LIGO-Virgo-KAGRA gravitational-wave background searches:

constraints on cosmological and high-energy physics models using O1-O4a data

Mairi Sakellariadou



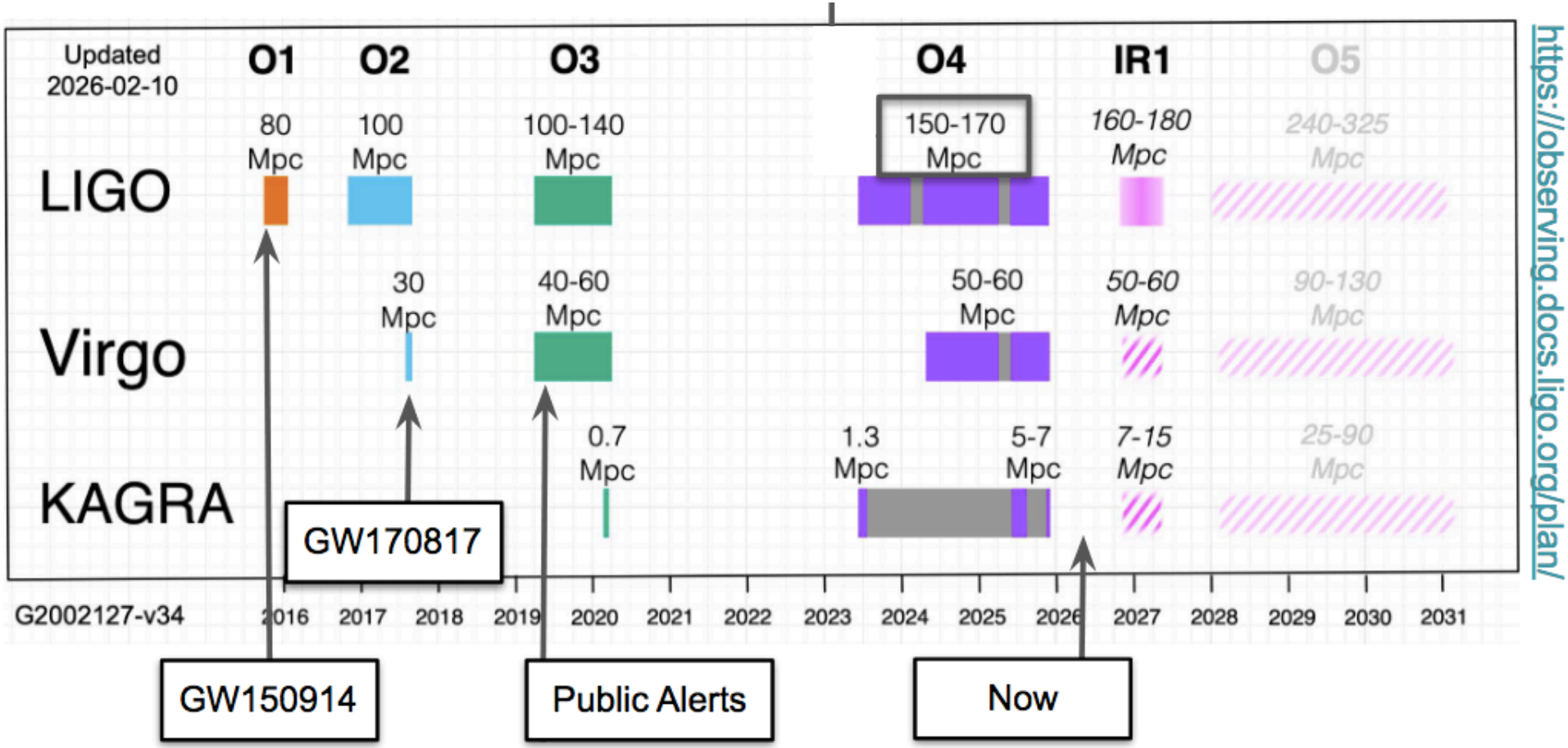




ICFP 2026
Fundamental Physics from Quanta to Cosmos
Beijing, 24-26 October 2026

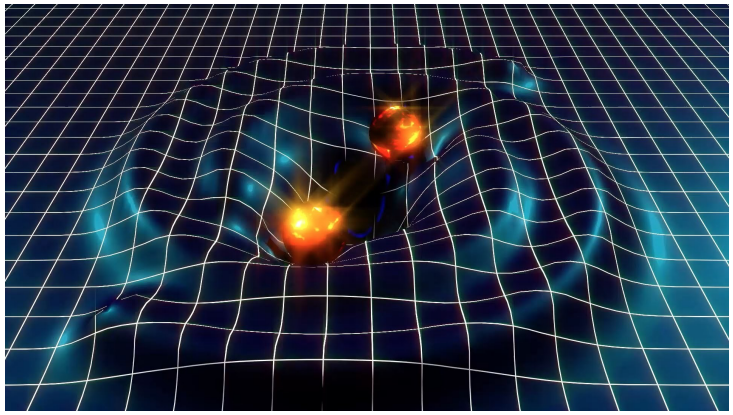
LVK Collaboration, PRX 16, 041023 (22 Oct 2026)

LIGO-Virgo-KAGRA (LVK) observing runs



GW detections

Transient phase coherent GW signals emitted by compact binaries coalescences (CBCs)



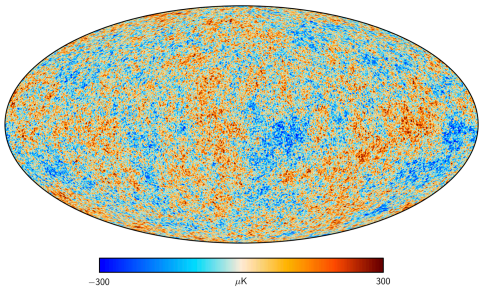
LIGO/Virgo :
Phys. Rev. X 9, 031040 (2019)
Phys. Rev. X 11, 021053 (2021)
Phys. Rev. D **109**, 022001 (2024)
Ap.J. Lett. **1004,** L22 (2026)

Detection method: **match-filtering techniques**

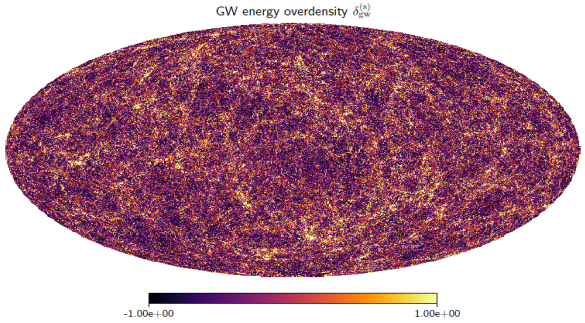
More than 450 detections so far !

Gravitational-Wave Background (GWB)

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



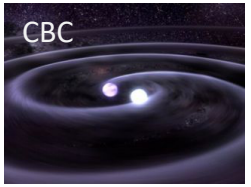
Planck Collaboration

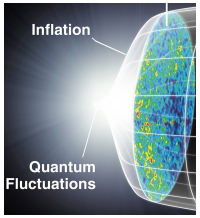


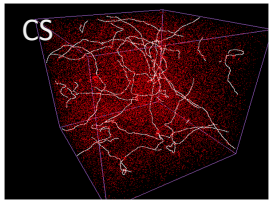
*Jenkins, **Sakellariadou,** Regimbau, Slezak, PRD 98, 063501 (2018)*



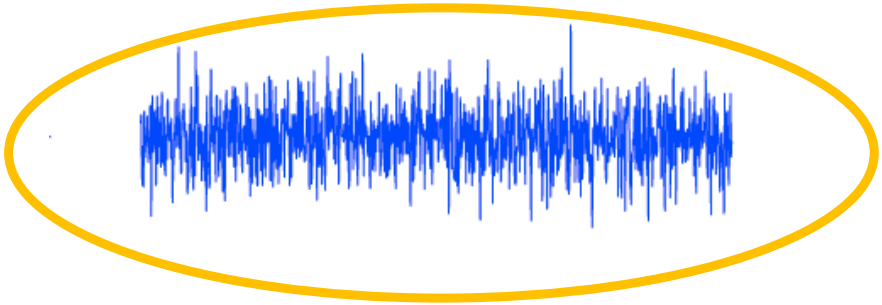








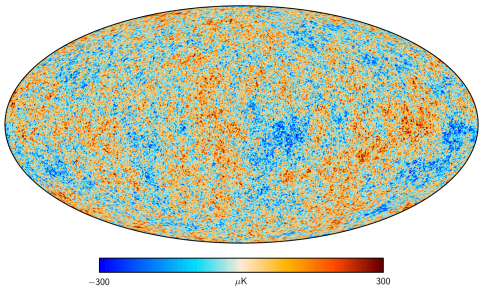




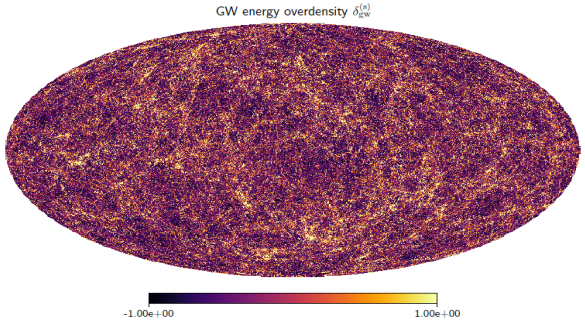
random nondeterministic phase evolution from a large number of distant sources

Gravitational-Wave Background (GWB)

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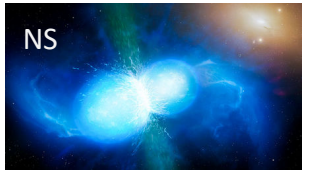


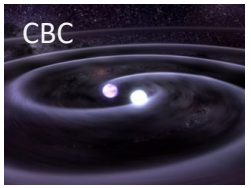
Planck Collaboration

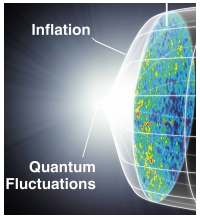


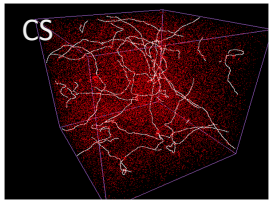
*Jenkins, **Sakellariadou,** Regimbau, Slezak, PRD 98, 063501 (2018)*



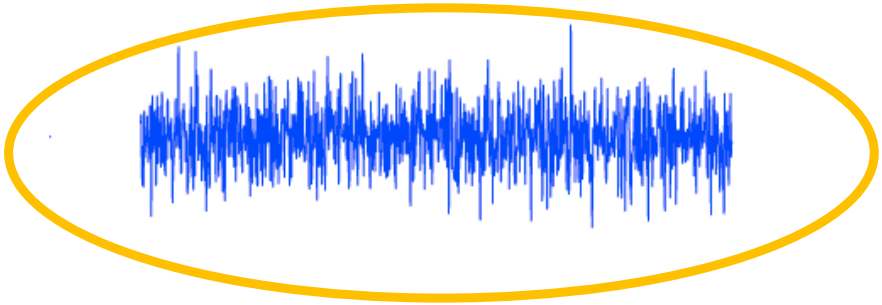












$$\rho_{\rm GW} \sim \dot{h}^2$$

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

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

random nondeterministic phase evolution from a large number of distant sources

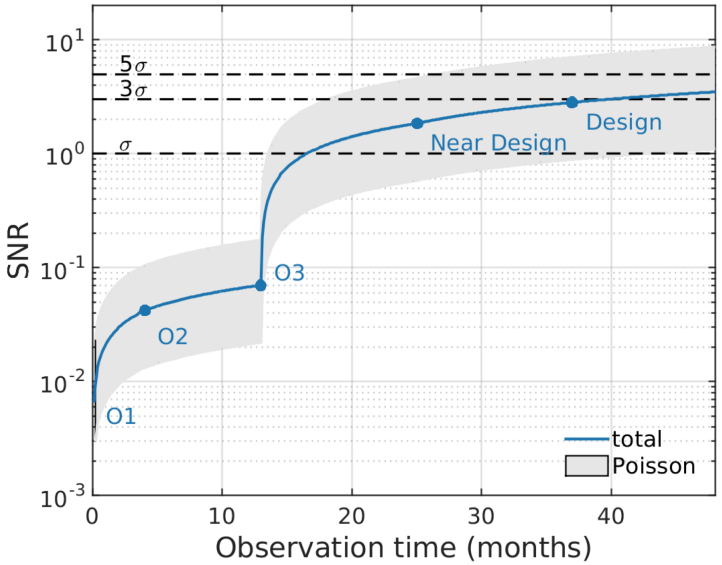
How do we detect a GWB ?

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*

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

$$\mathrm{SNR} \sim \sqrt{T_{\mathrm{obs}}}$$



How do we detect a GWB ?

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

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

In the absence of correlated noise: $\langle \hat{C}_{ij}(f) \rangle$ is an estimator for $\Omega_{\mathrm{gw}}(f)$

what if:

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

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

Schumann resonances (1952):
global extremely low frequency peaks in the electromagnetic field of the Earth

How do we detect a GWB ?

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

Assume the cross-correlation estimator is Gaussian-distributed

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

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

Parameter estimation: hybrid approach that combines frequentist and Bayesian analysis techniques

likelihood function:

$$p(\hat{\Omega}^{IJ}_{\mathrm{GW},f_i}|\boldsymbol{\theta},\lambda) \propto \exp\left[-\frac{1}{2}\sum_{IJ}\sum_{f_i}\left(\frac{\hat{\Omega}^{IJ}_{\mathrm{GW},f_i} - \lambda\Omega_{\mathrm{GW}}(f_i|\boldsymbol{\theta})}{\sigma^{IJ}_{f_i}}\right)^2\right]$$

Using the detector network

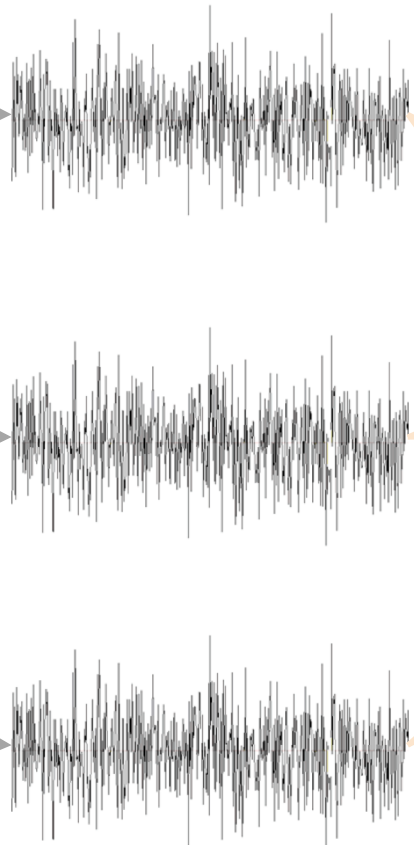
- Gaussian noise preferred over correlated magnetic noise
- Gaussian noise preferred over correlated magnetic noise + power-law GWB



Observe h(t)







Cross correlation

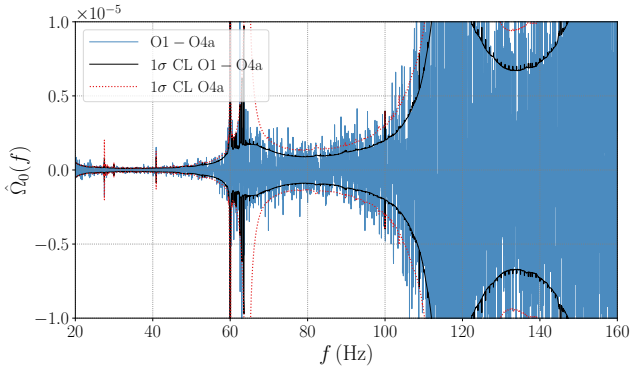
LVK Collaboration, arXiv:2508.20721

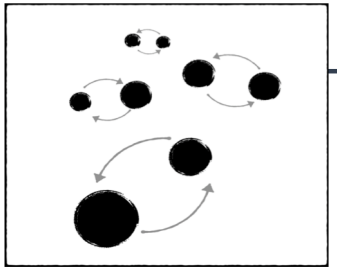
Optimal combination

HL

LV

C(f)





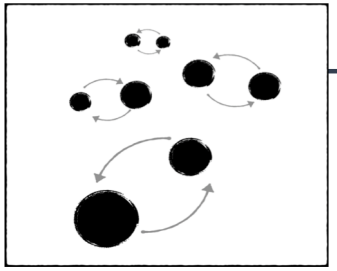
Implications for compact binaries: O1-O4a searches

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

$$\Omega_{\rm GW}(f) = \Omega_{\rm ref}\left(\frac{f}{f_{\rm ref}}\right)^{2/3}$$

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

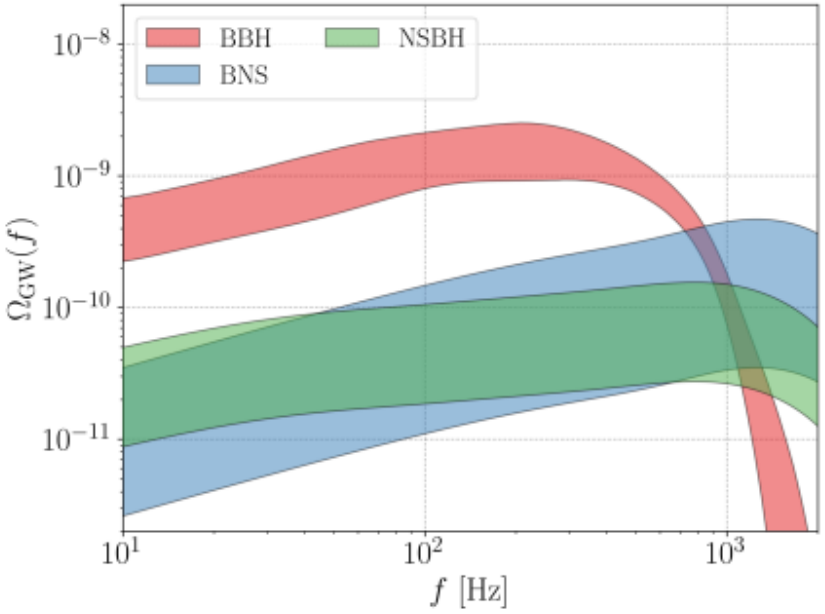
$$\frac{dE_{\rm GW}}{df} = \frac{(G\pi)^{2/3}}{3}\frac{m_1 m_2}{(m_1+m_2)^{1/3}} f^{-1/3}$$



Implications for compact binaries: O1-O4a searches

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

$$\Omega_{\rm GW}(f) = \Omega_{\rm ref}\left(\frac{f}{f_{\rm ref}}\right)^{2/3}$$



CBC: $\Omega_{\rm GW}(25\,{\rm Hz}) \leq 2.0 \times 10^{-9},$

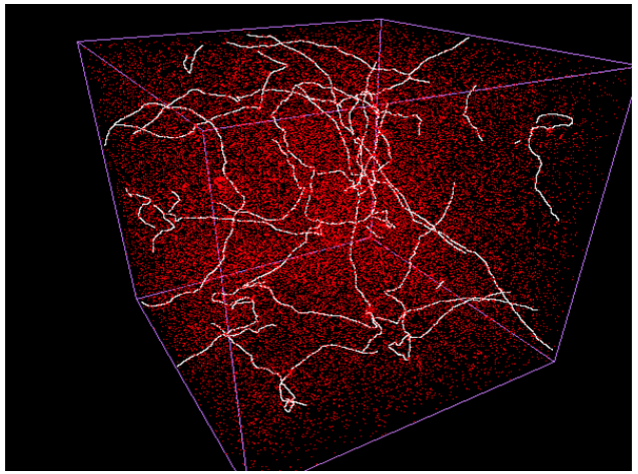
Combining with population models of CBCs from GWTC-5.0

$$\Omega_{\rm CBC}(25\,{\rm Hz}) = 6.3^{+5.0}_{-2.2} \times 10^{-10}$$

LVK Collaboration, arXiv:2608.23477 (PRD to appear)

GWs: info for high energy physics beyond SM





Methodology

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

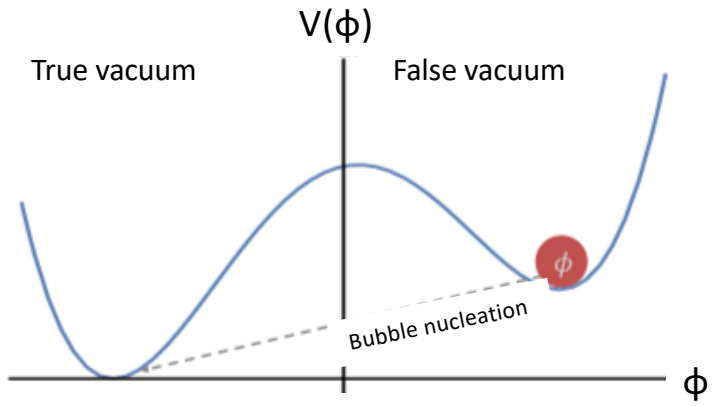
$$\Omega^{\rm PL}_{\rm GW}(f) = \Omega_{\rm ref} \left(\frac{f}{f_{\rm ref}} \right)^{\alpha}$$

$$p(\hat{\Omega}^{IJ}_{{\rm GW},f_i} | \boldsymbol{\theta}, \lambda) \propto \exp \left[-\frac{1}{2} \sum_{IJ} \sum_{f_i} \left(\frac{\hat{\Omega}^{IJ}_{{\rm GW},f_i} - \lambda \Omega_{\rm GW}(f_i|\boldsymbol{\theta})}{\sigma^{IJ}_{f_i}} \right)^2 \right]$$

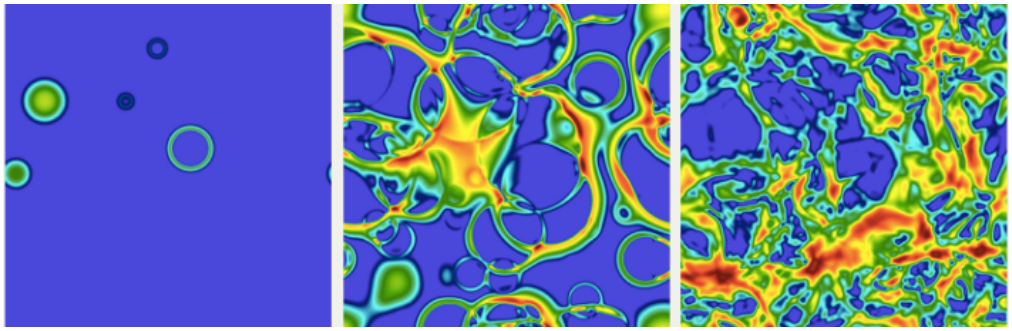
$$\Omega_{\rm GW}(f, \boldsymbol{\theta}) = \Omega_{\rm CBC}(f, \Omega_{\rm ref}, \alpha) + \Omega_{\rm Cosmo}(f, \boldsymbol{\theta}_{\rm Cosmo})$$

GWB from first order phase transition (FOPT)

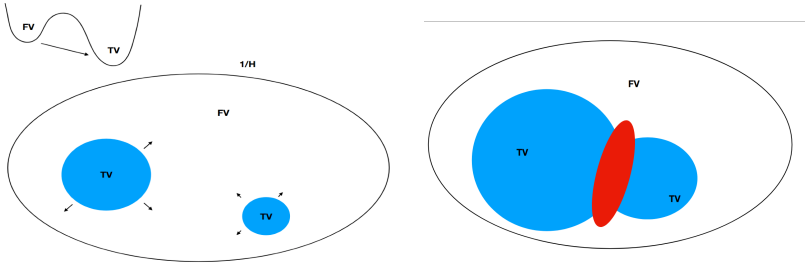
Many compelling extensions of the Standard Model predict strong FOPTs (e.g., GUTs, SUSY, extra dimensions, composite Higgs models, models with extended Higgs sector)



- 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)



Sources of GWs:

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

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

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

$$\Omega_{\rm bpl}(f) = \Omega_* \left(\frac{f}{f_*}\right)^{n_1} \left[1 + \left(\frac{f}{f_*}\right)^{\Delta}\right]^{(n_2 - n_1)/\Delta}$$

Model: *Numerical simulations*

Hindmarsh et al (2015)
Caprini et al (2016)
Huber et al (2008)

GWB from first order phase transition (FOPT)

main parameters: **strength α** of PT -- **inverse duration β** of PT – **temperature T** of PT -- **bubble wall velocity u**

Bayesian analysis

Parameter	Prior
$\alpha_{\rm PT}$	$\mathrm{LogUniform}[10^{-2}, 10^{2}]$
$\beta/H_{\rm PT}$	$\mathrm{LogUniform}[1, 10^{2}]$
$T_{\rm PT}/\mathrm{GeV}$	$\mathrm{LogUniform}[10^{5}, 10^{10}]$
$\Omega_{\rm ref}$	$\mathrm{LogUniform}[10^{-13}, 10^{-6}]$
v_w	fixed at 1

$$\ln \mathcal{B}^{\rm CBC+SW}_{\rm noise} = -0.647$$

$$\ln \mathcal{B}^{\rm CBC+BC}_{\rm noise} = -0.679$$

No evidence for a combined first order phase transition plus CBC GWB in the O1-O4a data

The data excludes at 95% CL part of the parameter space of the bubble collision dominated FOPT, especially the region of $T_{\rm PT} \gtrsim 10^{8}\,\mathrm{GeV}$ and $\beta/H_{\rm PT} \lesssim 3$

LVK Collaboration, PRX 16, 041023 (2026)

GWB from first order phase transition (FOPT)

Example: **supercooled PT**
(*often duration of FOPT increases, hence enhancement of GW signal*)

- 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*

well-motivated PP models:
- dark matter puzzle
- strong CP problem
- origin of neutrino masses
- unification of forces

Constrain parameters of particle physics models using GW data

No evidence for a combined first order phase transition plus CBC GWB in the O1-O4a data

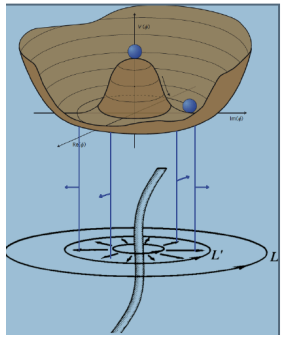
LVK Collaboration, PRX 16, 041023 (2026)

GWB from Cosmic Strings

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

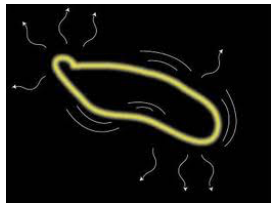
$G \to \cdots \to G_{\rm SM} \qquad \pi_1(\mathcal{M}) \neq 0$

Kibble (1976)



Generically formed in the context of GUTs

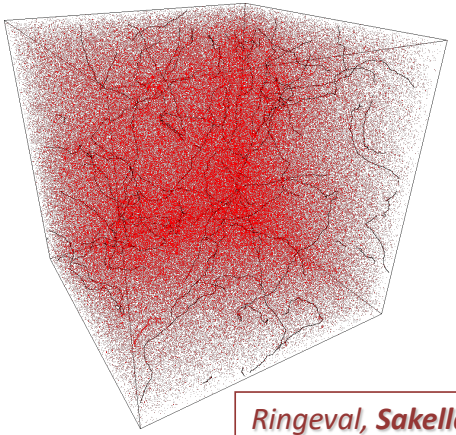
*Jeannerot, Rocher, **Sakellariadou**, PRD68 (2003) 103514*



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

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

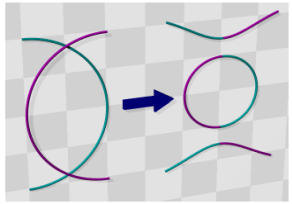
$$G\mu \sim T^2_{\rm SSB}$$



Evolution of the string loops in an expanding Universe: **scaling distribution**, with loop sizes proportional to the cosmic time or the Hubble radius.

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





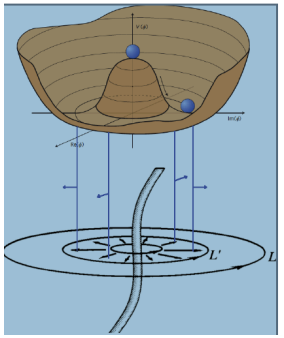
At high frequencies, the GWs dominated by cusps, kinks, and kink-kink collisions.

GWB from Cosmic Strings

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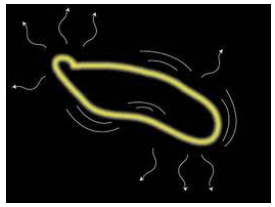
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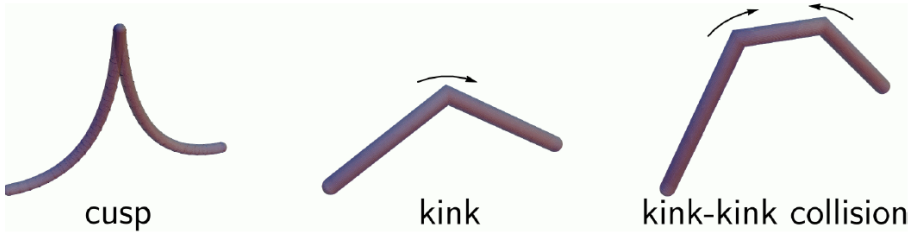
*Jeannerot, Rocher, **Sakellariadou**, PRD68 (2003) 103514*



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

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



Damour, Vilenkin (2001)

GWB from Cosmic Strings

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

$$\frac{d\rho_{\rm gw}}{df}(t_0, f) = f^2 \int_0^\infty dz \int_0^\infty d\ell h^2(f, z, \ell) \frac{d^2R(z,\ell)}{dz d\ell}$$

number of burst events per loop oscillation time

$$\frac{d^2R_i}{dz dl} = \frac{\varphi_V(z)}{H_0^3(1+z)} \frac{2N_i}{l} n(l,t)\Delta_i$$

$$\varphi_V(z) = H_0^3 dV(z)/dz$$

loop distribution function

fraction of burst events that can be detected

Numerical simulations of Nambu-Goto strings (Models A and B)

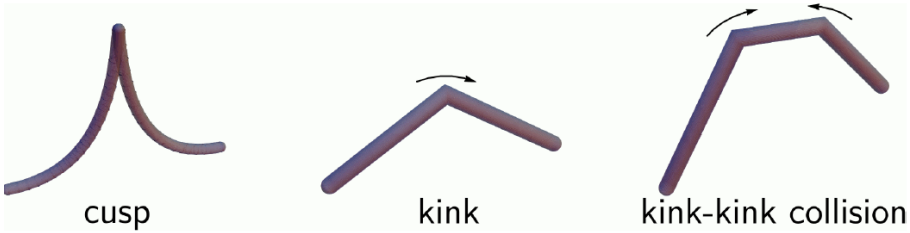
Model A: Blanco-Pillado, Olum, Shlaer (2014)
*Model B: Lorenz, Ringeval, **Sakellariadou** (2010)*
*Model C: Auclair, Ringeval, **Sakellariadou**, Steer (2019)*

Model B: effect of GW back-reaction on the loops.
Model B: higher number of small loops than model A

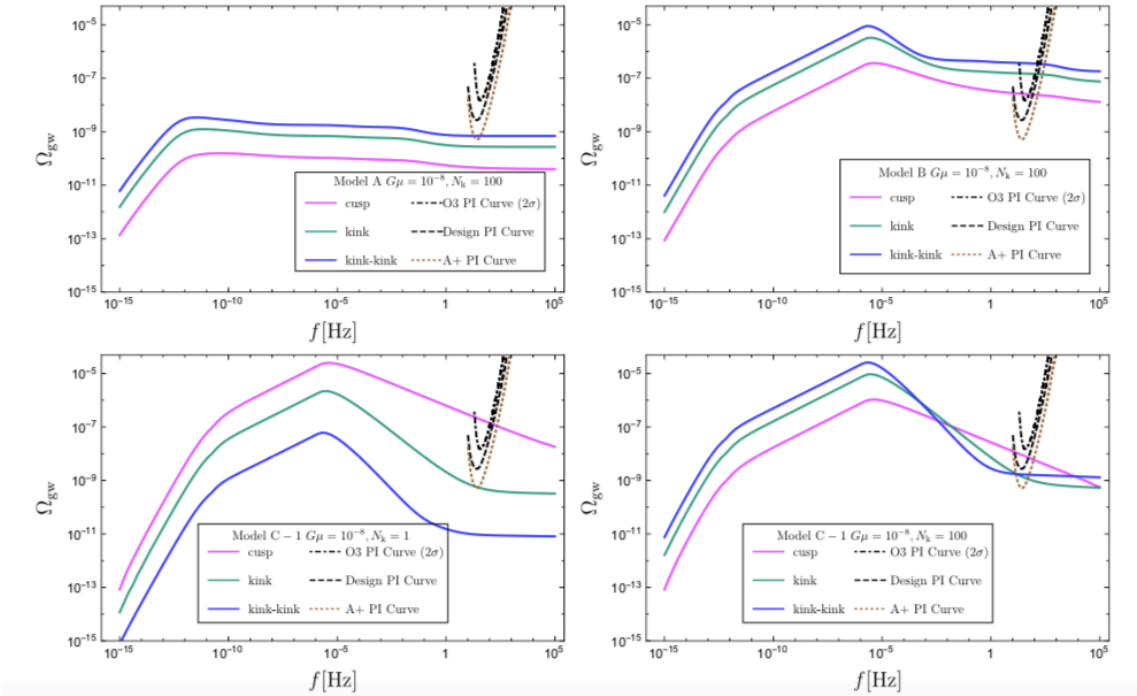
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Damour, Vilenkin (2001)



LVK, PRL 2021

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

GWB from Cosmic Strings

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

$$\frac{d\rho_{\rm gw}}{df}(t_0, f) = f^2 \int_0^\infty dz \int_0^\infty d\ell h^2(f, z, \ell) \frac{d^2R(z,\ell)}{dz d\ell}$$

Bayesian analysis

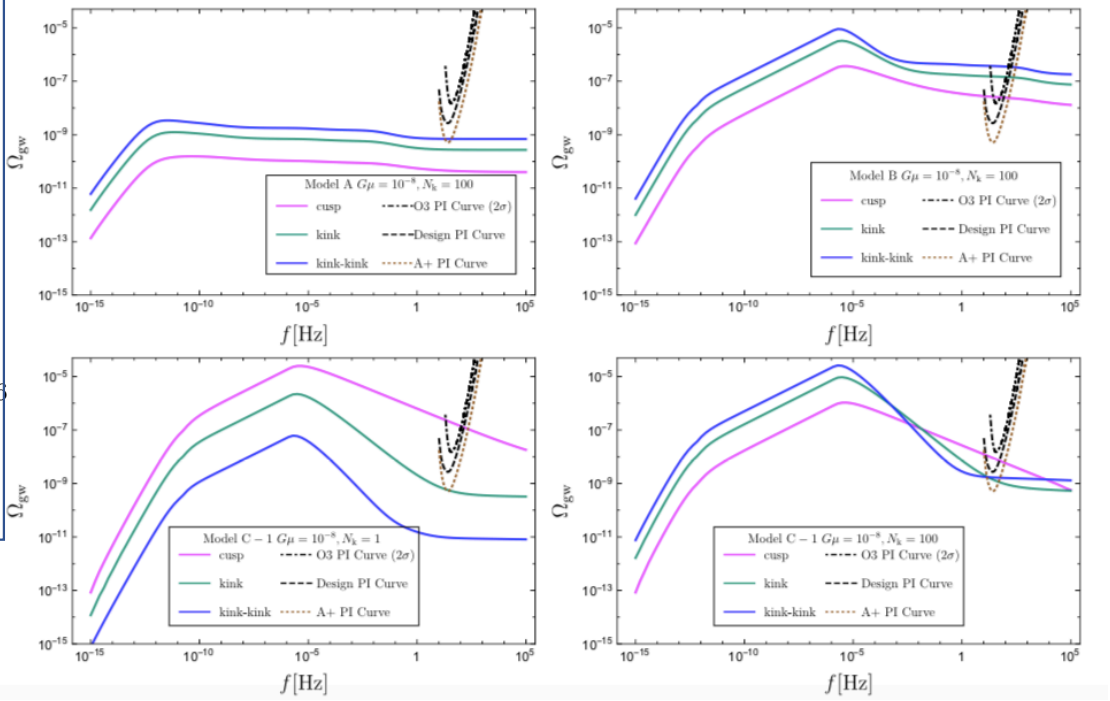
$$p(G\mu|N_k) \propto \mathcal{L}(\hat{C}_a^{IJ}|G\mu, N_k) p(G\mu|I, N_k)$$

$$\ln \mathcal{L} = -\frac{1}{2}\sum_{IJ,a} \frac{[\hat{C}_a^{IJ} - \Omega_{\rm CS}(f_a; G\mu, N_k)]^2}{\sigma_{IJ}^2(f_a)} \ ,$$

- log-uniform prior for Gμ in the range $10^{-18} \leq G\mu \leq 10^{-6}$

- for each value of N_k we keep $N_c = 1$ fixed

Model A: Blanco-Pillado, Olum, Shlaer (2014)
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LVK, PRL 2021

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	$G\mu \approx 10^{-34}$

GWB from Cosmic Strings

Excluded regions:

Model A: $G\mu \gtrsim (4.5 \times 10^{-9} \sim 5.1 \times 10^{-7})$

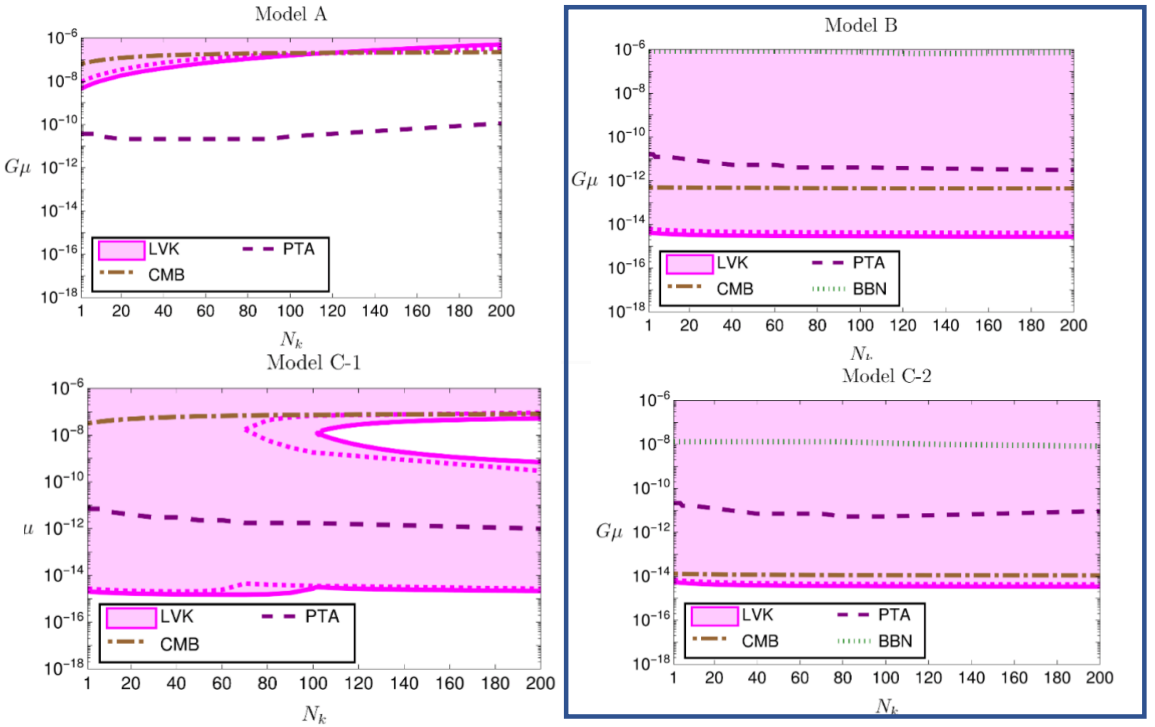
Model B: $G\mu \gtrsim (2.7 \sim 4.2) \times 10^{-15}$

Model C1: $G\mu \gtrsim (1.5 - 3.2) \times 10^{-15}$

Model C2: $G\mu \gtrsim (3.4 \sim 5.5) \times 10^{-15}$

Model A: Blanco-Pillado, Olum, Shlaer (2014)
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Exclusion region at the 95% confidence level



LVK Collaboration, PRX 16, 041023 (2026)

GWB from Domain Walls

Domain walls are formed when a discrete symmetry is spontaneously broken during the thermal history of the Universe.

Kibble (1976)

Dynamics: - **tension** (tends to stretch the DWs and reduce DW surface to minimise energy)
- **Hubble expansion and interaction of DWs with primordial plasma**

When particle friction can be neglected, DWs approach scaling regime

DWs reach a scaling regime with a constant O(1) number of walls per Hubble volume

Ryden, et al (1990); Hindmarsh (1996); Oliveira et al (2005); Avelino et al (2005); etc

Scaling regime: $\rho_{\rm DW} = 2\mathcal{A}\sigma_{\rm DW}H \qquad \text{where } \mathcal{A} = \mathcal{O}(1)$

the energy density of the network decreases more slowly than matter or radiation, leading to a DW–dominated epoch, inconsistent with cosmological observations

$$T_{\rm dom} = \left(\frac{80\ G}{\pi c^4 g_*}\right)^{1/4}\sqrt{\sigma_{\rm DW}}$$

GWB from Domain Walls

However, **a DW network may not be absolutely stable** (the underlying discrete symmetry may be only approximate).
Different vacua of the theory are biased by a small energy difference, ΔV (bias) ---> only a unique true vacuum state

Sikivie (1982)

Examples: discrete flavour symmetries, left–right symmetric models, supersymmetry, grand unification

DWs can annihilate before dominating the expansion of the Universe

$$\Delta V \sim \rho_{\rm DW} \quad \Longrightarrow \quad T_{\rm ann} \sim 10^8 \ {\rm GeV} \left(\frac{10^{11} \ {\rm GeV}}{\sigma_{\rm DW}^{1/3}} \right)^{\frac{3}{2}} \left(\frac{\Delta V^{1/4}}{10^8 \ {\rm GeV}} \right)^2 \left(\frac{100}{g_*} \right)^{\frac{1}{4}} .$$

annihilation temperature needs to be smaller than temperature at which DWs form

$$T_{\rm ann} \lesssim \sigma_{\rm DW}^{1/3}$$

GWB from Domain Walls

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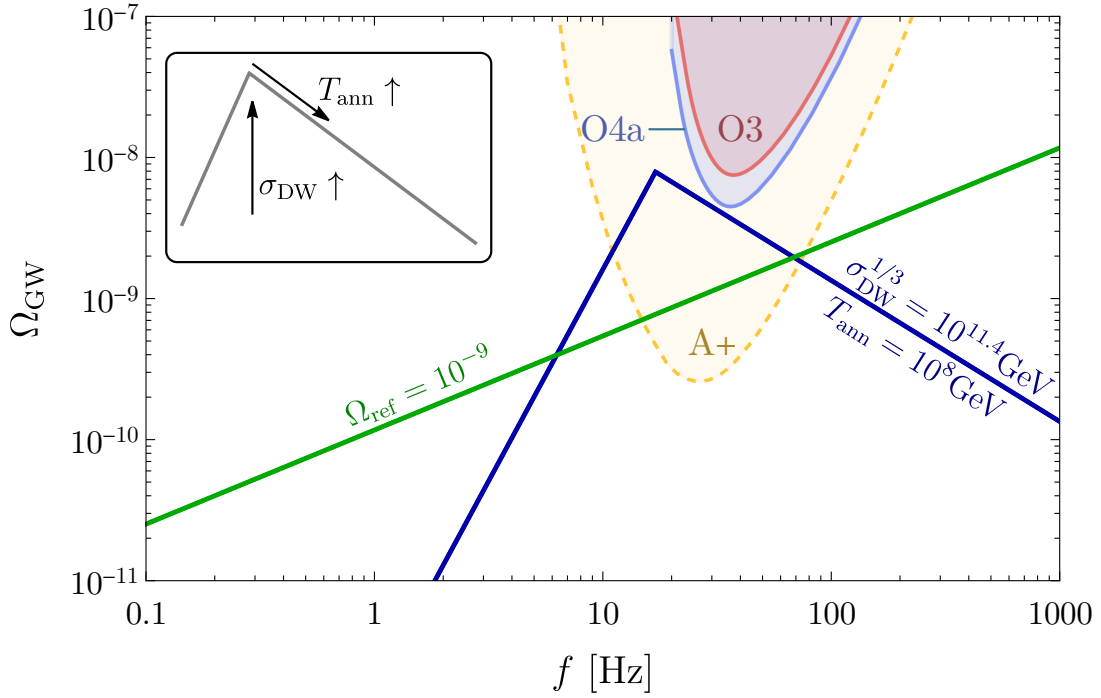
annihilation temperature needs to be smaller than temperature at which DWs form

$$T_{\rm ann} \lesssim \sigma_{\rm DW}^{1/3}$$

$$\Omega_{\rm DW}(f) = \Omega_{\rm DW}^{\rm peak} \times \begin{cases} (f/f_{\rm peak})^3 & f < f_{\rm peak} \\ (f/f_{\rm peak})^{-1} & f > f_{\rm peak} \end{cases}$$

Relativistic motion of the domain walls ⟹ GWs (broken power-law)
the emission is strongest around the final time of DW annihilation

GWB from Domain Walls



increasing the wall tension enhances the peak amplitude,
while a higher annihilation temperature T_{ann} reduces the amplitude and shifts the spectrum to higher frequencies

LVK Collaboration, PRX 16, 041023 (2026)

GWB from Domain Walls

Bayesian analysis

Parameter	Prior
$\Omega_{\rm ref}$	$\mathrm{LogUniform}[10^{-13}, 10^{-6}]$
$\sigma_{\rm DW}^{1/3}/\mathrm{GeV}$	$\mathrm{LogUniform}[10^{10}, 10^{13}]$
$T_{\rm ann}/\mathrm{GeV}$	$\mathrm{LogUniform}[10^{6}, 10^{10}]$

$$\ln \mathcal{B}^{\rm DW+CBC}_{\rm noise} = -1.15$$

$$\ln \mathcal{B}^{\rm CBC}_{\rm noise} = -0.52$$

$$\ln \mathcal{B}^{\rm DW+CBC}_{\rm CBC} = -0.63$$

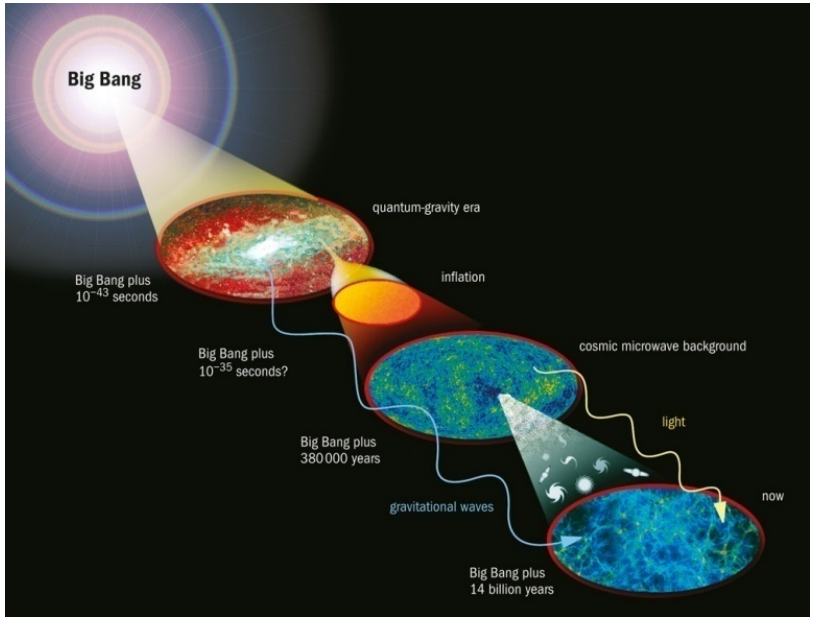
No evidence for a GW signal from a DW network , exclude regions of parameter space (σ_{DW}, T_{ann})

Rule out annihilation temperatures in the range

$$10^7 \mathrm{GeV} < T_{\rm ann} < 10^9 \mathrm{GeV}$$

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GWs : info about the EU



GWB from Inflation in an exotic model with a Stiff Era

Universe: cosmological fluid defined by equation of state $p = w\rho$

Standard cosmological model: inflation --> RD w=1/3 ---> MD w=0 ---> dark energy (DE) w=-1

Requirement: the Universe is RD during big bang nucleosynthesis

GWB from Inflation in an exotic model with a Stiff Era

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Standard cosmological model: inflation --> RD w=1/3 ---> MD w=0 ---> dark energy (DE) w=-1

Requirement: the Universe is RD during big bang nucleosynthesis

Exotic model: inflation ---> RD1 ---> exotic MD1 ---> exotic stiff era driven by stiff energy ---> RD2 ---> MD2

$1/3 < w \leq 1$ *inflationary GWB spectrum potentially detectable*

kination: $w_s=1$

- a stiff era leads to a blue tilt in the inflationary GW spectrum, making it observationally interesting
- including a MD era suppresses the GW spectrum at higher frequencies, allowing the model to evade indirect constraints from CMB and BBN

Models beyond the SM: quintessence models, axion inflation scenarios, models with string theory moduli, Peccei-Quinn inflation models, etc

GWB from Inflation in an exotic model with a Stiff Era

$$\Omega_{\rm SD}(f) = \Omega_{\rm SD}\big|^{(0)}_{\rm plateau} \begin{cases} \mathcal{A}_1 & \text{if} \quad f \ll f_{\rm RD} \\ \mathcal{A}_{\alpha_{\rm s}} \left(\frac{f}{f_{\rm RD}}\right)^{2(1-\alpha_{\rm s})} & \text{if} \quad f_{\rm RD} \ll f \ll f_{\rm SD} \\ \mathcal{A}_2 \left(\frac{f_{\rm SD}}{f_{\rm RD}}\right)^{2(1-\alpha_{\rm s})} \left(\frac{f_{\rm SD}}{f}\right)^2 & \text{if} \quad f_{\rm SD} \ll f \ll f_{\rm MD} \\ \mathcal{A}_1 \left(\frac{f_{\rm SD}}{f_{\rm RD}}\right)^{2(1-\alpha_{\rm s})} \left(\frac{f_{\rm SD}}{f_{\rm MD}}\right)^2 & \text{if} \quad f_{\rm MD} \ll f \end{cases}$$

*Duval, Kuroyanagi, Mariotti, Romero-Rpdriguez, **Sakellariadou**, PRD (2024)*

$$\mathcal{A}_{\alpha_{\rm era}} \equiv \frac{\Gamma^2(\alpha_{\rm era}+1/2)}{\pi} \left(\frac{2}{\alpha_{\rm era}}\right)^{2\alpha_{\rm era}} , \quad \alpha_{\rm era} \equiv \frac{2}{1+3w_{\rm era}}$$

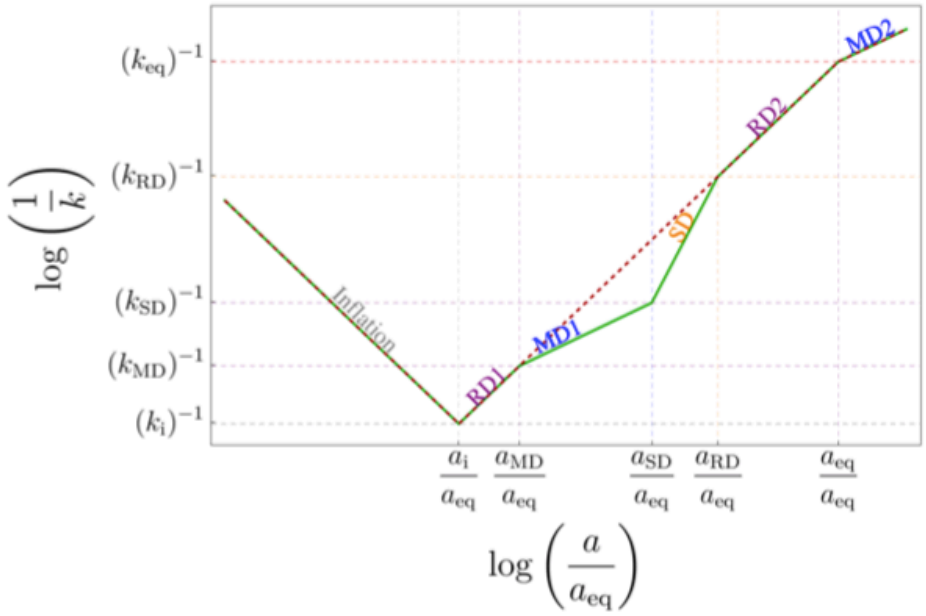
$$\Omega^{(0)}_{\rm SD}|_{\rm plateau} \equiv G_{\rm k} \frac{\Omega^{(0)}_{\rm rad}}{12\pi^2} \left(\frac{H_{\rm inf}}{M_{\rm Pl}}\right)^2$$

$$\Omega^{(0)}_{\rm rad} \approx 9 \times 10^{-5}$$

$$H_{\rm inf} < H_{\rm inf,max} = 5.12 \times 10^{13} \ \text{GeV}$$

GWB from Inflation in an exotic model with a Stiff Era

Schematic diagram illustrating the evolution of the co-moving Hubble radius



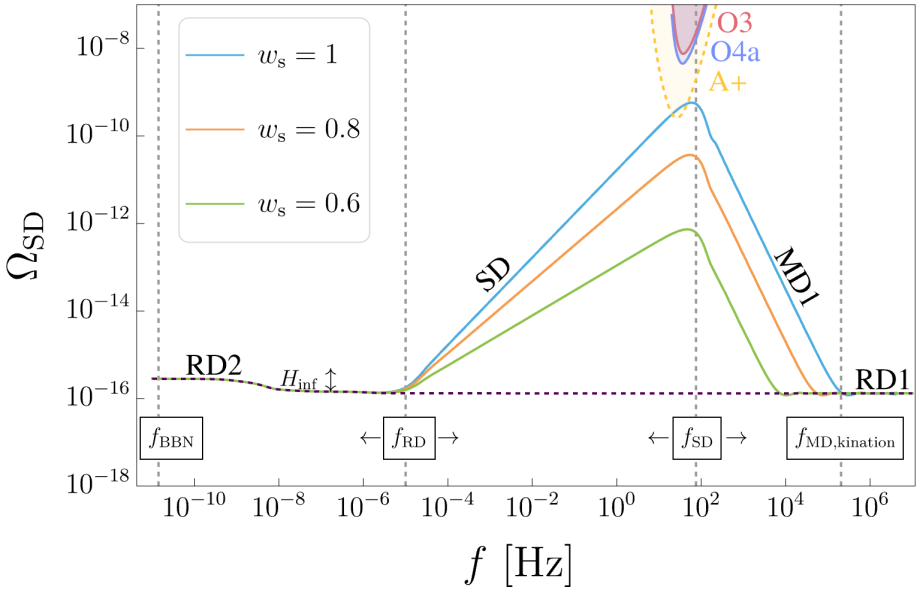
The parameters that influence the GW spectrum are:

H_inf (the overall amplitude of the GWB spectrum), H_inf= 10^{13}GeV

f_RD (the low-frequency part of the spectrum)

and f_SD (the peak frequency of the spectrum)

GWB from Inflation in an exotic model with a Stiff Era



$$\ln(\mathcal{B}^{\text{kination+CBC}}_{\text{Noise}}) = -1.16$$

$$\ln(\mathcal{B}^{\text{SD+CBC}}_{\text{Noise}}) = -0.62$$

$$\ln(\mathcal{B}^{\text{kination+CBC}}_{\text{CBC}}) = -0.62$$

$$\ln(\mathcal{B}^{\text{SD+CBC}}_{\text{CBC}}) = -0.09$$

Bayesian analysis:

Parameters θ	Prior
Ω_{ref}	$\text{LogUniform}[10^{-13}, 10^{-6}]$
f_{RD}/Hz	$\text{LogUniform}[10^{-10}, 10^{-5}]$
f_{SD}/Hz	$\text{LogUniform}[10^{-3}, 10^{6}]$
α_s	$\text{Uniform}[0.5, 1]$

No evidence in the O1-O4a data for a GWB coming from a stiff epoch

95% CL upper limits on some of the parameters characterising this unconventional cosmology

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GWB from Axion Inflation

Pseudo-scalar axion coupled to a Non-Abelian gauge field

Example : SU(2) --- it can have an isotropic background value (contrary to U(1))
---> GW production can be computed using linear analysis

Chromo-natural inflation

$$S = \int d^4x\sqrt{-\bar{g}}\Big[\frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{\alpha_f}{4}\phi F^a_{\mu\nu}\tilde{F}^{a\mu\nu}\Big]$$

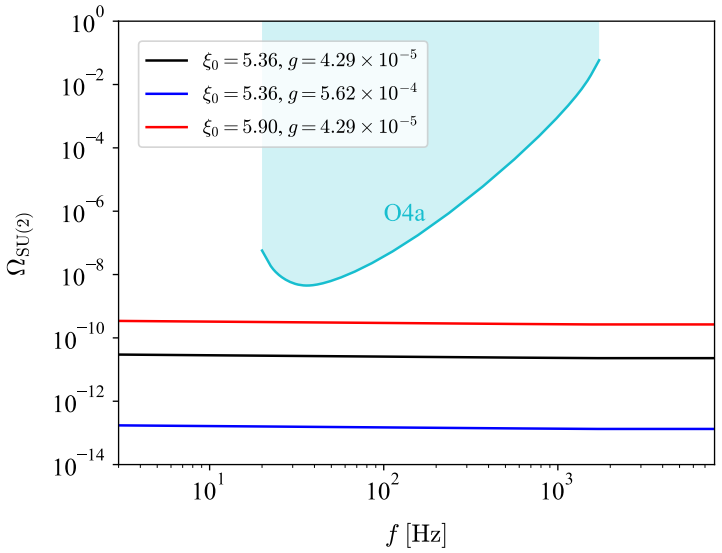
Carr, Lidsey (1993); Dimastrogiovanni, Peloso (2013)

Isotropic ansatz for homogeneous component of gauge field:

$$A^a_0 = 0, \quad A^a_i = \delta^a_i a(t)Q(t)$$

GWB from Axion Inflation

Non-Abelian GWB spectra for varying velocity parameter of inflaton field and axion-gauge coupling



$$V(\phi) = \begin{cases} V_0 + A_+(\phi - \phi_0), & \text{for } \phi > \phi_0 \\ V_0 + A_-(\phi - \phi_0), & \text{for } \phi < \phi_0 \end{cases}$$

Bayesian analysis

Parameter	Prior
Ω_{ref}	$\mathrm{LogUniform}[10^{-12}, 10^{-7}]$
N_{CMB}	$\mathrm{Uniform}[50, 60]$
f_0/Hz	$\mathrm{LogUniform}[10^{-6}, 10]$
$\phi_{\mathrm{end}}/M_{\mathrm{Pl}}$	$\mathrm{Uniform}[0, 25]$
A_+/M_{Pl}^3	$\mathrm{LogUniform}[10^{-20}, 10^{-6}]$
A_-/M_{Pl}^3	$\mathrm{LogUniform}[10^{-20}, 10^{-6}]$
V_0/M_{Pl}^4	$\mathrm{LogUniform}[10^{-20}, 10^{-6}]$
$\alpha_f/M_{\mathrm{Pl}}^{-1}$	$\mathrm{Uniform}[0, 250]$
g	$\mathrm{LogUniform}[10^{-5}, 1]$

LVK Collaboration, PRX 16, 041023 (2026)

GWB from Axion Inflation

Parameters	$H_{\rm CMB}$ free	$H_{\rm CMB} = 10^{-5}\ M_{\rm Pl}$	$H_{\rm CMB} = 10^{-6}\ M_{\rm Pl}$	$H_{\rm CMB} = 10^{-7}\ M_{\rm Pl}$
$\Omega_{\rm ref}$	2.48×10^{-9}	3.18×10^{-9}	3.37×10^{-9}	2.72×10^{-9}
g	0.411	0.421	0.322	0.325
V_0	4.41×10^{-9}	2.36×10^{-10}	2.37×10^{-12}	2.50×10^{-14}
A_+	2.77×10^{-12}	3.73×10^{-11}	3.77×10^{-13}	3.69×10^{-15}
A_-	2.01×10^{-10}	1.60×10^{-11}	2.23×10^{-13}	2.36×10^{-15}
ξ_0	5.936	4.104	4.976	5.884
$H_{\rm CMB}/M_{\rm Pl}$	4.18×10^{-5}	-	-	-

95% upper bounds on the SU(2)+CBC model under different constant $H_{\rm CMB}$ priors

LVK Collaboration, PRX 16, 041023 (2026)

GWB from second-order scalar perturbations

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

⇨ tensor modes are dynamically generated by the gravitational instability of scalar fluctuations

Matarrese, Pantano, Saez (1994)

➡ observational test for probing directly the epoch of inflation

GWB from second-order scalar perturbations

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Matarrese, Pantano, Saez (1994)

➡ observational test for probing directly the epoch of inflation

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

GWB from second-order scalar perturbations

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

$$\mathcal{P}_h \sim \int \mathrm{d}k \int \mathrm{d}k' \left(\int \mathrm{d}t f(k, k', t) \right)^2 \mathcal{P}_\zeta(k) \mathcal{P}_\zeta(k')$$

power spectrum of induced GWs (peaked around same wavenumber as the curvature power spectrum)

some oscillatory function

power spectrum of primordial curvature perturbations

$$\Omega_{\mathrm{GW}}(\eta, k) = \frac{\rho_{\mathrm{GW}}(\eta, k)}{\rho_{\mathrm{tot}}(\eta)} = \frac{1}{24} \left(\frac{k}{a(\eta) H(\eta)} \right)^2 \overline{\mathcal{P}_h(\eta, k)},$$

Kohri, Teradah (2018)

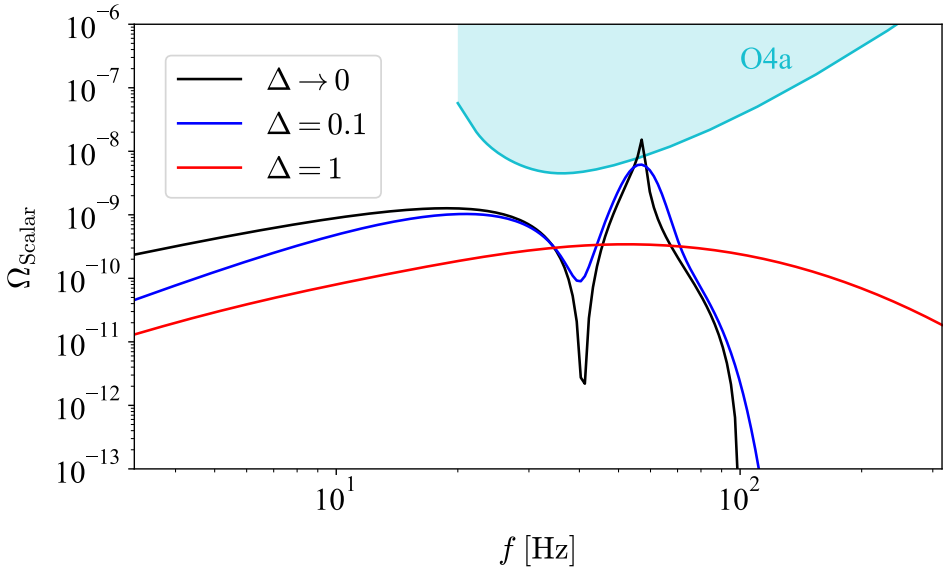
GWB from second order scalar perturbations: information about early universe

GWB sourced by second-order terms of scalar perturbations, in the context of cosmological perturbation theory

➡ observational test for probing directly the epoch of inflation

O1-O4a: upper limits on the amplitude of power spectrum and fraction of the DM in terms of ultralight PBHs

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



PBHs produced by collapse when large enough curvature perturbations of scale k *re-enter* horizon,

------> **PBH mass set by the horizon mass at horizon re-entry time of scale k**

➡ $M_{\rm PBH} \lesssim 10^{16}\,{\rm g}.$

LVK sensitivity:

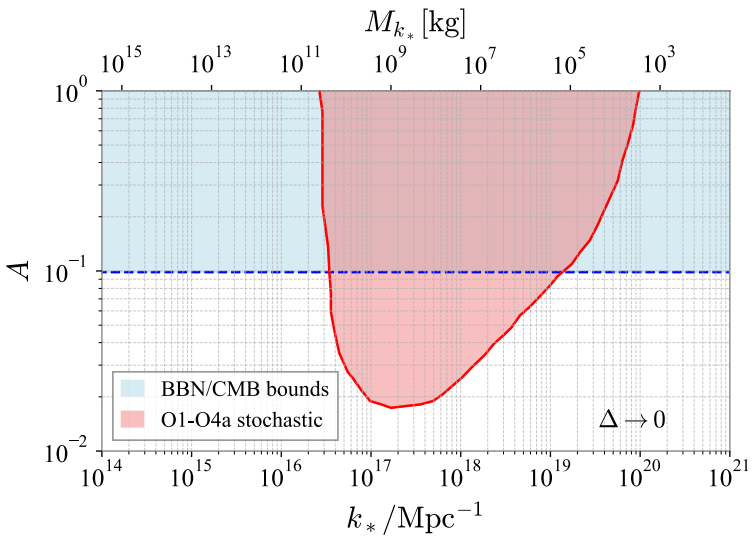
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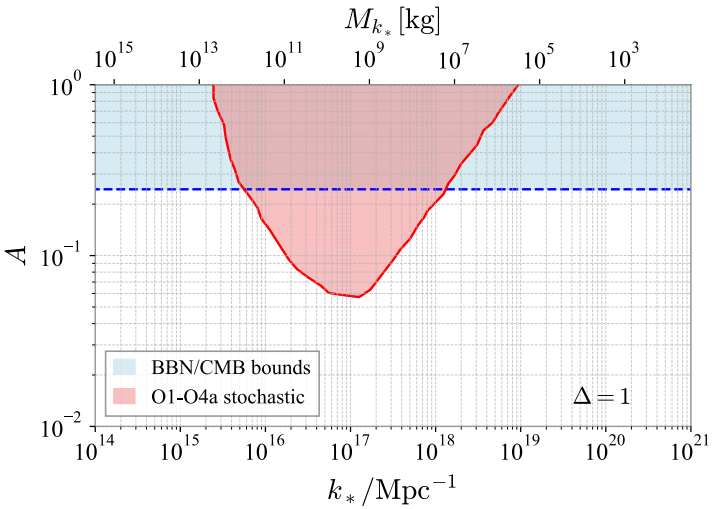
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$$\mathcal{P}_\zeta(k) = \frac{A}{\sqrt{2\pi}\Delta} \exp\left[-\frac{\ln^2(k/k_*)}{2\Delta^2}\right]$$

Bayesian parameter estimation

Parameter	Prior
$\Omega_{\rm ref}$	$\mathrm{LogUniform}(10^{-10}, 10^{-7})$
A	$\mathrm{LogUniform}(10^{-3}, 10^{0.5})$
k_*/Mpc^{-1}	$\mathrm{LogUniform}(10^{13}, 10^{21})$
Δ	$\mathrm{LogUniform}(0.05, 5)$





95% CL Upper bounds on the curvature perturbation amplitude

LVK Collaboration, PRX 16, 041023 (2026)

Parity violation

Models: string-theory, scalar-tensor gravity, phase transitions, chromo-natural inflation, etc

When GWs propagate from the source to the detector, the amplitudes of left versus right polarised modes are exponentially enhanced or suppressed, a **parity-violating effect**

$$\langle \hat{C}_{d_1 d_2} \rangle = \frac{3H_0^2 T}{10\pi^2} \int_0^\infty df \frac{\Omega'_{\rm GW}(f)\gamma_I^{d_1 d_2}(f)\tilde{Q}(f)}{f^3}$$

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

Polarisation degree: $$\Pi(f) = V(f)/I(f) = \frac{P_R(f) - P_L(f)}{P_R(f) + P_L(f)}$$

Parity violation

Generic search for a PV GWB exhibiting power-law behaviour

- Π constant between -1 and 1
- Π varies with frequency $\Pi(f) = \pm(f/1\ \mathrm{Hz})^{\beta}$

LVK Collaboration, PRX 16, 041023 (2026)

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Early universe turbulence

A PV turbulent source during a PT ----> circularly polarised GWs

Broken power-law spectrum with a peak at a frequency related to temperature of FOPT

$$\Omega_{\mathrm{Turbulence}}(f) = \begin{cases} \Omega_{\mathrm{peak}}(f/f_{\mathrm{peak}}) & , \quad f \leq f_{\mathrm{peak}} \\ \Omega_{\mathrm{peak}}(f/f_{\mathrm{peak}})^{-8/3} & , \quad f > f_{\mathrm{peak}} \end{cases}$$

Roper et al (2020)

LVK Collaboration, PRX 16, 041023 (2026)

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Roper et al (2020)

Non-Abelian axion inflation

Chromo-natural inflation

$$S = \int d^4x\sqrt{-\bar{g}}\Big[\frac{M_{\mathrm{Pl}}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} + \frac{\alpha_f}{4}\phi F^a_{\mu\nu}\tilde{F}^{a\mu\nu}\Big]$$

Carr, Lidsey (1993); Dimastrogiovanni, Peloso (2013)

The coupling between the inflaton and the SU(2) gauge field ---> tachyonic instability in one heliciity mode of SU(2)

⇒ exponential amplification of that mode

⇒ parity-violating GWB

LVK Collaboration, PRX 16, 041023 (2026)

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⇒ parity-violating GWB

No evidence of such a model
nor a preference for a polarised model over a non-chiral one

LVK Collaboration, PRX 16, 041023 (2026)

GWs : constraints on dark matter



Primordial black holes

PBHs larger than $10^{15}\,\mathrm{g}$, which are unaffected by Hawking radiation, could provide the dark matter which comprises 25% of the critical density

Chapline (1975)
Meszaros (1975)

$f(M)$: the fraction of the dark matter in PBHs of mass M

$$f \equiv \frac{\Omega_{\rm PBH}}{\Omega_{\rm CDM}}$$

Constraints suggest that there are only a few ranges where f can be significant:

- asteroidal to sublunar range $10^{17} - 10^{23}\,\mathrm{g}$
- intermediate range $10 - 10^{2}\,M_{\odot}$
- extremely large range $M > 10^{11}\,M_{\odot}$ (irrelevant to the dark matter in galaxies)

has attracted a lot of attention as a result of the LIGO/Virgo detections of merging binary black holes with mass in the range $10 - 50\,M_{\odot}$

GWB from Primordial Black Holes

log-normal mass function: $$p(m) = \frac{1}{\rho_{\rm PBH}} \frac{d\rho_{\rm PBH}}{d\ln m}$$

For a log-normal distribution, the mass function is:

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

μ is the median mass and σ controls the width of the distribution in logarithmic space

$$\Omega_{\rm PBH}(f) = \frac{f}{\rho_{c,0}} \int_0^{z_{\rm max}} dz \int d\ln m_1 \; d\ln m_2 \; \frac{p(m_1)p(m_2)}{(1+z)H(z)} \; \frac{d^2 R_{\rm EB/LB}}{d\ln m_1 d\ln m_2} \frac{dE_{\rm GW}}{df_{\rm r}}$$

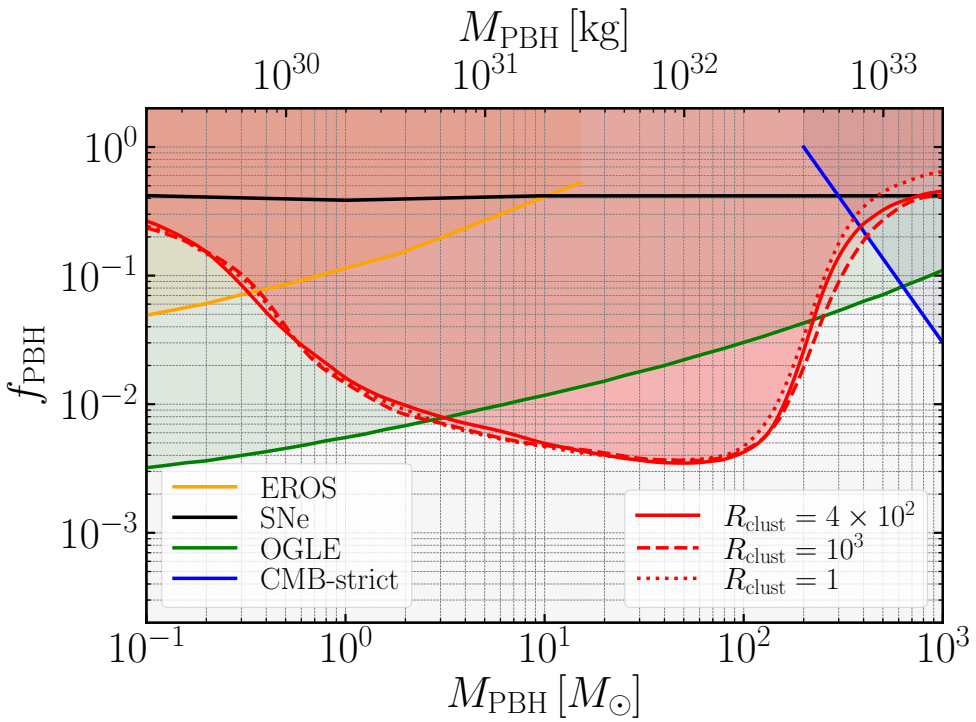
Early binaries: formed in RDE shortly after PBH formation

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

GWB from Primordial Black Holes

Bayesian analysis

95% CL constraints on f as a function of the PBH mass from Bayesian analysis



Parameter	Prior
$\Omega_{\rm ref}$	LogUniform$[10^{-12}, 10^{-7}]$
$\mu\,/M_\odot$	LogUniform$[10^{-1}, 10^{3}]$
σ	LogUniform$[10^{-2}, 1]$
$f_{\rm PBH}$	LogUniform$[10^{-5}, 1]$

No significant GWB associated with PBH or CBCs has been detected over the noise hypothesis, with logarithmic Bayes factors ~ -1

LVK Collaboration, PRX 16, 041023 (2026)

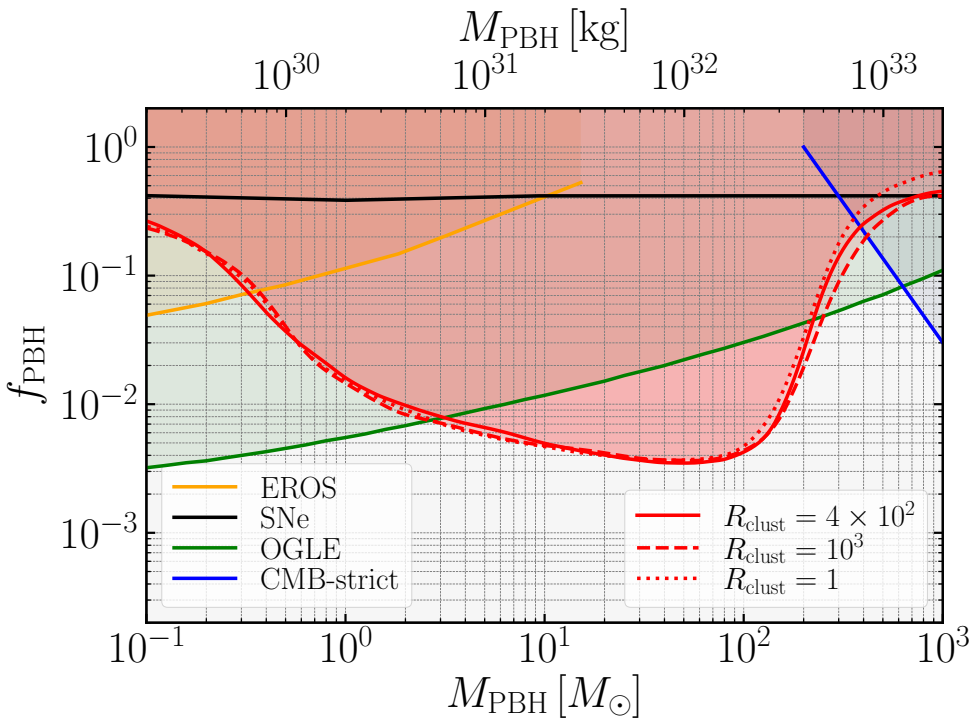
GWB from Primordial Black Holes

Bayesian analysis

Degeneracy: PBH and CBC during inspiral

$$\Omega_{\rm GW}(f) = \Omega_{\rm ref}\left(\frac{f}{f_{\rm ref}}\right)^{2/3}$$

95% CL constraints on f as a function of the PBH mass from Bayesian analysis



Highest sensitivity to PBH masses ~ 100 M⊙

- dominant contribution from merger

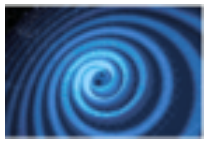
- characteristic frequency dependence
  (shape sensitive merger rate and mass distribution)

Break degeneracy between astrophysical BHs and PBHs for masses ~ 100 M⊙

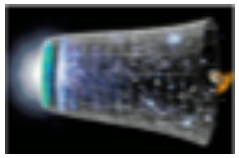
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Can we distinguish between astrophysical vs cosmological sources?

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



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



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



- 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*

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

*Einsle, Bizouard, Regimbau, **Sakellariadou**, PRD 112 (2025) 063056*
*Einsle, Bizouard, Regimbau, **Sakellariadou,** Suresh (2026)*

Conclusions

No GWB signal has been detected for any of the considered cosmological and high energy physics models

- *first-order phase transitions*
- *cosmic strings*
- *domain walls*
- *stiff equation of state*
- *axion inflation*
- *second-order*
- *scalar perturbations*
- *primordial black hole binaries*
- *parity violation*



constraints on their parameters

LIGO-Virgo-KAGRA data can already be used to derive new constraints on several BSM theories



tests of early universe scenarios and particle physics models otherwise inaccessible

LVK Collaboration, PRX 16, 041023 (2026)

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谢谢