Gravitational Waves: the theorist’s Swiss knife

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Peng Huanwu Innovation Research Center for Theoretical Physics
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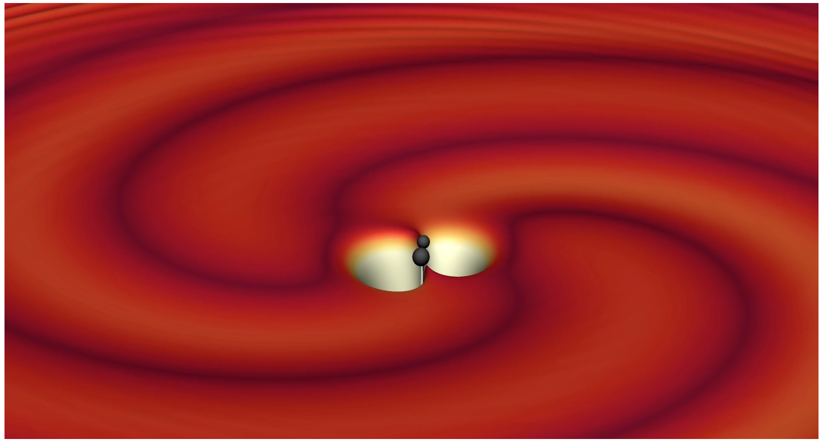
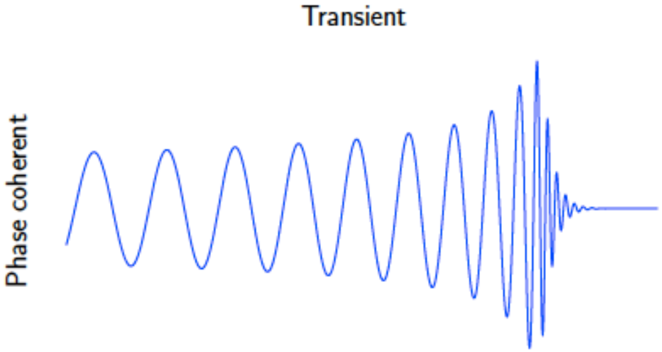
Outline

- Introduction
- GWB from compact binary coalescences (BBH): astrophysics
- GWB from first order phase transitions; cosmic strings: high energy physics
- GWB from 2nd 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; PBH)
- Transient GWs: theories of gravity
- Conclusions

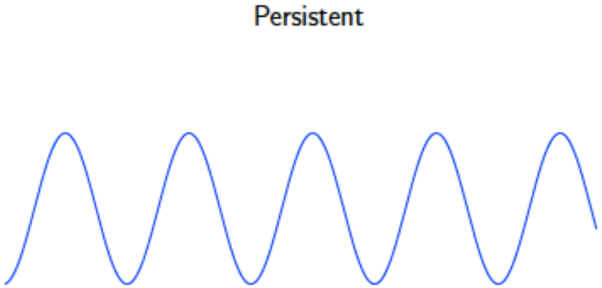
Introduction



Classification of GW signal morphologies

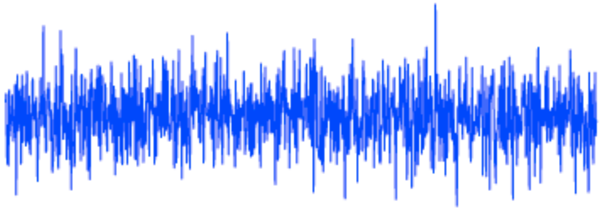


emitted by compact binaries



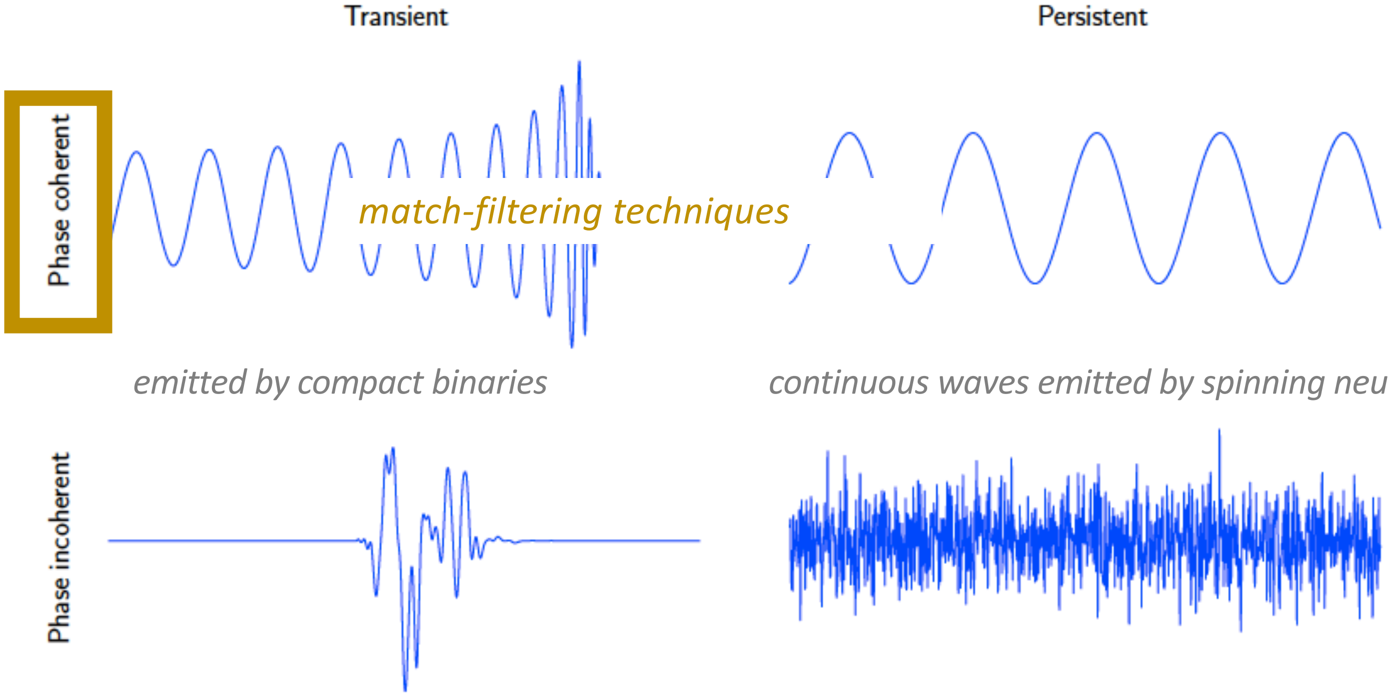
continuous waves emitted by spinning neutron stars

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

bursts emitted by core-collapse supernova

stochastic GW background

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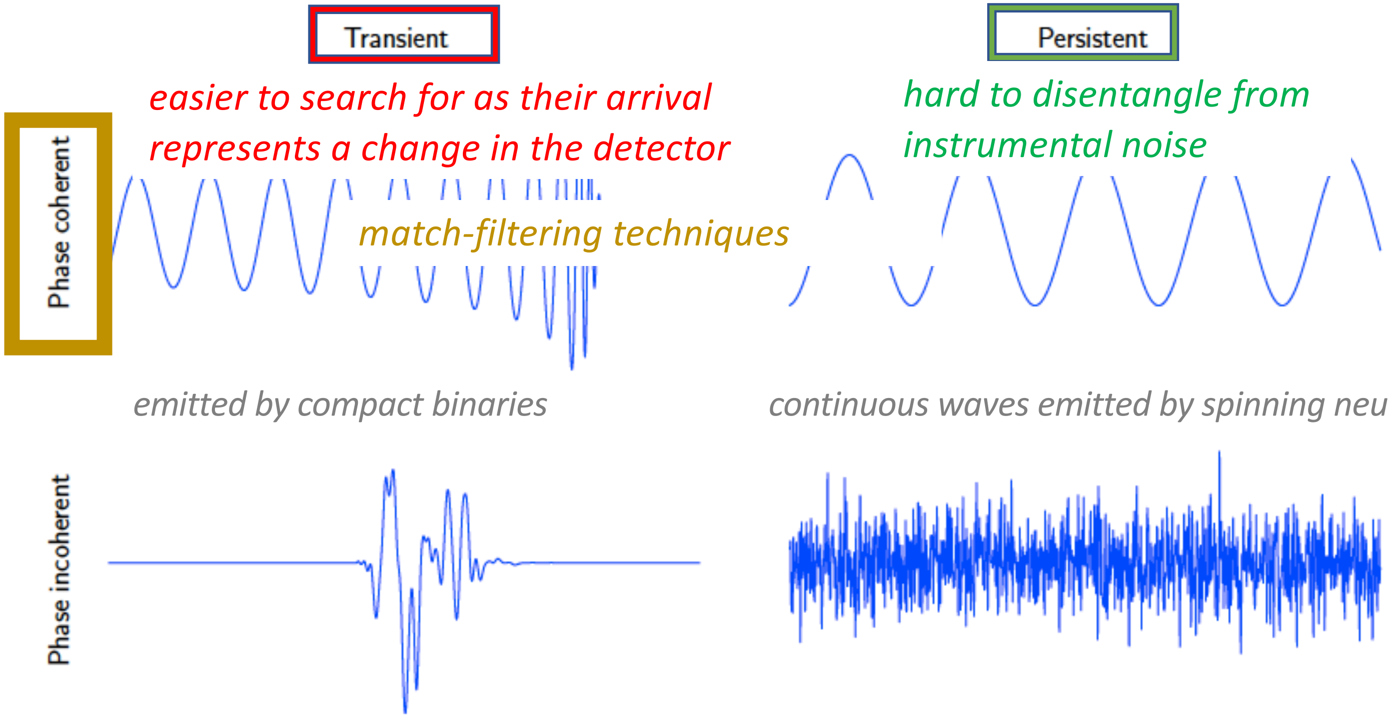


Transient

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

Persistent

hard to disentangle from instrumental noise

Phase coherent

match-filtering techniques

LVK Collaboration, arXiv: 1811.12907
arXiv:2010.14527
arXiv:2108.01045
arXiv: 2508.18082

emitted by compact binaries

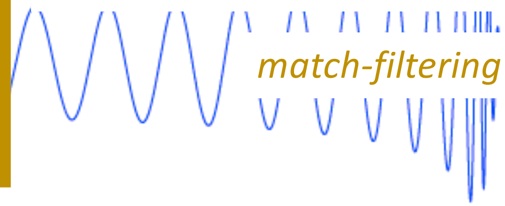
continuous waves emitted by spinning neutron stars

Phase incoherent

bursts emitted by core-collapse supernova

GW background

Classification of GW signal morphologies



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arXiv:2010.14527
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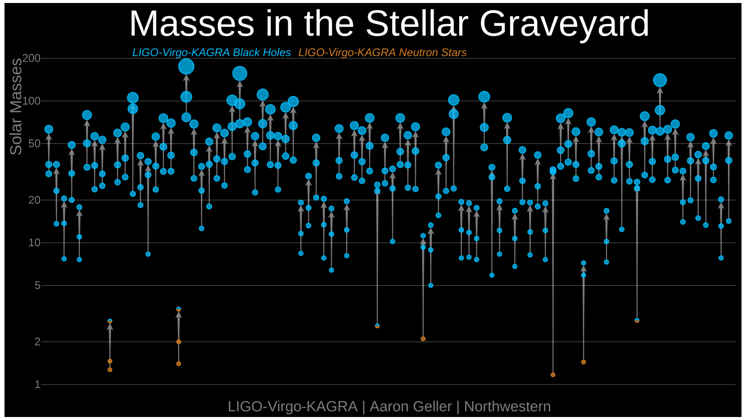
Current GW detection pipelines are based on match-filtering
-- quite successful, with over 200 confident detections



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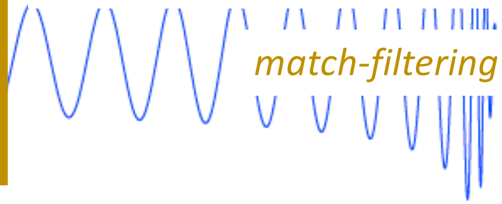
Phase coherent



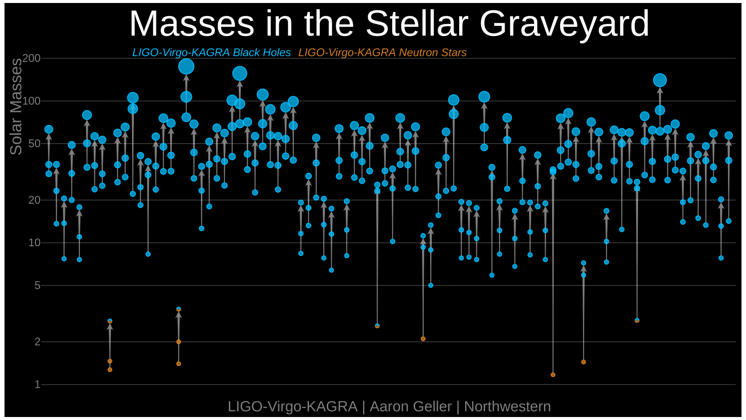
match-filtering techniques

emitted by compact binaries

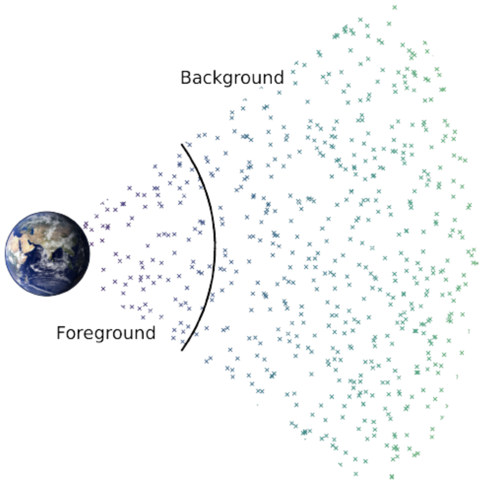
Algorithm to rapidly detect GWs from BBHs using **sparse dictionary coding**

*Badger, Srinivasa, Torres-Forne, Bizouard, Font, **Sakellariadou**, Lamberts, PRD (2025)*

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

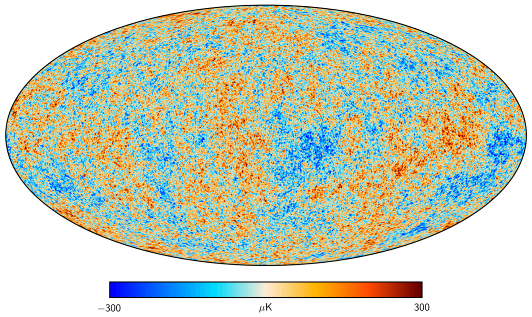


Gravitational-Wave Background (GWB)

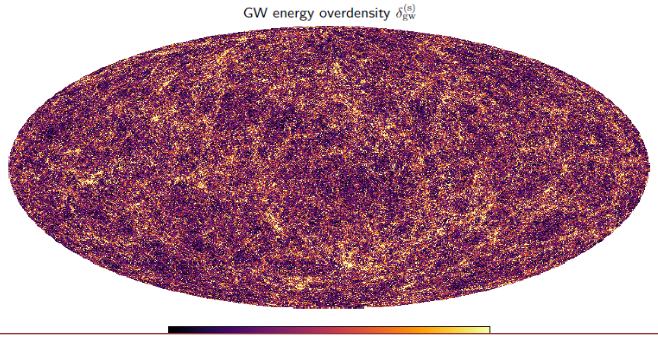


Credit: Alex Jenkins

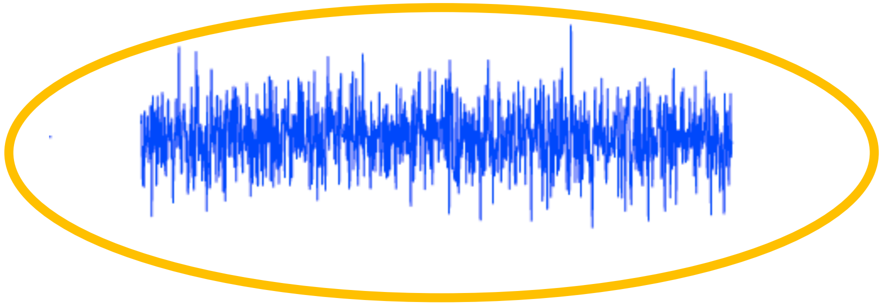
The Universe is permeated by a GWB generated in the early Universe



Planck Collaboration



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



random nondeterministic phase evolution
from a large number of distant sources

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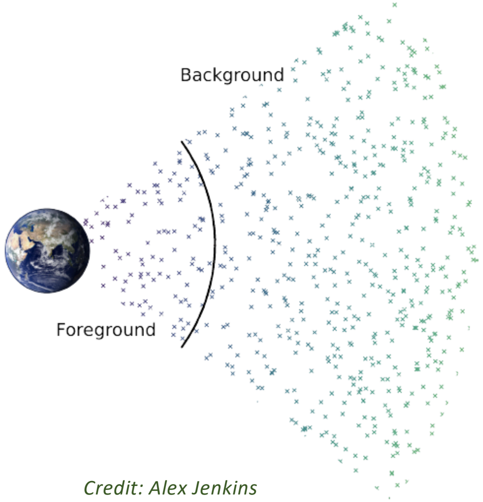

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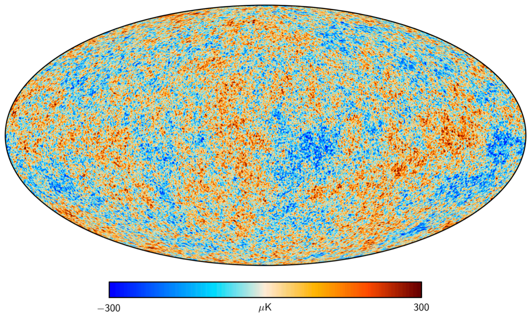

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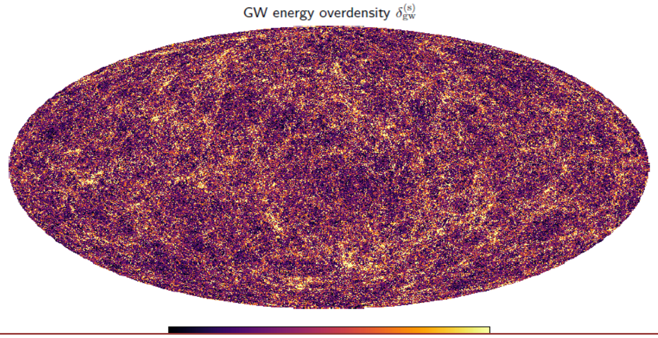
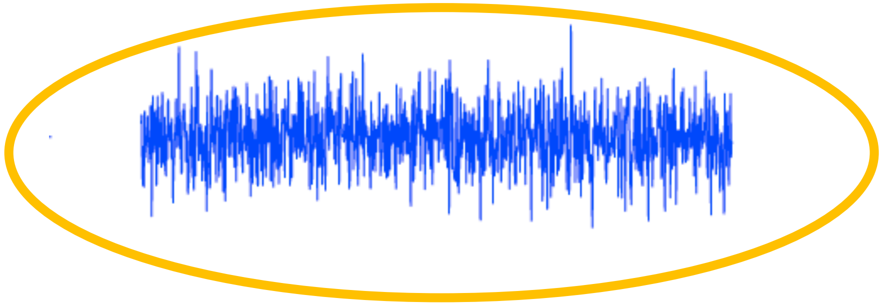


*Jenkins, **Sakellariadou,** Regimbau, Slezak, PRD 98, 063501 (2018)*

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

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

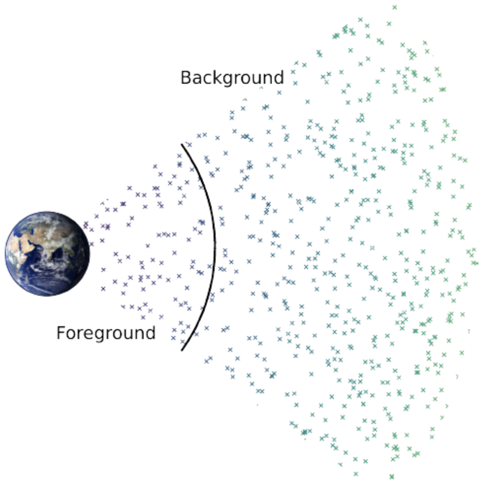
$$\Omega_{\mathrm{GW}}(f) = \Omega_{\mathrm{ref}}\left(\frac{f}{f_{\mathrm{ref}}}\right)^{\alpha}$$



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



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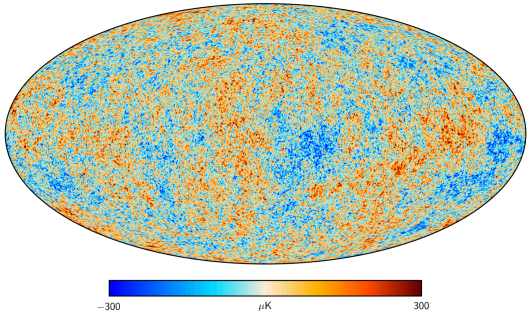
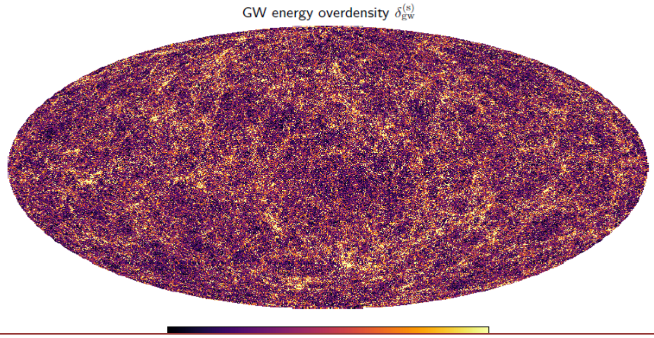


Planck Collaboration



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

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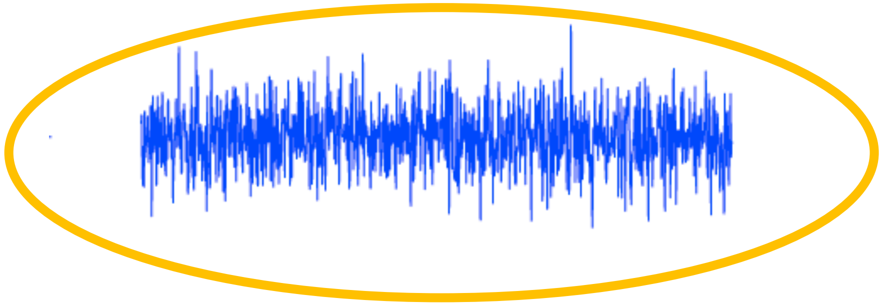
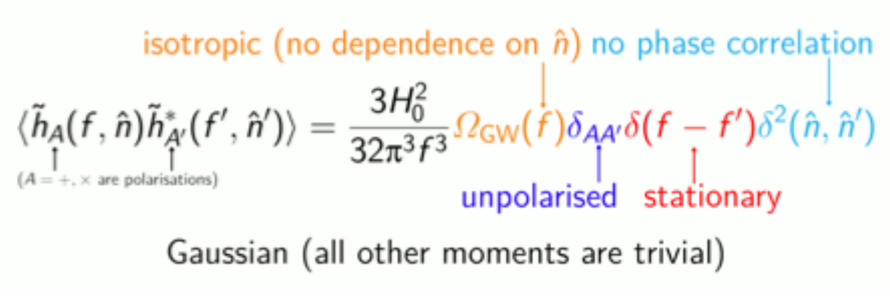


random nondeterministic phase evolution from a large number of distant sources



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

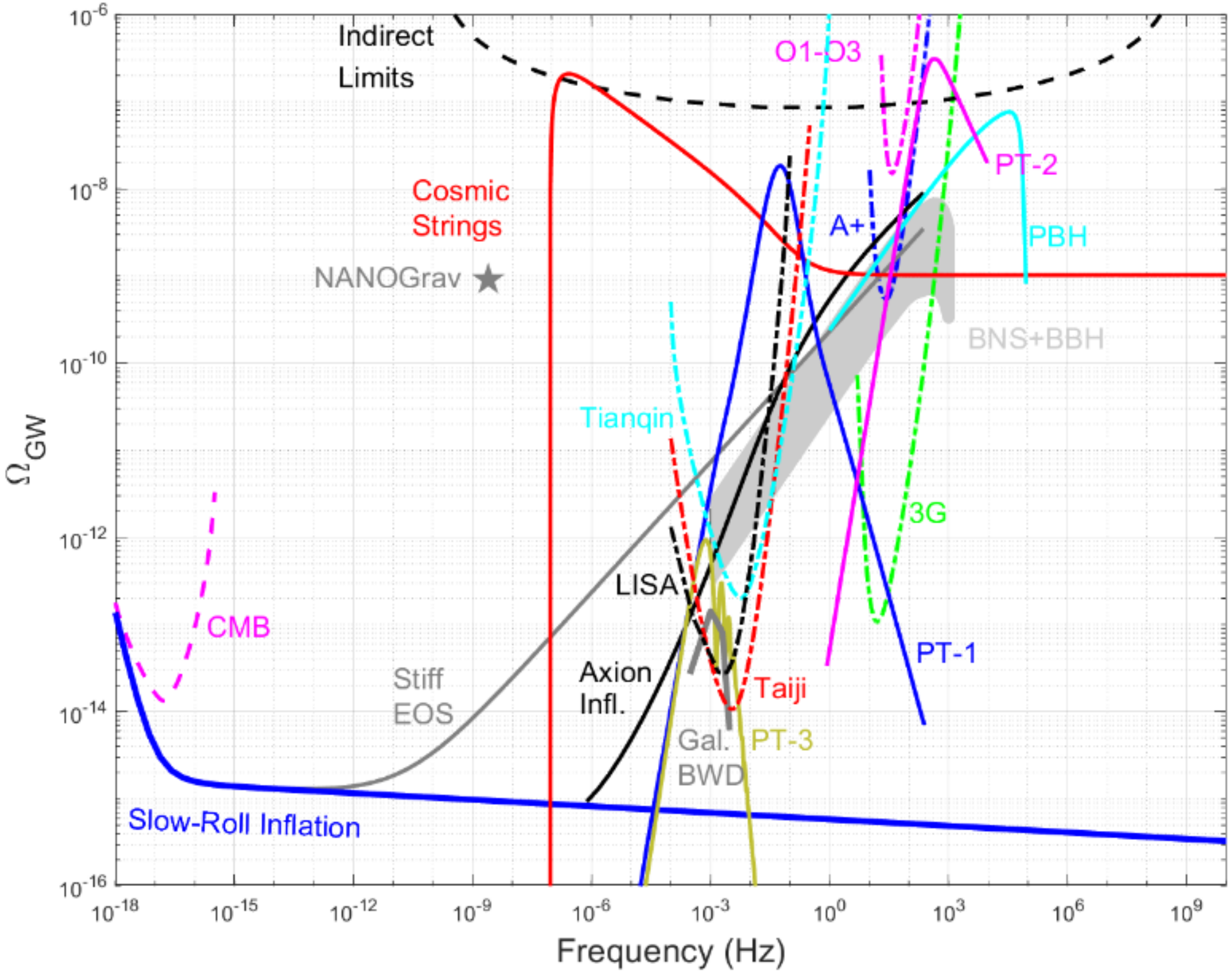
$$\langle \tilde{h}_A(f,\hat{n})\tilde{h}^*_{A'}(f',\hat{n}')\rangle = \frac{3H_0^2}{32\pi^3 f^3}\Omega_{\rm GW}(f)\delta_{AA'}\delta(f-f')\delta^2(\hat{n},\hat{n}')$$

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

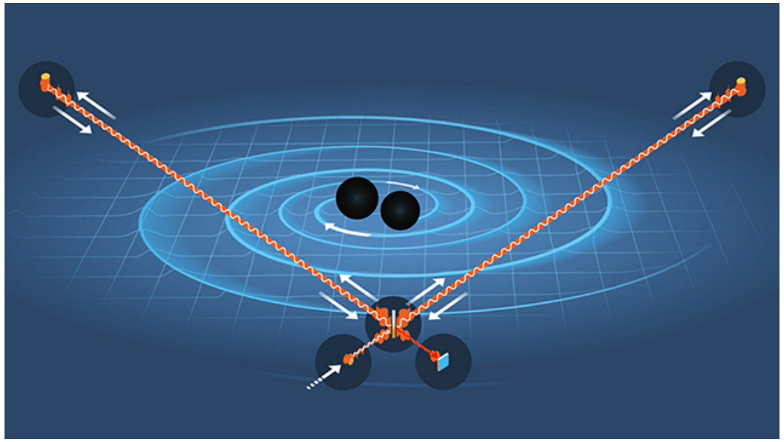
unpolarised stationary

Gaussian (all other moments are trivial)

Gravitational-Wave Background (GWB)



GWB: Detection methods



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:

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

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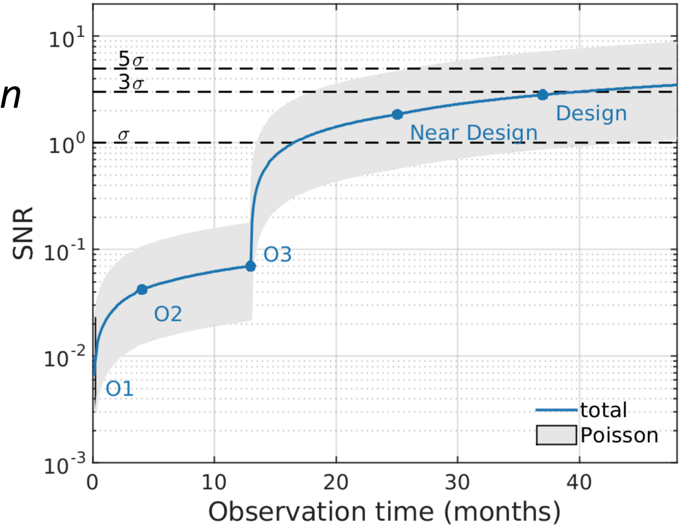

To detect a GWB take the correlation between two detector outputs:

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SNR grows (slowly) over time:

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

How do we detect a GWB ?

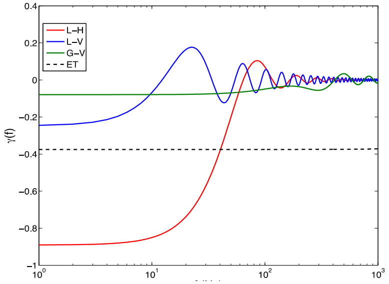
Assuming the GWB to be isotropic, Gaussian, stationary and unpolarised:

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

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

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

$\Gamma_{ij}(f)$



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

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

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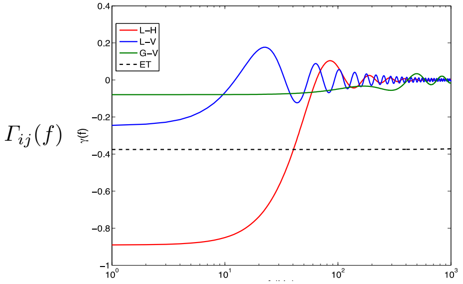


$$\boxed{\langle\tilde{h}_i^*(f)\tilde{h}_j(f')\rangle = \frac{1}{2}\delta_T(f-f')\Gamma_{ij}(f)S_{\mathrm{gw}}(f)}$$

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

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

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

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

what if:

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

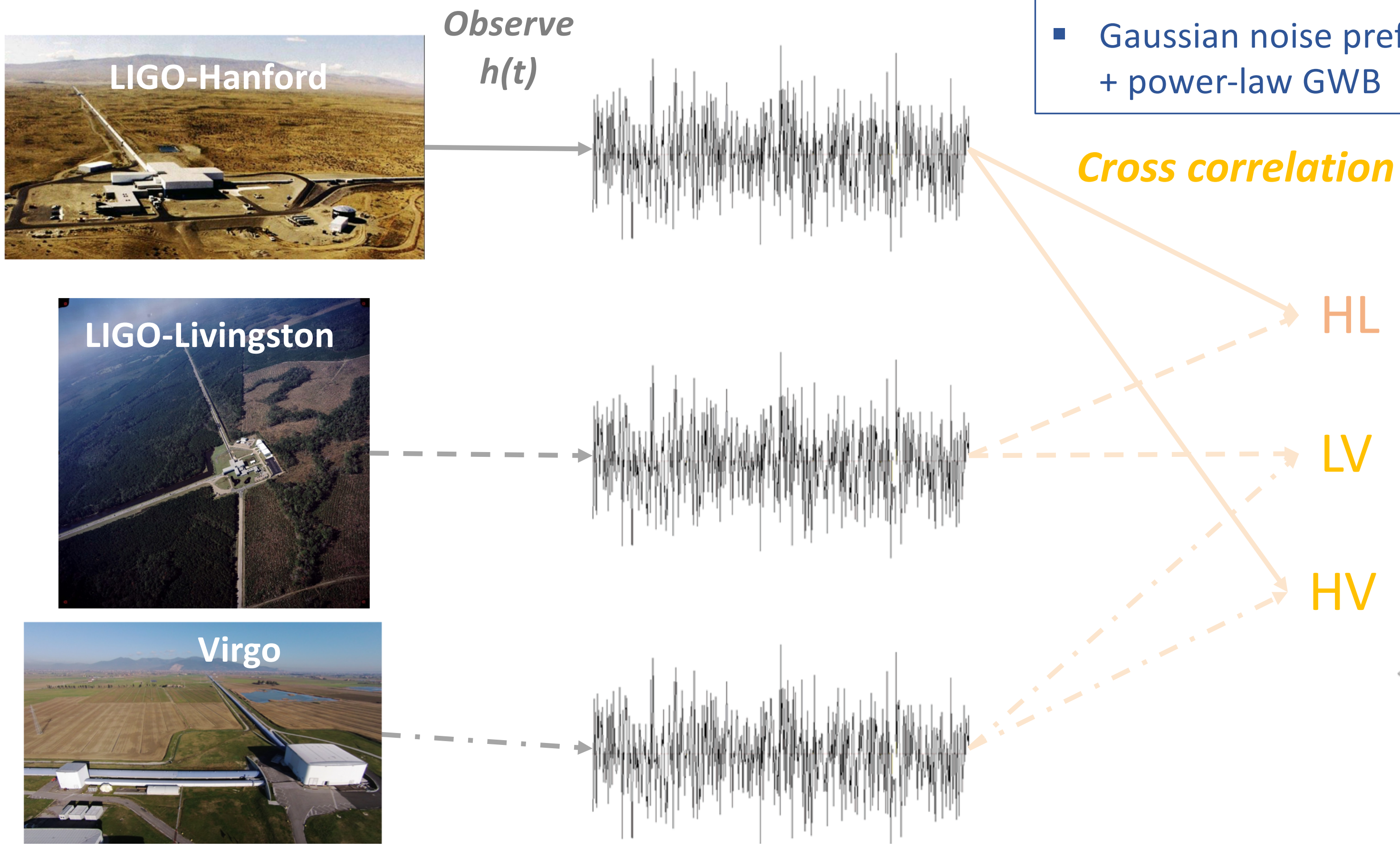
Joint magnetic +GWB fit : a novel approach

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

LVK Collaboration: GWB searches

Using the detector network

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



Cross correlation

HL

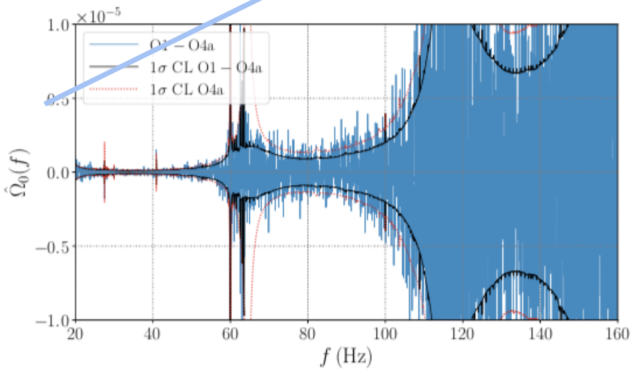
LV

HV

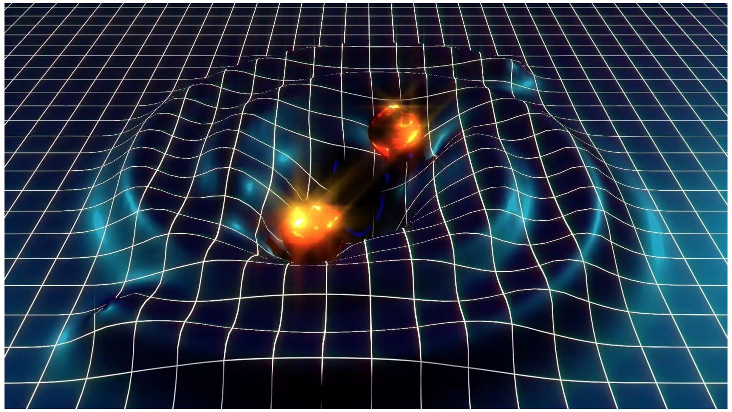
LVK Collaboration, arXiv:2508.20721

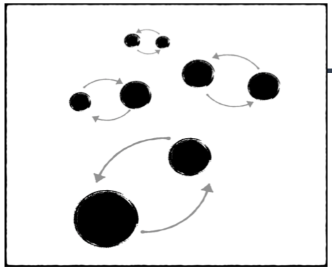
Optimal combination

C(f)



GWB : info about astrophysics





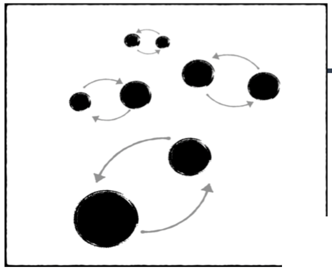
Implications for compact binaries: O4a search

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

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

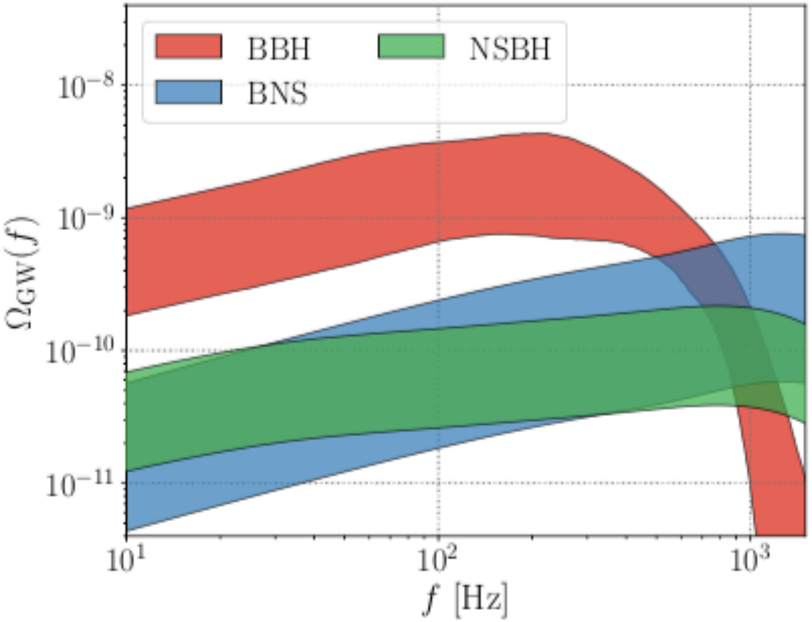
$$\frac{dE_{\mathrm{GW}}}{df} = \frac{(G\pi)^{2/3}}{3} \frac{m_1 m_2}{(m_1+m_2)^{1/3}} f^{-1/3}$$

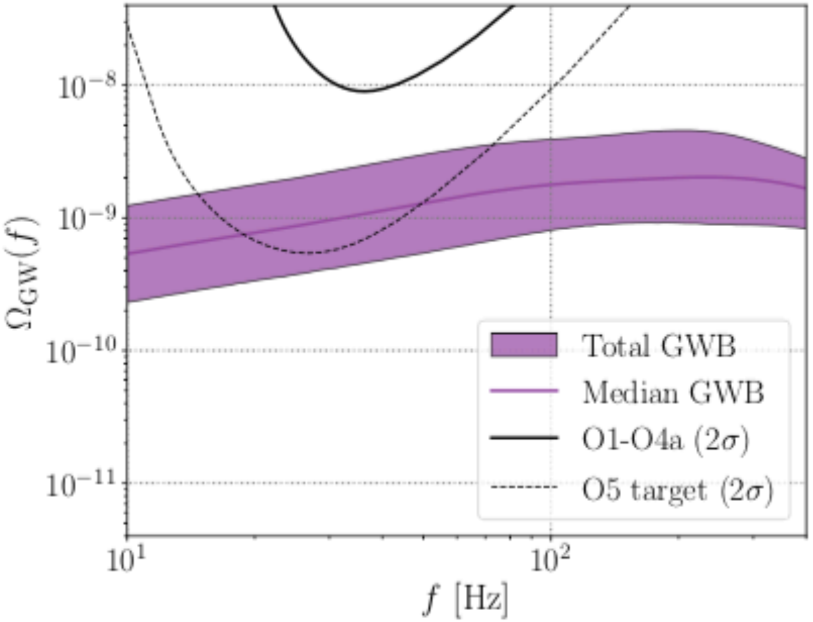
➡ CBC: α=2/3



Implications for compact binaries: O3 search

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





$$\boxed{\Omega_{\rm CBC}(25{\rm Hz}) = 0.9^{+1.1}_{-0.5} \times 10^{-9}}$$

$$\boxed{\Omega_{\rm BBH}(25\,{\rm Hz}) = 0.8^{+1.1}_{-0.5} \times 10^{-9}}$$

LVK Collaboration, arXiv:2508.20721

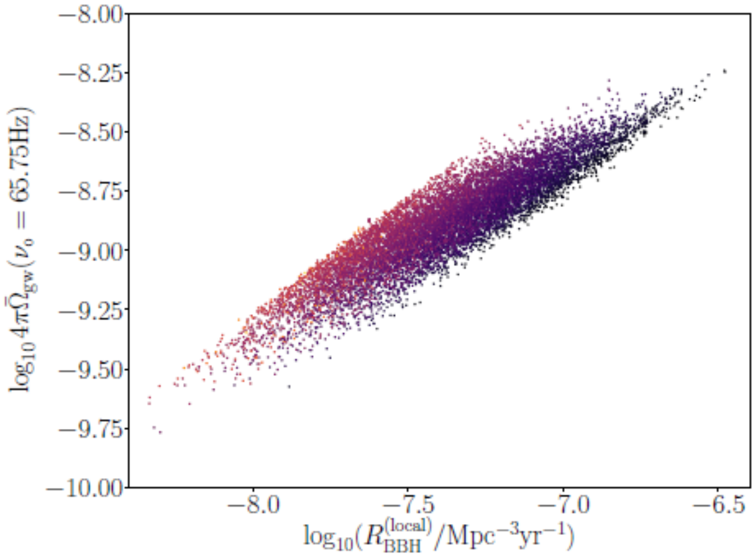
GWB from CBC: info about Compact Binaries

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

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

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

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 110 (2024) 023017*

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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

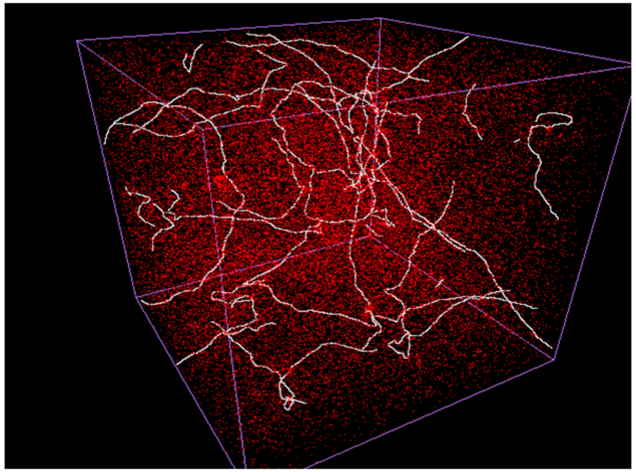
- GW background will present **anisotropies**

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

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

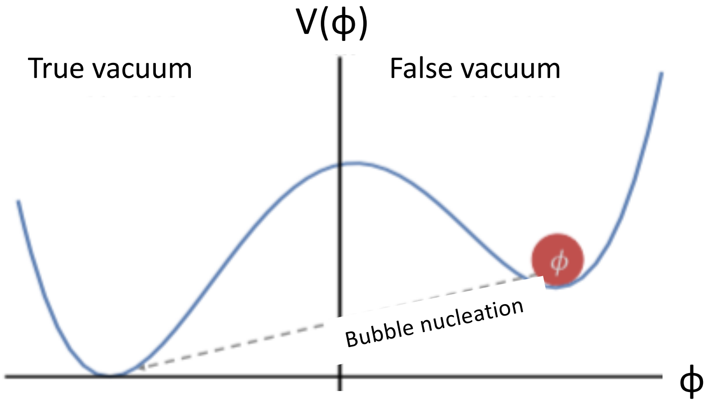
$$\int_{S^2} P(\hat{\Omega})d\hat{\Omega} = 1$$

GWB from cosmological sources

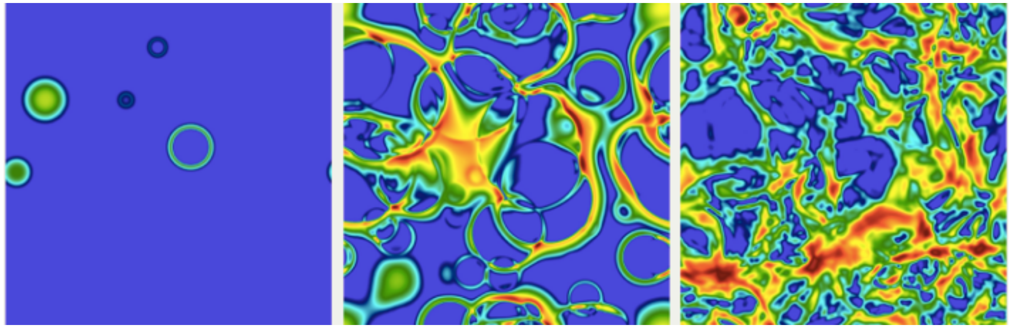


GWB from first order phase transition (FOPT): info Beyond the Standard Model

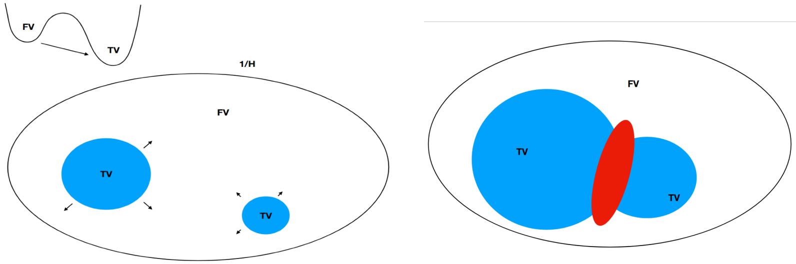
Many compelling extensions of the Standard Model predict strong FOPTs (e.g., GUTs, SUSY, extra dimensions, composite Higgs models, models with extended Higgs sector)



- 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)
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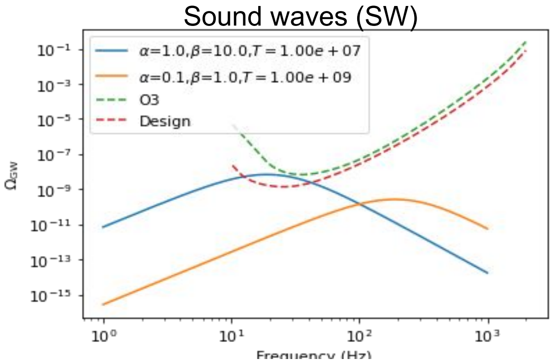
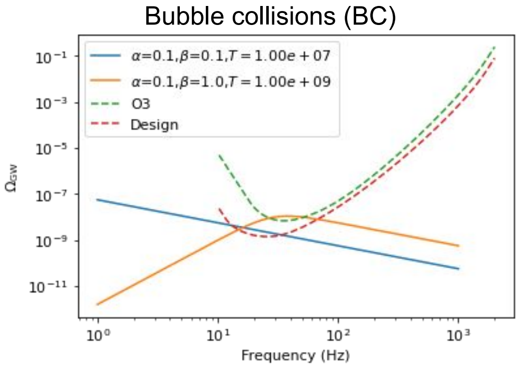
- Magnetohydrodynamic turbulence

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

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


Sound waves (SW)


Bubble collisions (BC)

α : strength of FOPT

β : inverse duration of FOPT

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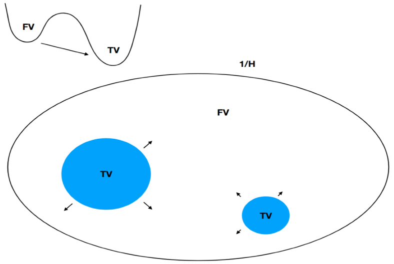

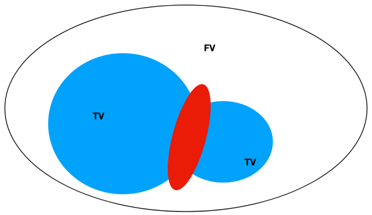

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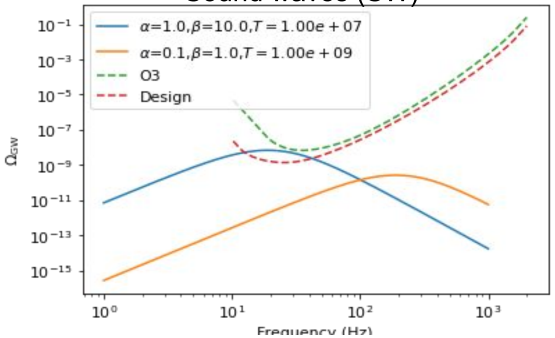

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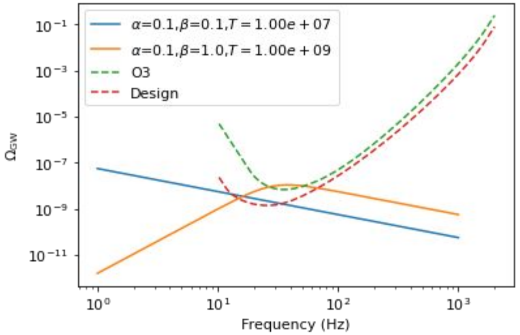

O1+O2+O3: For FOPT above 10^8 GeV

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

α : strength of FOPT

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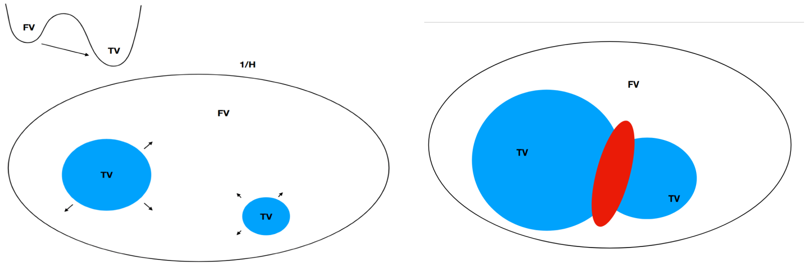
GWB from first order phase transition (FOPT): info Beyond the Standard Model



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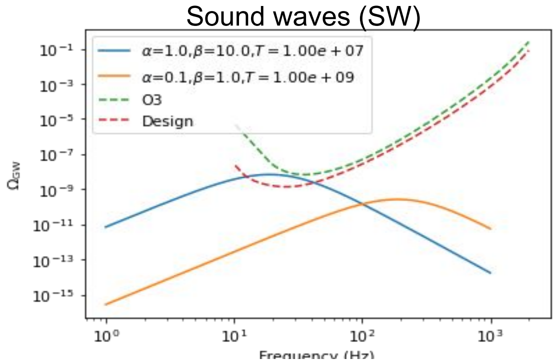
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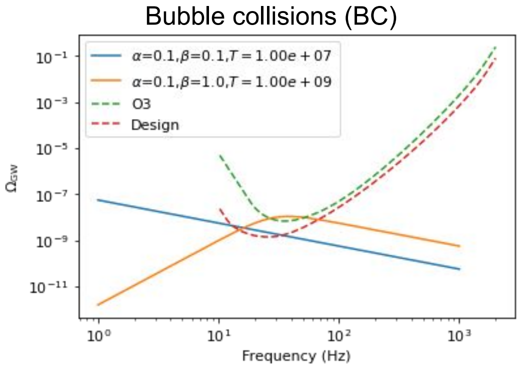
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O1+O2+O3: For FOPT above 10^8 GeV

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

Constrain parameters of particle physics models using GW data:

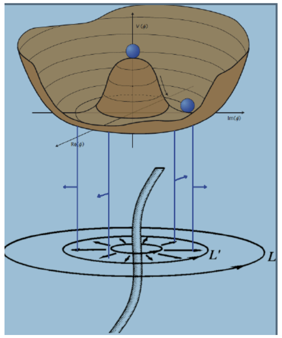
Supercooled FOPT

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



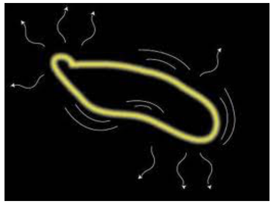
1dim topological defects formed in the early universe as a result of a PT followed by SSB, characterised by a vacuum manifold with non-contractible closed curves

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

Kibble (1976)

Generically formed in the context of GUTs

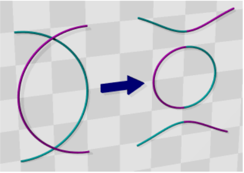
*Jeannerot, Rocher, **Sakellariadou**, PRD68 (2003) 103514*

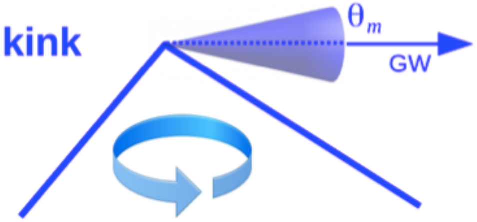


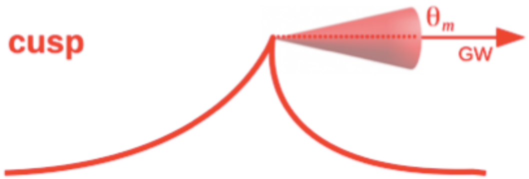
CS loops (length ℓ) oscillate periodically ($T = \ell/2$) in time emitting GWs (fundamental frequency $\omega = 4\pi/\ell$)

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

$G\mu \sim T^2_{\mathrm{SSB}}$







GWB from cosmic strings: info beyond Standard Model

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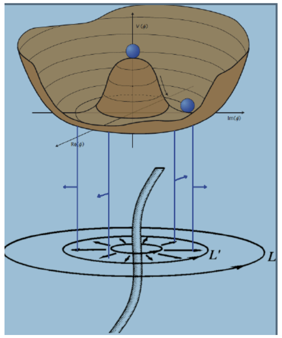

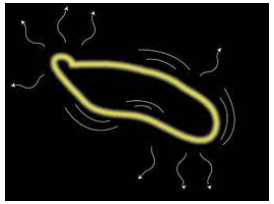

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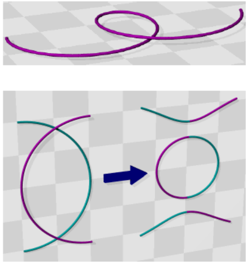
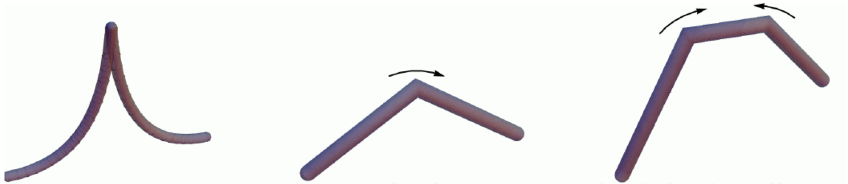




cusp
$\tilde{h} \sim f^{-4/3}$
beamed

kink
$\tilde{h} \sim f^{-5/3}$
beamed

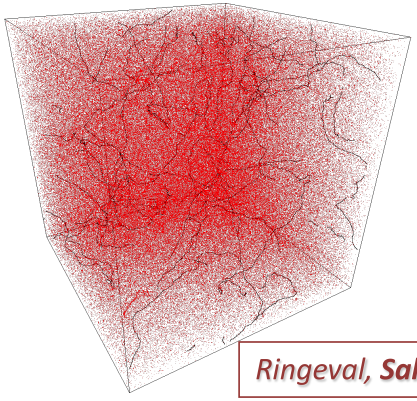
kink-kink collision
$\tilde{h} \sim f^{-2}$
isotropic

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

GWB from cosmic strings: info beyond Standard Model

$$\bar{\Omega}_{\rm gw} = \frac{2(G\mu)^2}{3\pi^2 H_0^2 \nu_0} \int_0^{t_*} \frac{{\rm d}t}{t^4} a^5 \int_0^{\gamma_*} \frac{{\rm d}\gamma}{\gamma} \bar{\mathcal{F}} \Theta\left(\gamma - \frac{2a}{\nu_0 t}\right) \left[N_{\rm k}^2 + 4A N_{\rm k} \left(\frac{\nu_0 \gamma t}{a}\right)^{1/3} + A^2 N_{\rm c} \left(\frac{\nu_0 \gamma t}{a}\right)^{2/3} \right]$$

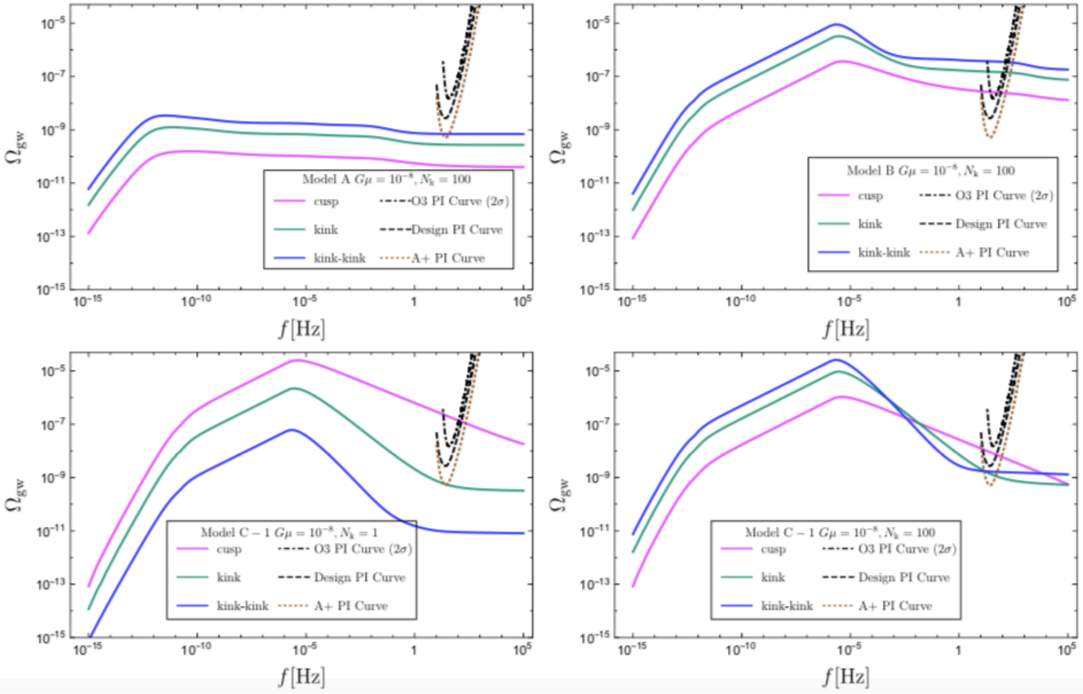


*Ringeval, **Sakellariadou**, Bouchet (2007)*

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

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

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

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

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)*
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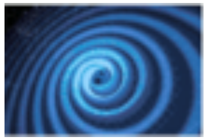
LVK Collaboration, PRL 126 (2021) 24, 241102

Can we distinguish between astrophysical vs cosmological sources?

GW models:

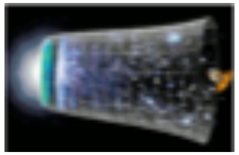
- CBC background

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



- 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 approximate sound waves contribution

Can we distinguish between astrophysical vs cosmological sources?

log-likelihood for a single detector pair

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

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

Model selection

To compare two models we use Bayes factors

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**

Martinovic, Meyers, Sakellariadou, Christensen, PRD 103 (2021) 4, 043023

GWB detection using machine learning

Novel hybrid approach that combines **deep learning** with **Bayesian inference** to identify and characterise the GWB more rapidly than current (cross-correlation) techniques.

- custom-designed multi-scale multi-headed autoencoder architecture to separate GWB signals from detector noise
- physics-informed training, curriculum learning (*start with easily separable, high-amplitude signals and progressively reduce amplitude to reach realistic low SNR*) for low SNR signals
- Marcov Chain Monte Carlo parameter estimation to disentangle the GWB components

A+ design sensitivity

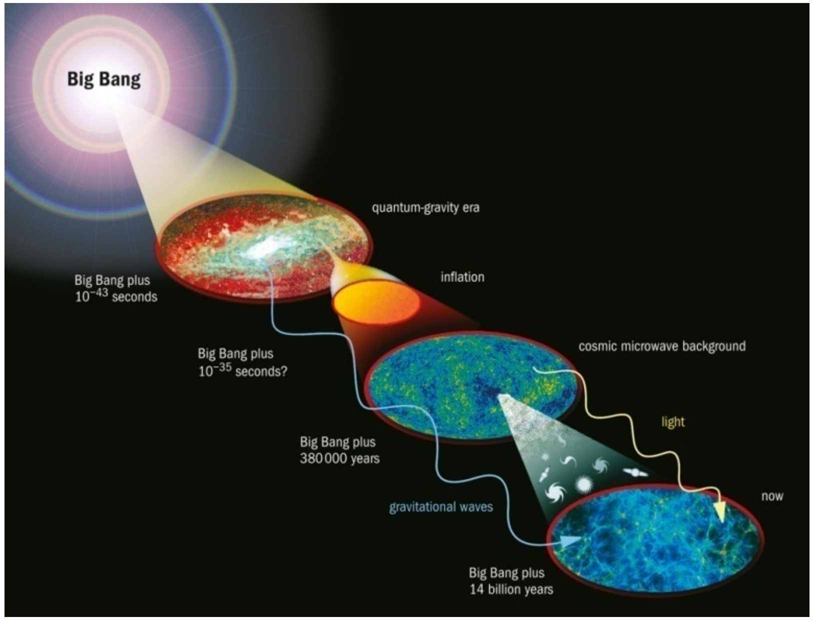
$$\Omega_{\mathrm{BBH}} \approx 10^{-9}$$

$$\Omega_{\mathrm{Cosmo}} \approx 1.3 \times 10^{-10}$$

using 47.4 days of training data

Einsle, Bizouard, Regimbau, ***Sakellariadou,*** *PRD (2025)*

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 $O\ (10^{-9})$

Planck (2020)

GWB extremely weak

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

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Matarrese, Pantano, Saez (1994)

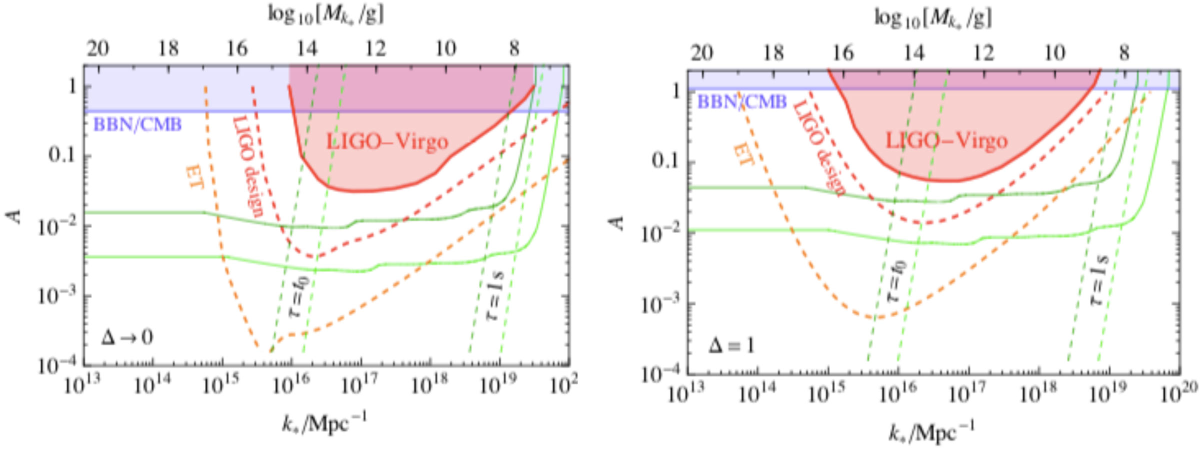
O1+O2+O3: upper limits on the amplitude of power spectrum and fraction of the DM in terms of ultralight PBHs

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

Khori, Terada (2018)

⬇

Ω_{GW}

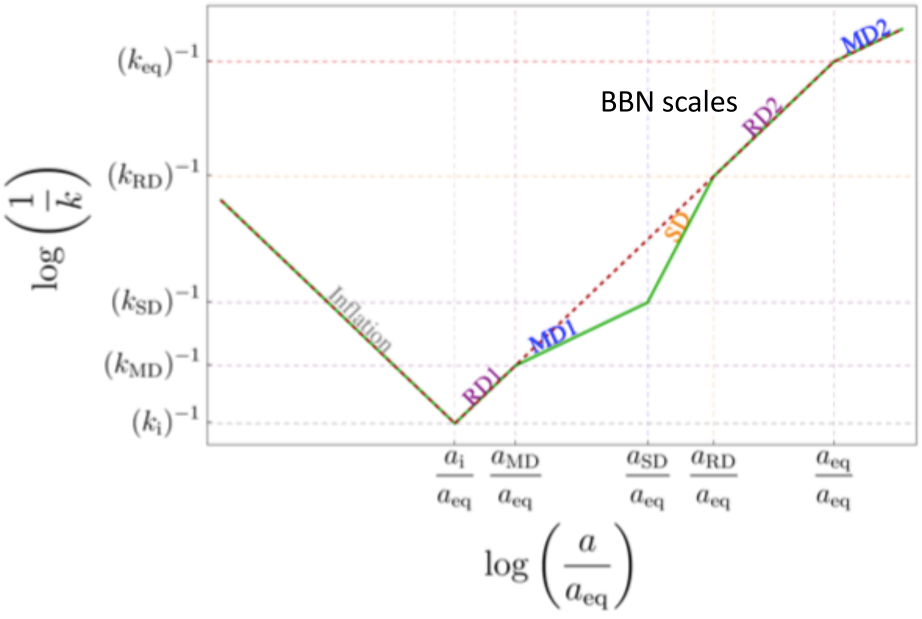


No evidence for such a GWB

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

*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

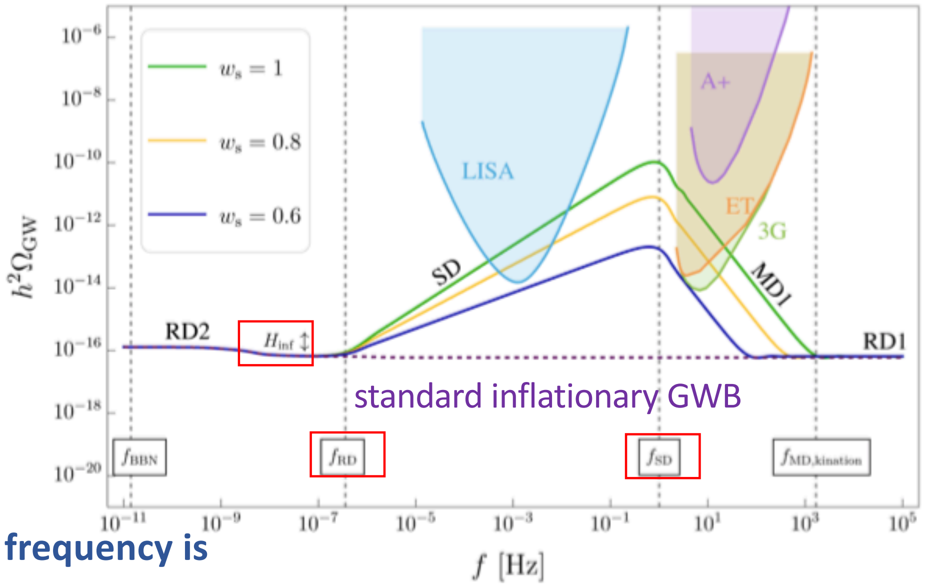


$1/3 < w \leq 1$

Stiff dominated era: blue-tilted inflationary GWB spectrum at f>f BBN

→ potentially detectable GWs

Giovannini (1998)



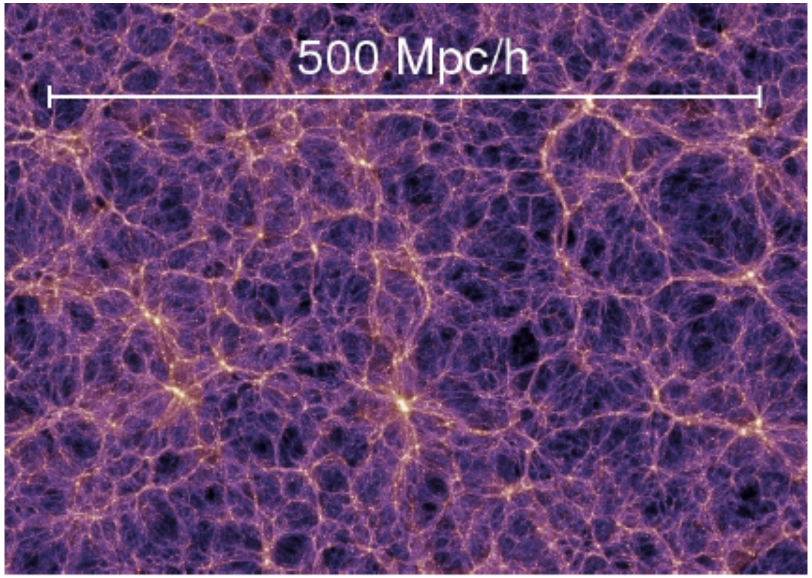
Most promising scenario for GWB detection, **kination**, with $w_s = 1$

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

Large parameter region that can be tested by future GW experiments (A+, LISA, 3g)

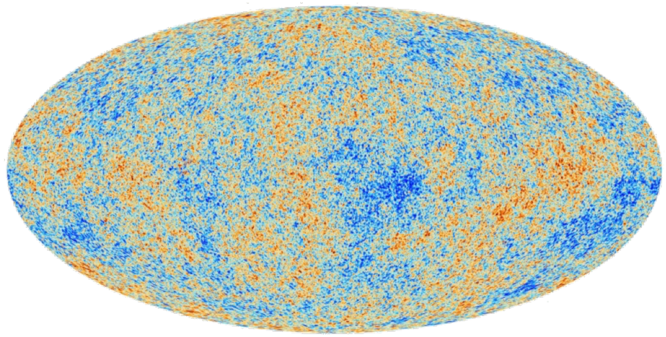
Duval, Kuroyanagi, Mariotti, Romero-Rodriguez, ***Sakellariadou****, PRD 110 (2024) 023017*

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)



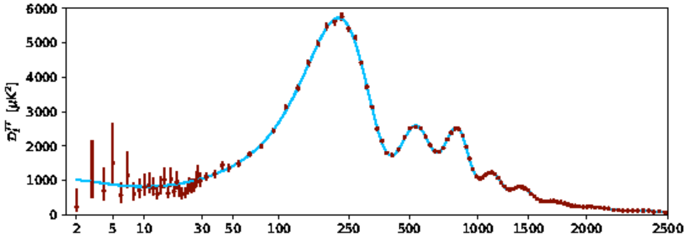


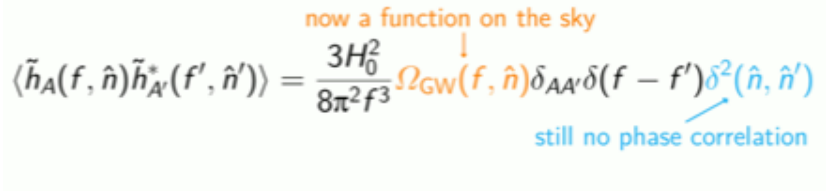
Image credit: Planck collaboration

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

GWB

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

→ LSS



now a function on the sky

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

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:

$$\boxed{\Omega_{\mathrm{gw}}(f_0, \hat{e}_0) \equiv \bar{\Omega}_{\mathrm{gw}}(1+\delta_{\mathrm{gw}})}$$

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

2PCF :

$$\boxed{C_{\mathrm{gw}}(\theta_0, f_0) \equiv \langle \delta^{(\mathrm{s})}_{\mathrm{gw}}(f_0, \hat{e}_0)\delta^{(\mathrm{s})}_{\mathrm{gw}}(f_0, \hat{e}'_0)\rangle}$$

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

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

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

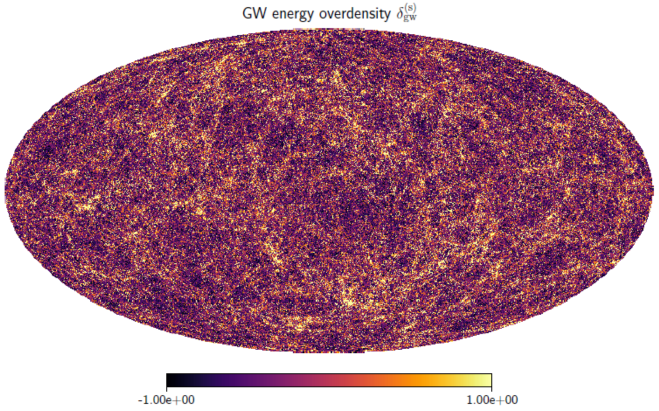
$$\boxed{C_{\rm gw}(\theta,f_0) = \sum_{\ell=0}^{\infty}\frac{2\ell+1}{4\pi}C_\ell(f_0)P_\ell(\cos\theta_0)}$$

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

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

$$\boxed{C_\ell^{1/2} \sim 10^{-12}\,{\rm sr}^{-1}\ \text{for}\ 1\leq\ell\leq 4.}$$

*Jenkins, Regimbau, **Sakellariadou**, Slezak, PRD 98, 063501 (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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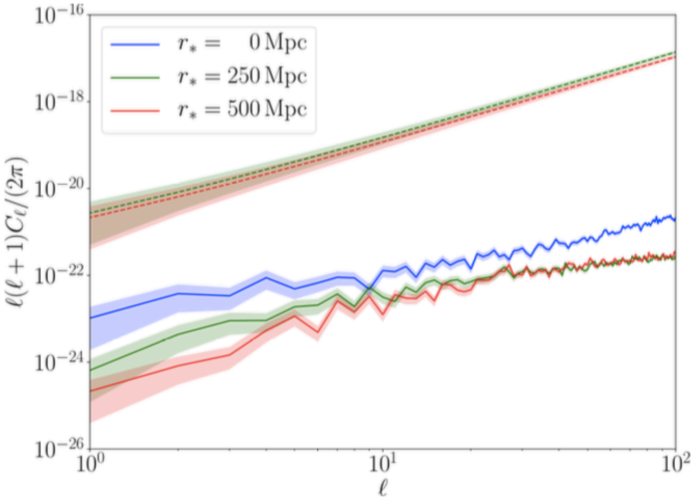
*Bellomo, **Sakellariadou**, et al, JCAP 06 (2022) 06, 030*

- 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*



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*

- 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*

- 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

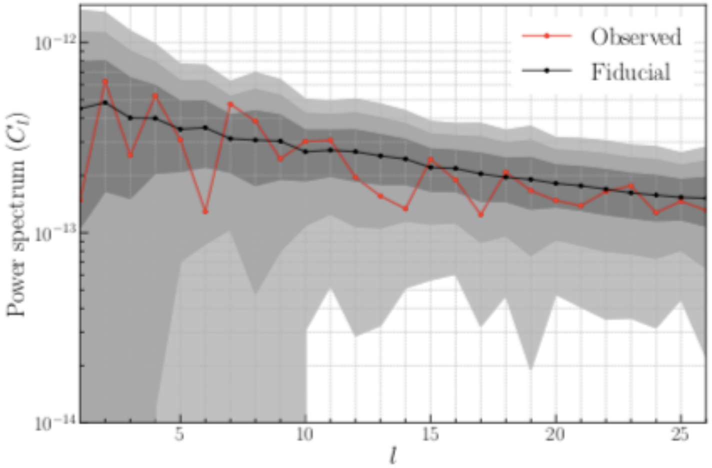
*Kouvatsos, Jenkins, Renzini, Romano, **Sakellariadou**, PRD 109 (2024) 103535*

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**

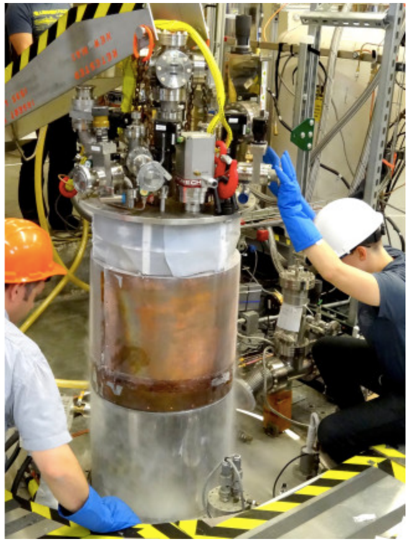
As a first application, we use the BBH mergers observed during the O3 to test the spatial distribution of these sources



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



- **Dark matter**: microphysics ---- 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**

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**

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

Boehm, Fayet, Schaeffer (2001)

Predict a cutoff in the linear matter power spectrum at large wave numbers k

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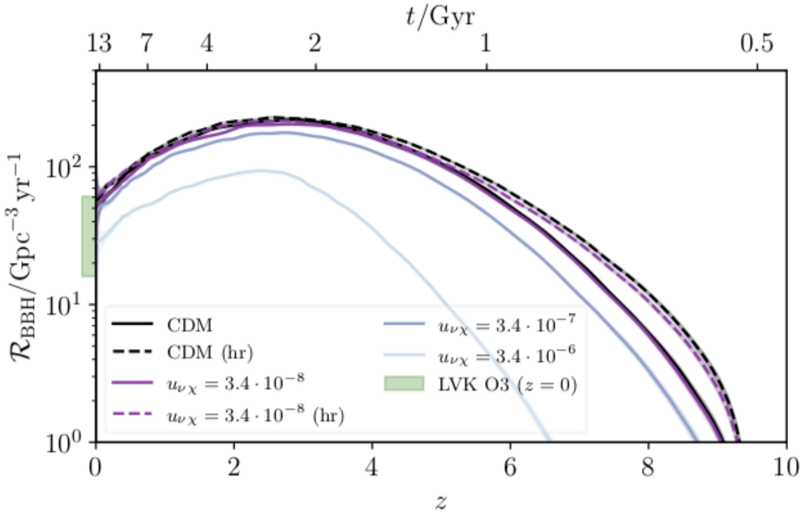
- **Warm Dark Matter** --- **Interacting Dark Matter** --- **Fuzzy Dark Matter**

Predict a cutoff in the linear matter power spectrum at large wave numbers k

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



DM neutrino interacting model

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

interaction strength

Suppression of small-scale structure

— caused by interacting, warm, or fuzzy DM —leads to a significant **reduction in the rate of BBH mergers at** z>5

detectable by 3g detectors

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

- **Dark matter**: axion fields ---- First Constraints on Nuclear Coupling of Axionlike Particles from BNS GW170817

Inside NS axion potential receives finite density corrections

Phase transition shifting VEV of axion field from 0 to a non-zero value

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***

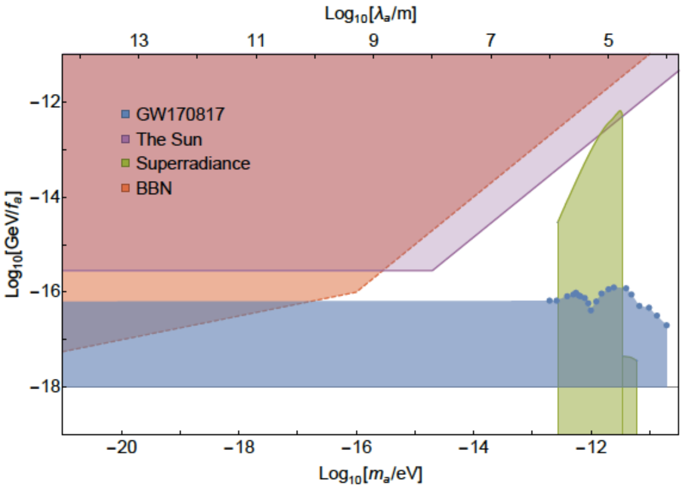
Huang, Johnson, Sagunski, ***Sakellariadou****, Zhang,* Phys. Rev. D 99, 063013 (2019)

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

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

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

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



- **Dark matter**: primordial black holes ---- GWB from PBH binaries using data from O1-O3 LVK observing runs

$$f_{\rm PBH} = \Omega_{\rm PBH}/\Omega_{\rm DM}$$

mass function of PBHs

$$p(m) = \frac{1}{\rho_{\rm PBH}} \frac{{\rm d}\rho_{\rm PBH}}{{\rm d}\ln m}.$$

Consider *monochromatic* (MN) and *agnostic log-normal* (ALN) Gaussian distribution

$$p(m) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(\ln m - \ln \mu)^2}{2\sigma^2}\right]$$

*Boybeyi, Clesse, Kuroyanagi, **Sakellariadou**, PRD (2025)*

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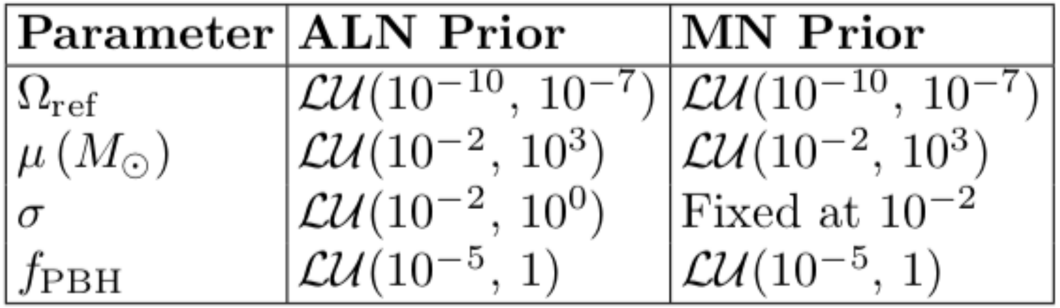

Parameter	**ALN Prior**	**MN Prior**
Ω_{ref}	$\mathcal{LU}(10^{-10},\, 10^{-7})$	$\mathcal{LU}(10^{-10},\, 10^{-7})$
$\mu\,(M_\odot)$	$\mathcal{LU}(10^{-2},\, 10^{3})$	$\mathcal{LU}(10^{-2},\, 10^{3})$
σ	$\mathcal{LU}(10^{-2},\, 10^{0})$	Fixed at 10^{-2}
f_{PBH}	$\mathcal{LU}(10^{-5},\, 1)$	$\mathcal{LU}(10^{-5},\, 1)$

*Boybeyi, Clesse, Kuroyanagi, **Sakellariadou**, PRD (2025)*

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$f_{\rm PBH}$	$\mathcal{LU}(10^{-5}, 1)$	$\mathcal{LU}(10^{-5}, 1)$

Consider early and late binaries formation

Early binaries: formed in RDE shortly after PBH formation

Late binaries**: formed much later due to clustering of PBHs during MDE. This clustering increases likelihood of PBH encounters and interactions, **enhancing the merger rate

*Boybeyi, Clesse, Kuroyanagi, **Sakellariadou**, PRD (2025)*

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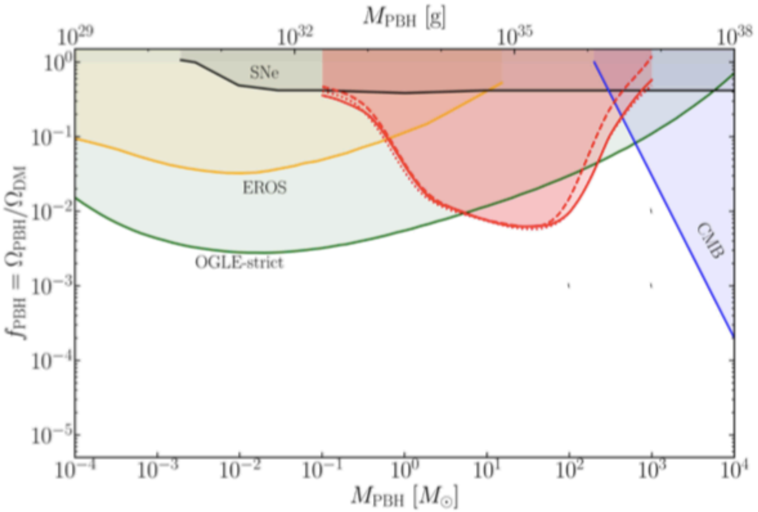
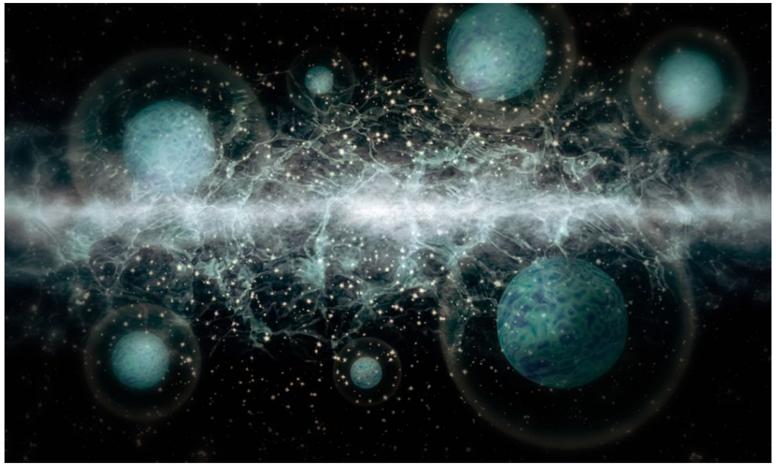


No significant GWB associated with PBHs from O1-O3

*Boybeyi, Clesse, Kuroyanagi, **Sakellariadou**, PRD (2025)*

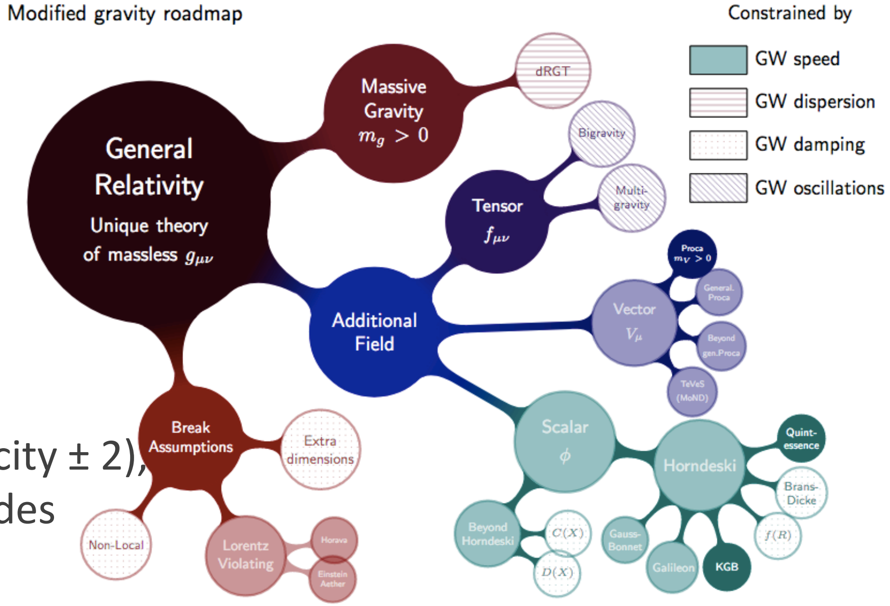
Information about theories of gravity



- **Models of Gravity**:

GWs in a modified theory of gravity may differ from GR in:

- **generation** : relates outgoing radiation to properties of source
  (*hard problem even in GR*)
- **propagation** : e.g., dispersion, birefringence, amplitude damping
- **polarisation** : up to six modes of polarisation -- two tensor (helicity ± 2),
  two vector (helicity ± 1), two scalar (helicity 0) modes
- **remnant properties**



Ezquiaga, Zumalacarregu (2018)

Tests of GW propagation : dispersion

phenomenological parameters

$$E^2 = p^2c^2 + \underbrace{A_\alpha p^\alpha c^\alpha}$$

massive gravity

$A_0 > 0$

$m_g = A_0^{1/2}/c^2$

doubly special relativity

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

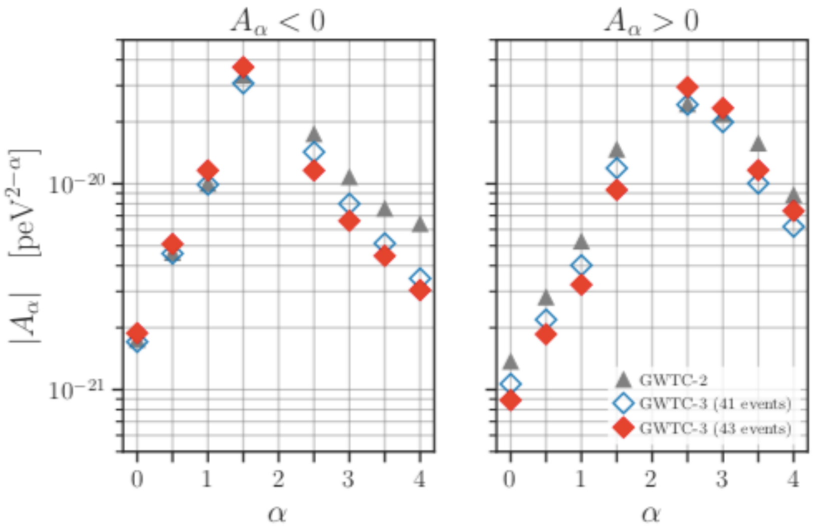
multi-fractal ST

Horava-Lifshitz & extra dim

Frequency dependence of speed of GWs

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

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



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

LVK (2021)

Tests of GW propagation : parity violation

$$\begin{pmatrix}\langle h_R(f,\hat{\Omega})h_R^*(f',\hat{\Omega}')\rangle \\ \langle h_L(f,\hat{\Omega})h_L^*(f',\hat{\Omega}')\rangle\end{pmatrix} = \frac{\delta(f-f')\delta^2(\hat{\Omega}-\hat{\Omega}')}{4\pi}\begin{pmatrix}I(f,\hat{\Omega})+V(f,\hat{\Omega}) \\ I(f,\hat{\Omega})-V(f,\hat{\Omega})\end{pmatrix}$$

V=0: the correlator of unpolarised GWB

$$\boxed{\Omega'_{\mathrm{GW}} = \Omega_{\mathrm{GW}}\left[1+\Pi(f)\frac{\gamma_V^{d_1 d_2}(f)}{\gamma_I^{d_1 d_2}(f)}\right]}$$

Polarisation degree

$$\Pi(f) = V(f)/I(f)$$

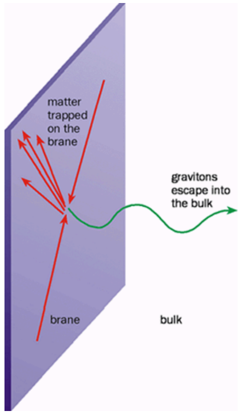
-1 : fully L polarisation
1 : fully R polarisation
0 : unpolarised isotropic GWB

Search for parity violation in O3 data with a uniform power in Π in [-1,1]

No evidence for parity violation in the O3 data of LVK Collaboration

*Martinovic, Badger, **Sakellariadou**, Mandic, PRD 104 (2021) 8, L081101*

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

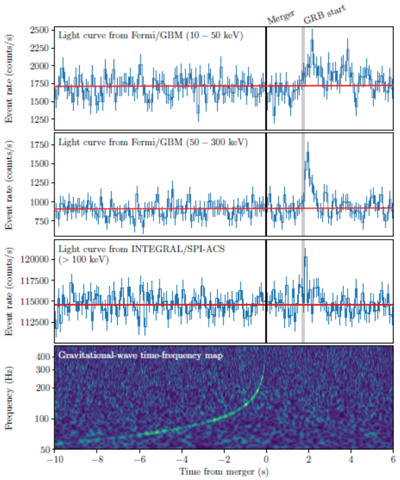
$$\boxed{h \propto \frac{1}{d_L^{\mathrm{GW}}} = \frac{1}{d_L^{\mathrm{EM}}}\left[1+\left(\frac{d_L^{\mathrm{EM}}}{R_c}\right)^n\right]^{-(D-4)/(2n)}}$$

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

***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

What if there is no electromagnetic counterpart?

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

Hordenski theories, Beyond-Hordenski theories and Degenerate Higher-Order Scalar-Tensor (DHOST) theories

Spontaneously break Lorentz invariance $c_T < 1$

If UV completion is required to be Lorentz invariant ⟶ graviton speed becomes luminal at high energies

Frequency-dependent propagation speed can also arise in any scenario of gravity where the **spectral dimension of spacetime changes with the probed scale**

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

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

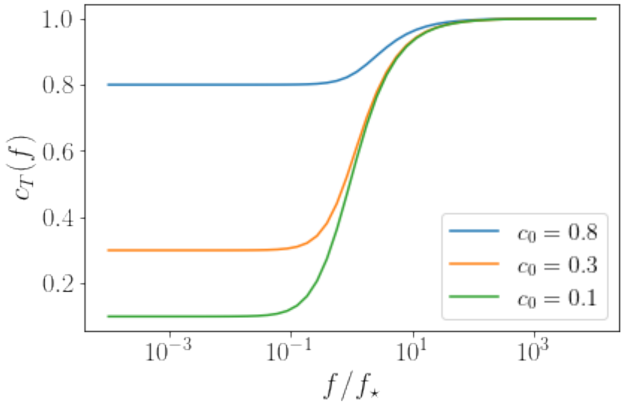
Construct a function for $c_T(f)$ which satisfies the LIGO-Virgo bounds whilst modify the millihertz regime significantly

What if there is no electromagnetic counterpart?

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

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

- Polynomial ansatz $$c_T(f) = 1 + \sum_n \beta_n \left(\frac{f}{f_*}\right)^n$$ LIGO bound implies: $$|\beta_n| \lesssim 10^{-15-n}(f_*/\mathrm{Hz})^n$$
- EFT-inspired ansatz $$c_T(f) = \left[1 + \frac{f_\star^2}{f^2} - \frac{f_\star^2}{f^2}\sqrt{1 + 2\left(1 - c_0^2\right)\frac{f^2}{f_\star^2}}\right]^{1/2}$$

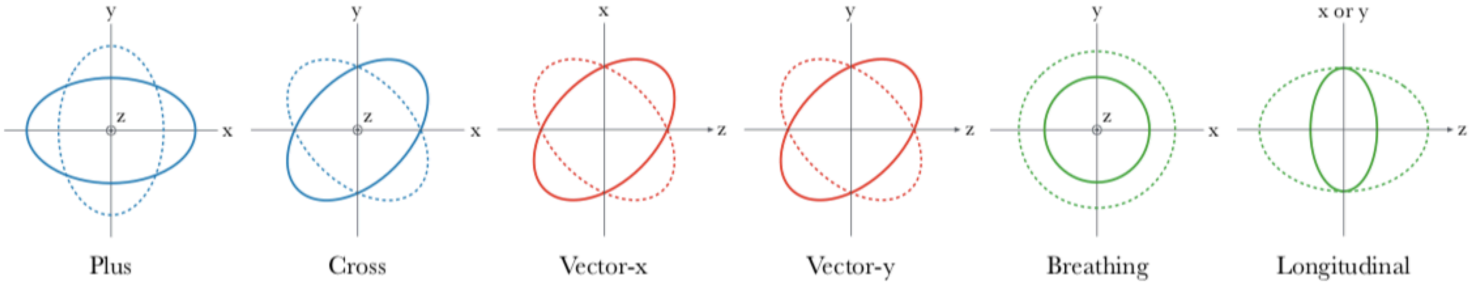


Derive how GW waveforms (amplitude; phase) are modified wrt GR

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

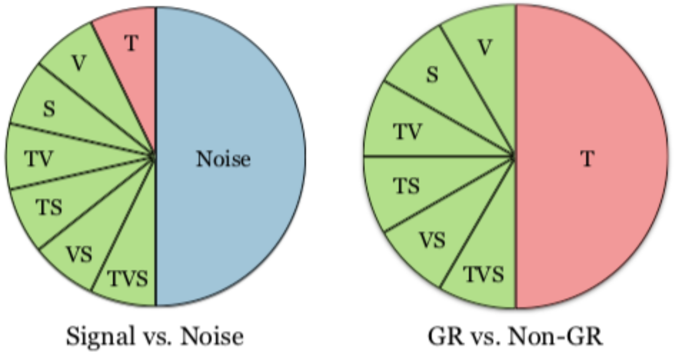
*Baker , **Sakellariadou**, et al, JCAP2022*

Polarisations : GW background



$$\Omega_{\rm TVS}(f) = \Omega_0^T \left(\frac{f}{f_0}\right)^{\alpha_T} + \Omega_0^V \left(\frac{f}{f_0}\right)^{\alpha_V} + \Omega_0^S \left(\frac{f}{f_0}\right)^{\alpha_S}$$

Bayesian method to detect and characterise GWB polarisation



The population of events observed by LIGO/Virgo is consistent with the pure tensorial hypothesis, as predicted by GR

*Callister, **Sakellariadou**, et al, PRX (2017)*

Remnant properties

- ○ **Ringdown**

GR: **no-hair conjecture**

Remnant from coalescence of two astrophysical BHs: perturbed Kerr BH

It relaxes to its Kerr stationary state by emitting GWs corresponding to specific characteristic quasi-normal modes (**frequency f and damping time τ depend solely on BH mass and dimensionless spin χ)**

LVK data agreement with Kerr remnants

LVK (2021)

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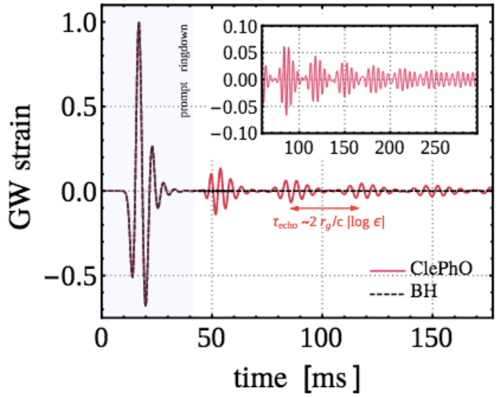
LVK (2021)

○ Echoes

Exotic Compact Objects (ECOs), more massive than neutron stars but without horizons

Cardoso, Pani (2017)



- GW pulse traveling interacts with the object
- Pulse is semi-trapped between the object and the photosphere
- Upon each interaction, **a fraction exits to outside observers**

Observers see a **series of echoes whose amplitude is getting smaller and whose frequency content is also going down**

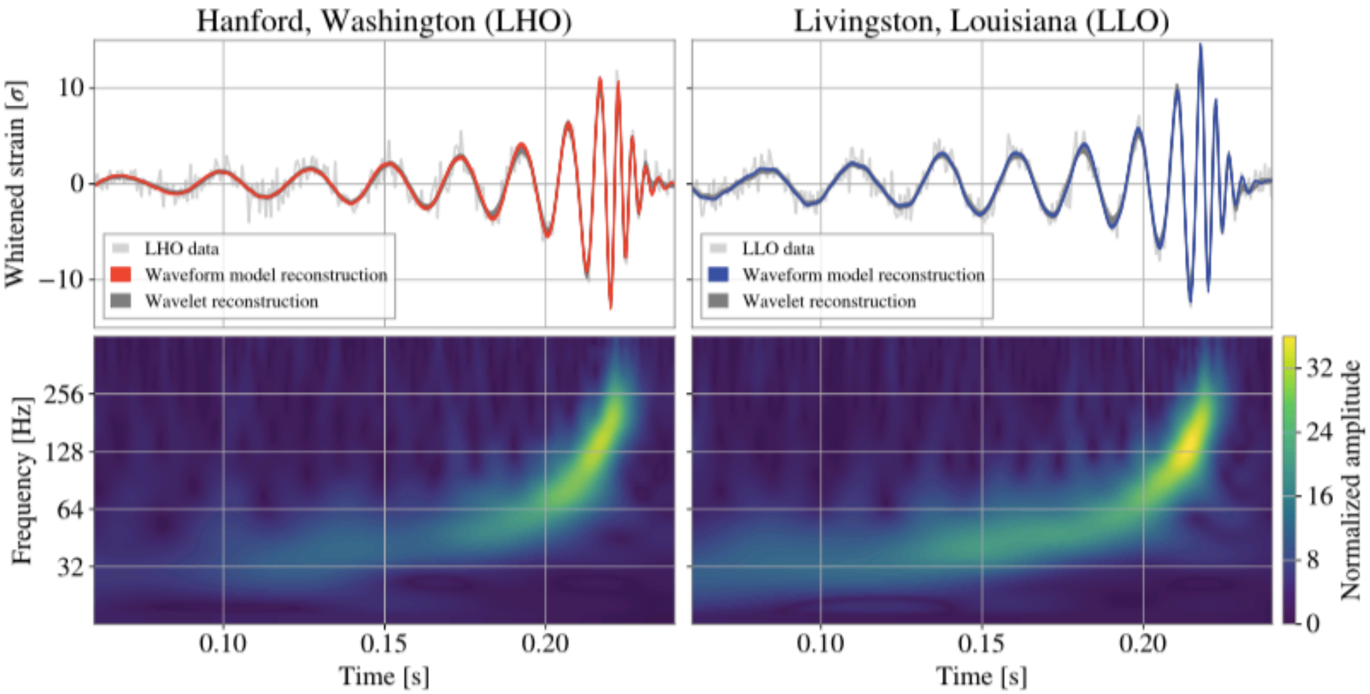
Consistency with the absence of echoes within 90% credible region

LVK (2021)

GW250114: Testing Hawking’s Area Law and the Kerr Nature of Black Holes

Hawking’s area law:
The BH horizon area cannot decrease in time

Data are consistent with **multiple quasinormal modes of a remnant Kerr black hole** and with **Hawking’s area law**



BH masses about 30 solar masses, SNR ~ 80

LVK (2025)

Can GWs tell us something about Quantum Gravity?

Long-range nonperturbative mechanism found in most QG candidates:
Dimensional flow (dim of spacetime changes with probed scale)

't Hooft (1993) ; Carlip (2017)

ST distorted by QG effects characterised by ST measure ρ (how volume scales) and kinetic term K (modified dispersion relations)

Perturbed action for a small perturbation h over background

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

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

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

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

$$h(z) \sim f_h(z) \left[\frac{\ell_*}{d_L^{\rm EM}(z)} \right]^{\Gamma}$$

GW amplitude h is the product of a dimensionless function and a power-law distance behavior

*The **strain** measured in a GW interferometer*

*Calcagni, Kyroyamagi, Morsat, **Sakellariadou**, Tamanini, Tasinato , PLB 2019; JCAP2019*

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$$\Downarrow$$

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GFT/SF/LQG
Causal dynamical triangulations
Stelle gravity
String theory
Asymptotic safety
Horava-Lifshitz gravity
κ-Minkowski

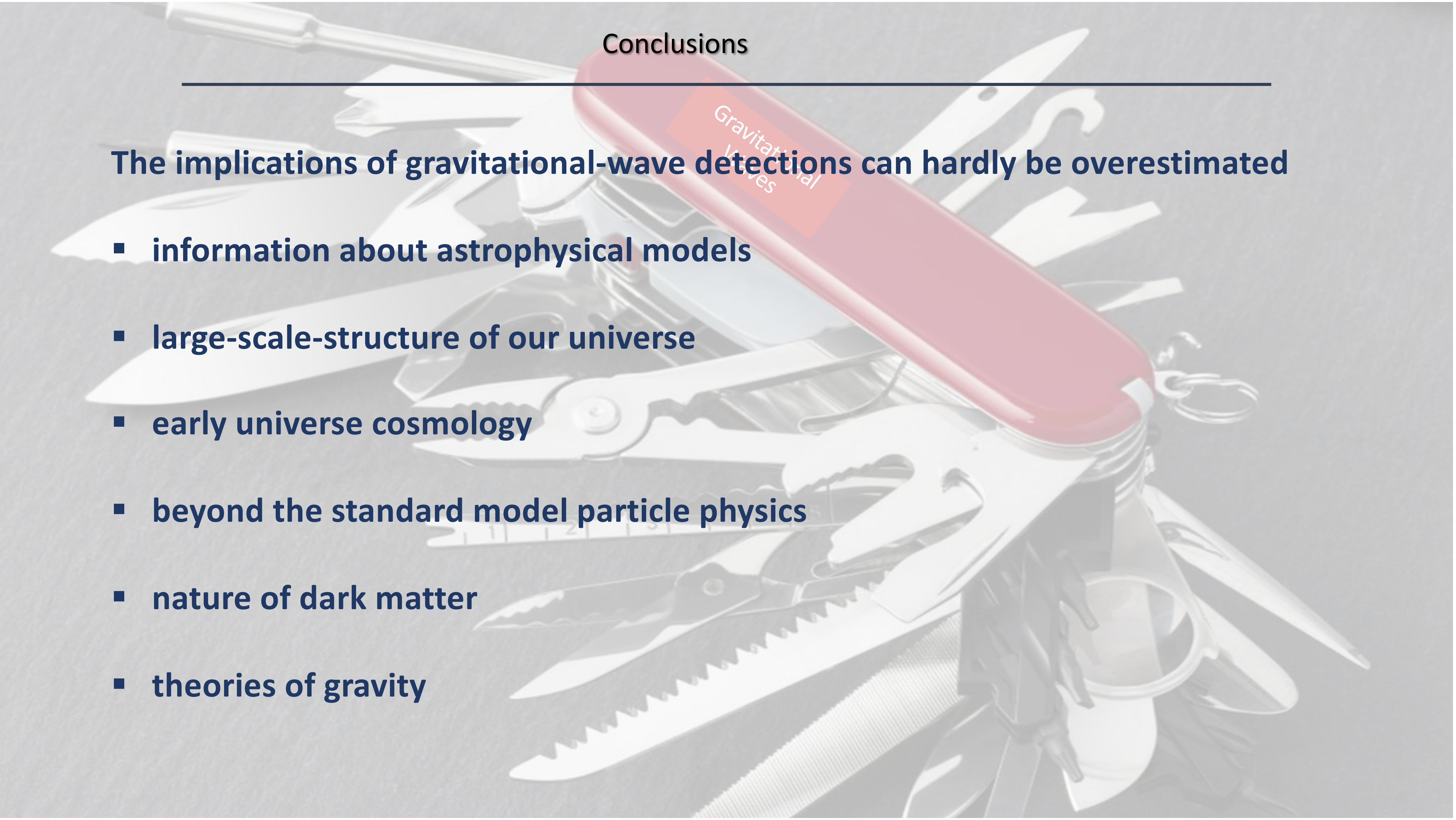
Standard sirens:

- NS merger GW170817
- simulated z=2 supermassive BH merger (LISA detectability)

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

*Calcagni, Kyroyamagi, Morsat, **Sakellariadou**, Tamanini, Tasinato , PLB 2019; JCAP2019*

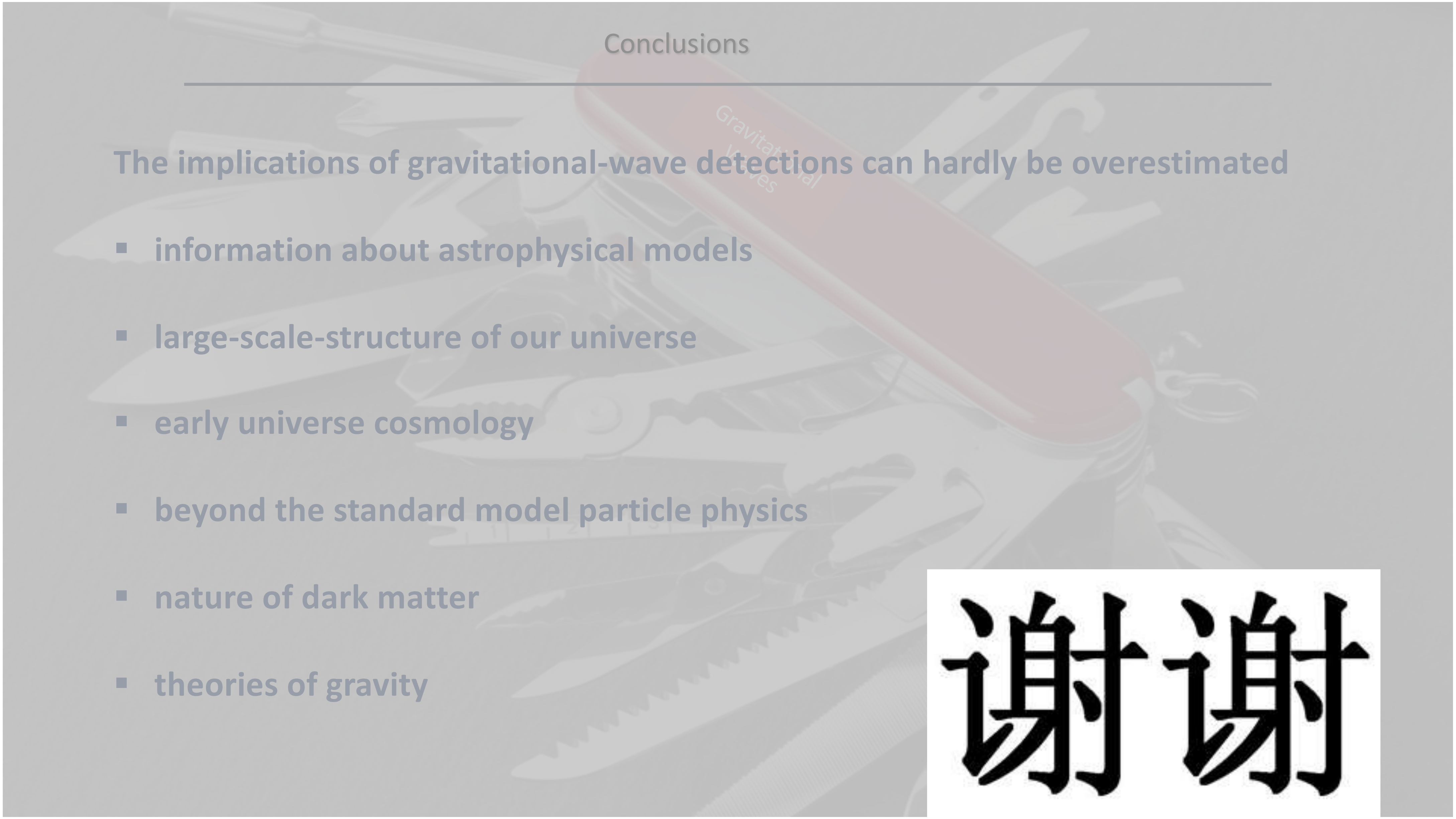
Conclusions



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



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谢谢