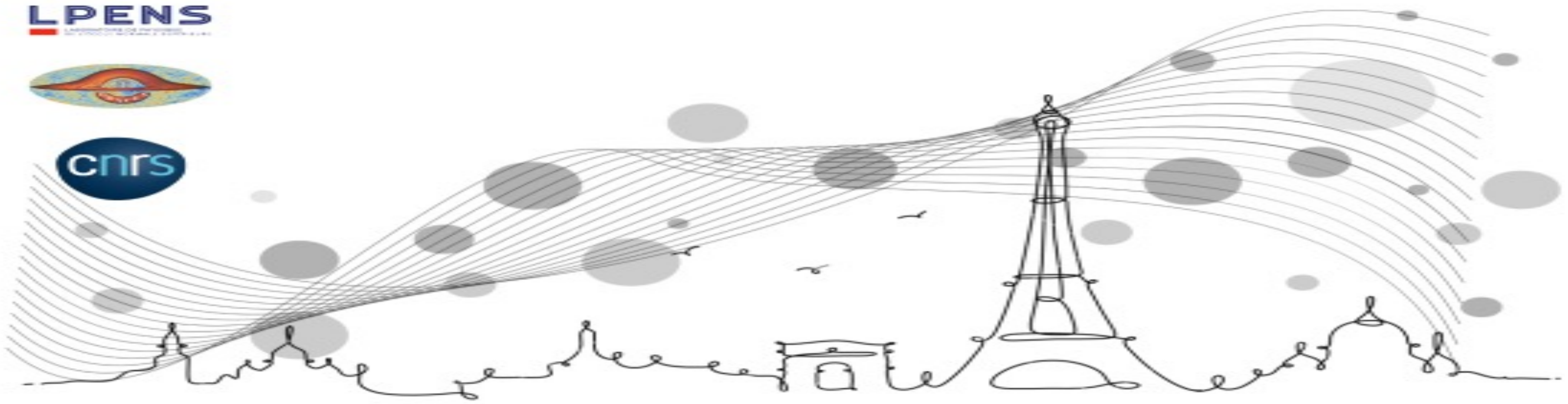


Paris workshop on primordial black holes and gravitational waves

University of Southampton

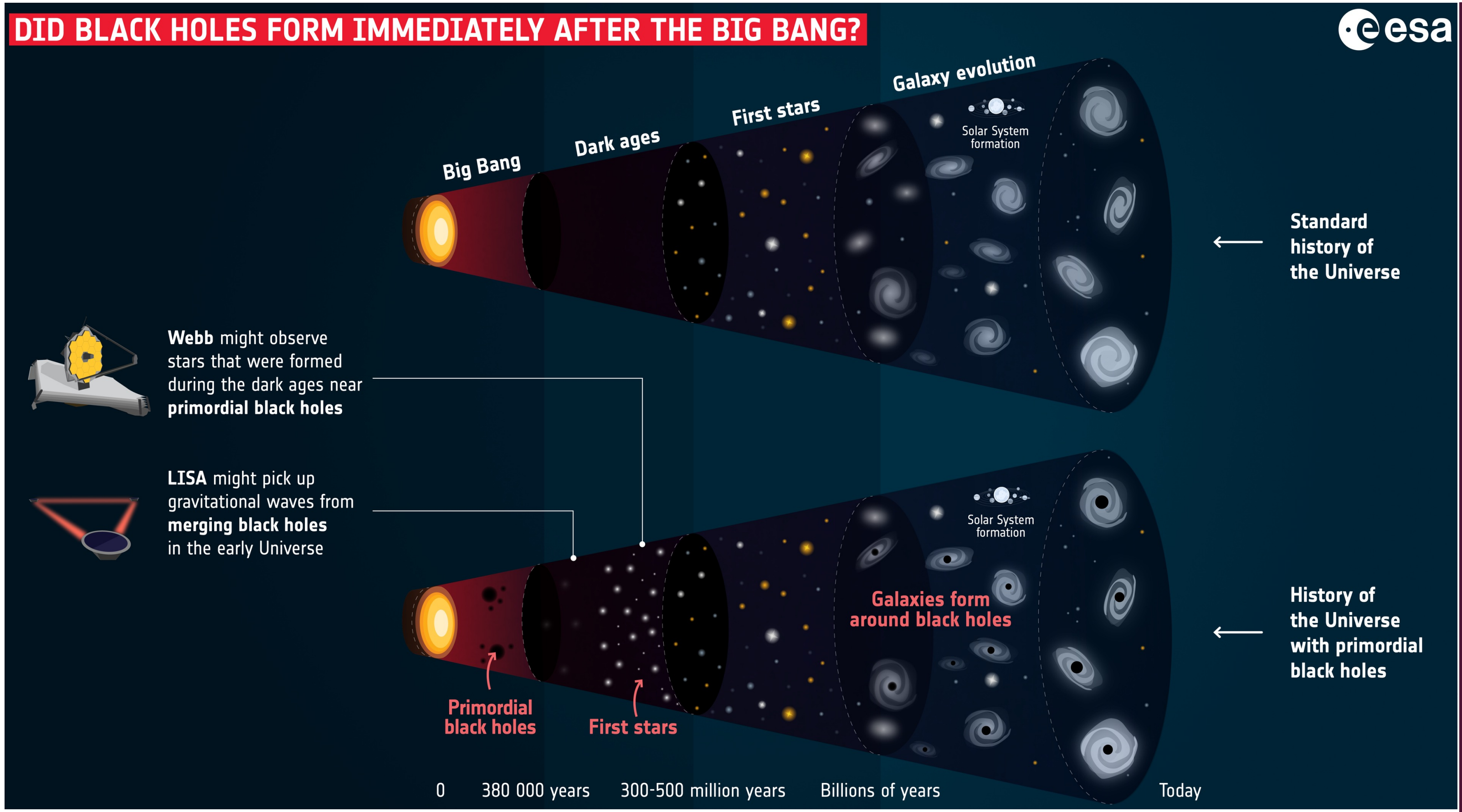
Rishav Roshan

School of Physics and Astronomy,
University of Southampton

28/11/2023

IMPRINT OF PBH DOMINATION ON GRAVITATIONAL WAVES GENERATED BY COSMIC STRINGS

Based on: **Phys.Rev.D 108 (2023) 2, 023531**



MOTIVATION AND BACKGROUND

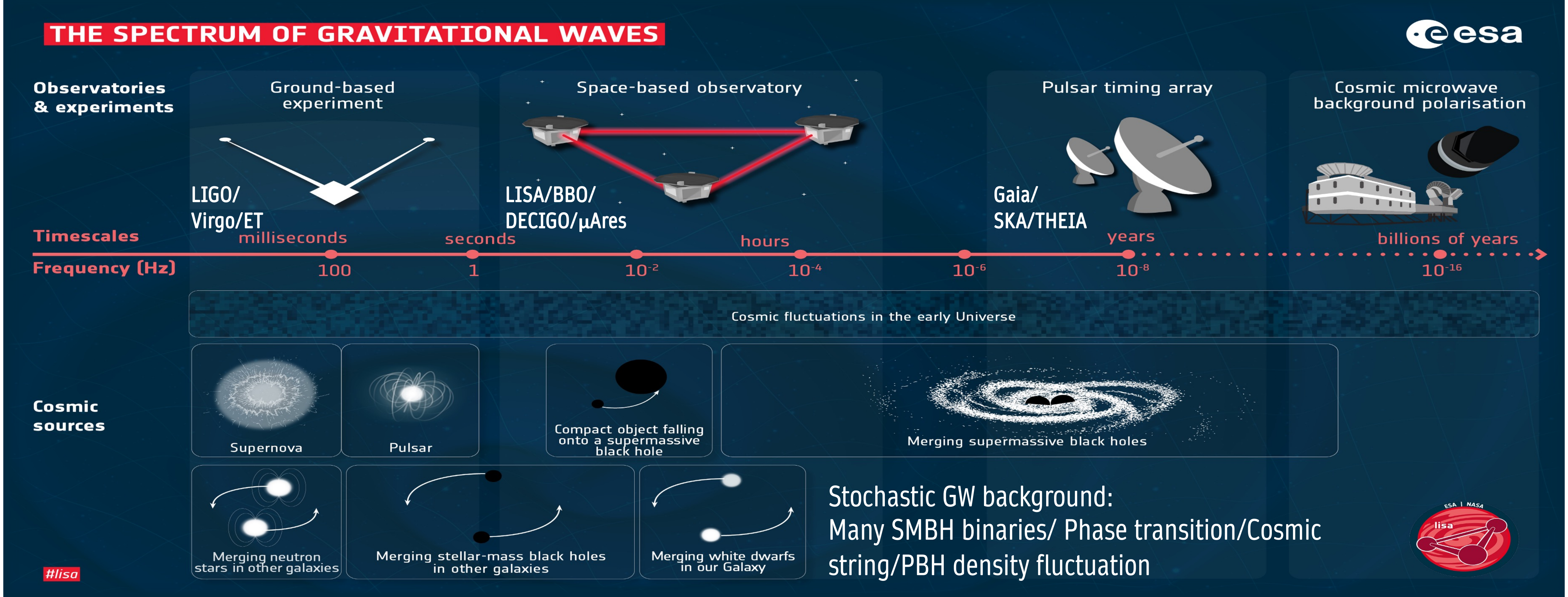
Cosmological Puzzles

1. Matter-Antimatter asymmetry
2. Dark Matter
3. Neutrino masses

Motivation for BSM Physics

Cosmological Observations: a powerful investigative tool

Gravitational Waves: a probe to the early Universe



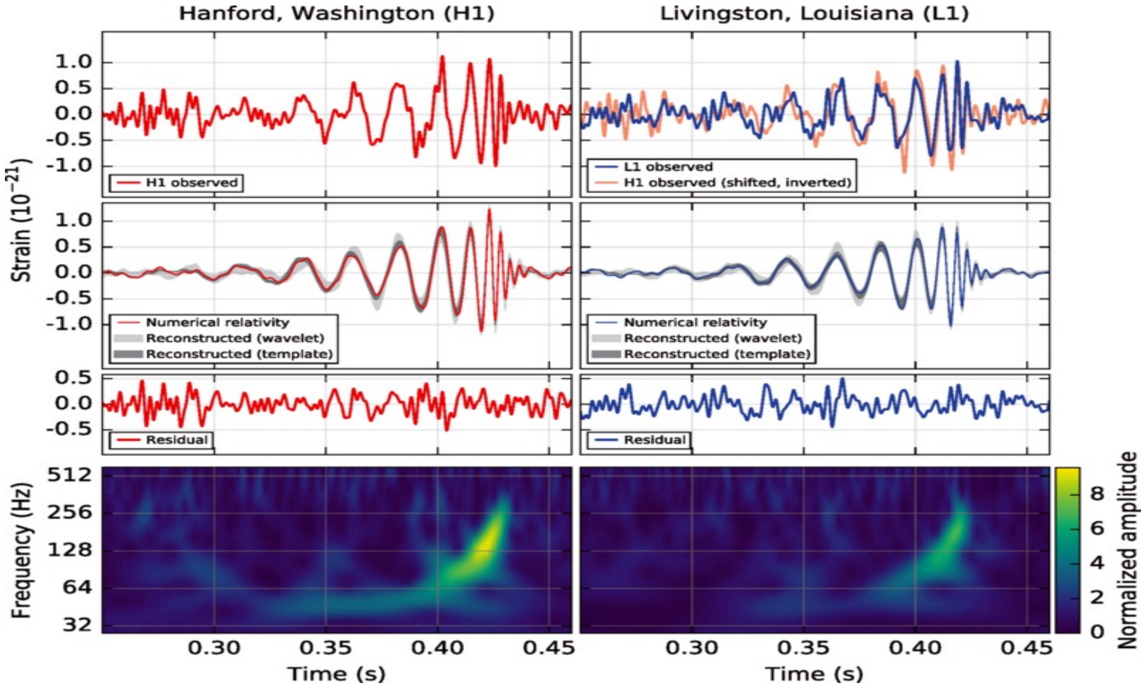
Stochastic GW background:
Many SMBH binaries/ Phase transition/Cosmic string/PBH density fluctuation

Credit to ESA

Gravitational Waves: a probe to the early Universe!

Recent GW discoveries

Discovery of GW by LIGO-VIRGO Col.



PRL 116, 061102 (2016)

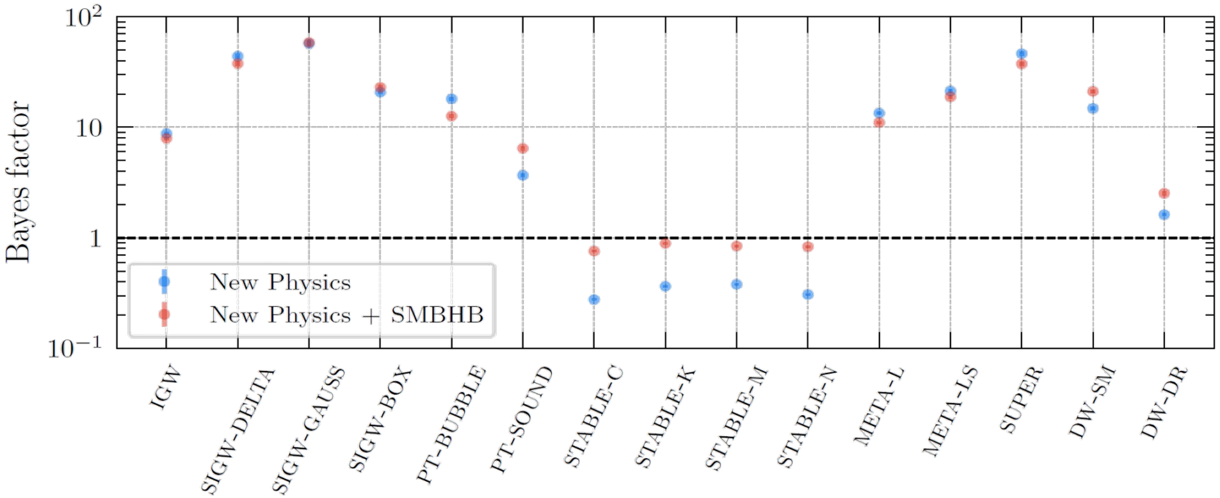
Source of GW: Merging of pair of BHs at z = 0.09

Recent results reported by PTA projects

Several PTA projects have reported positive evidence of a stochastic gravitational wave background.

Source of SGWB: Merging of SMBH Binaries/Cosmological origin/combination of Both.

NANOGrav, 2306.16219



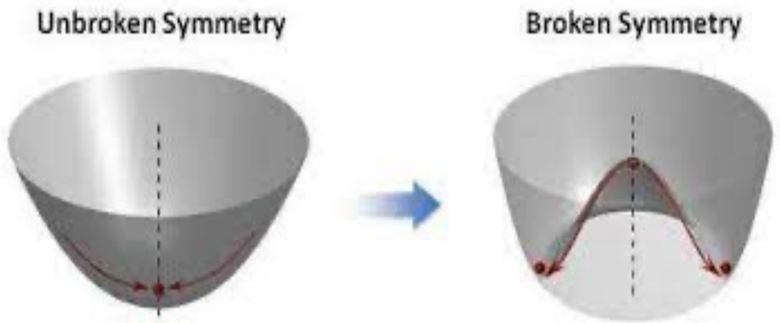
Cosmic Strings: A topological defect

Spontaneous Symmetry breaking and topological defects

U(1) gauge theory → **Cosmic string**

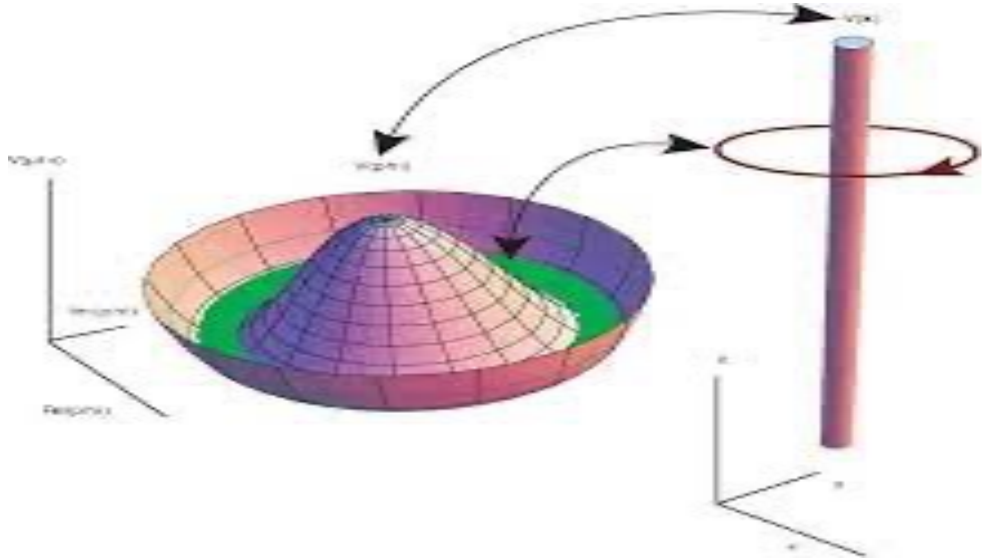
Discrete symmetry → Domain wall

Chiral symmetry to U(1) → Monopole

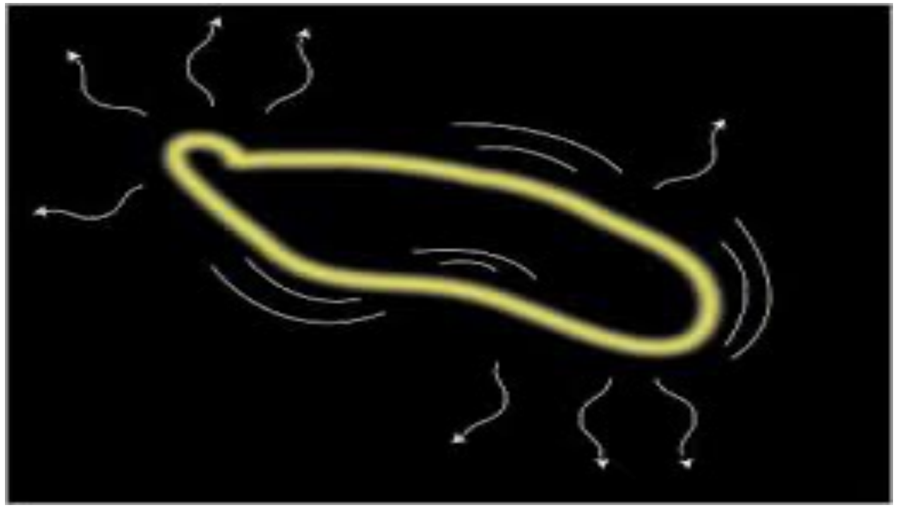


Cosmic Strings

CS is a 1-d defect originating from SSB of U(1) symmetry.
a. Breaking of global U(1) symmetry: **Global string**
b. Breaking of local U(1) symmetry: **Local string**



GWs from Cosmic Strings



At a later time, the size of a loop's initial length $l_i = \alpha t_i$ can be expressed as:

$$l(t) \simeq \alpha t_i - \Gamma G\mu(t - t_i).$$

$G\mu$: String Tension $\quad \Gamma = 50$

Set of normal mode oscillation with frequency $f_k = 2k/l \;\; (k = 1, 2, 3, \ldots.\infty)$

$$\Omega_{GW}(t_0, f) = \sum_k \Omega_{GW}^{(k)}(t_0, f) \qquad f \equiv f(t_0) = f_k a(t_0)/a(t)$$

GWs from Cosmic Strings

- Present-day GW energy density:

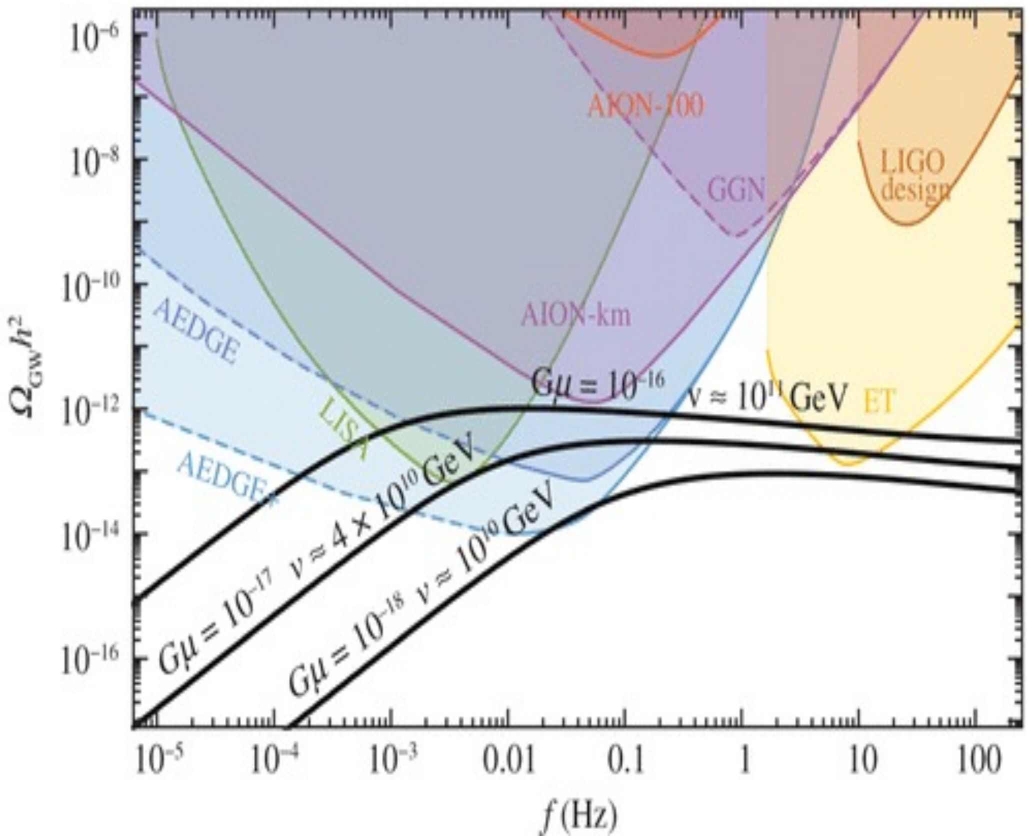
$$\Omega_{\rm GW}^{(k)}(f) = \frac{1}{\rho_c}\frac{2k}{f}\frac{\mathcal{F}_\alpha \Gamma^{(k)} G\mu^2}{\alpha(\alpha+\Gamma G\mu)}\int_{t_F}^{t_0} d\tilde{t}\frac{C_{\rm eff}(t_i^{(k)})}{t_i^{(k)\,4}}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5\left[\frac{a(t_i^{(k)})}{a(\tilde{t})}\right]^3 \Theta(t_i^{(k)} - t_F)\,,$$

- Typical feature:

$$\Omega_{\rm GW}^{(k=1),{\rm plateau}}(f) = \frac{128\pi G\mu}{9\zeta(\delta)}\frac{A_r}{\epsilon_r}\Omega_r\left[(1+\epsilon_r)^{3/2} - 1\right]$$

$$\epsilon_r = \alpha/\Gamma G\mu \qquad \Omega_r \simeq 9\times 10^{-5}$$

$$A_r = 5.4$$



Phil.Trans.Roy.Soc.Lond.A 380 (2022) 20210060

Primordial Black Holes (PBH): Hawking 1975

PBH formation →

- Collapse of large inhomogeneities
- Collapse of cosmic string loops
- Bubble collisions

PBH mass at formation:

$$M_{\rm BH}(T_{\rm in}) = \frac{4}{3}\pi\gamma\left(\frac{1}{\mathcal{H}(T_{\rm in})}\right)^3 \rho_{\rm rad}(T_{\rm in})$$

Black hole Temperature:

$$T_{\rm BH} = \frac{1}{8\pi G M_{\rm BH}} \approx 1.06 \left(\frac{10^{13}\,{\rm g}}{M_{\rm BH}}\right)\,{\rm GeV}$$

Bound on PBH mass:

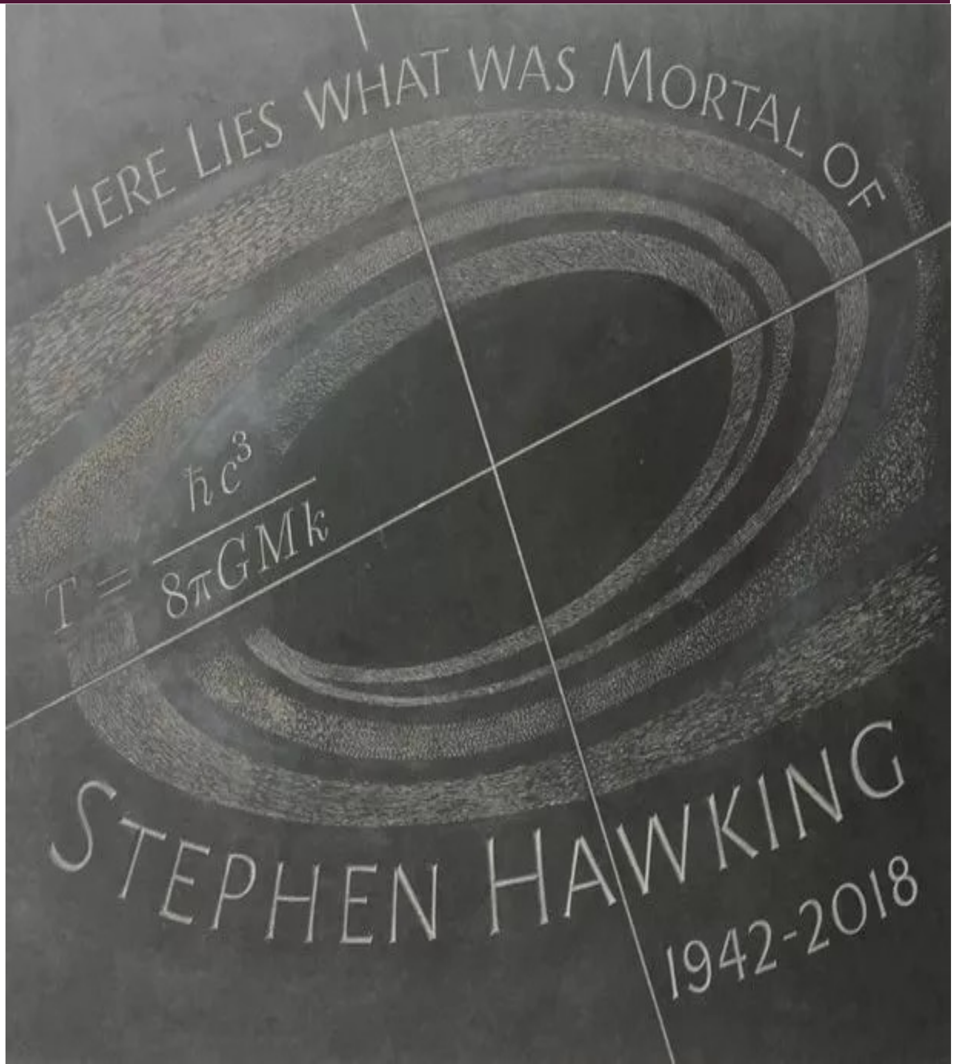
$$0.1\,{\rm g} \lesssim m_{\rm in} \lesssim 3.4\times 10^{8}\,{\rm g}$$

Hawking evaporation:

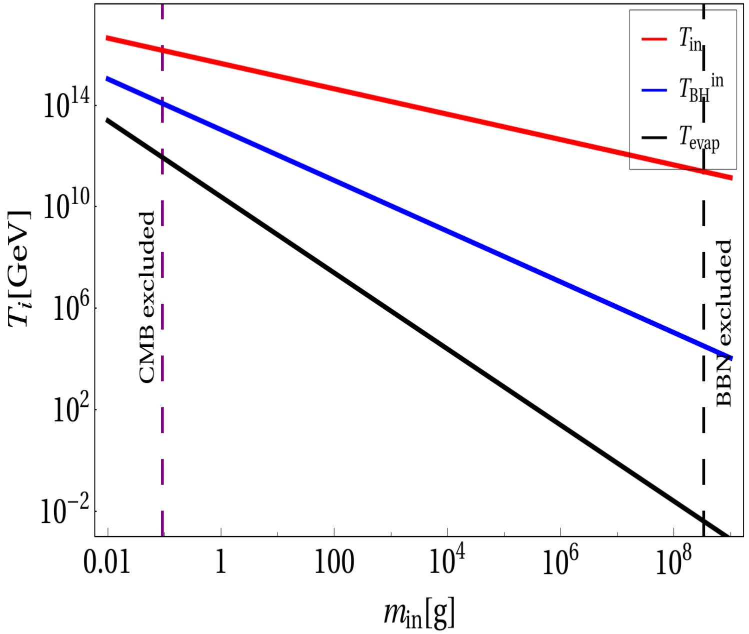
$$\frac{dm_{\rm BH}(t)}{dt} = -\frac{\mathcal{G}\, g_\star(T_{\rm BH})}{30720\,\pi}\,\frac{M_{\rm pl}^4}{m_{\rm in}(t)^2}$$

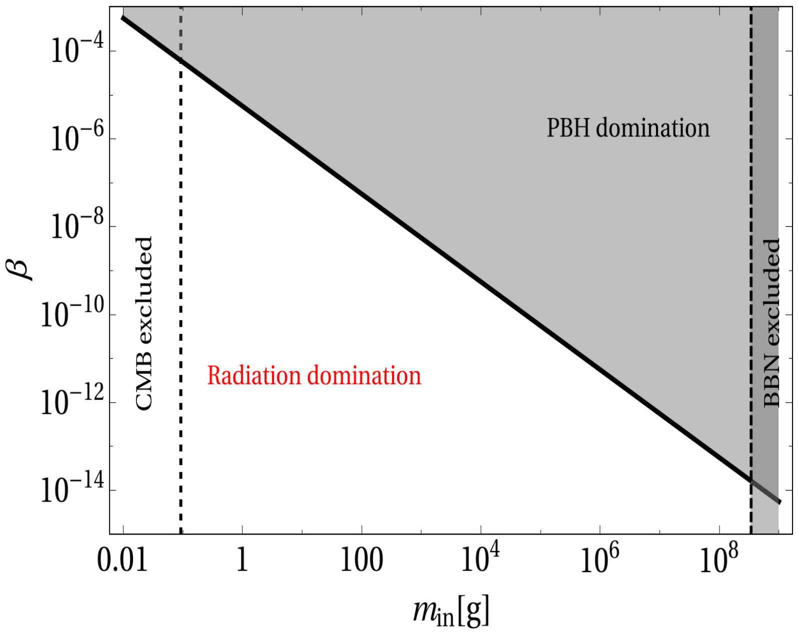
$$\beta \equiv \frac{\rho_{\rm BH}(T_{\rm in})}{\rho_{\rm rad}(T_{\rm in})}$$

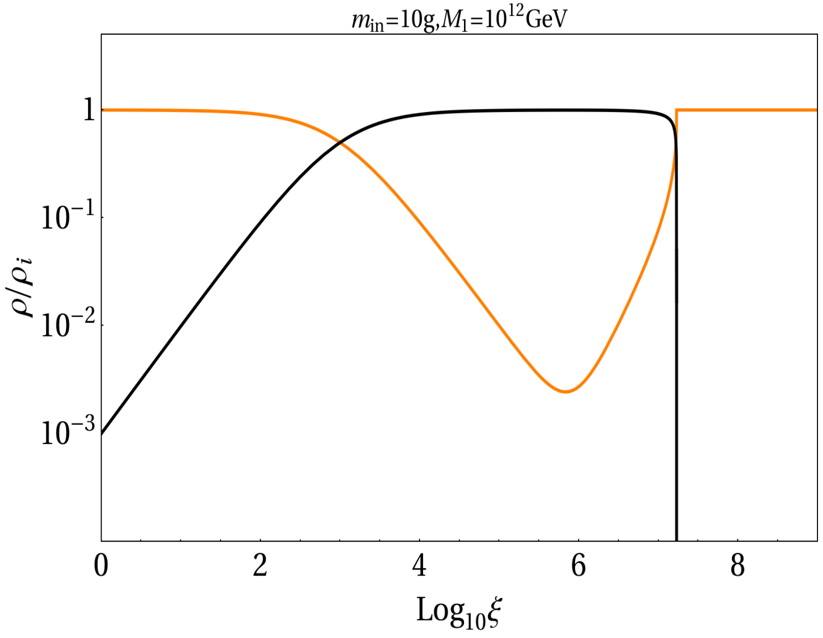
$$\beta < \beta_{\rm crit} \equiv \gamma^{-1/2}\sqrt{\frac{\mathcal{G}\, g_\star(T_{\rm BH})}{10640\,\pi}}\,\frac{M_{\rm pl}}{m_{\rm in}}$$



Primordial Black Holes : Characteristics







$$T_{\rm in} = \left(\frac{45\,\gamma^2}{16\,\pi^3\,g_\star\,(T_{\rm in})}\right)^{1/4}\sqrt{\frac{M_{\rm pl}}{M_{\rm BH}(T_{\rm in})}}\,M_{\rm pl}$$

$$T_{\rm BH} = \frac{1}{8\pi\,G\,M_{\rm BH}} \approx 1.06\,\left(\frac{10^{13}\,{\rm g}}{M_{\rm BH}}\right)\;{\rm GeV}$$

$$T_{\rm evap} \equiv \left(\frac{45\,M_{\rm pl}^2}{16\,\pi^3\,g_\star\,(T_{\rm evap})\,\tau^2}\right)^{1/4}$$

GWs from PBH density fluctuations

GWs from PBH

1. Evaporation of the PBH
2. PBH mergers
3. **Inhomogeneity in the distribution of the PBH**

Inhomogeneity in PBH distribution

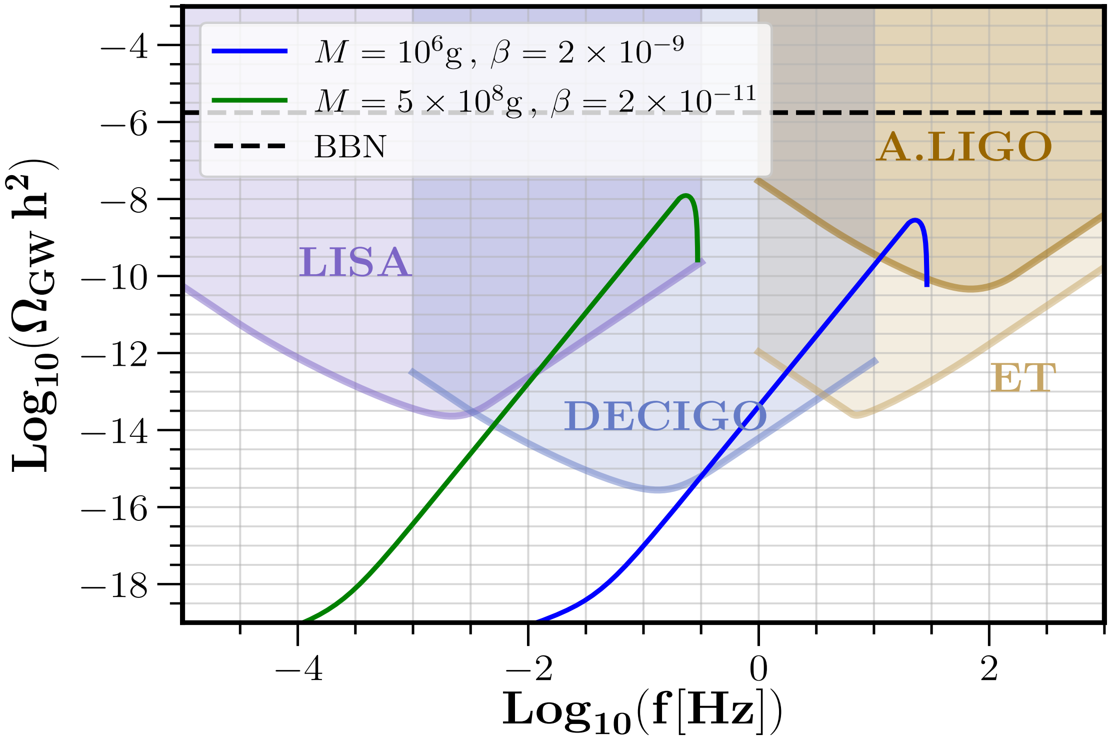
↓

Induces GW at second order when PBH dominates

$$\Omega_{\rm GW}(t_0, f) \simeq \Omega_{\rm GW}^{\rm peak}\left(\frac{f}{f_{\rm peak}}\right)^{11/3}\Theta\left(f_{\rm peak} - f\right)$$

$$\Omega_{\rm GW}^{\rm peak} \simeq 2\times 10^{-6}\left(\frac{\beta}{10^{-8}}\right)^{16/3}\left(\frac{m_{\rm in}}{10^7 {\rm g}}\right)^{34/9} \qquad f_{\rm peak} \simeq 1.7\times 10^3\ {\rm Hz}\left(\frac{m_{\rm in}}{10^4 {\rm g}}\right)^{-5/6}$$

JCAP04(2021)062



MOTIVATION

Idea: We study the effect of an ultralight PBH-dominated phase on the GW spectrum generated by a CS network formed as a result of a high-scale U(1) symmetry-breaking

Features:

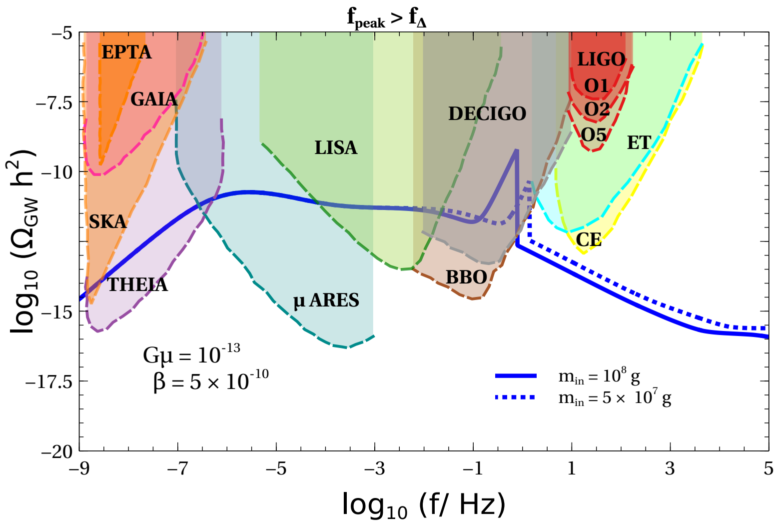
The presence of ultralight PBHs with $\beta > \beta c$ can affect the CS-generated GW spectrum in two ways:

a. Introducing spectral break due to PBH domination plus evaporation
b. Introducing a new GW source from density fluctuations.

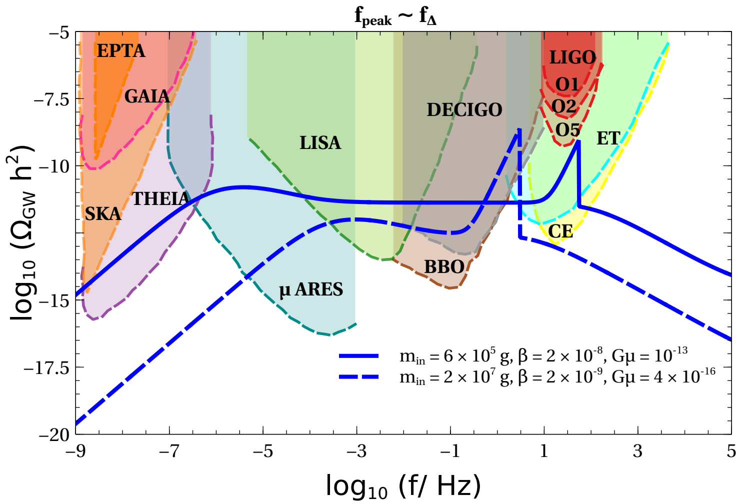
Due to PBH-induced early matter domination before BBN, the plateau region of the CS-generated GW spectrum gets broken at a turning point frequency $f\Delta$:

$$f_\Delta = \frac{4}{\alpha t_\Delta}\frac{a_M}{a_0} = \sqrt{\frac{8}{\alpha \Gamma G\mu}} t_\Delta^{-1/2} t_{\rm eq}^{1/6} t_0^{-2/3} \simeq \sqrt{\frac{8 z_{\rm eq}}{\alpha \Gamma G\mu}} \left(\frac{t_{\rm eq}}{t_\Delta}\right)^{1/2} t_0^{-1}$$

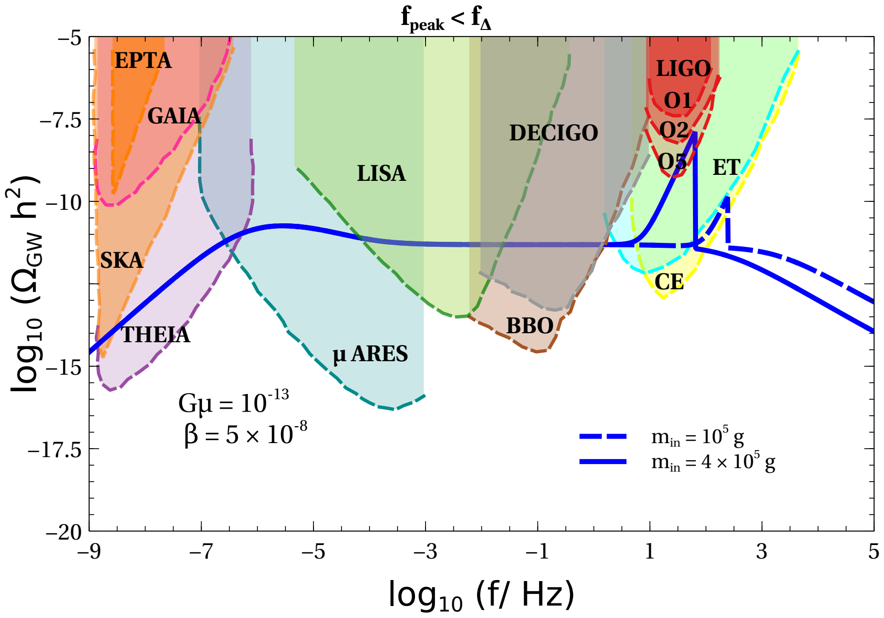
RESULTS



$f_{peak} > f_{\Delta}$
EPTA
GAIA
SKA
THEIA
LISA
μ ARES
DECIGO
BBO
LIGO
O1
O2
O5
ET
CE
$G\mu = 10^{-13}$
$\beta = 5 \times 10^{-10}$
$m_{in} = 10^{8}$ g
$m_{in} = 5 \times 10^{7}$ g
$\log_{10} (\Omega_{GW} h^2)$
$\log_{10}$ (f/ Hz)

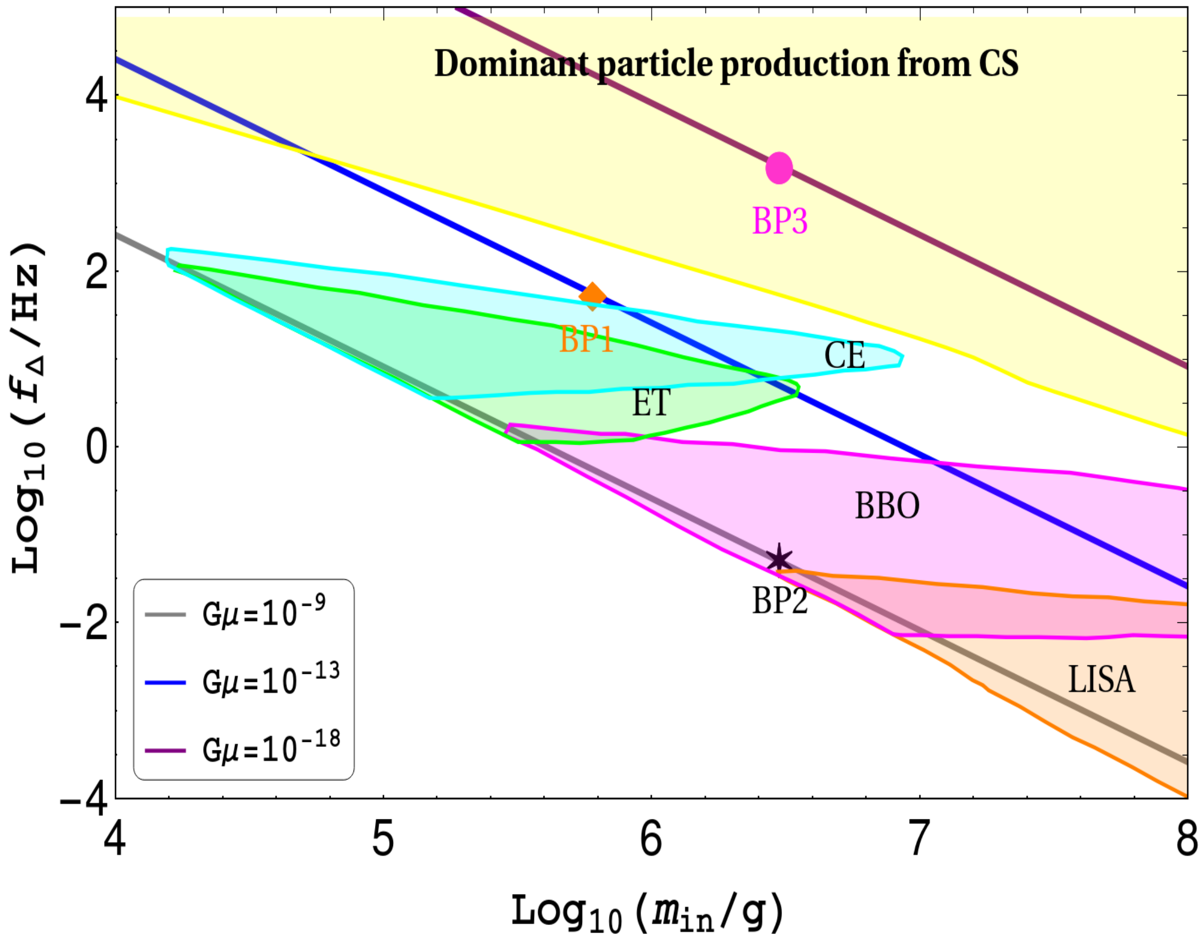


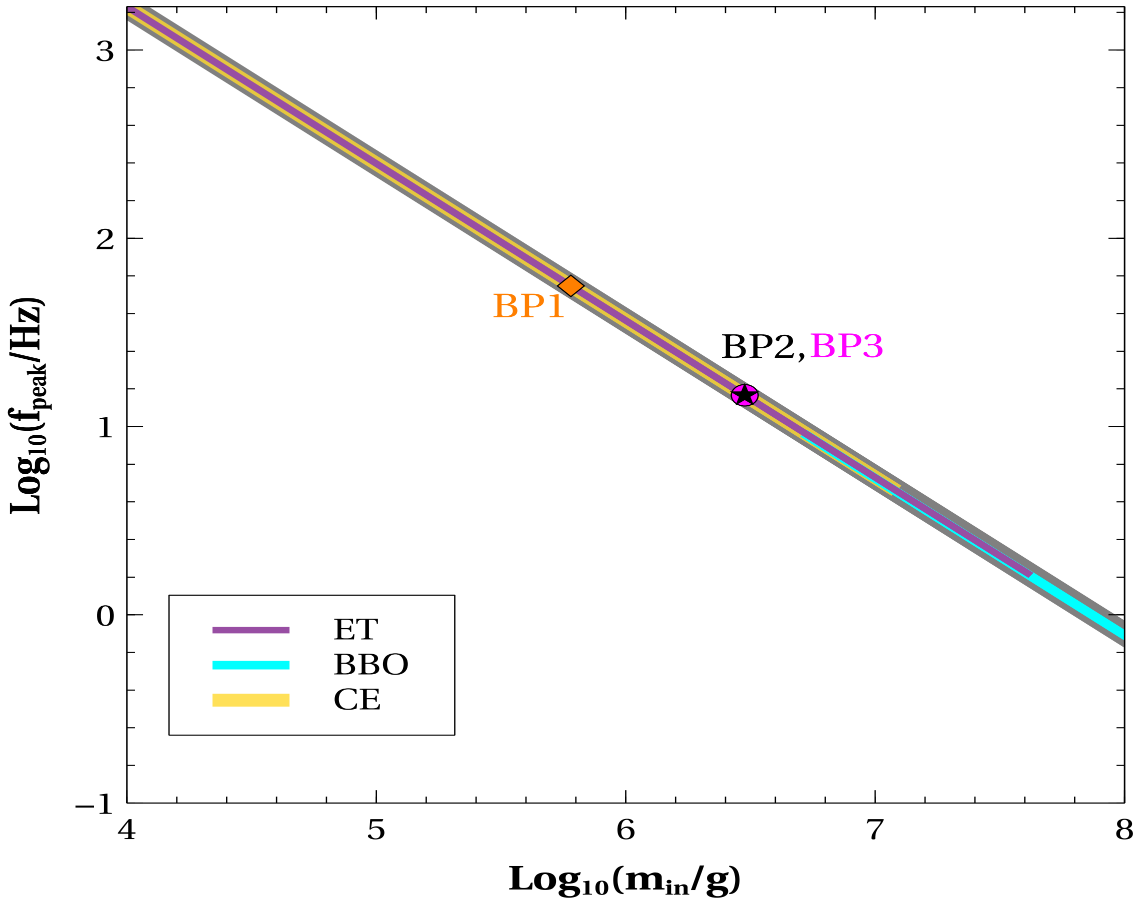
$f_{peak} \sim f_{\Delta}$
EPTA
GAIA
SKA
THEIA
LISA
μ ARES
DECIGO
BBO
LIGO
O1
O2
O5
ET
CE
$m_{in} = 6 \times 10^{5}$ g, $\beta = 2 \times 10^{-8}$, $G\mu = 10^{-13}$
$m_{in} = 2 \times 10^{7}$ g, $\beta = 2 \times 10^{-9}$, $G\mu = 4 \times 10^{-16}$
$\log_{10} (\Omega_{GW} h^2)$
$\log_{10}$ (f/ Hz)



$f_{peak} < f_{\Delta}$
EPTA
GAIA
SKA
THEIA
LISA
μ ARES
DECIGO
BBO
LIGO
O1
O2
O5
ET
CE
$G\mu = 10^{-13}$
$\beta = 5 \times 10^{-8}$
$m_{in} = 10^{5}$ g
$m_{in} = 4 \times 10^{5}$ g
$\log_{10} (\Omega_{GW} h^2)$
$\log_{10}$ (f/ Hz)

SUMMARY PLOTS





CONNECTION TO REALISTIC BSM SCENARIOS

- Let us point out how such a spectrum could be a probe of particle physics models.
- PBH evaporation can produce both stable and unstable relics

  a. Stable Relic: Dark Matter

  b. Right-handed neutrinos ➡ May seed baryogenesis via leptogenesis
- PBHs can act as a portal between gravitational waves and the parameters of high-energy particle physics models.
- Such models featuring a high-scale gauged U(1)symmetry breaking would exhibit the combined spectrum discussed in this article.
- Studying this framework in the context of global strings, which generically appear in QCD-axion (including axionlike particles) models, might be interesting to explore in future works.

CONCLUSION

- We have proposed a unique gravitational wave-based probe of super high scale U(1) symmetry breaking with a PBH-dominated epoch before the BBN era.
- While cosmic strings resulting from U(1) breaking lead to a typical scale-invariant GW spectrum, ultralight PBH domination leads to an additional observable GW spectrum from density fluctuations.
- When combined, the GW spectrum has a unique shape with a plateau, a sharp tilted peak, and a characteristic falloff behavior.
- Depending on the cosmic string and the PBH parameters, different parts of the spectrum fall within reach of ongoing and planned future experiments.
- In addition to such marked features verifiable in GW detectors, the setup discussed in our work can also have very rich phenomenological implications connected to the production of dark matter from PBH evaporation, high-scale leptogenesis, and seesaw for neutrino mass related to U(1) symmetry breaking.

Multumesc
Spasibo
Thank You
Raibh Maith Agat
Maake
Chokrane
Obrigado
Danke
Asante
Salamat
Merci
Dank Je
Kiitos
Dankon
Matur Nuwun
Kia Ora
Matondo
Mochchakkeram
Grazie
Ua Tsaug Rau Koj
Terma Kasih
Niringrazzjak
Mamana
Vinaka
Welalin
BIGSTOCK