariadou**, Wong, PRD (2023)*

Information about theories of gravity



Mairi Sakellariadou

Testing gravity theories through GW propagation

phenomenological parameters

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

massive gravity

$$A_0 > 0$$
$$m_g = A_0^{1/2}/c^2.$$

doubly special relativity

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

multi-fractal ST

Horava-Lifshitz & extra dim

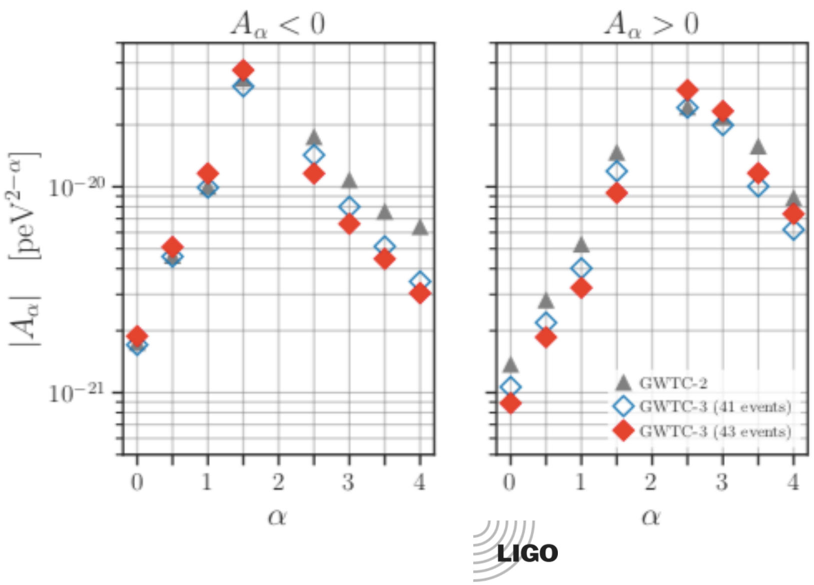
$$\tilde{h}(\nu) = A(\nu)e^{i\Phi(\nu)}$$

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

90% credible upper bounds on the absolute value of the modified dispersion relation parameter A_α

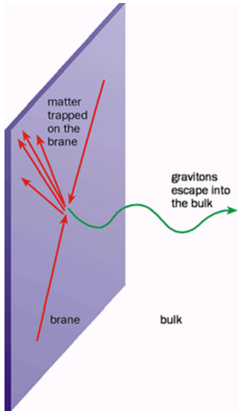
$$m_g \leq 1.27 \times 10^{-23} \mathrm{eV}/c^2.$$

~ 2 times more stringent than the most recent Solar System bound



LVK Collaboration 2021

Tests of GW propagation : amplitude damping



Constraints on the number of spacetime dimensions from GWs

Damping of the waveform due to gravitational leakage (beyond R_c) into extra dim

Deviation from $h_{\rm GR} \propto d_L^{-1}$ depends on number of dimensions D>4 and would result to a systematic **overestimation of the source** $d_L^{\rm EM}$ **inferred from GW data**

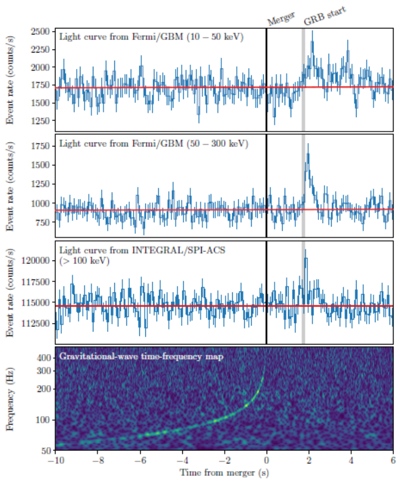
$$h \propto \frac{1}{d_L^{\rm GW}} = \frac{1}{d_L^{\rm EM}}\left[1+\left(\frac{d_L^{\rm EM}}{R_c}\right)^n\right]^{-(D-4)/(2n)}$$

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

***Strain** measured in a GW interferometer* ⟷ ***Luminosity distance** measured for the optical counterpart of the standard siren*

- Consistency with GR in D=4 dim
- Some high-dimensional models are ruled out

LVC PRL 2019



BNS merger at 40 Mpc

GRB 170817A and GW170817

GW event 1.7 s before γ-ray observation

Tests of GW propagation in the absence of electromagnetic counterparts

Propagation speed of GWs may vary as a function of the energy scale

- Frequency-dependent propagation speed

  - **spectral dimension of spacetime changes with probed scale**

  - **brane-world models**

  - **massive gravity**

- Horndeski theories and their extensions spontaneously break Lorentz invariance
  If UV completion is required to be Lorentz invariant, then **graviton becomes luminal at high energies**

LVC: BNS GW170817 ⟹ $-3\times 10^{-15} \leq c_T - 1 \leq 7\times 10^{-16}$ (in $c = 1$ units)

Construct a function for $c_T(f)$ which satisfies the LIGO-Virgo bounds whilst modify the millihertz regime significantly

Tests of GW propagation   in the absence of electromagnetic counterparts

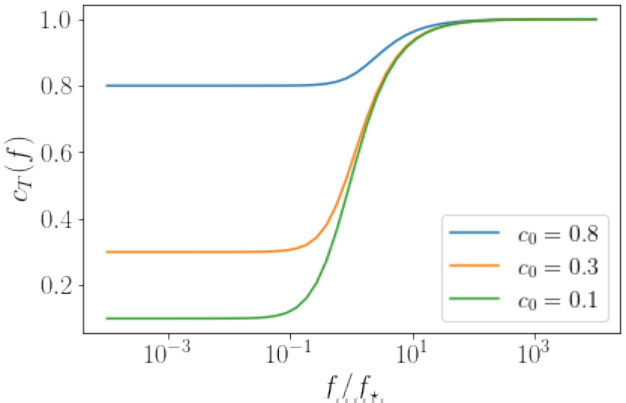
Quadratic action for the linearised transverse-traceless GW modes

$$S_T = \frac{M_{\rm Pl}^2}{8} \int dt\, d^3x\, a^3(t)\, \bar{\alpha} \left[\dot{h}_{ij}^2 - \frac{c_T^2(f)}{a^2(t)} (\vec{\nabla} h_{ij})^2 \right]$$

Sharp transitions for c_T in the frequency band between LISA and LIGO frequencies, to ensure consistency with results from GW170817

- Polynomial ansatz $c_T(f) = 1 + \sum_n \beta_n \left(\frac{f}{f_*} \right)^n$ LIGO bound implies: $|\beta_n| \lesssim 10^{-15-n} (f_*/\text{Hz})^n$

- EFT-inspired ansatz $c_T(f) = \left[1 + \frac{f_\star^2}{f^2} - \frac{f_\star^2}{f^2} \sqrt{1 + 2\left(1 - c_0^2\right) \frac{f^2}{f_\star^2}} \right]^{1/2}$



LIGO

Baker, Sakellariadou, et al, JCAP2022

KING'S College LONDON

Mairi Sakellariadou

Tests of GW propagation in the absence of electromagnetic counterparts

Derive how the GW waveforms (amplitude and phase) are modified wrt GR

- LISA can obtain good constraints on both the GR and the new parameters involved, even without electromagnetic counterparts

*Baker , **Sakellariadou**, et al, JCAP2022*

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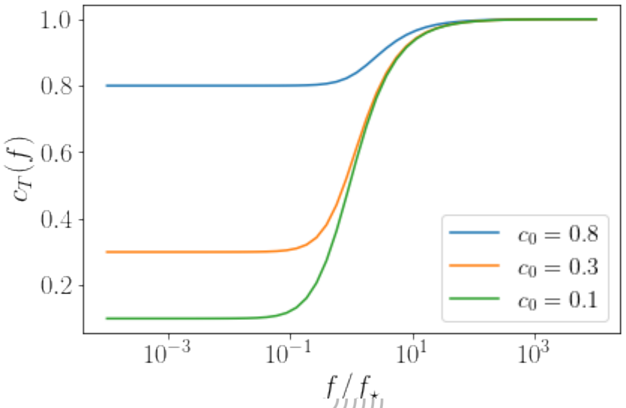
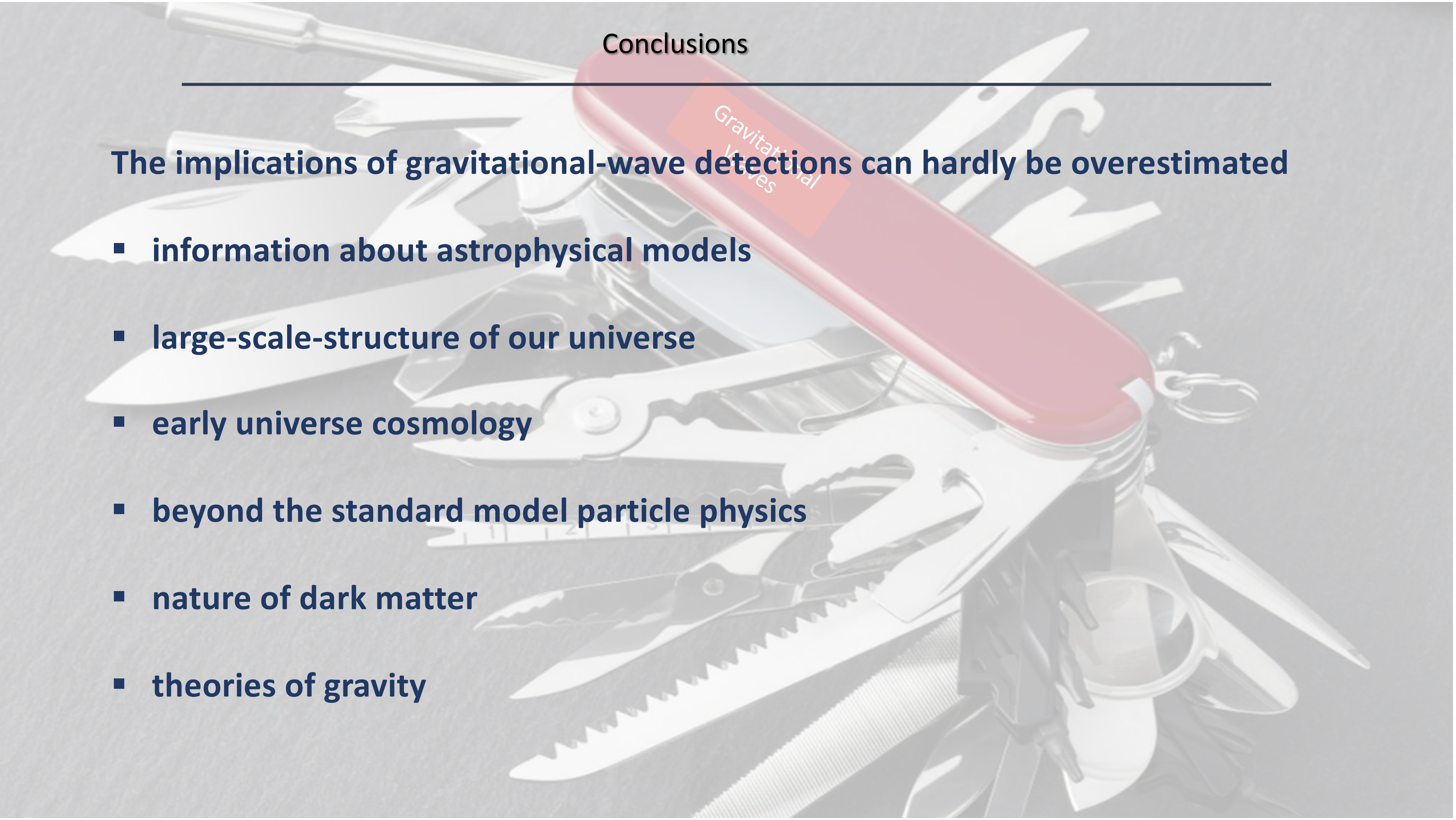


Baker , Sakellariadou, et al, JCAP2022

Conclusions



The implications of gravitational-wave detections can hardly be overestimated

- **information about astrophysical models**
- **large-scale-structure of our universe**
- **early universe cosmology**
- **beyond the standard model particle physics**
- **nature of dark matter**
- **theories of gravity**

Conclusions

The implications of gravitational-wave detections can hardly be overestimated.

- information about astrophysical models
- large-scale-structure of our universe
- early universe cosmology
- beyond the standard model particle physics
- nature of dark matter
- classical and quantum theories of gravity

grazie