

GWs and phase transitions from NANOGrav

Andrea Mitridate

Invisibles23 Workshop | Aug. 31, 2023



NANOGrav
Physics Frontiers Center

image credit: Aurore Simonnet / NANOGrav

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PTAs FAQs

- evidence for a GWB

- how?

- evidence? why not detection?

- are all PTAs seeing the same thing? if not, why not?

- source still unknown

- supermassive BH binaries?

- can it be new physics?

- how can we tell?

PULSARS

**Rotation
Axis**

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

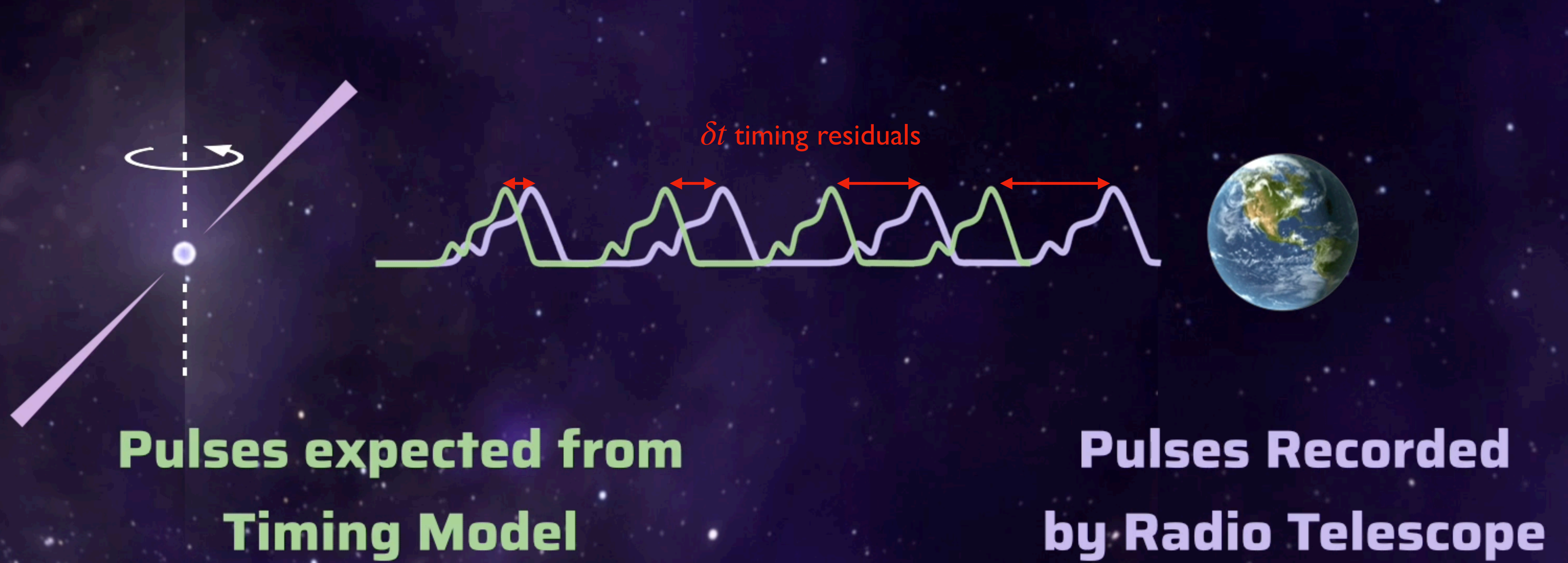
$$\dot{\nu}_0/\nu_0 \sim 10^{-23} - 10^{-20} \text{ Hz}$$



**Magnetic
Field Axis**

Radiation Beams

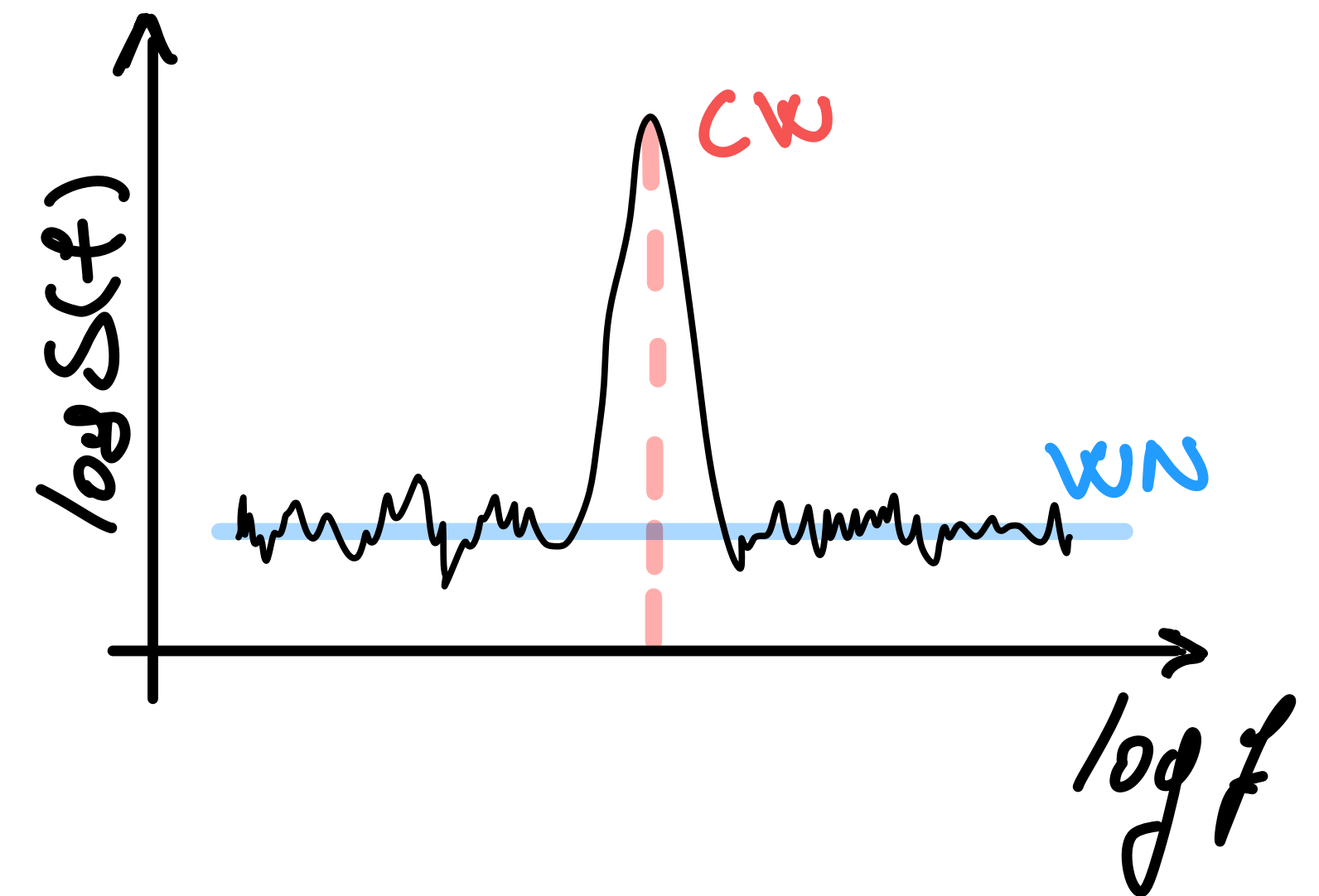
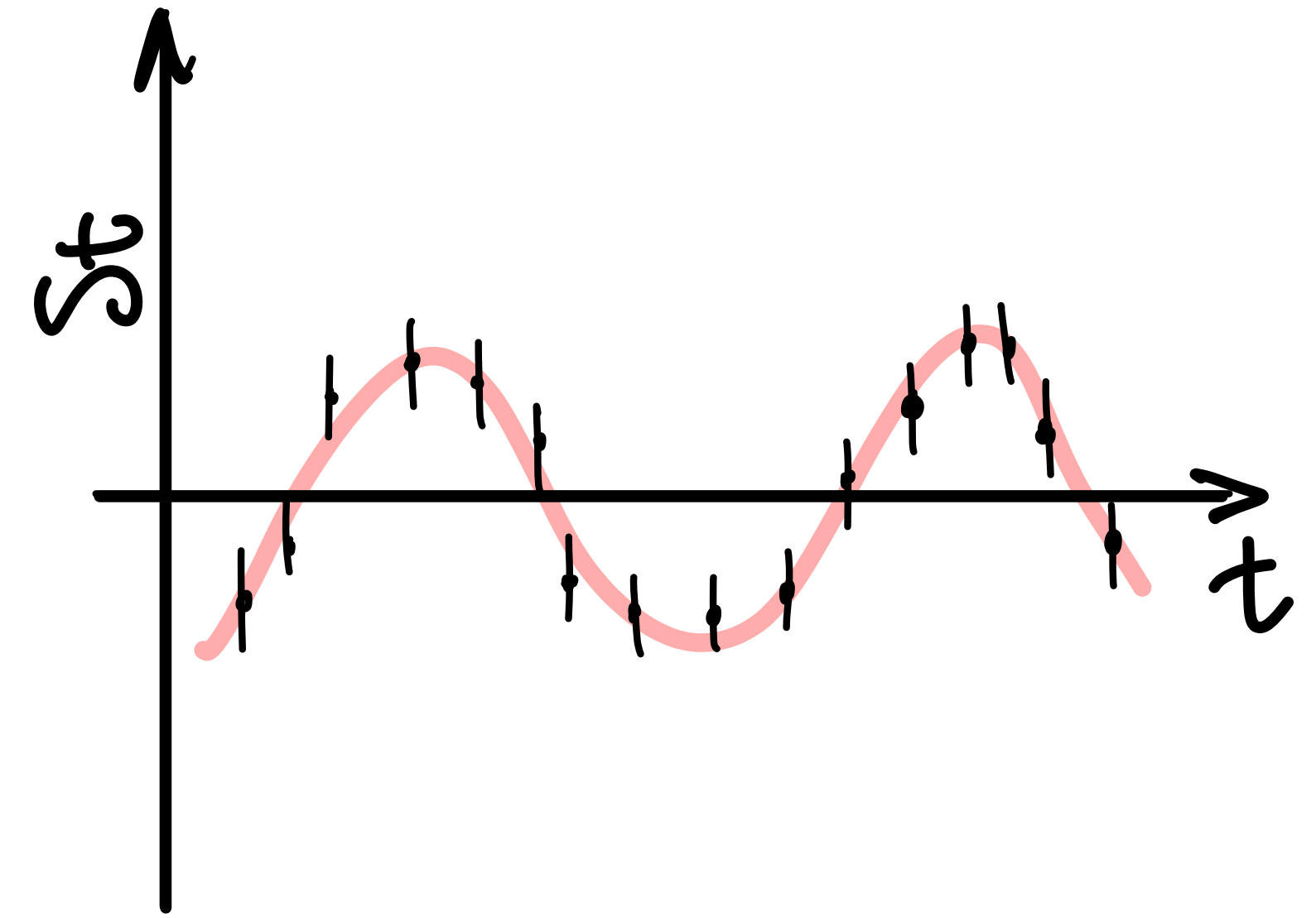
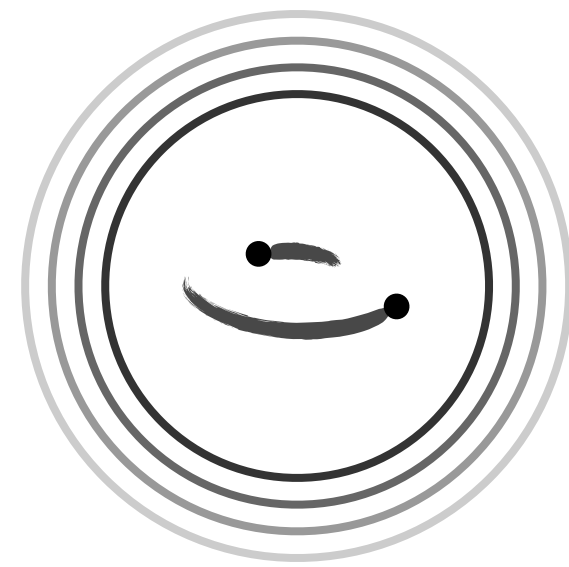
TIMING RESIDUALS



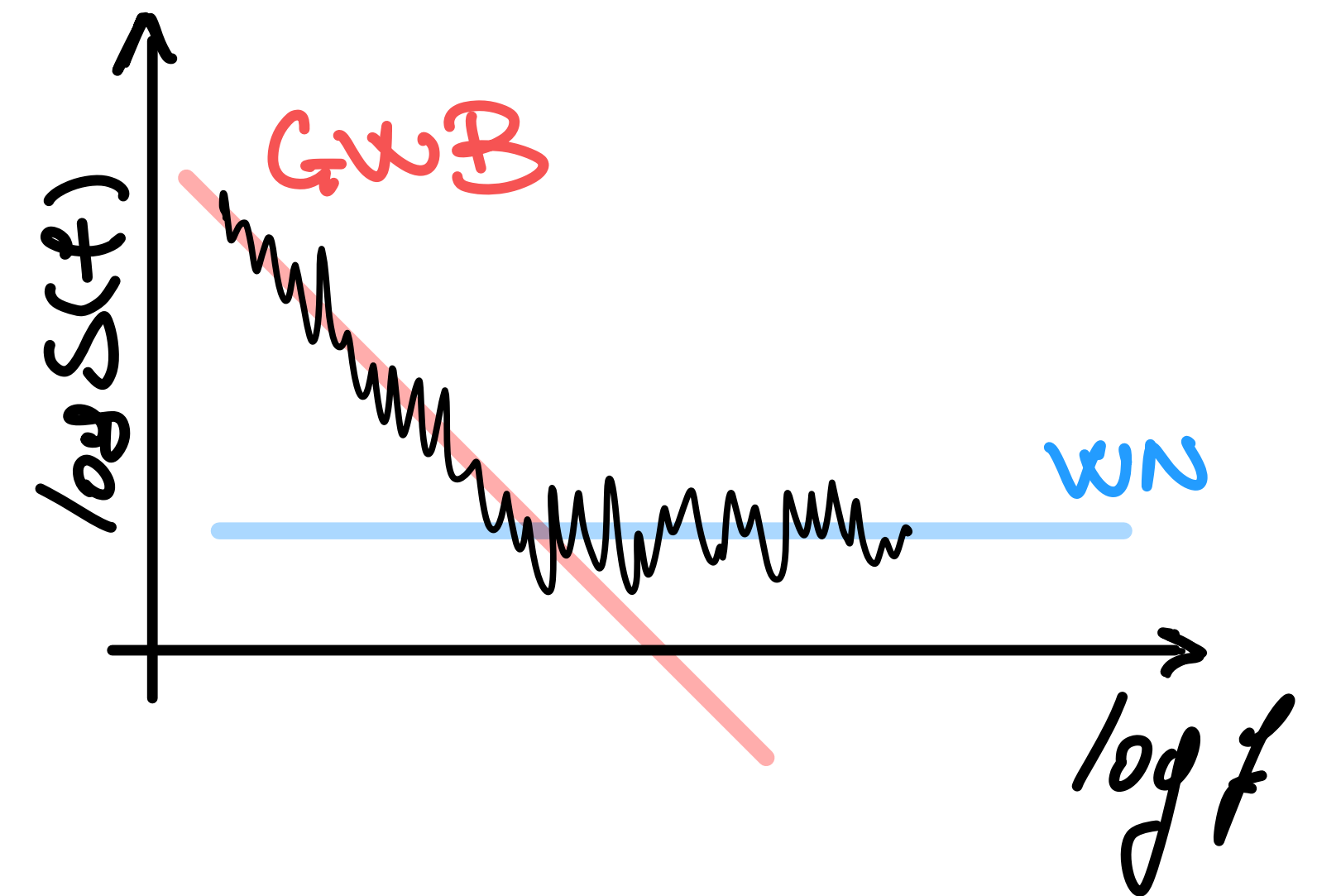
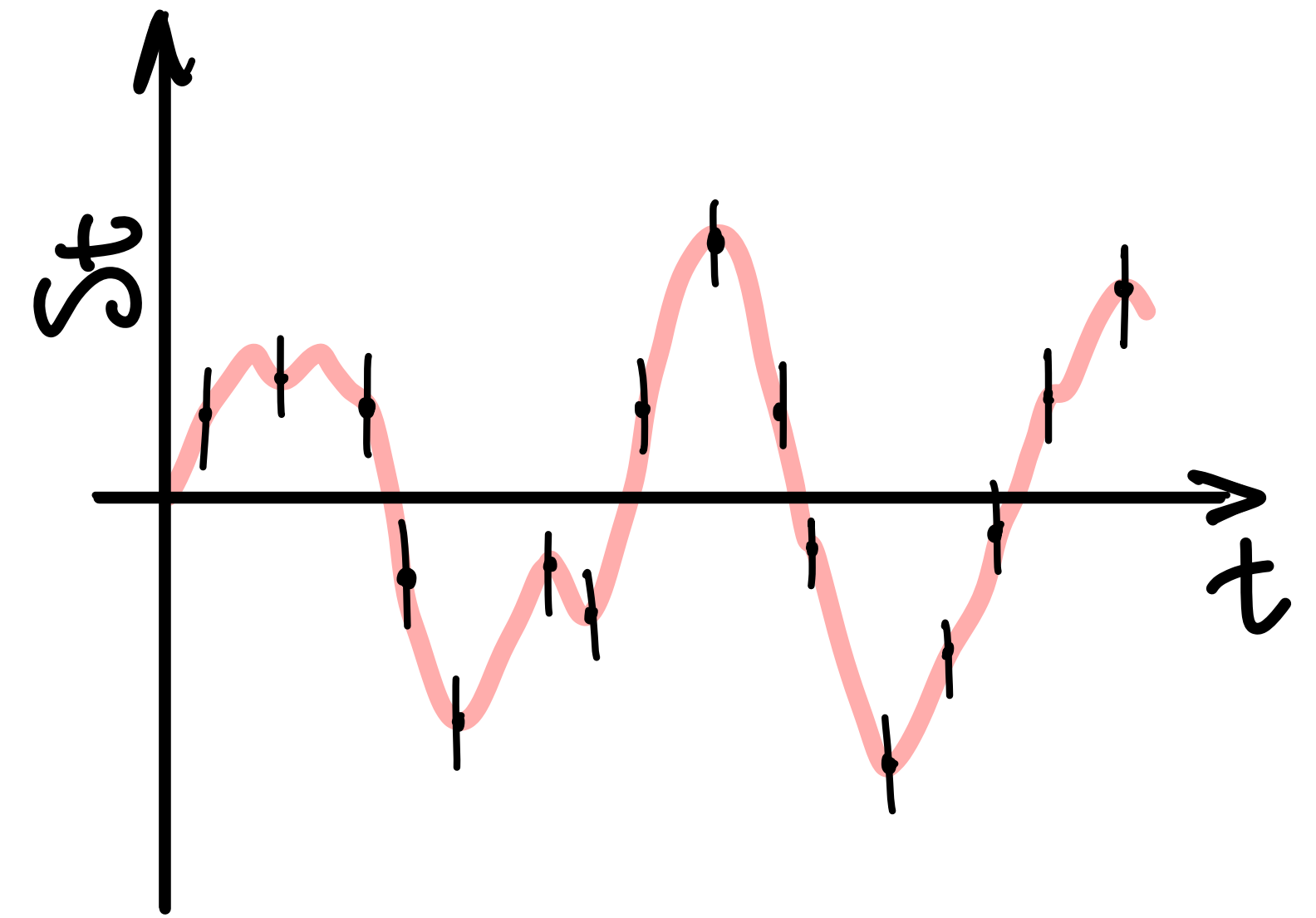
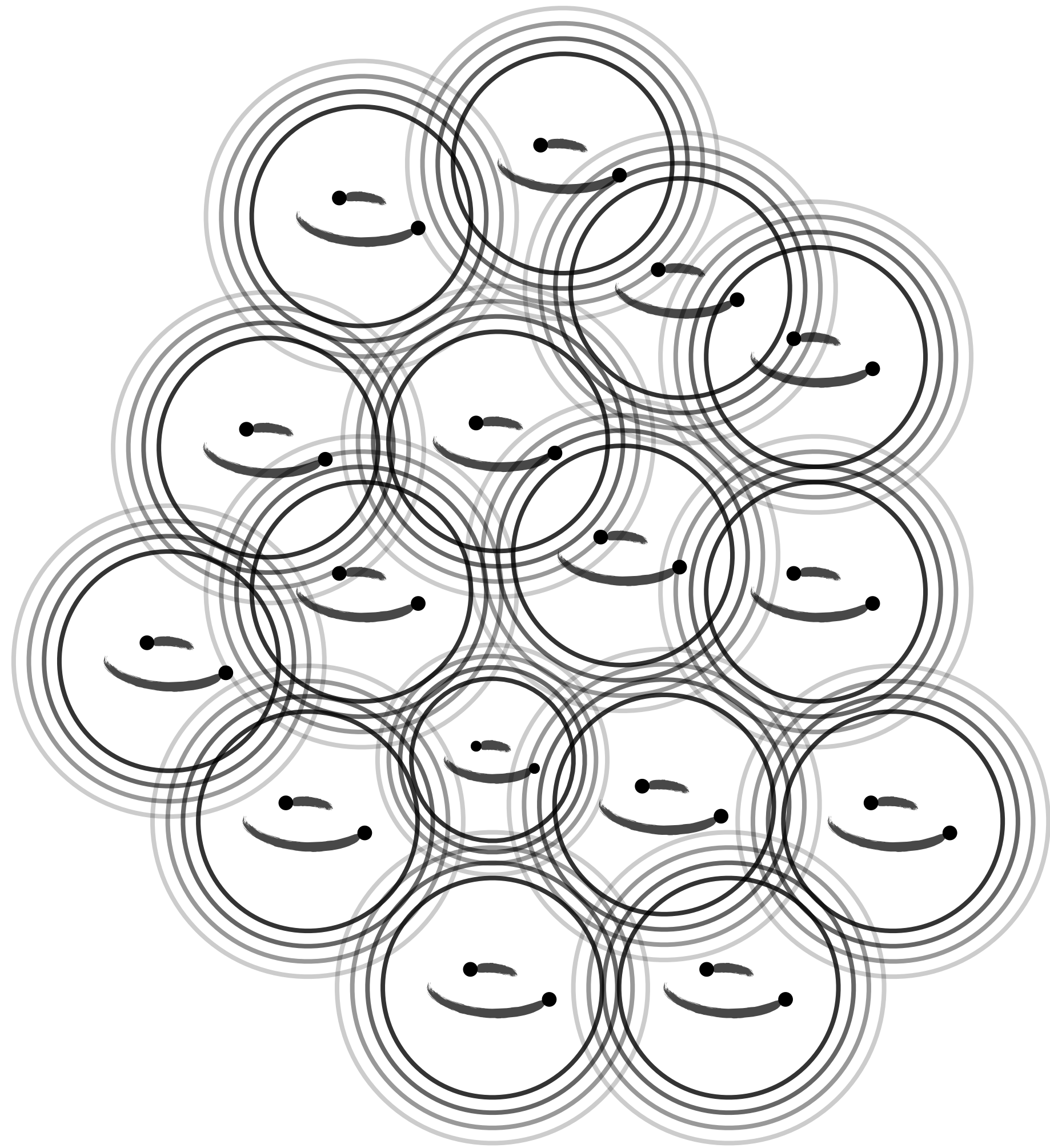
A GALAXY-SIZE DETECTOR FOR GWs



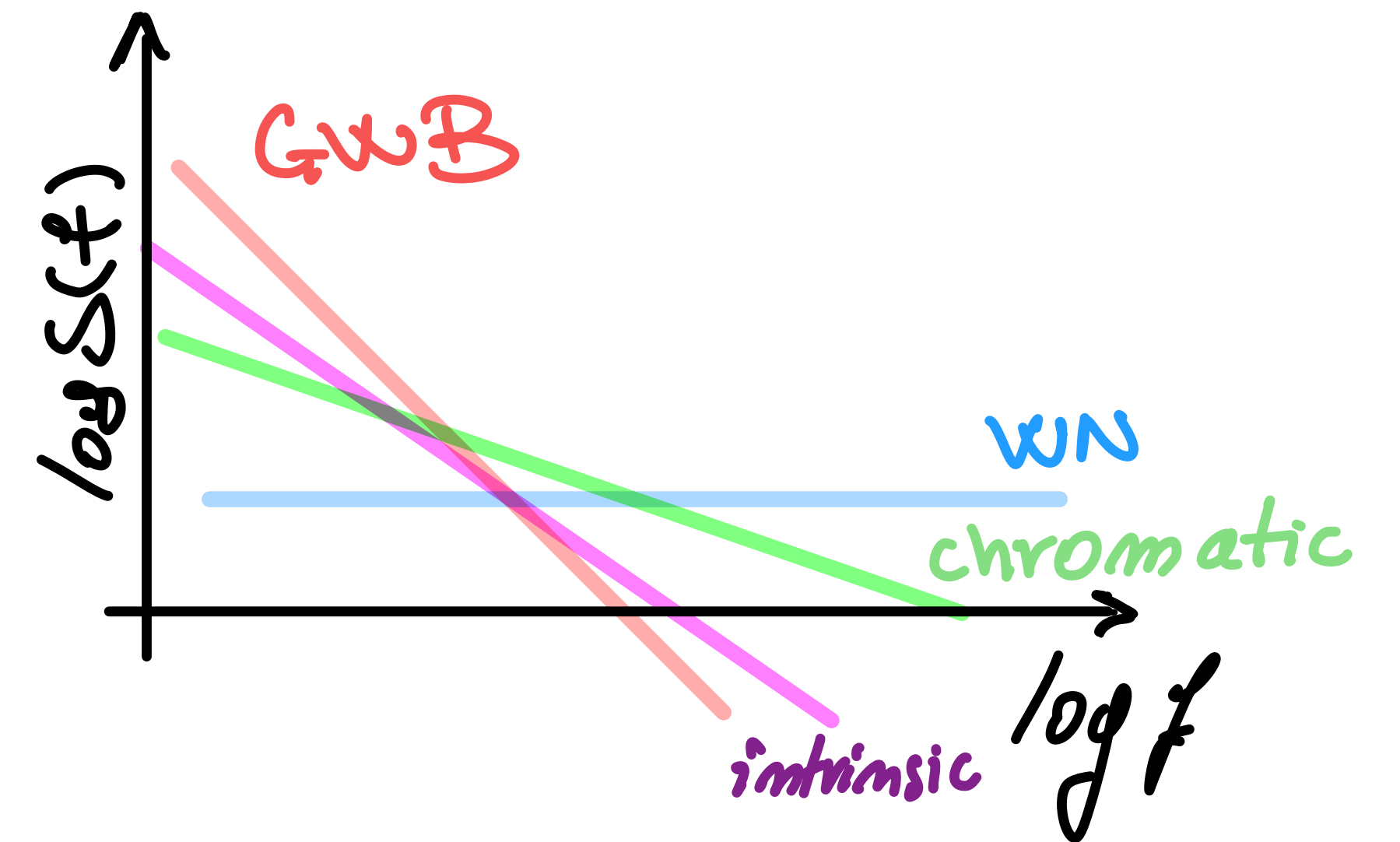
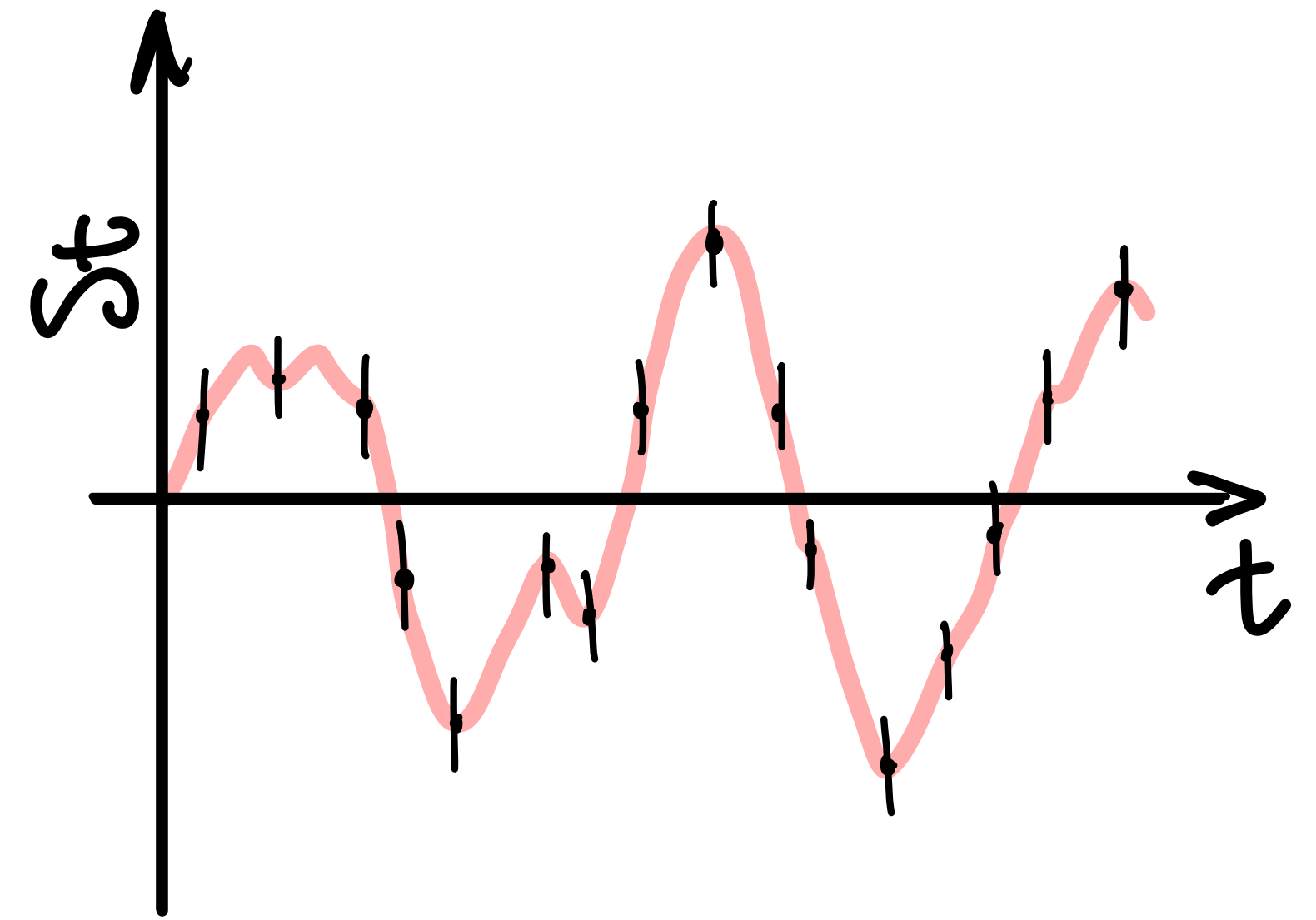
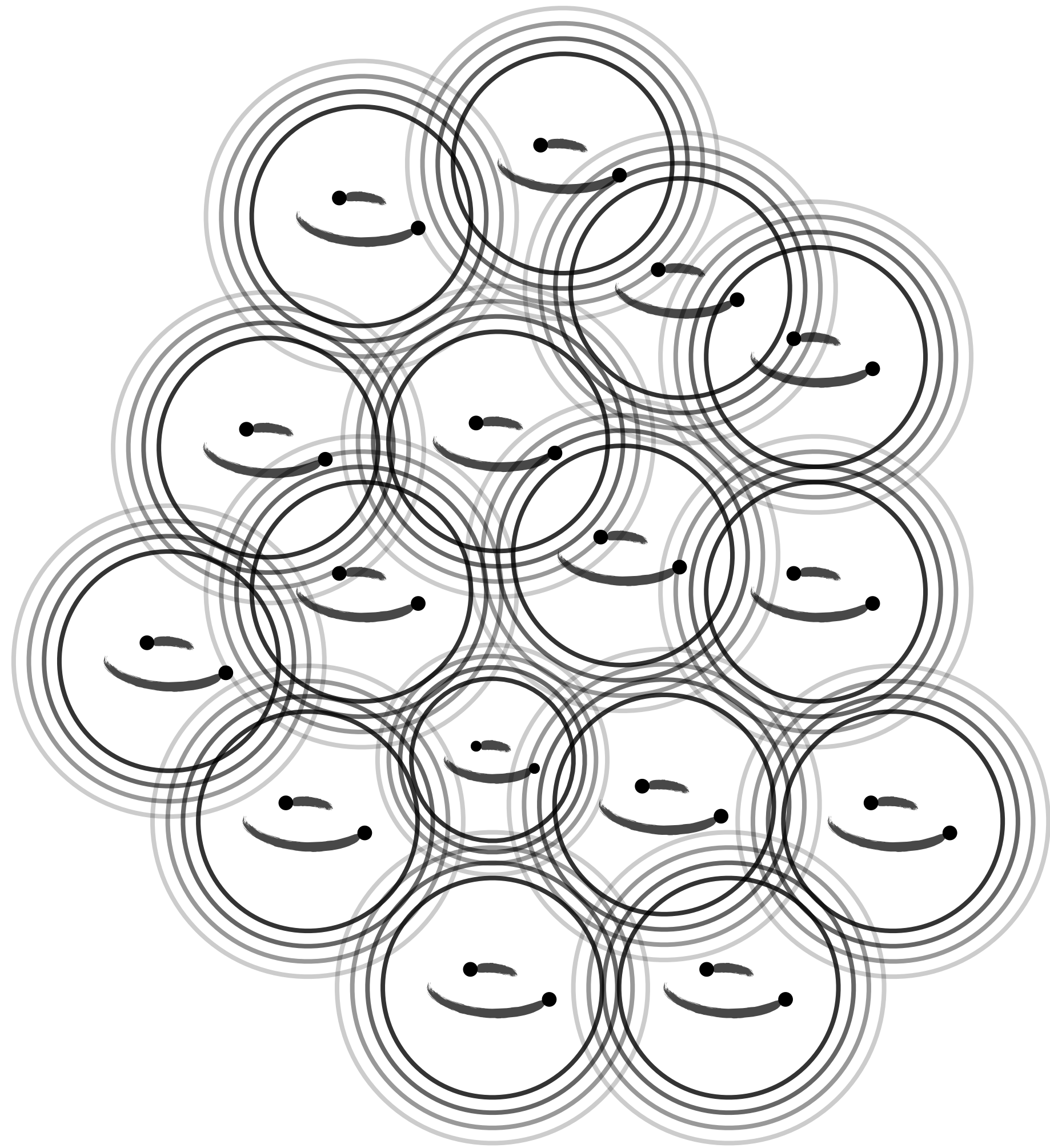
DETERMINISTIC vs STOCHASTIC



DETERMINISTIC vs STOCHASTIC

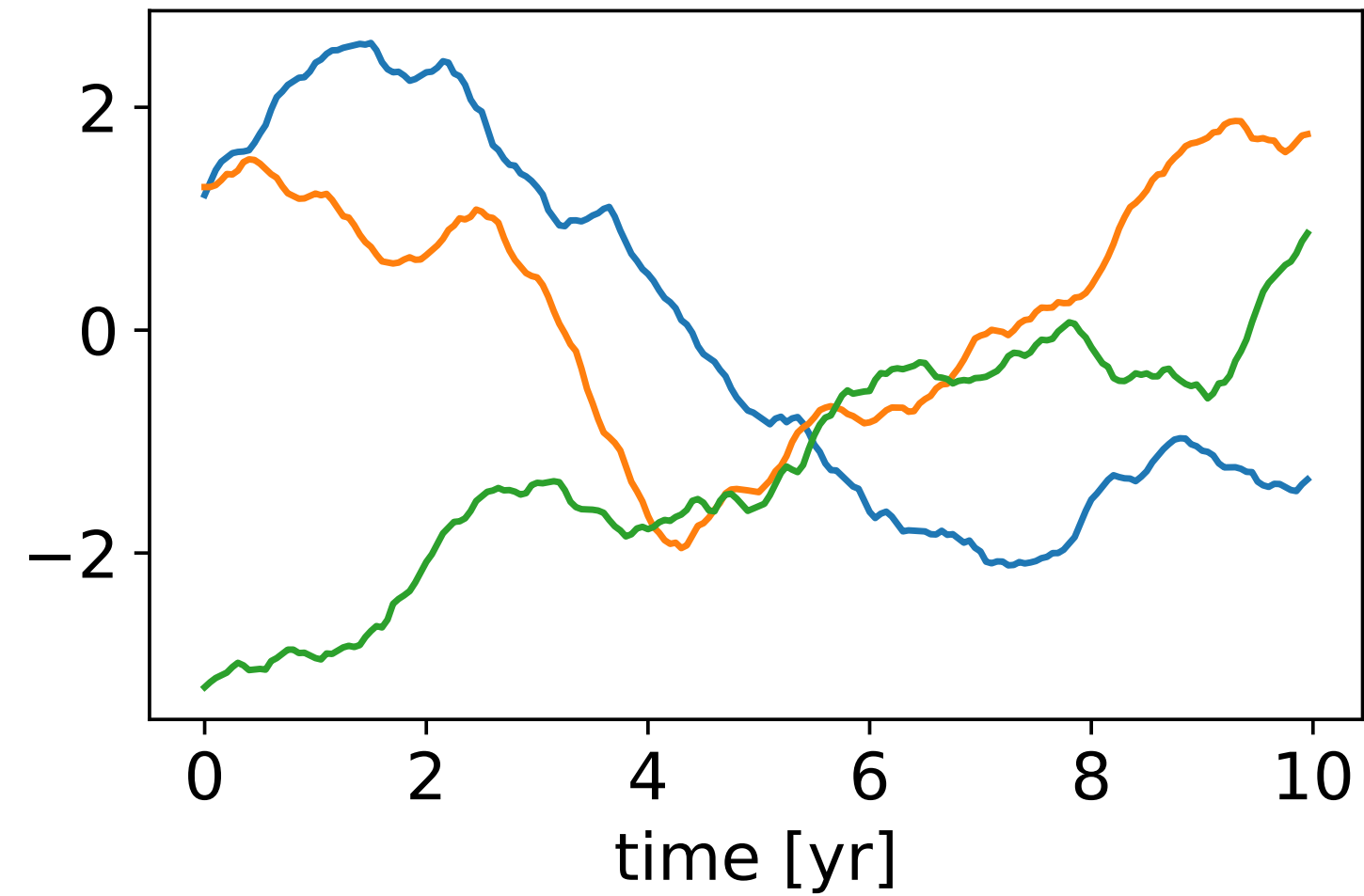


DETERMINISTIC vs STOCHASTIC



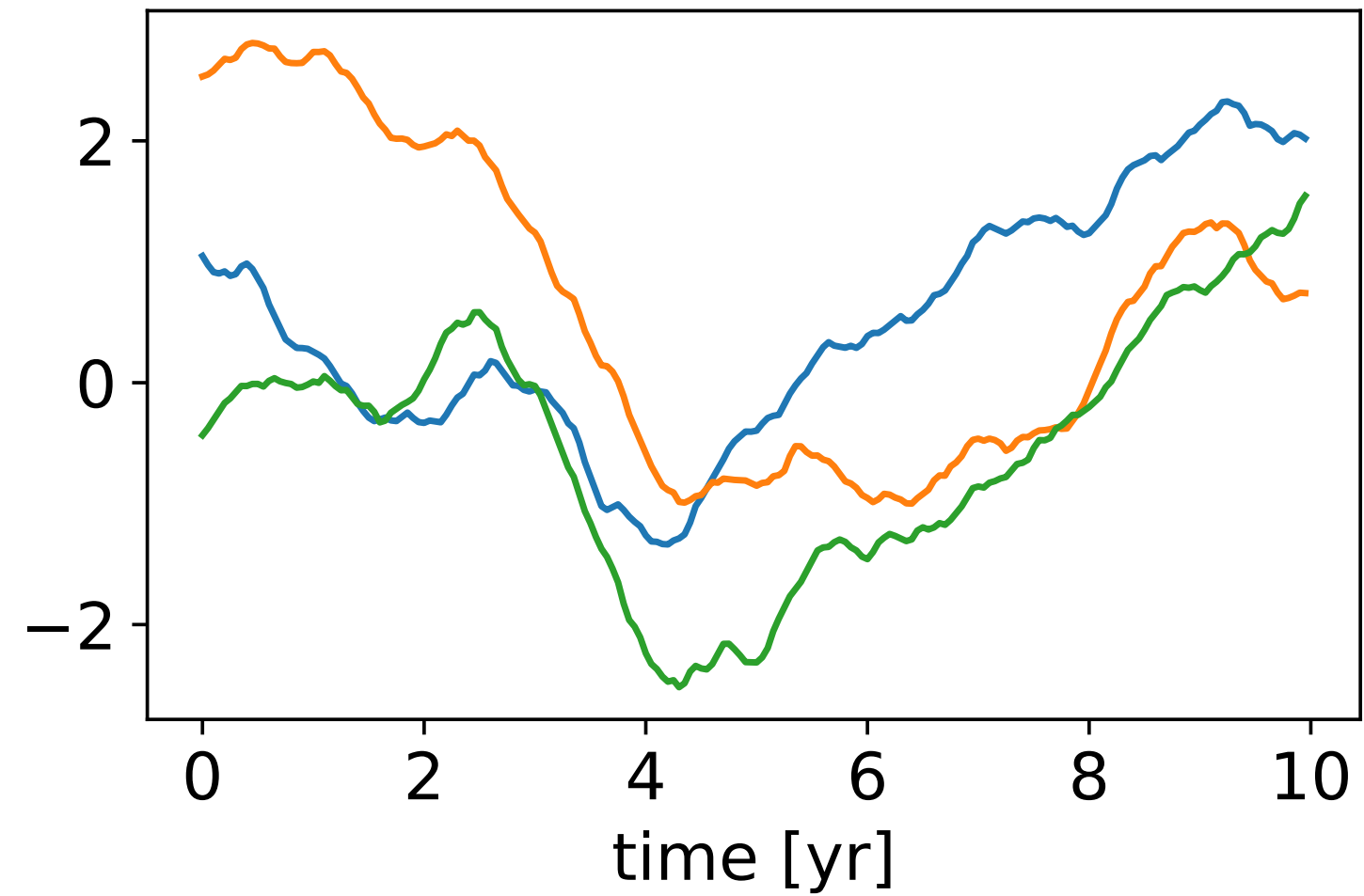
CORRELATIONS EXAMPLE

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



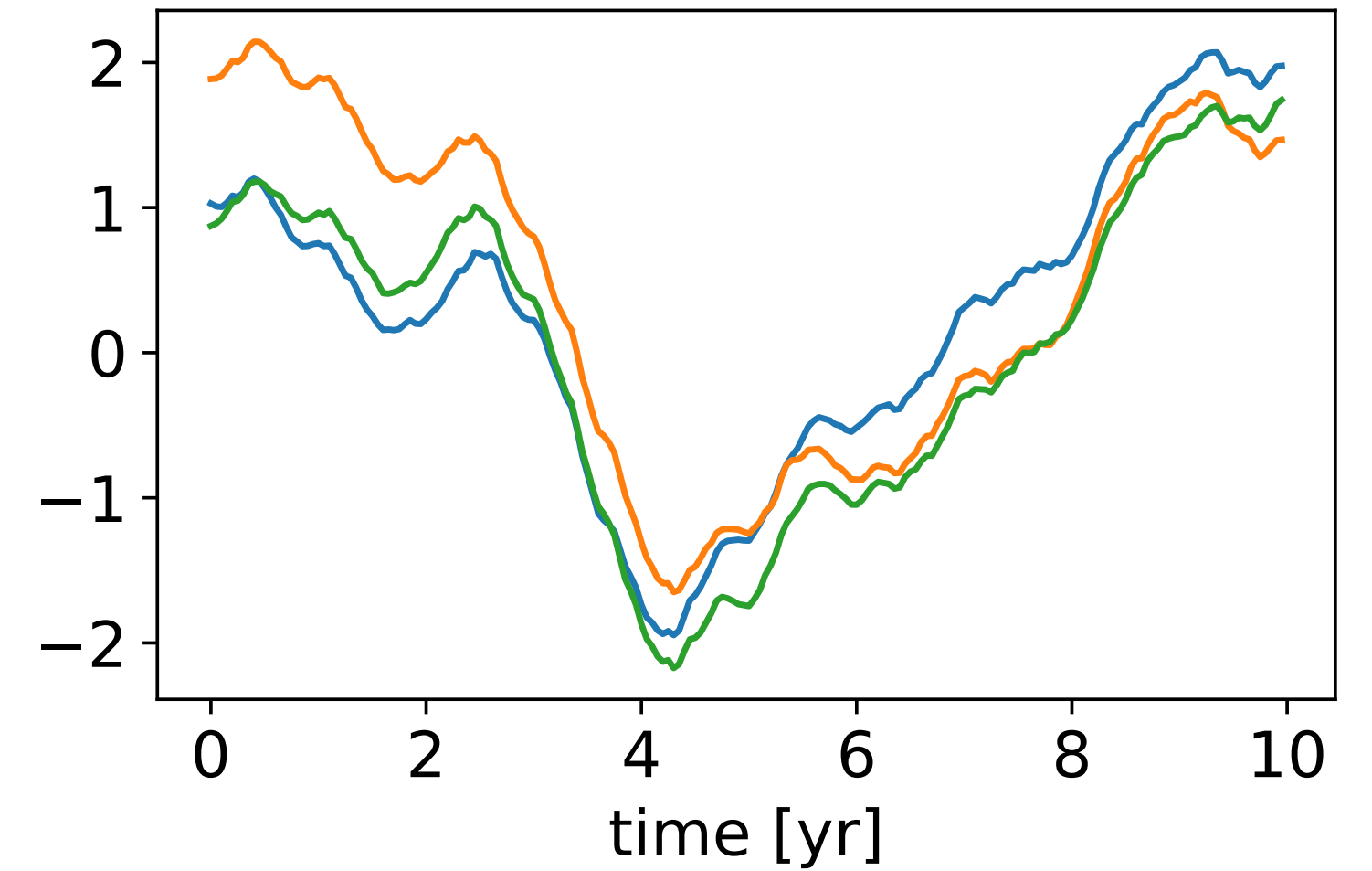
uncorrelated

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



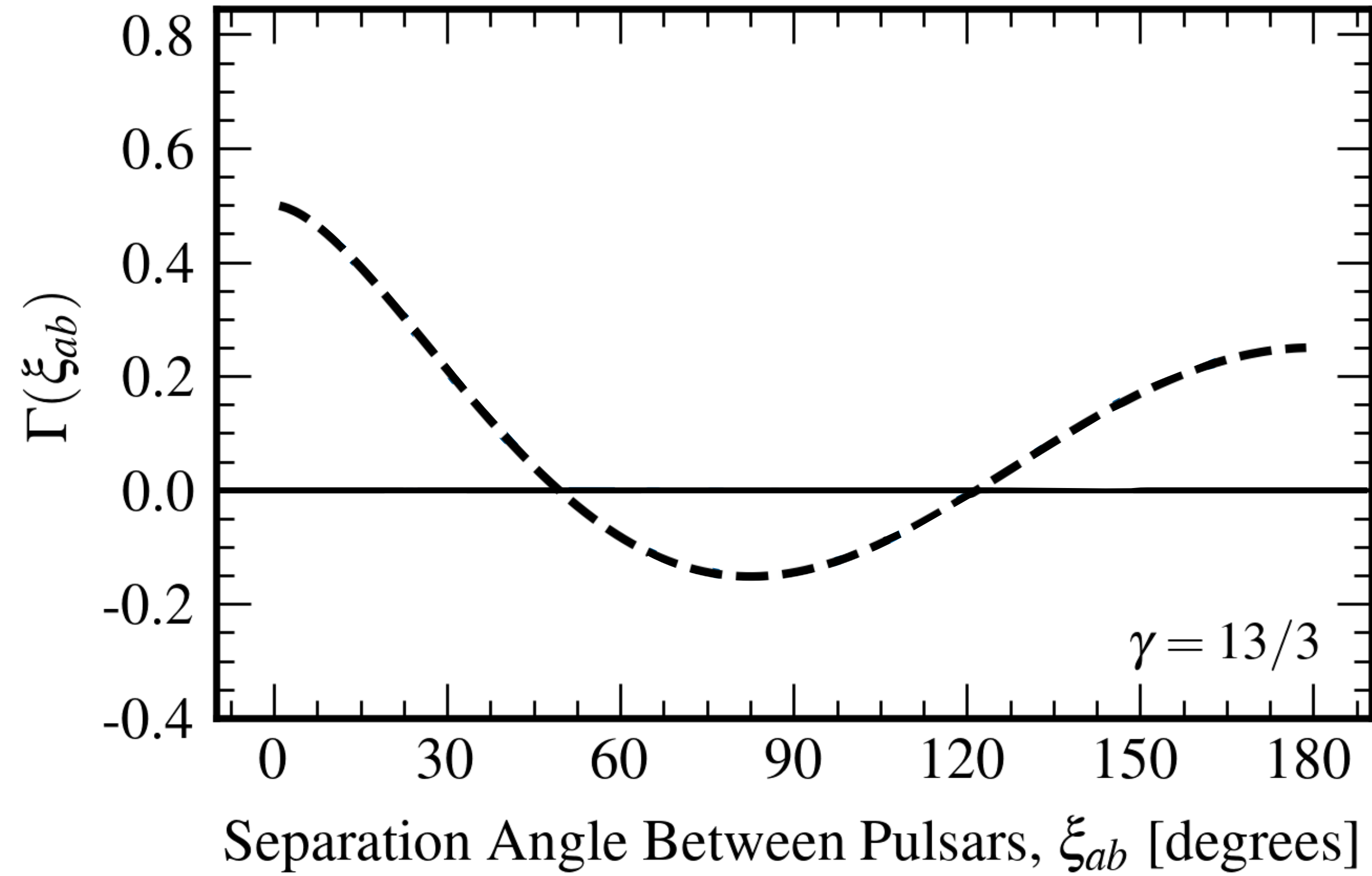
moderately correlated

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

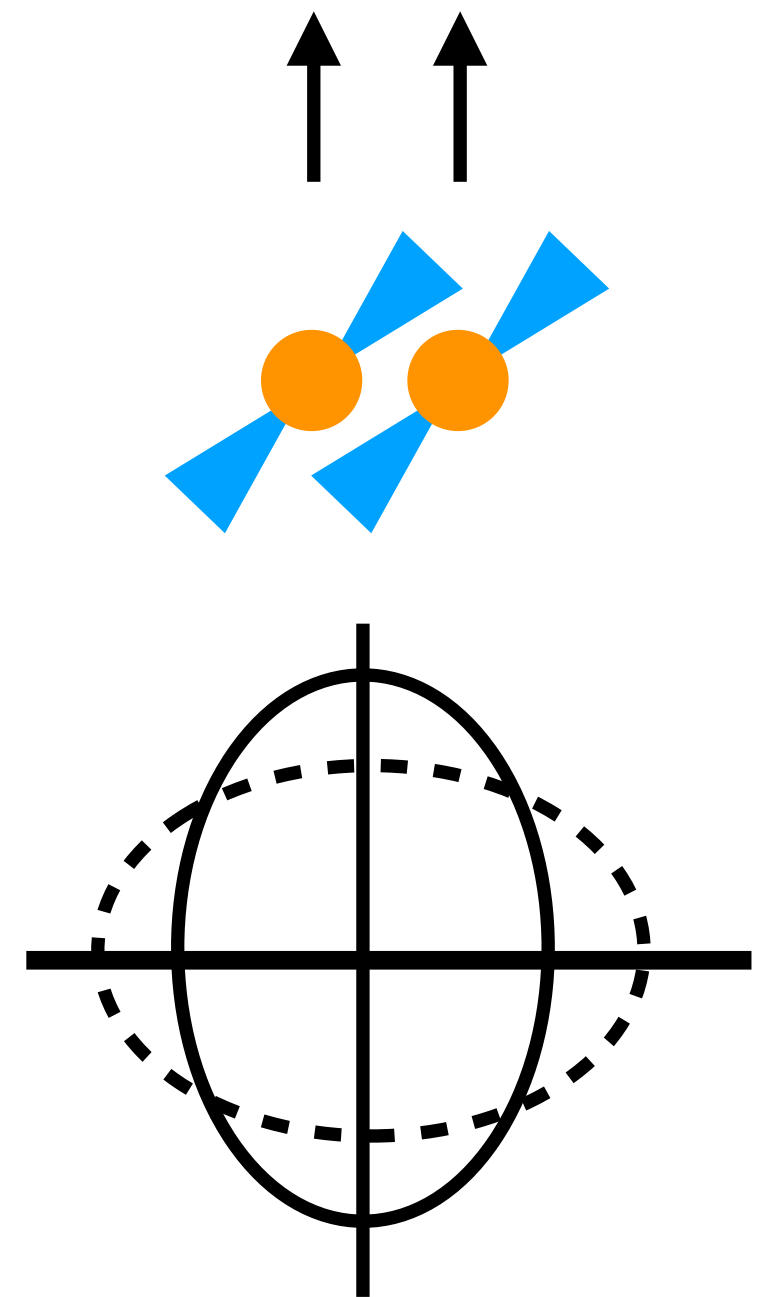
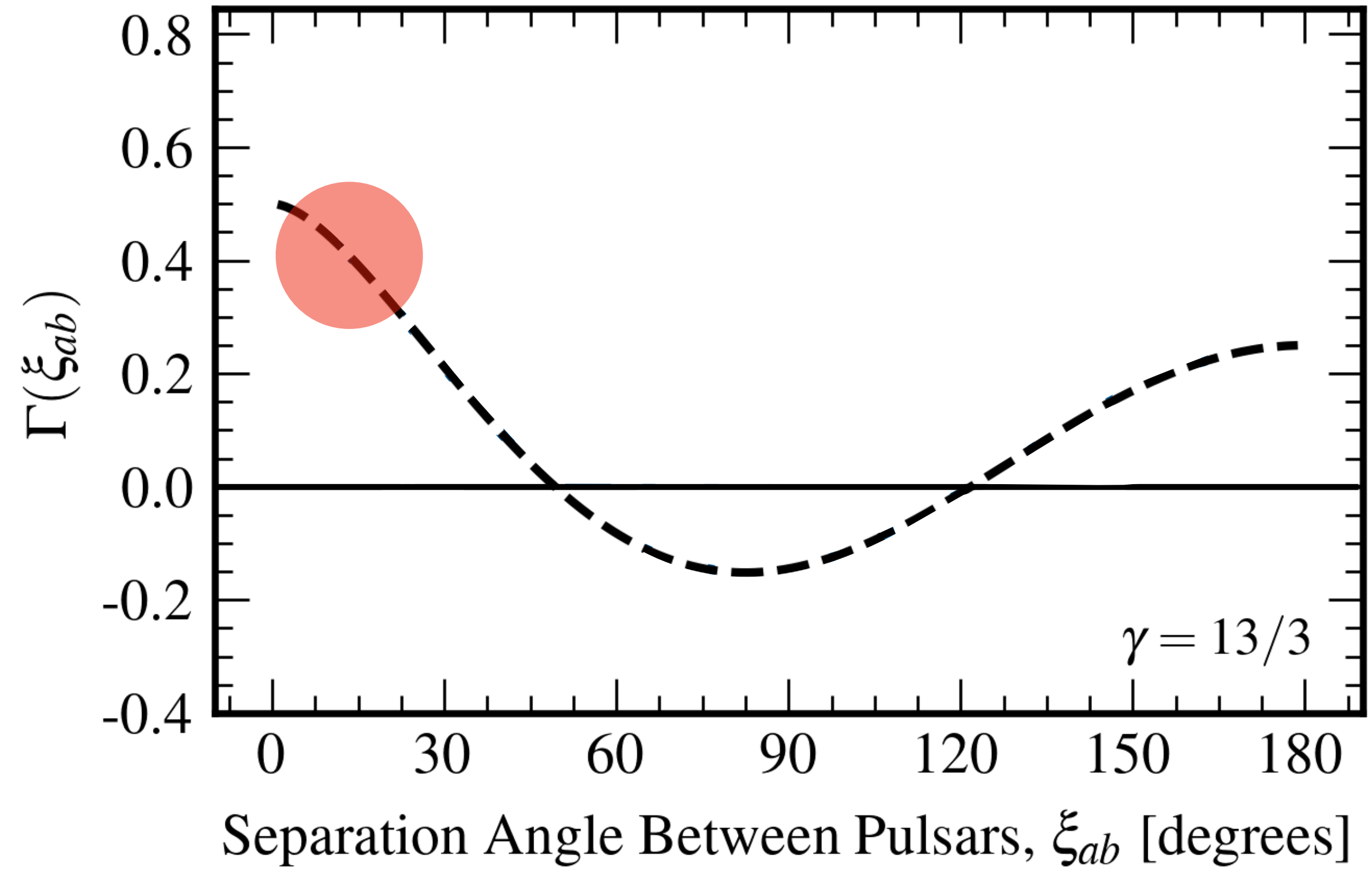


strongly correlated

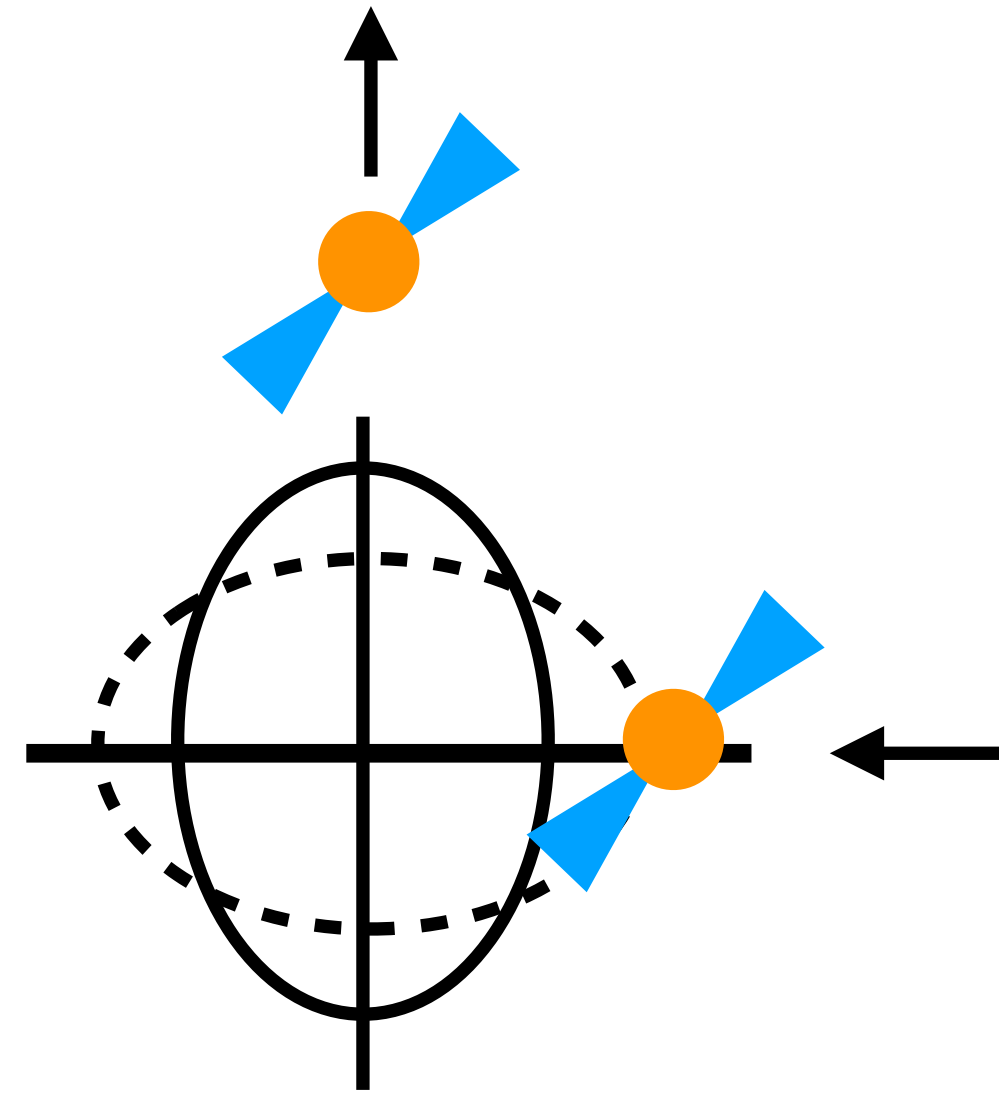
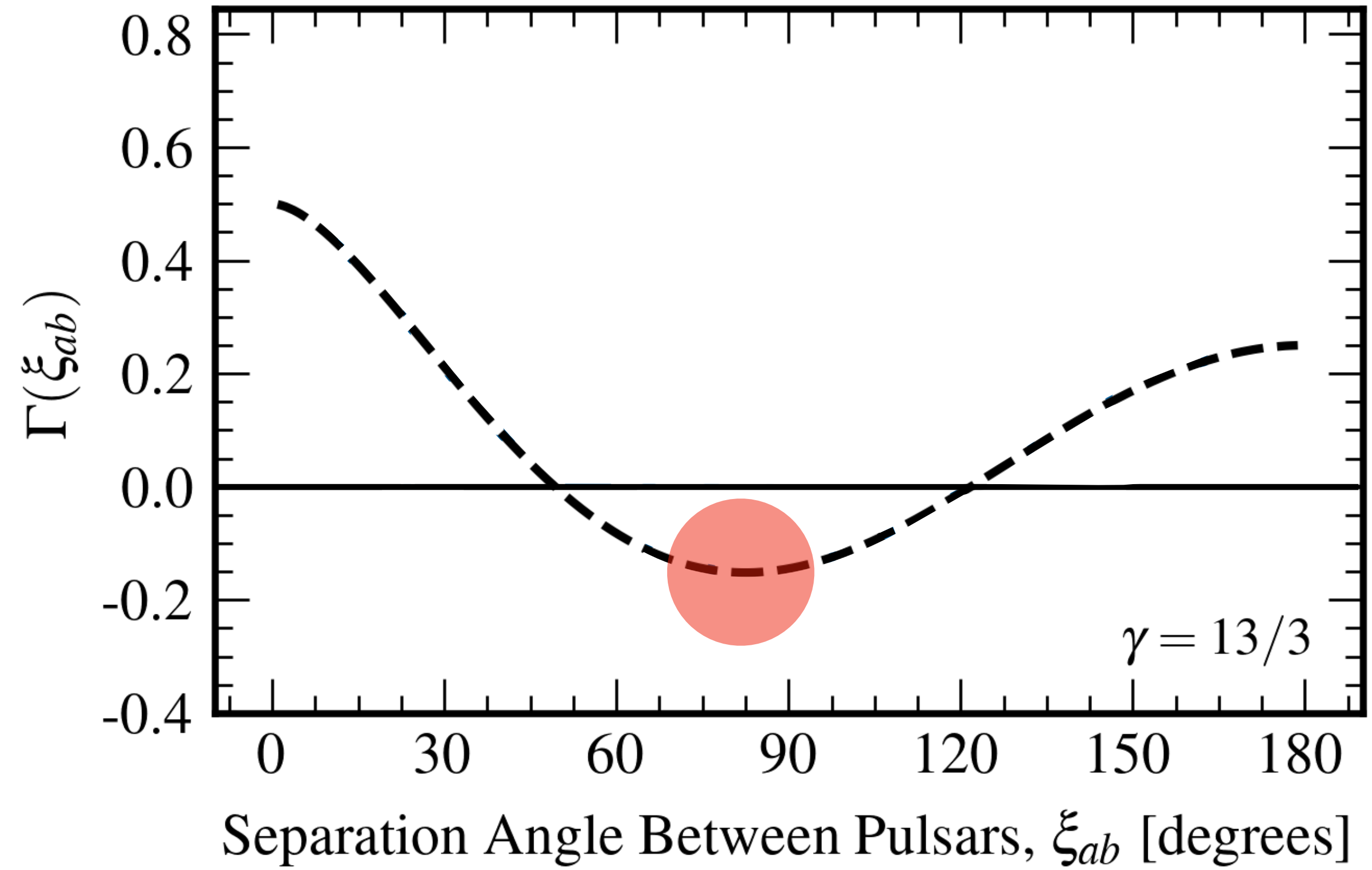
HELLINGS & DOWNS CURVE



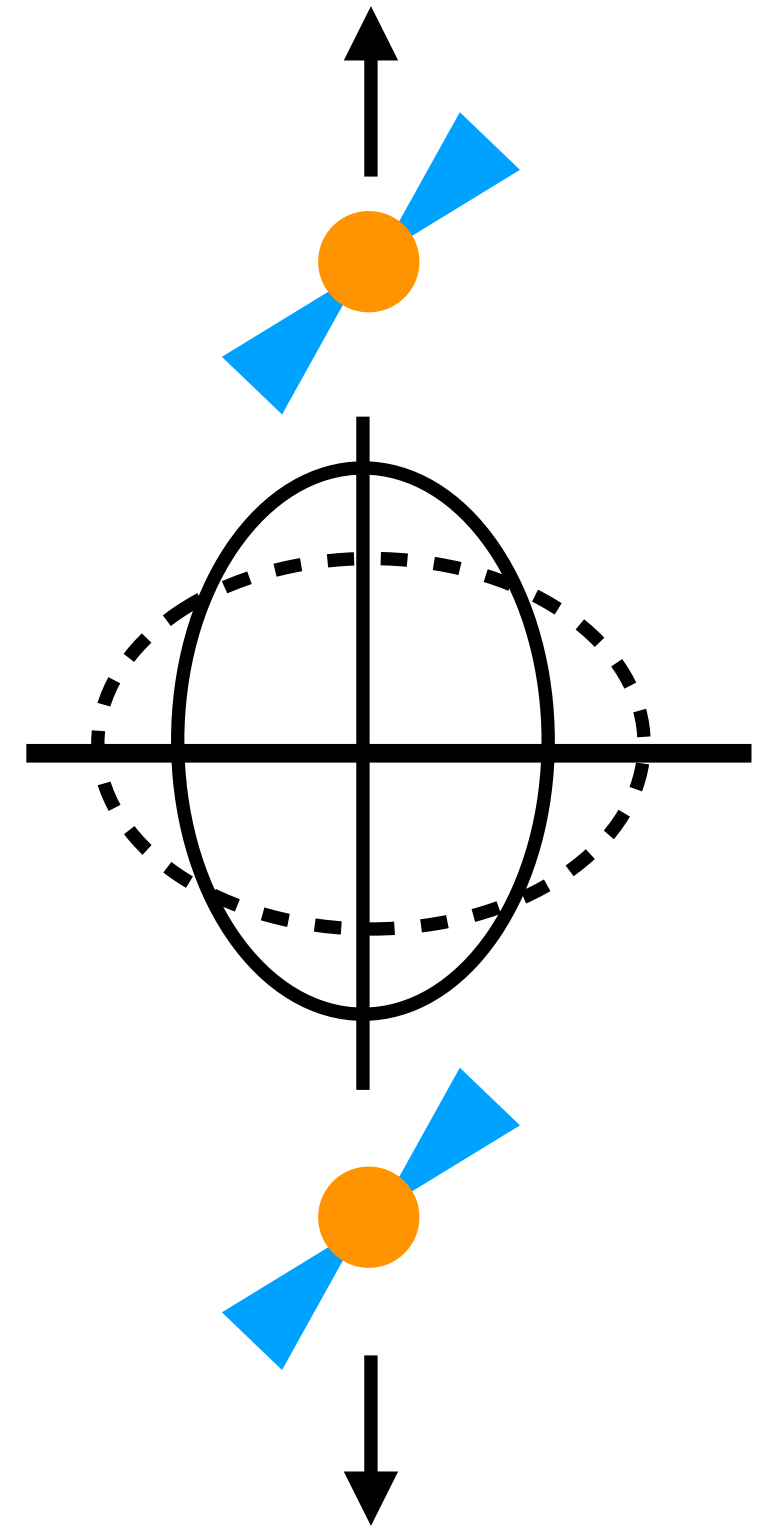
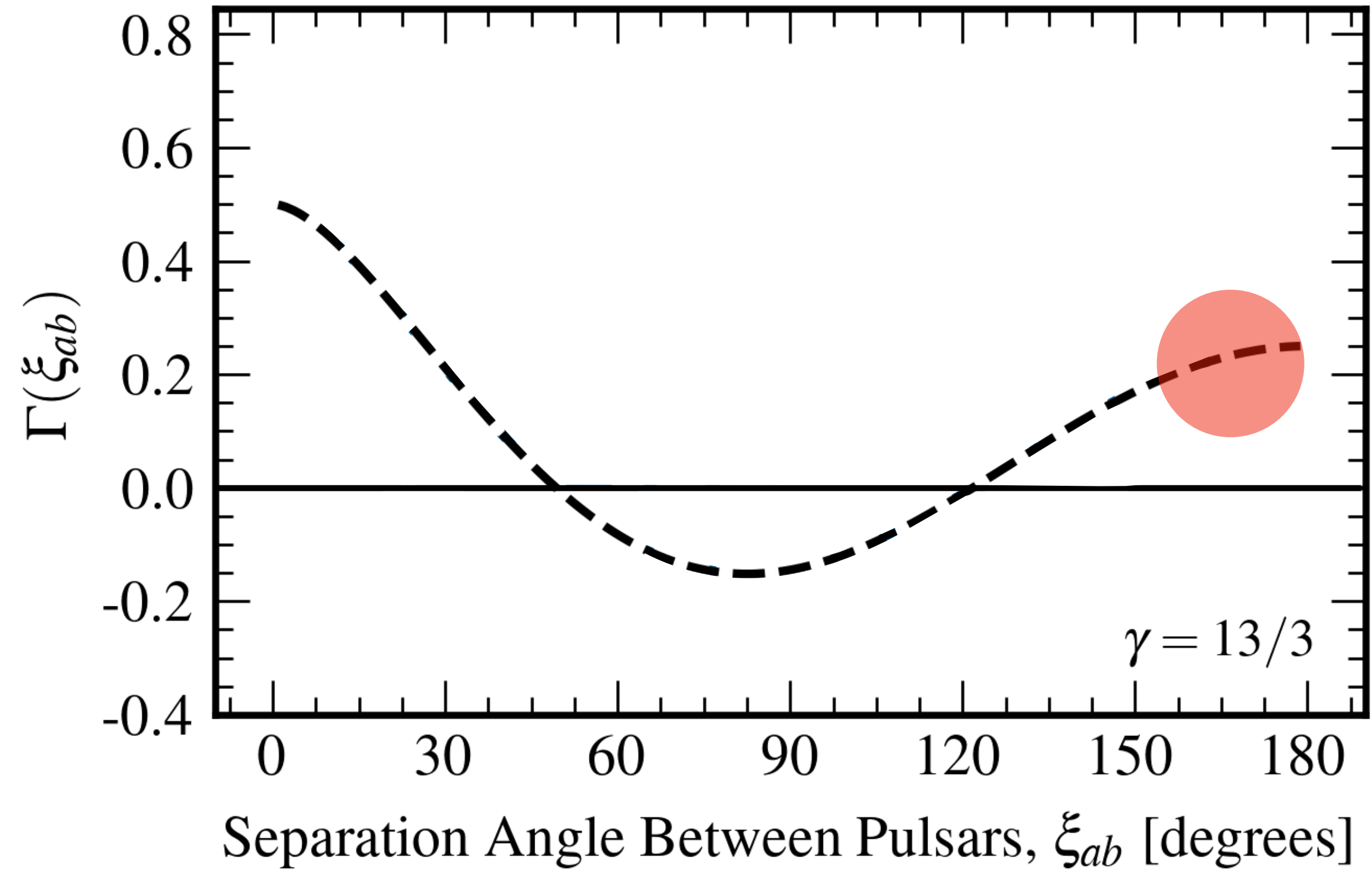
HELLINGS & DOWNS CURVE



HELLINGS & DOWNS CURVE

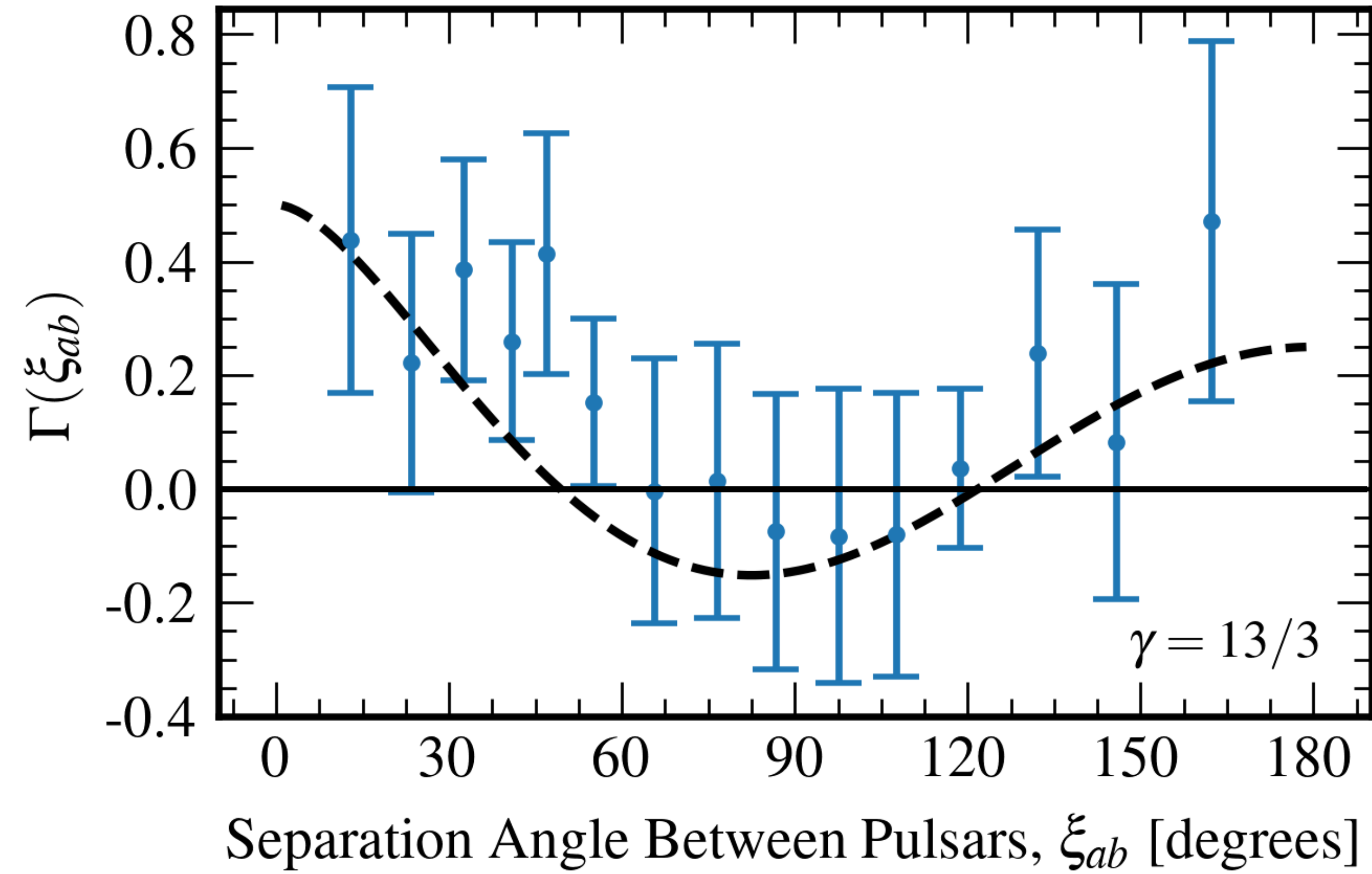


HELLINGS & DOWNS CURVE



EVIDENCE FOR GWB

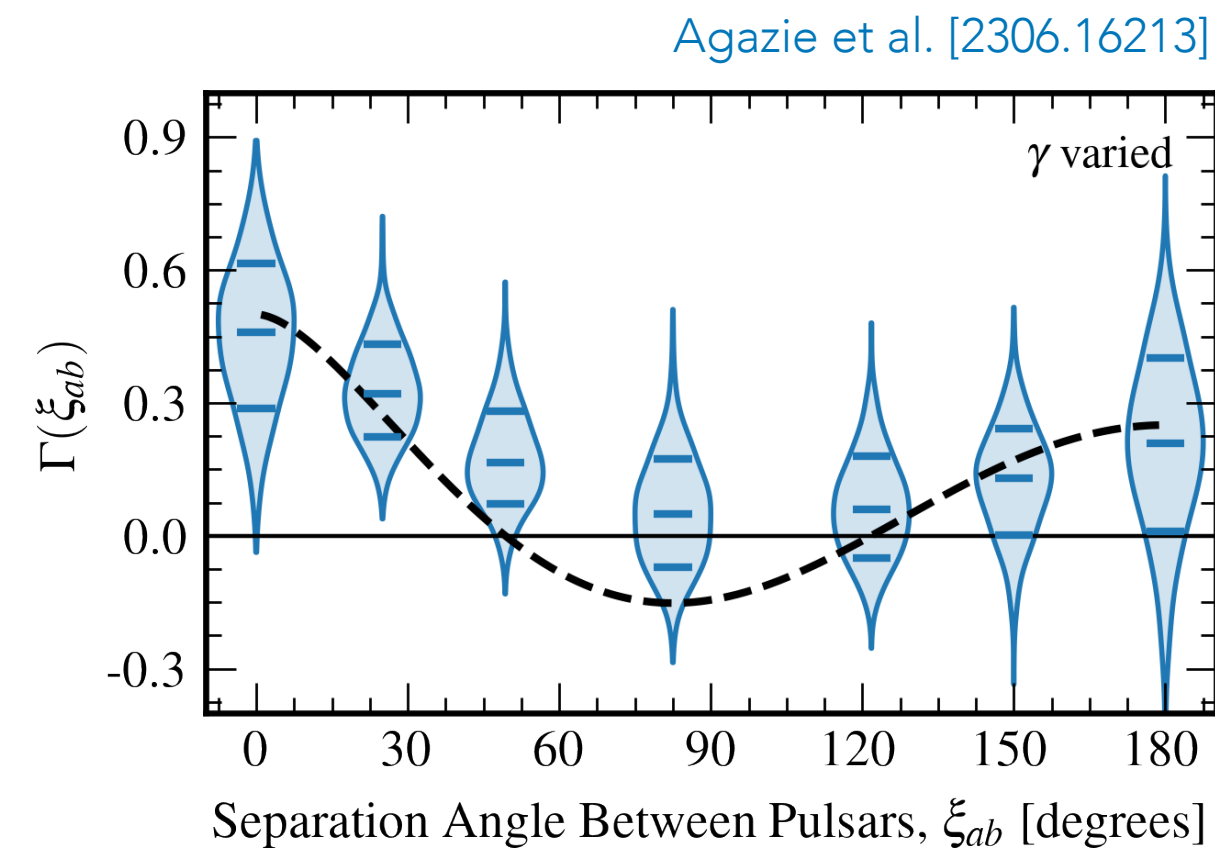
Agazie et al. [2306.16213]



EVIDENCE FOR GWB

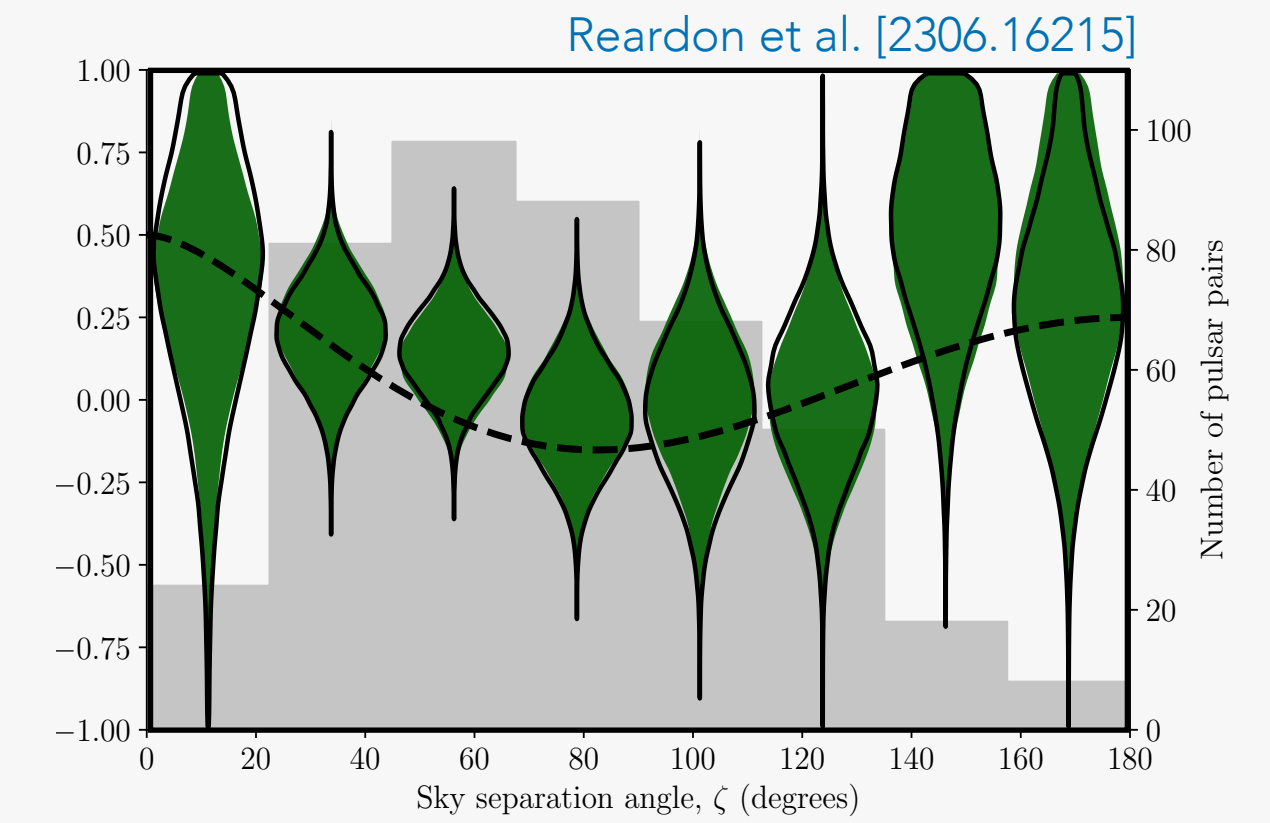
NANOGrav:

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



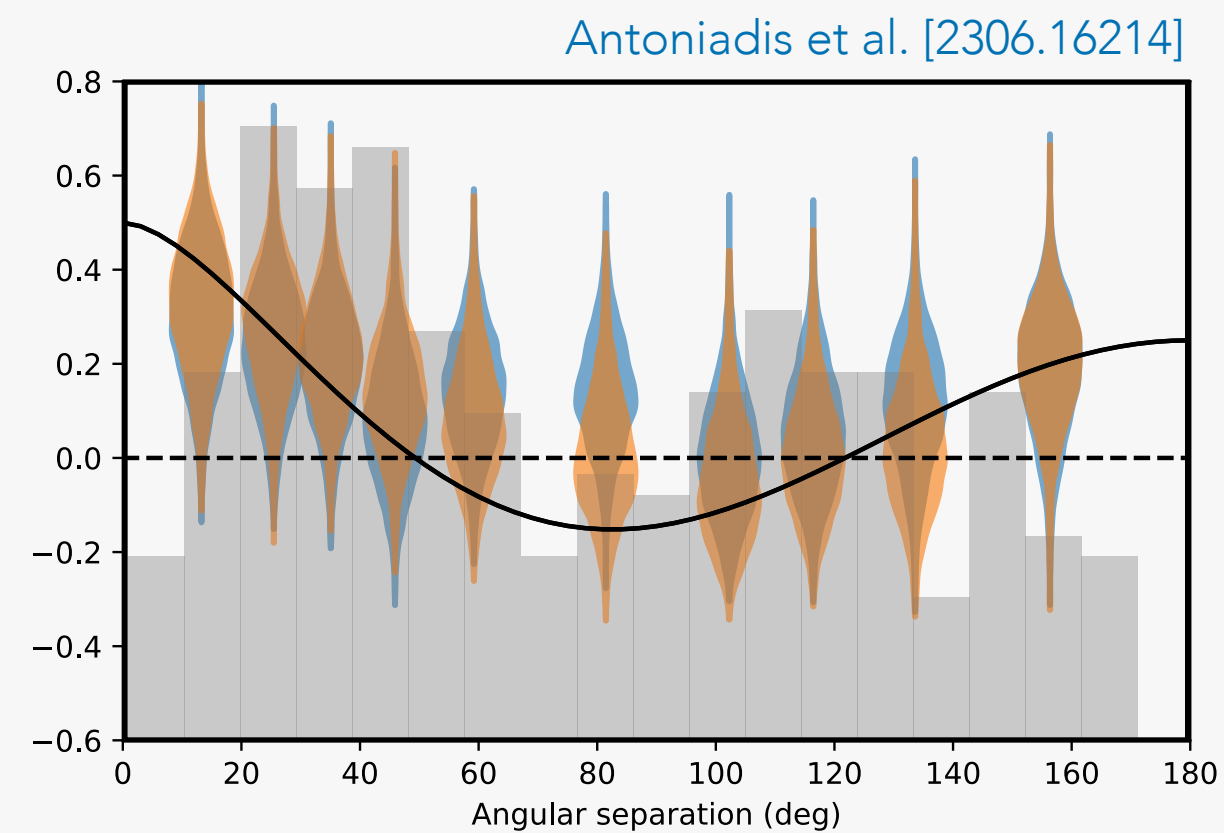
PPTA:

32 pulsars, 18yr of data
 ~2 σ significance



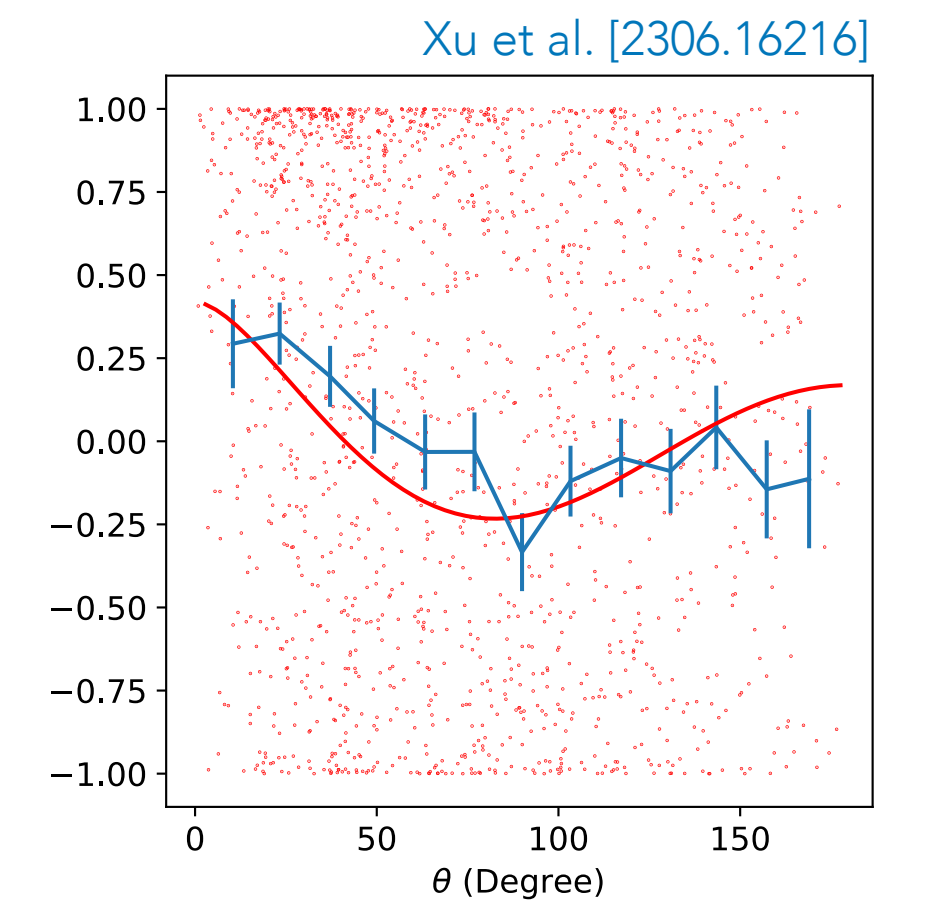
EPTA + InPTA:

25 pulsars, 24yr of data
 ~3 σ significance



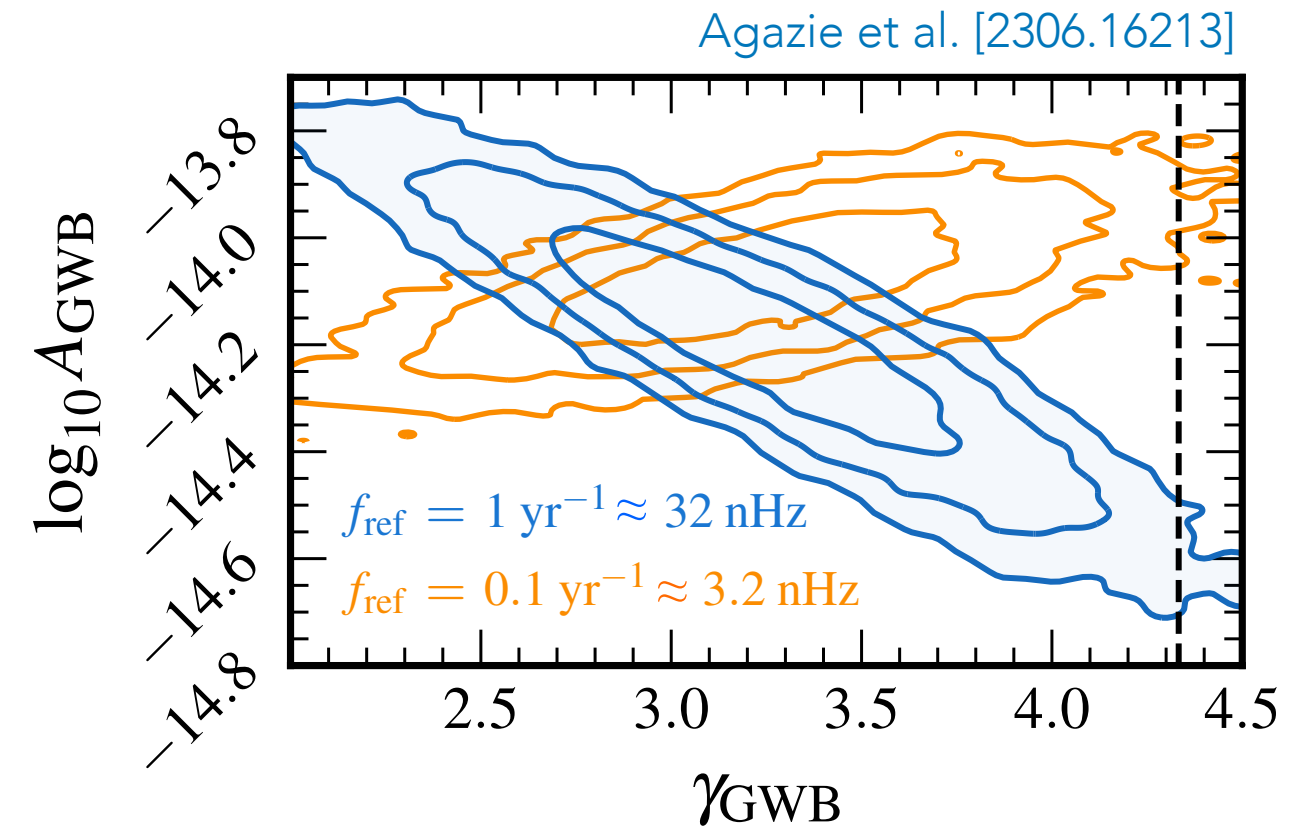
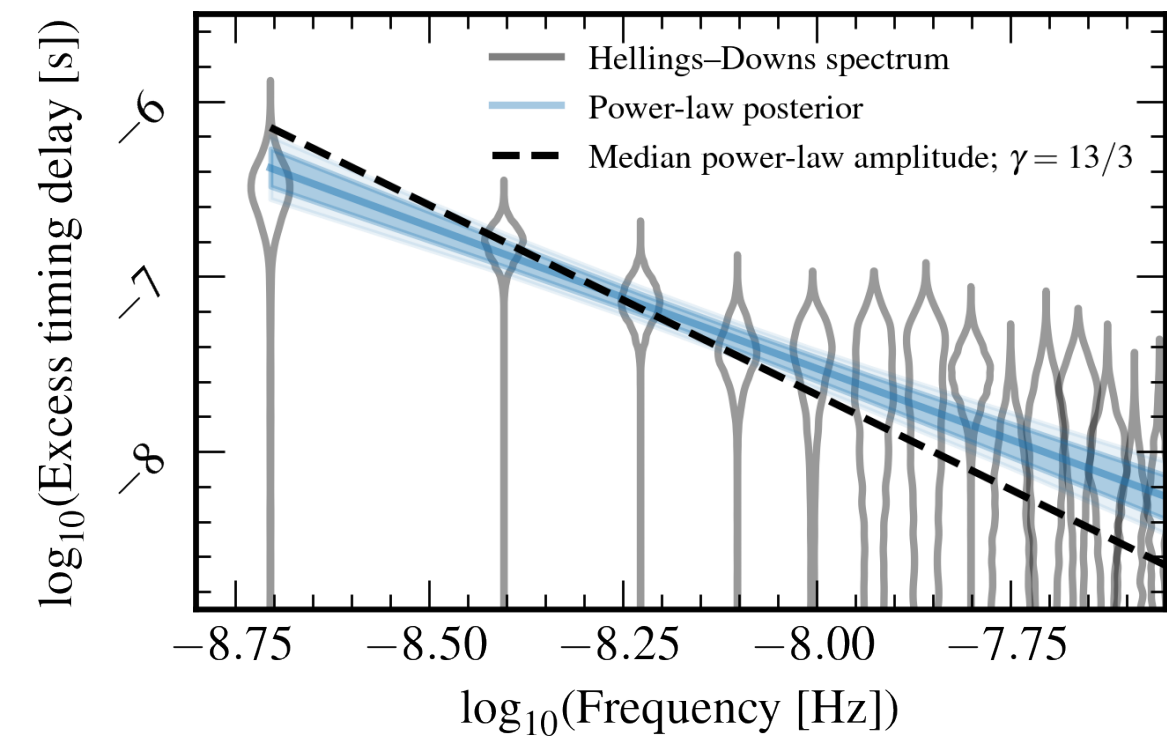
CPTA:

57 pulsars, 3yr of data
 ~4.6 σ significance

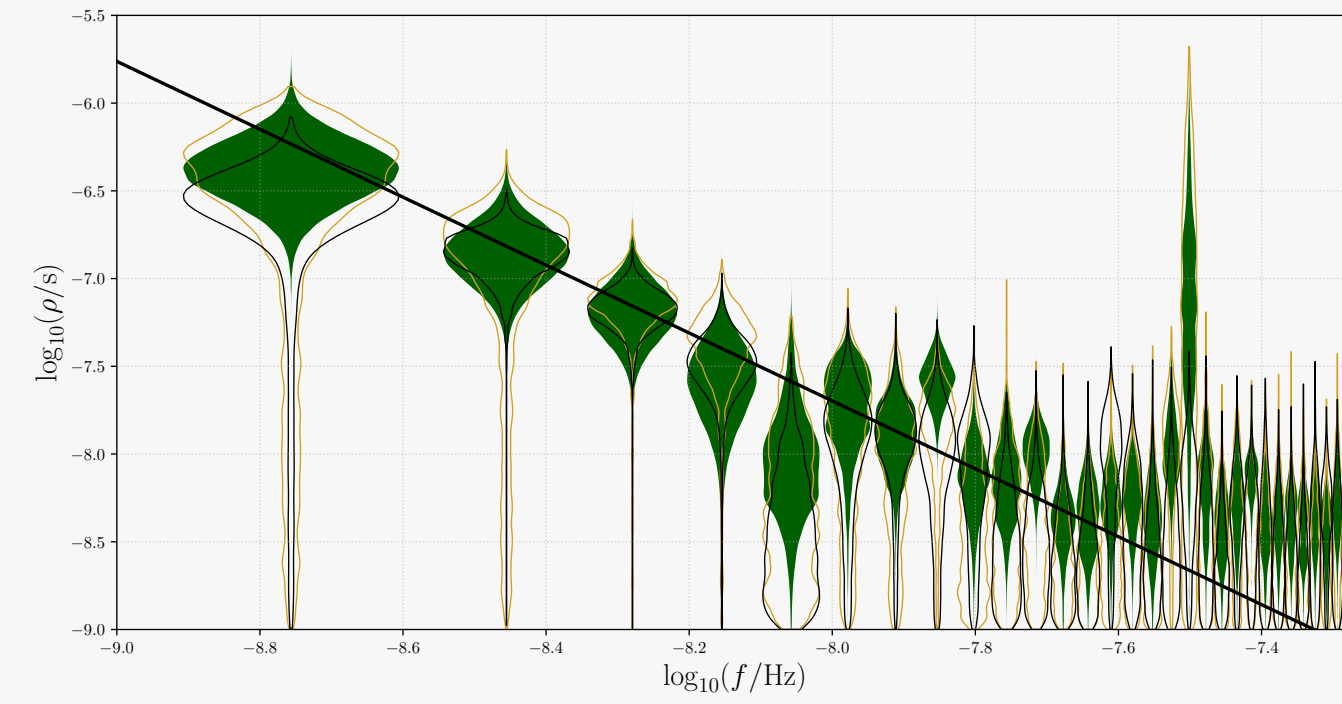


SPECTRUM

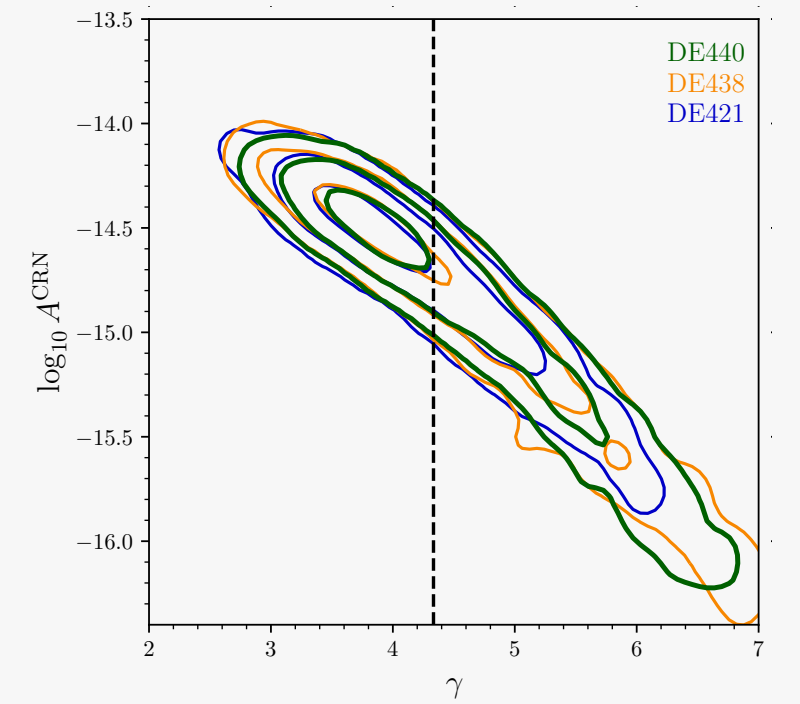
NANOGrav



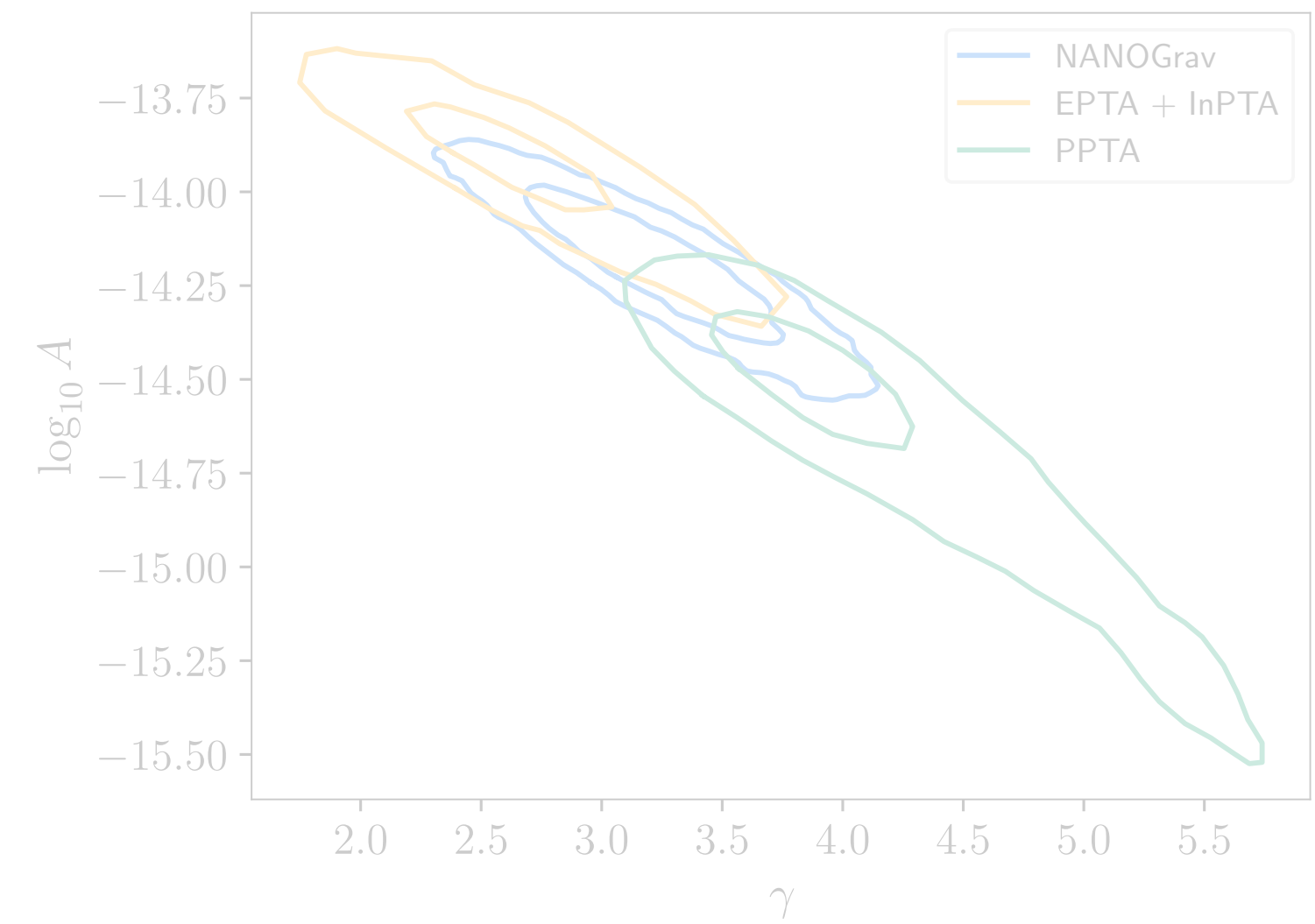
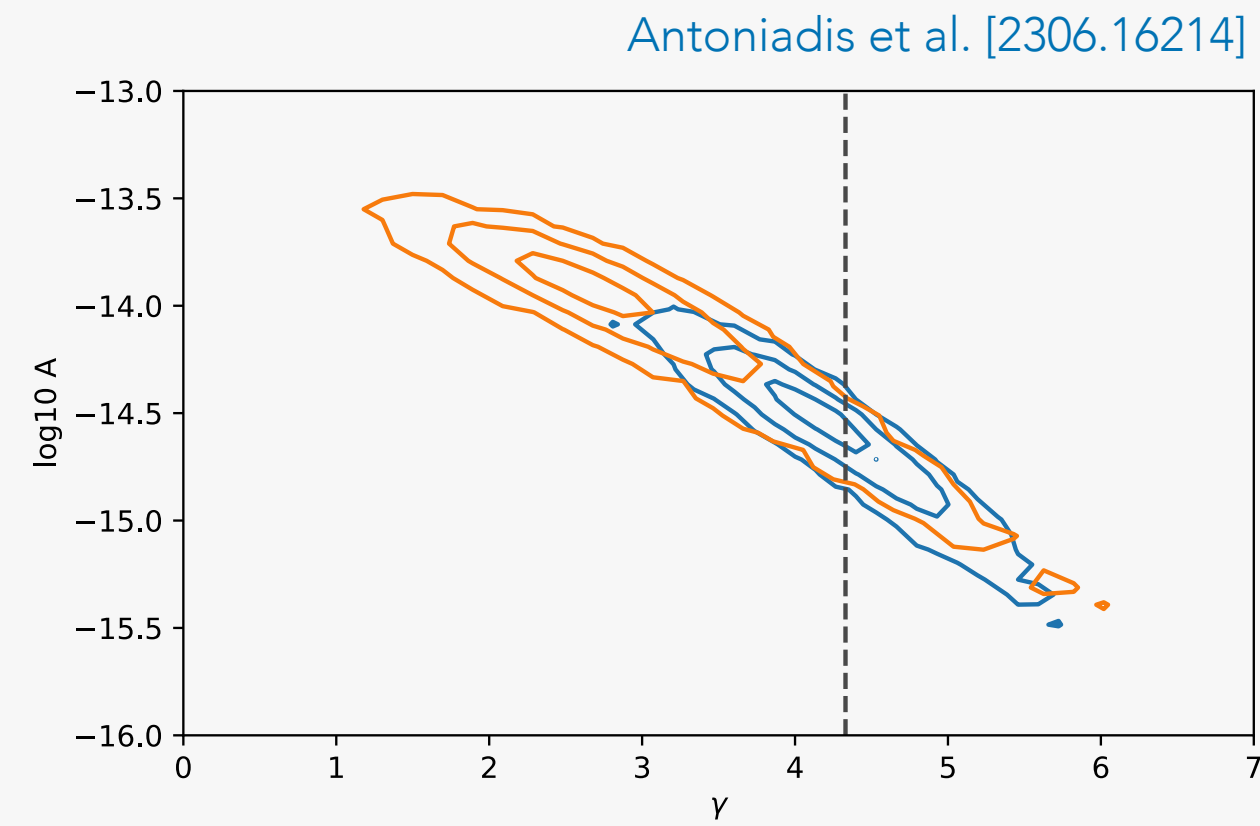
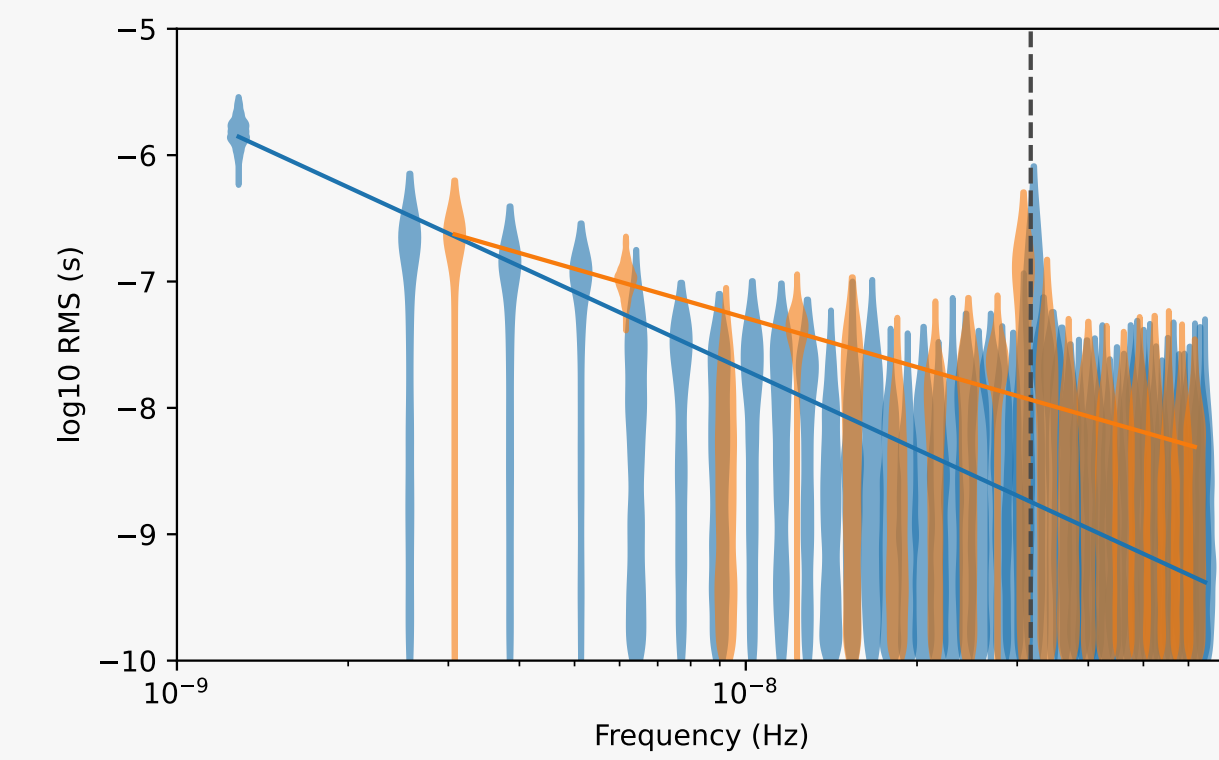
PPTA



Reardon et al. [2306.16215]

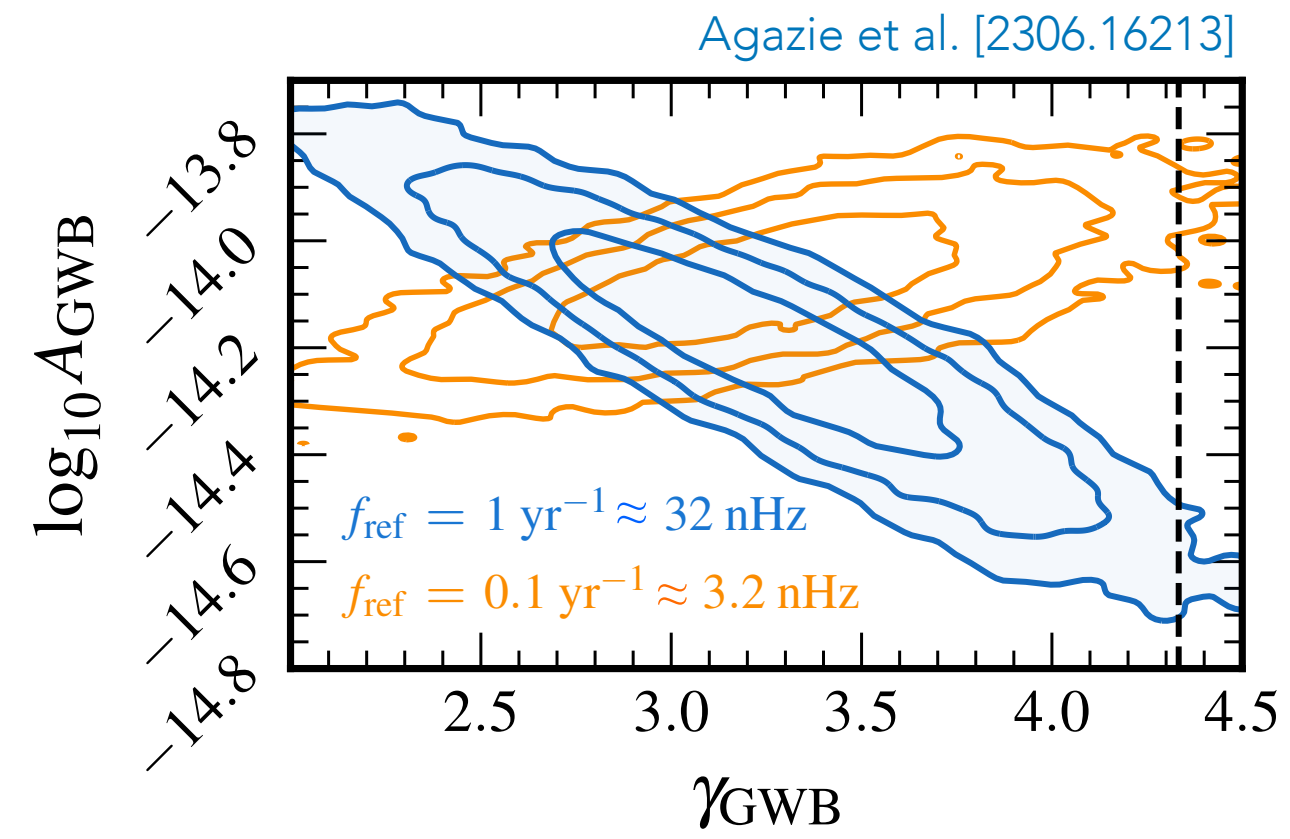
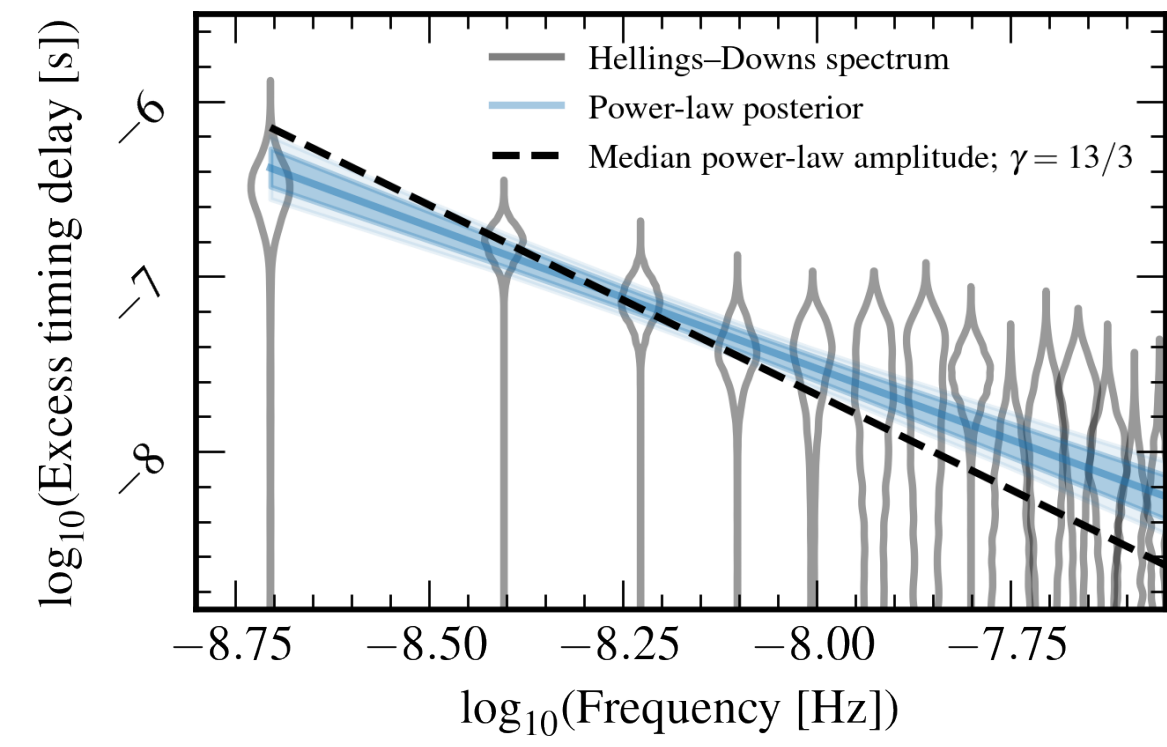


EPTA + InPTA

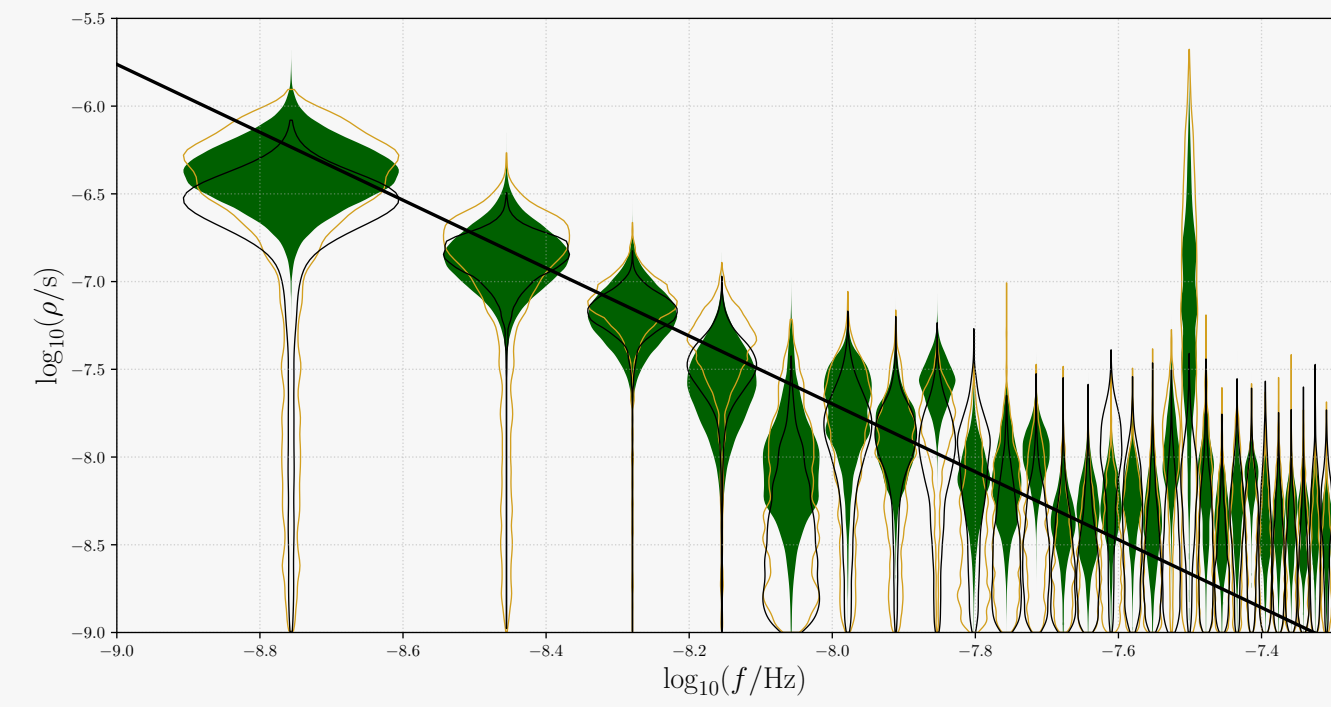


SPECTRUM

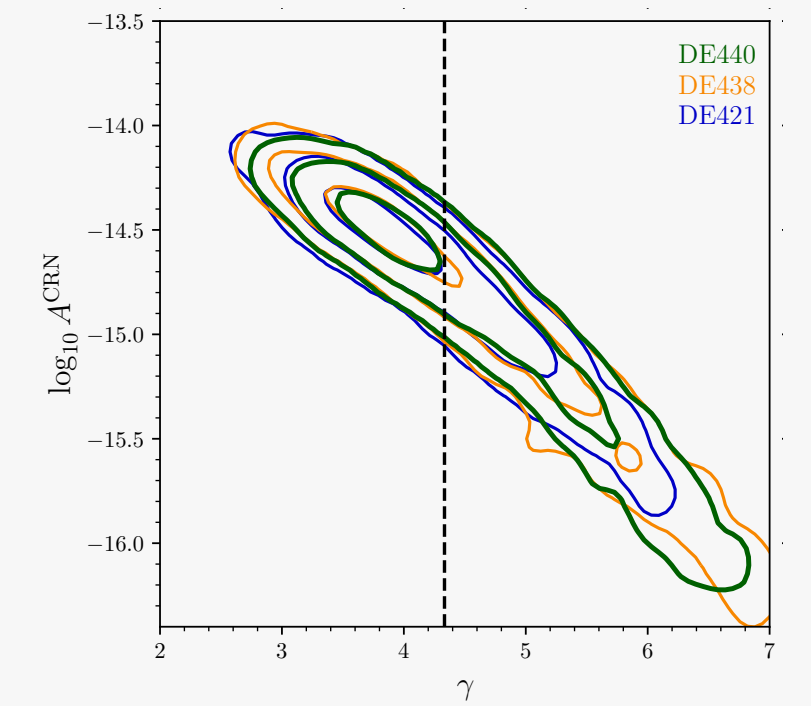
NANOGrav



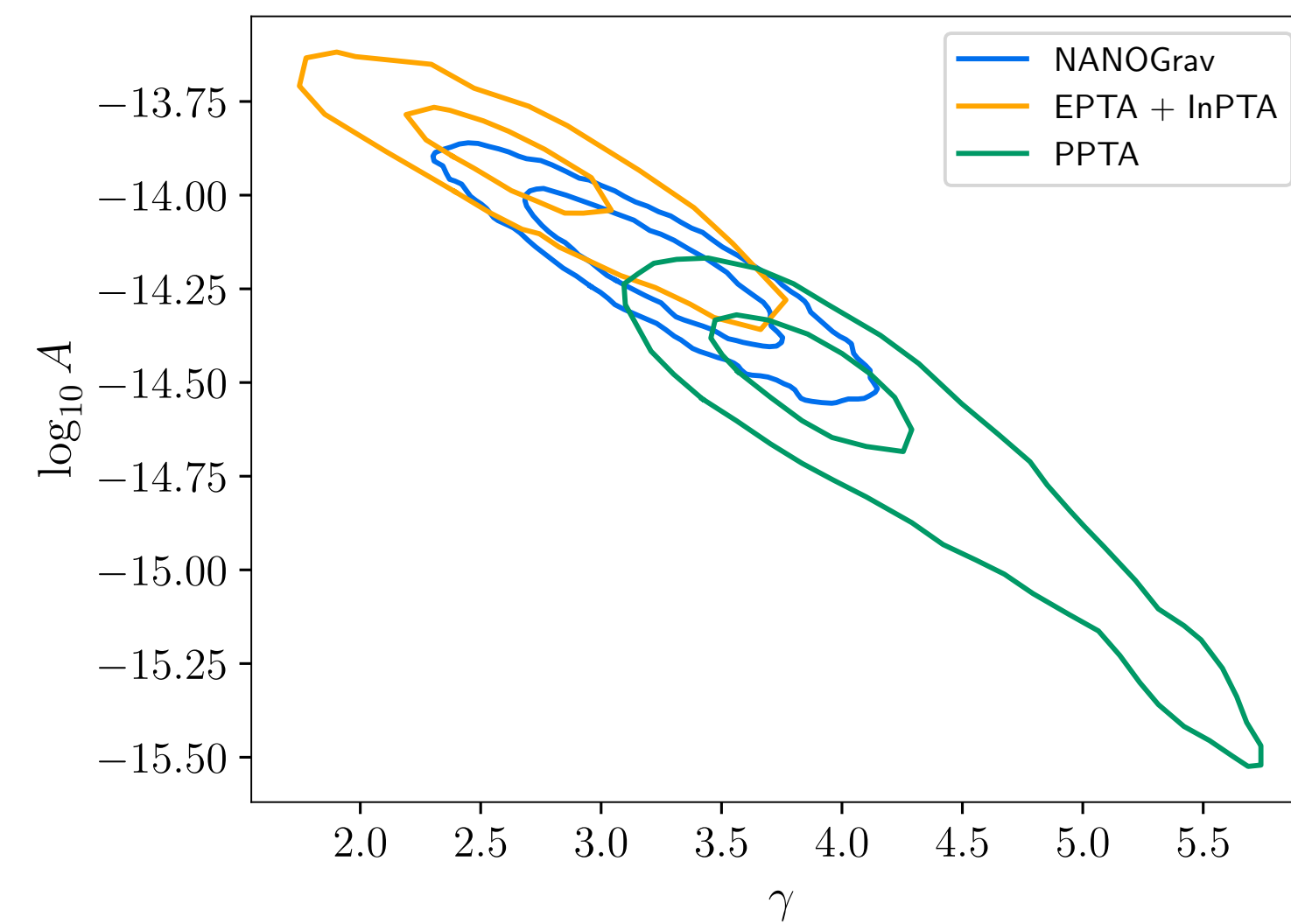
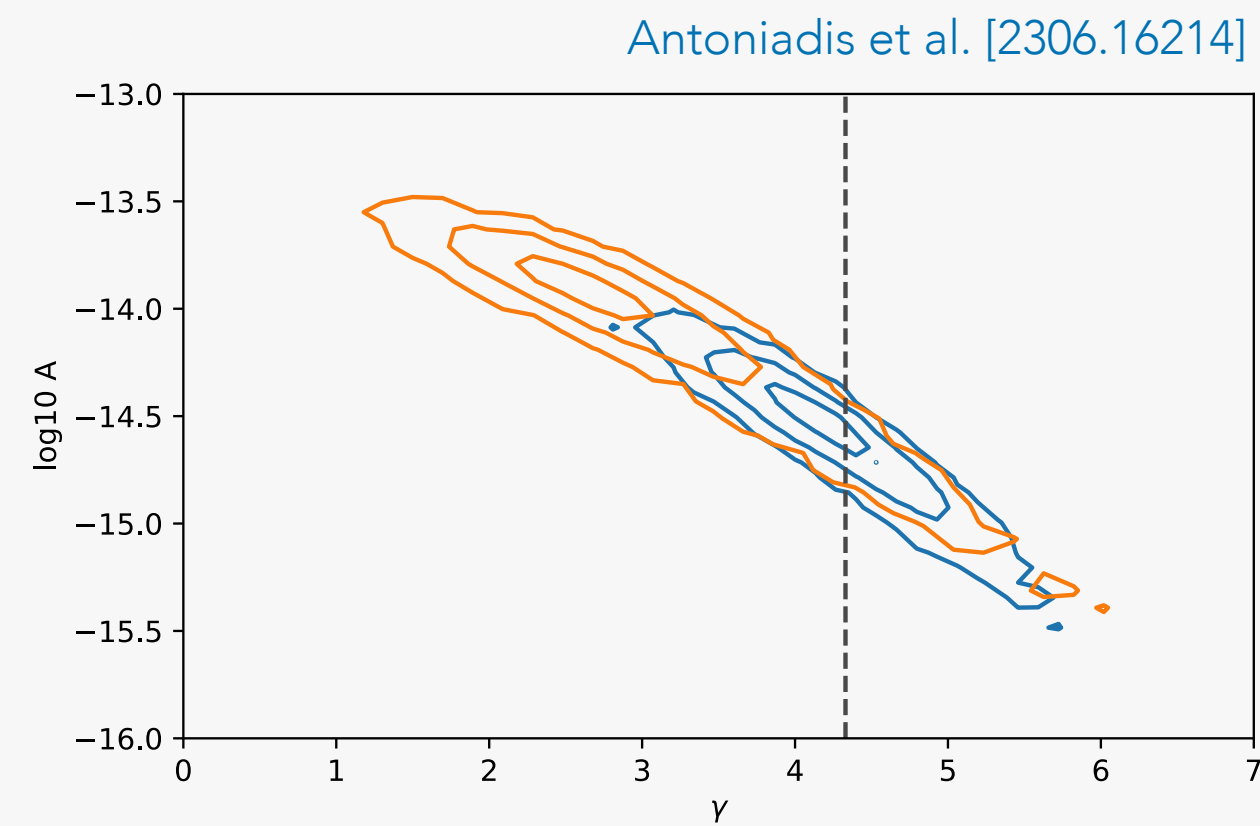
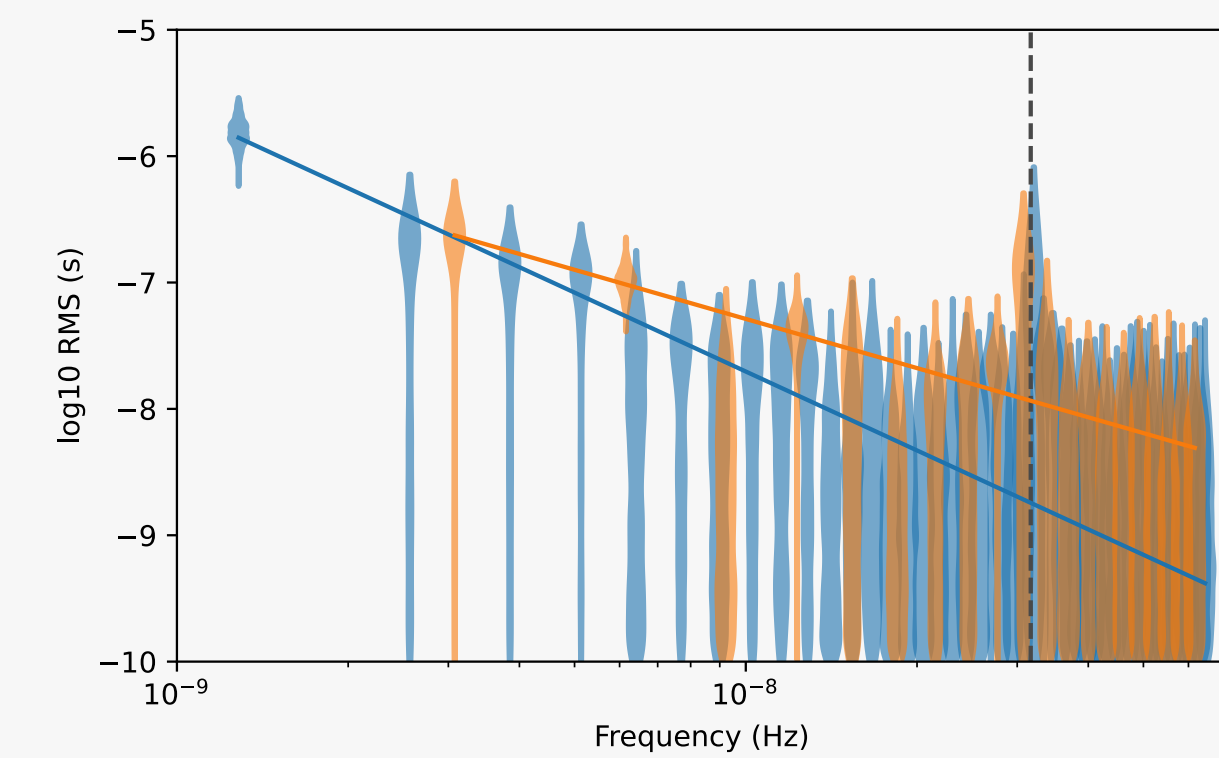
PPTA



Reardon et al. [2306.16215]



EPTA + InPTA



ANISOTROPIES

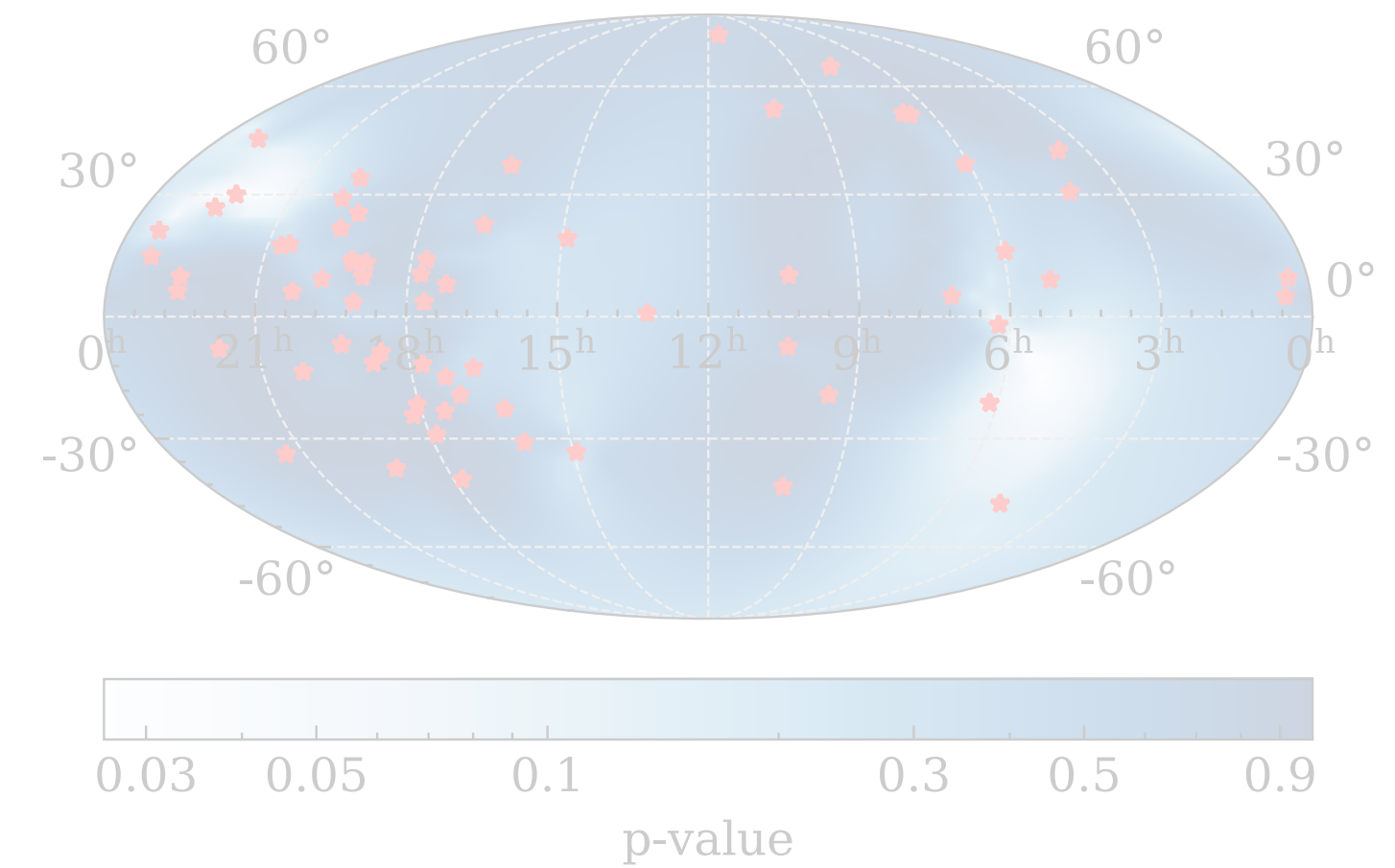
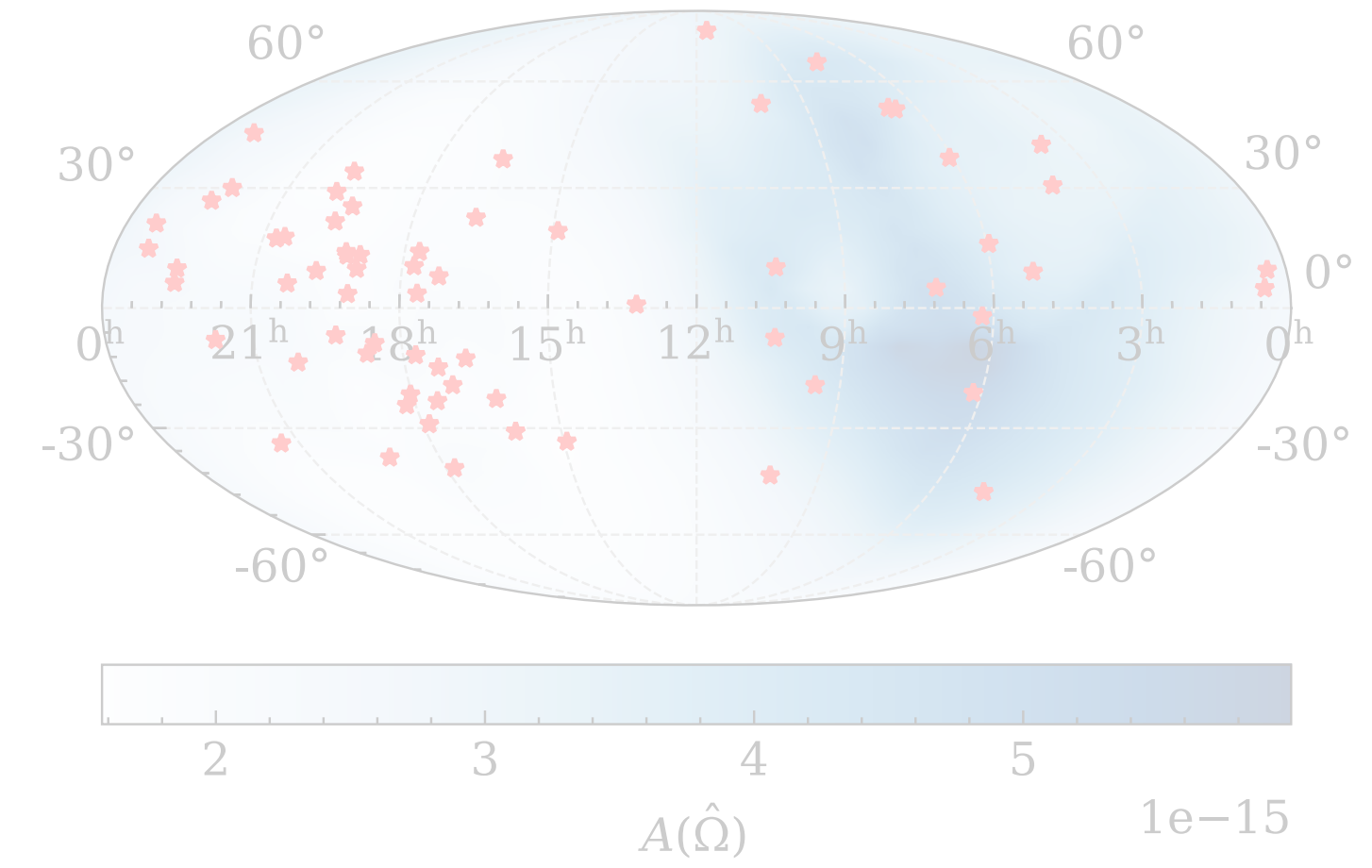
$$\Gamma_{ab} \propto \sum_k R_{ab,k} \cdot P_k$$

\uparrow
 overlap reduction function

\uparrow
 PTA response function

\uparrow
 GWB power

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

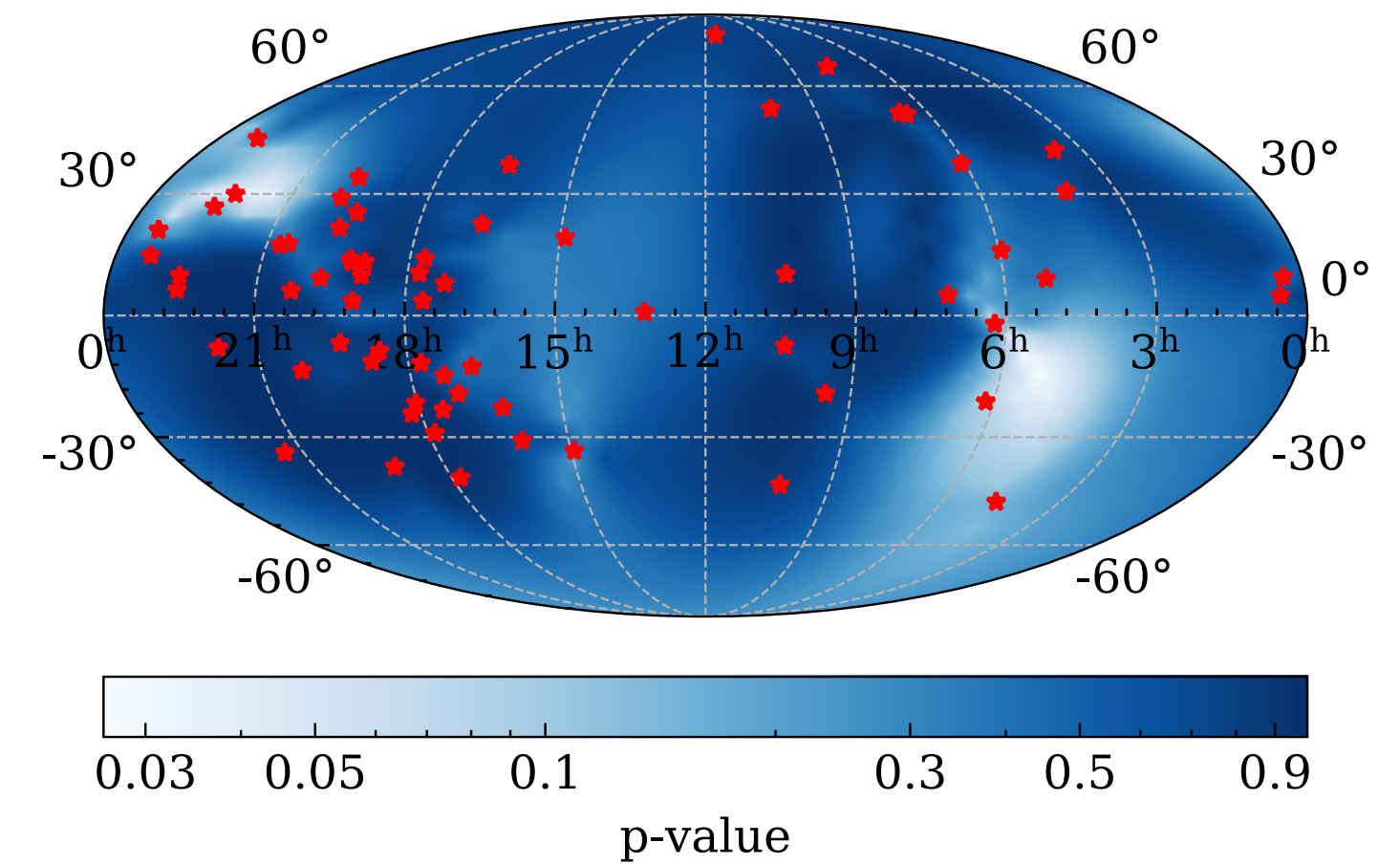
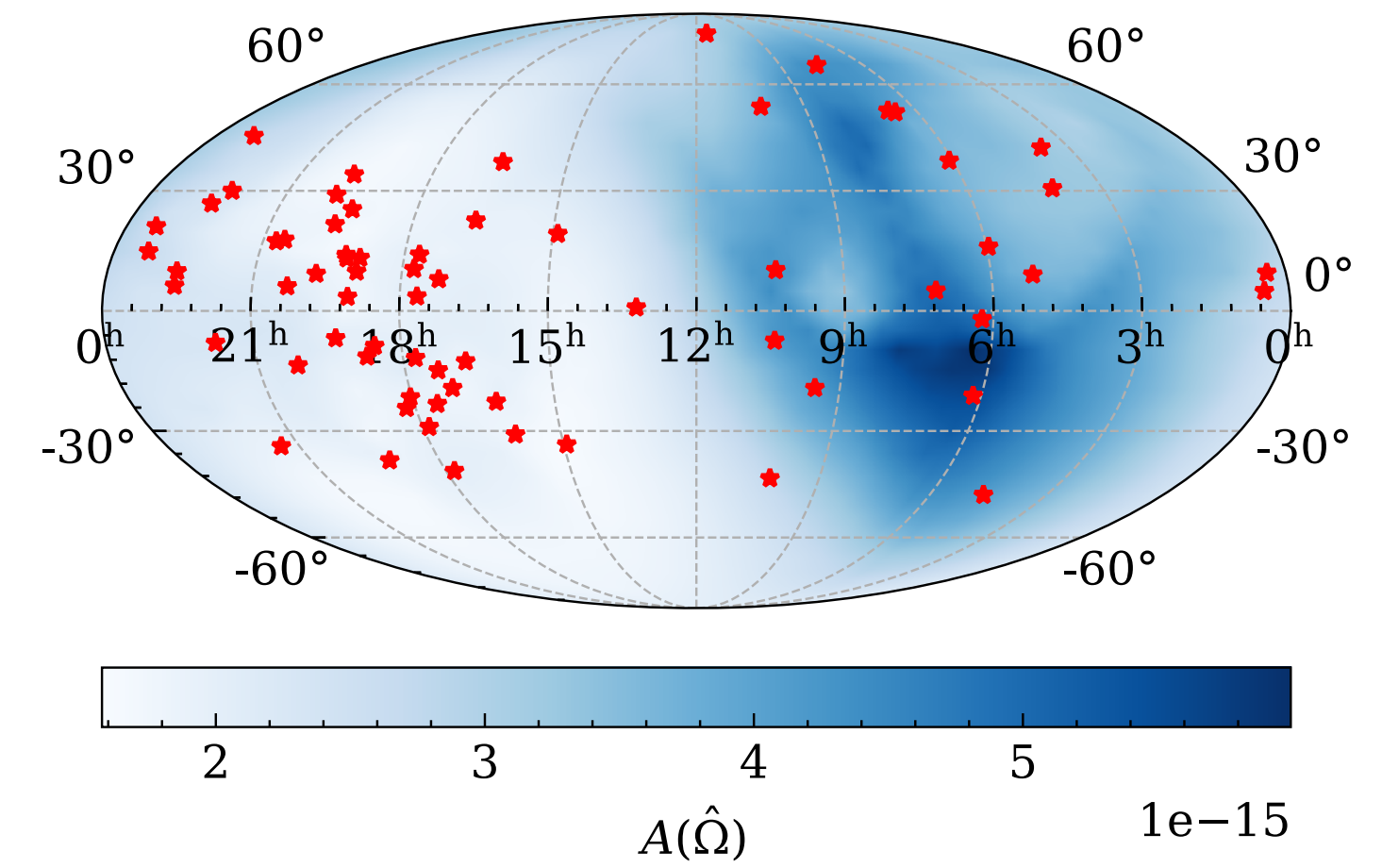


ANISOTROPIES

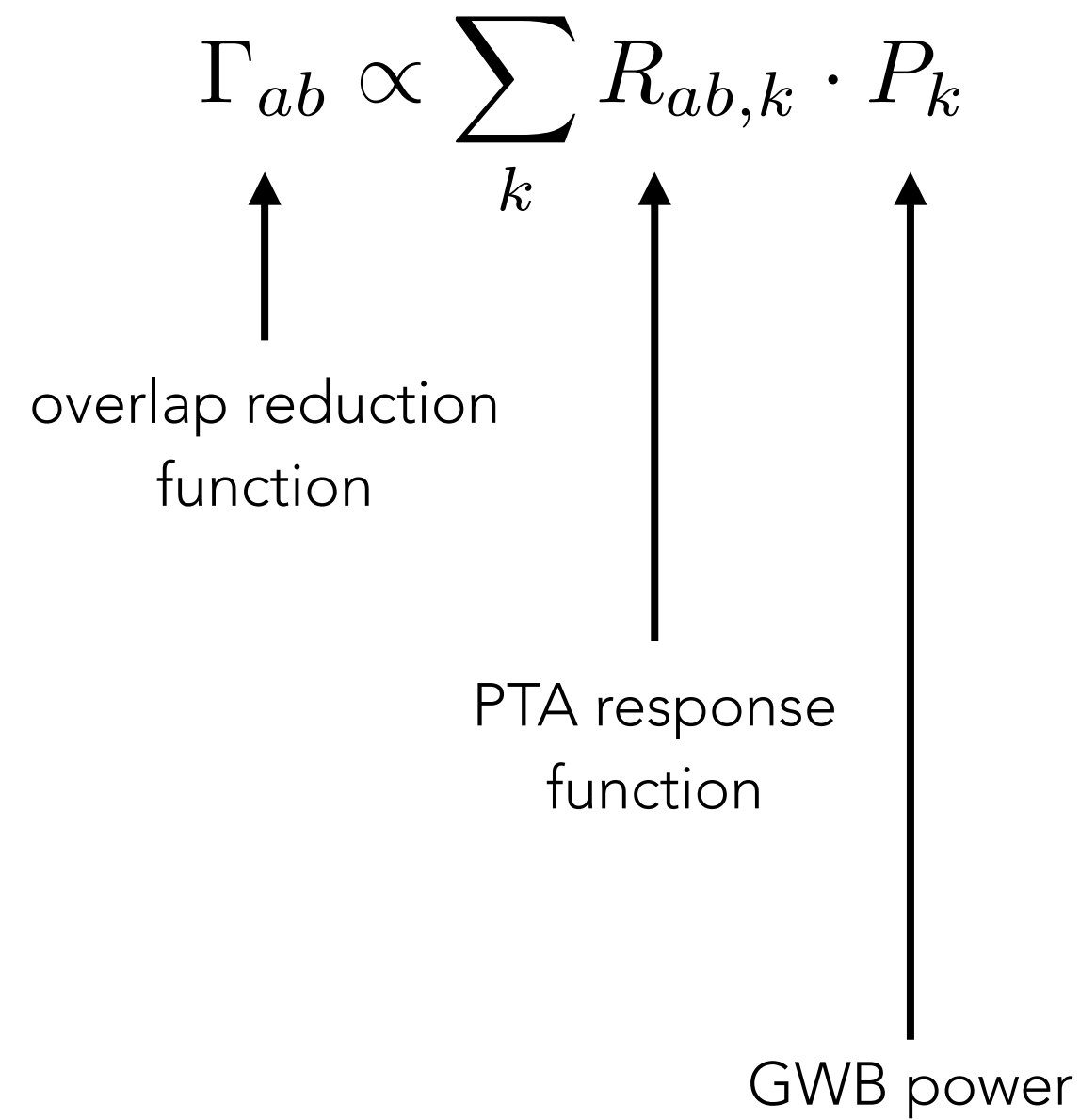
$$\Gamma_{ab} \propto \sum_k R_{ab,k} \cdot P_k$$

\uparrow overlap reduction function
 \uparrow PTA response function
 \uparrow GWB power

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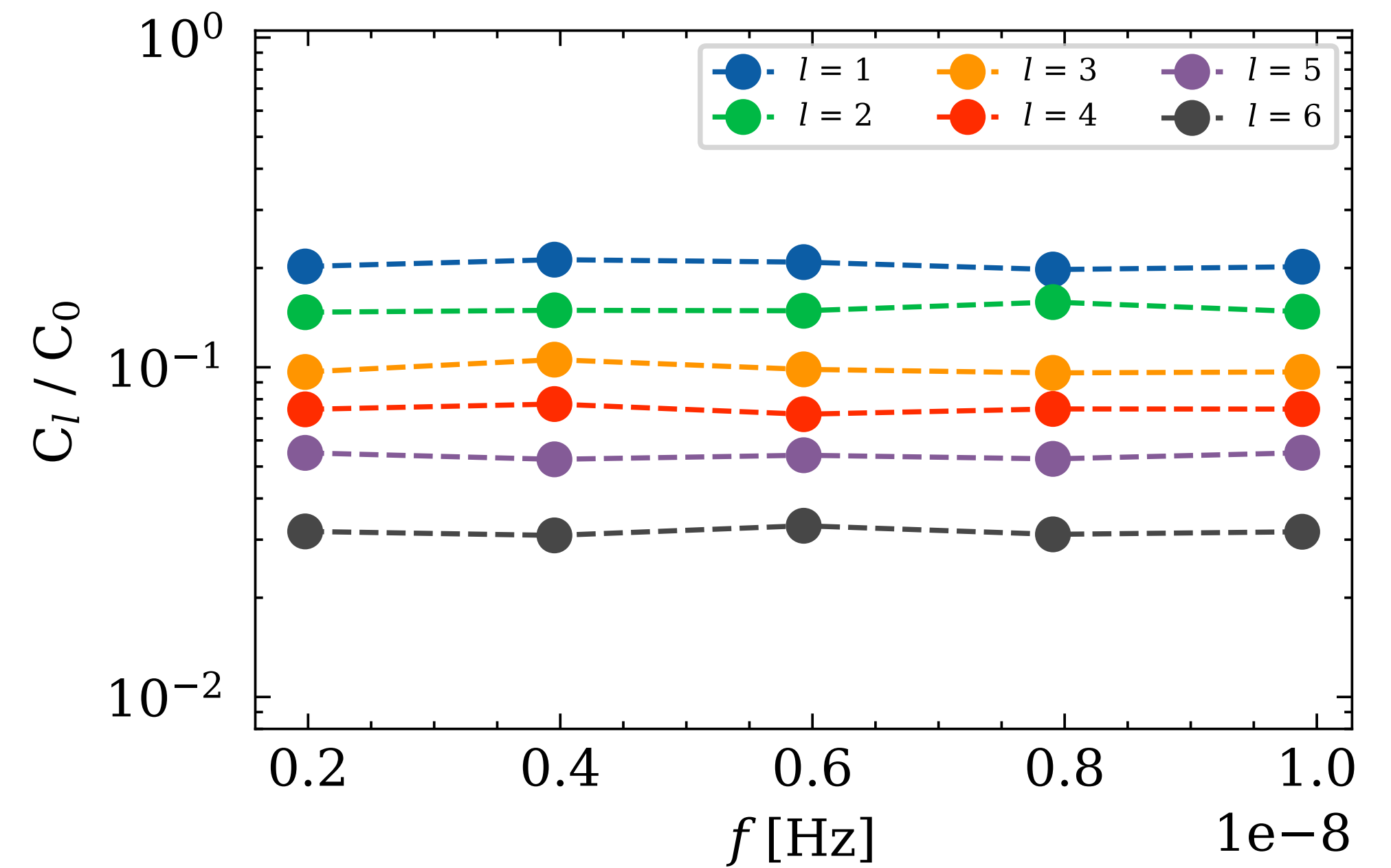


ANISOTROPIES



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

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

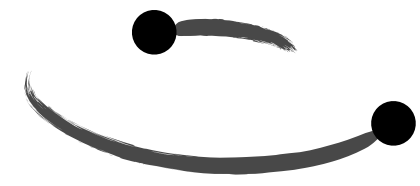


what is the source?

CONTENDER #1

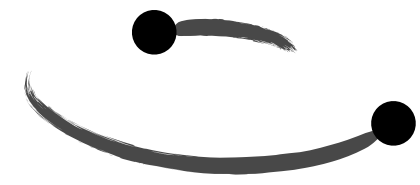


CONTENDER #1



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

Phinney 2001, Wyithe & Loeb 2003



GW signal from individual SMBHB

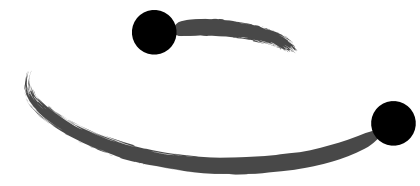
$$h_c^2(f) = \int dM dq dz \frac{\partial^4 N}{\partial M \partial q \partial z \partial \ln f_p} h_s^2(f_p)$$

Phinney 2001, Wyithe & Loeb 2003

averaged strain for a circular
SMBHB

$$h_s^2(f) = \frac{32}{5} \frac{(GM)^{10/3}}{d_c^2} (2\pi f_p)^{4/3}$$

Finn & Thorne 2000



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

number density of SMBHB binaries

averaged strain for a circular
SMBHB

$$h_s^2(f) = \frac{32}{5} \frac{(GM)^{10/3}}{d_c^2} (2\pi f_p)^{4/3}$$

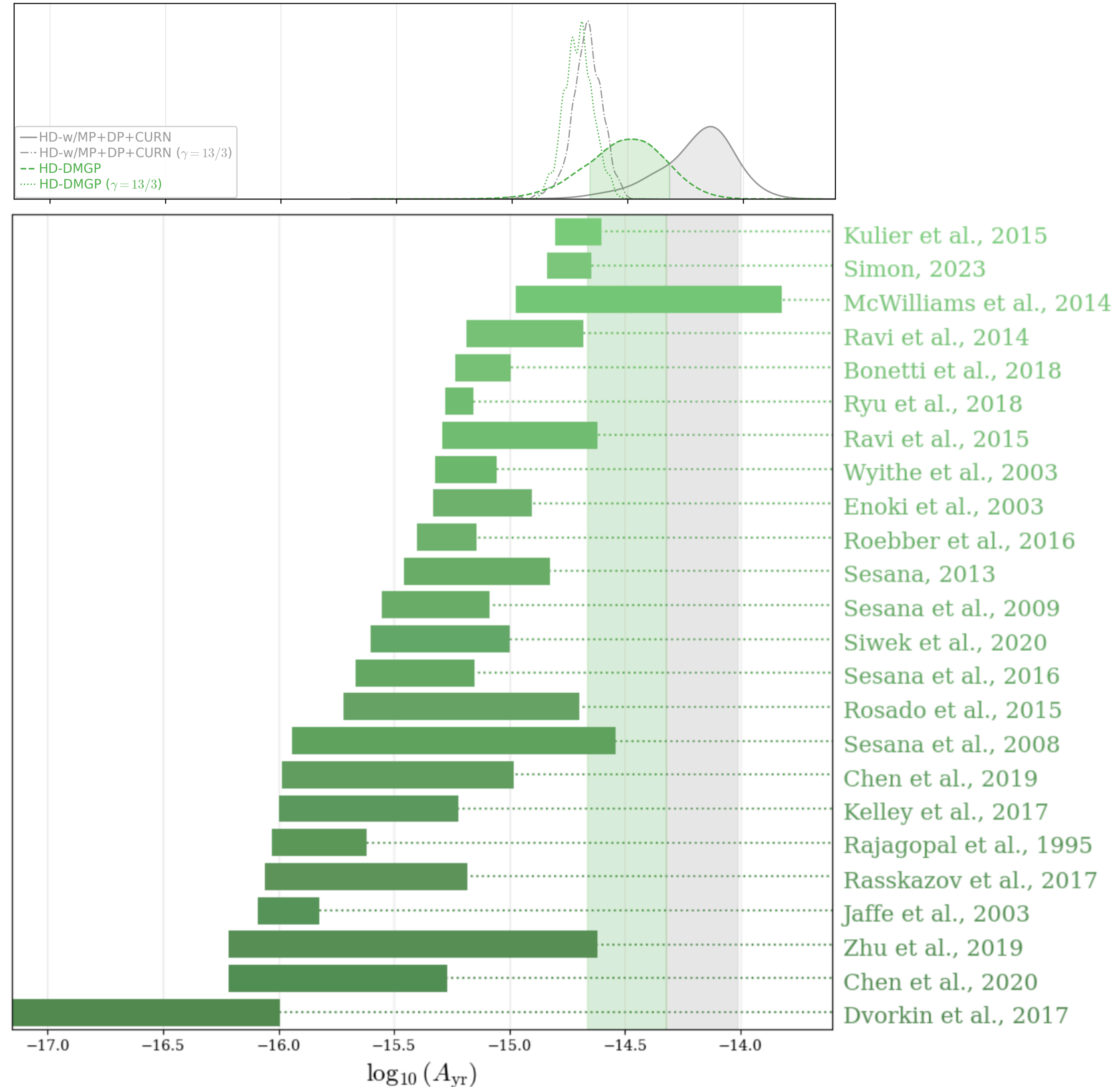
Finn & Thorne 2000

the SMBHB density depends on

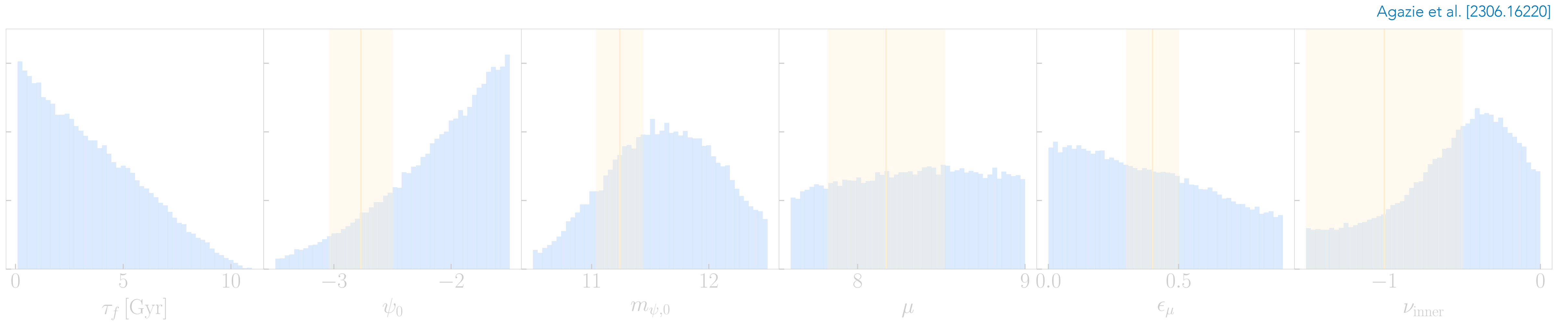
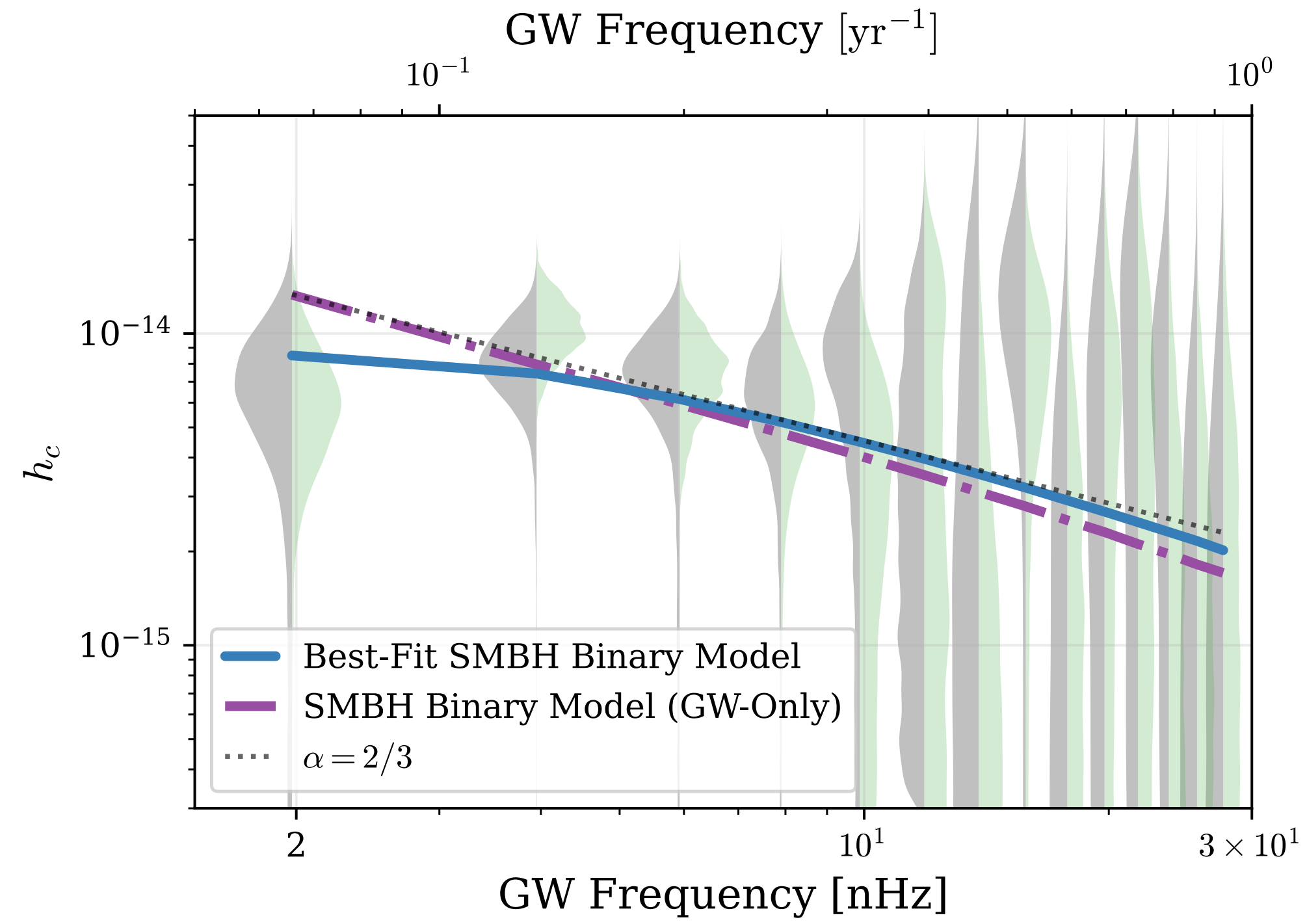
1. galaxies merger rate
2. SMBHB - galaxy mass relation
3. SMBHB binary evolution

EXPECTATIONS

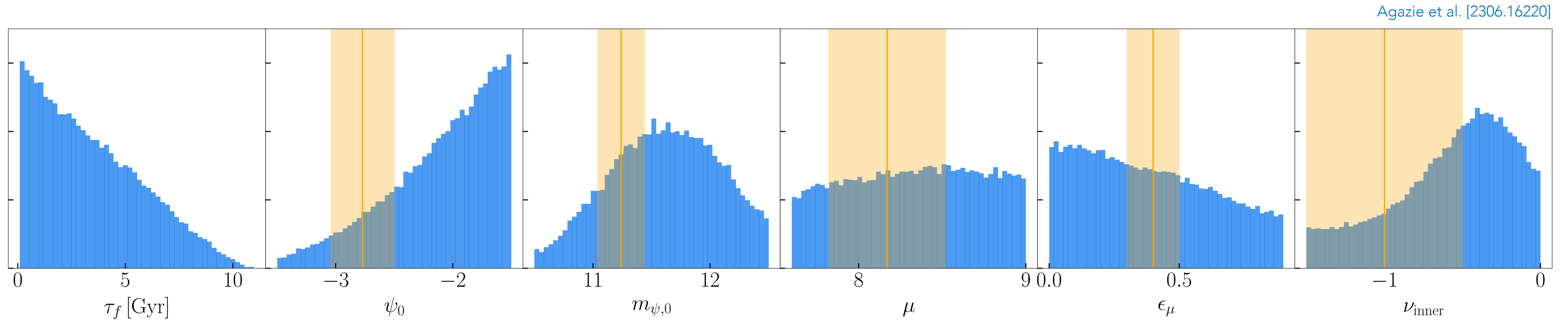
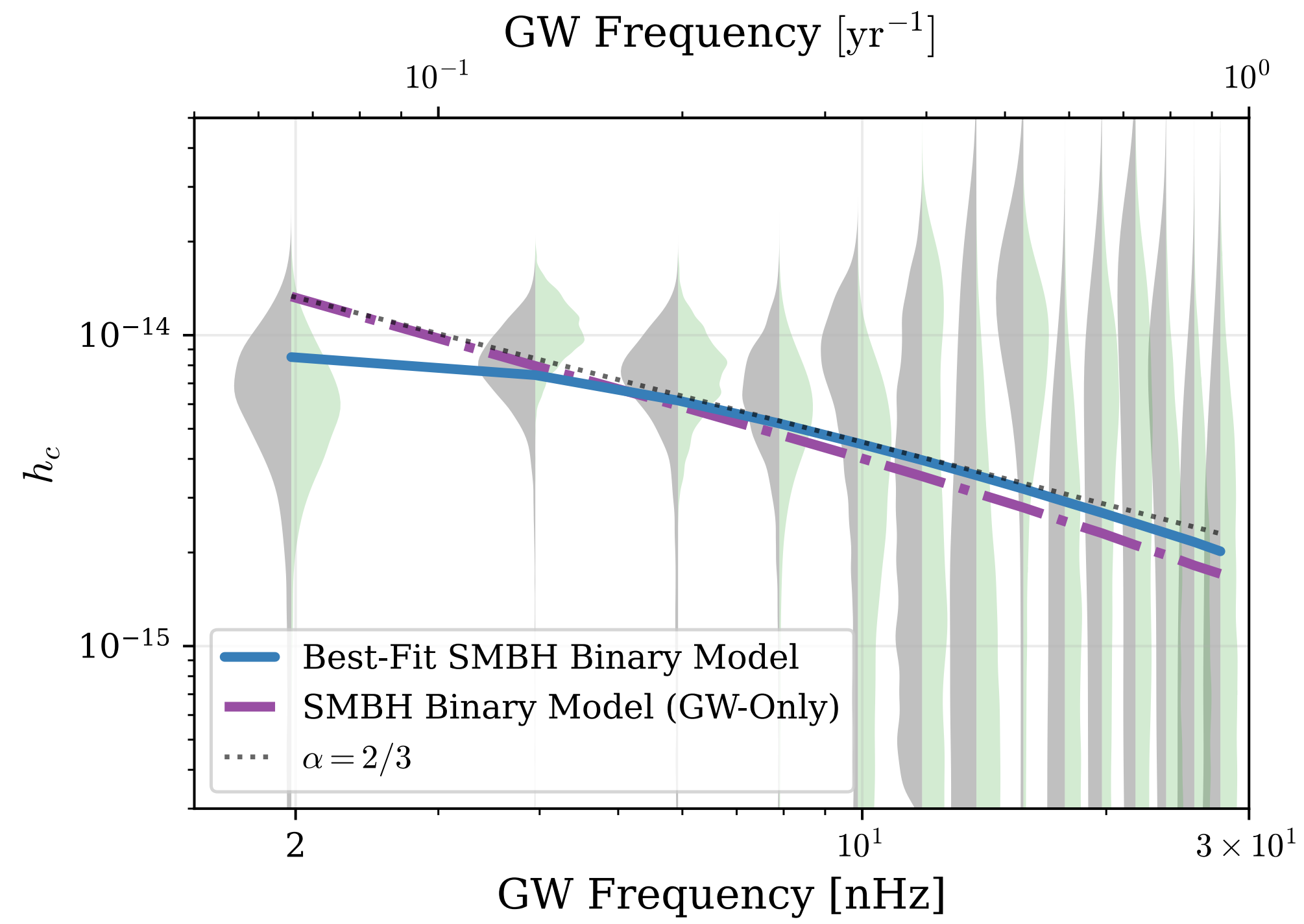
Agazie et al. [2306.16220]



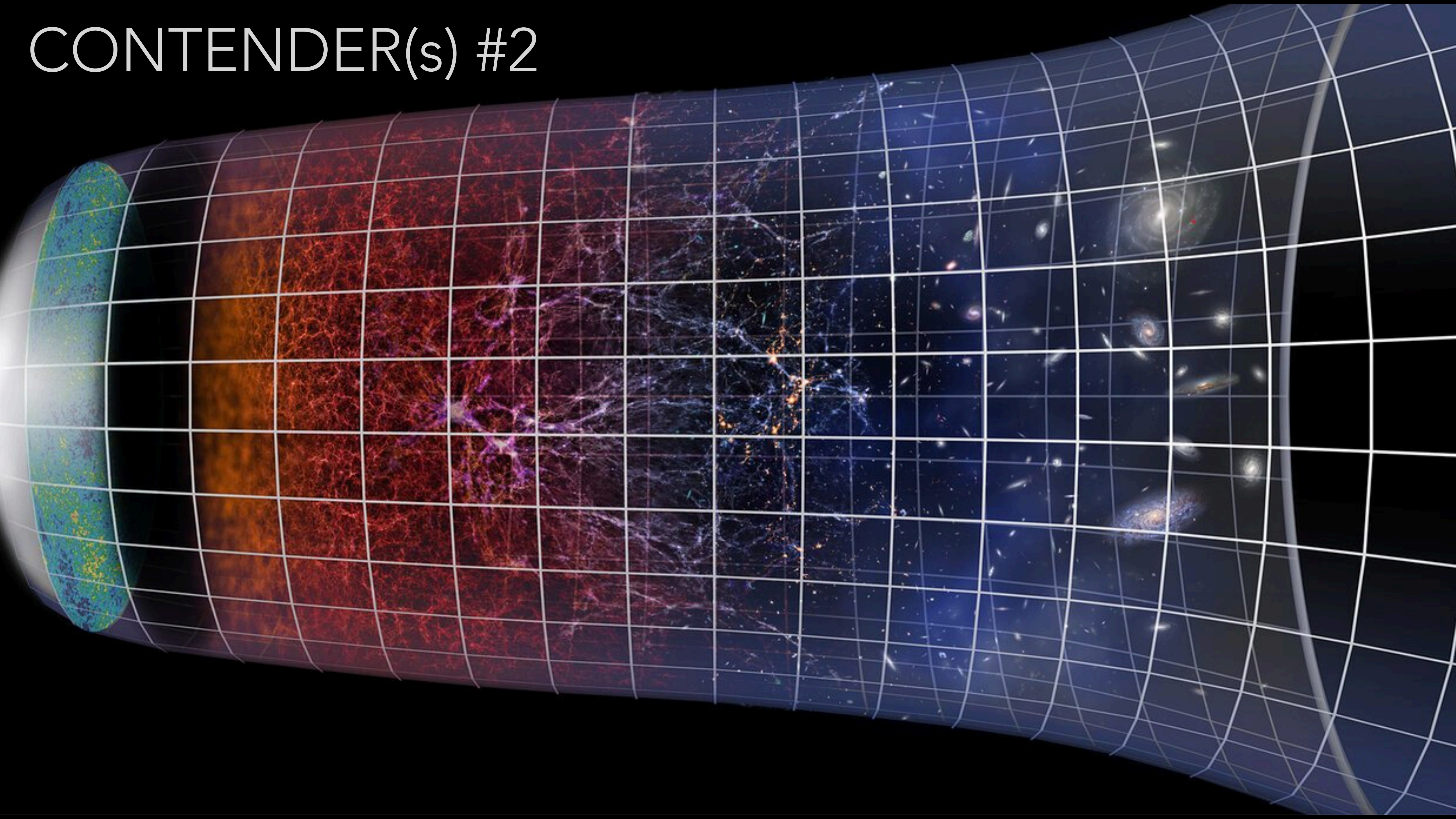
ADJUSTING EXPECTATIONS



ADJUSTING EXPECTATIONS

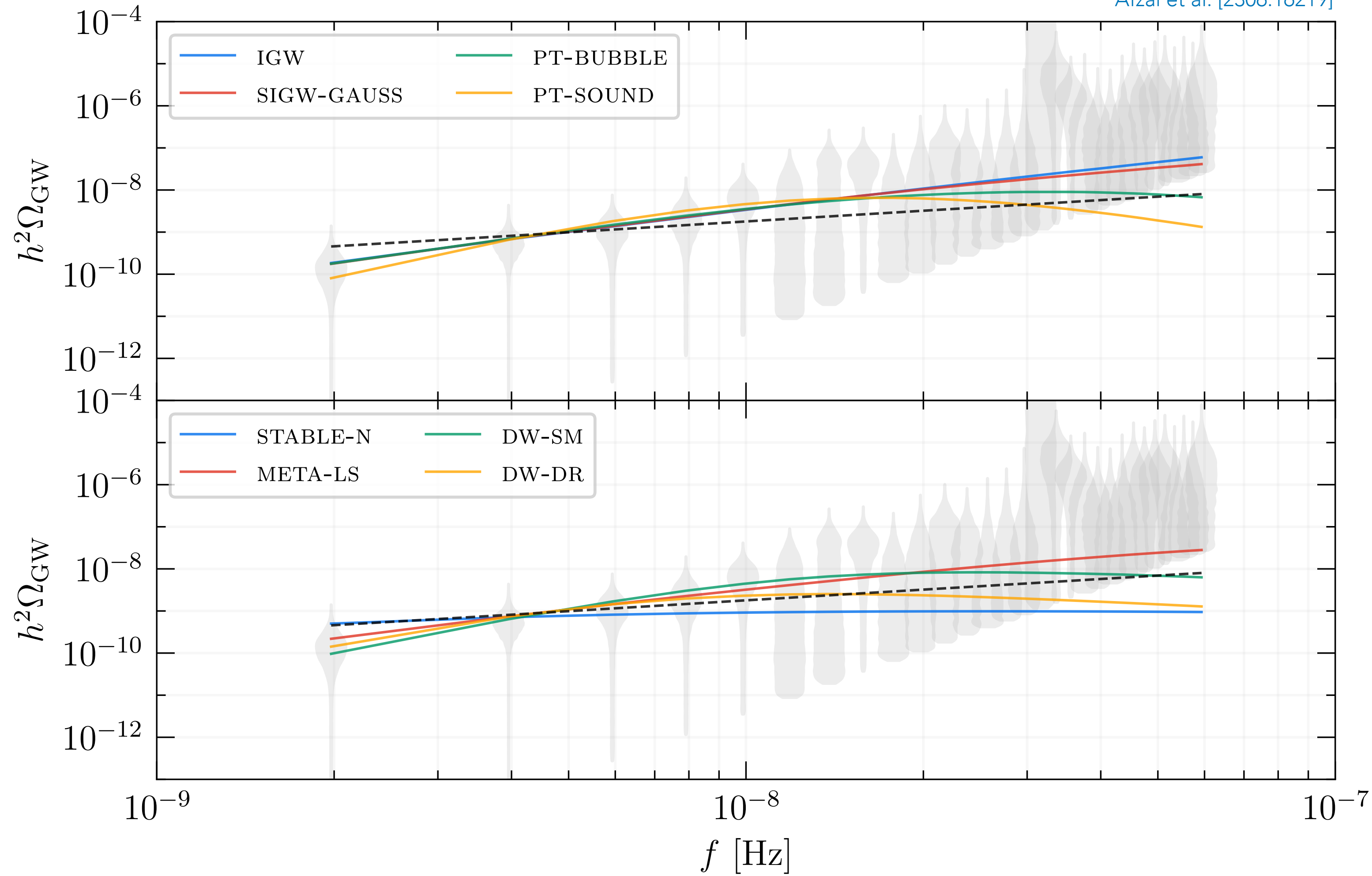


CONTENDER(s) #2



COSMOLOGICAL SIGNALS

Afzal et al. [2306.16219]



inflation

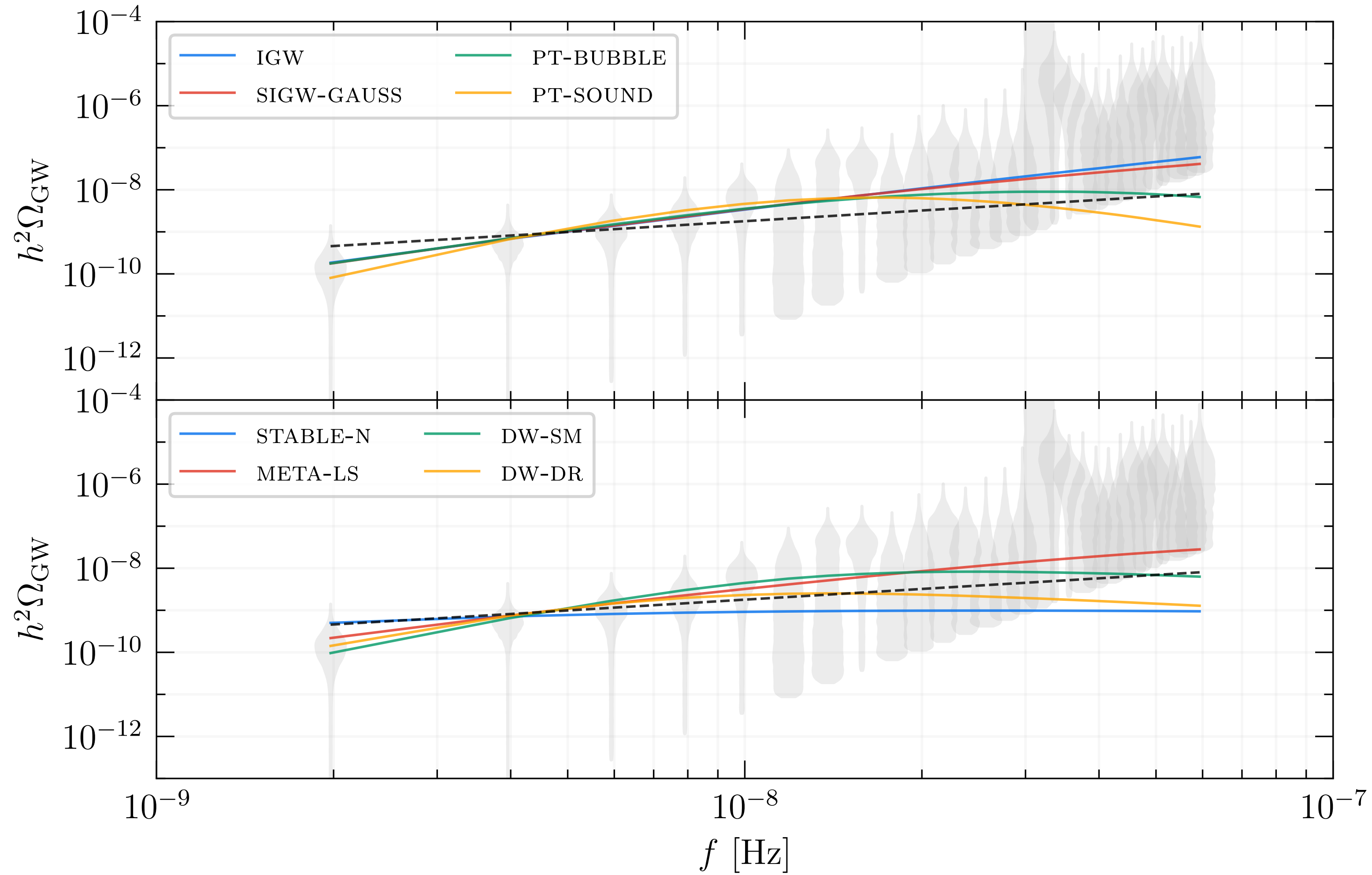
scalar induced GW

phase transitions

cosmic strings

domain walls

COSMOLOGICAL SIGNALS



inflation

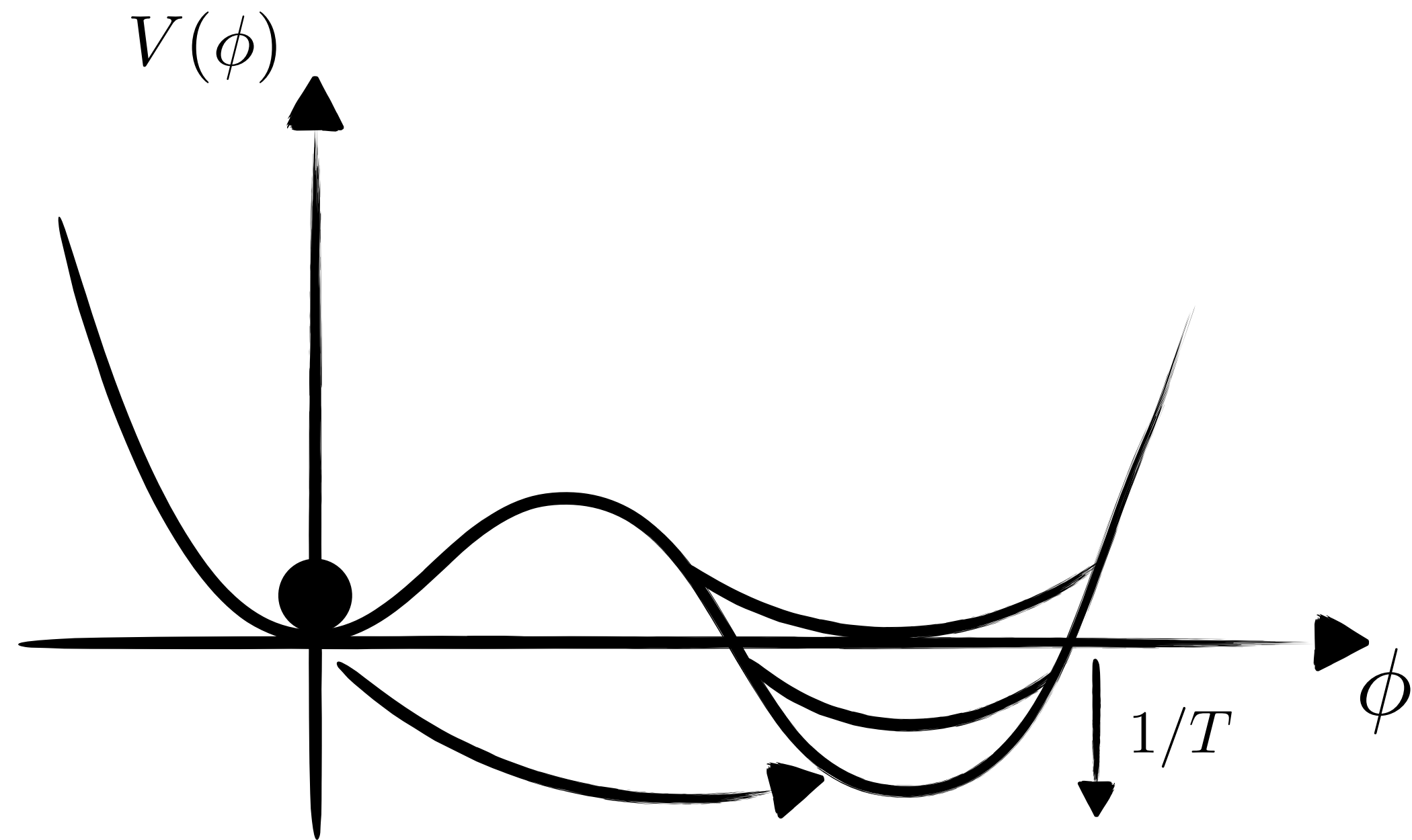
scalar induced GW

phase transitions

cosmic strings

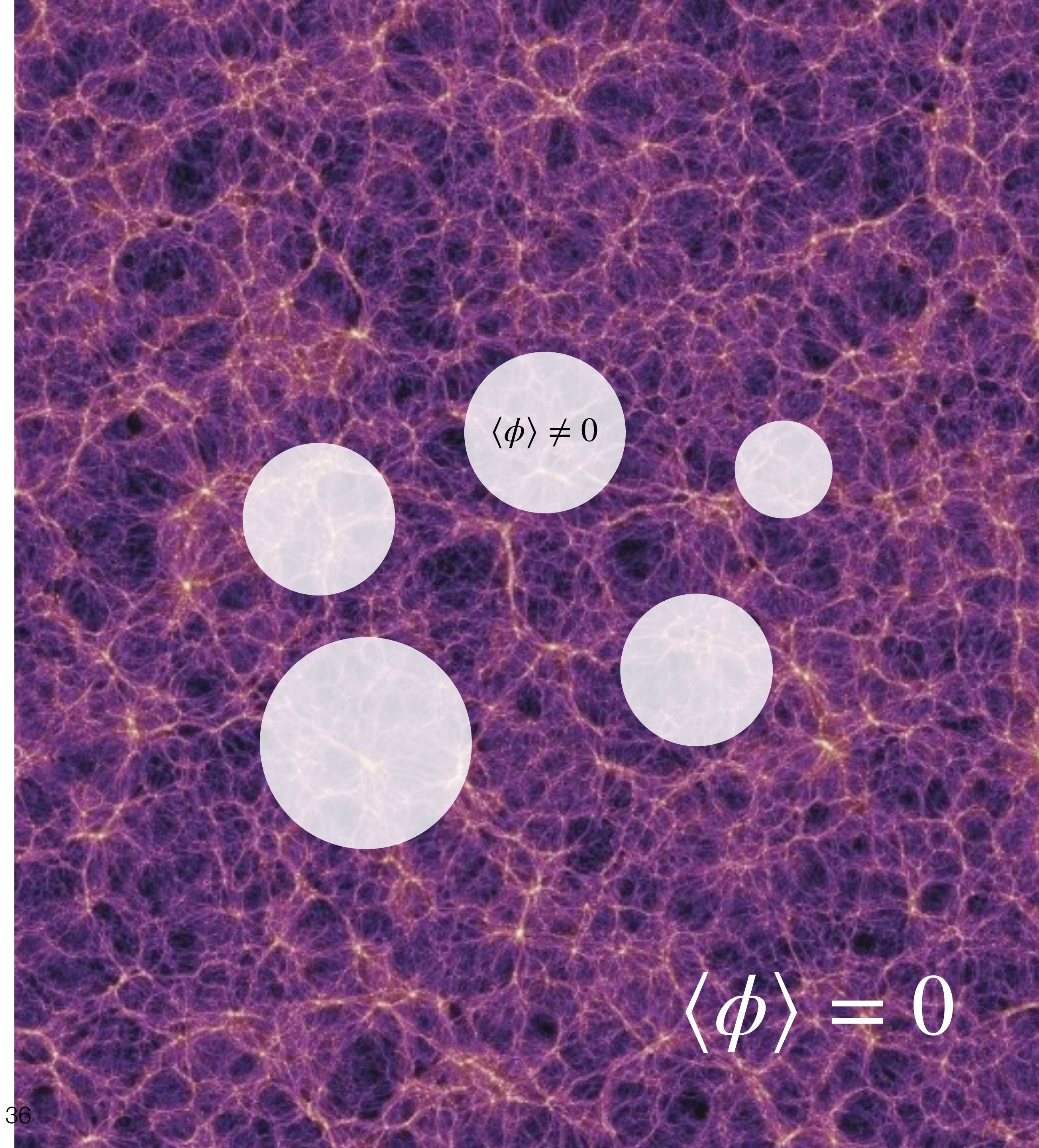
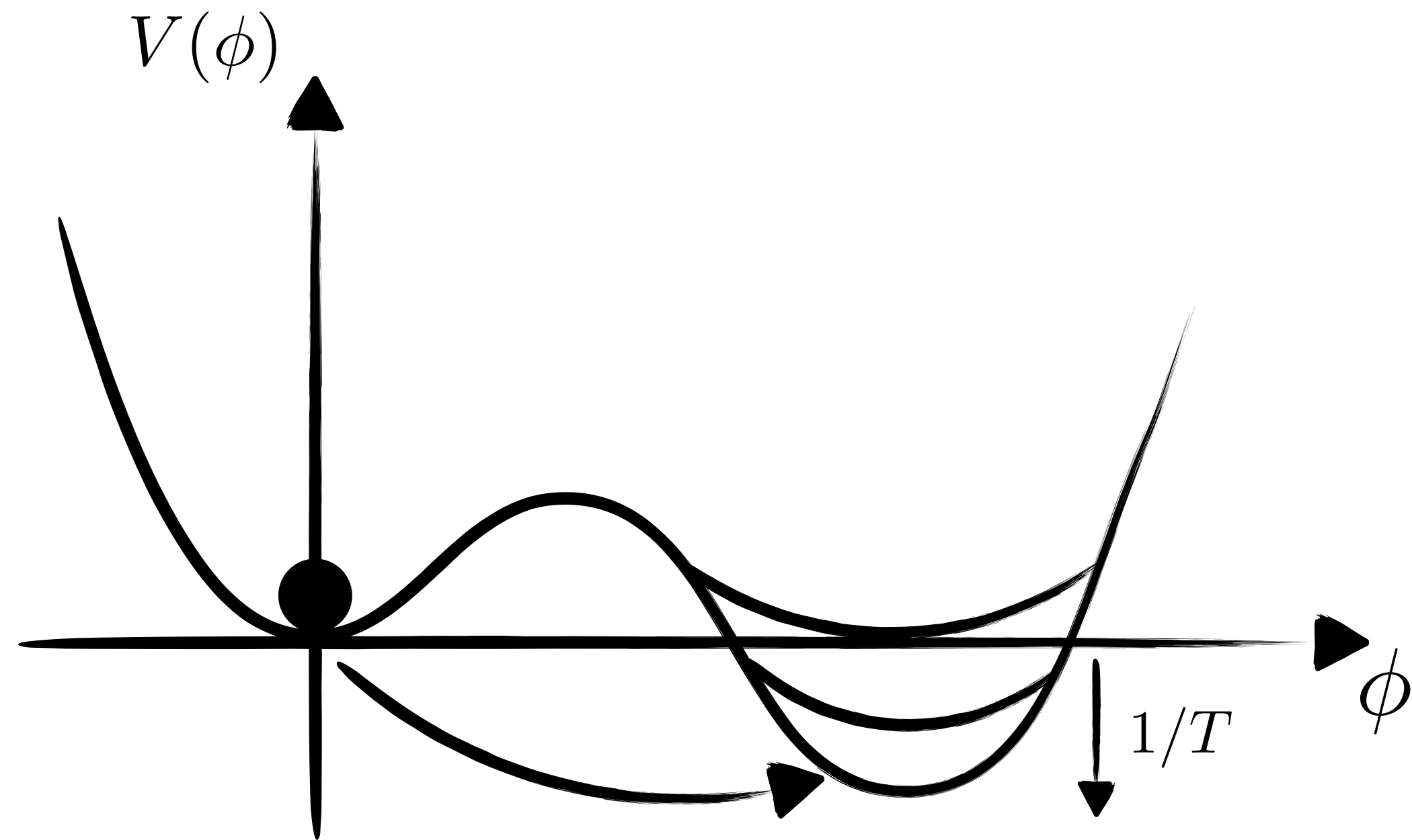
domain walls

PHASE TRANSITIONS

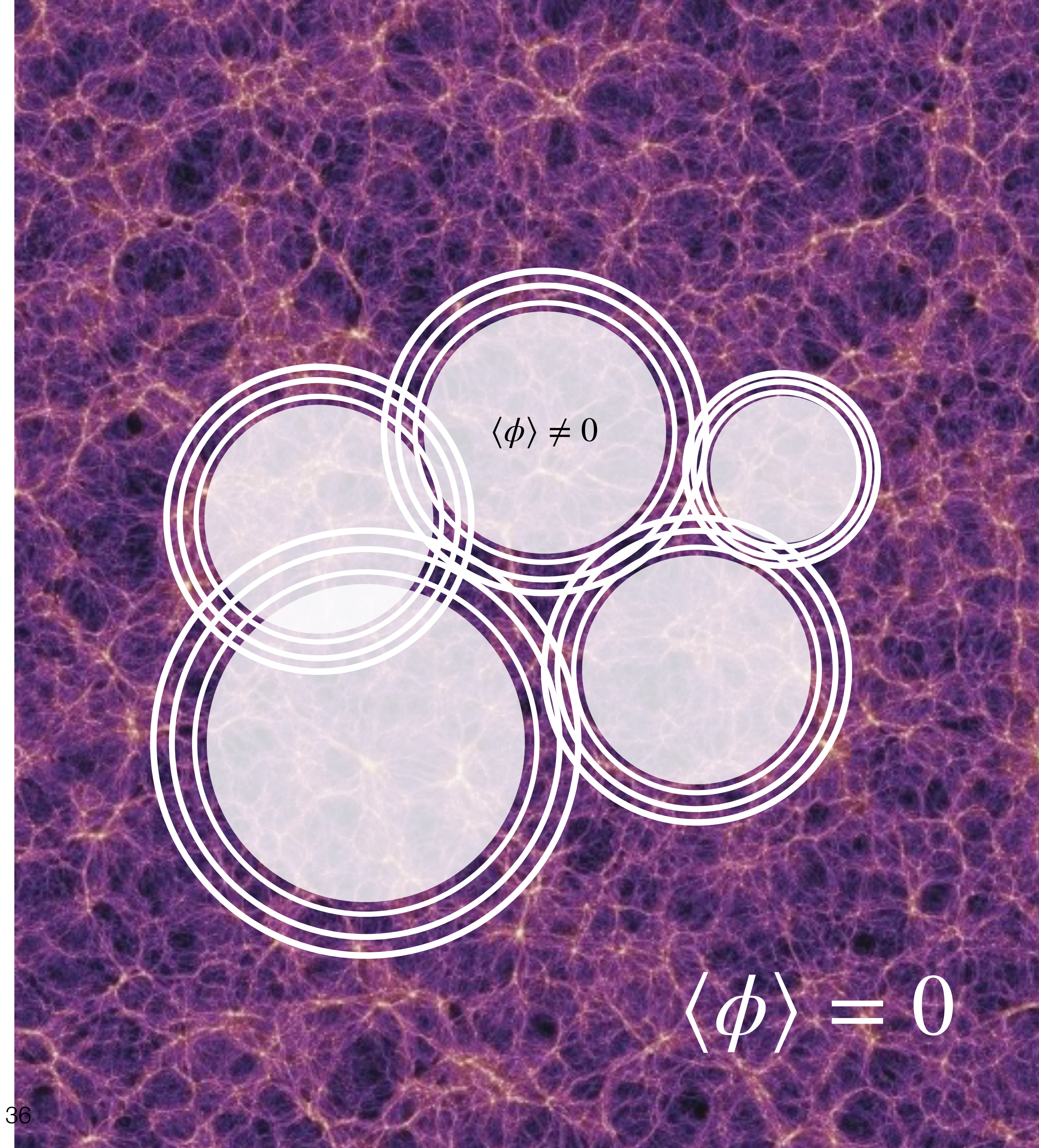
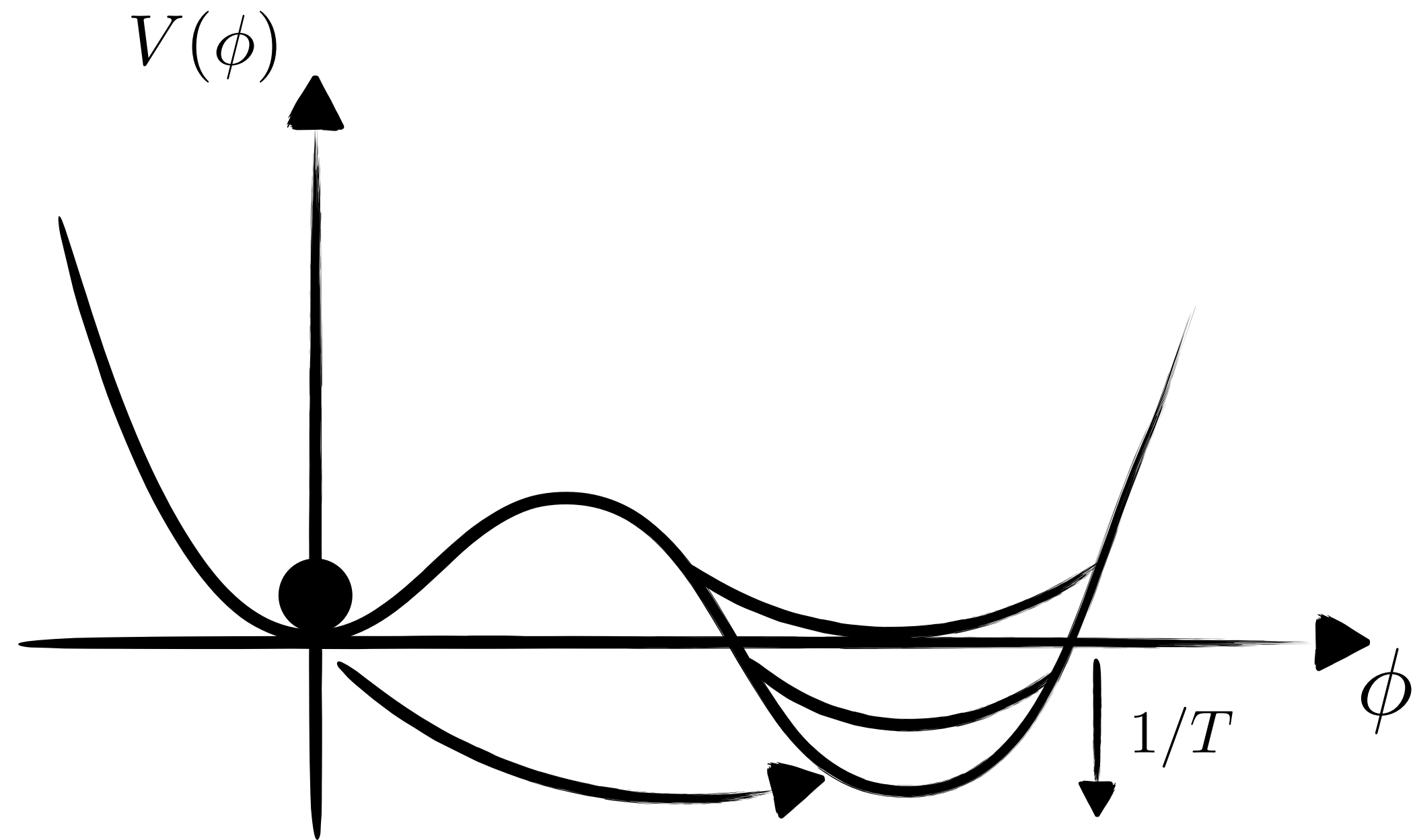


$$\langle \phi \rangle = 0$$

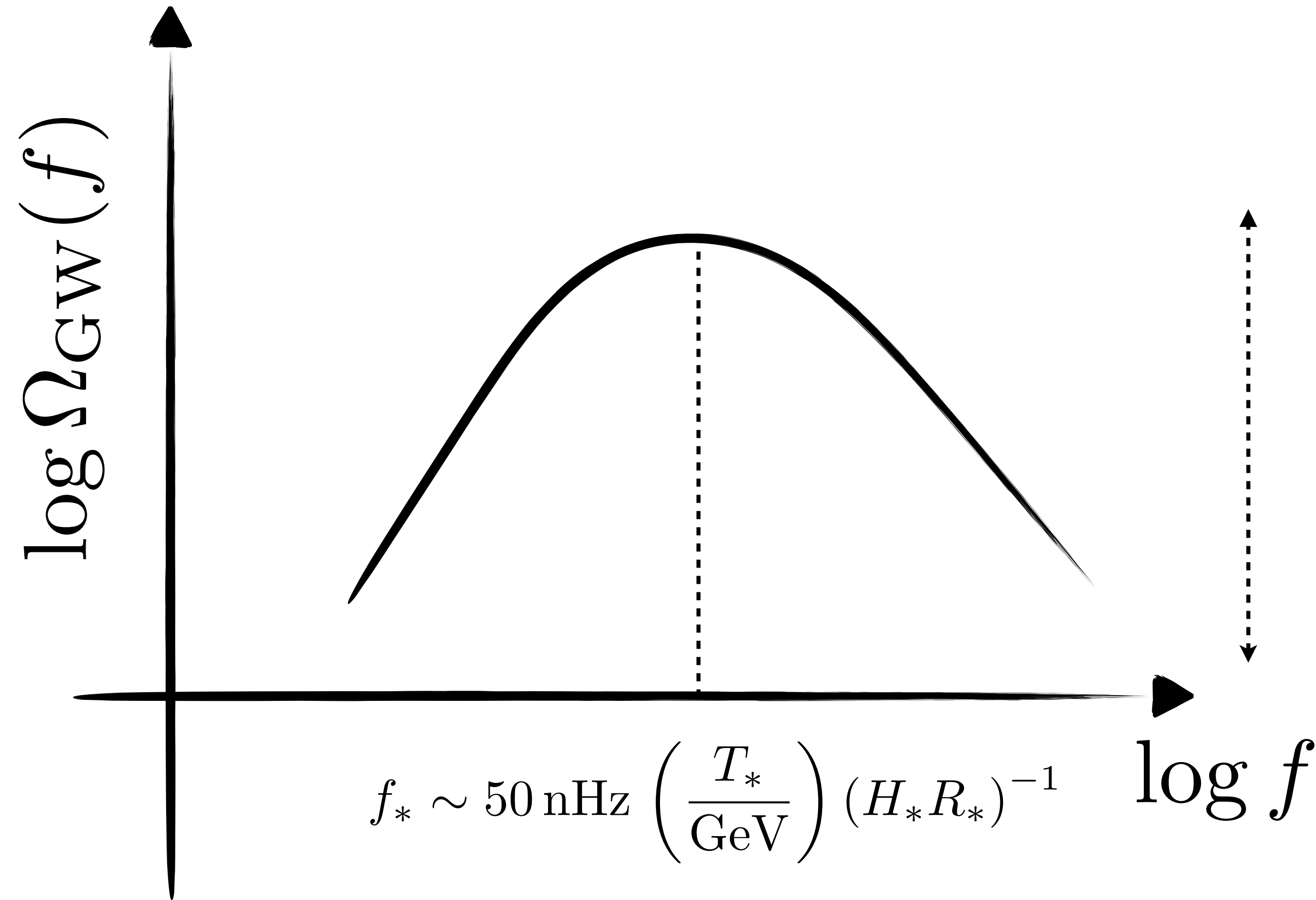
PHASE TRANSITIONS



PHASE TRANSITIONS

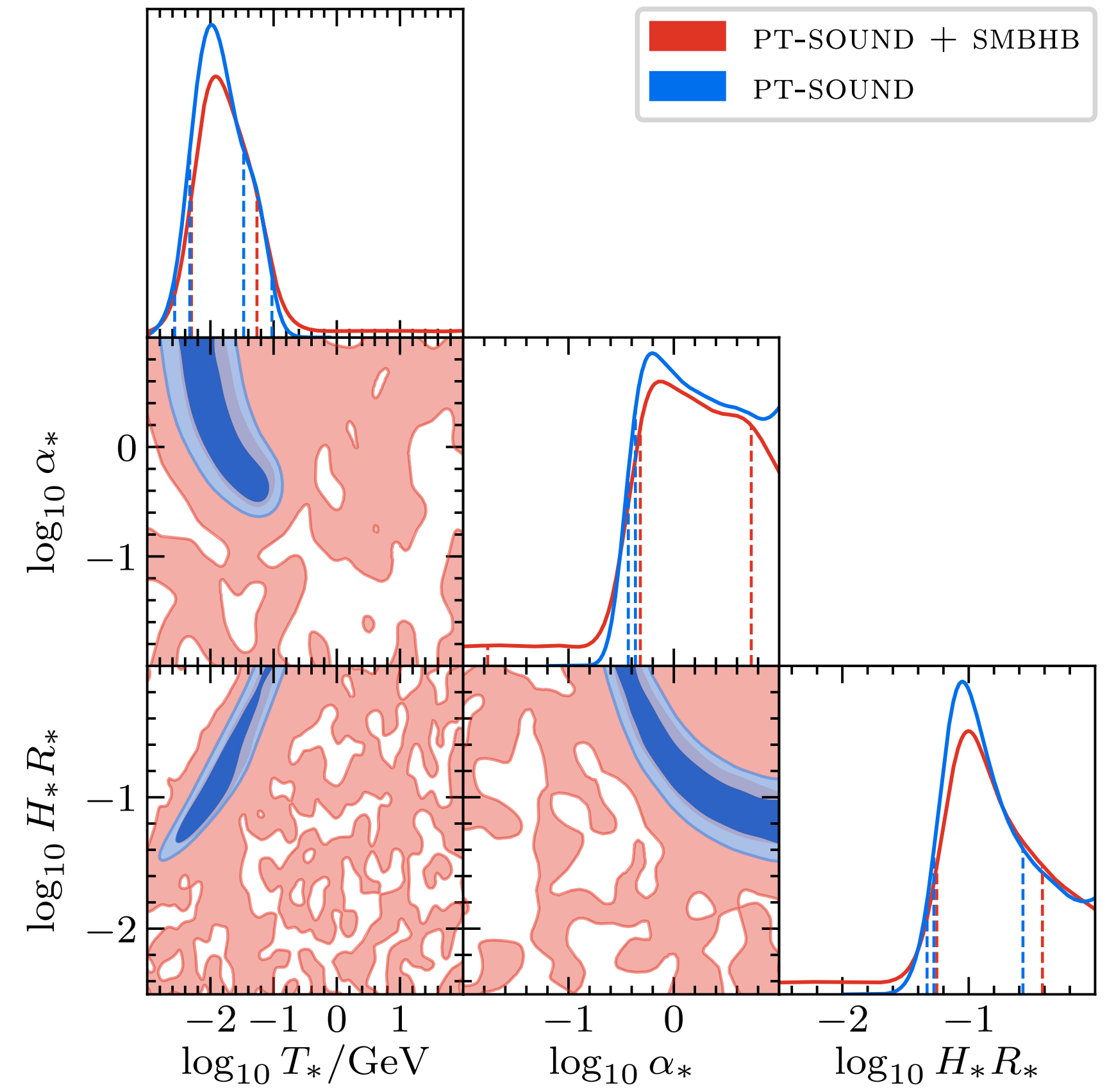
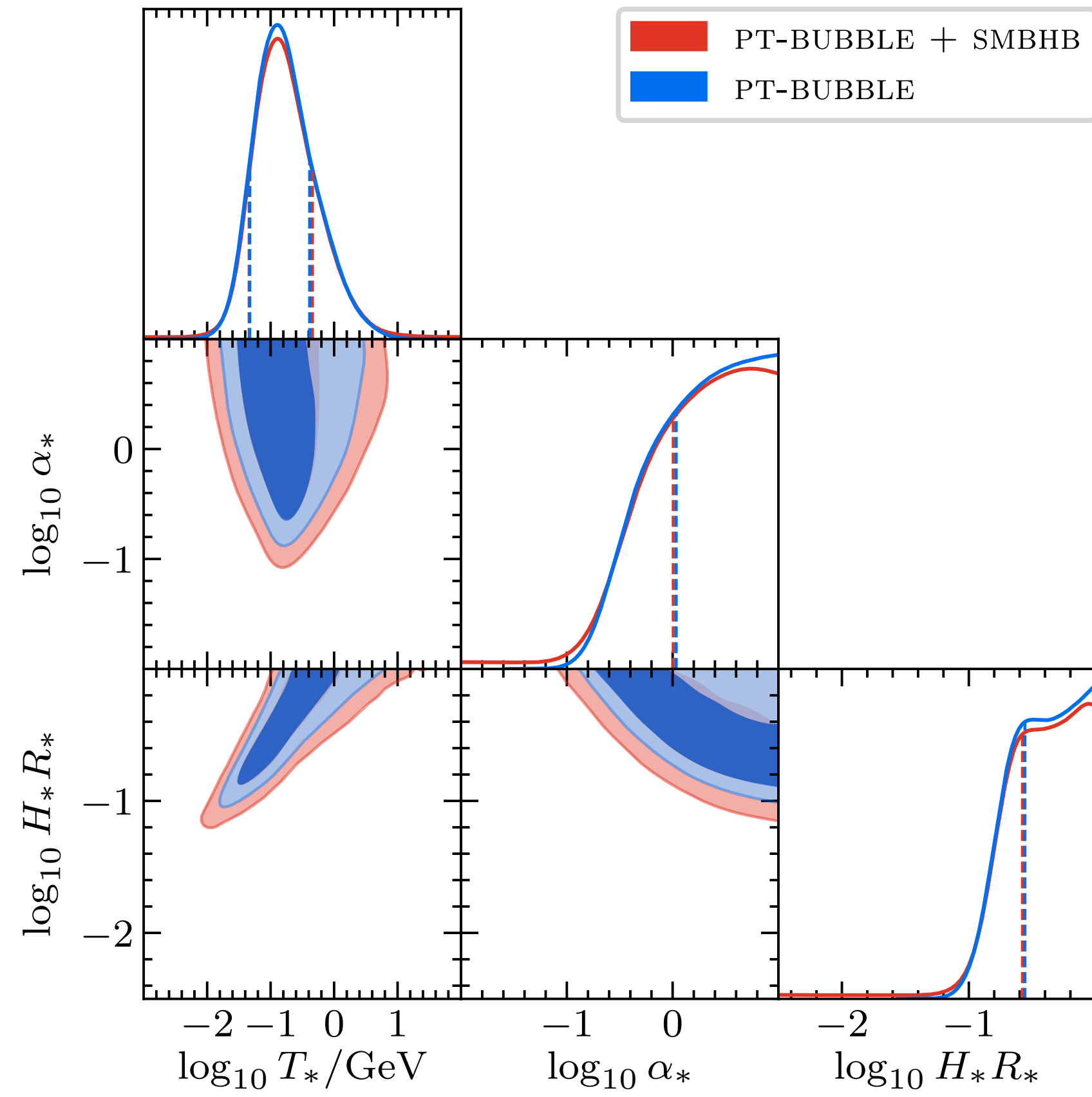


PHASE TRANSITIONS



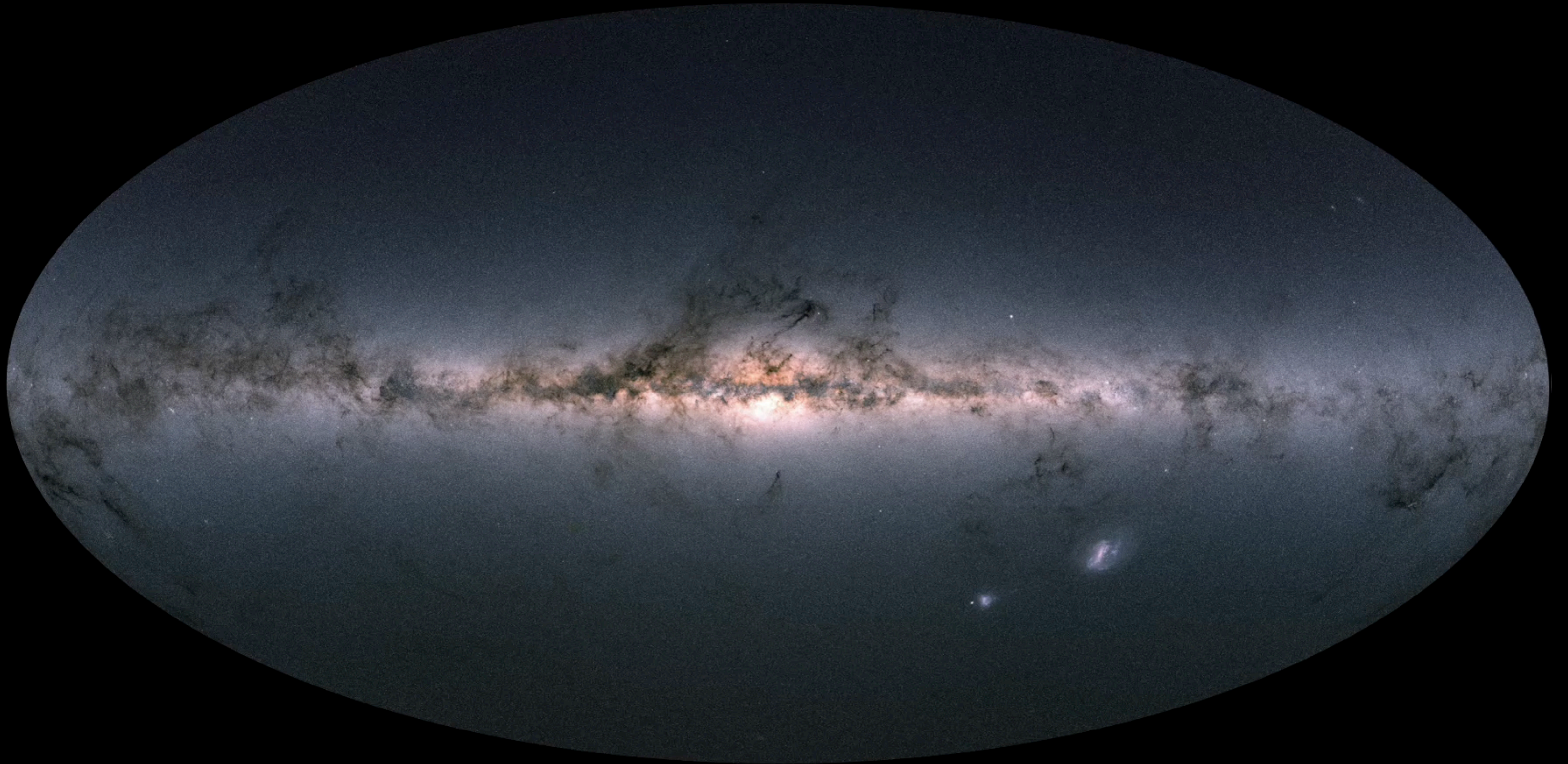
$$\sim 10^{-5} \left(\frac{\alpha_*}{1 + \alpha_*} \right)^2 (H_* R_*)^p$$

PHASE TRANSITIONS



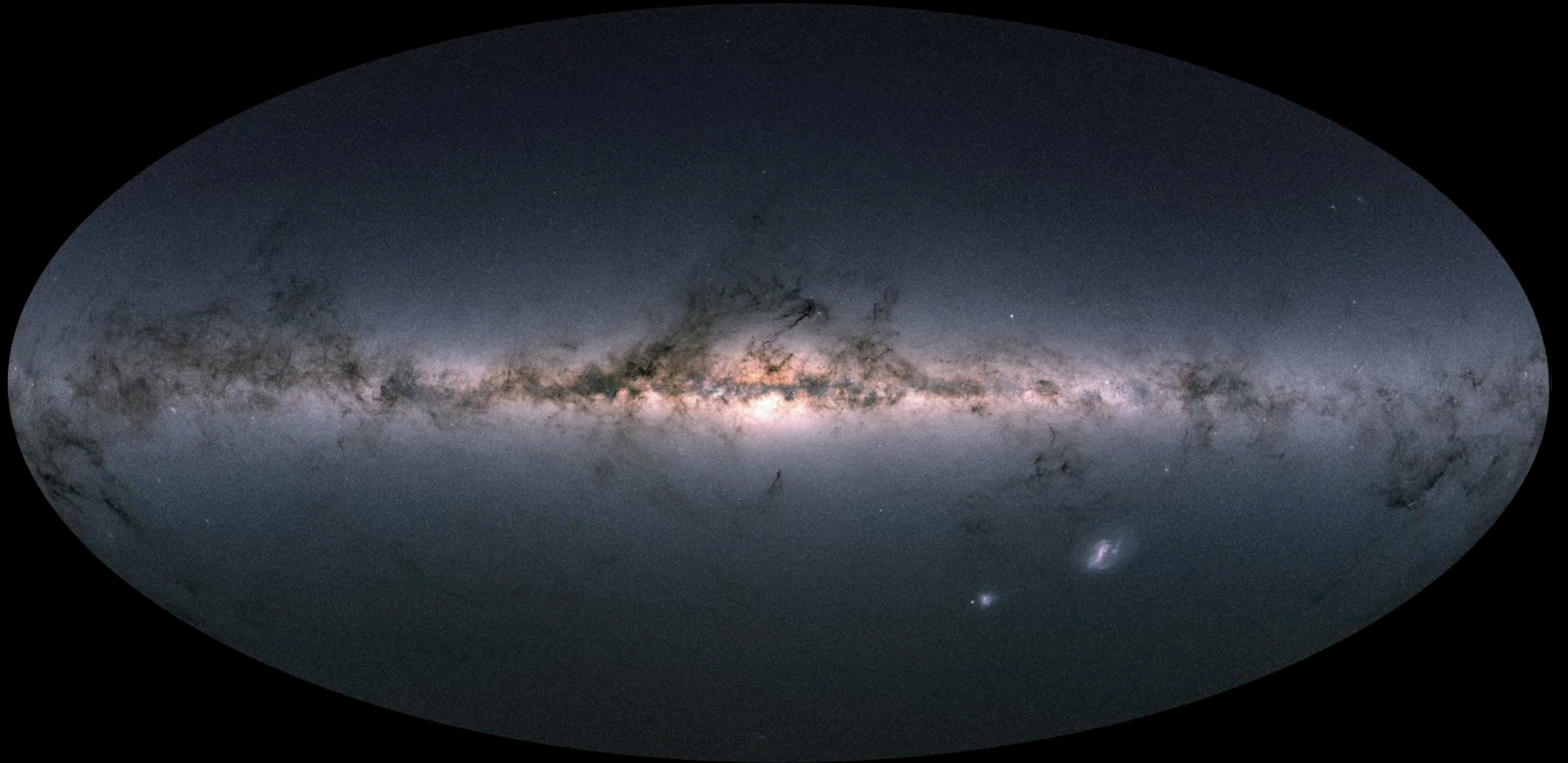
where do we go from here?

ANISOTROPIES



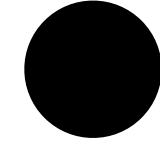
Credit: ESA/Gaia/DPAC

ANISOTROPIES

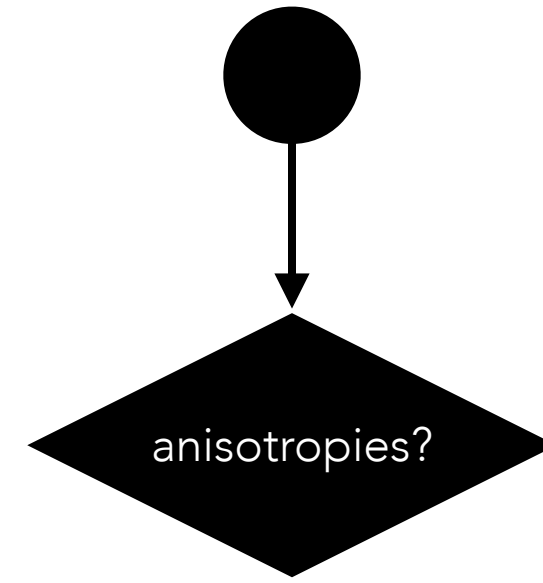


Credit: ESA/Gaia/DPAC

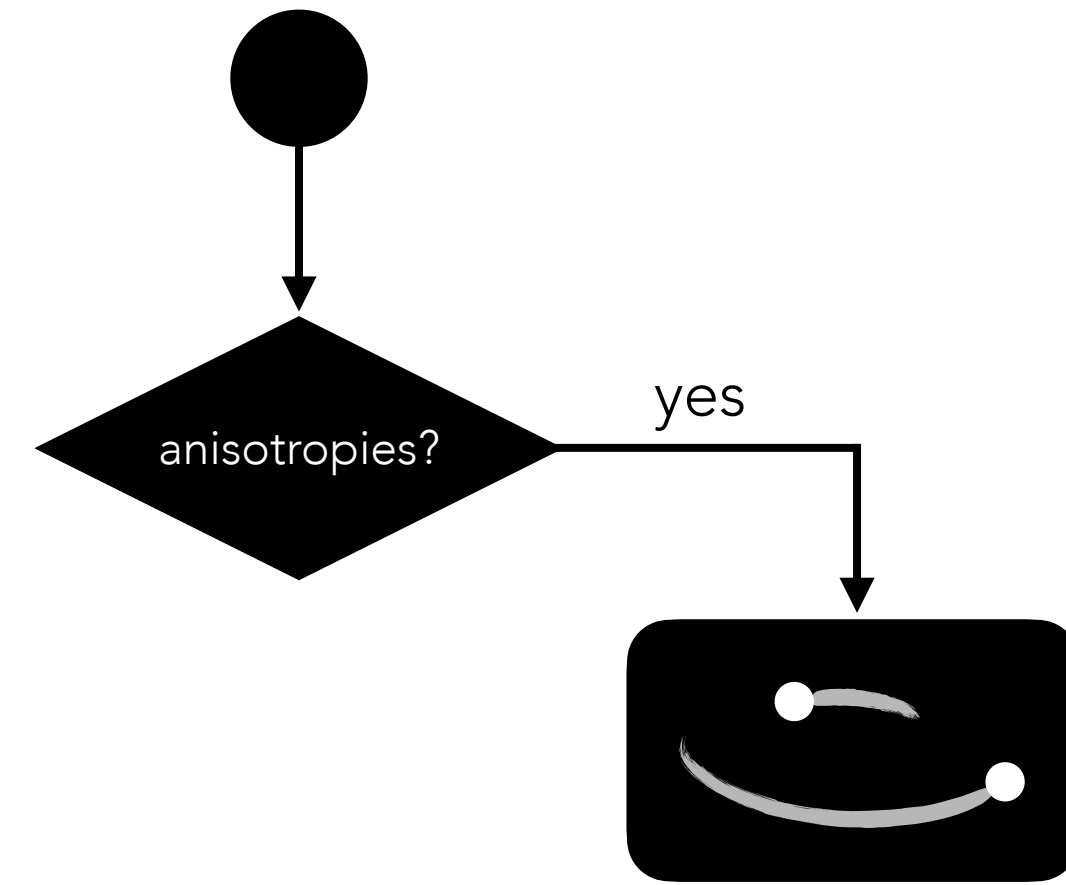
SMBHB or NEW PHYSICS?



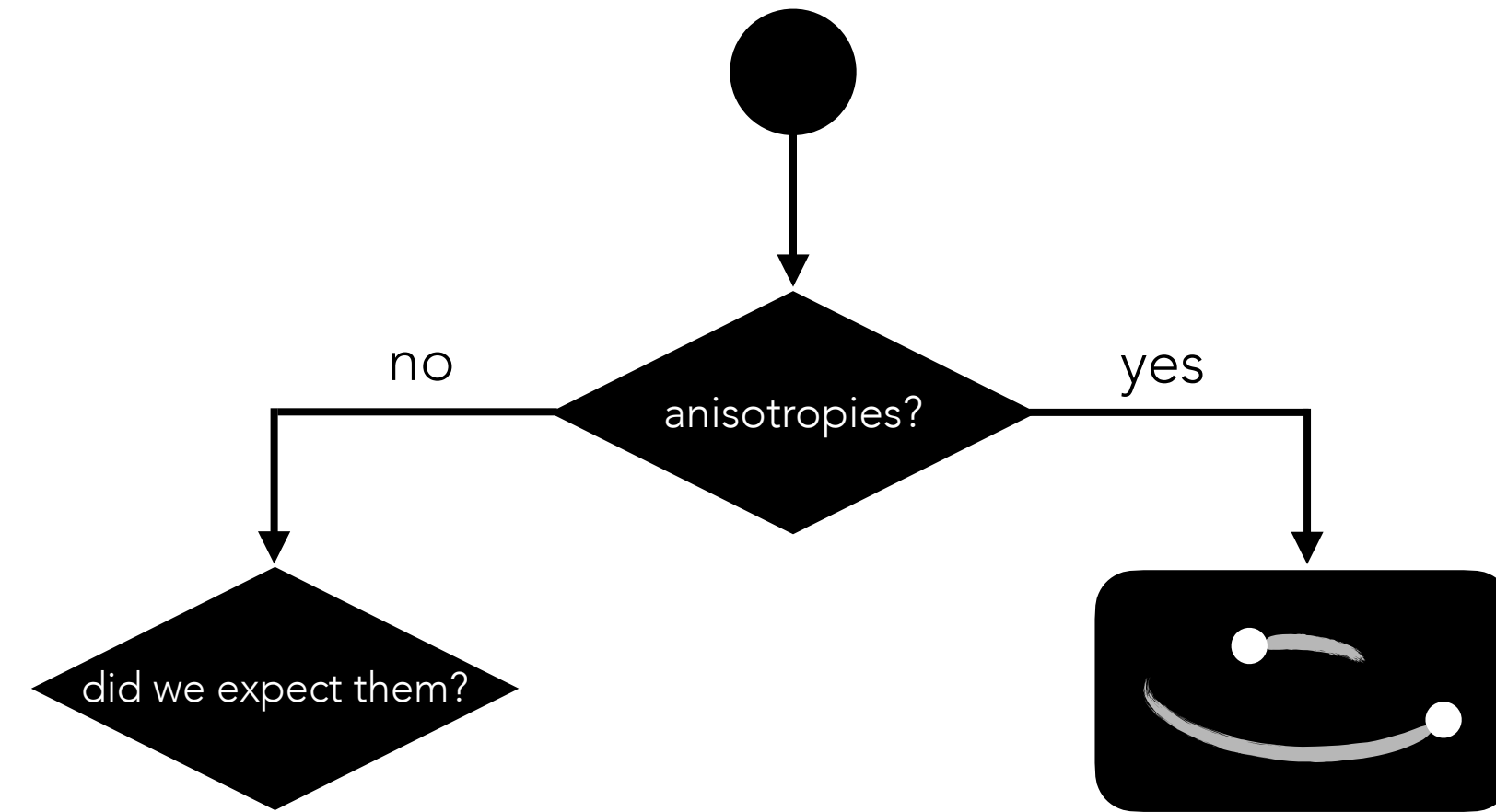
SMBHB or NEW PHYSICS?



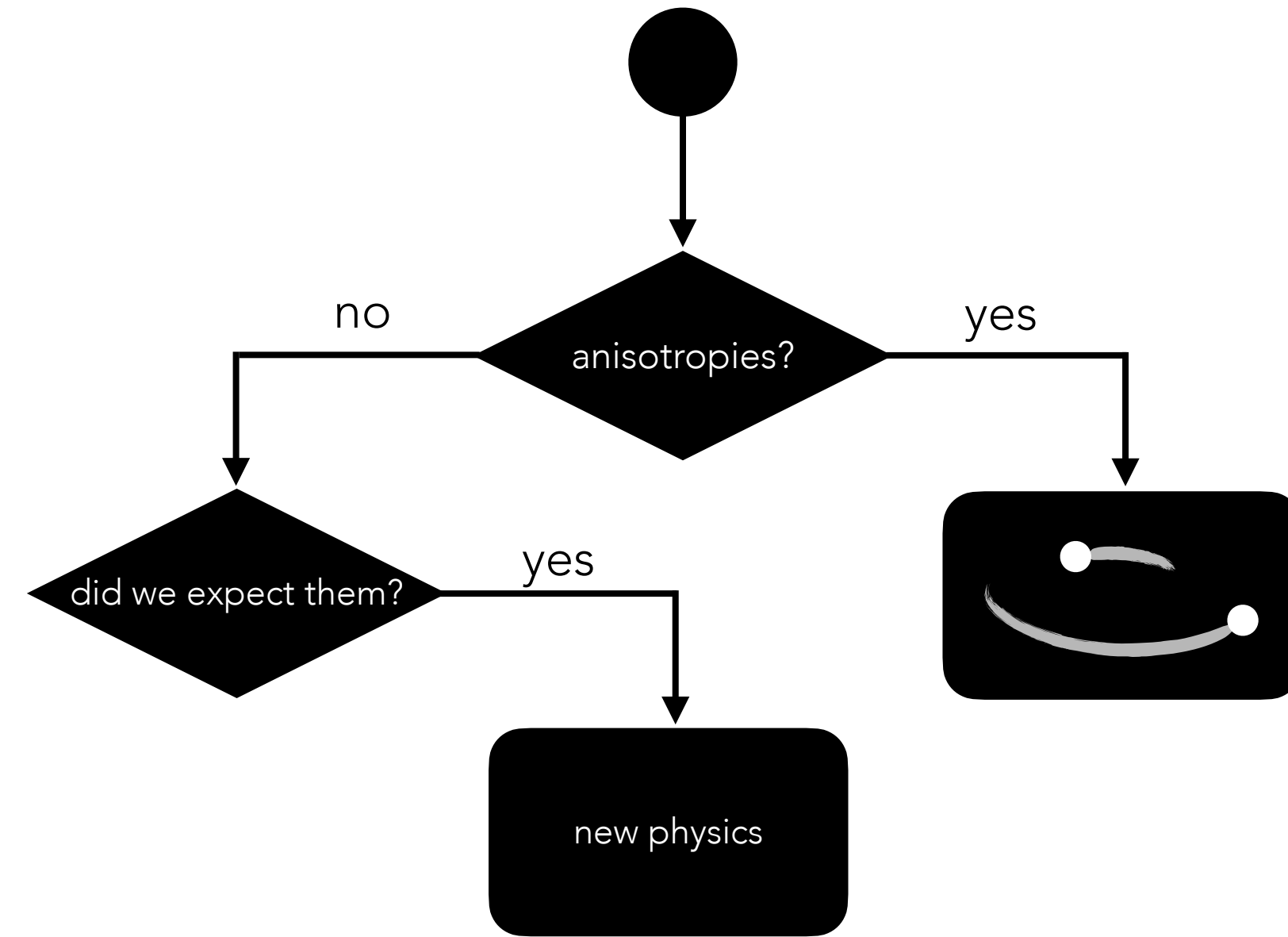
SMBHB or NEW PHYSICS?



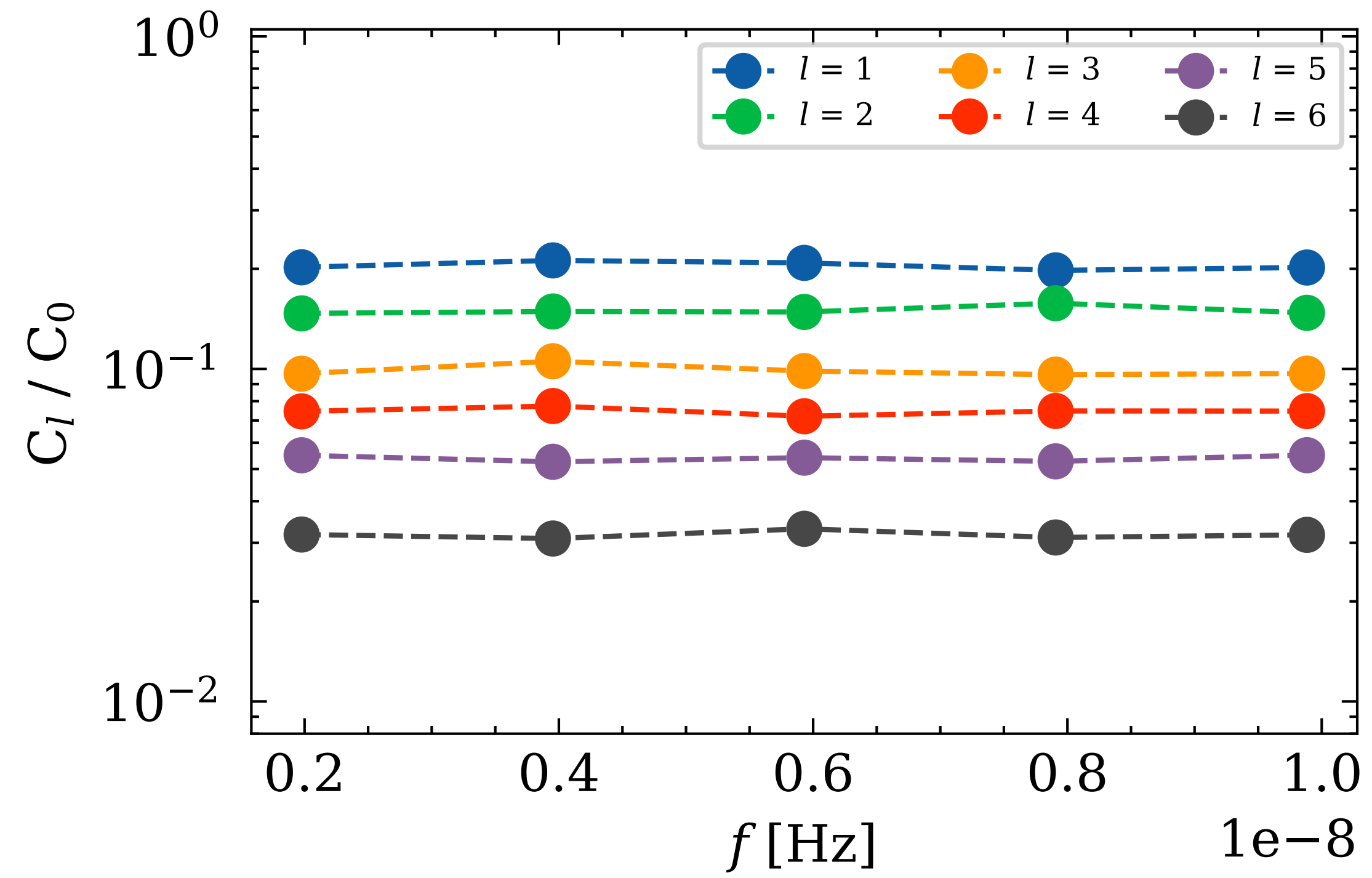
SMBHB or NEW PHYSICS?



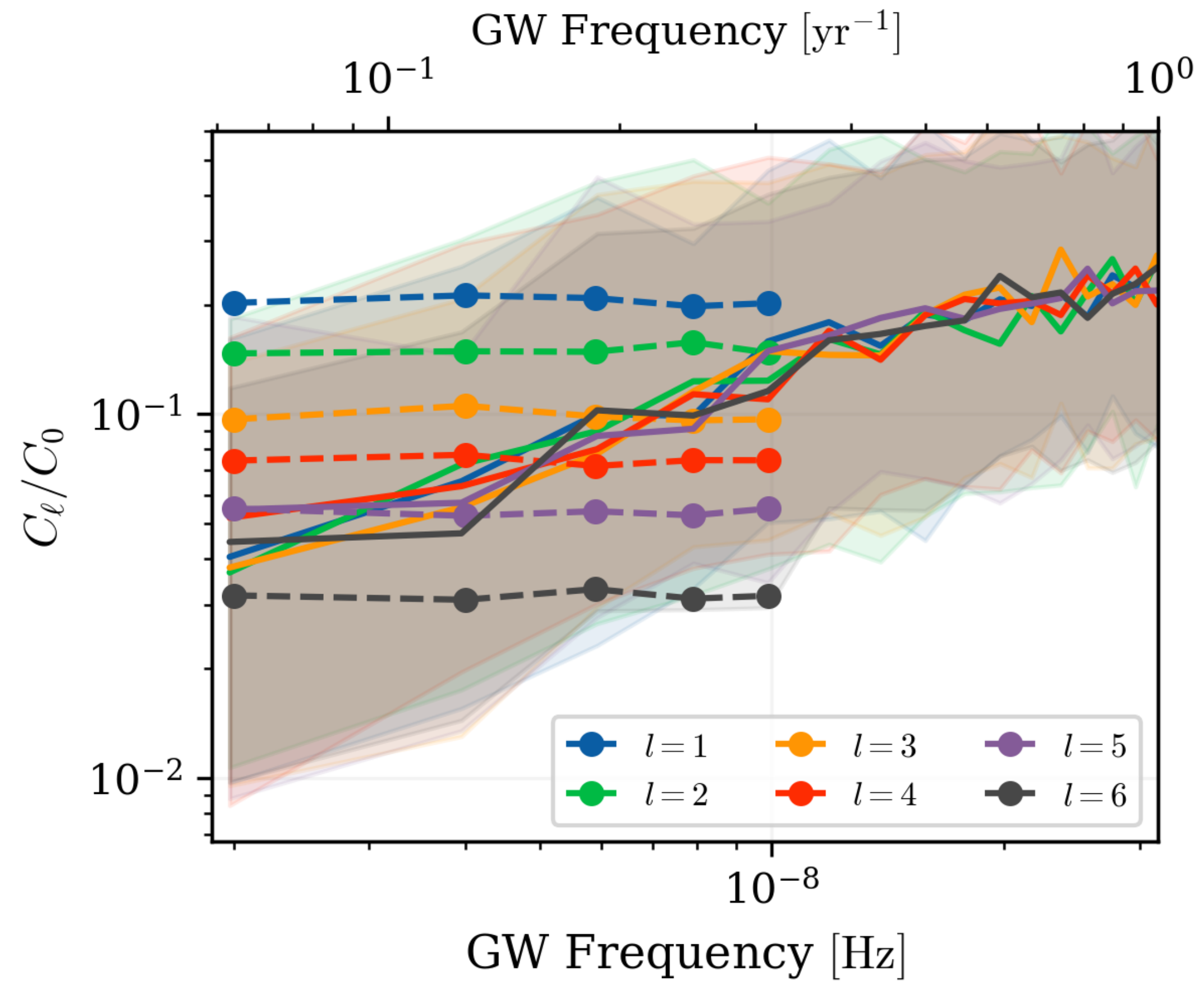
SMBHB or NEW PHYSICS?



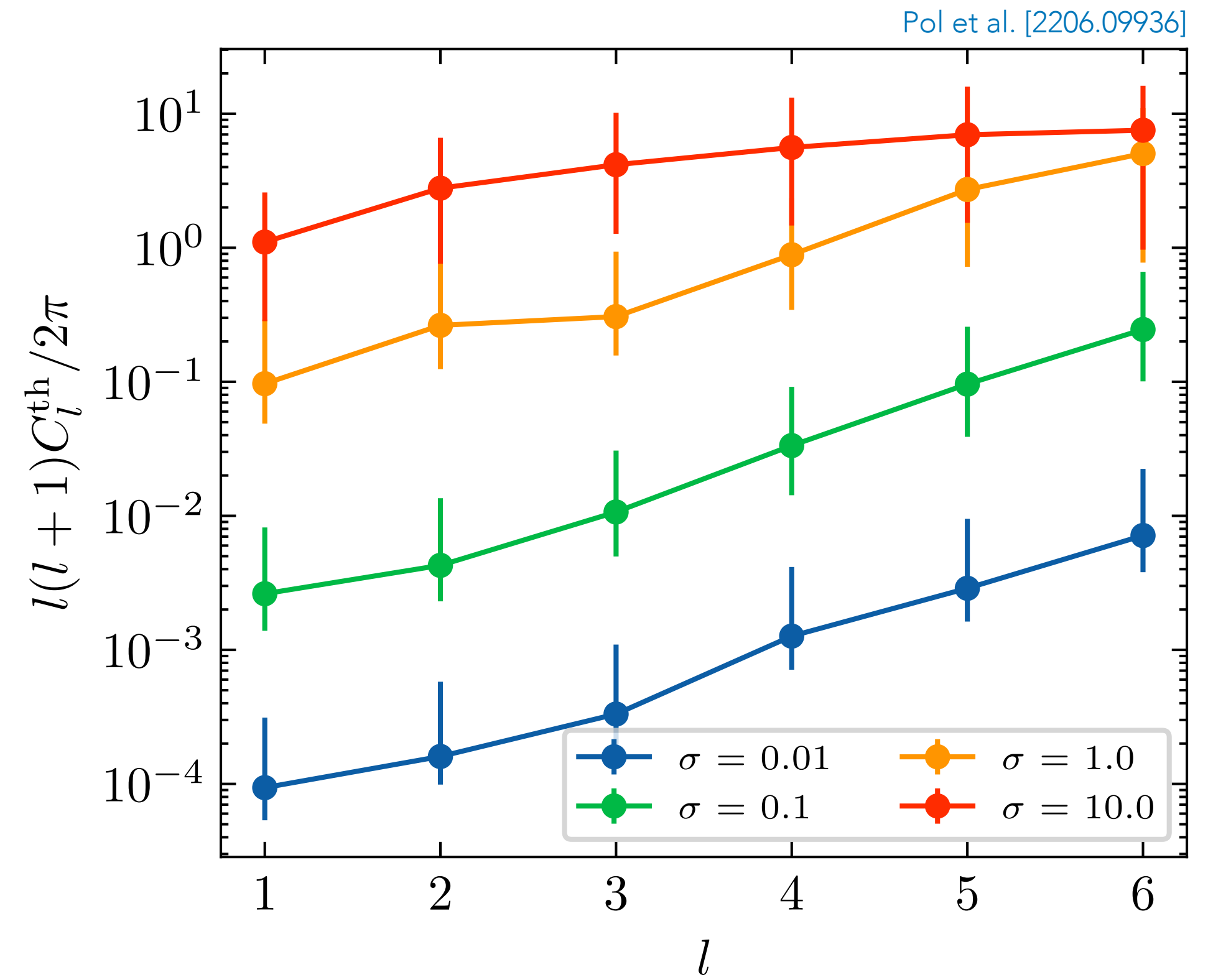
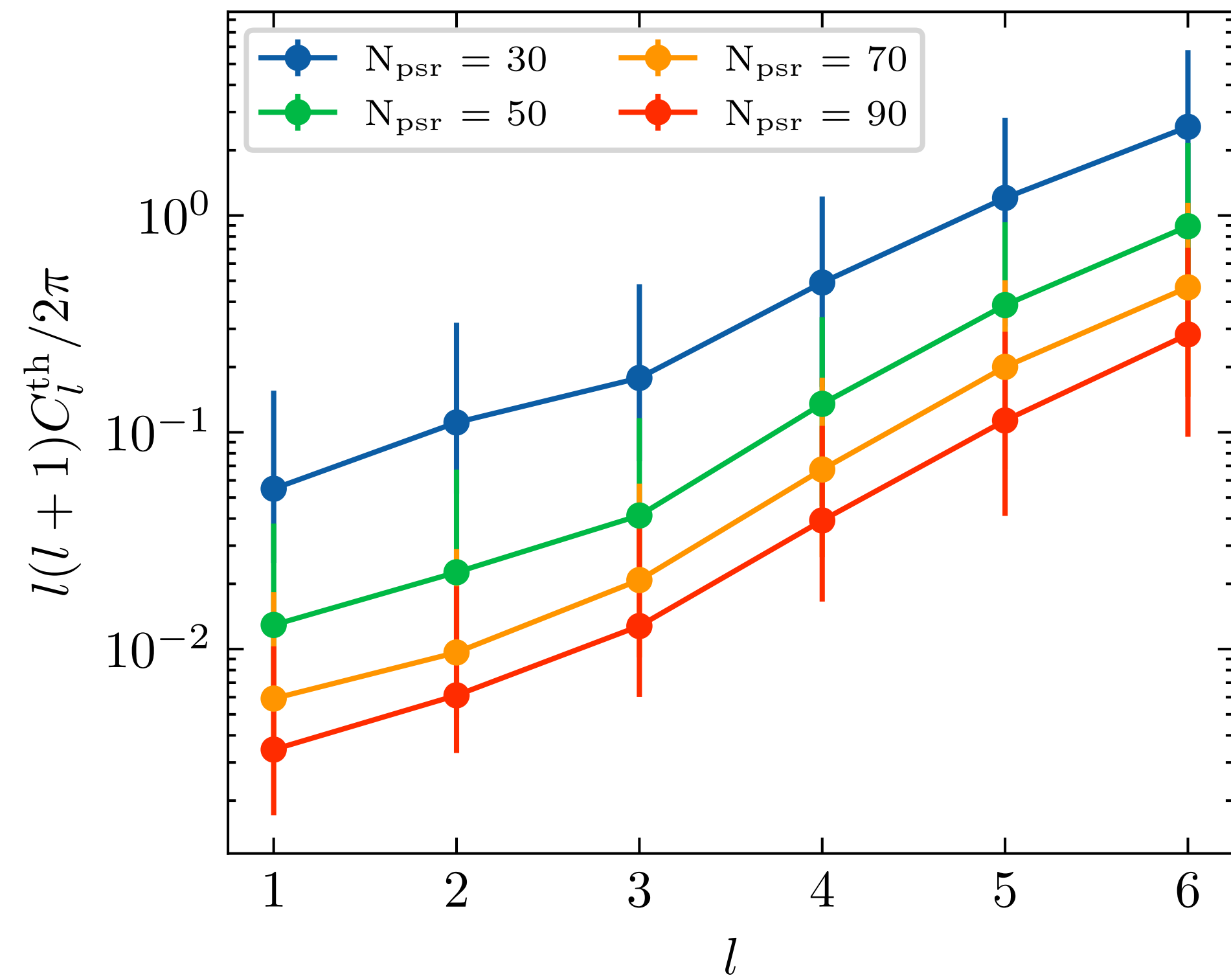
ANISOTROPIES



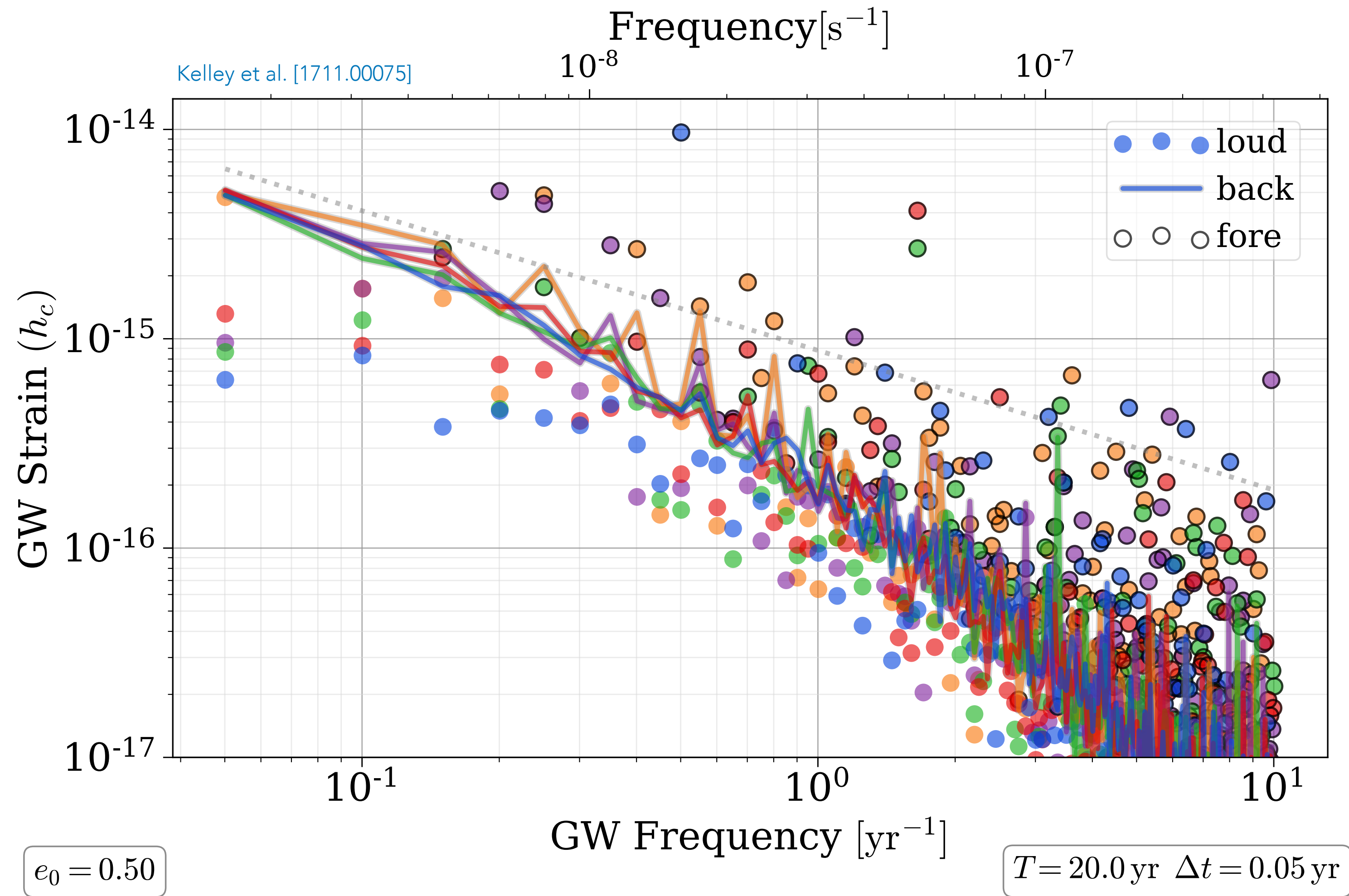
ANISOTROPIES



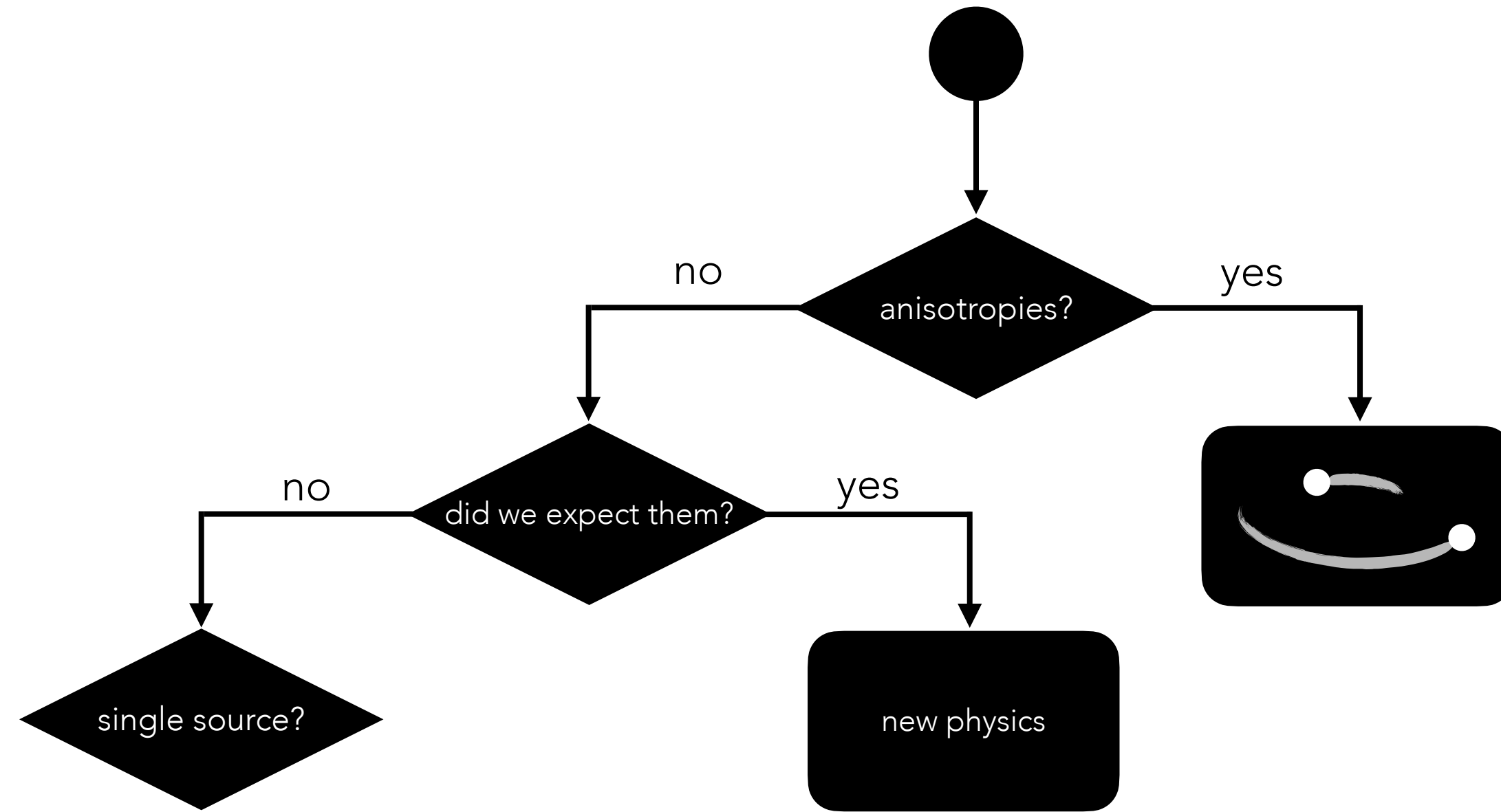
ANISOTROPIES



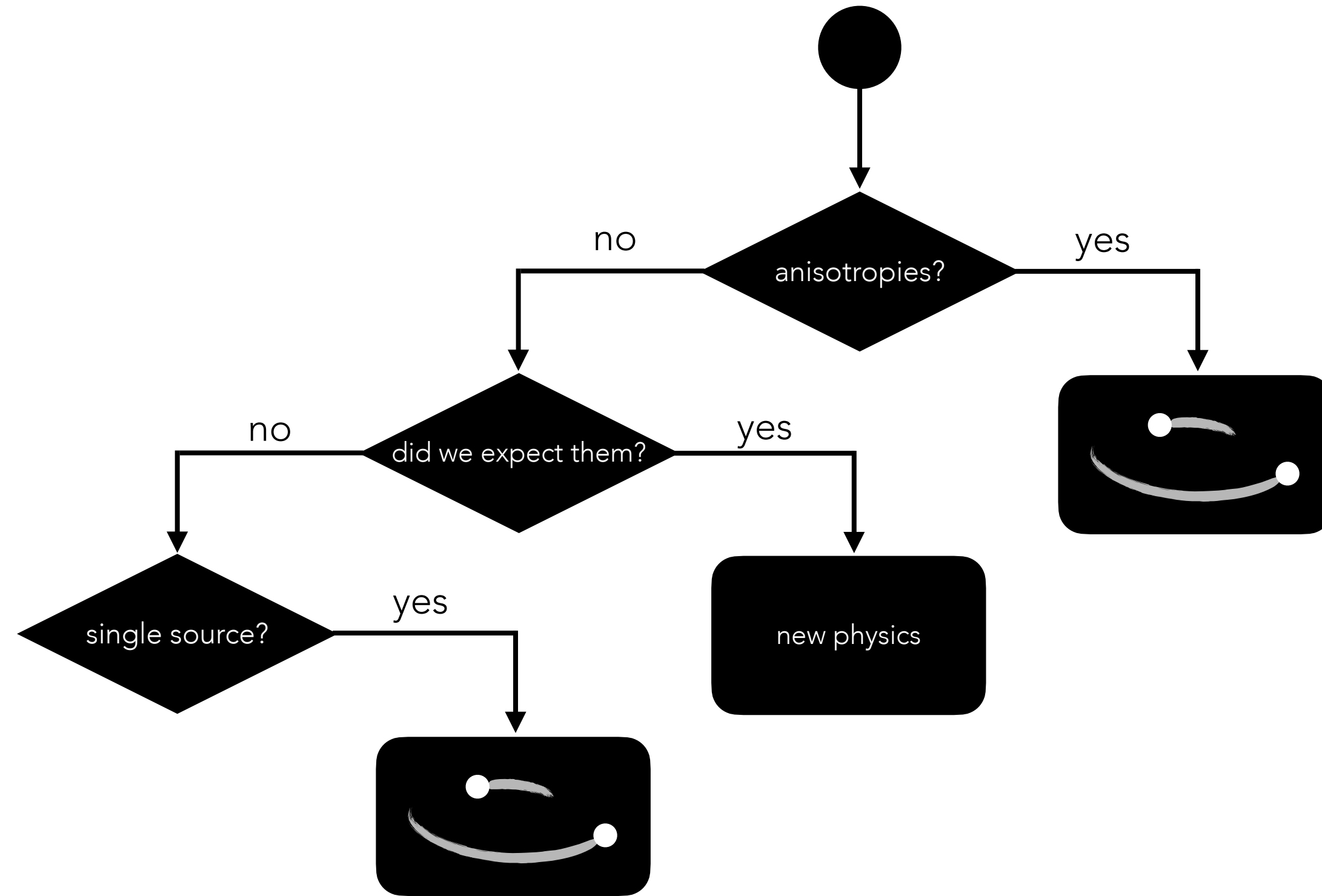
SINGLE SOURCE



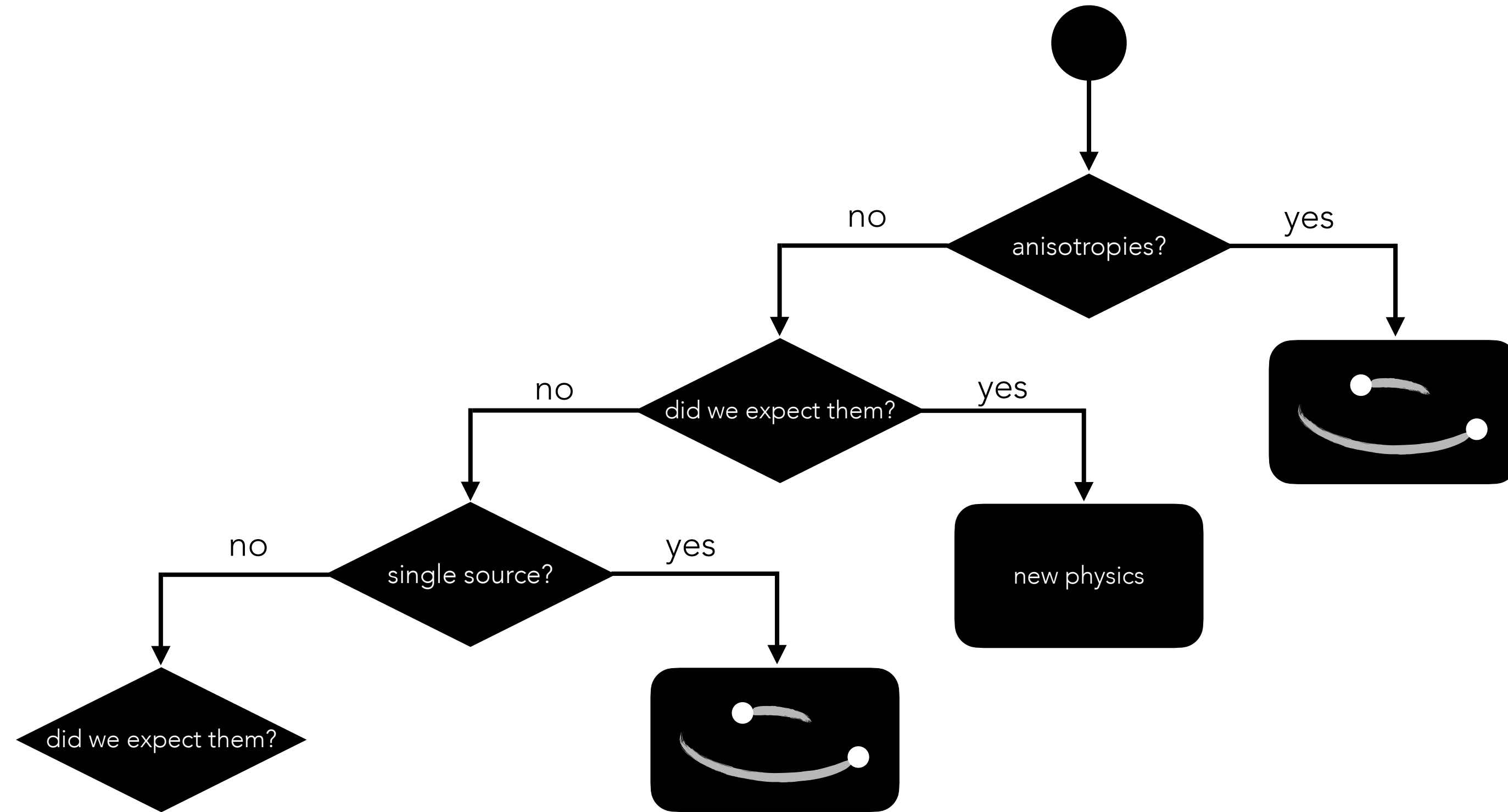
SMBHB or NEW PHYSICS?



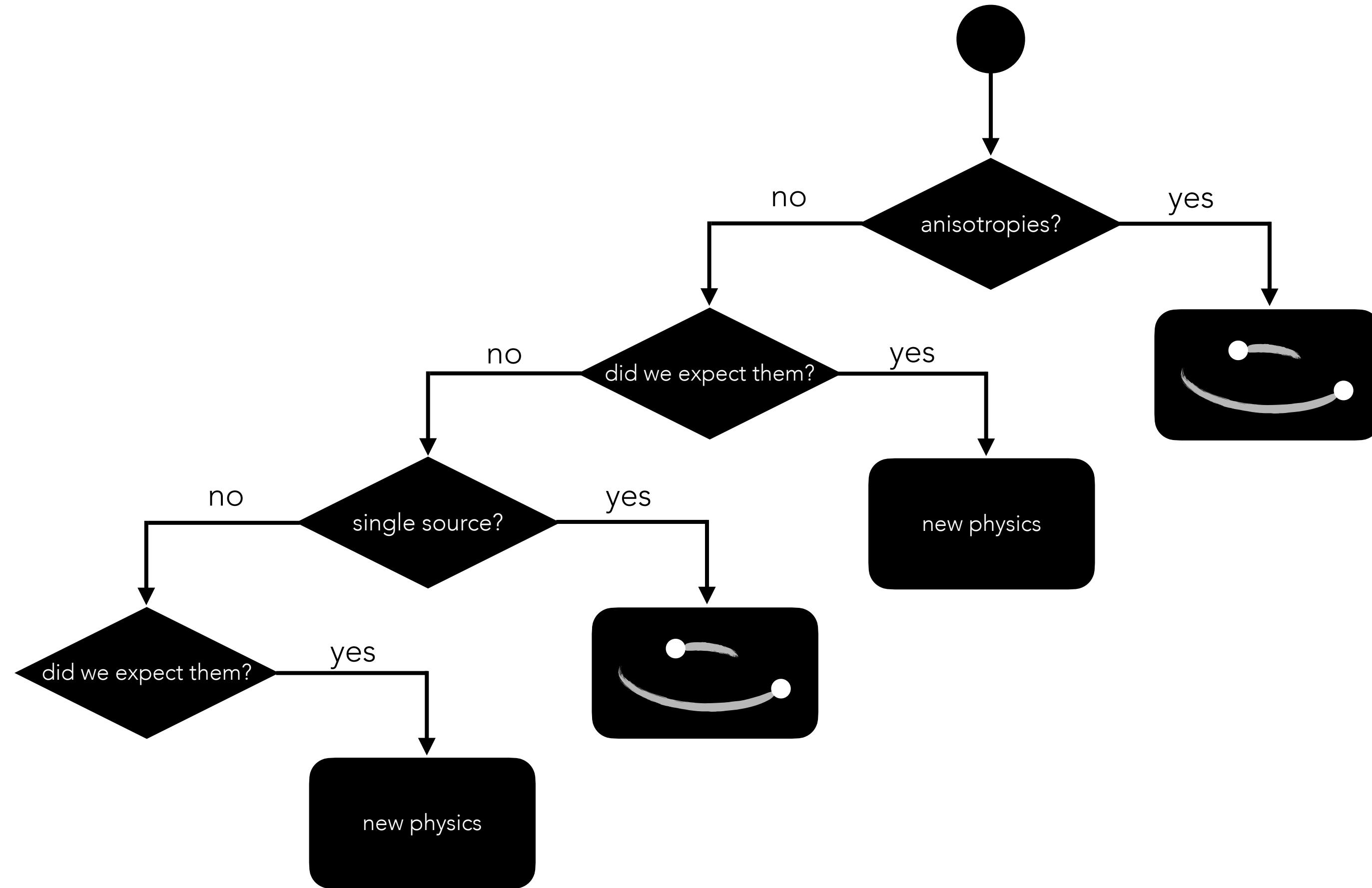
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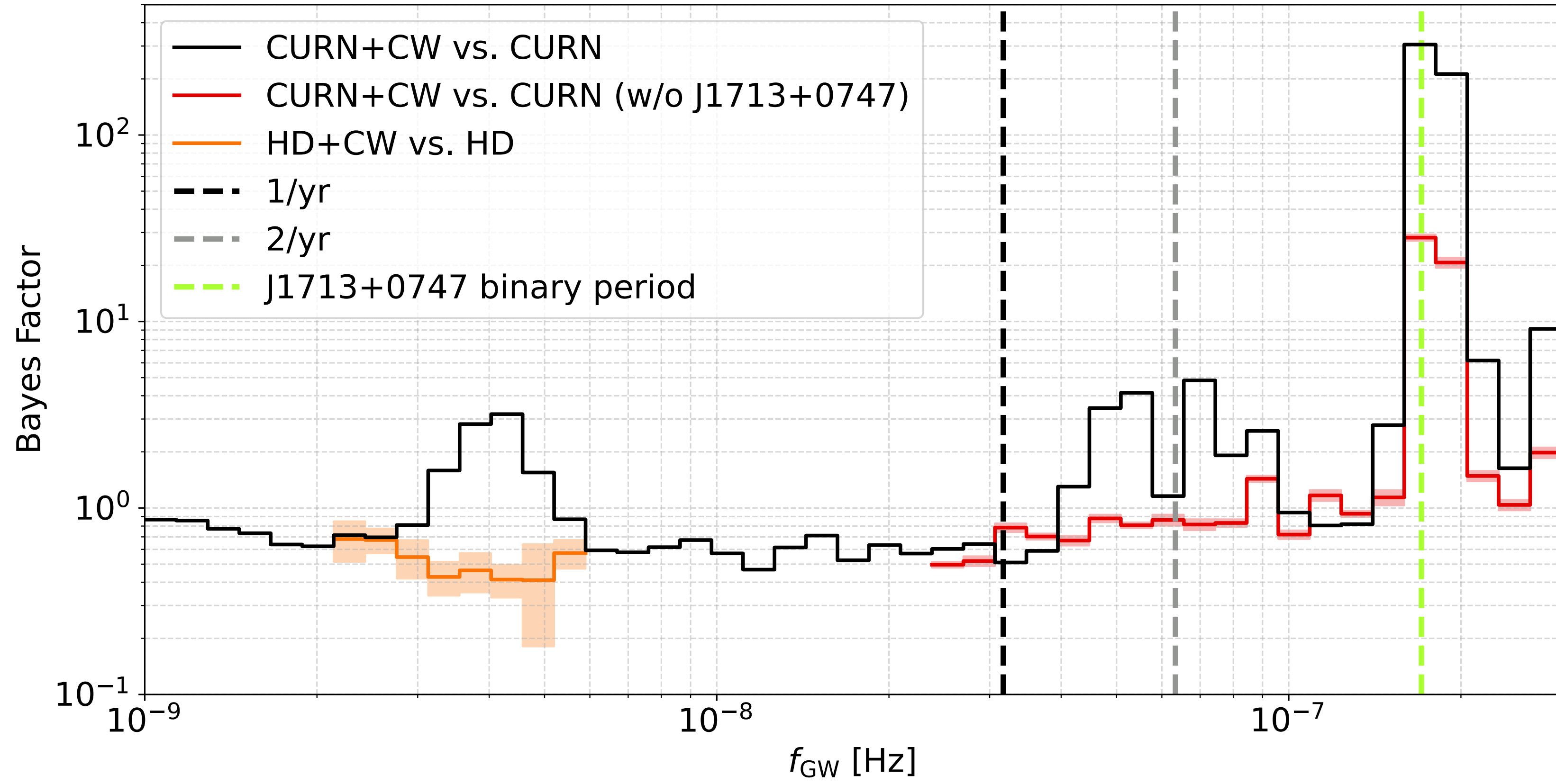


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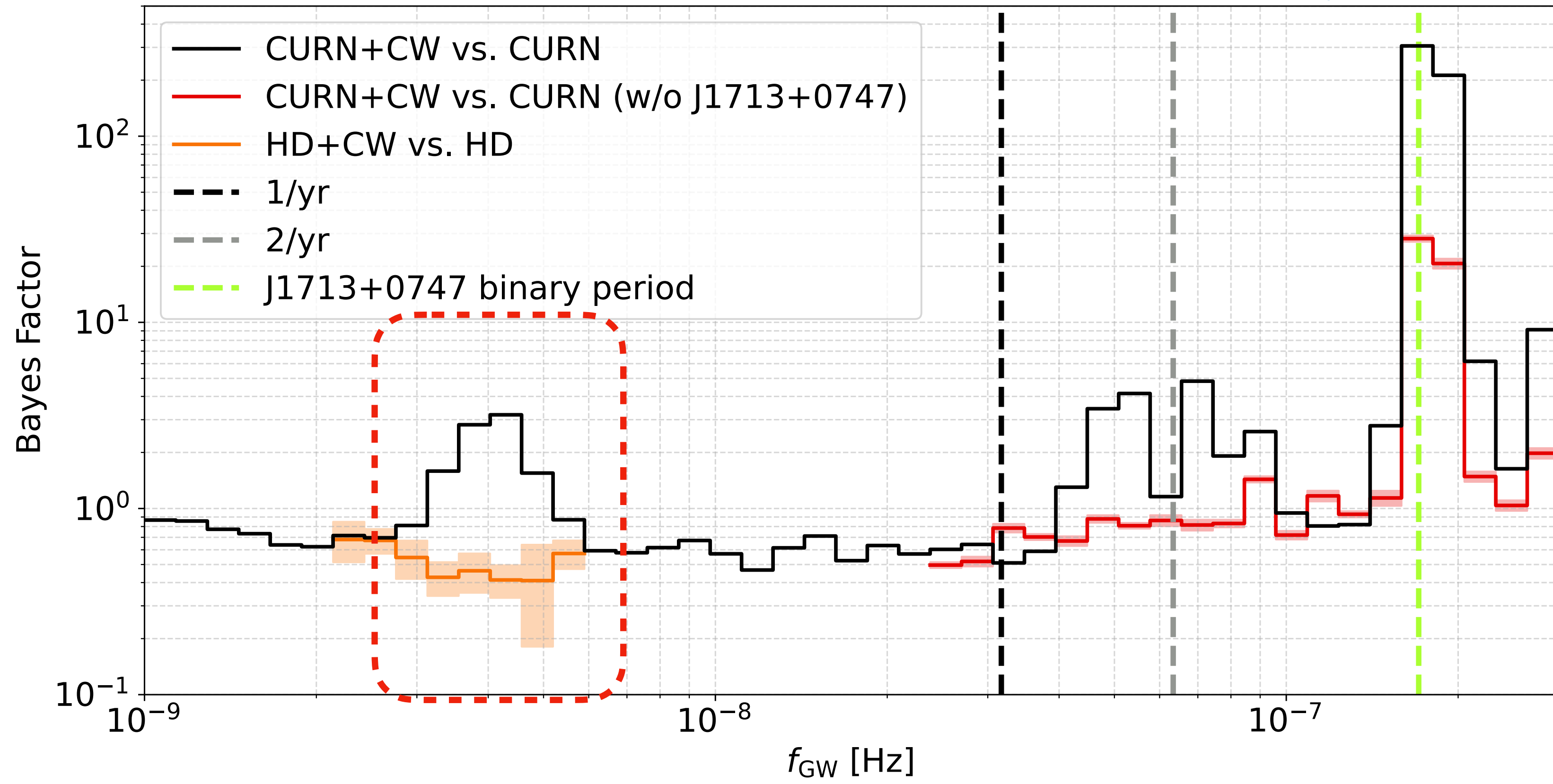
SINGLE SOURCE

Agazie et al. [2306.16222]

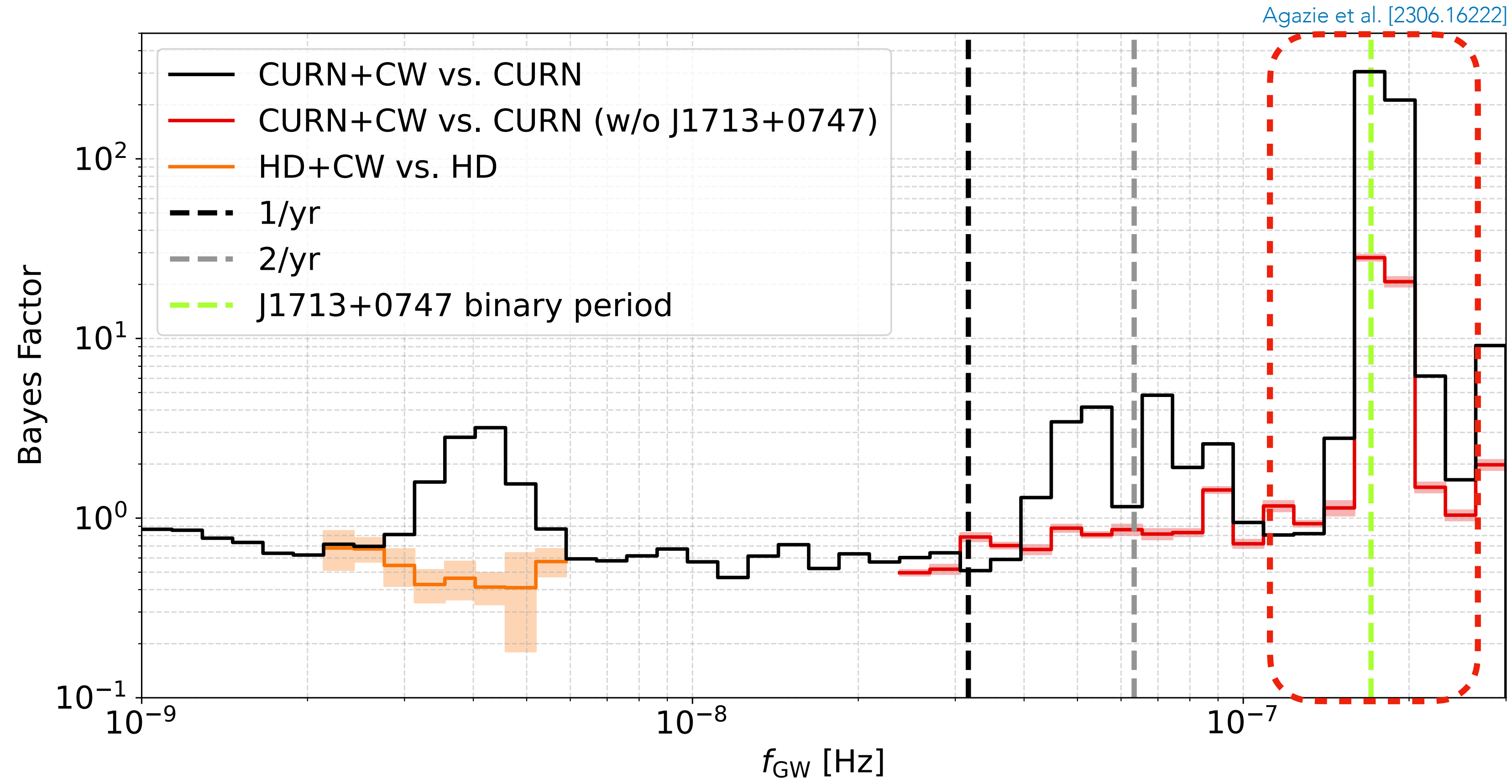


SINGLE SOURCE

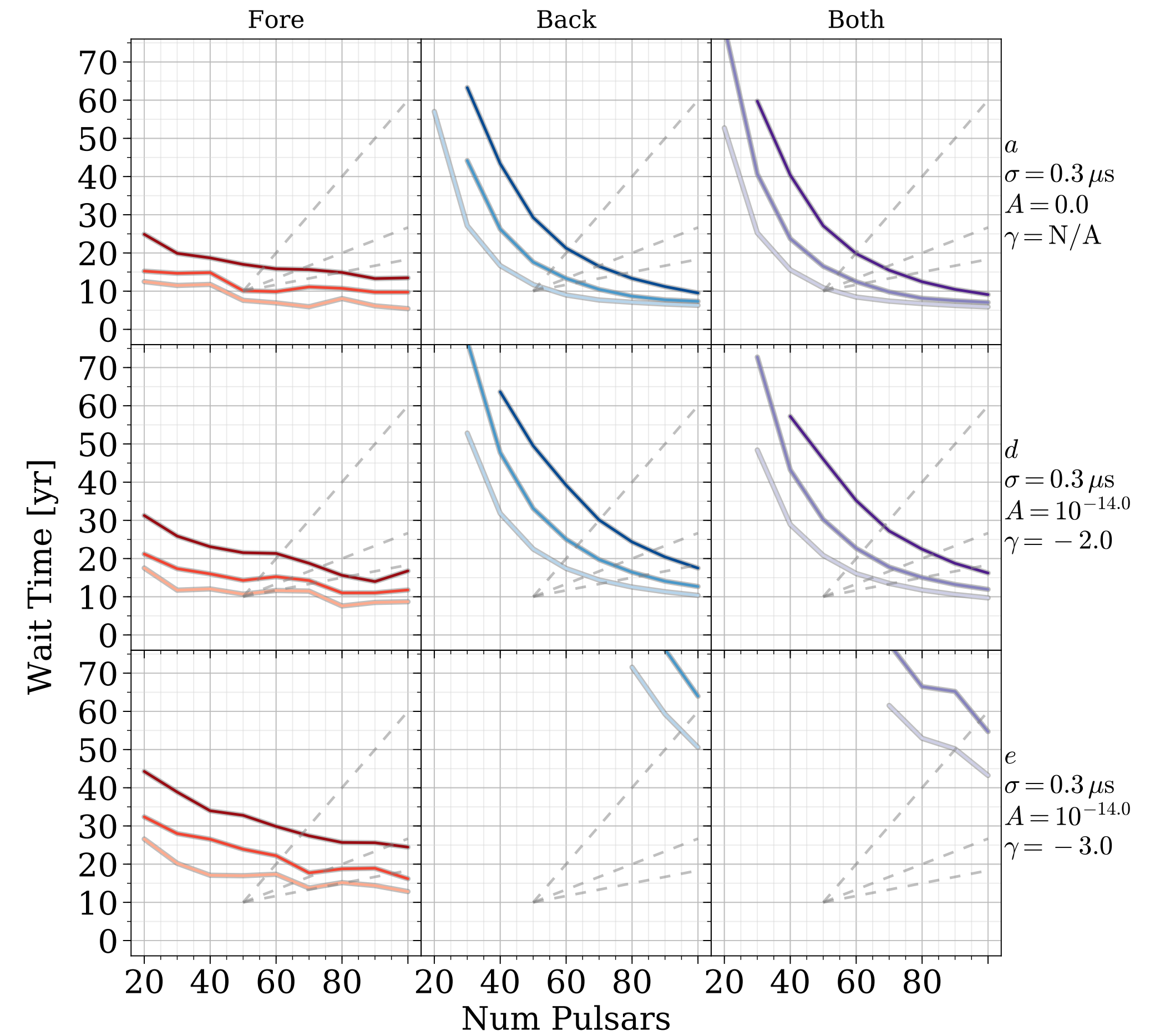
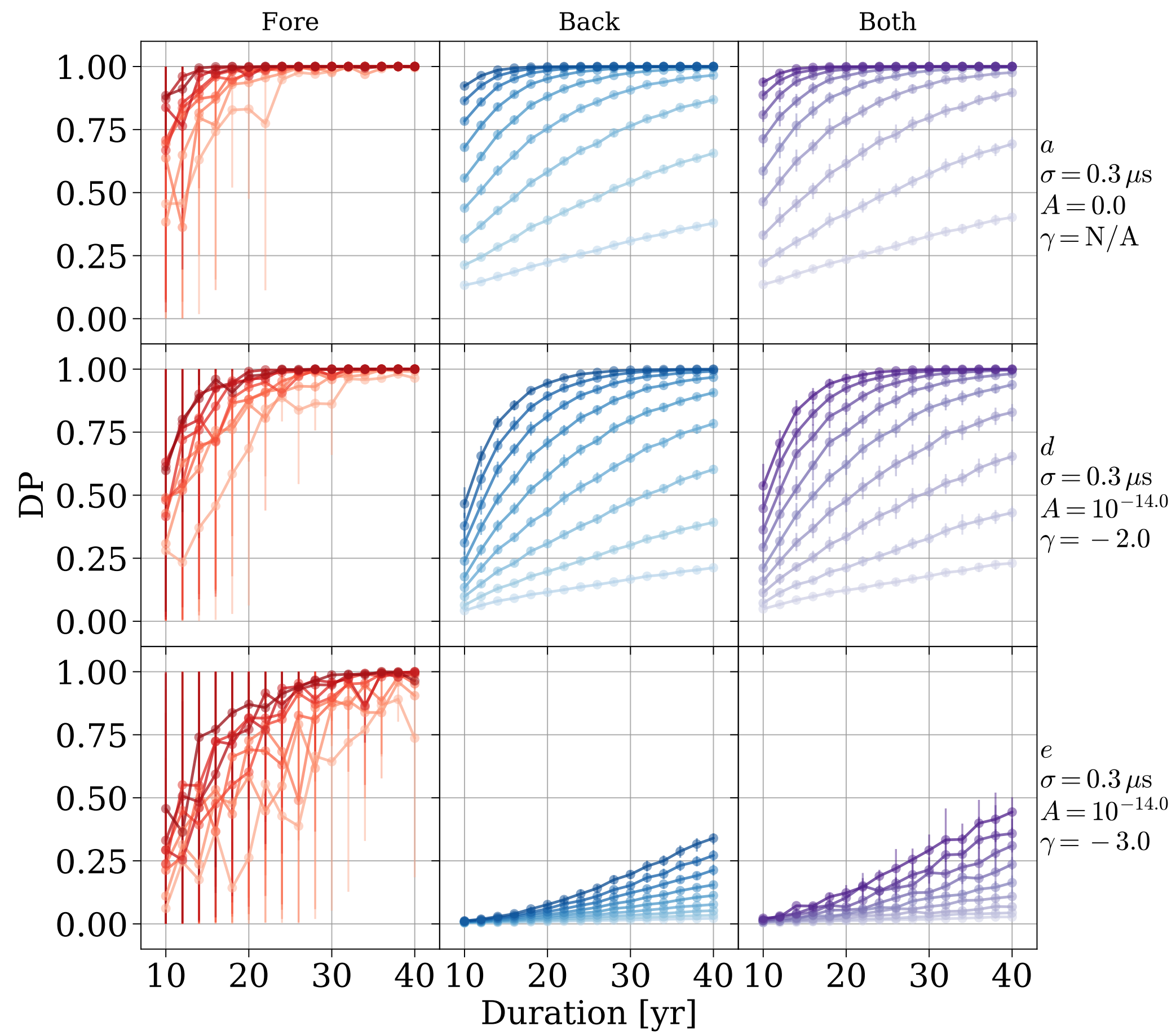
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SINGLE SOURCE



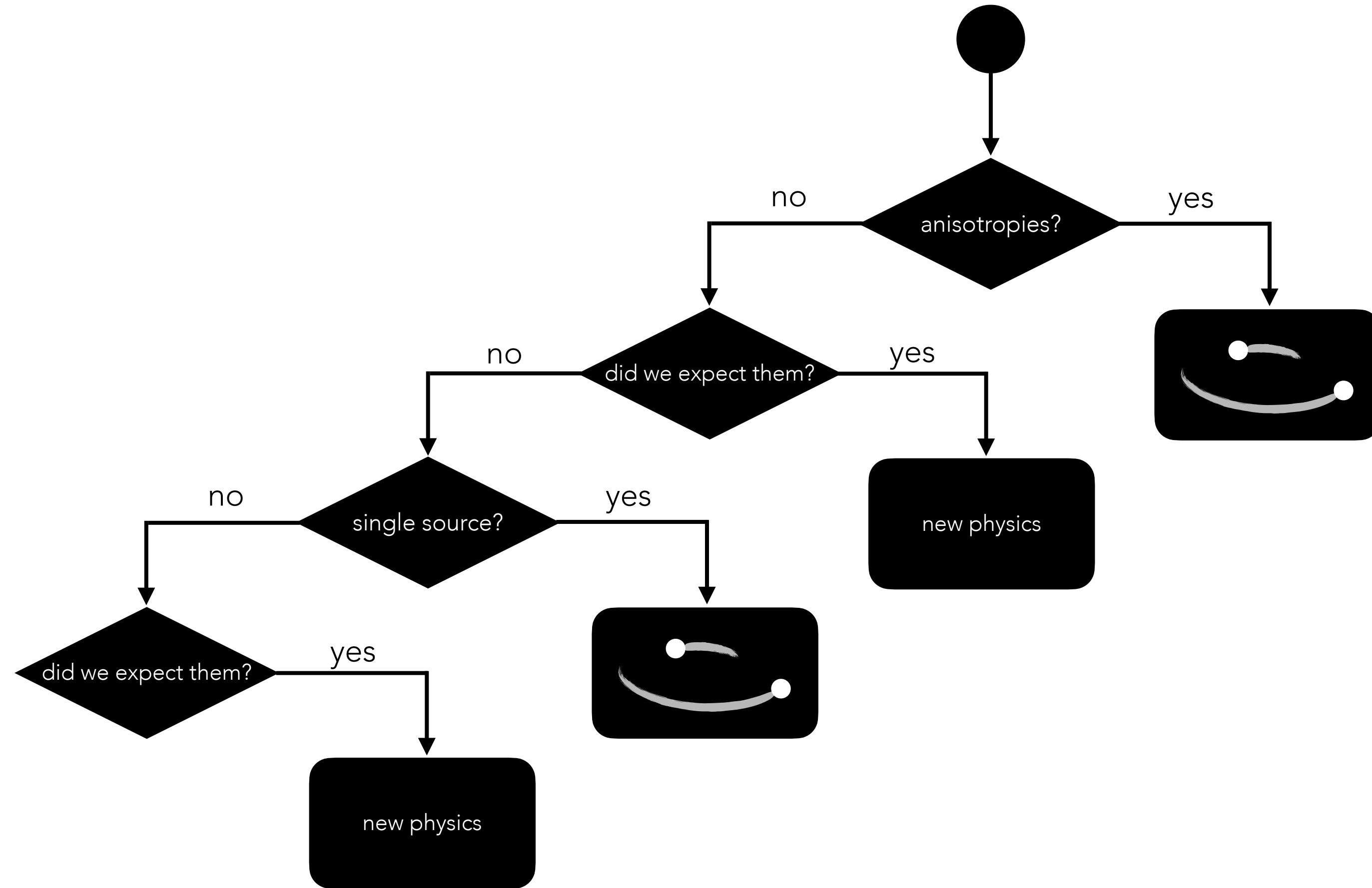
SINGLE SOURCE EXPECTATIONS



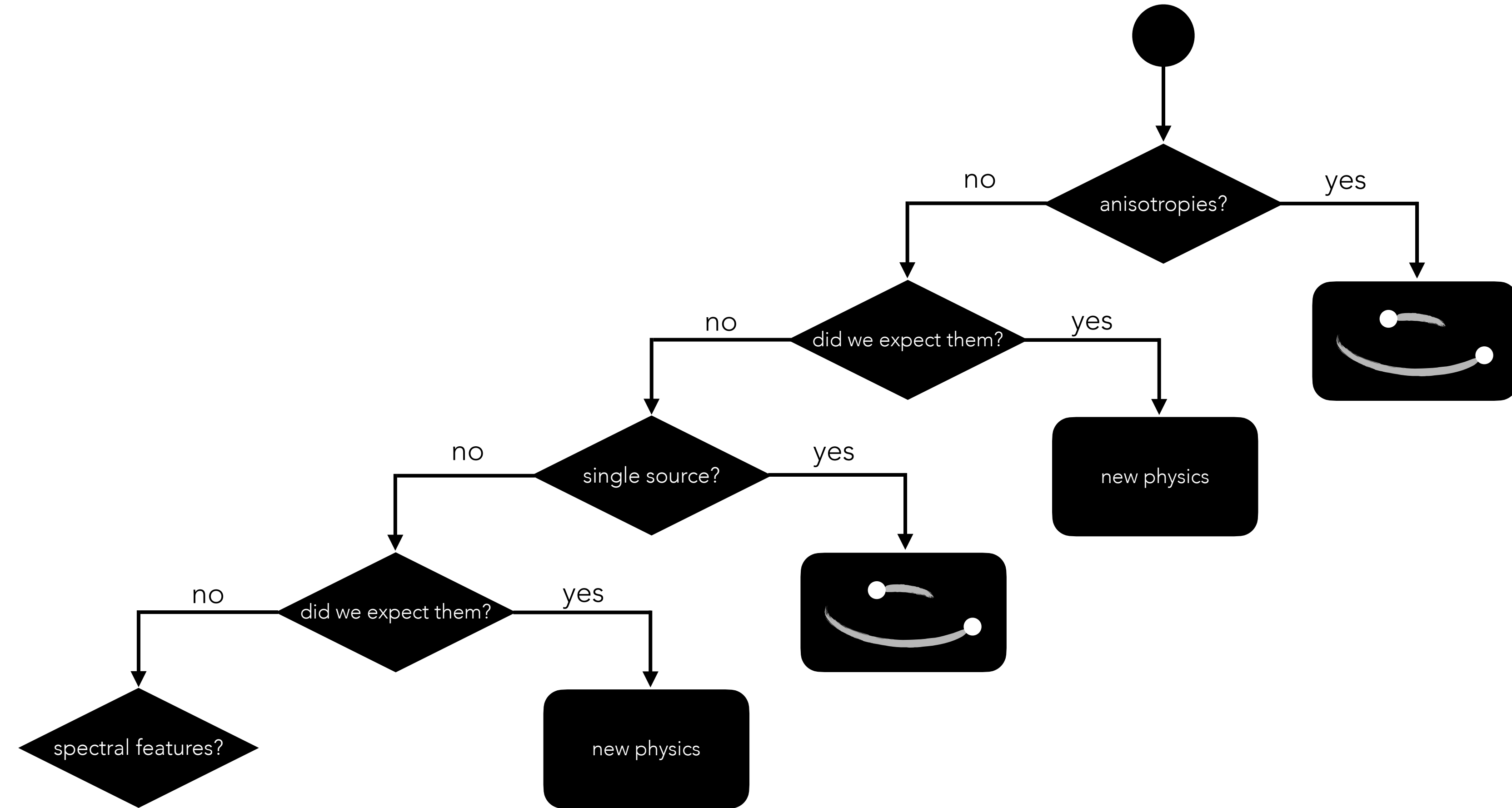
$e_0 = 0.50$



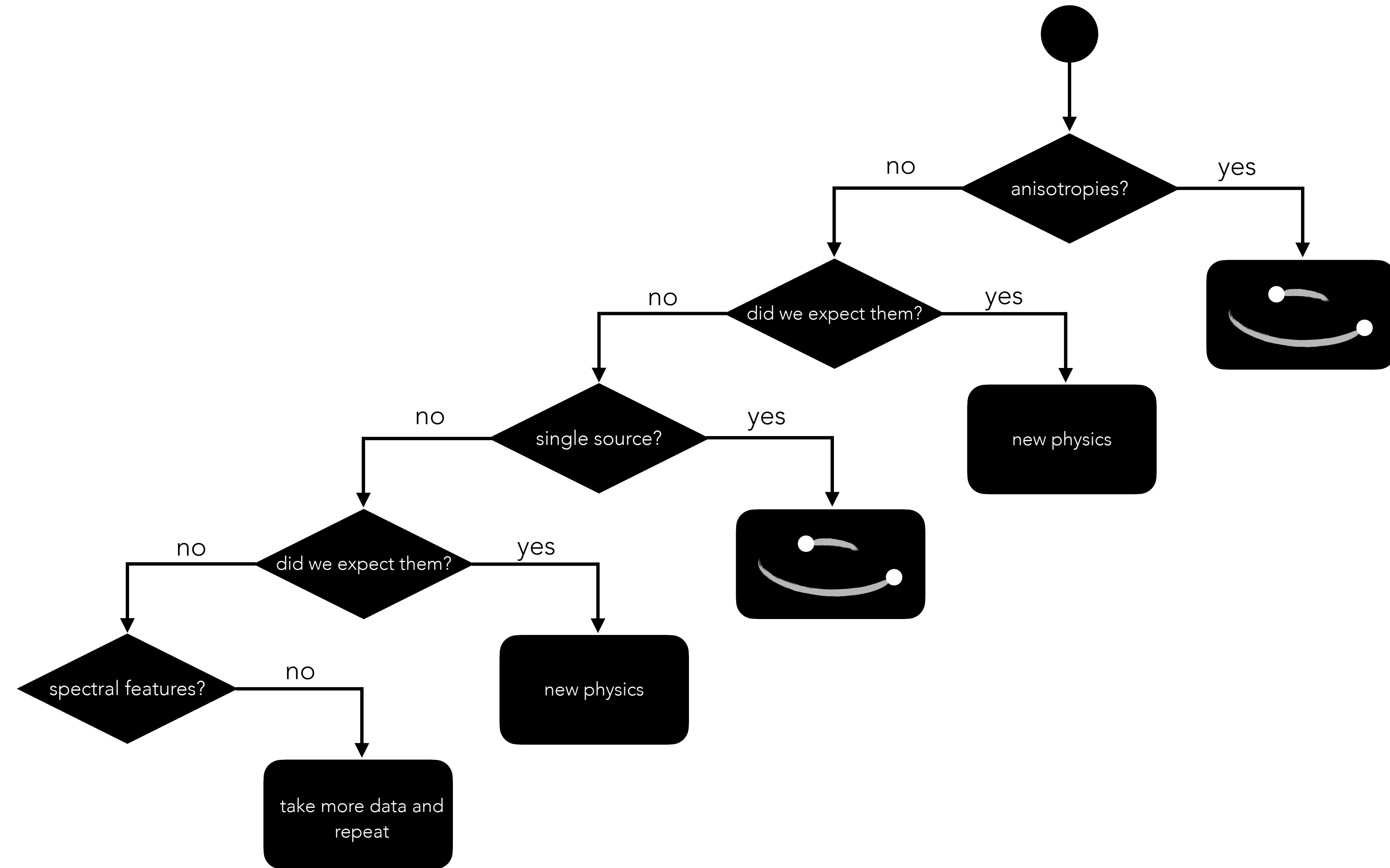
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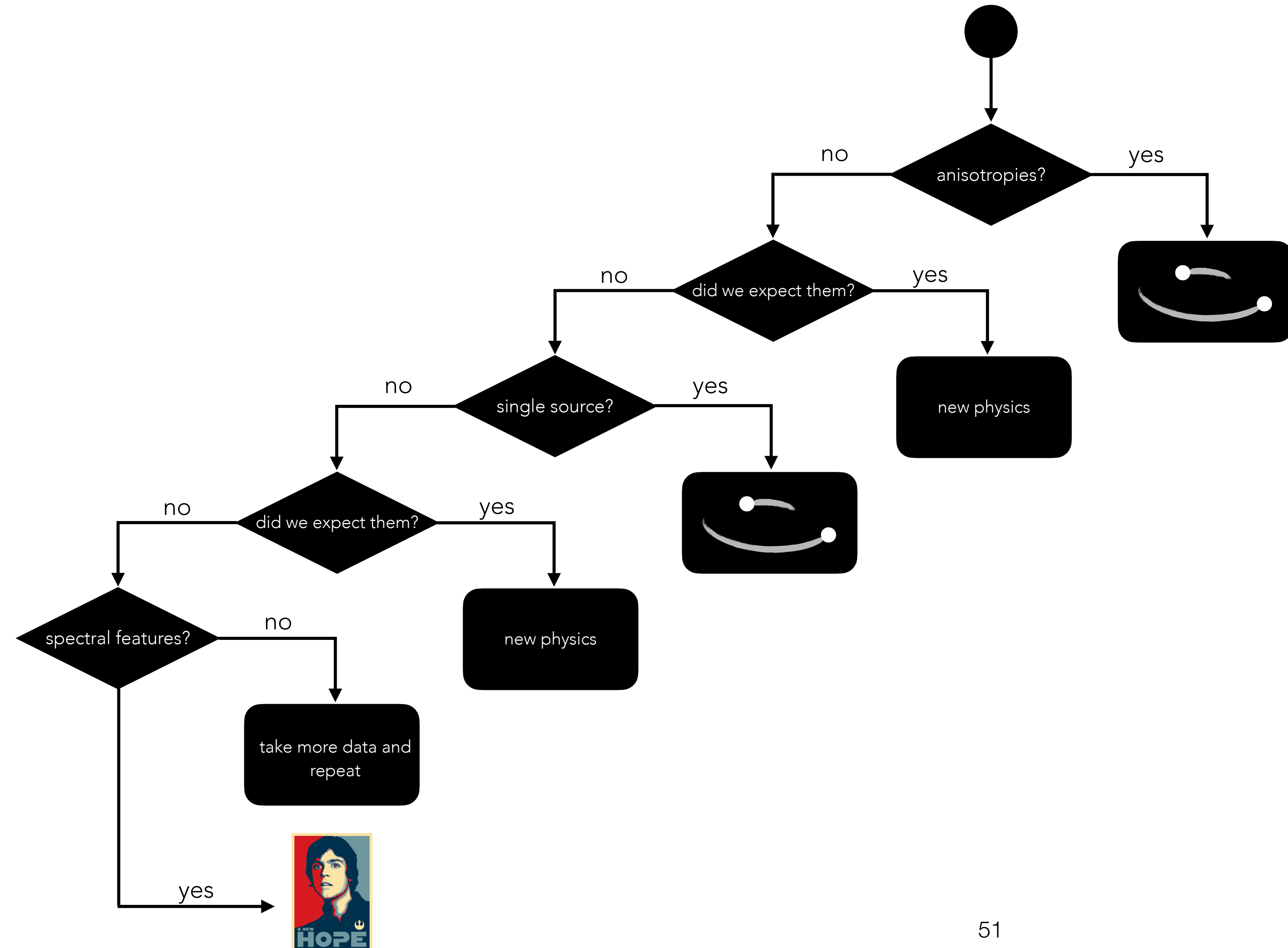
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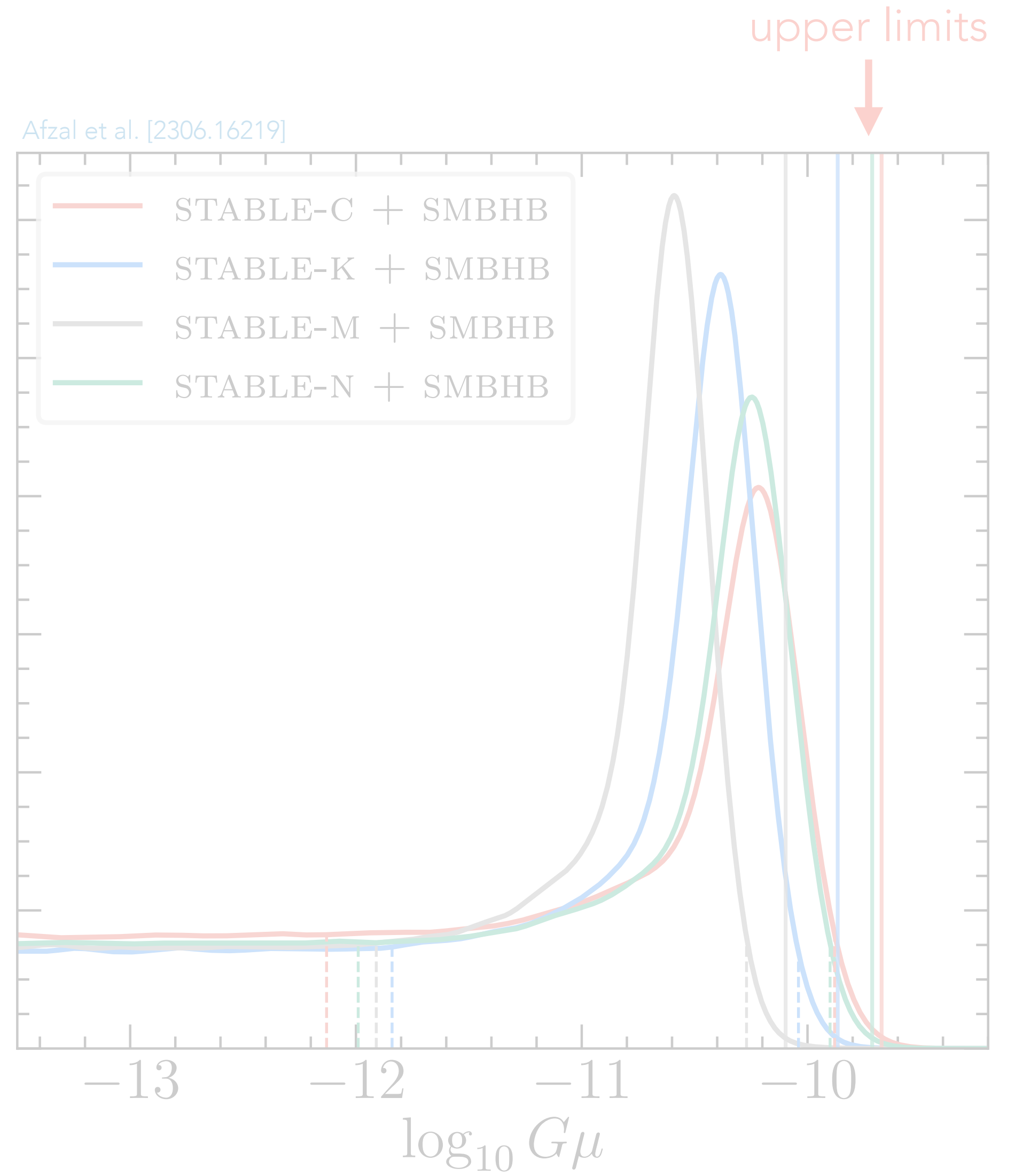
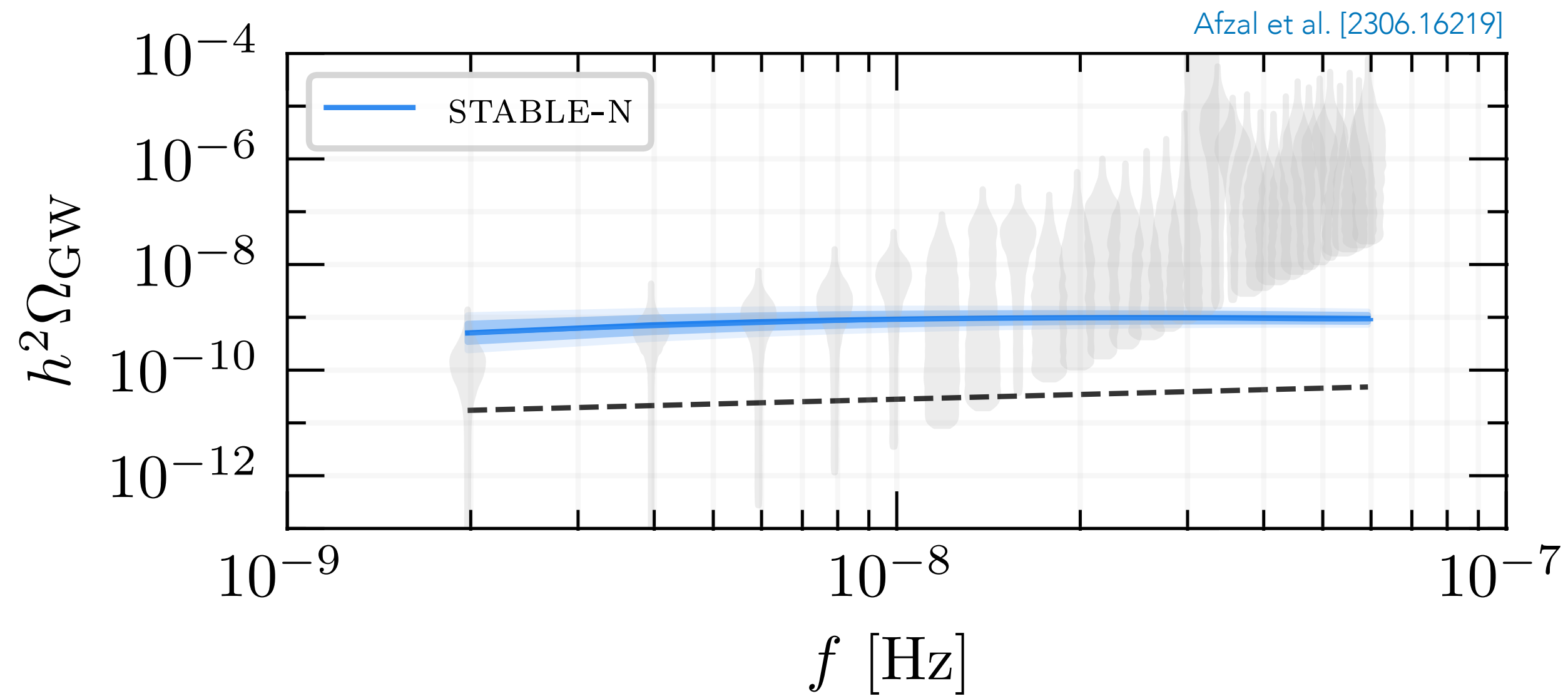
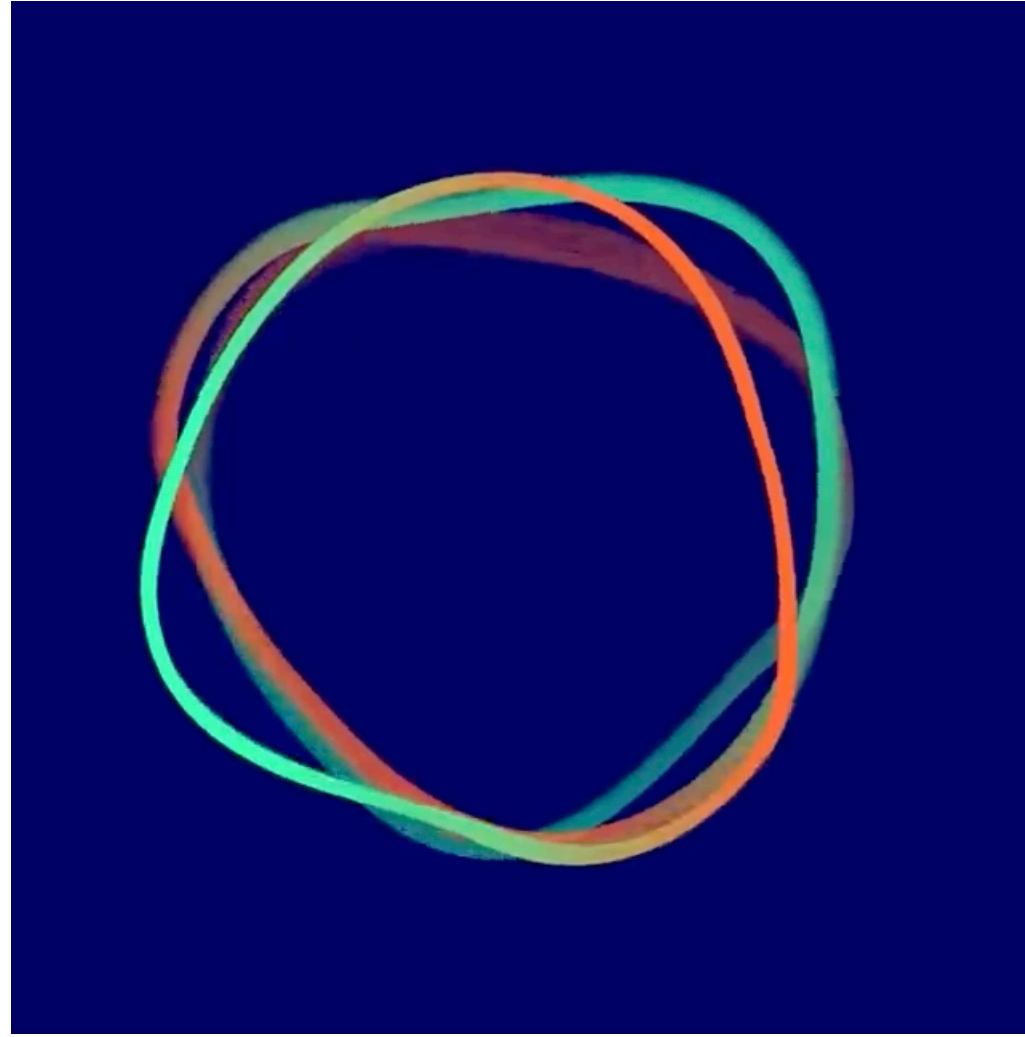


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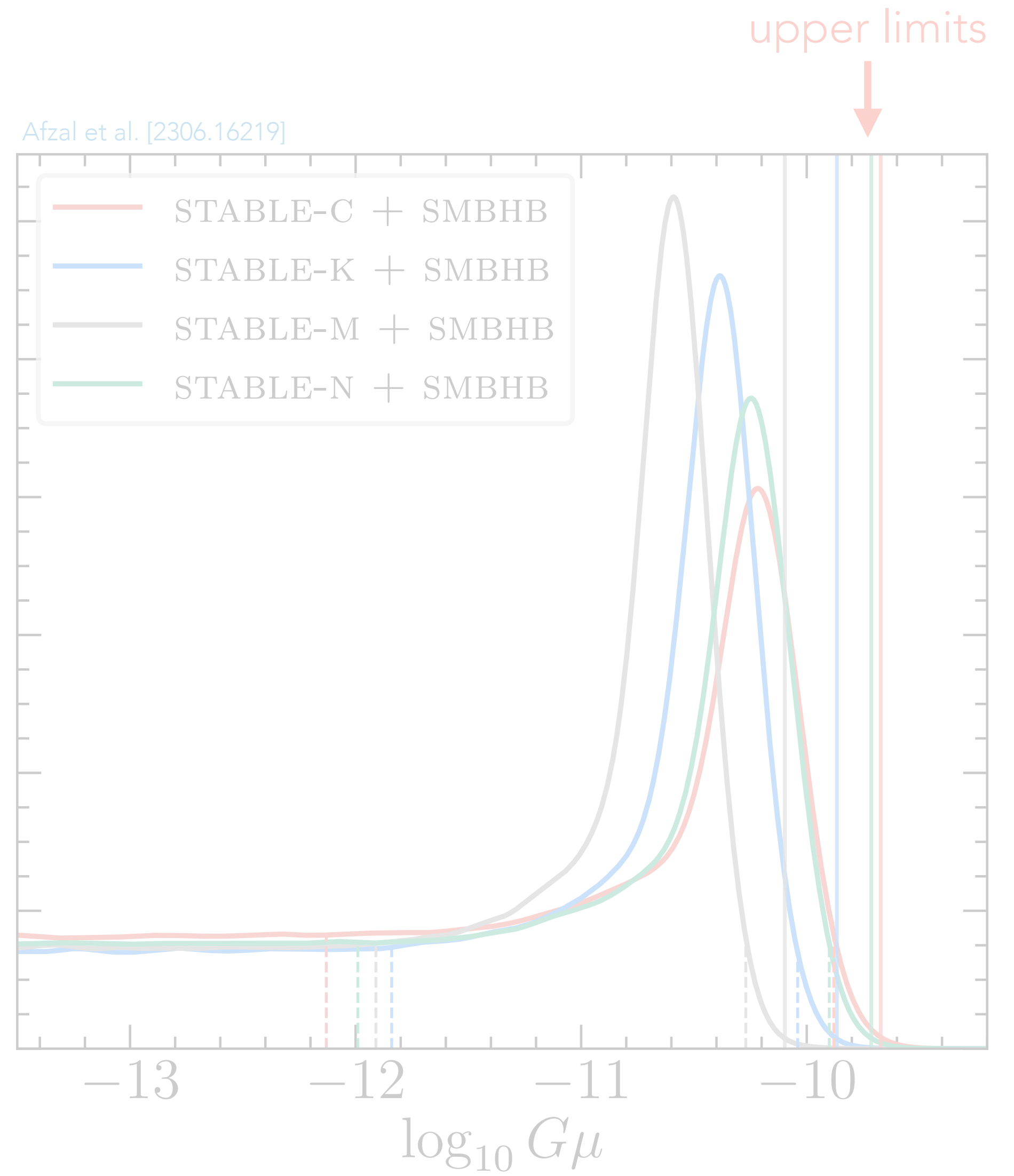
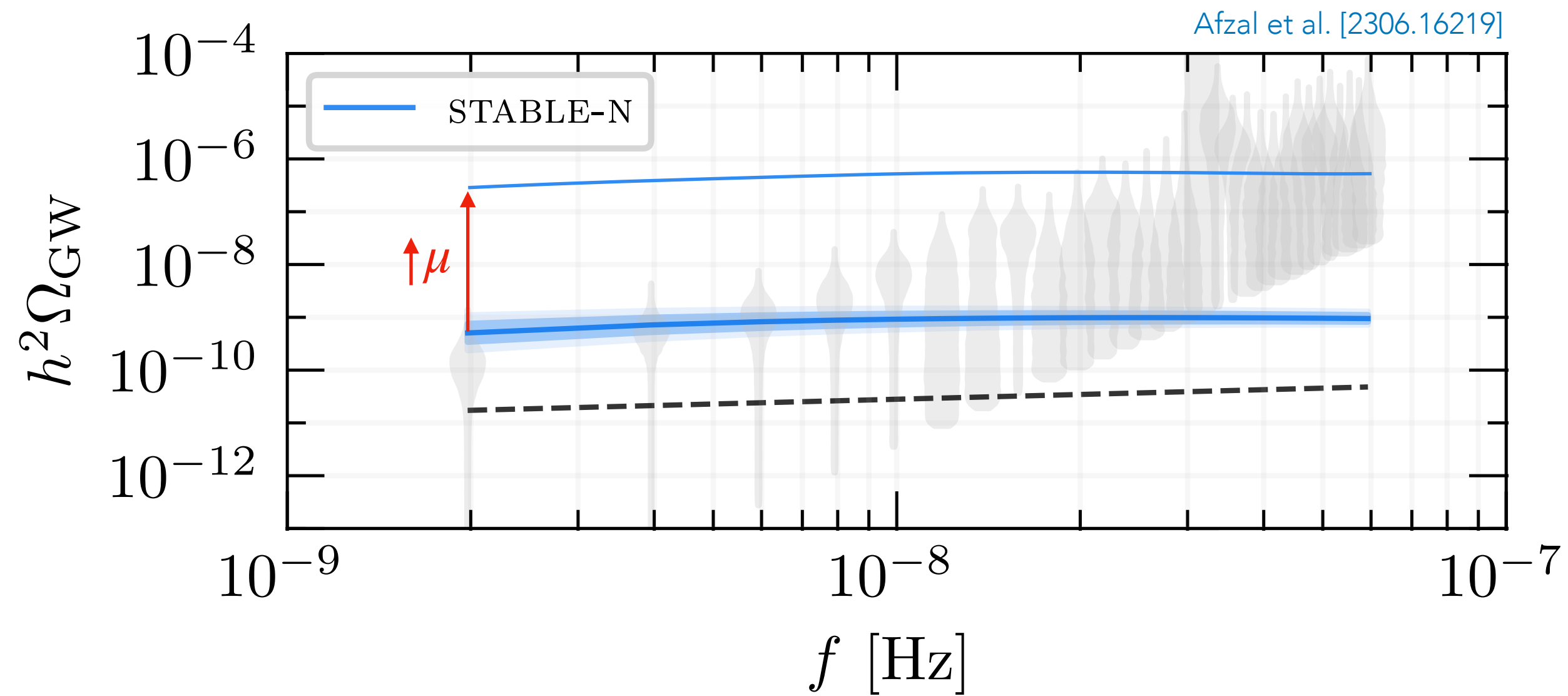
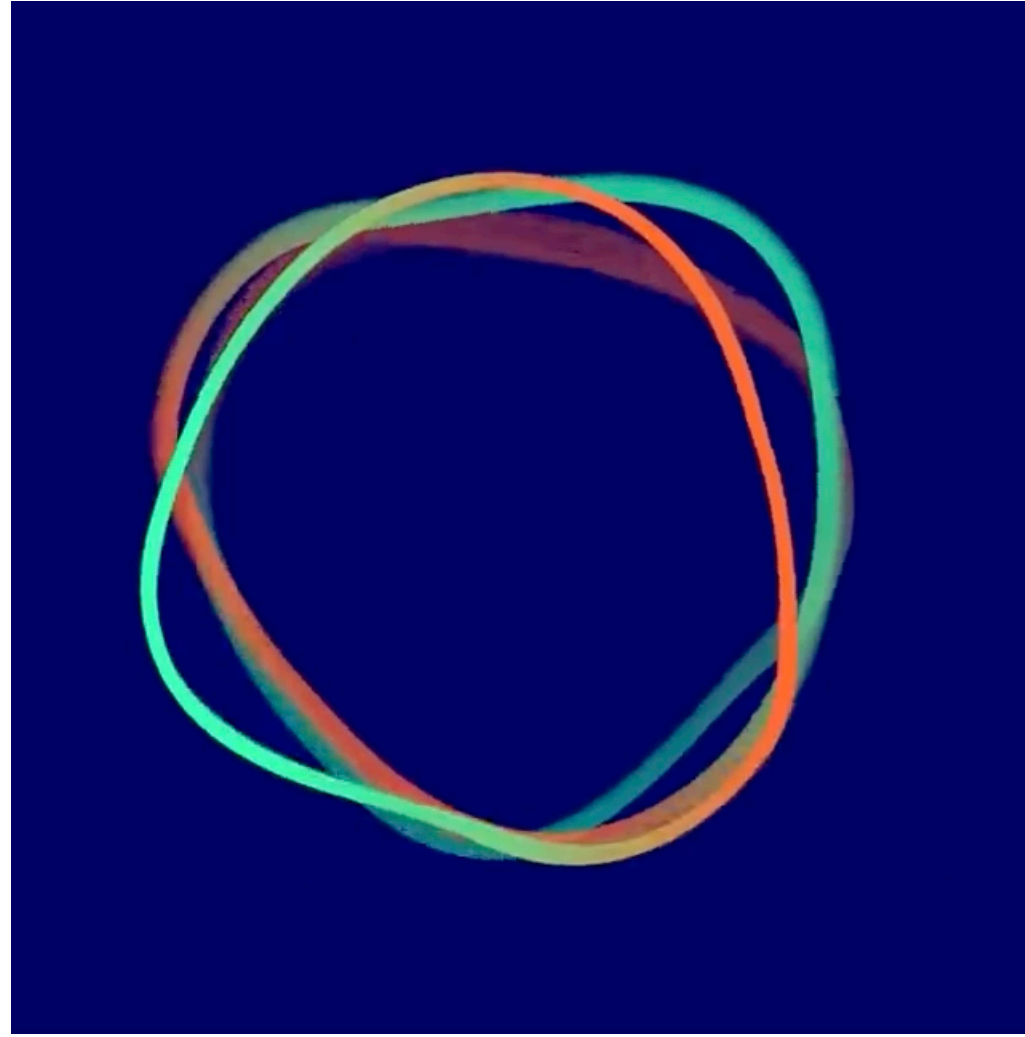


what if it's not new physics

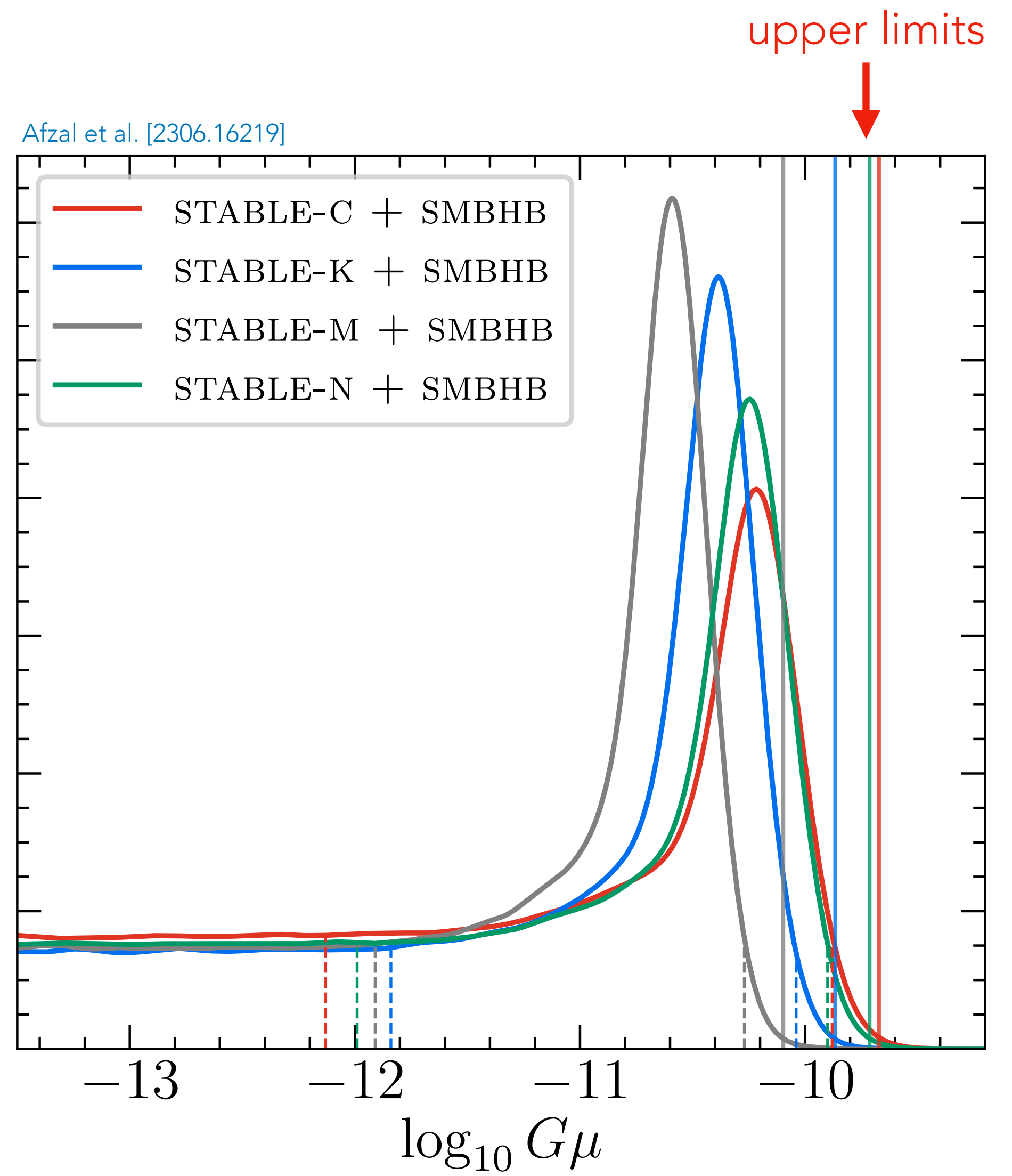
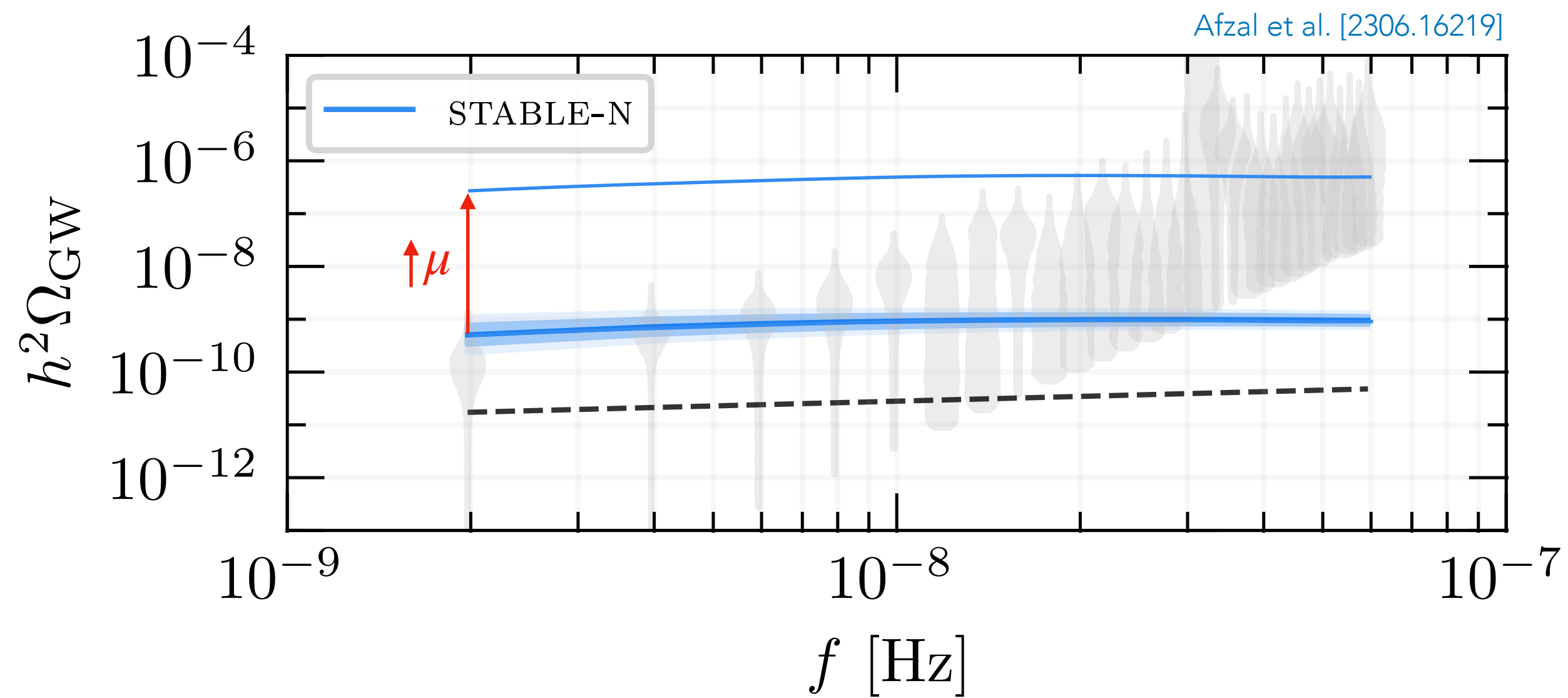
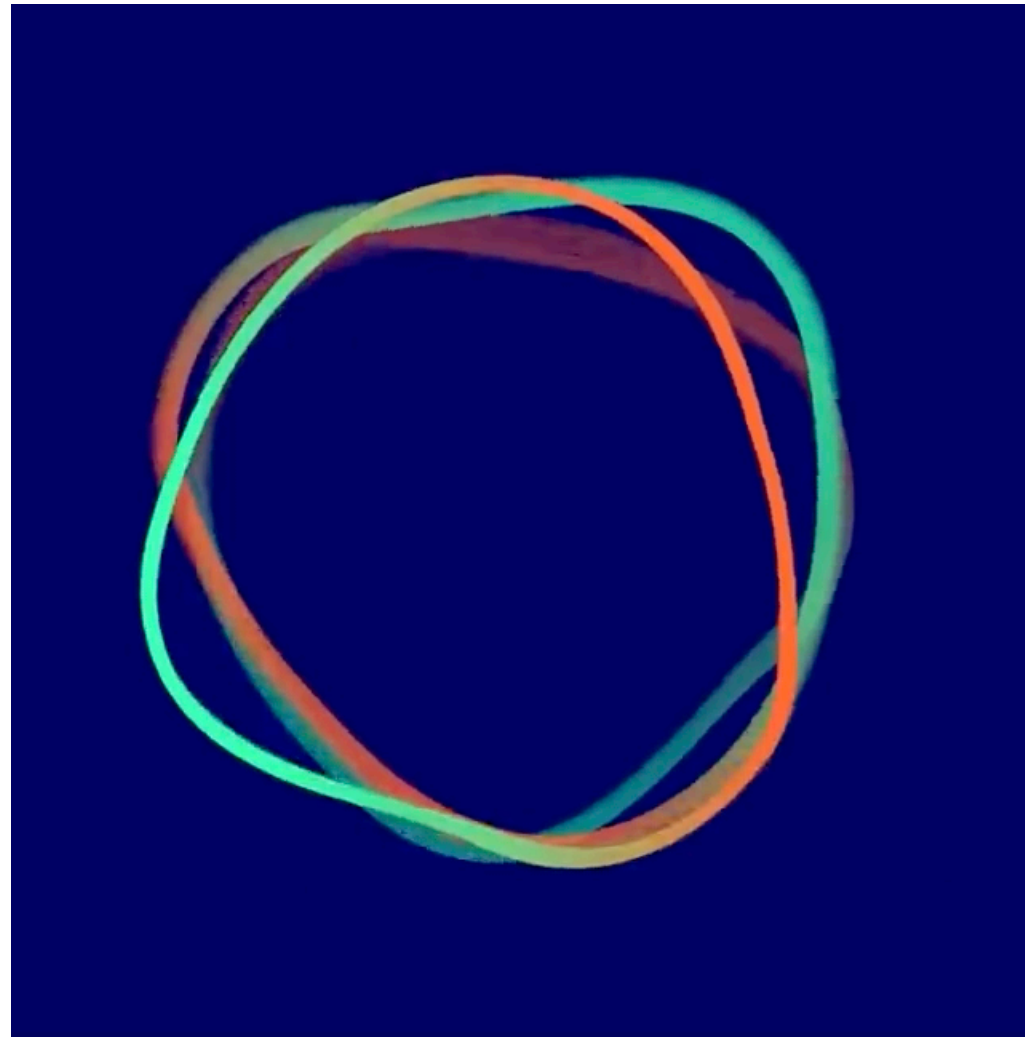
COSMIC STRINGS



COSMIC STRINGS



COSMIC STRINGS



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

DM density

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

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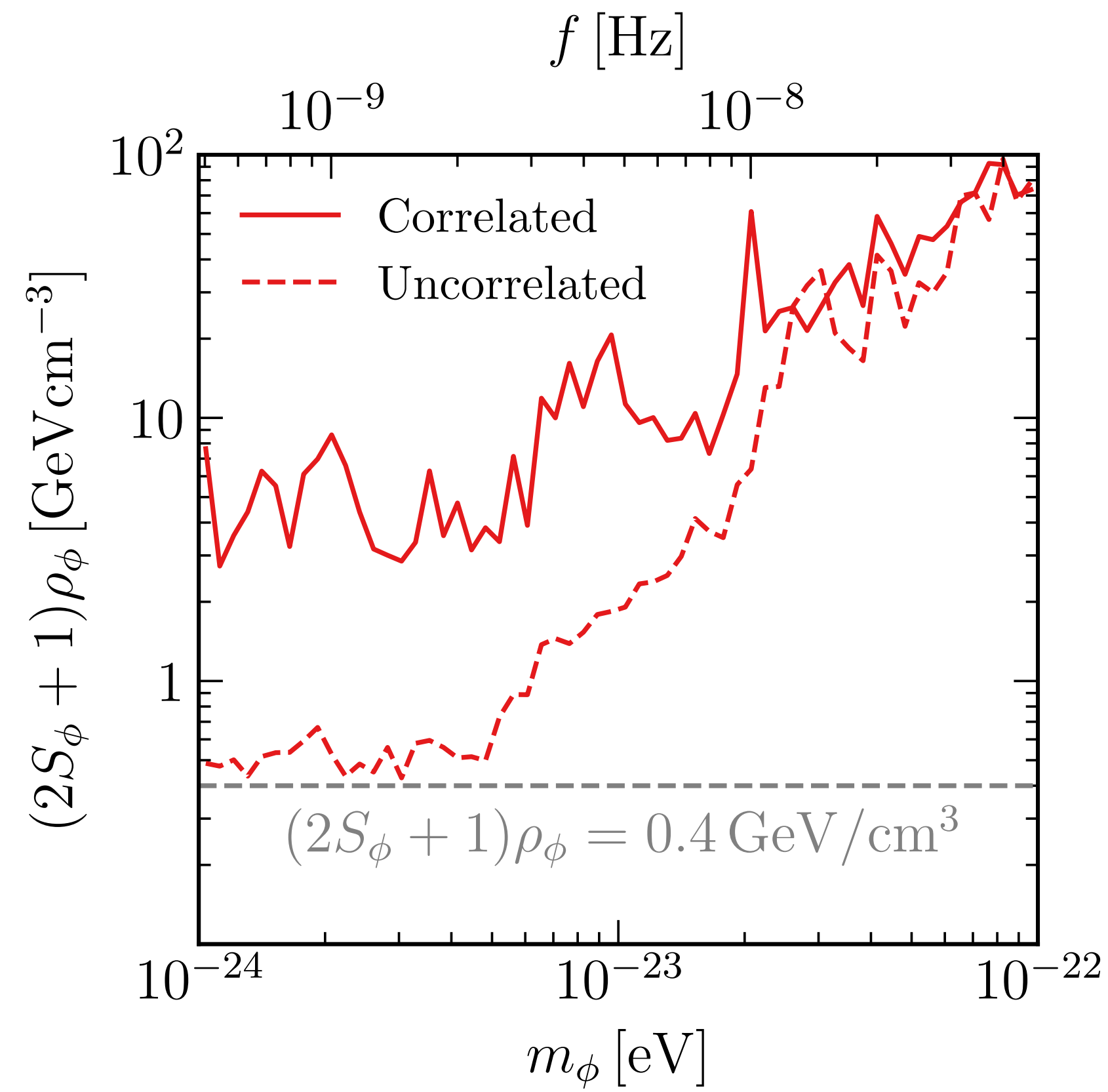
gravitational signal

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

[Khmelnitsky, Rubakov \[1309.5888\]](#)

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

Afzal et al. [2306.16219]



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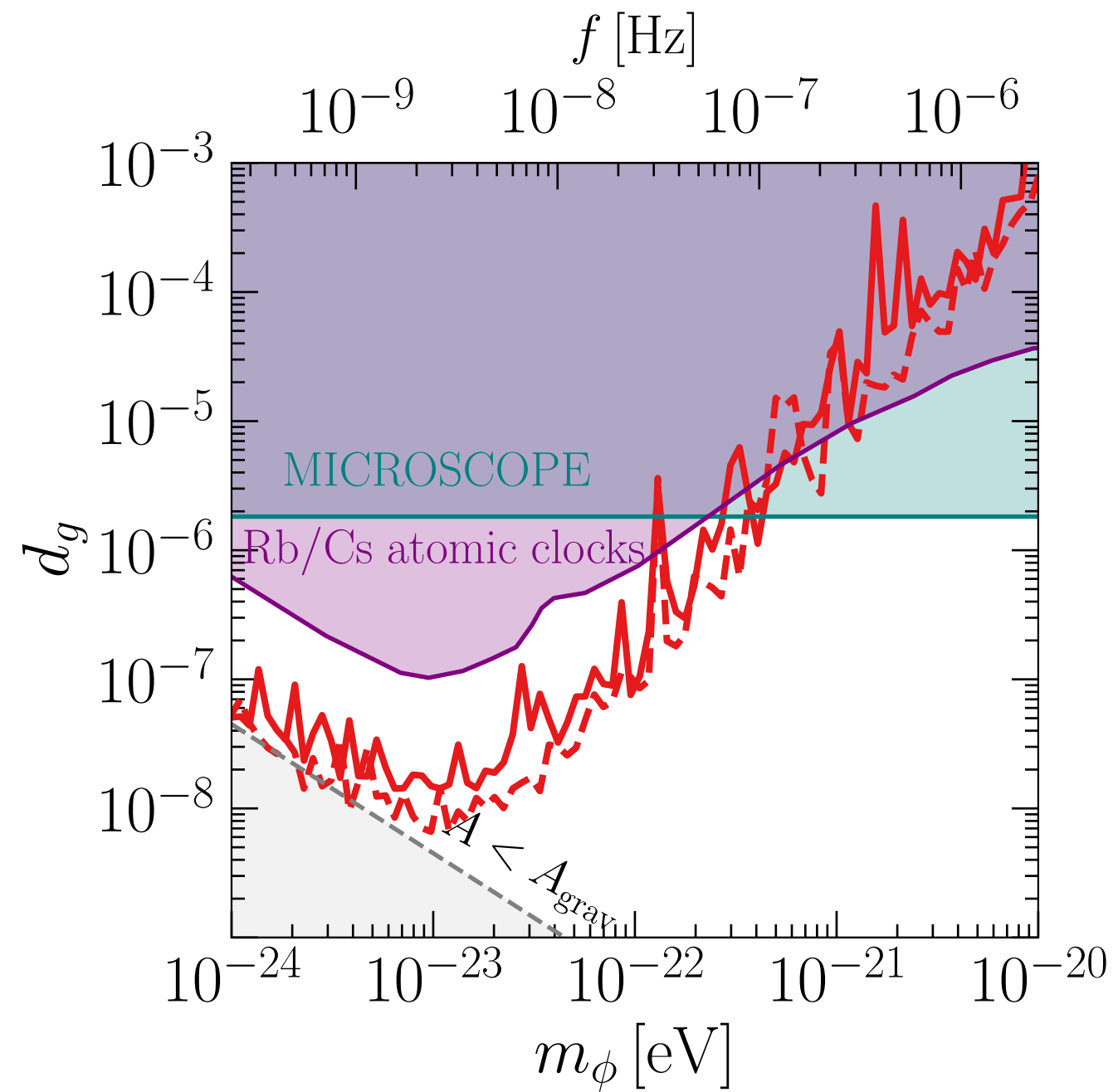
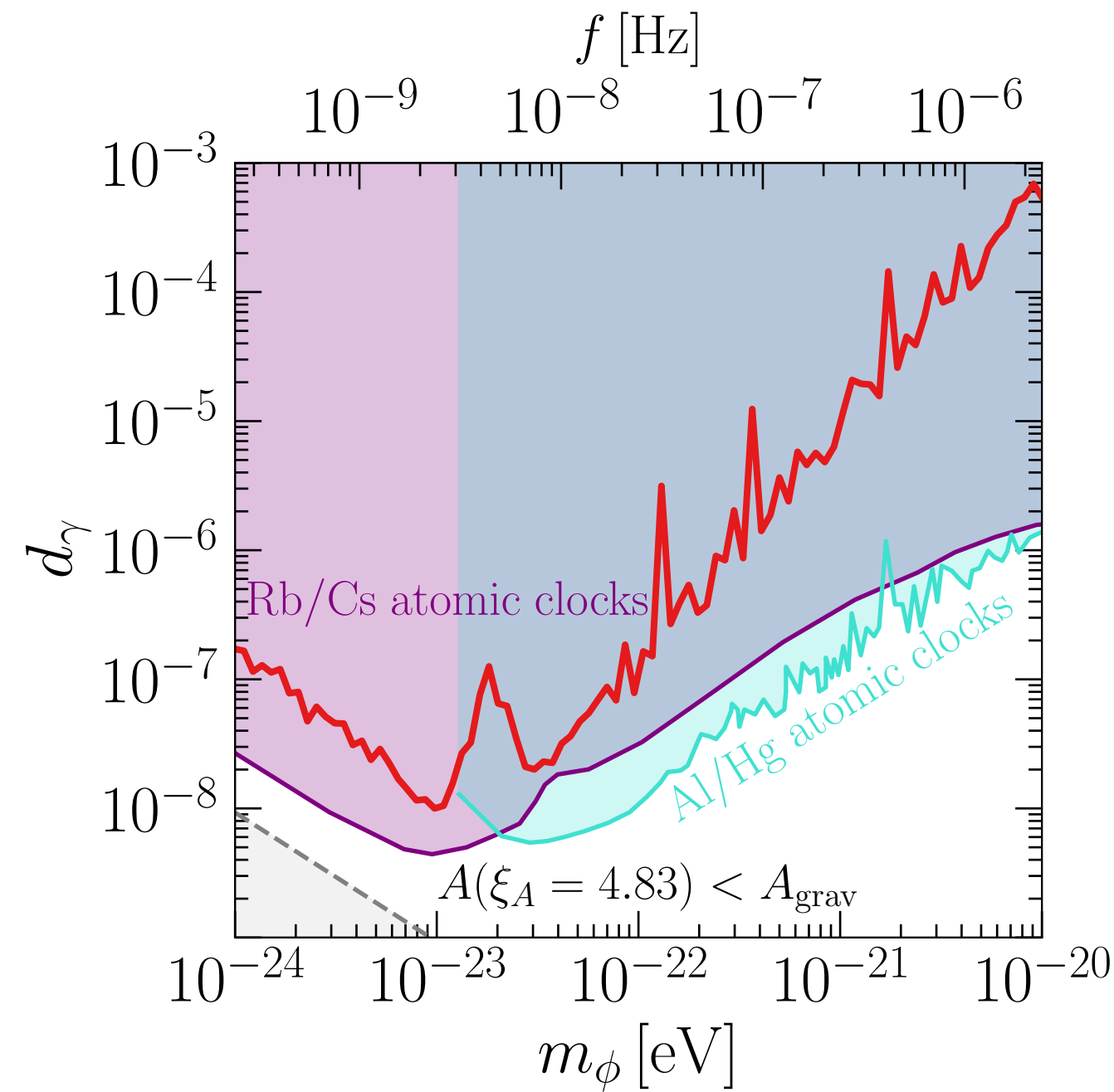
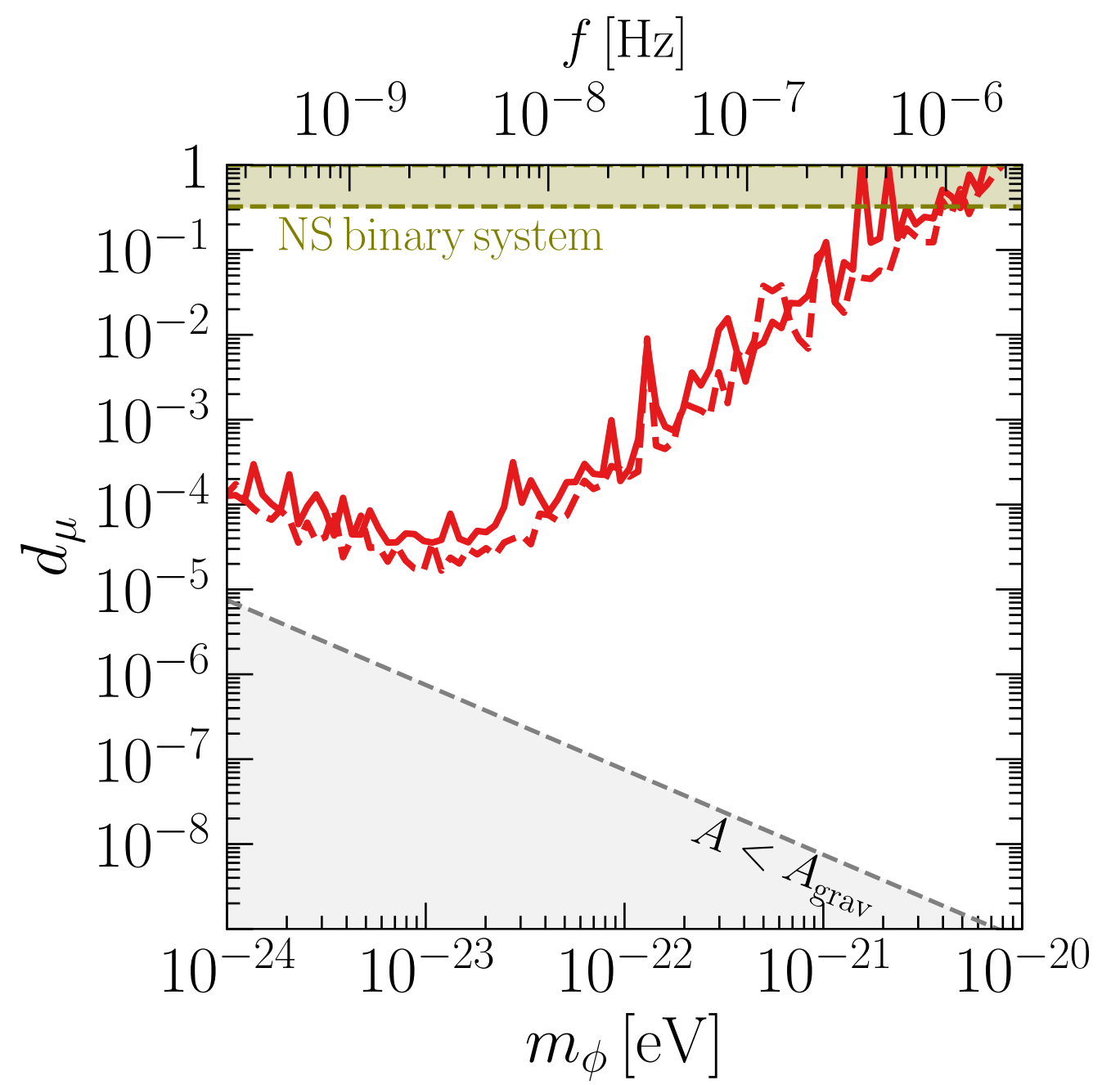
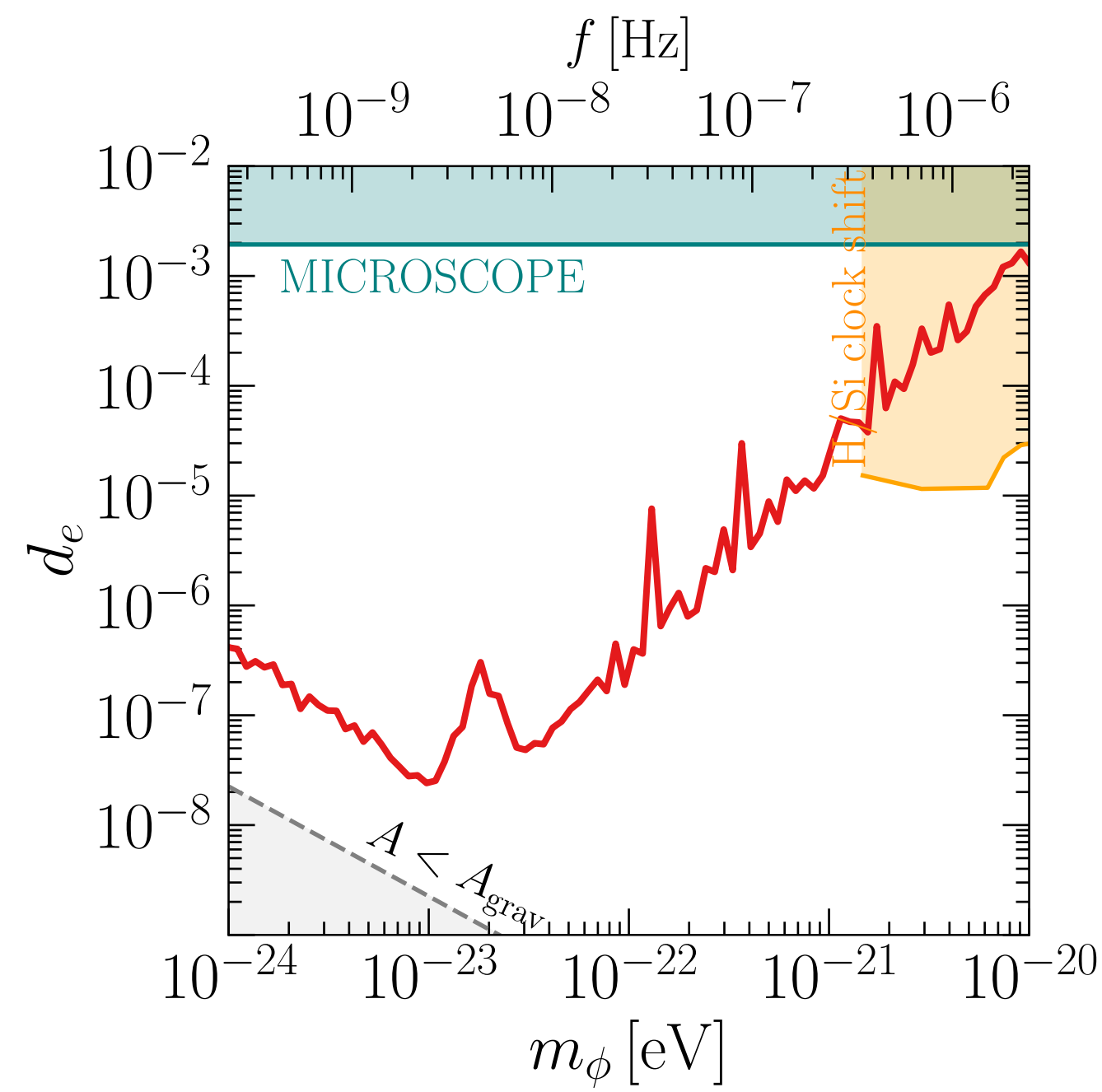
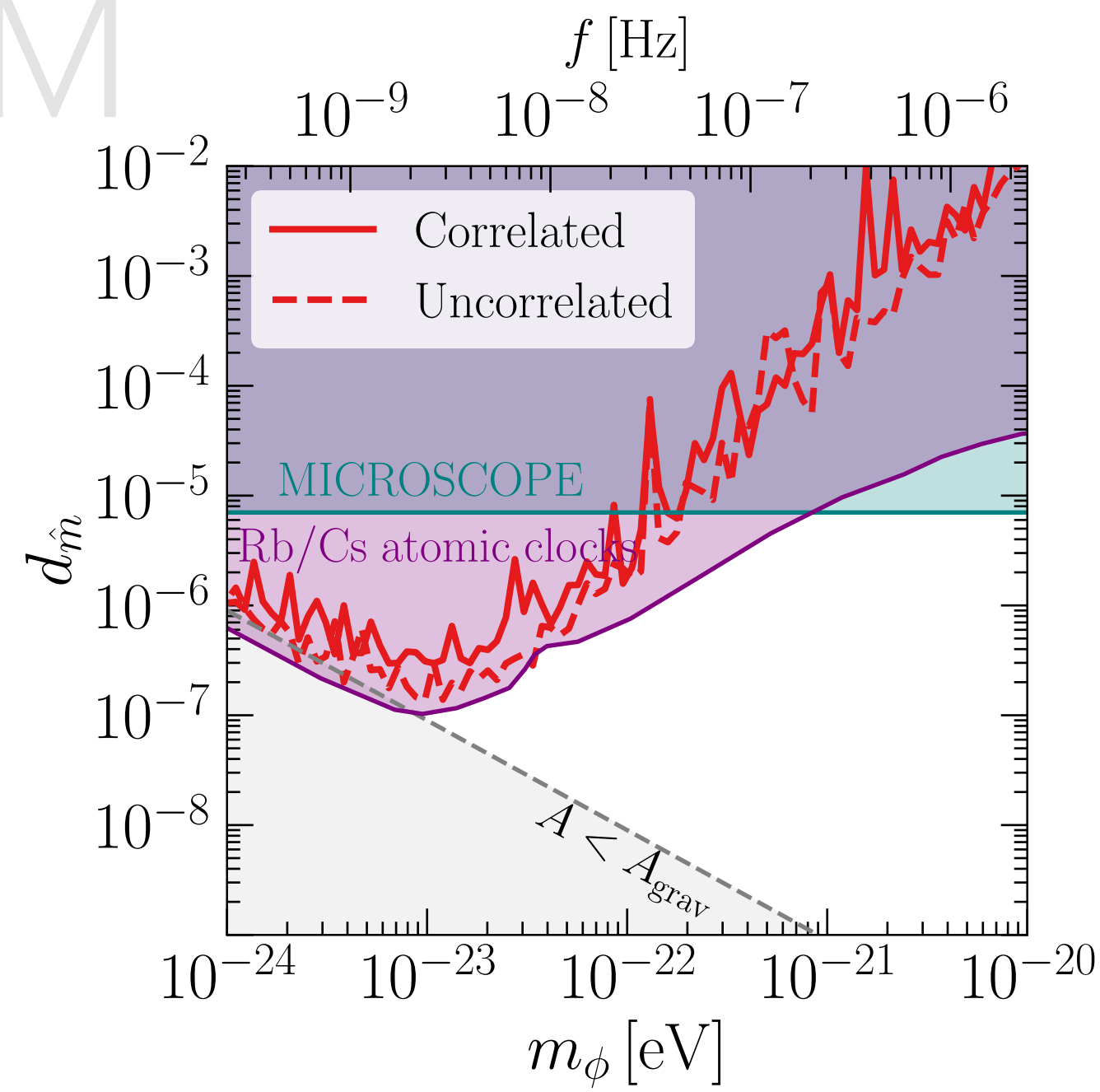
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[Khmelnitsky, Rubakov \[1309.5888\]](#)

direct coupling signals

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

[Kaplan, AM, Trickle \[2205.06817\]](#)



OUTLOOK

- strong evidence for a GWB in the nHz band

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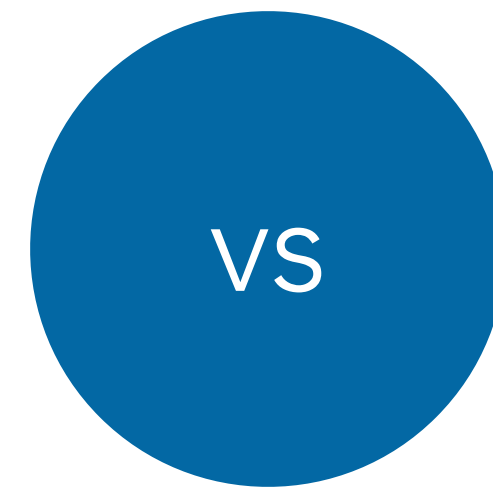
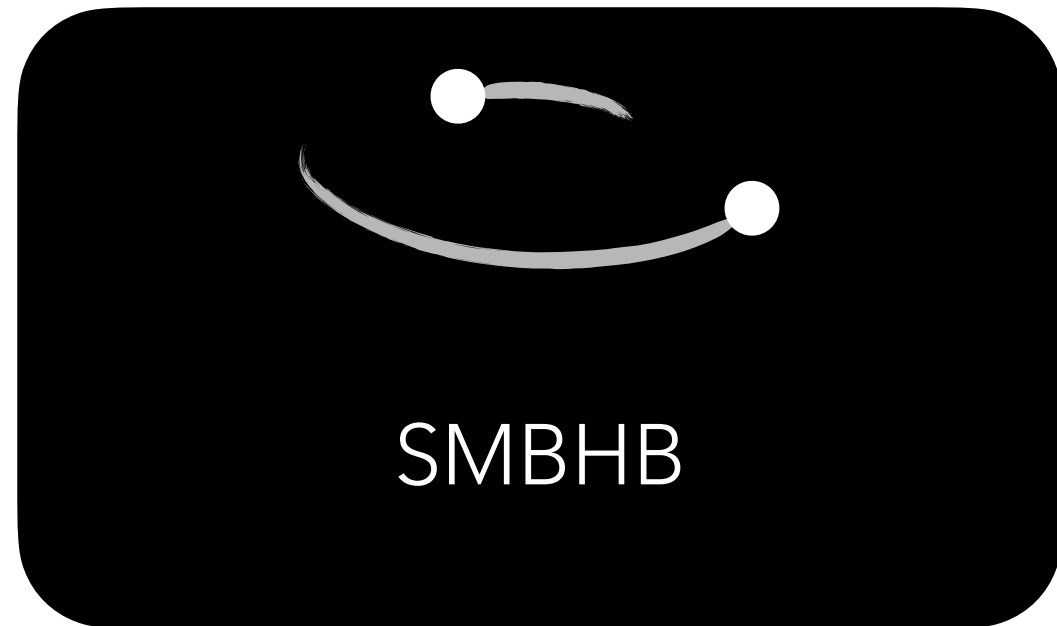
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- SMBH or cosmological signal? still unclear
- anisotropies and CW searches will help discriminating
- precise estimates of detection probabilities are needed
- PTAs can be used to set tight constraints on NP models

backup

FACE-OFF



inflation

scalar induced GW

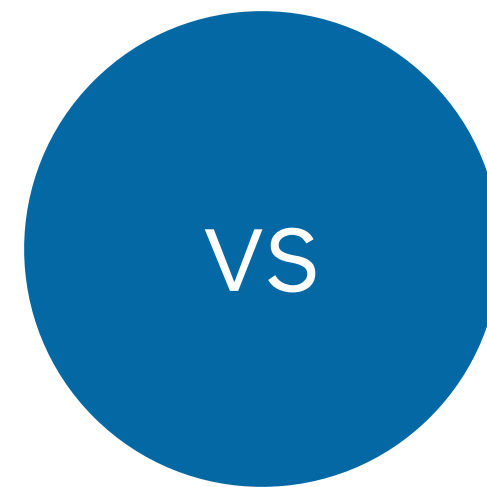
phase transitions

cosmic strings

domain walls

FACE-OFF

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



inflation

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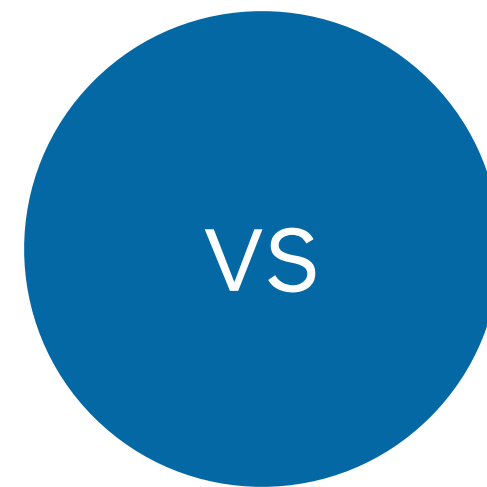
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free parameters



inflation

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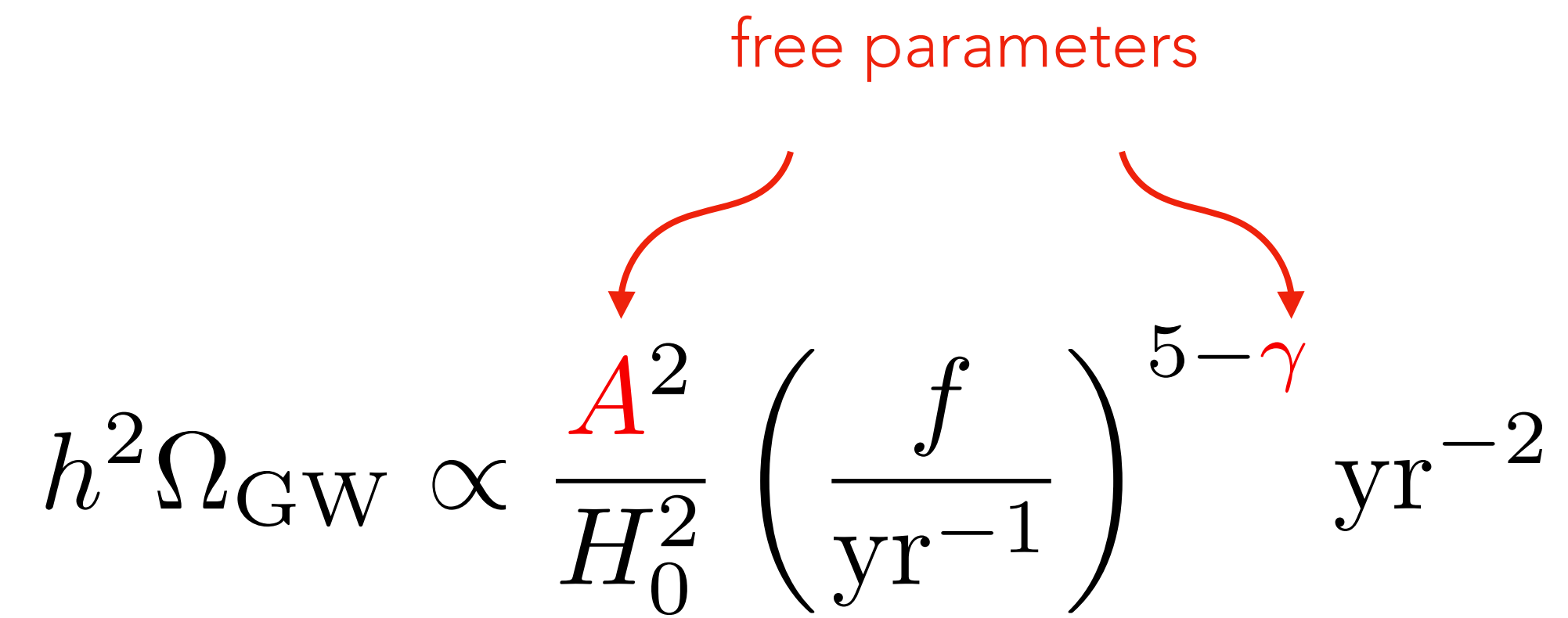
cosmic strings

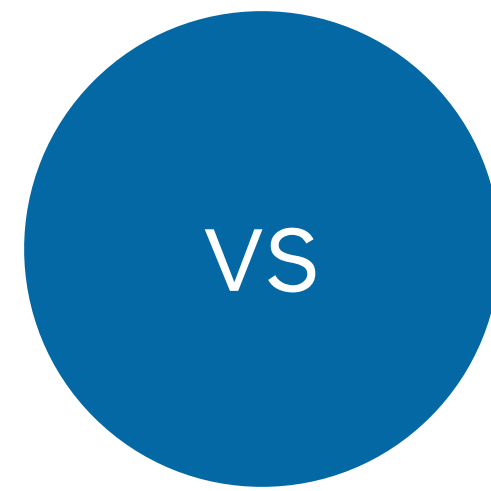
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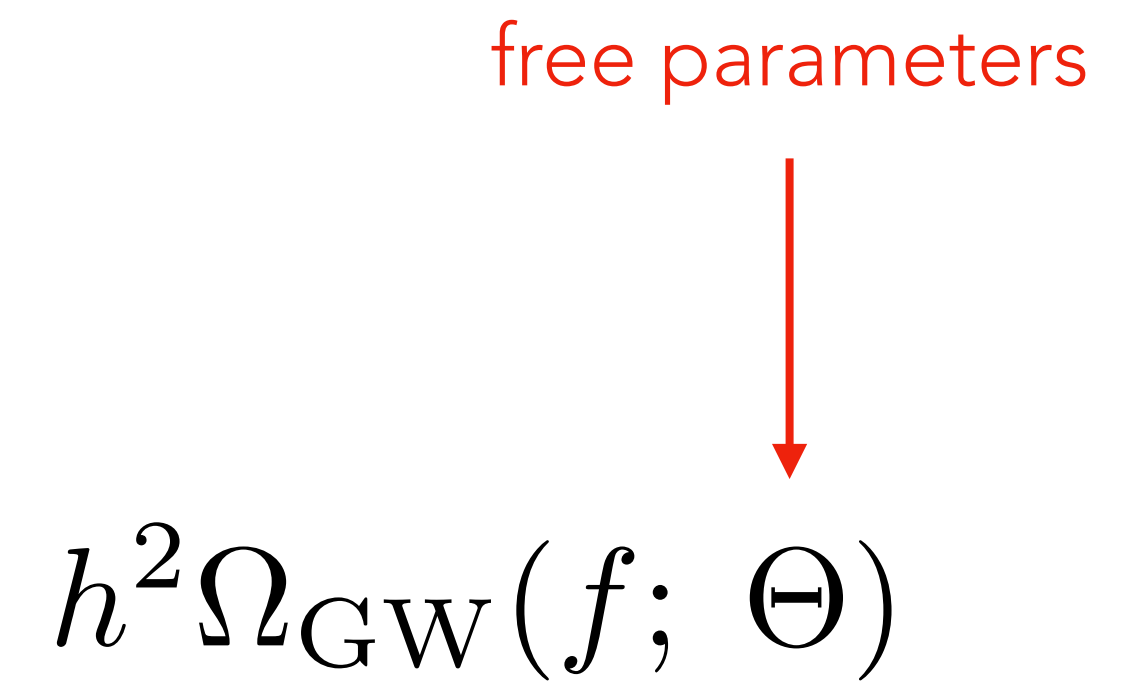
free parameters





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

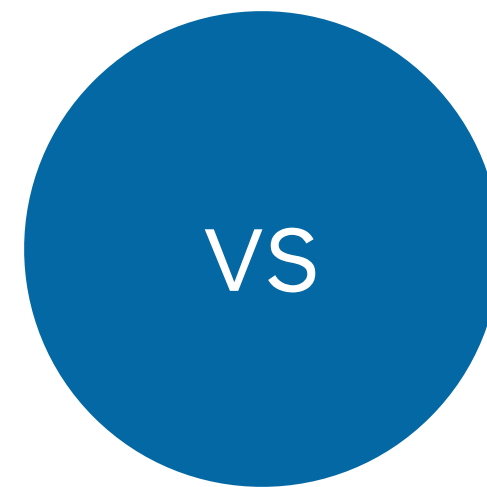
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FACE-OFF

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free parameters



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

free parameters

FACE-OFF

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

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

FACE-OFF

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likelihood function

FACE-OFF

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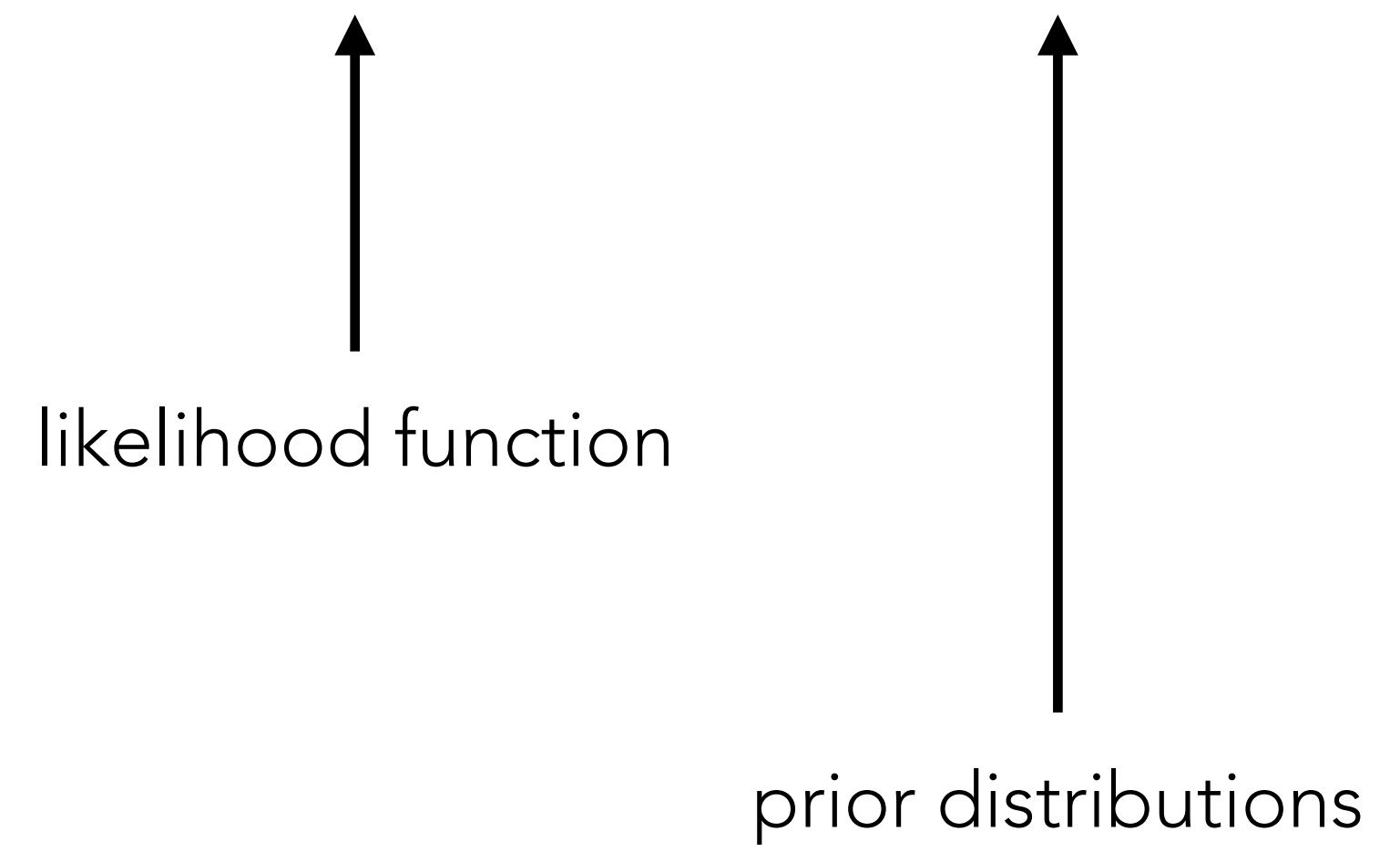
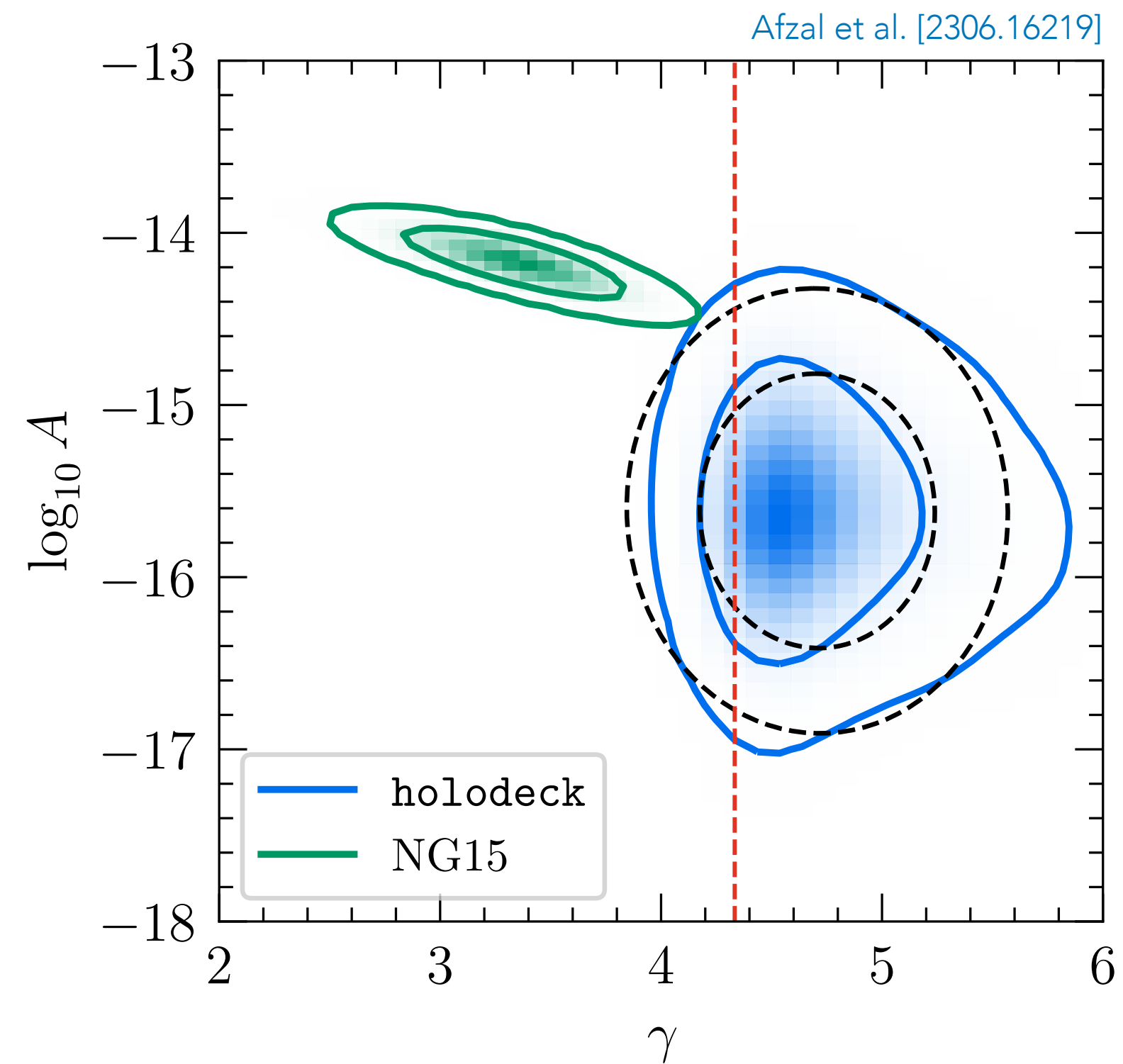
↑
likelihood function

↑
prior distributions

FACE-OFF

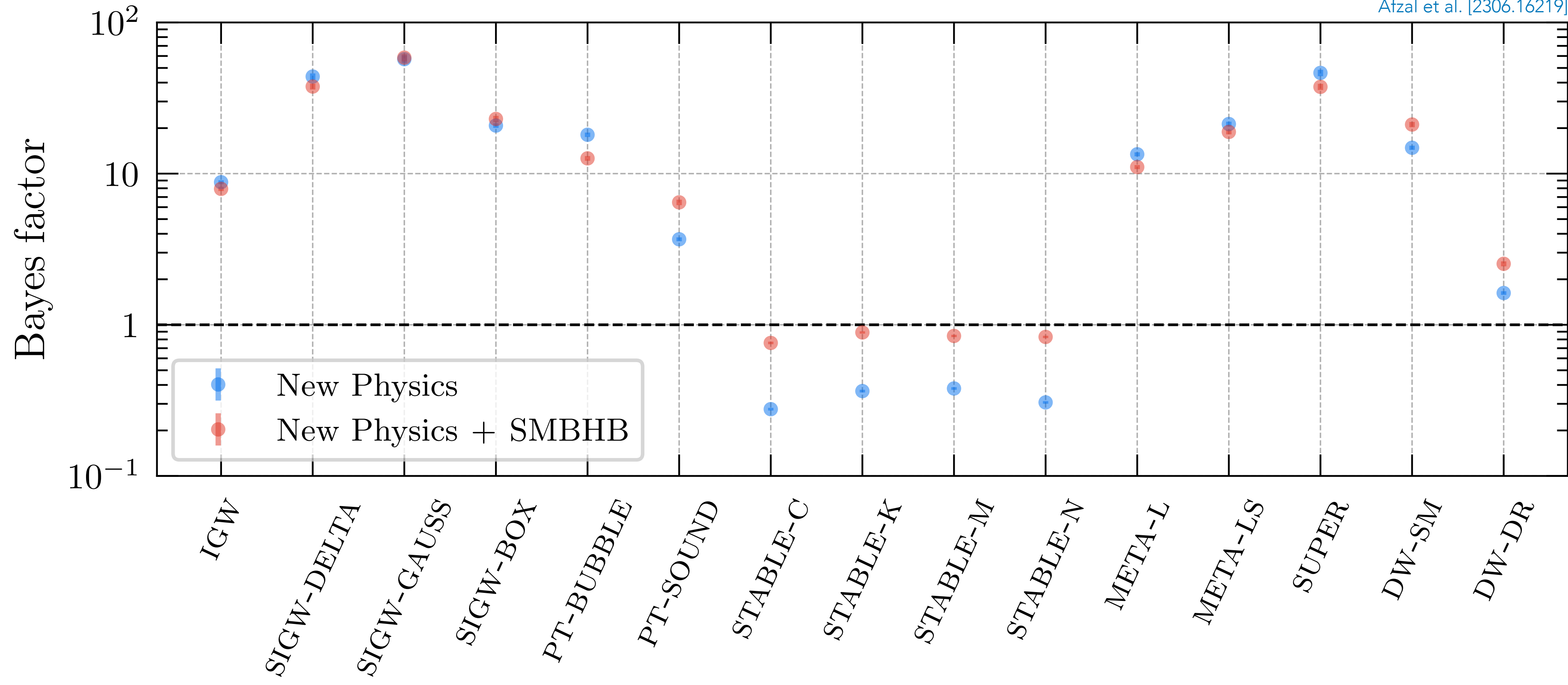
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FACE-OFF

Afzal et al. [2306.16219]



toy model

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

Step 1

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pip install ptarcade
```

Step 2

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from ptarcade.models_utils import prior

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

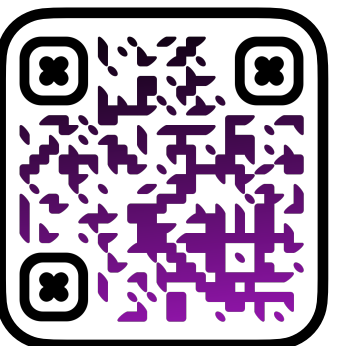
def S(x):
    return 1 / (1/x + x)

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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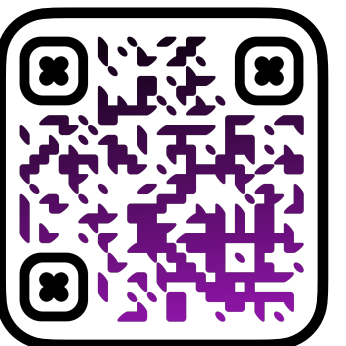
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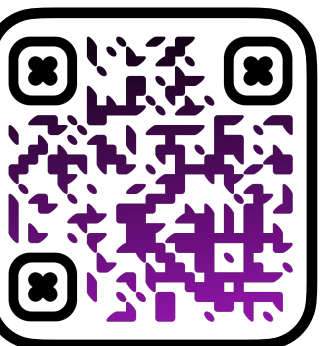
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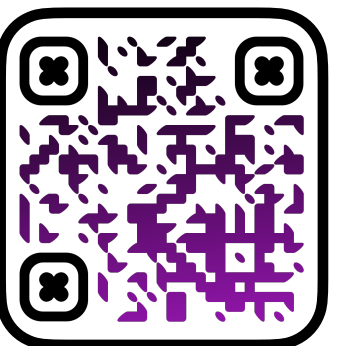
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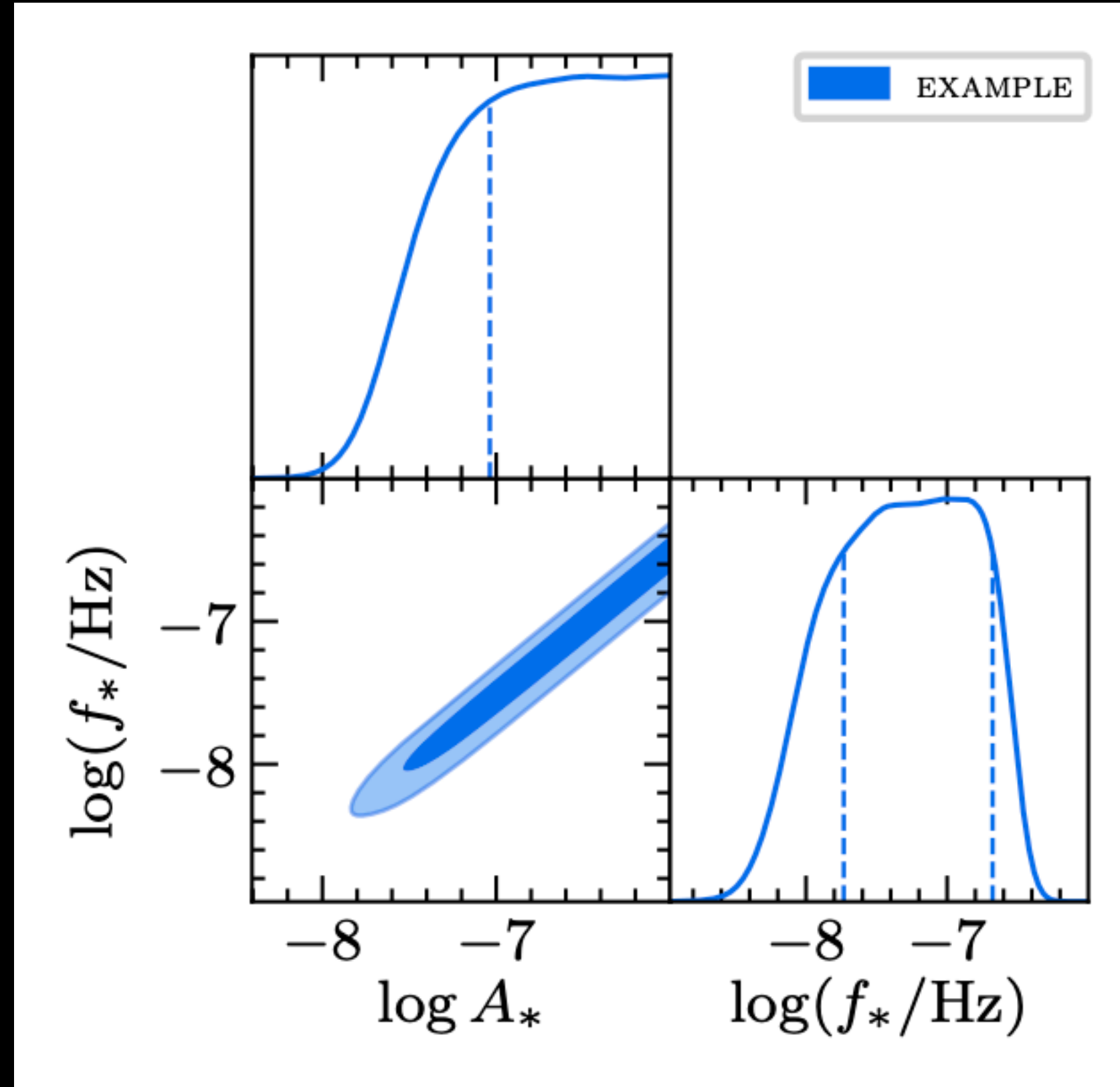
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