Exploring the Gravitational Wave Universe with PTAs

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DESY.
NANOGrav Physics Frontiers Center

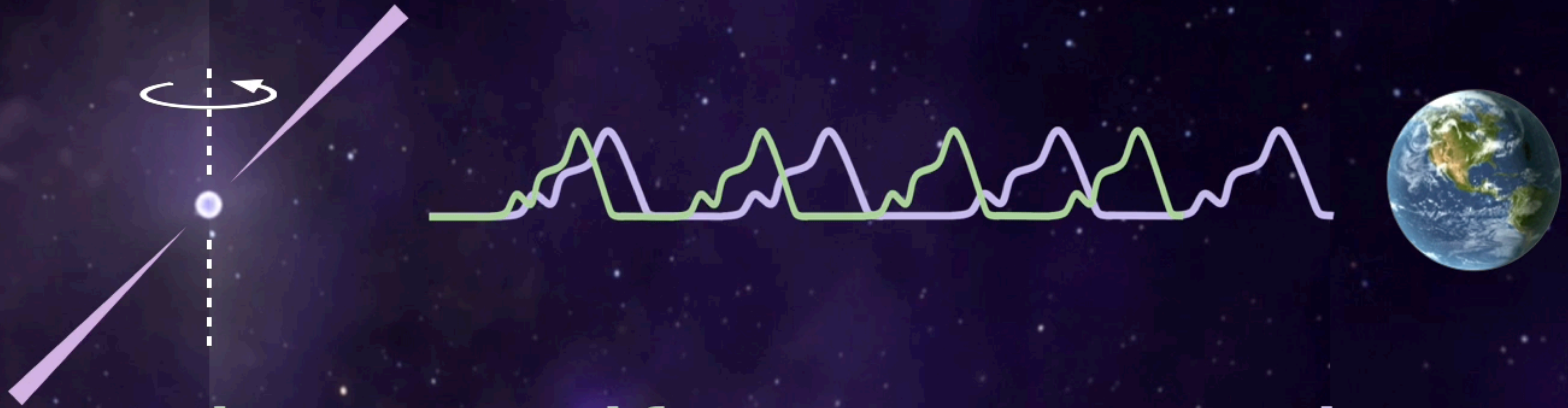
PULSARS

$$\nu(t) = \nu_0 + \dot{\nu}_0\, t$$

$$\dot{\nu}_0/\nu_0 \sim 10^{-23} - 10^{-20}\ \mathrm{Hz}$$

Animation by NASA's Goddard Space Flight Center

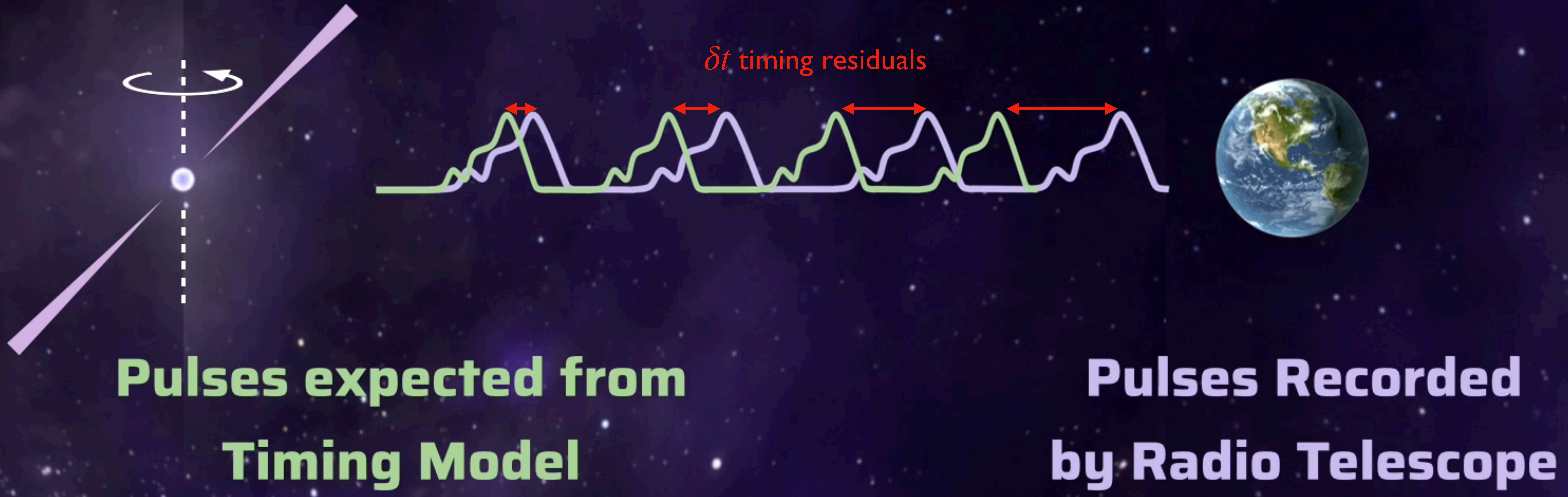
TIMING RESIDUALS



Pulses expected from Timing Model

Pulses Recorded by Radio Telescope

TIMING RESIDUALS



A GALAXY-SIZE DETECTOR FOR GWs

A GALAXY-SIZE DETECTOR FOR GWs

68 pulsars observed by NG

observing baseline of 15 yrs

distance to pulsars up to ~kpc

IPTA DR3 will contain >100 pulsars

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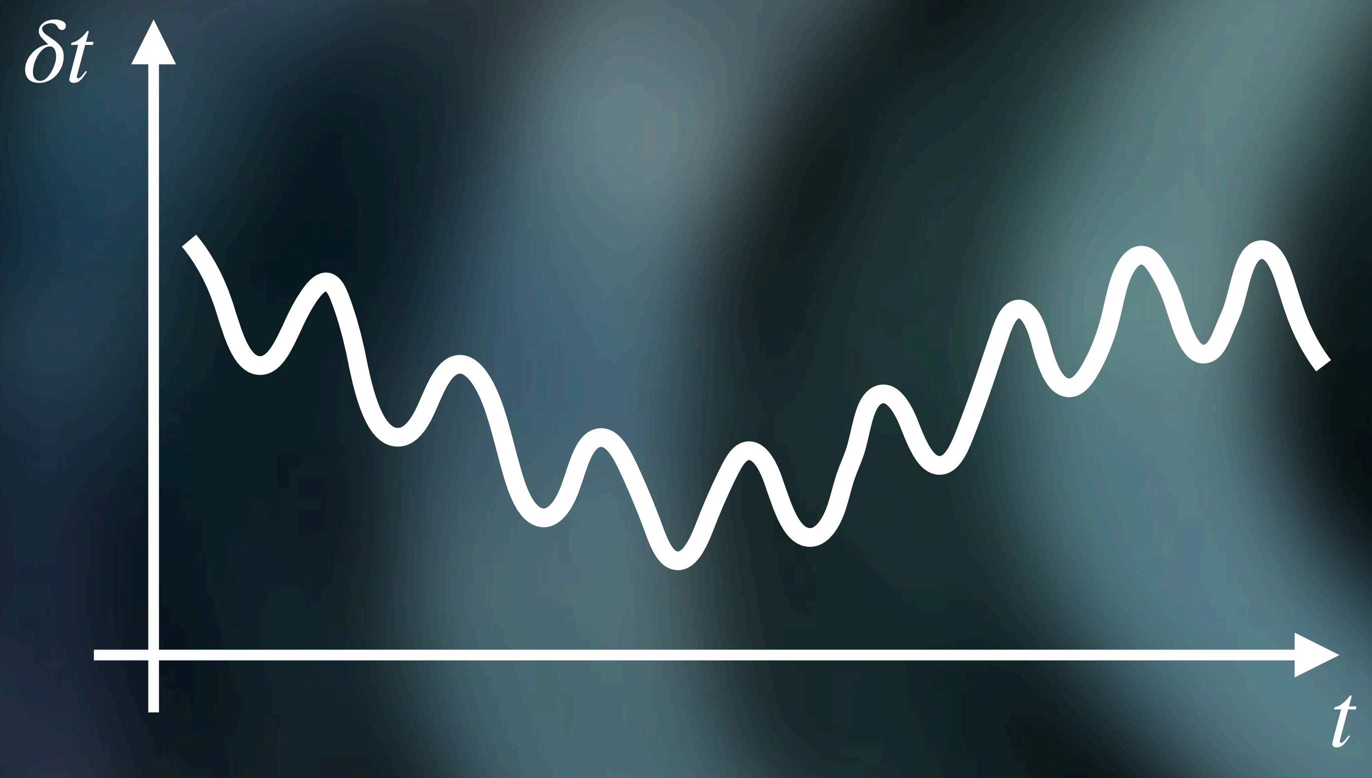
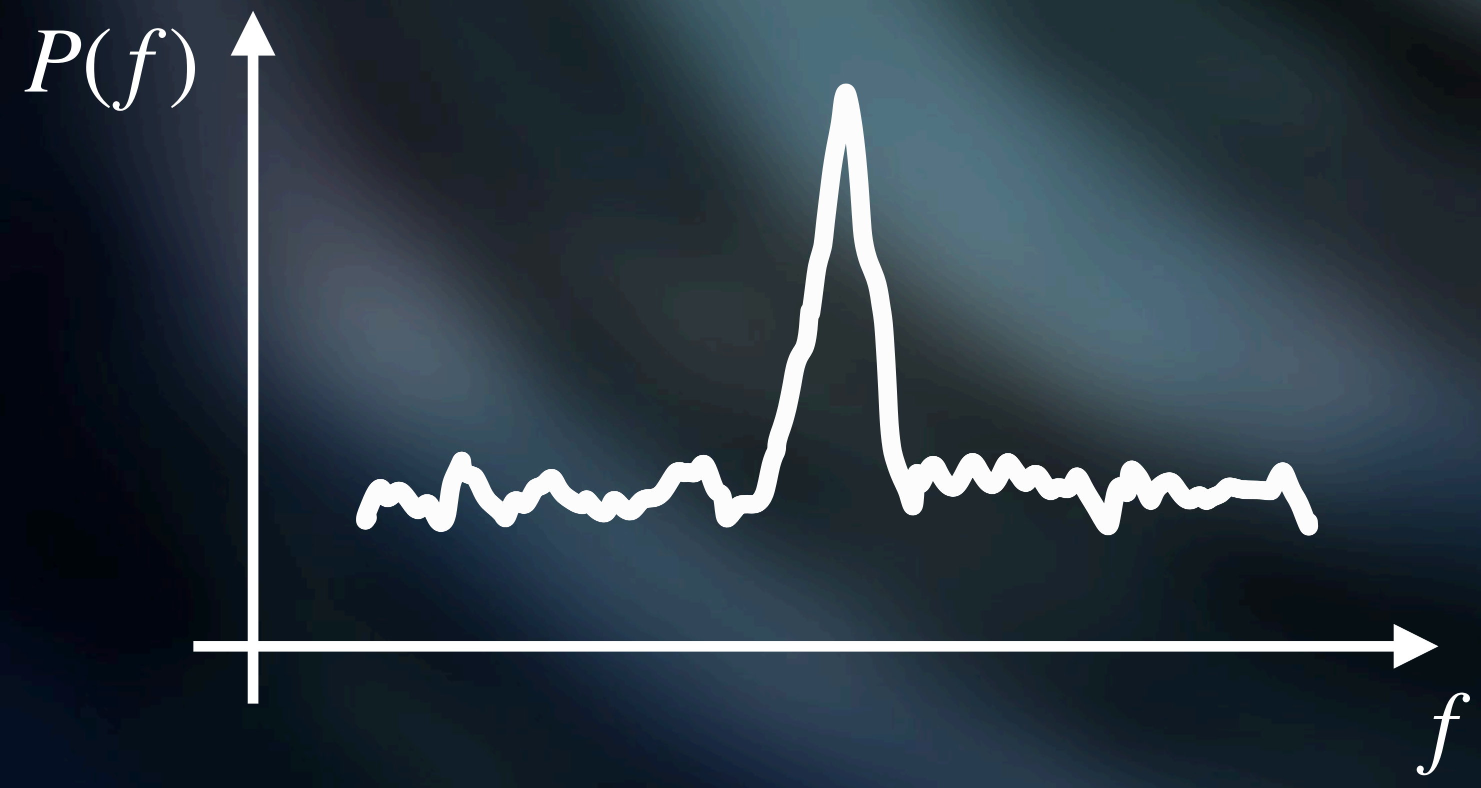
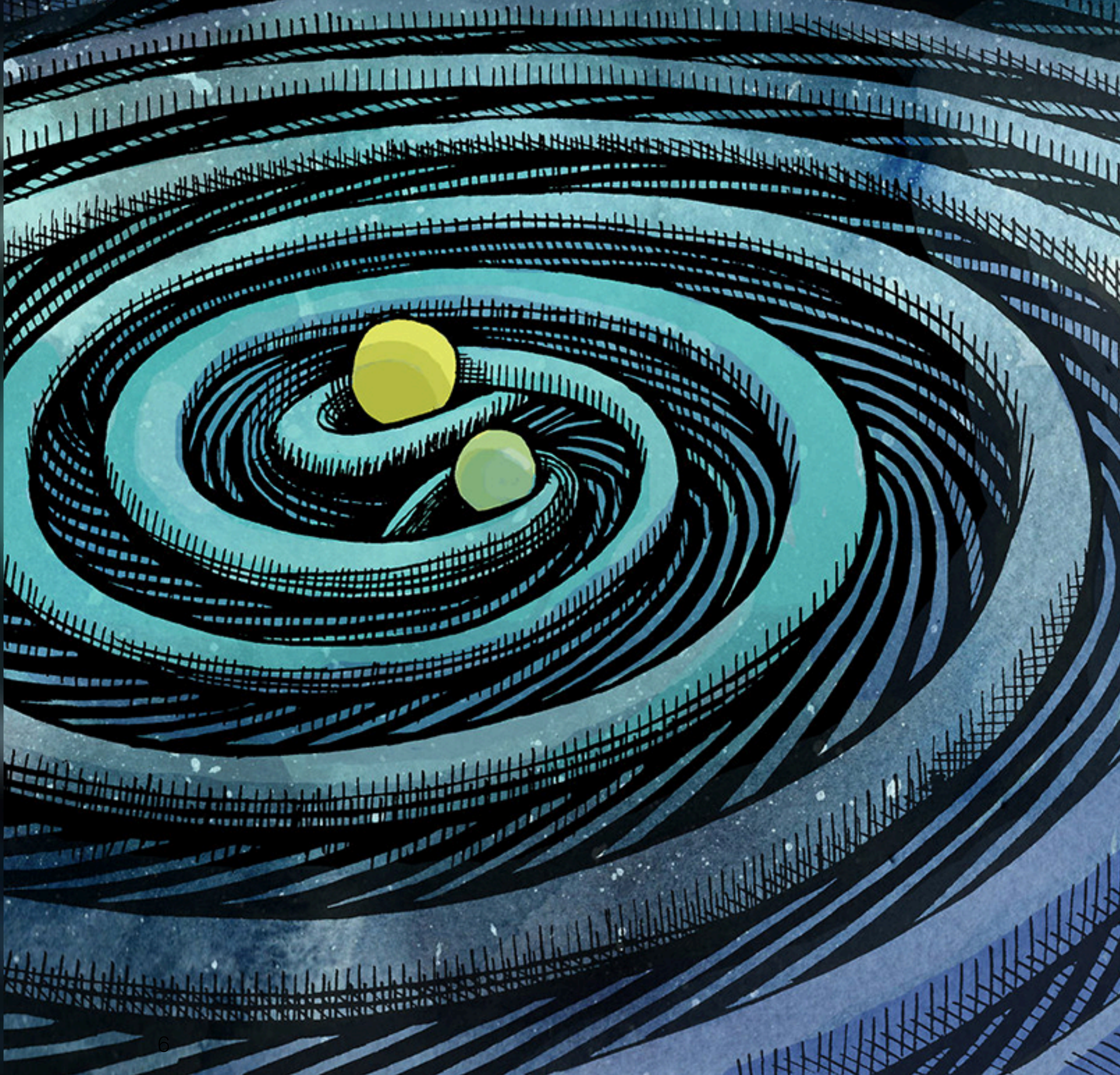
CONTINUOUS WAVE

$$h_{ij}(t, \mathbf{x}) = \sum_{A=+,\times} e^A_{ij}(\hat{n}) \cos\left[\omega(t - \hat{n}\cdot\mathbf{x})\right]$$





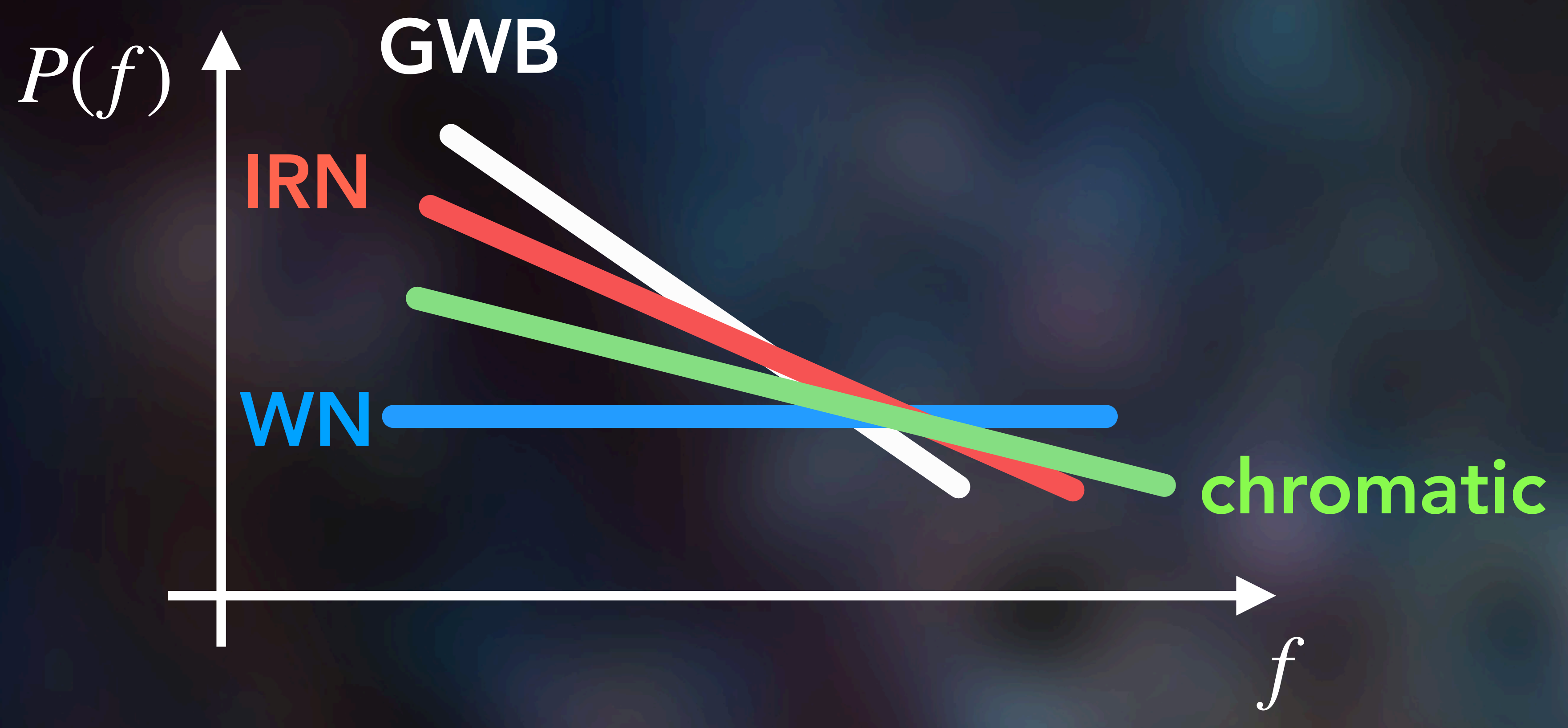


GW BACKGROUND

$$h_{ij}(t,\mathbf{x}) = \sum_{A=+,\times} \int df \int d^2\hat{n}\; \tilde{h}_A(f,\hat{n})\; e^{A}_{ij}(\hat{n})\; e^{-2\pi i f(t-\hat{n}\cdot x)}$$

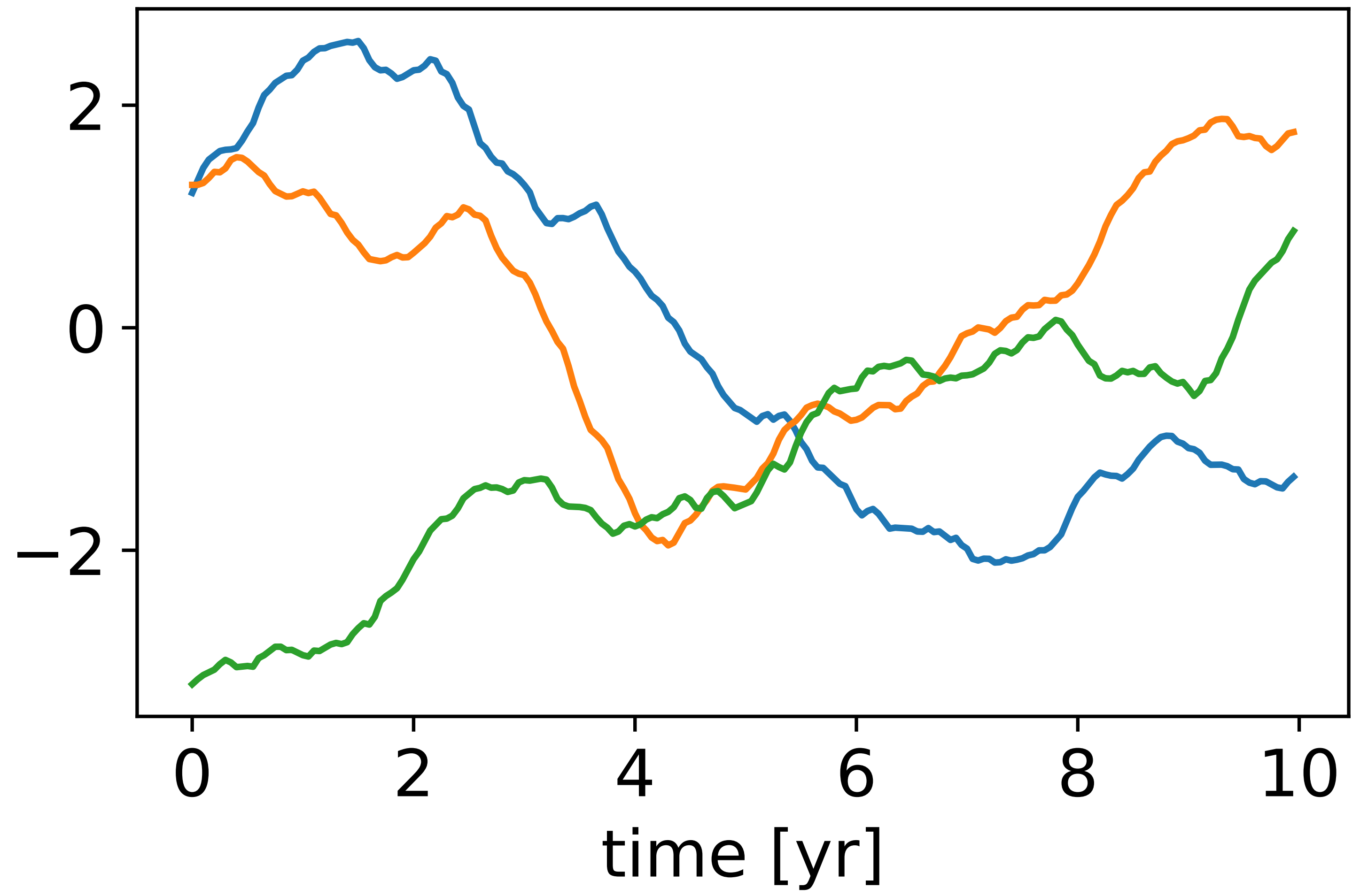
GW BACKGROUND

$$h_{ij}(t,\mathbf{x}) = \sum_{A=+,\times} \int df \int d^2\hat{n}\, \tilde{h}_A(f,\hat{n})\, e^{A}_{ij}(\hat{n})\, e^{-2\pi i f(t-\hat{n}\cdot x)}$$



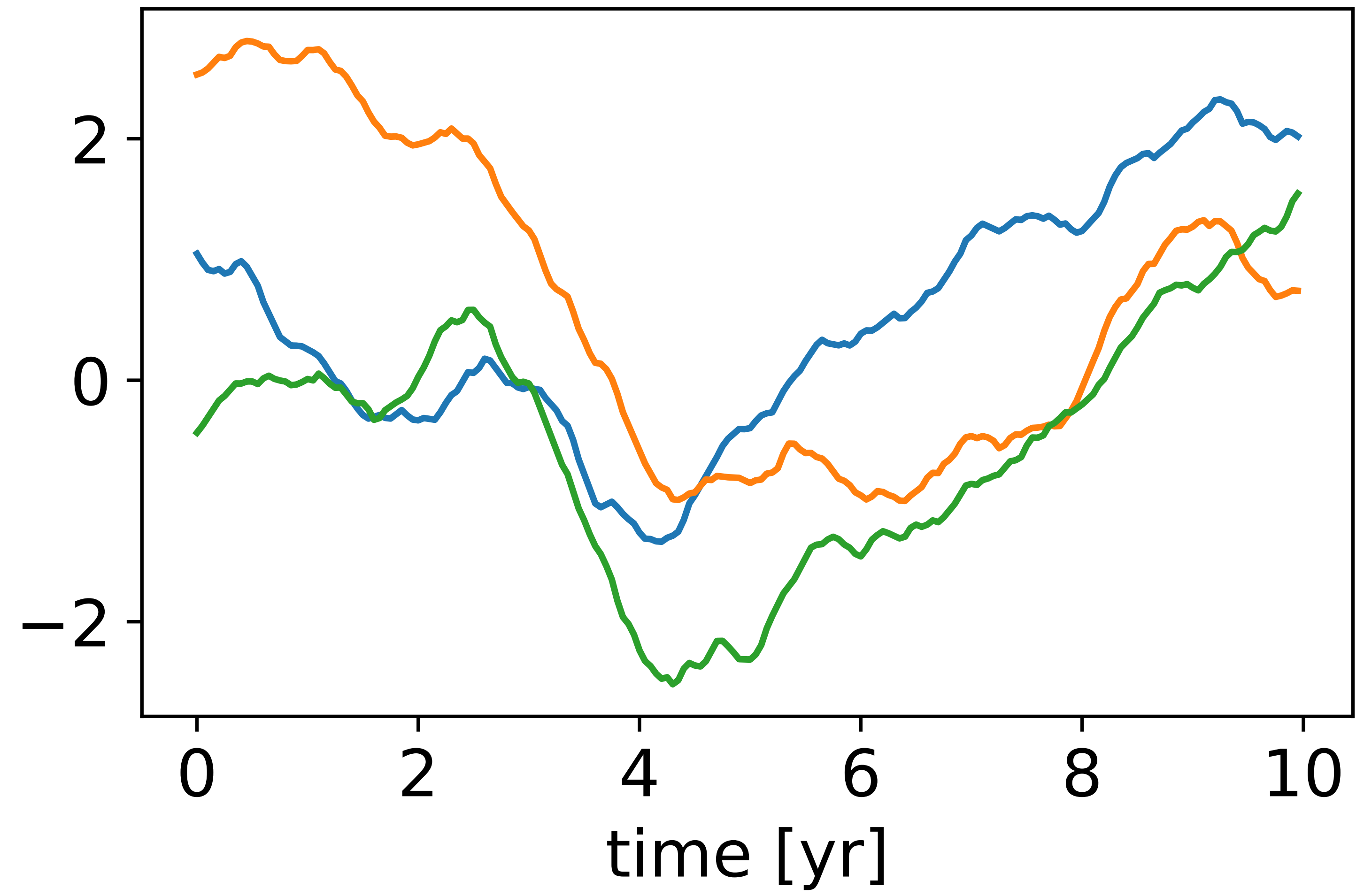
CORRELATIONS EXAMPLE

$$\Gamma_{ab} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



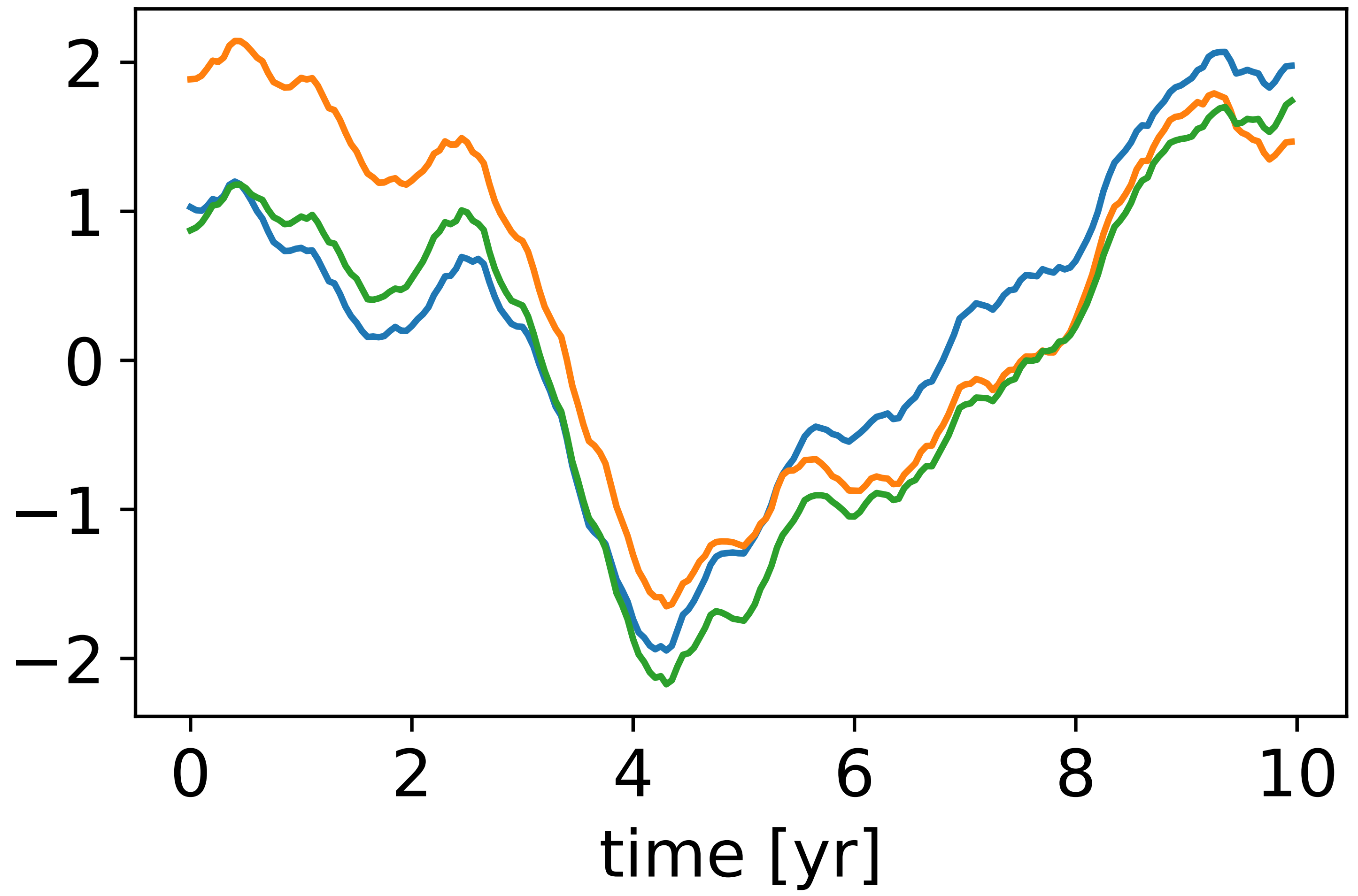
uncorrelated

$$\Gamma_{ab} = \begin{pmatrix} 1 & 0.5 & 0.5 \\ 0.5 & 1 & 0.5 \\ 0.5 & 0.5 & 1 \end{pmatrix}$$



moderately correlated

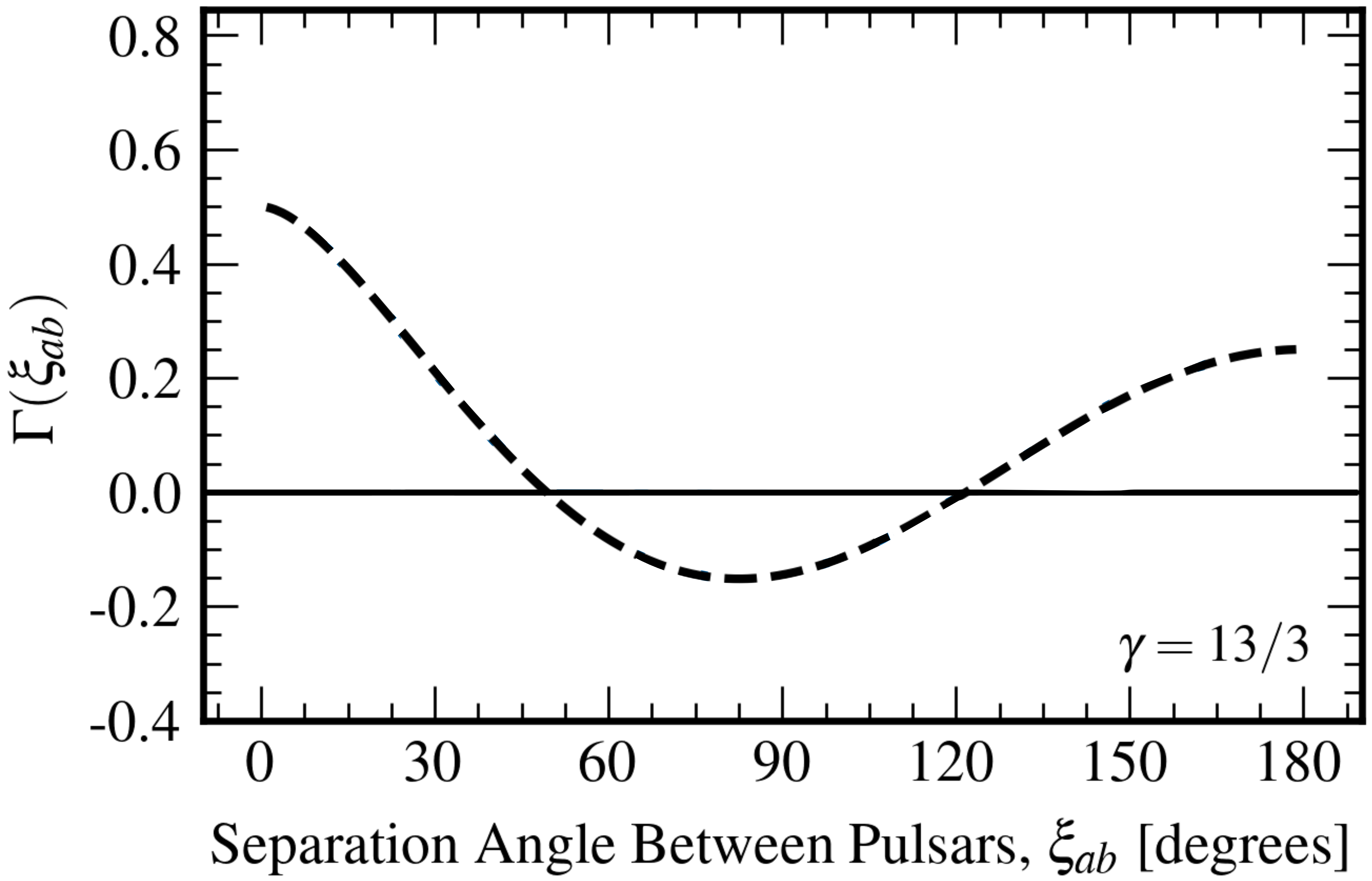
$$\Gamma_{ab} = \begin{pmatrix} 1 & 0.95 & 0.95 \\ 0.95 & 1 & 0.95 \\ 0.95 & 0.95 & 1 \end{pmatrix}$$



strongly correlated

slide from Joe Romano

HELLINGS & DOWNS CURVE



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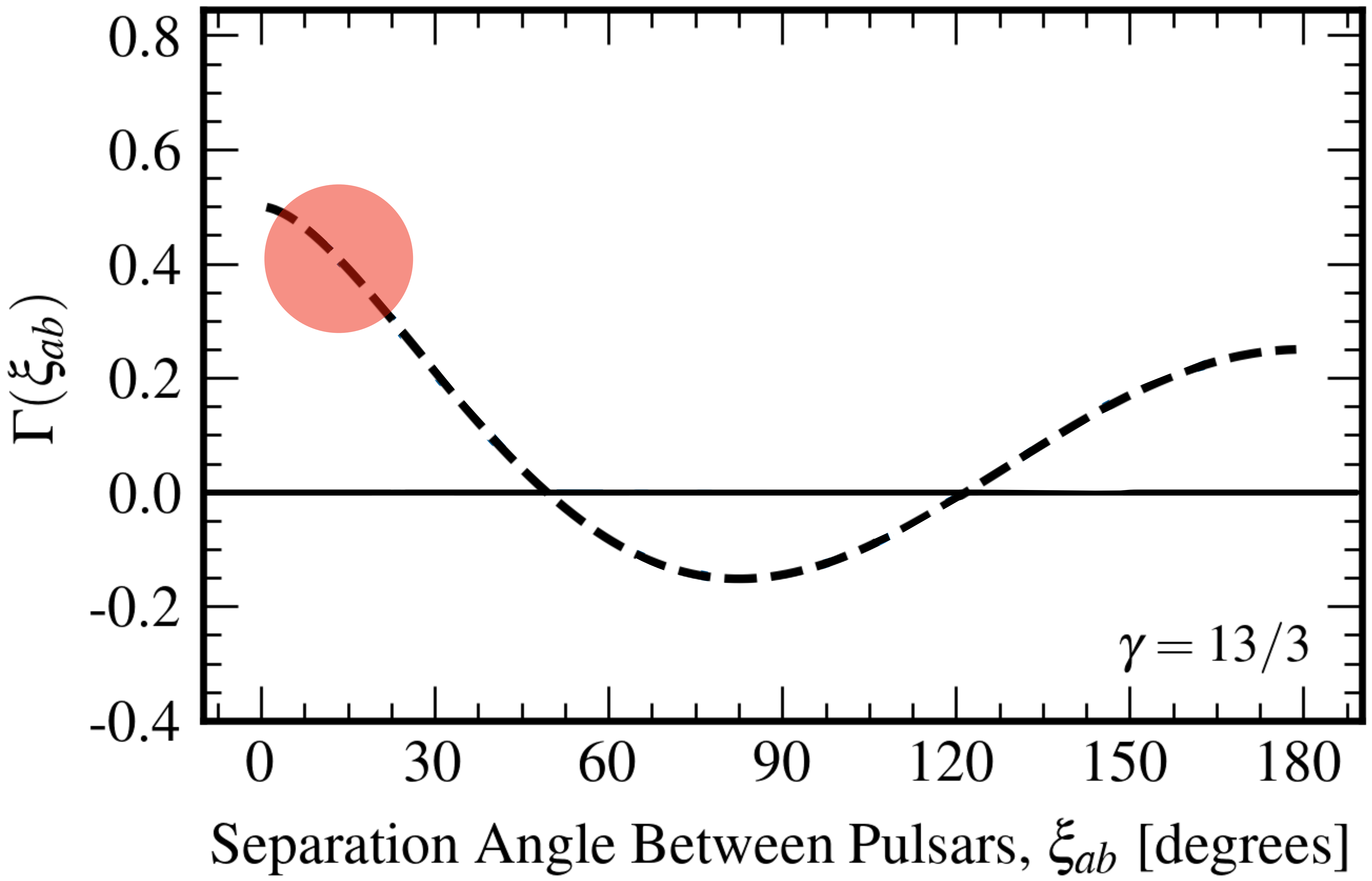

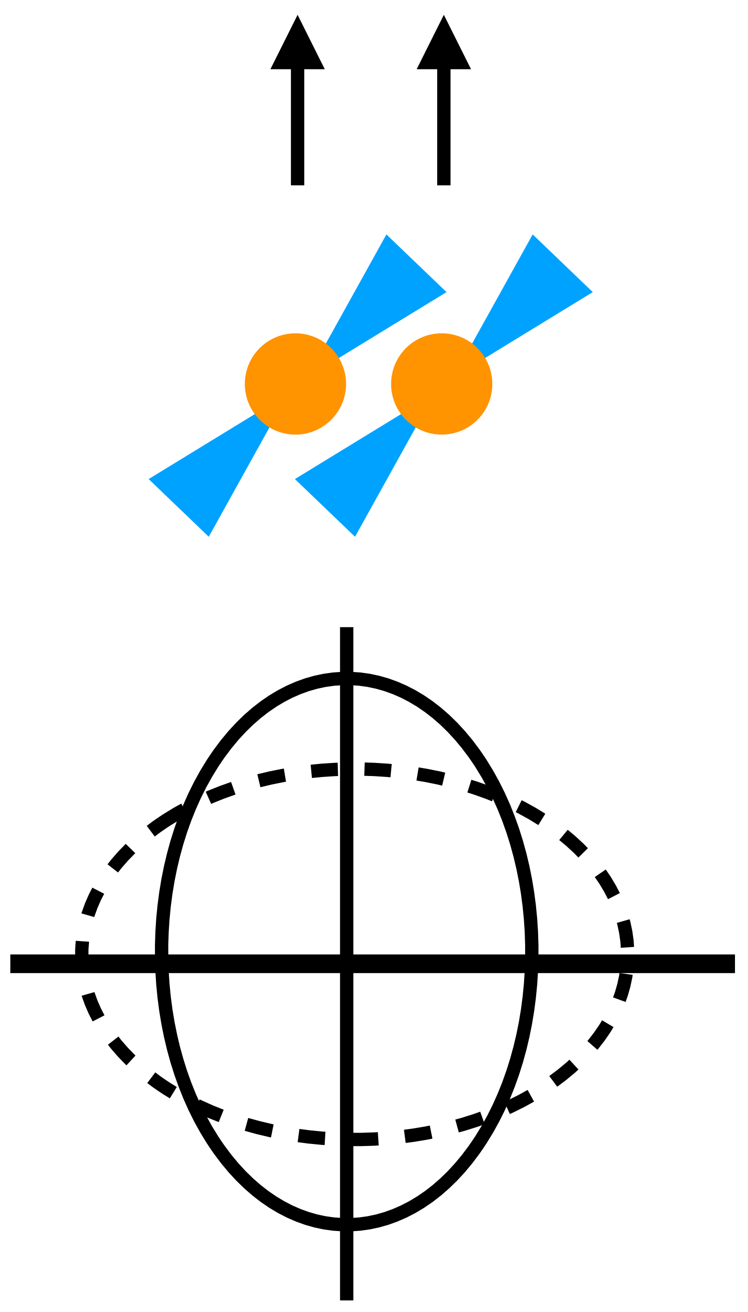

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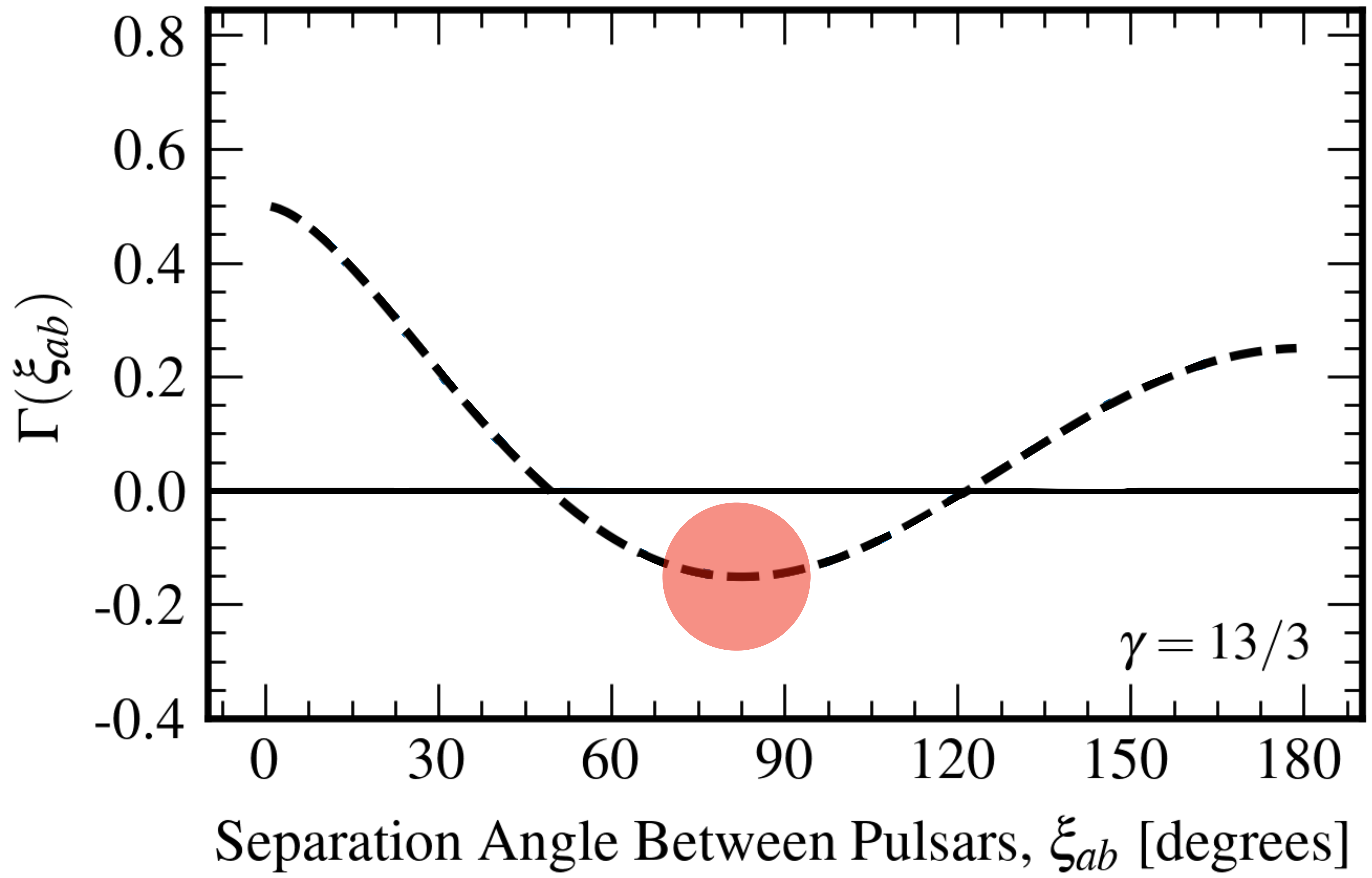

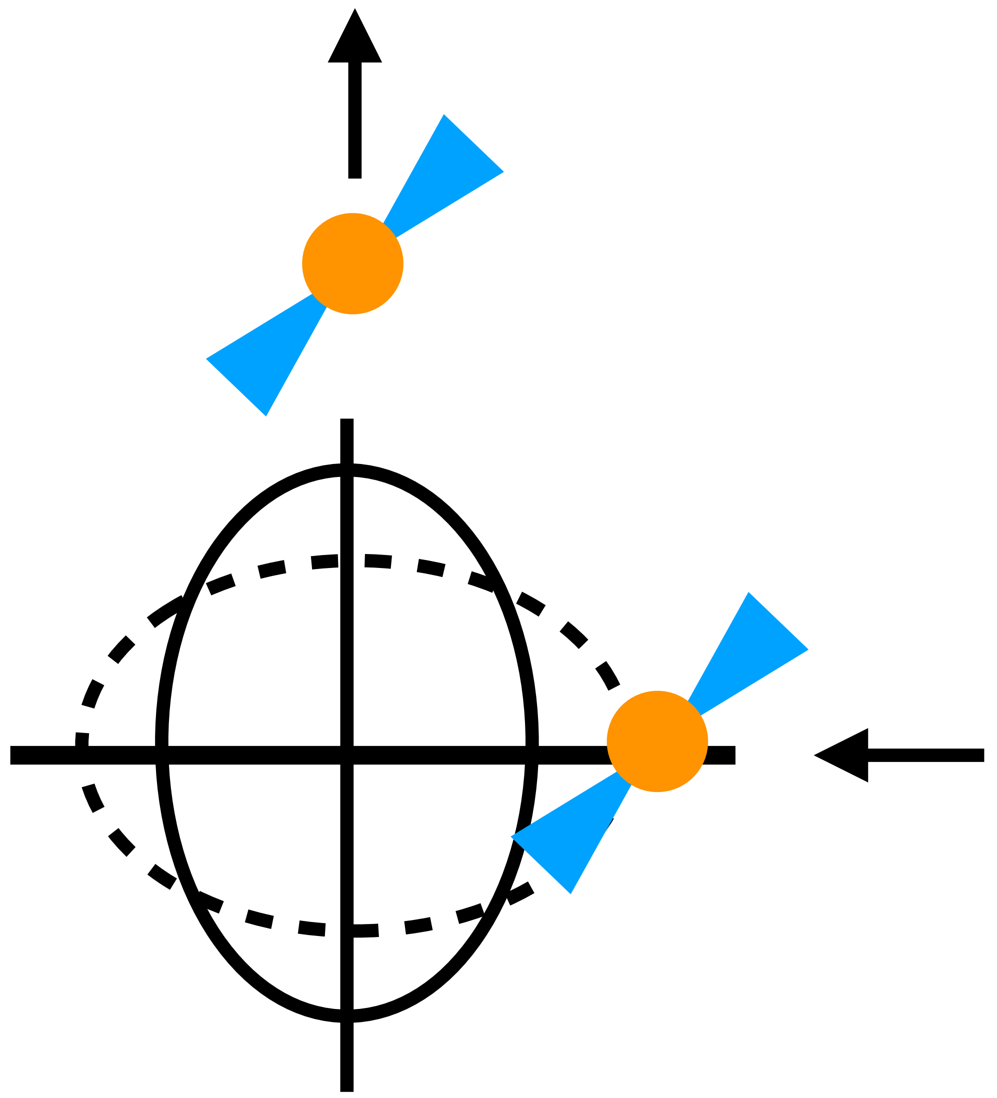

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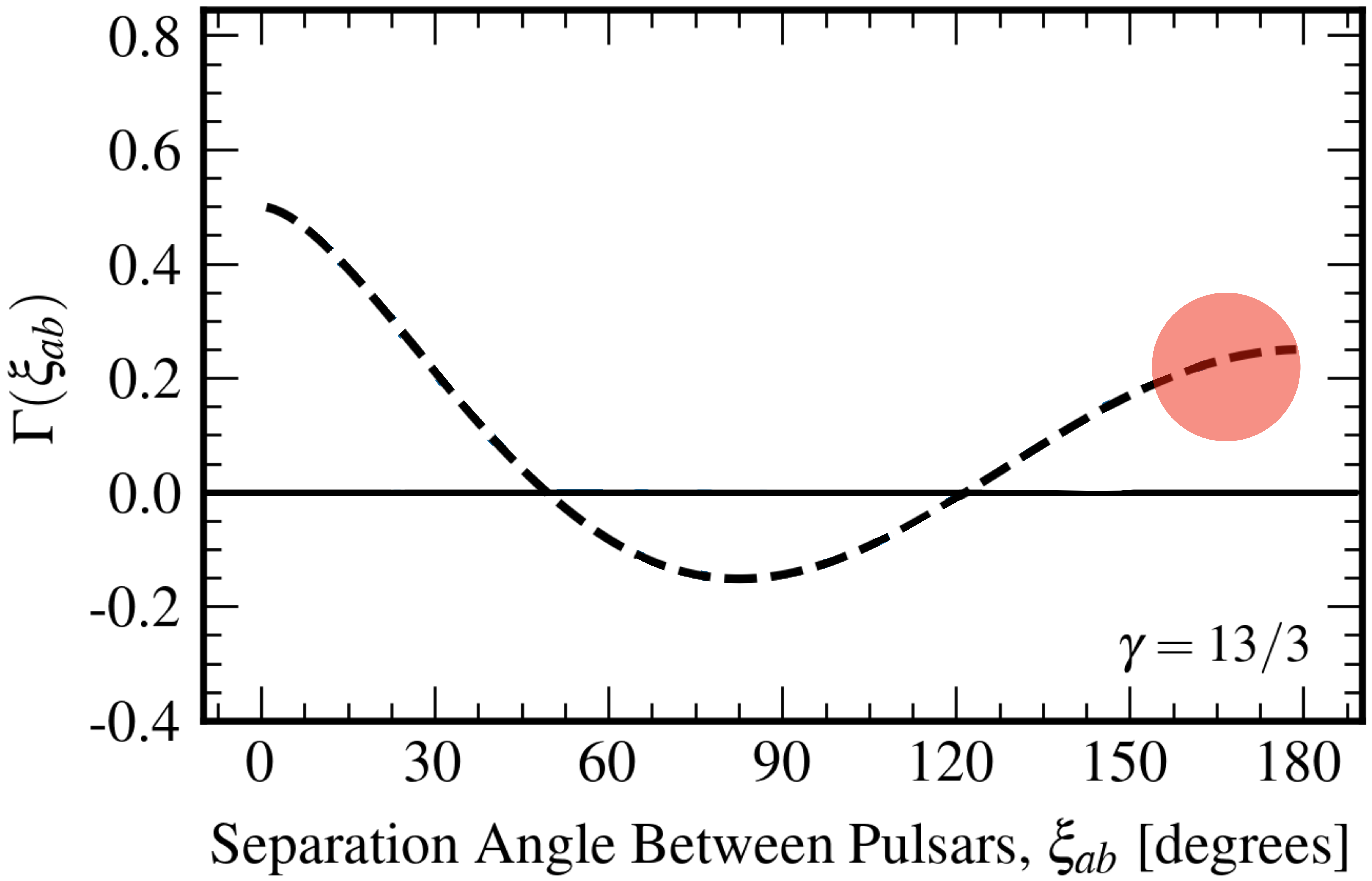
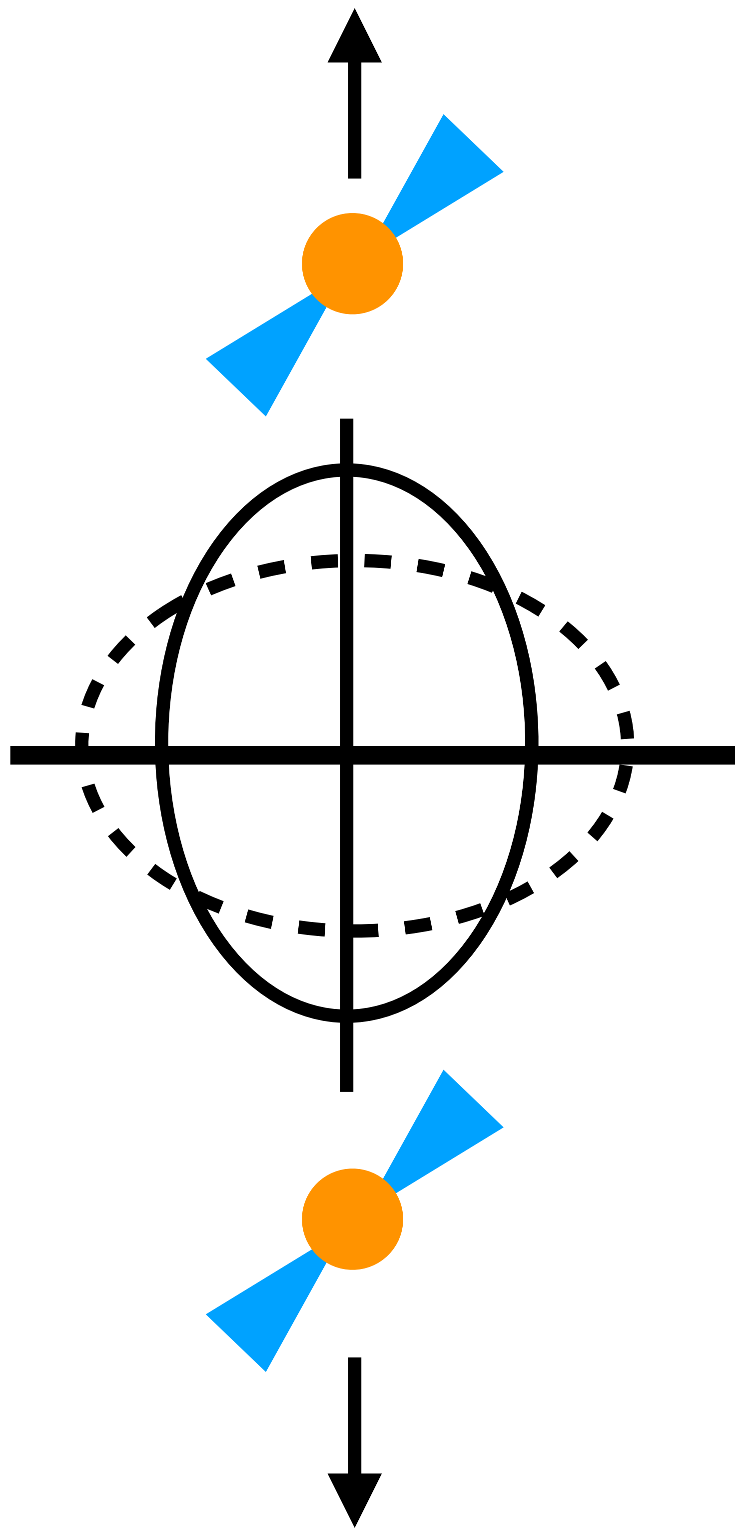
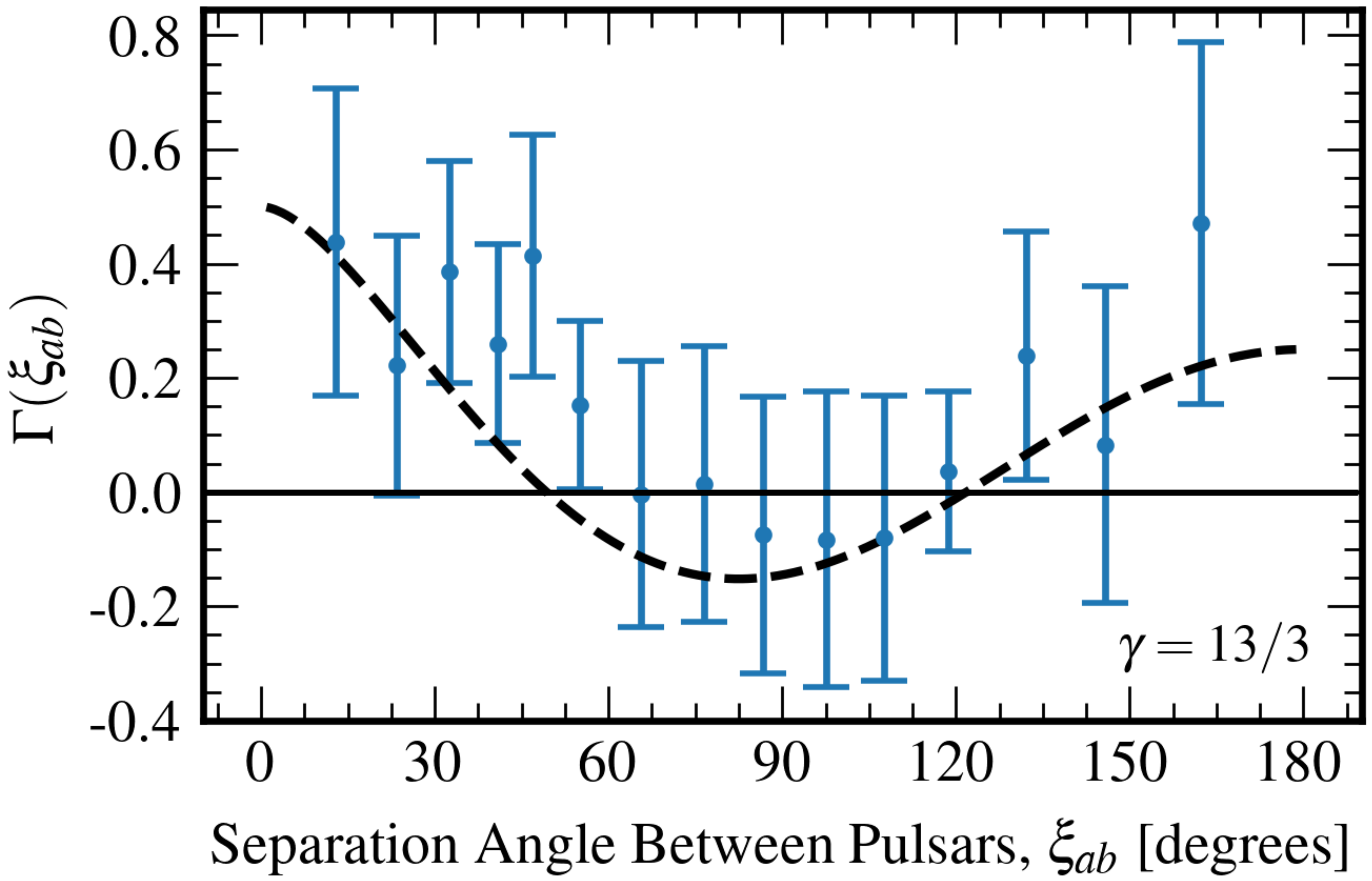




EVIDENCE FOR GWB

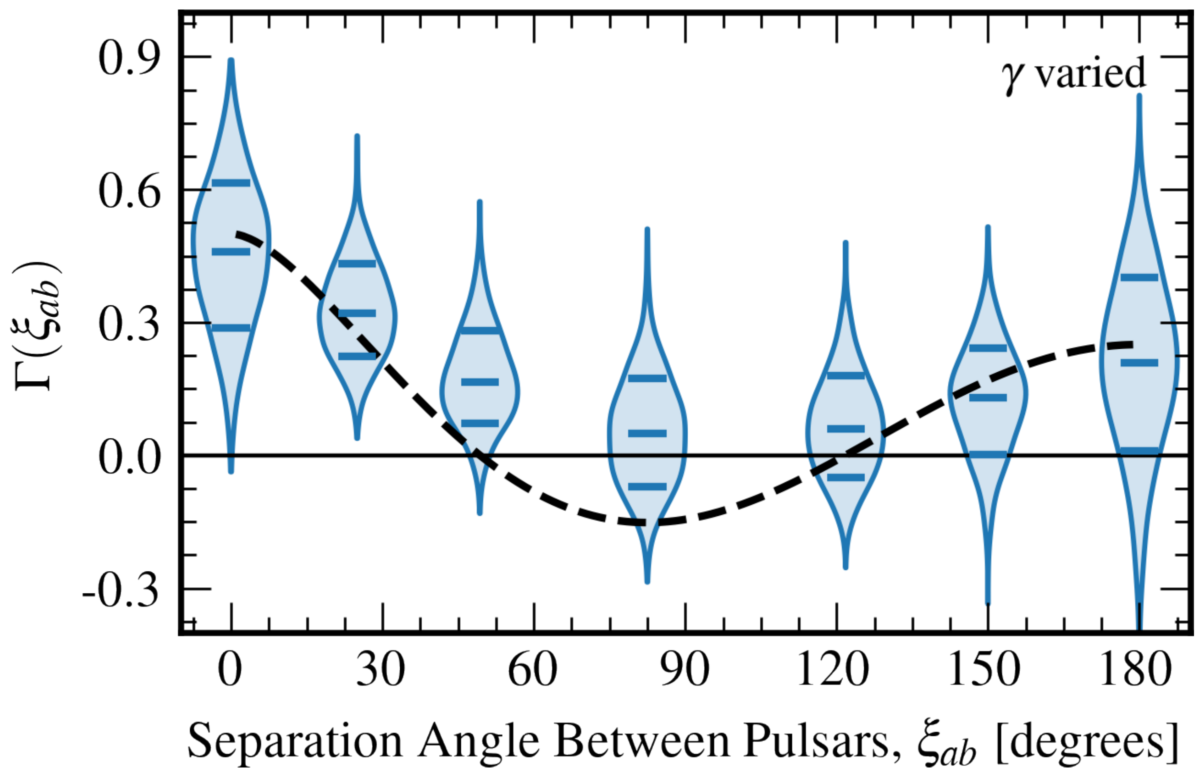
Agazie et al. [2306.16213]



EVIDENCE FOR GWB

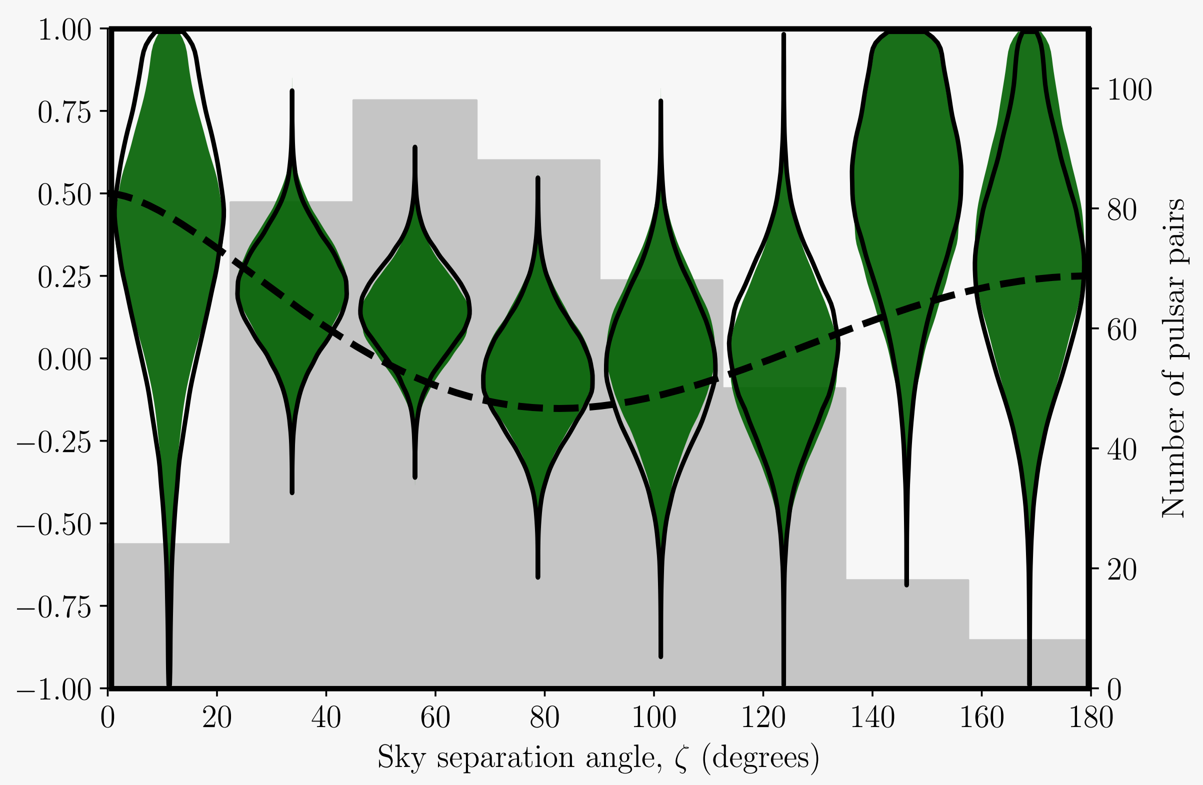
NANOGrav:
68 pulsars, 16yr of data
~3-4σ significance

Agazie et al. [2306.16213]



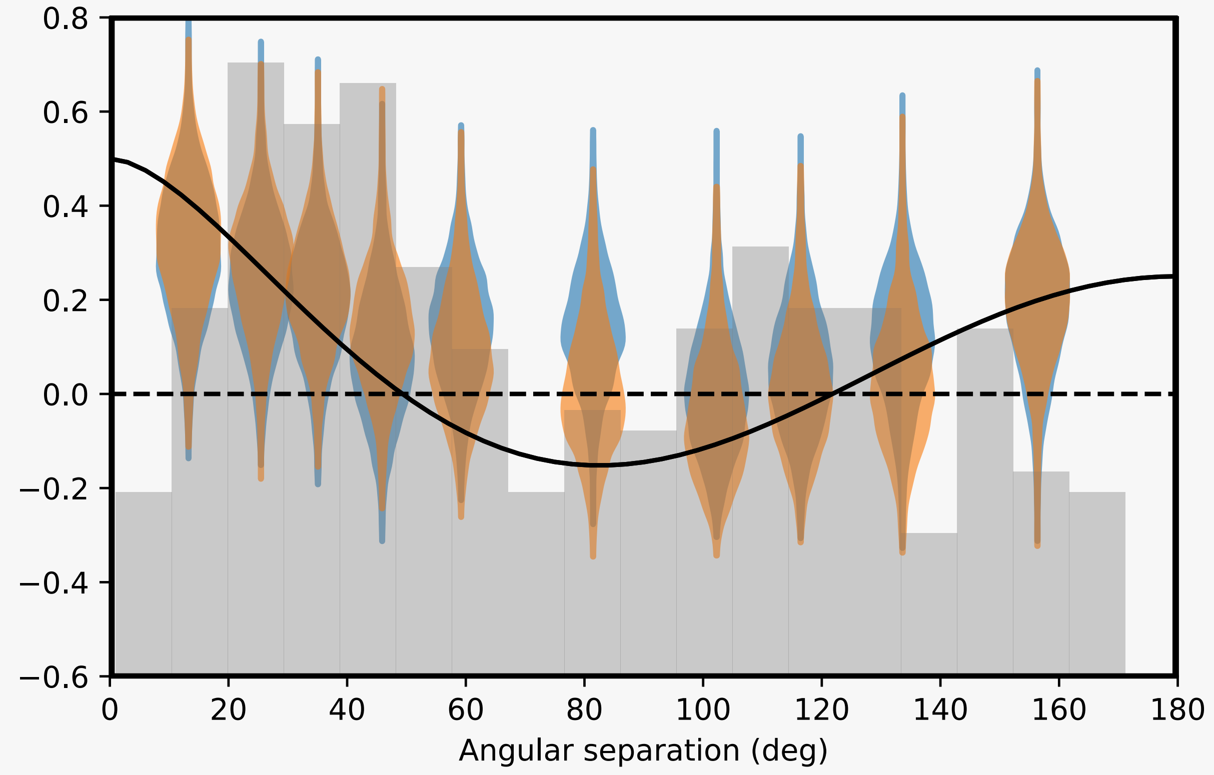
PPTA:
32 pulsars, 18yr of data
~2σ significance

Reardon et al. [2306.16215]



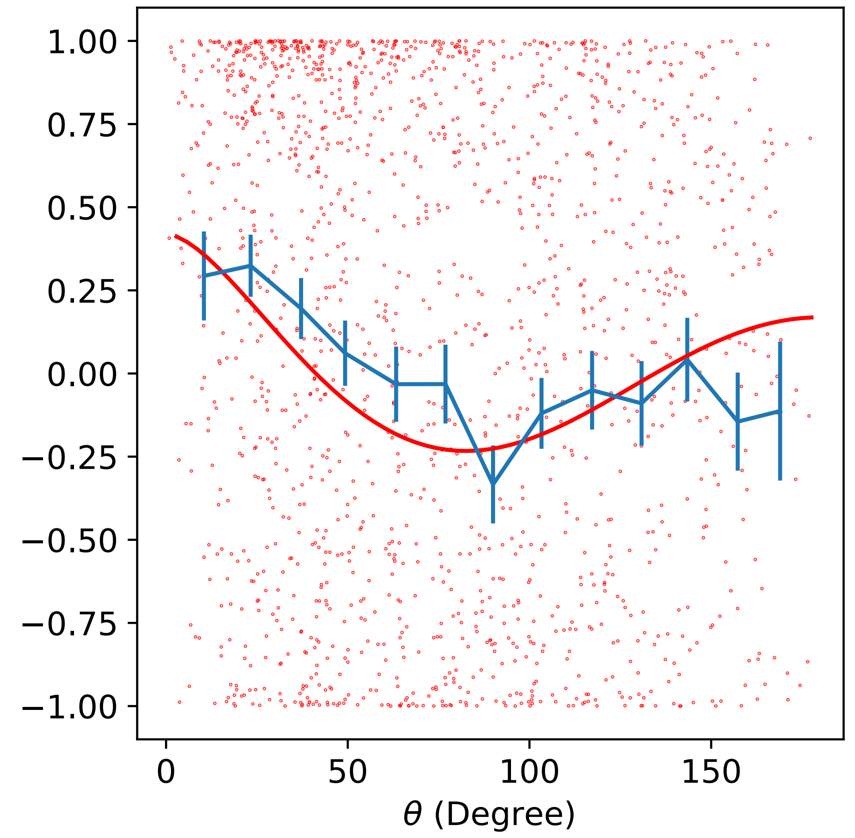
EPTA + InPTA:
25 pulsars, 24yr of data
~3σ significance

Antoniadis et al. [2306.16214]

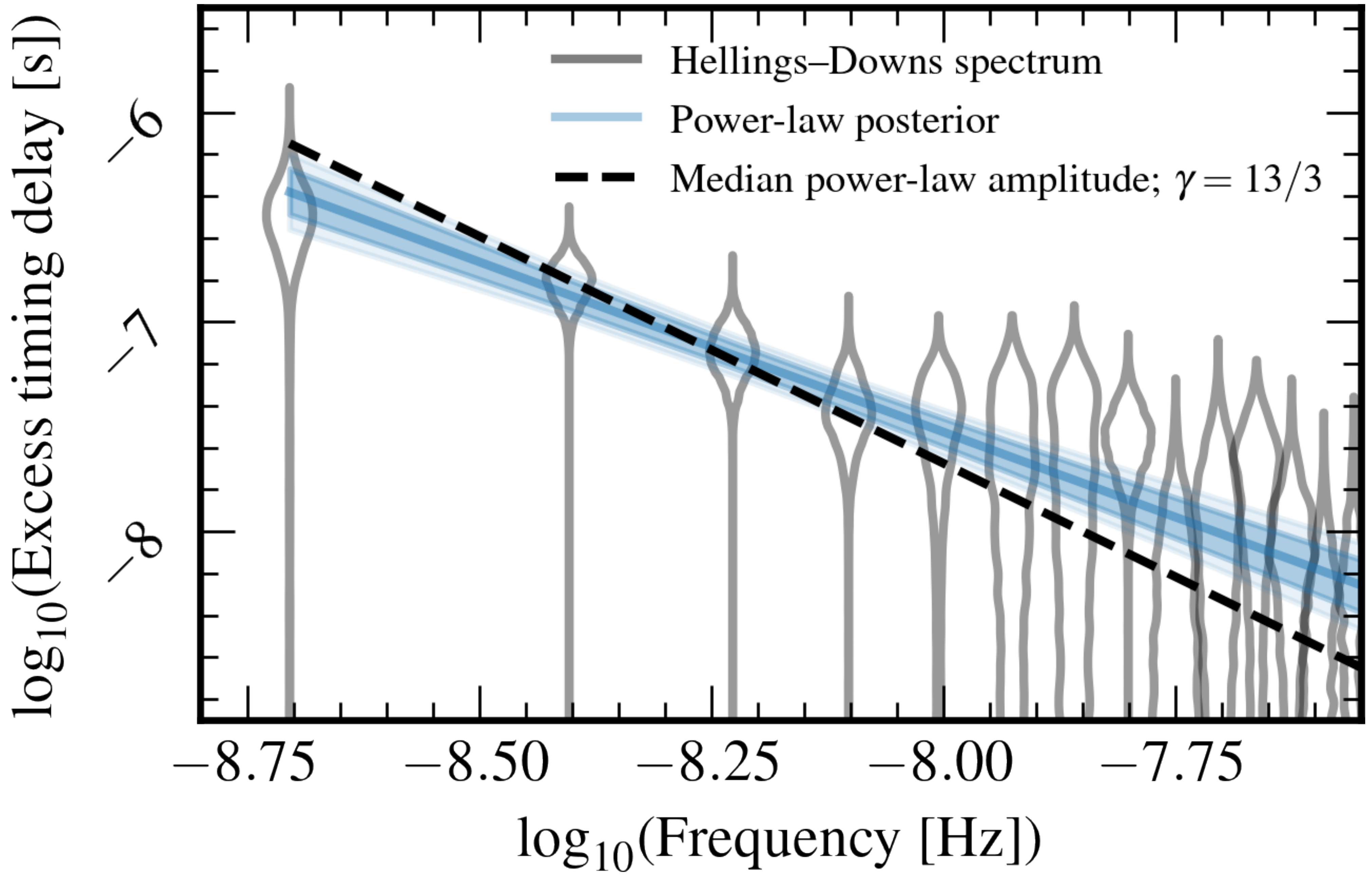


CPTA:
57 pulsars, 3yr of data
~4.6σ significance

Xu et al. [2306.16216]



SPECTRUM



Agazie et al. [2306.16213]

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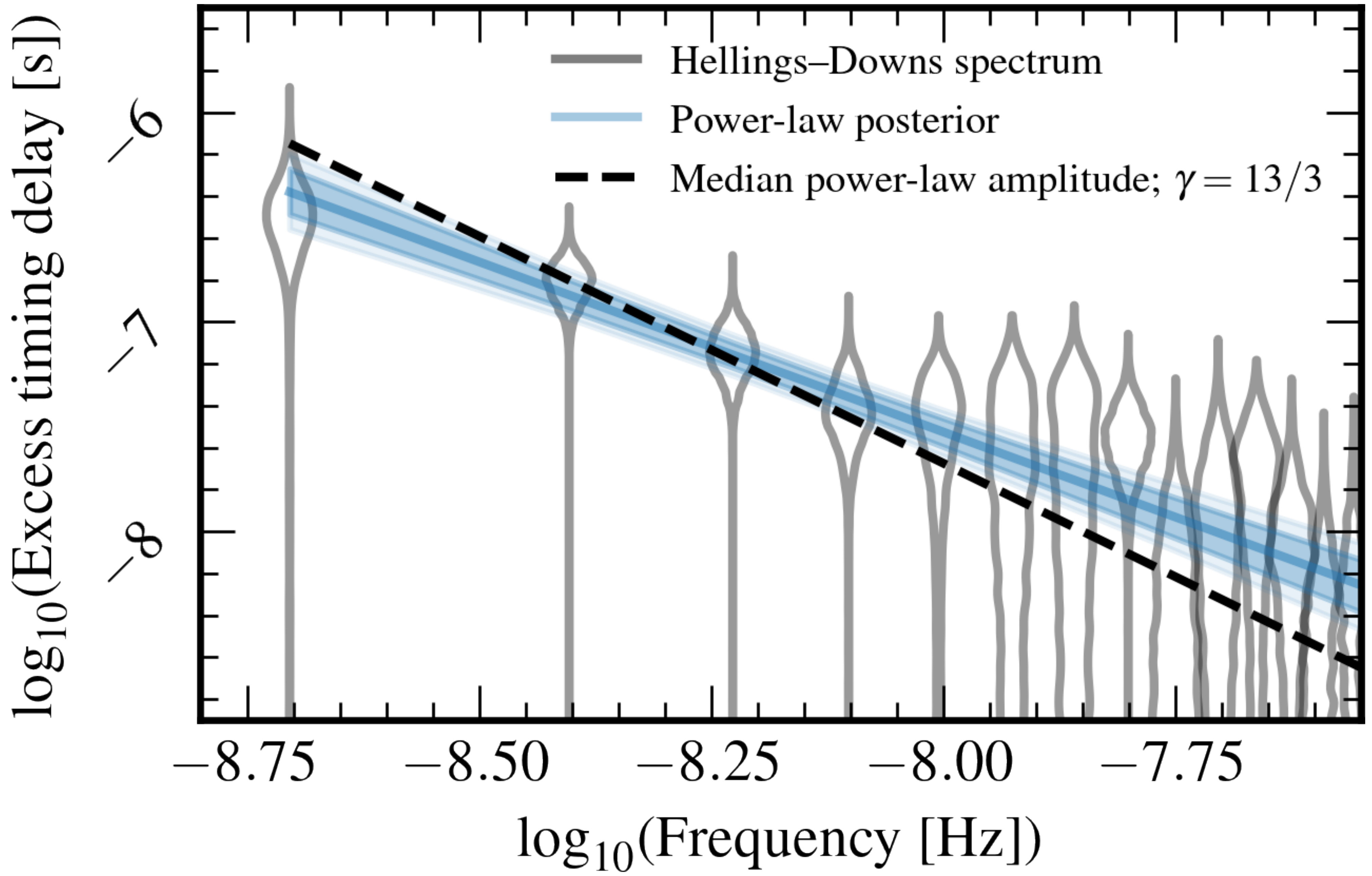

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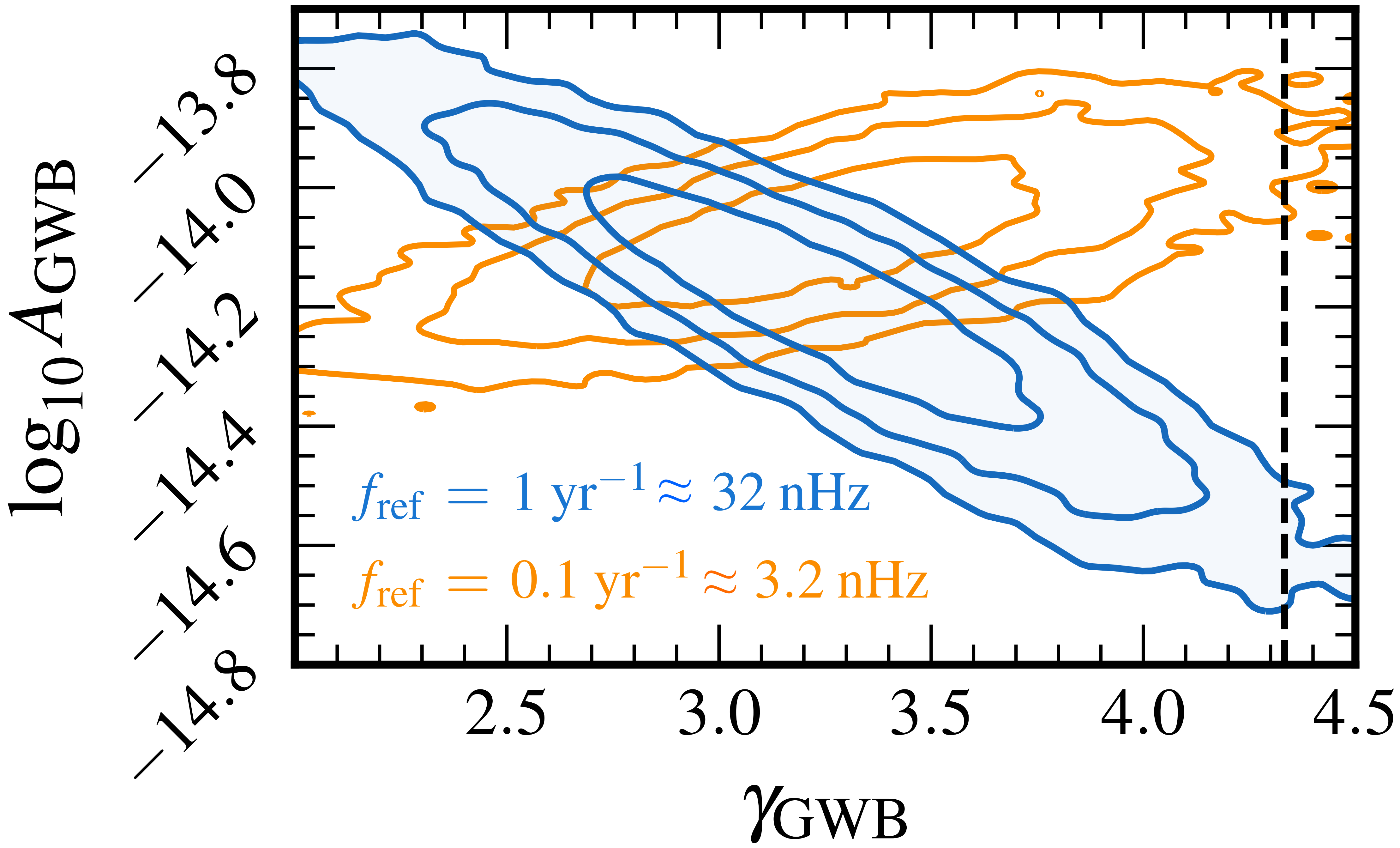
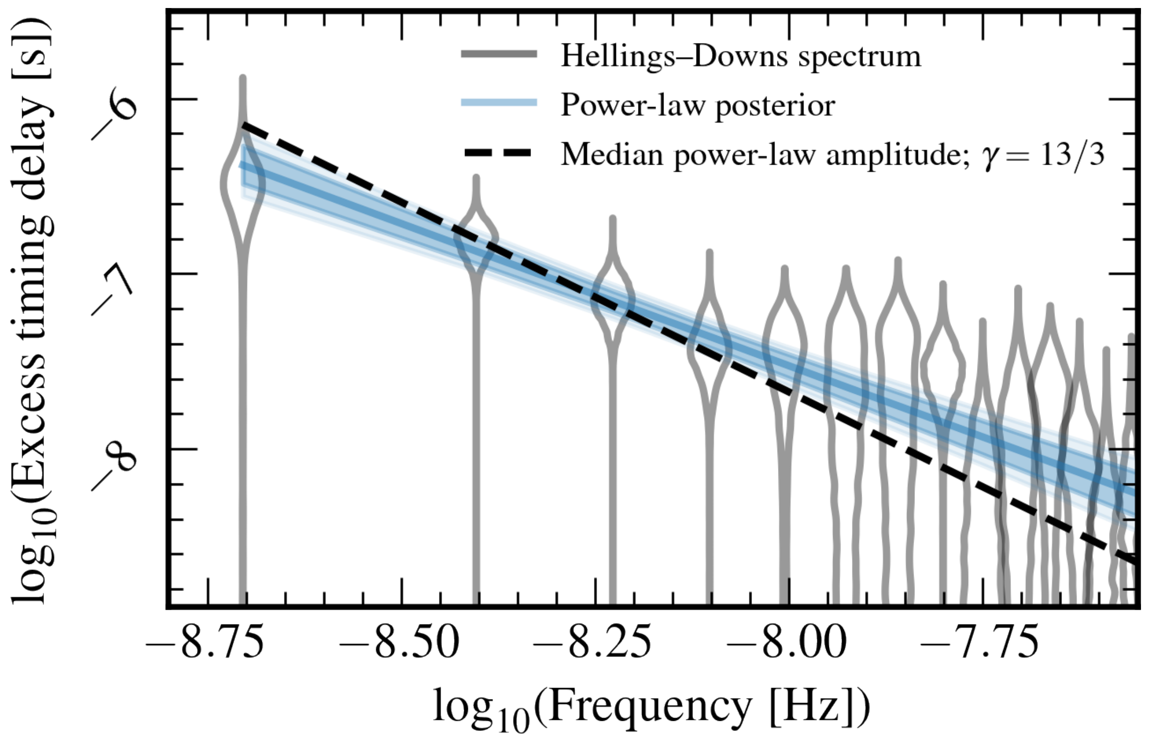
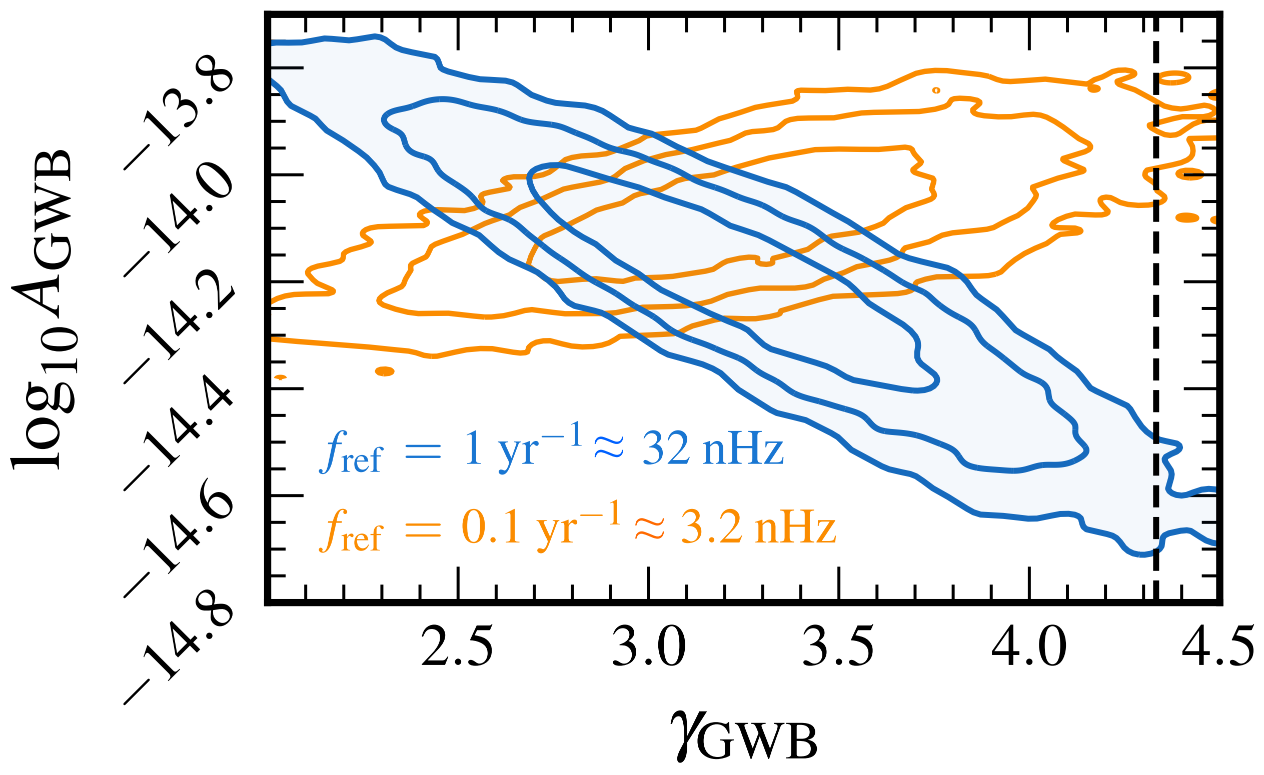


SPECTRUM

NANOGrav

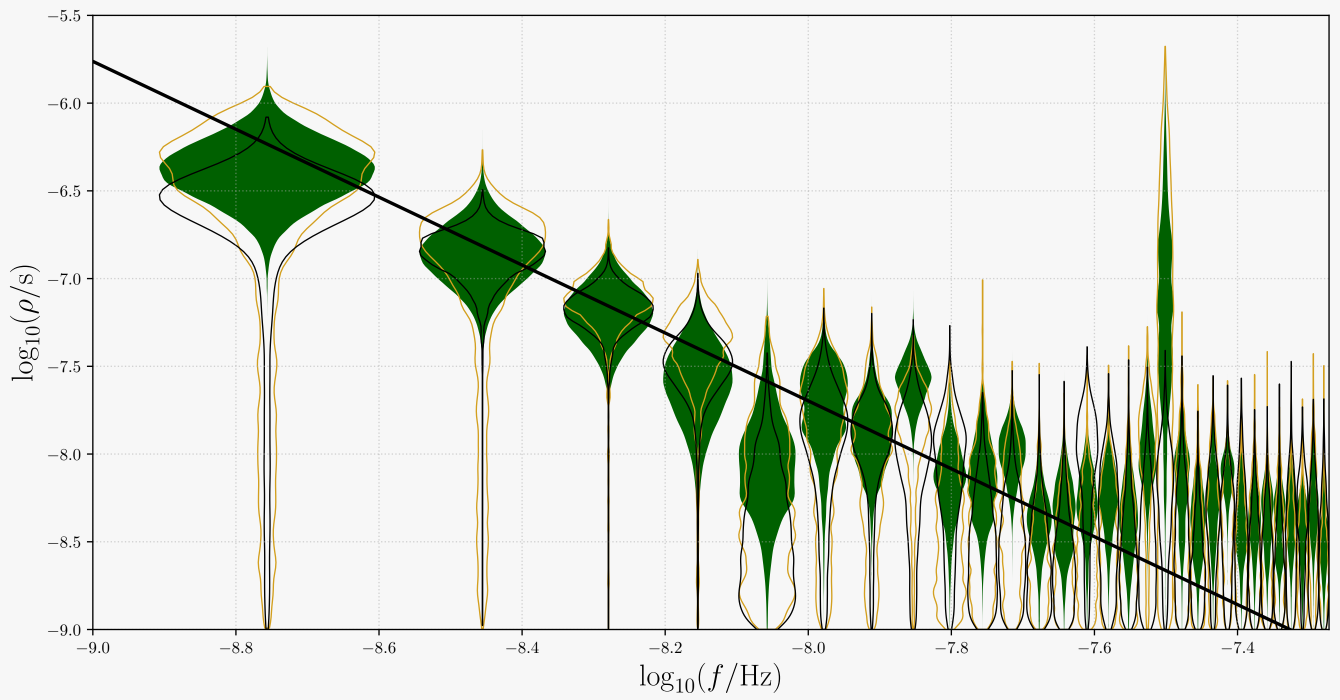
Agazie et al. [2306.16213]

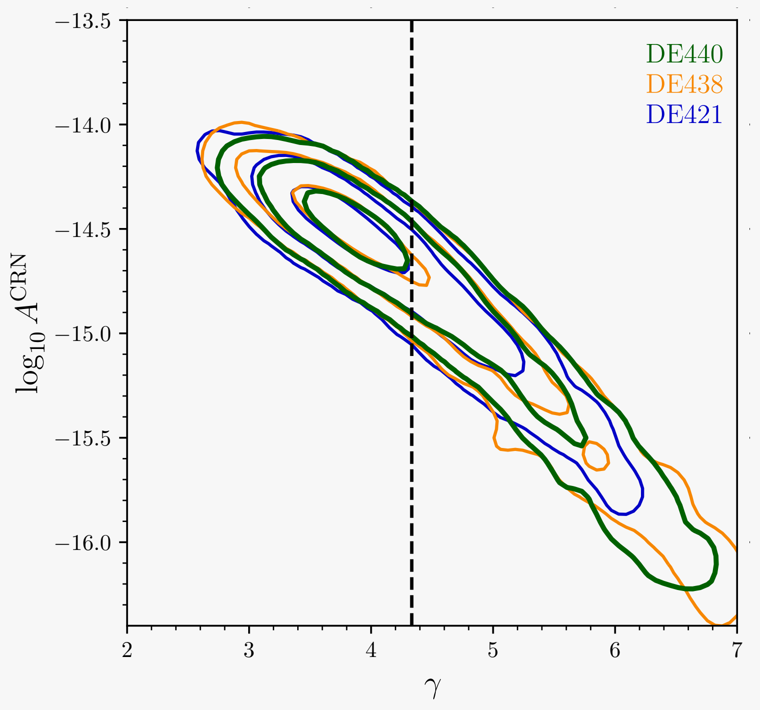




PPTA

Reardon et al. [2306.16215]





EPTA + InPTA

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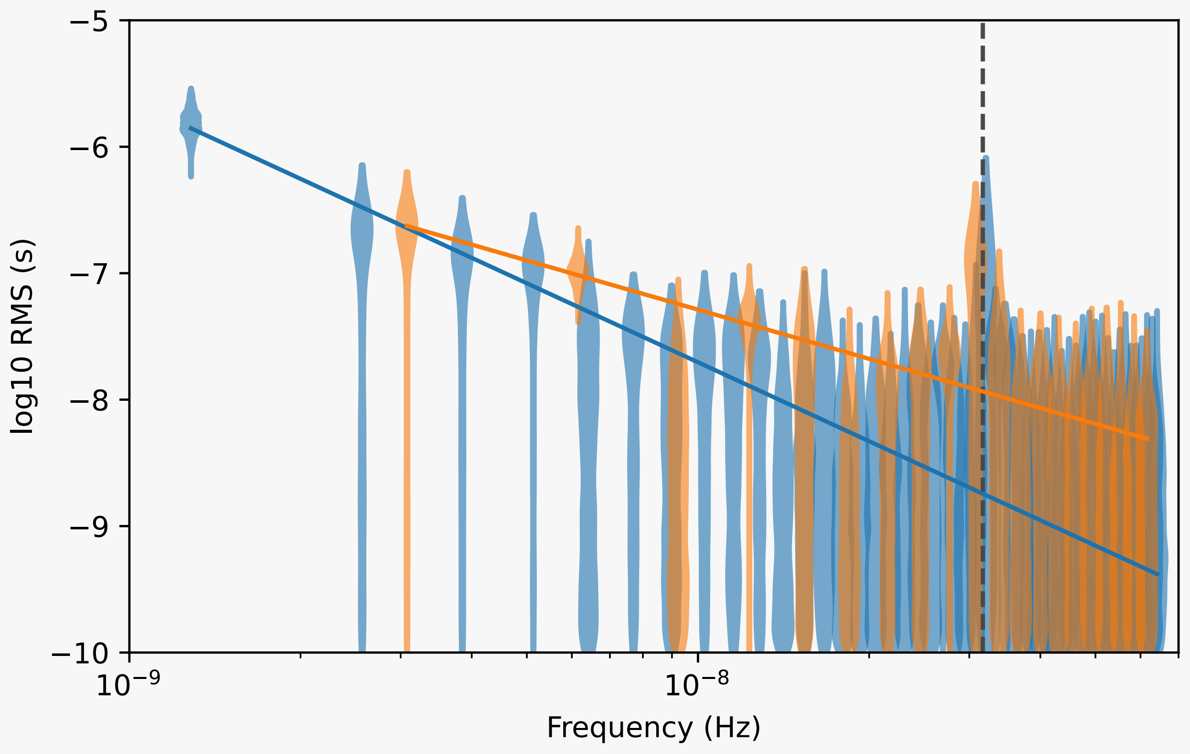
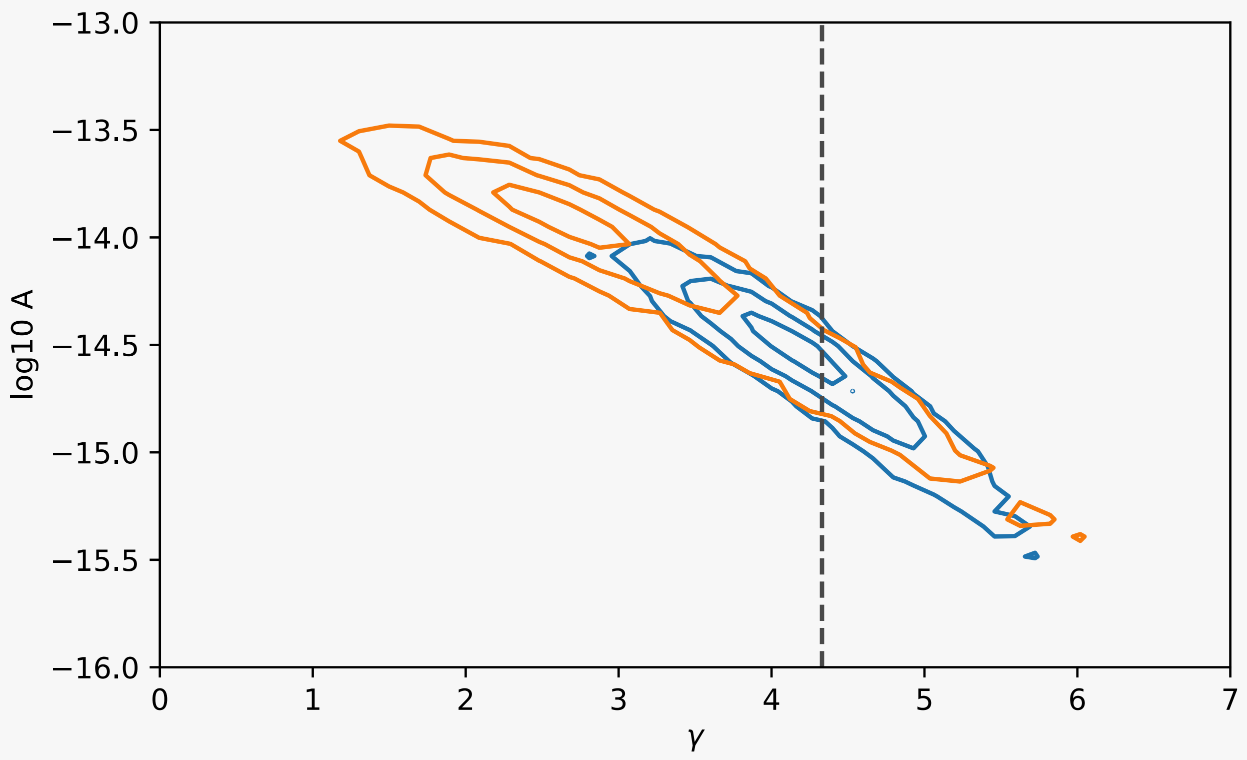
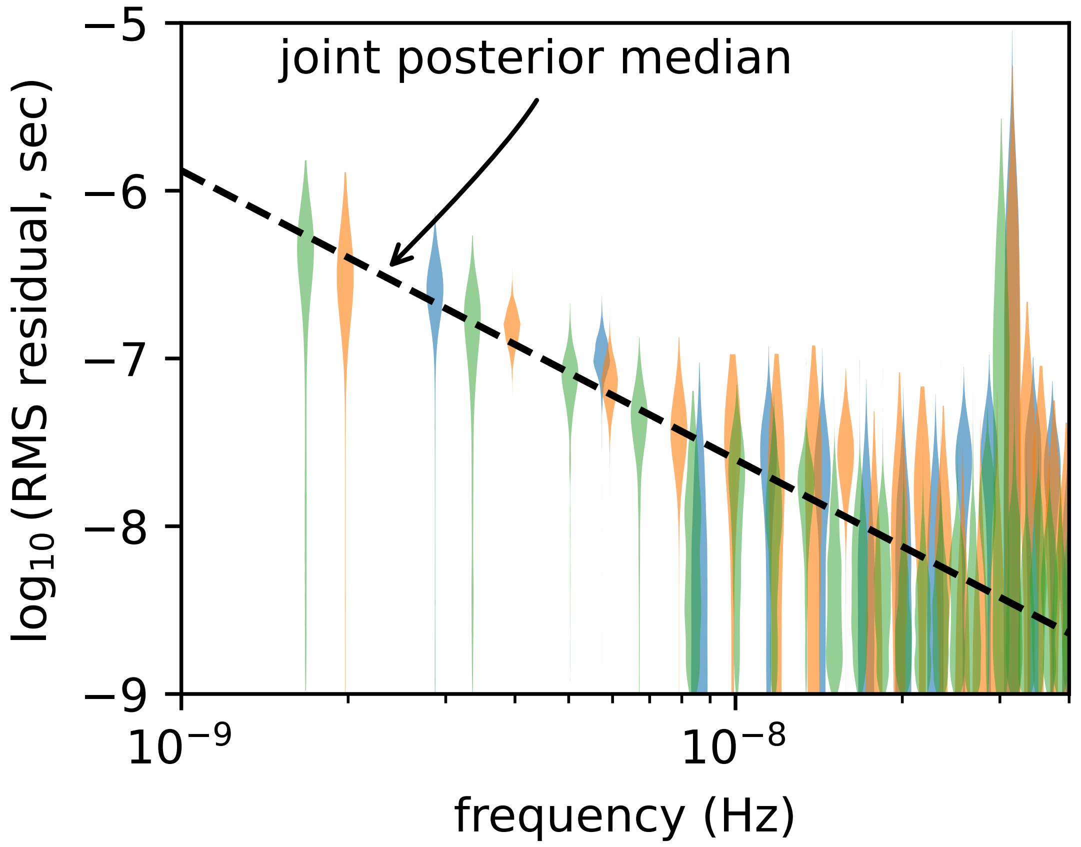
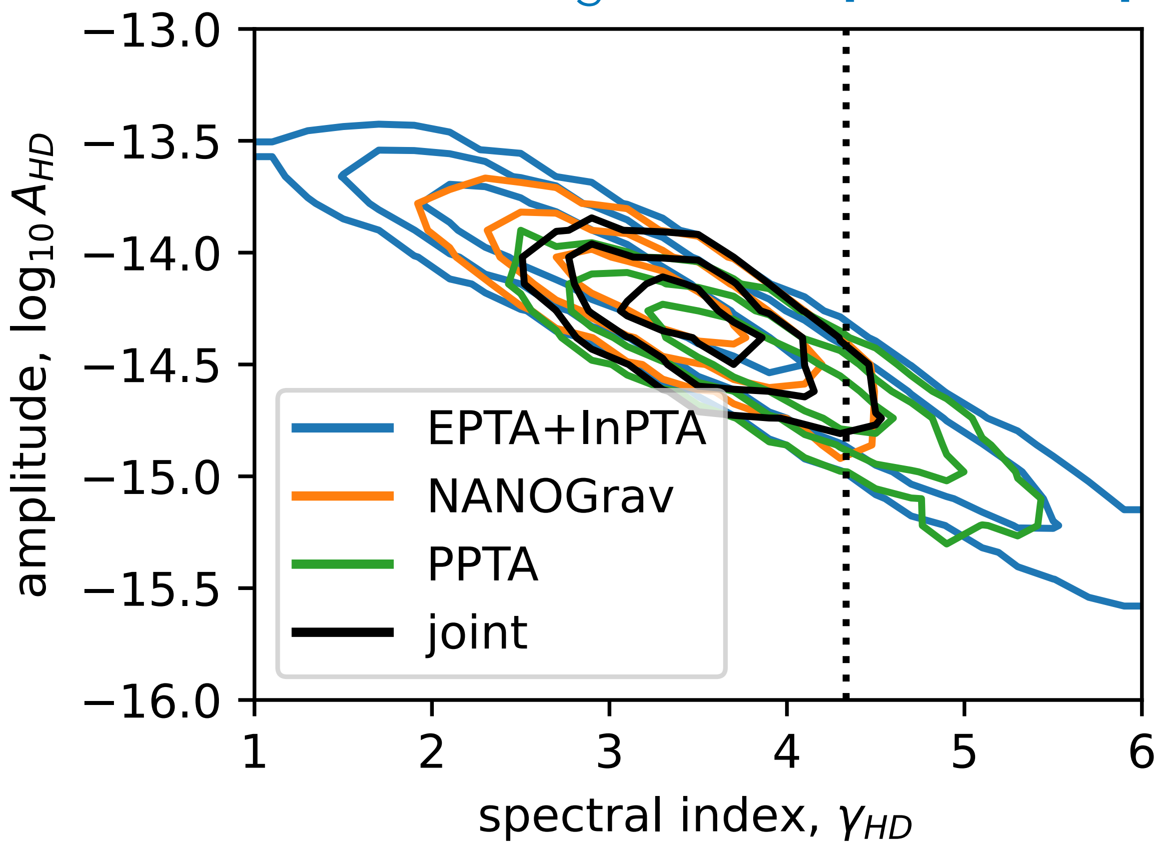




IPTA early data combination

Agazie et al. [2309.00693]





ANISOTROPIES

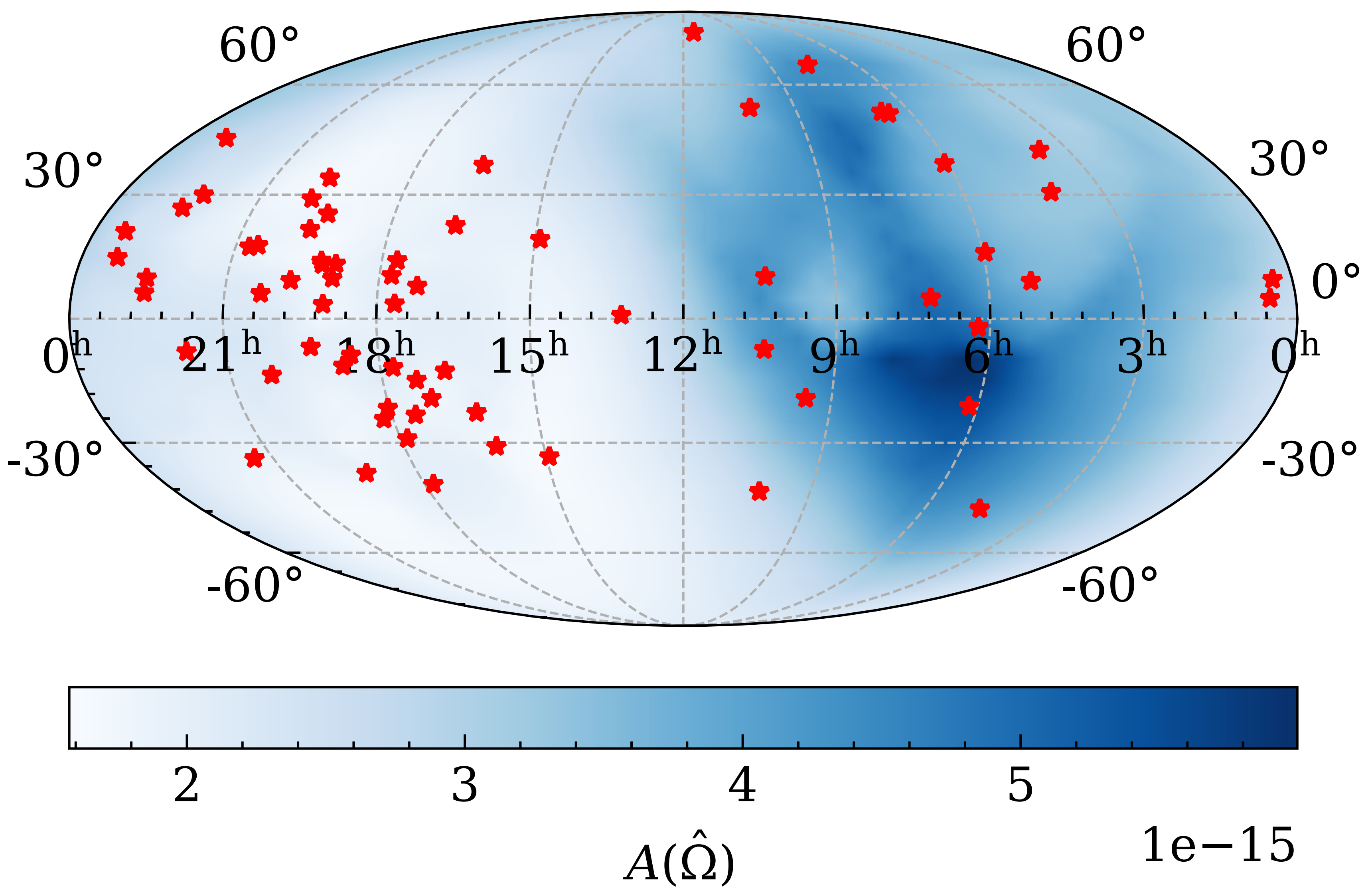
$$\Gamma_{ab} \propto \sum_k R_{ab,k} \cdot P_k$$

overlap reduction function

PTA response function

GWB power

for P_k = const, Γ_{ab} reduces to the HD overlap reduction function



Agazie et al. [2306.16221]

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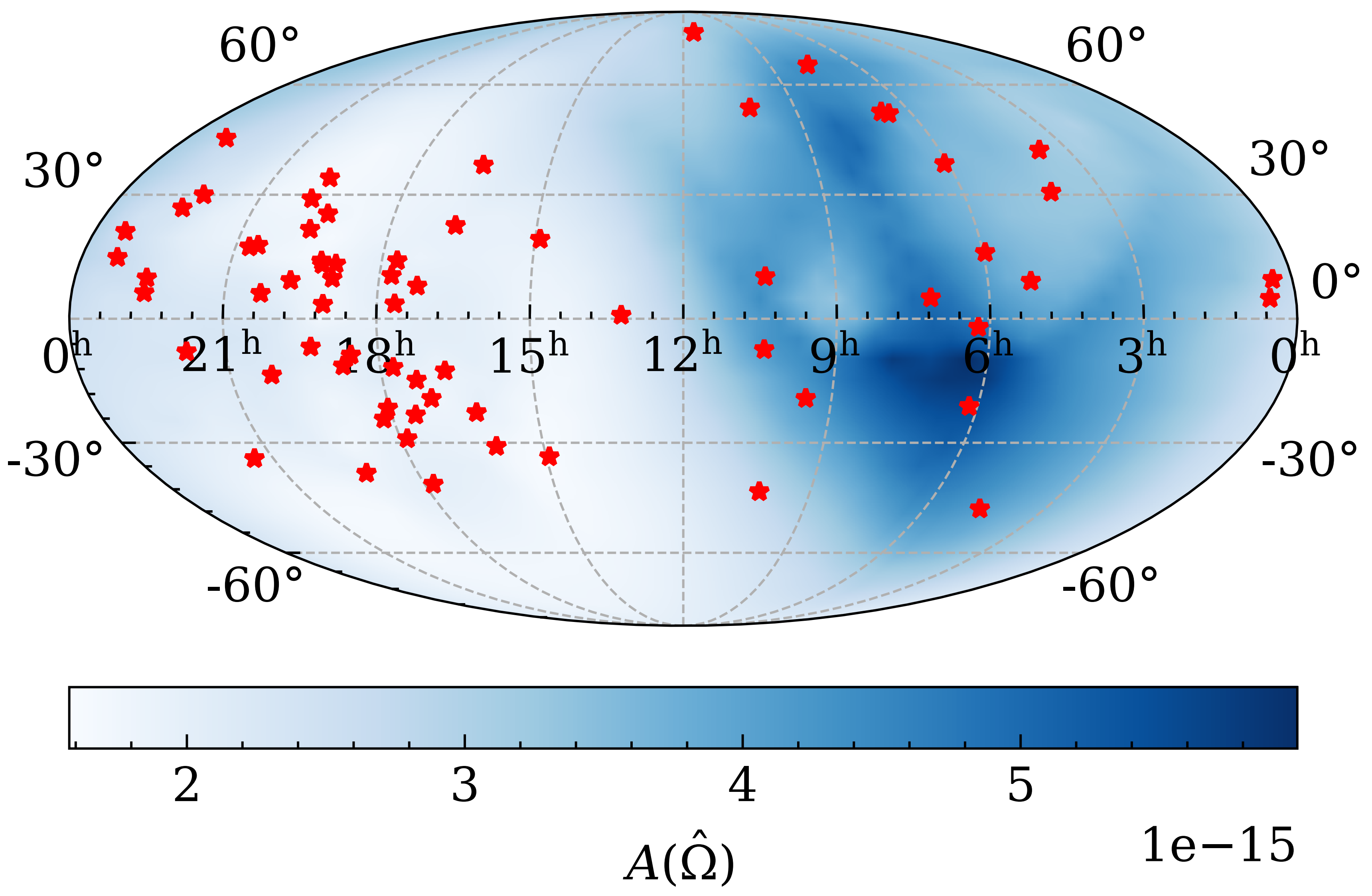

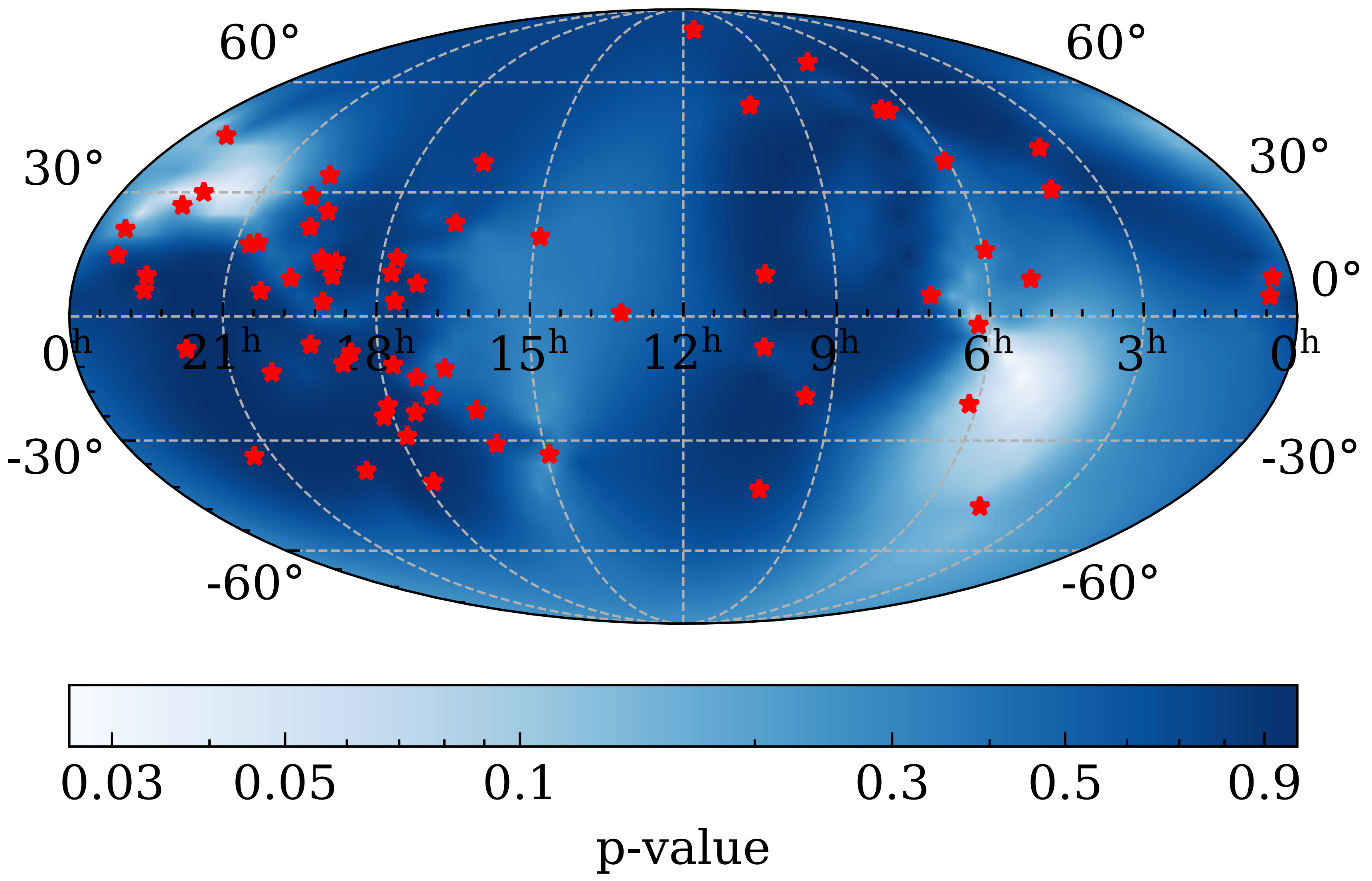

Agazie et al. [2306.16221]

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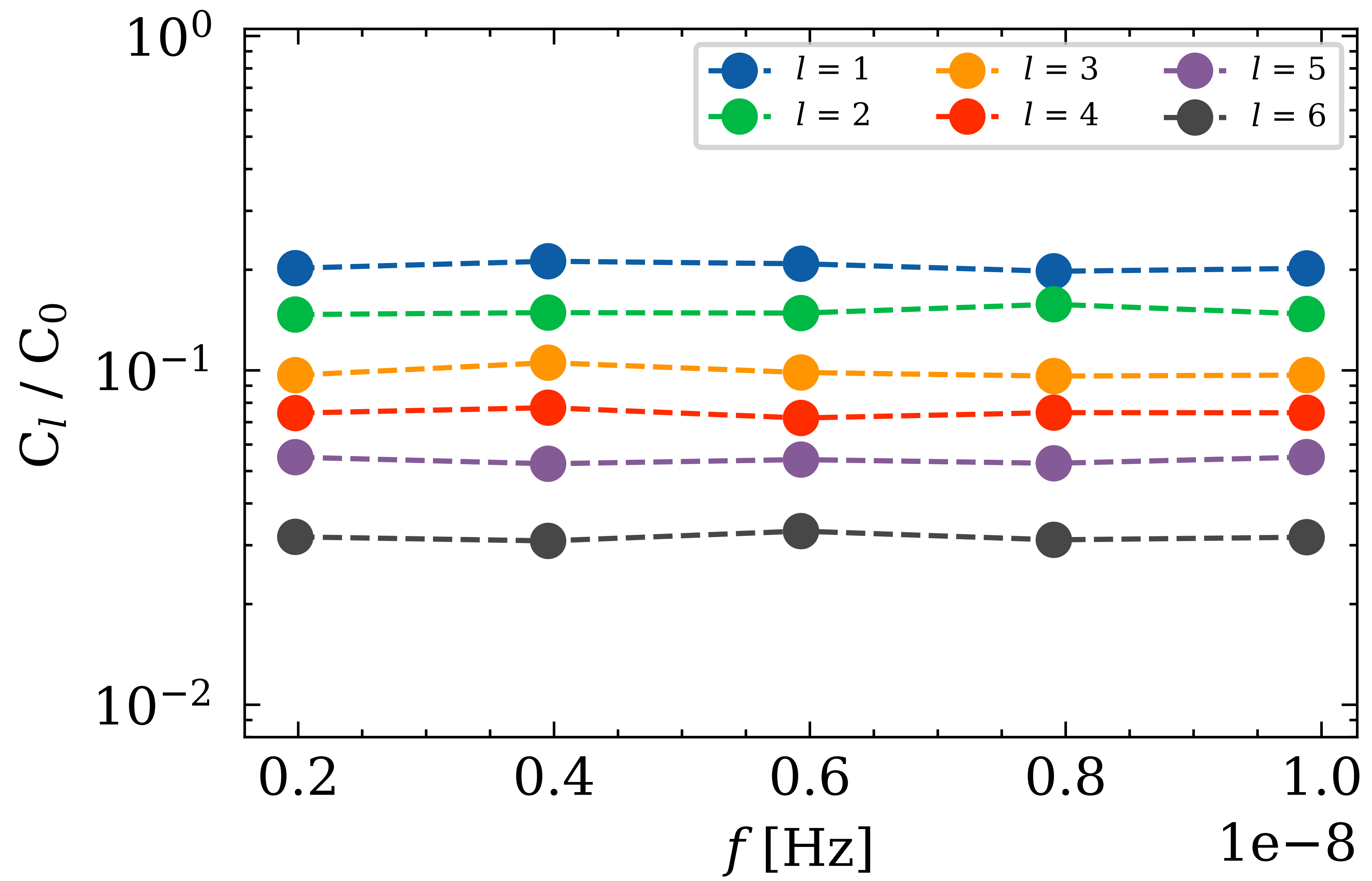
$$P_k = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} c_{lm} Y_{lm}(\hat{\Omega}_k) \qquad C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |c_{lm}|^2$$



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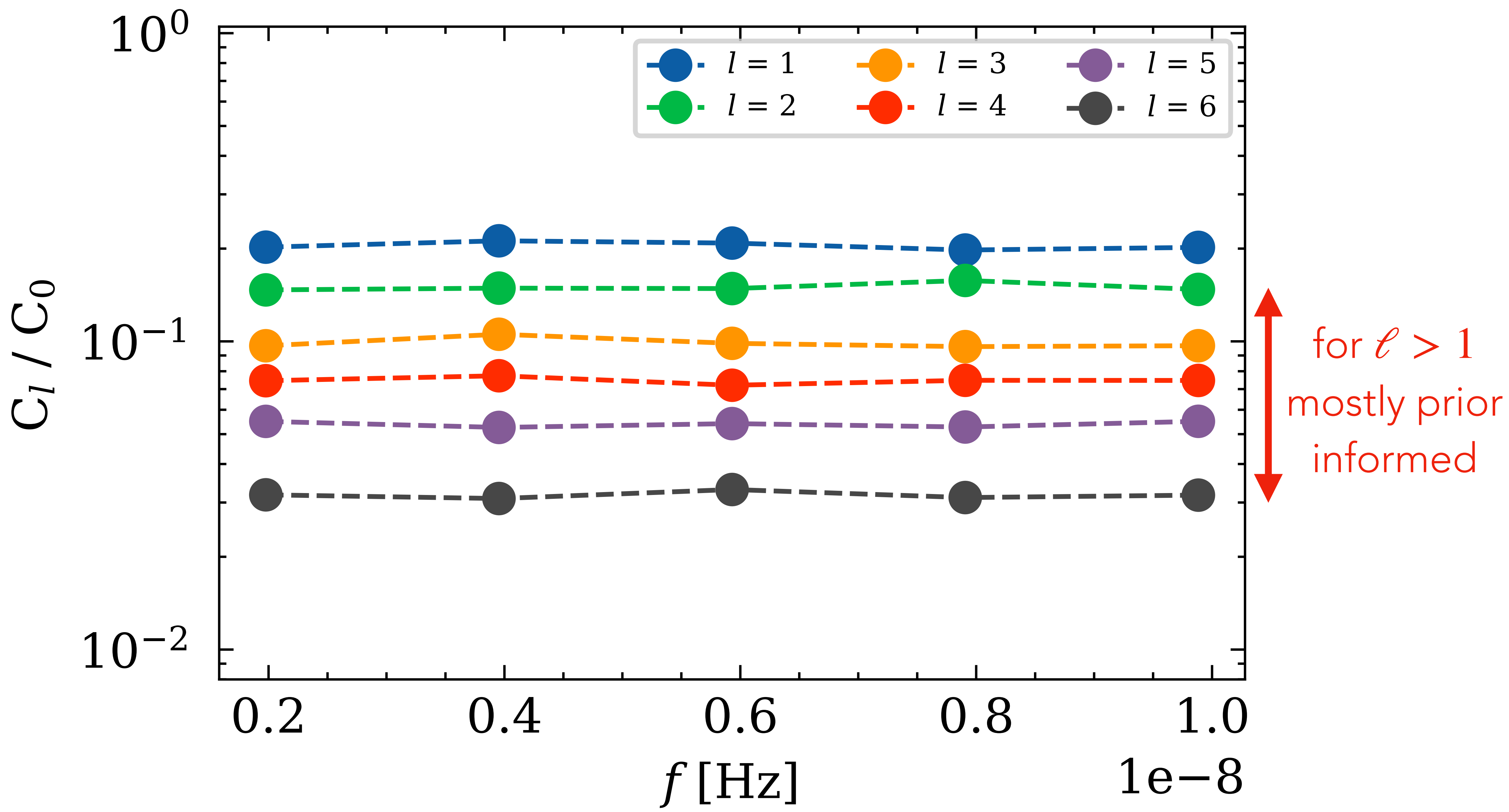


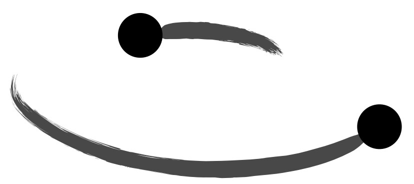
Agazie et al. [2306.16221]

what is the source?

SUPERMASSIVE BH

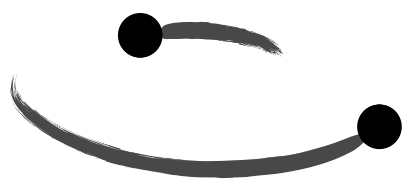
most massive galaxies host supermassive black holes at their center

CONTENDER #1



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

Phinney 2001, Wyithe & Loeb 2003

CONTENDER #1 

GW signal from individual SMBHB

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

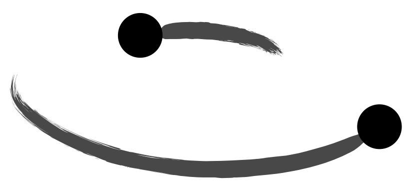
Phinney 2001, Wyithe & Loeb 2003

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

CONTENDER #1



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Phinney 2001, Wyithe & Loeb 2003

number density of SMBHB binaries

averaged strain for a circular SMBHB

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

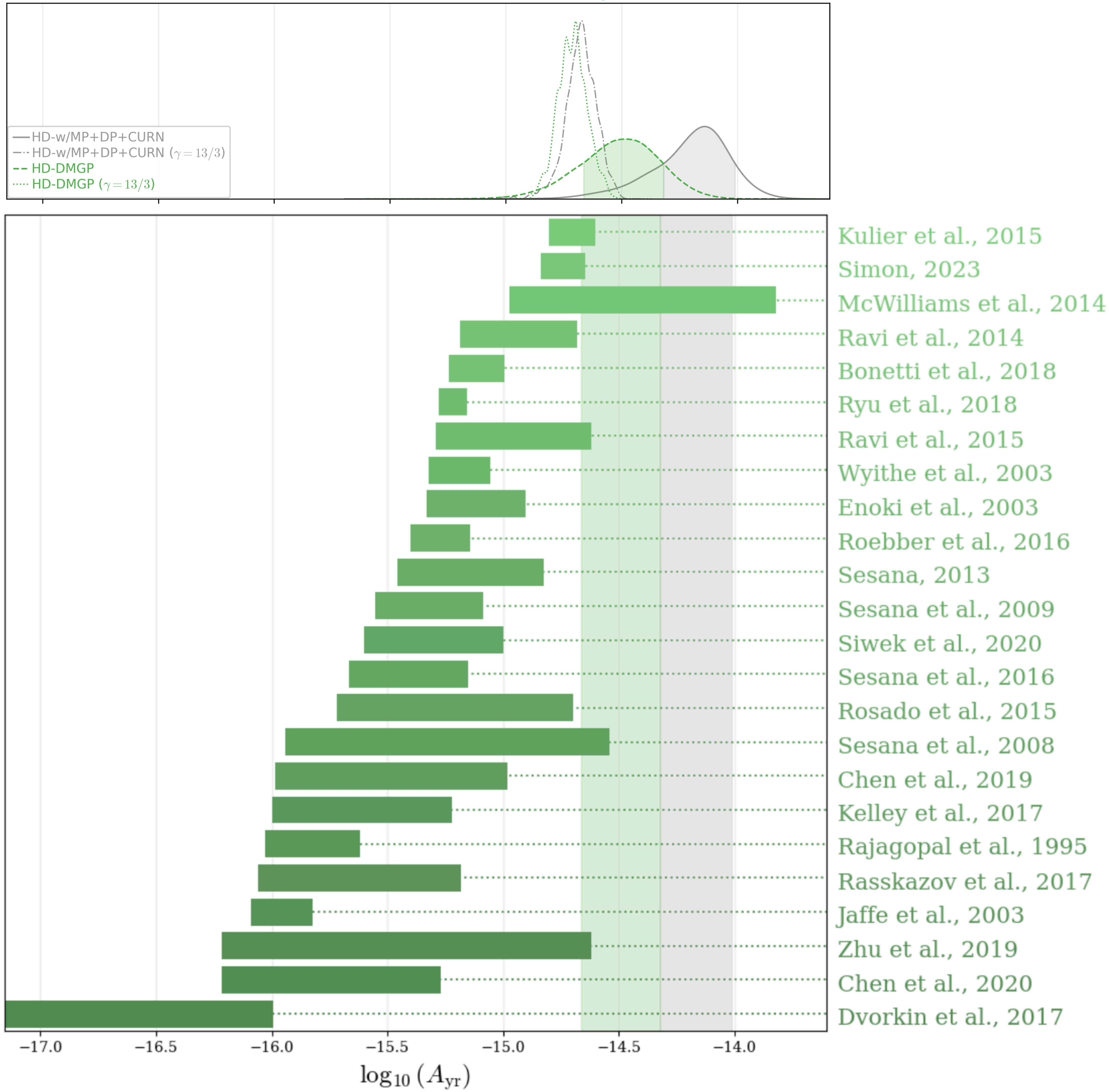
Finn & Thorne 2000

the SMBHB density depends on

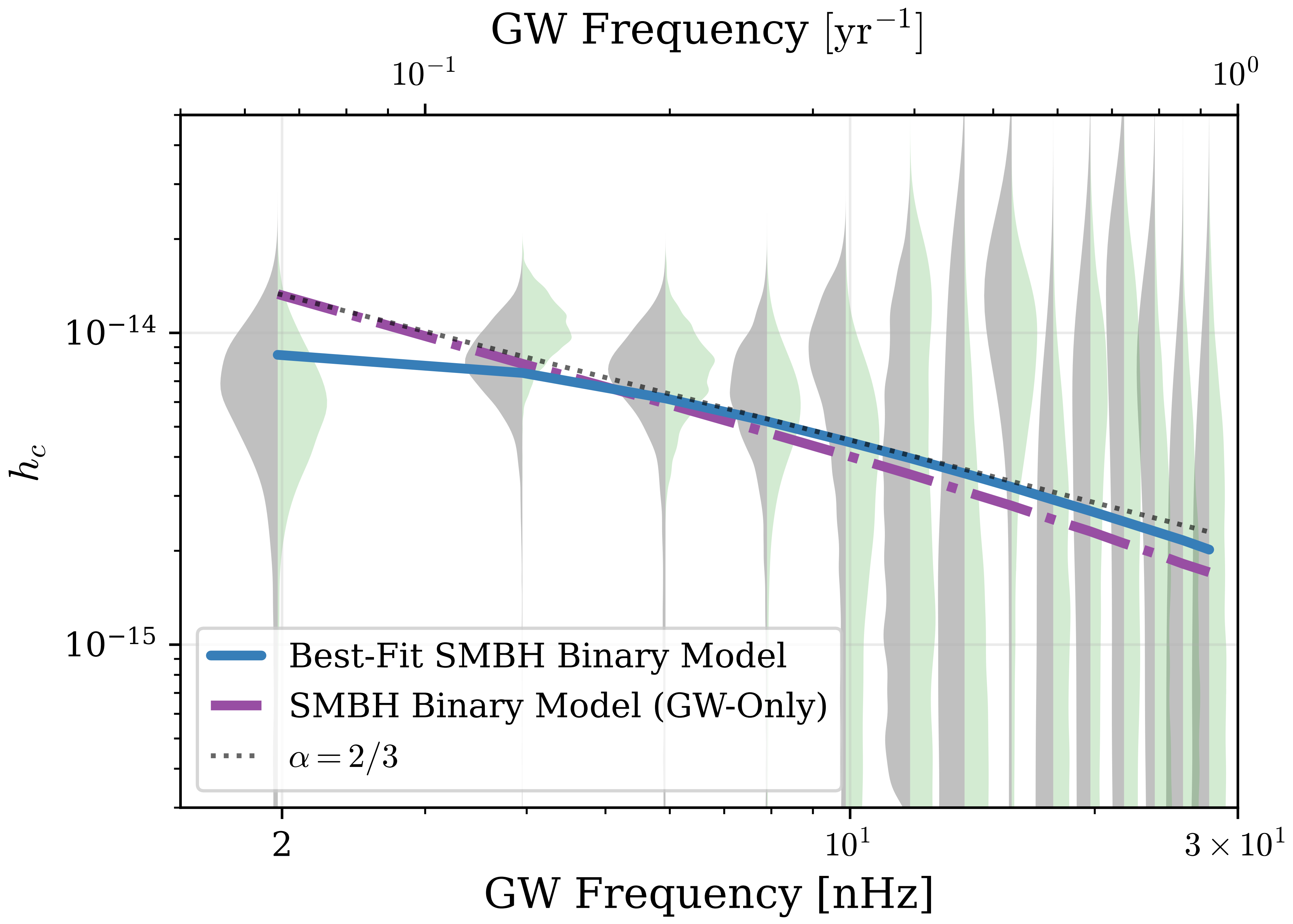
1. galaxies merger rate
2. SMBHB - galaxy mass relation
3. SMBHB binary evolution

EXPECTATIONS

Agazie et al. [2306.16220]

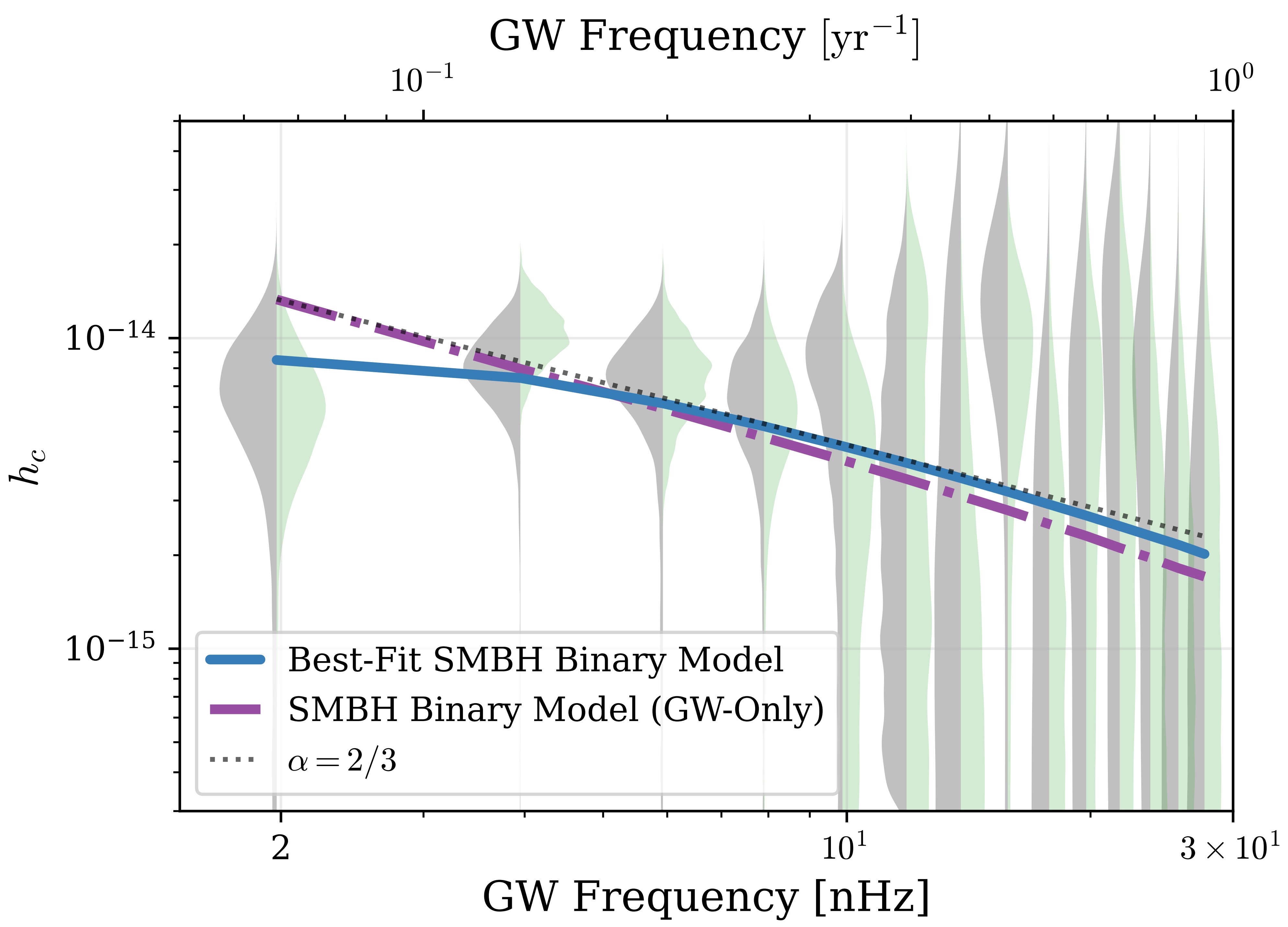


ADJUSTING EXPECTATIONS

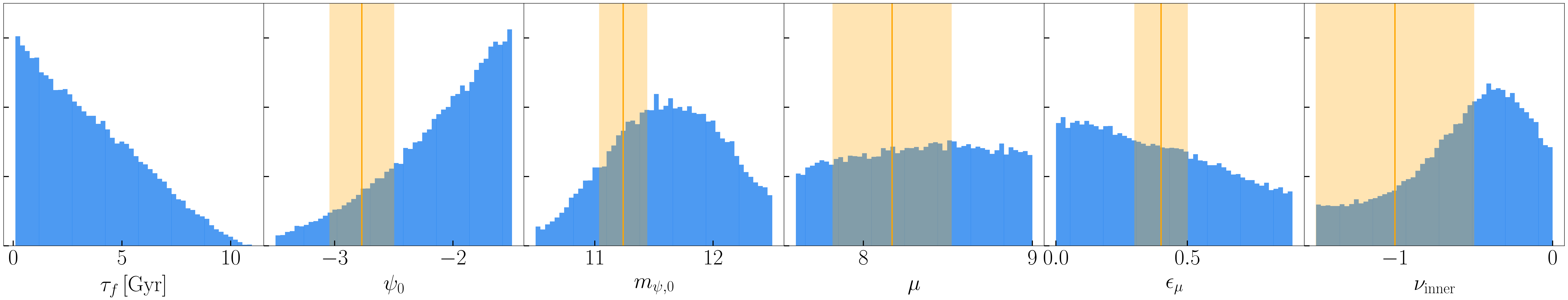


Agazie et al. [2306.16220]

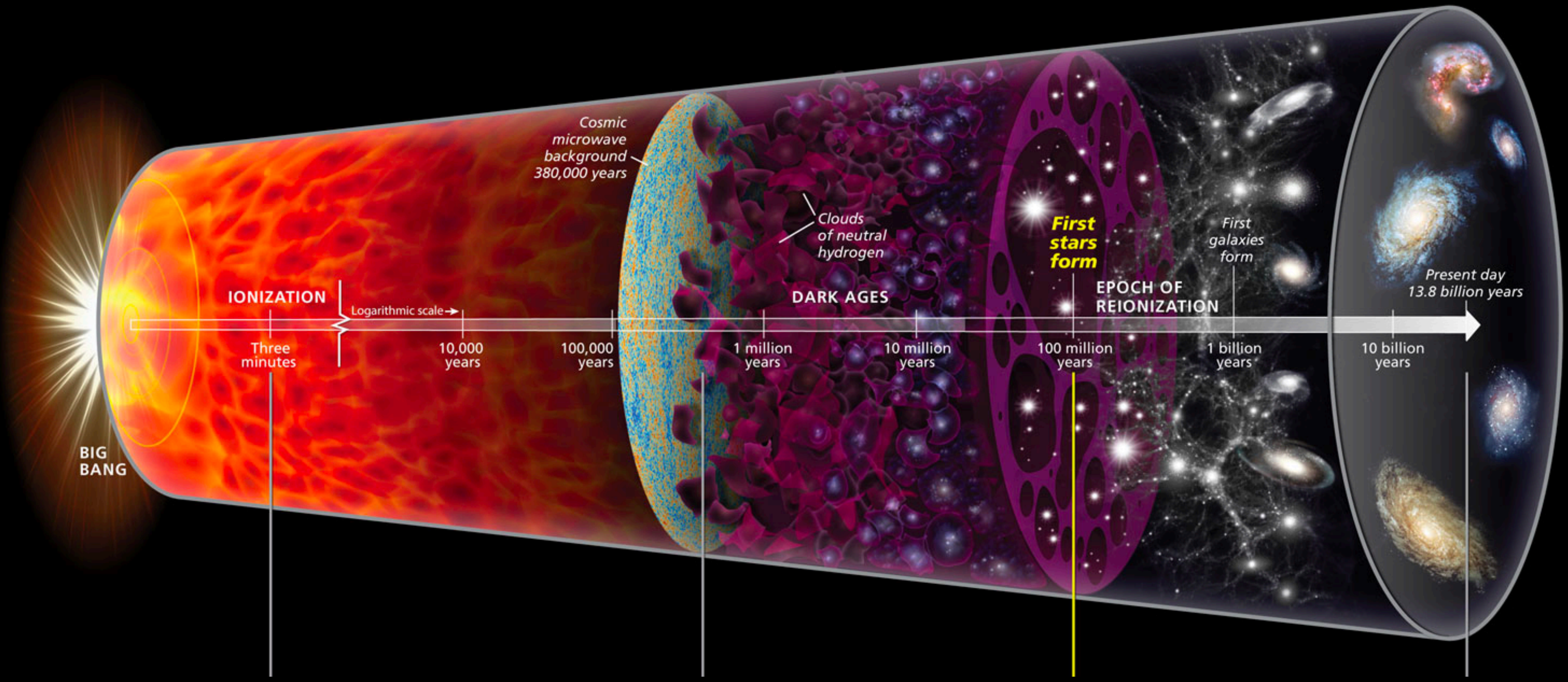
ADJUSTING EXPECTATIONS



Agazie et al. [2306.16220]



PRIMORDIAL SOURCES

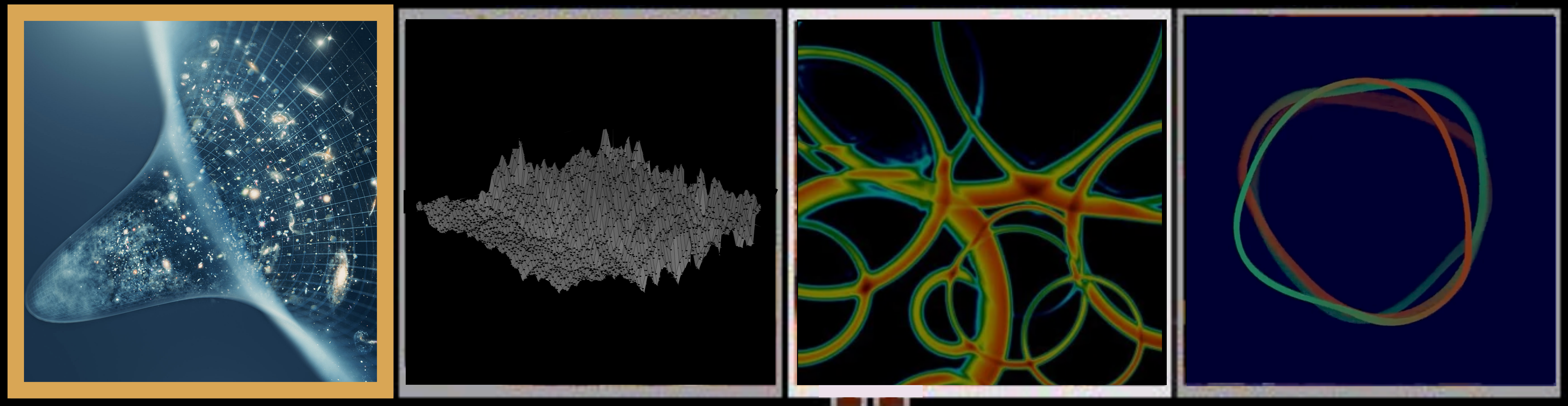


inflation
baryogengesis
DM formation?
???

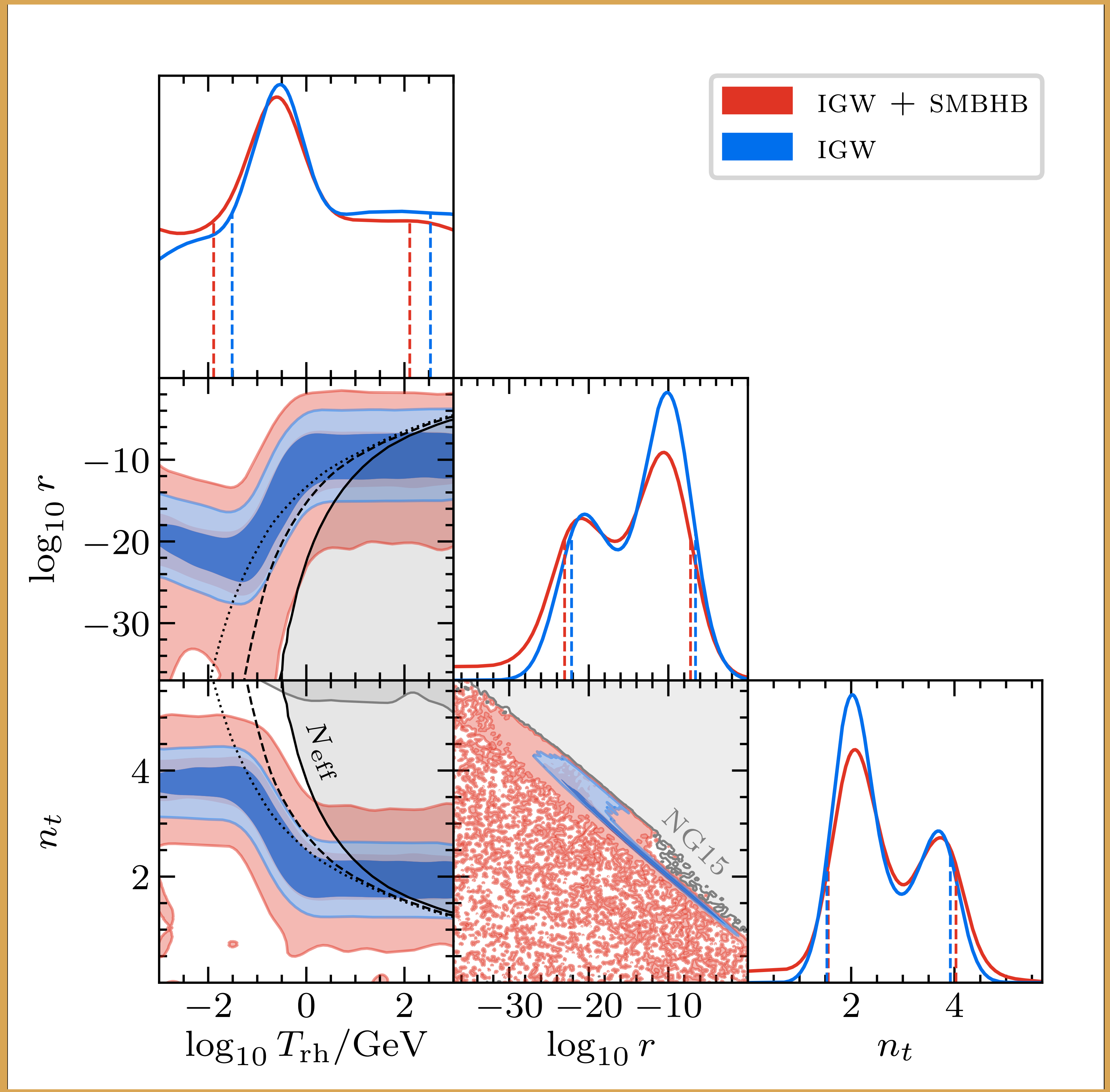
light starts to free stream

SELECT PLAYER

INFLATION SIGW PT STRINGS



Afzal et al. [2306.16219]

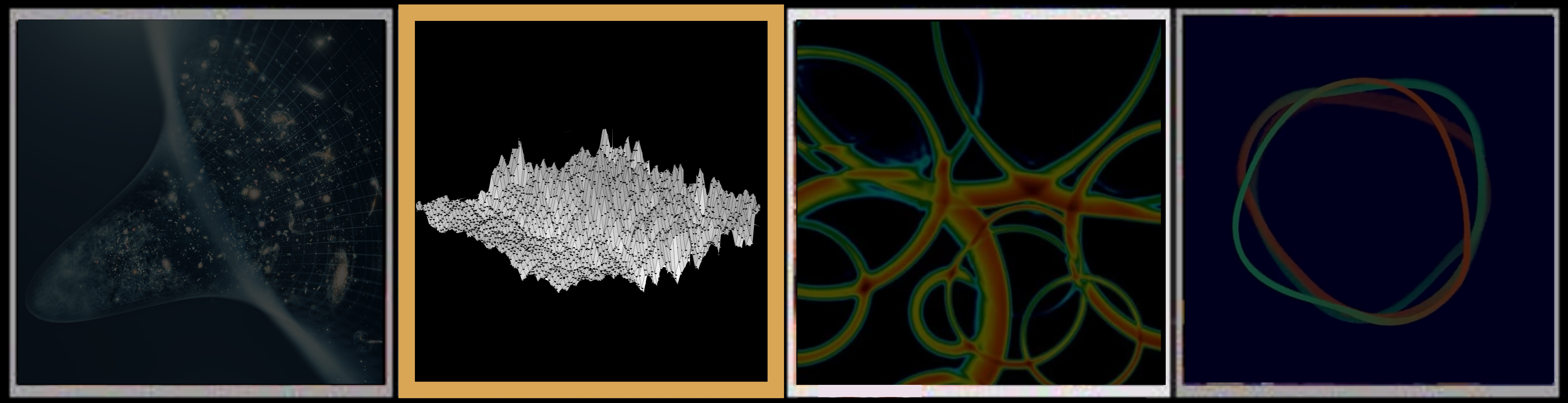


STRONG (RED) SPECTRAL TILT NEEDED

REHEATING TEMP. BELOW 100 GEV AVOIDS NEFF CONST.

SELECT PLAYER

INFLATION SIGW PT STRINGS



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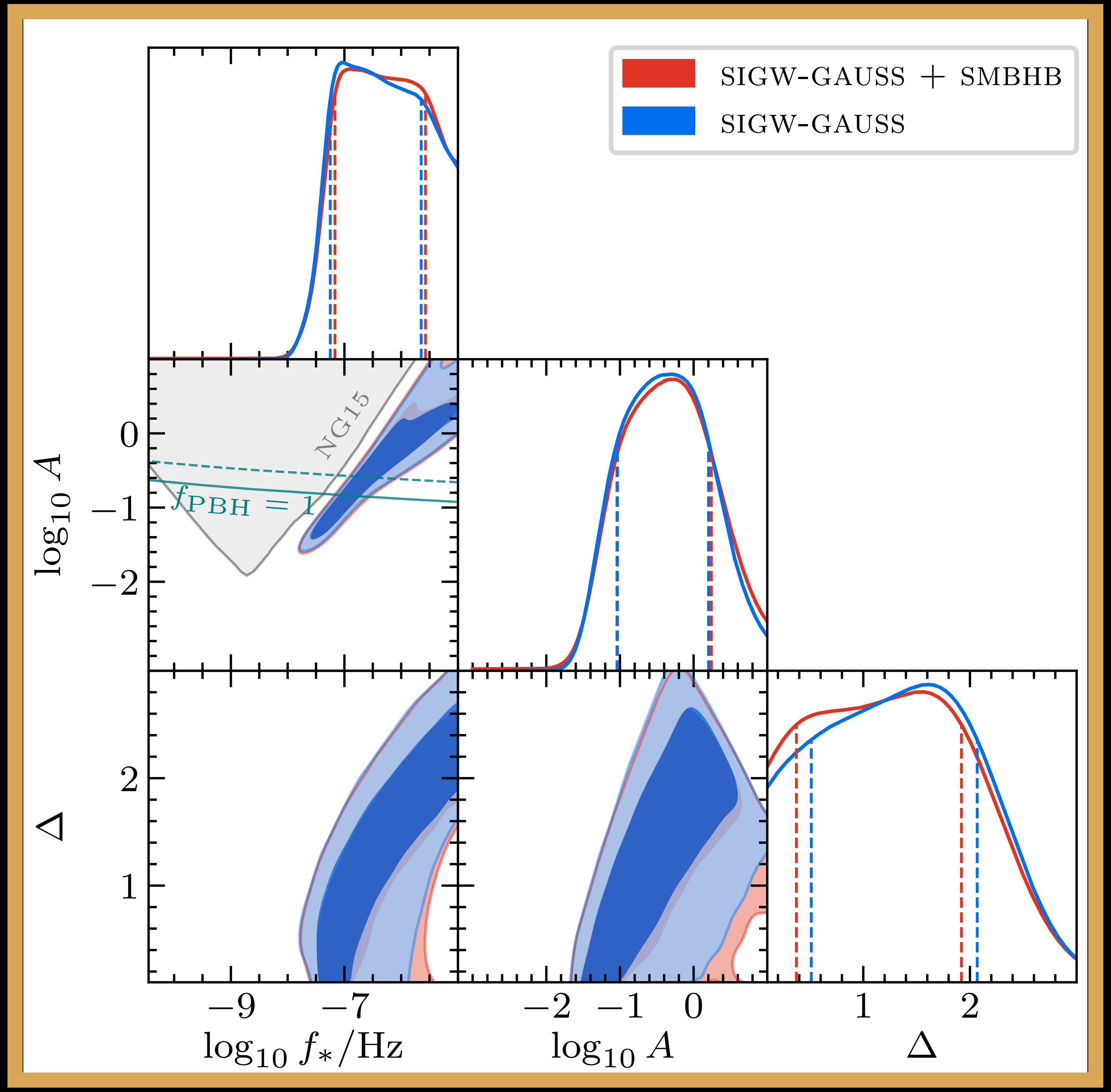
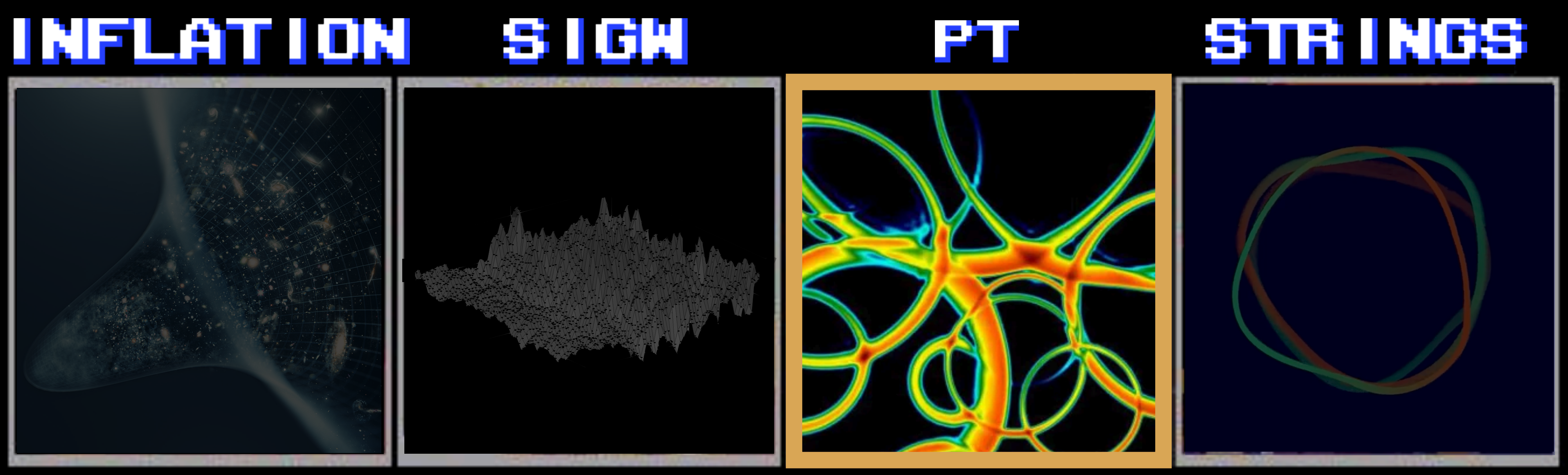


LARGE FEATURE AT MPC SCALES NEEDED

RISK OF OVERPRODUCING PBH

SELECT PLAYER



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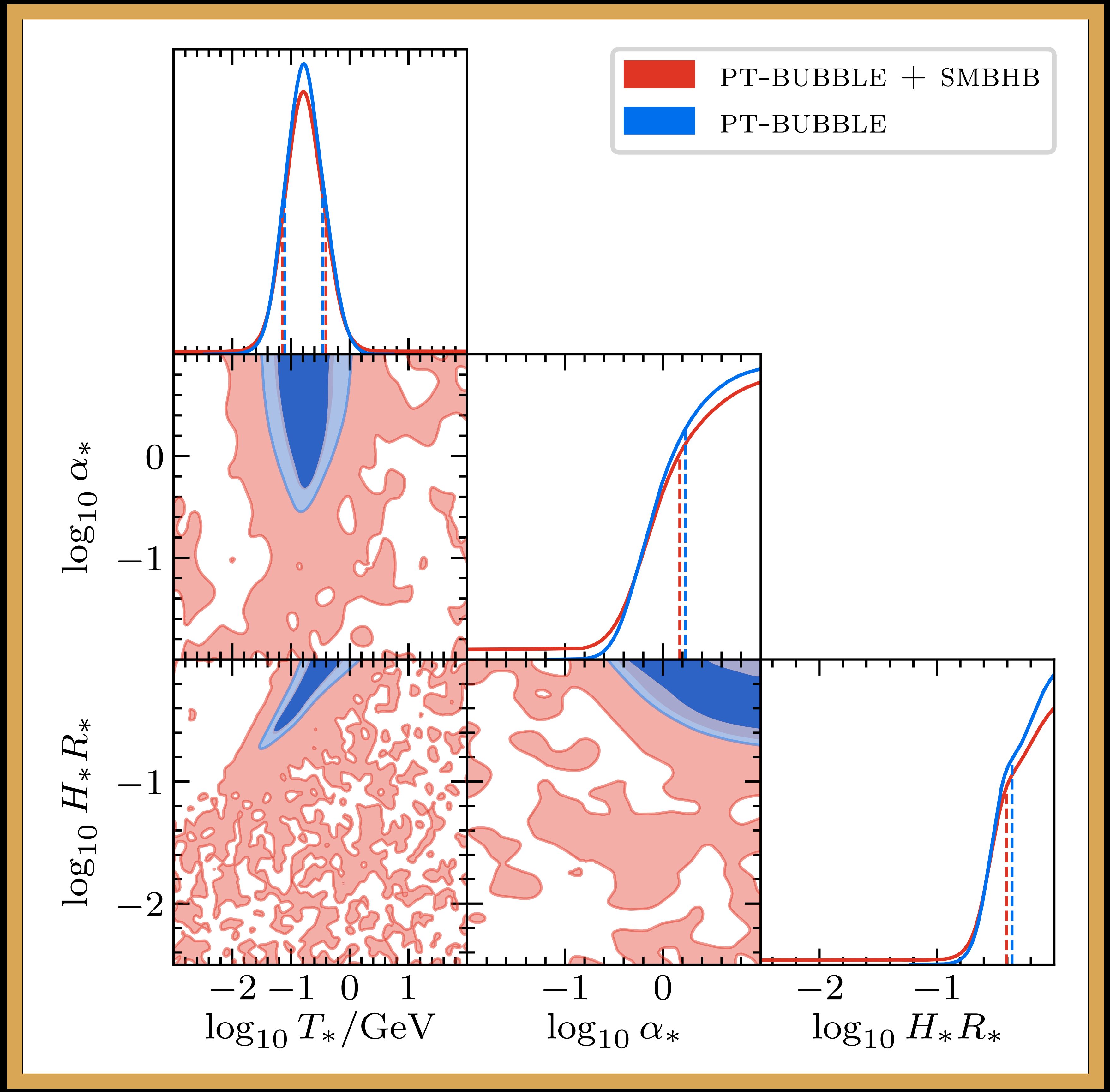
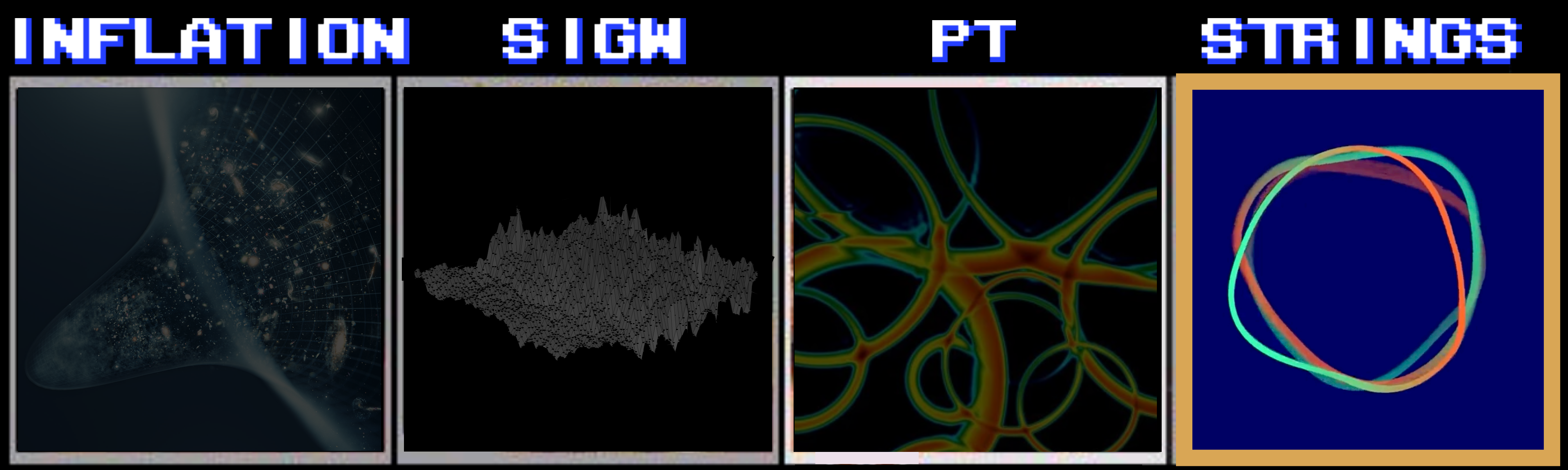


10-100 MEV TRANSITION TEMP. NEEDED

SLOW TRANSITION NEEDED

EXTREMELY STRONG TRANSITION NEEDED

SELECT PLAYER



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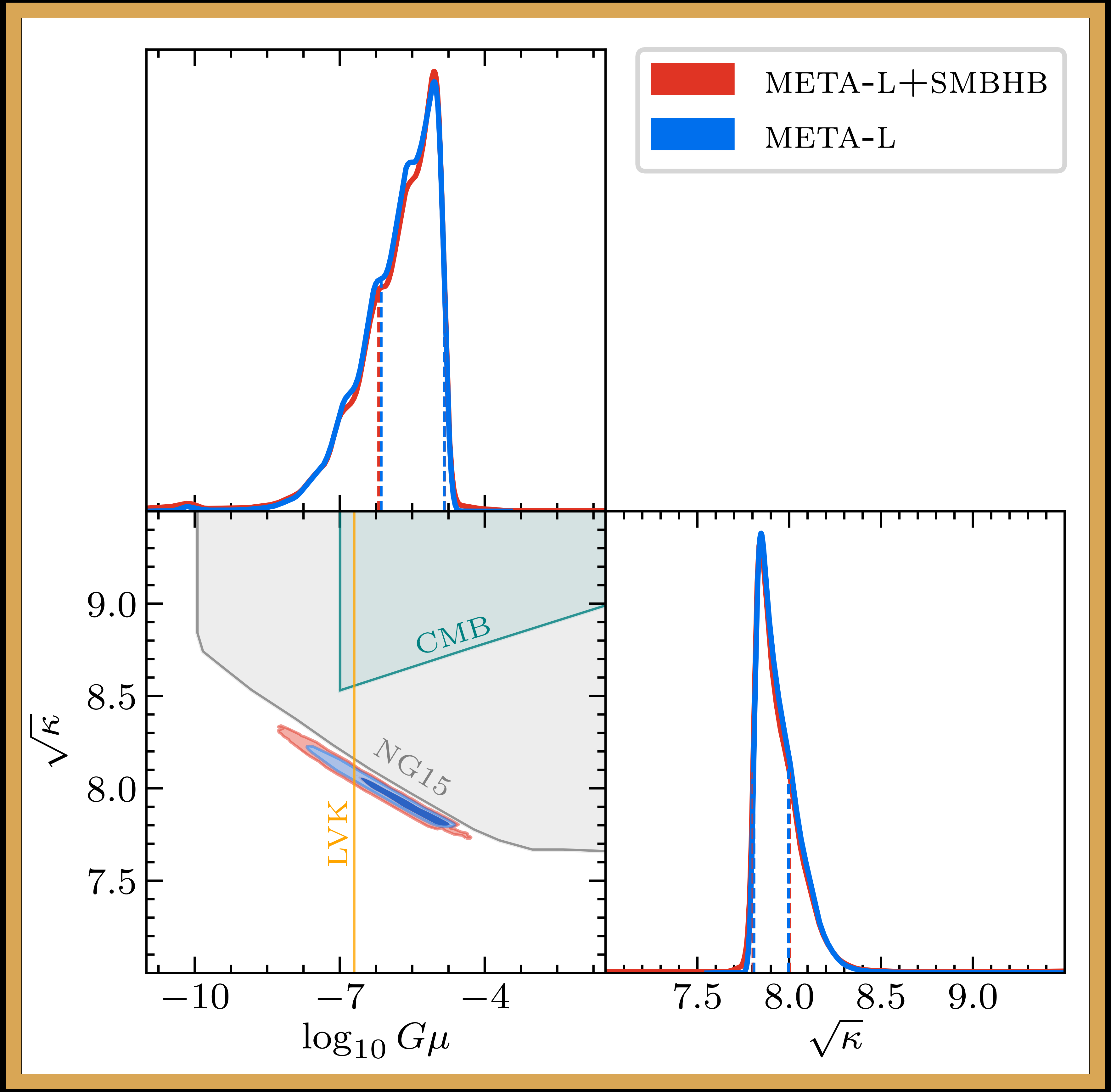


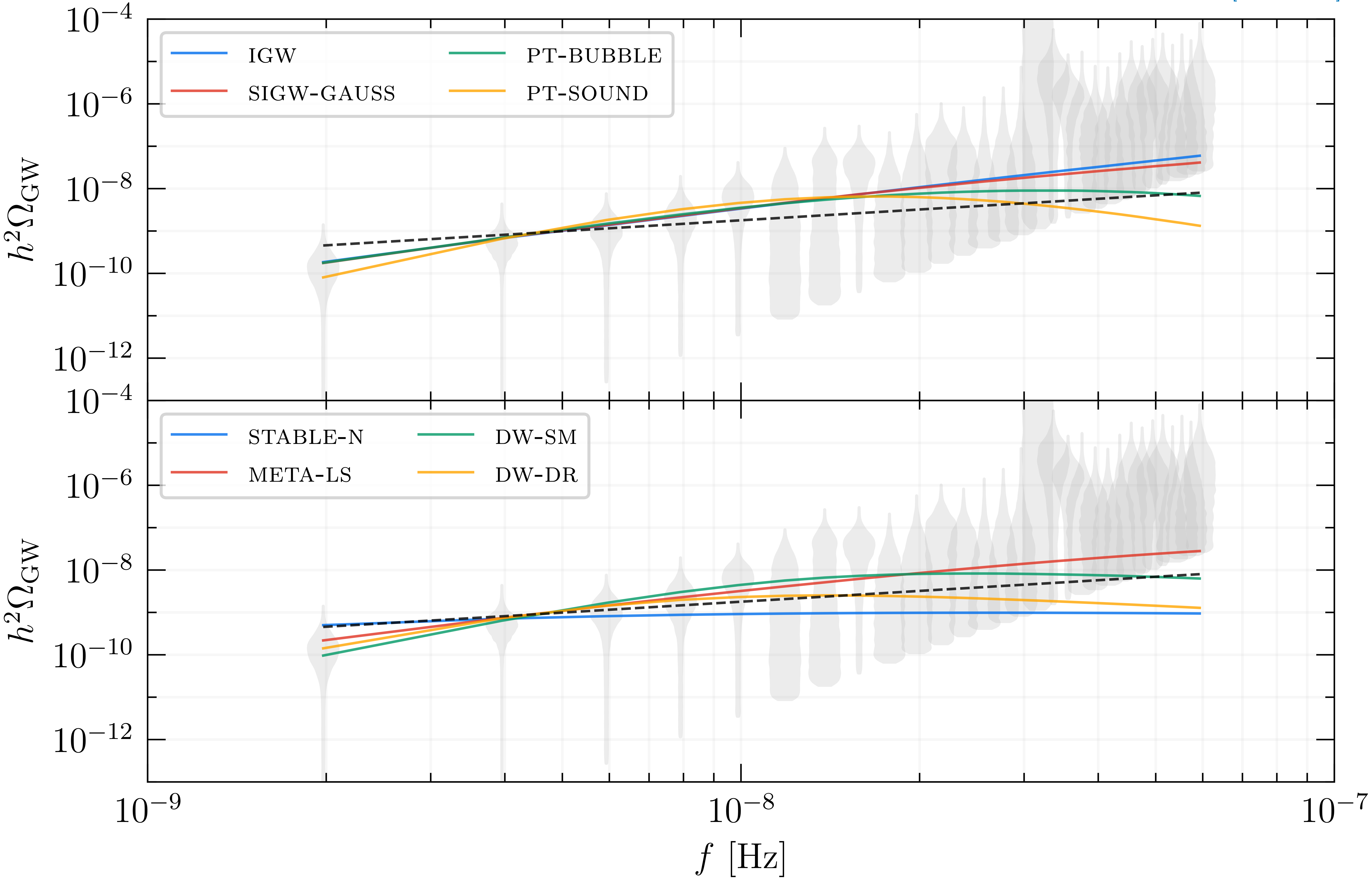
STABLE STRING DO NOT WORK

METASTABLE STRING DO WORK

GUT SCALE STRING TENSION COULD WORK

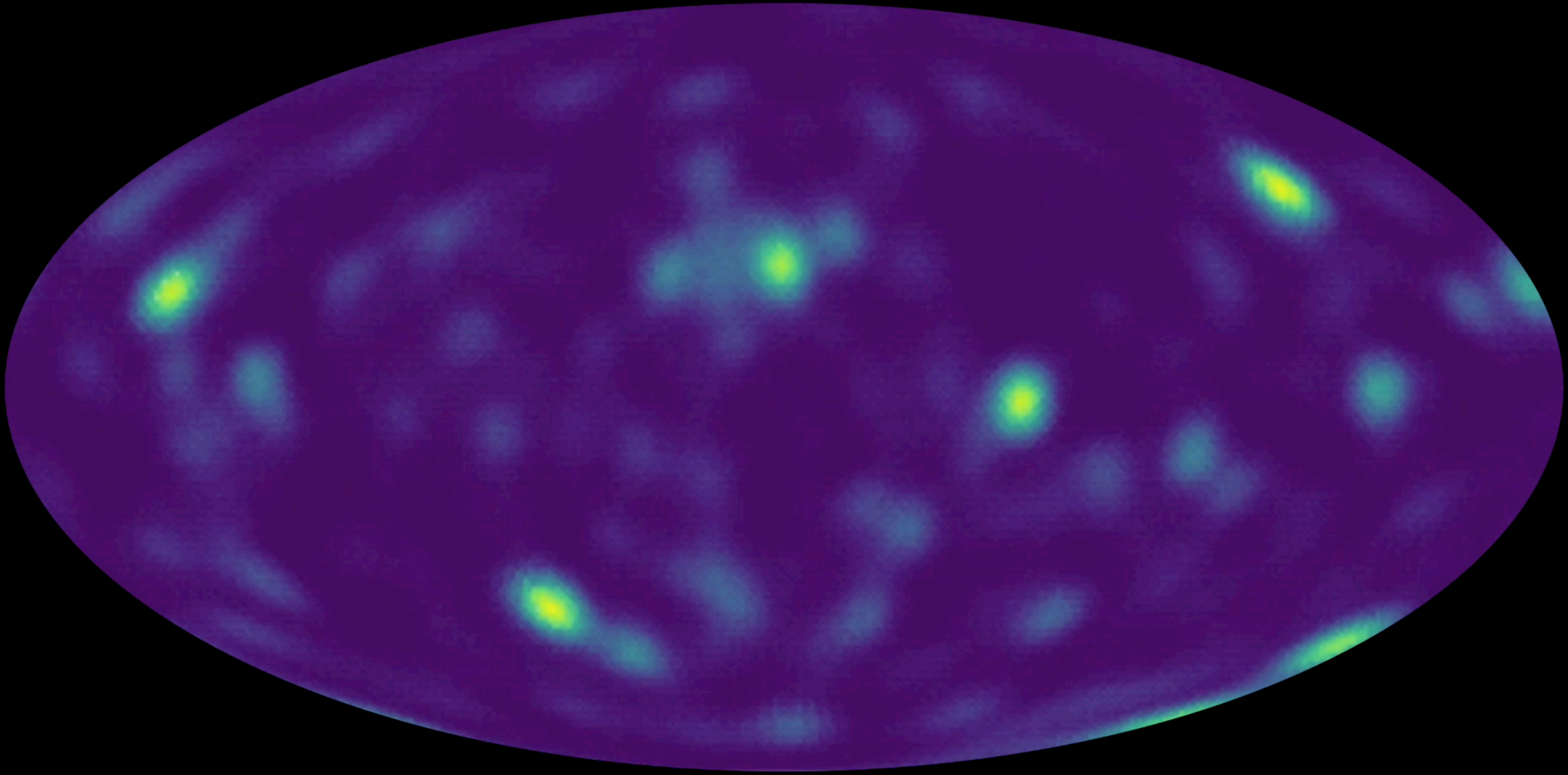
COSMOLOGICAL SIGNALS

Afzal et al. [2306.16219]



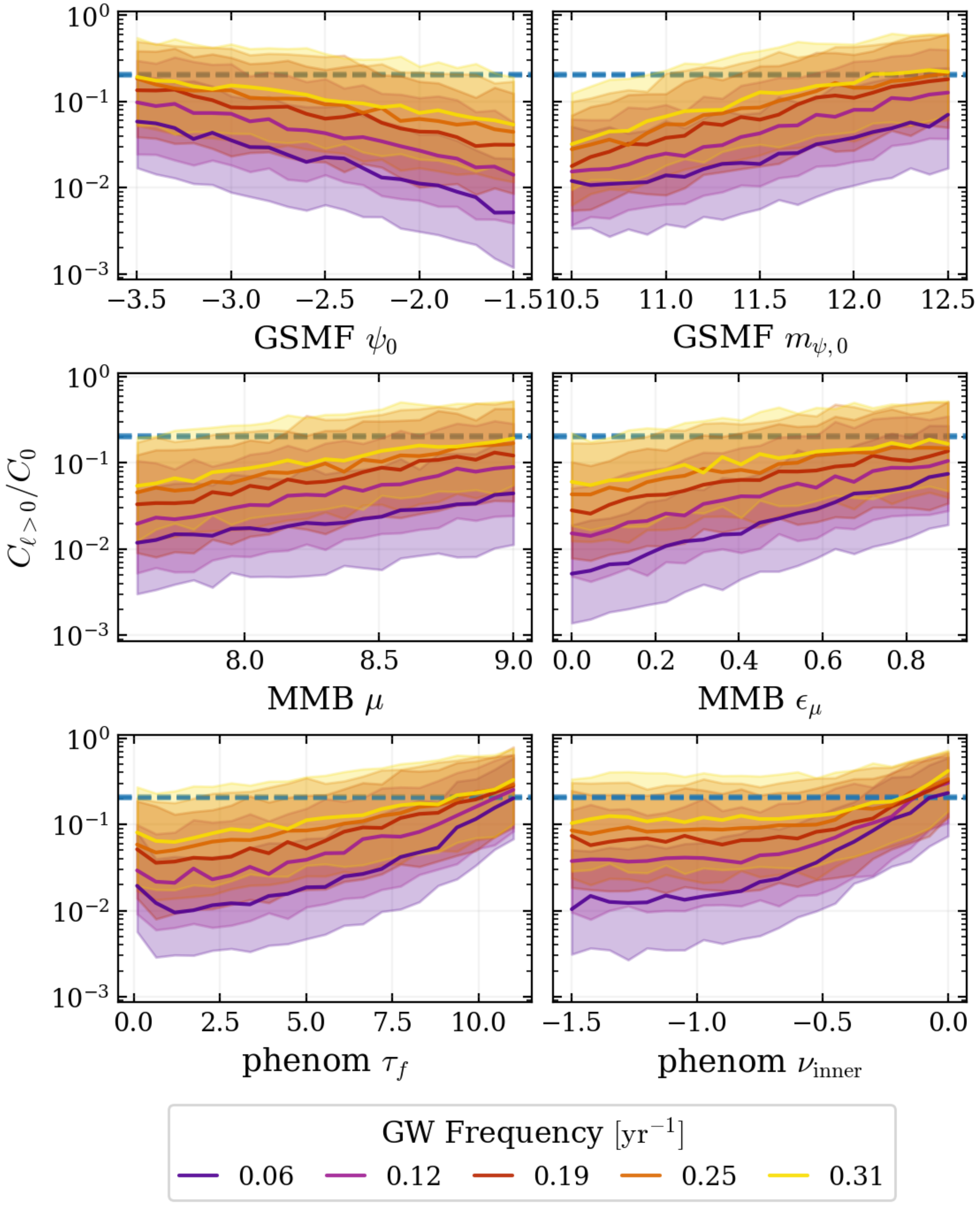
where do we go from here?

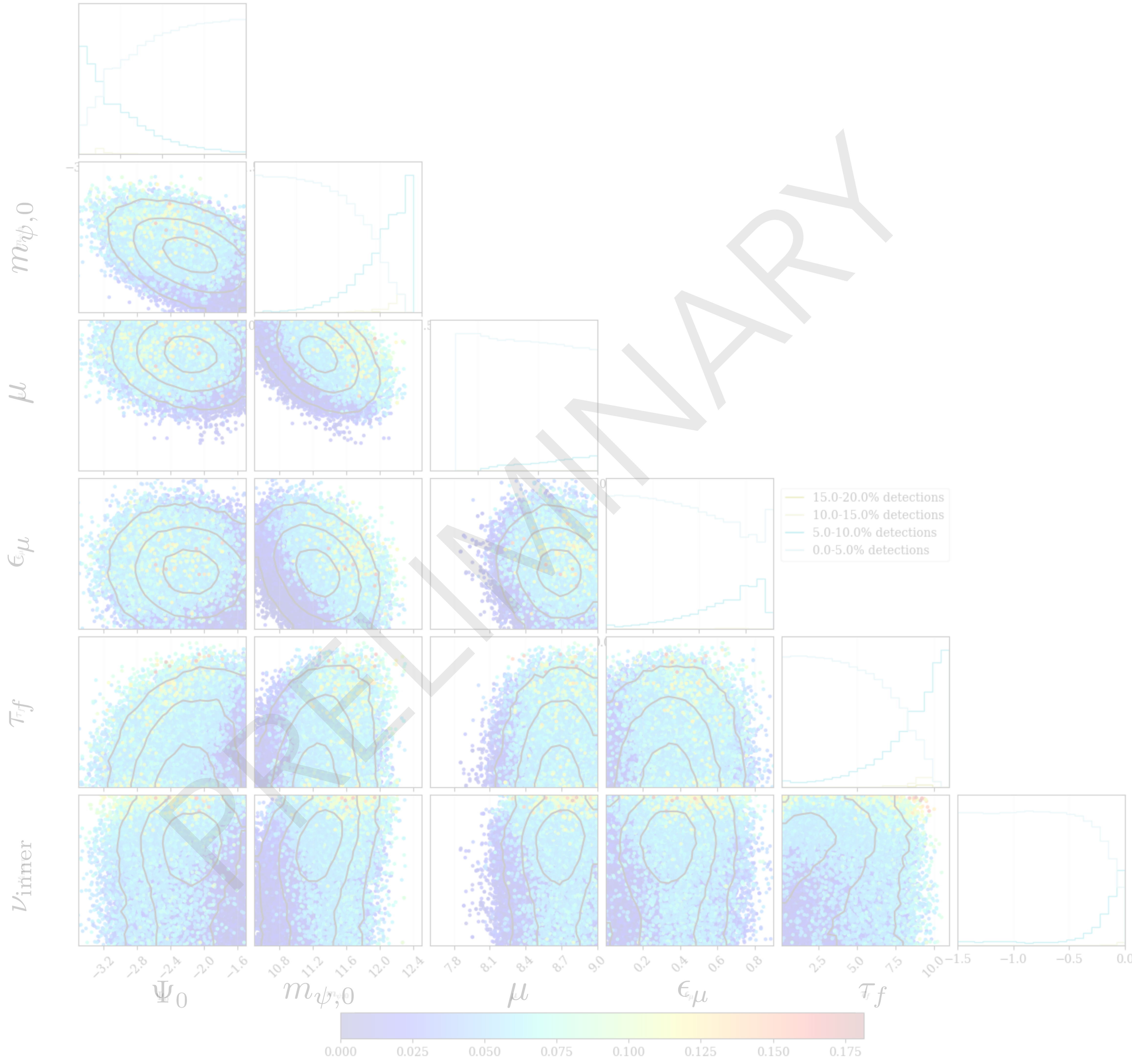
ANISOTROPIES



Simulated Data

ANISOTROPIES

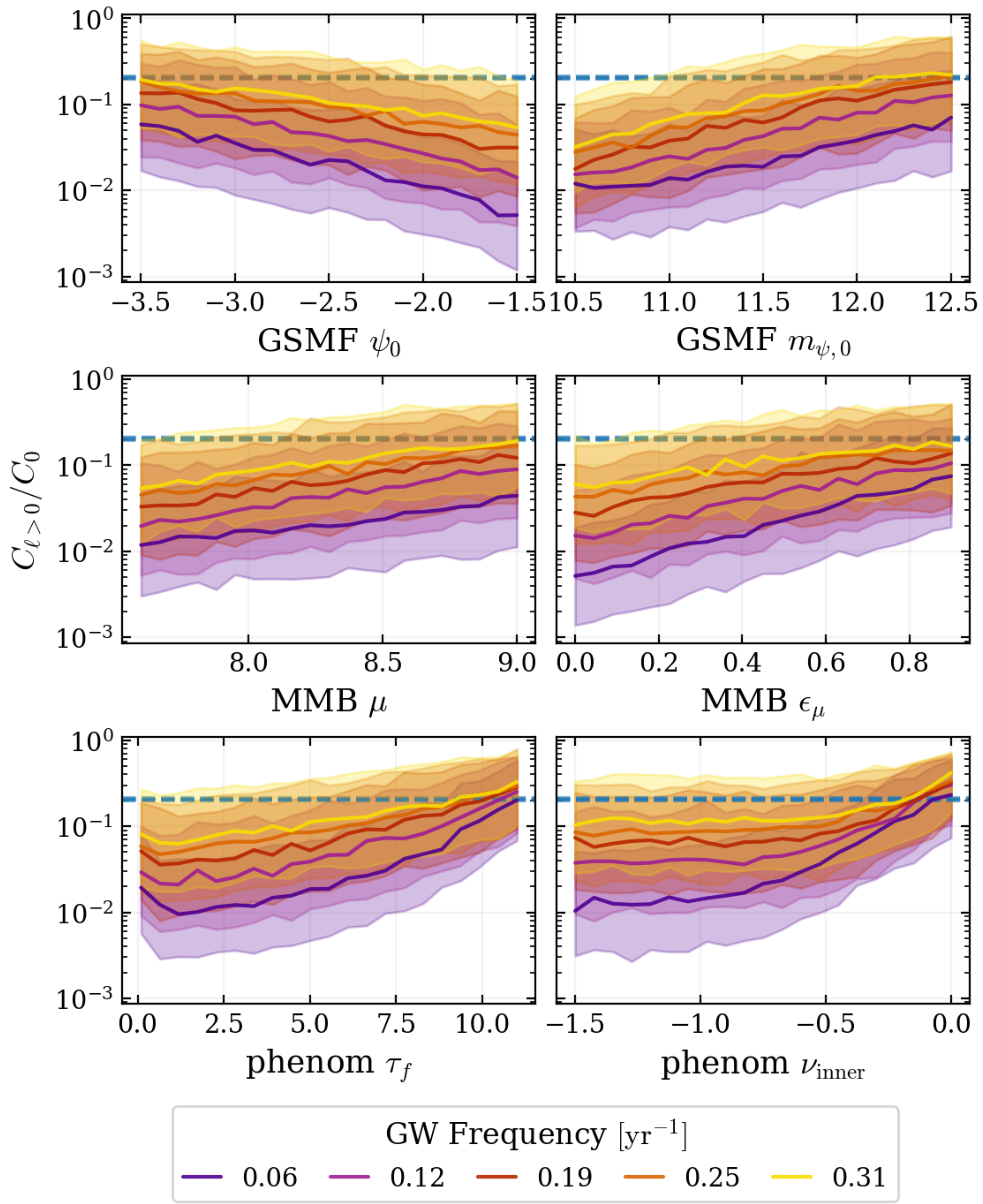


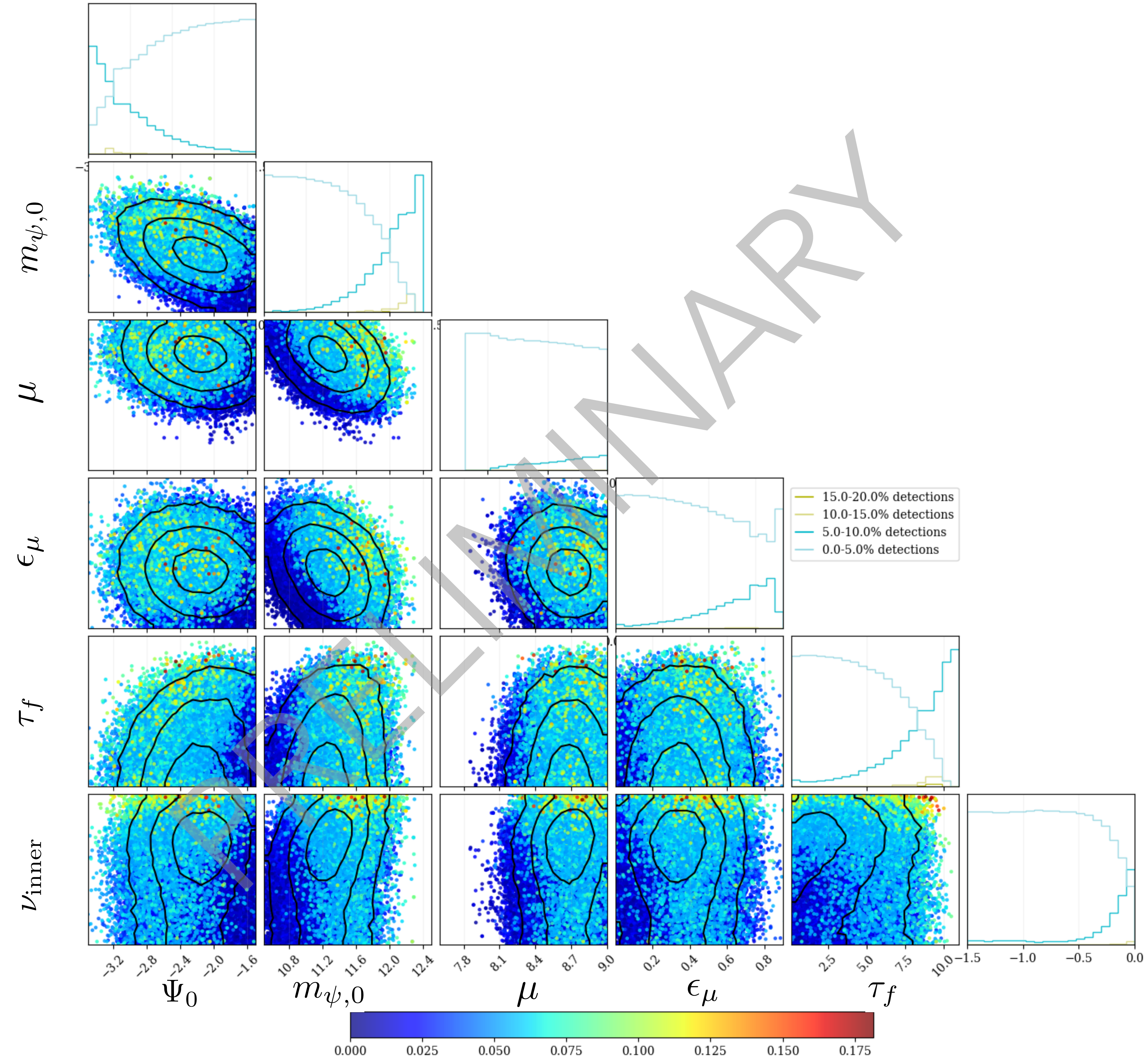


[Gardiner, Kelley, Lemke, AM [2309.07227]](https://arxiv.org/abs/2309.07227)

Lemke, AM, et al., in preparation

ANISOTROPIES





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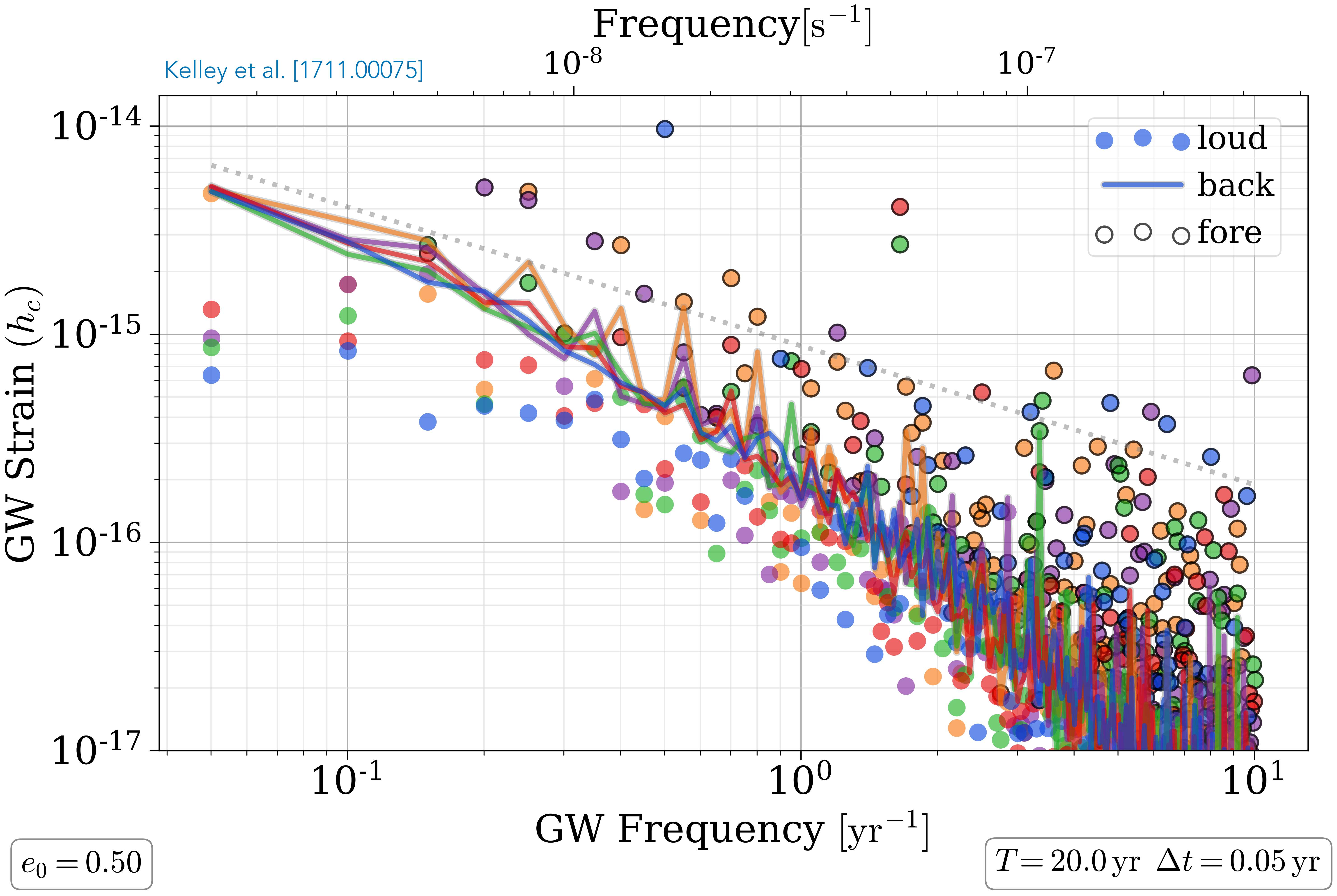
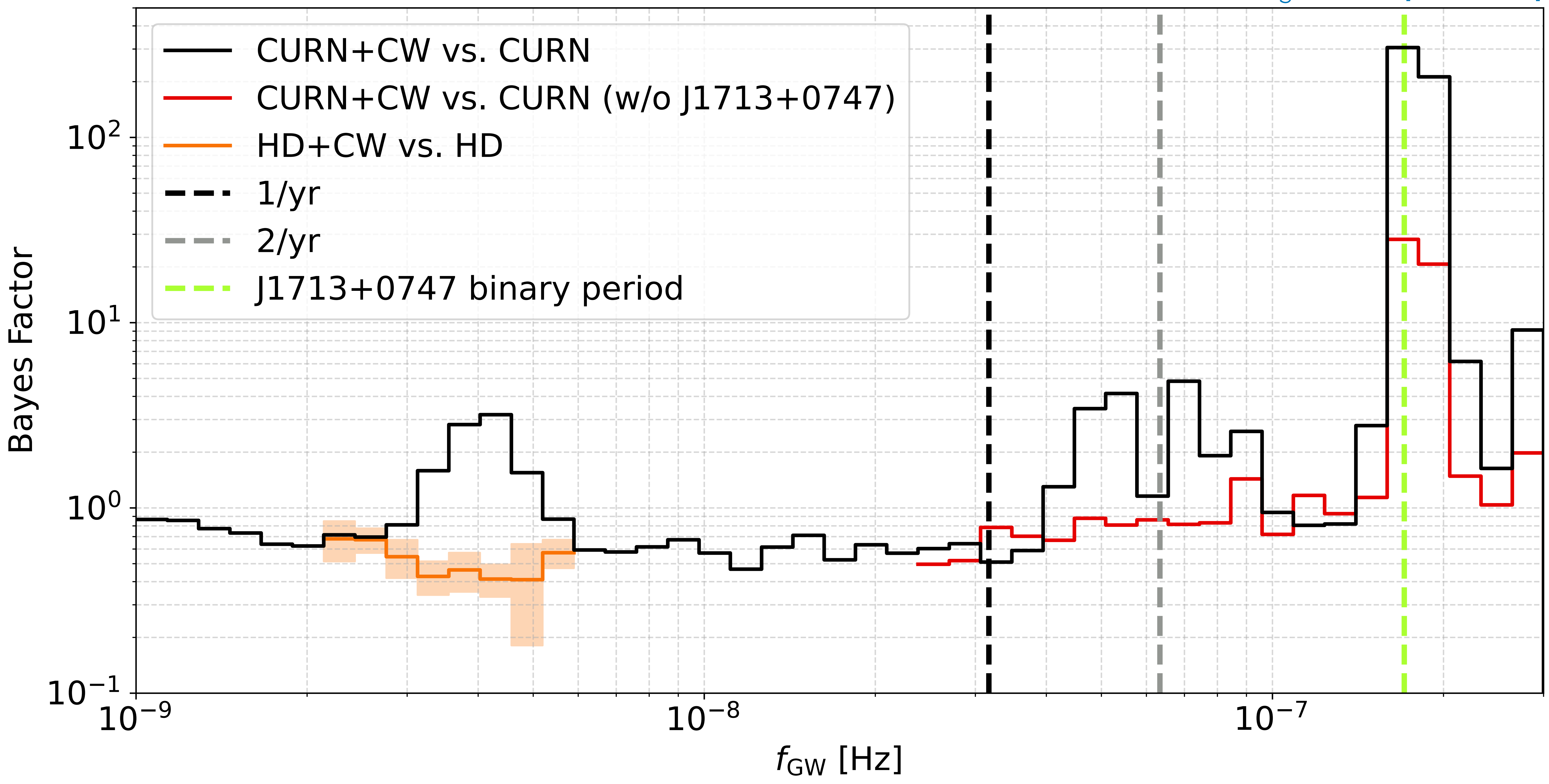
SINGLE SOURCE



SINGLE SOURCE

Agazie et al. [2306.16222]



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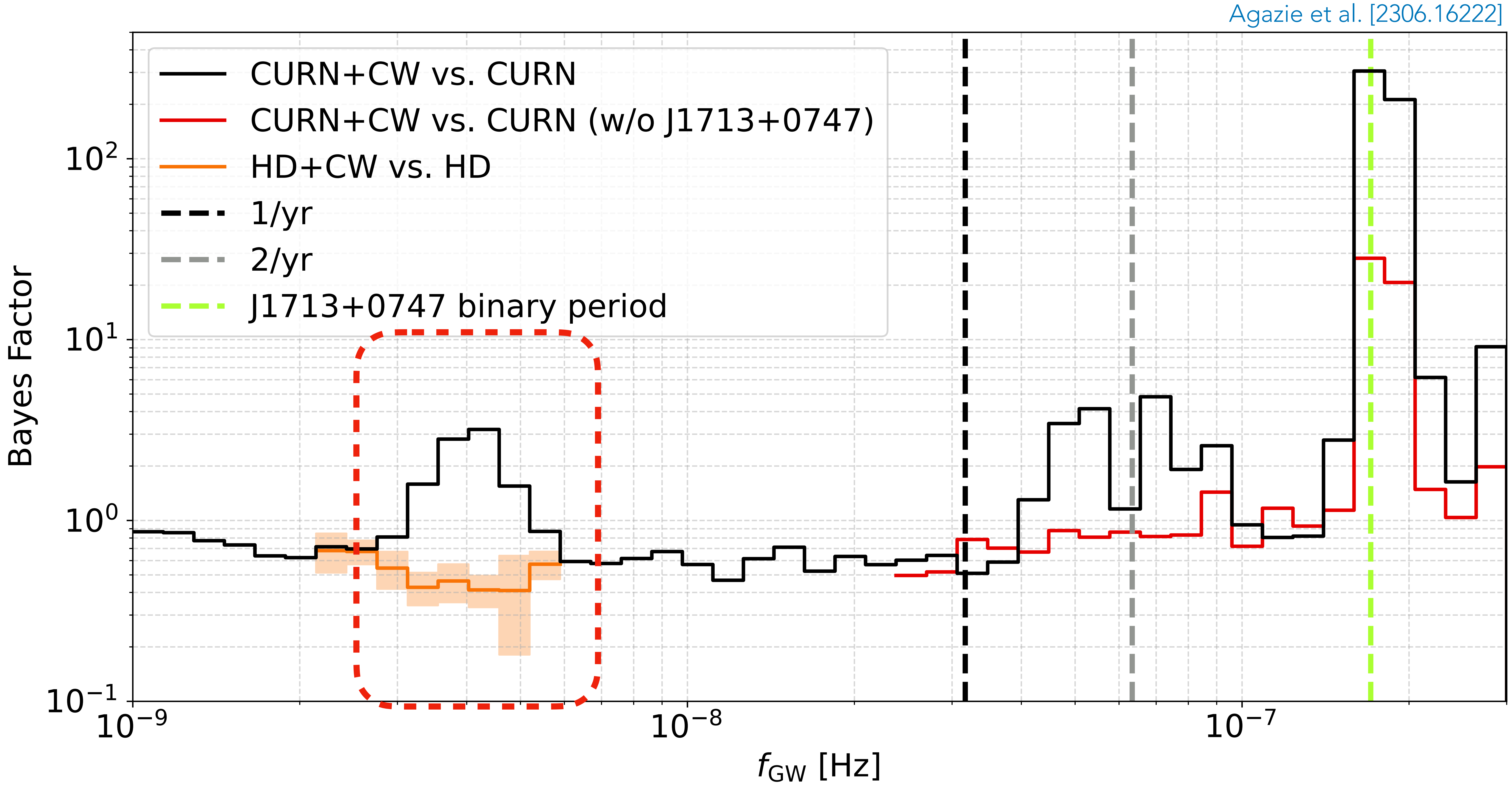

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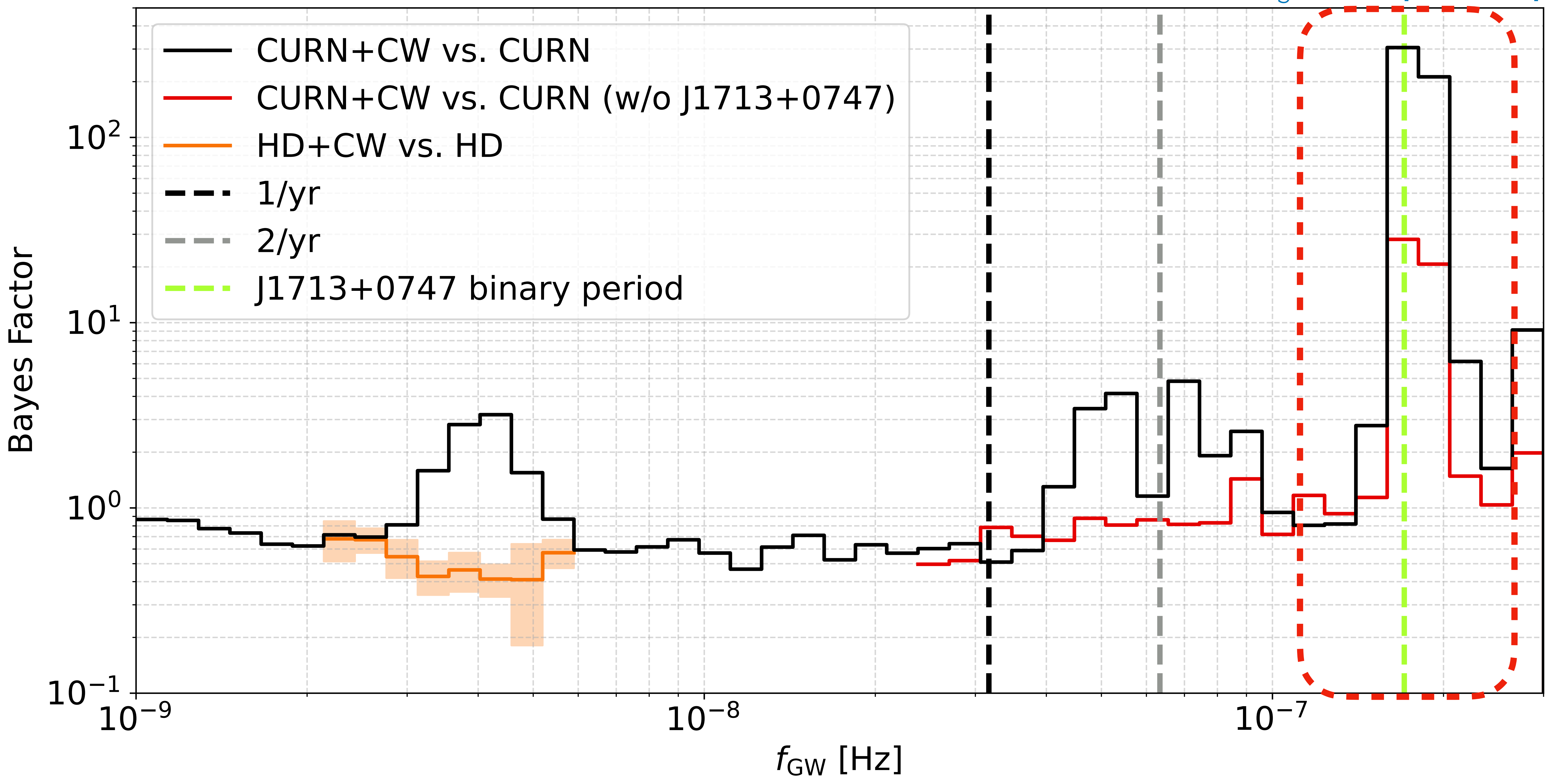
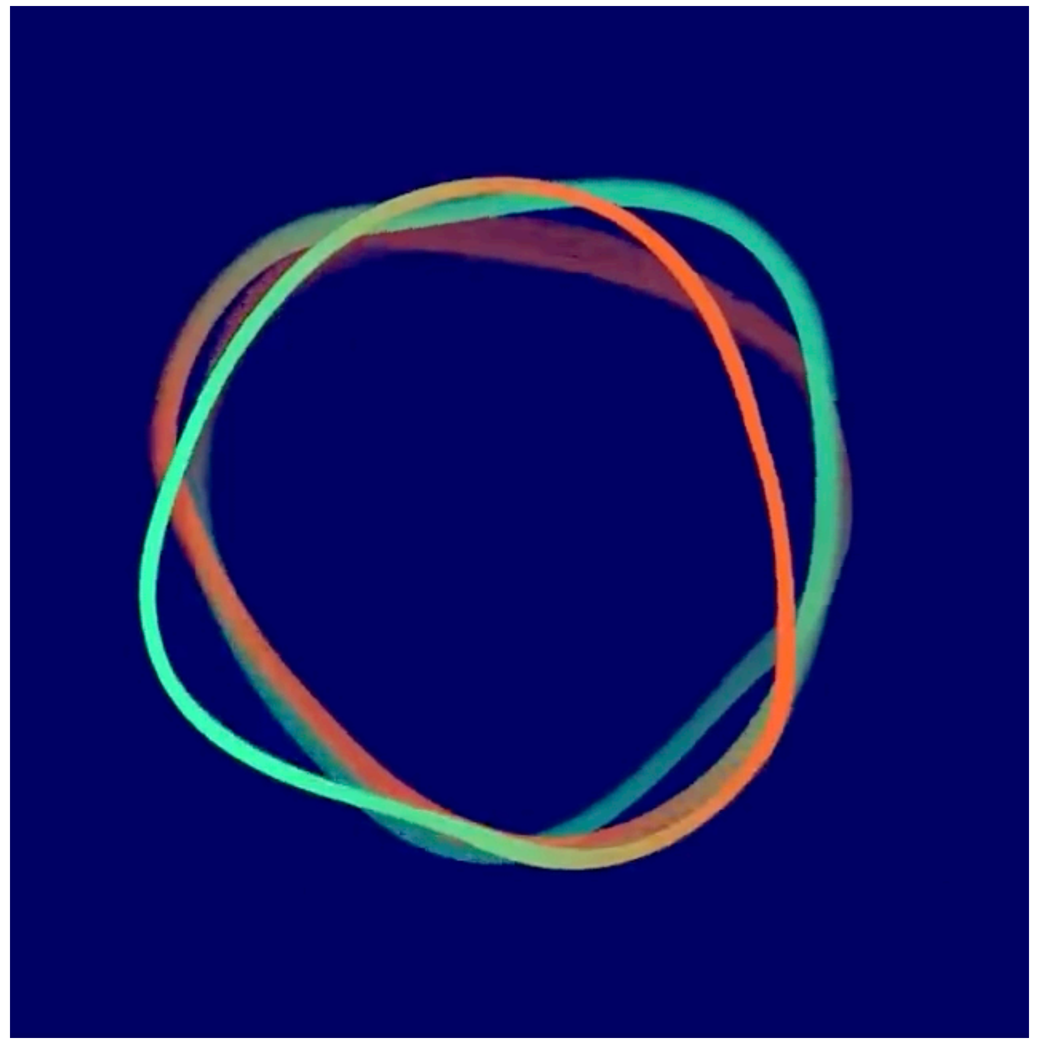
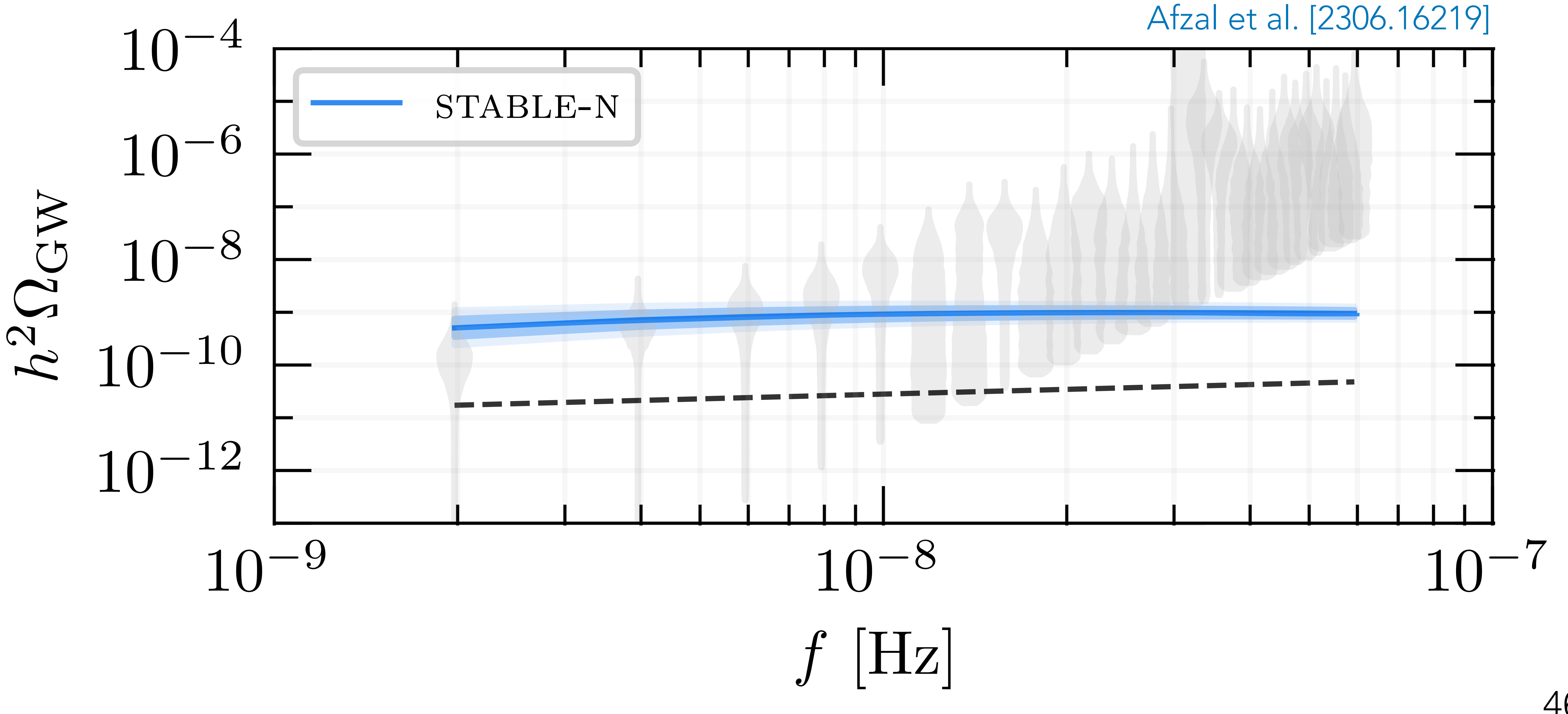


what if it’s not new physics

COSMIC STRINGS



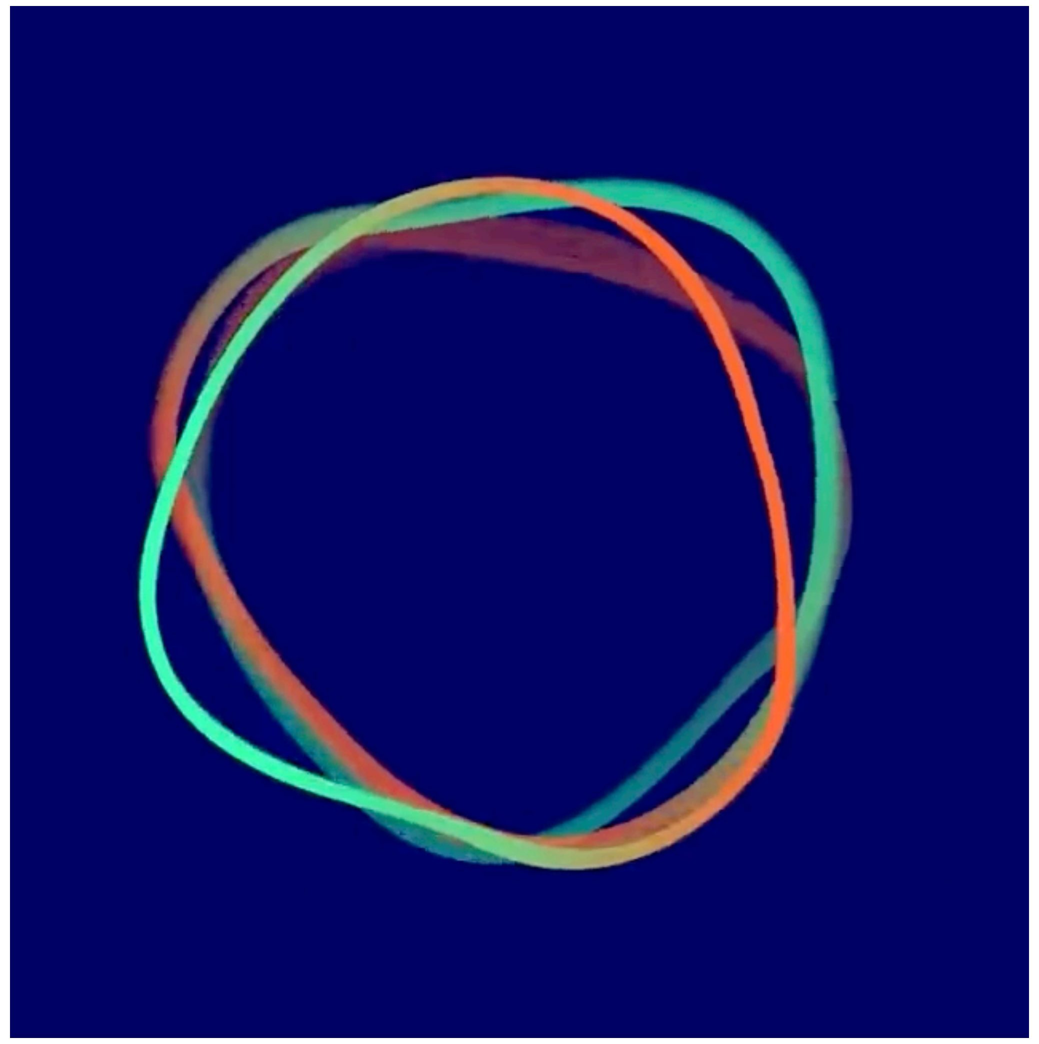
Afzal et al. [2306.16219]

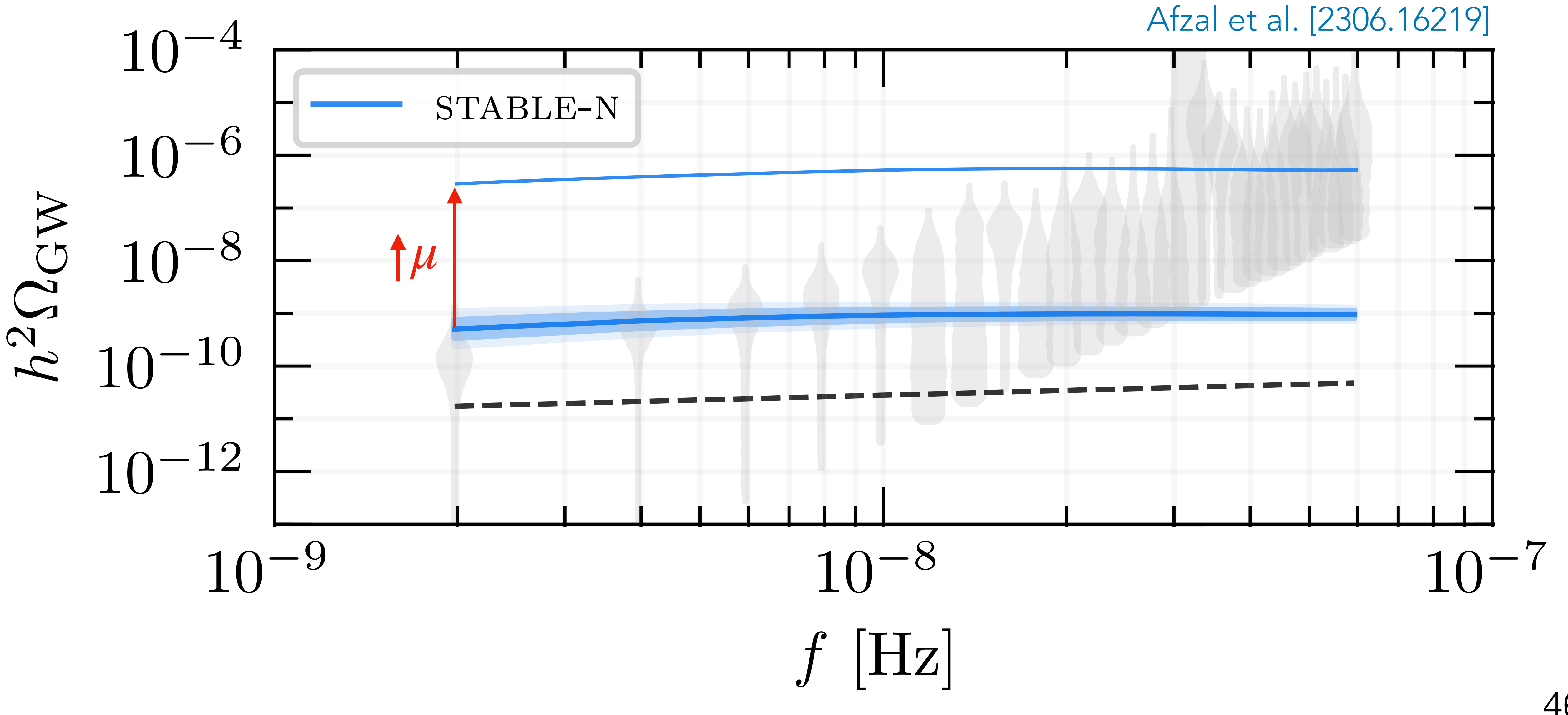


upper limits

Afzal et al. [2306.16219]

COSMIC STRINGS





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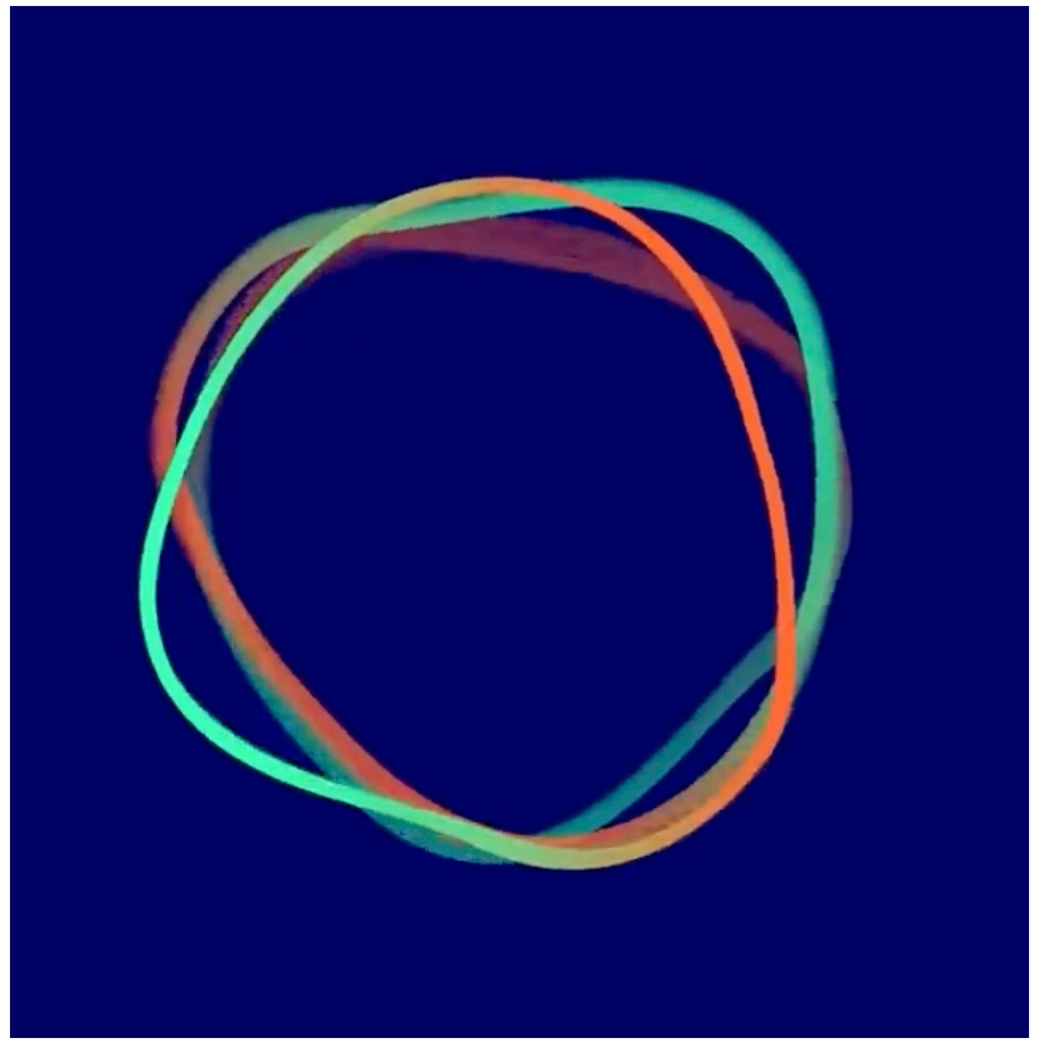

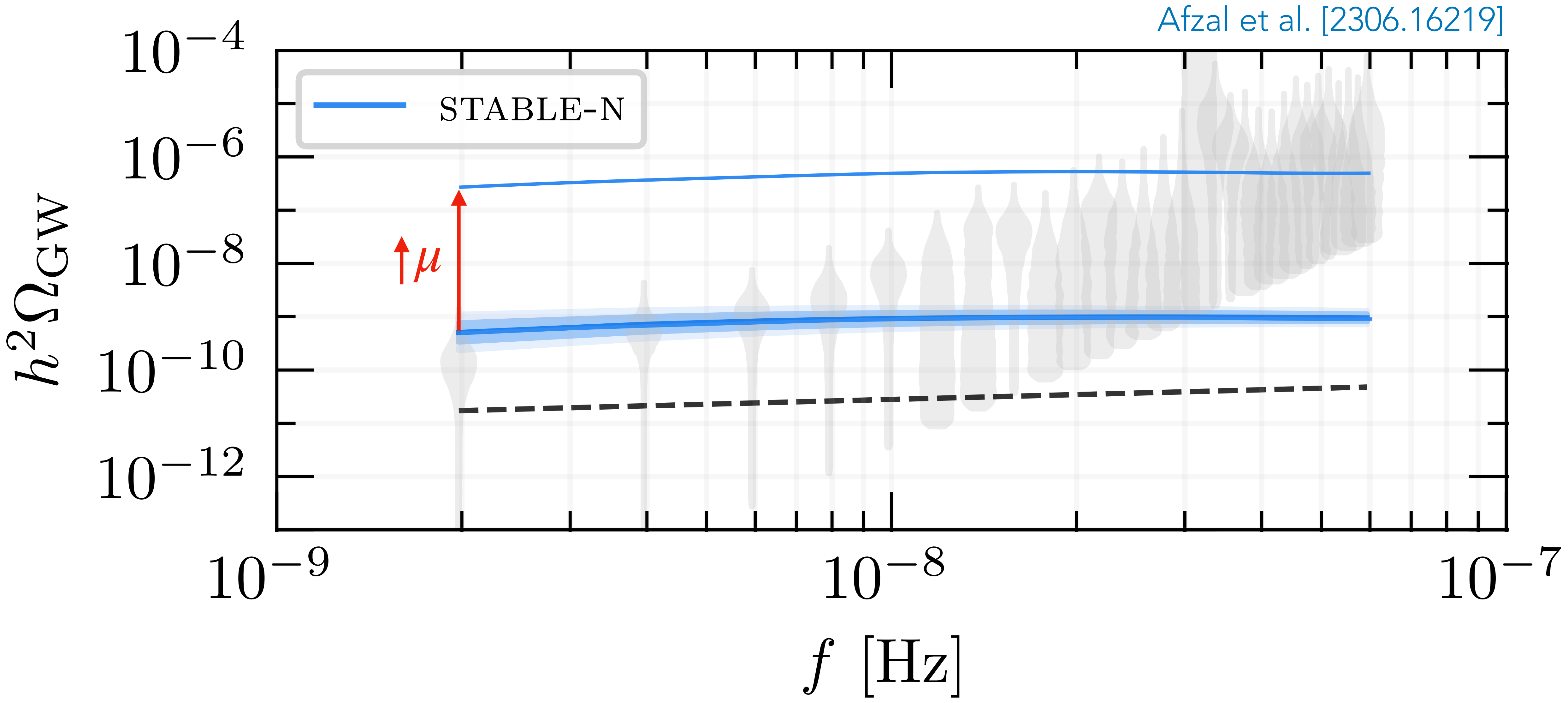

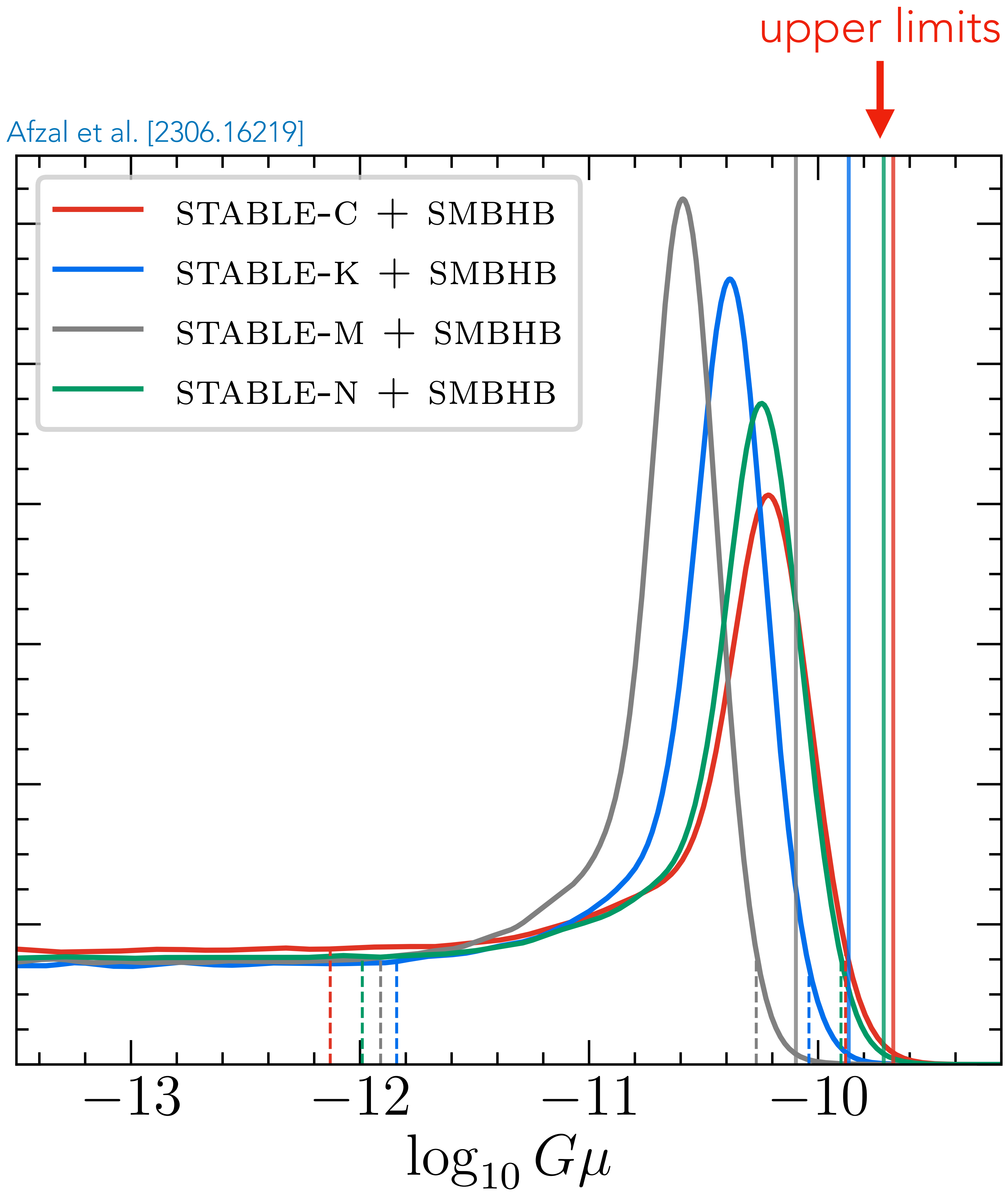

ULDM

$$\phi(\vec{x}, t) = \frac{\sqrt{2\rho_\phi}}{m_\phi}\hat{\phi}(\vec{x})\cos\left(m_\phi t + \gamma(\vec{x})\right)$$ **+ stochastic low-f fluctuations**

DM density

ULDM

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

+ stochastic low-f fluctuations

DM mass

$$\phi(\vec{x},t) = \frac{\sqrt{2\rho_\phi}}{m_\phi}\hat{\phi}(\vec{x})\cos\left(m_\phi t + \gamma(\vec{x})\right)$$ **+ stochastic low-f fluctuations**

gravitational signals

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

Khmelnitsky, Rubakov [1309.5888]

$$\langle ss' \rangle \sim \frac{G^2\rho^2}{m^3 f^4 \sigma^4} K_0\left(\frac{\omega}{m\sigma^2}\right)$$

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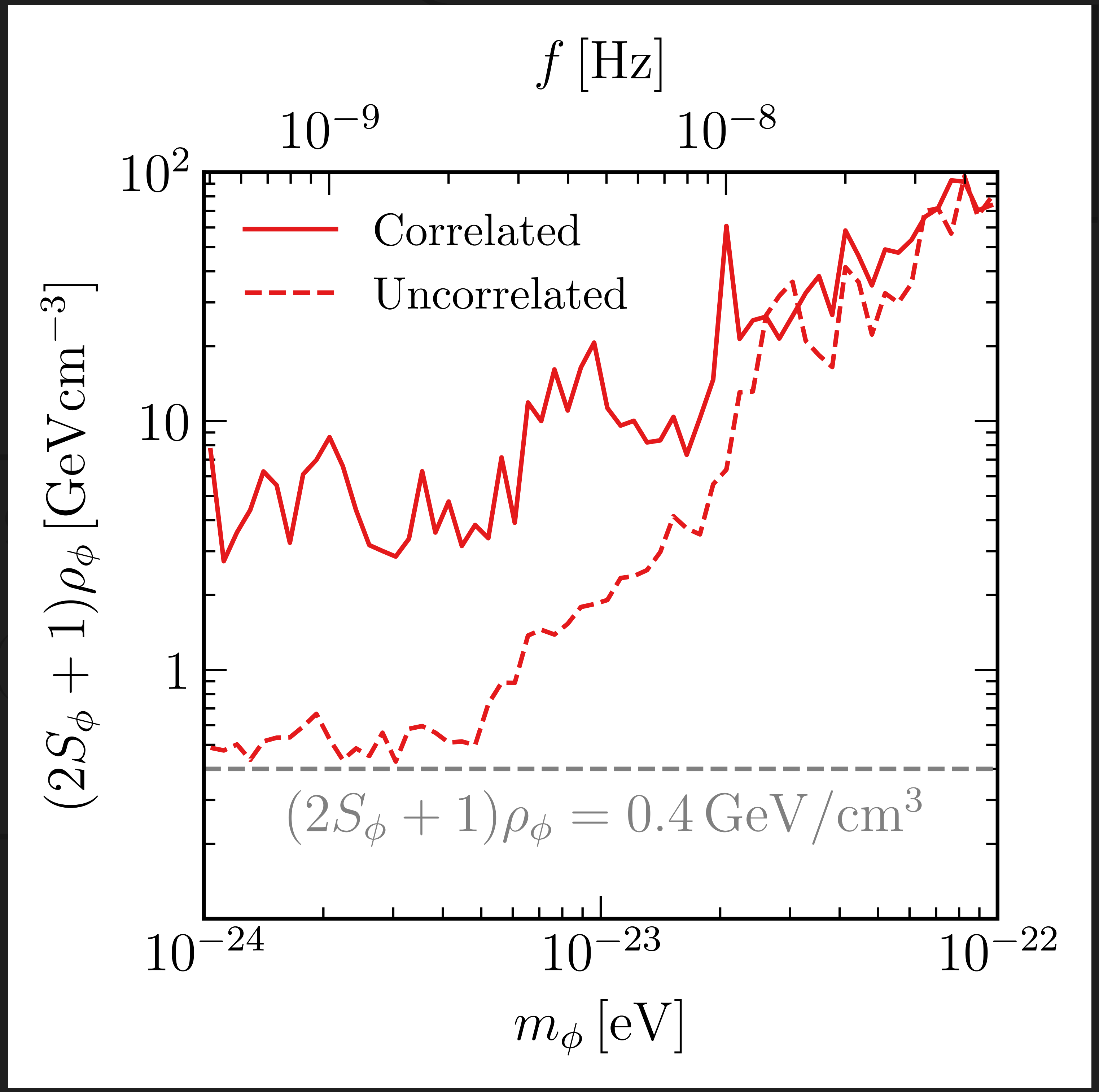
ULDM

[Afzal et al. [2306.16219]](#)



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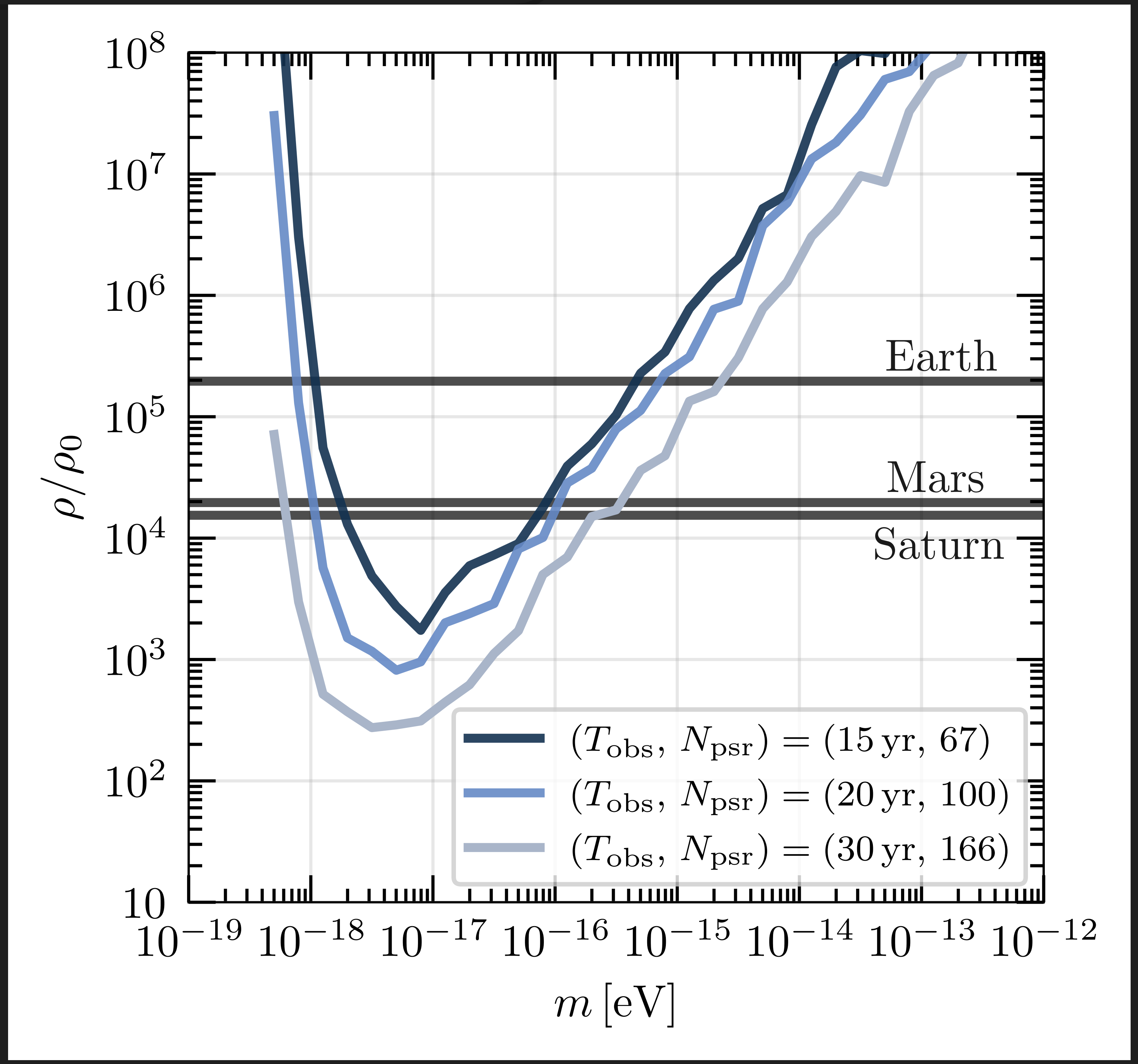

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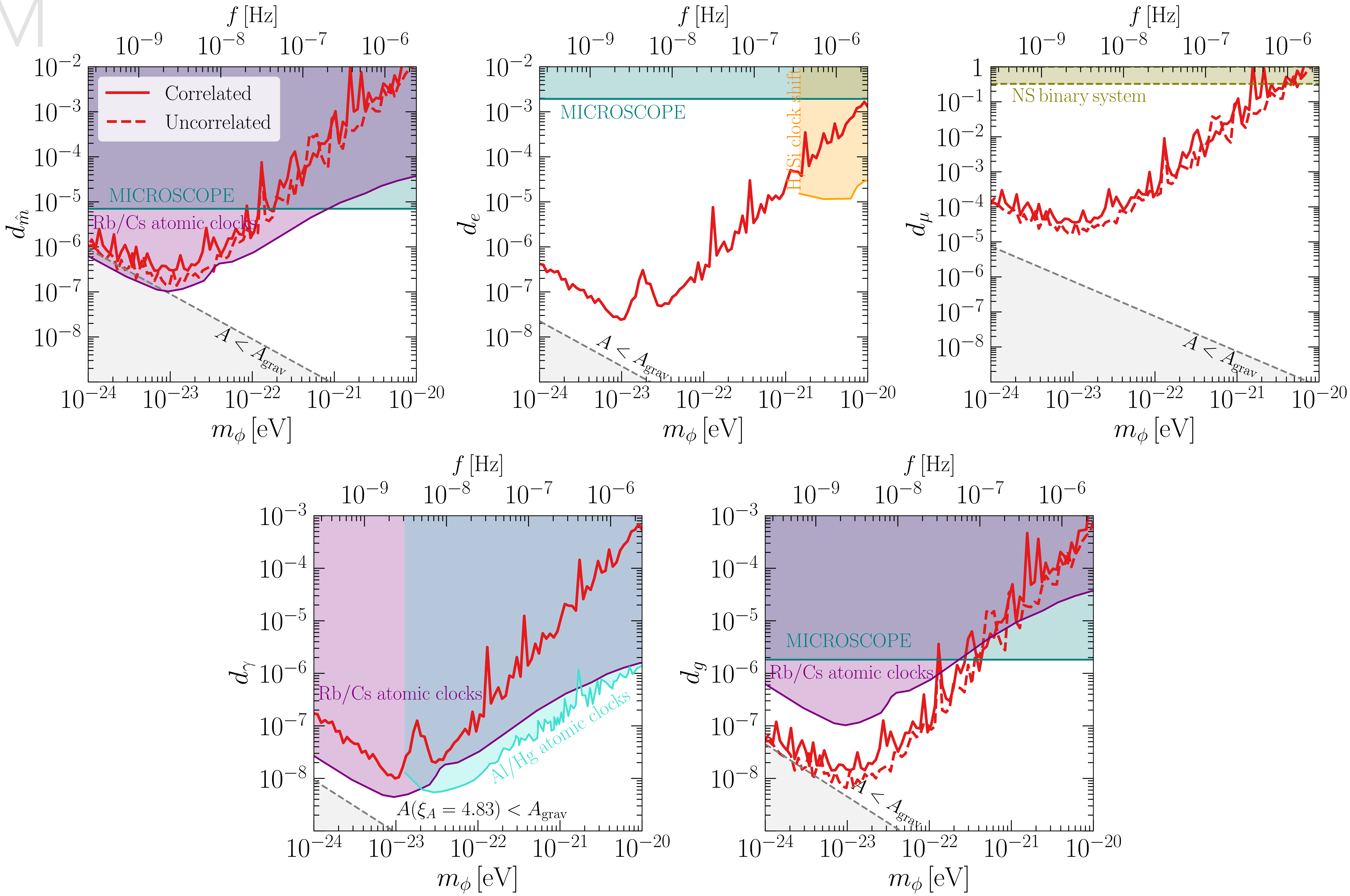
direct coupling signals

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

Kaplan, AM, Trickle [2205.06817]

ULDM



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strong evidence for a GWB in the nHz band

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cosmology or astrophysics?

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CW and anisotropies will help us discriminating

strong evidence for a GWB in the nHz band

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CW and anisotropies will help us discriminating

PTA can be used to constrain new physics

backup

have a model you want to test against PTA data?

say hello to PTArcade

PTArcade

toy model

$$h^2\Omega_{\rm GW}(f) = \frac{A_*}{f/f_* + f_*/f}$$

Step 1

```
conda install ptarcade
```

Step 2

```
from ptarcade.models_utils import prior

parameters = {
            'log_A_star' : prior("Uniform", -14, -6),
            'log_f_star' : prior("Uniform", -10, -6)
            }

def S(x):
    return 1 / (1/x + x)

def spectrum(f, log_A_star, log_f_star):
    A_star = 10**log_A_star
    f_star = 10**log_f_star

    return A_star * S(f/f_star)
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Step 3

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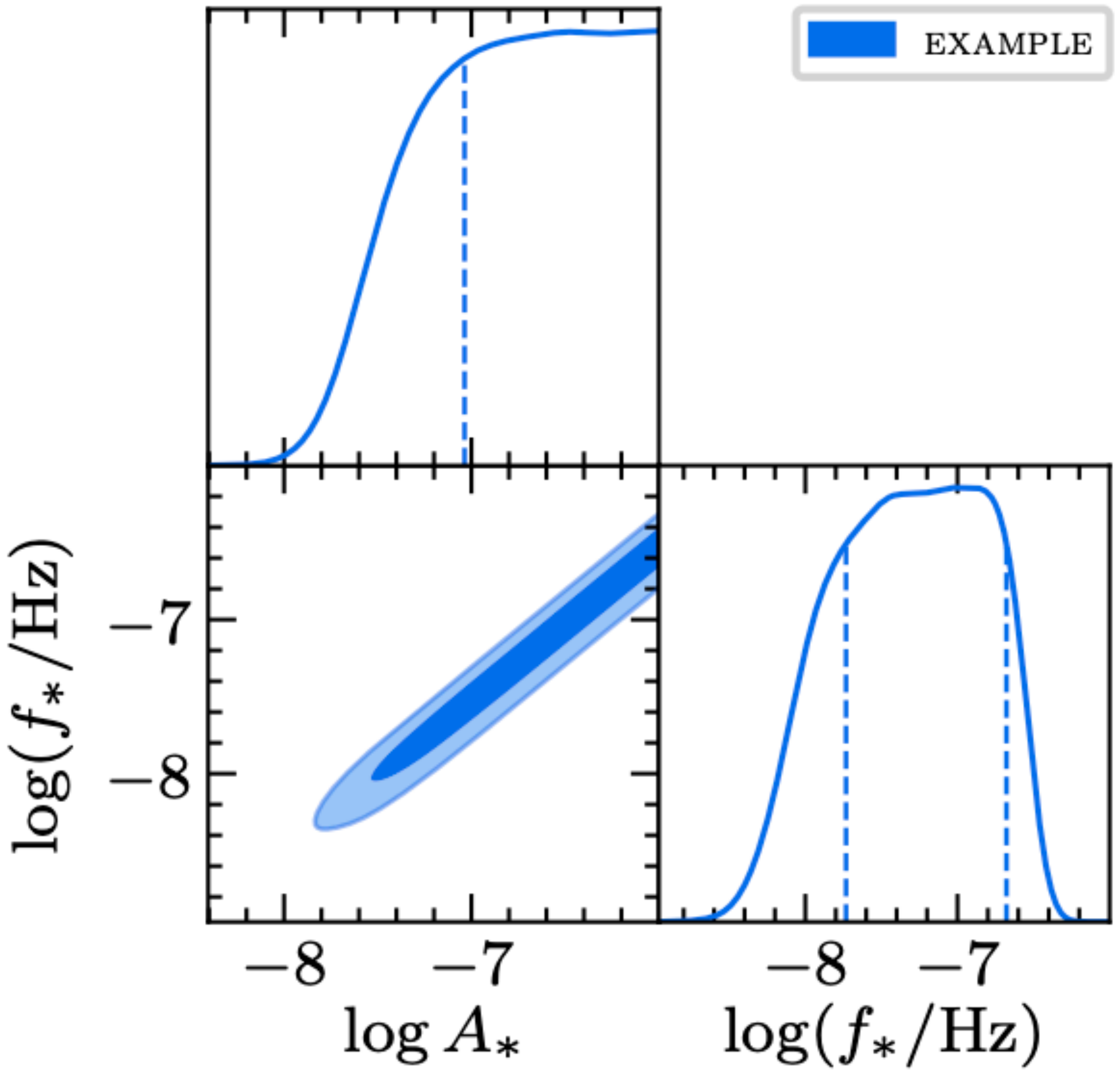


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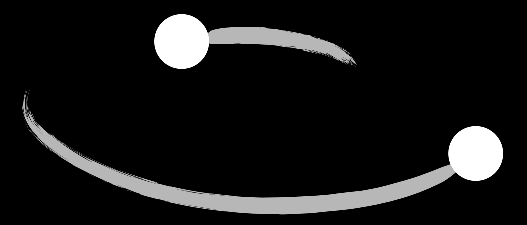
FACE-OFF



SMBHB

VS

inflation

scalar induced GW

phase transitions

cosmic strings

domain walls

FACE-OFF

$$h^2\Omega_{\rm GW} \propto \frac{A^2}{H_0^2}\left(\frac{f}{\rm yr^{-1}}\right)^{5-\gamma} {\rm yr}^{-2}$$

VS

inflation

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FACE-OFF

free parameters

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VS

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VS

free parameters

$$h^2\Omega_{\rm GW}(f;\ \Theta)$$

FACE-OFF

free parameters

$$h^2\Omega_{\rm GW} \propto \frac{A^2}{H_0^2}\left(\frac{f}{\rm yr^{-1}}\right)^{5-\gamma} {\rm yr}^{-2}$$

VS

free parameters

$$h^2\Omega_{\rm GW}(f;\ \alpha_*, T_*, HR_*)$$

FACE-OFF

$$\mathcal{B} = \frac{\mathcal{Z}_{\rm NP}}{\mathcal{Z}_{\rm BHB}}$$

$$\mathcal{Z} = \int d\Theta \; P(\mathcal{D}|\Theta, \mathcal{H}) \times P(\Theta|\mathcal{H})$$

FACE-OFF

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↑ likelihood function

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likelihood function

prior distributions

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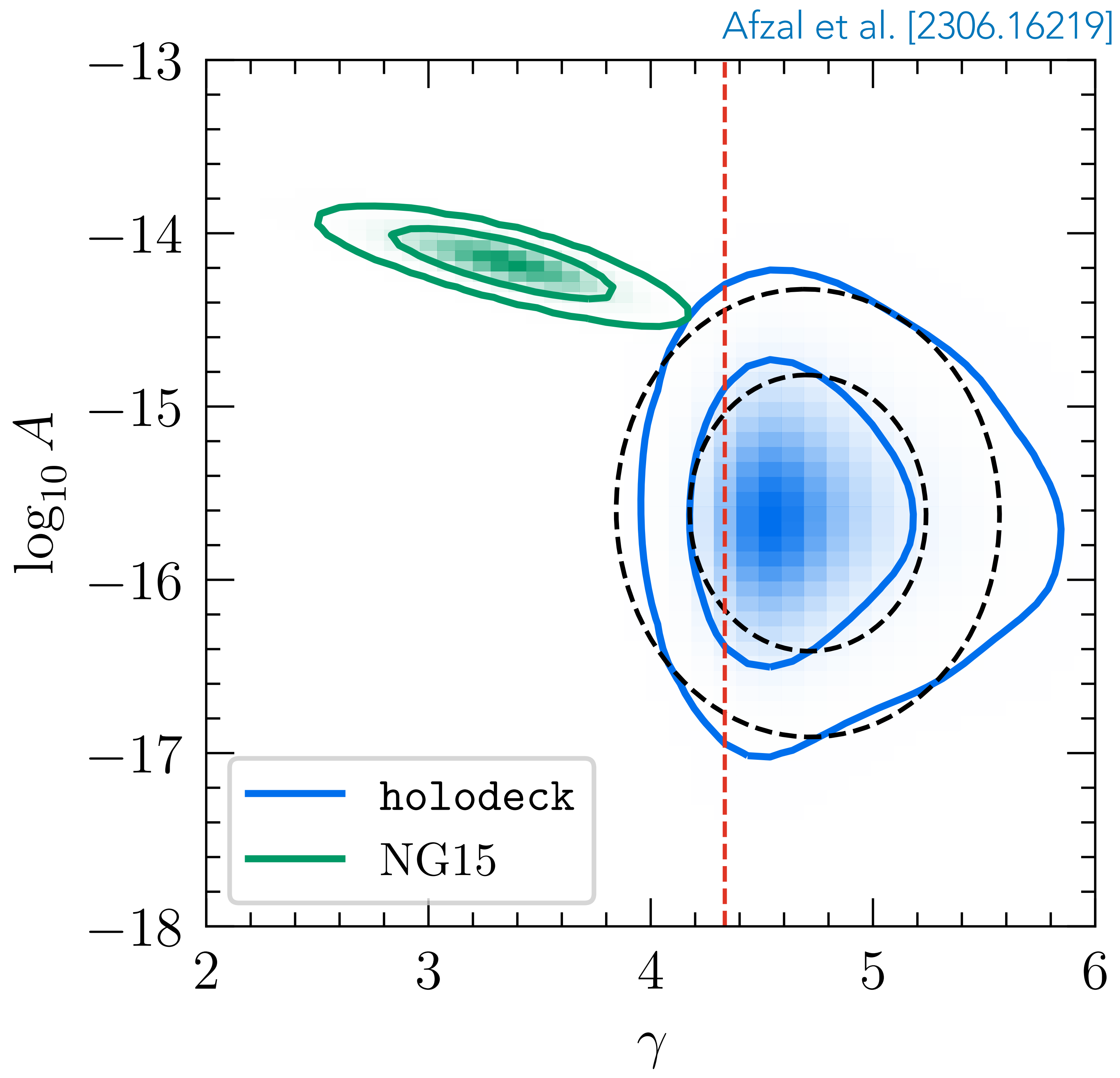

FACE-OFF

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