PTAs: where we are and where we are going

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MITP | Aug. 14, 2023

NANOGrav Physics Frontiers Center

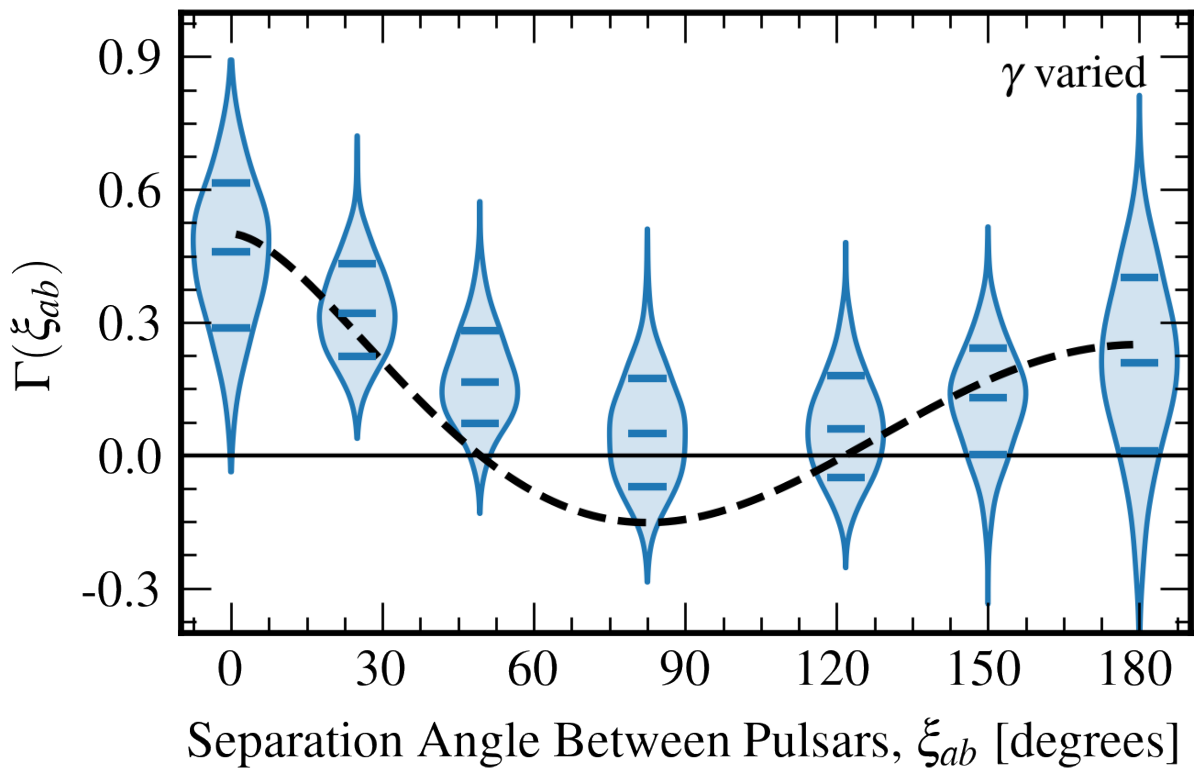
credits: Aurore Simonnet / NANOGrav

where we are

EVIDENCE FOR GWB

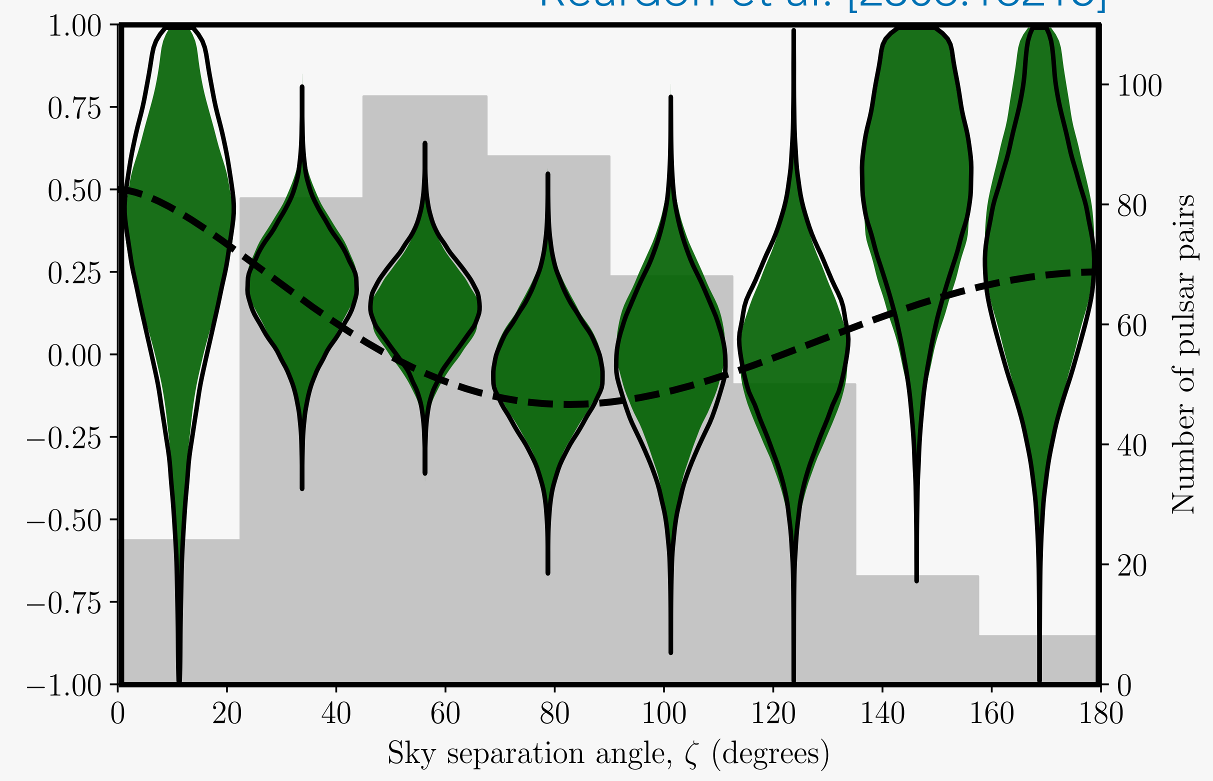
NANOGrav:
68 pulsars, 16yr of data
~3-4σ significance

Agazie et al. [2306.16213]



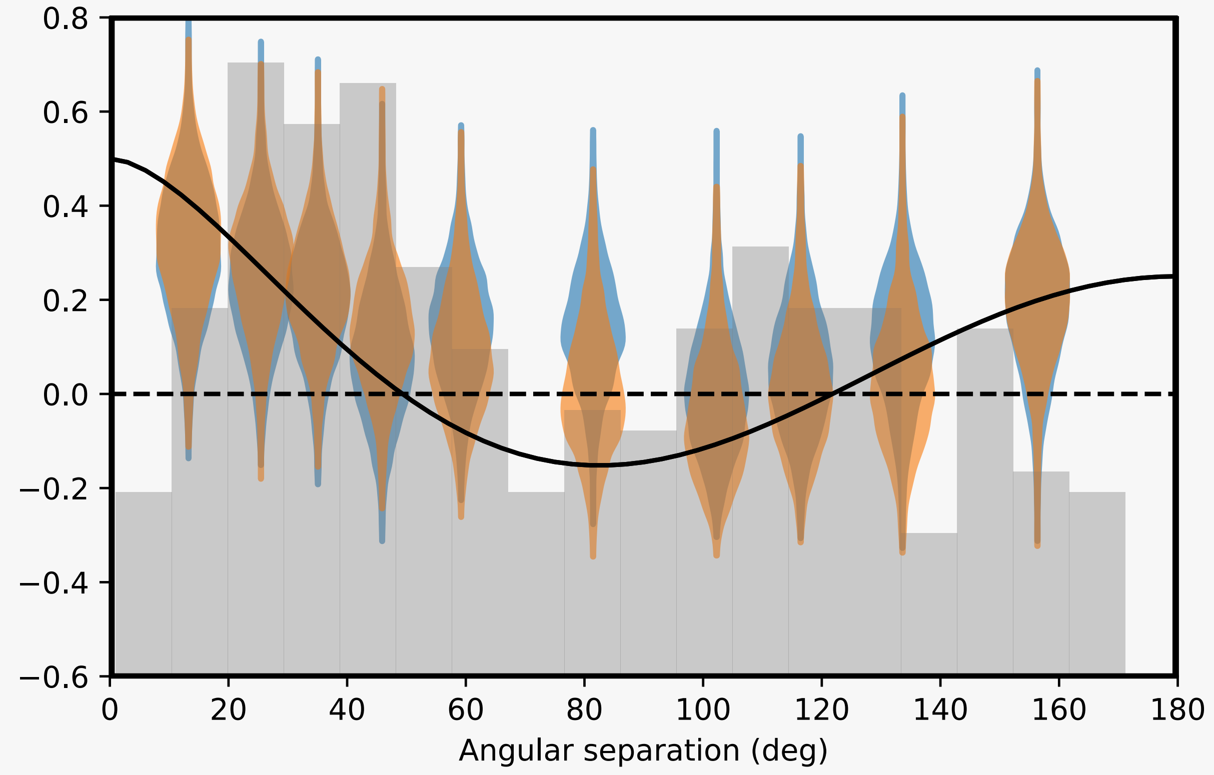
PPTA:
32 pulsars, 18yr of data
~2σ significance

Reardon et al. [2306.16215]



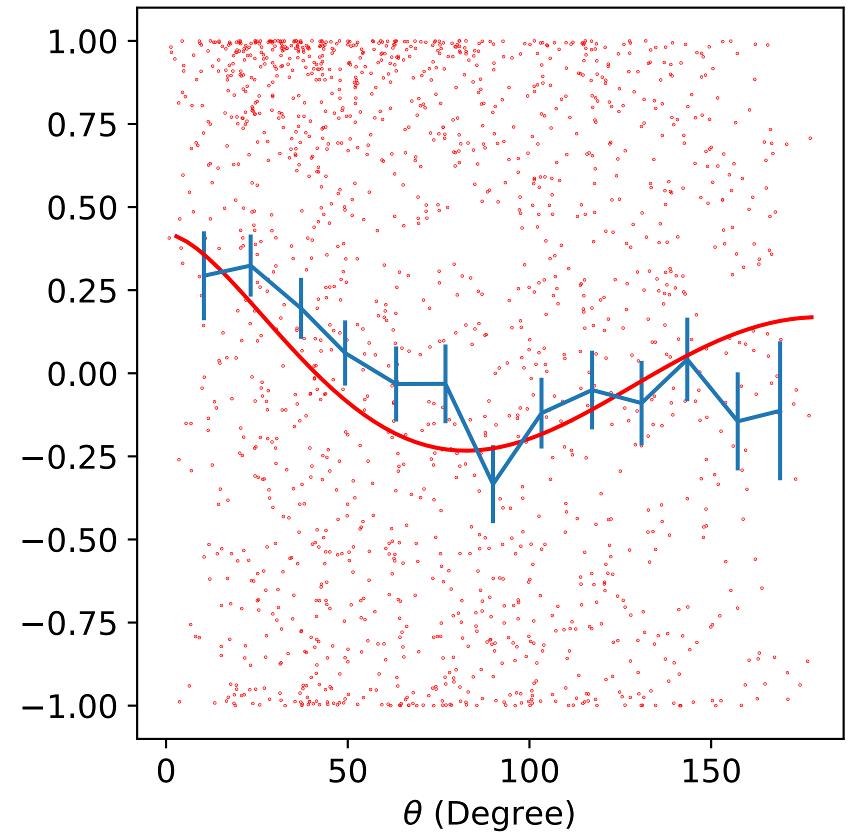
EPTA + InPTA:
25 pulsars, 24yr of data
~3σ significance

Antoniadis et al. [2306.16214]



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

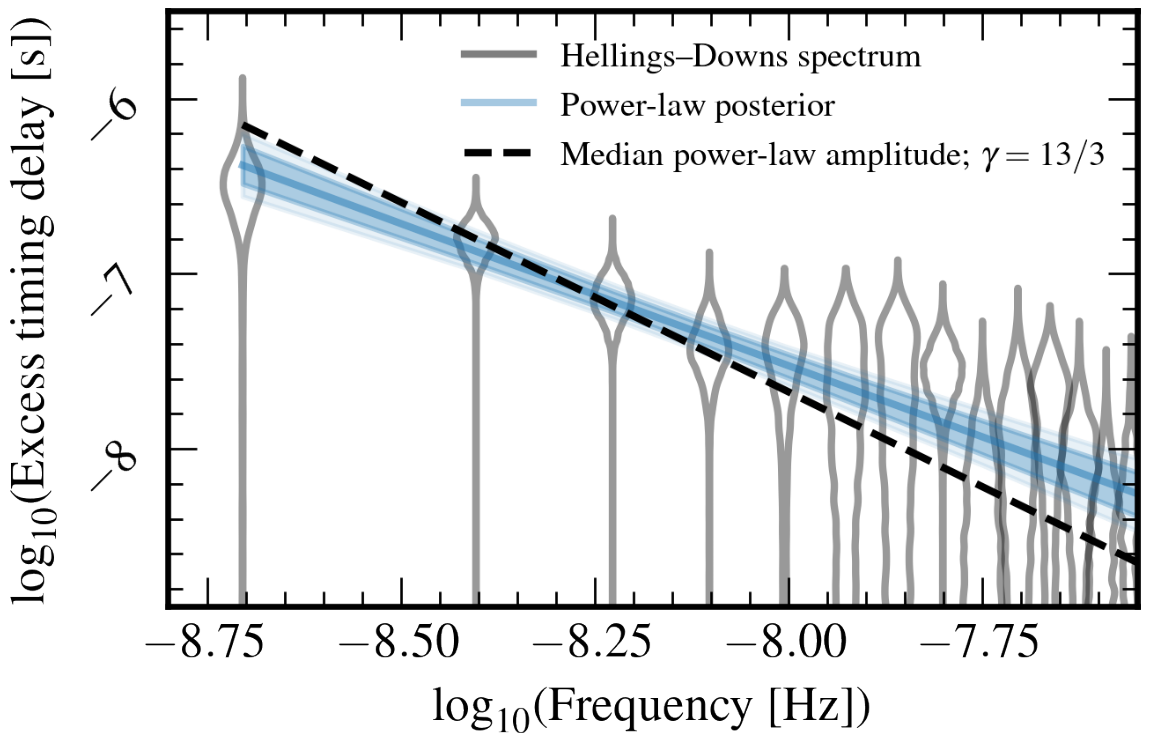
Xu et al. [2306.16216]

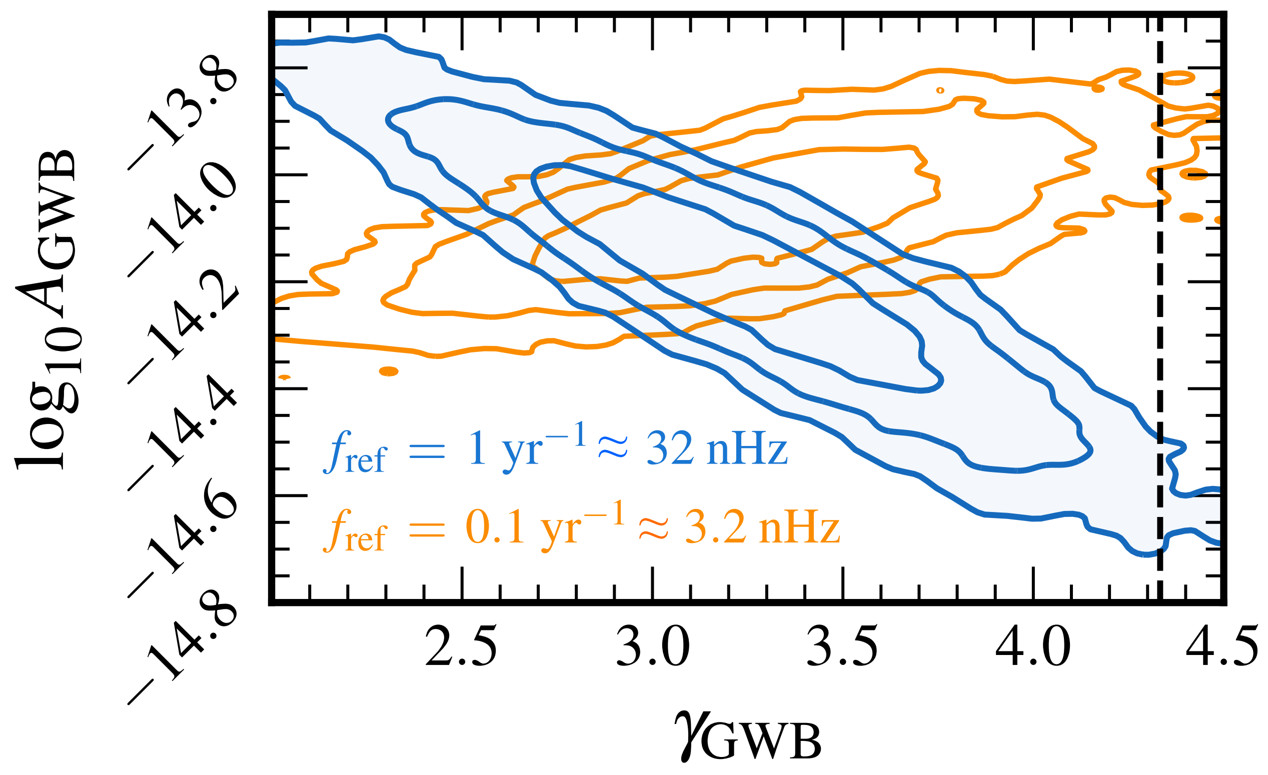


SPECTRUM

NANOGrav

Agazie et al. [2306.16213]





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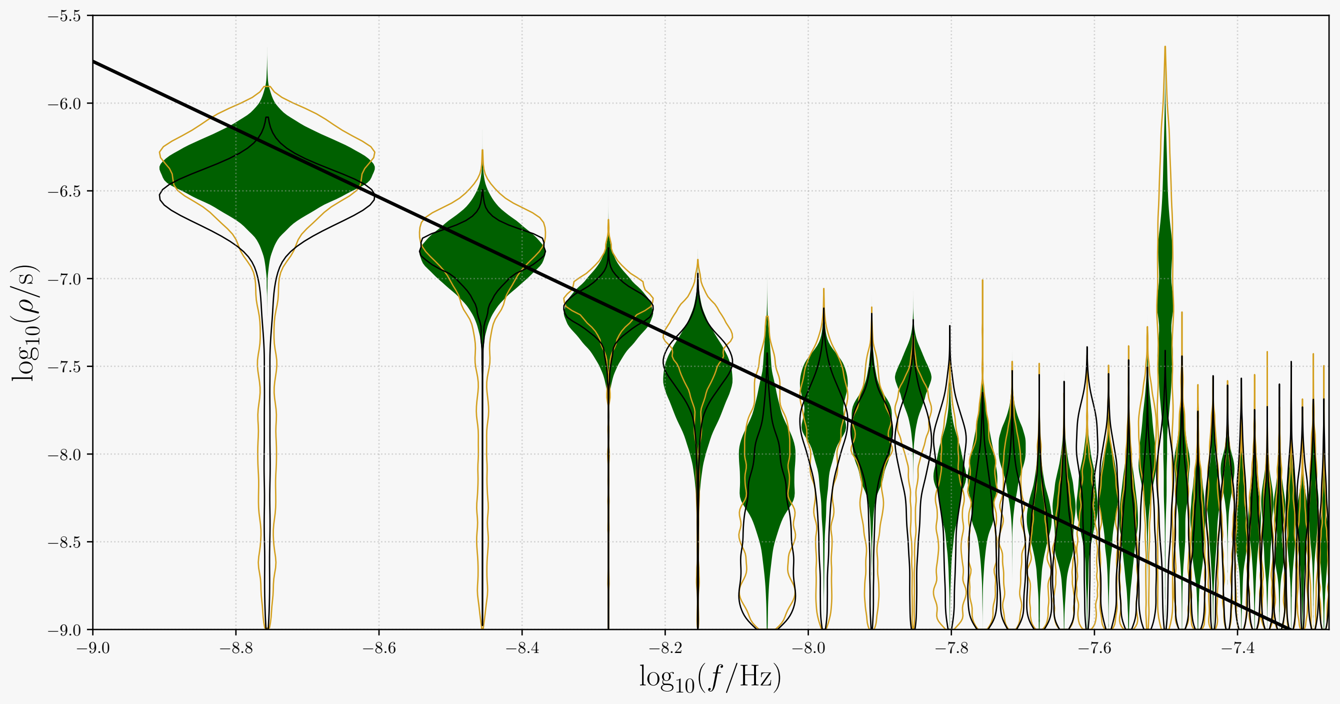

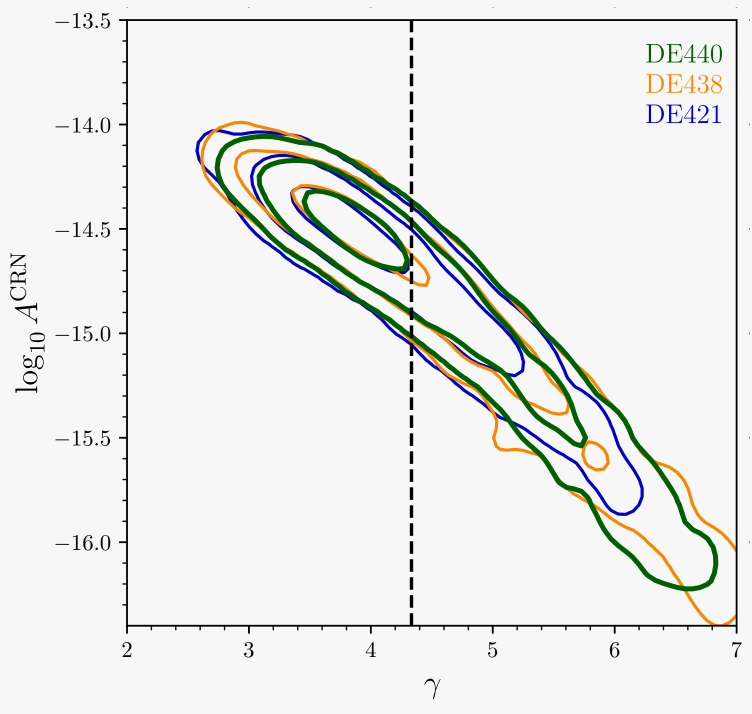

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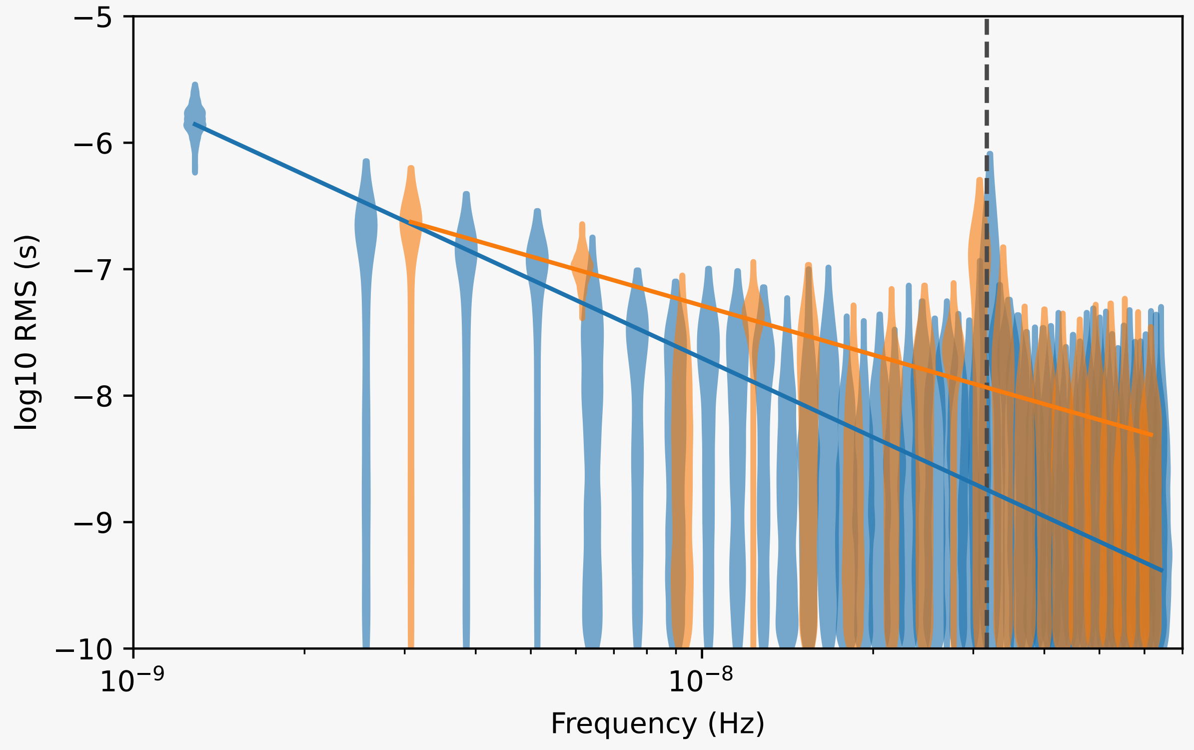

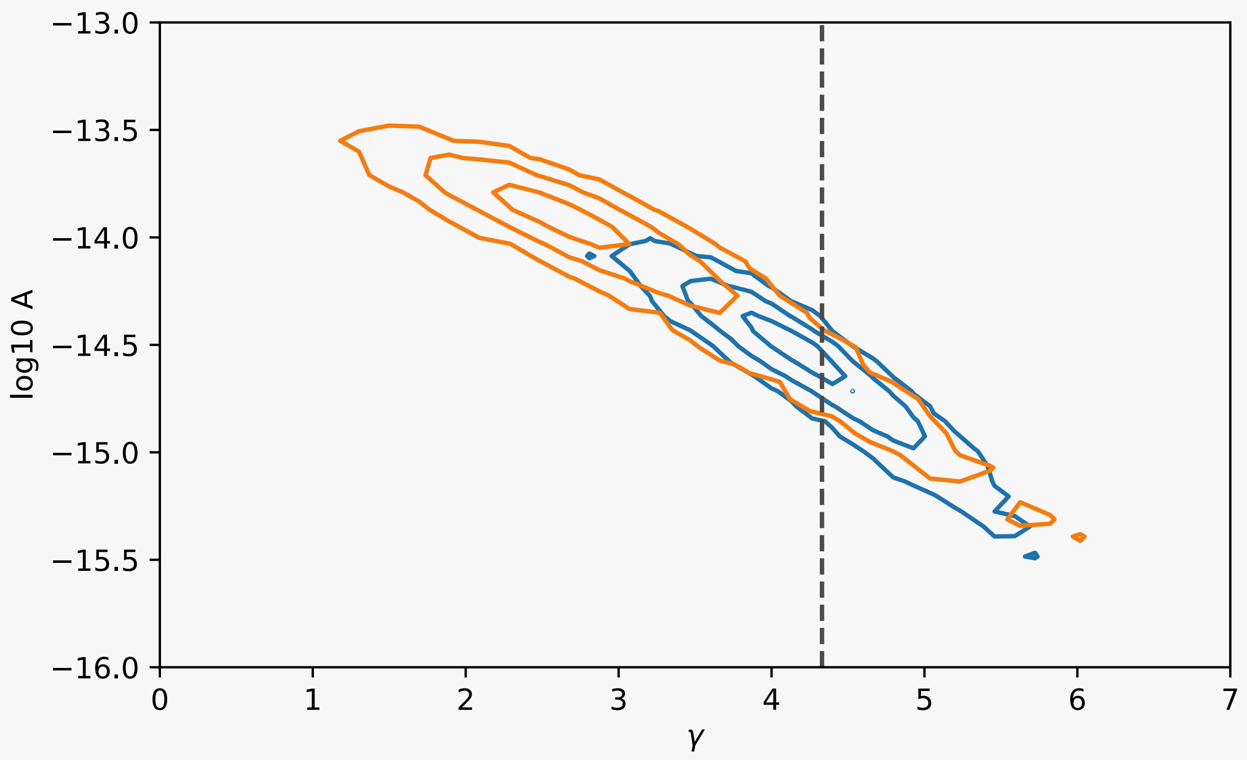

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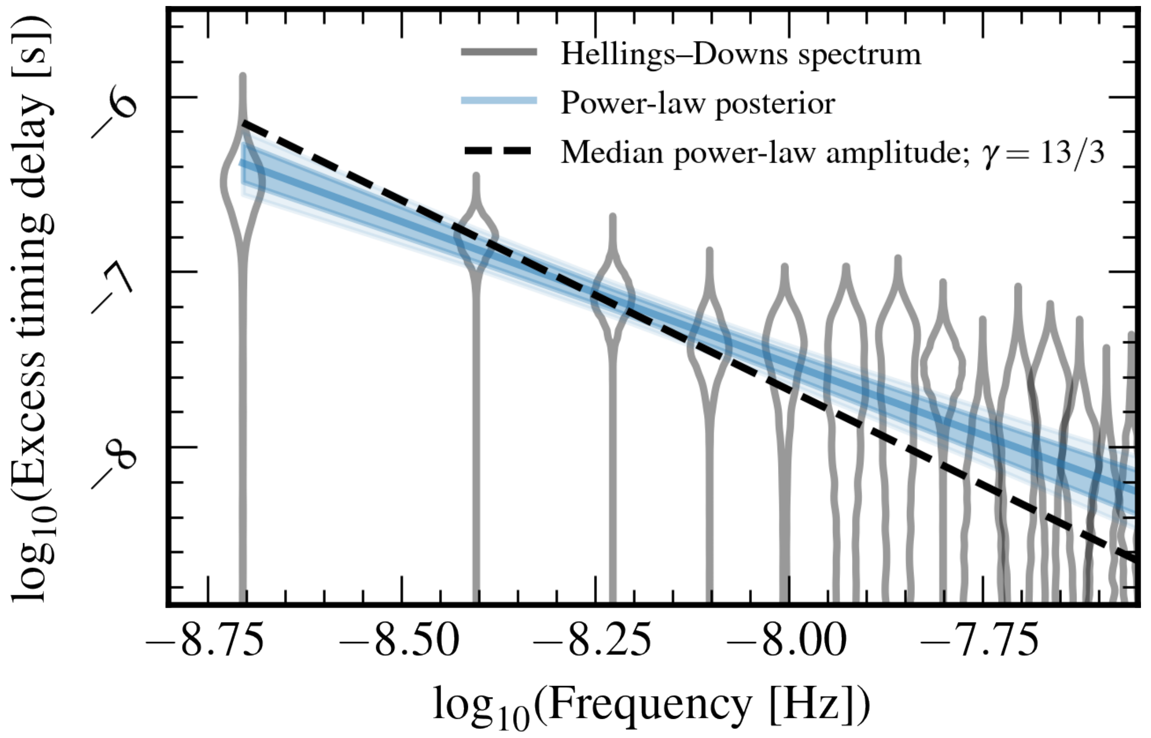

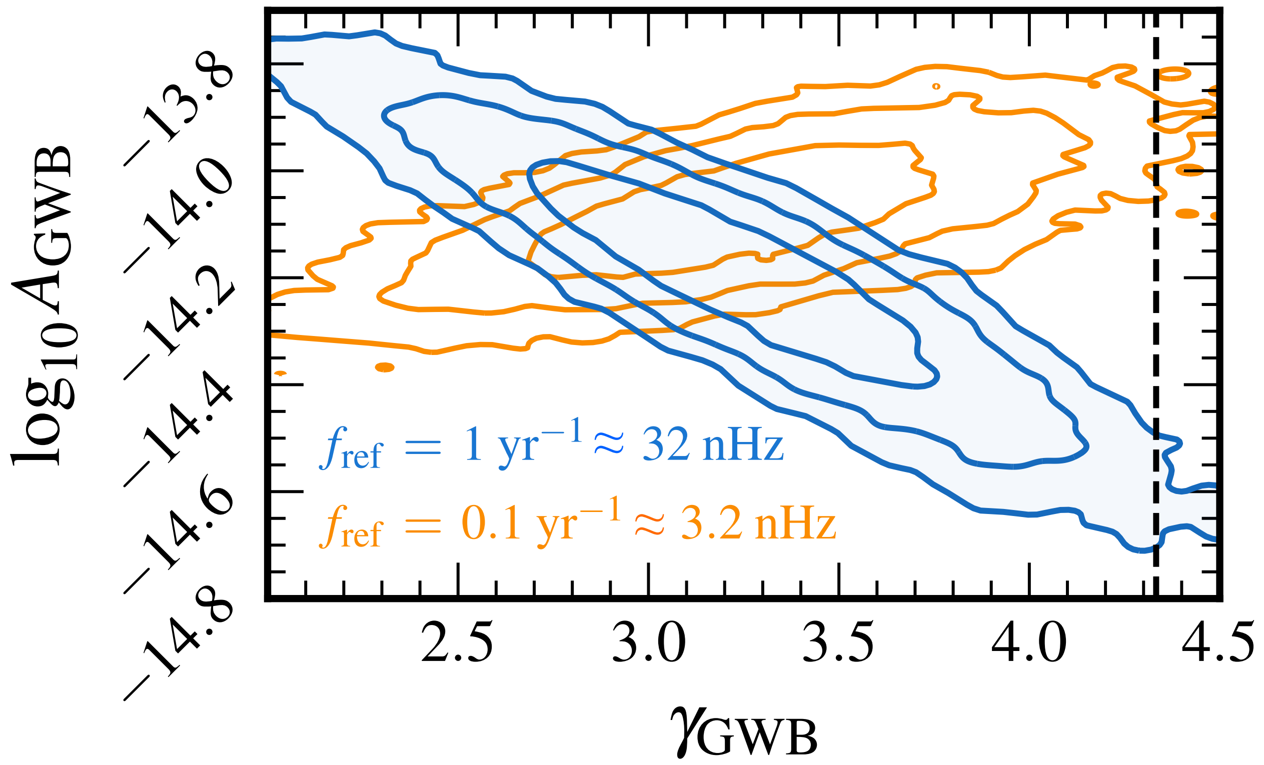

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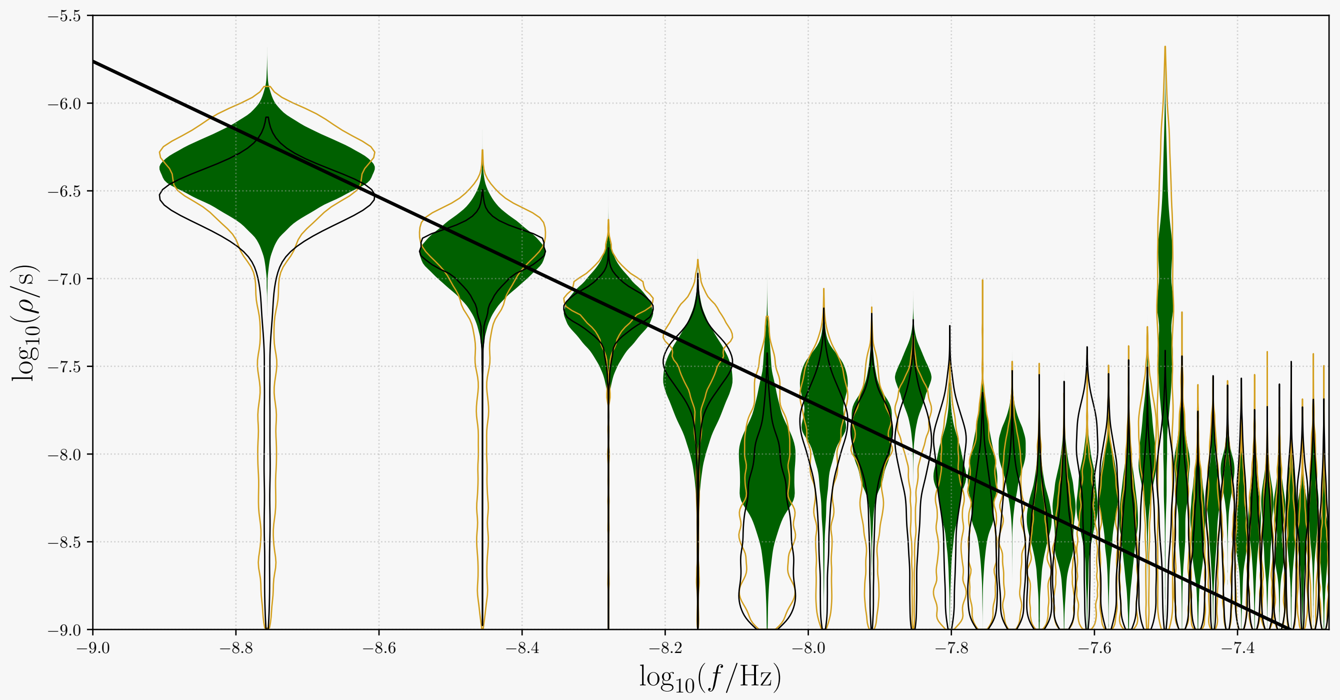

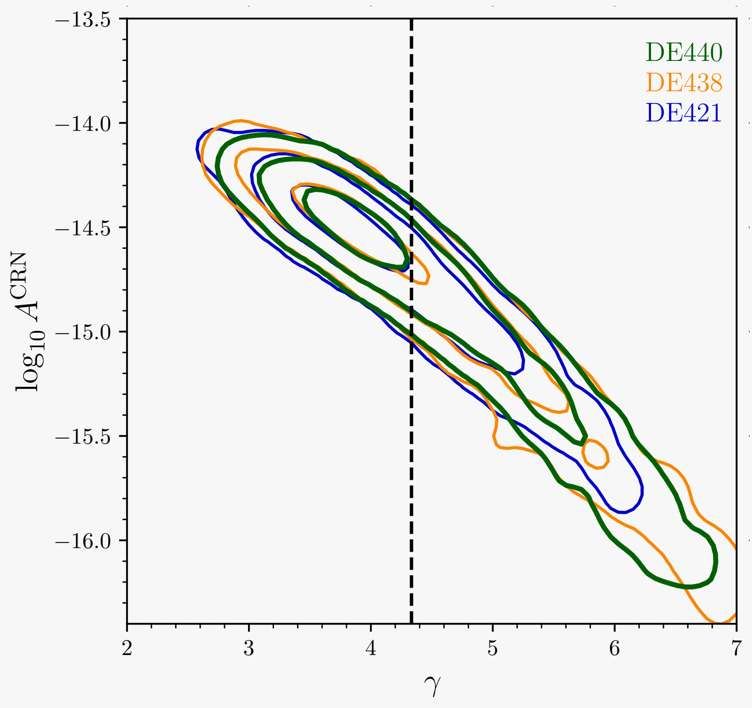

EPTA + InPTA

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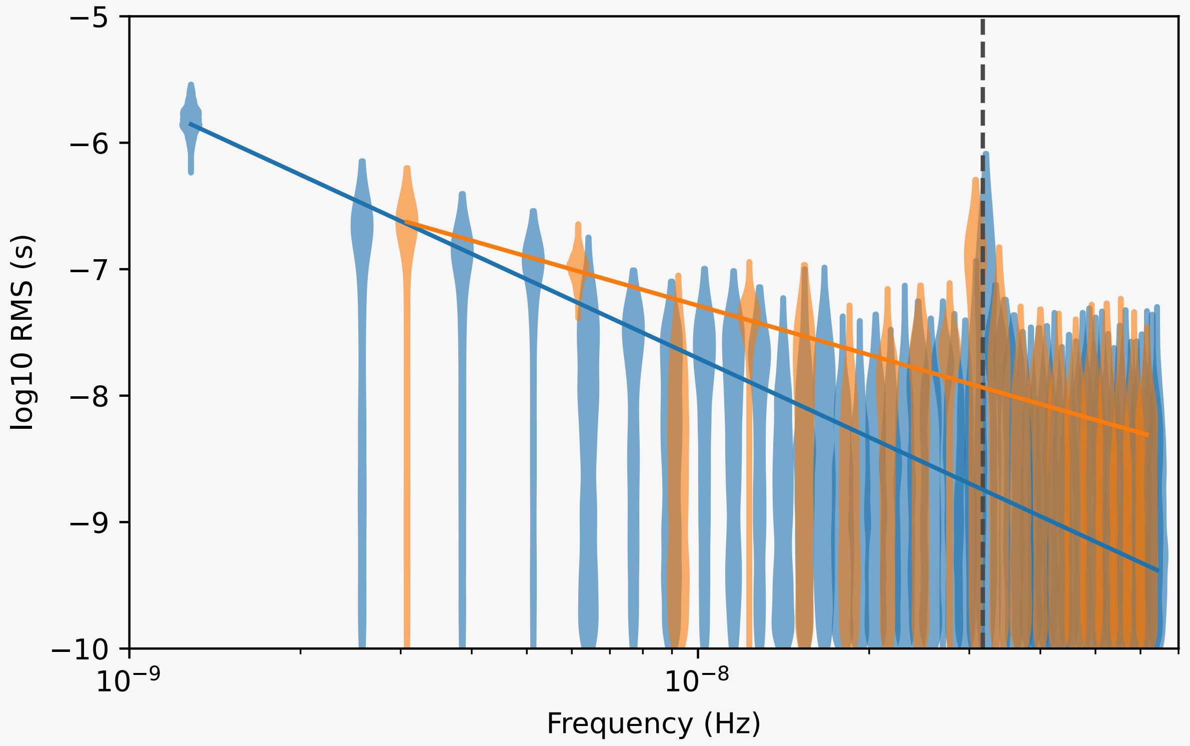

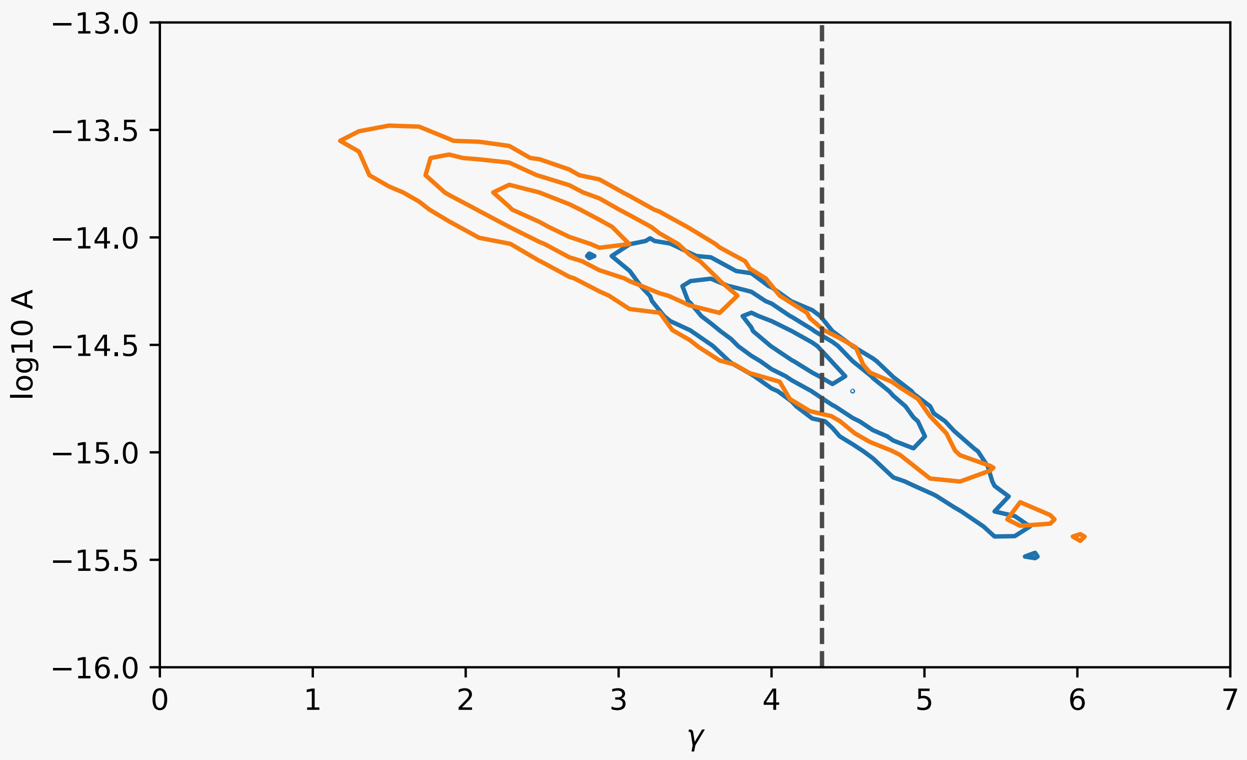

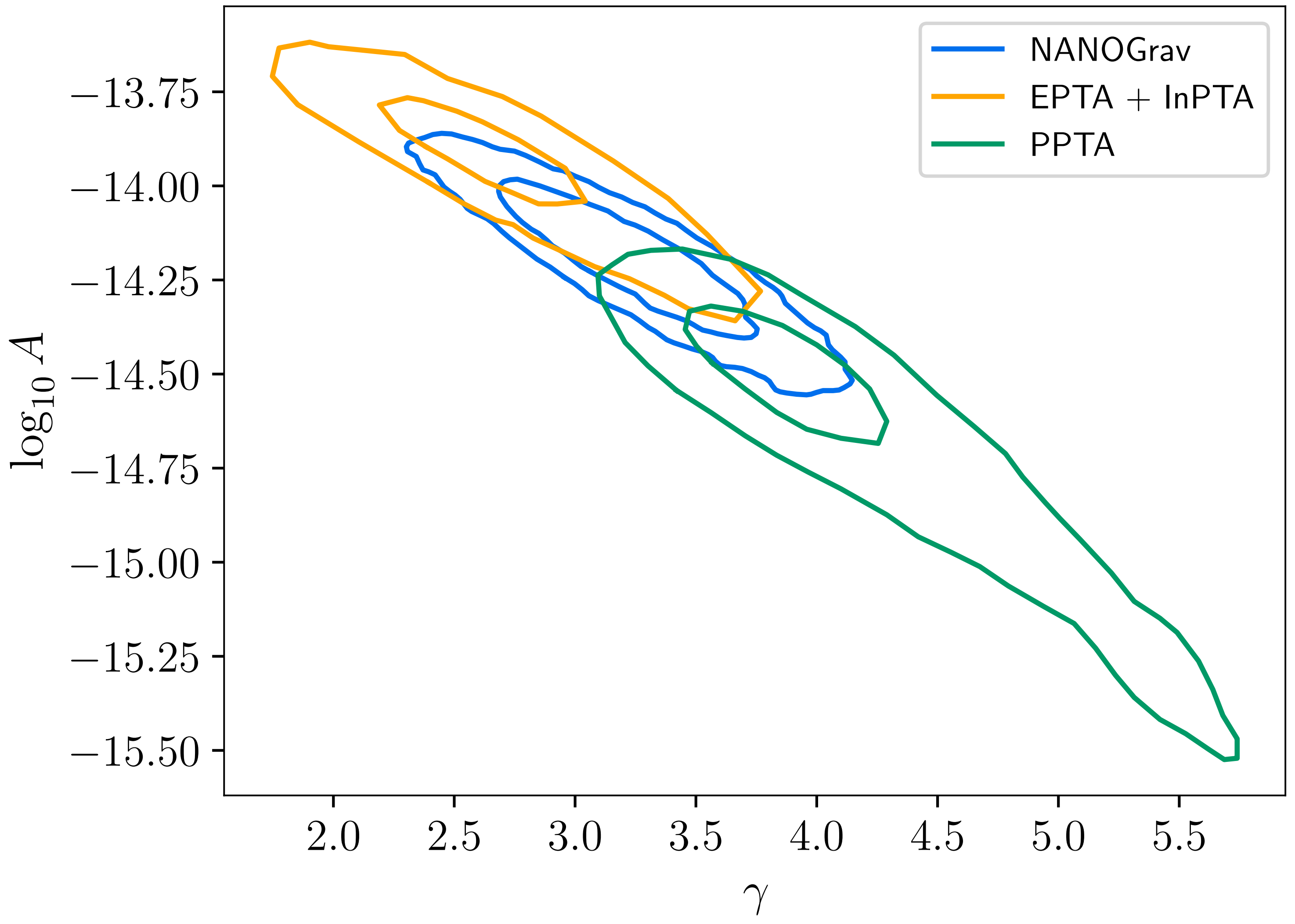

ANISOTROPIES

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

overlap reduction function

PTA response function

GWB power

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

Agazie et al. [2306.16221]

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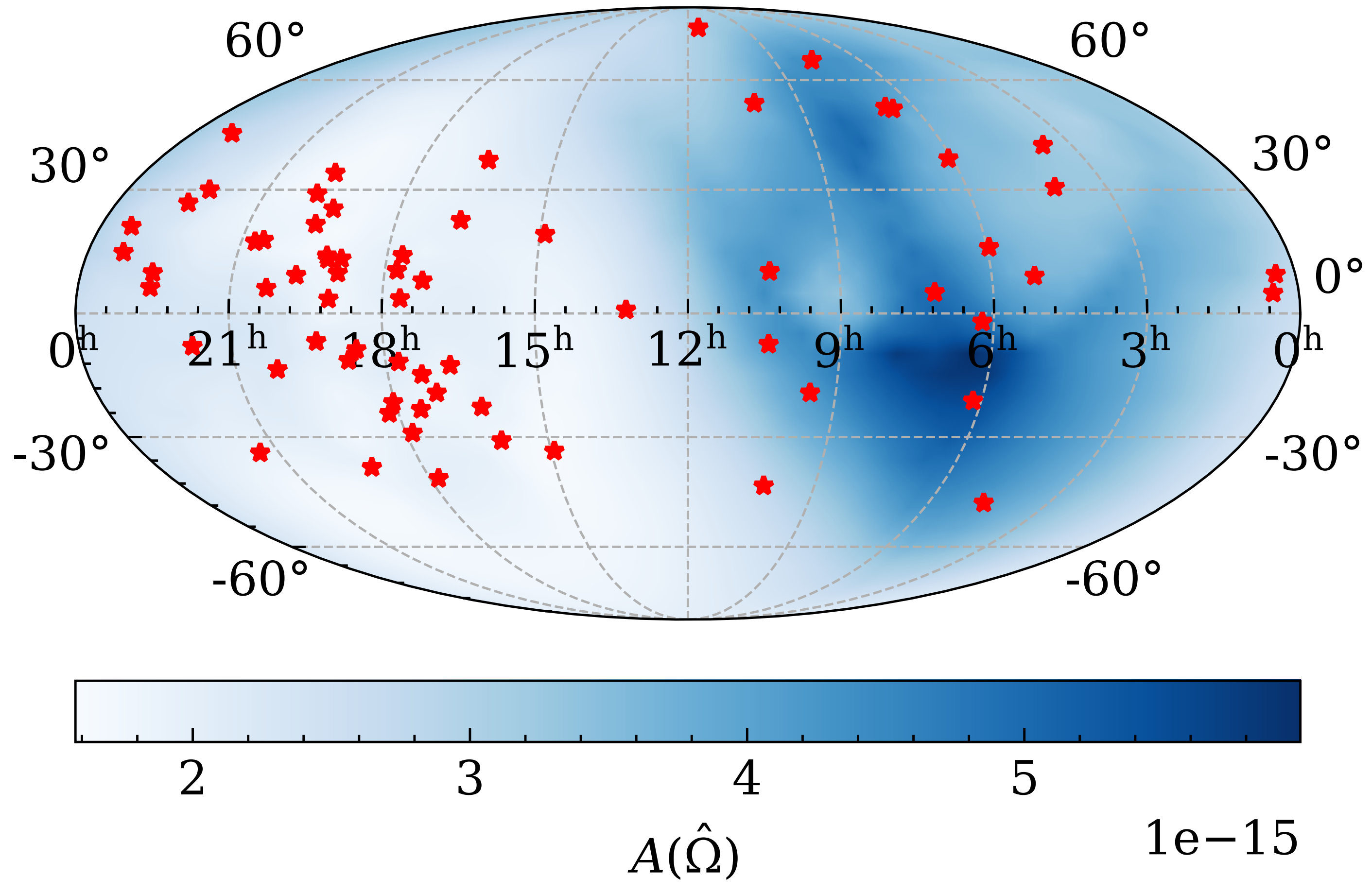
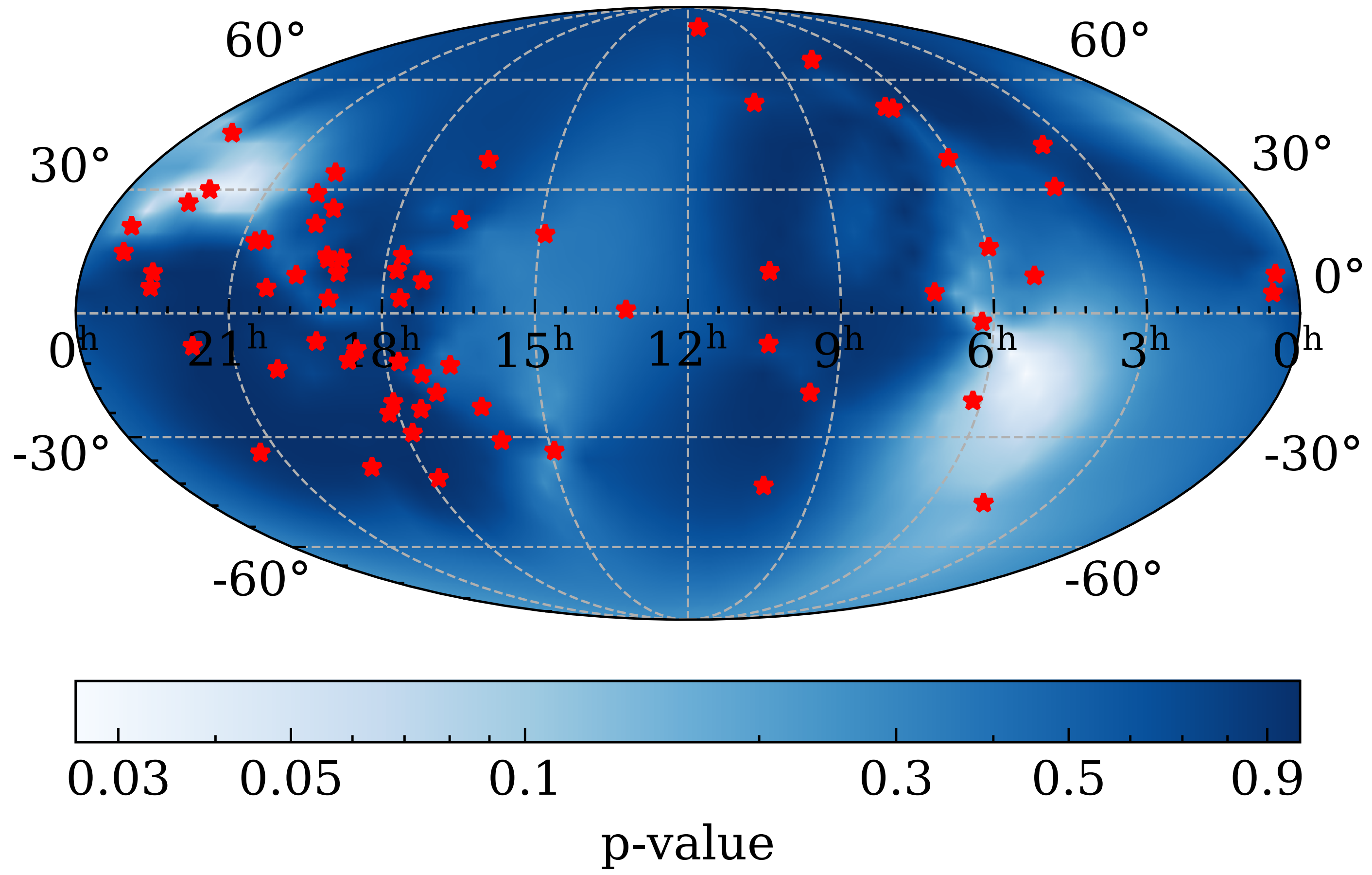




Agazie et al. [2306.16221]

ANISOTROPIES

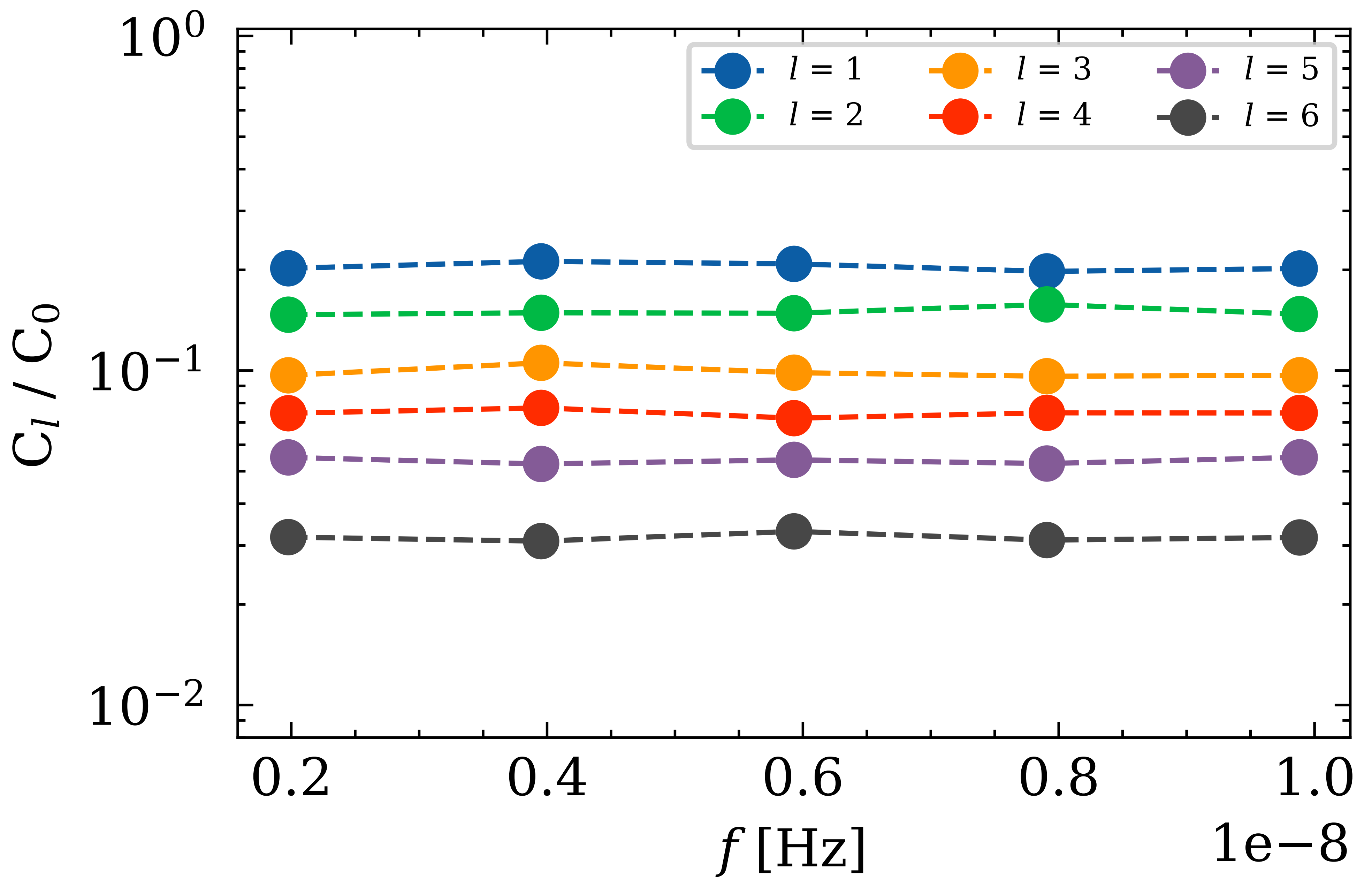
$$P_k = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} c_{lm} Y_{lm}(\hat{\Omega}_k) \qquad C_l = \frac{1}{2l+1} \sum_{m=-l}^{l} |c_{lm}|^2$$

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

overlap reduction function

PTA response function

GWB power



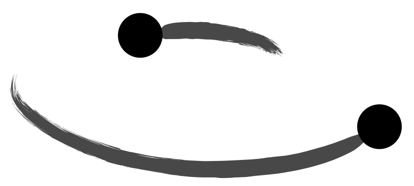
for P_k = const, Γ_{ab} reduces to the HD overlap reduction function

Agazie et al. [2306.16221]

CONTENDER #1

Graphics by Little Shadow

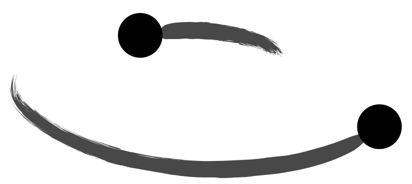
CONTENDER #1



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

Phinney 2001, Wyithe & Loeb 2003

CONTENDER #1



GW signal from individual SMBHB

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

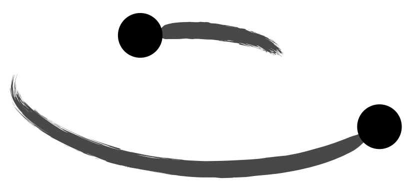
Phinney 2001, Wyithe & Loeb 2003

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

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

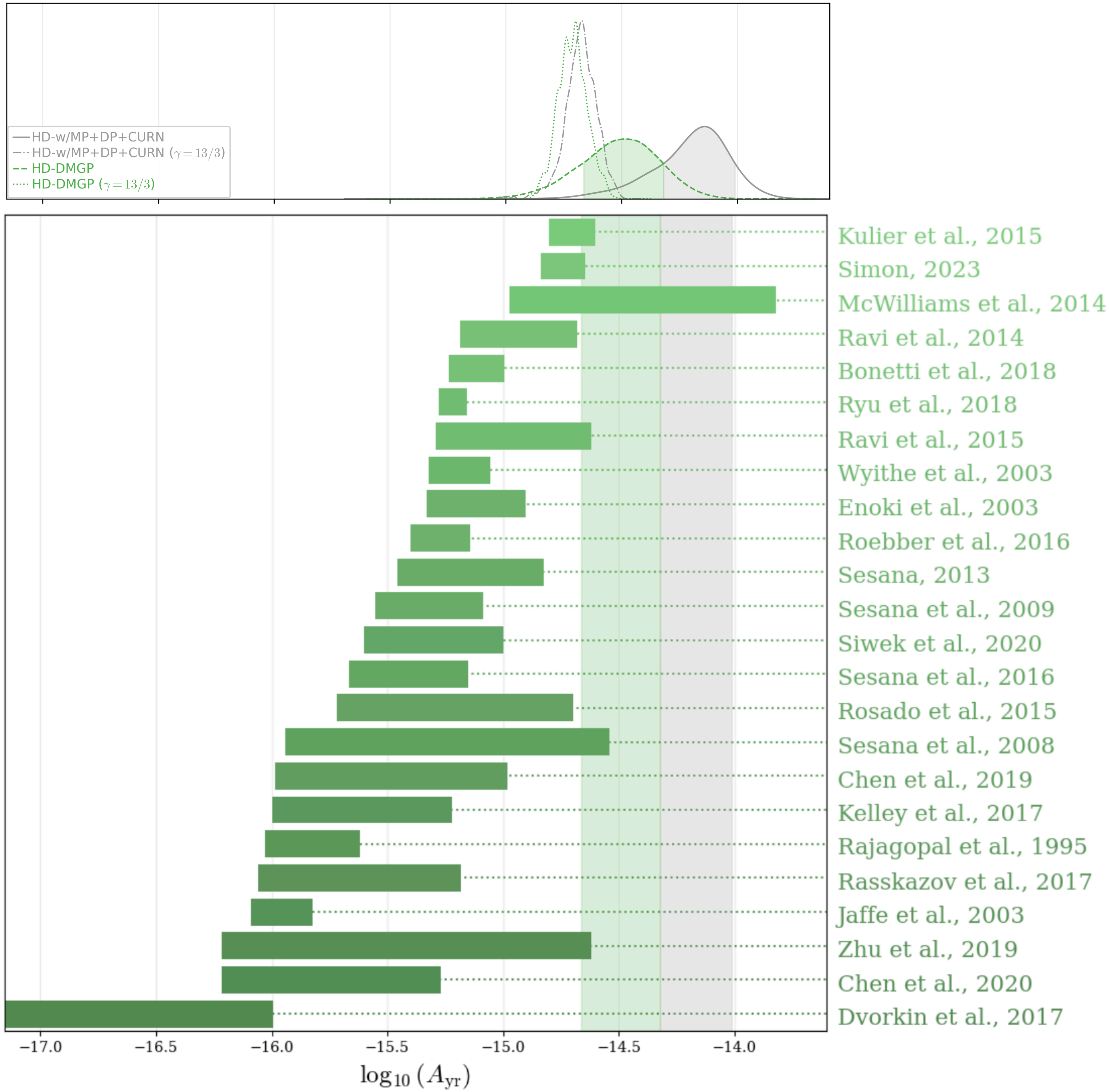
Finn & Thorne 2000

the SMBHB density depends on

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

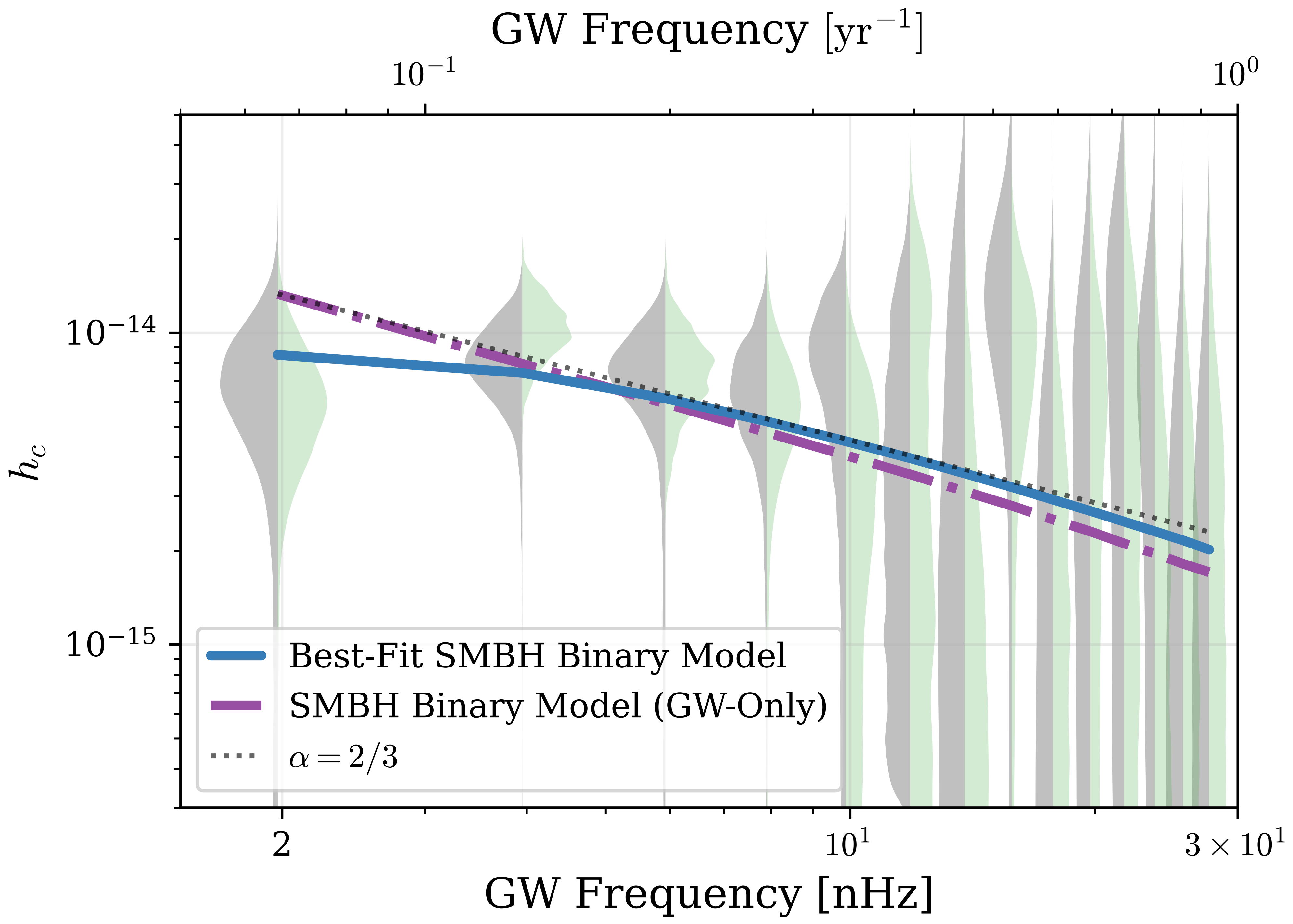
EXPECTATIONS

Agazie et al. [2306.16220]



ADJUSTING EXPECTATIONS

see **Luke's talk tomorrow** for more on this



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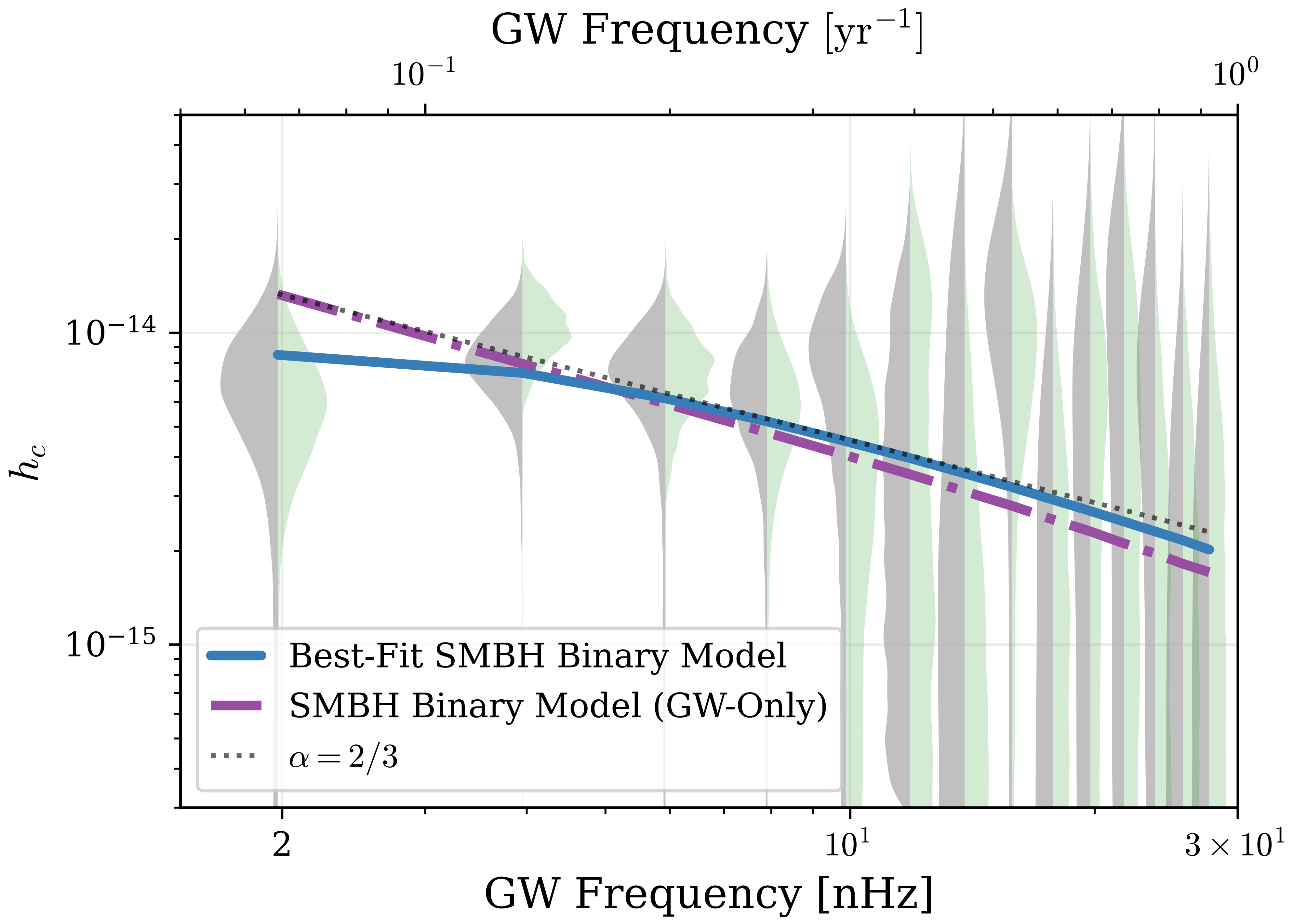

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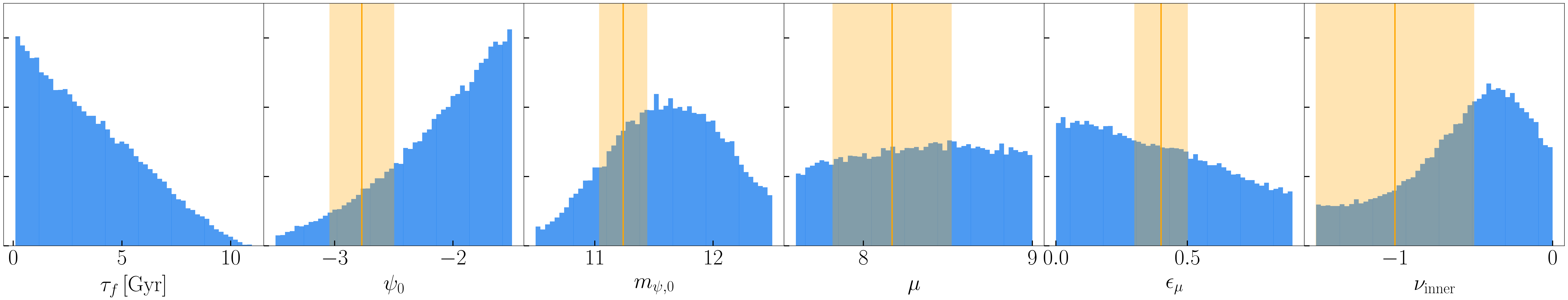
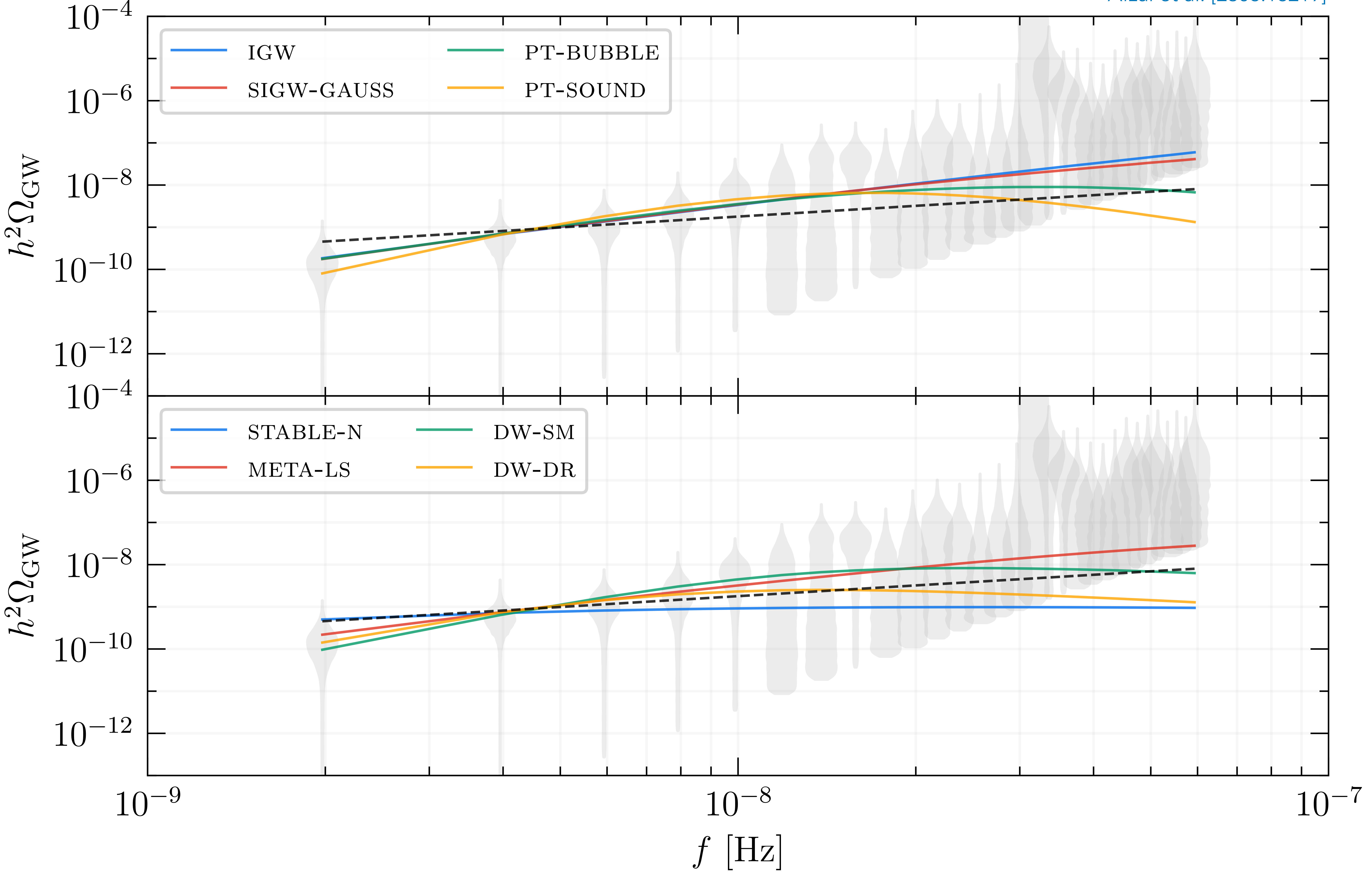


CONTENDER(s) #2

CONTENDER(s) #2

COSMOLOGICAL SIGNALS

Afzal et al. [2306.16219]



inflation

scalar induced GW

phase transitions

cosmic strings

domain walls

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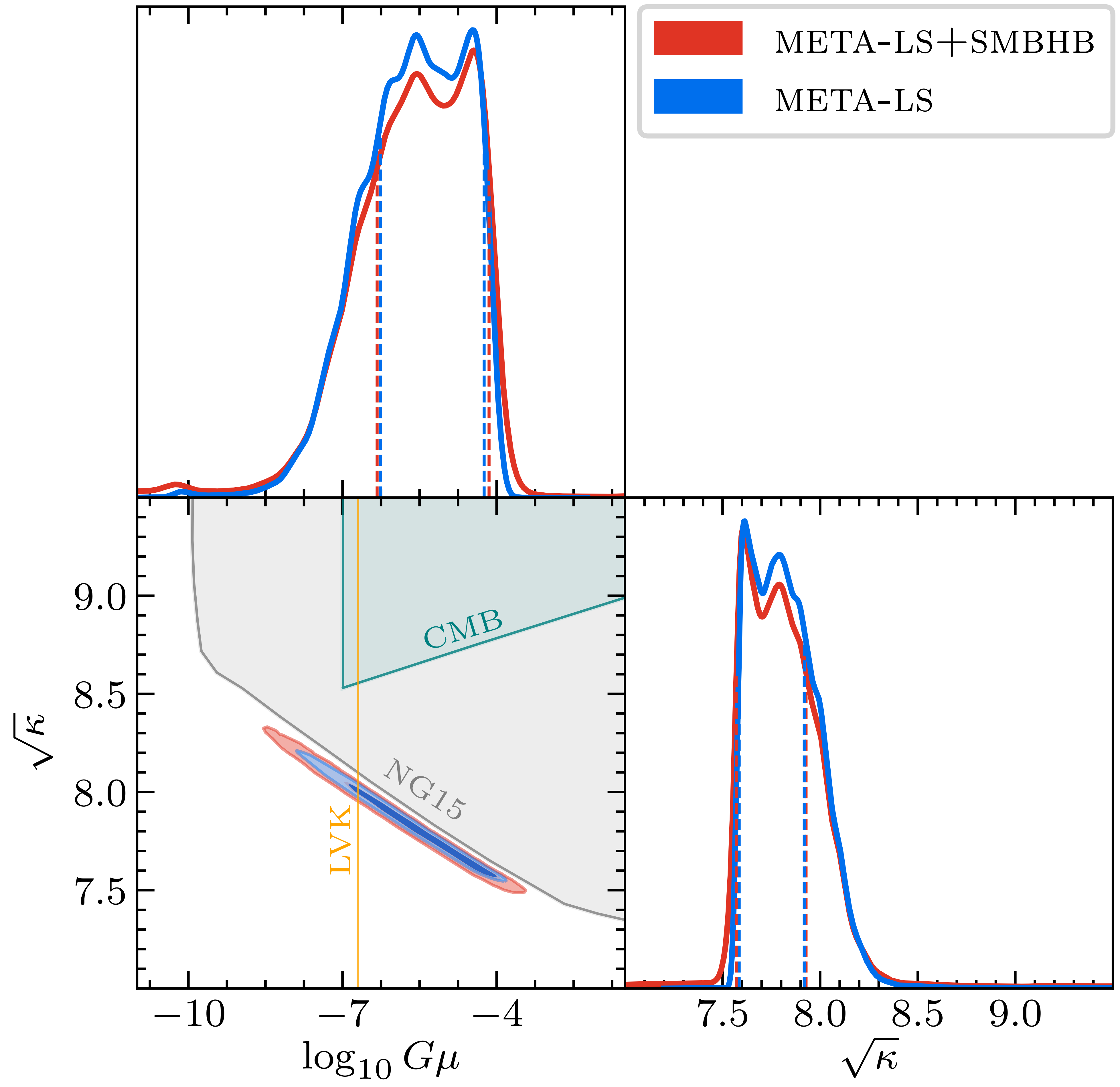

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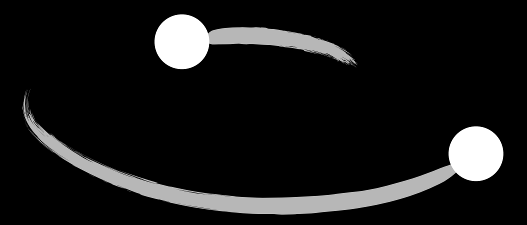
FACE-OFF



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

scalar induced GW

phase transitions

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domain walls

FACE-OFF

free parameters

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

VS

inflation

scalar induced GW

phase transitions

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domain walls

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

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

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

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

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

$$\mathcal{Z} = \int d\Theta \; \underbrace{P(\mathcal{D}|\Theta, \mathcal{H})}_{\text{likelihood function}} \times P(\Theta|\mathcal{H})$$

FACE-OFF

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FACE-OFF

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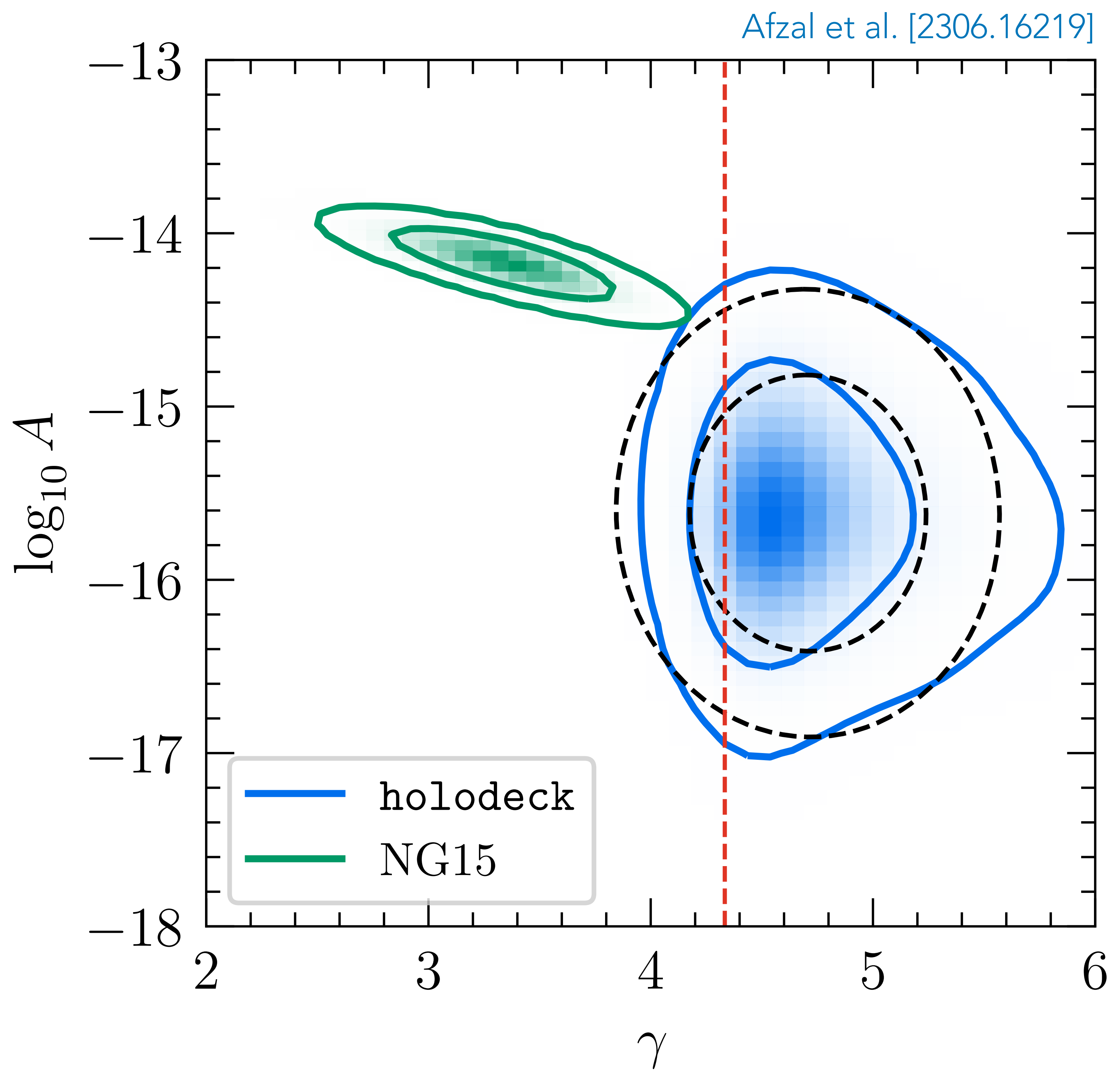
likelihood function

prior distributions



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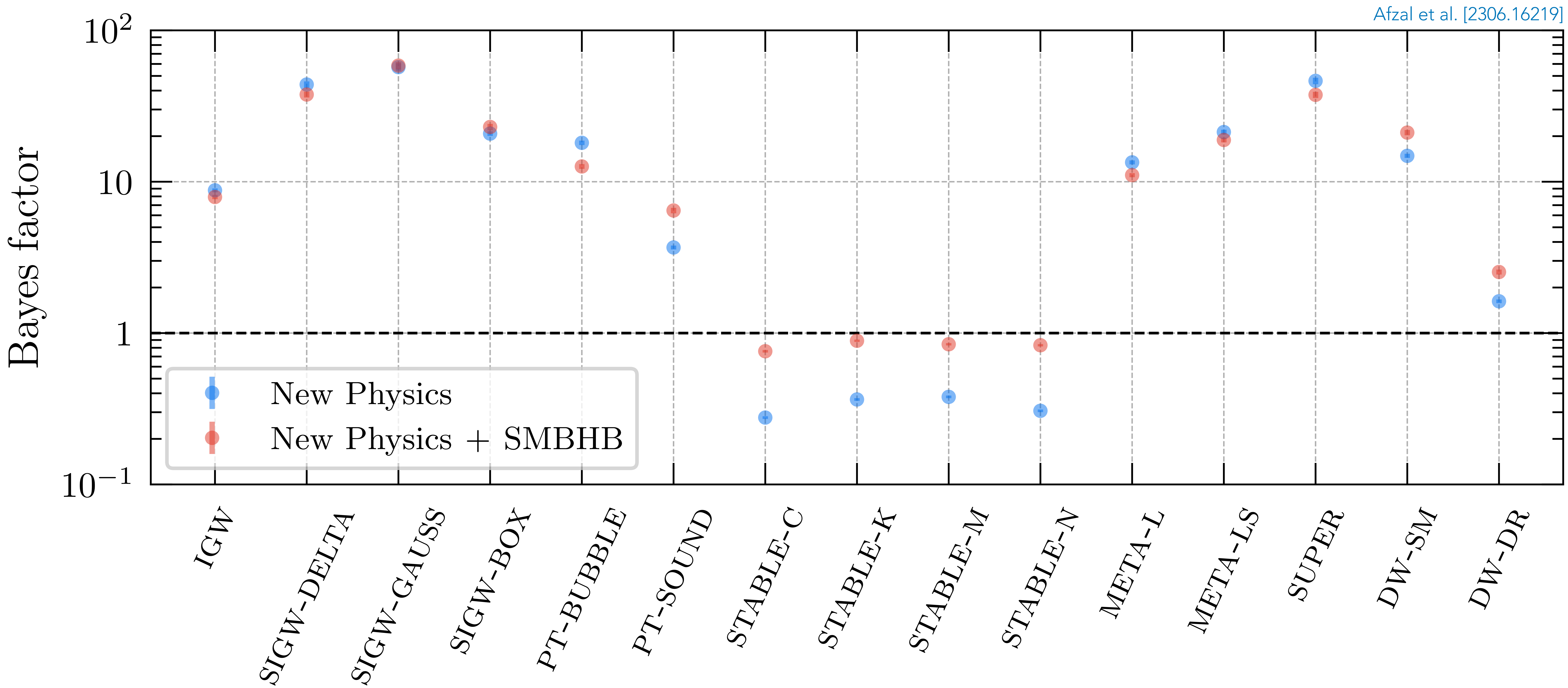

Afzal et al. [2306.16219]
10^2
10
1
10^{-1}
Bayes factor
New Physics
New Physics + SMBHB
IGW
SIGW-DELTA
SIGW-GAUSS
SIGW-BOX
PT-BUBBLE
PT-SOUND
STABLE-C
STABLE-K
STABLE-M
STABLE-N
META-L
META-LS
SUPER
DW-SM
DW-DR

PTArcade

toy model

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

Step 1

```
pip 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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ptarcade -m model.py
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PTArcade

Step 1

toy model

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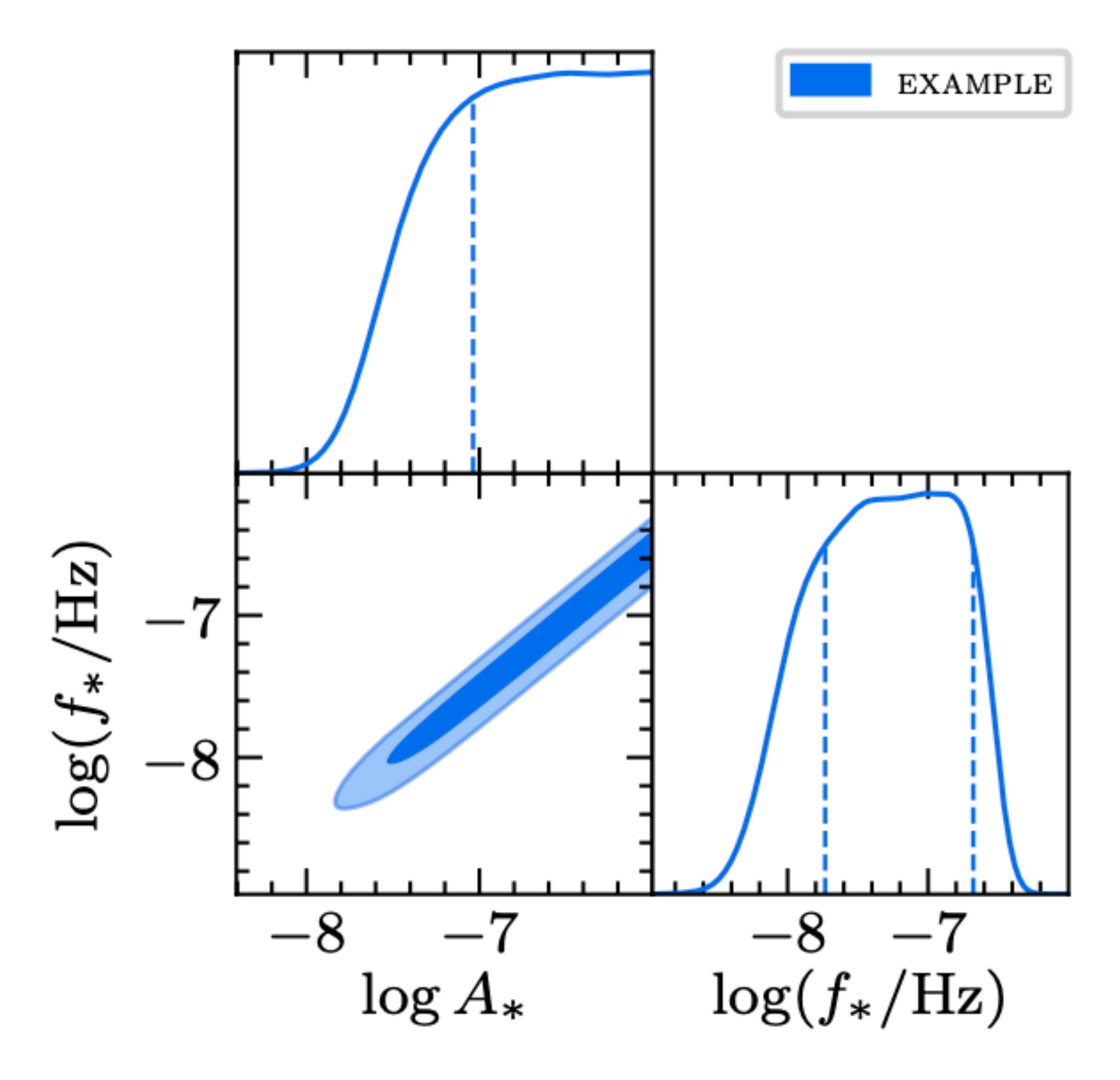
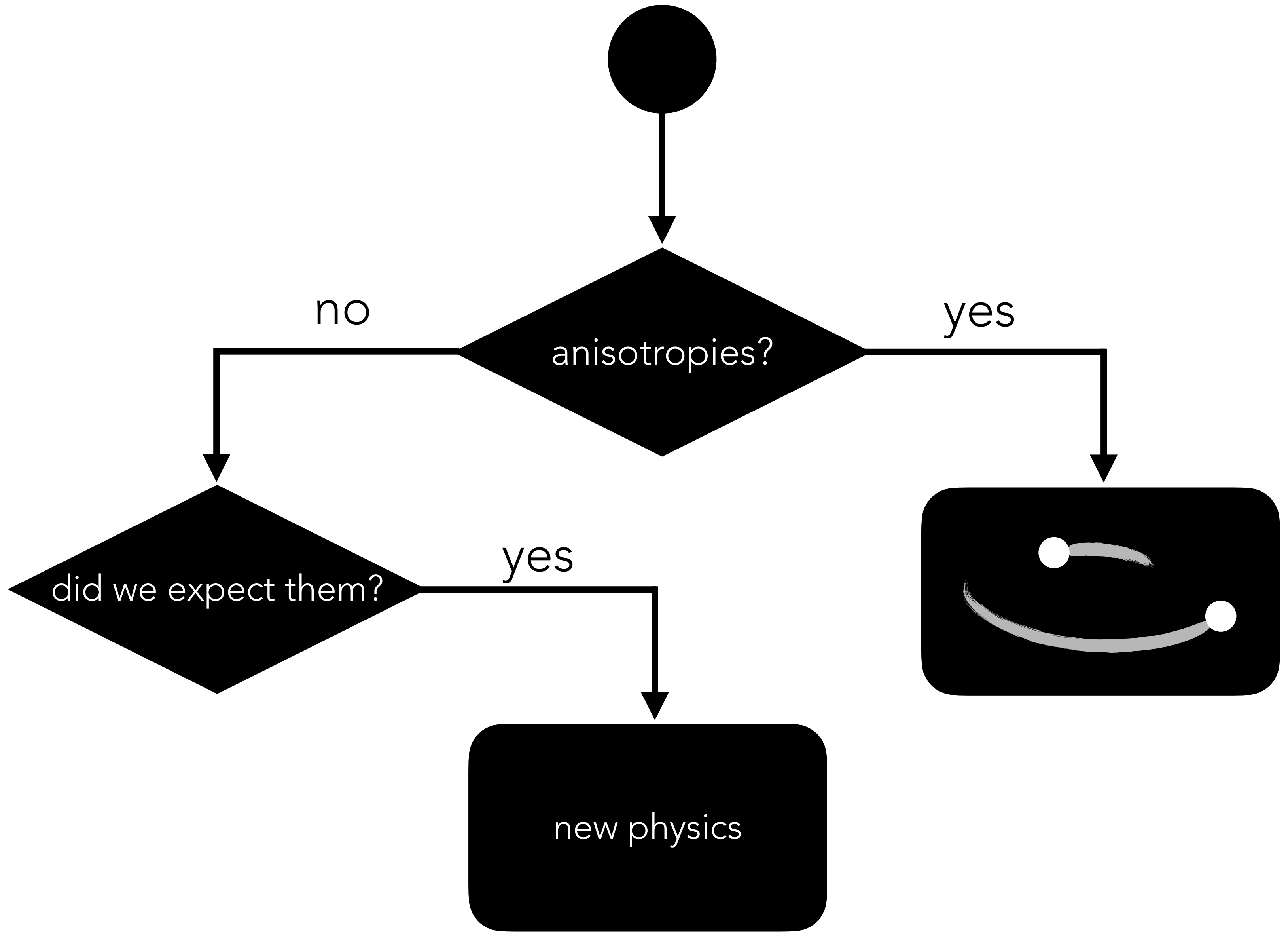


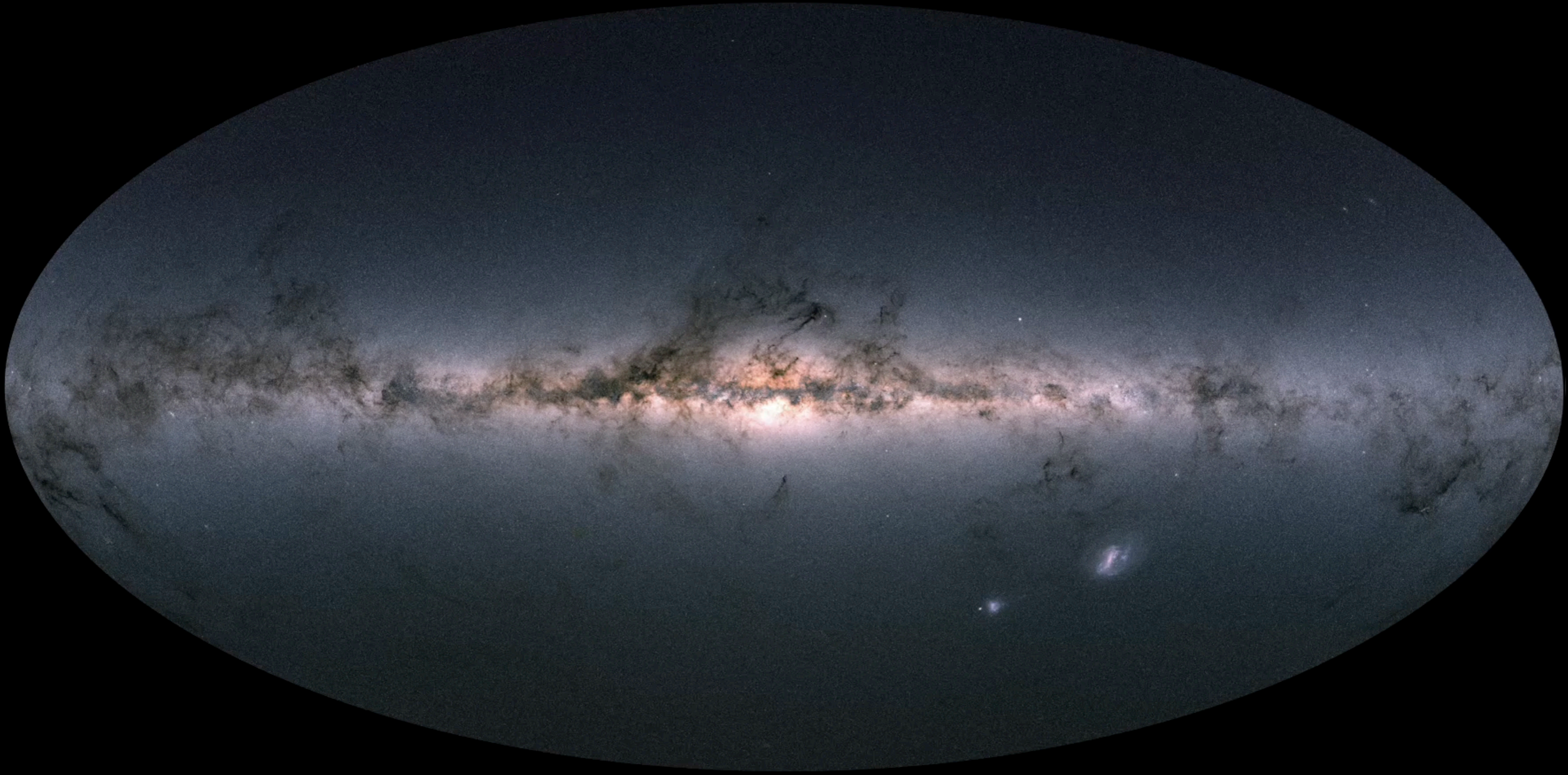

```
ptarcade -m model.py
```

where we are going

SMBHB or NEW PHYSICS?

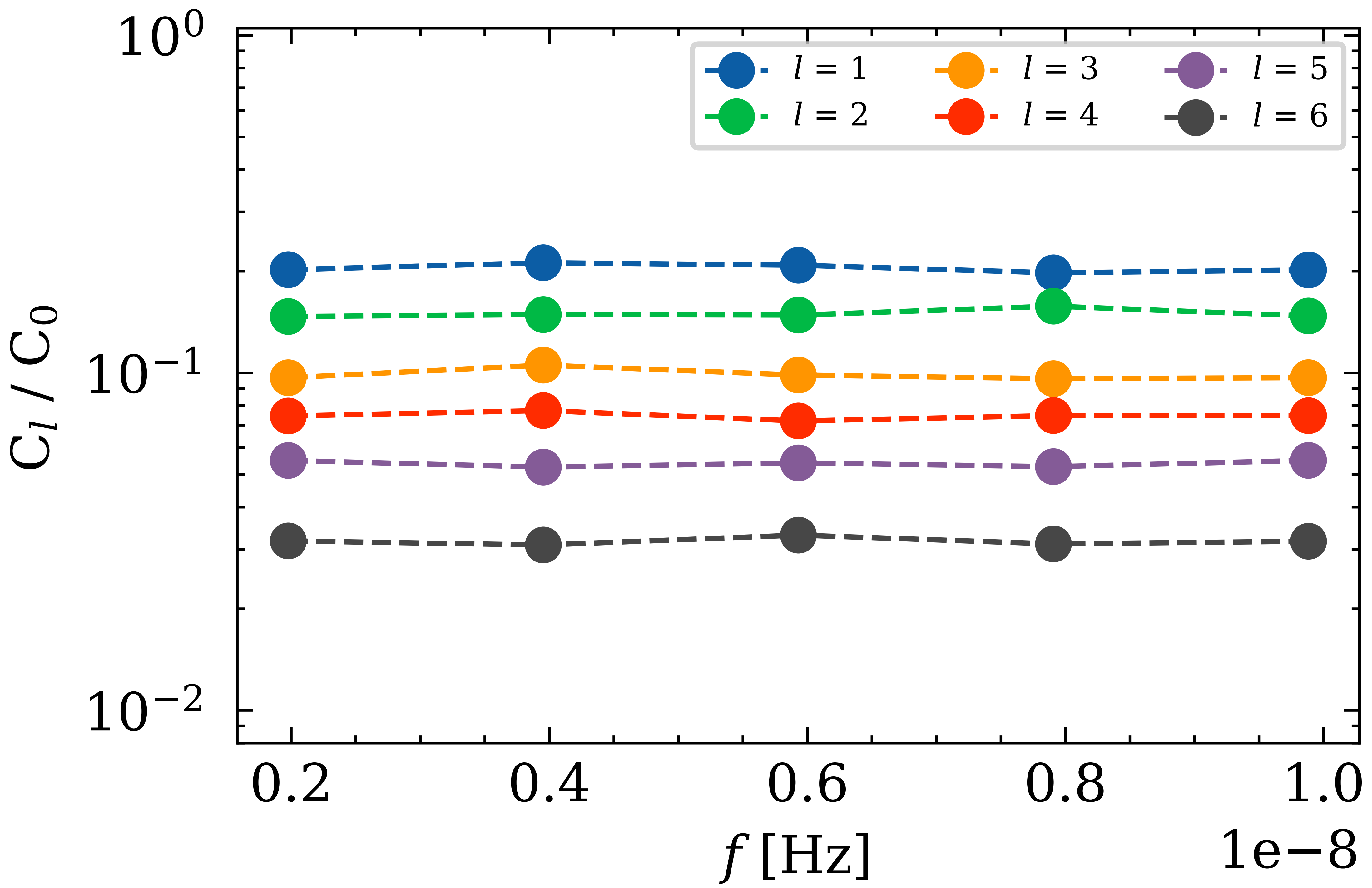


ANISOTROPIES



Credit: ESA/Gaia/DPAC

ANISOTROPIES



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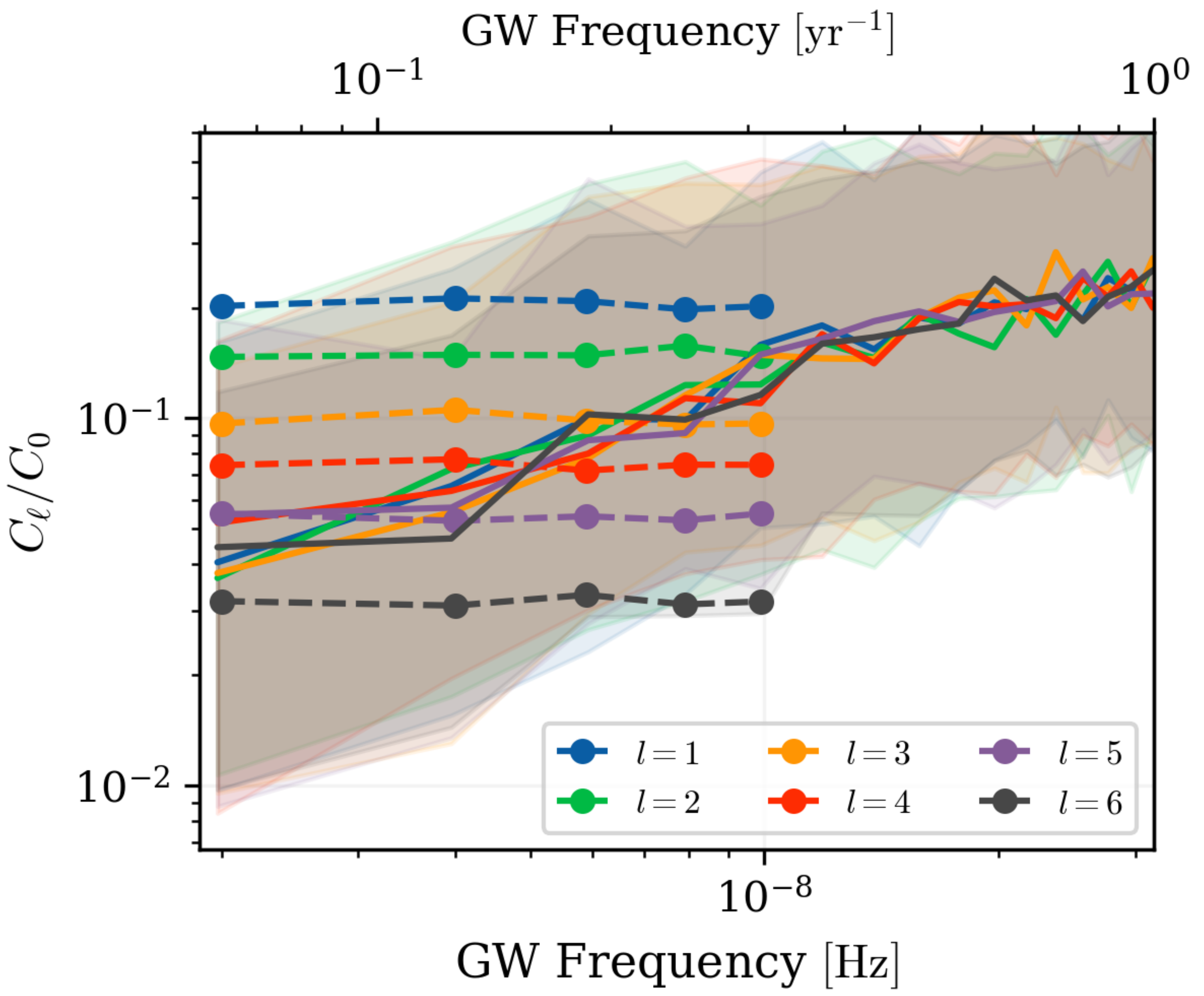
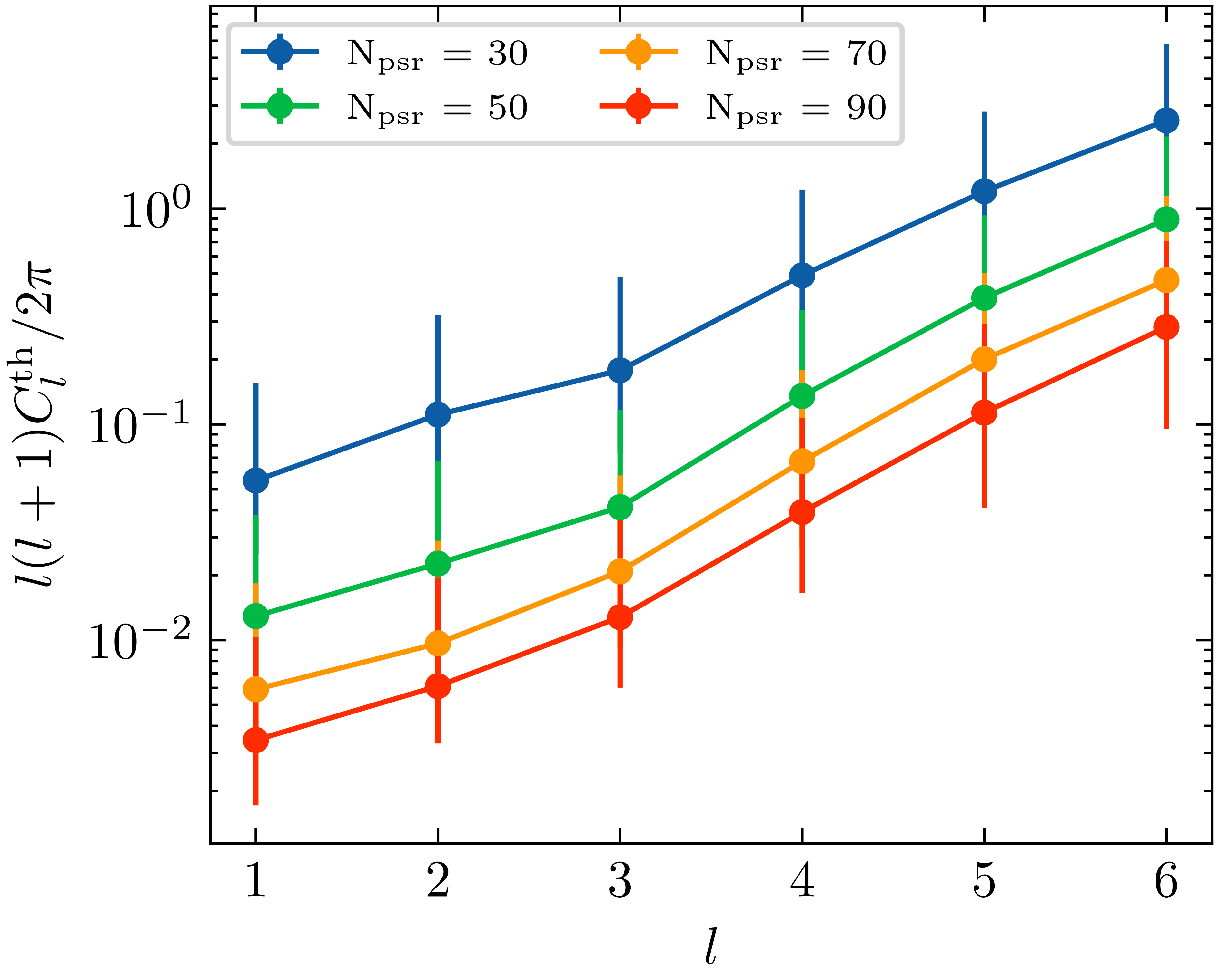
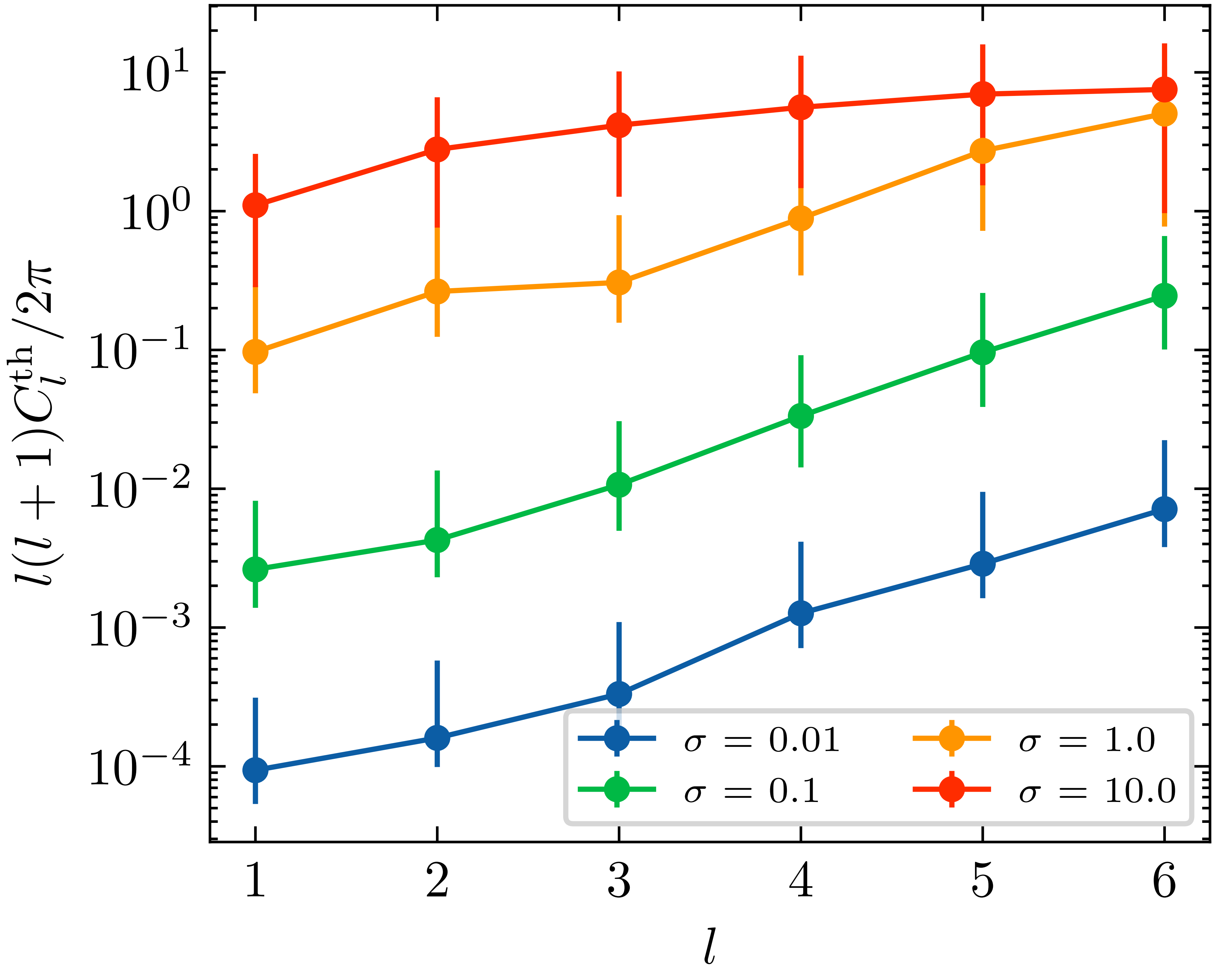


ANISOTROPIES



Pol et al. [2206.09936]



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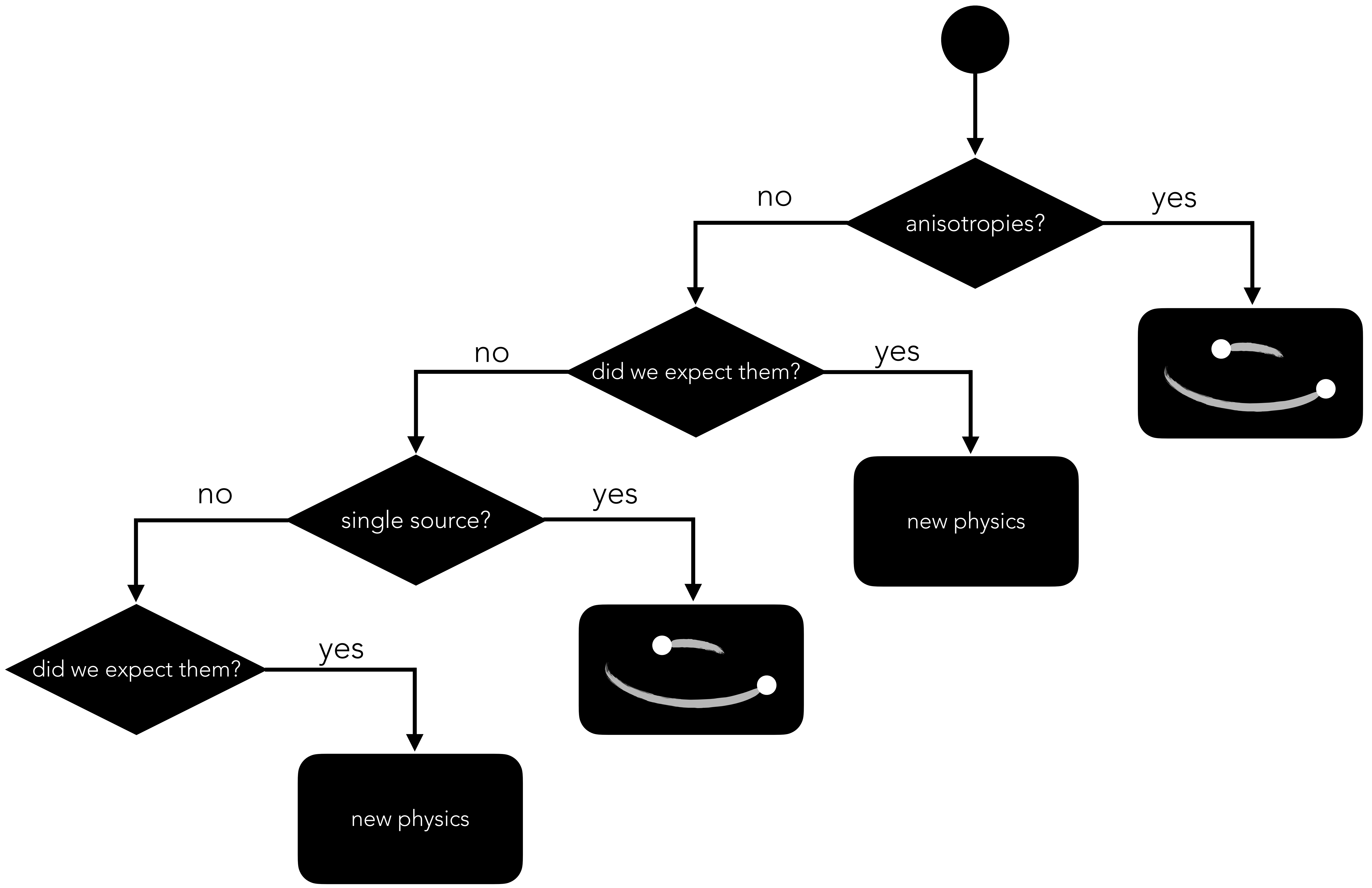
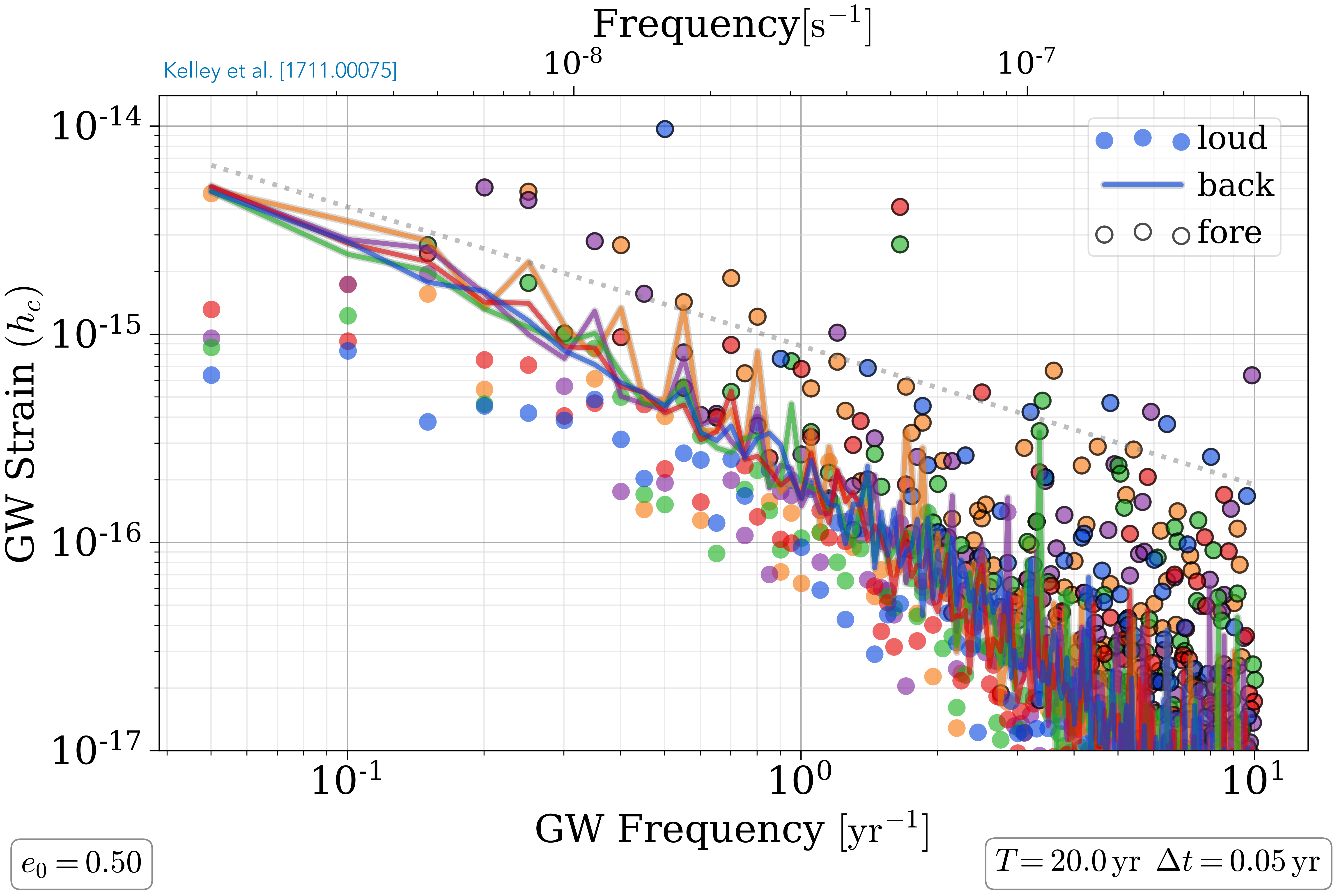


SINGLE SOURCE



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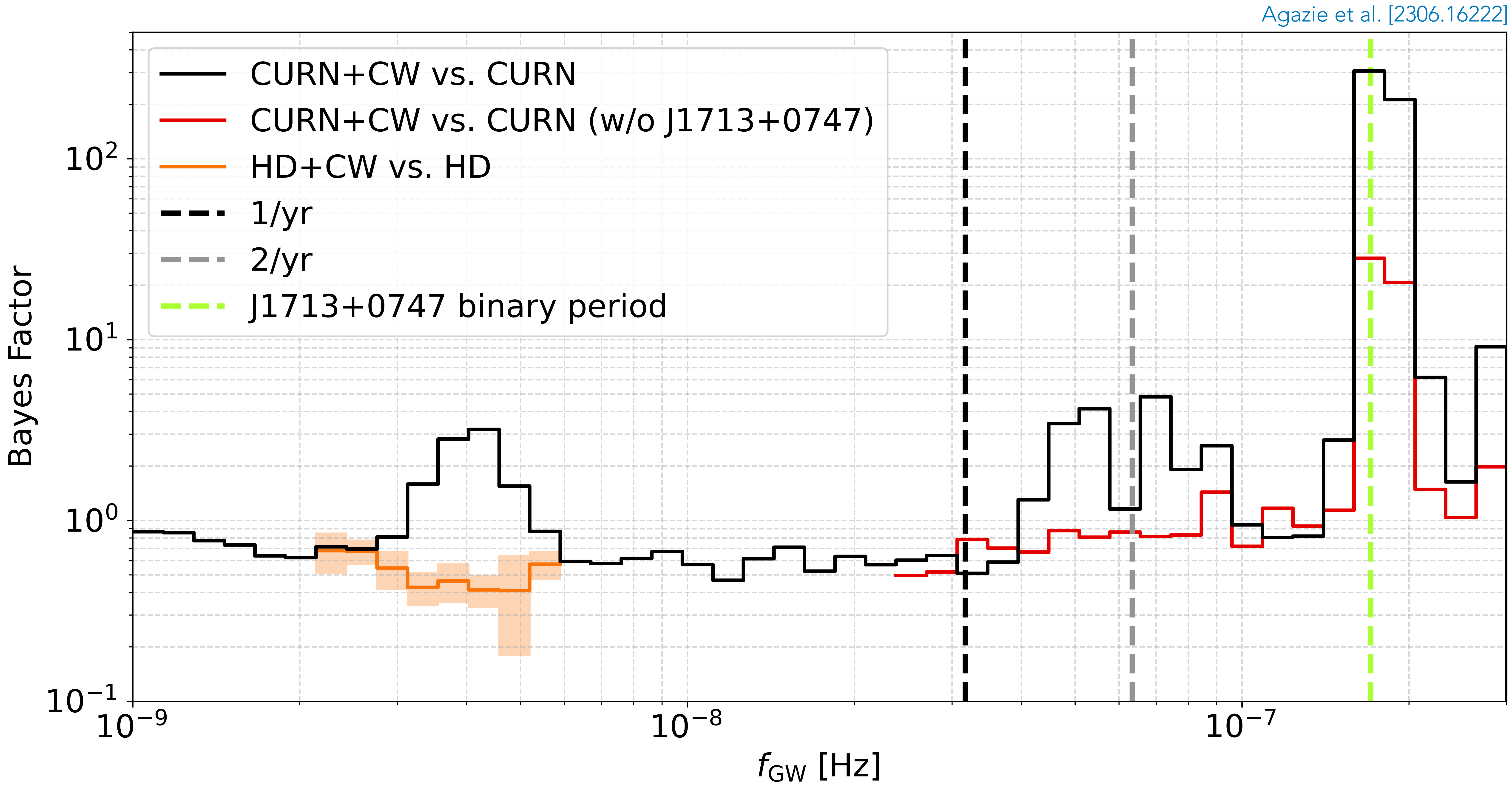

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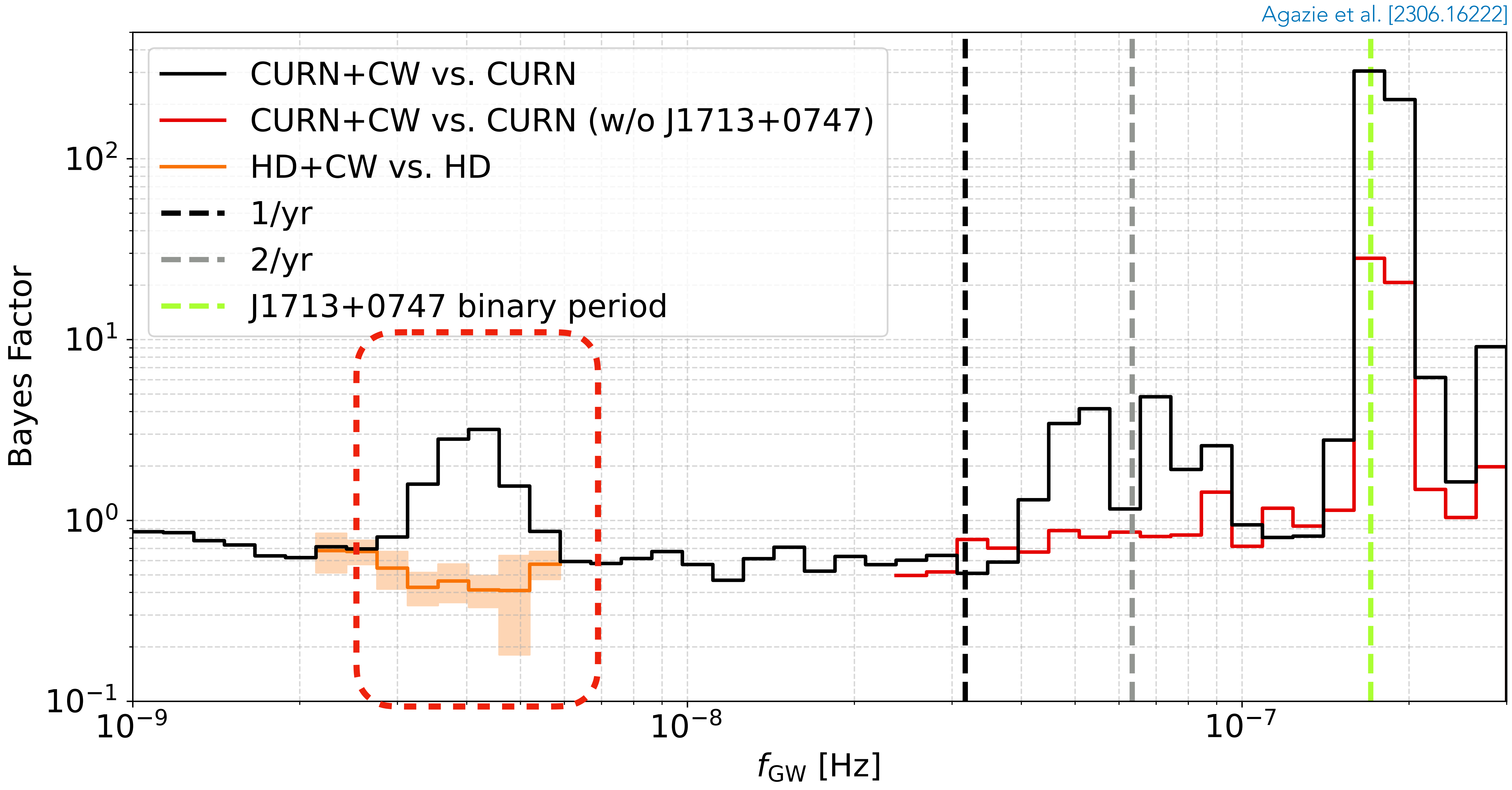

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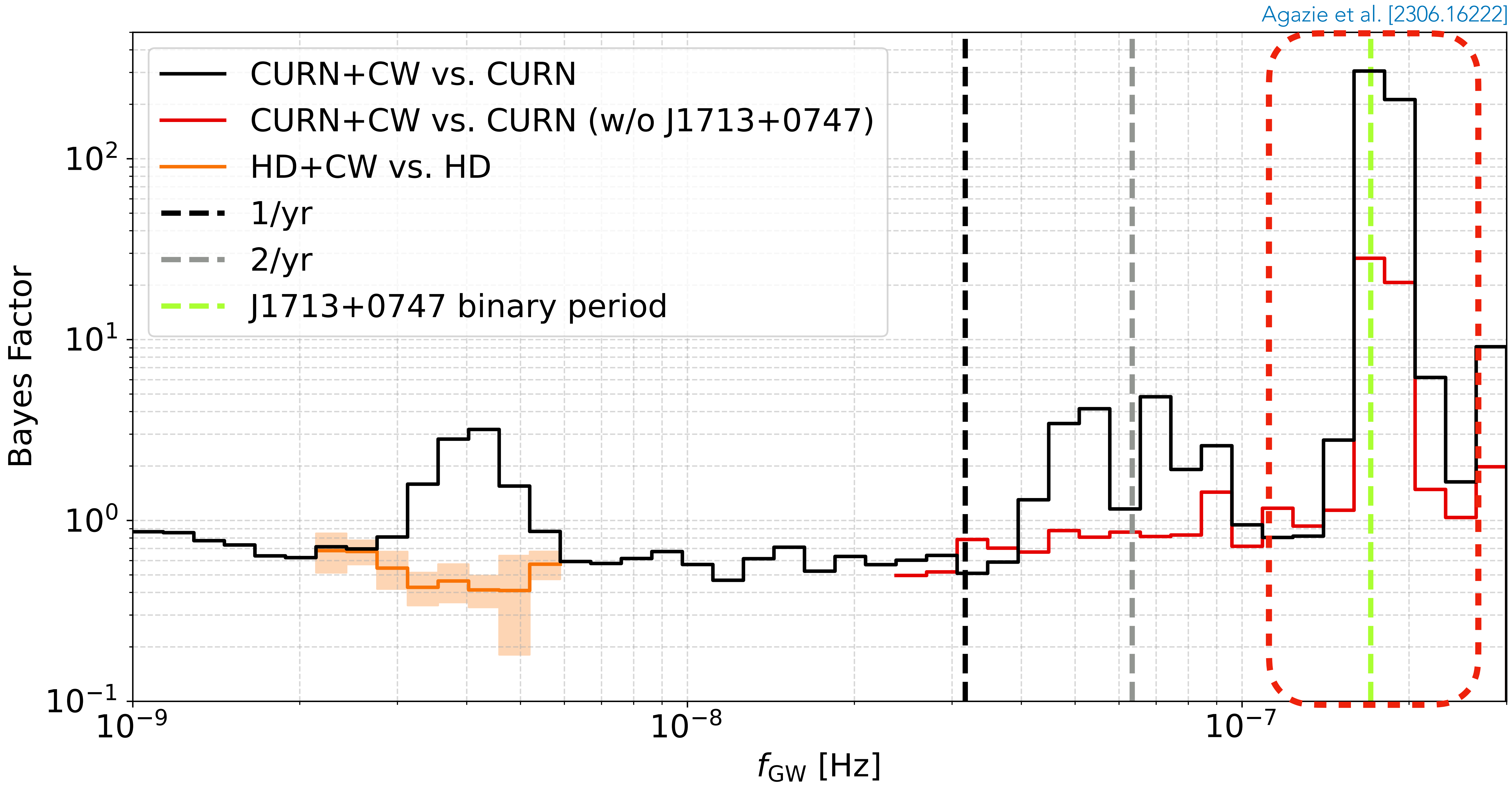
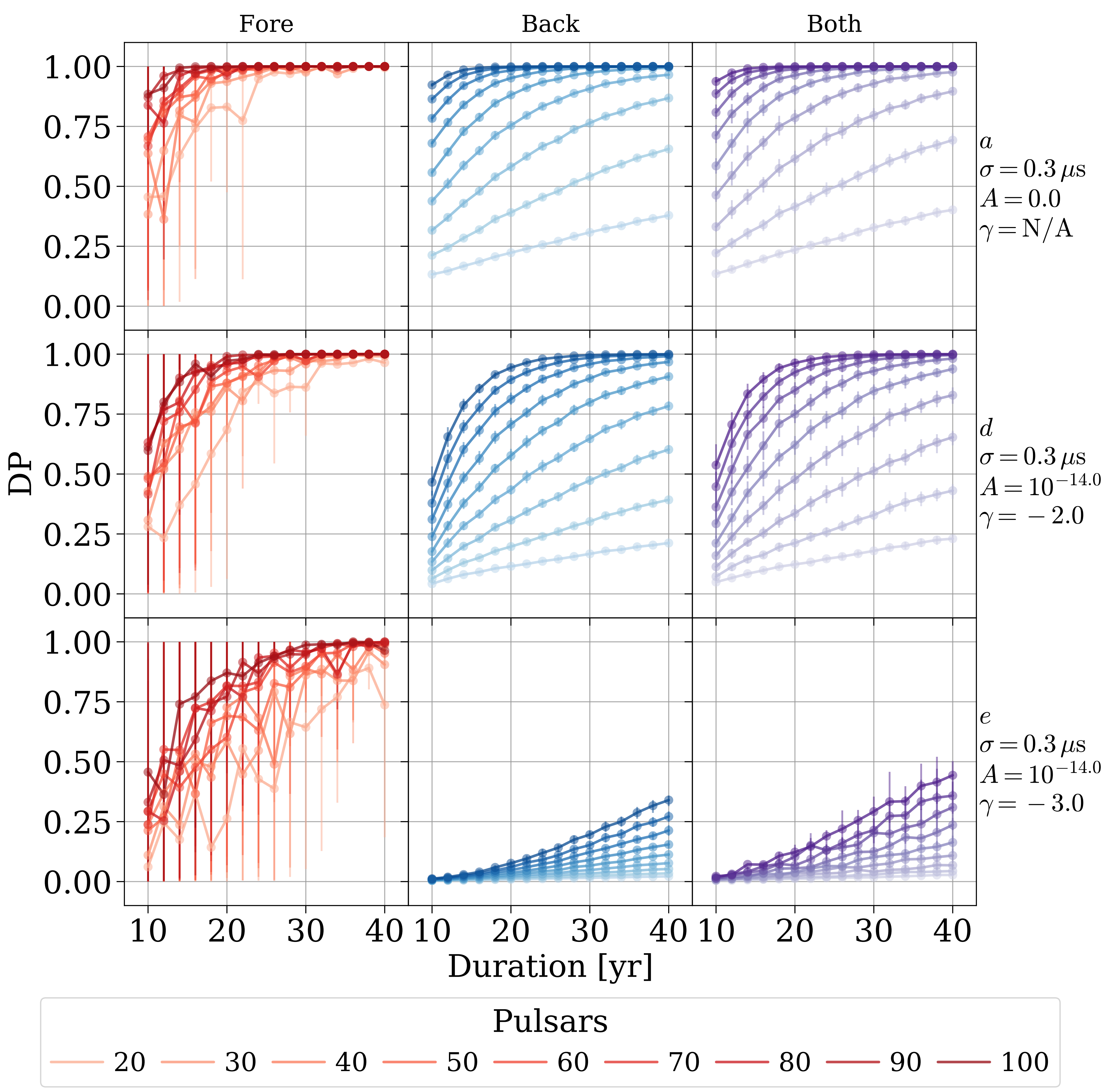
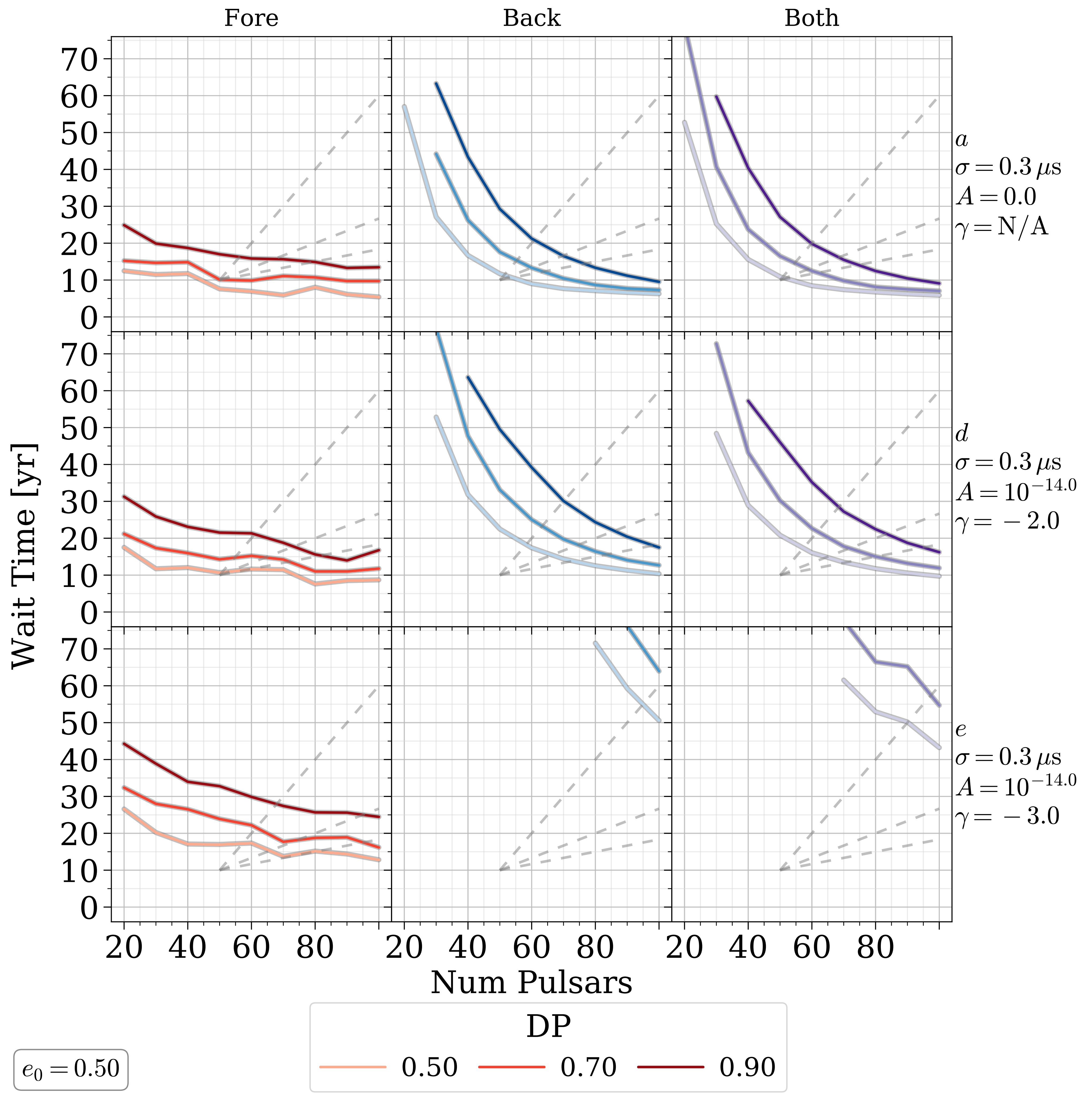


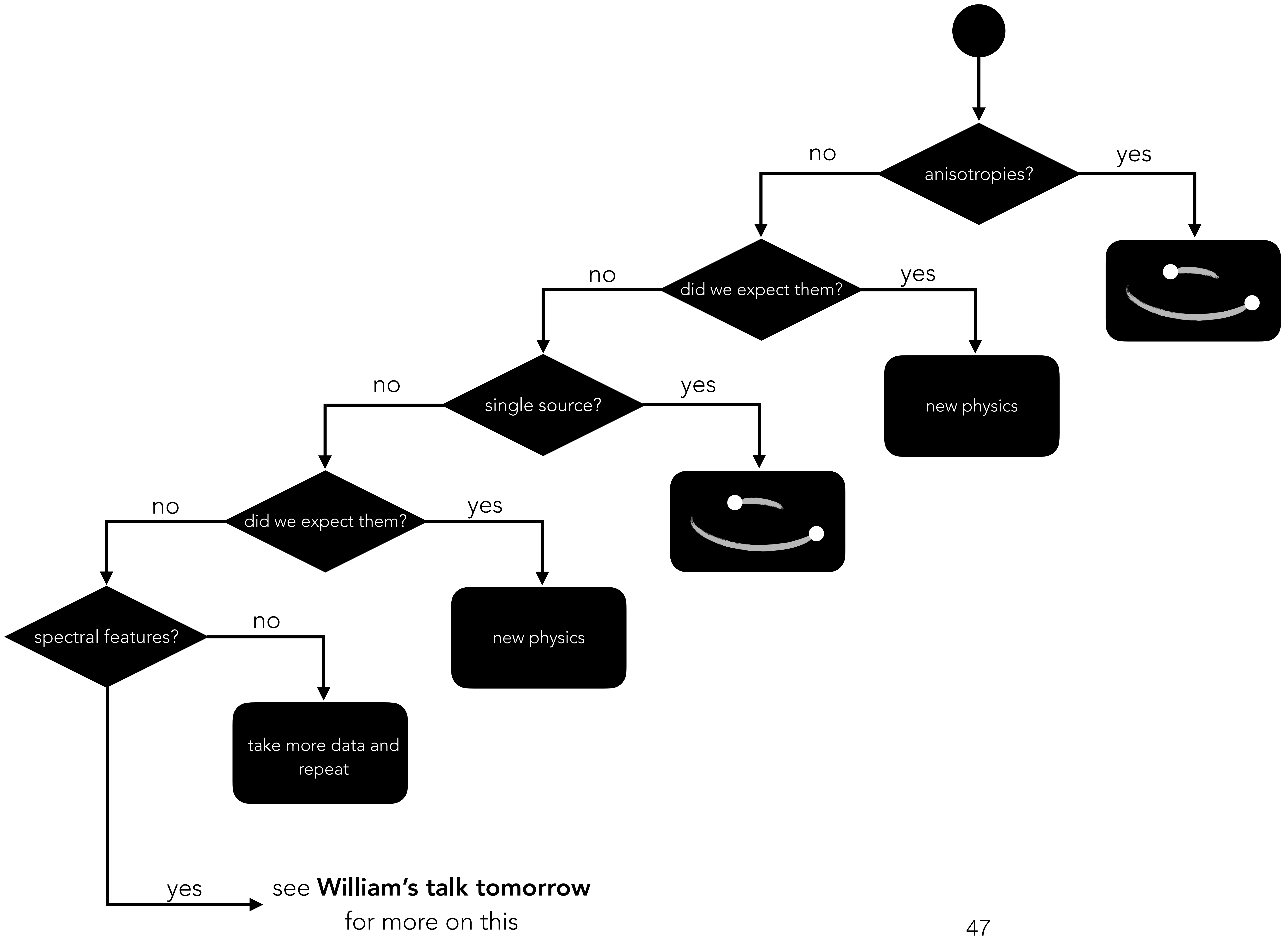
SINGLE SOURCE EXPECTATIONS





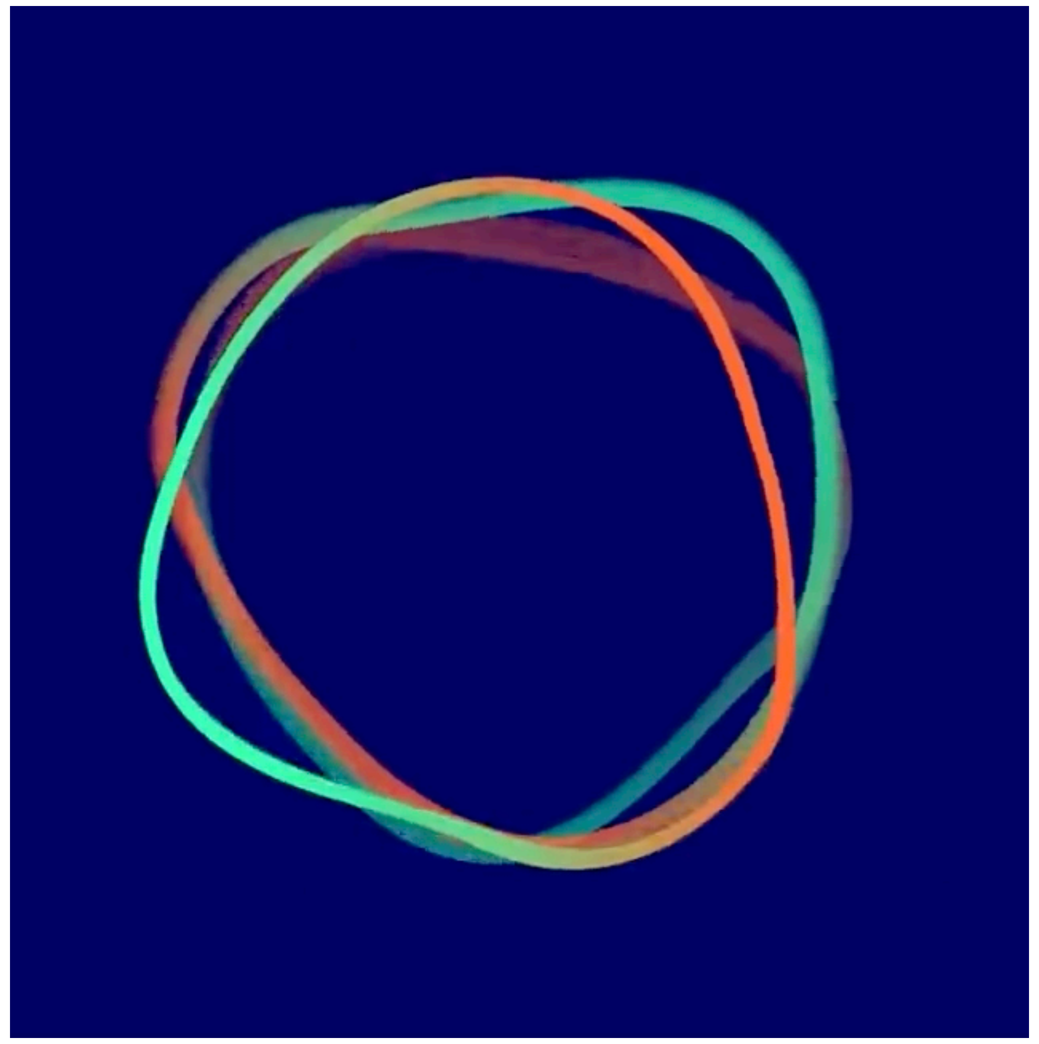
Kelley et al. [1711.00075]

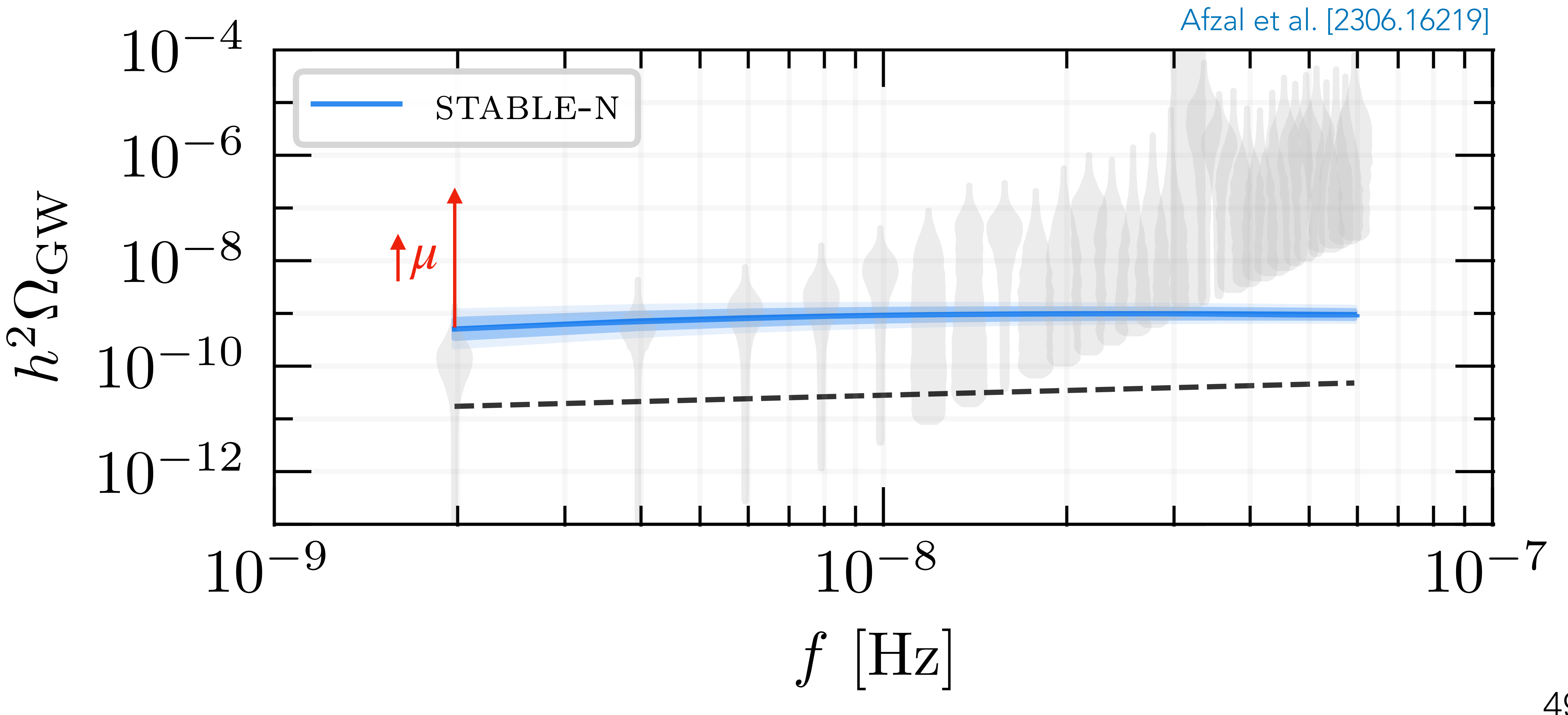
SMBHB or NEW PHYSICS?



what if it’s not new physics

COSMIC STRINGS





upper limits

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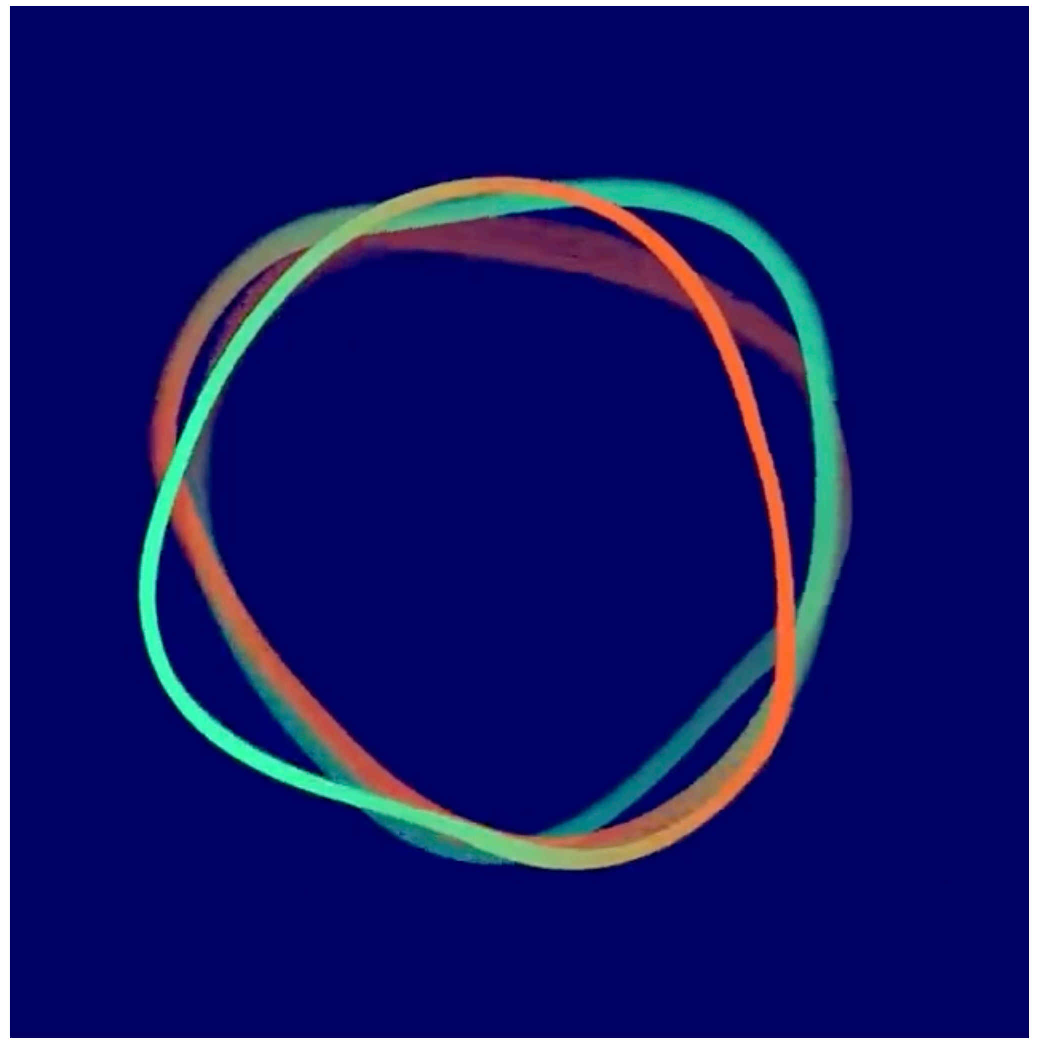

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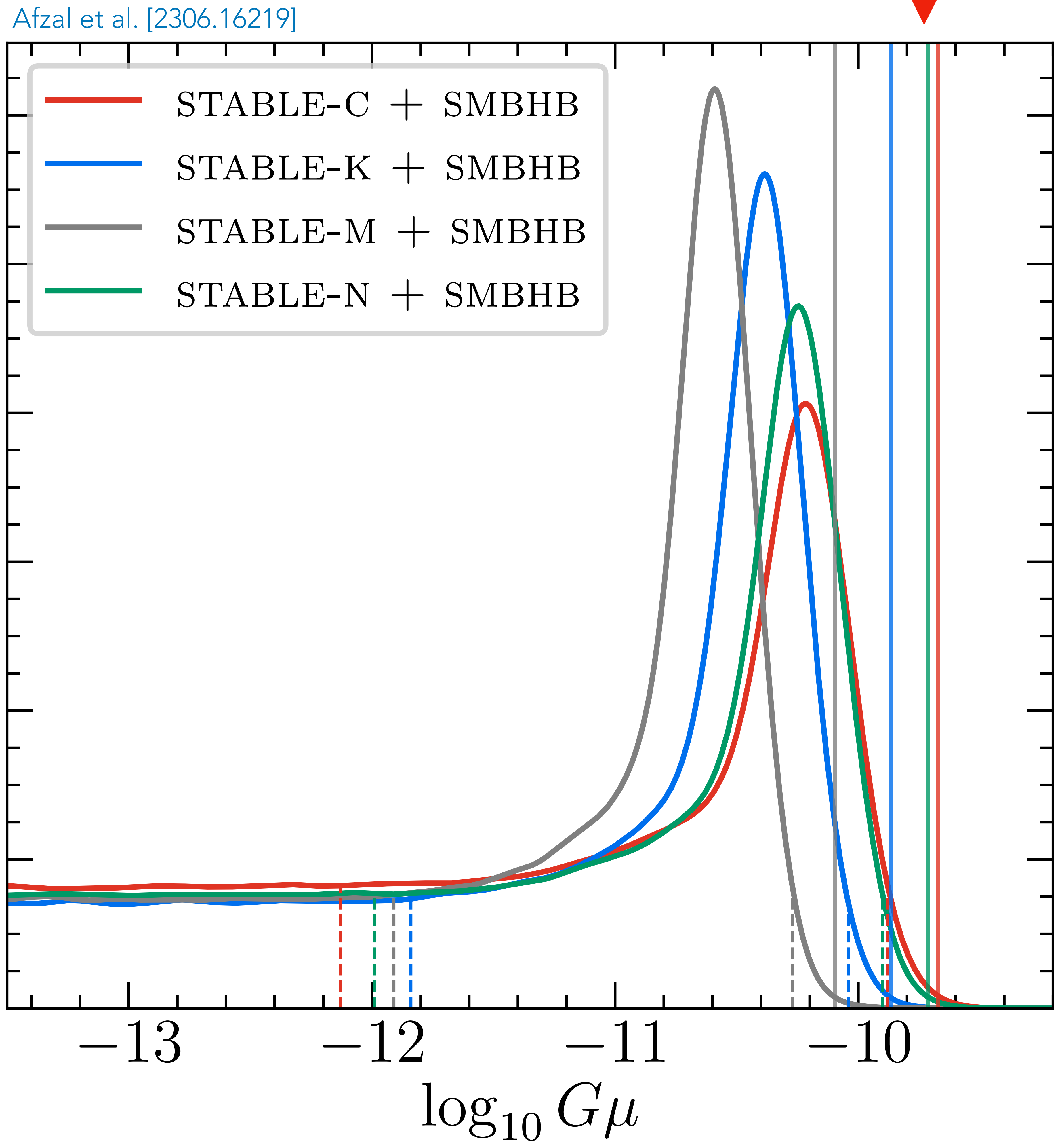

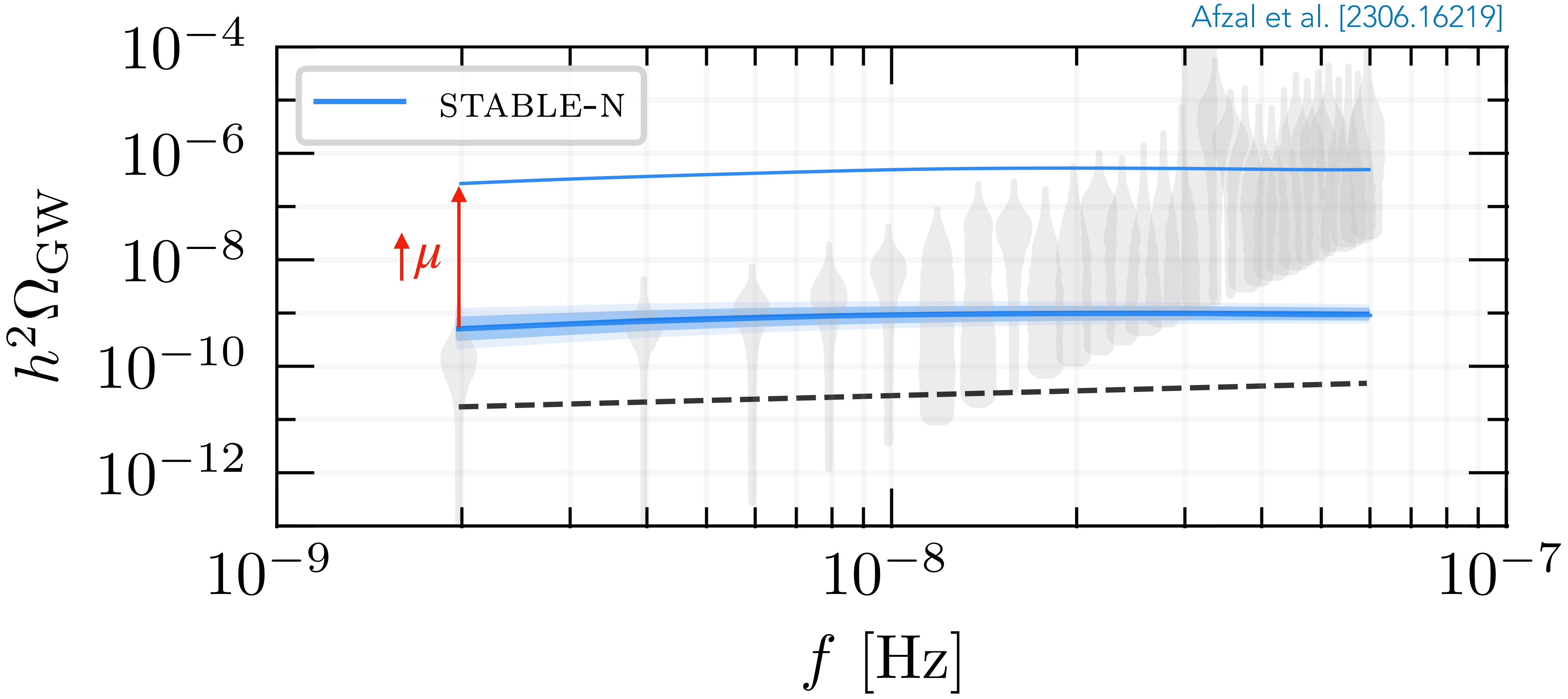

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DM density

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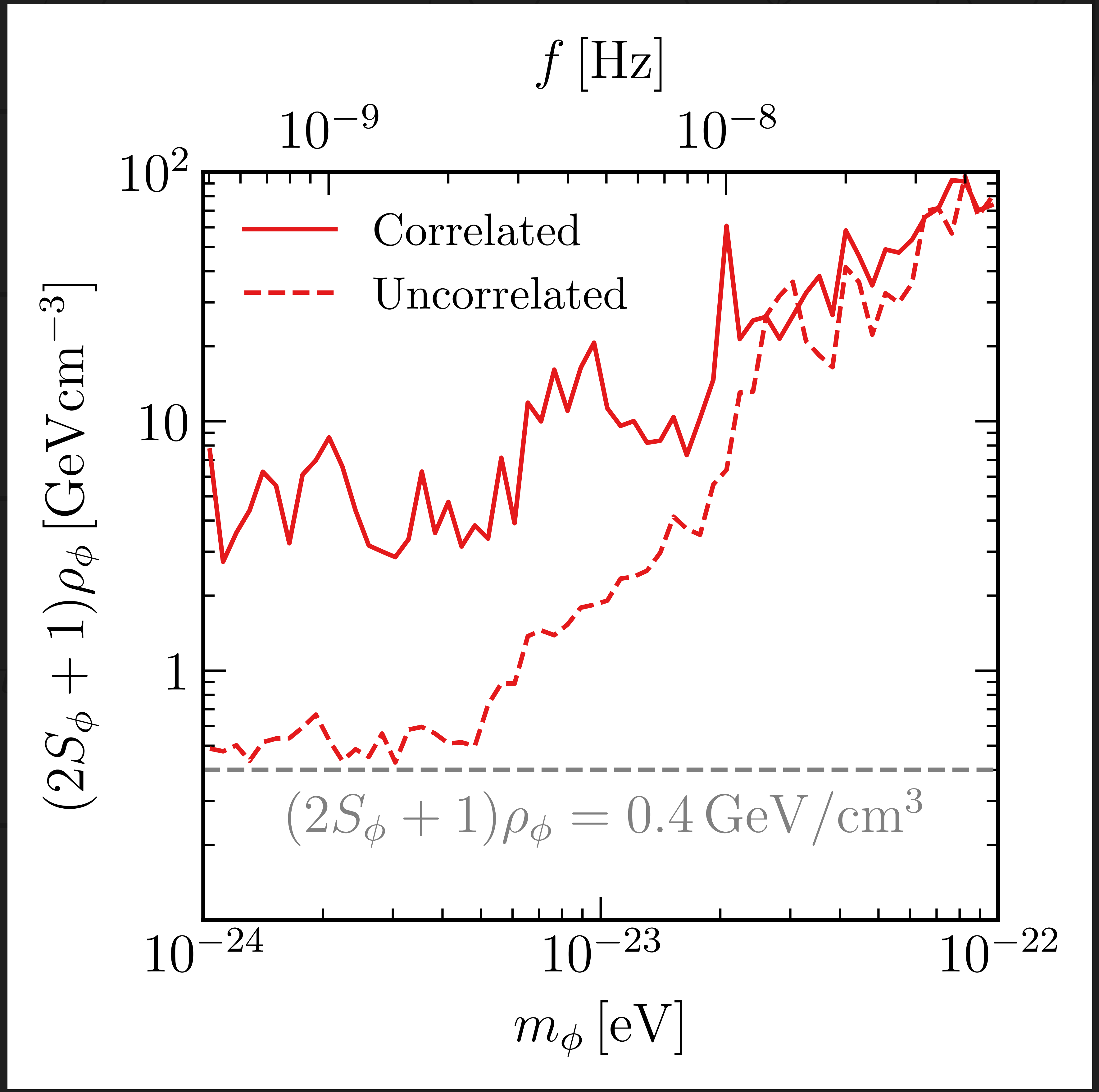
gravitational signal

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

Khmelnitsky, Rubakov [1309.5888]

ULDM

Afzal et al. [2306.16219]



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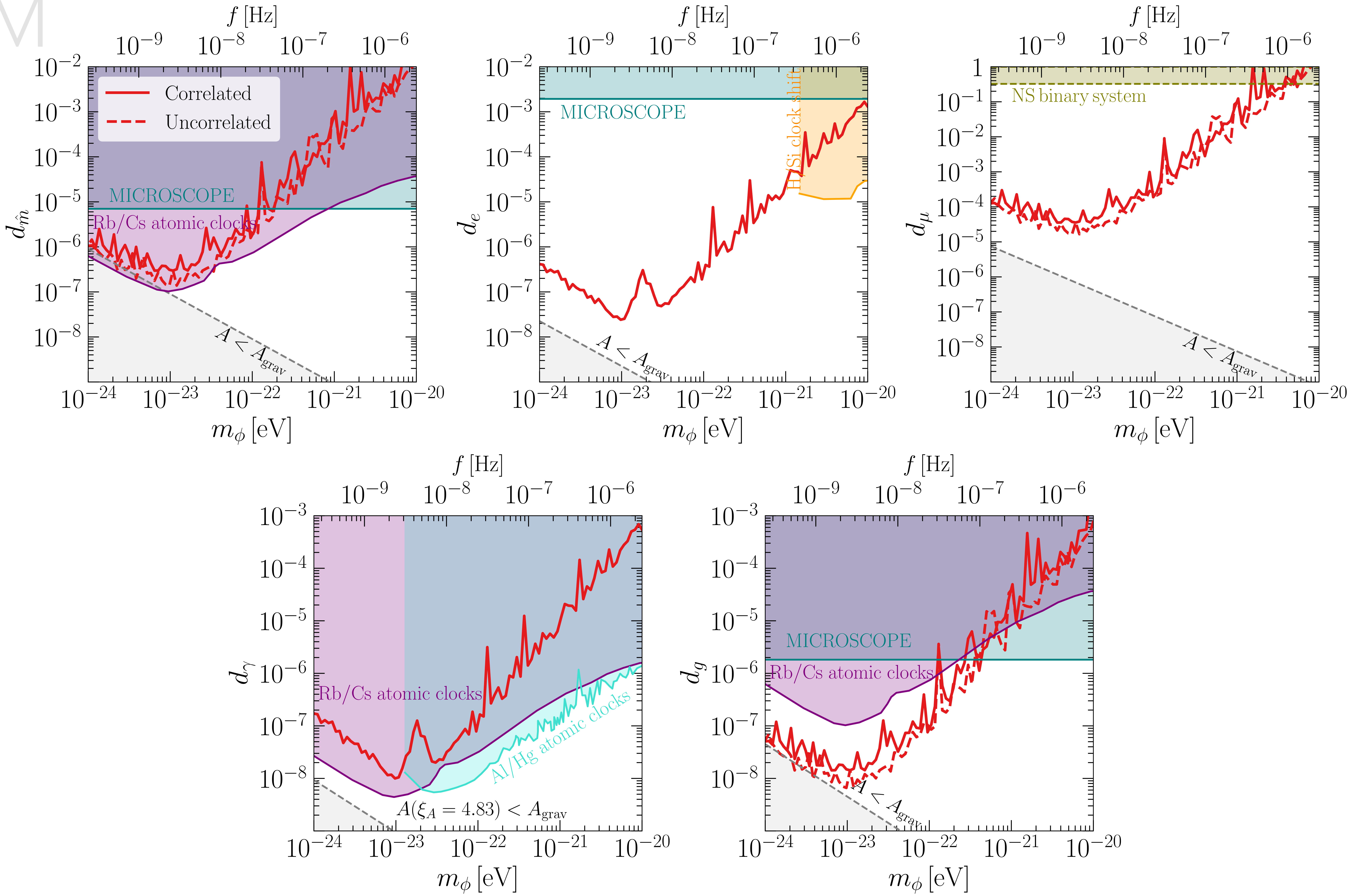
direct coupling signals

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

Kaplan, AM, Trickle [2205.06817]

ULDM



Afzal et al. [2306.16219]

OUTLOOK

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- PTAs can be used to set tight constraints on NP models