Probing New Physics with Pulsar Timing Arrays

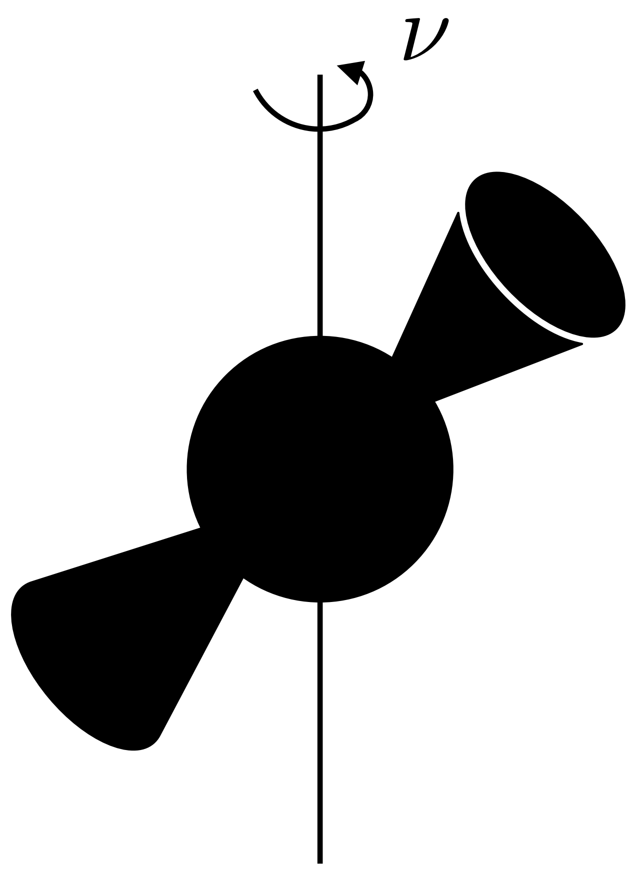
Andrea Mitridate

Caltech

based on: 2205.06817, 2104.13930, and work in progress with D. E. Kaplan, T. Trickle, and NANOGrav collab.

NANOGrav Physics Frontiers Center

PULSARS AS COSMIC CLOCKS

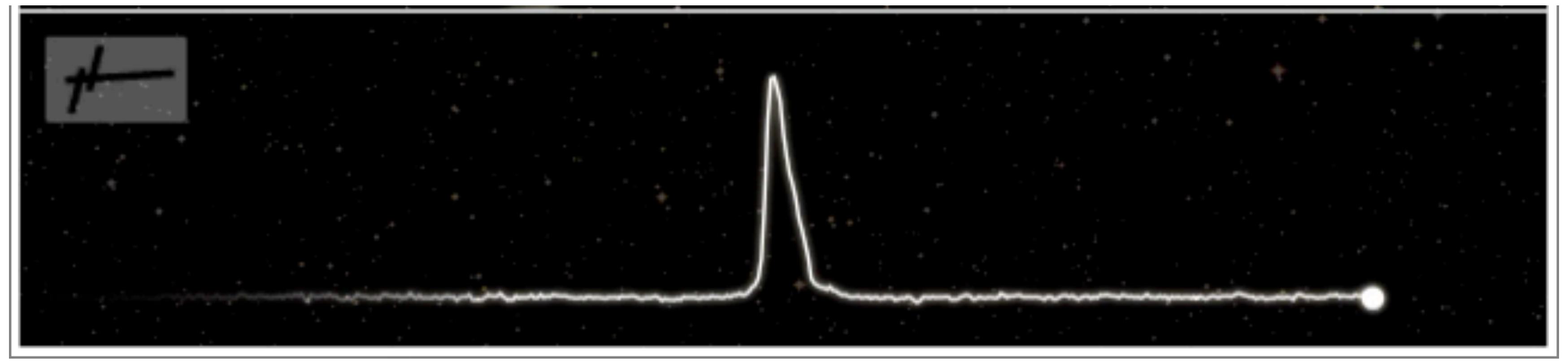


we see a pulse of radiation each time a full rotation is completed

$$\phi \equiv \int \nu(t)dt = \text{integer}$$

for millisecond pulsar the rotation frequency is extremely stable

$$\nu(t) = \nu_0 + \dot{\nu}_0 \, t \qquad\qquad \nu_0/\dot{\nu}_0 \sim 10^{-23} - 10^{-20}\,\text{Hz}$$



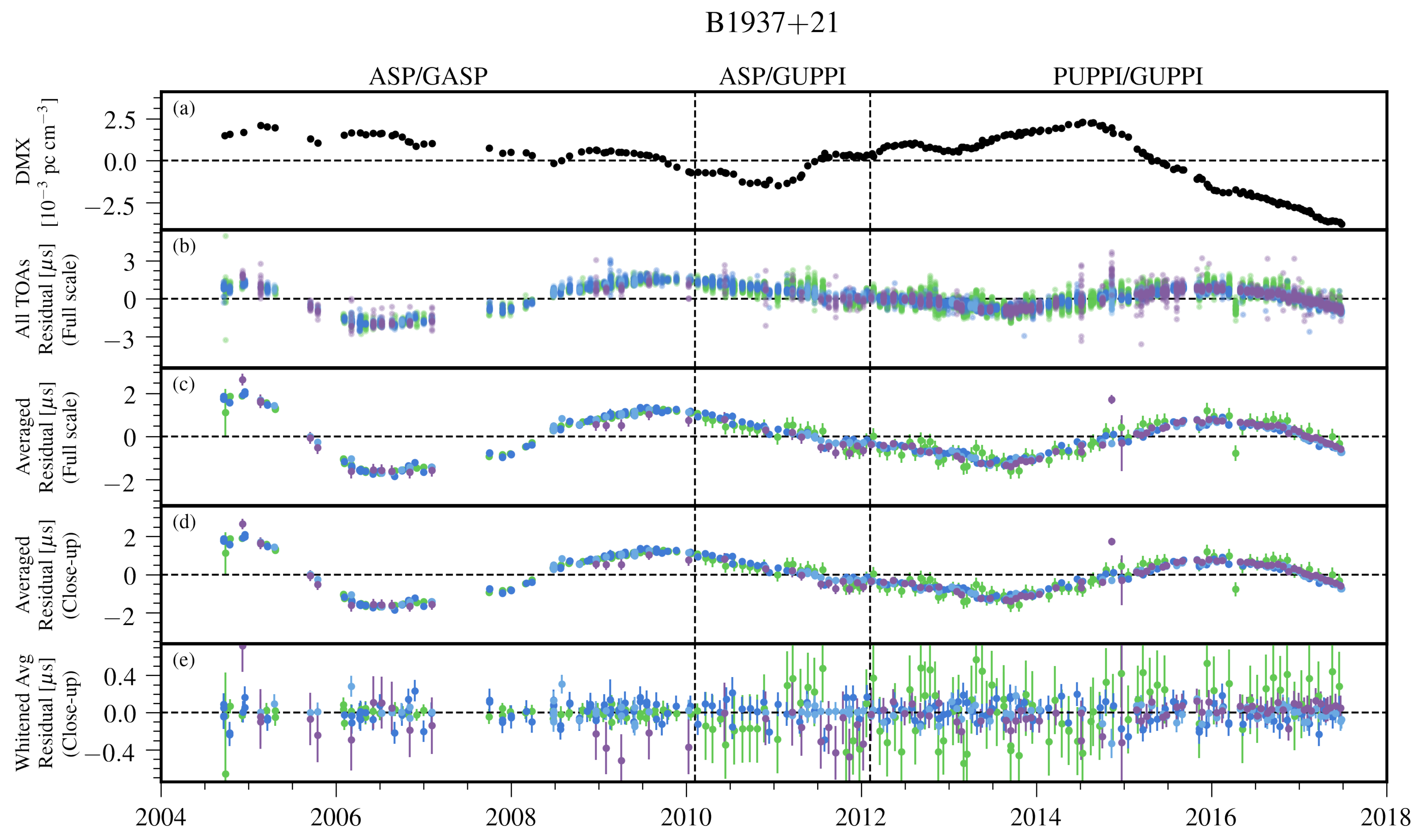
the pulse arrival times, $\vec{t}_{\text{TOA},p}$, can be accurately determined

timing residuals

$$\vec{\delta t} \equiv \vec{t}_{\text{TOA}} - \vec{t}_{\text{TOA},p}$$

THE TIMING RESIDUALS

$$\vec{\delta t} = \vec{n} + \mathbf{F}\vec{a} + \mathbf{M}\vec{\epsilon} + \vec{h}(\vec{\theta})$$



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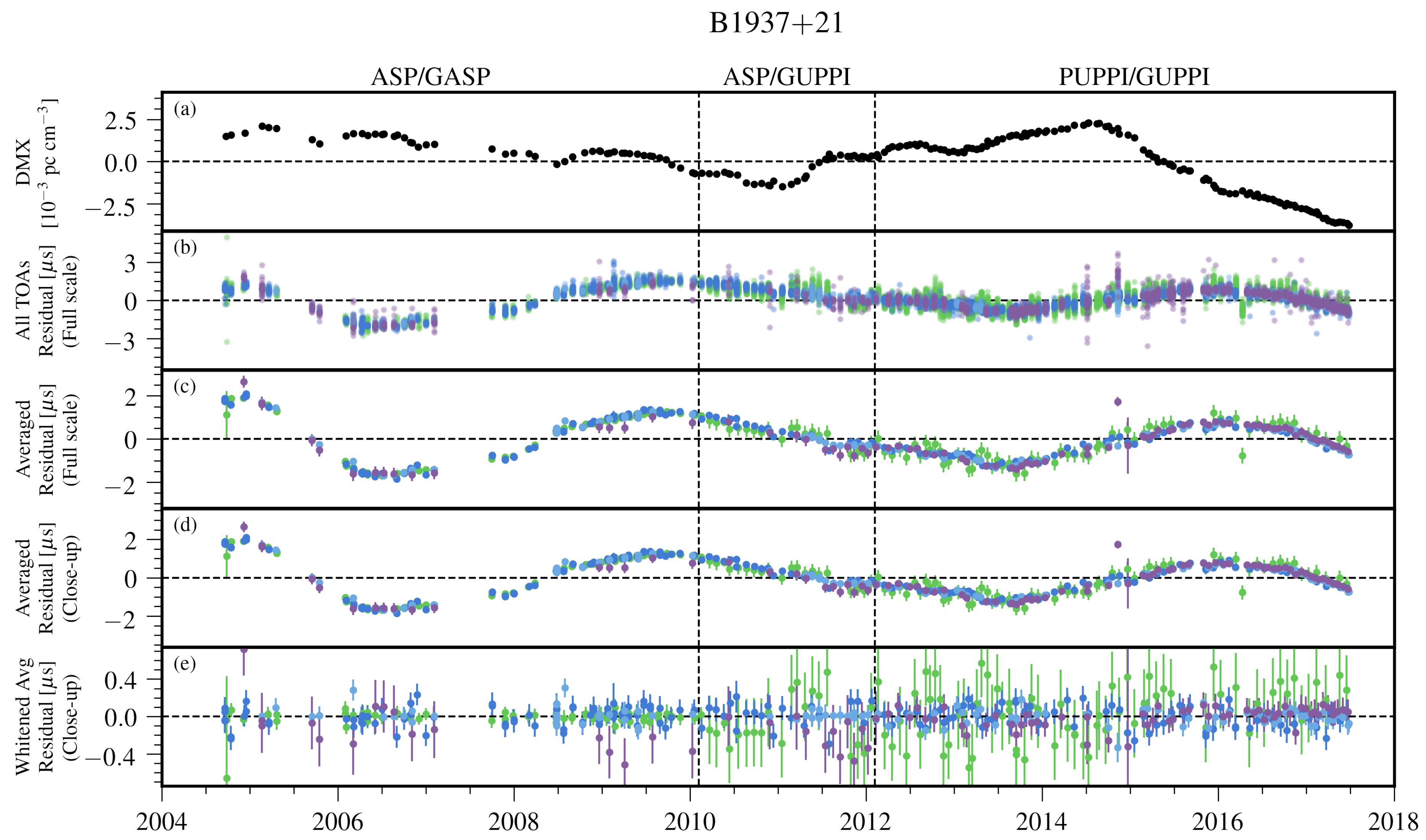
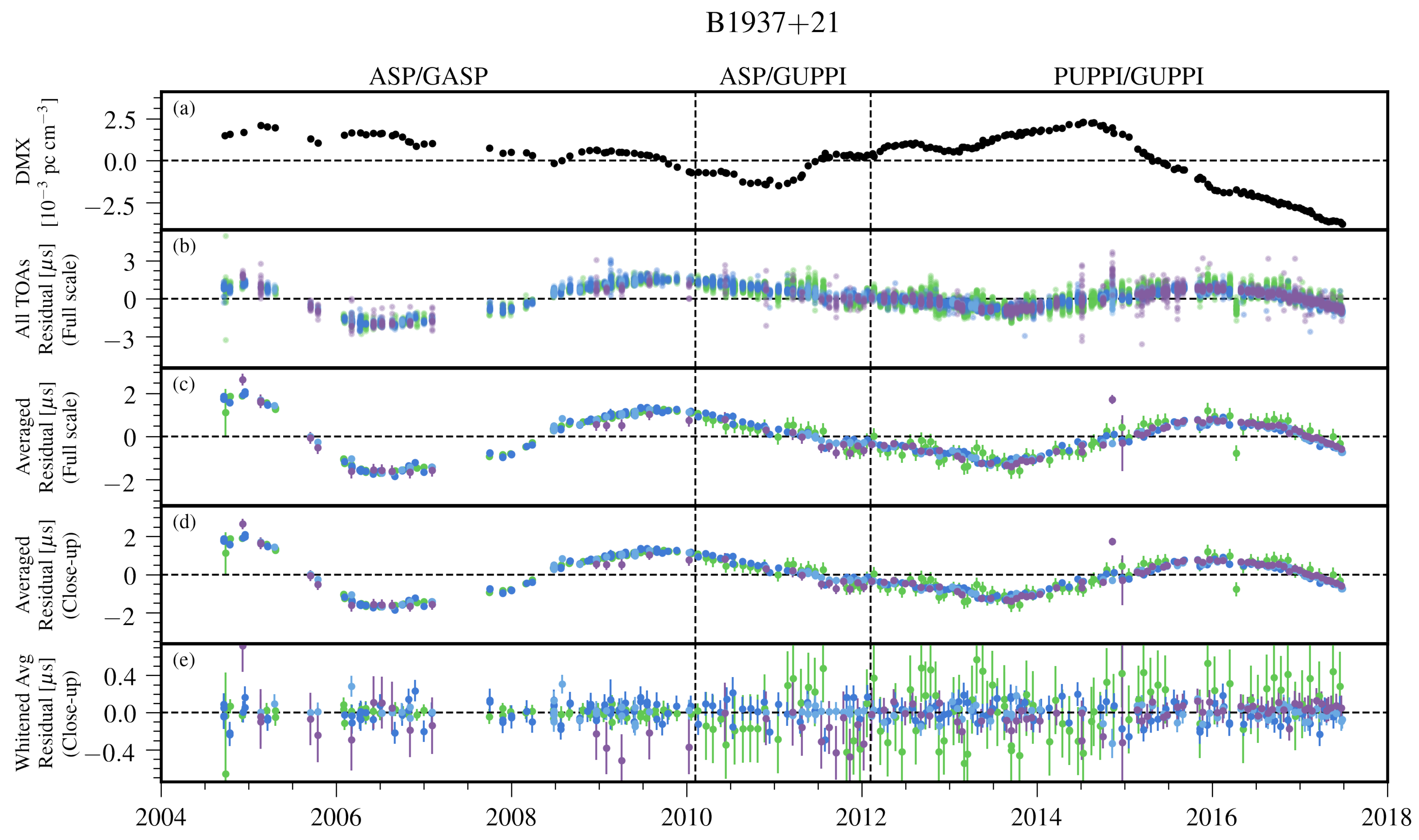


white noise

$$\langle n_{i,\mu} n_{j,\nu} \rangle = E_\mu^2 \sigma_i \delta_{ij} \delta_{\mu\nu} + Q_\mu^2 \delta_{ij} \delta_{\mu\nu}$$

EFAC EQUAD

THE TIMING RESIDUALS



$$\vec{\delta}t = \vec{n} + \mathbf{F}\vec{a} + \mathbf{M}\vec{\epsilon} + \vec{h}(\vec{\theta})$$

red noise

$$\mathbf{F} = \begin{pmatrix} \sin(2\pi t_1/T) & \cos(2\pi t_1/T) & \dots & \sin(2\pi N_f t_1/T) & \cos(2\pi N_f t_1/T) \\ \sin(2\pi t_2/T) & \cos(2\pi t_2/T) & \dots & \sin(2\pi N_f t_2/T) & \cos(2\pi N_f t_2/T) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \sin(2\pi t_N/T) & \cos(2\pi t_N/T) & \dots & \sin(2\pi N_f t_N/T) & \cos(2\pi N_f t_N/T) \end{pmatrix}$$

THE TIMING RESIDUALS

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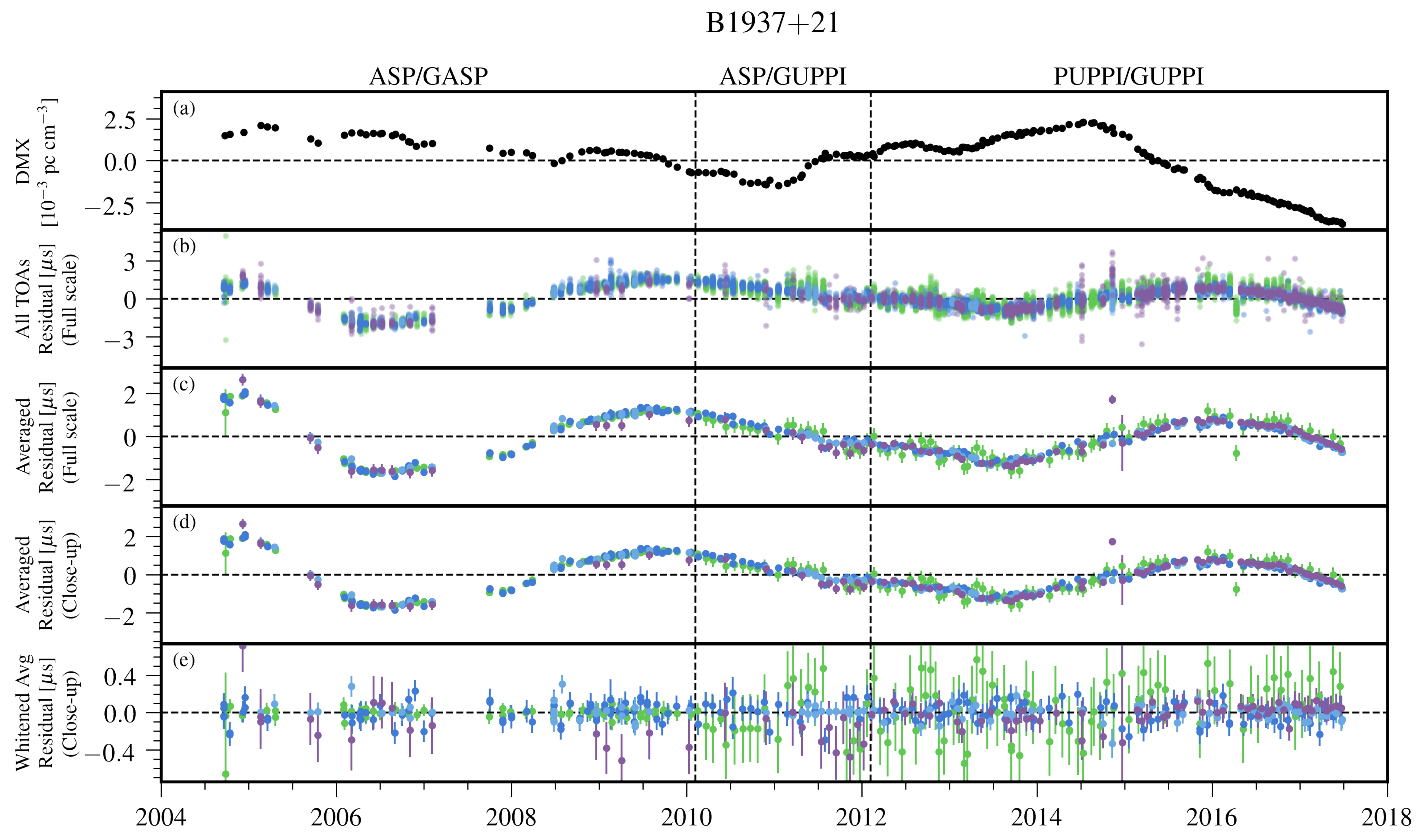

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$$p(\vec{a}|\eta) = \frac{\exp\left(-\frac{1}{2}\vec{a}^{\mathrm{T}}\boldsymbol{\phi}^{-1}\vec{a}\right)}{\sqrt{\det(2\pi\boldsymbol{\phi})}}$$

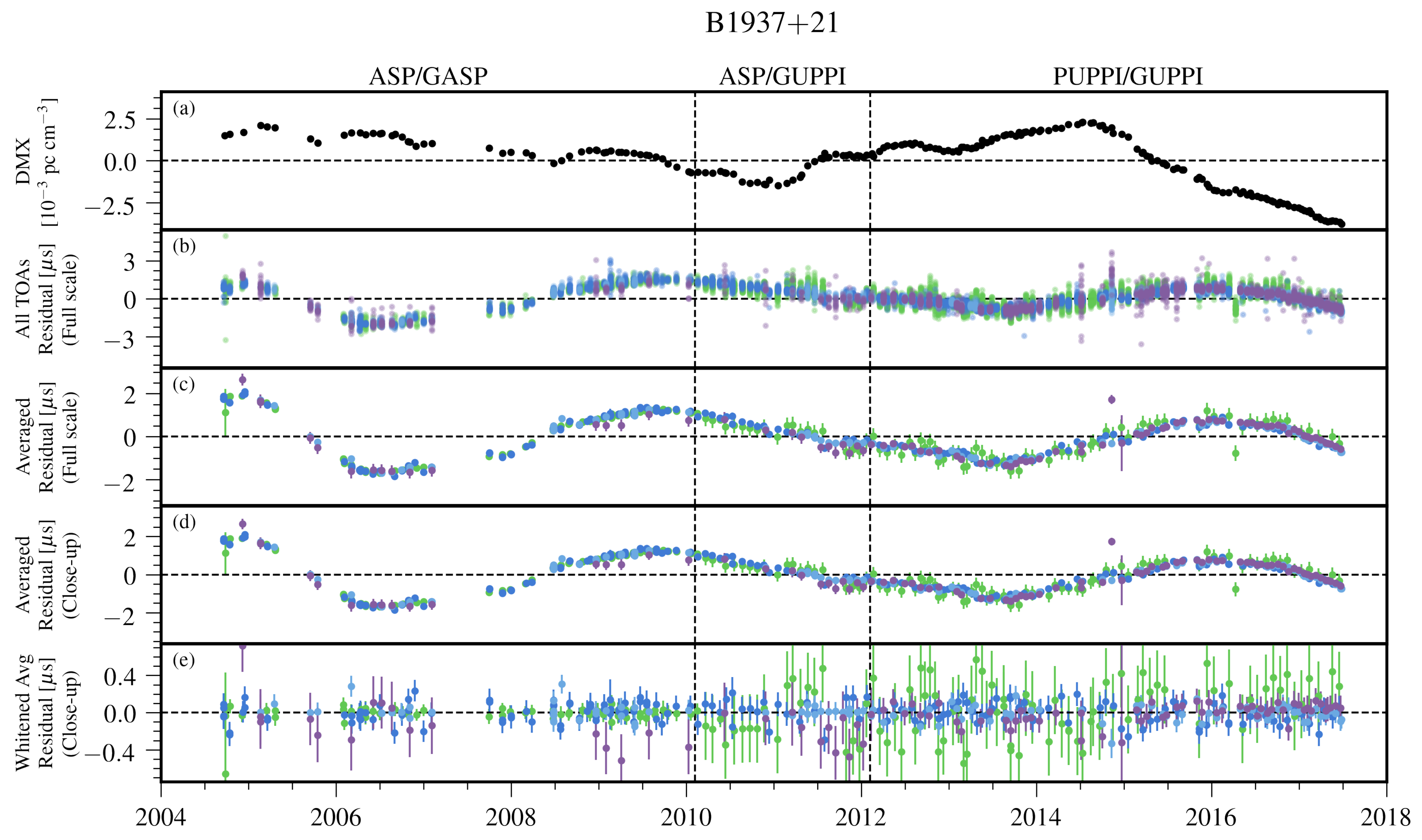
$$[\phi]_{(ak)(bj)} = \Gamma_{ab}\rho_k\delta_{kj} + \kappa_{ak}\delta_{kj}\delta_{ab}$$

common process

intrinsic noise

THE TIMING RESIDUALS

$$\vec{\delta t} = \vec{n} + \mathbf{F}\vec{a} + \mathbf{M}\vec{\epsilon} + \vec{h}(\vec{\theta})$$



timing-ephemeris model variations

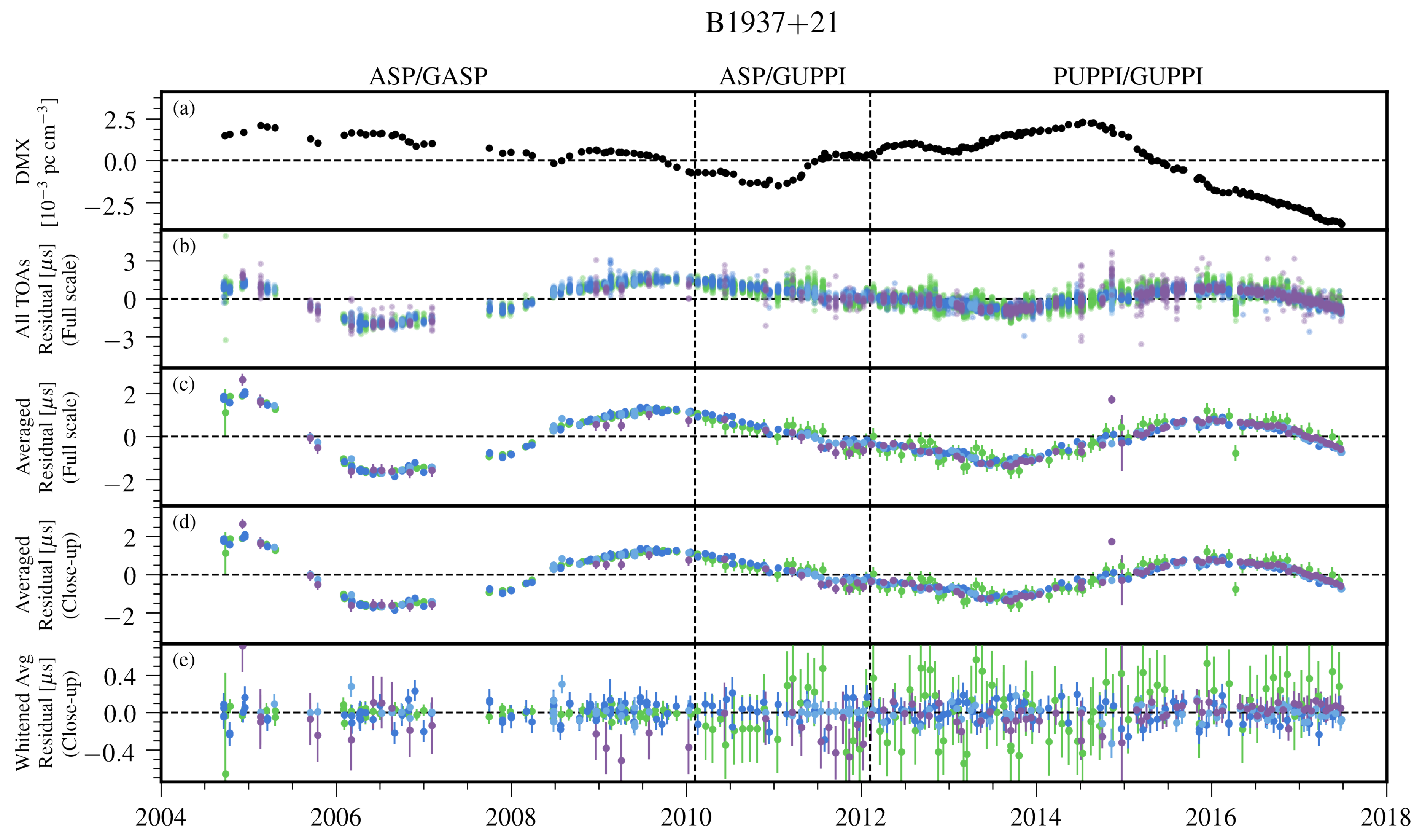
$$M_{ij} = \frac{\partial t_i}{\partial \beta_j}$$

$$\epsilon_j = \beta_j - \beta_{0,j}$$

THE TIMING RESIDUALS

$$\vec{\delta t} = \vec{n} + \mathbf{F}\vec{a} + \mathbf{M}\vec{\epsilon} + \vec{h}(\vec{\theta})$$

deterministic signal



THE PTA LIKELIHOOD

$\vec{\eta} = \{\texttt{EFAC},\ \texttt{EQUAD}, \phi\}$

$\mathbf{T} = [\mathbf{M},\ \mathbf{F}]$ $\quad \vec{b} = \begin{bmatrix} \vec{\epsilon} \\ \vec{a} \end{bmatrix}$ $\quad \mathbf{B} = \begin{pmatrix} \infty & \mathbf{0} \\ \mathbf{0} & \boldsymbol{\phi} \end{pmatrix}$

$$p(\vec{\delta t}|\vec{b},\vec{\eta}) = \frac{\exp\left(-\frac{1}{2}(\vec{\delta t} - \mathbf{T}\vec{b})^{\mathrm{T}}\mathbf{N}^{-1}(\vec{\delta t} - \mathbf{T}\vec{b})\right)}{\sqrt{\det(2\pi\mathbf{N})}} \times \frac{\exp\left(-\frac{1}{2}\vec{b}^{\mathrm{T}}\mathbf{B}^{-1}\vec{b}\right)}{\sqrt{\det(2\pi\mathbf{B})}} \times p(\vec{\eta})$$

priors

THE PTA LIKELIHOOD

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priors

we do not care about the specific noise realization, all the physics is in the parameters controlling the noise statistical properties (i.e. η)

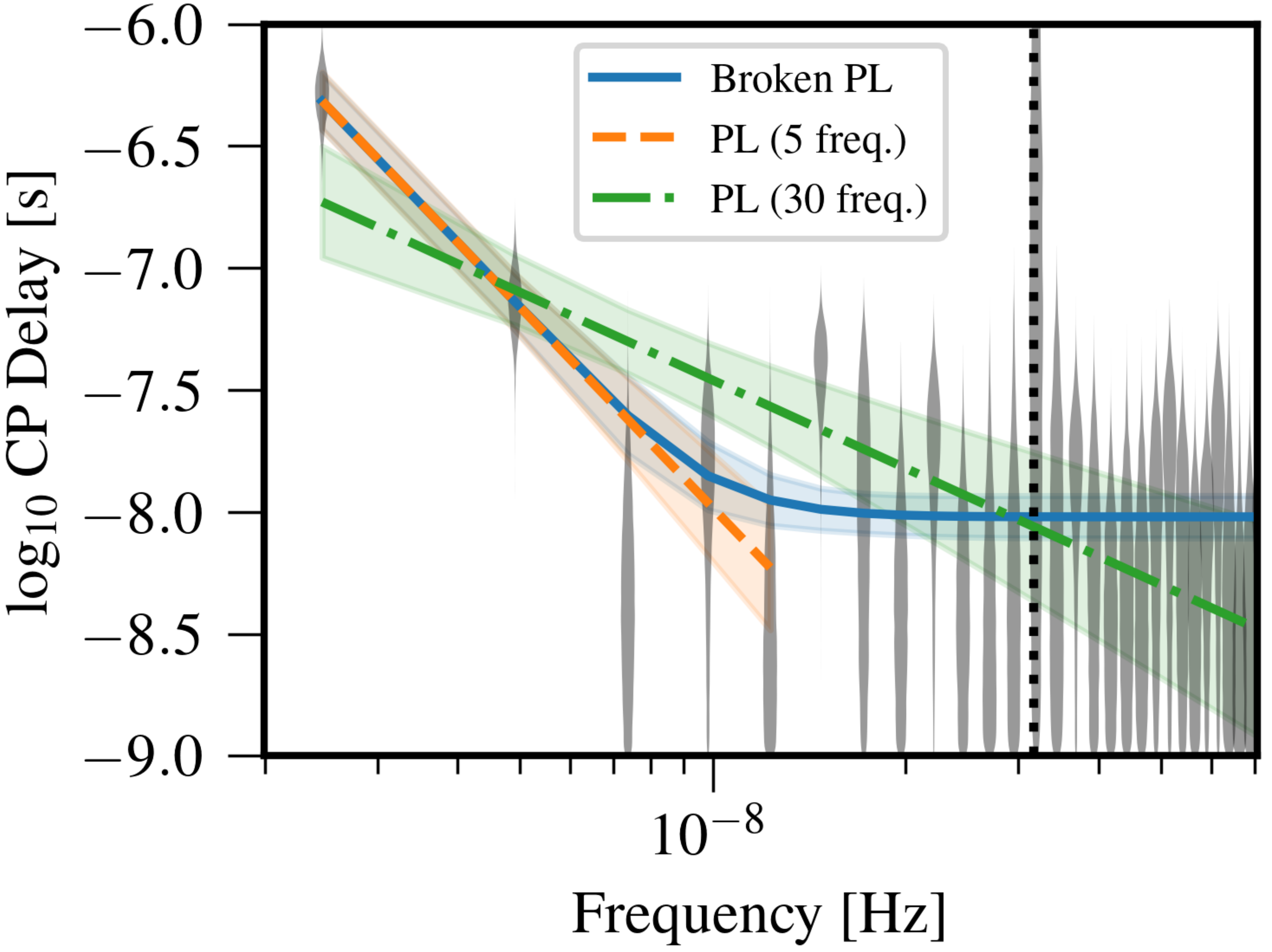
$$p(\{\vec{\delta t}\}|\vec{\eta}) = \int p(\{\vec{\delta t}\}|\{\vec{b}\},\vec{\eta})\, d^{N_p}\vec{b} = \frac{\exp\left(-\frac{1}{2}\vec{\delta t}^{\mathrm{T}}\mathbf{C}^{-1}\vec{\delta t}\right)}{\sqrt{\det(2\pi\mathbf{C})}} \times p(\vec{\eta})$$

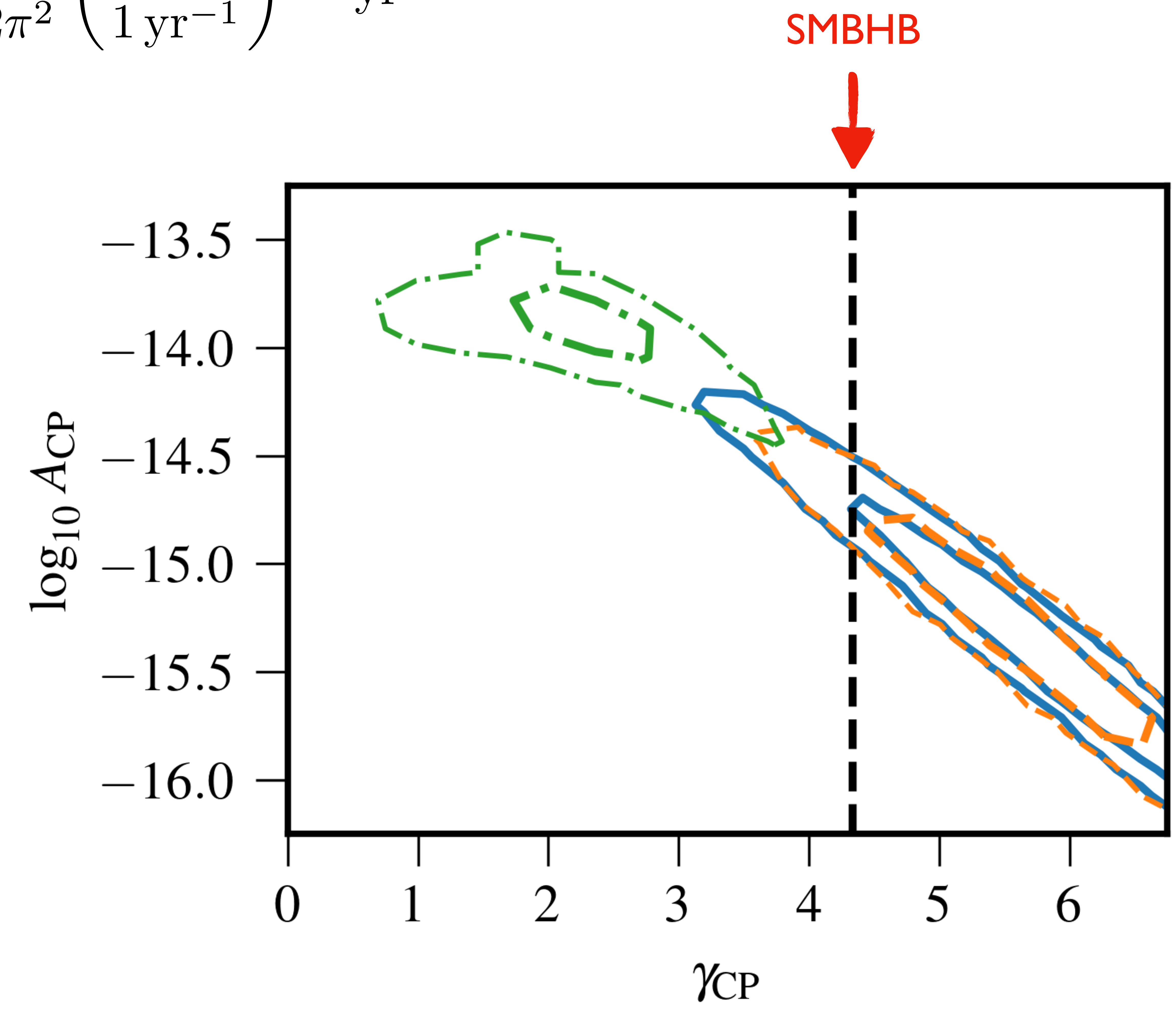
$\mathbf{C} = \mathbf{N} + \mathbf{T}\mathbf{B}\mathbf{T}^{\mathrm{T}}$

A FIRST GLIMPSE?

NANOGrav 12.5 yr [2009.04496]

$$\rho(f) = \frac{A^2}{12\pi^2}\left(\frac{f}{1\,\mathrm{yr}^{-1}}\right)^{-\gamma}\,\mathrm{yr}^2$$

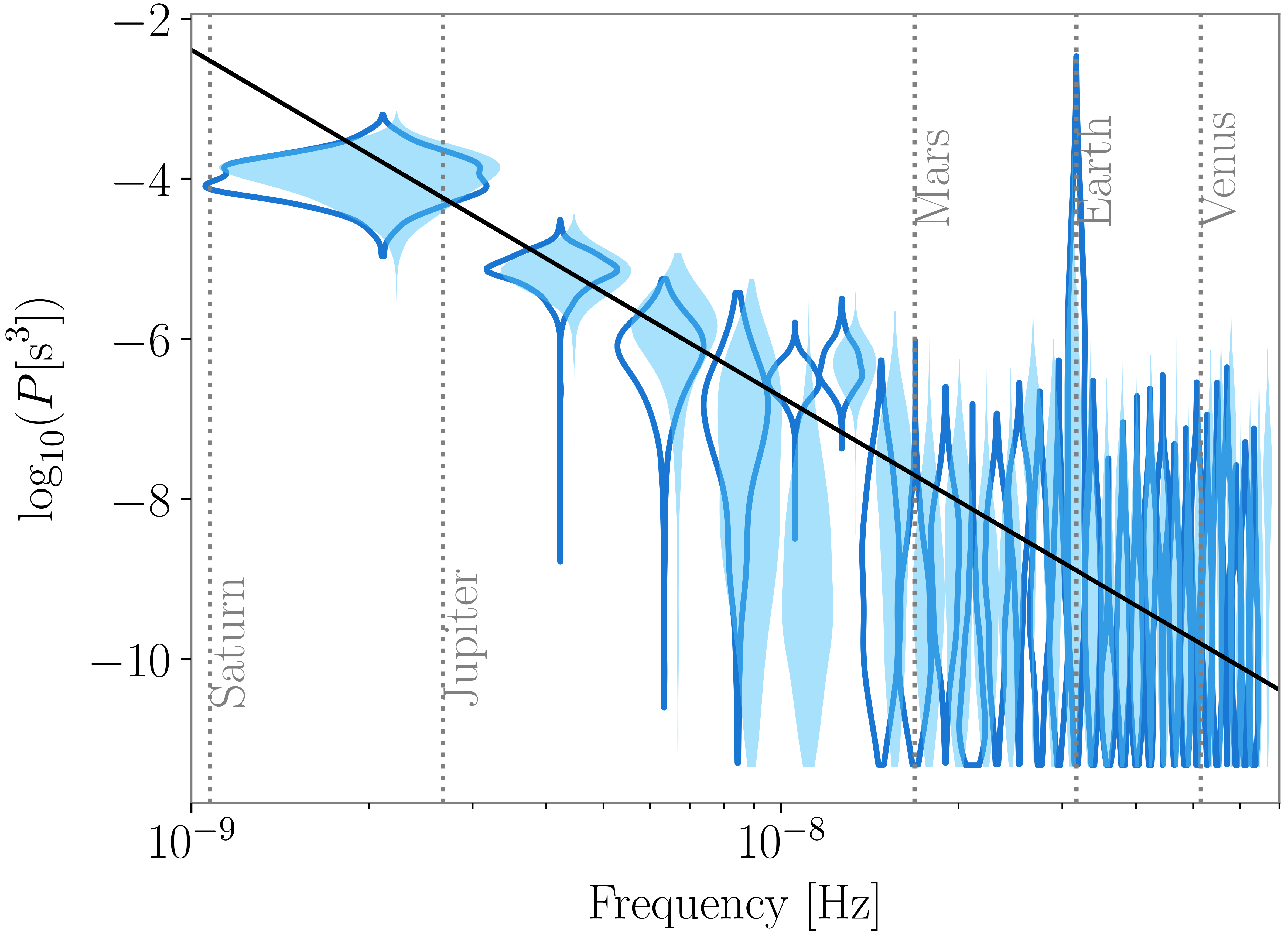


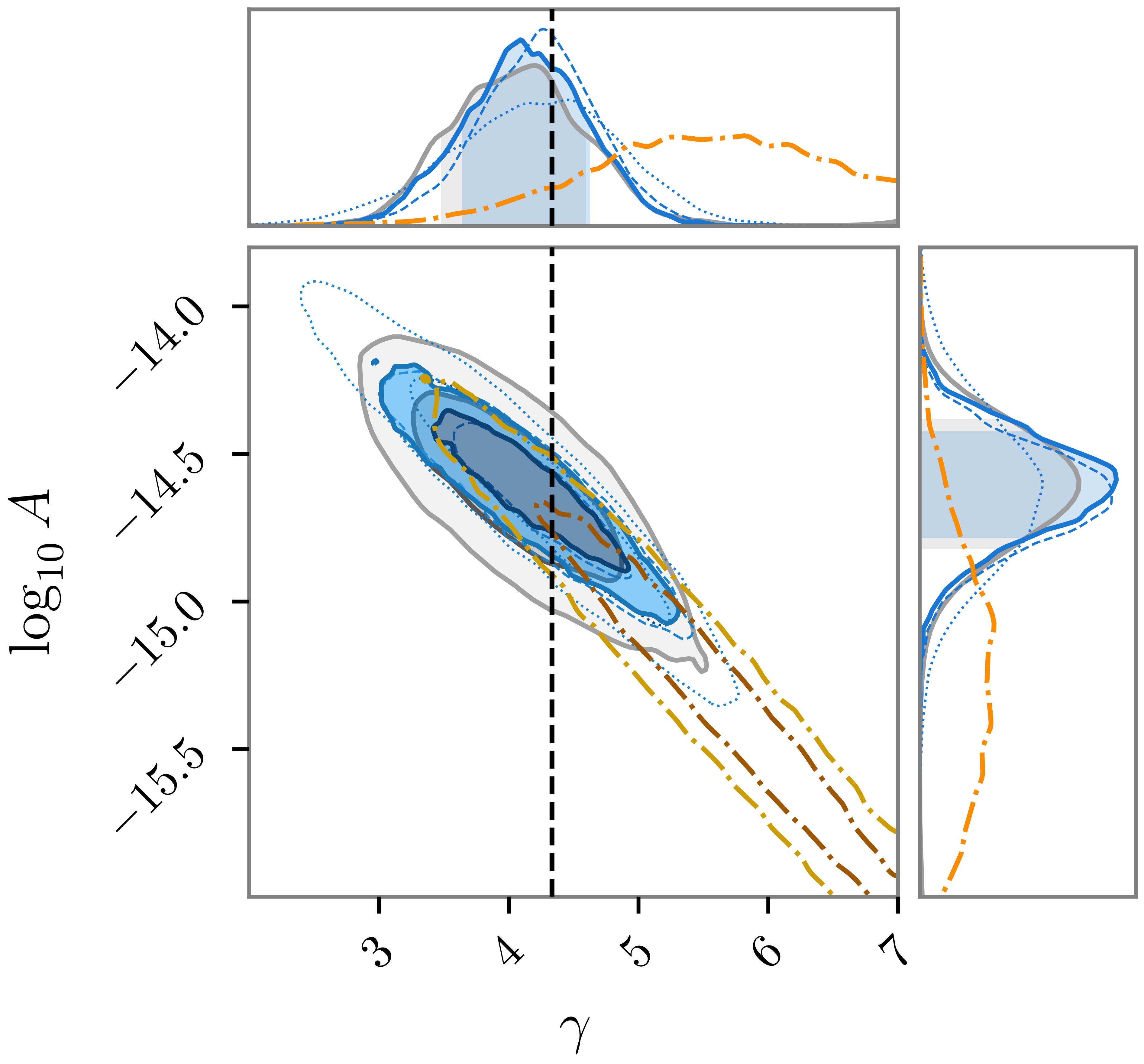


A FIRST GLIMPSE?

[PPTA DR2 [2107.12112]]

$$\rho(f) = \frac{A^2}{12\pi^2}\left(\frac{f}{1\,\mathrm{yr}^{-1}}\right)^{-\gamma}\,\mathrm{yr}^2$$

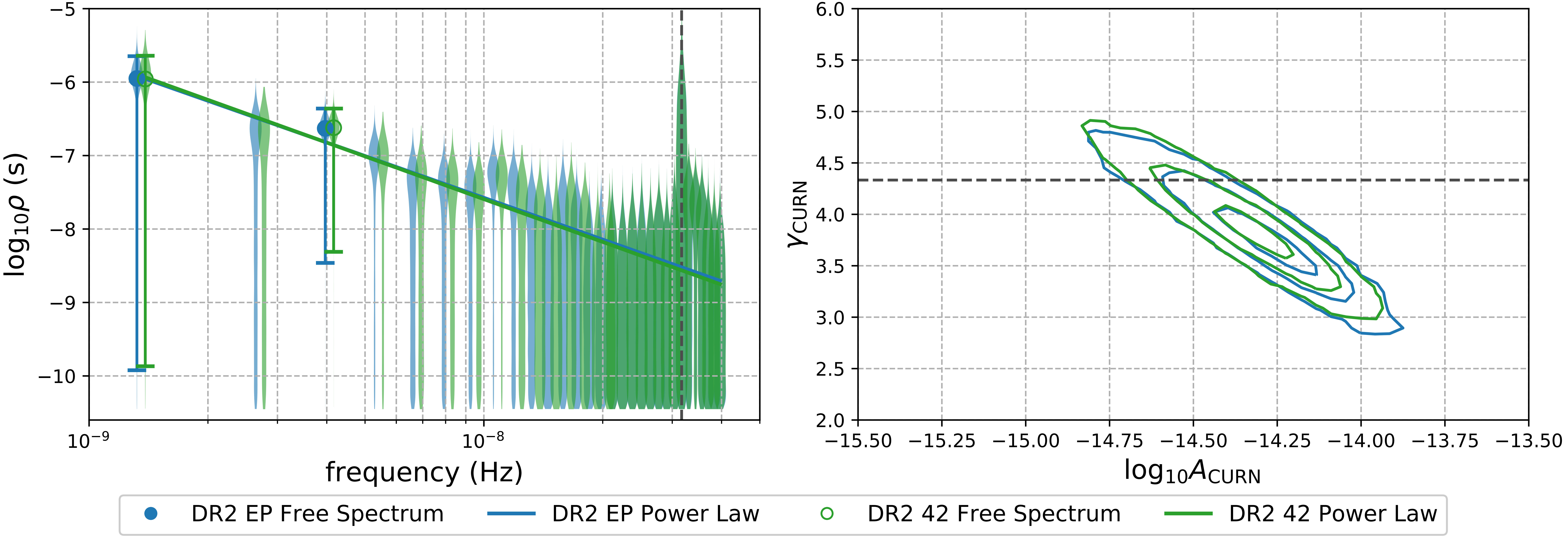




A FIRST GLIMPSE?

EPTA DR2 [2110.13184]

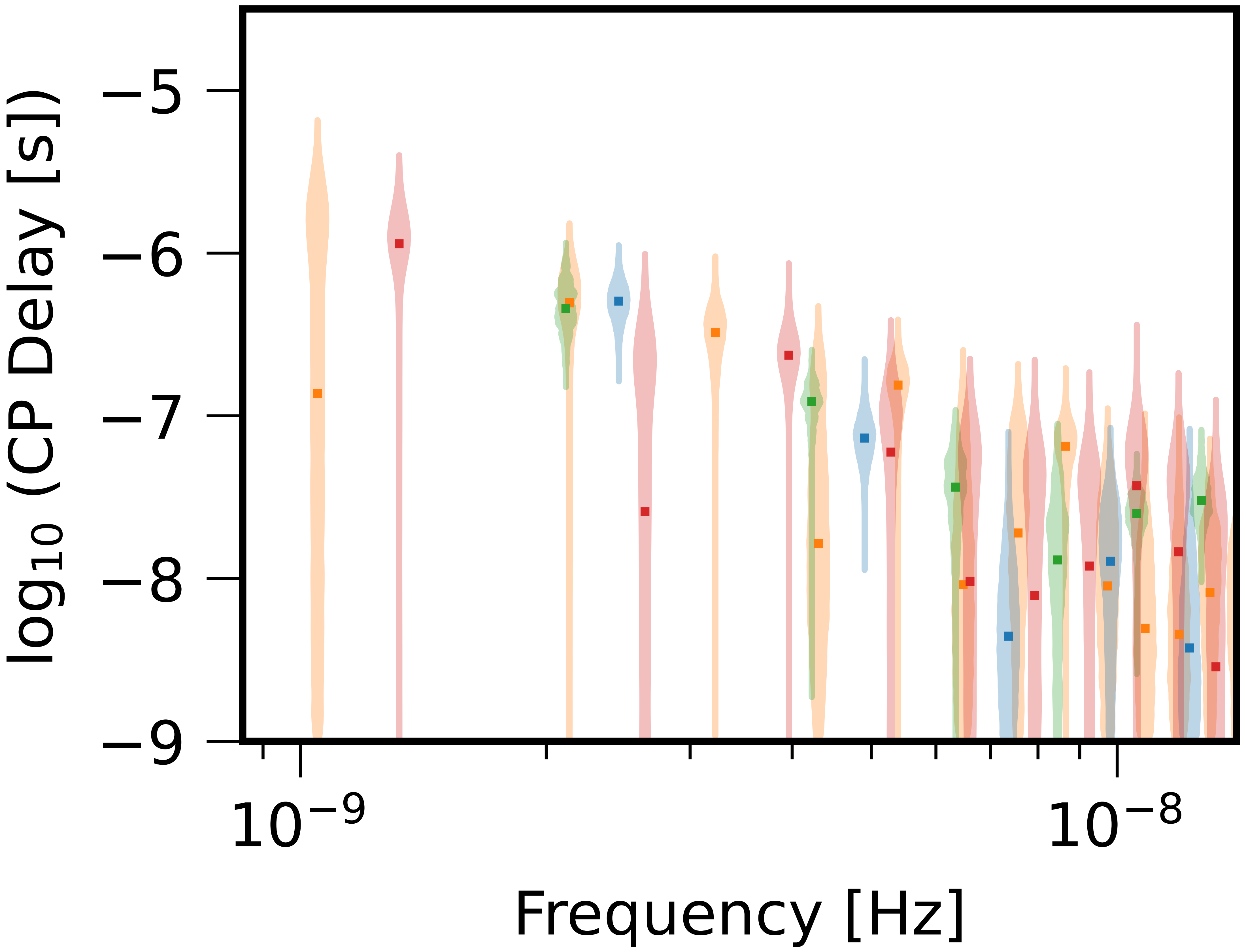
$$\rho(f) = \frac{A^2}{12\pi^2}\left(\frac{f}{1\,\mathrm{yr}^{-1}}\right)^{-\gamma}\mathrm{yr}^2$$

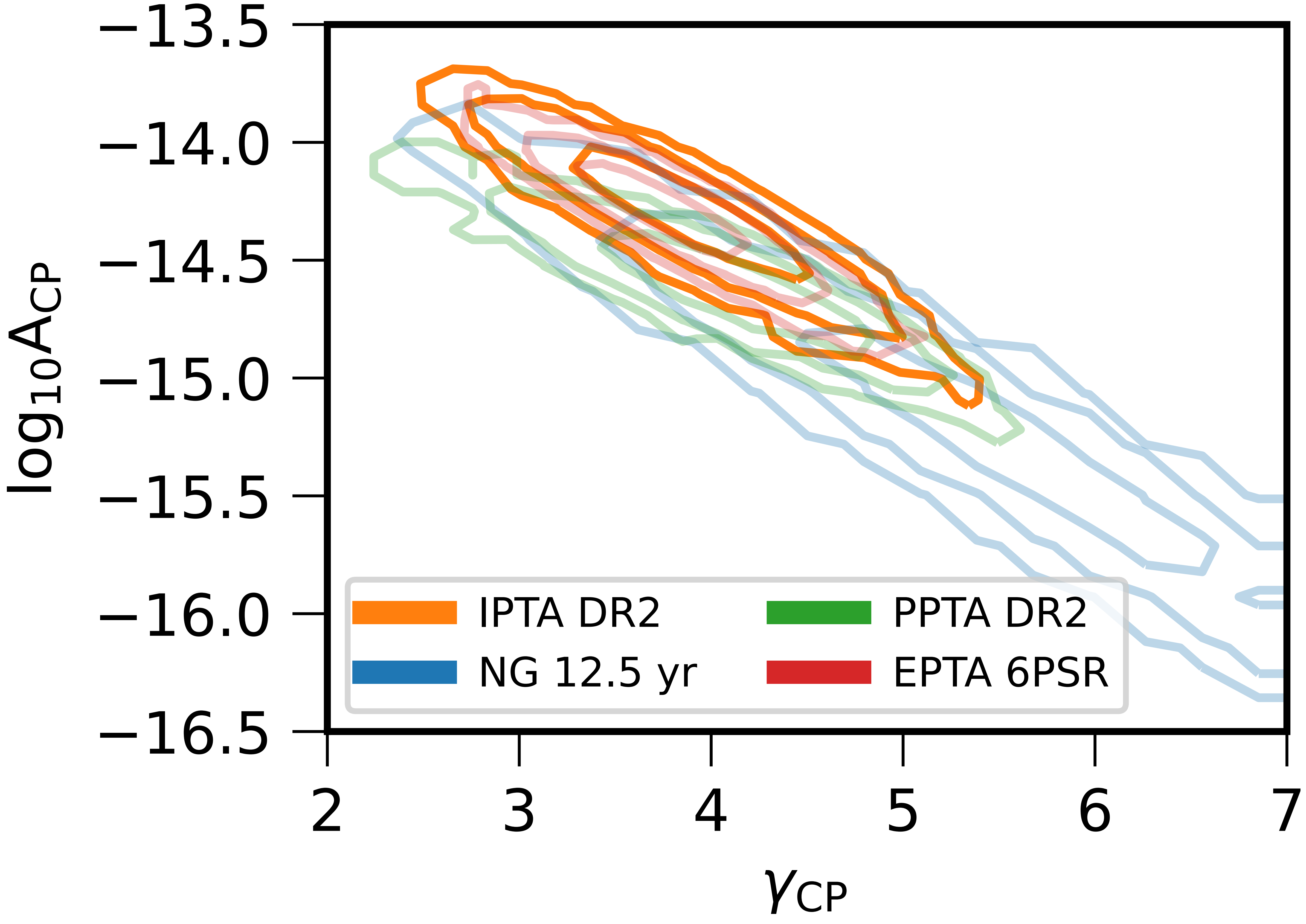


A FIRST GLIMPSE?

[IPTA DR2 [2201.03980]]

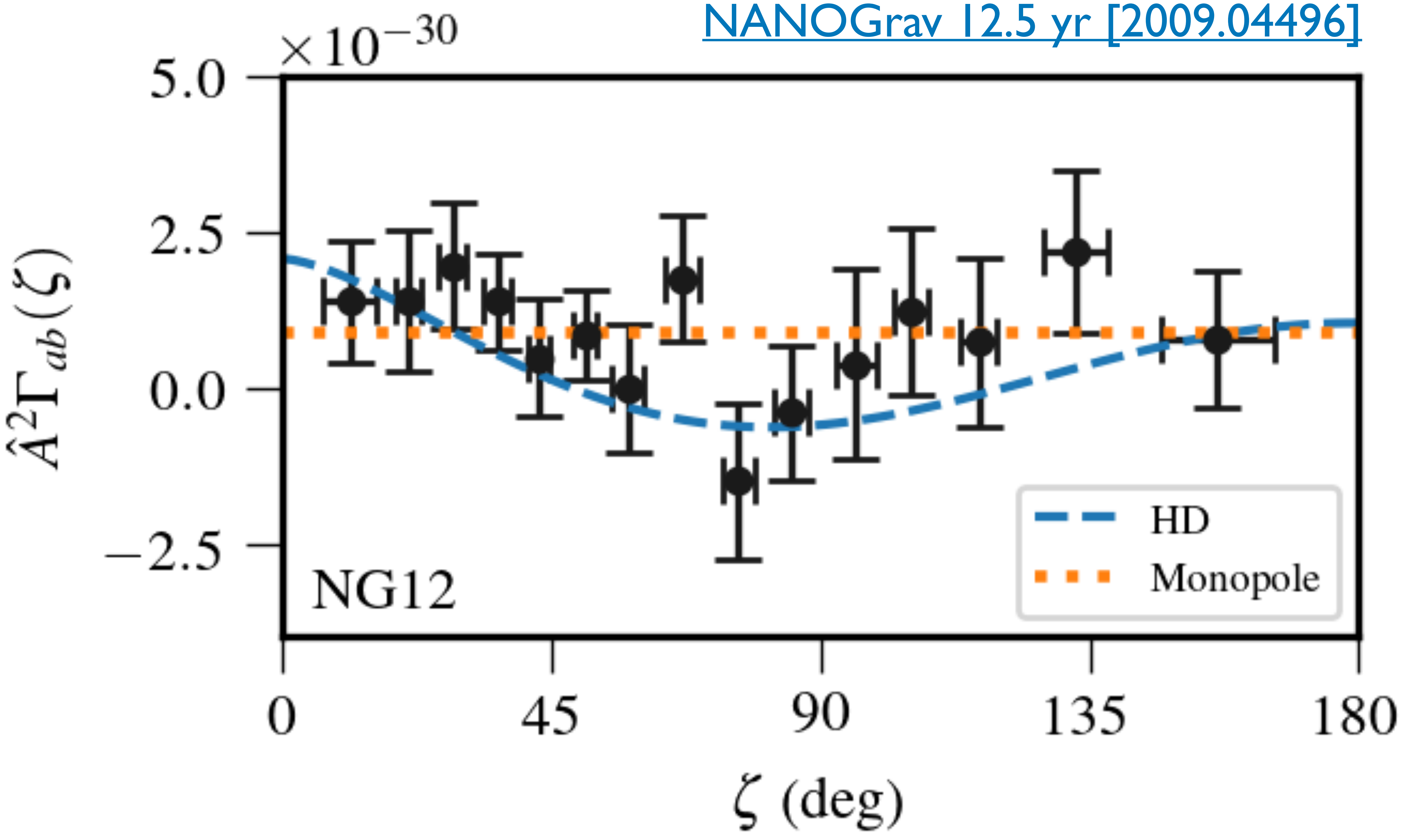
$$\rho(f) = \frac{A^2}{12\pi^2}\left(\frac{f}{1\,\mathrm{yr}^{-1}}\right)^{-\gamma}\mathrm{yr}^2$$



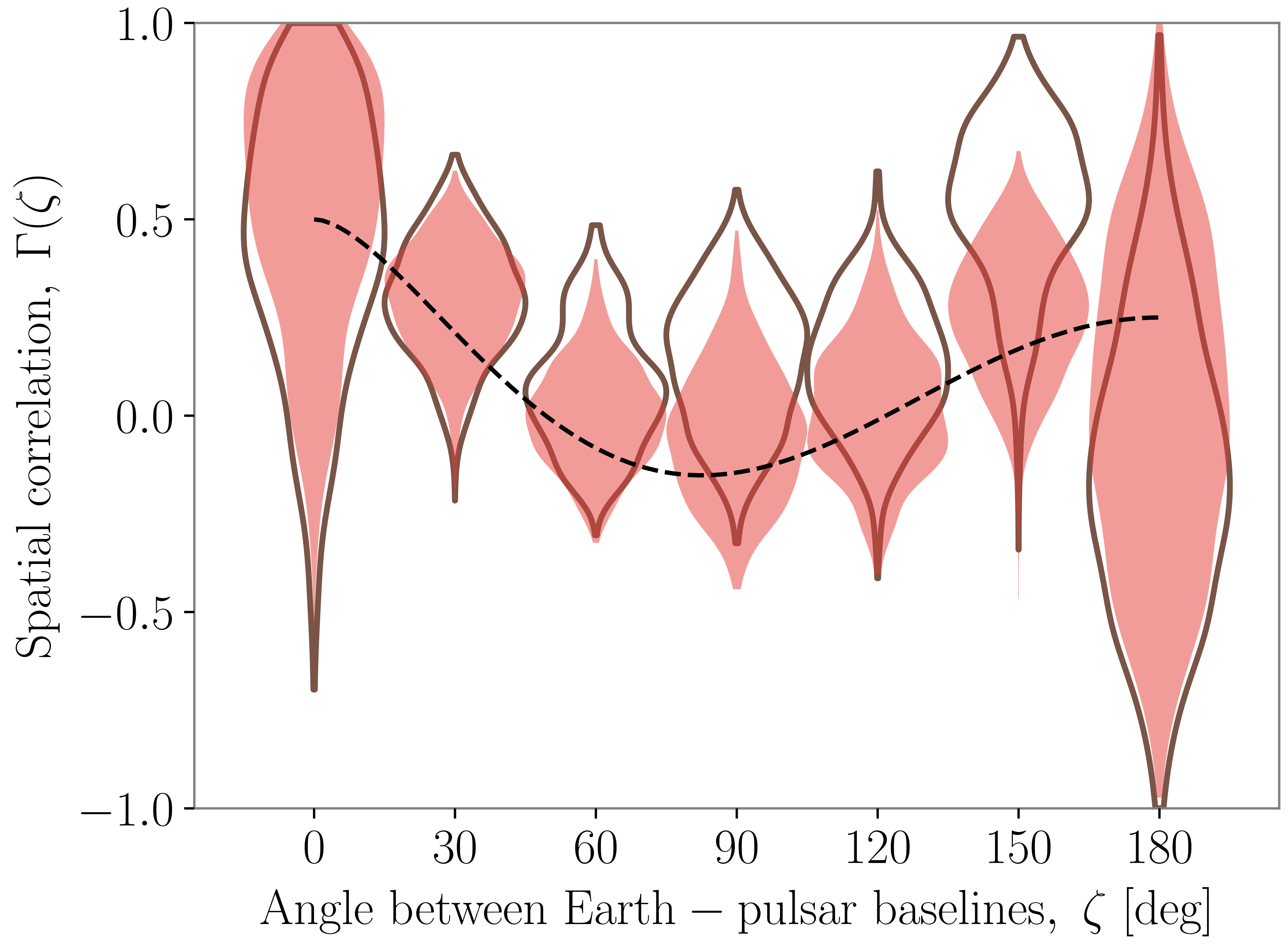


WHAT ABOUT CORRELATIONS?

NANOGrav 12.5 yr [2009.04496]



PPTA DR2 [2107.12112]

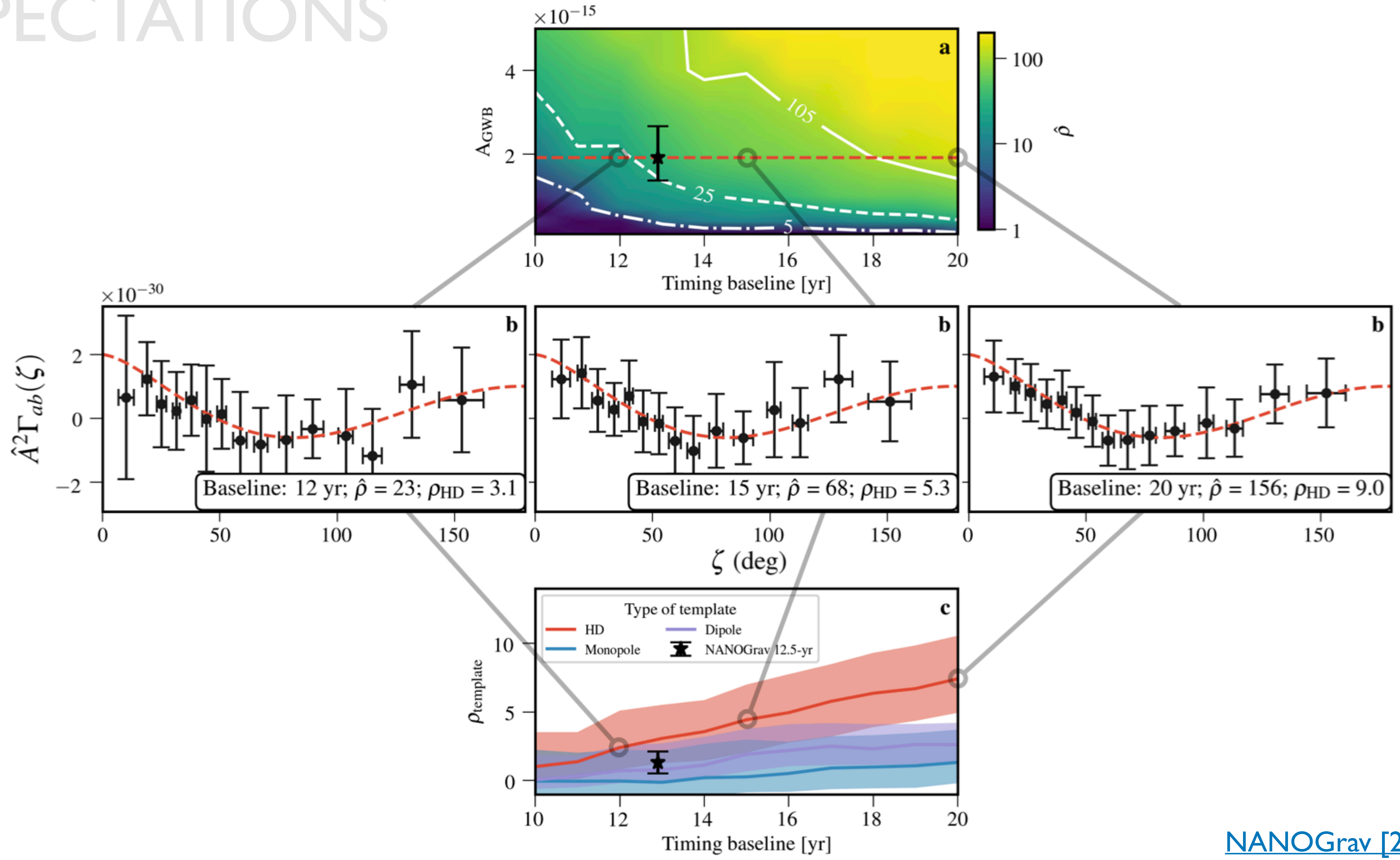


no evidence for **monopole** correlation (error in reference clocks)

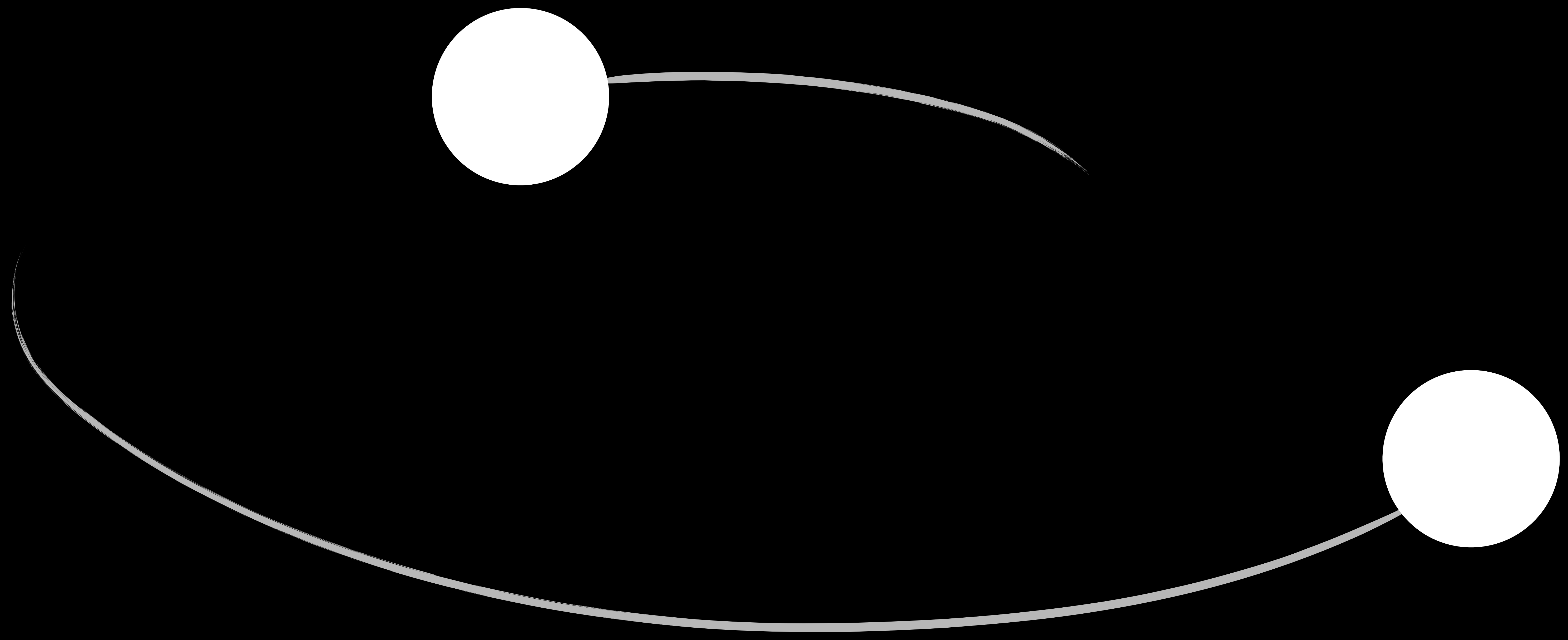
no evidence for **dipole** correlation (error in position of SSB)

evidences for Hellings and Downs correlation not yet conclusive

EXPECTATIONS



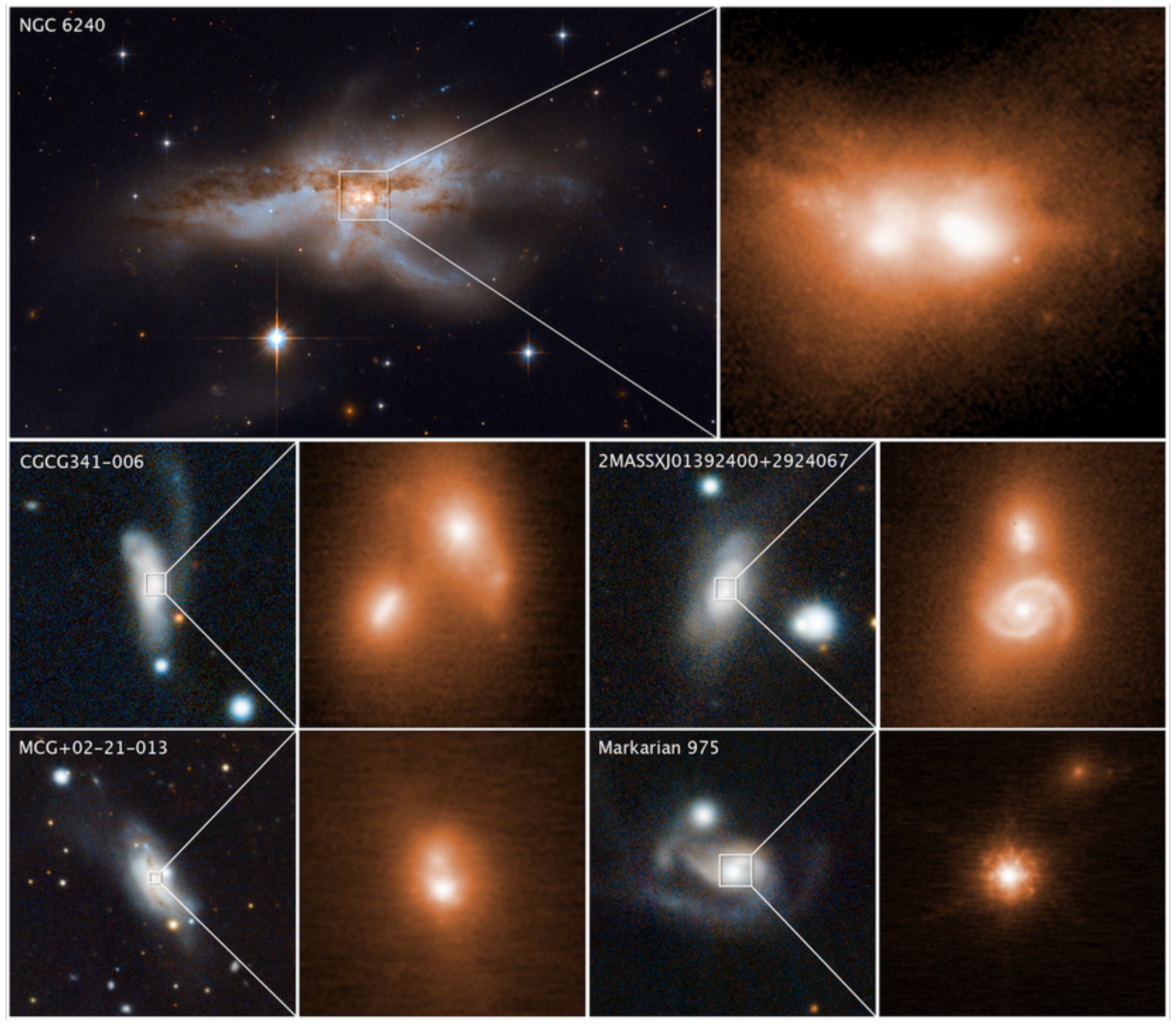
NANOGrav [2010.11950]



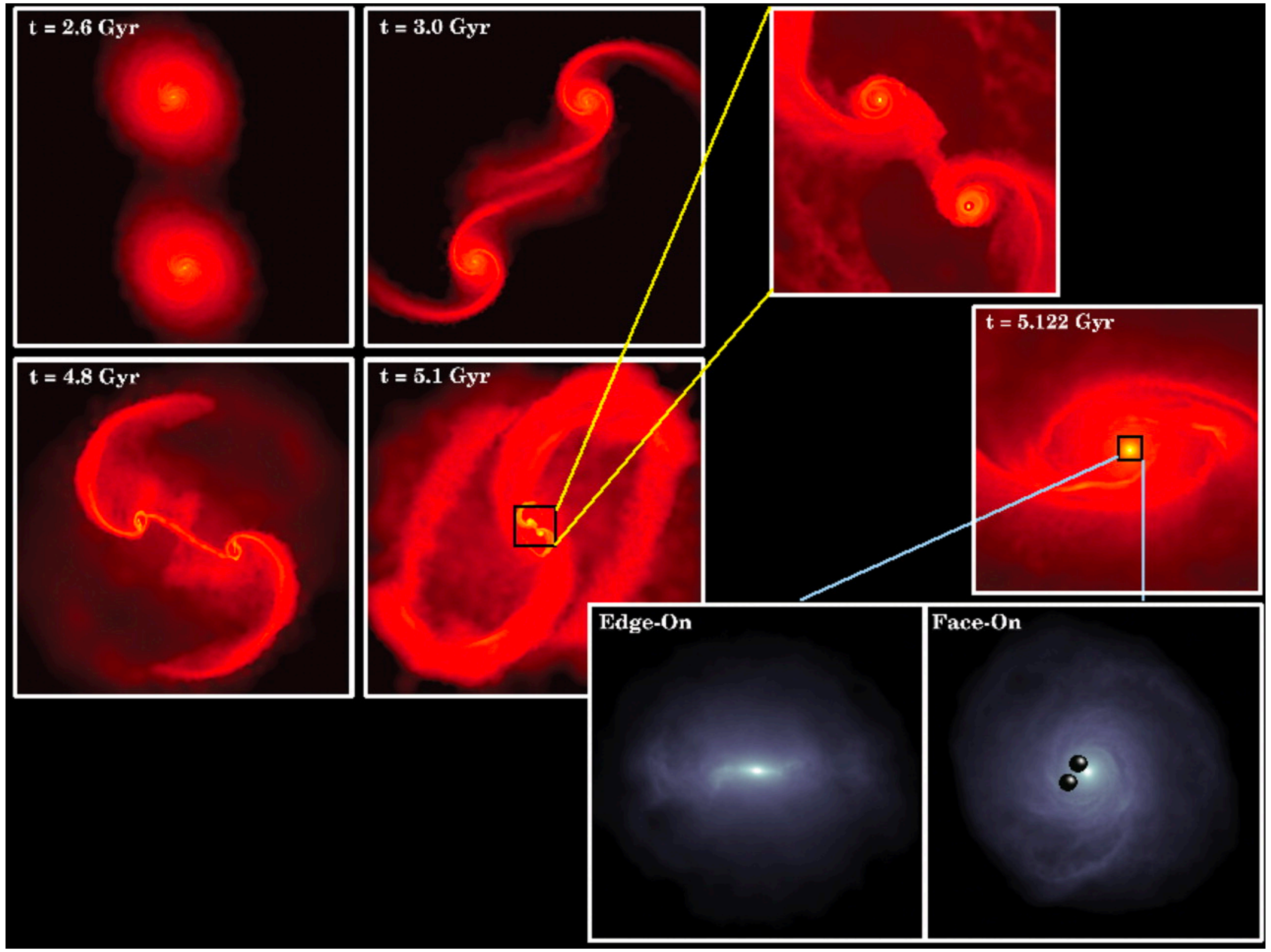
GWB from Supermassive Black Holes Binaries

THE PRIMARY SUSPECT

[Aaron Evans [HST Proposal 10592]]



[Mayer et al. [0706.1562]]



Super Massive Black Holes Binaries (SMBHBs) formed in galaxy mergers

BHBMs GW SPECTRUM

merger rate ↓ chirp mass ↓

$$h_c^2(f) \sim \underbrace{f^{-4/3}}_{\text{spectral shape}} \underbrace{\int dz d\mathcal{M} \frac{dN^2}{dz d\mathcal{M}} \frac{\mathcal{M}^{5/3}}{(1+z)^{1/3}}}_{A^2_{\rm GWB}}$$

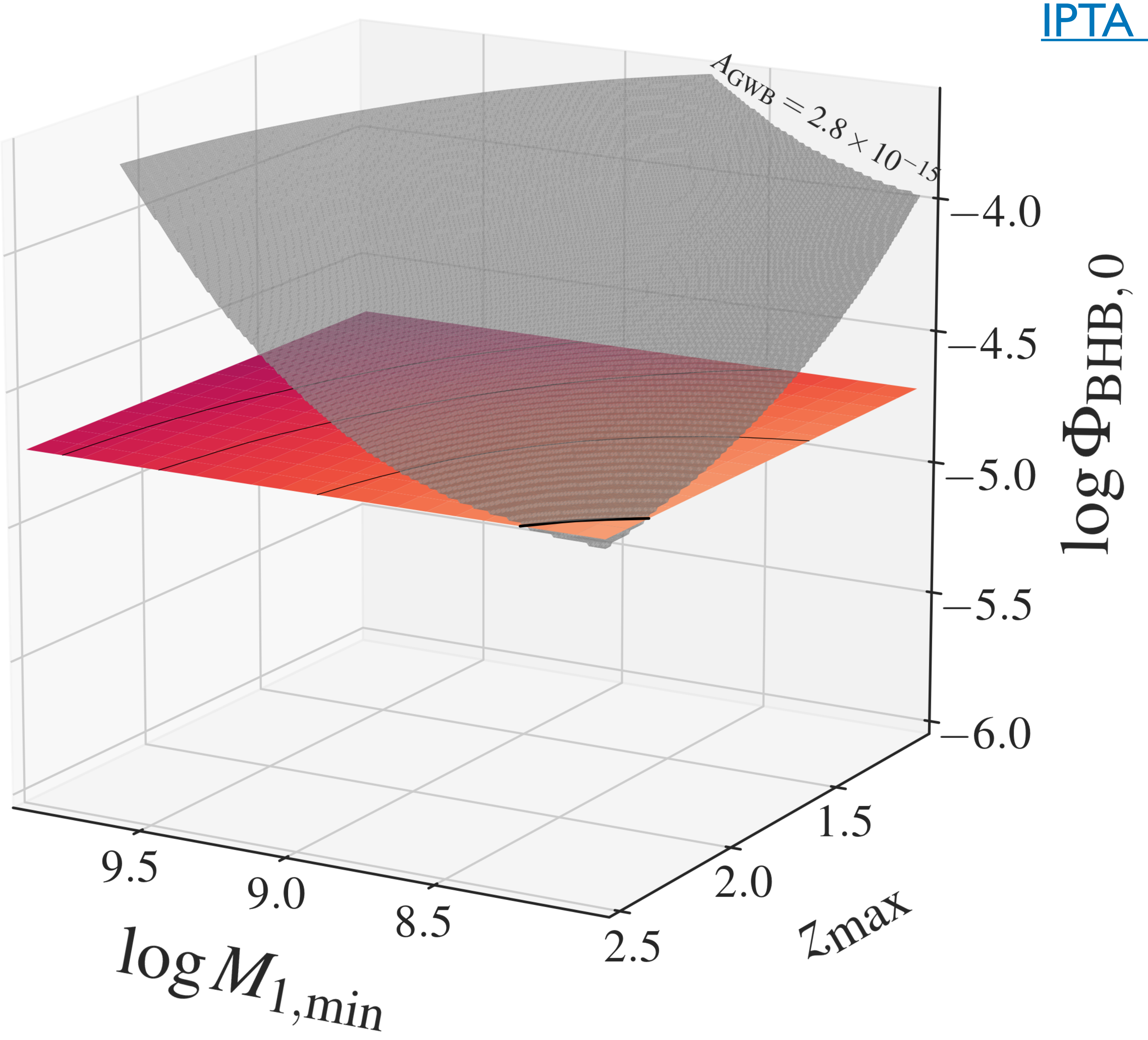
Phinney [astro-ph:/0108028]

$$h_c(f) = A_{\rm GWB} \left(\frac{f}{\rm yr^{-1}}\right)^{-2/3} \quad \Leftrightarrow \quad S_{ab}(f) = \Gamma_{ab} \frac{A^2_{\rm GWB}}{12\pi^2} \left(\frac{f}{f_{\rm yr}}\right)^{-13/3}$$

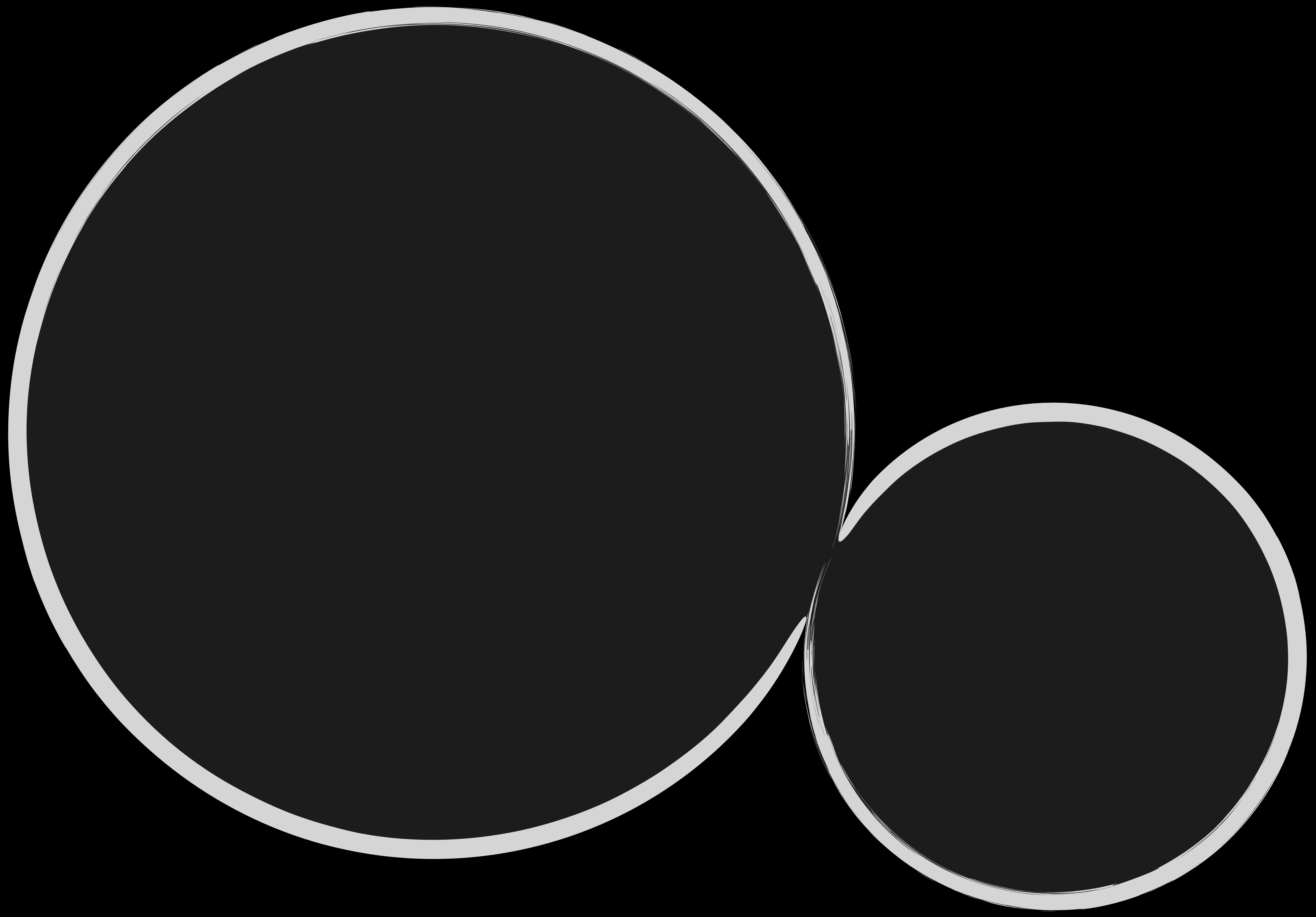
Many open questions: Origin? Delay after galaxy merger? Final-parsec problem? ...

IS THE AMPLITUDE RIGHT?

[IPTA DR2 [2201.03980]](#)



local SMBHB density, $\Phi_{BHB,0}$, needs to be larger than previous estimates, e.g., 1708.03491, by a factor of $\mathcal{O}(20)$ in order to explain the observed signal.

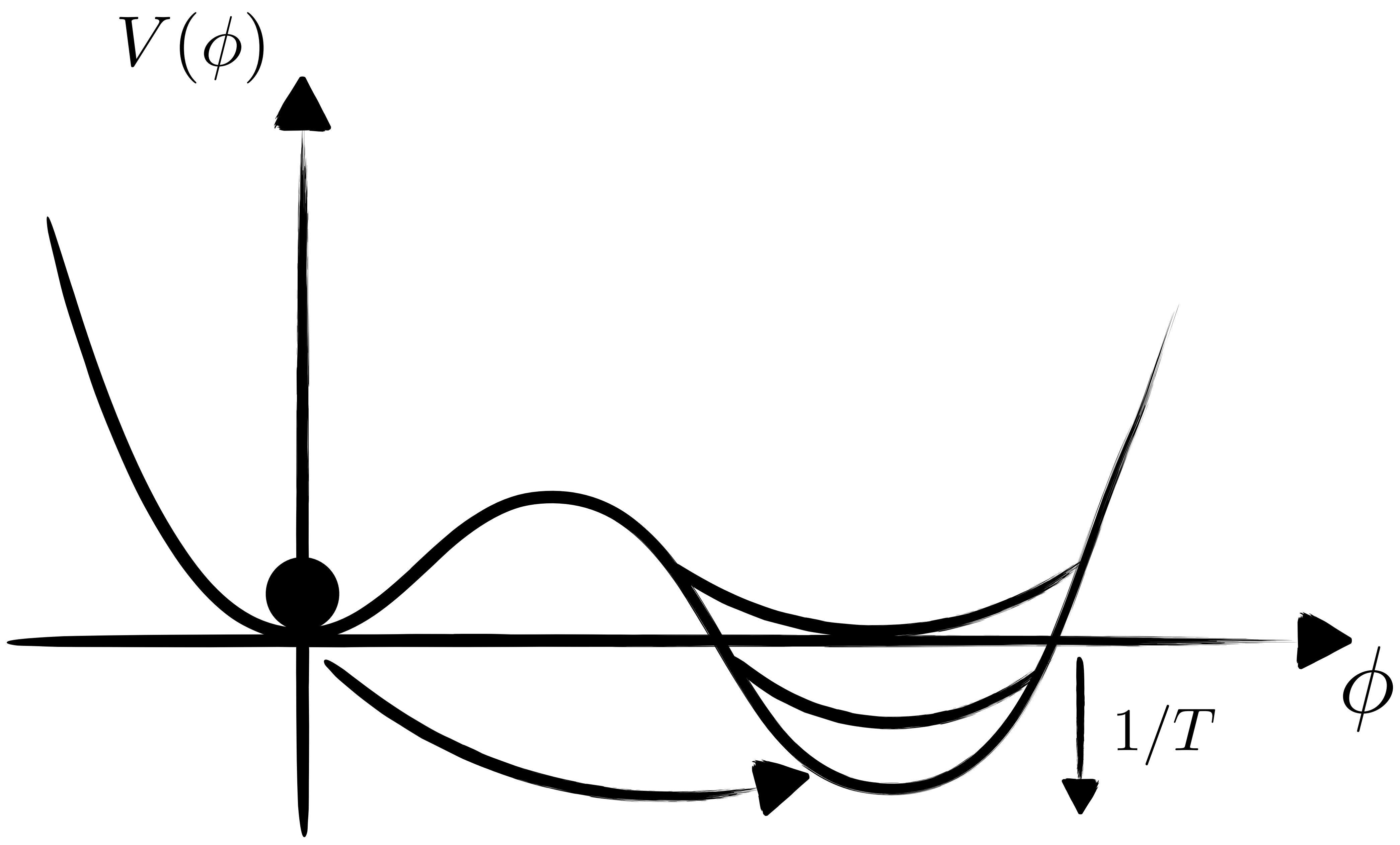


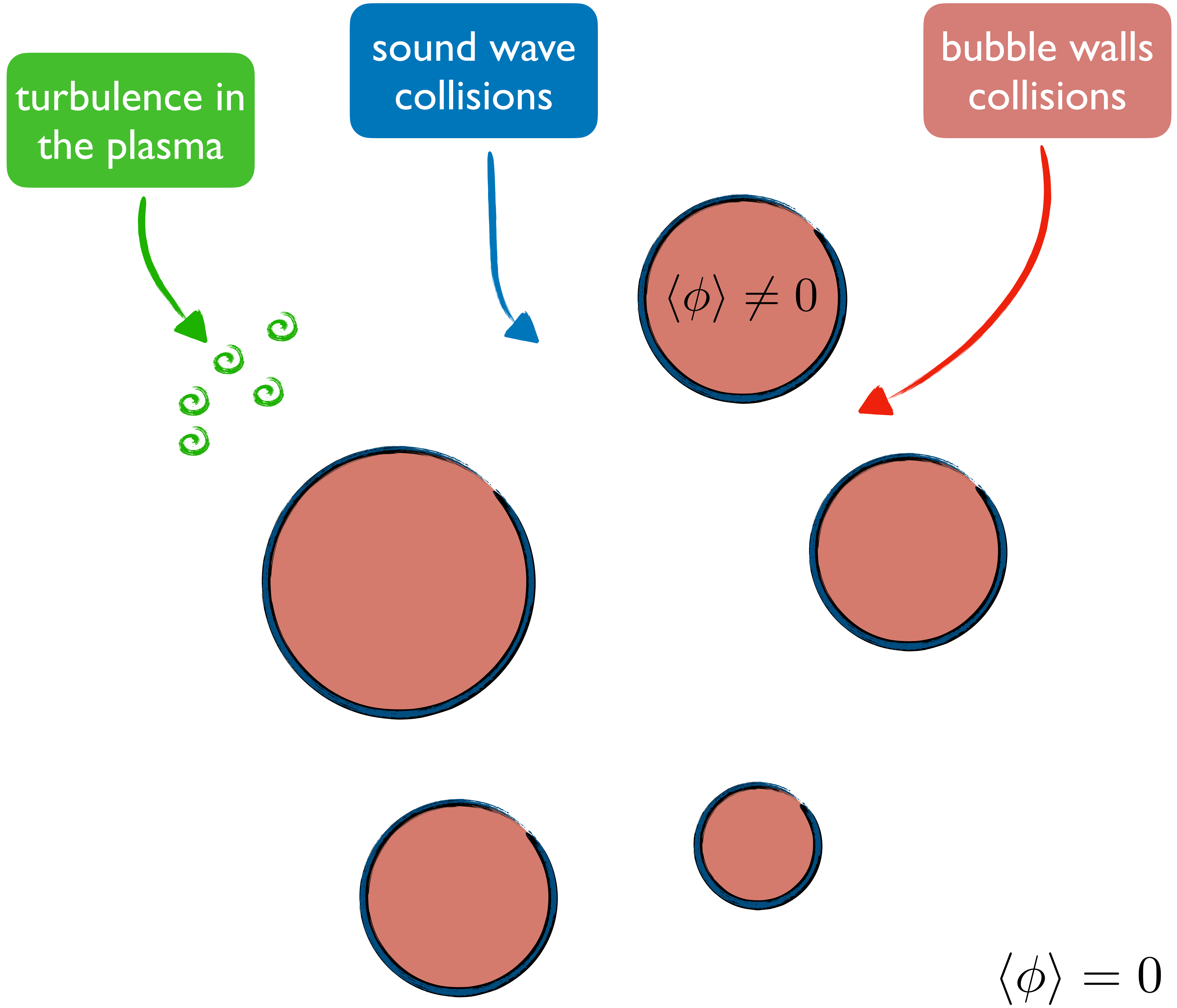
GWB from cosmological phase transitions

TEXT

three sources of GW

$$\Omega_{\rm GW}(f) = \Omega_\phi(f) + \Omega_{\rm sw}(f) + \Omega_{\rm turb}(f)$$





SPECTRUM PARAMETRIZATION

$$\Omega_{\rm gw}(f) \equiv \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\log f} = \frac{4\pi^2}{3H_0^2} f^3 S_h(f)$$

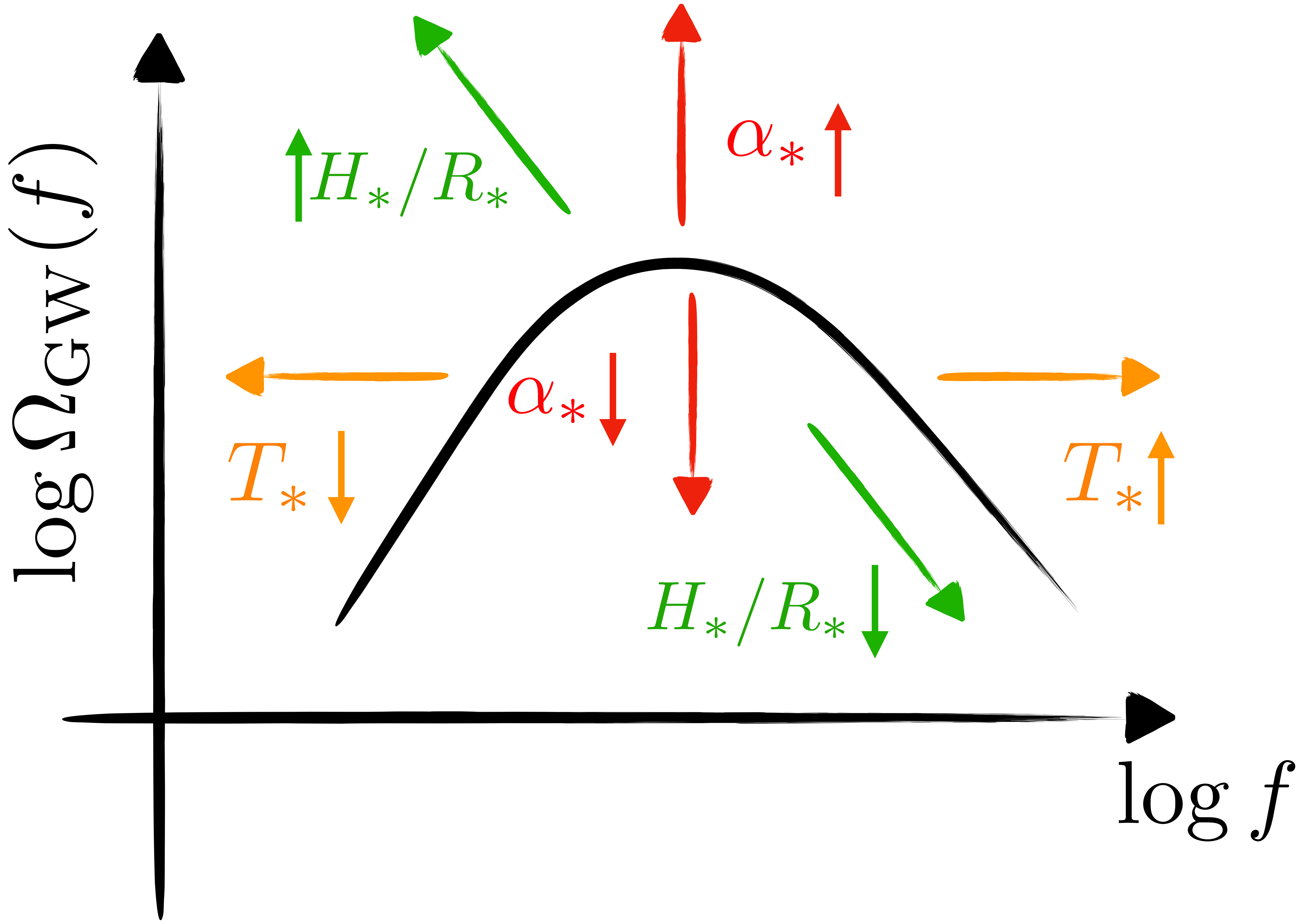
$$\Omega(f) = \mathcal{R}\,\Delta(v_w)\left(\frac{\kappa\alpha_*}{1+\alpha_*}\right)^p \left(\frac{H_*}{R_*}\right)^q \mathcal{S}(f/f_*^0)$$

$$f_*^0 \sim 10^{-10}\,\mathrm{Hz}\left(\frac{\beta}{R_*}\right)\left(\frac{T_*}{\mathrm{MeV}}\right)$$

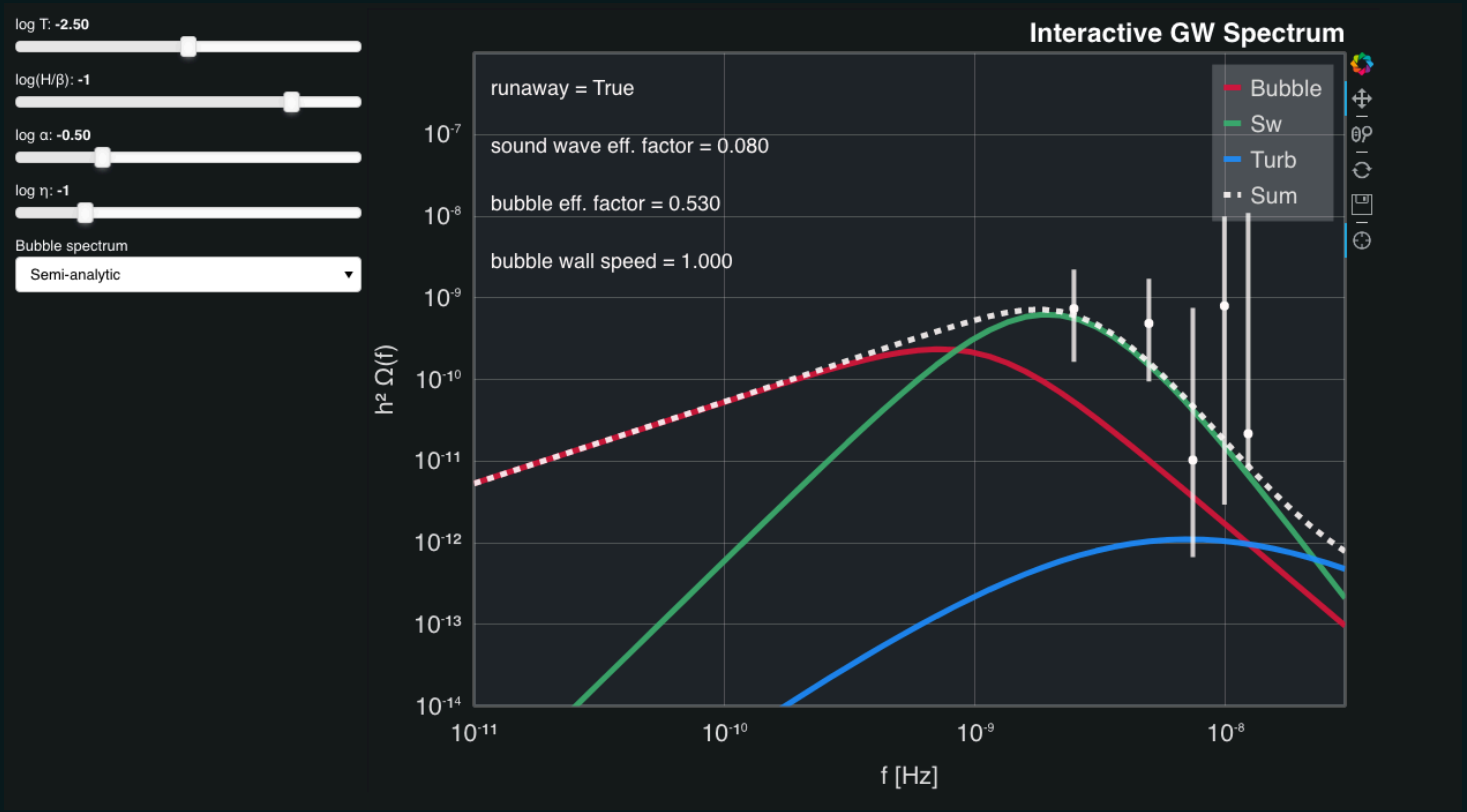
α_* : transition strength

H_*/R_* : transition timescale

T_* : transition temperature

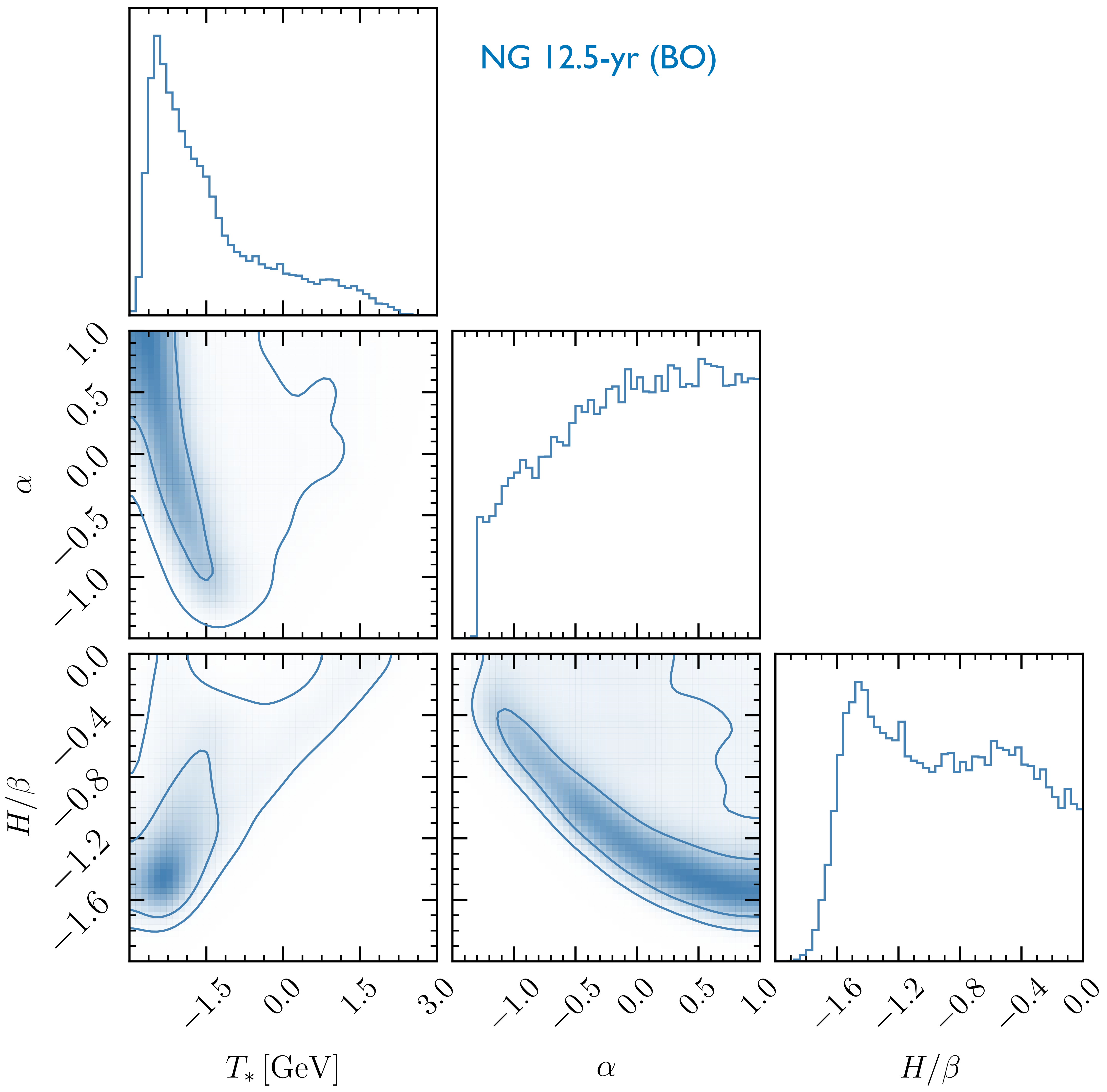


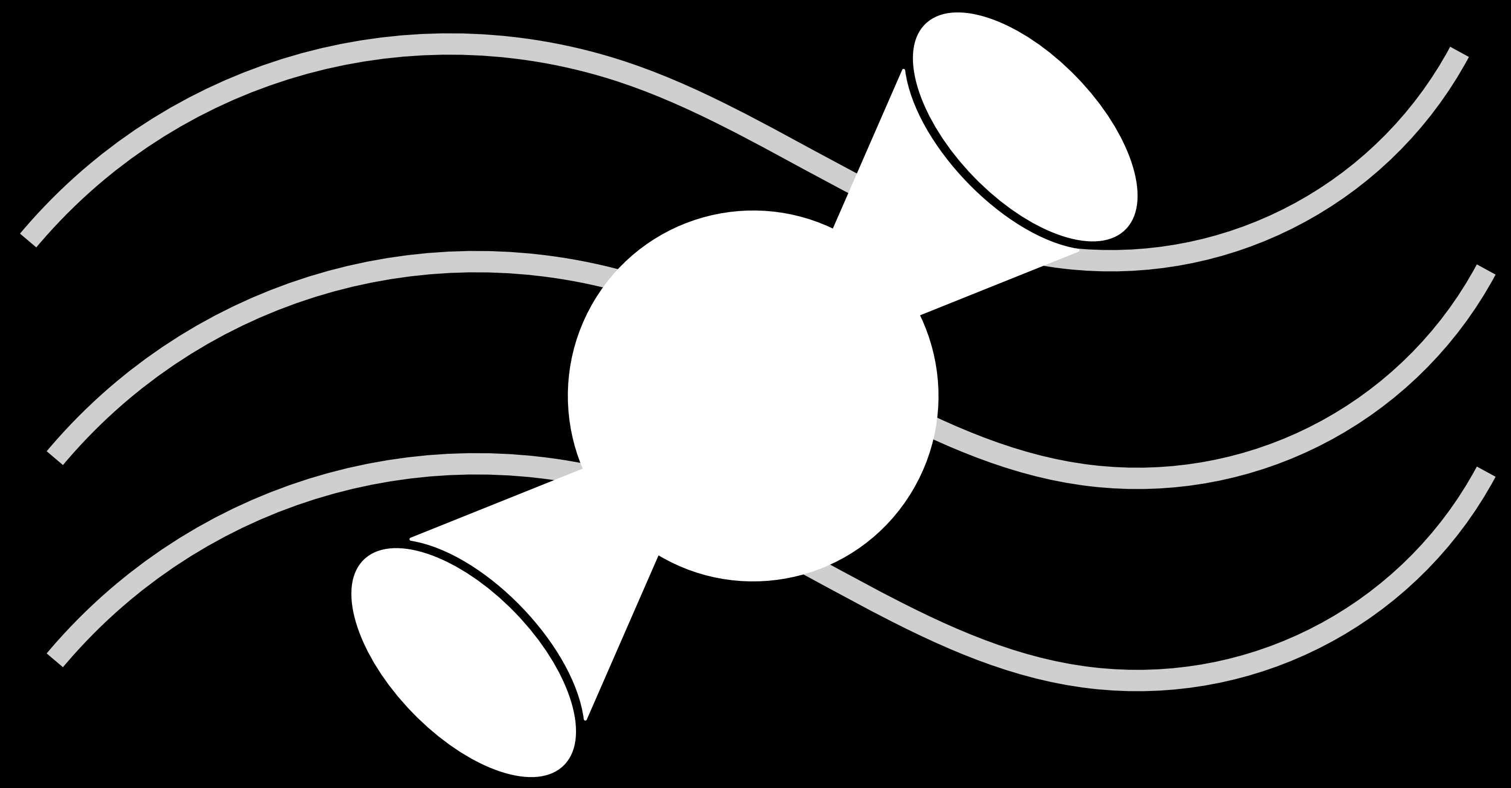
SPECTRUM PARAMETRIZATION

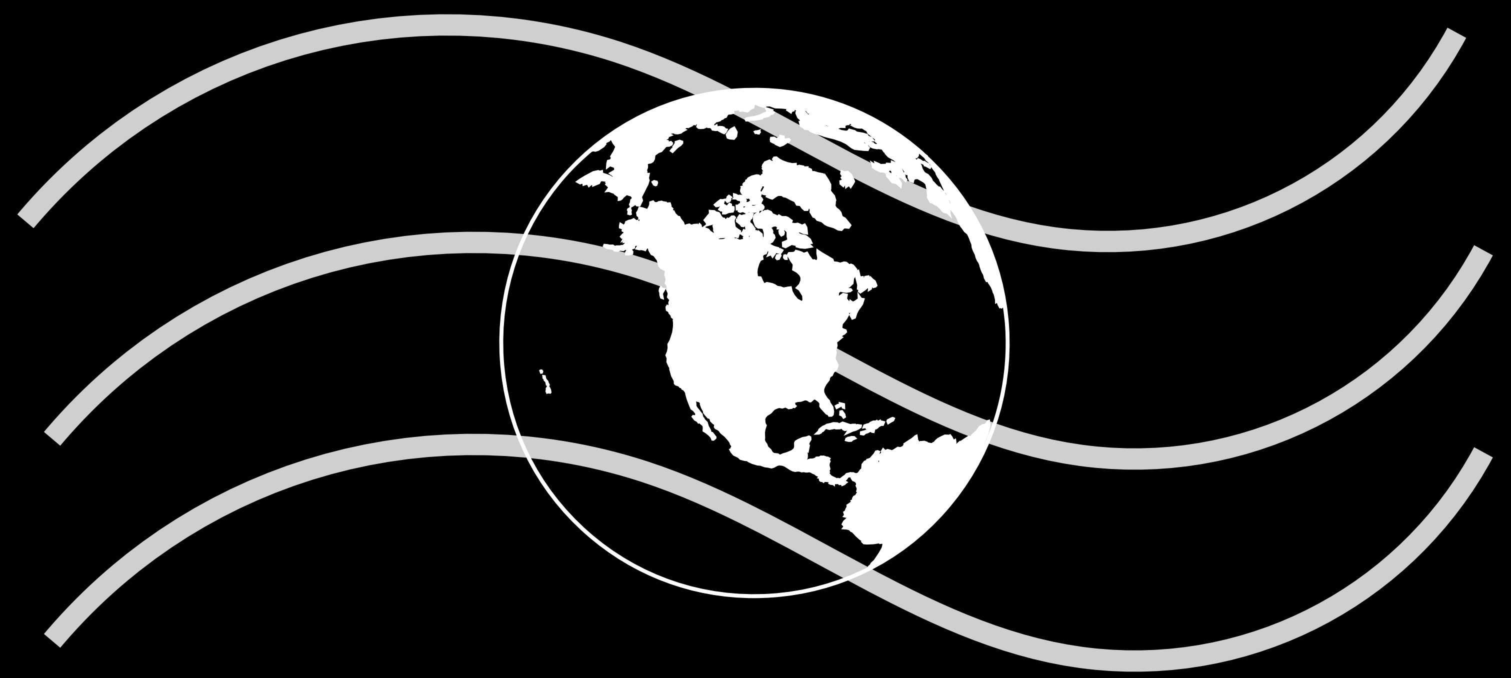


interactive spectrum is publicly available

SOME RESULTS







ULDM signals in PTAs

ULDM FIELD

$$10^{-24}\ \mathrm{eV} \lesssim m_\phi \ll \mathrm{eV}$$

lower masses are already ruled out by CMB observables

$$\rho_\phi \sim 0.4\,\mathrm{GeV\,cm^{-3}}$$

local ULDM density

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

$$\hat{\phi}(\vec{x})$$

random amplitude with zero mean and unit variance

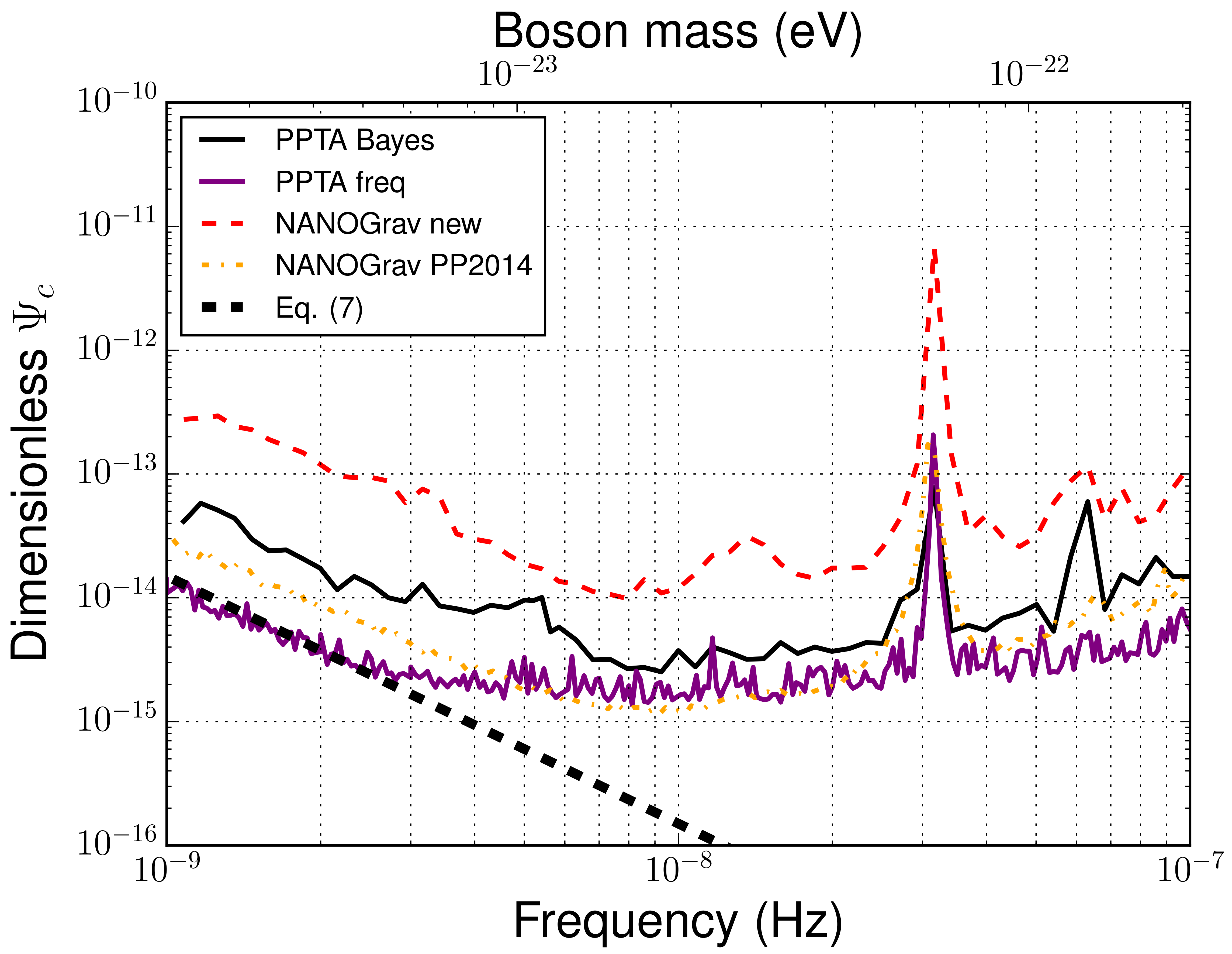
$$\gamma(\vec{x}) = \vec{k}\cdot\vec{x} + \tilde{\gamma}$$

phase of the signal

PREVIOIUS SEARCHES - gravitational

$$\rho_\phi(t) \Rightarrow \delta g_{\mu\nu}(t) \Rightarrow \frac{\delta\omega}{\omega} \sim \int \dot{\Phi}\, dz$$

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



PPTA [1810.03227]

- Pulsar timing signal from ultralight scalar dark matter
- Search for ultralight scalar dark matter with NANOGrav pulsar timing arrays
- Constraints on ultralight scalar dark matter from pulsar timing
- Parkes Pulsar Timing Array constraints on ultralight scalar-field dark matter

PREVIOIUS SEARCHES - direct couplings

- **Doppler shift**
  - Scalar DM $\mathbf{a} \sim \nabla \phi$ velocity suppressed
  - Vector DM $\mathbf{E} \sim \partial_t \phi$ High-precision search for dark photon dark matter with the Parkes Pulsar Timing Array - Phys. Rev. Research 4, L012022 (2022)

- **Fifth force**
  - Test of the Equivalence Principle Using a Rotating Torsion Balance - Phys. Rev. Lett. 100, 041101 (2008)
  - MICROSCOPE Mission: First Constraints on the Violation of the Weak Equivalence Principle by a Light Scalar Dilaton - Phys. Rev. Lett. 120, 141101 (2018)

- **Atomic clock shifts**
  - Dark Matter Direct Detection with Accelerometers - [1512.06165]
  - Precision Metrology Meets Cosmology: Improved Constraints on Ultralight Dark Matter from Atom-Cavity Frequency Comparisons - PRL 125, 201302 (2020)

- **Orbital period in binary pulsars**
  - Ultralight Dark Matter Resonates with Binary Pulsars - Phys. Rev. Lett. 118, 261102 (2017)

NEW PTA SIGNALS - spin fluctuations

$$\mathcal{L}_{\phi,\mathrm{QCD}} \supset \frac{\phi}{\Lambda}\left(\frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{\mu\nu}_A - \sum_{q=u,d}(d_q+\gamma_q d_g)m_q\bar{q}q\right)$$

NEW PTA SIGNALS - spin fluctuations

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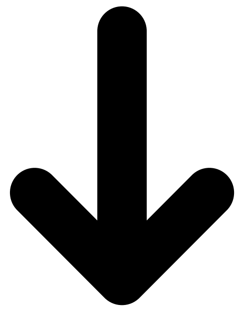

$$\frac{\delta m_{p,n}}{m_{p,n}} \simeq \frac{1}{\Lambda}\Big(d_g + C_n\, d_{\hat{m}}\Big)\phi$$

$$C_n \sim 0.048$$

T. Damour, J. F. Donoghue [1007.2792]

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↓

$$\frac{\delta m_{p,n}}{m_{p,n}} \simeq \frac{1}{\Lambda}\left(d_g + C_n\, d_{\hat{m}}\right)\phi$$

QCD scale fluctuations (d_g) — quark masses fluctuations ($C_n\, d_{\hat{m}}$)

$C_n \sim 0.048$

T. Damour, J. F. Donoghue [1007.2792]

NEW PTA SIGNALS - spin fluctuations

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T. Damour, J. F. Donoghue [1007.2792]

$$\downarrow$$

$$\frac{\delta I}{I_0} = \eta \frac{\delta M}{M_0} + \delta\eta \frac{\delta m_n}{m_n}$$

NEW PTA SIGNALS - spin fluctuations

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↓

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$C_n \sim 0.048$

T. Damour, J. F. Donoghue [1007.2792]

↓

in the simplest model of a spherical non-rotating neutron star

$\eta = 1/3$

$\delta\eta = -16/3$

$$\frac{\delta I}{I_0} = \eta\frac{\delta M}{M_0} + \delta\eta\frac{\delta m_n}{m_n}$$

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↓

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[T. Damour, J. F. Donoghue [1007.2792]]

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$$\eta = 1/3$$

$$\delta\eta = -16/3$$

$$\frac{\delta I}{I_0} = \eta \frac{\delta M}{M_0} + \delta\eta \frac{\delta m_n}{m_n}$$

$$\frac{\delta M}{M_0} = \sum_{f\in\{e,\mu,p,n\}} Y_f \frac{m_f}{m_n} \frac{\delta m_f}{m_f}$$

NEW PTA SIGNALS - spin fluctuations

$$\mathcal{L}_{\phi,\mathrm{QCD}} \supset \frac{\phi}{\Lambda}\left(\frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{\mu\nu}_A - \sum (d_q+\gamma_q d_g)m_q\bar{q}q\right)$$

$$h(t) = \frac{\sqrt{2\rho_\phi}}{m_\phi^2\Lambda}\left(\vec{y}\cdot\vec{d}\right)\hat{\phi}_P \sin\left(m_\phi t + \gamma(\vec{x}_P)\right)$$

where $\vec{d}$ contains the ULDM couplings an $\vec{y}$ contains the sensitivity parameters:

$$\{y_g,\, y_{\hat{m}},\, y_\mu,\, y_e\} = \eta\left\{1,\, C_n,\, 6\times10^{-3},\, 5\times10^{-5}\right\} + \delta\eta\left\{1,\, C_n,\, 0,\, 0\right\}$$

792]

in the

$\delta\eta = -16/3$

NEW PTA SIGNALS - clock shift

pulses arrival time are measured with atomic clocks (most of them based on the hyperfine transition of the ground state of the Cesium atom)

$$f \propto \left(m_e \alpha^2\right)\left[\alpha^2 F_{\rm rel}(Z\alpha)\right]\left(\mu \frac{m_e}{m_p}\right)^{\zeta}$$

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atomic energy scale — relativistic correction — hyperfine splitting

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ULDM fluctuations induce frequency fluctuations

$$\frac{\delta f_A}{f_A} \simeq \left[\frac{\delta m_e}{m_e} + (4 + K_A)\frac{\delta \alpha}{\alpha} + \zeta \left(\frac{\delta m_e}{m_e} + C_A \sum_{q=u,d} \frac{\delta m_q}{m_q} - \frac{\delta m_p}{m_p}\right)\right]$$

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$$\frac{\delta F_{\rm rel}}{F_{\rm rel}} = K_A \frac{\delta \alpha}{\alpha} \qquad \frac{\delta\mu}{\mu} = C_A \frac{\delta m_q}{m_q}$$

NEW PTA SIGNALS - clock shift

pulses arrival time are measured with atomic clocks (most of them based on the hyperfine transition of the ground state of the Cesium atom)

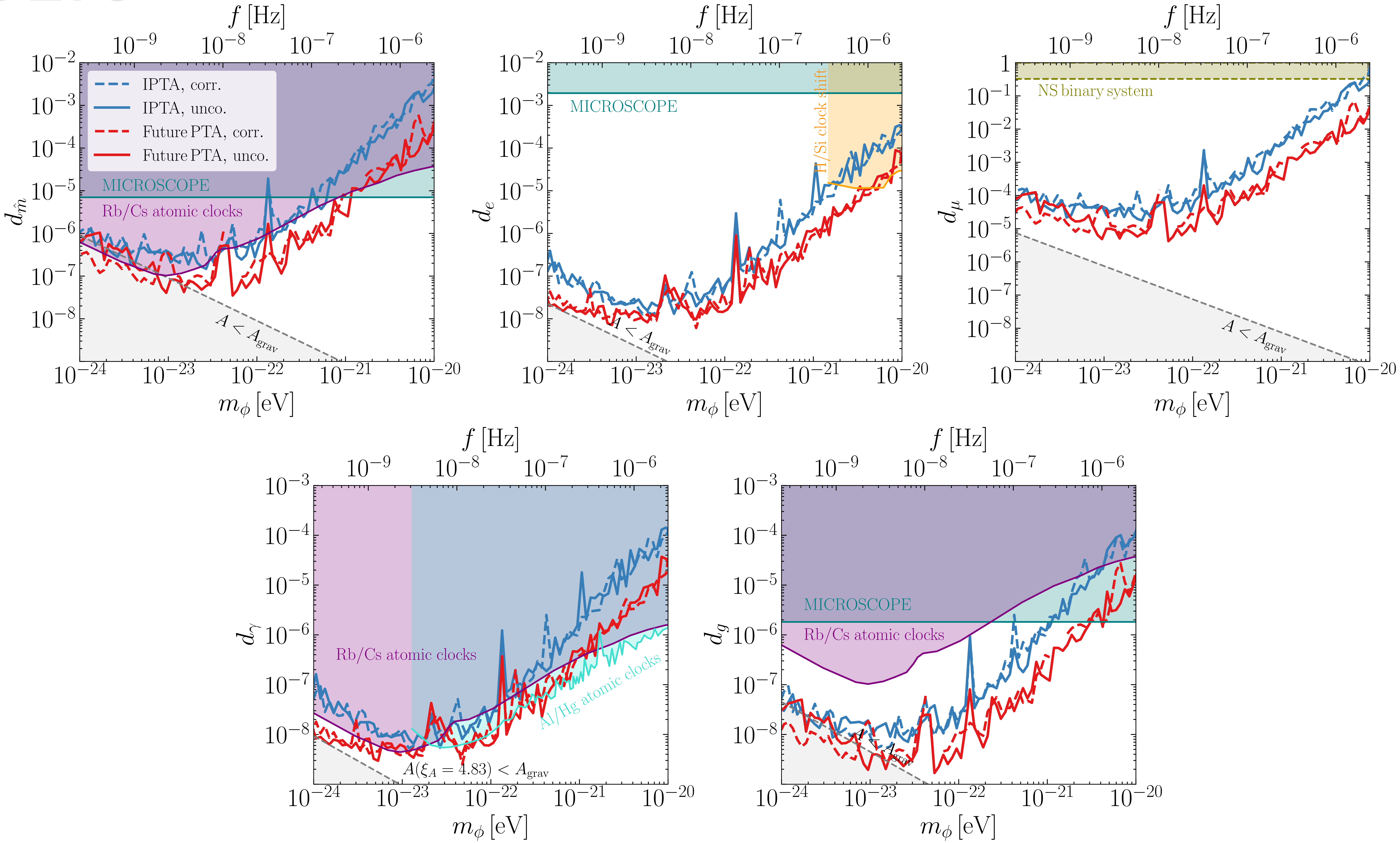
$$h(t) = \frac{\sqrt{2\rho_\phi}}{m_\phi^2 \Lambda} \left(\vec{y} \cdot \vec{d}\right) \hat{\phi}_E \sin\left(m_\phi t + \gamma(\vec{x}_E)\right)$$

where $\vec{d}$ contains the ULDM couplings an $\vec{y}$ contains the sensitivity parameters:

$$\{y_g,\, y_\gamma,\, y_{\hat{m}},\, y_e\} \simeq \left\{\zeta,\, \xi_A,\, \zeta\left(C_n + \hat{C}_A\right), 1 + \zeta\right\}$$

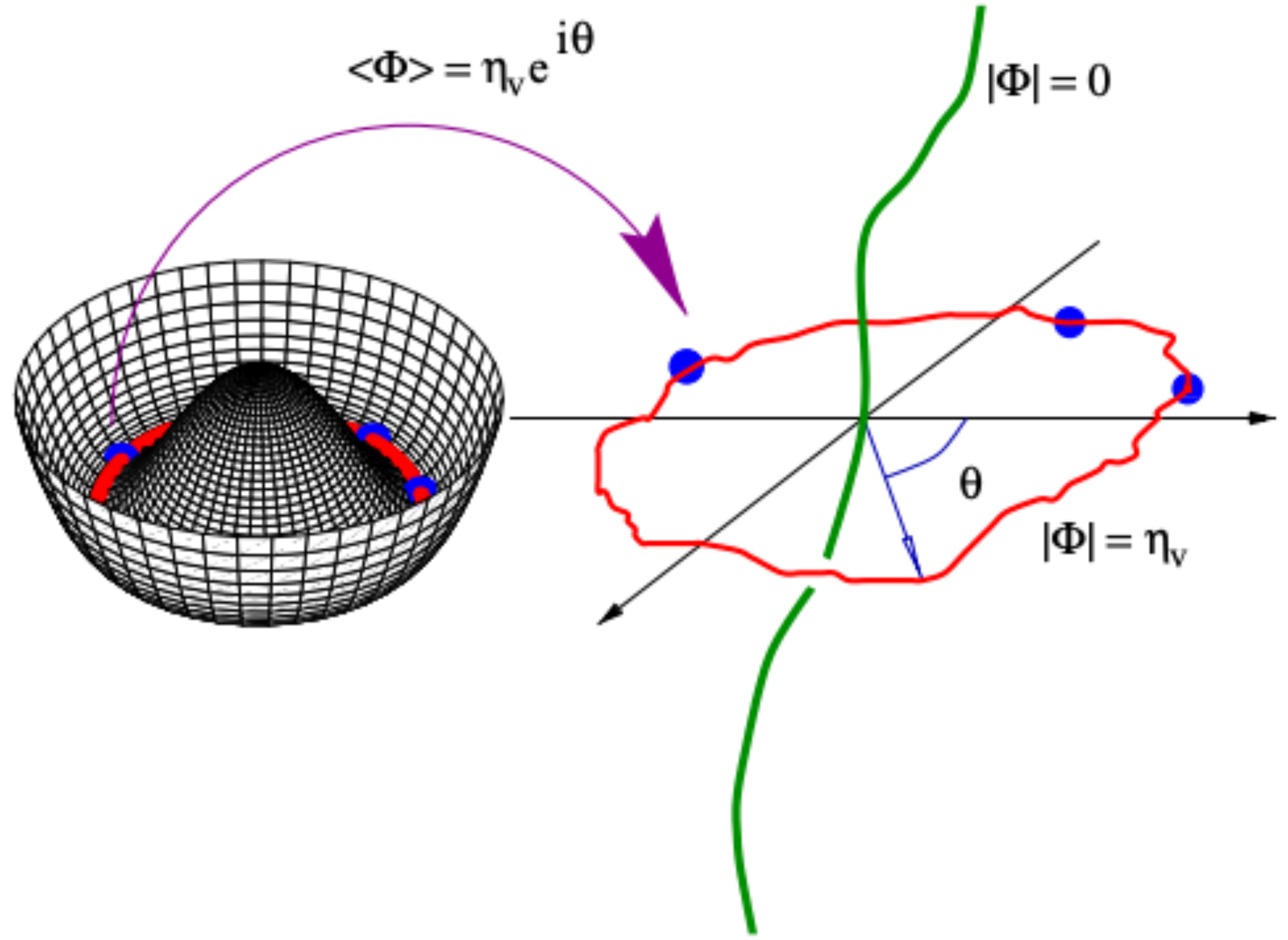
$F_{\rm rel}$ α μ m_q

RESULTS

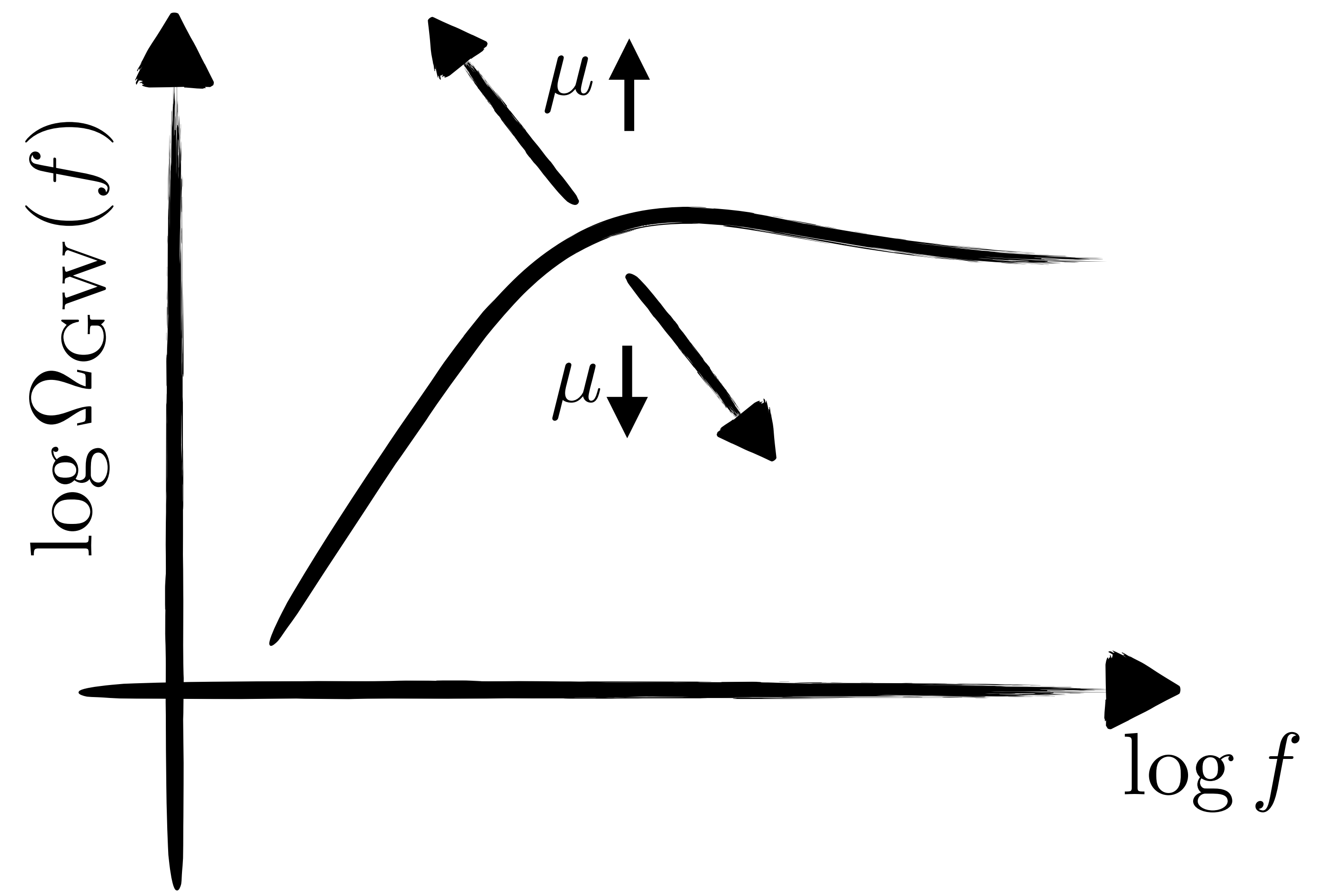


f [Hz]
IPTA, corr.
IPTA, unco.
Future PTA, corr.
Future PTA, unco.
MICROSCOPE
Rb/Cs atomic clocks
A < A_grav
H/Si clock shift
NS binary system
Al/Hg atomic clocks
A(ξ_A = 4.83) < A_grav
m_φ [eV]
d_m̂
d_e
d_μ
d_γ
d_g

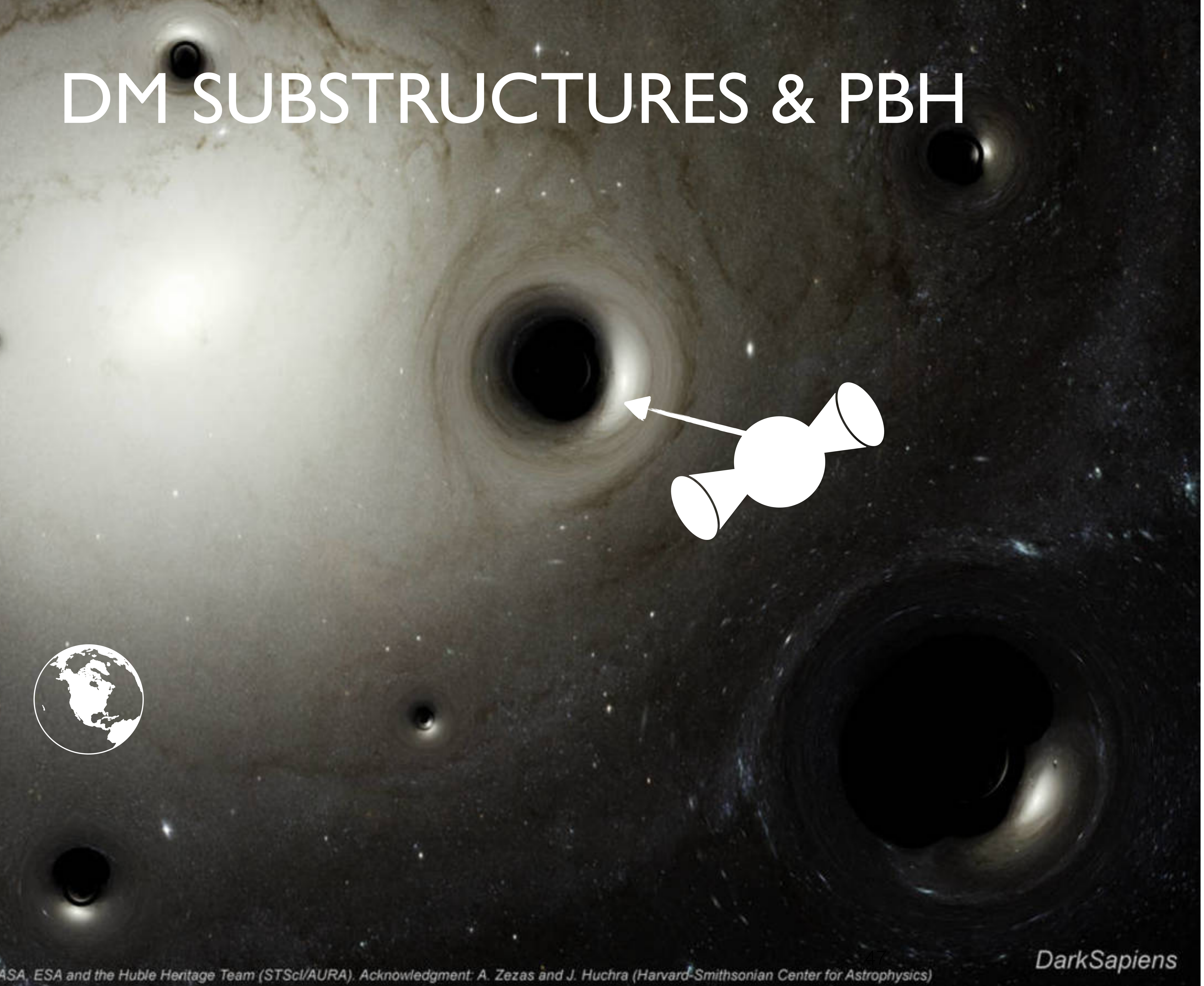
COSMIC STRINGS



μ : string tension



DM SUBSTRUCTURES & PBH



single transiting objects give deterministic signal that can be easily parametrized

dynamic events ($\tau \ll T_{\rm obs}$)

$$h(t) \sim (t - t_0)\theta(t - t_0)$$

static events ($\tau \gg T_{\rm obs}$)

$$h(t) \sim t^3$$

at low masses the single event is not detectable but the “noise” induce by the entire population could. Still an open problem!

CONCLUSIONS

Are we close to the detection of a GWB (?)

Astrophysical or new-physics?

PTAs can be a powerful discovery tool (see Phase Transitions, Cosmic Strings, DM substructures …)

PTAs can set stringent constraint on new-physics model

work needs to be done to fully exploit PTAs as anomalies detectors