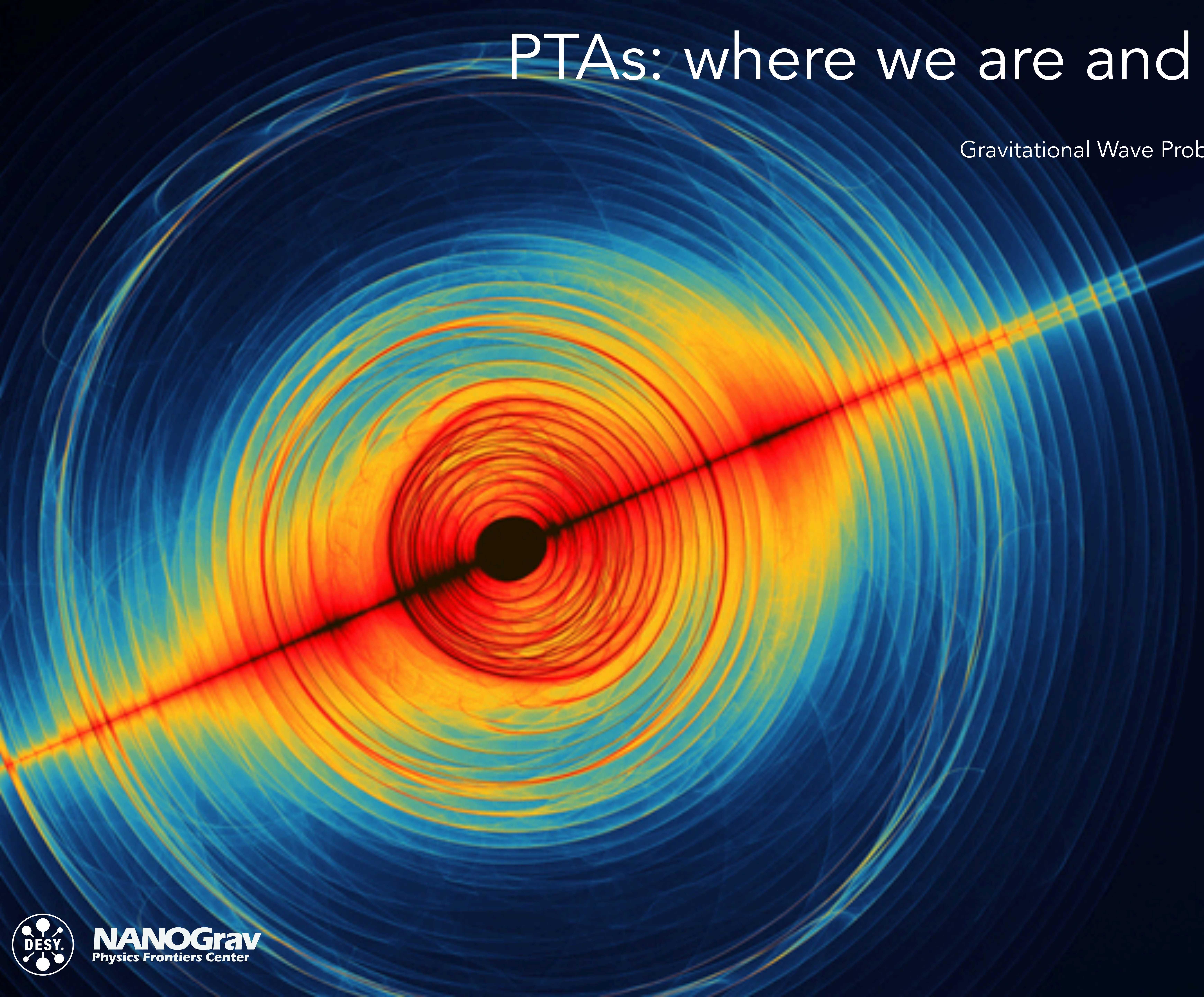


PTAs: where we are and were we are going

Andrea Mitridate

Gravitational Wave Probes of Physics Beyond Standard Model | Nov. 7, 2023

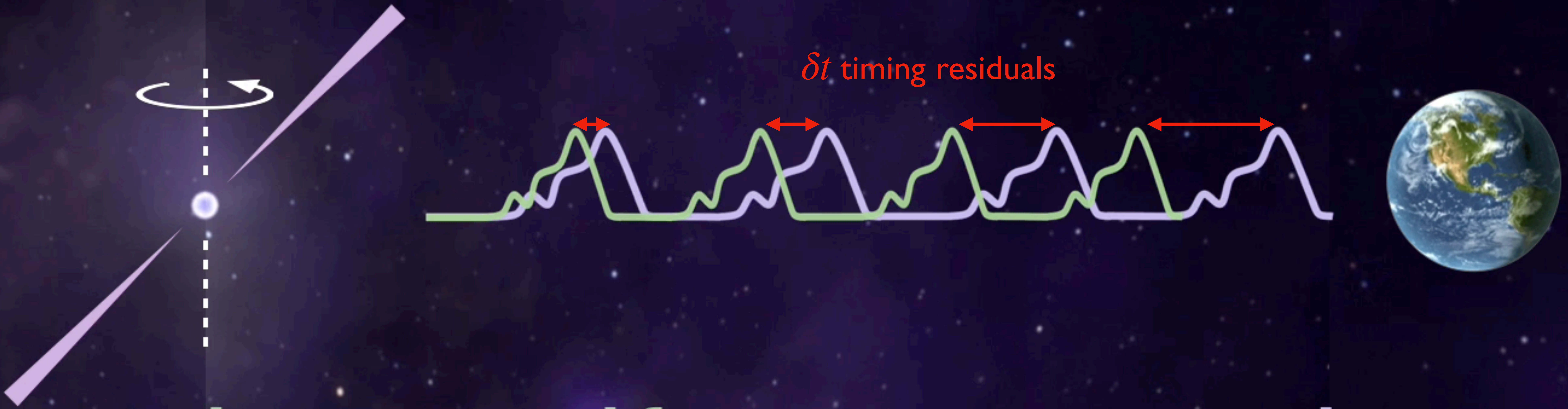
DESY.

NANOGrav
Physics Frontiers Center

PULSARS

Animation by NASA's Goddard Space Flight Center

TIMING RESIDUALS



δt timing residuals

Pulses expected from Timing Model

Pulses Recorded by Radio Telescope

A GALAXY-SIZE DETECTOR FOR GWs

67 pulsars observed by NG

observing baseline of 15 yrs

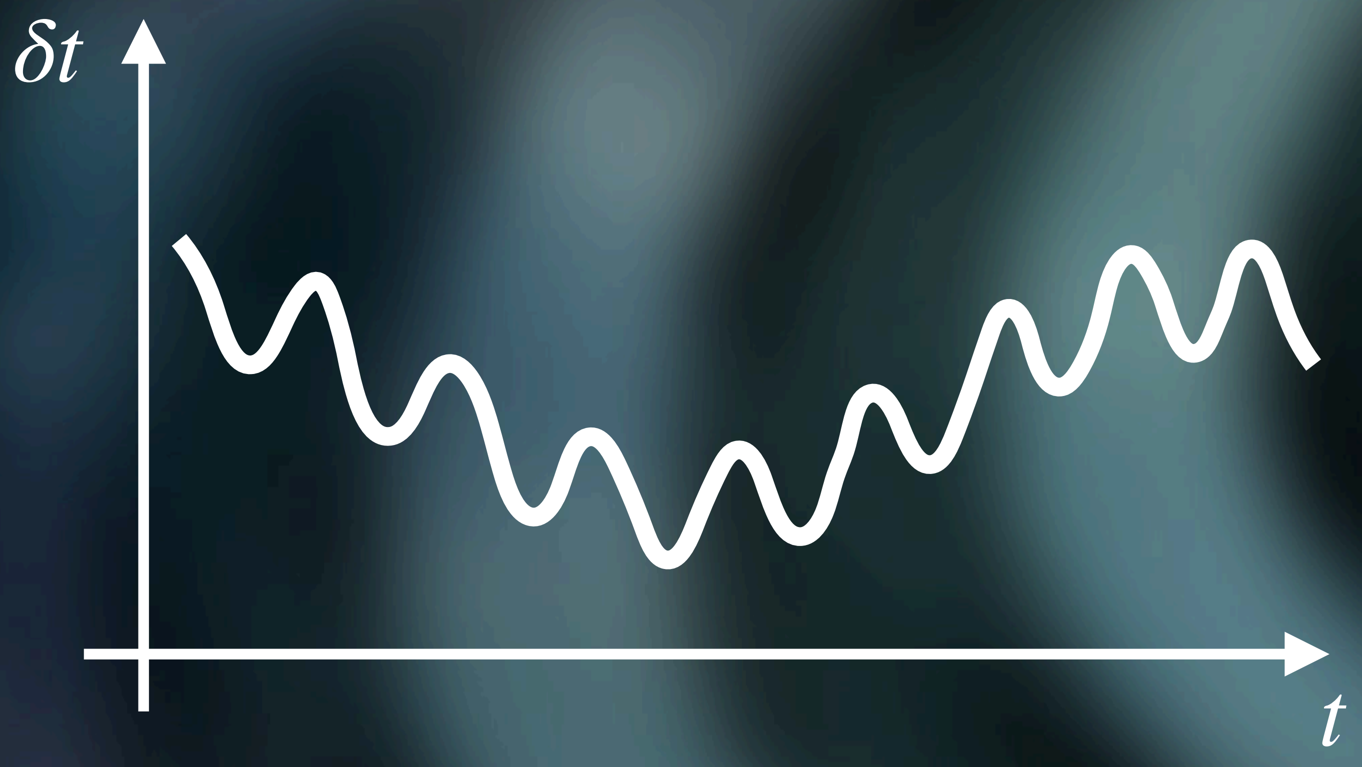
distance to pulsars up to ~kpc

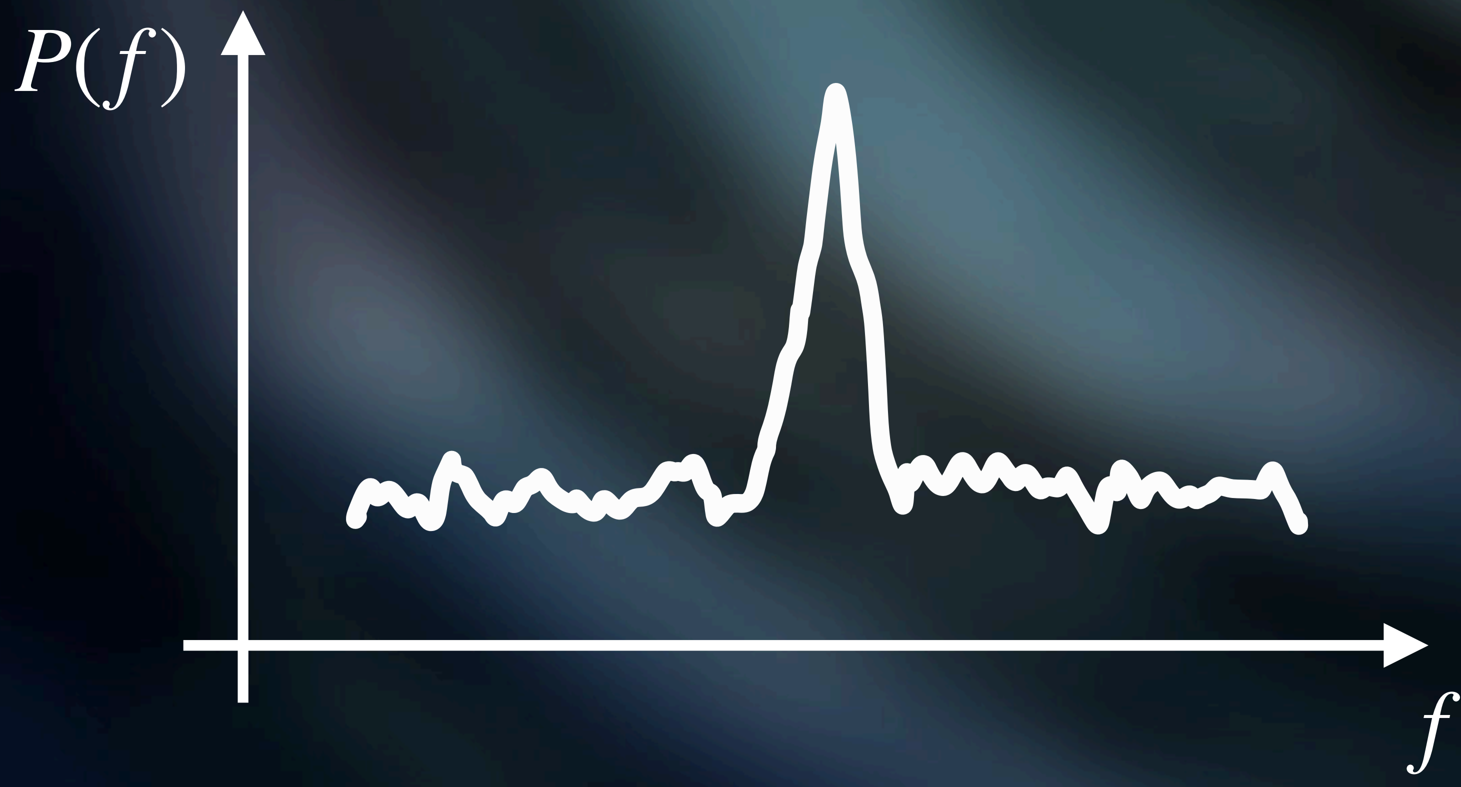
IPTA DR3 will contain >100 pulsars

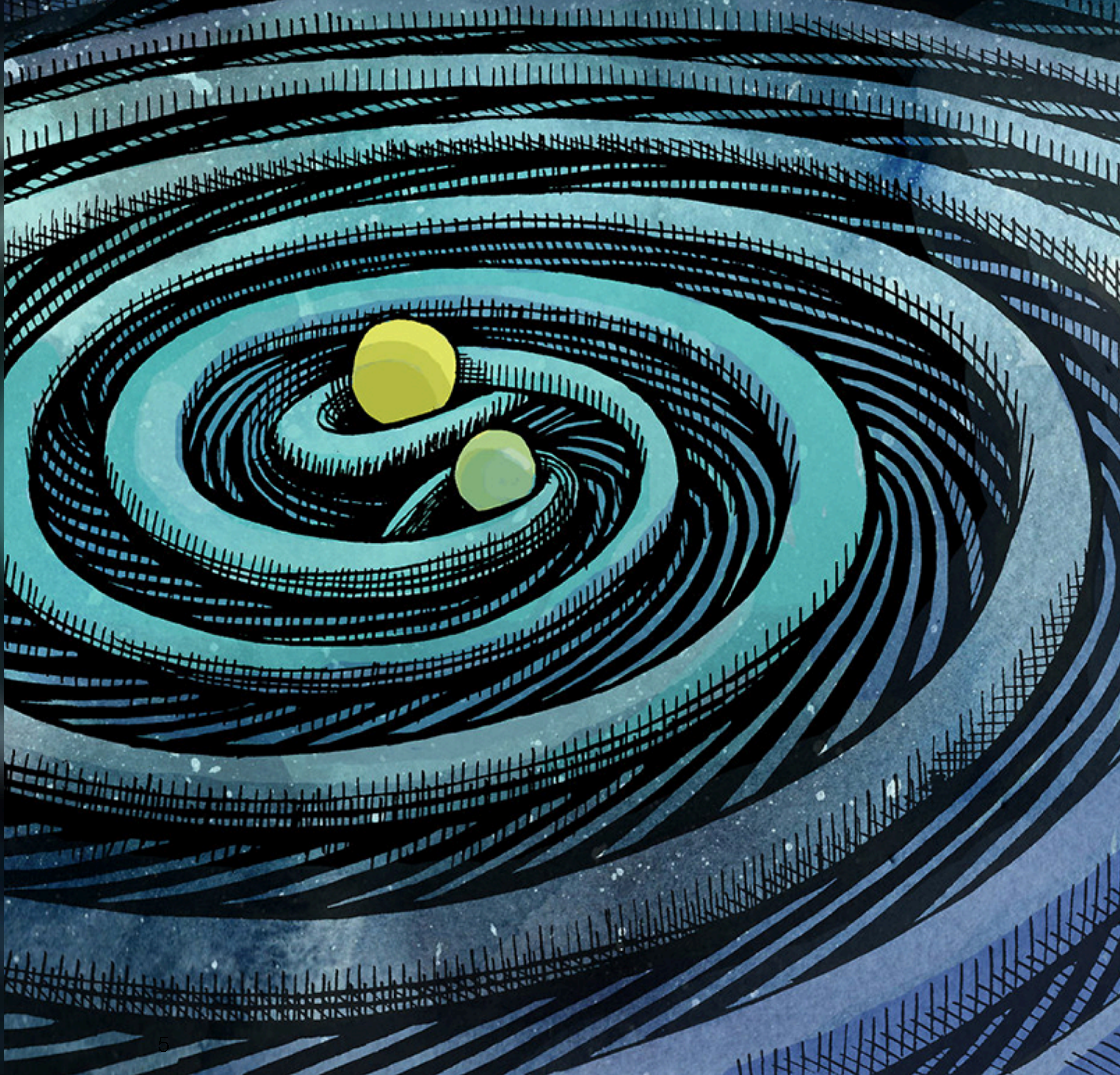
credits Keyi "Onyx" Li / NSF / NANOGrav

CONTINUOUS WAVE

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

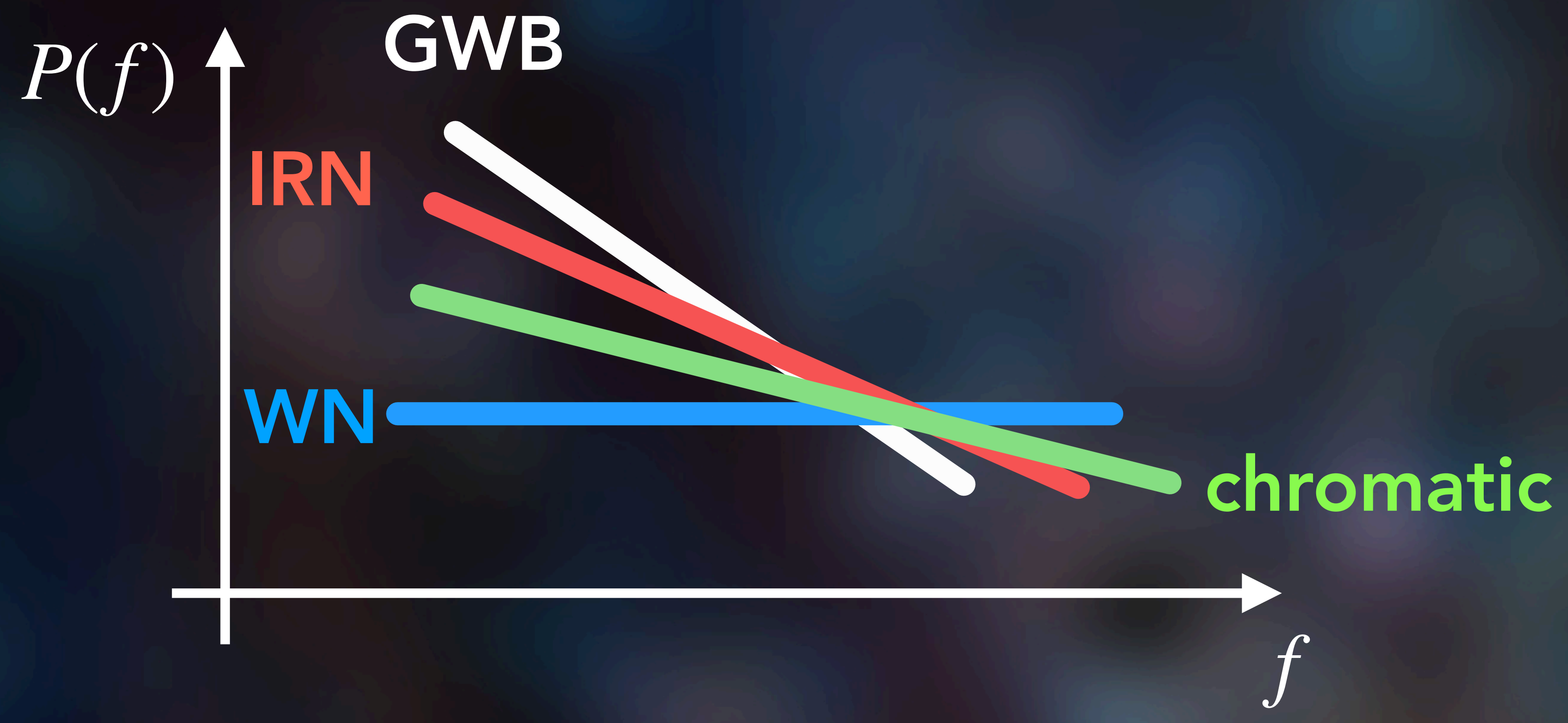






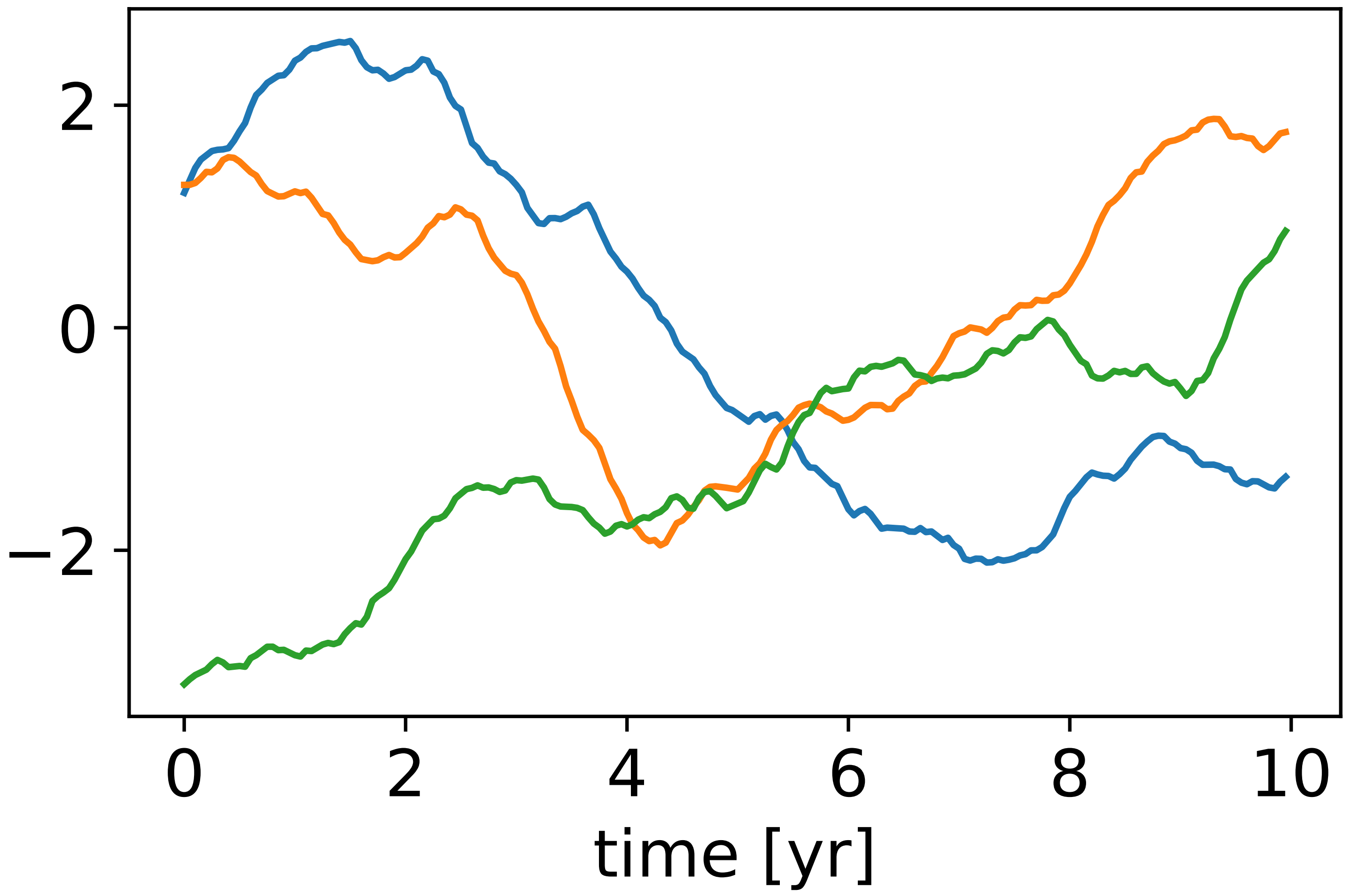
GW BACKGROUND

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



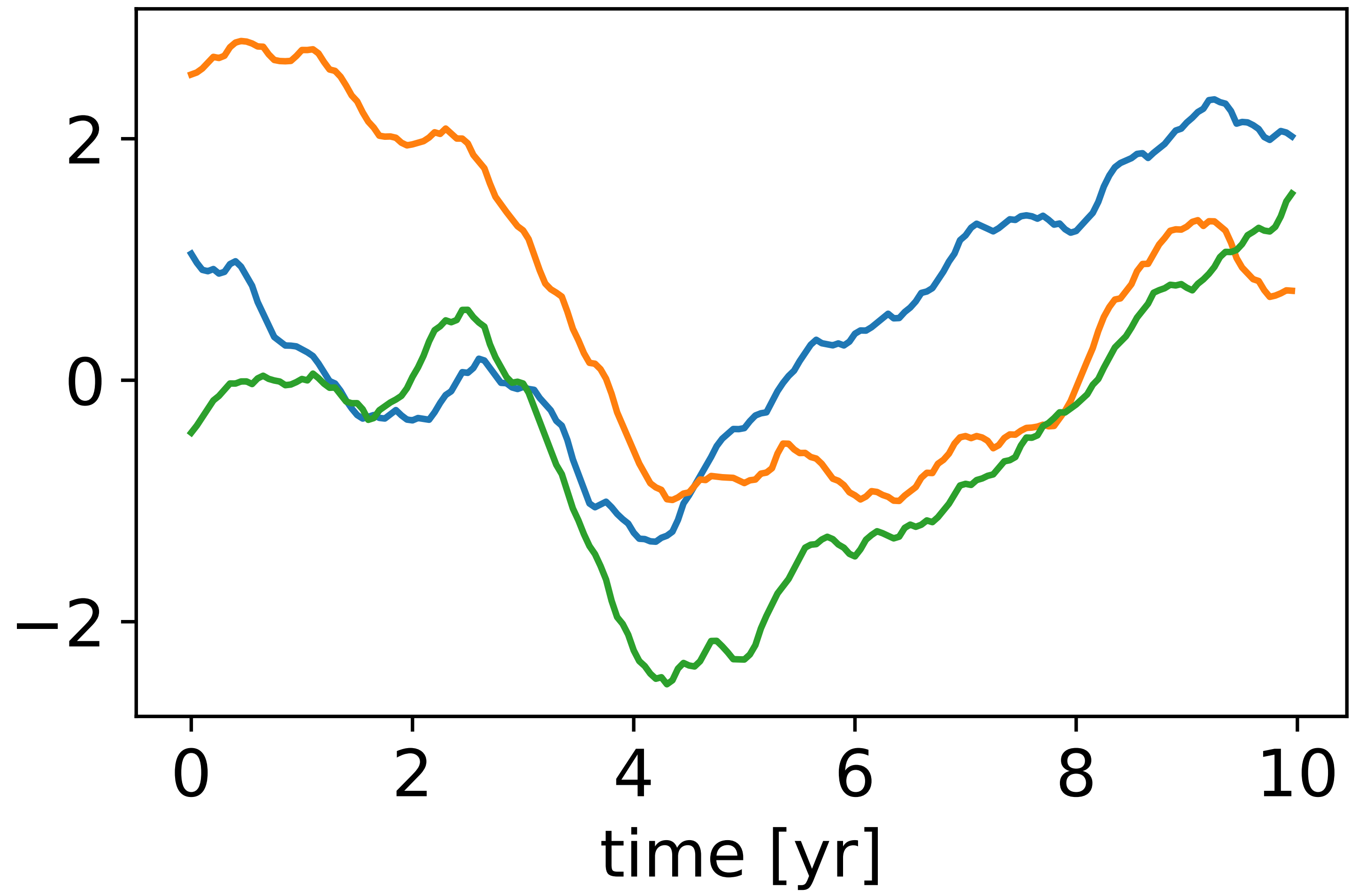
CORRELATIONS EXAMPLE

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



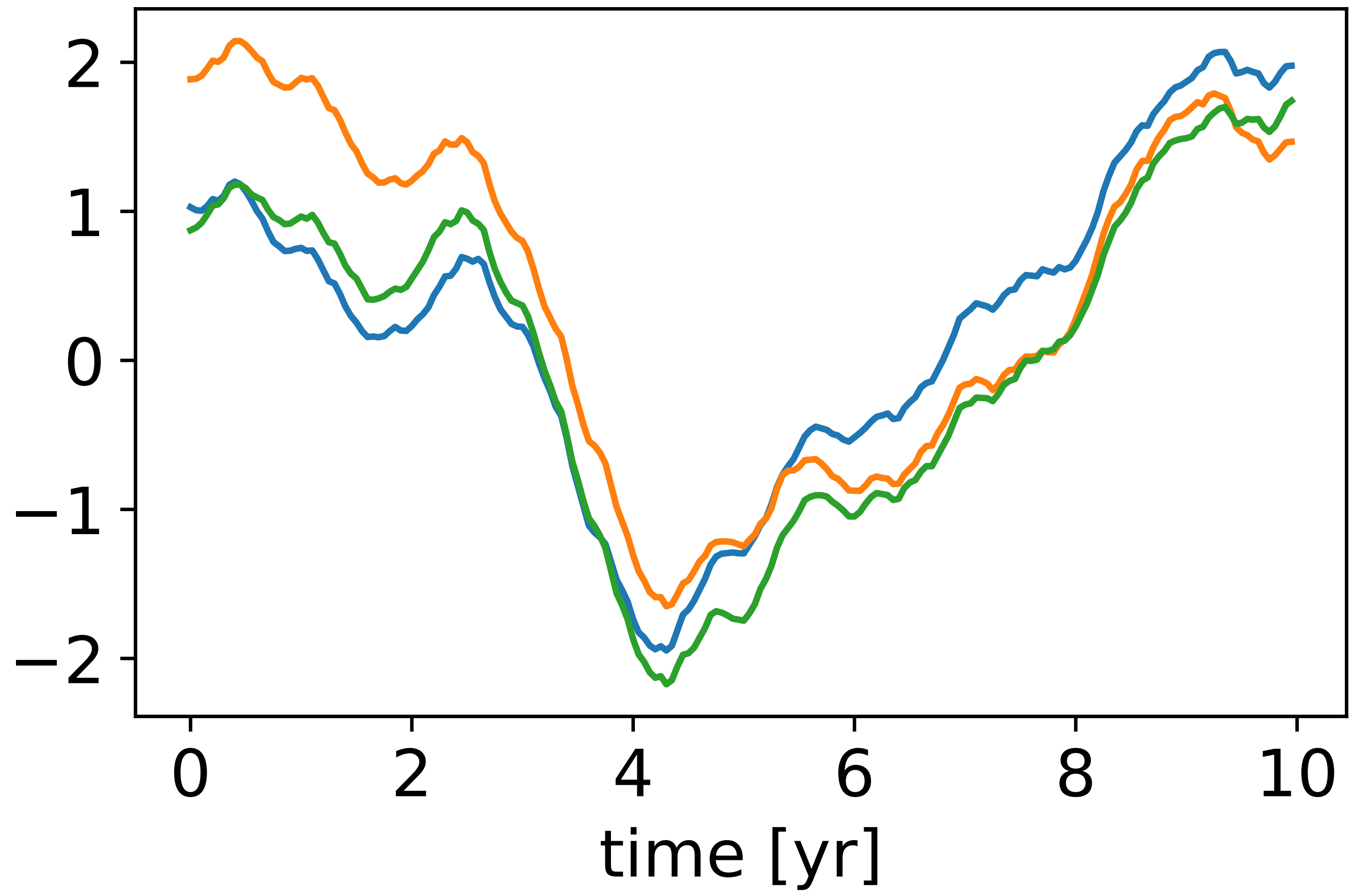
uncorrelated

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



moderately correlated

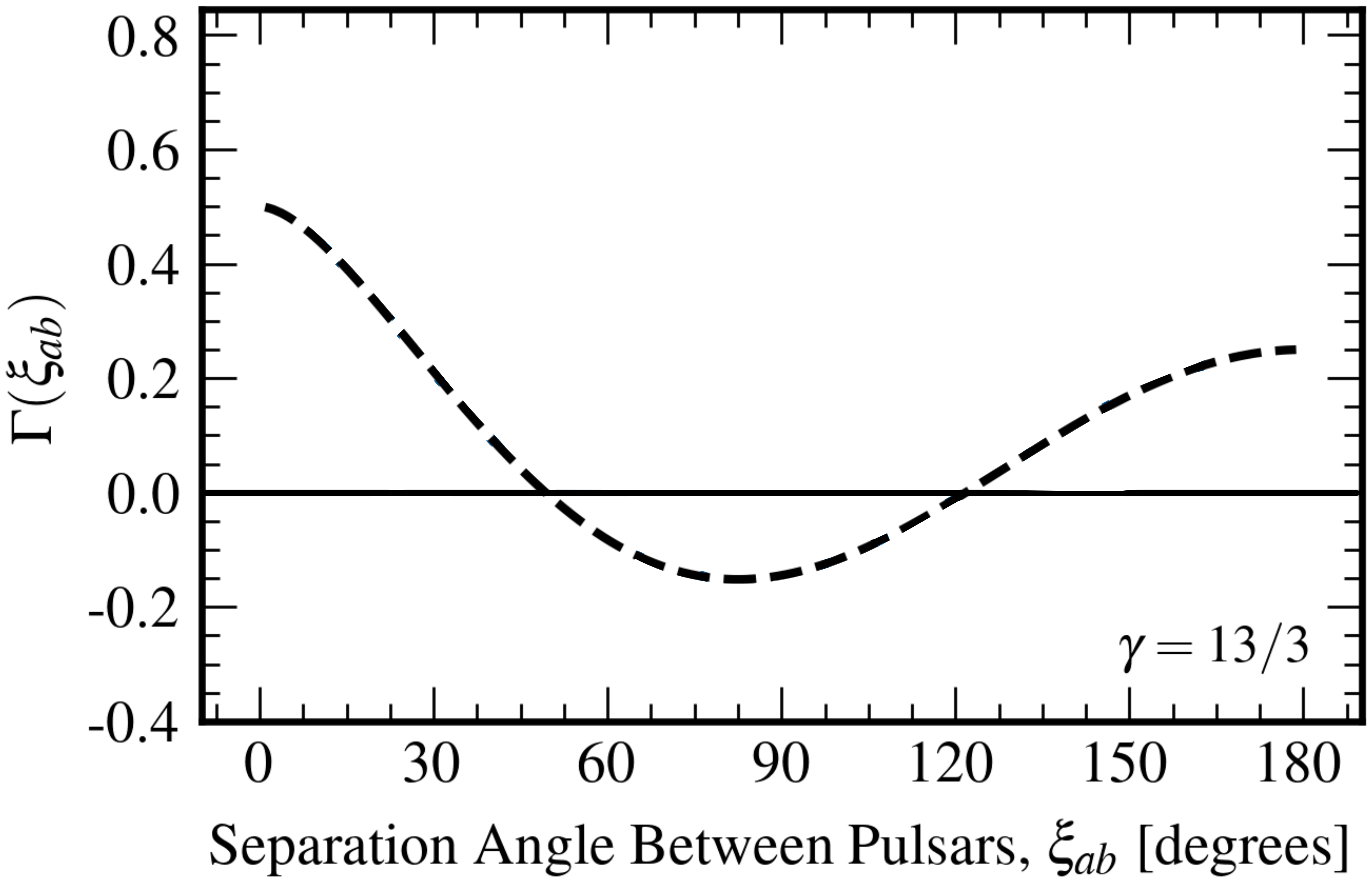
$$\Gamma_{ab} = \begin{pmatrix} 1 & 0.95 & 0.95 \\ 0.95 & 1 & 0.95 \\ 0.95 & 0.95 & 1 \end{pmatrix}$$



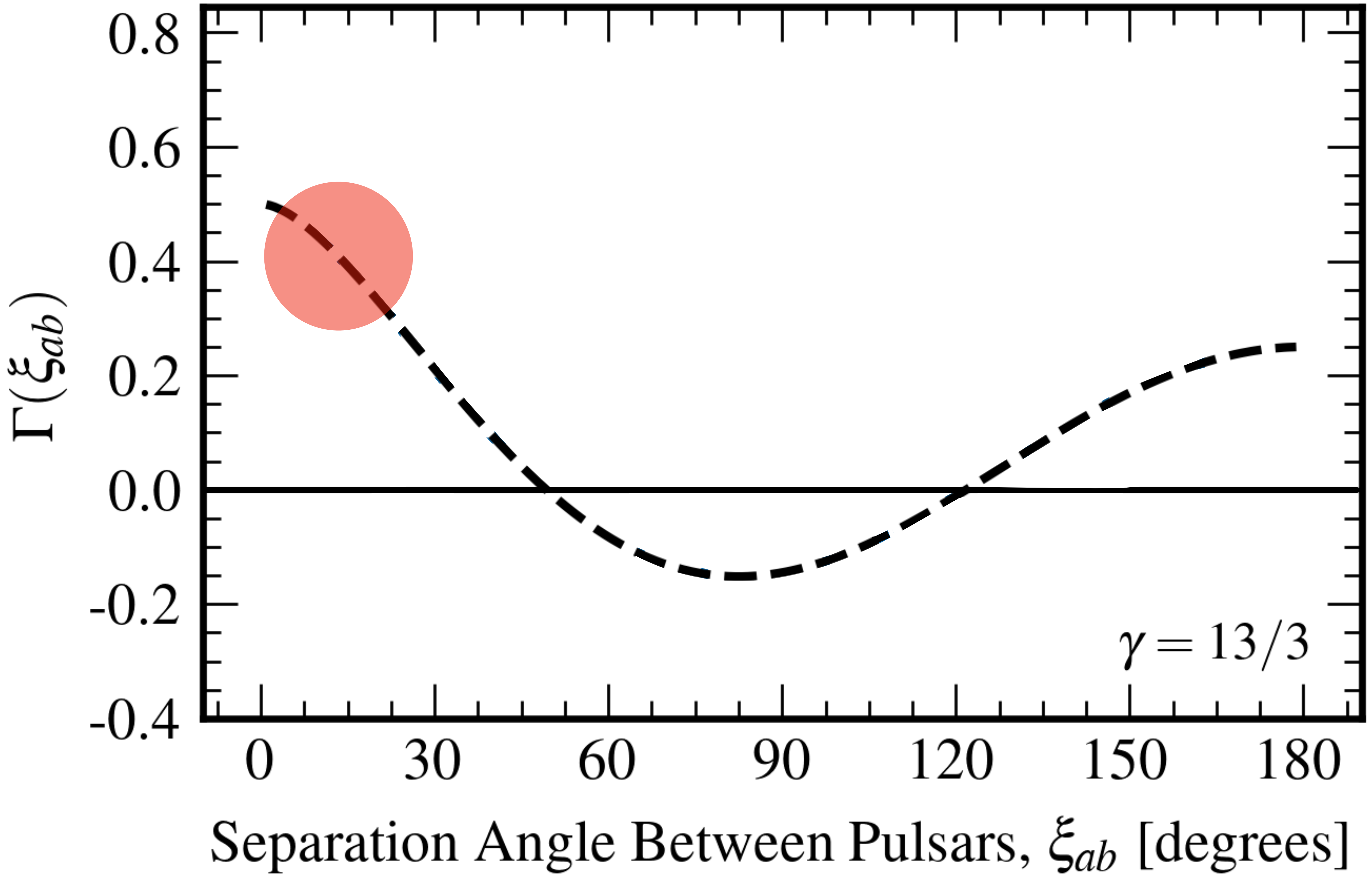
strongly correlated

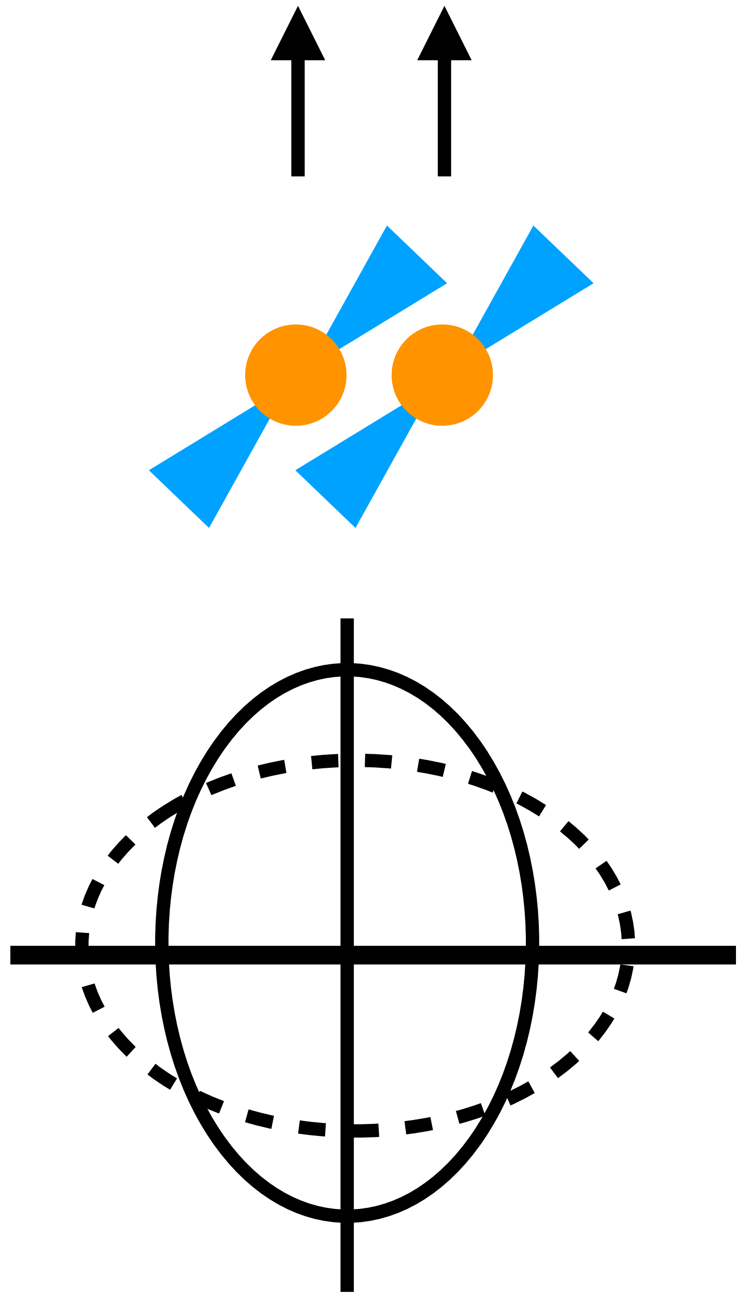
slide from Joe Romano

HELLINGS & DOWNS CURVE

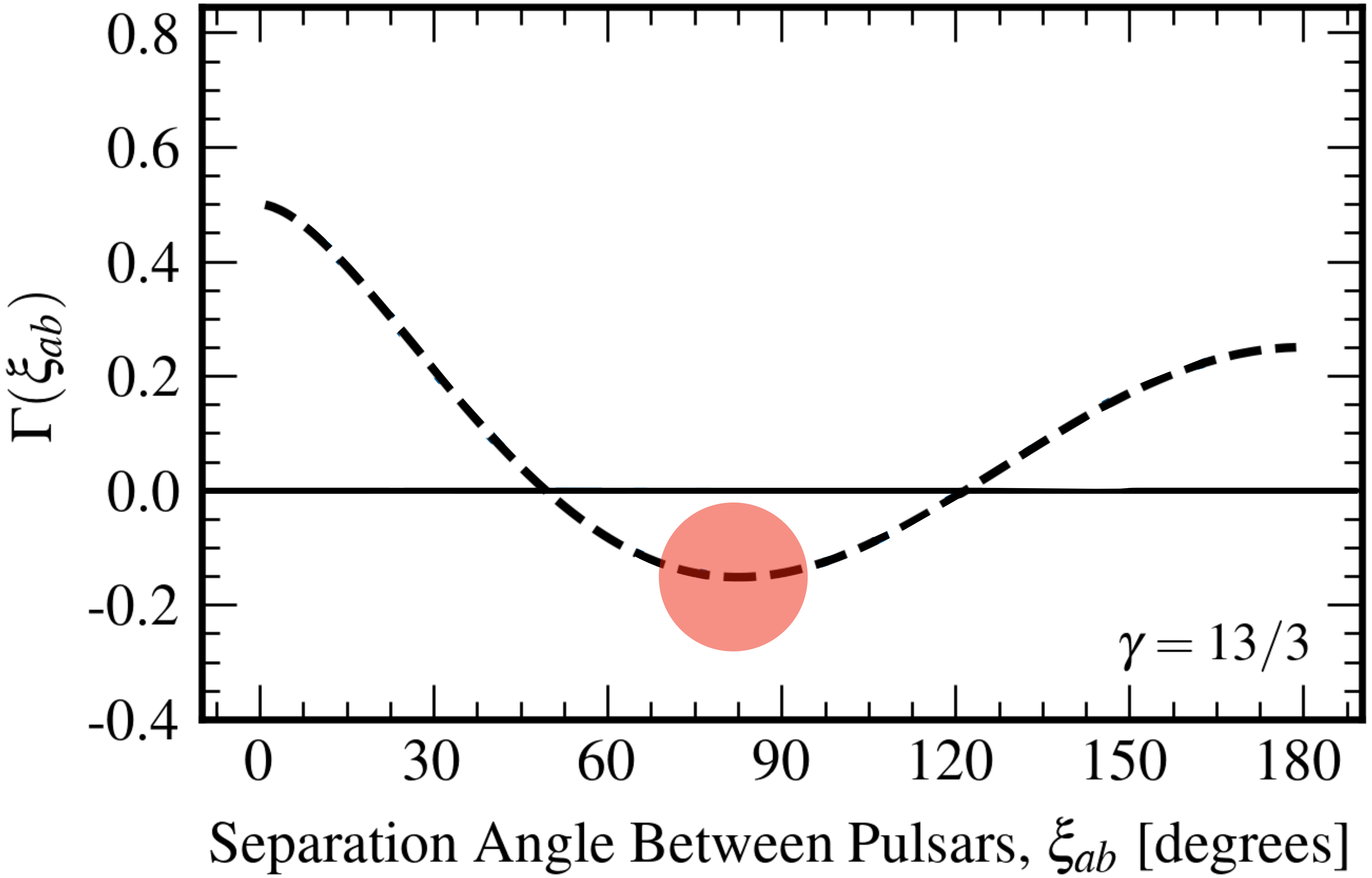


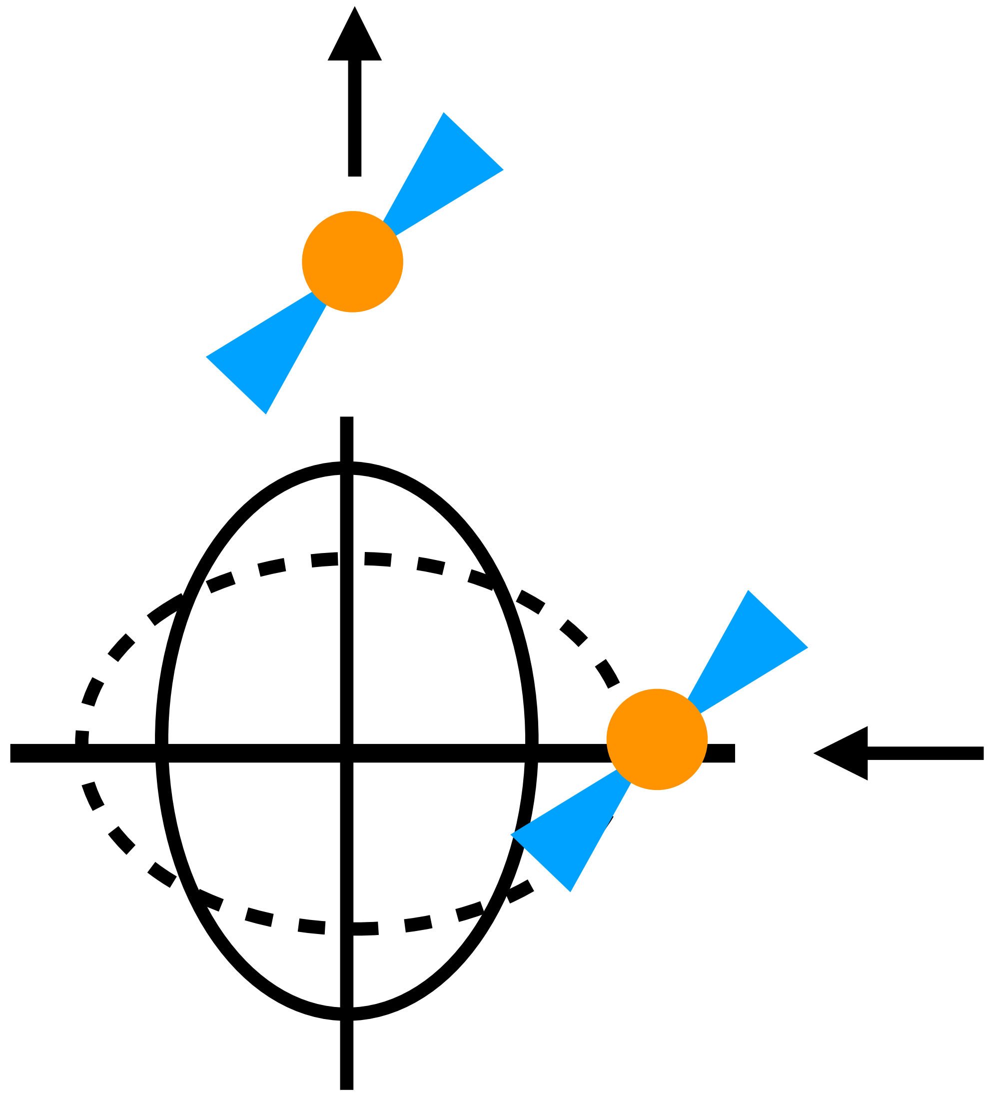
HELLINGS & DOWNS CURVE



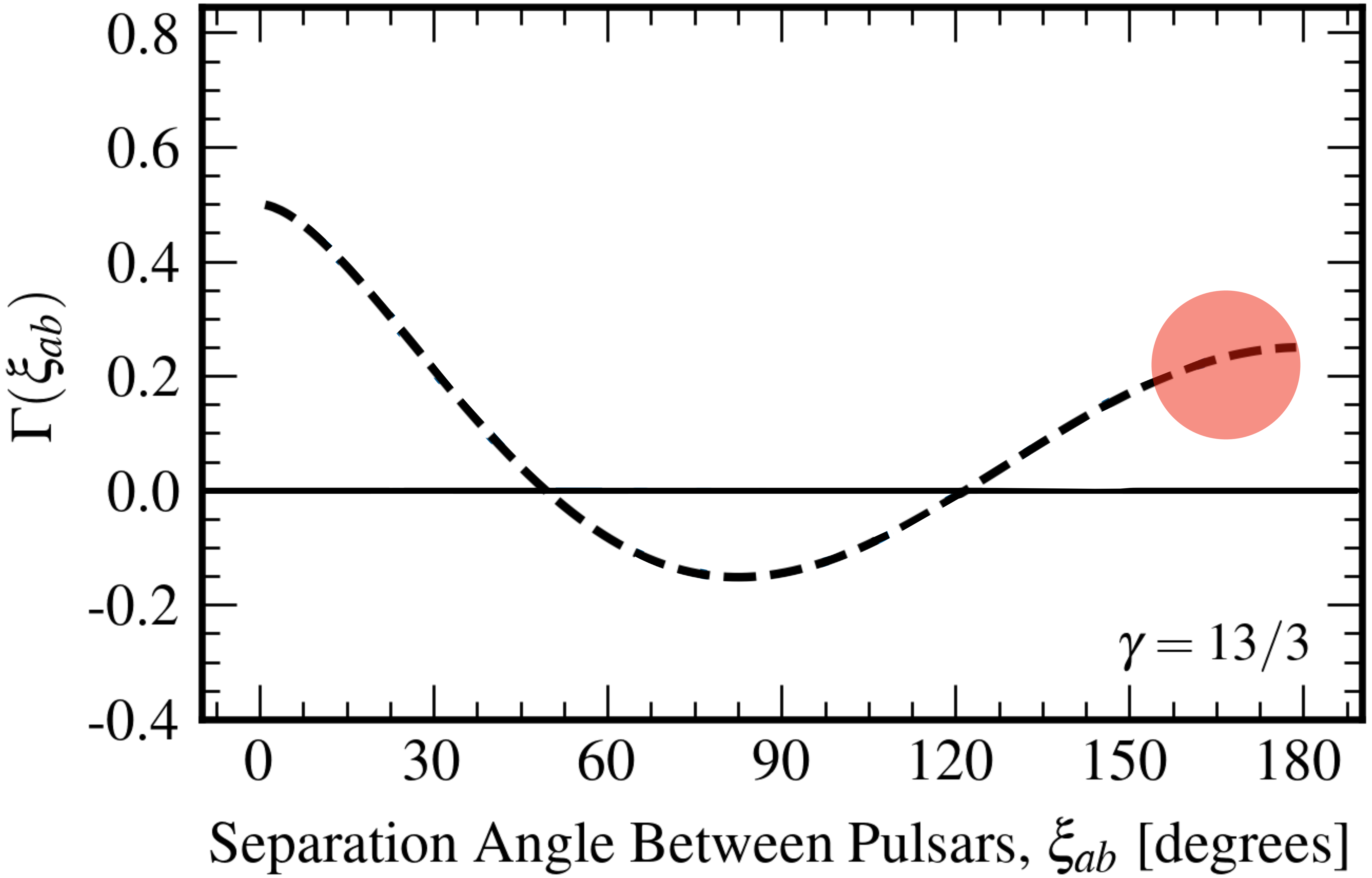


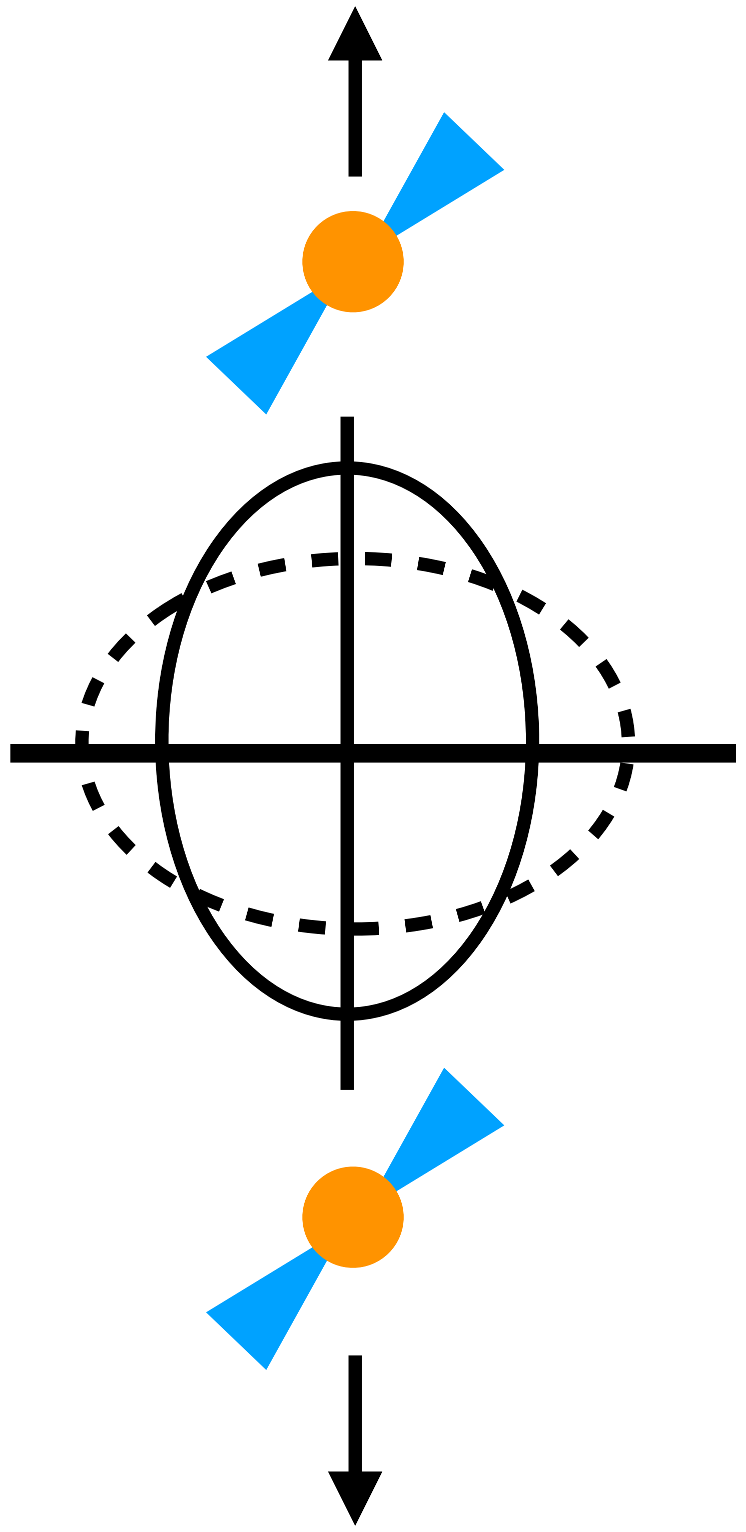
HELLINGS & DOWNS CURVE





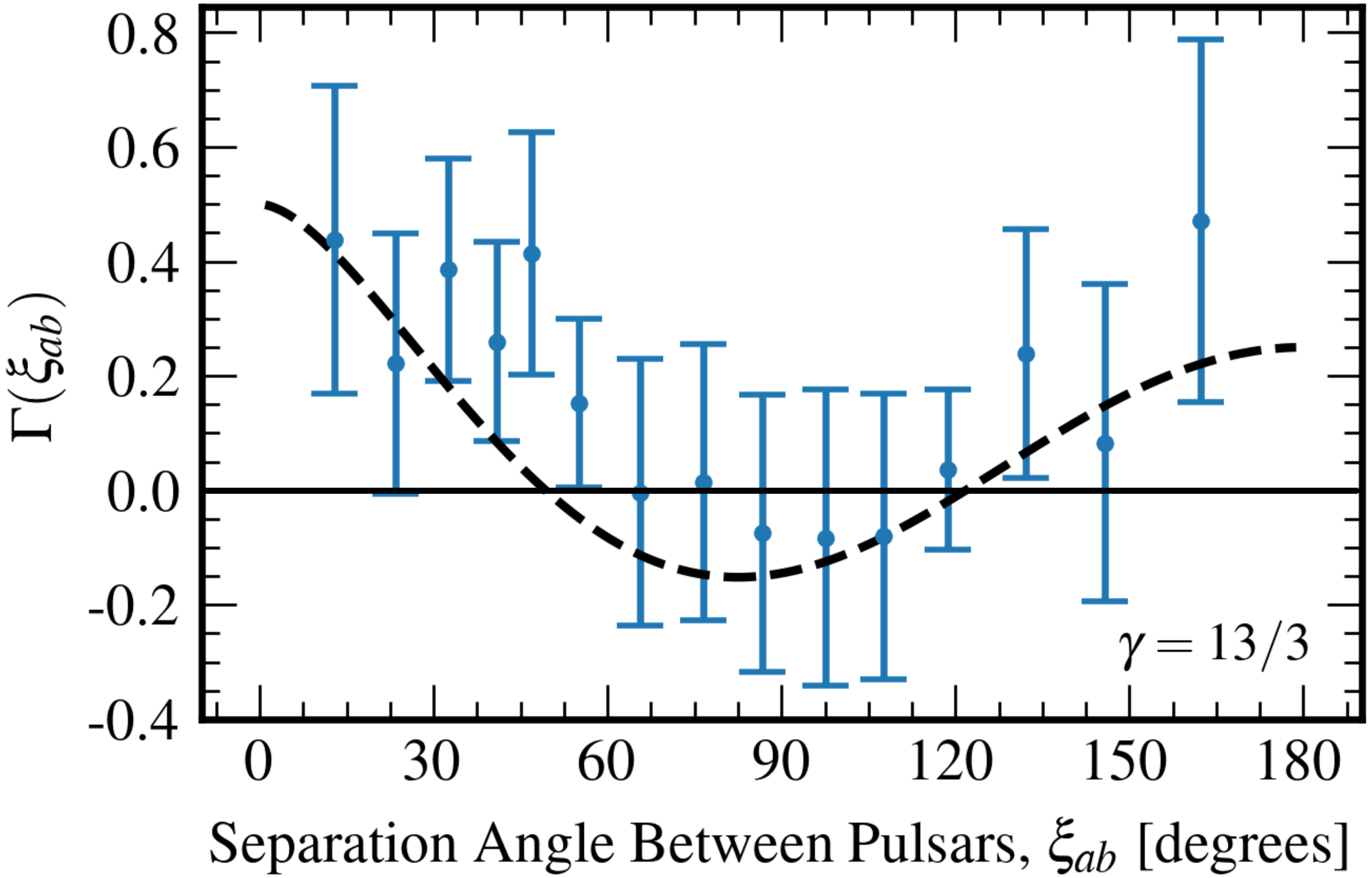
HELLINGS & DOWNS CURVE





EVIDENCE FOR GWB

Agazie et al. [2306.16213]



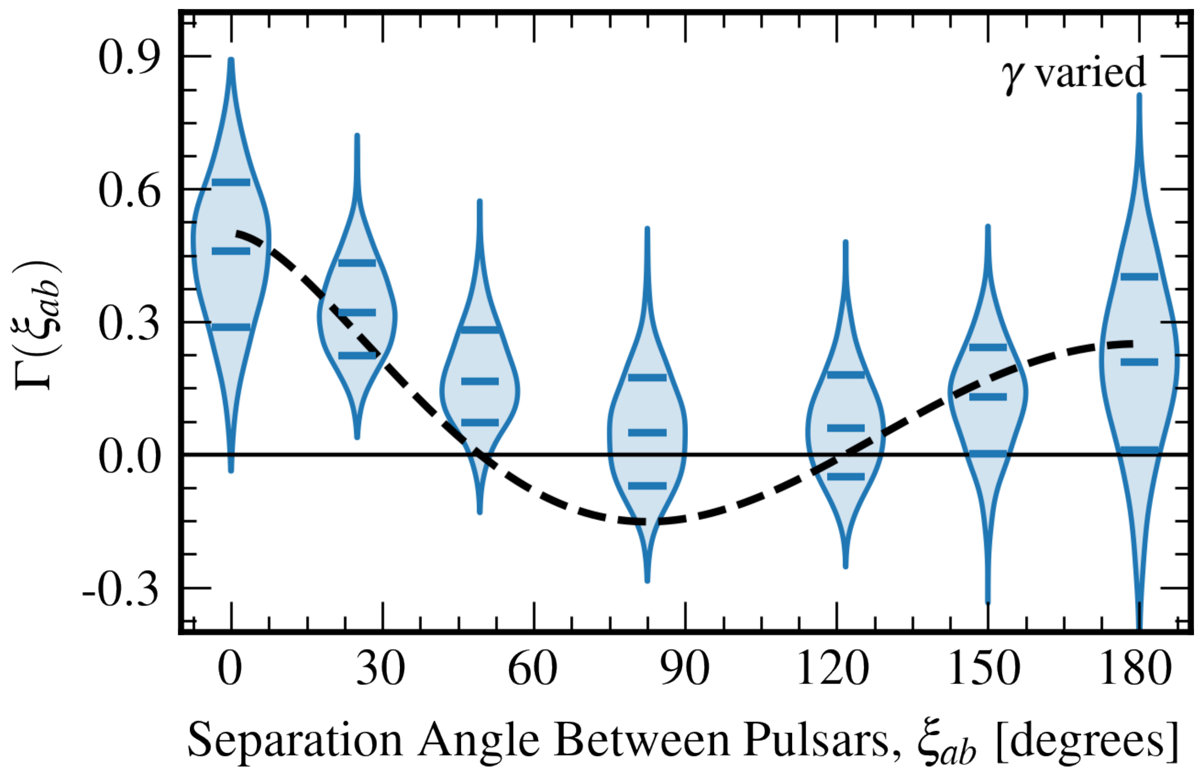
EVIDENCE FOR GWB

NANOGrav:

68 pulsars, 16yr of data

~3-4σ significance

Agazie et al. [2306.16213]

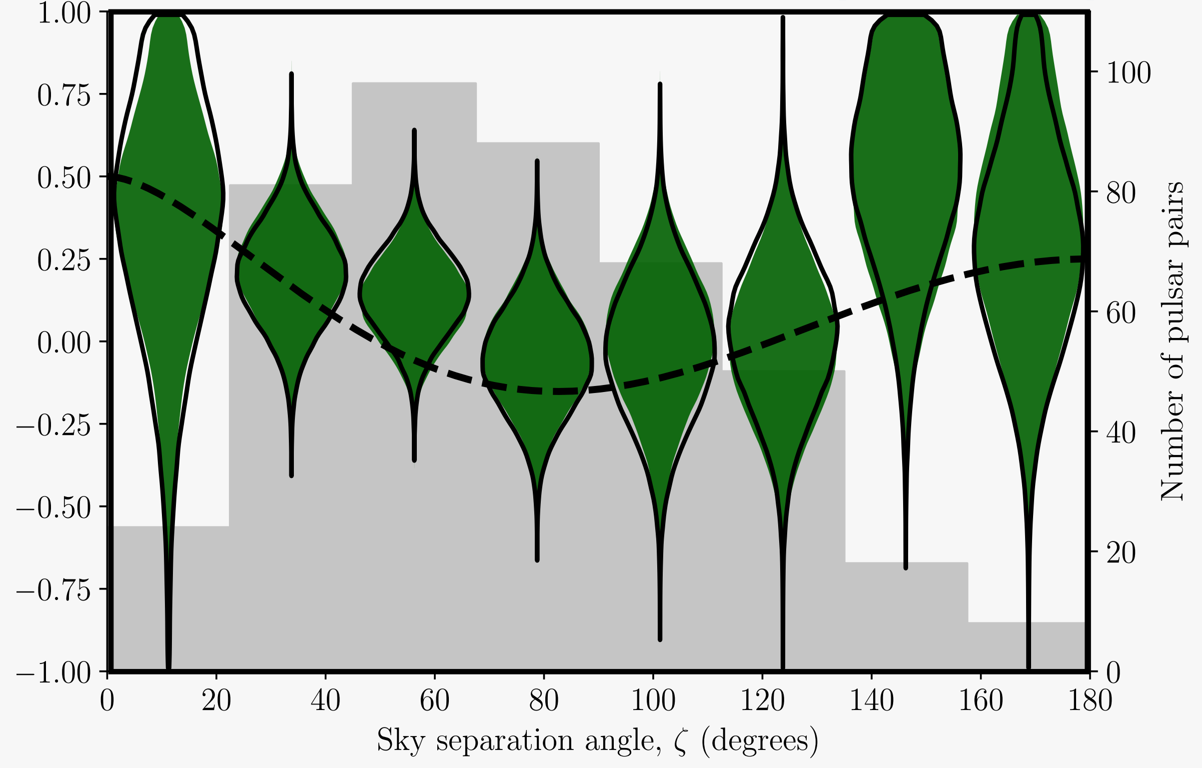


PPTA:

32 pulsars, 18yr of data

~2σ significance

Reardon et al. [2306.16215]

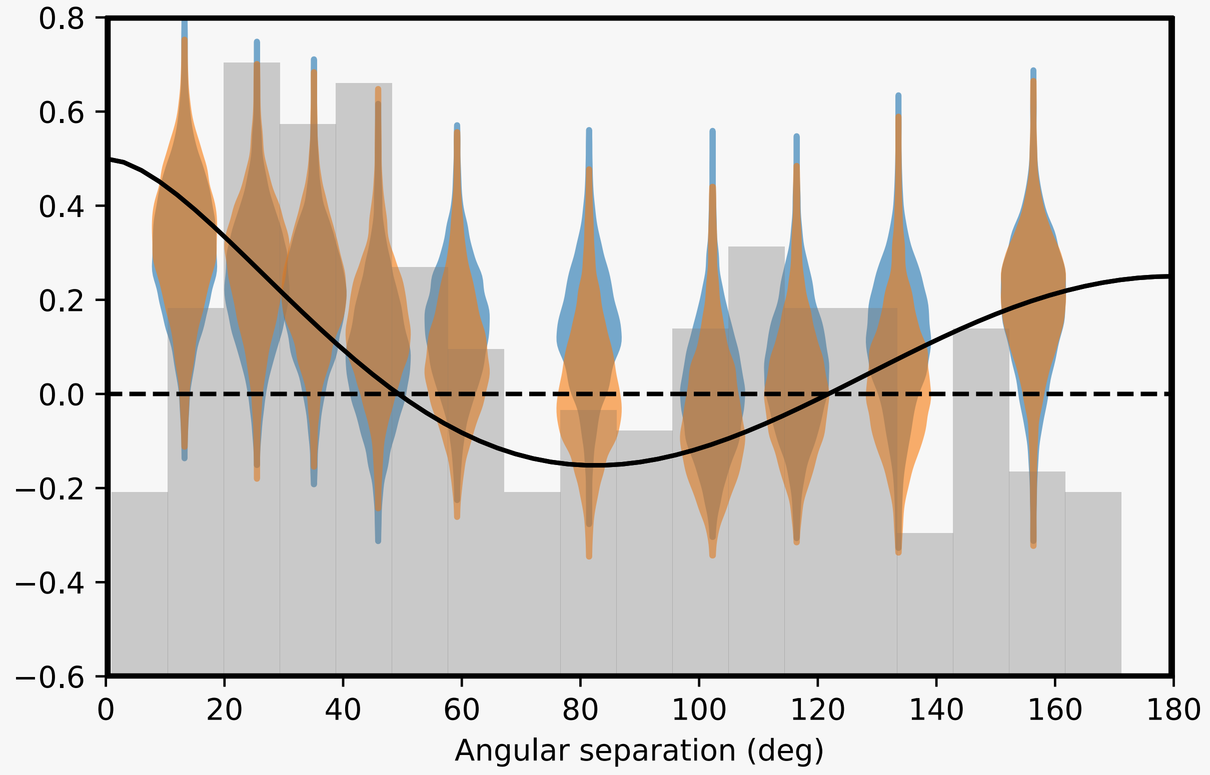


EPTA + InPTA:

25 pulsars, 24yr of data

~3σ significance

Antoniadis et al. [2306.16214]

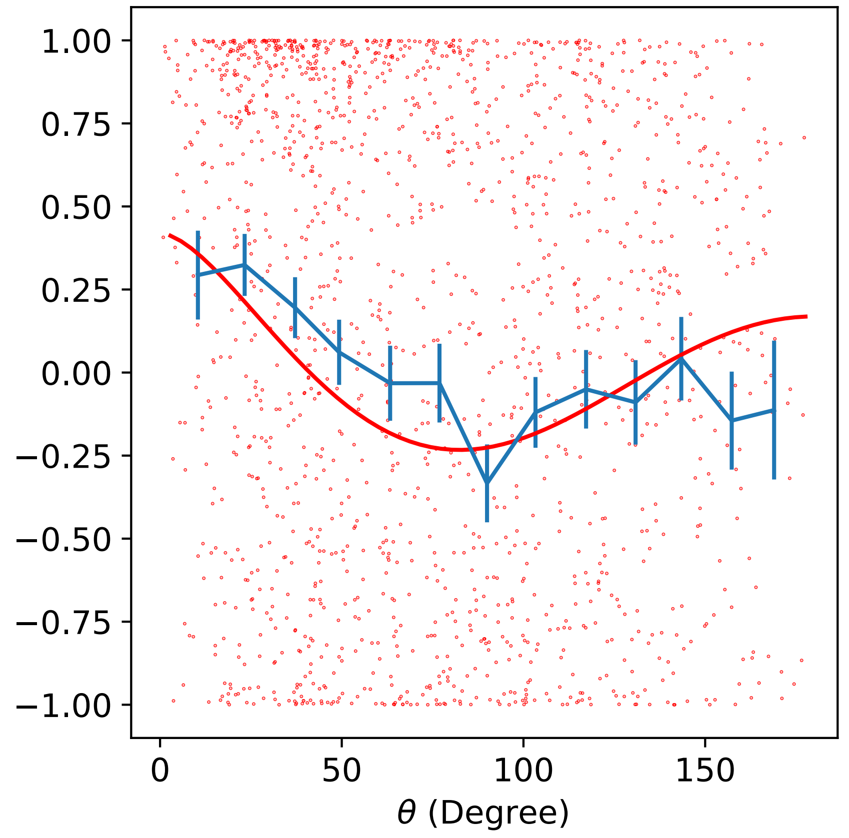


CPTA:

57 pulsars, 3yr of data

~4.6σ significance

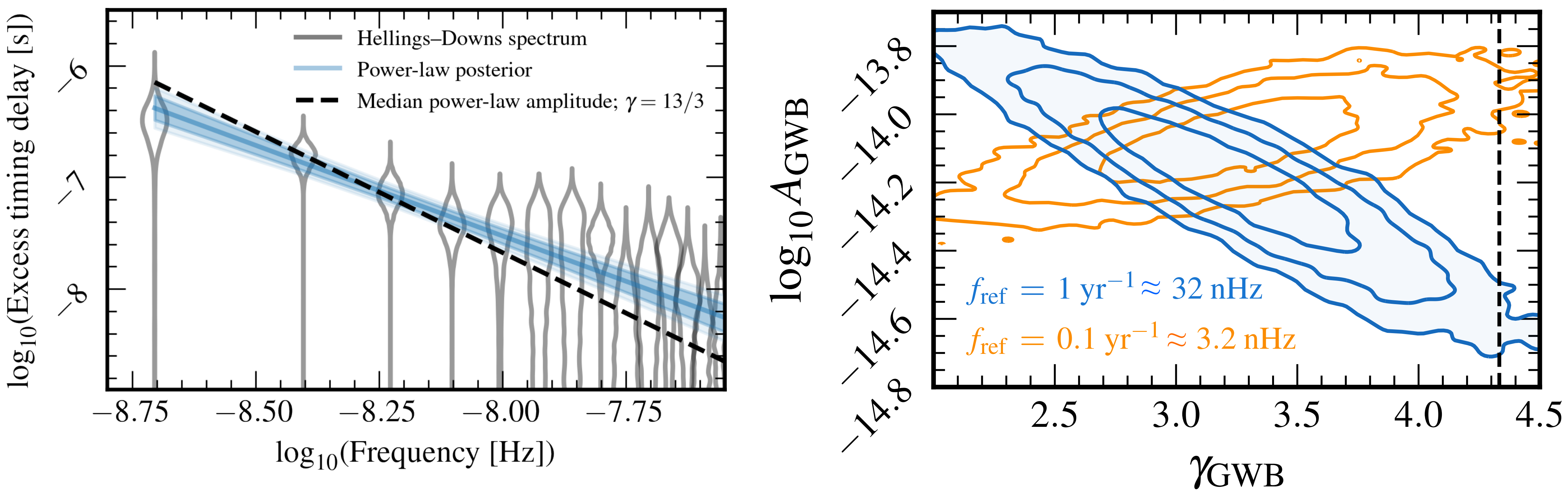
Xu et al. [2306.16216]



SPECTRUM

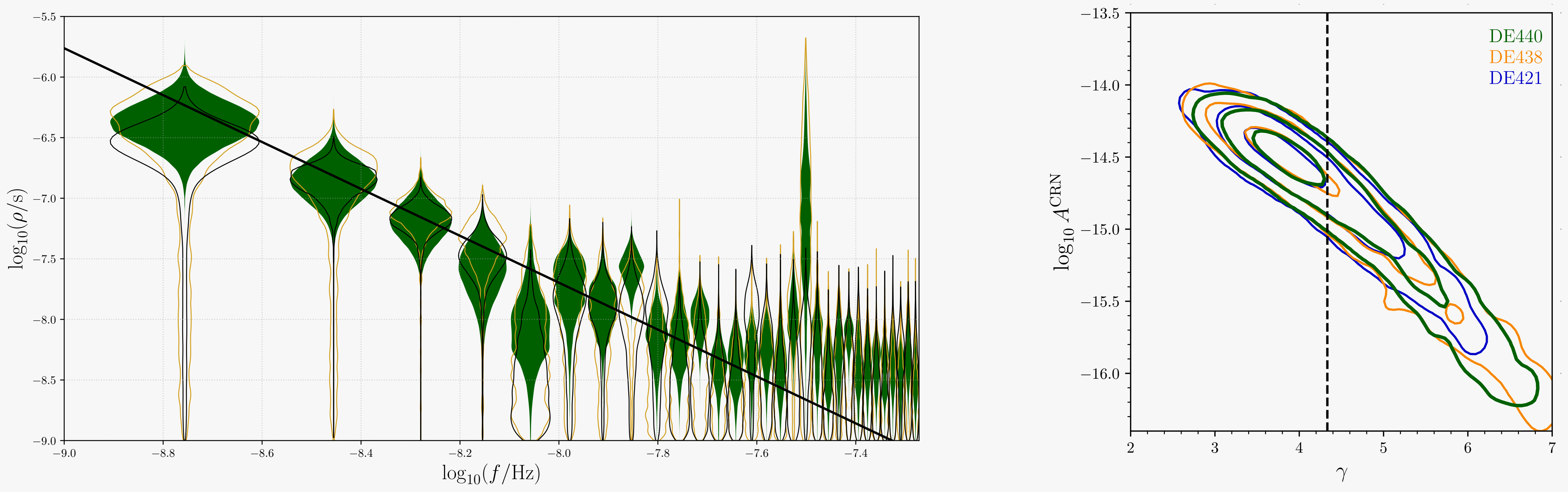
NANOGrav

Agazie et al. [2306.16213]



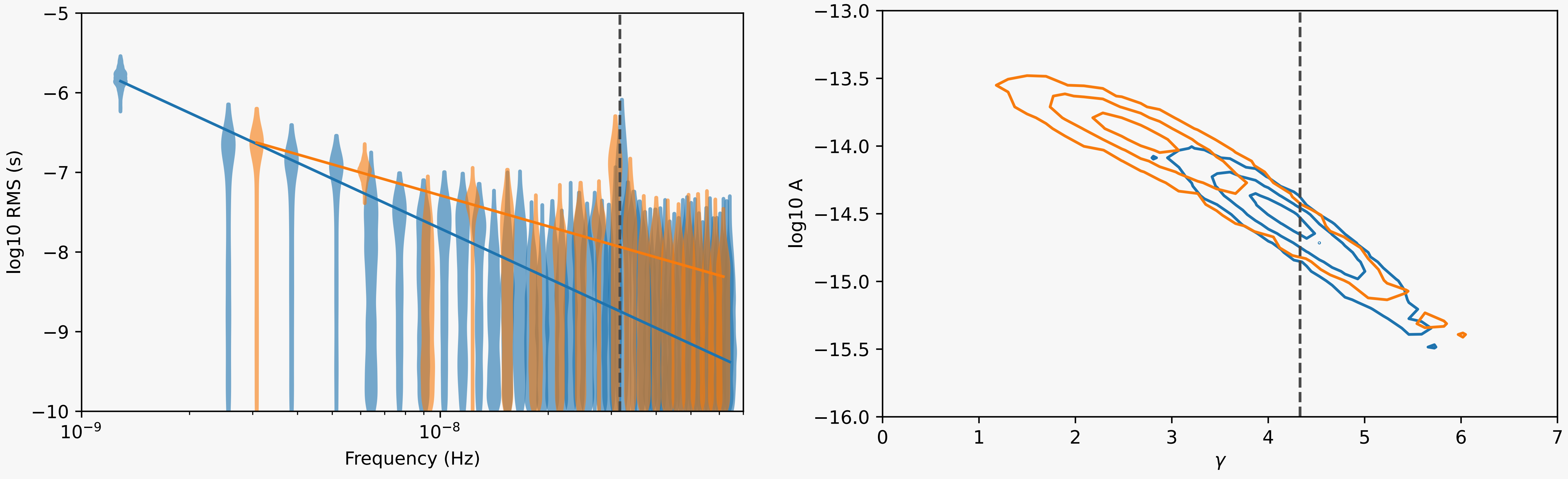
PPTA

Reardon et al. [2306.16215]



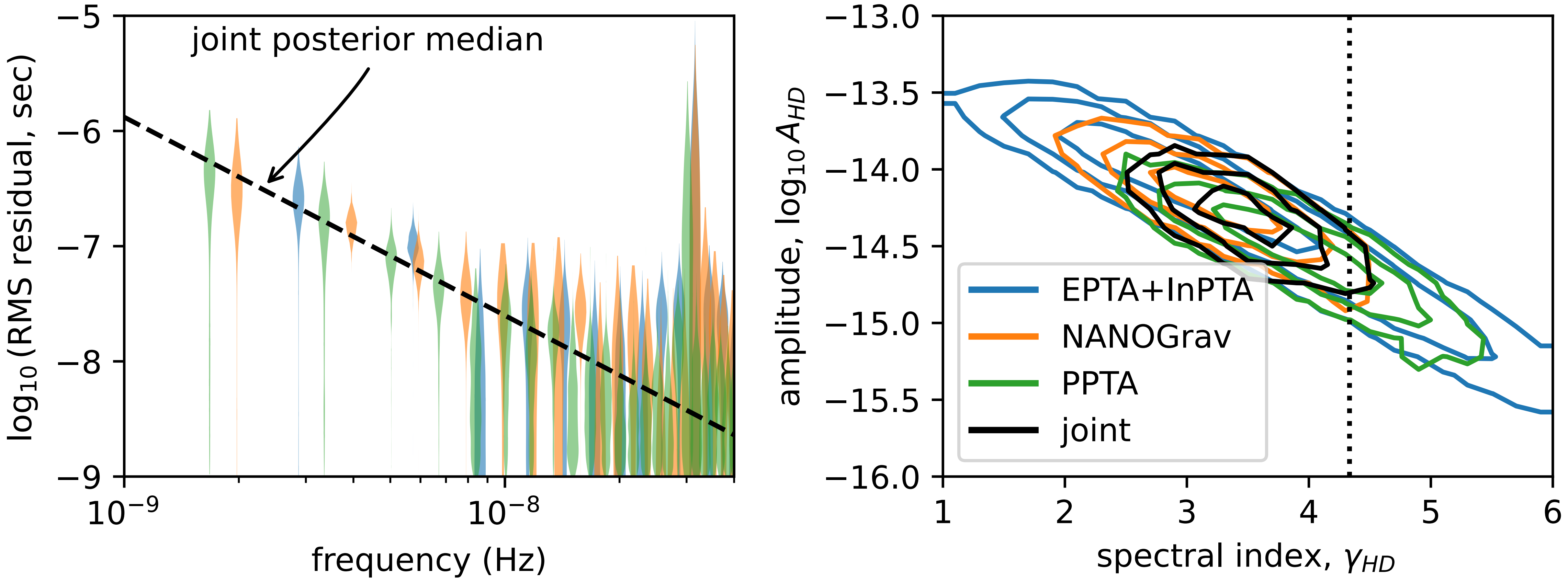
EPTA + InPTA

Antoniadis et al. [2306.16214]



IPTA early data combination

Agazie et al. [2309.00693]



ANISOTROPIES

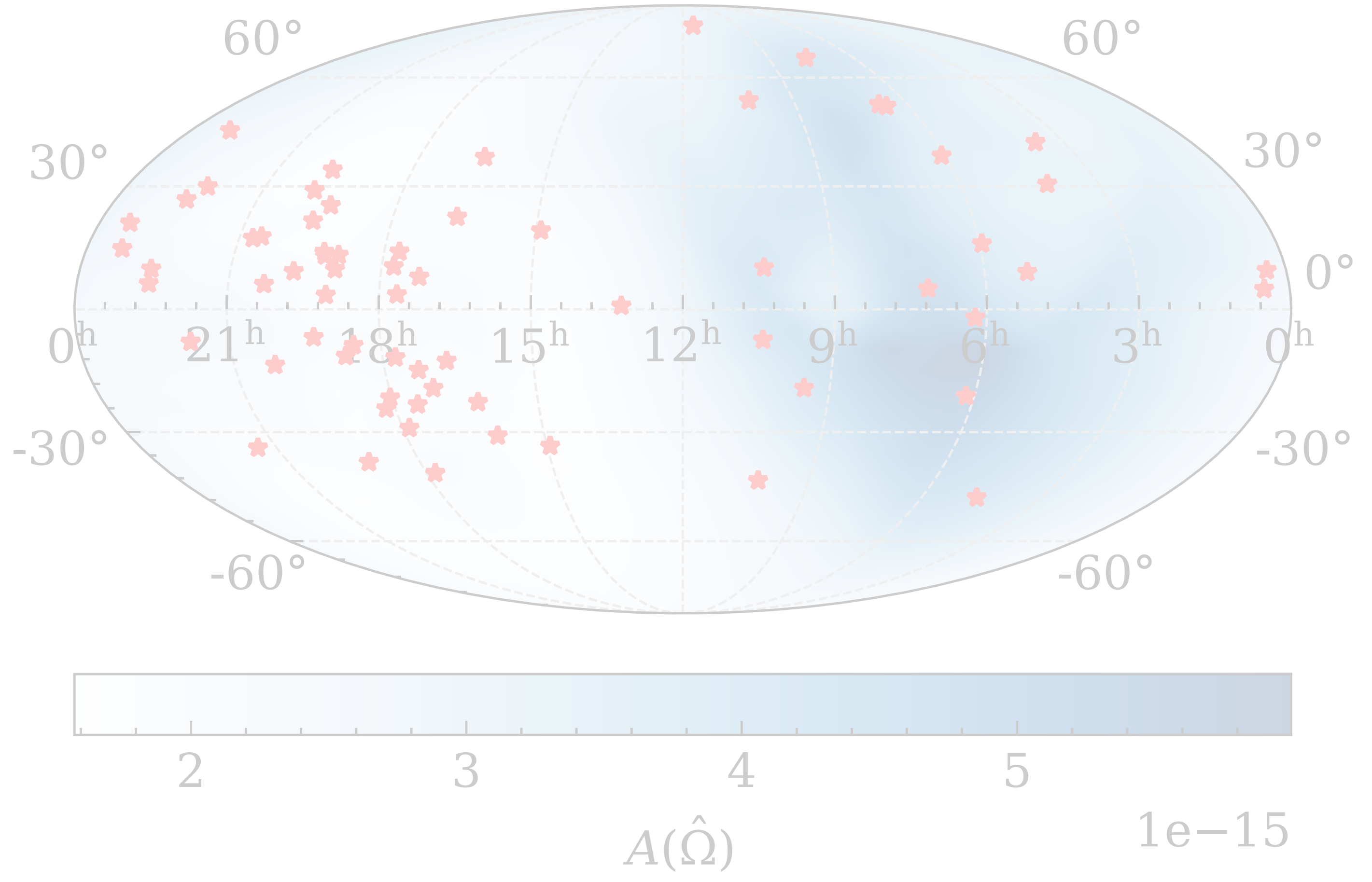
$$\Gamma_{ab} \propto \sum_k R_{ab,k} \cdot P_k$$

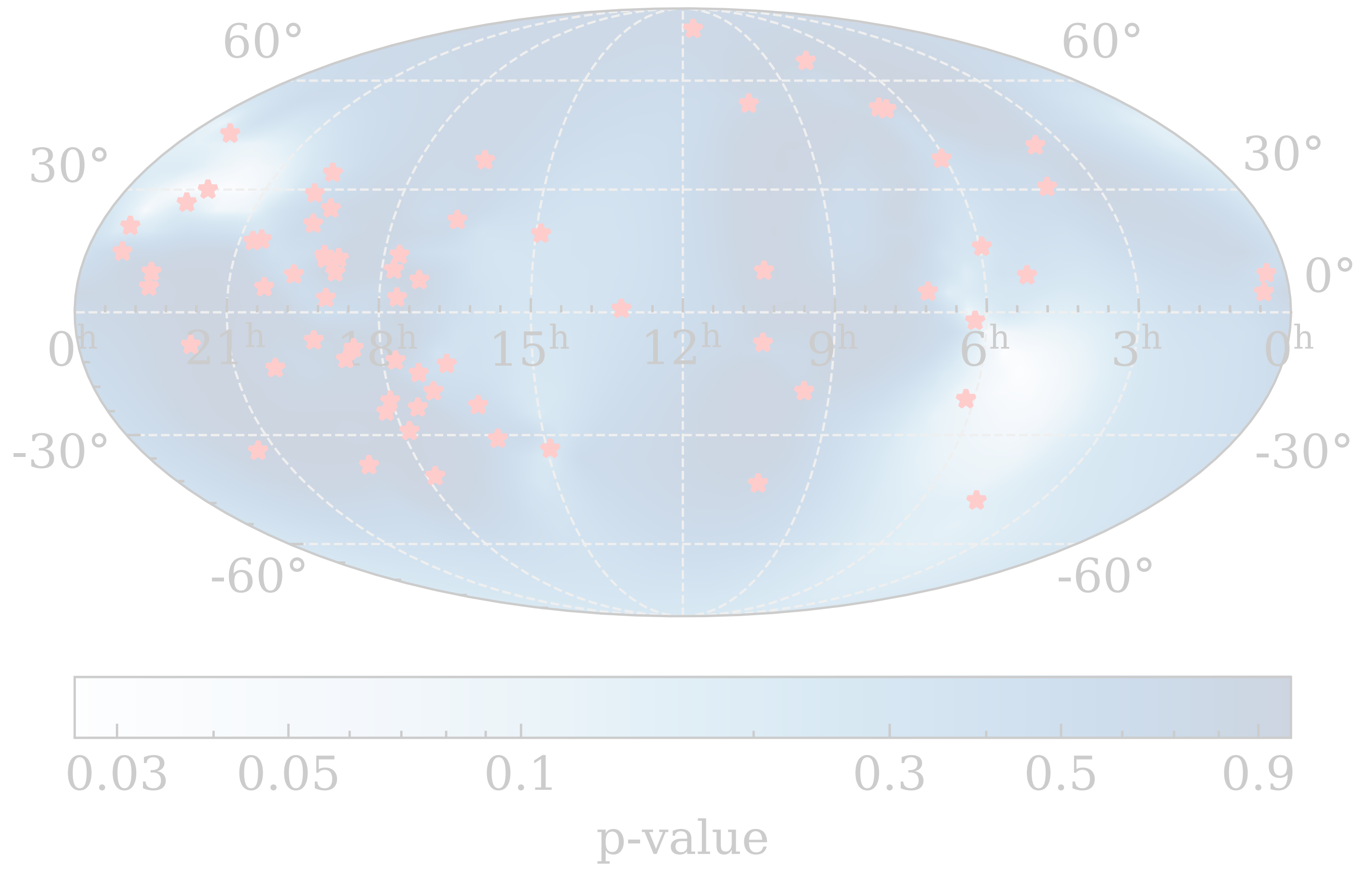
overlap reduction function

PTA response function

GWB power

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





Agazie et al. [2306.16221]

ANISOTROPIES

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

overlap reduction function

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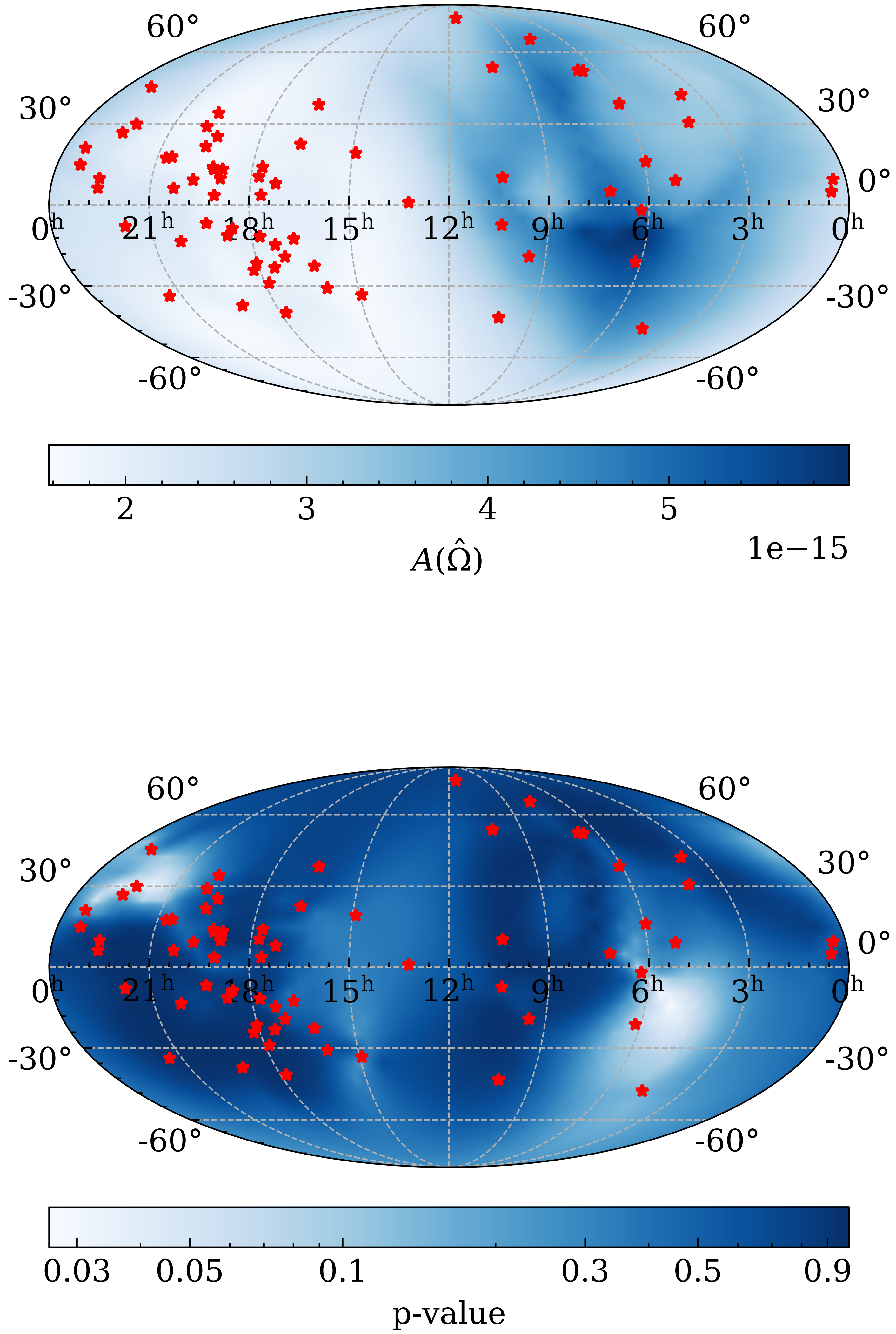


Agazie et al. [2306.16221]

ANISOTROPIES

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

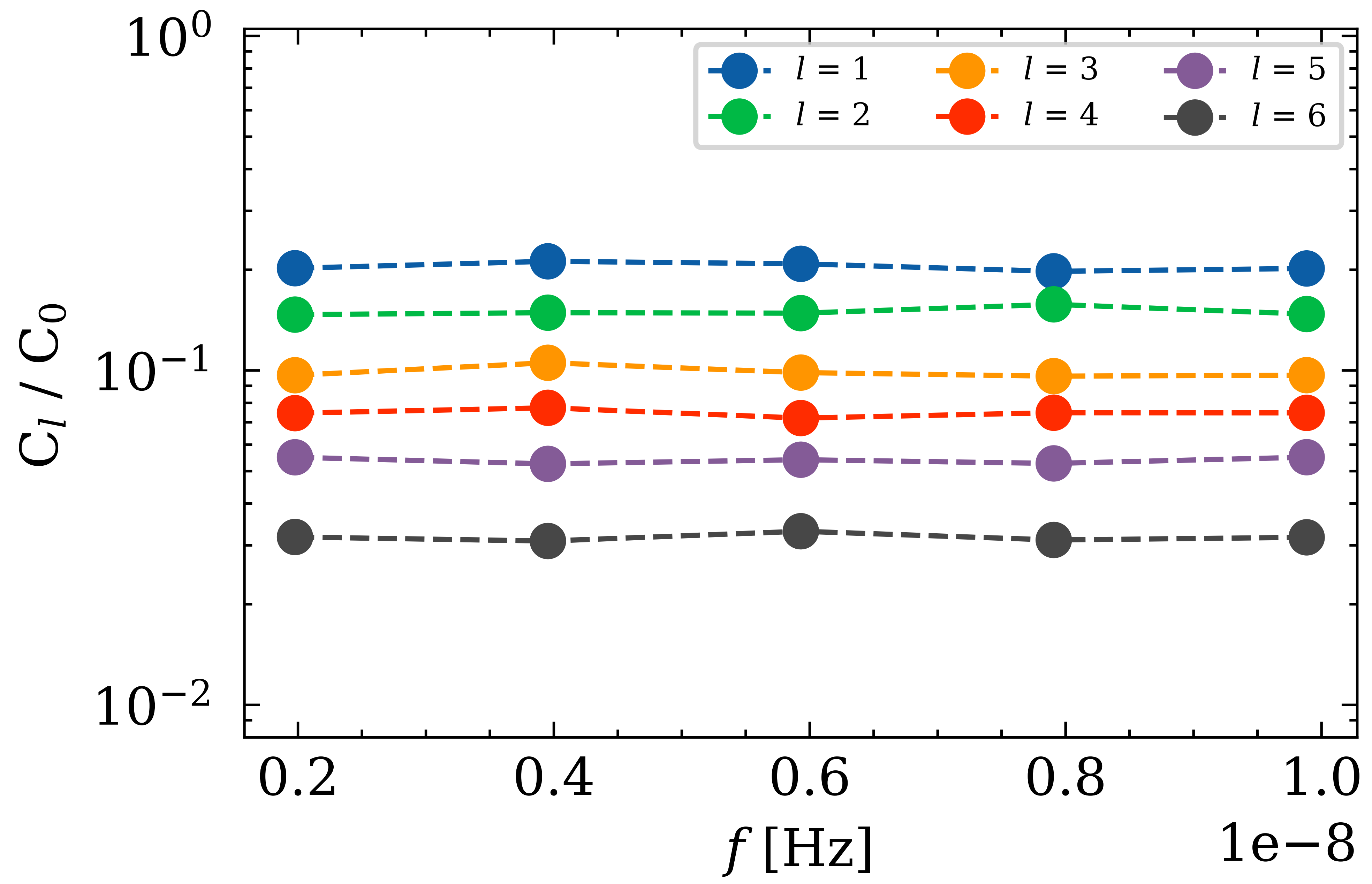
overlap reduction function

PTA response function

GWB power

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

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



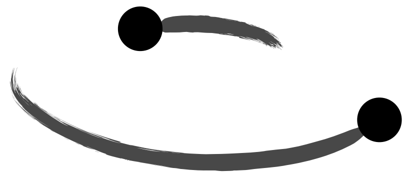
Agazie et al. [2306.16221]

what is the source?

CONTENDER #1

Graphics by Little Shadow

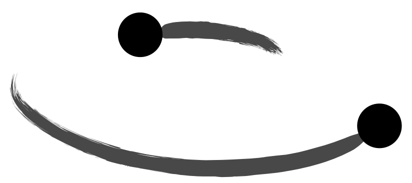
CONTENDER #1



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

Phinney 2001, Wyithe & Loeb 2003

CONTENDER #1



GW signal from individual SMBHB

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

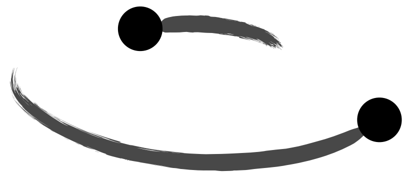
Phinney 2001, Wyithe & Loeb 2003

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



GW signal from individual SMBHB

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

number density of SMBHB binaries

Phinney 2001, Wyithe & Loeb 2003

averaged strain for a circular SMBHB

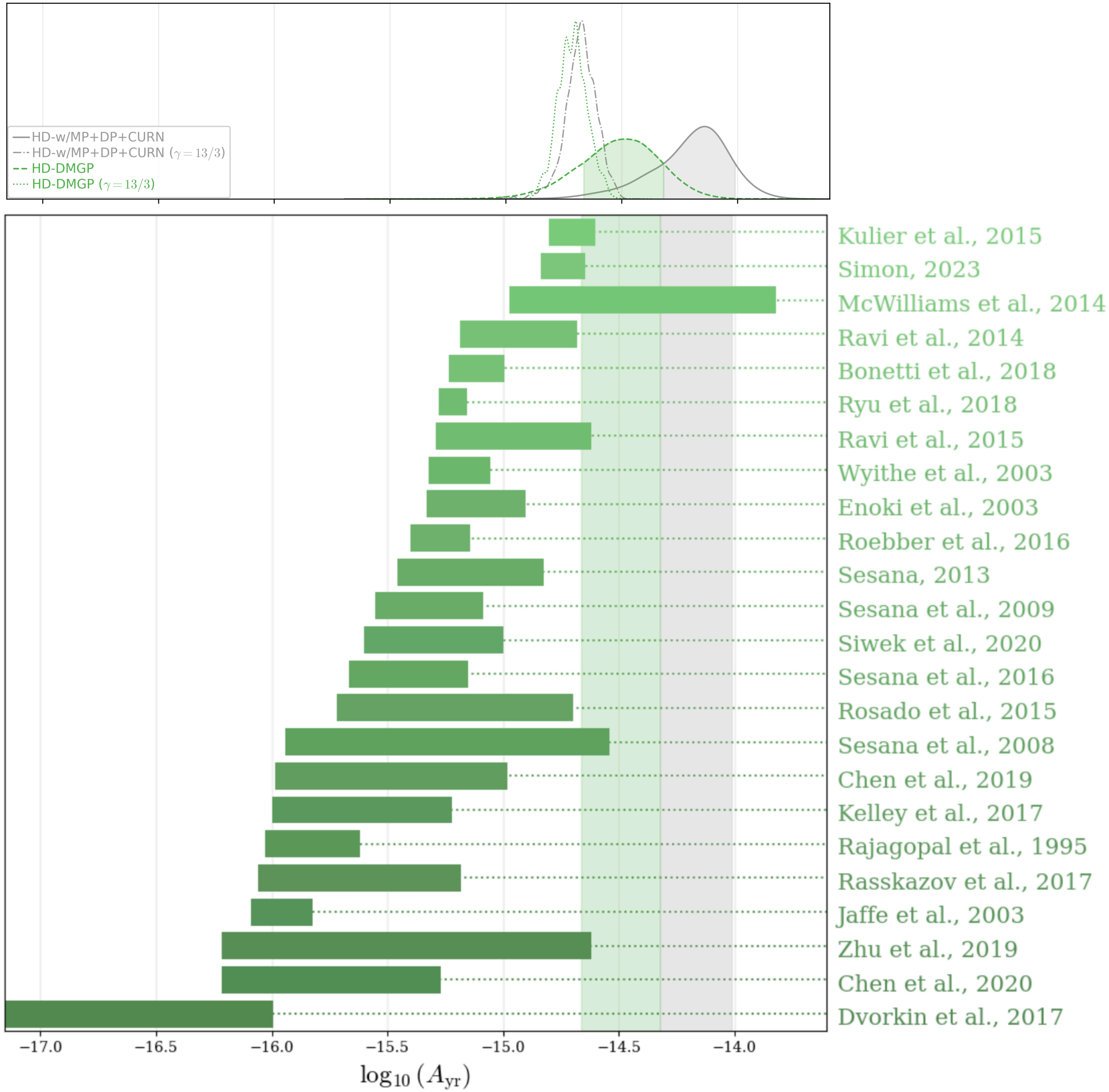
$$h_s^2(f) = \frac{32}{5} \frac{(G\mathcal{M})^{10/3}}{d_c^2} \left(2\pi f_p\right)^{4/3}$$

Finn & Thorne 2000

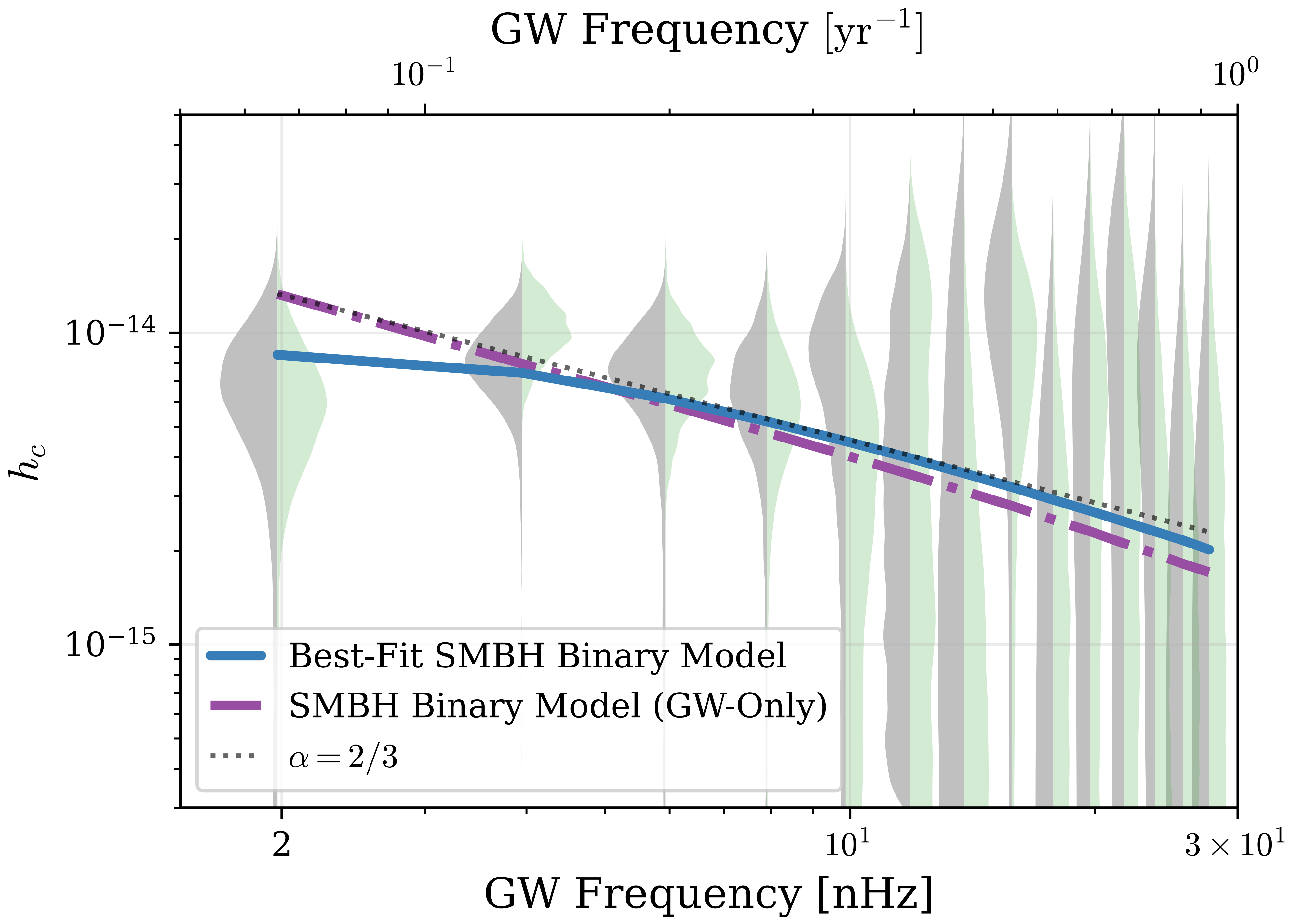
the SMBHB density depends on

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

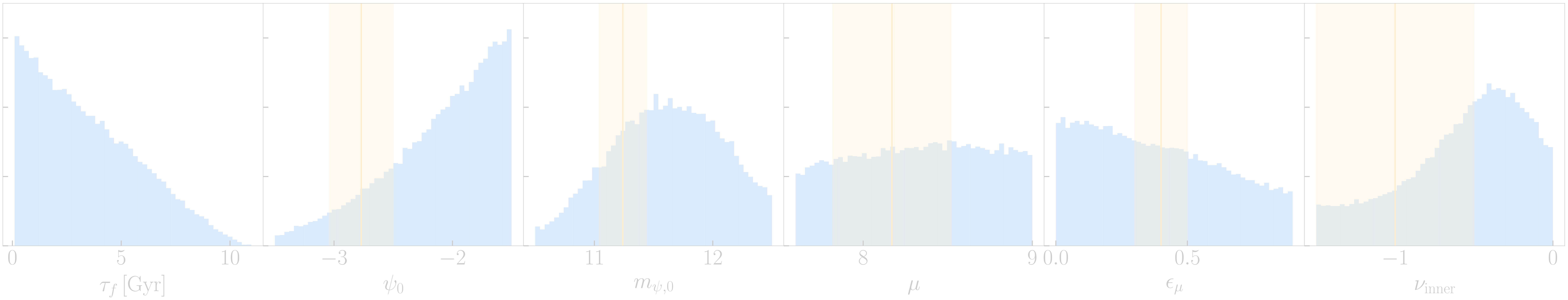
EXPECTATIONS


Agazie et al. [2306.16220]

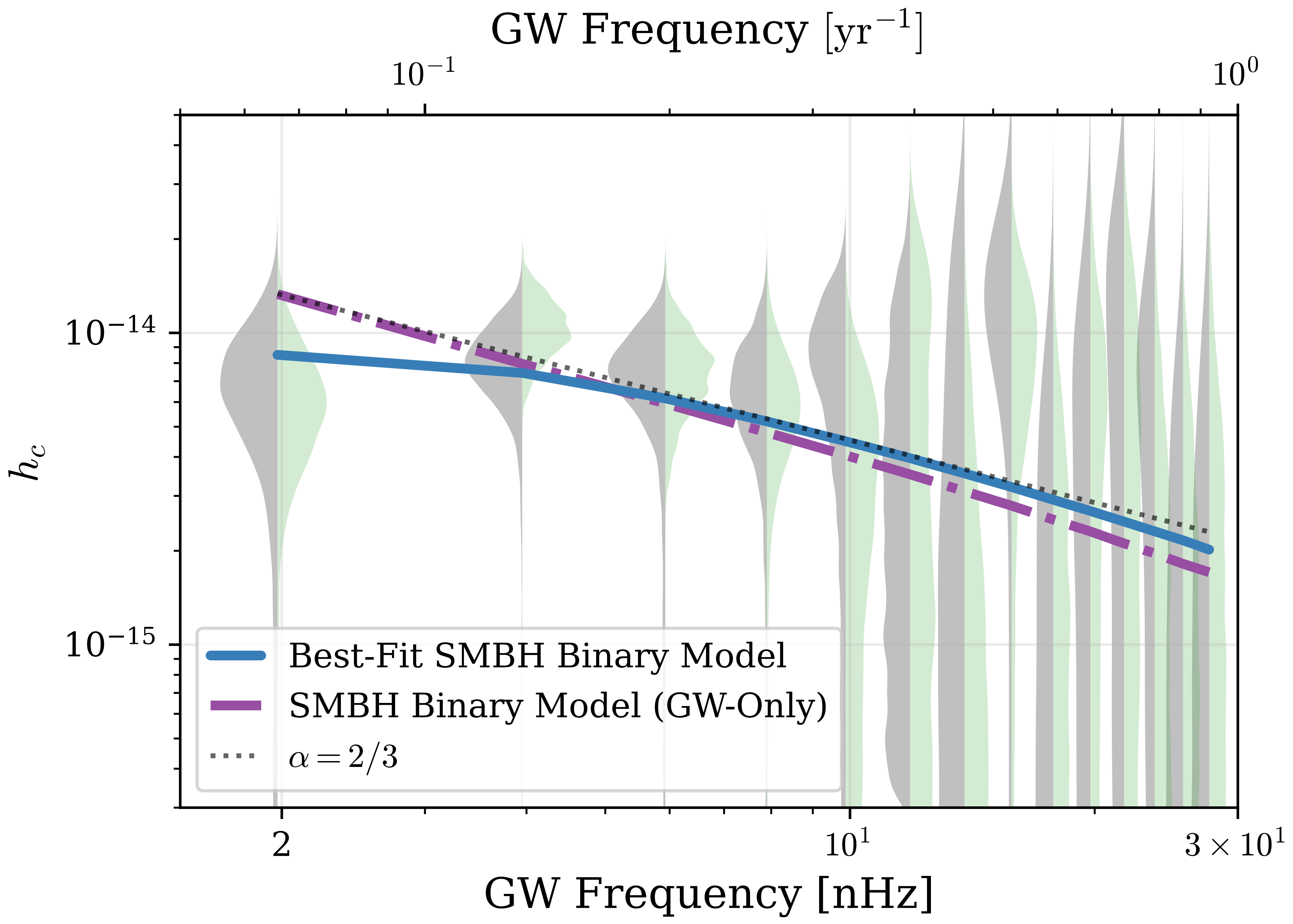
ADJUSTING EXPECTATIONS

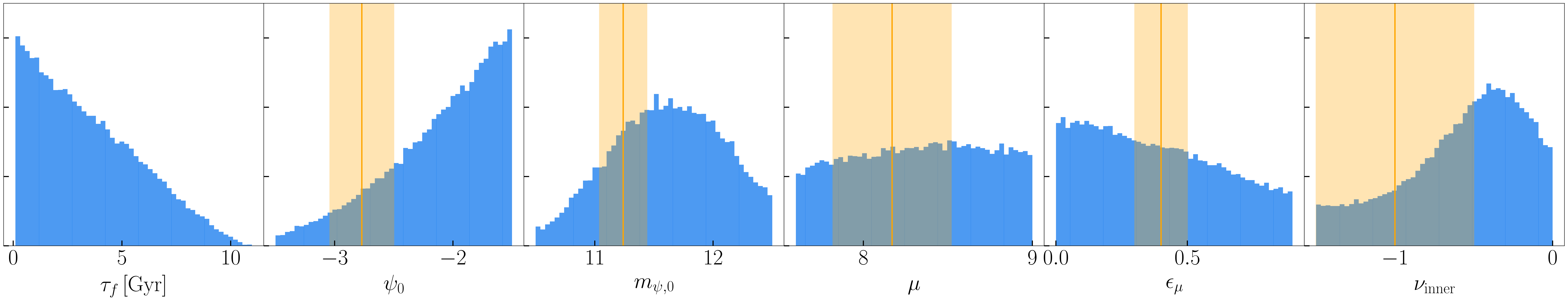


Agazie et al. [2306.16220]



ADJUSTING EXPECTATIONS



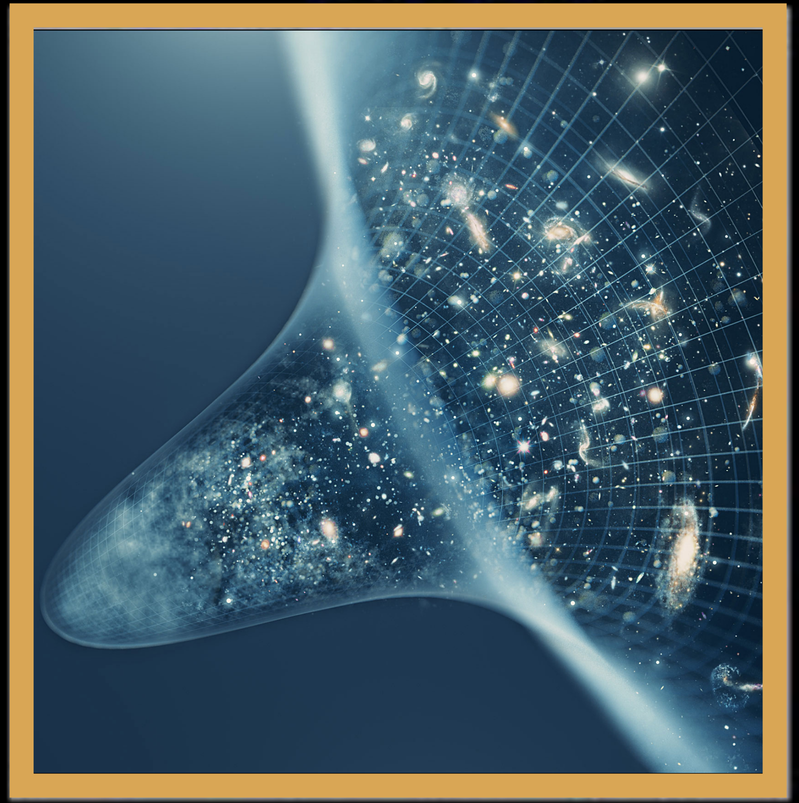


Agazie et al. [2306.16220]

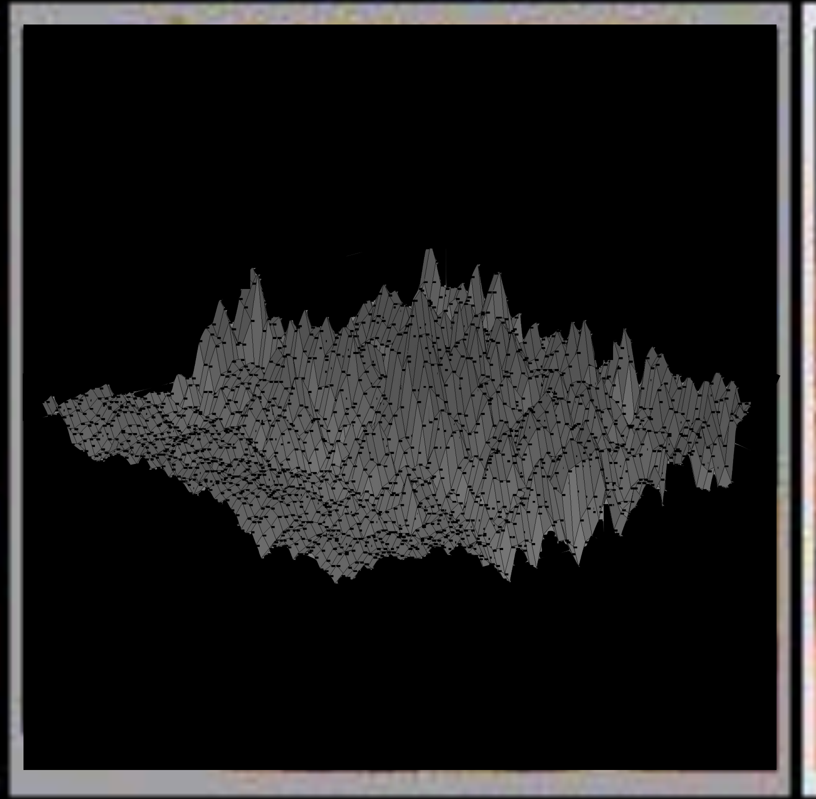
CONTENDER(s) #2

SELECT PLAYER

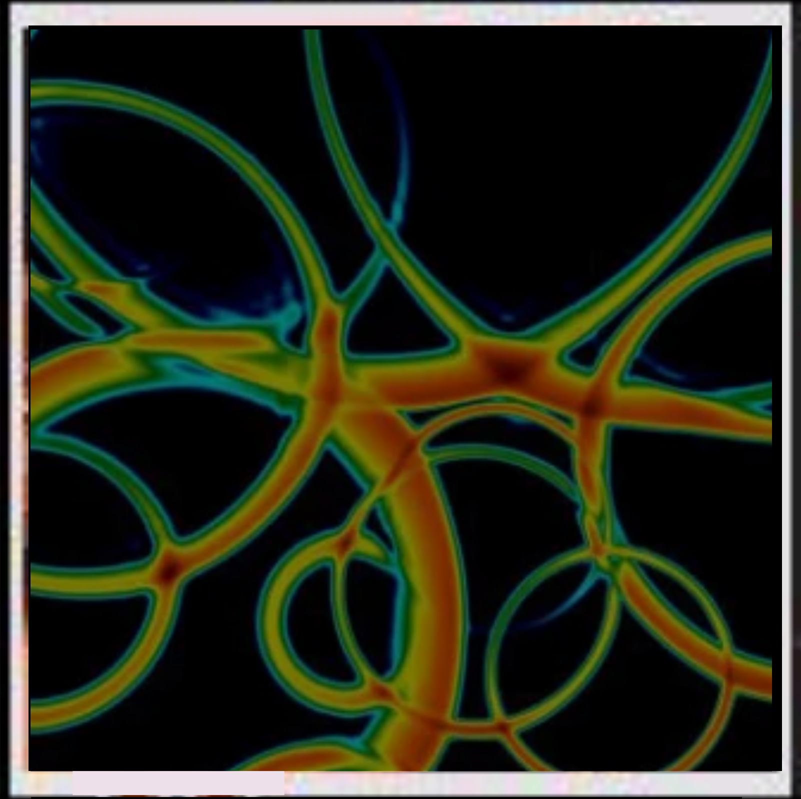
INFLATION



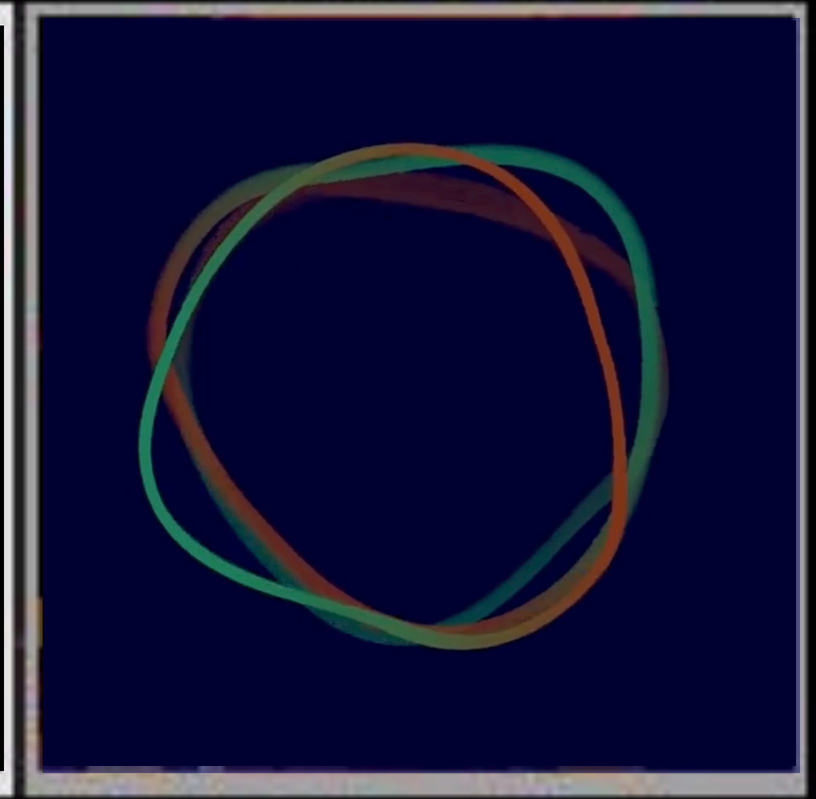
SIGW

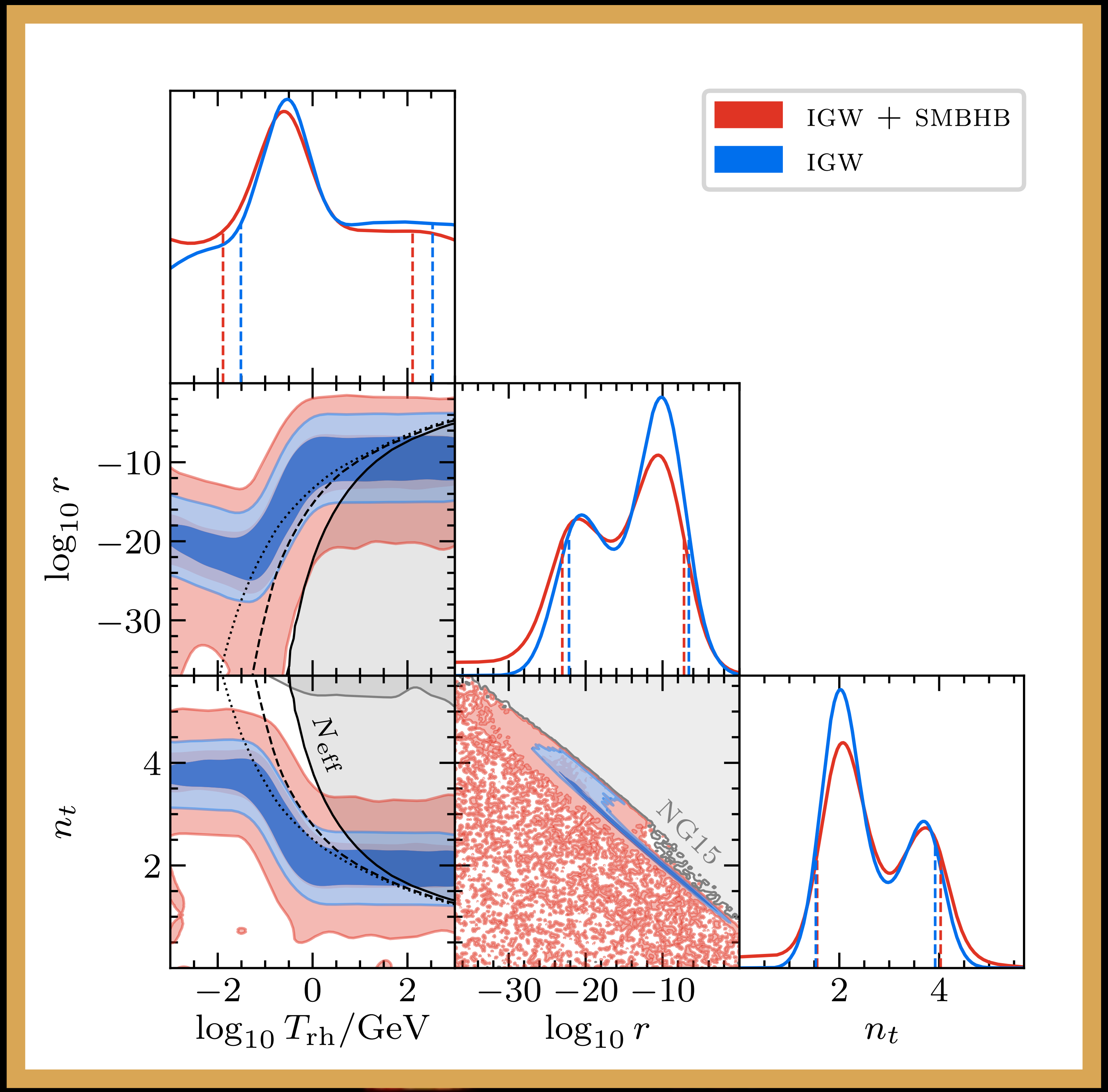


PT



STRINGS



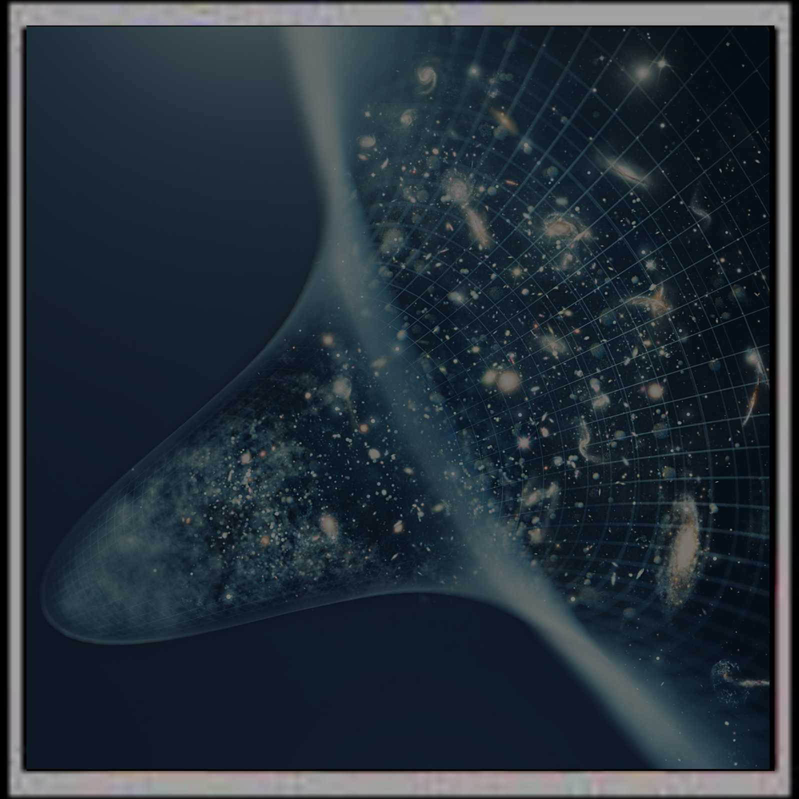


STRONG (RED) SPECTRAL TILT NEEDED

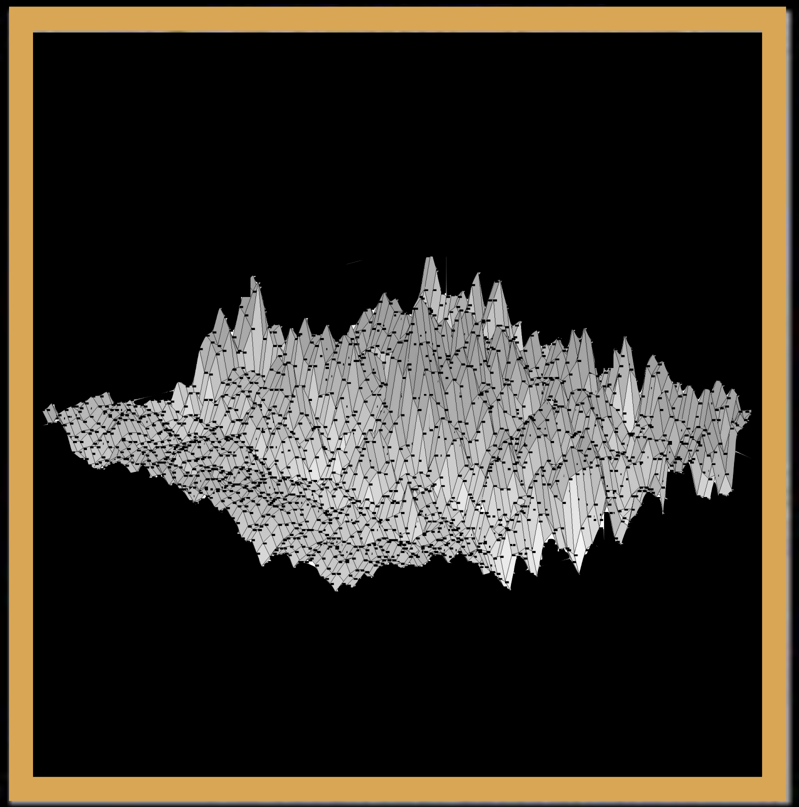
REHEATING TEMP. BELOW 100 GEV AVOIDS NEFF CONST.

SELECT PLAYER

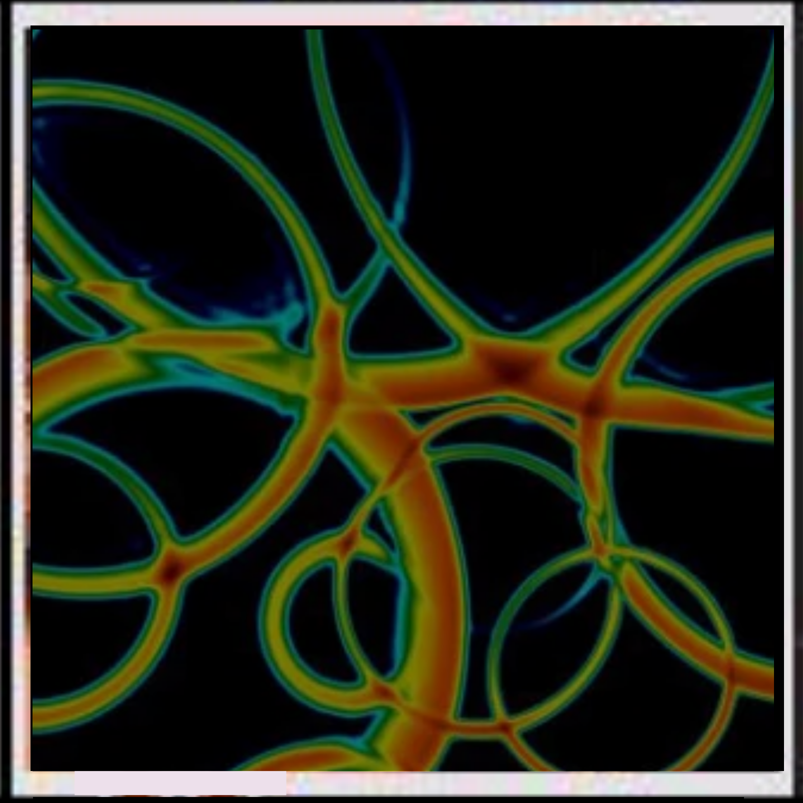
INFLATION



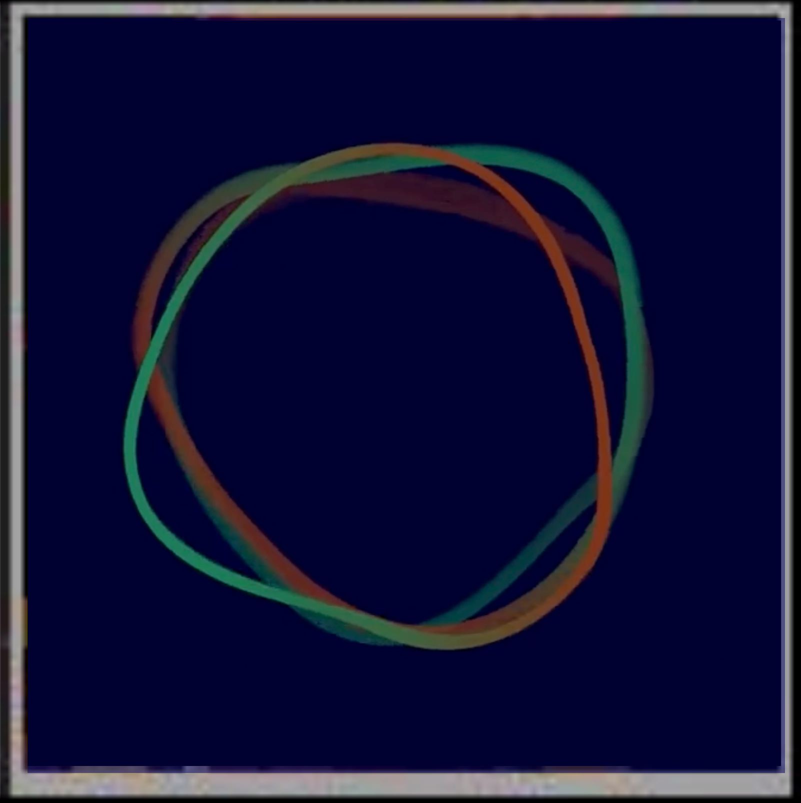
SIGW

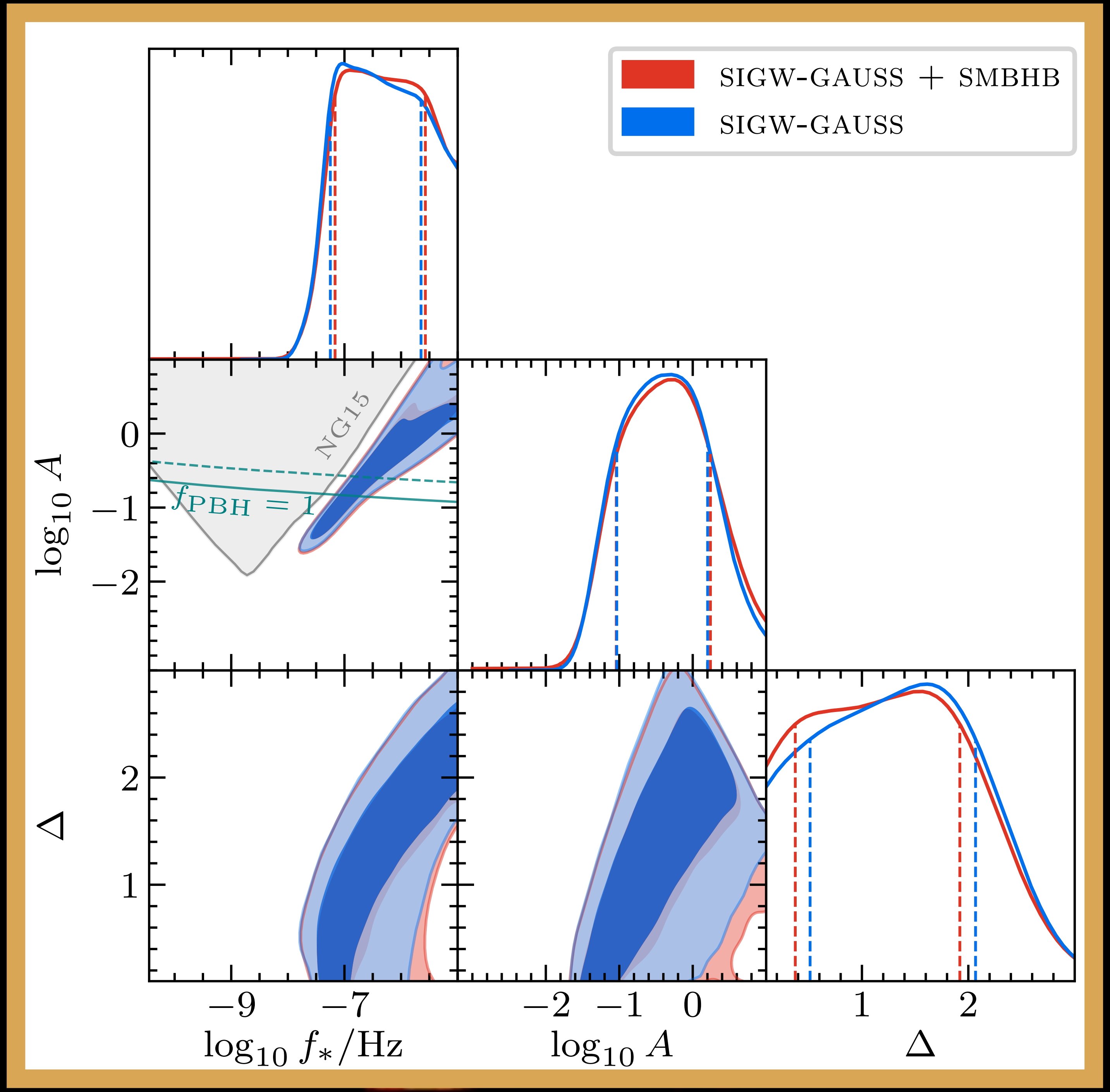


PT



STRINGS



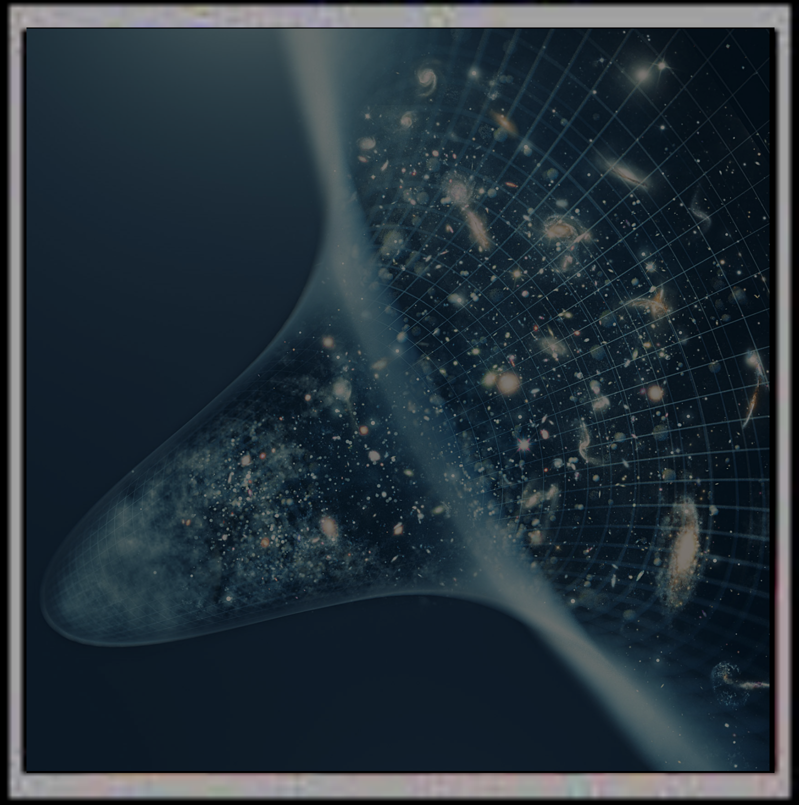


LARGE FEATURE AT MPC SCALES NEEDED

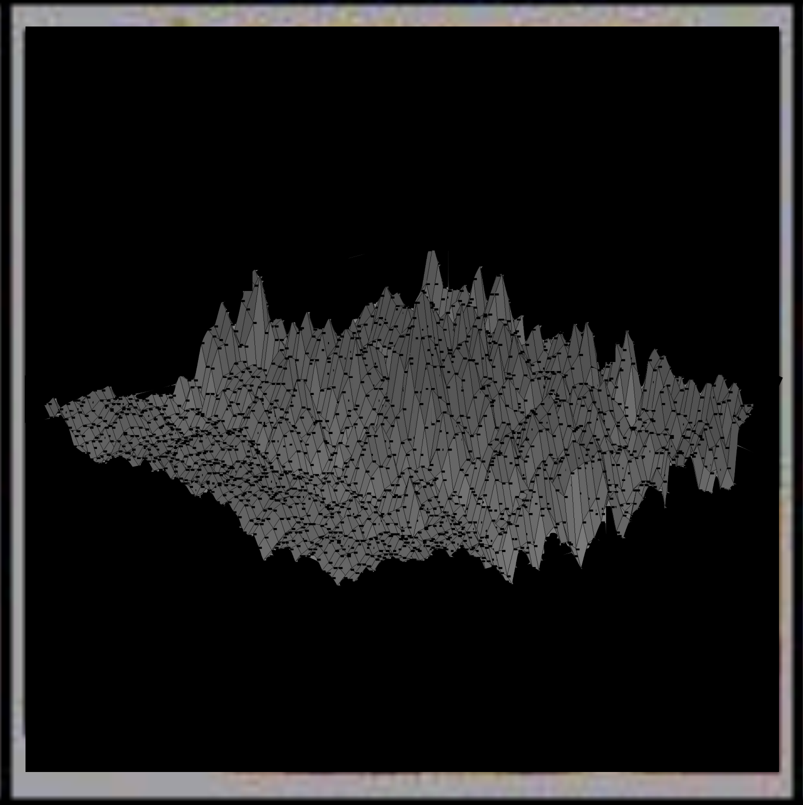
RISK OF OVERPRODUCING SMBH

SELECT PLAYER

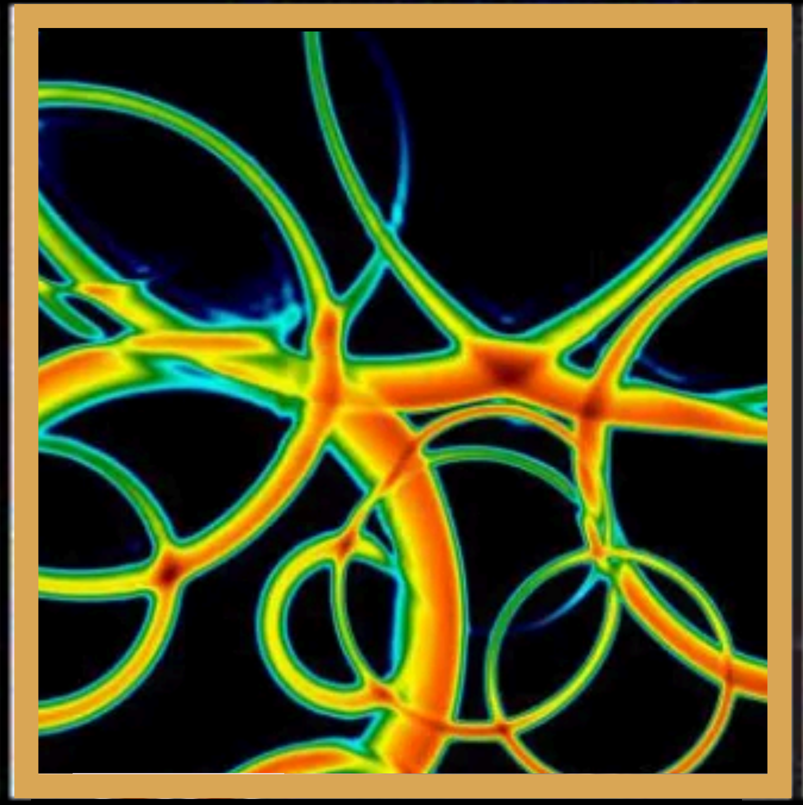
INFLATION



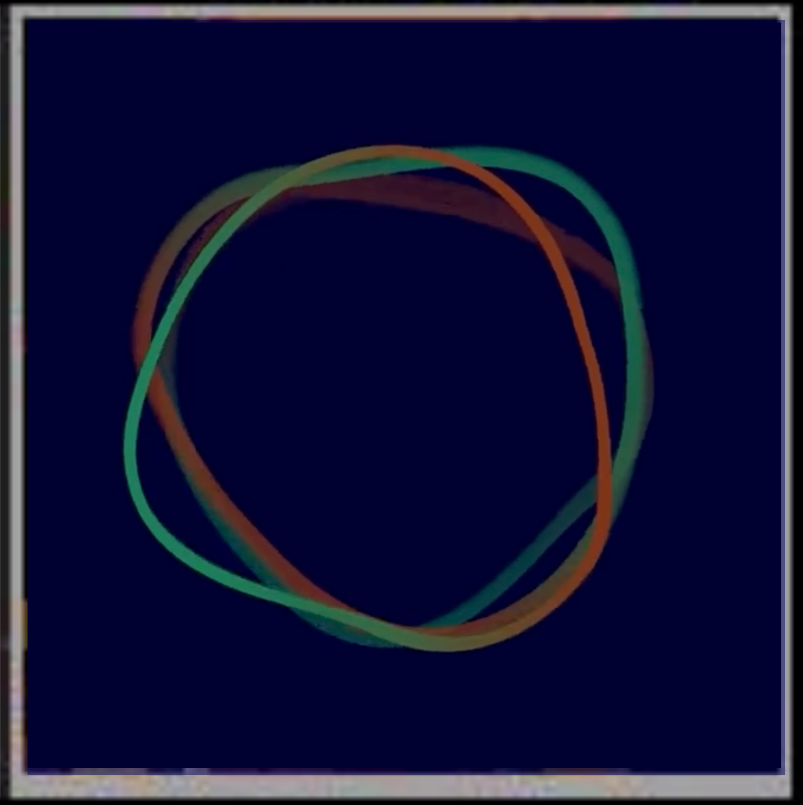
SIGW

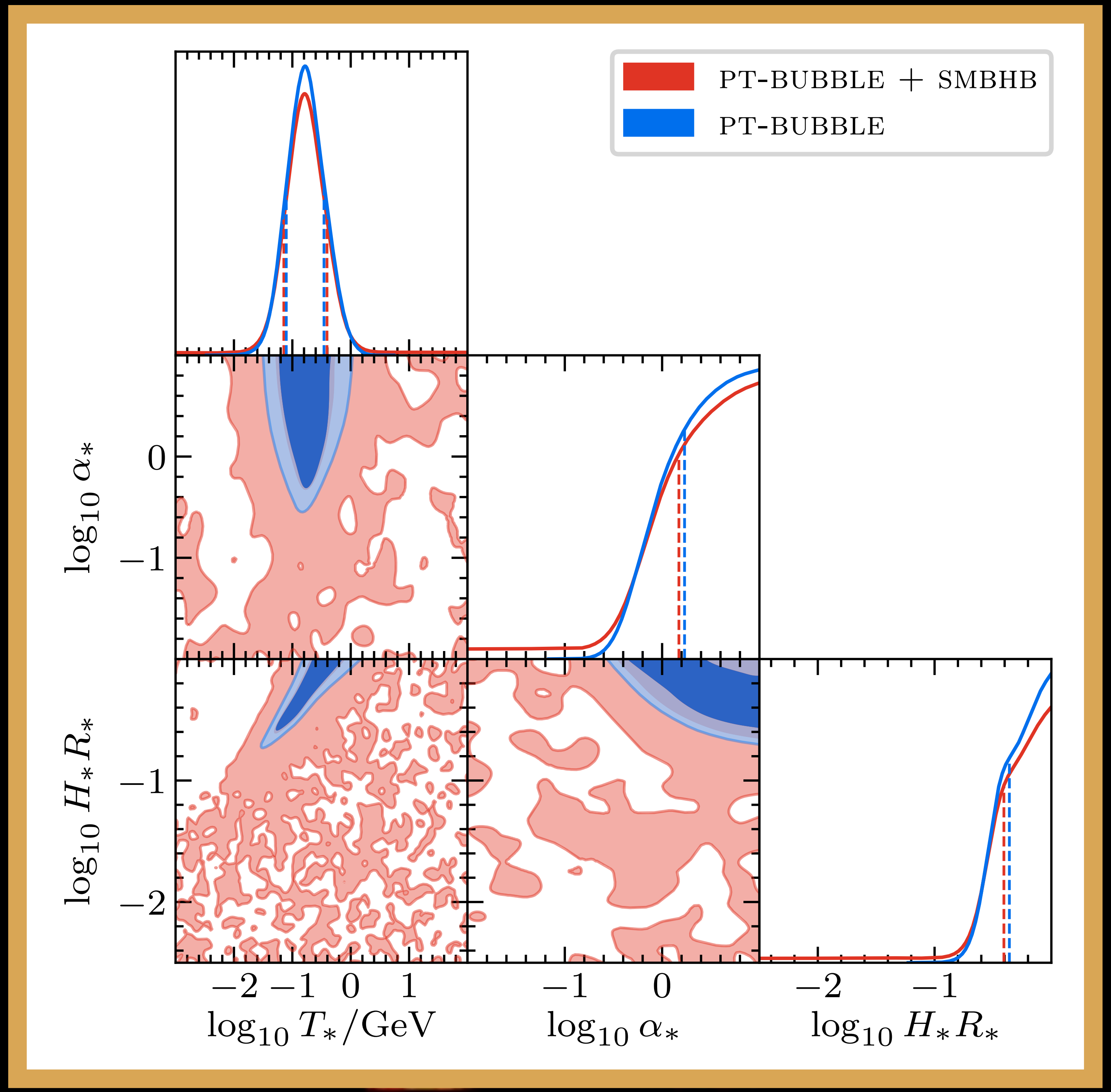


PT



STRINGS





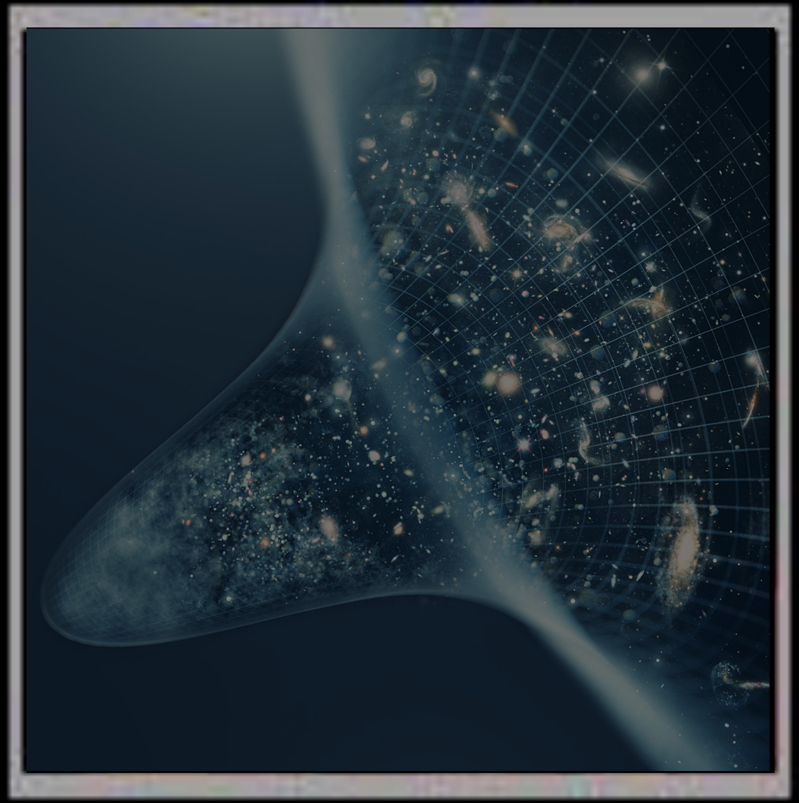
10–100 MEV TRANSITION TEMP. NEEDED

SLOW TRANSITION NEEDED

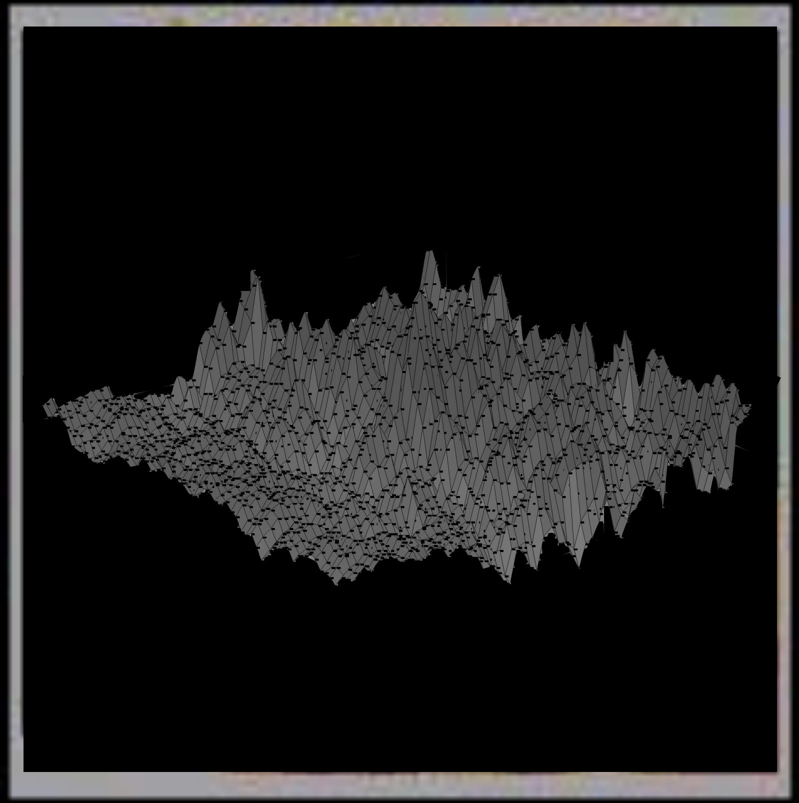
EXTREMELY STRONG TRANSITION NEEDED

SELECT PLAYER

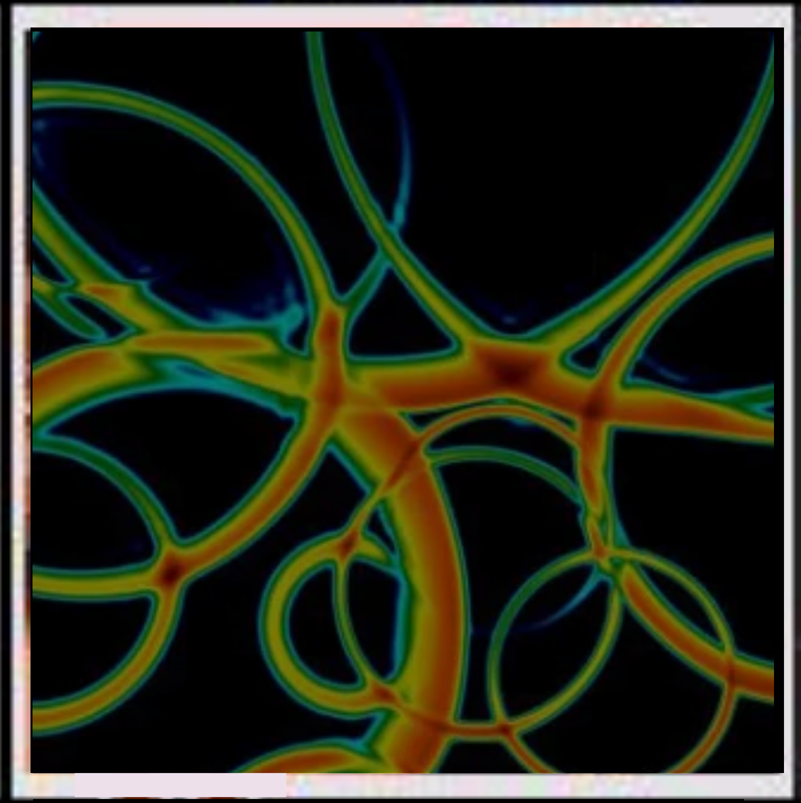
INFLATION



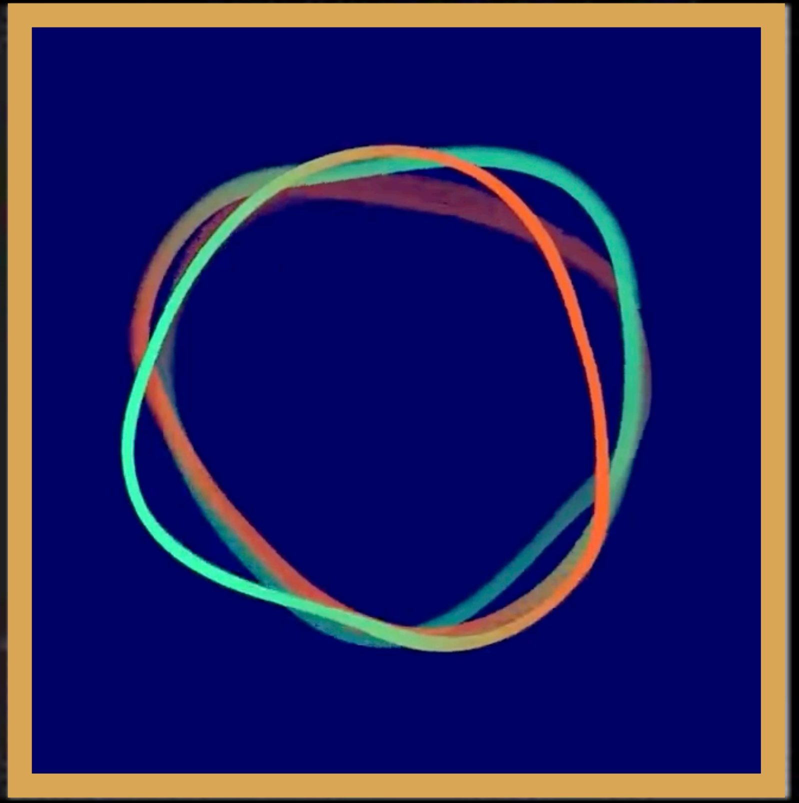
SIGW

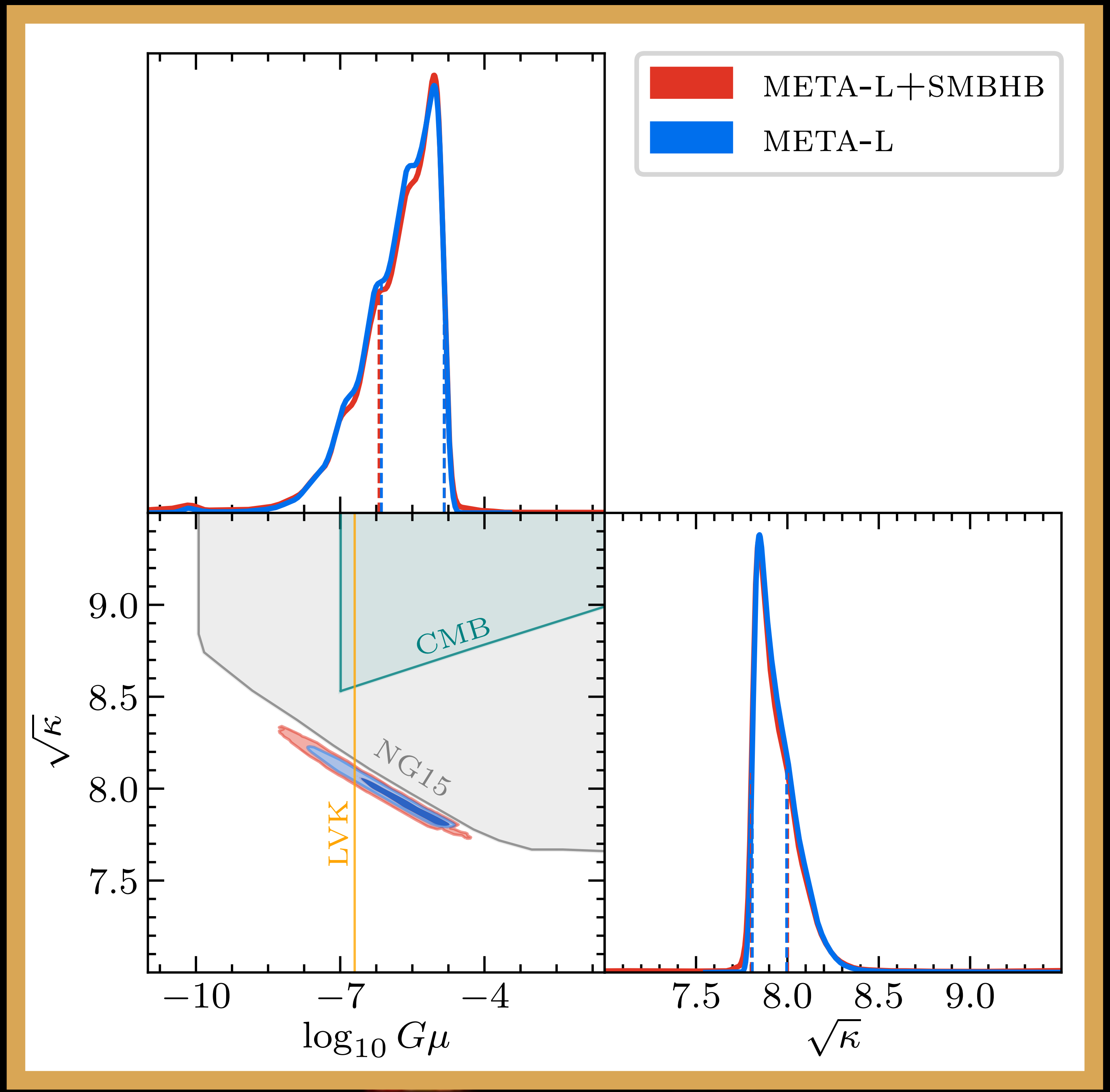


PT



STRINGS





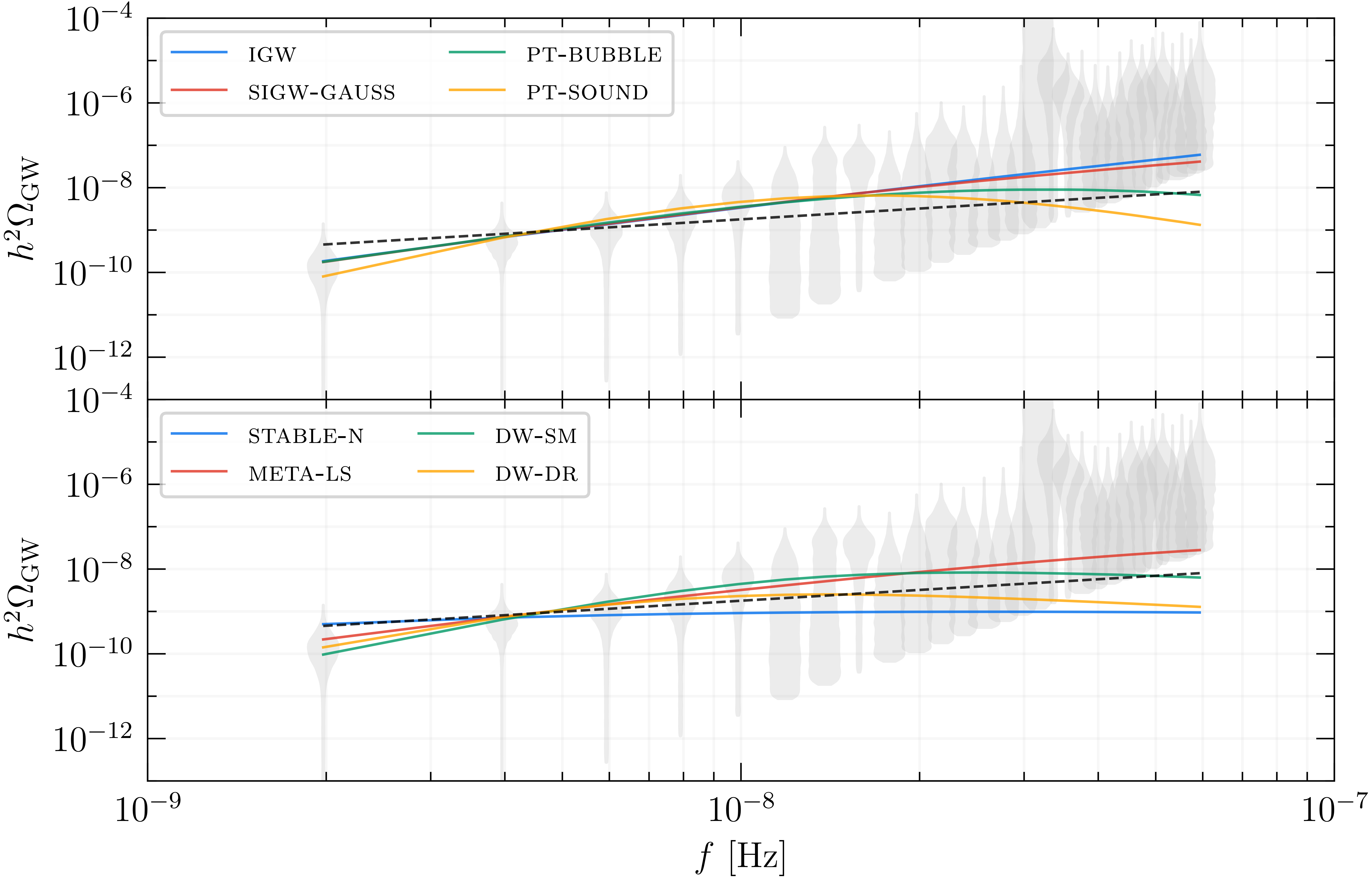
STABLE STRING DO NOT WORK

METASTABLE STRING DO WORK

GUT SCALE STRING TENSION COULD WORK

COSMOLOGICAL SIGNALS

Afzal et al. [2306.16219]



PTArcade

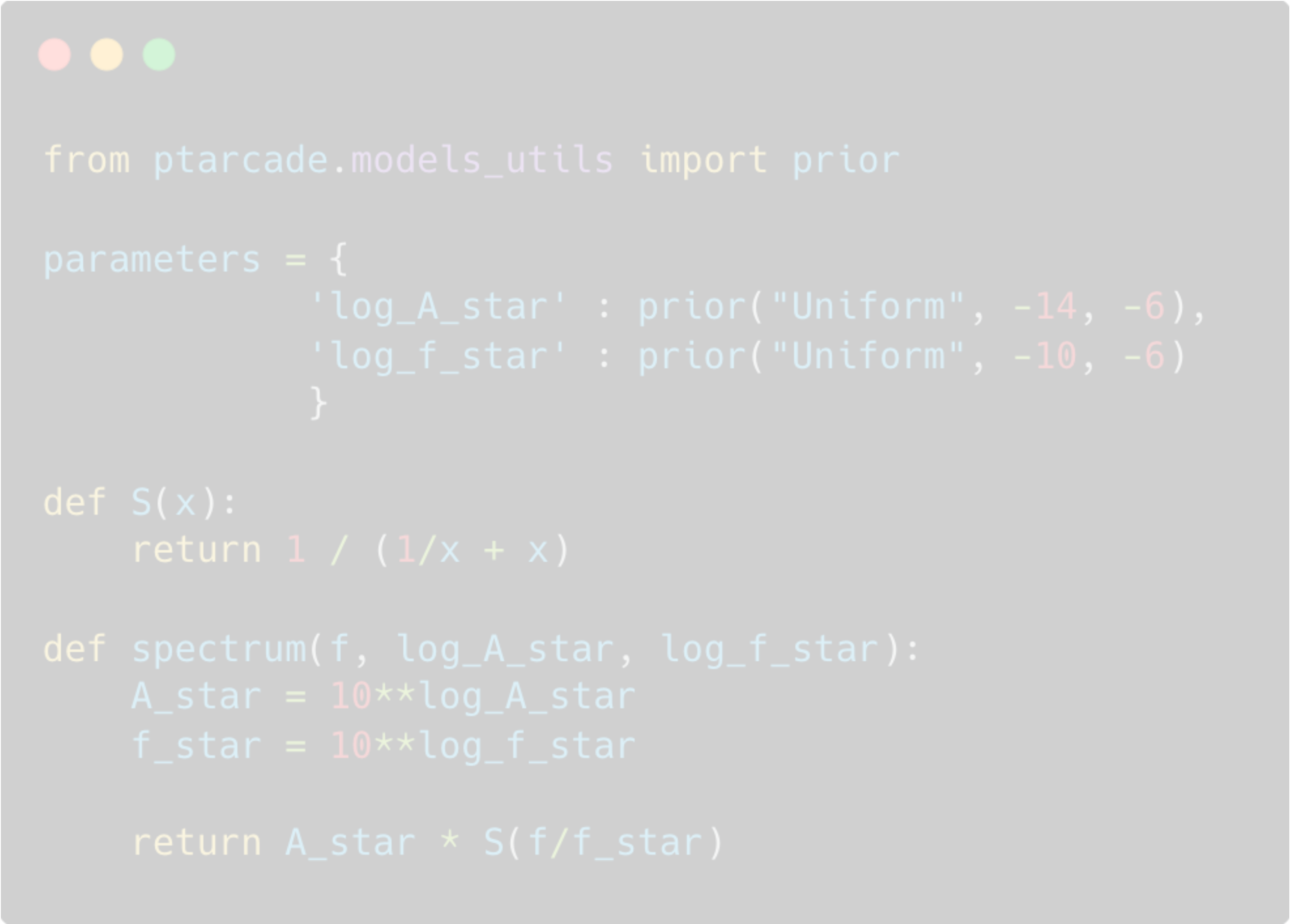
toy model

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

Step 1

```
conda install ptarcade
```

Step 2



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from ptarcade.models_utils import prior

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    f_star = 10**log_f_star

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Step 3

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

PTArcade

toy model

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

Step 1

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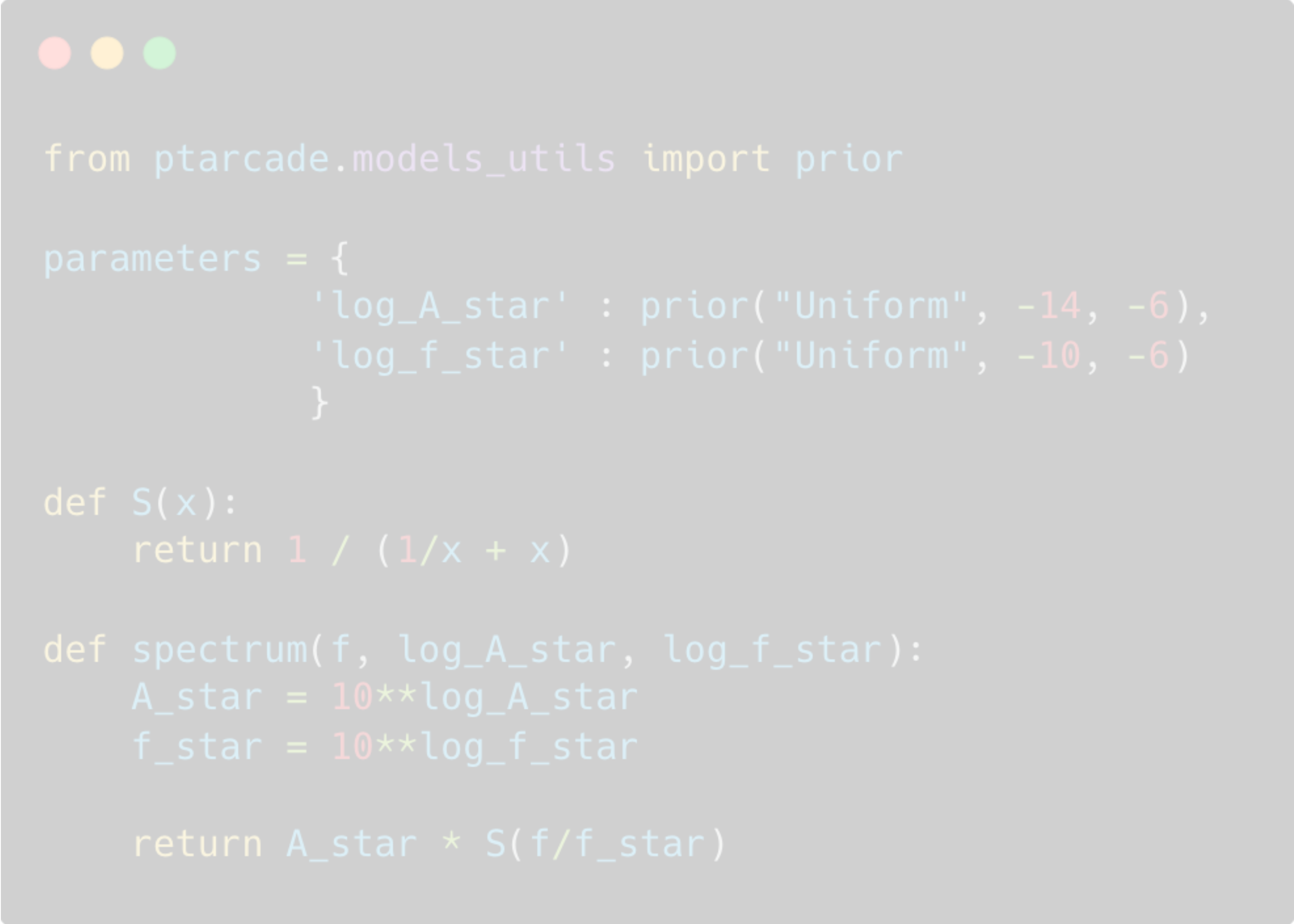
conda install ptarcade
```

Step 2



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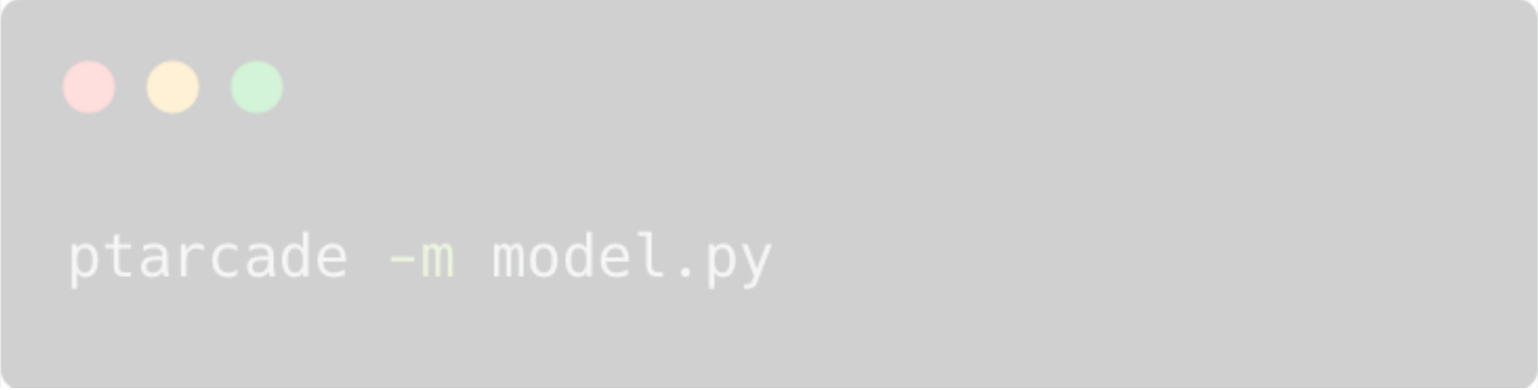

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PTArcade

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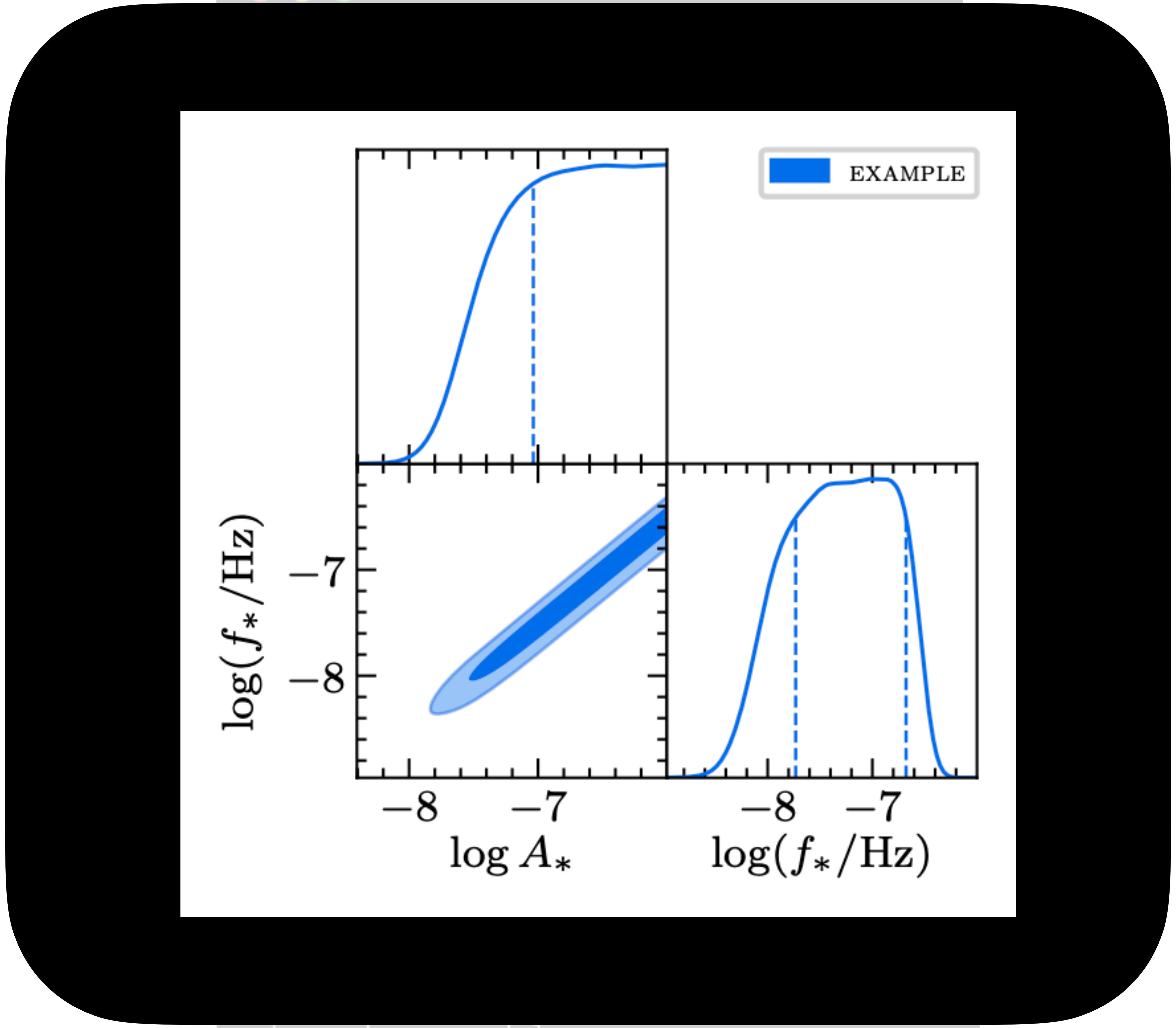

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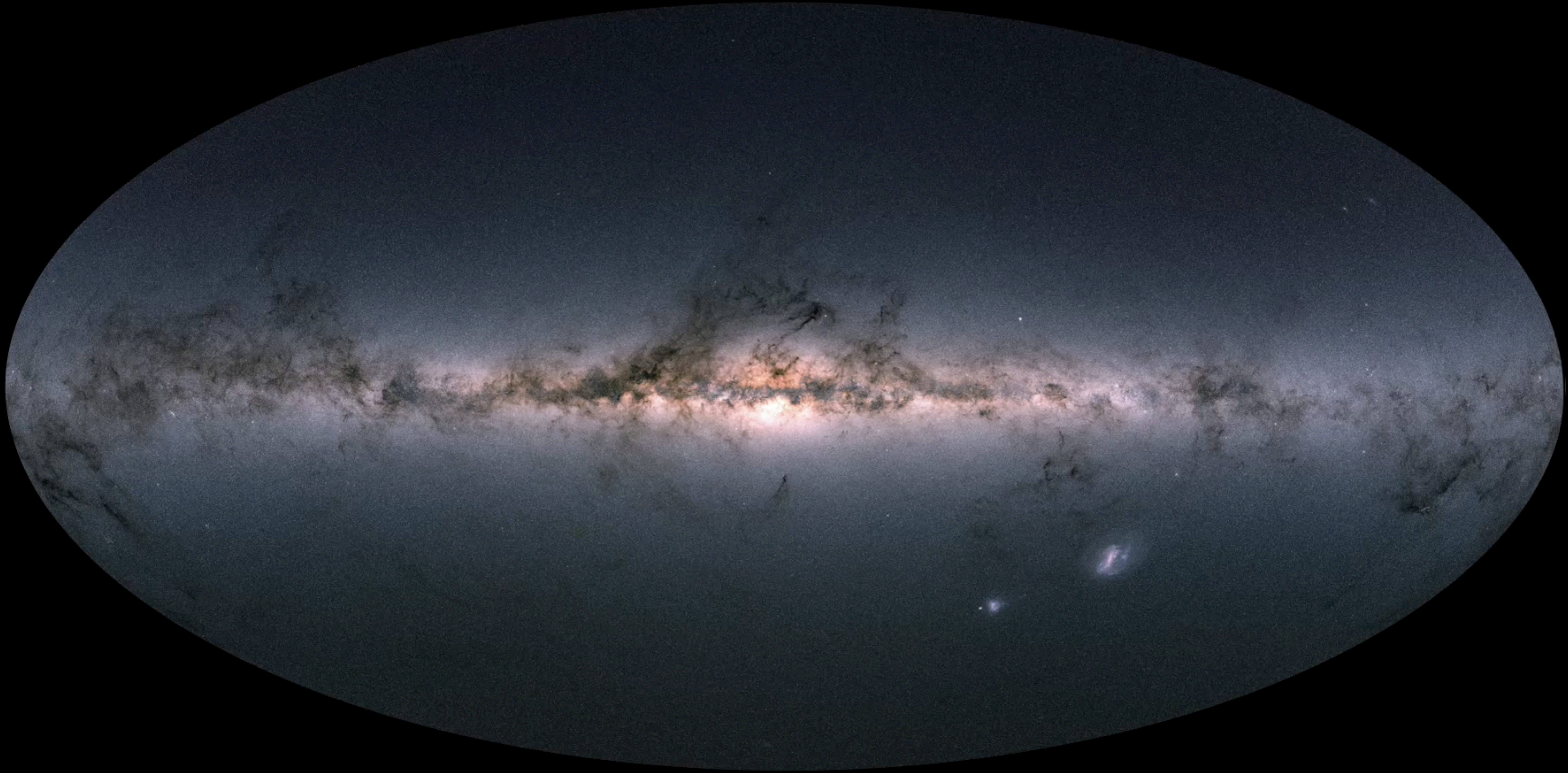
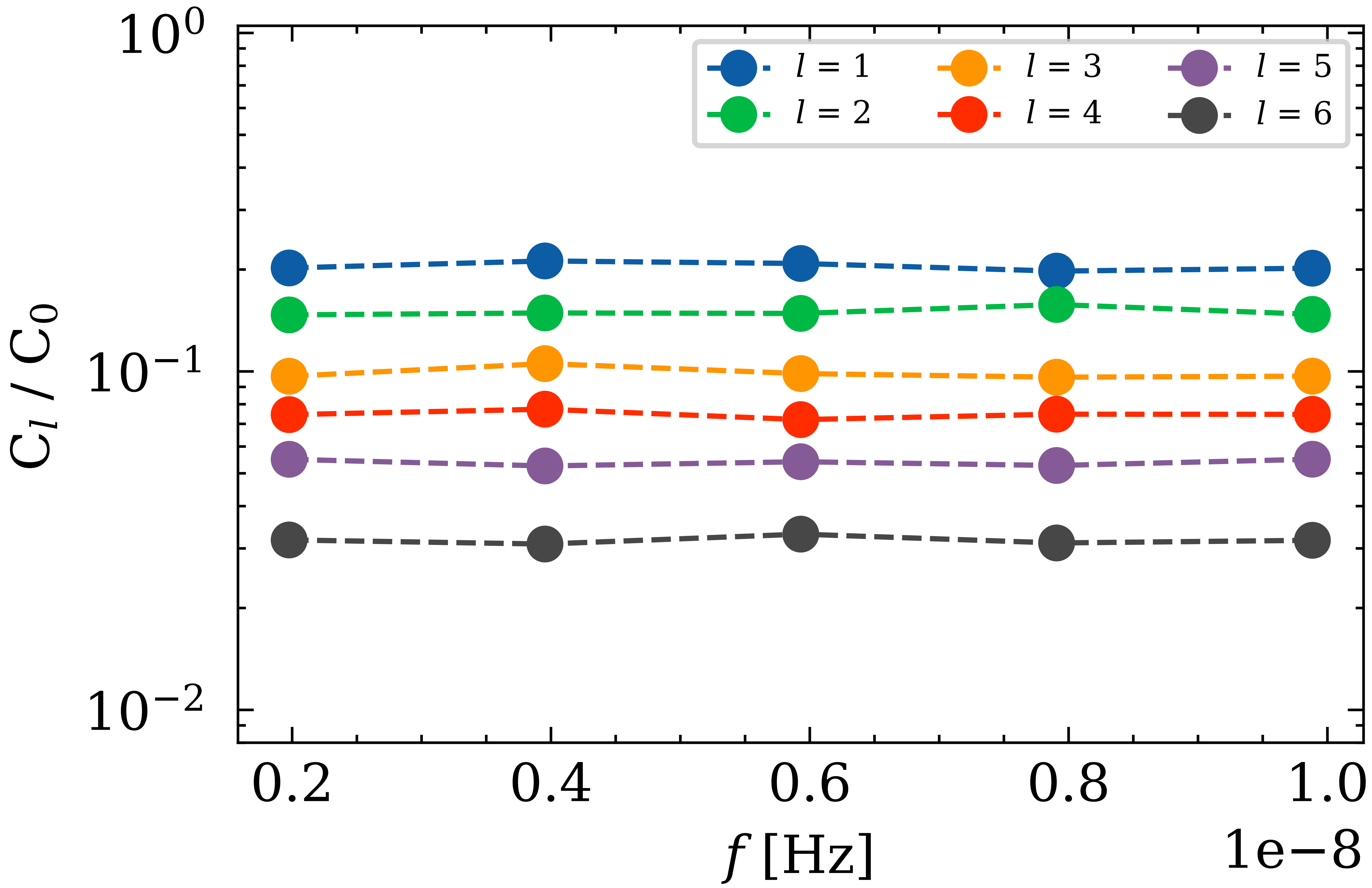
where do we go from here?

ANISOTROPIES



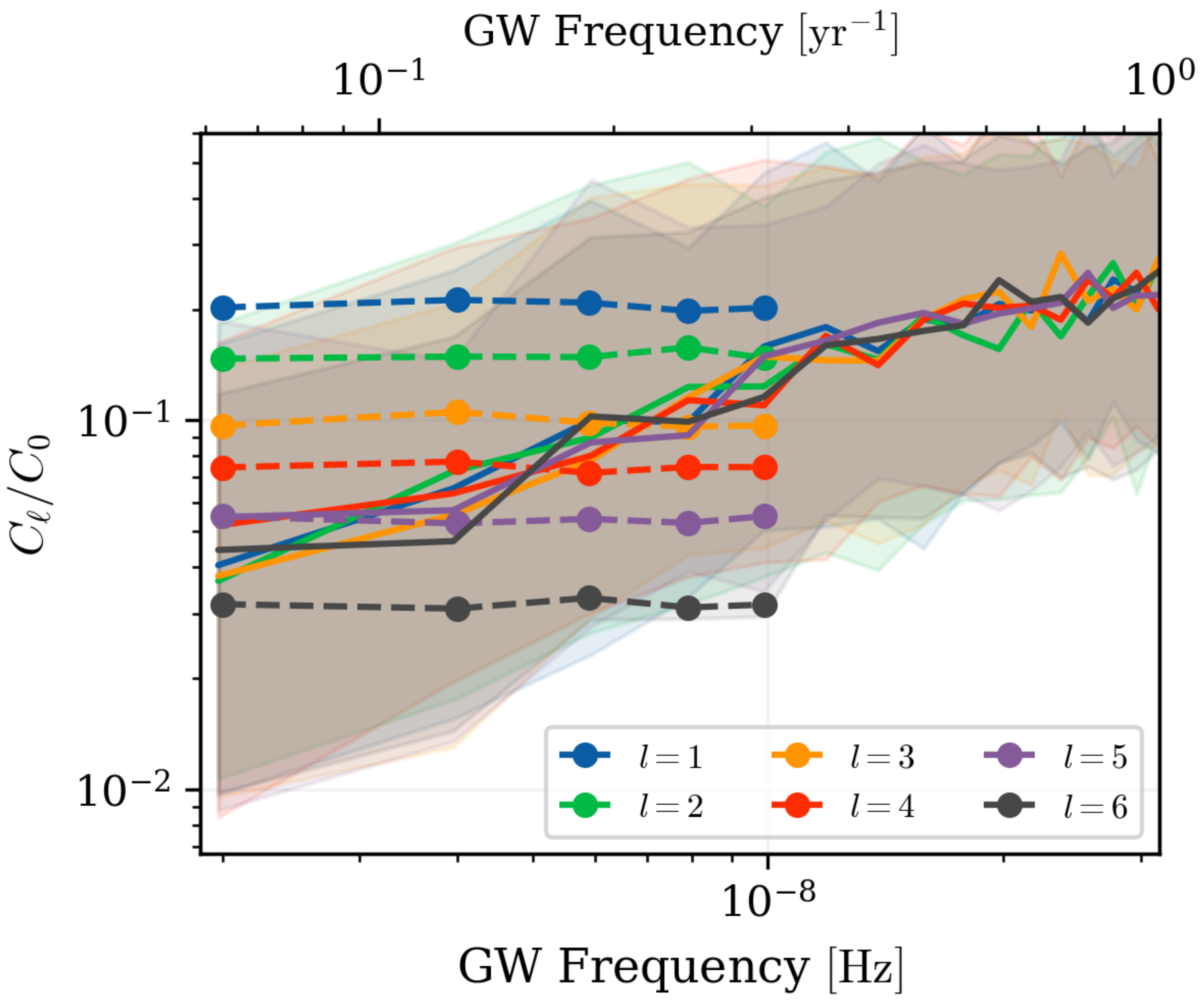
Credit: ESA/Gaia/DPAC

ANISOTROPIES



Agazie et al. [2306.16221]

ANISOTROPIES



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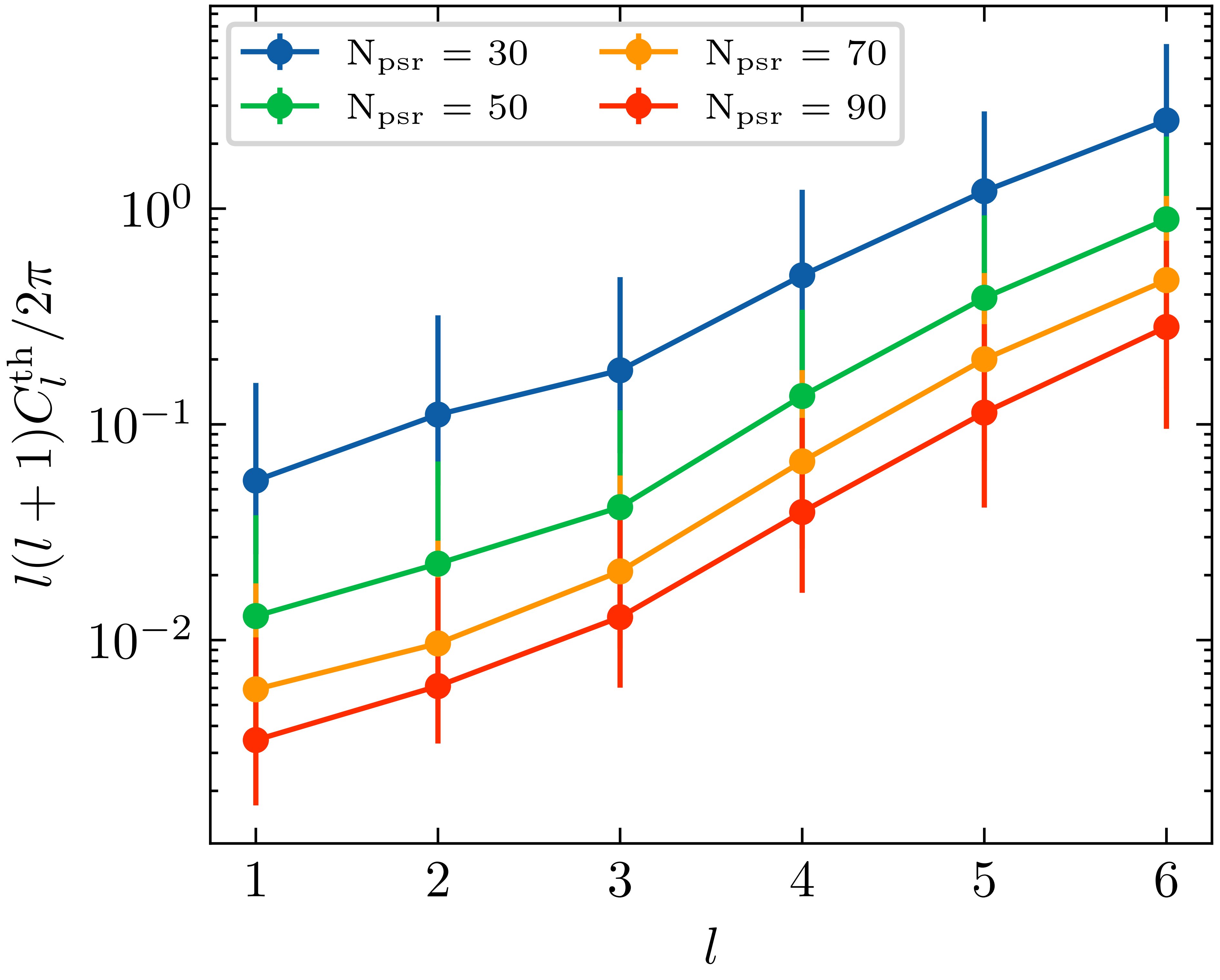
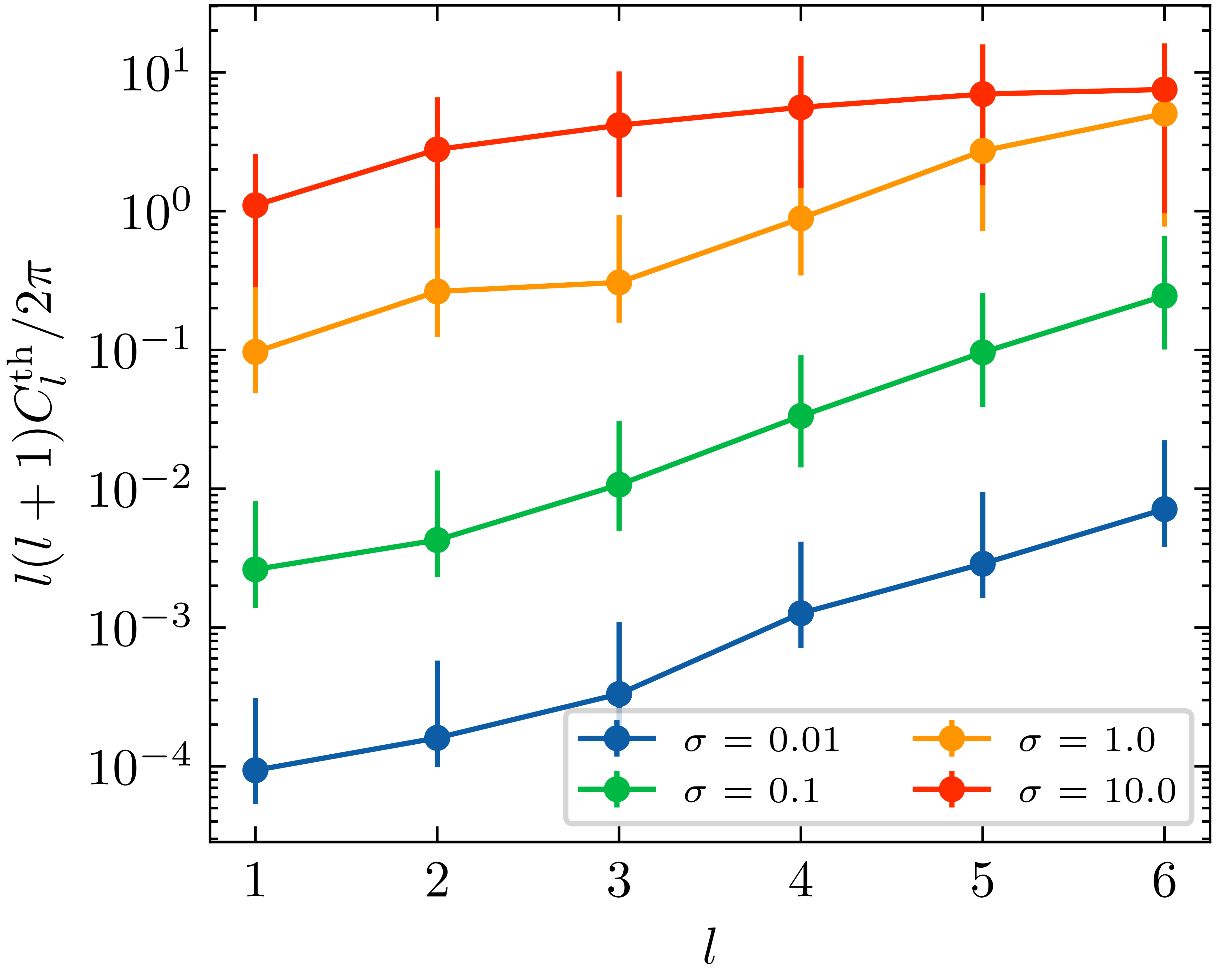
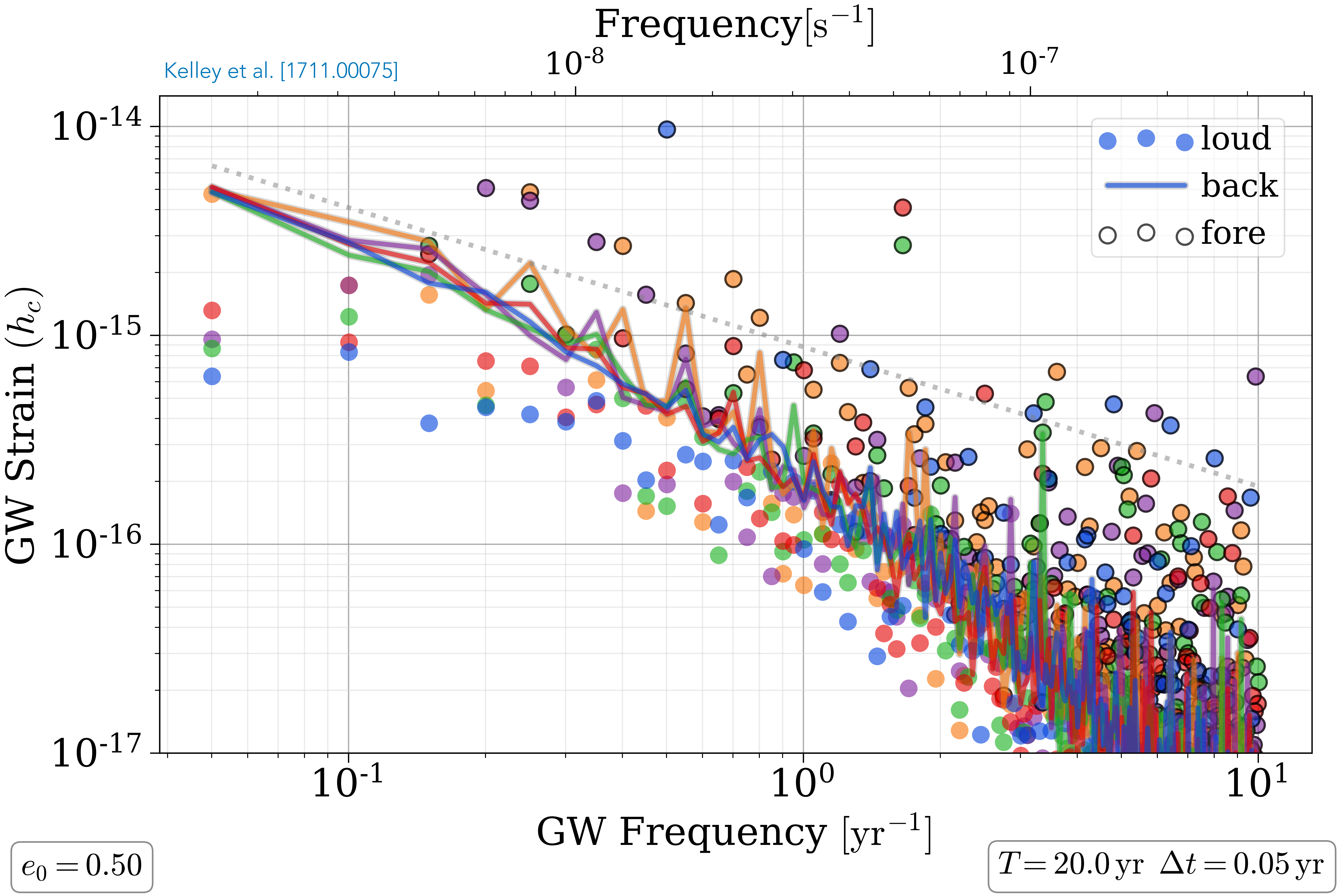


Pol et al. [2206.09936]



SINGLE SOURCE

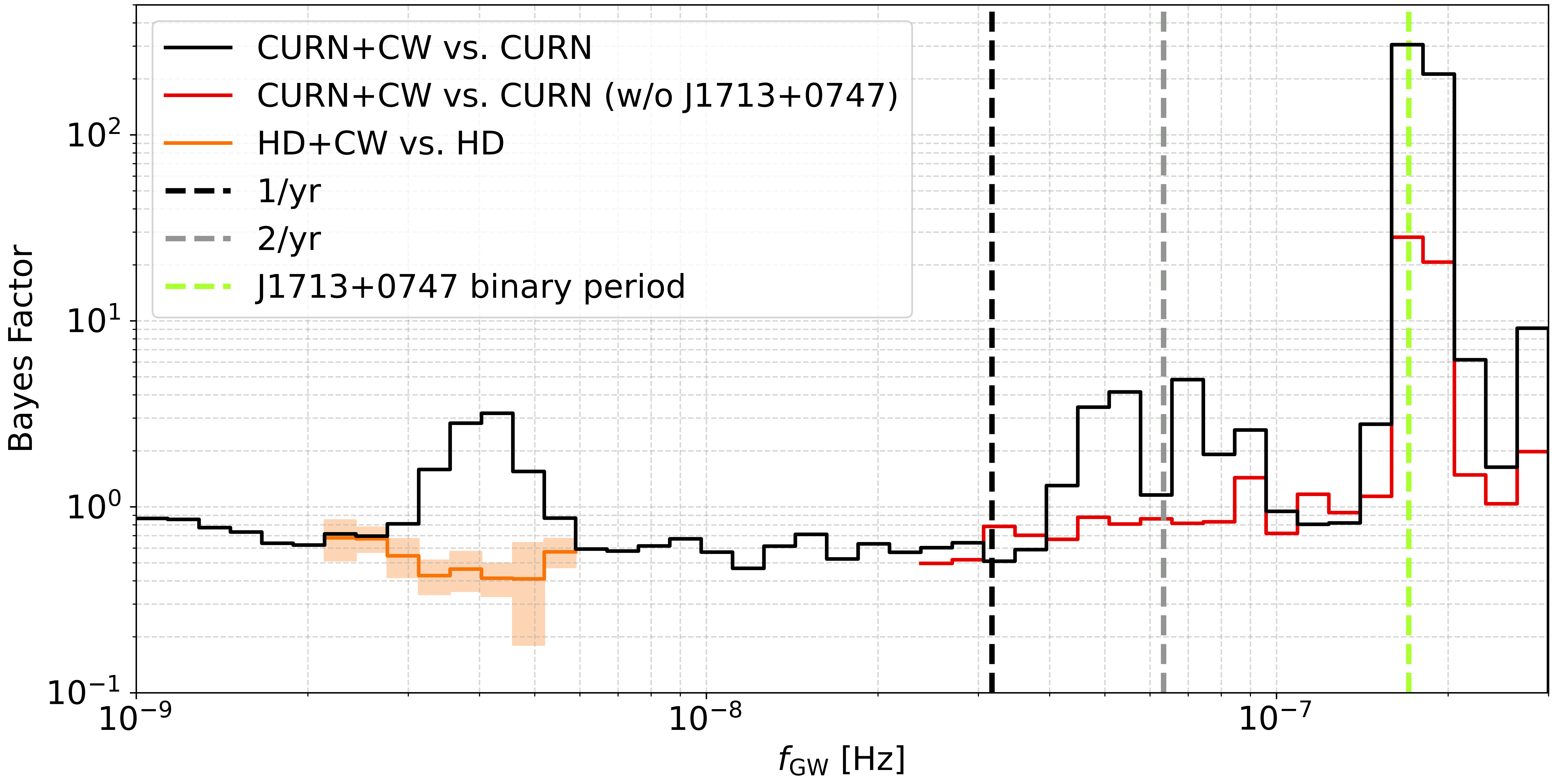
Kelley et al. [1711.00075]



$e_0 = 0.50$

$T = 20.0\,\mathrm{yr}$ $\Delta t = 0.05\,\mathrm{yr}$

SINGLE SOURCE



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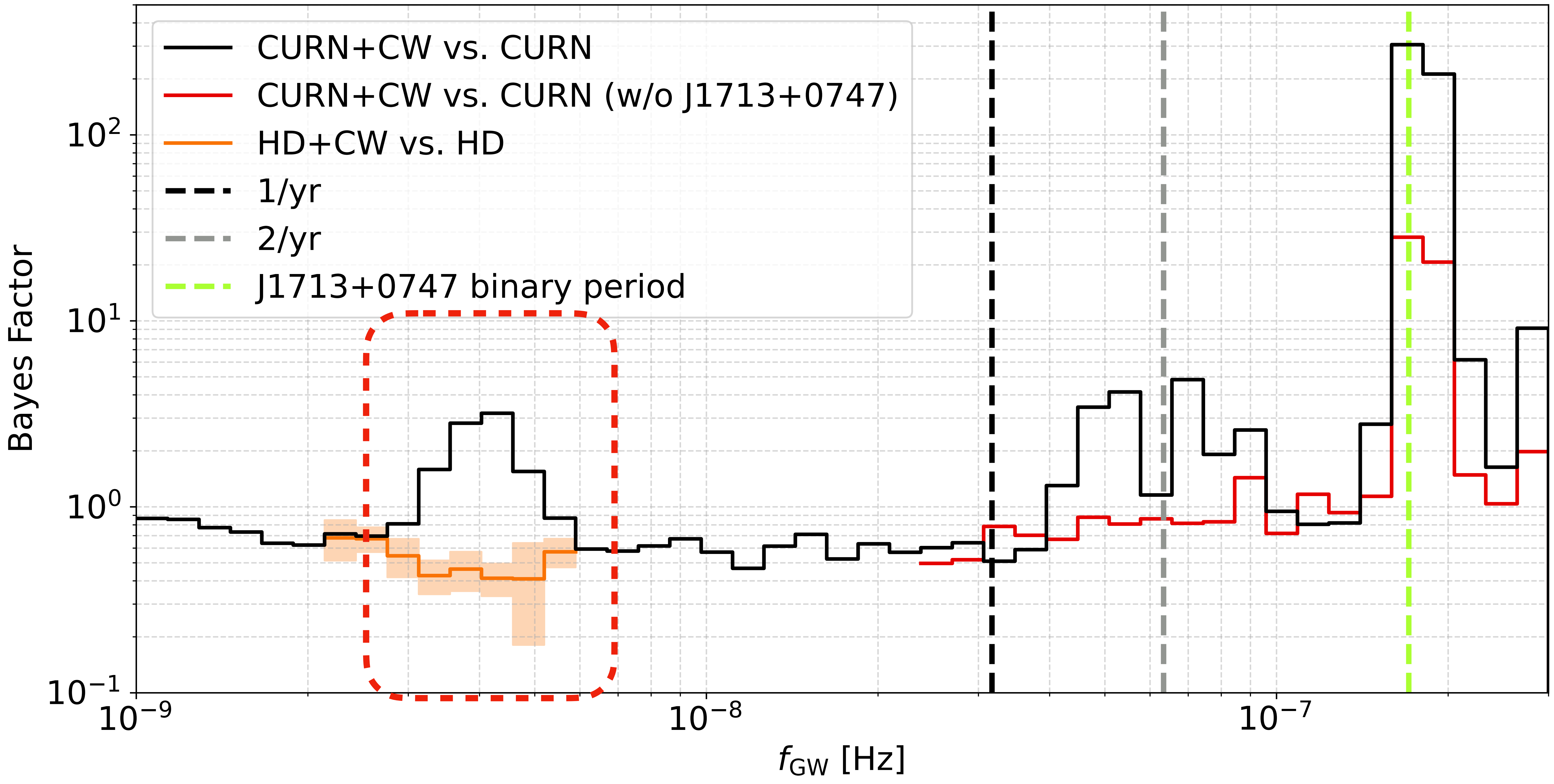

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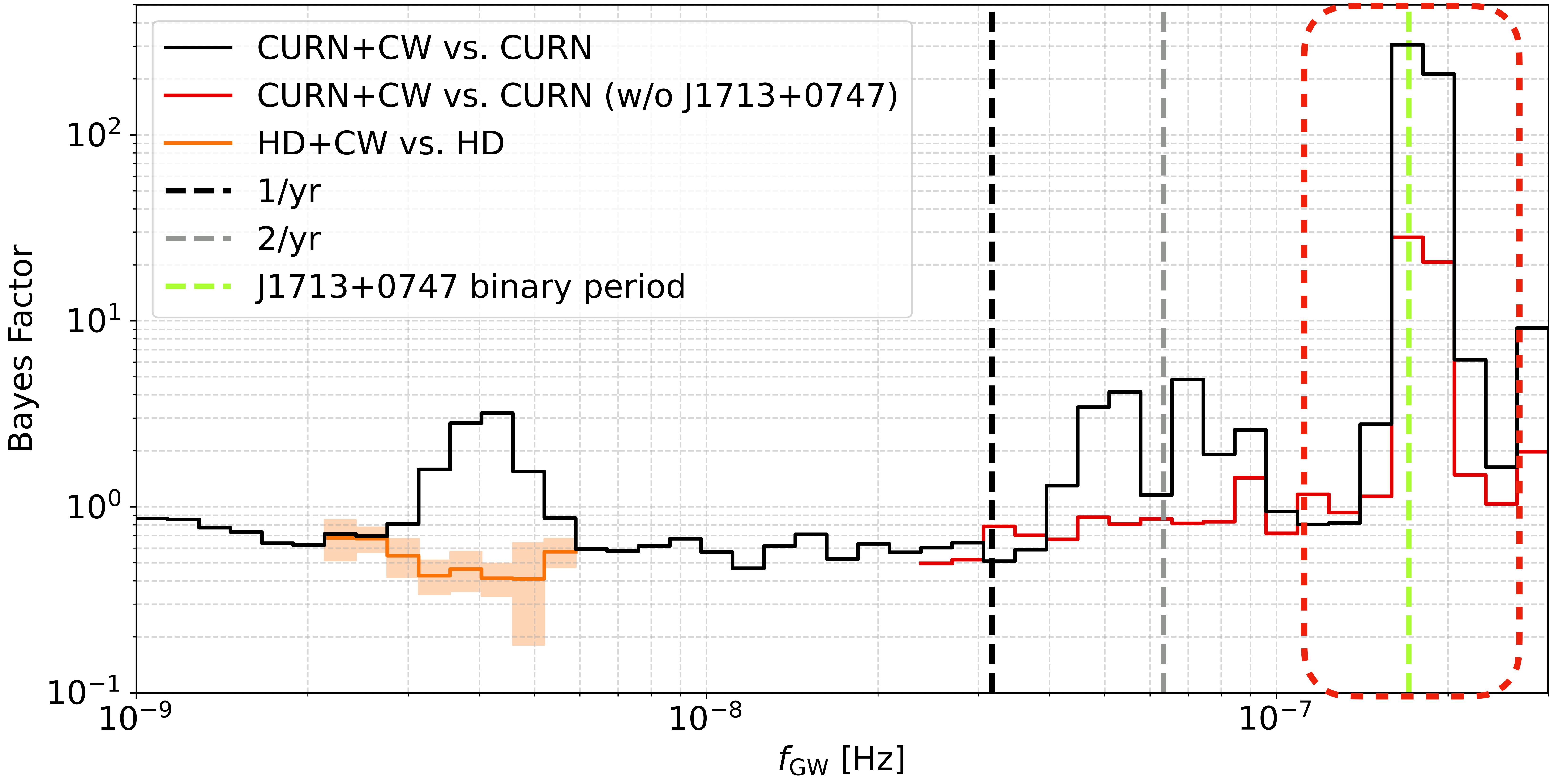
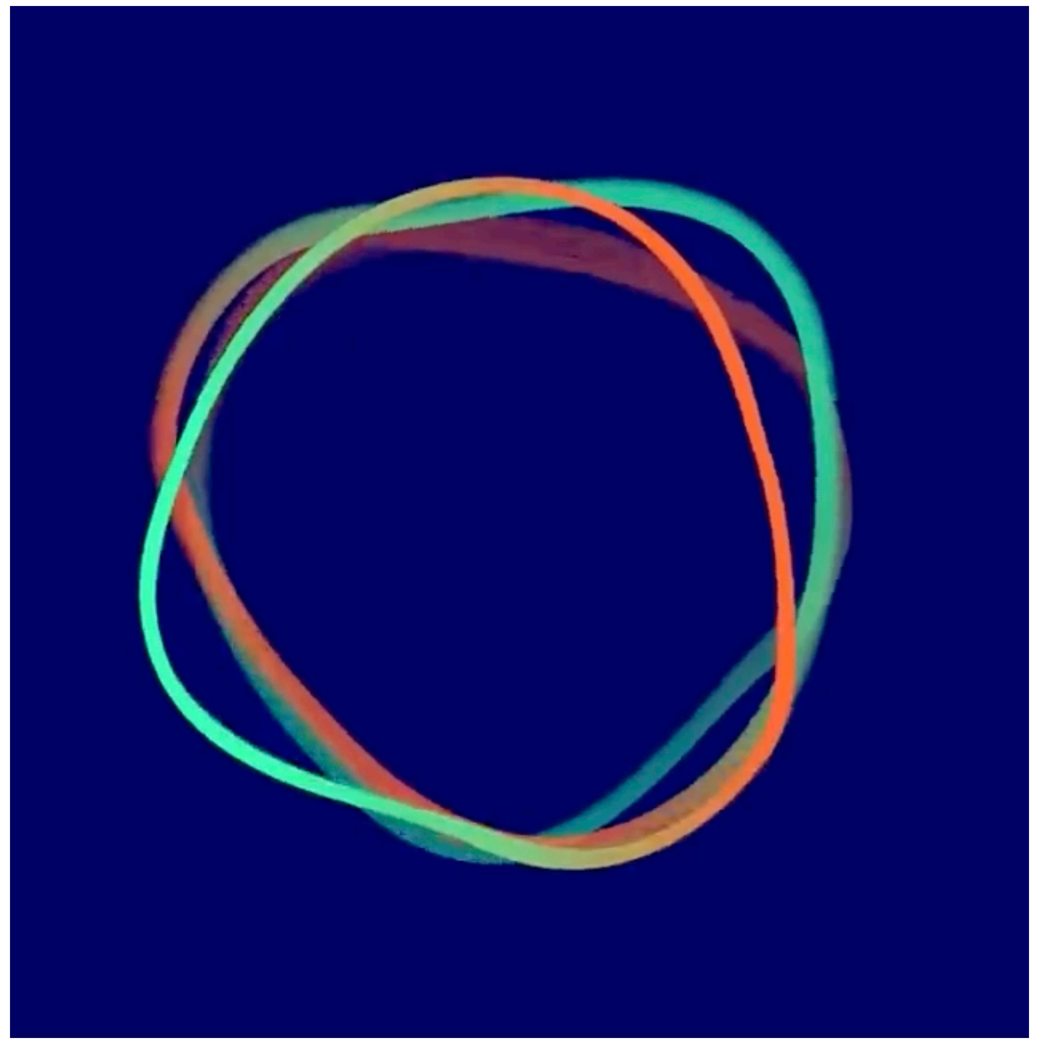
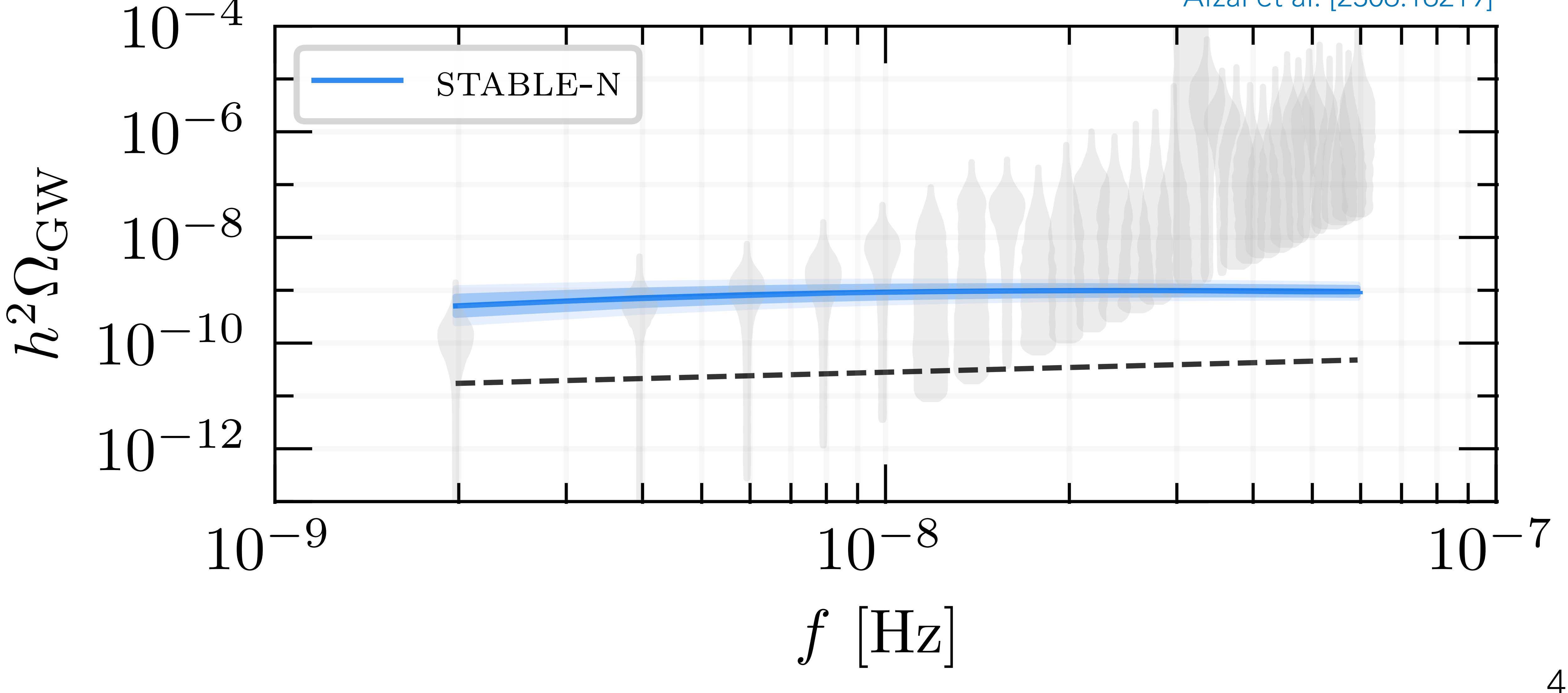


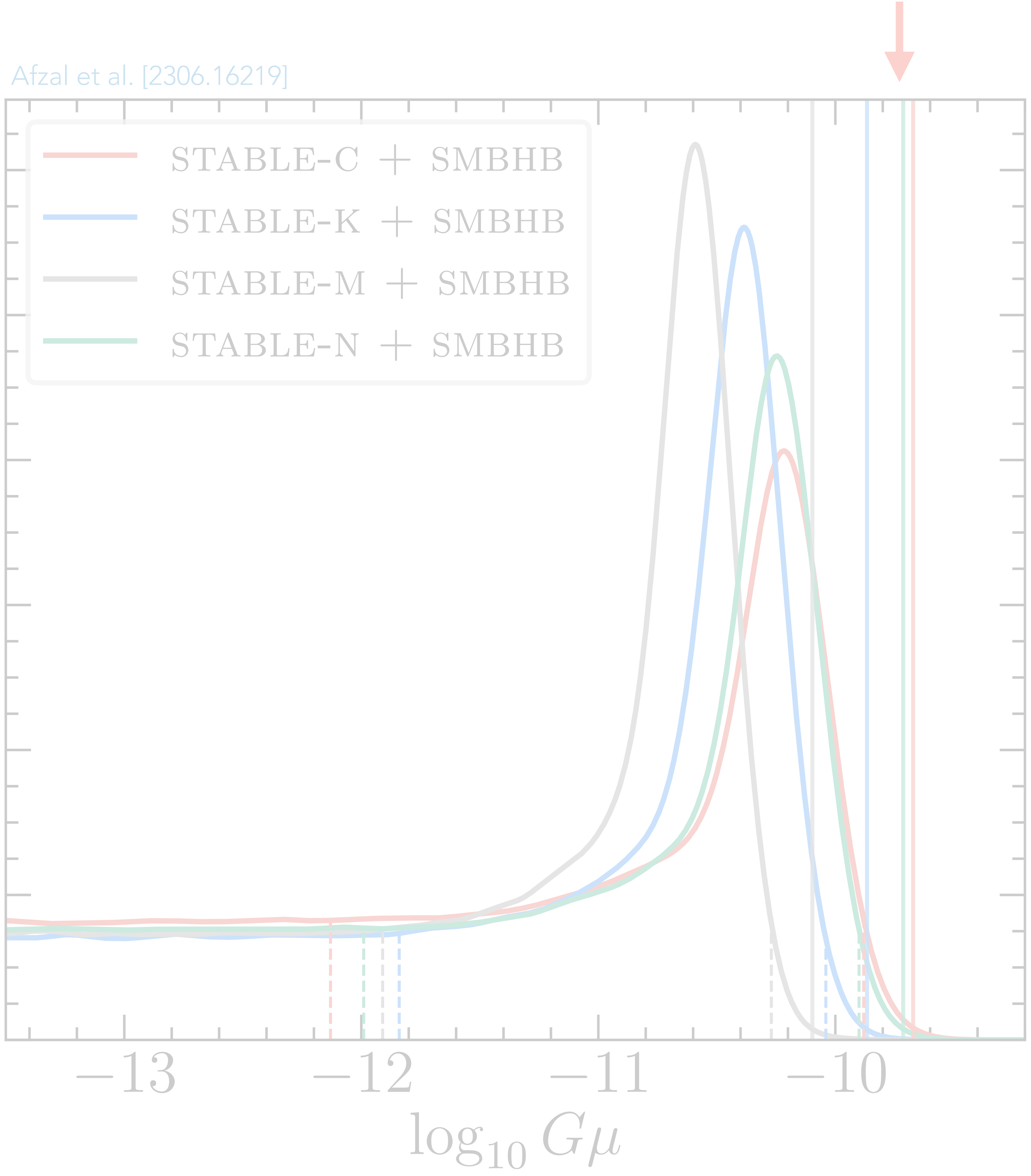
what if it’s not new physics

COSMIC STRINGS




Afzal et al. [2306.16219]

upper limits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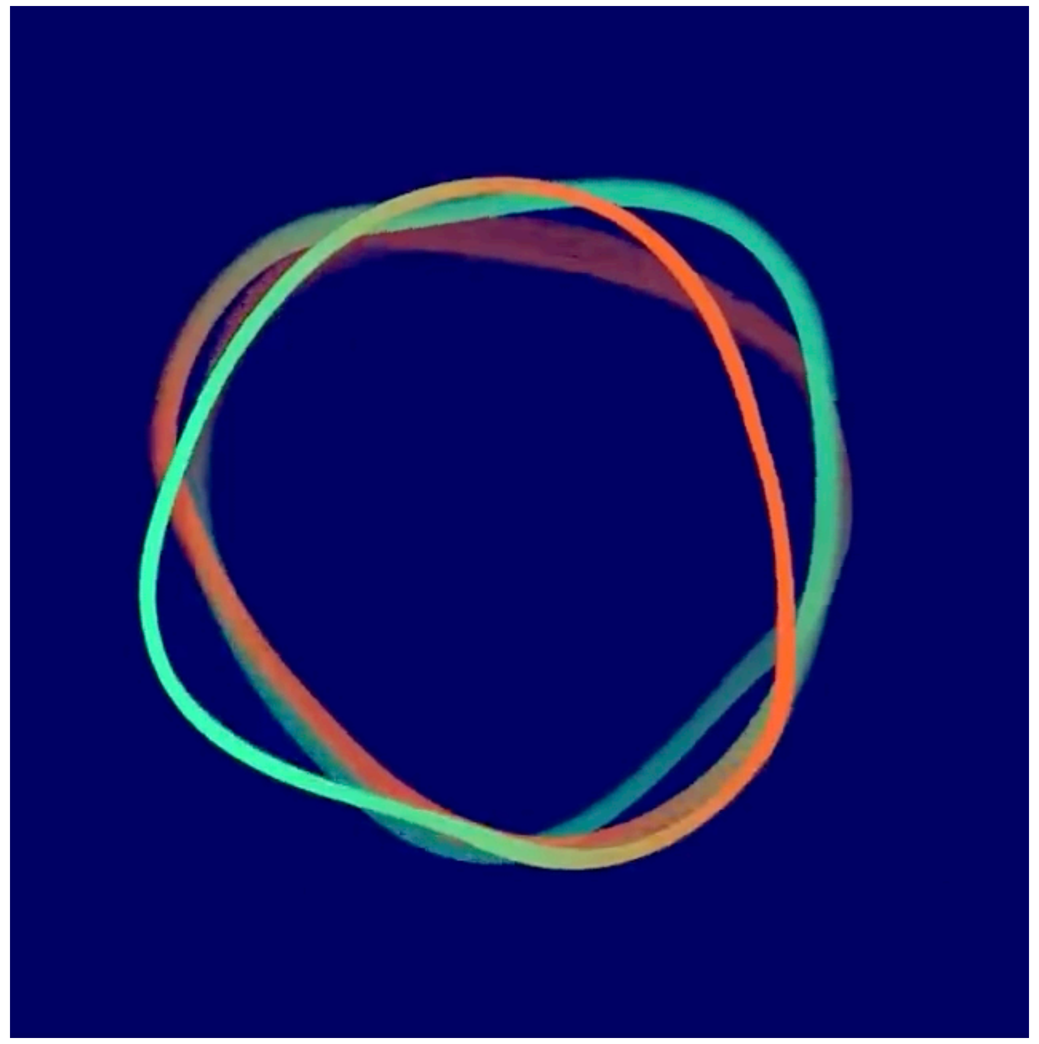

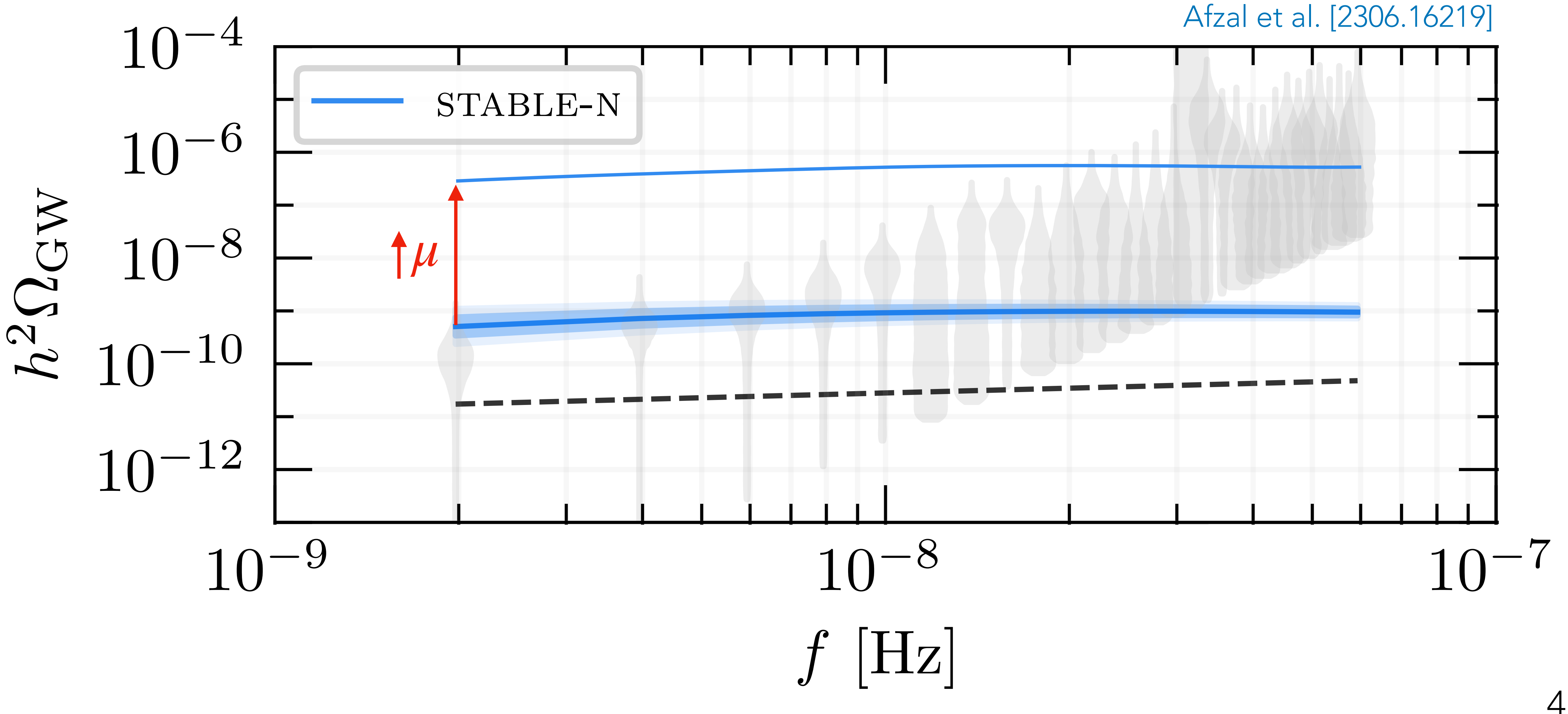

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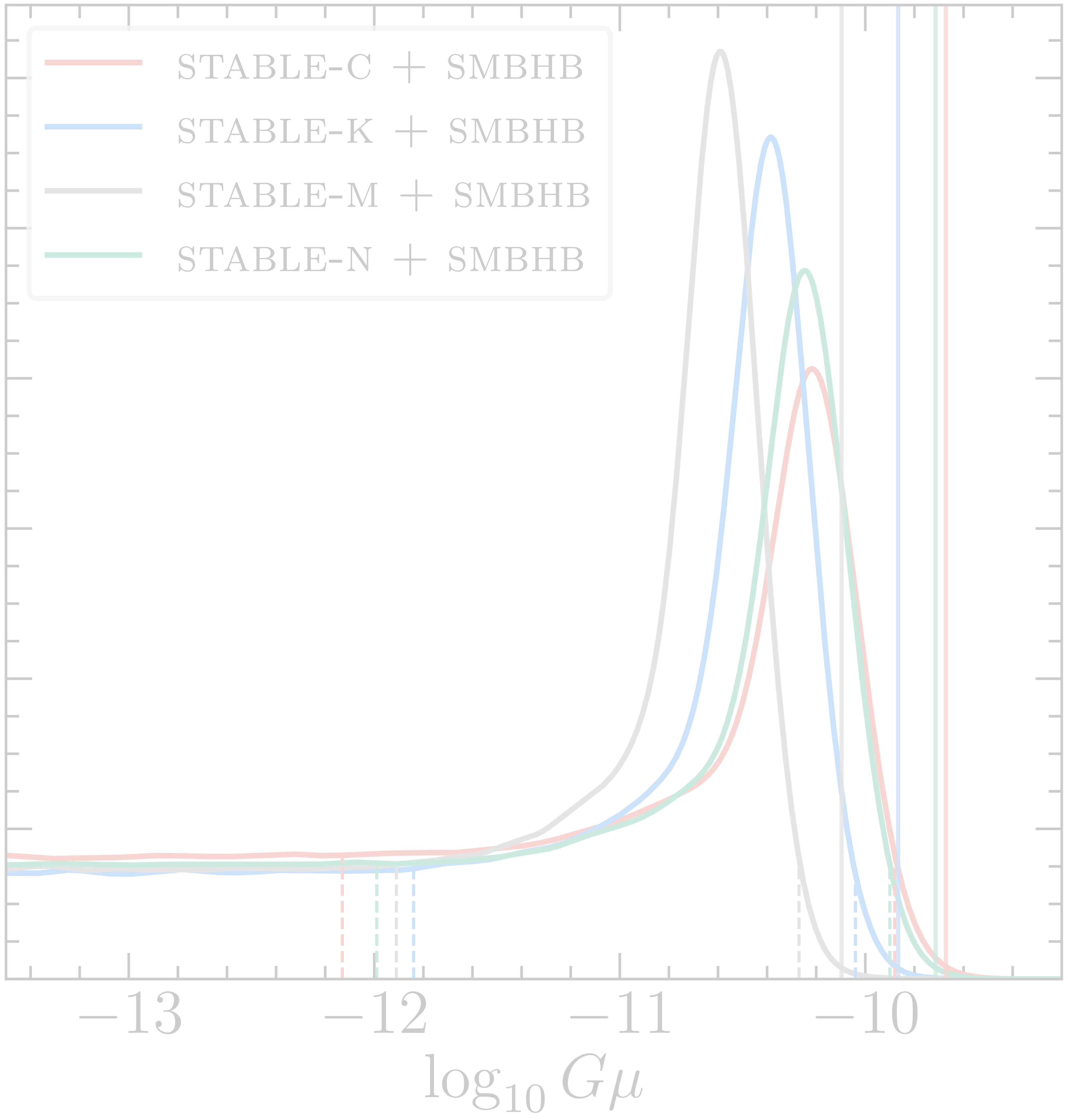

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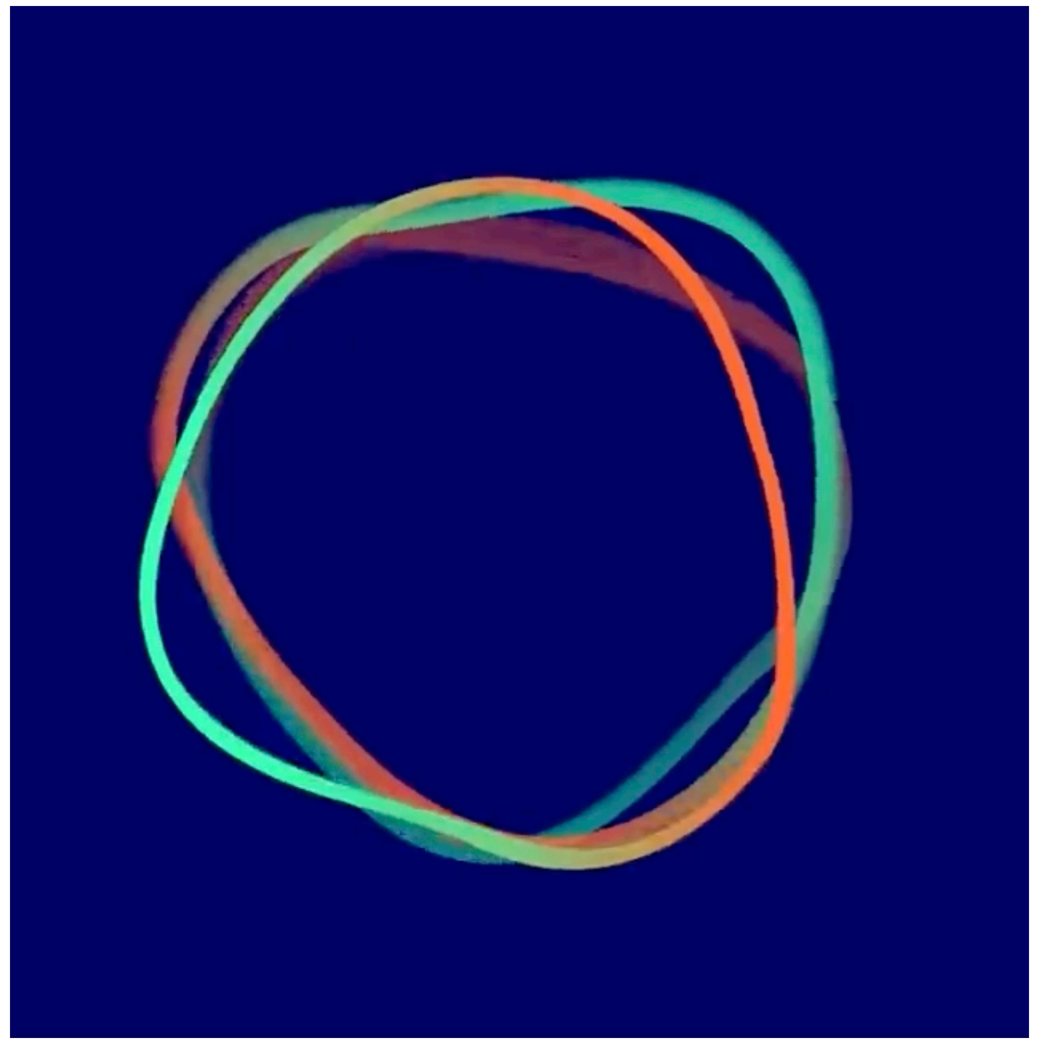

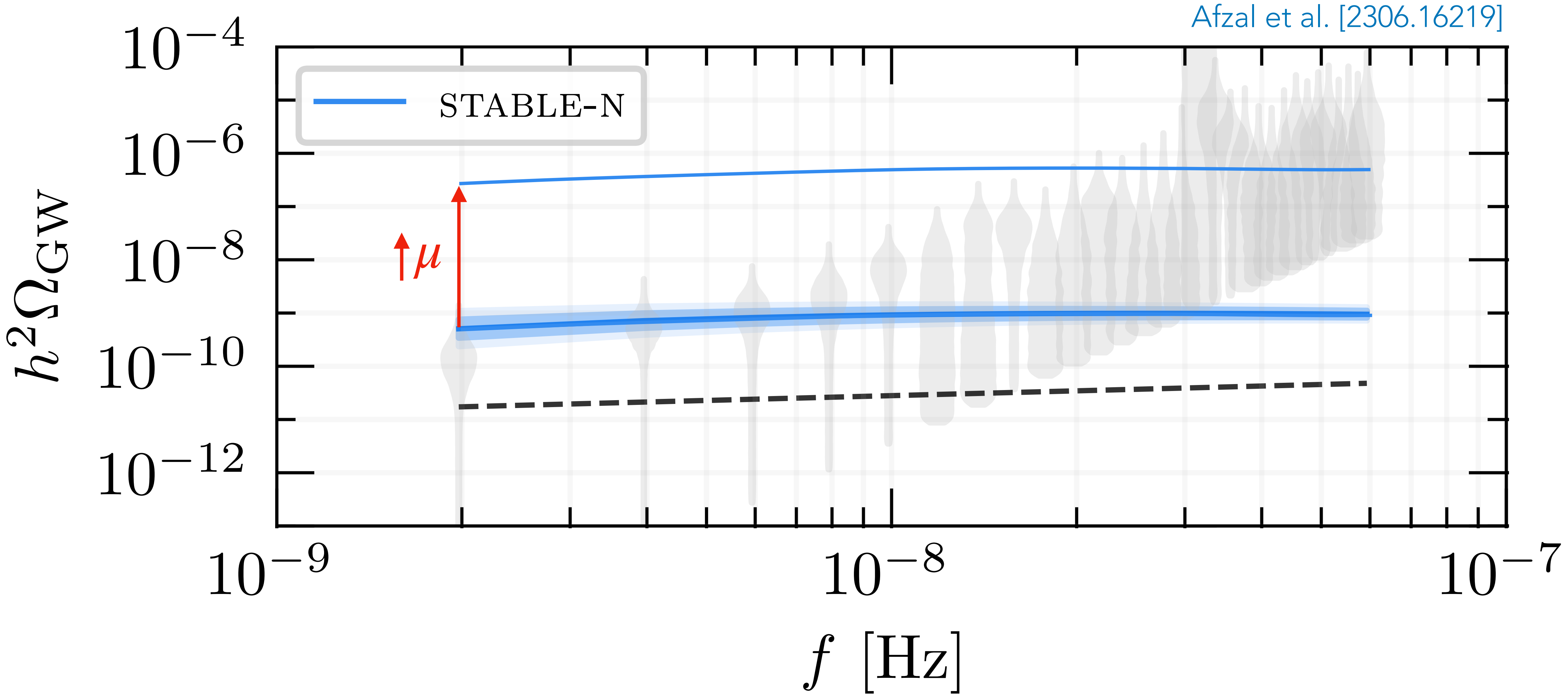

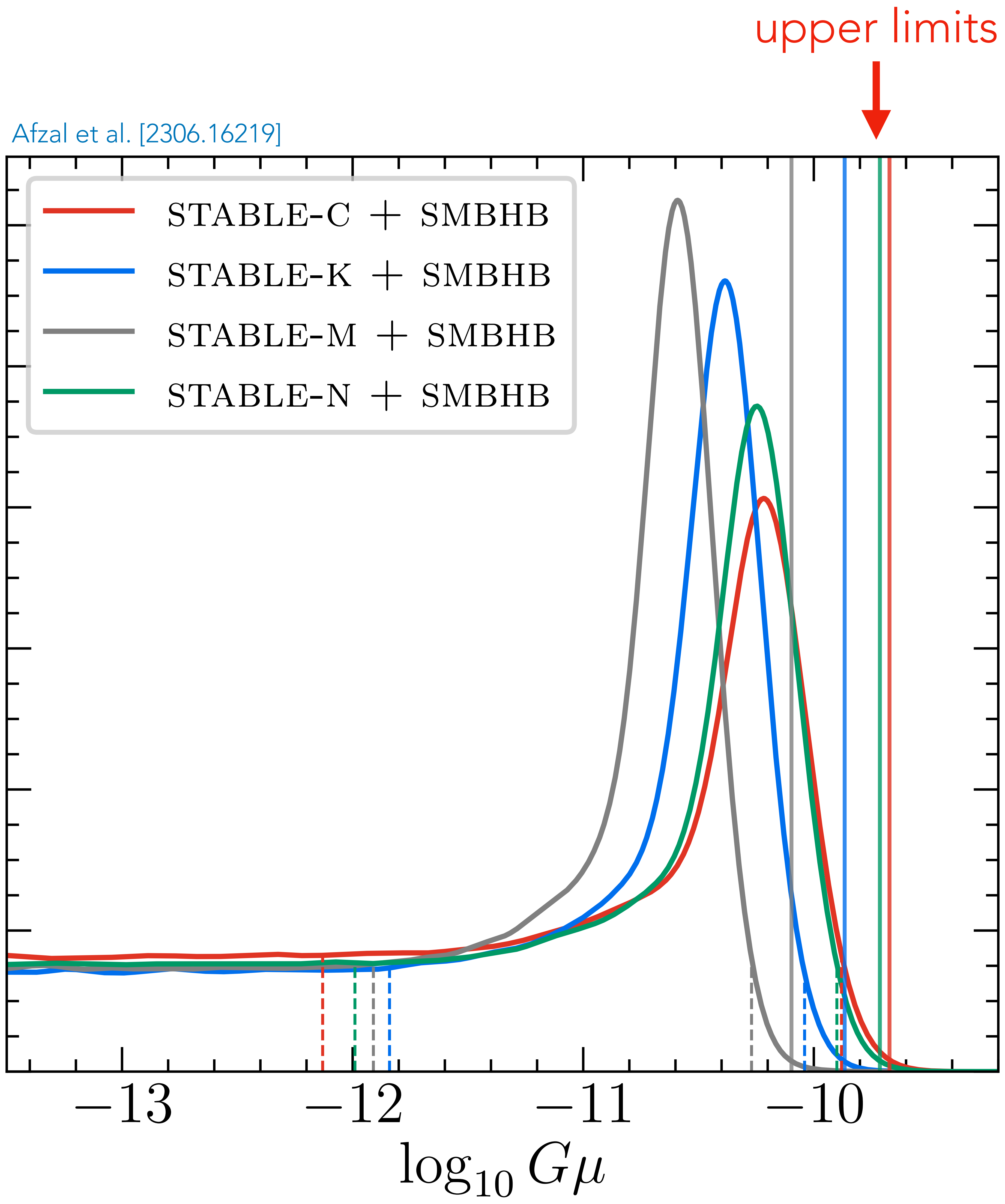

ULDM

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

DM density

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gravitational signals

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

Khmelnitsky, Rubakov [1309.5888]

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

Kim, AM [2311.xxxx]

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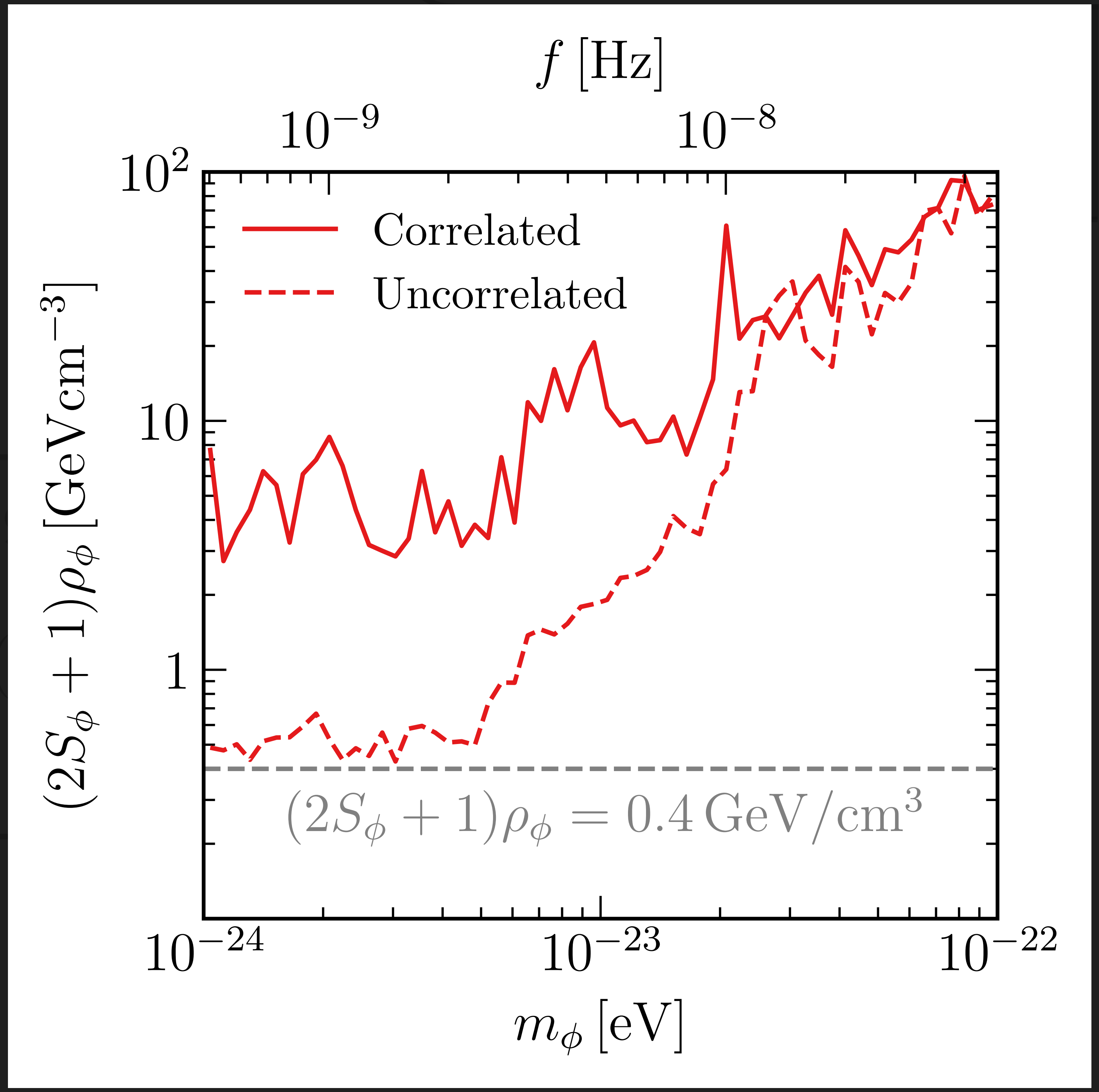

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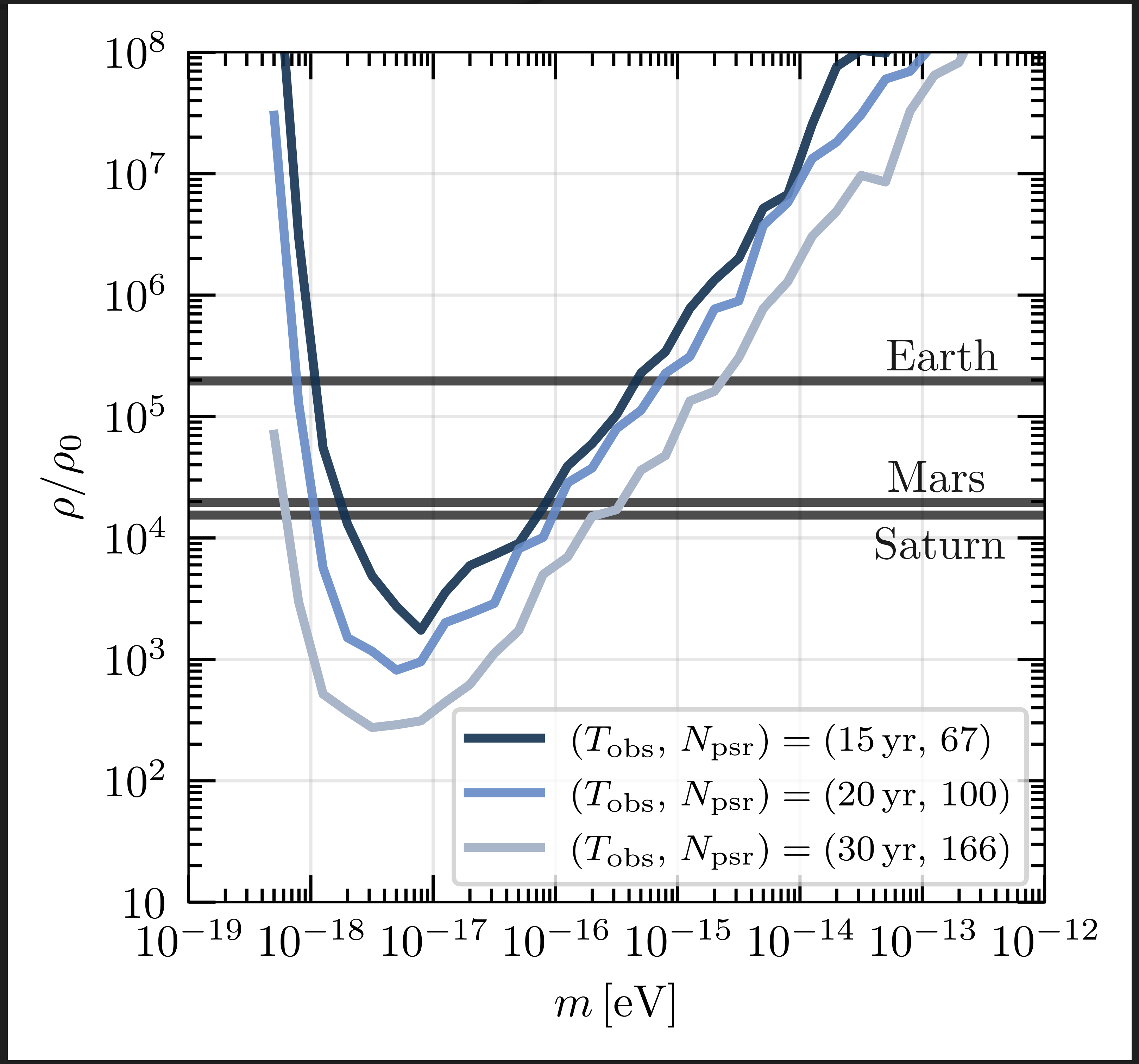

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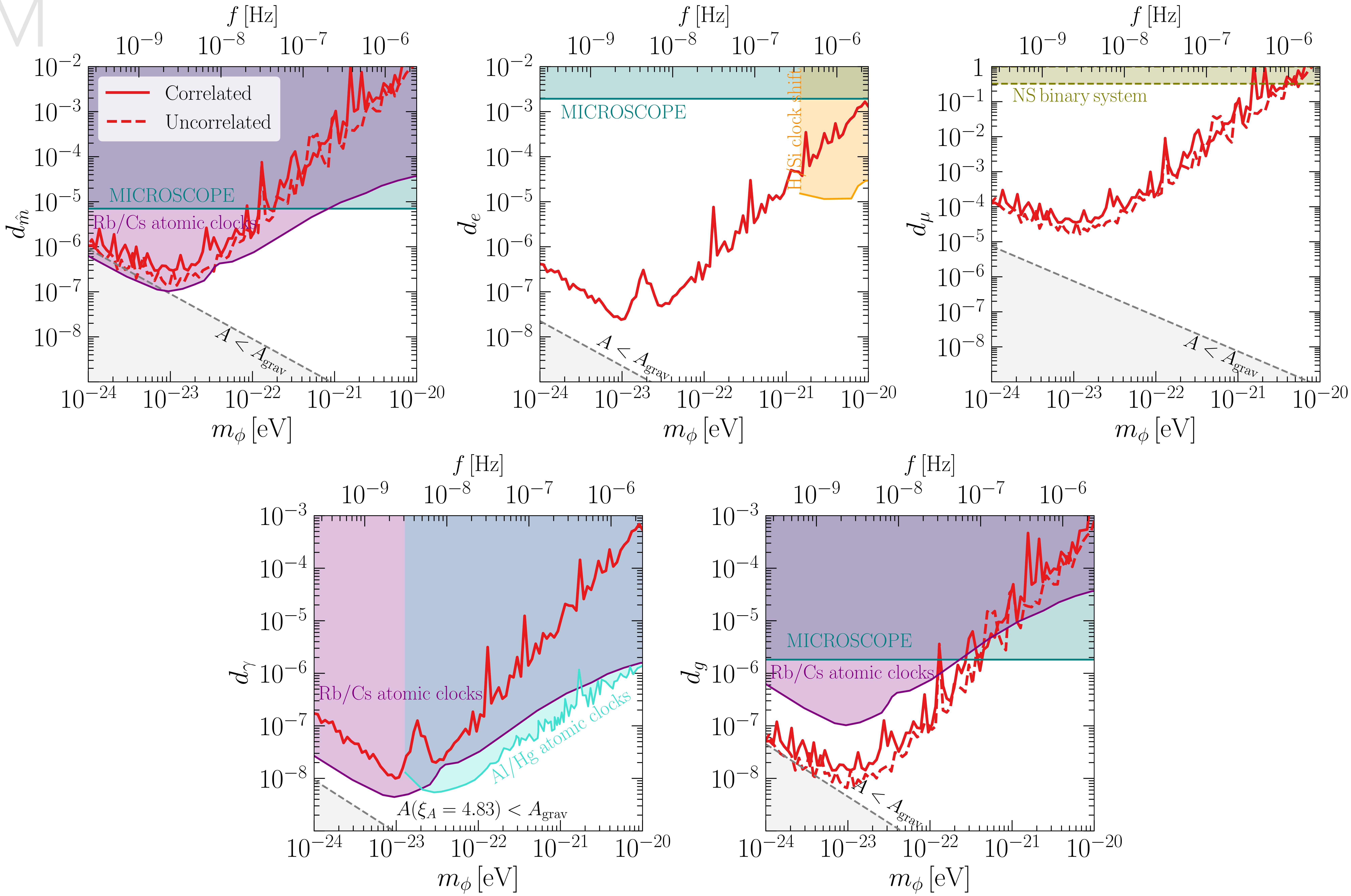
Kim, AM [2311.xxxx]

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]

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

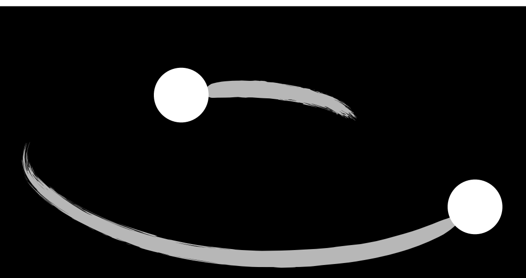
cosmology or astrophysics?

CW and anisotropies will help us discriminating

PTA can be used to constrain new physics

backup

FACE-OFF



SMBHB

VS

inflation

scalar induced GW

phase transitions

cosmic strings

domain walls

FACE-OFF

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

vs

- inflation
- scalar induced GW
- phase transitions
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- domain walls

FACE-OFF

free parameters

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VS

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FACE-OFF

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VS

free parameters

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

FACE-OFF

free parameters

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VS

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

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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prior distributions

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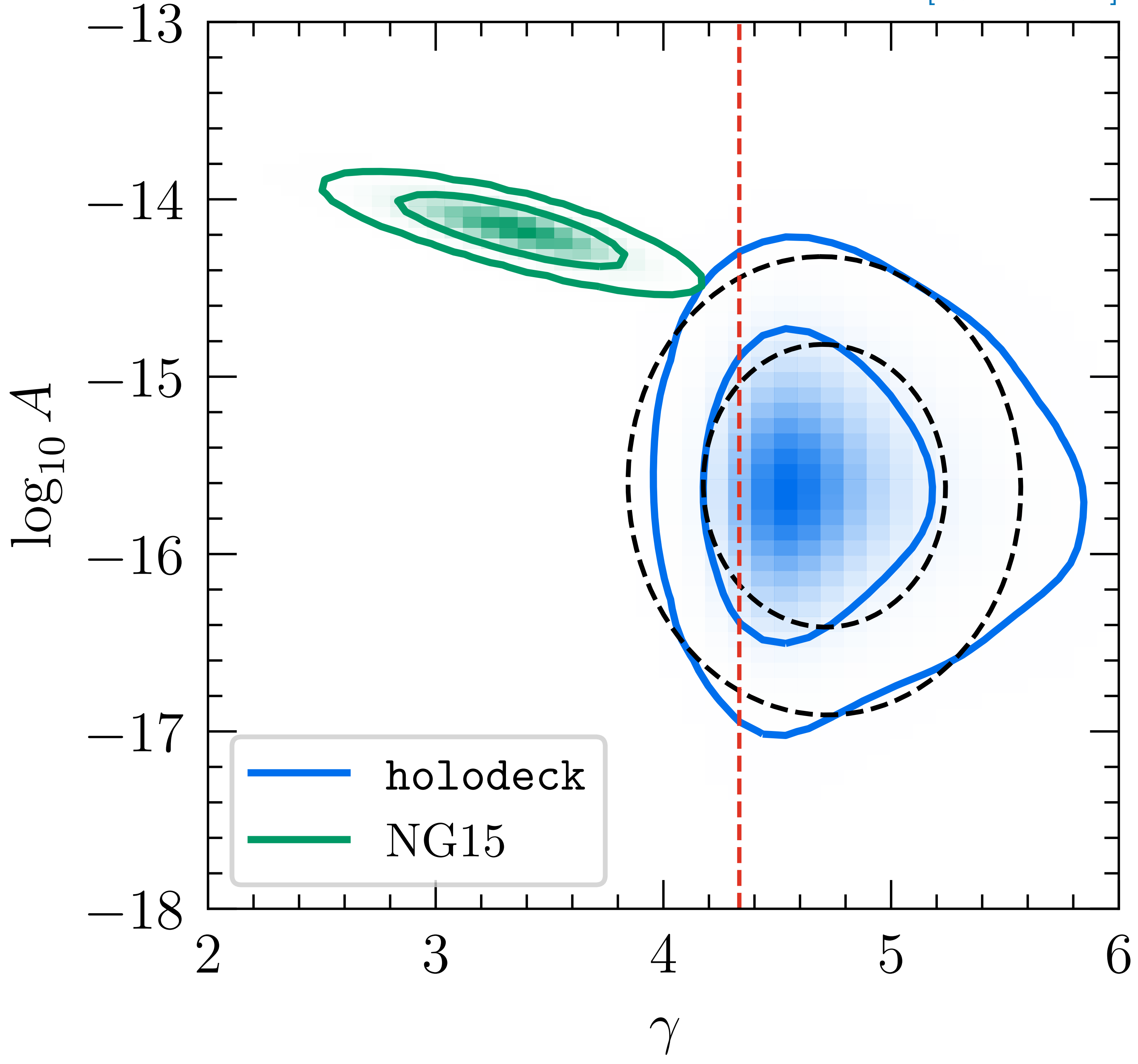
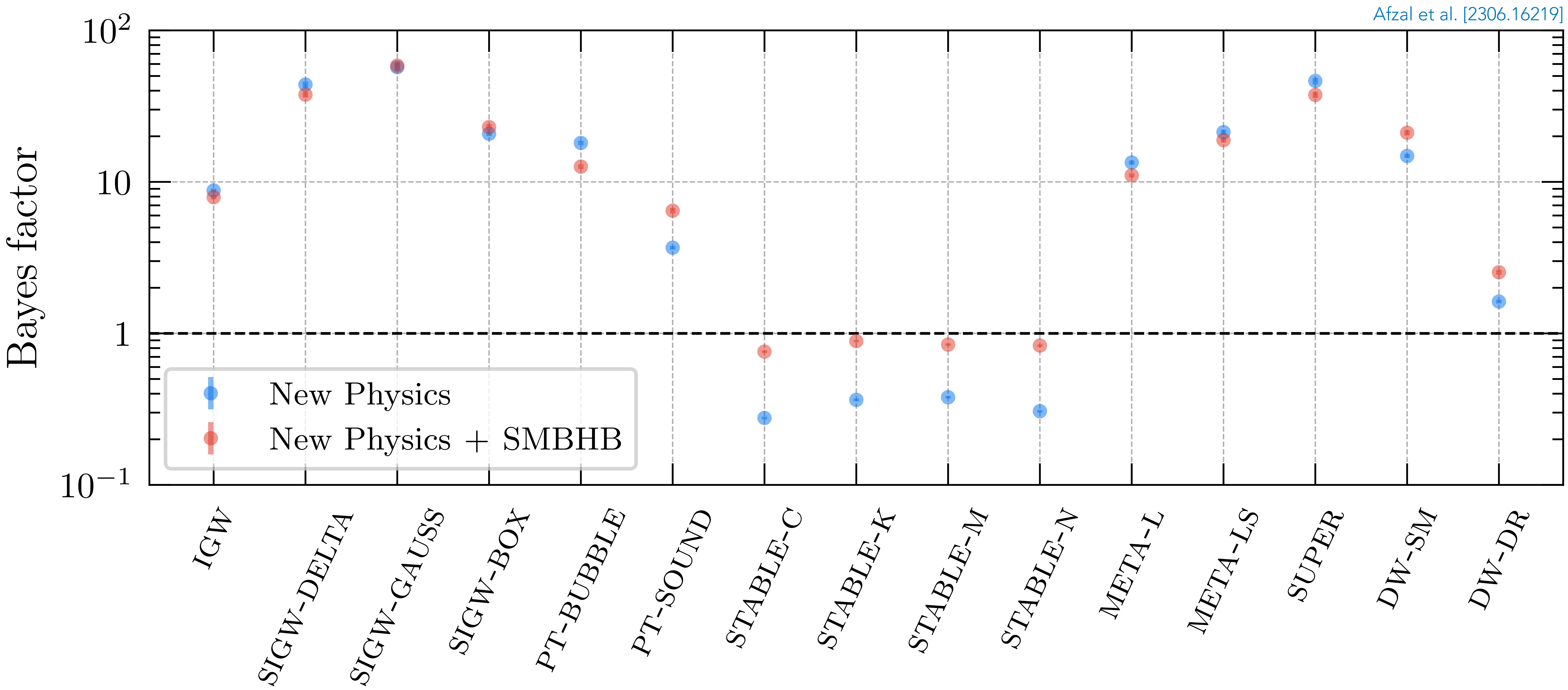
Afzal et al. [2306.16219]



FACE-OFF


Afzal et al. [2306.16219]
Bayes factor
10^2
10
1
10^{-1}
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