Opening a new window into the gravitational-wave Universe with PTAs

Andrea Mitridate

SOME ASTRONOMY MILESTONES

first documented observations
1800 - 1600 BC

telescope is invented
(1608)

confirmation of heliocentric theory

Kepler's laws (1609 - 1619)

Newton's laws (1687)

…

Hubble discovery of Universe expansion (1929)

first radio telescope
(1937)

CMB discovery (1964)

first binary pulsar is discovered (1974)

first millisecond pulsar is discovered (1983)

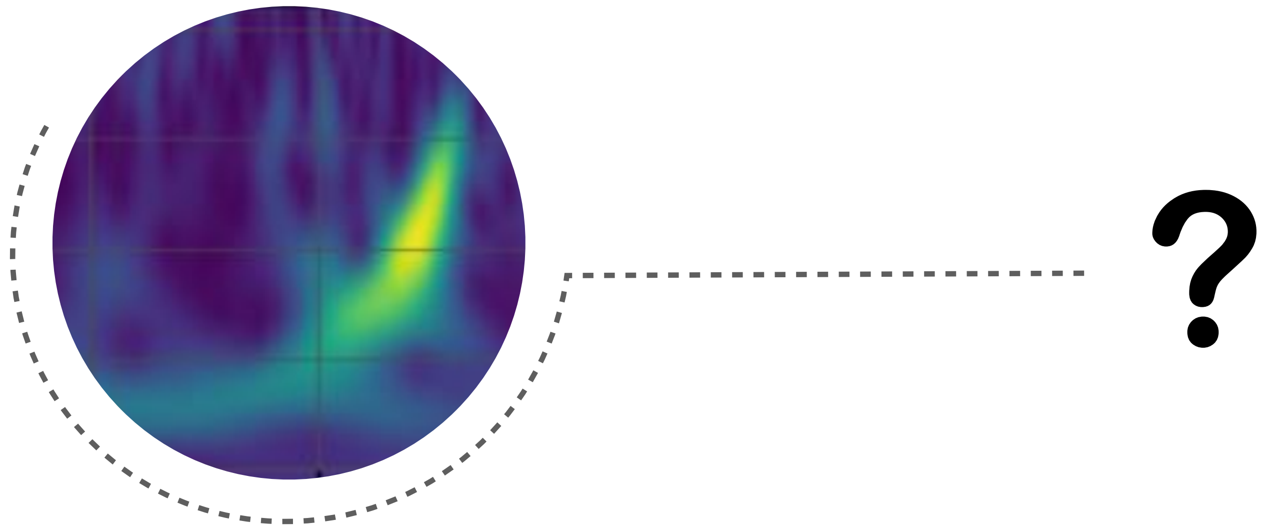
first space-based telescope
(1968)

full access to the electromagnetic spectrum

test of DM self-interactions (bullet cluster)

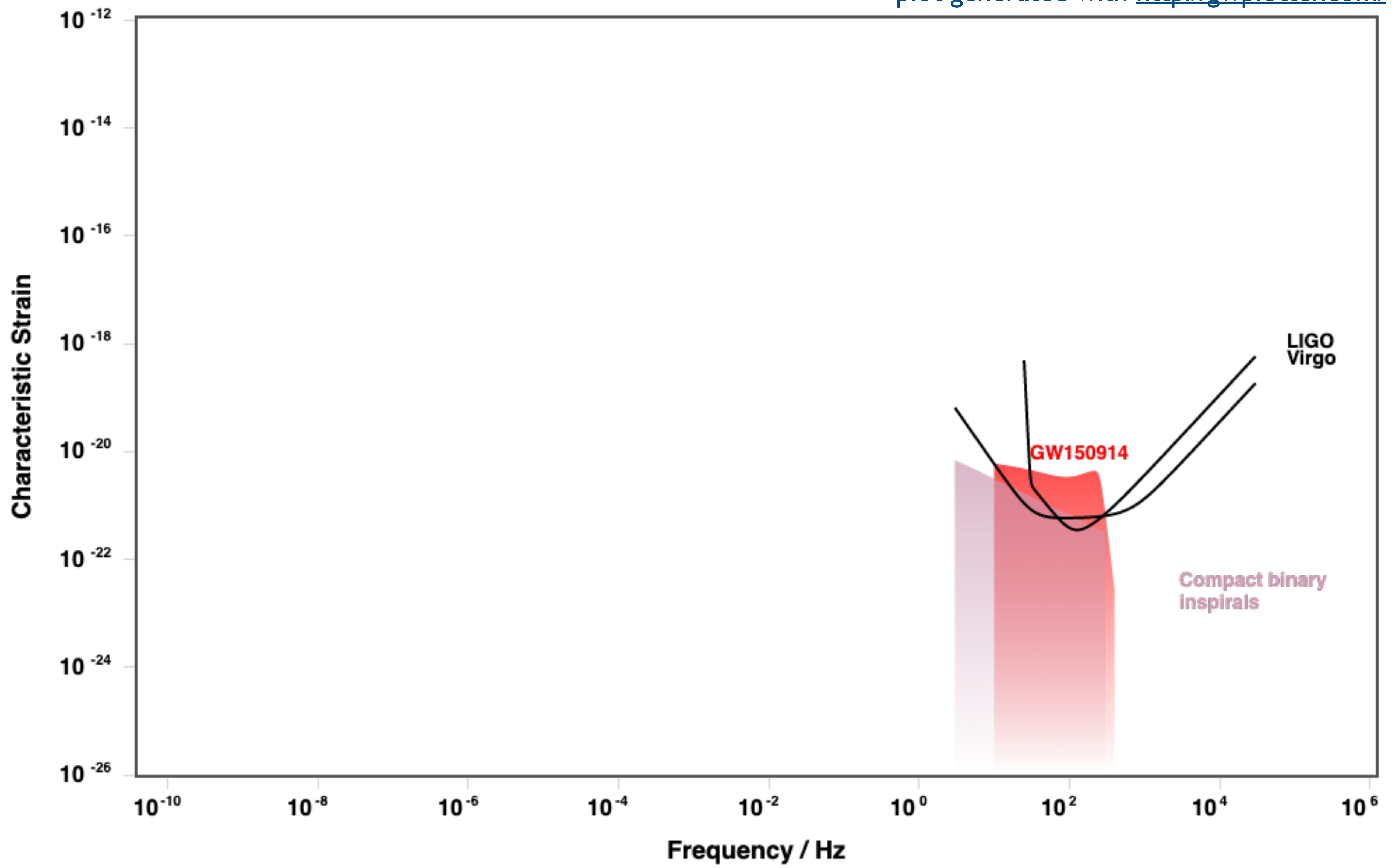
…

THE BEGINNING OF A NEW JOURNEY



first GW observation (2015)

plot generated with http://gwplotter.com/



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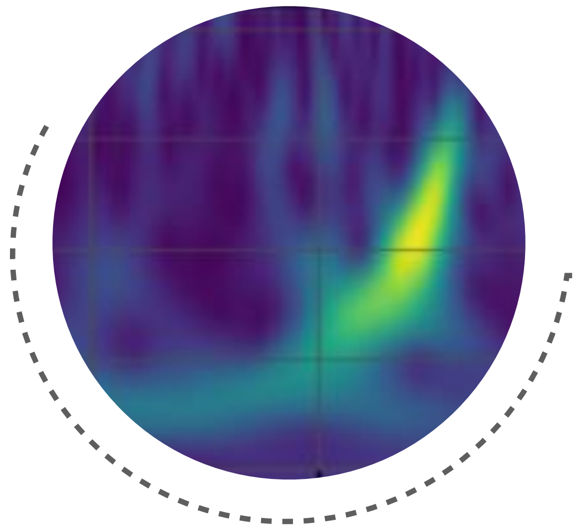

first GW observation (2015)

?

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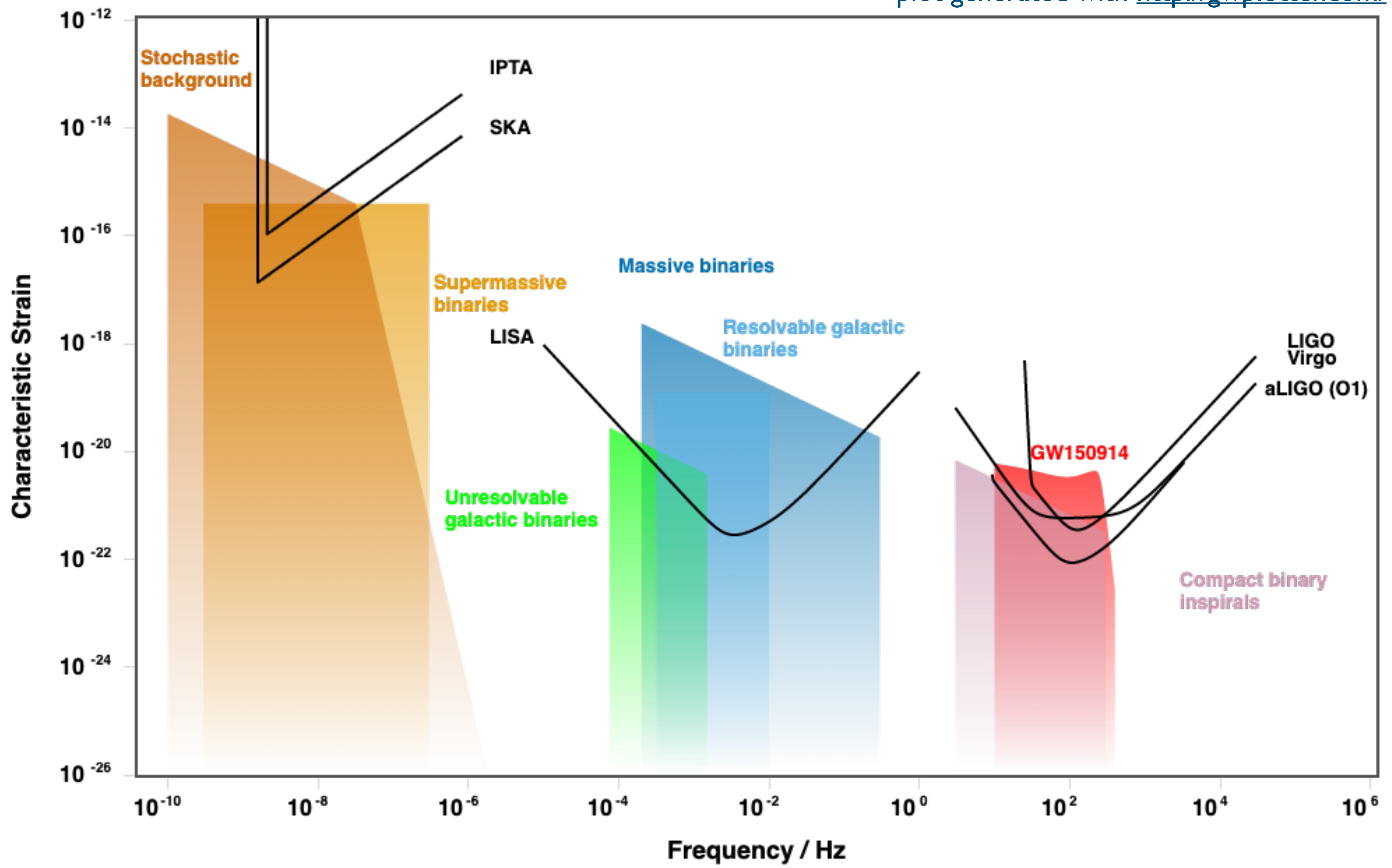

PULSARS

Animation by NASA's Goddard Space Flight Center

PULSARS AS CLOCKS

A GALAXY-SIZED DETECTOR FOR GW

NOISE vs SIGNAL

NOISE vs SIGNAL

NOISE

pulsar dependent

spatially uncorrelated

SIGNAL

common across pulsars

spatially **correlated**

EVIDENCE FOR A COMMON SIGNAL

The NANOGrav 12.5-year Data Set:
Search For An Isotropic Stochastic Gravitational-Wave Background

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The NANOGrav Collaboration

ABSTRACT

We search for an isotropic stochastic gravitational-wave background (GWB) in the 12.5-year pulsar-timing data set collected by the North American Nanohertz Observatory for Gravitational Waves. Our analysis finds strong evidence of a stochastic process, modeled as a power-law, with common amplitude and spectral slope across pulsars. Under our fiducial model, the Bayesian posterior of the amplitude for an $f^{-2/3}$ power-law spectrum, expressed as the characteristic GW strain, has median 1.92×10^{-15} and 5%–95% quantiles of $1.37\text{–}2.67 \times 10^{-15}$ at a reference frequency of $f_{\rm yr} = 1\ {\rm yr}^{-1}$; the Bayes factor in favor of the common-spectrum process versus independent red-noise processes in each pulsar exceeds $10,000$. However, we find no statistically significant evidence that this process has quadrupolar spatial correlations, which we would consider necessary to claim a GWB detection consistent with general relativity. We find that the process has neither monopolar nor dipolar correlations, which may arise from, for example, reference clock or solar system ephemeris systematics, respectively. The amplitude posterior has significant support above previously reported upper limits; we explain this in terms of the Bayesian priors assumed for intrinsic pulsar red noise. We examine potential implications for the supermassive black hole binary population under the hypothesis that the signal is indeed astrophysical in nature.

Arzoumanian et al. [2009.04496]

EVIDENCE FOR A COMMON SIGNAL

ABSTRACT

We search for an isotropic stochastic gravitational-wave background (GWB) in the 12.5-year pulsar-timing data set collected by the North American Nanohertz Observatory for Gravitational Waves. Our analysis finds strong evidence of a stochastic process, modeled as a power-law, with common amplitude and spectral slope across pulsars. Under our fiducial model, the Bayesian posterior of the amplitude for an $f^{-2/3}$ power-law spectrum, expressed as the characteristic GW strain, has median 1.92×10^{-15} and 5%–95% quantiles of 1.37–2.67×10^{-15} at a reference frequency of $f_{\rm yr} = 1\ {\rm yr}^{-1}$; the Bayes factor in favor of the common-spectrum process versus independent red-noise processes in each pulsar exceeds $10,000$. However, we find no statistically significant evidence that this process has quadrupolar spatial correlations, which we would consider necessary to claim a GWB detection consistent with general relativity. We find that the process has neither monopolar nor dipolar correlations, which may arise from, for example, reference clock or solar system ephemeris systematics, respectively. The amplitude posterior has significant support above previously reported upper limits; we explain this in terms of the Bayesian priors assumed for intrinsic pulsar red noise. We examine potential implications for the supermassive black hole binary population under the hypothesis that the signal is indeed astrophysical in nature.

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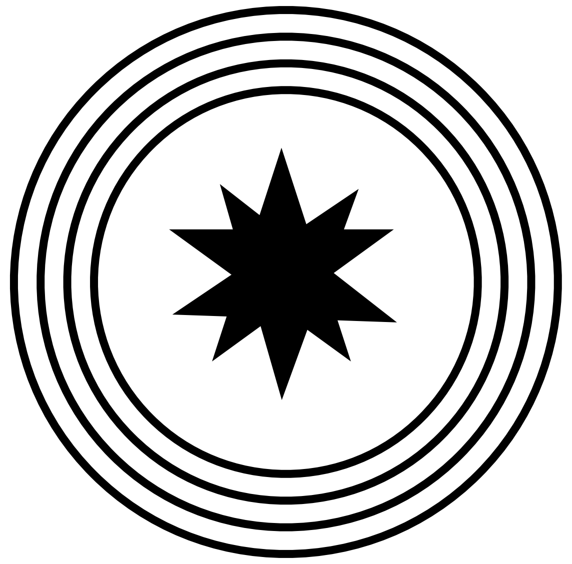
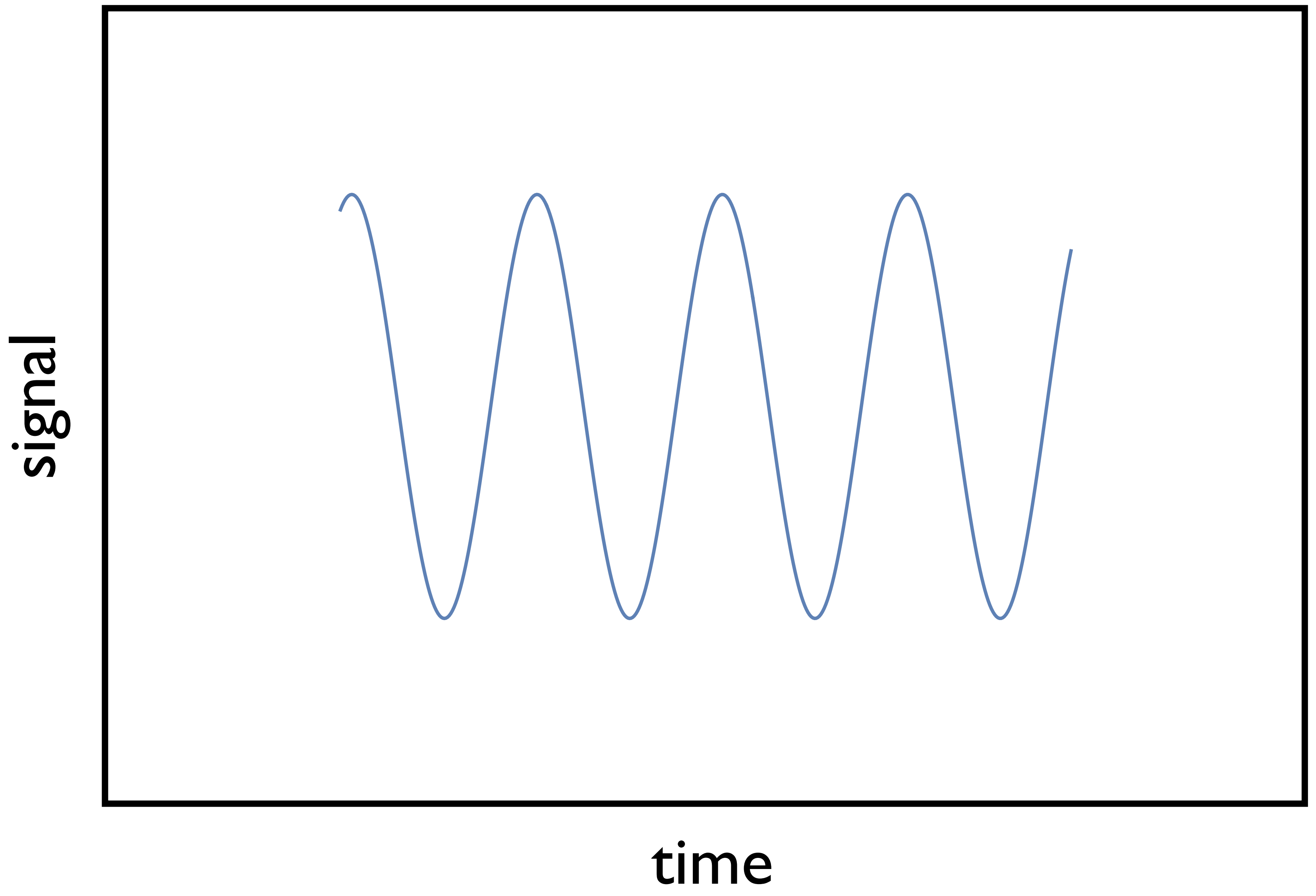
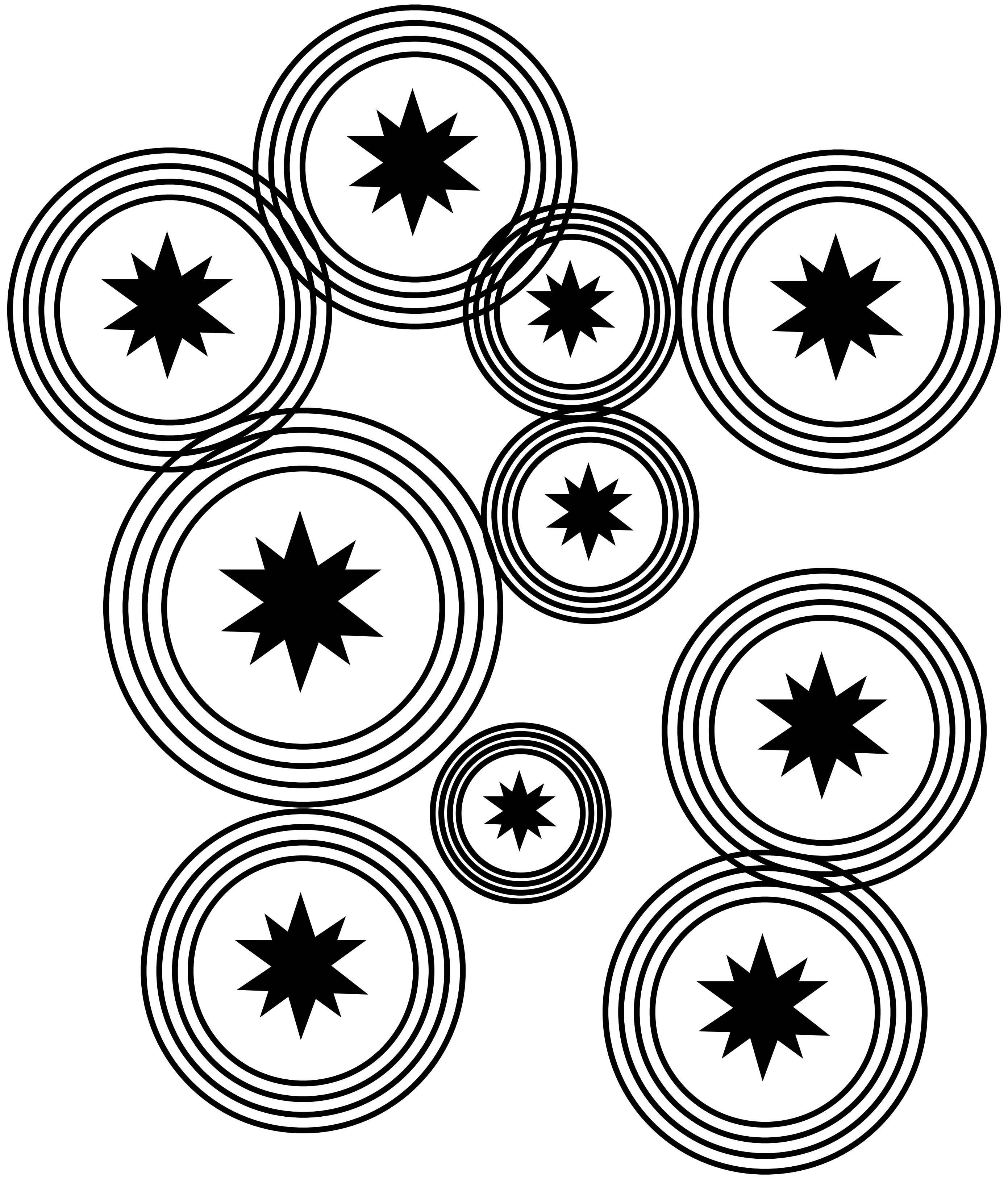
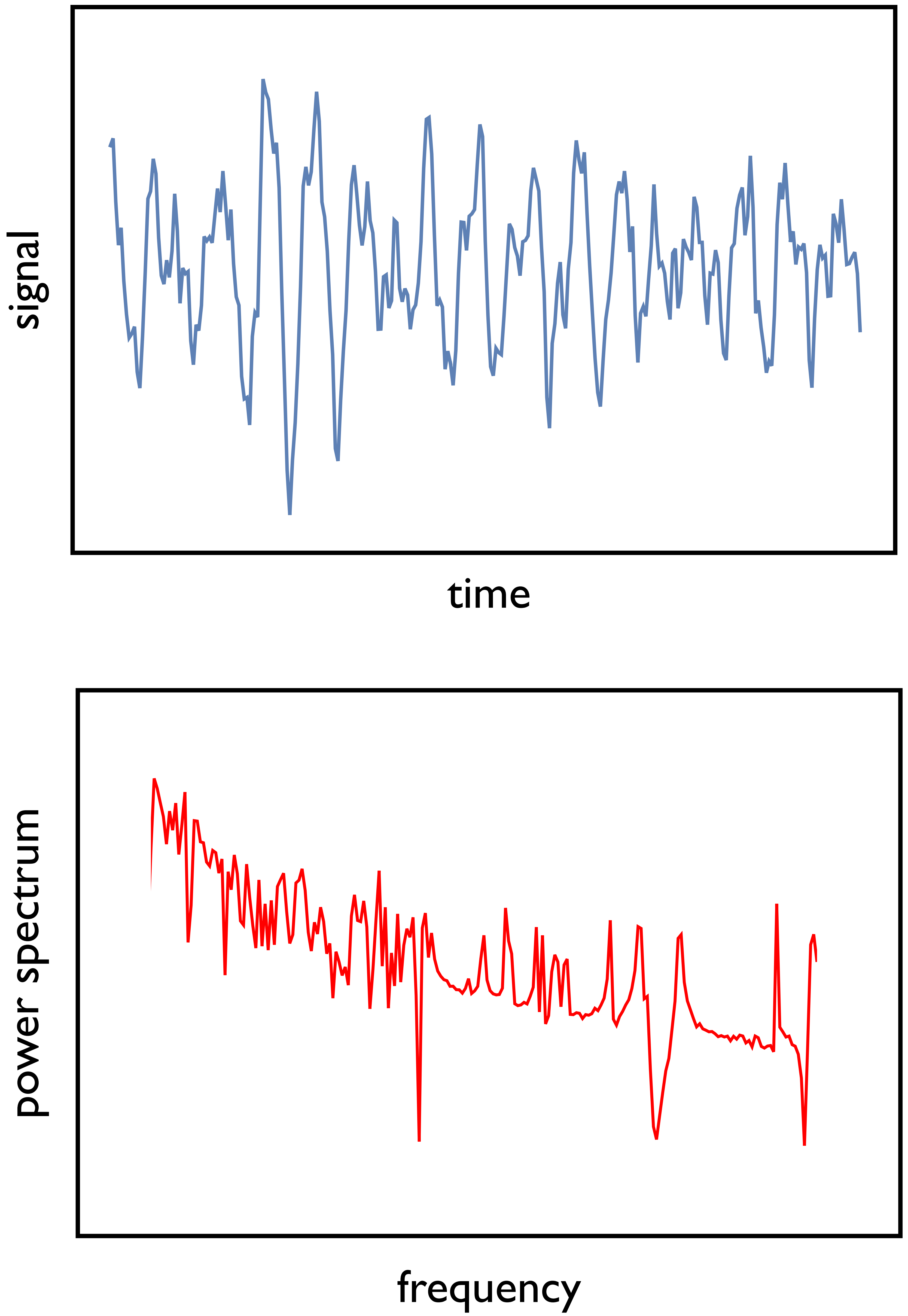
DETERMINISTIC vs STOCHASTIC





DETERMINISTIC vs STOCHASTIC





EVIDENCE FOR A COMMON SIGNAL

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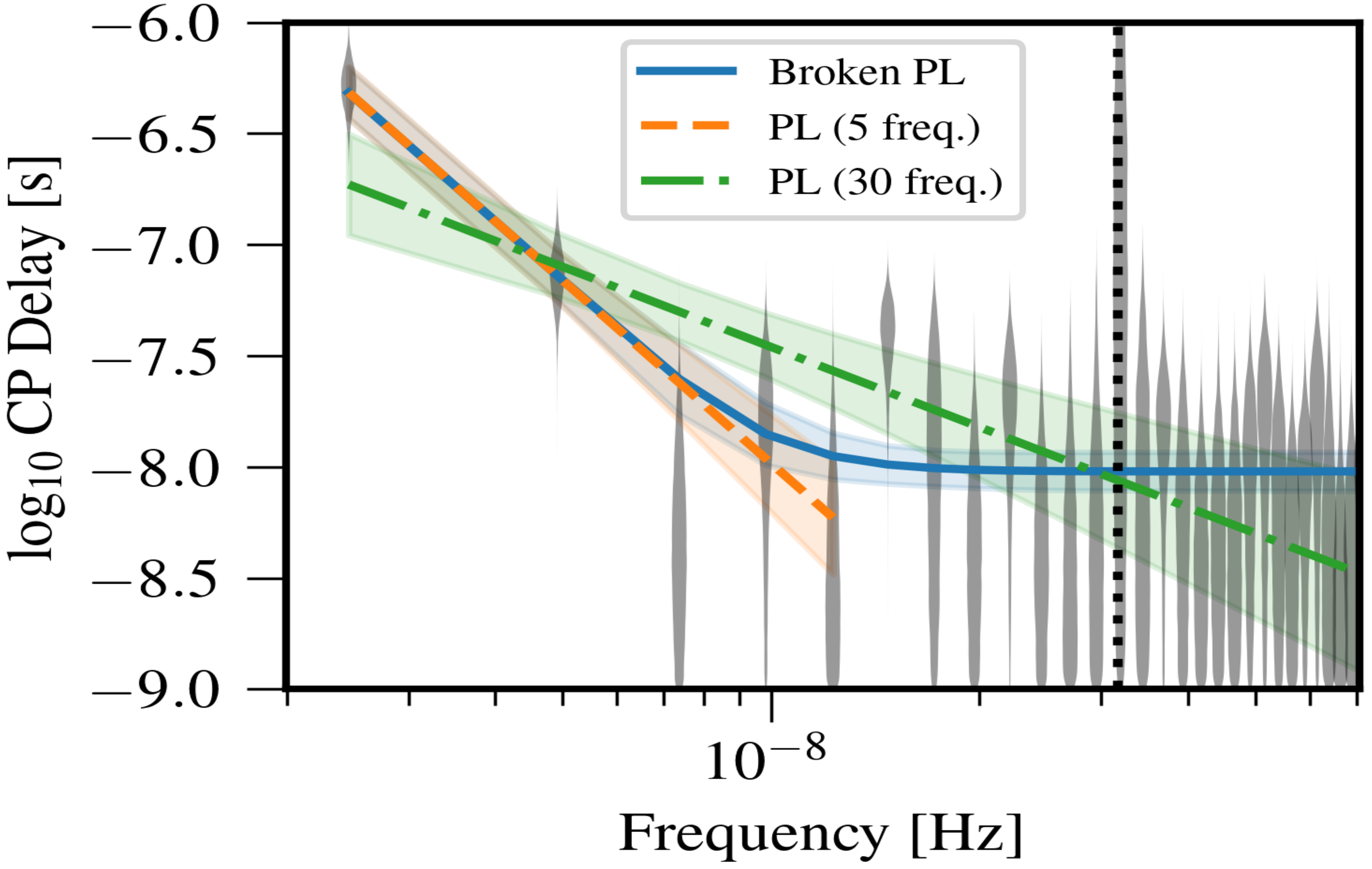
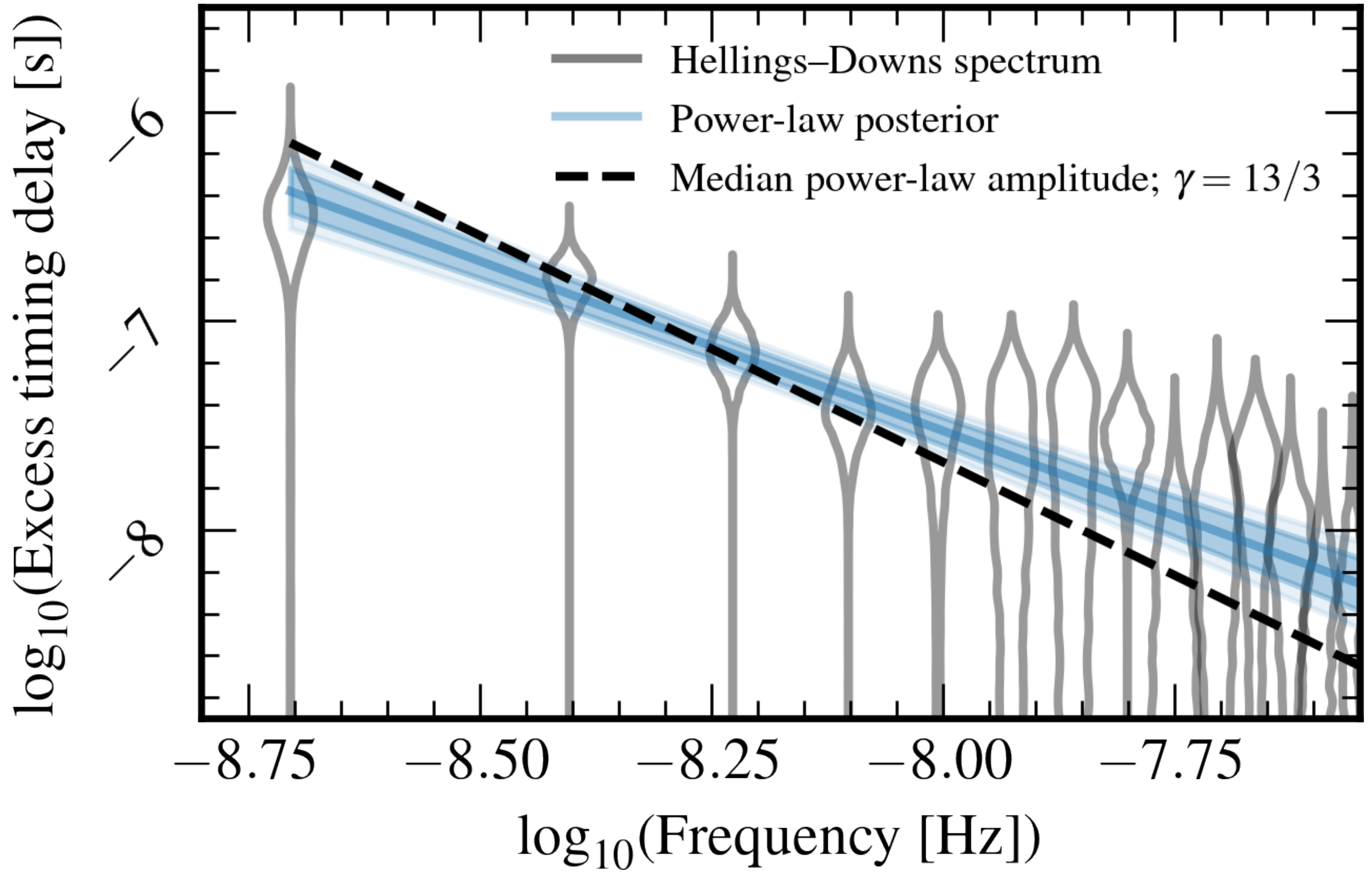
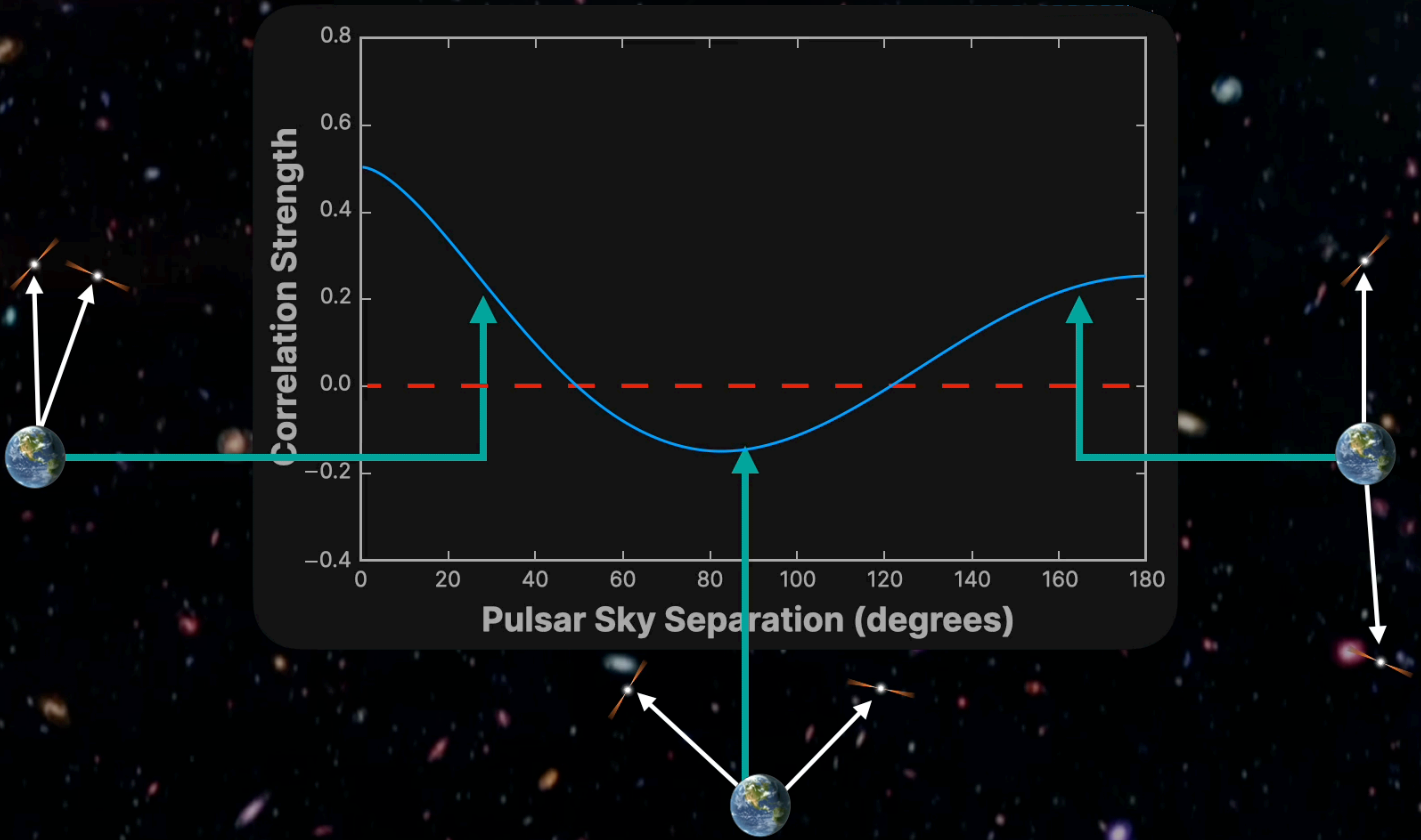


Agazie et al. [2306.16213]



WHAT ABOUT CORRELATIONS?



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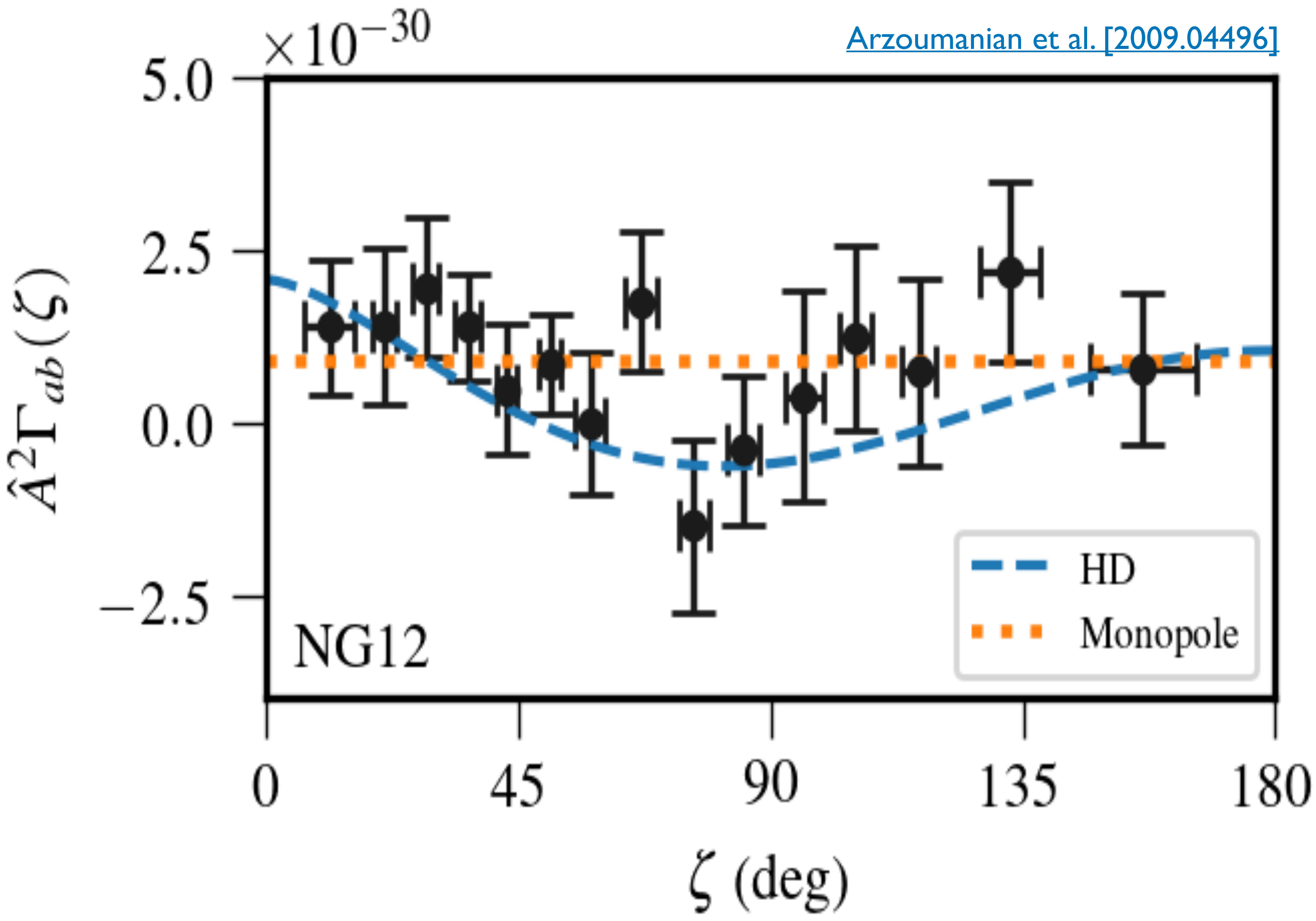

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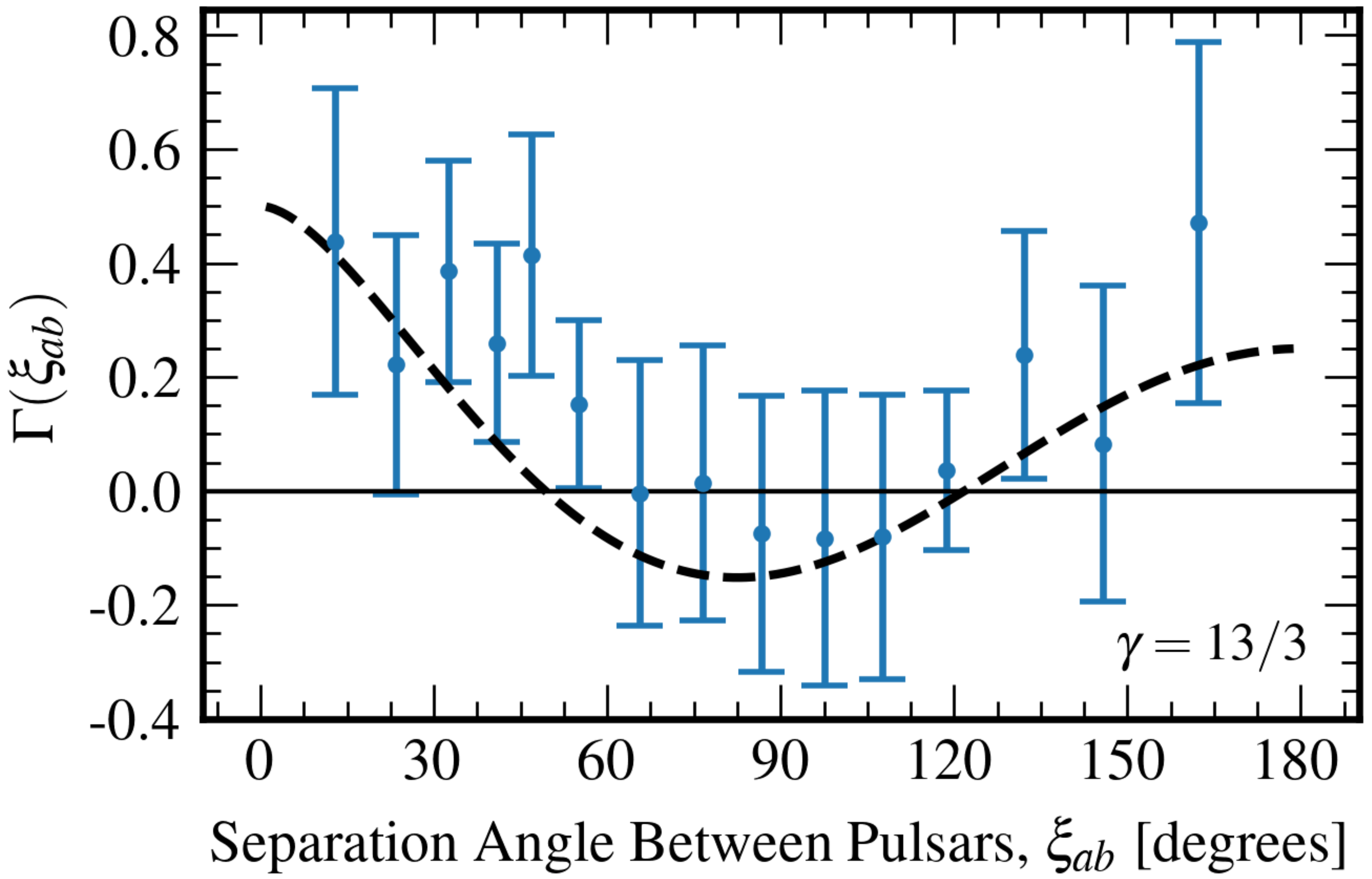


we find evidence for Hellings & Downs correlation with a p-value of $5 \times 10^{-5} - 1.9 \times 10^{-4}$ (approx. $3.5 - 4\sigma$)

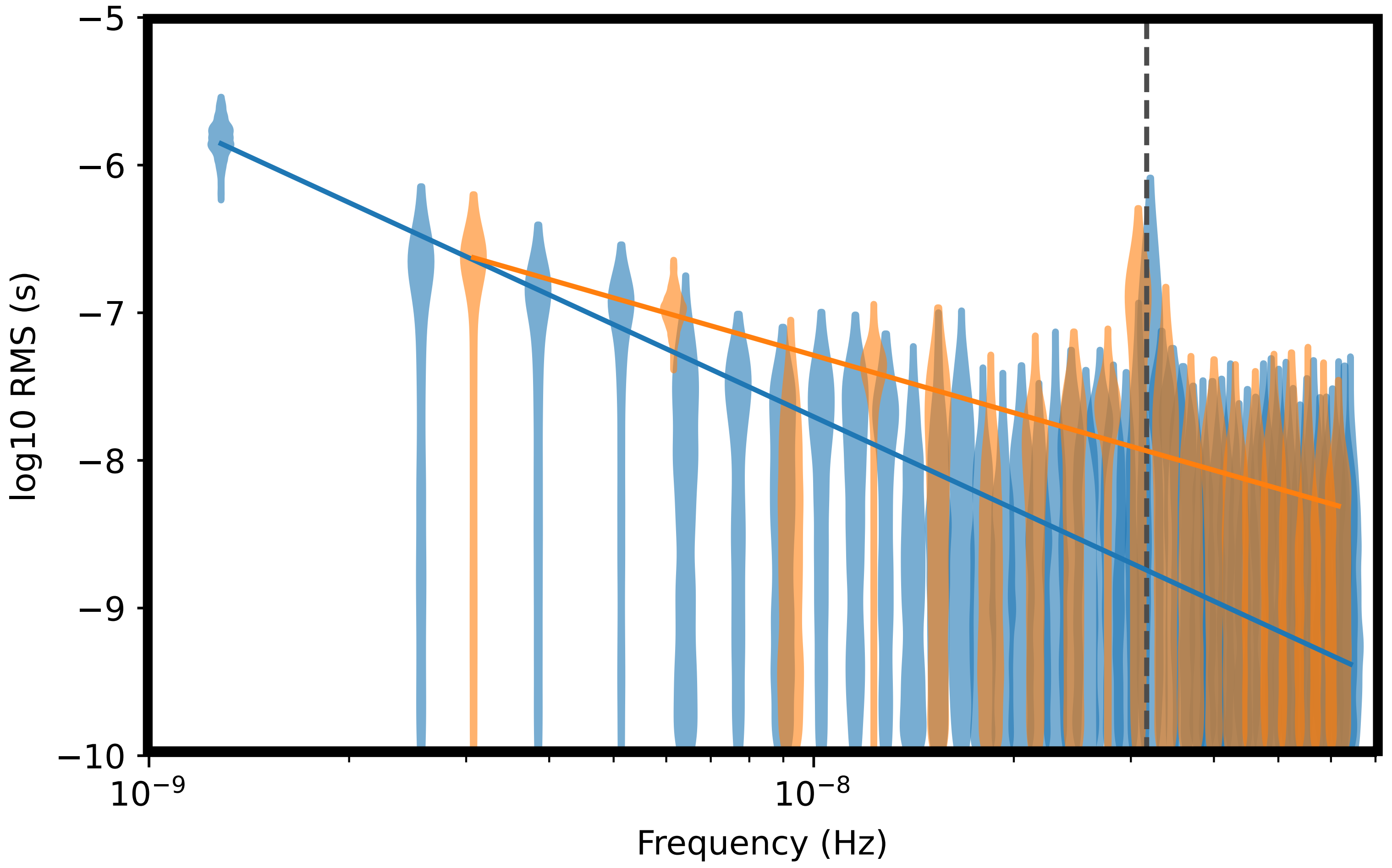
OTHER PTAs

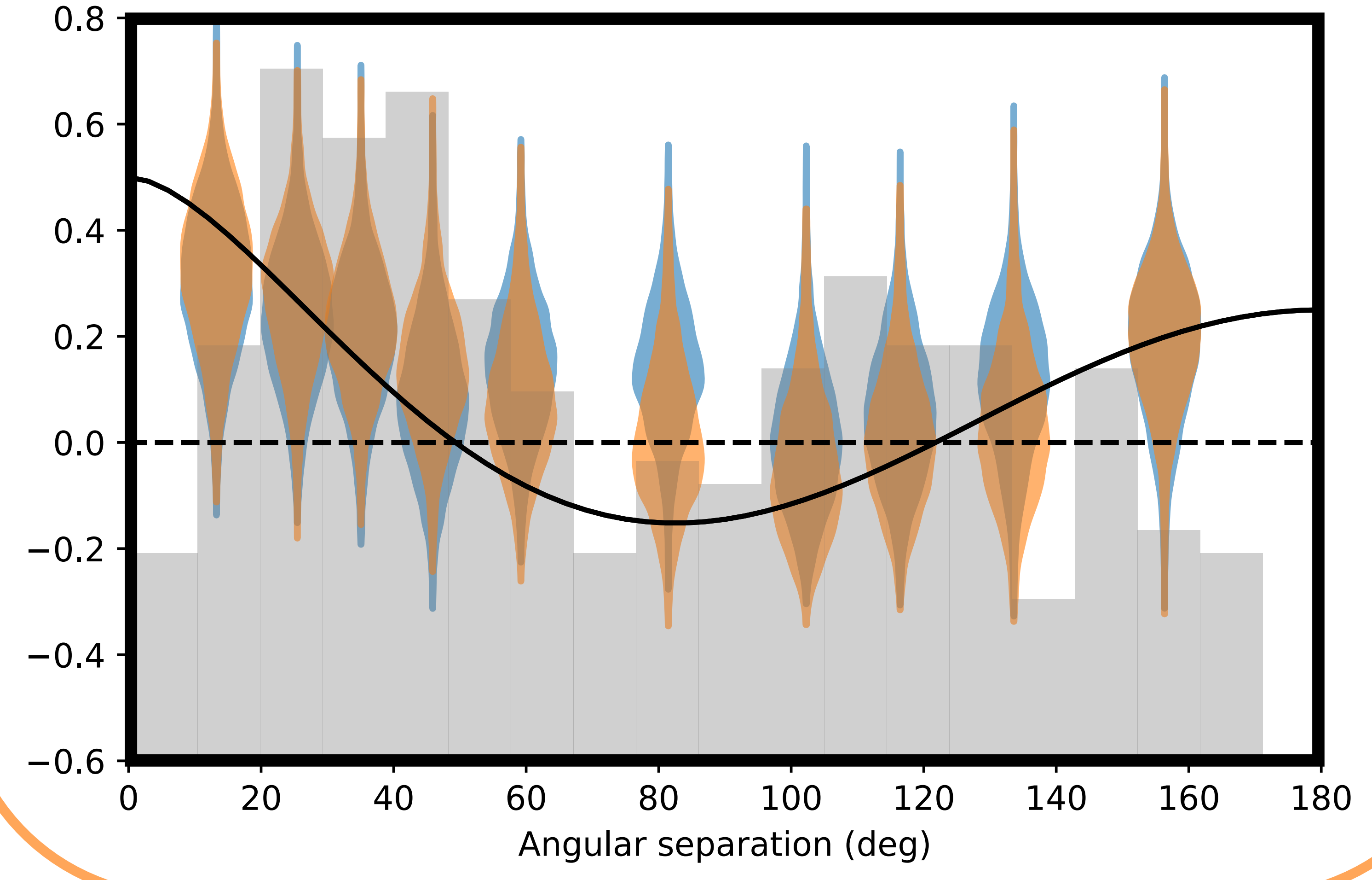
credits: Thankful Cromartie

OTHER PTAs

EPTA: 3σ

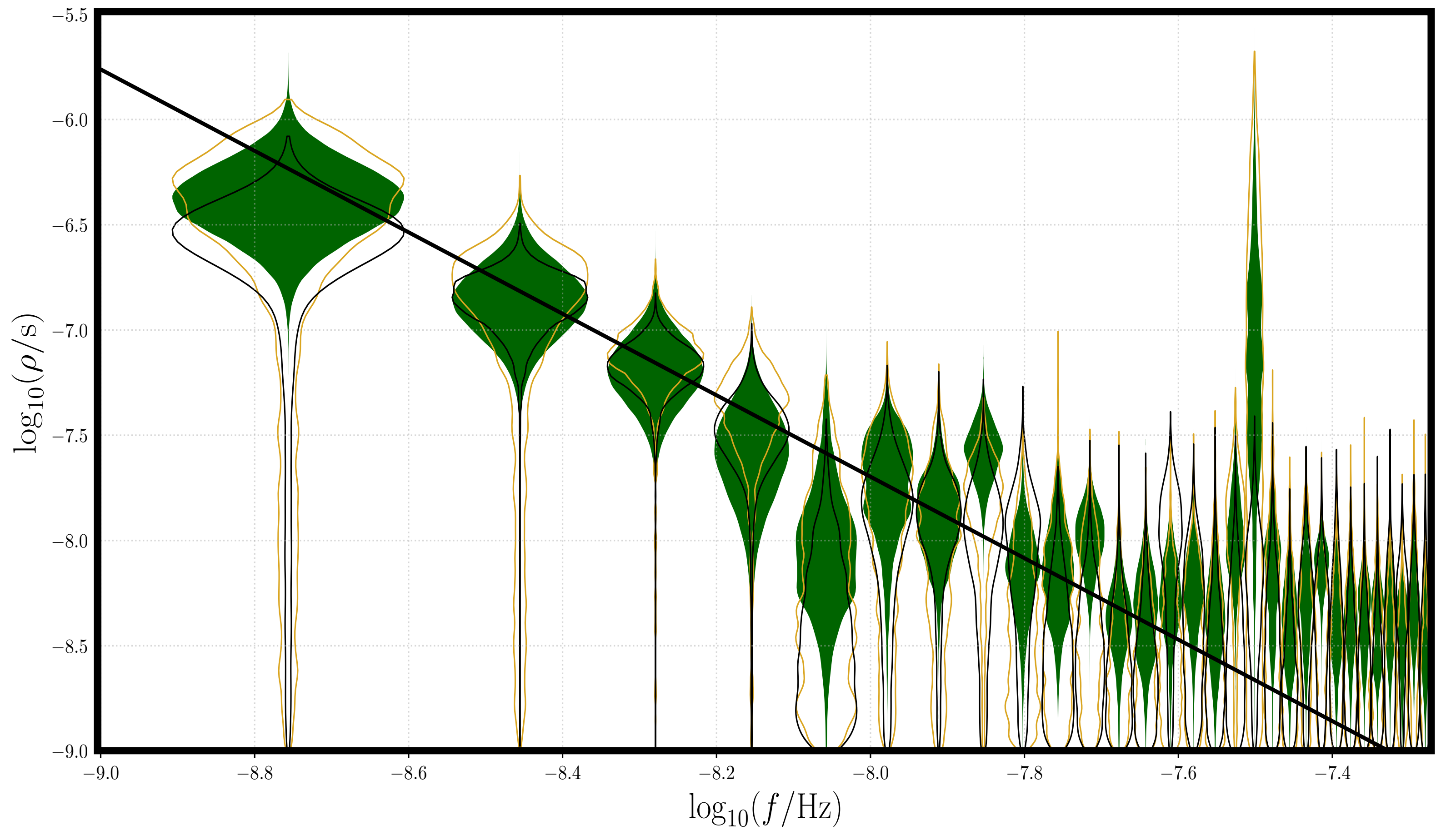
[Antoniadis et al. [2306.16214]]

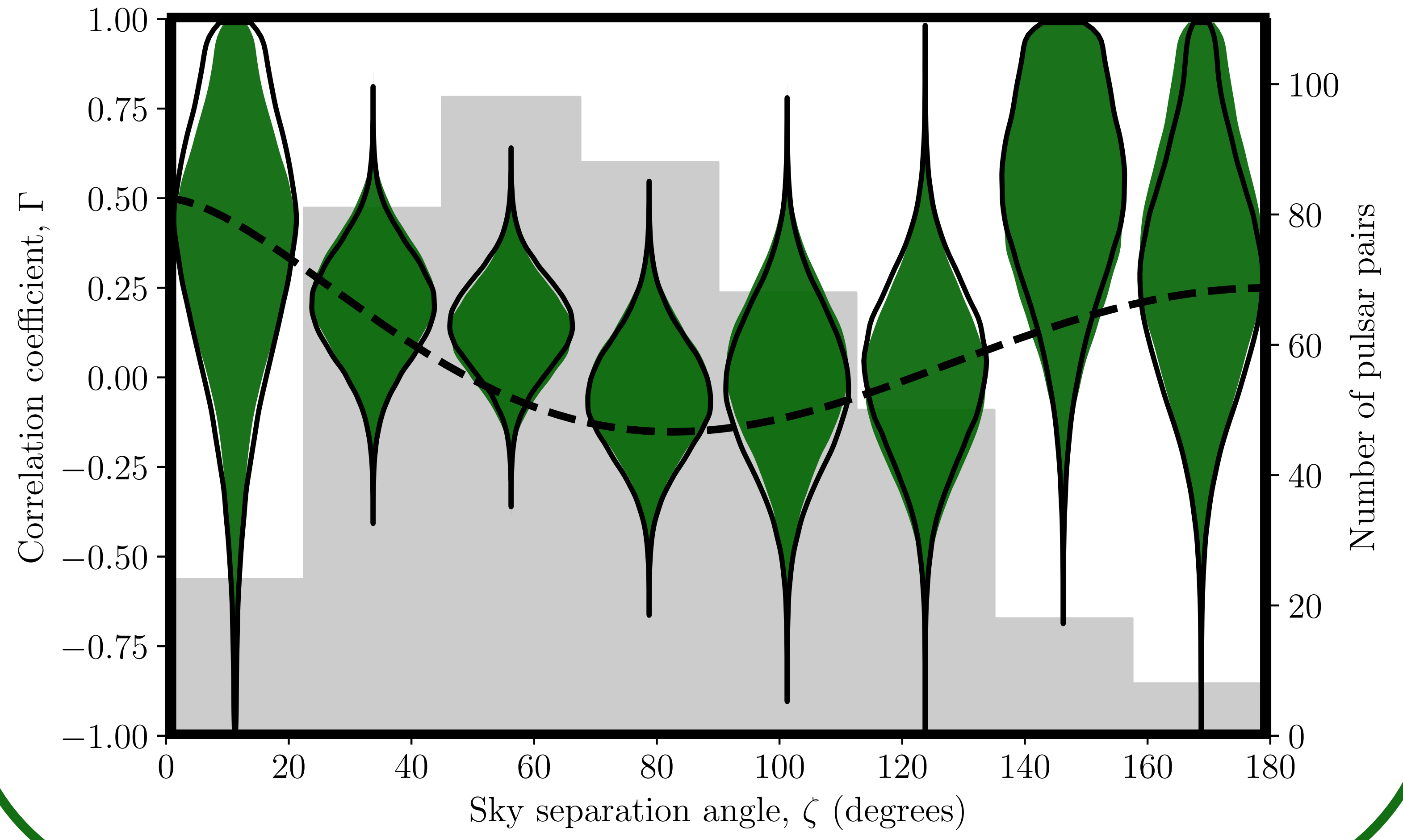




PPTA

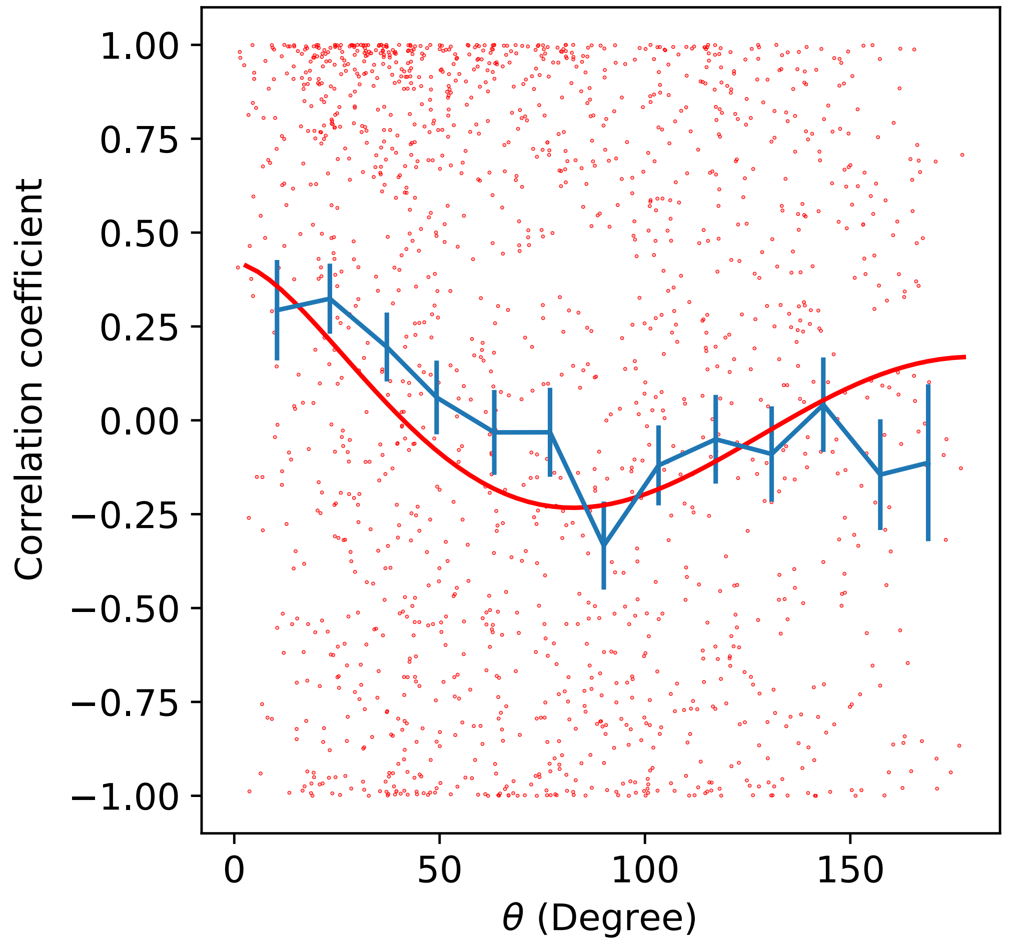
[Reardon et al. [2306.16215]]



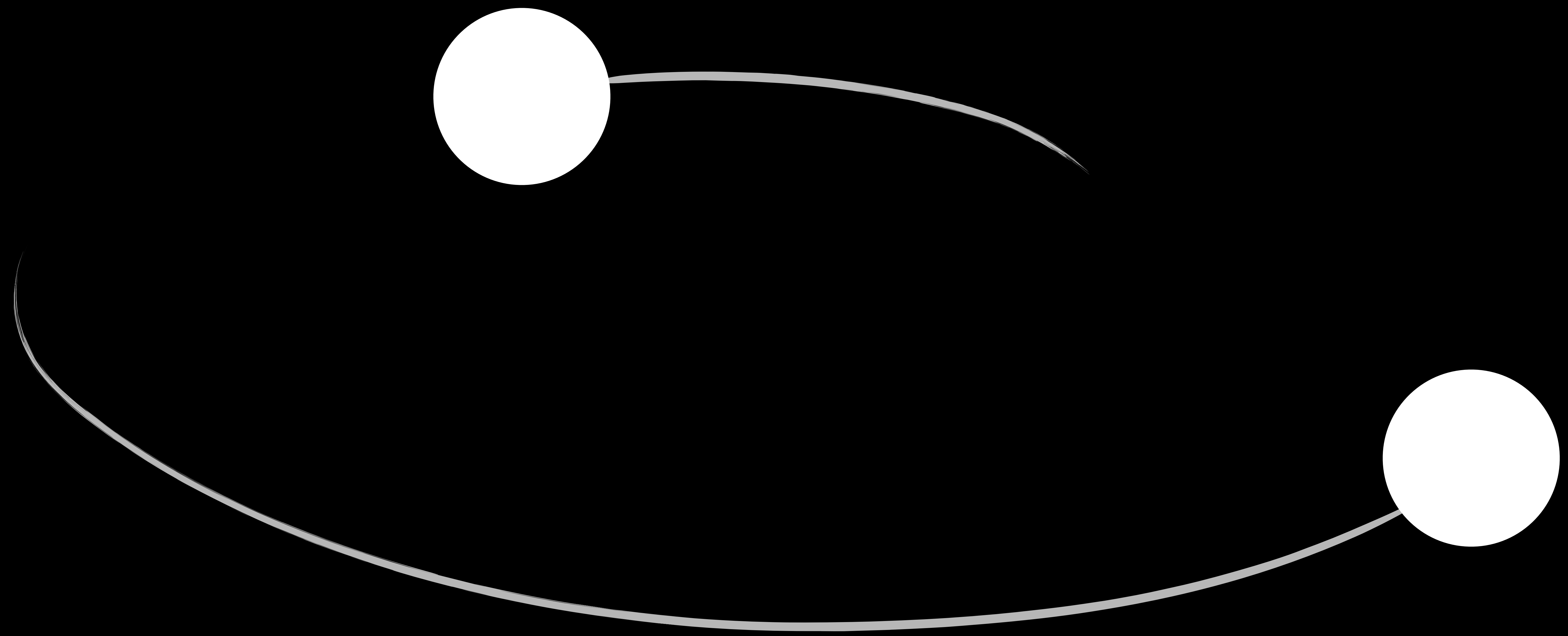


CPTA: 4.6σ

[Xu et al. [2306.16216]]



what is the source?



Supermassive Black Holes Binaries


Graphics by Little Shadow


Graphics by Little Shadow

Graphics by Little Shadow

GWB FROM SMBHB

$$h_c^2(f) = \int dM dq dz \, \frac{\partial^4 N}{\partial M \, \partial q \, \partial z \, \partial \ln f_p} \, h_s^2(f_p)$$

Phinney 2001, Wyithe & Loeb 2003

GWB FROM SMBHB

GW signal from individual SMBHB

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averaged strain for a circular SMBHB

$$h_s^2(f) = \frac{32}{5} \frac{(G\mathcal{M})^{10/3}}{d_c^2} \left(2\pi f_p\right)^{4/3}$$

Finn & Thorne 2000

GWB FROM SMBHB

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Phinney 2001, Wyithe & Loeb 2003

number density of SMBHB binaries

averaged strain for a circular SMBHB

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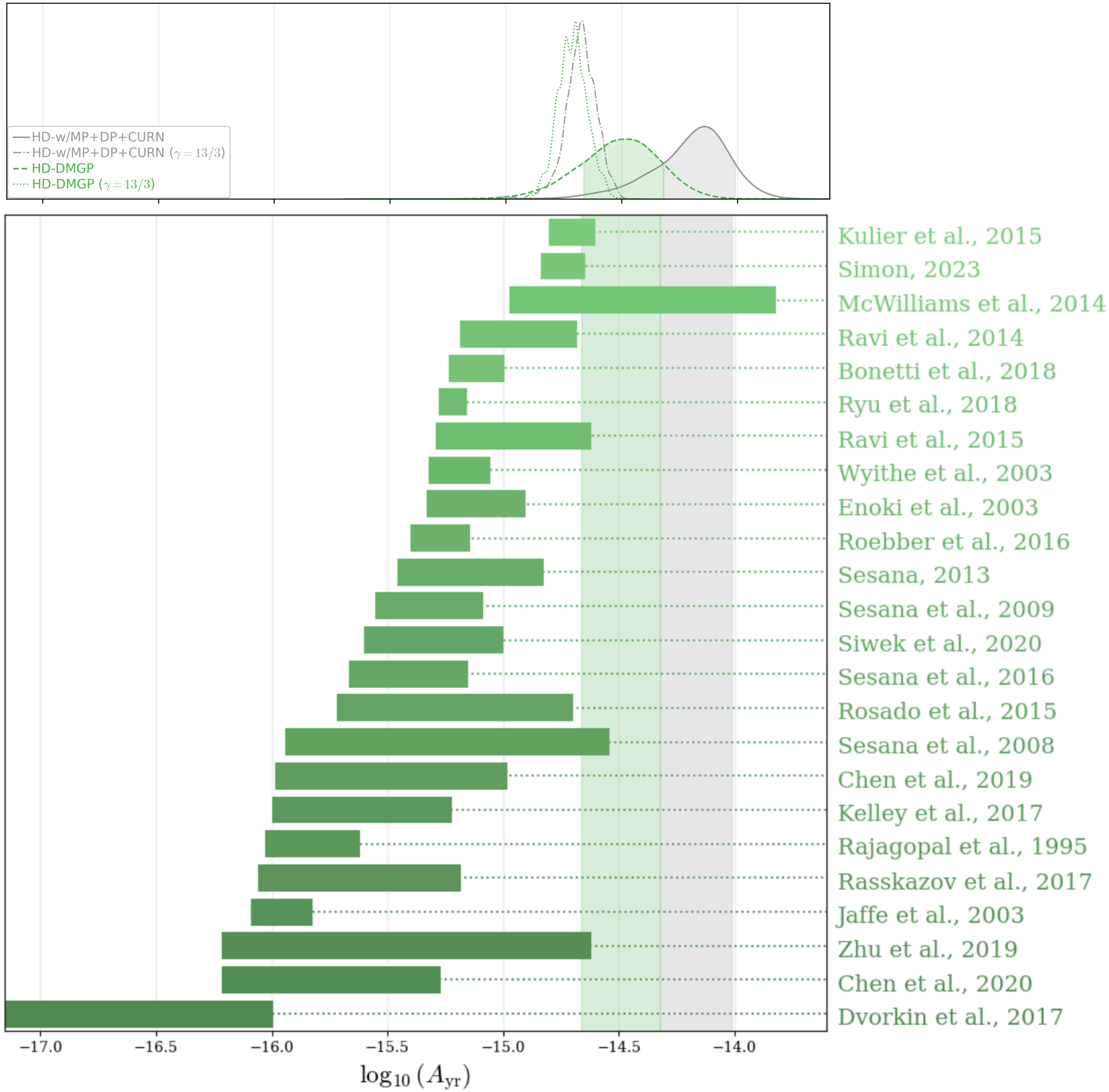
Finn & Thorne 2000

the SMBHB density depends on

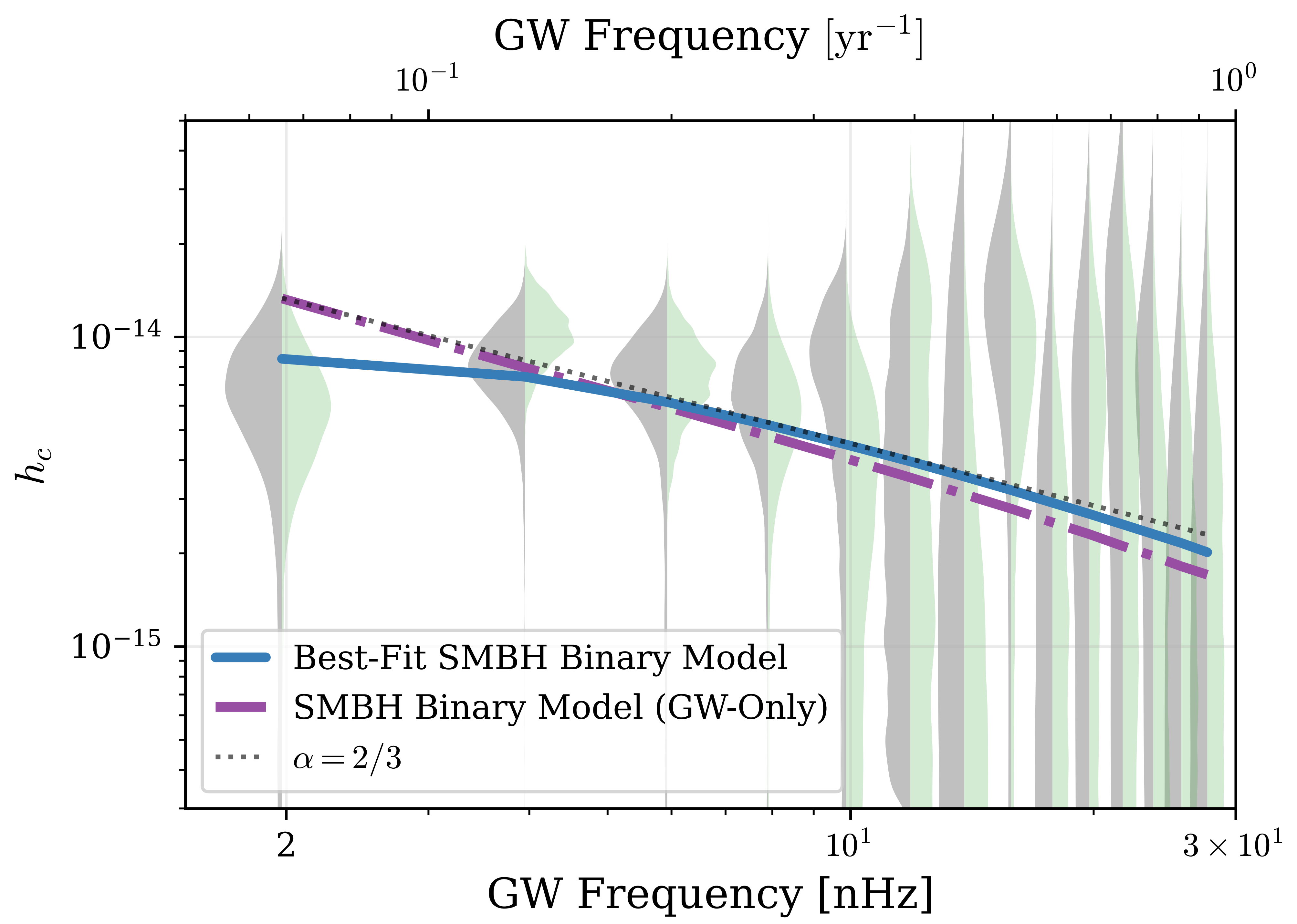
1. galaxies merger rate
2. SMBHB - galaxy mass relation
3. SMBHB binary evolution

EXPECTATIONS

Agazie et al. [2306.16220]



ADJUSTING EXPECTATIONS



Agazie et al. [2306.16220]

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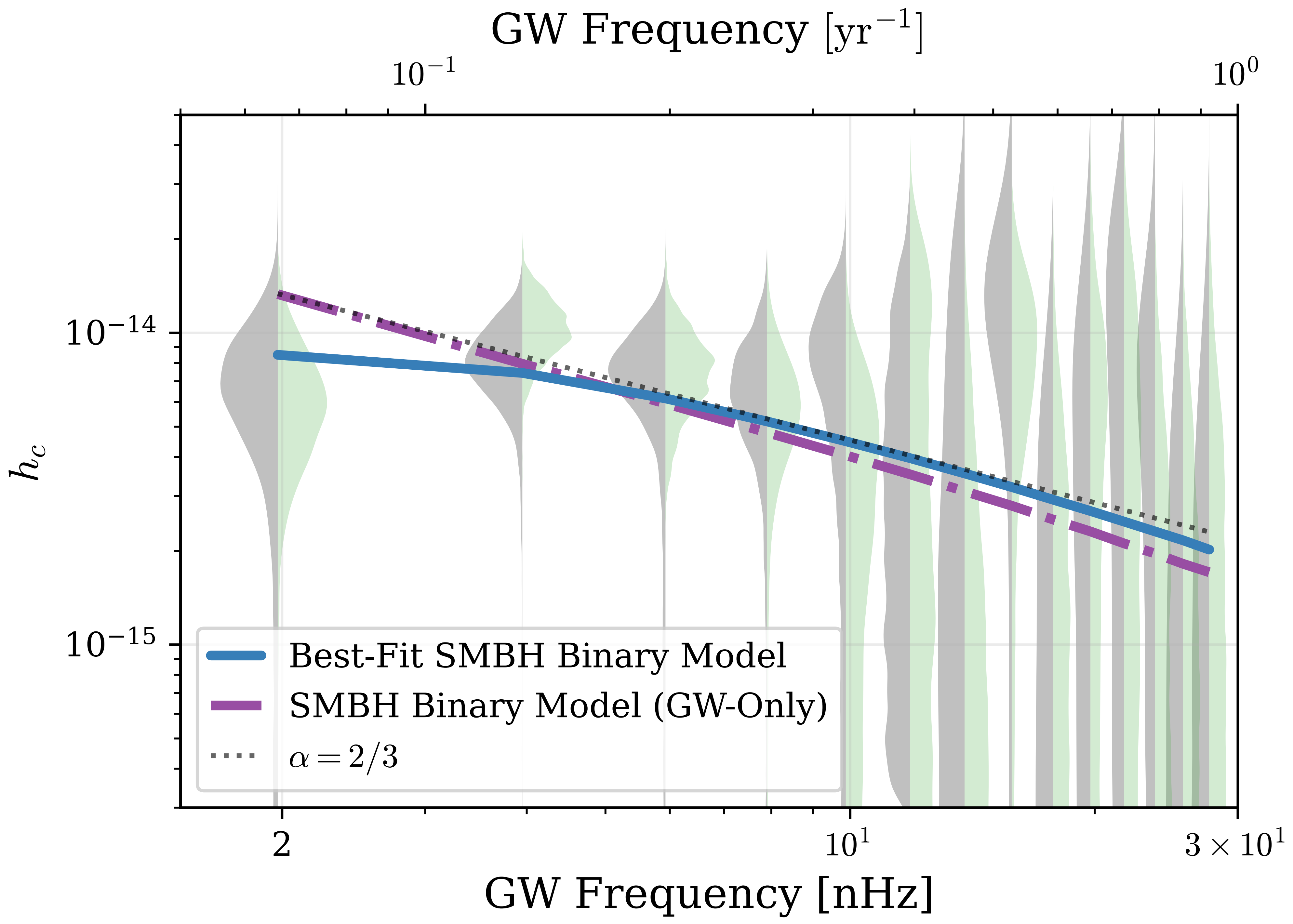

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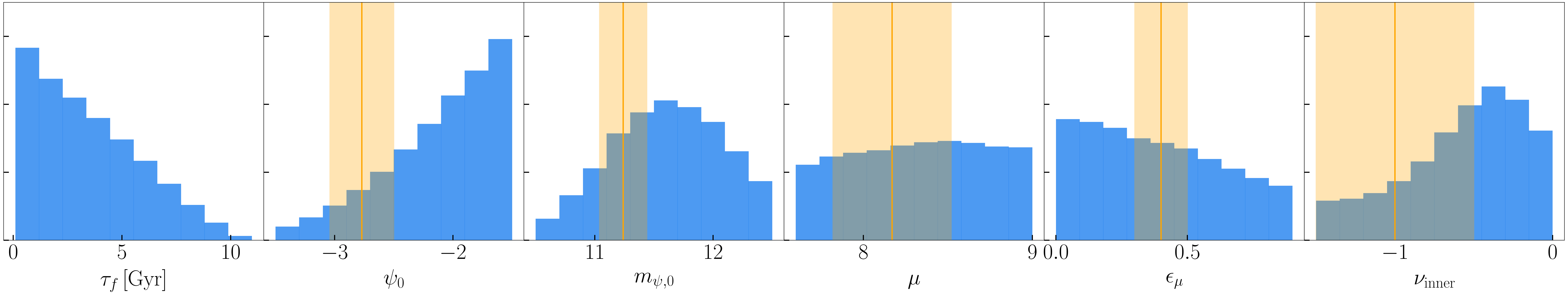
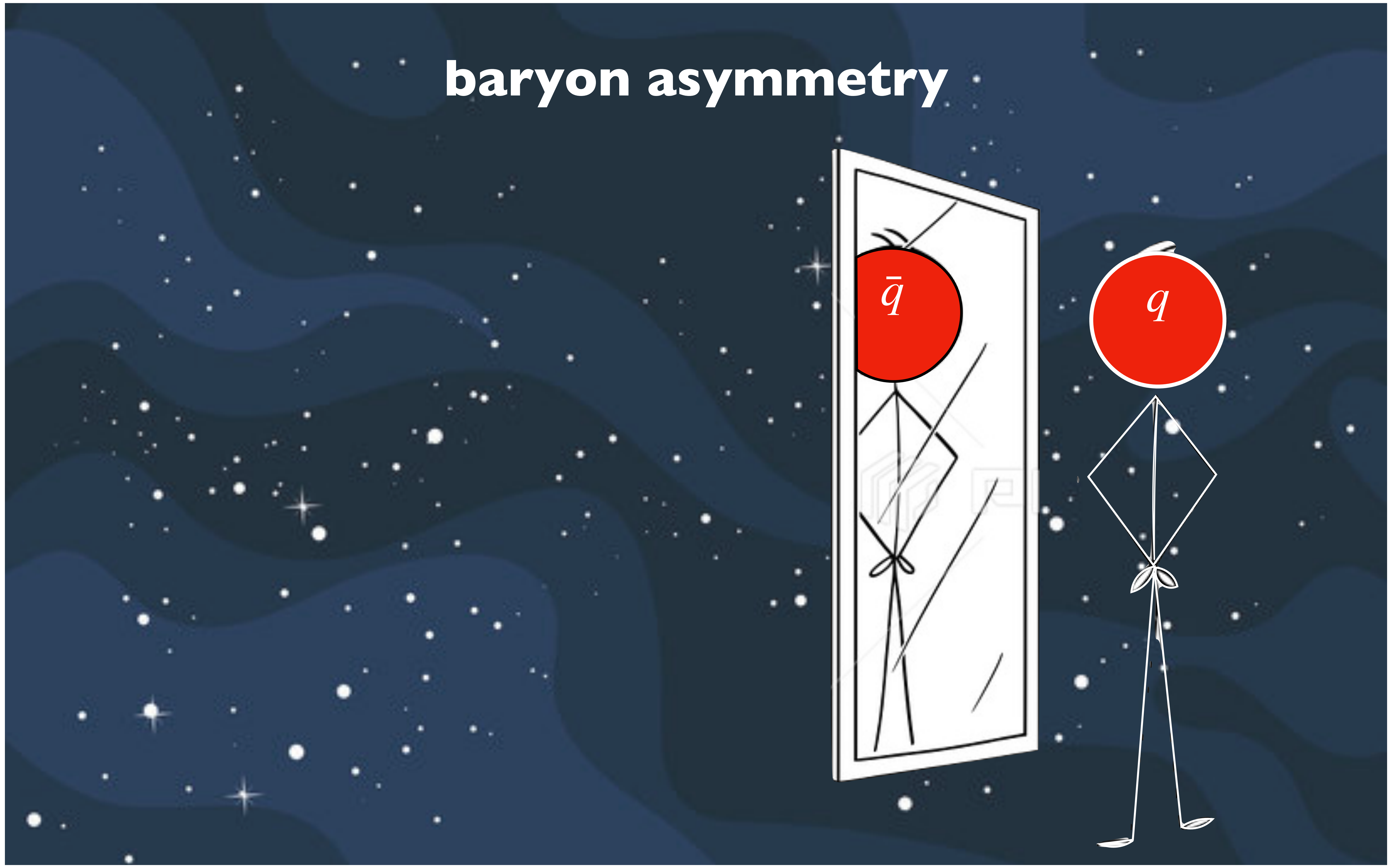


can it be something else?

THE BIG PUZZLES



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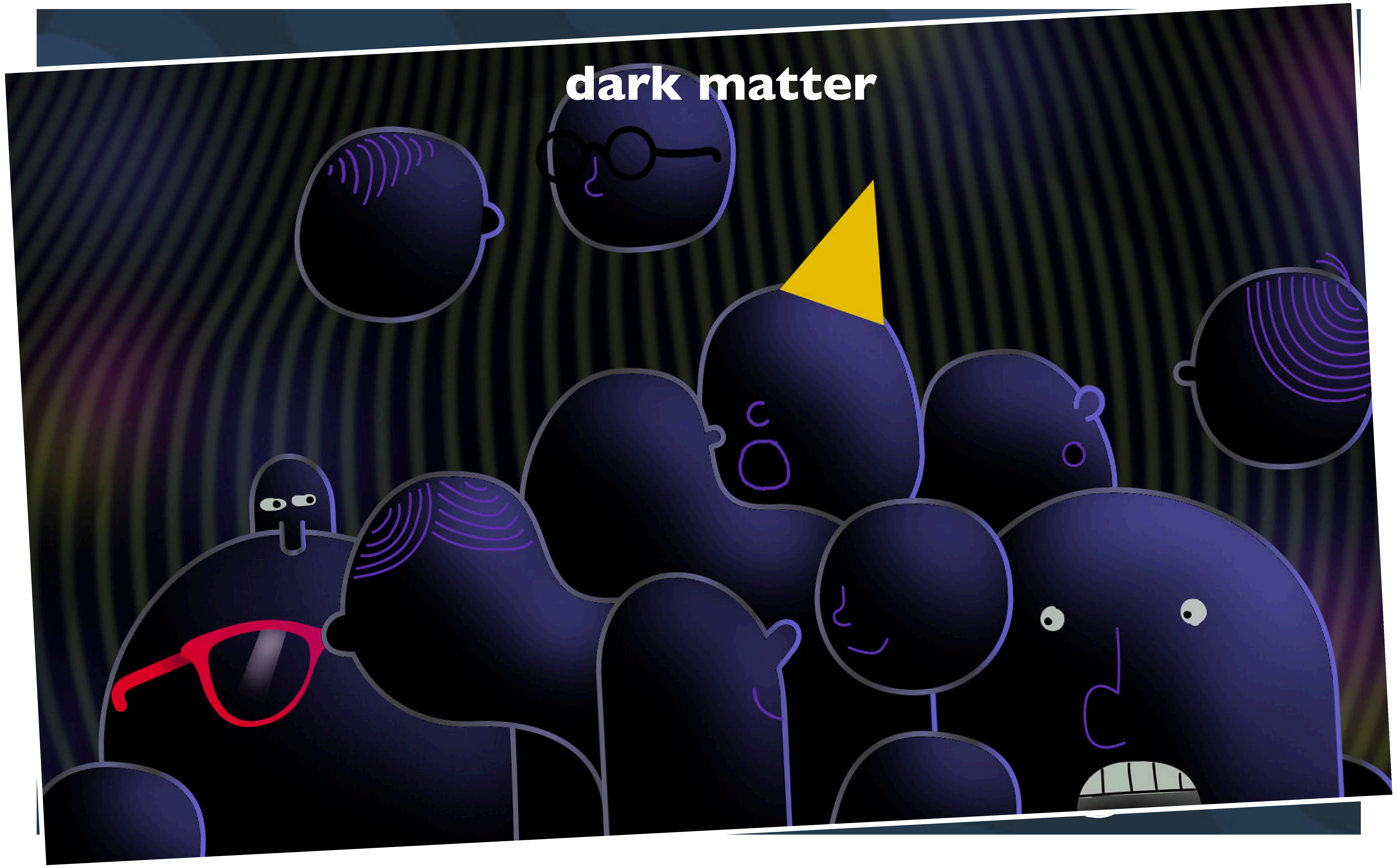
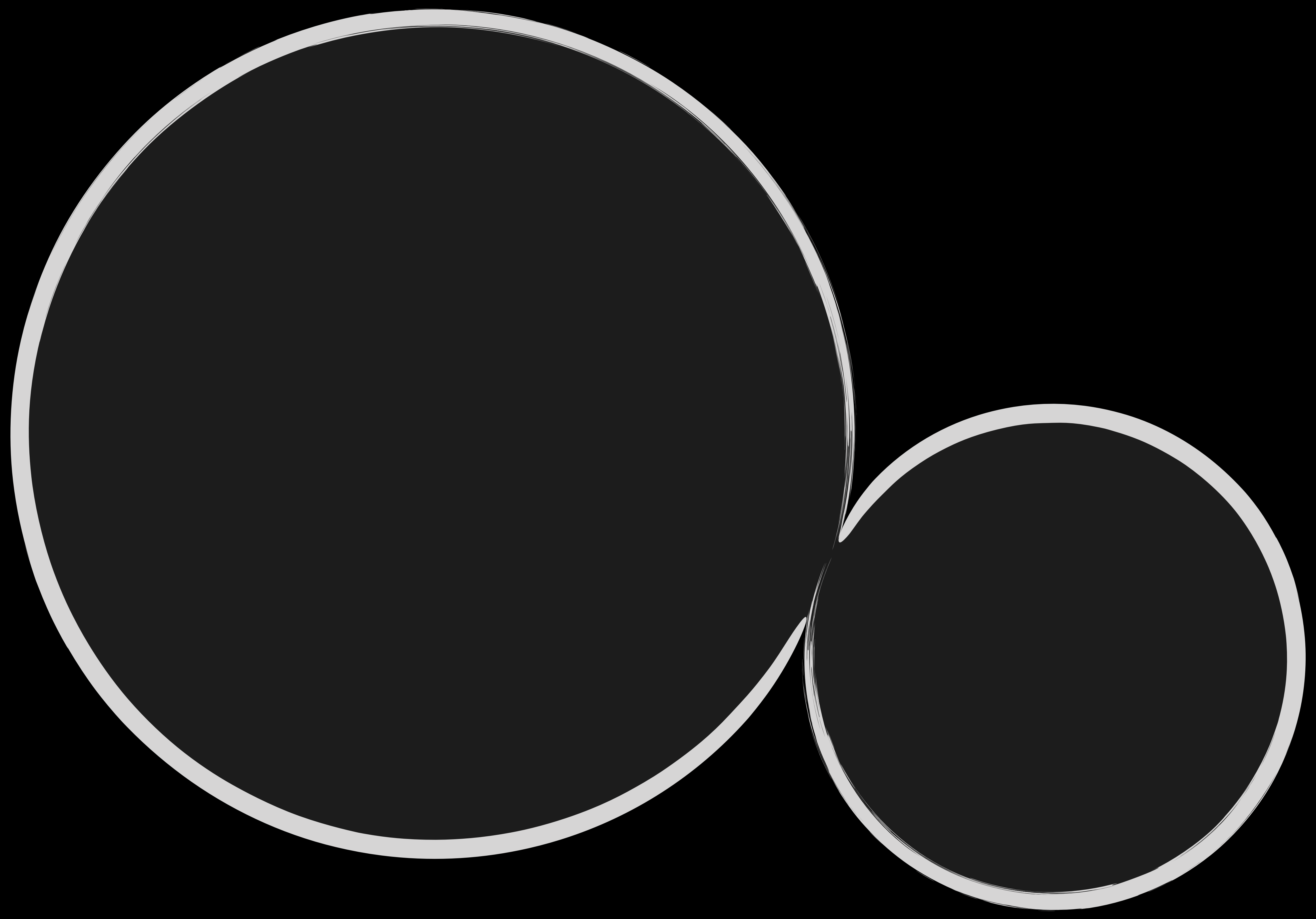


THE BIG PUZZLES

THE BIG PUZZLES

THE BIG PUZZLES

FINDING THE RIGHT THEORY



GWB from cosmological phase transitions

PHASE TRANSITIONS

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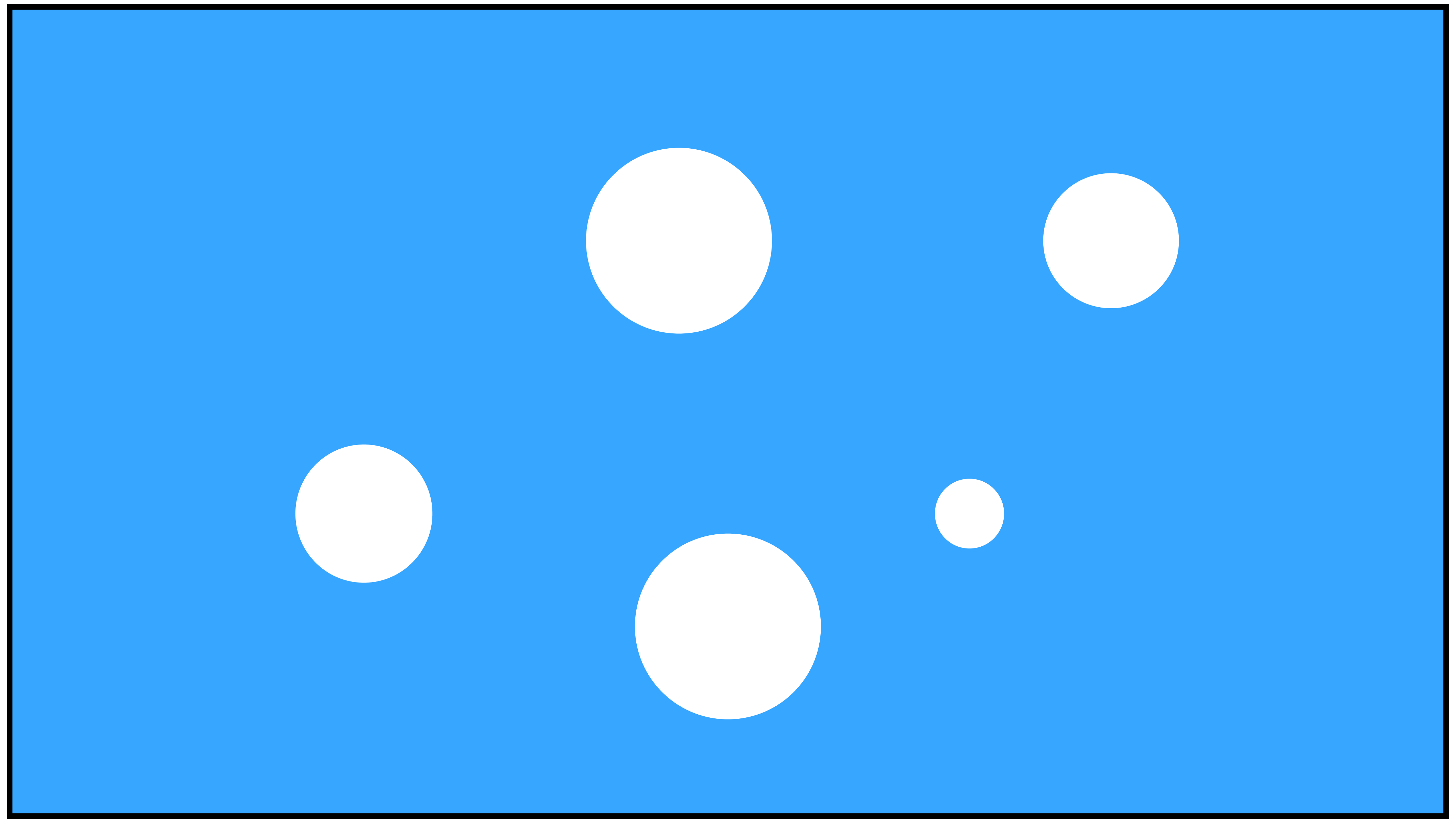

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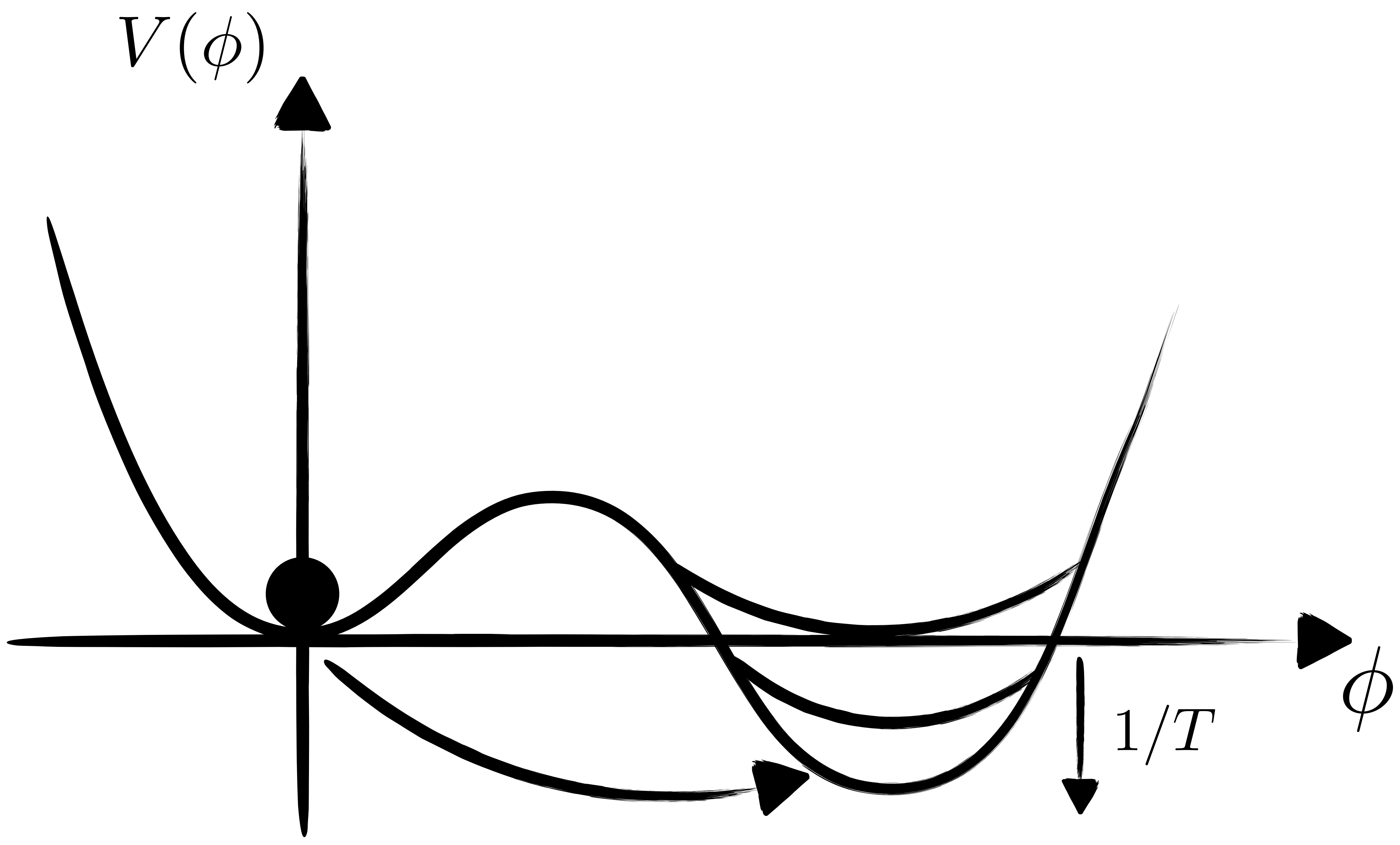
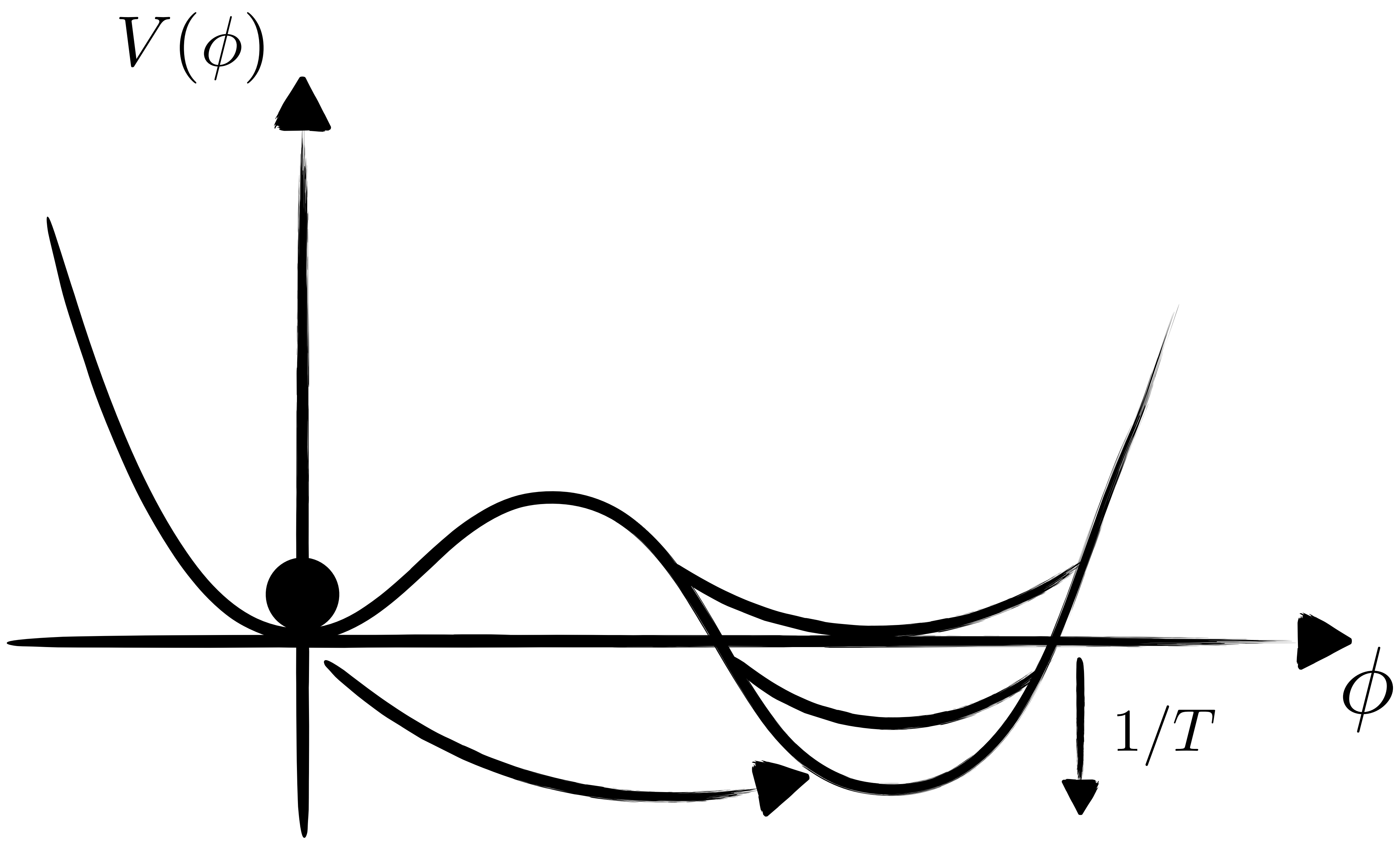
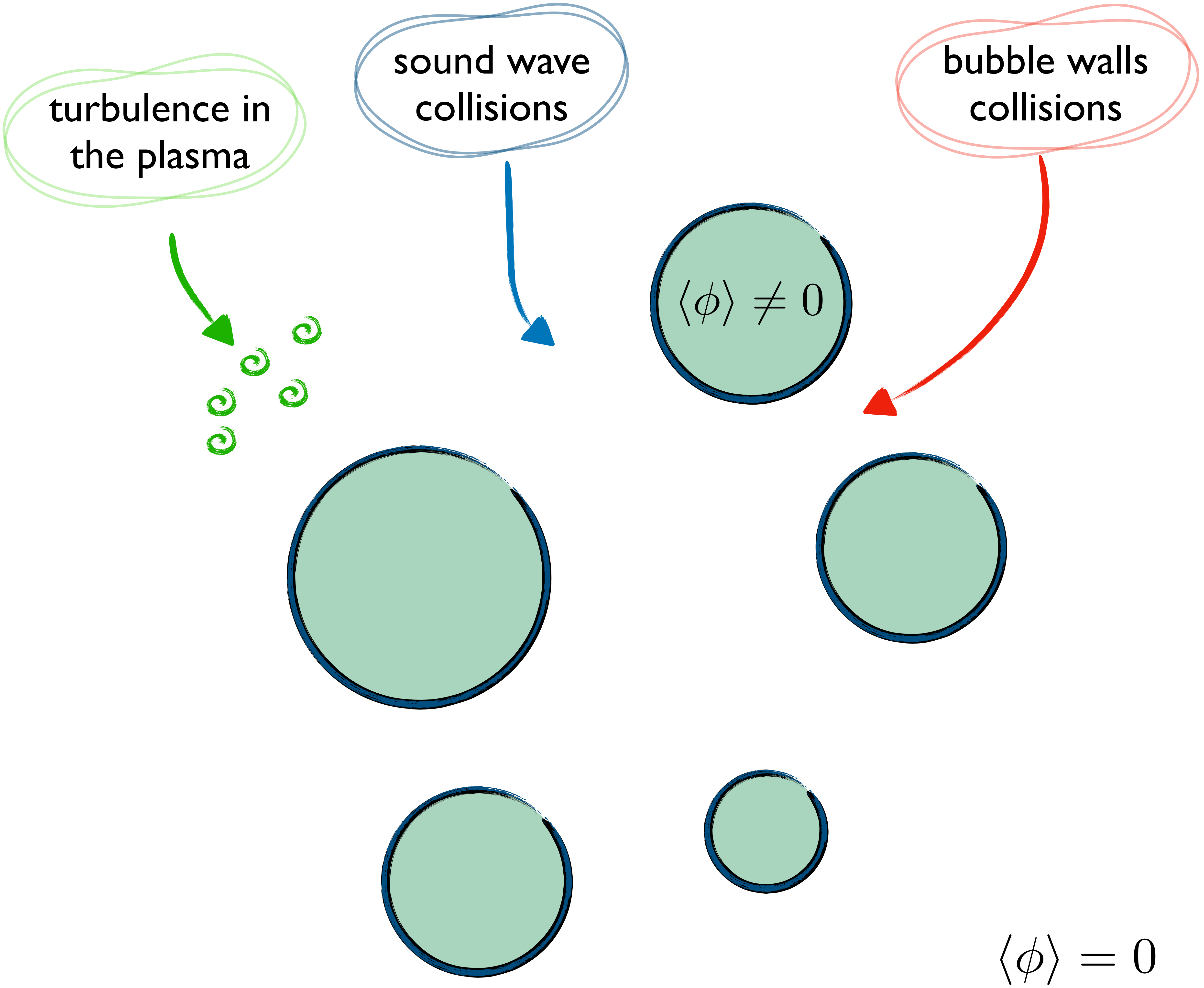


$\langle \phi \rangle = 0$

PHASE TRANSITIONS





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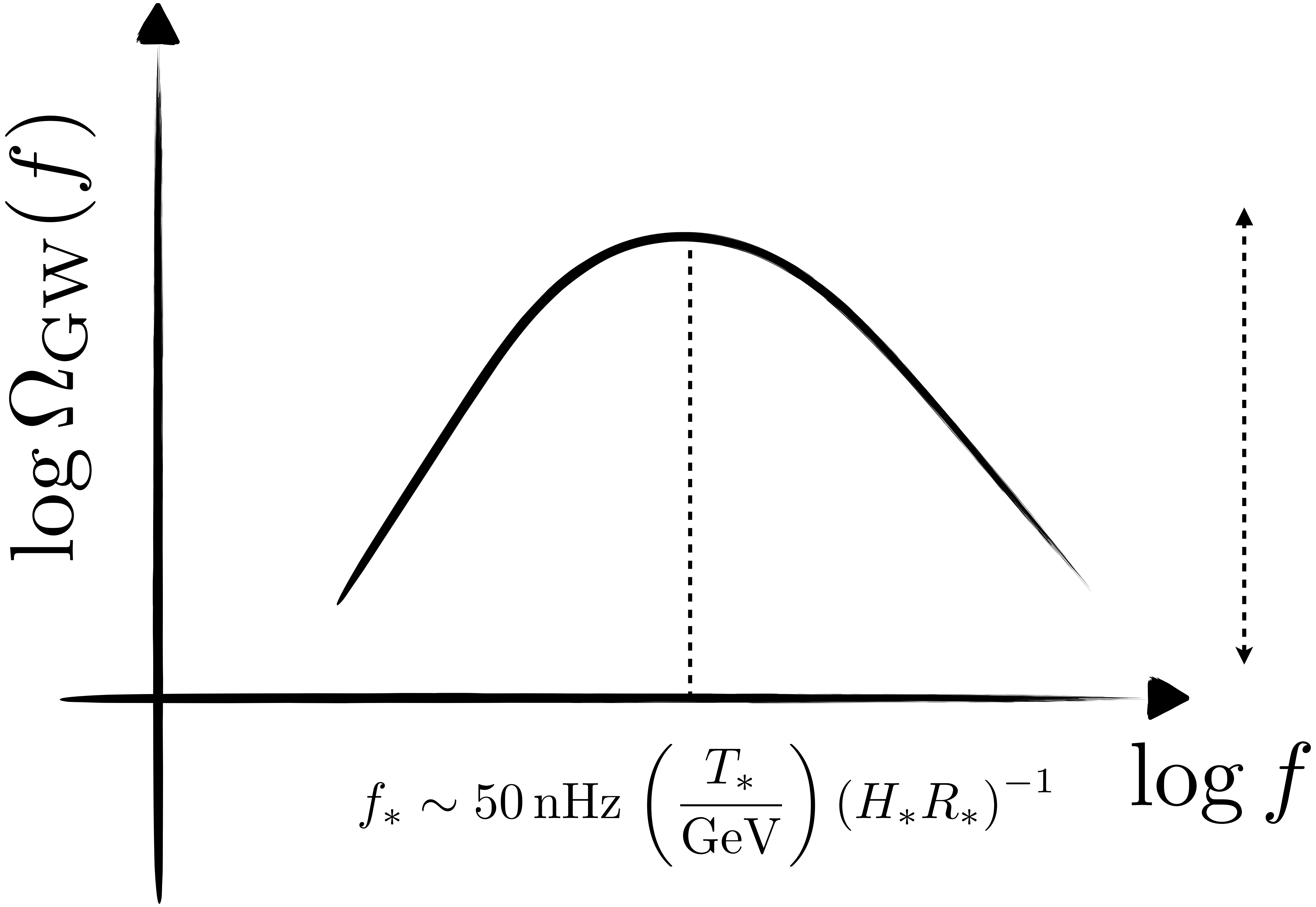
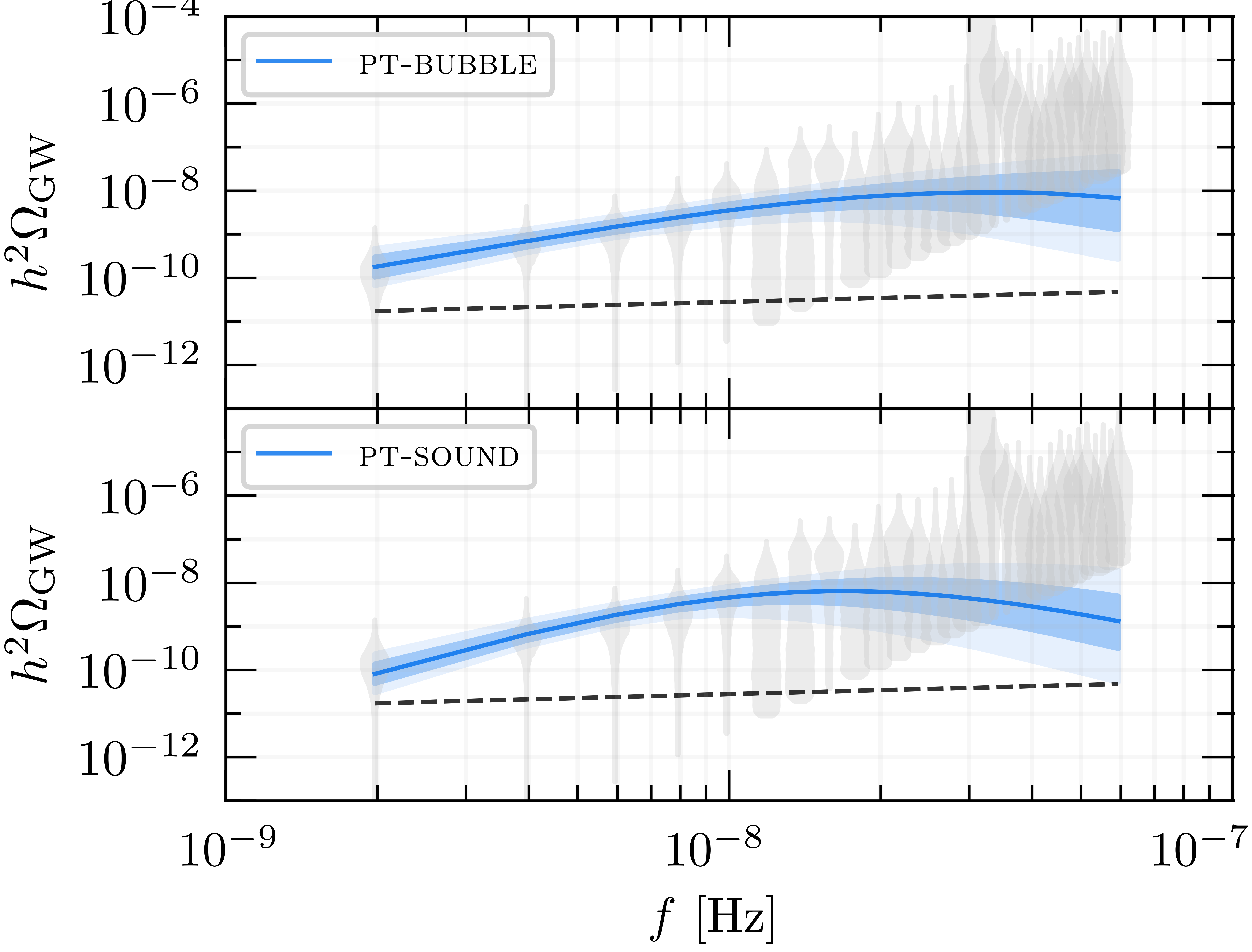


$$f_* \sim 50\,\mathrm{nHz} \left(\frac{T_*}{\mathrm{GeV}}\right) (H_* R_*)^{-1}$$

$$\sim 10^{-5} \left(\frac{\alpha_*}{1+\alpha_*}\right)^2 (H_* R_*)^p$$

PHASE TRANSITIONS

Afzal et al. [2306.16219]



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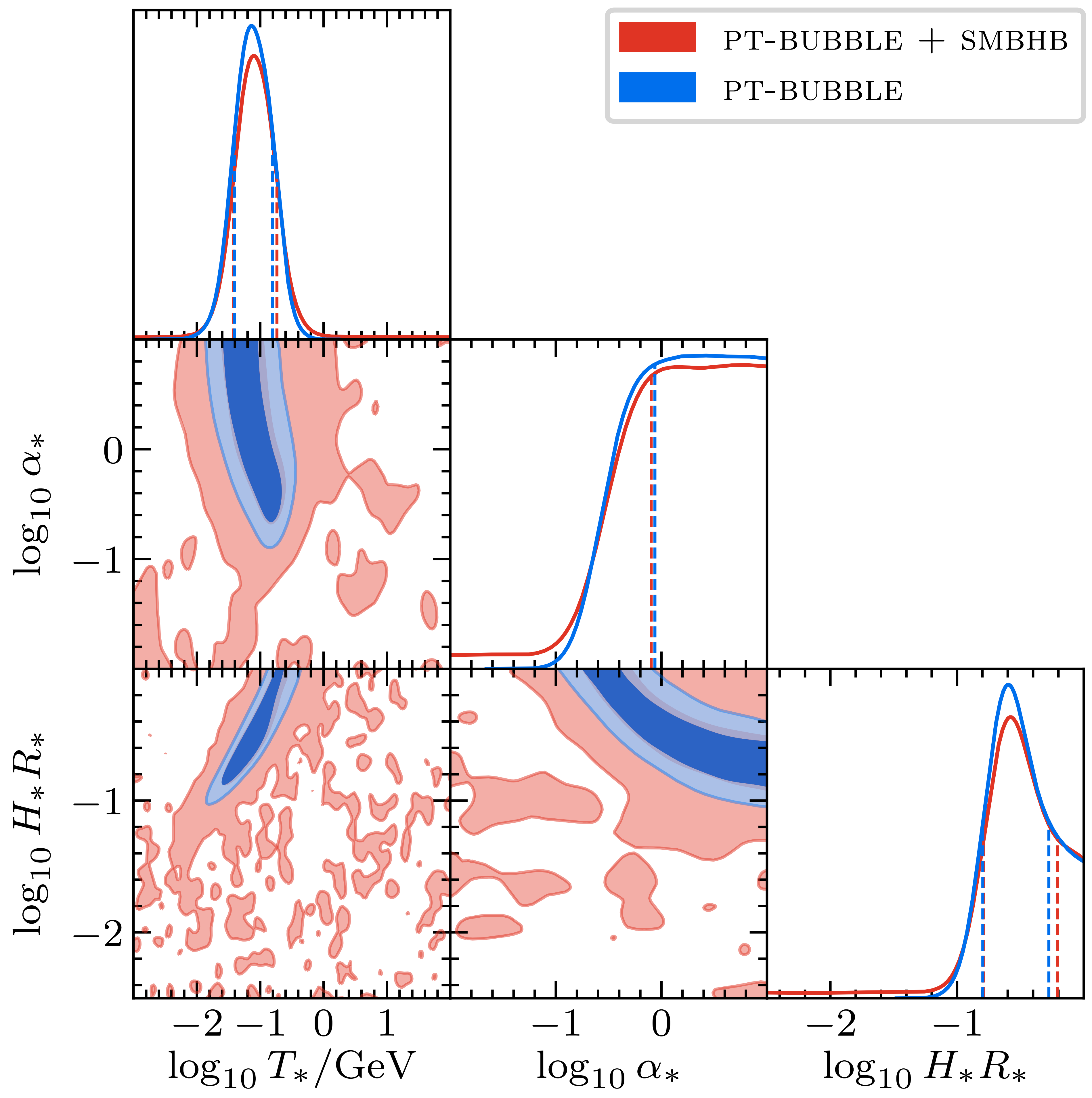

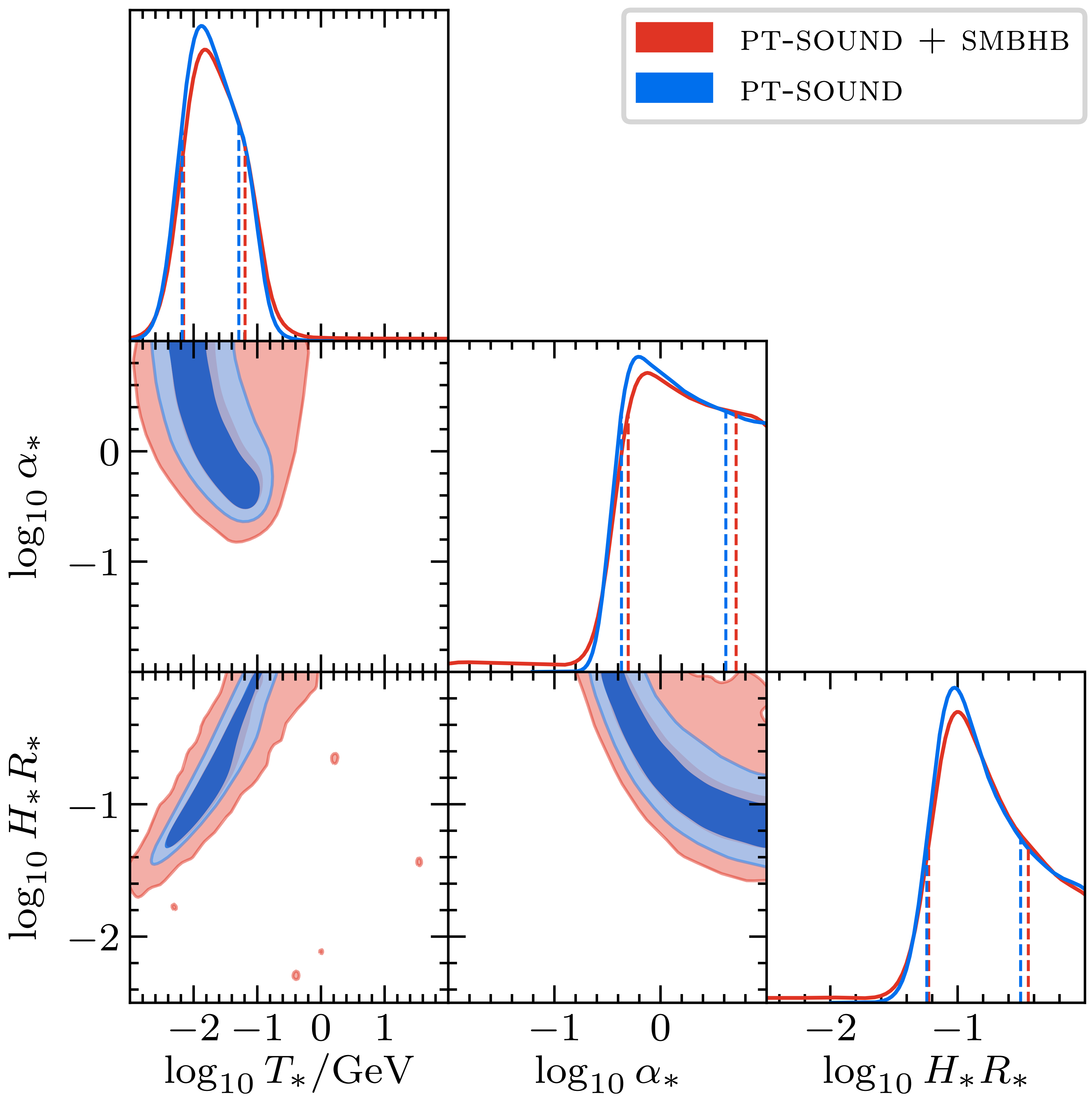

Afzal et al. [2306.16219]

OTHER SUSPECTS

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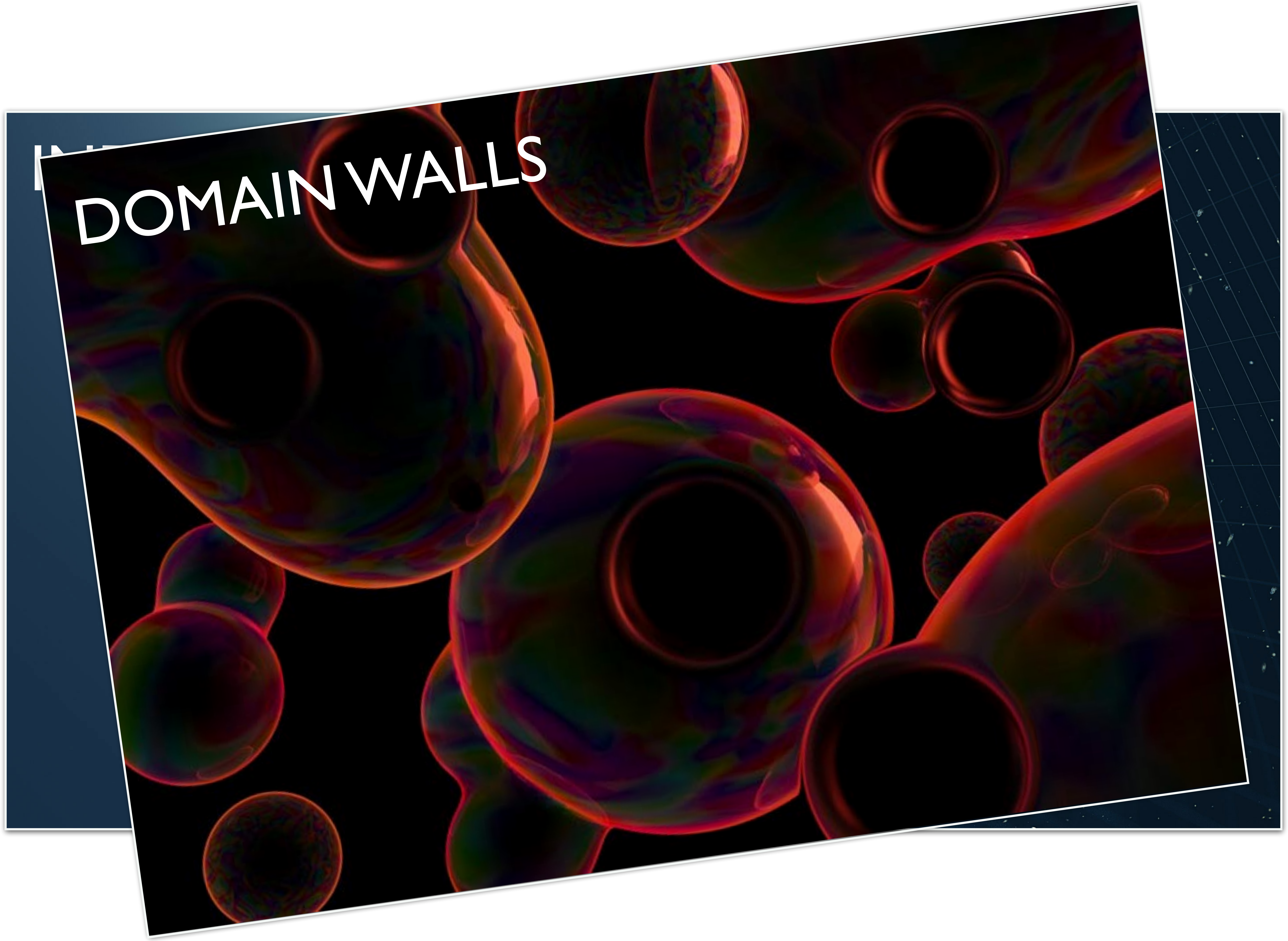

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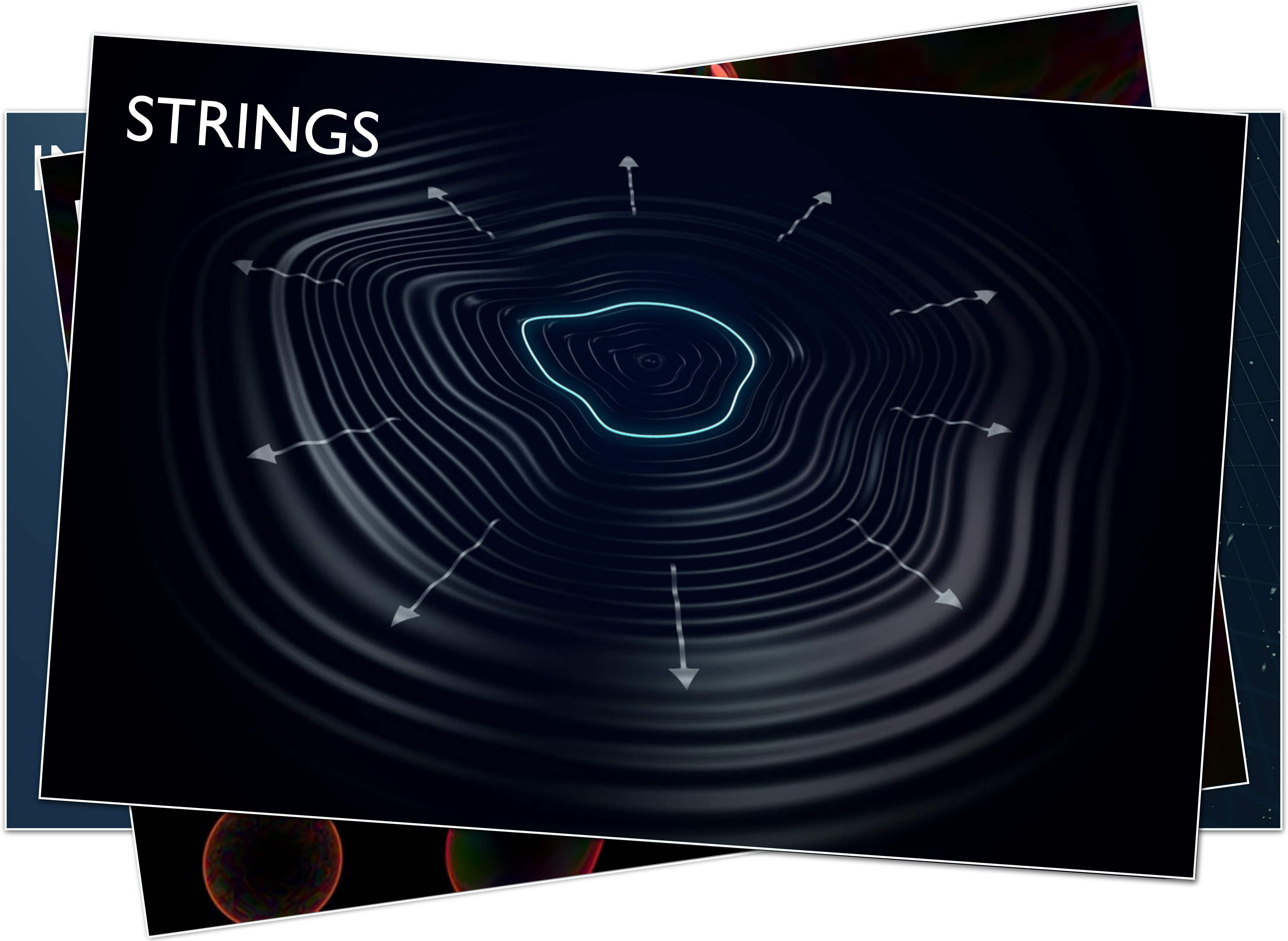

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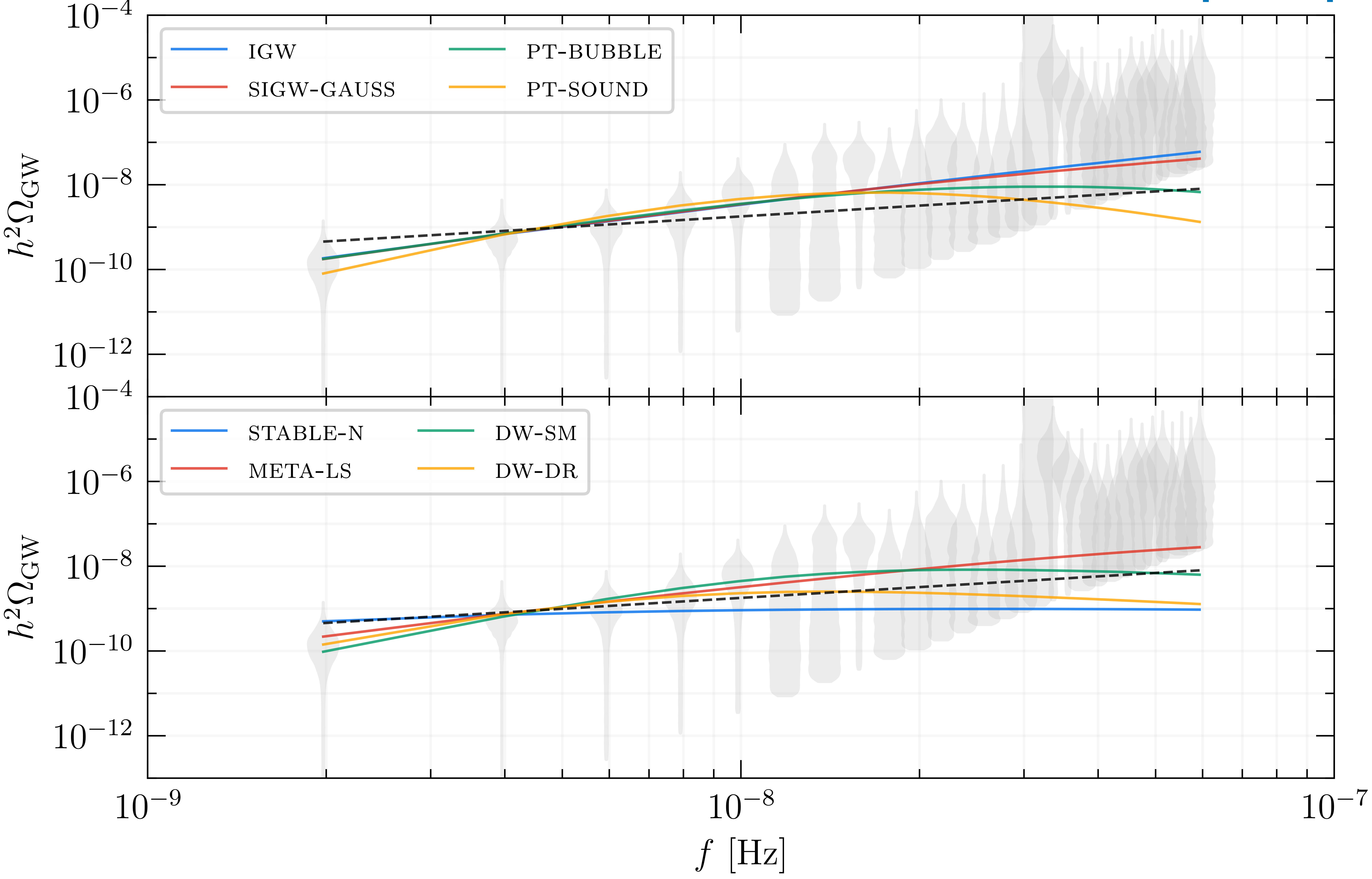
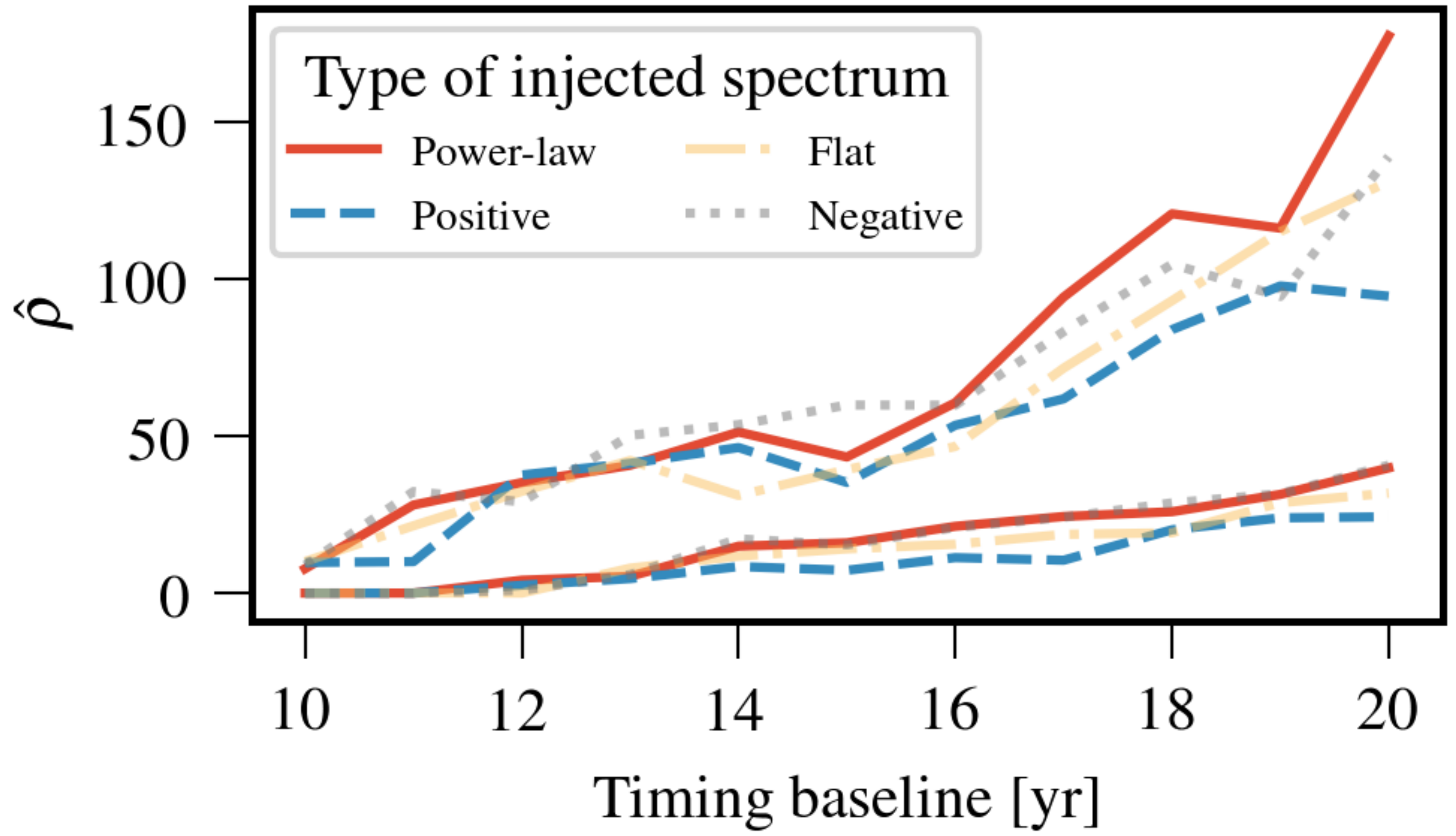
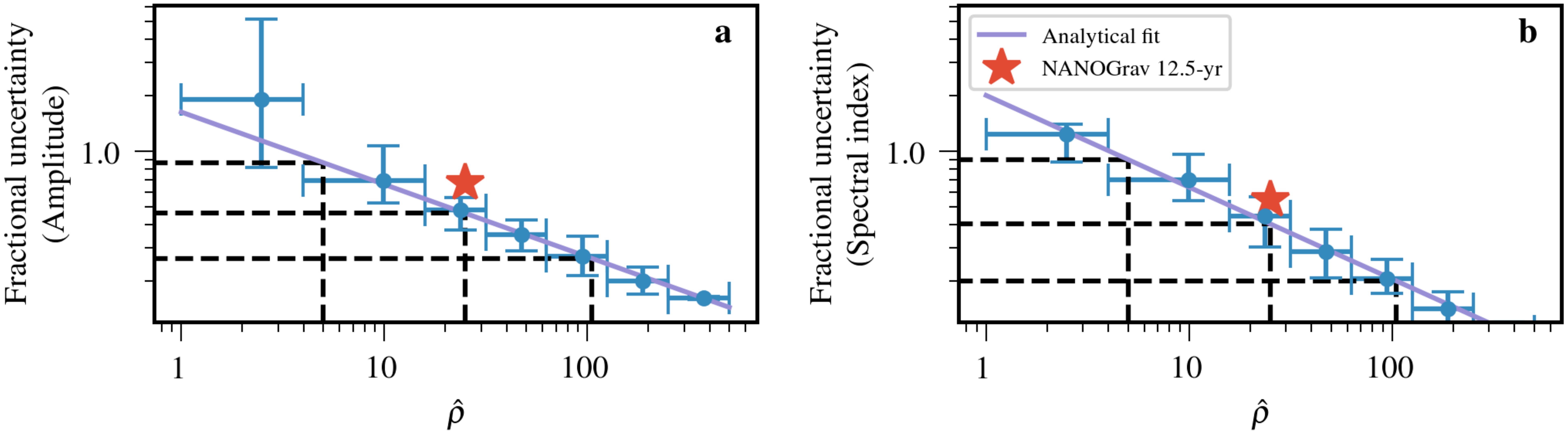


astrophysics or new physics?

SPECTRAL SHAPE

Pol et al. [2010.11950]

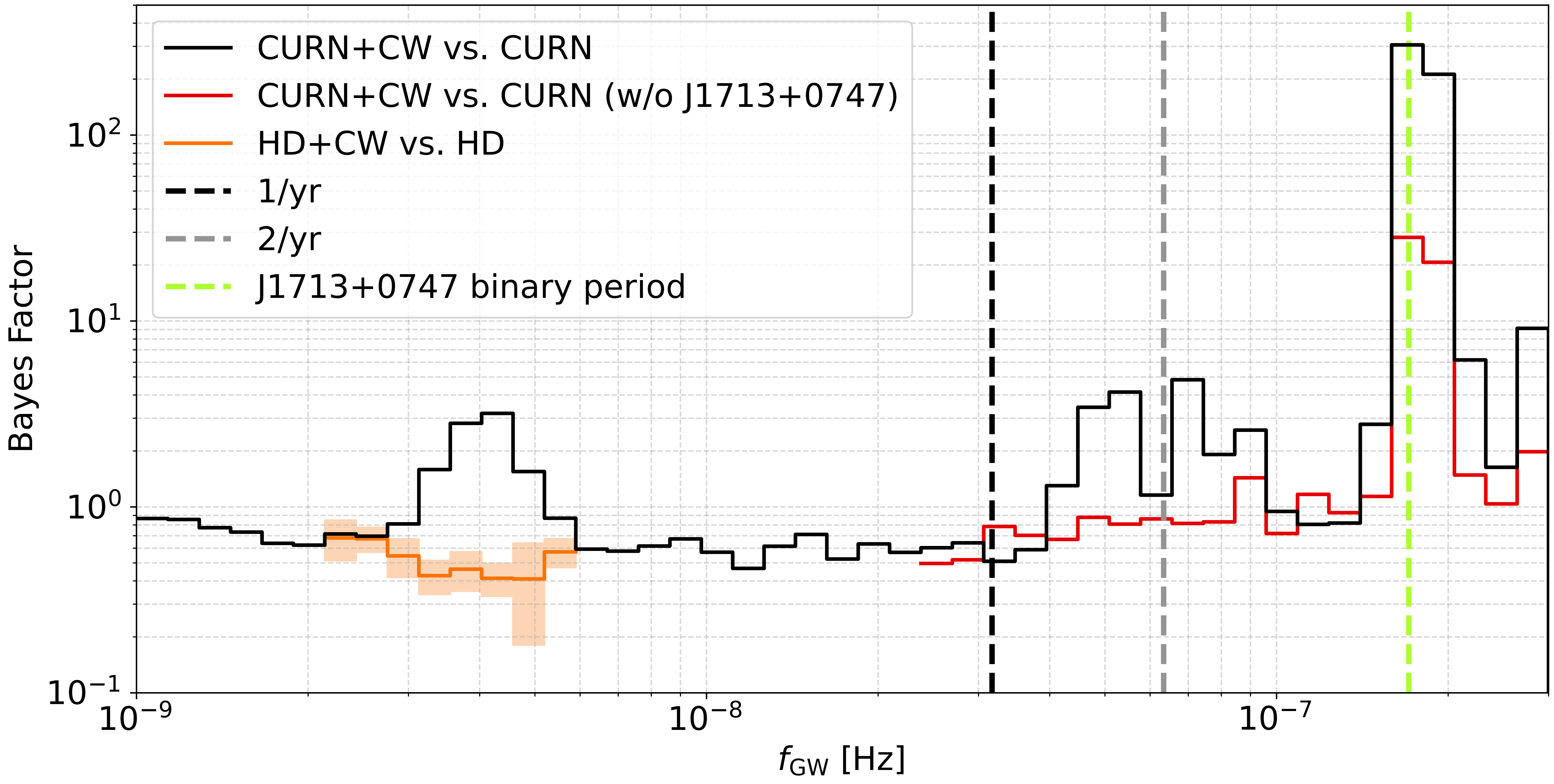




SINGLE SOURCE

SINGLE SOURCE

Agazie et al. [2306.16222]



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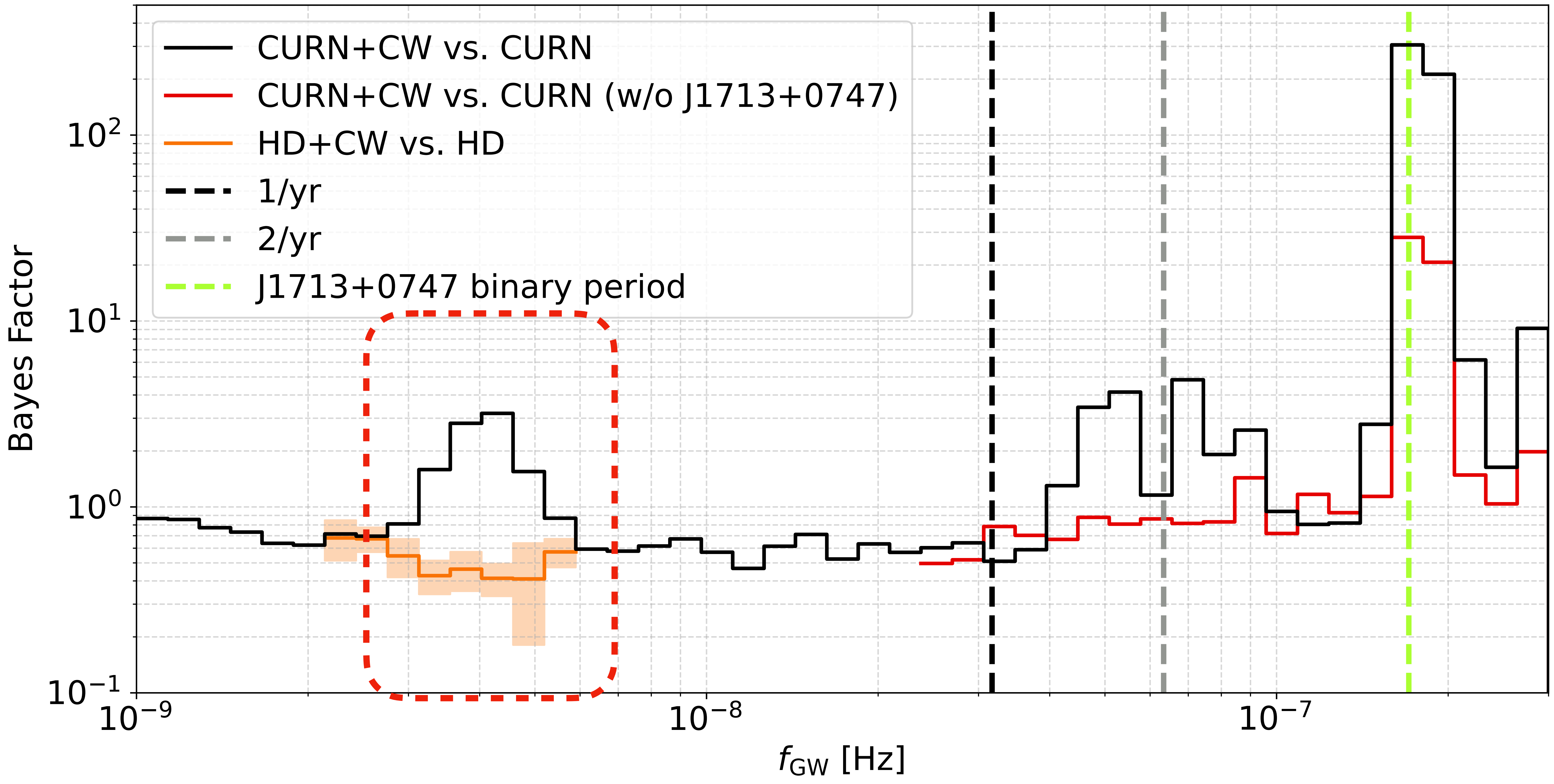

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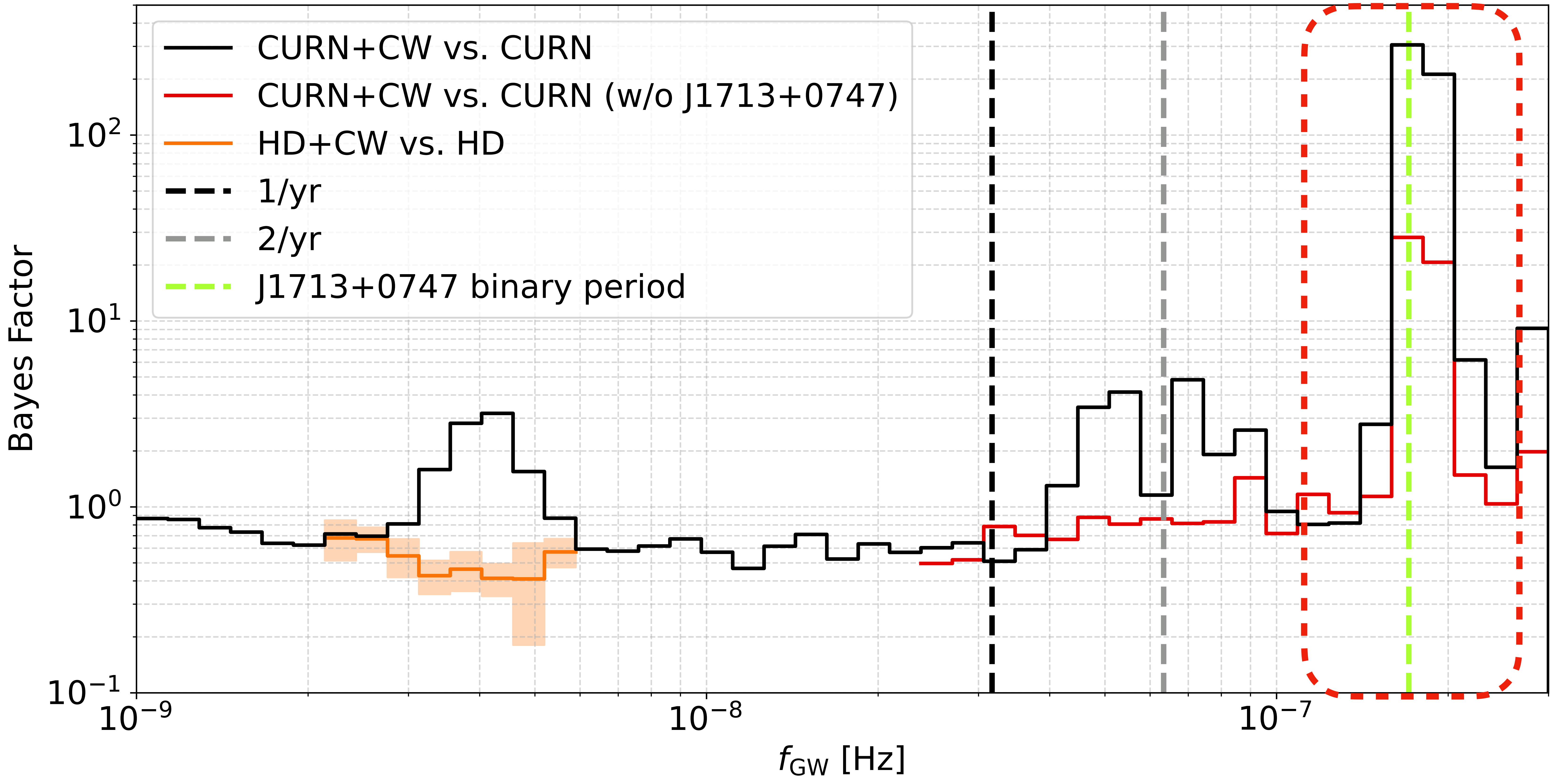
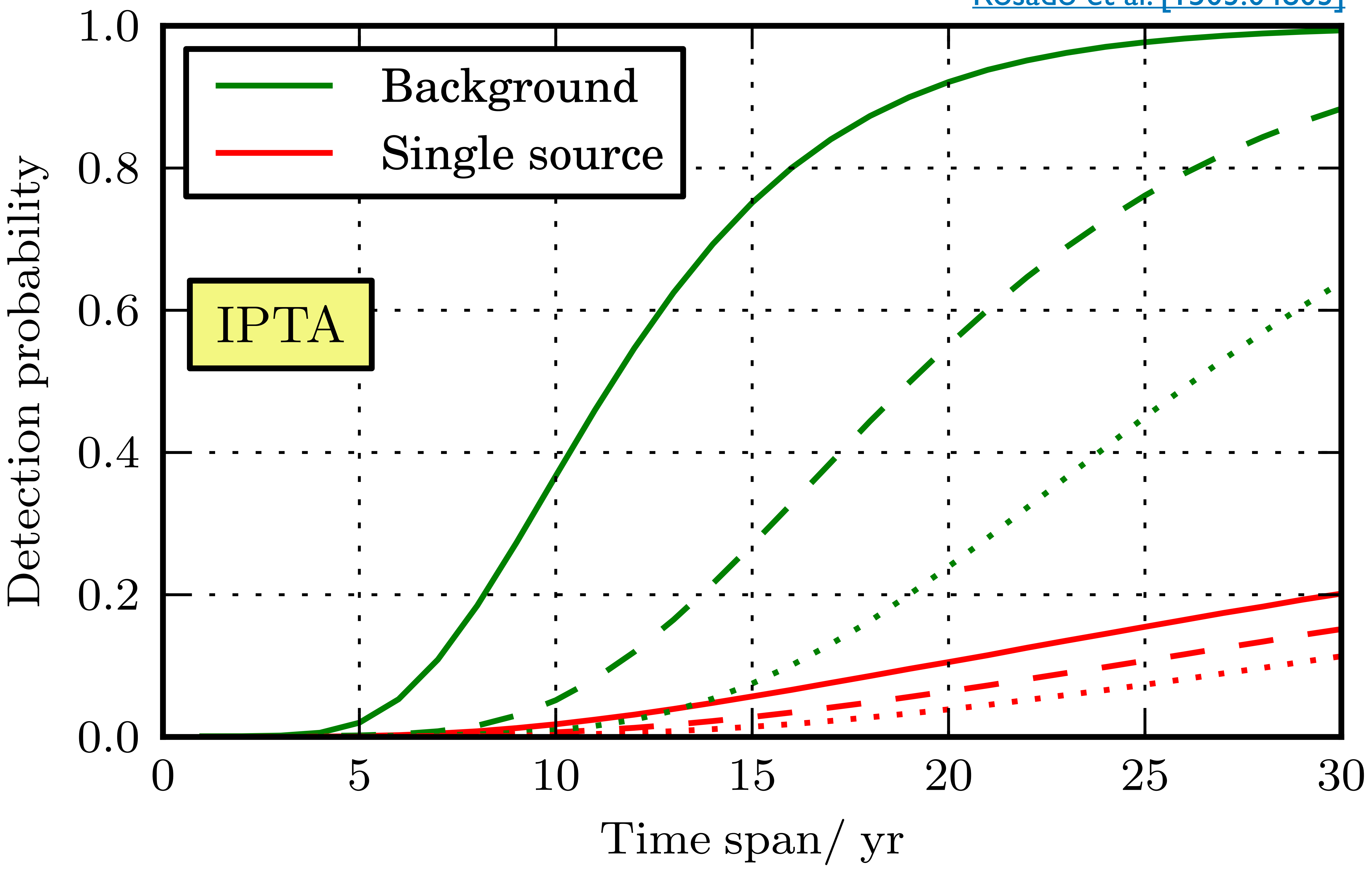
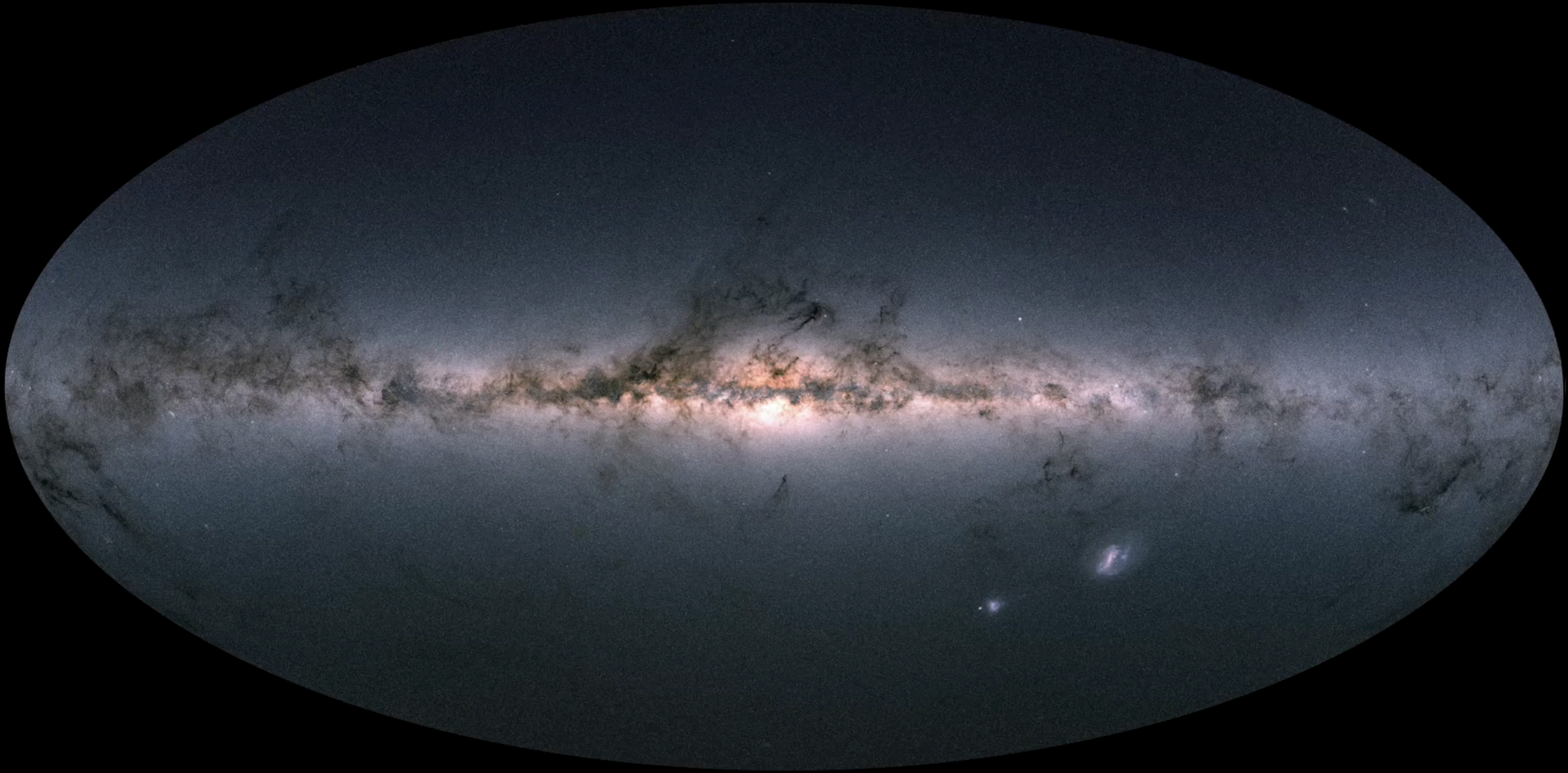


SINGLE SOURCE

Rosado et al. [1503.04803]

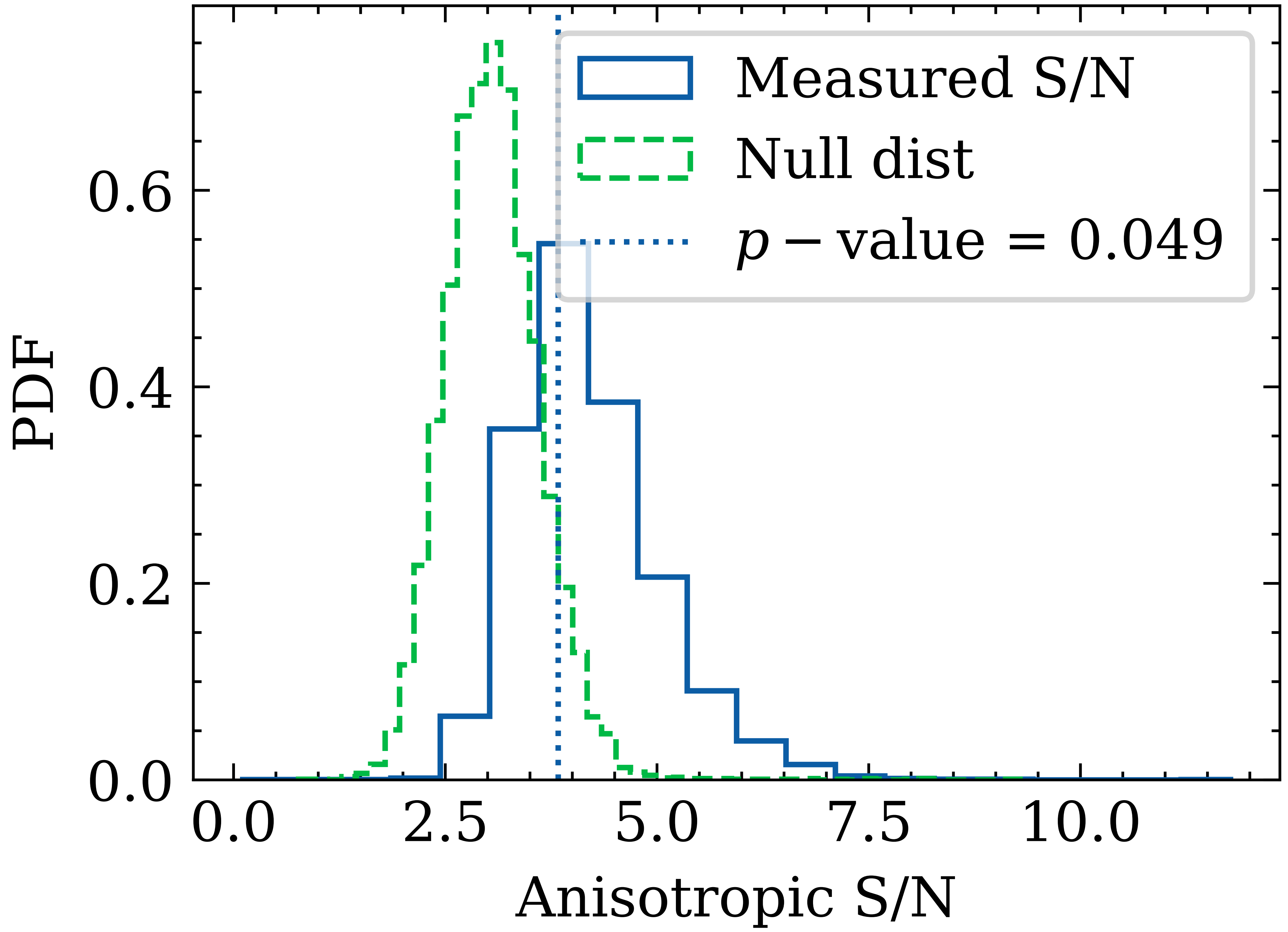


ANISOTROPIES



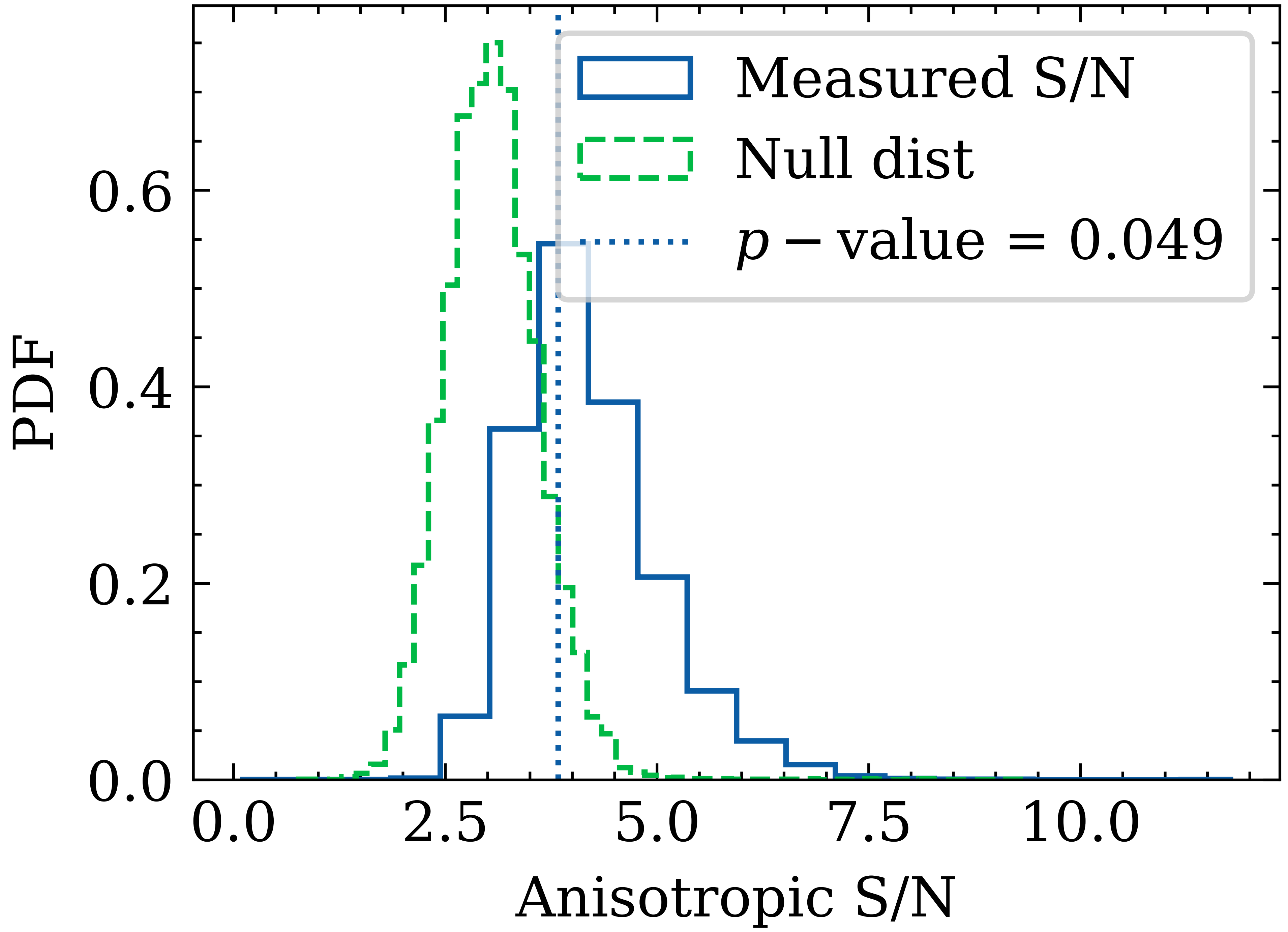
Credit: ESA/Gaia/DPAC

ANISOTROPIES

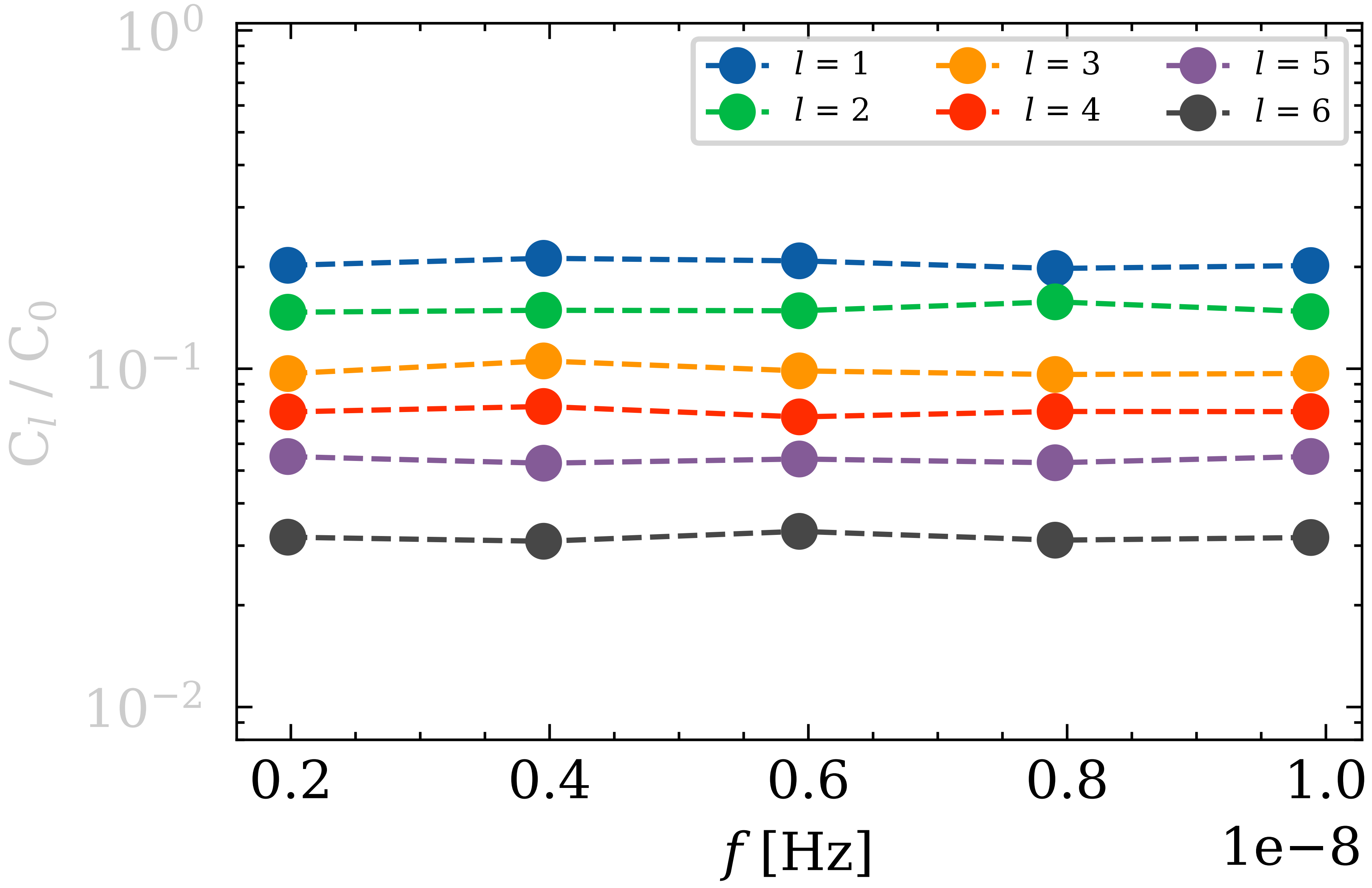


Agazie et al. [2306.16221]

ANISOTROPIES



$$P(\hat{\Omega}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} c_{lm} Y_{lm}(\hat{\Omega}) \qquad C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |c_{lm}|^2$$



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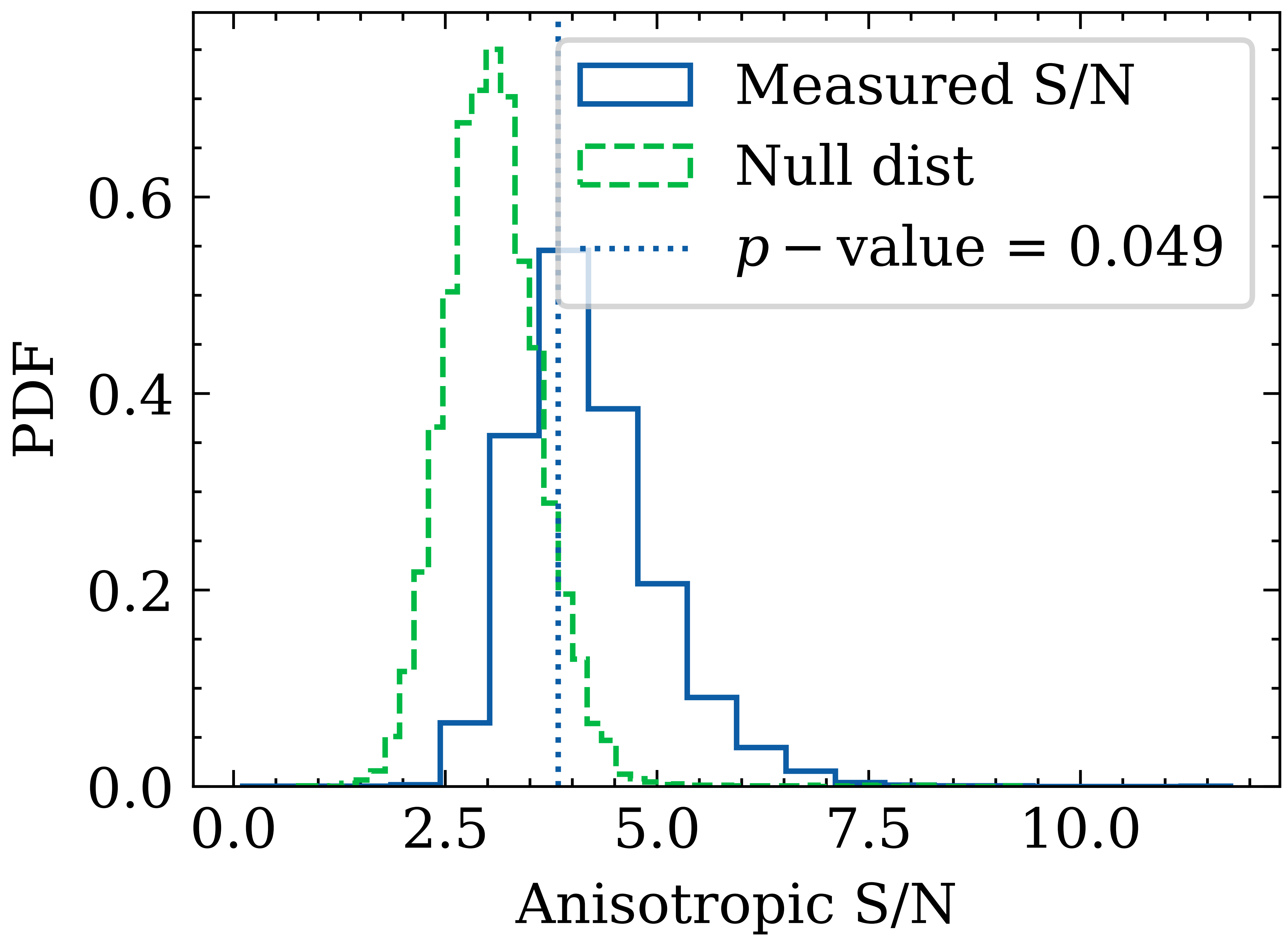
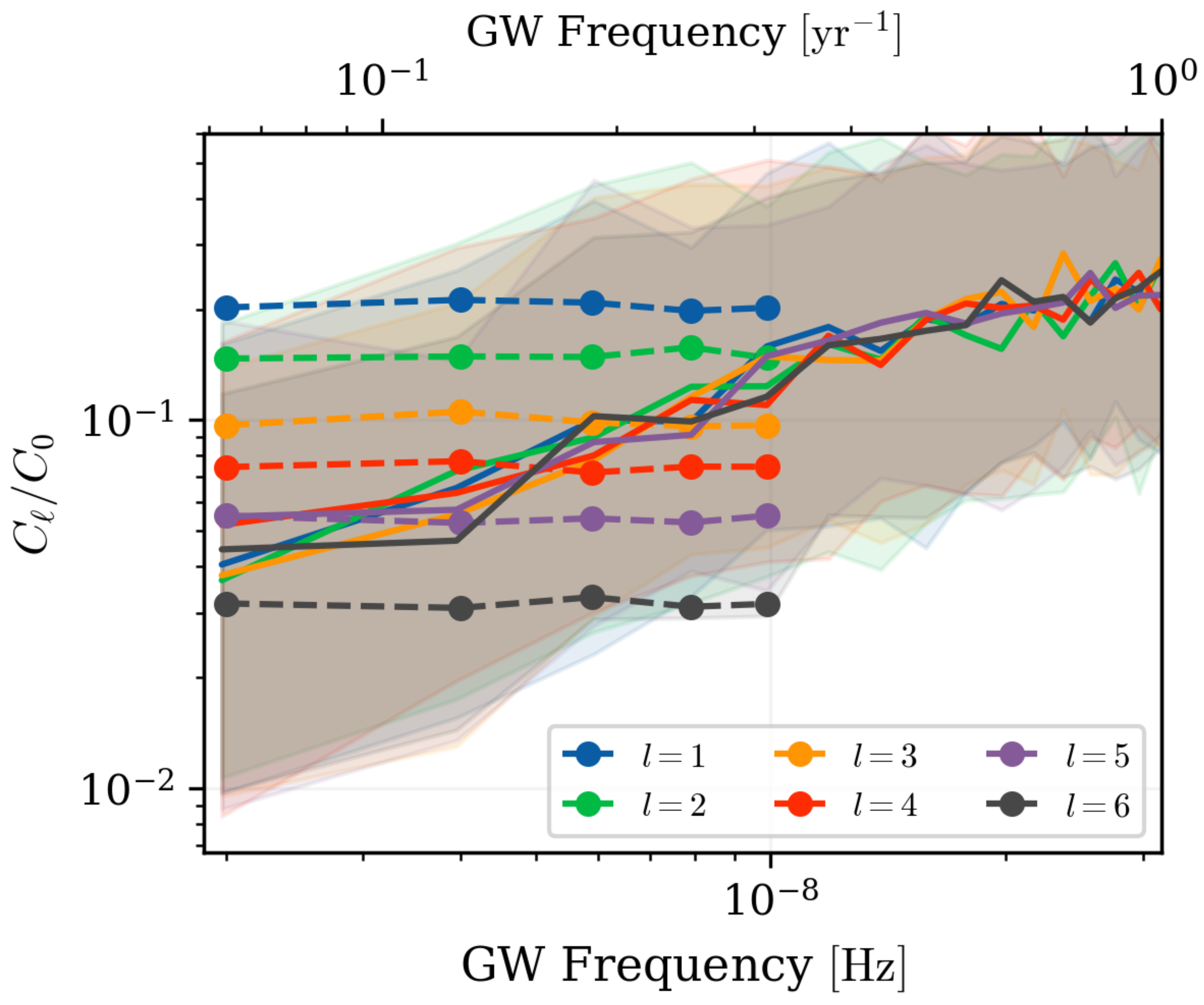
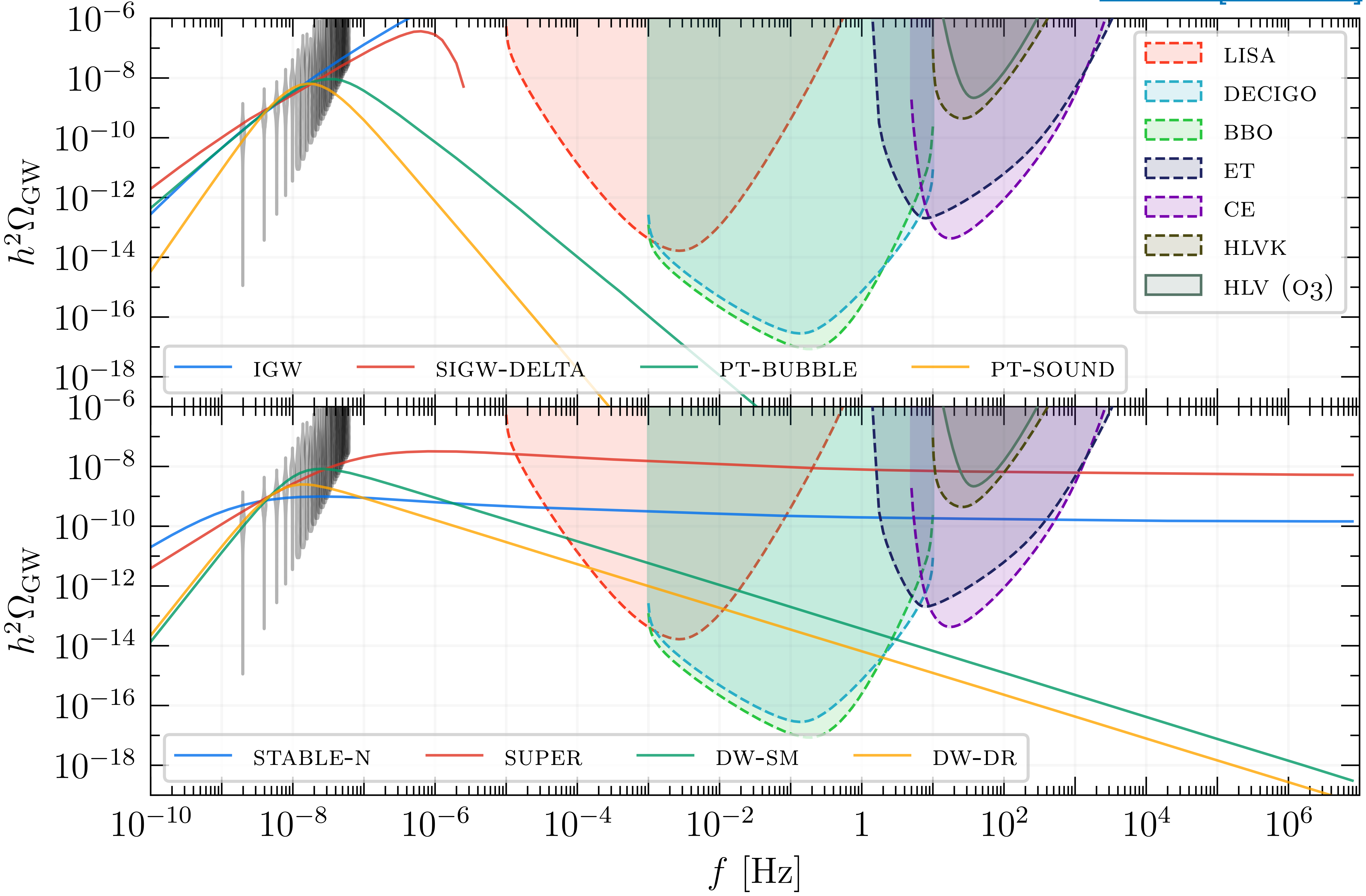




Agazie et al. [2306.16221]

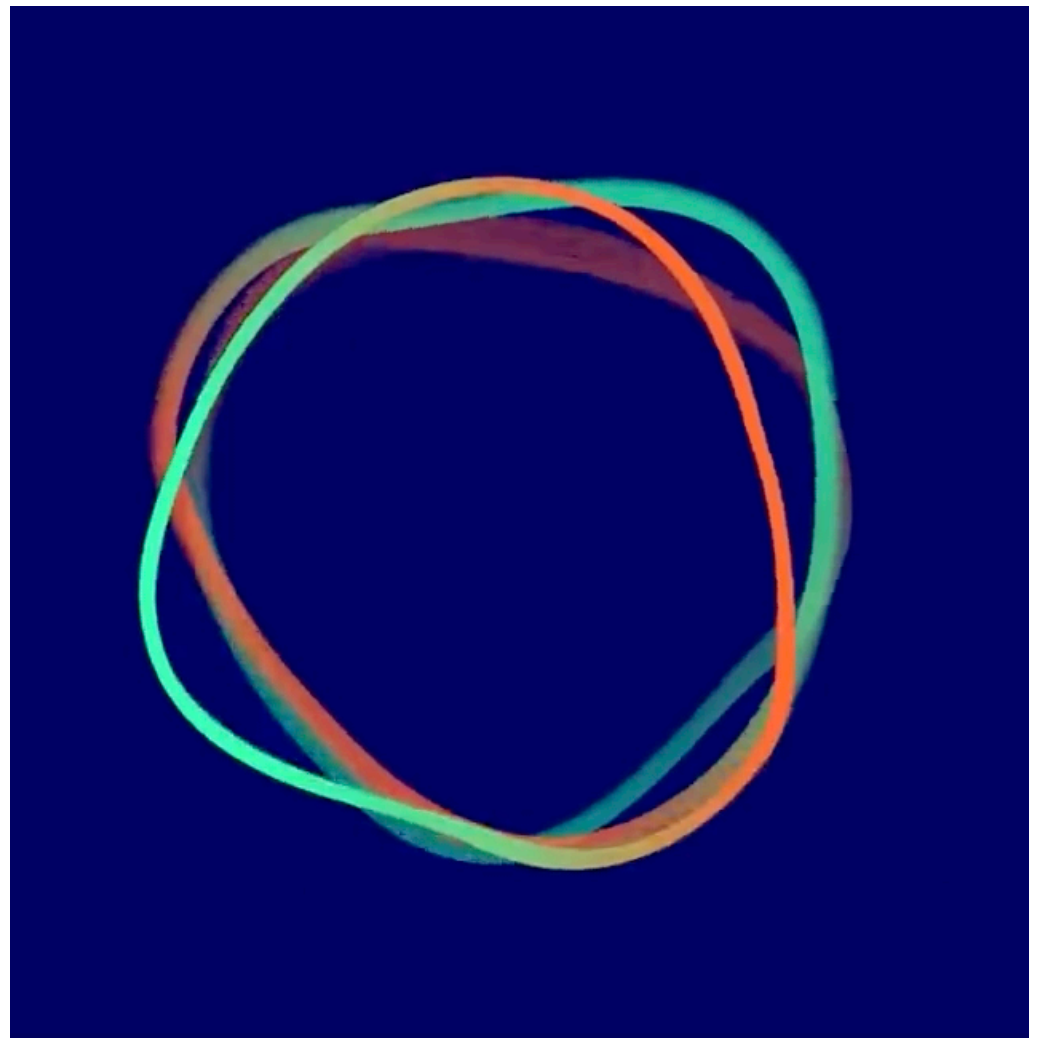
OTHER GWs EXPERIMENTS

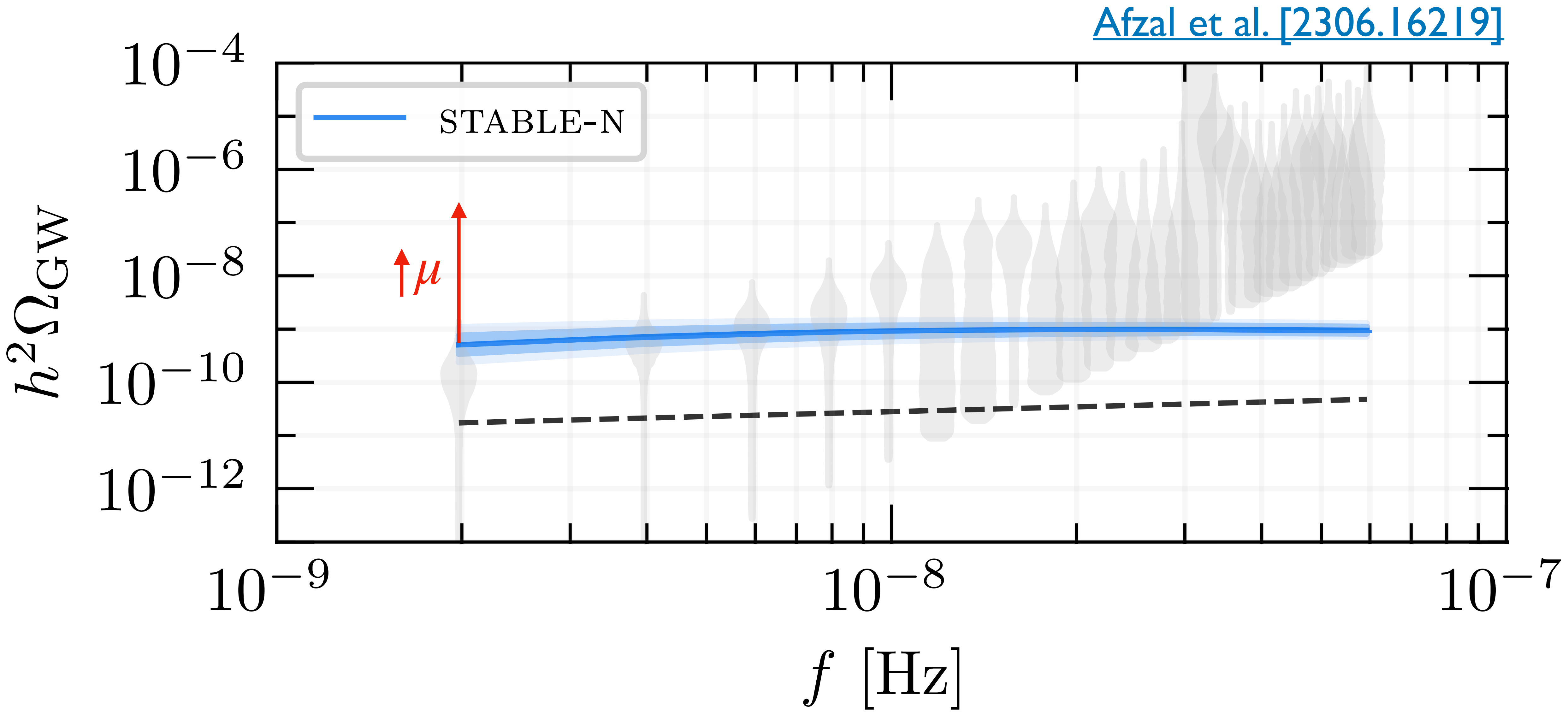
Afzal et al. [2306.16219]



PTAs are not only a discovery tool!

COSMIC STRINGS





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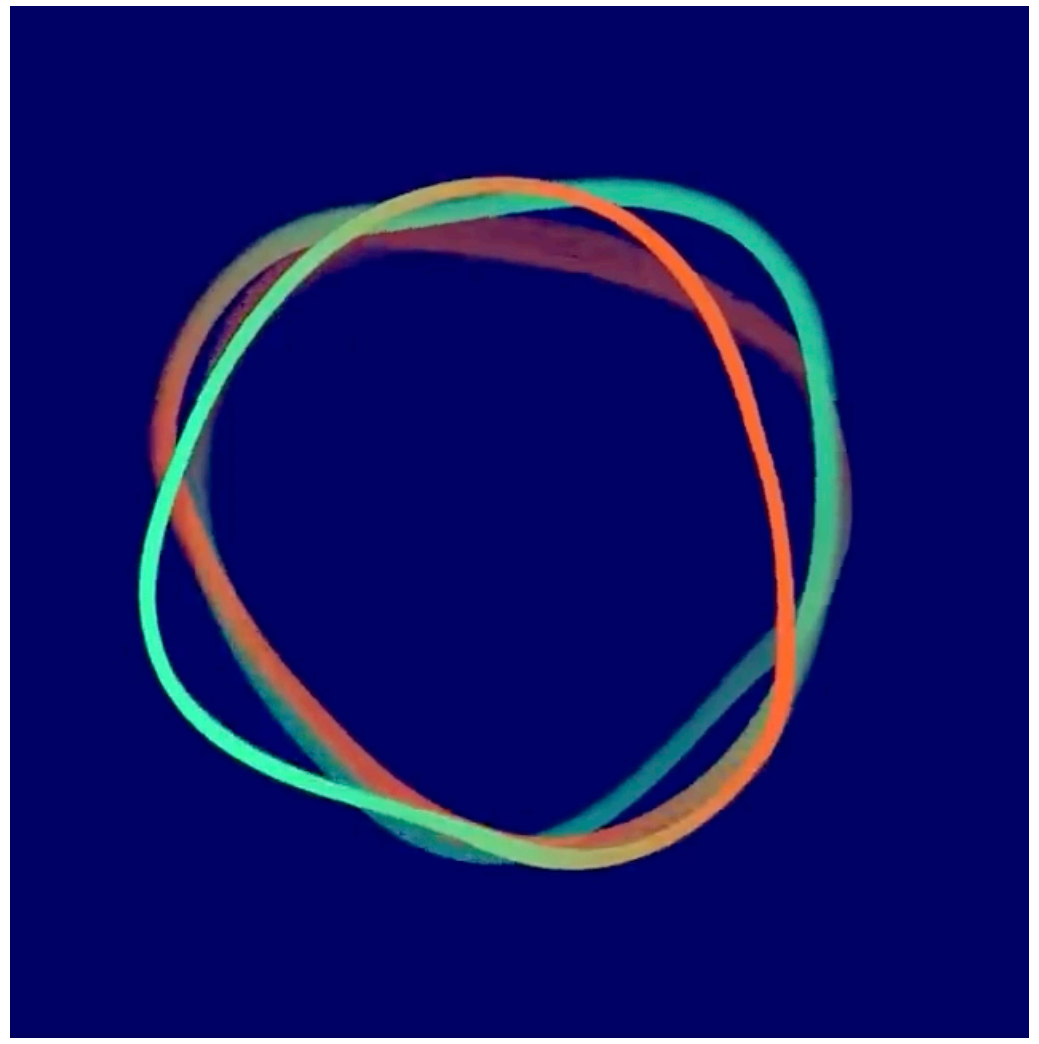

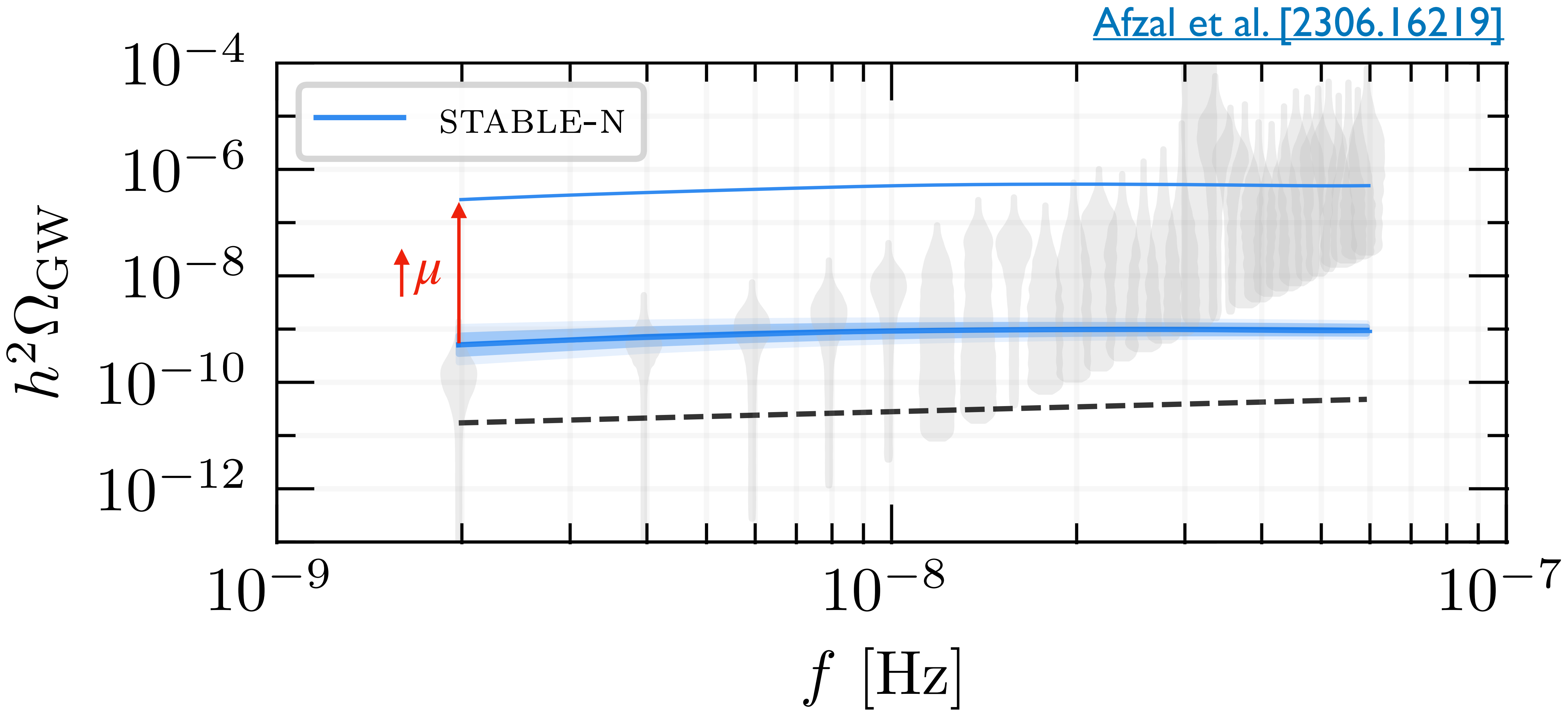

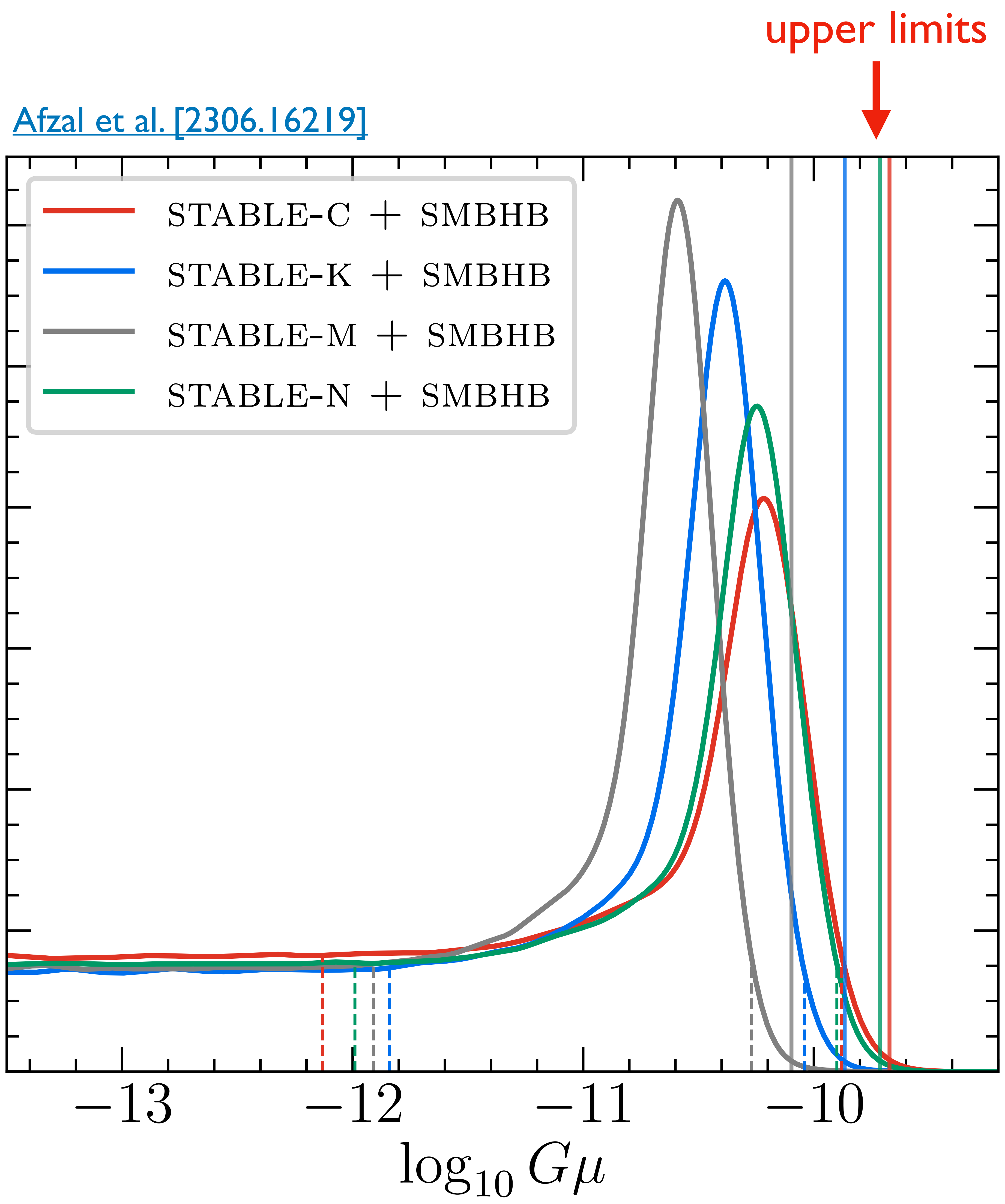

ULDM

$$\phi(\vec{x},t) = \frac{\sqrt{2\rho_\phi}}{m_\phi}\hat{\phi}(\vec{x})\cos\left(m_\phi t + \gamma(\vec{x})\right)$$

DM density

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DM mass

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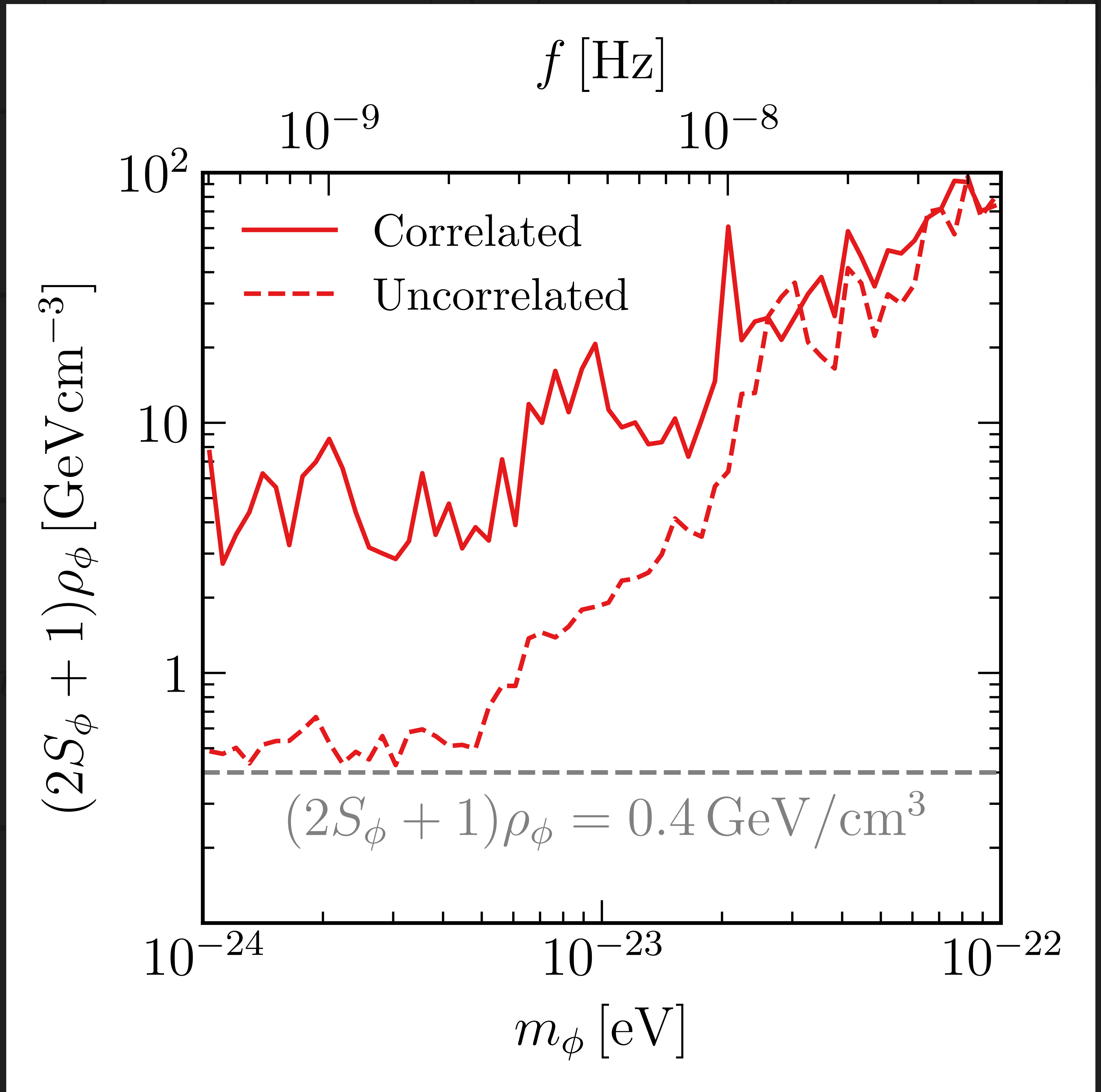
gravitational signal

$$s(t) \sim \frac{G\rho_\phi}{m_\phi^3}\sin(2m_\phi t)$$

Khmelnitsky, Rubakov [1309.5888]

ULDM

[Afzal et al. [2306.16219]](https://arxiv.org/abs/2306.16219)



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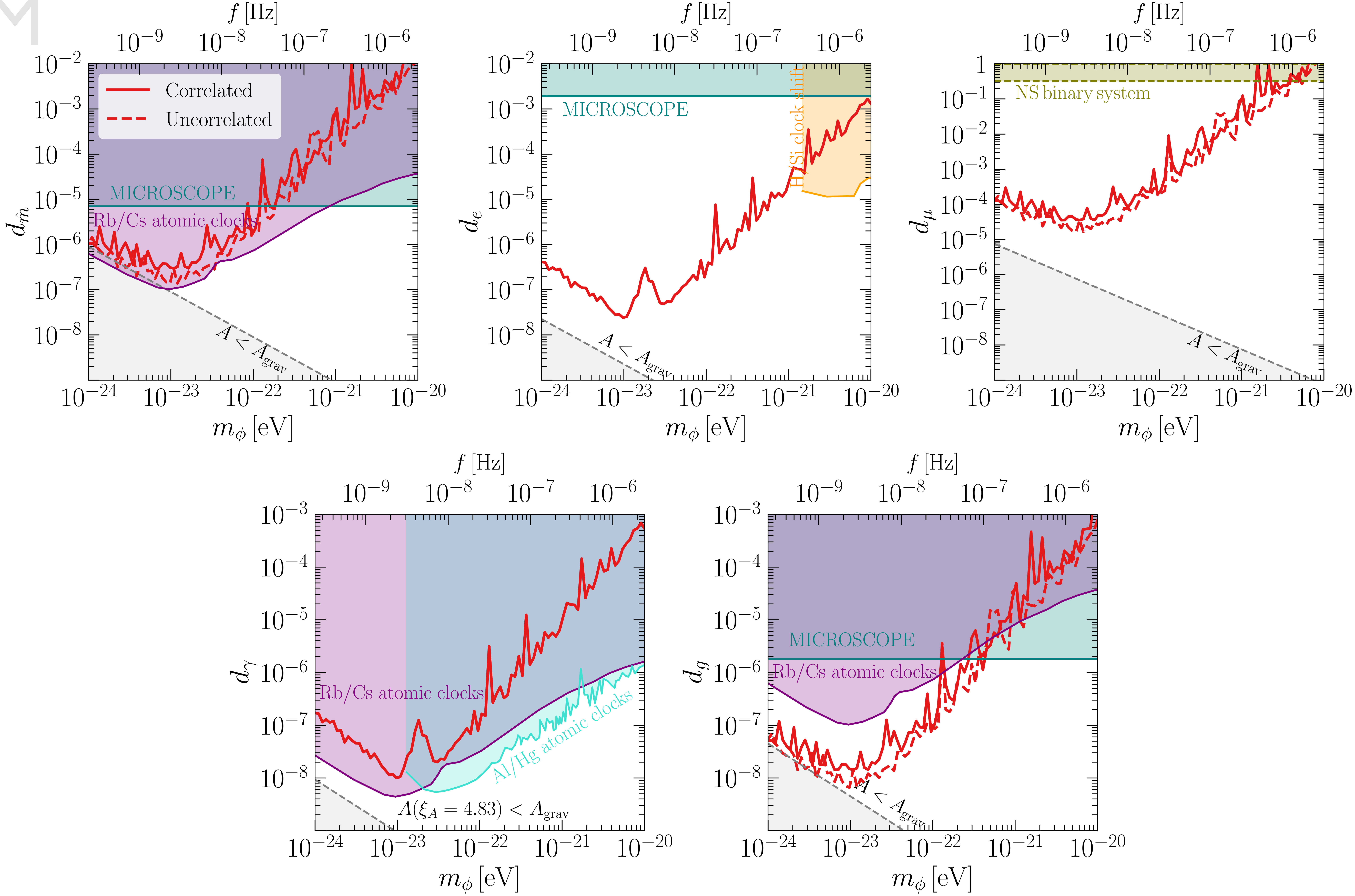
direct coupling signals

$$s(t) \sim d\frac{\sqrt{\rho_\phi}}{m_\phi^2\Lambda}\sin(m_\phi t)$$

Kaplan, AM, Trickle [2205.06817]

ULDM



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