Hearing the Universe Hum with Pulsar Timing Array: Gravitational Waves and Black Holes

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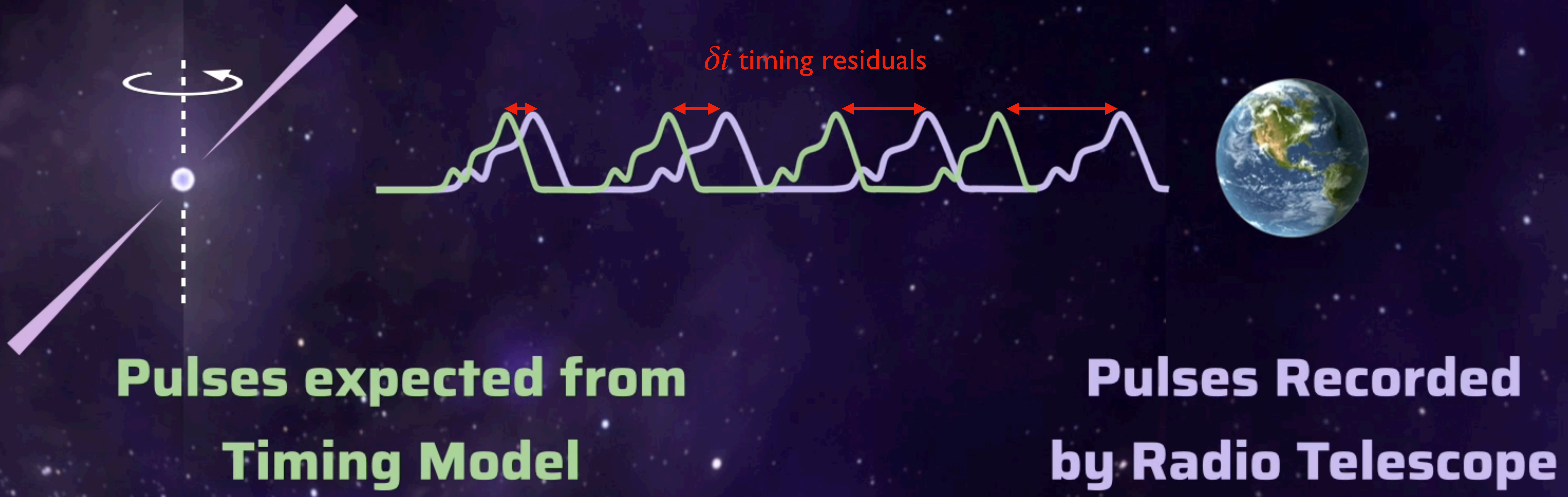
Broader Perspective:

- Recent pulsar timing array measurements of stochastic GW signal.
- Supermassive Black Hole Mergers
- Presence of Dark Matter and Dark Matter annihilation
- Tomography of Dark Matter Profiles
- Conclusions

PULSARS

Animation by NASA's Goddard Space Flight Center

TIMING RESIDUALS



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

Animation by NSF

credits Keyi "Onyx" Li / NSF / NANOGrav

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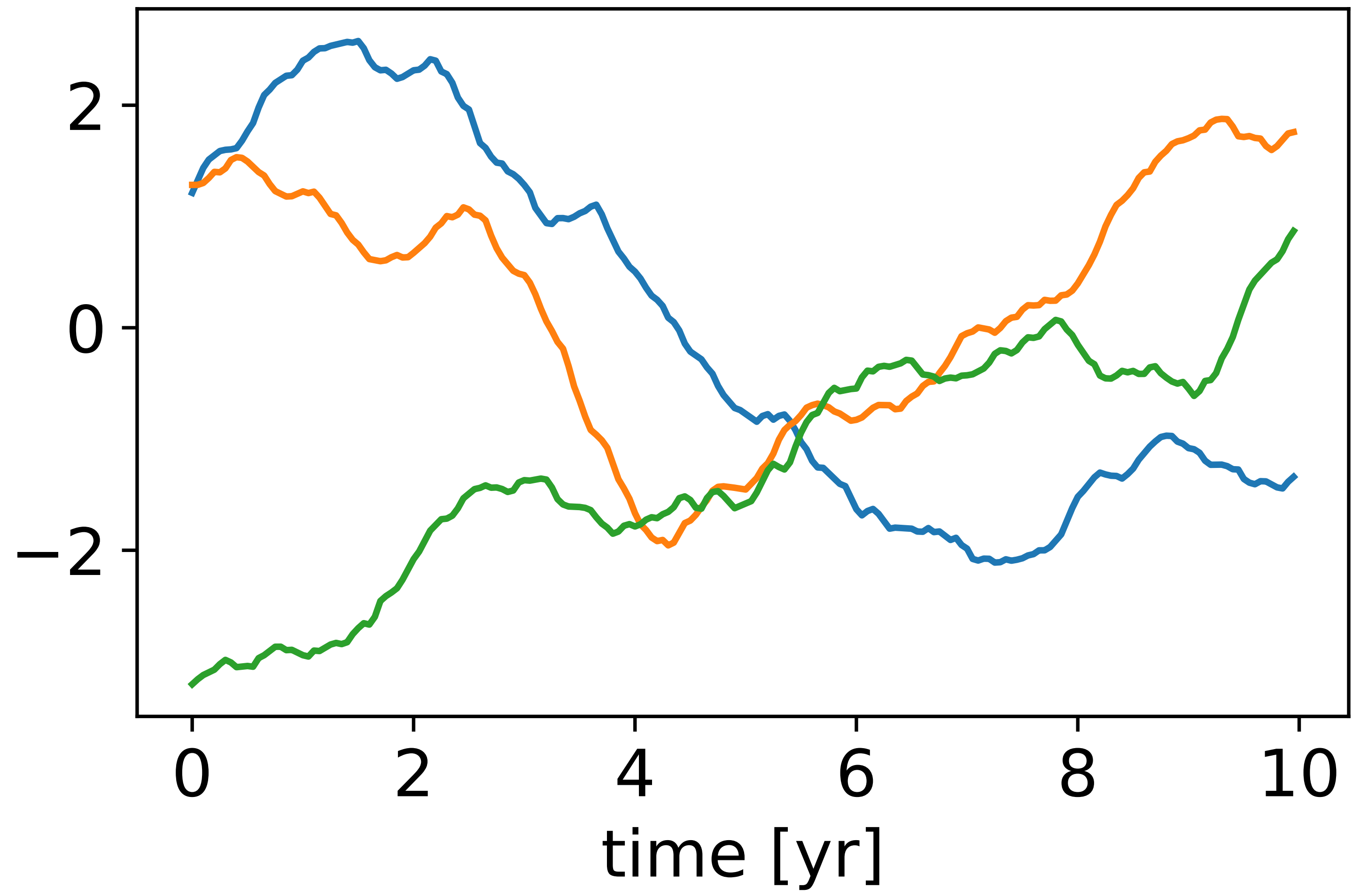
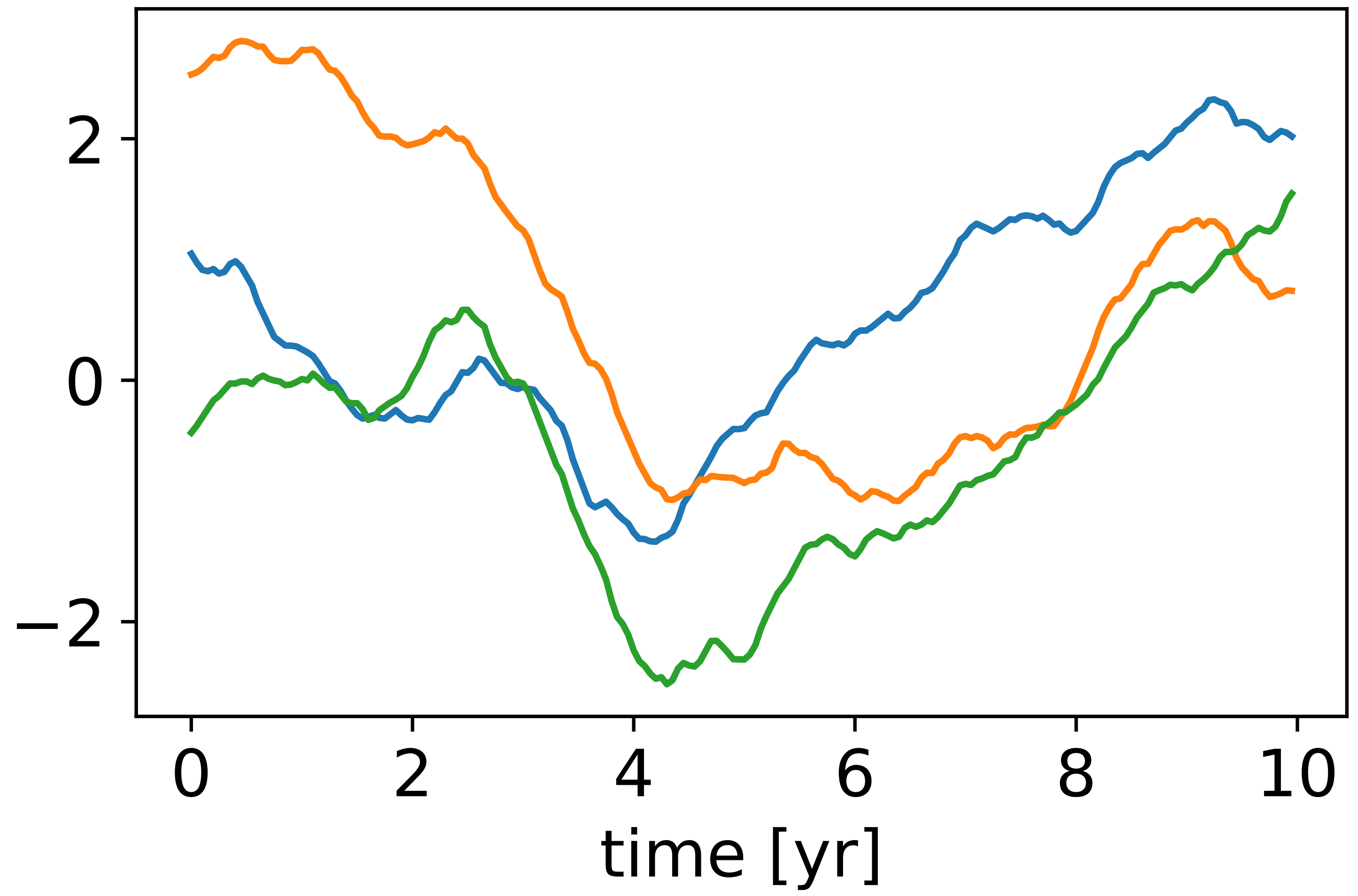
CORRELATIONS EXAMPLE

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



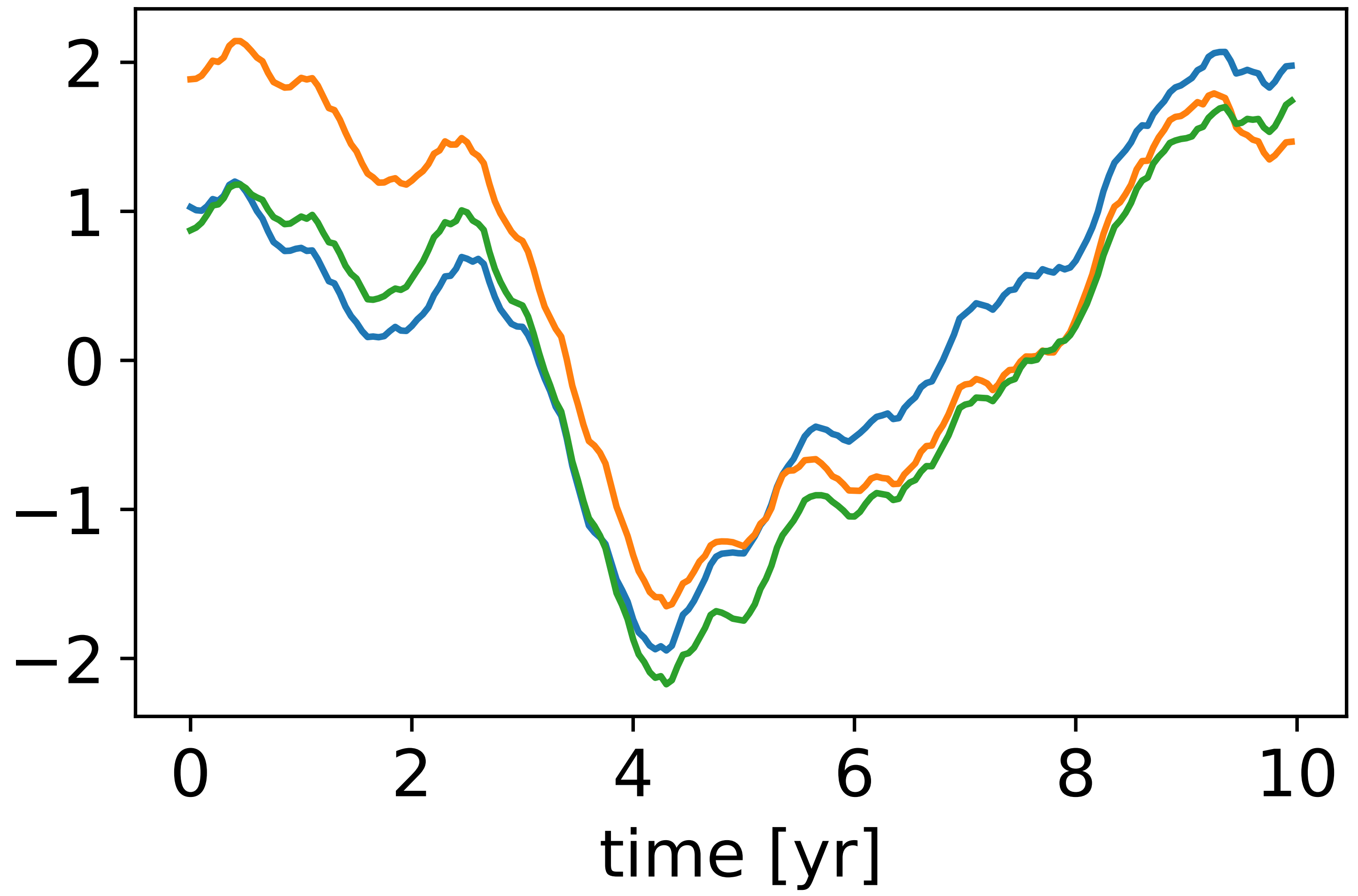
uncorrelated

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



moderately correlated

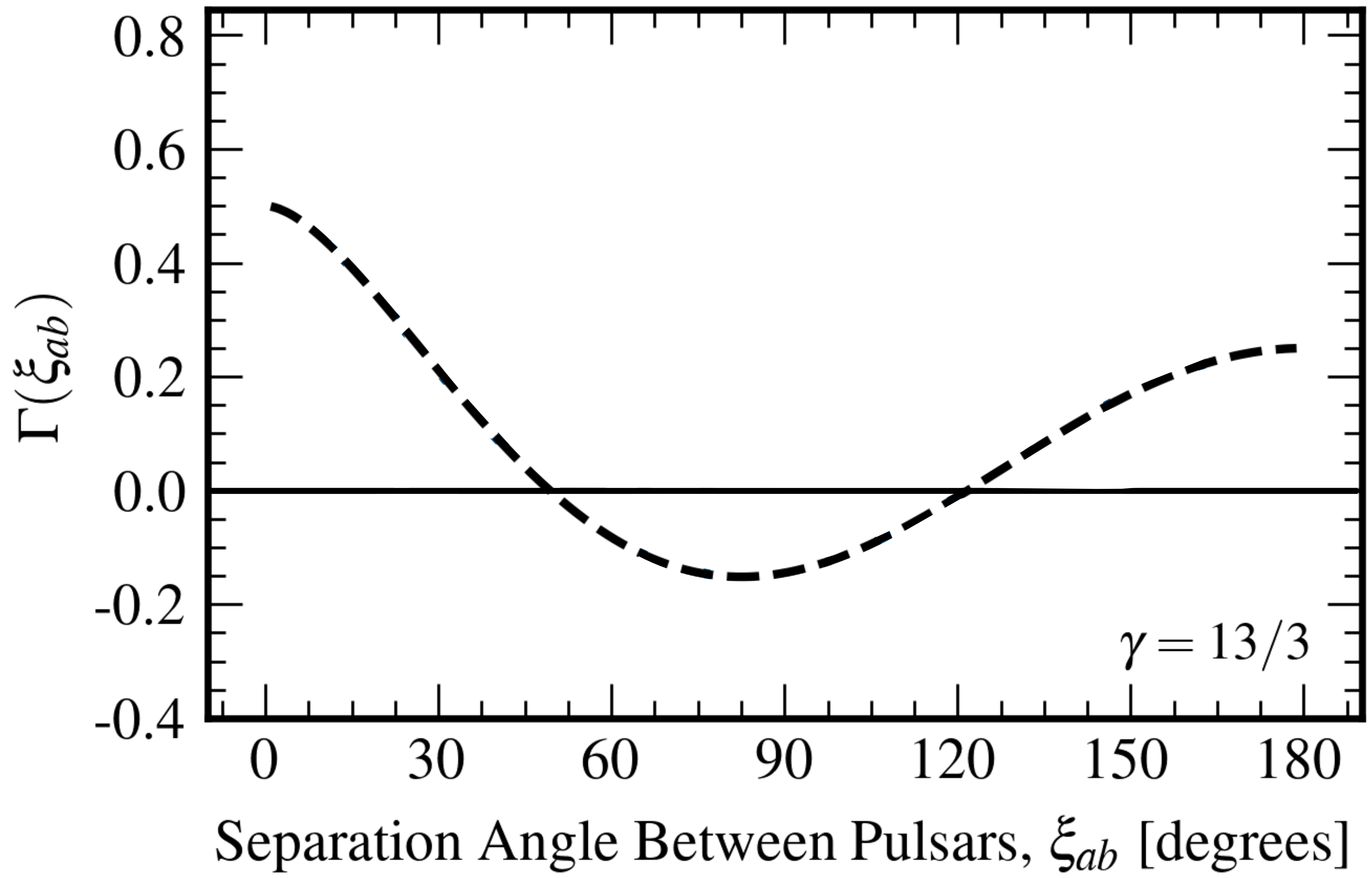
$$\Gamma_{ab} = \begin{pmatrix} 1 & 0.95 & 0.95 \\ 0.95 & 1 & 0.95 \\ 0.95 & 0.95 & 1 \end{pmatrix}$$



strongly correlated

slide from Joe Romano

HELLINGS & DOWNS CURVE



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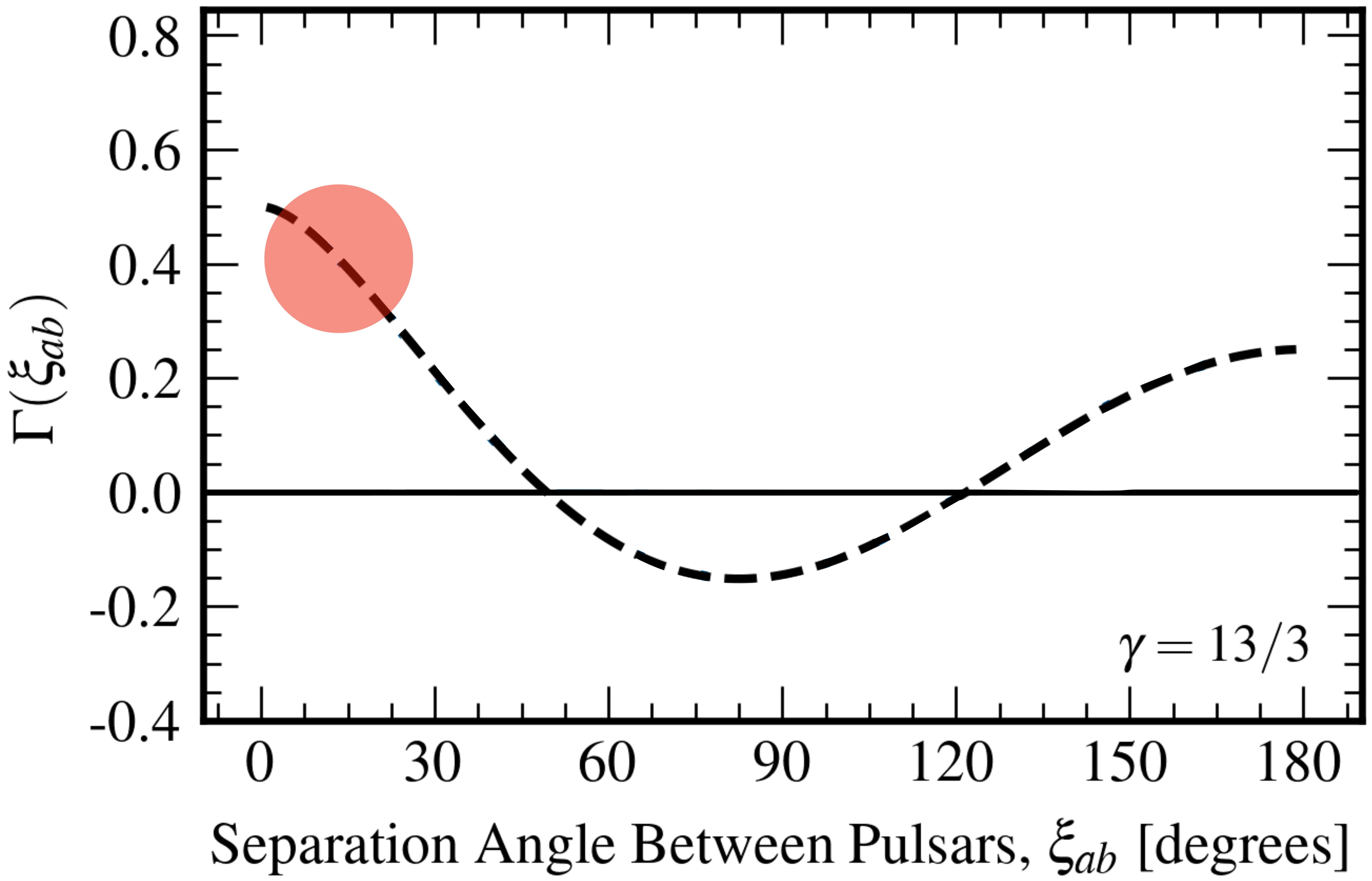

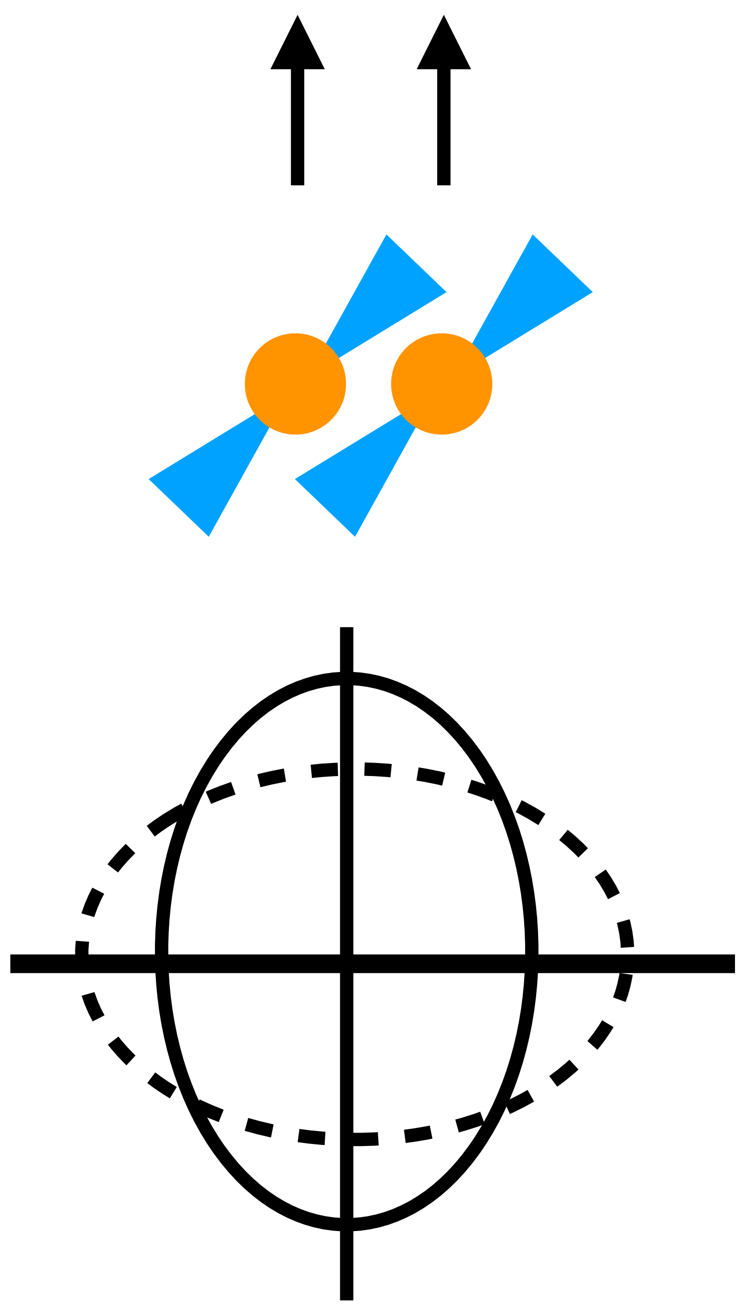

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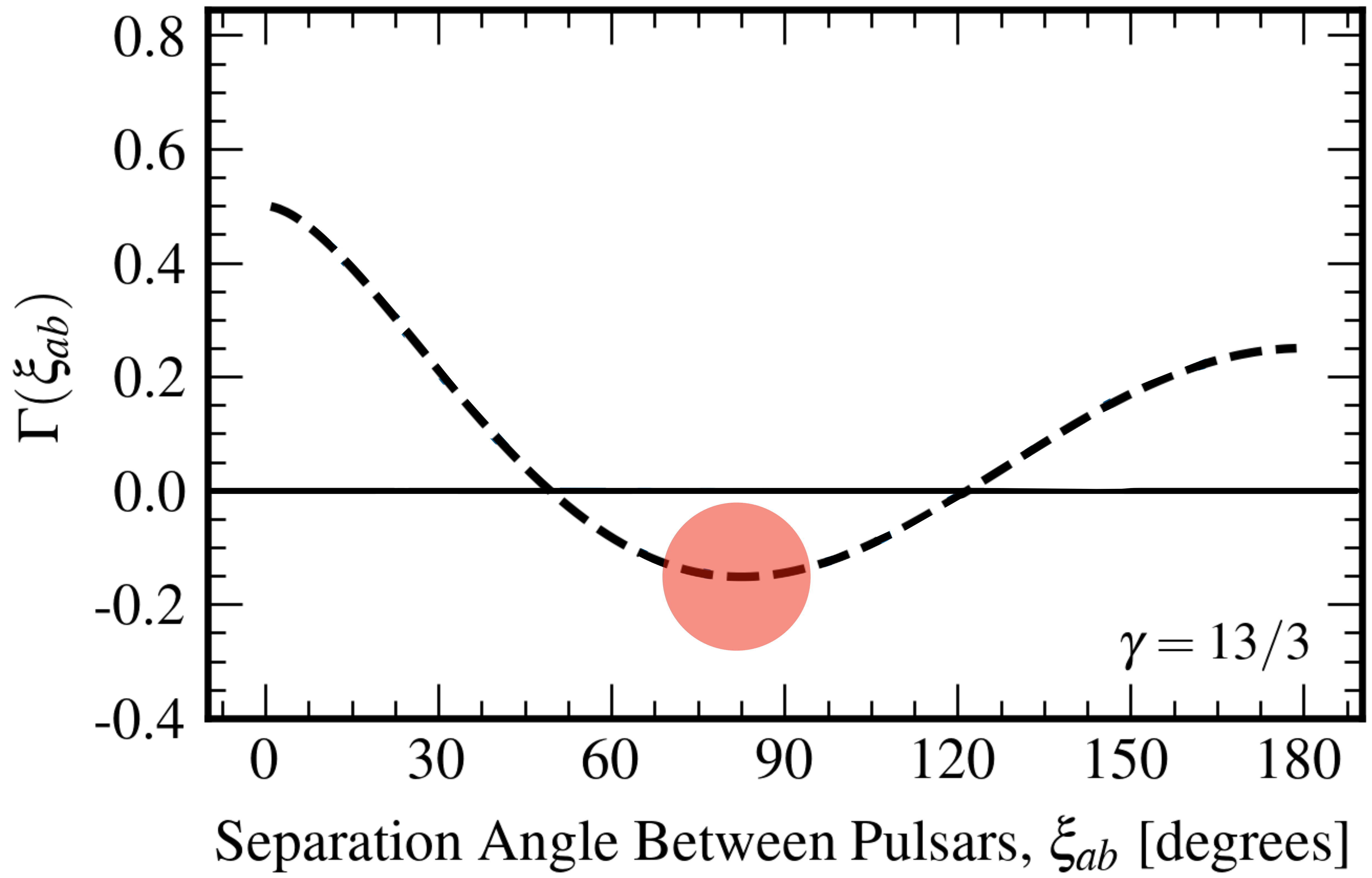

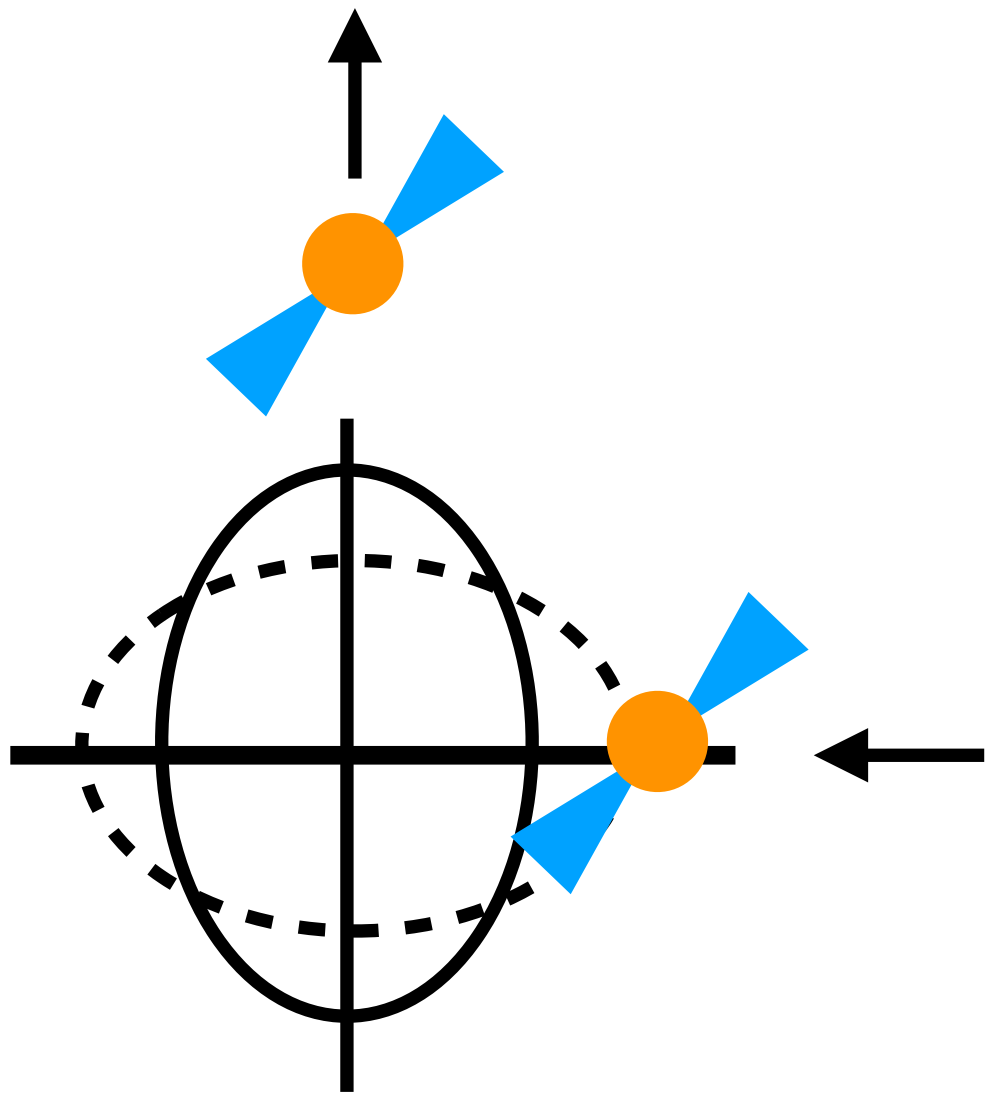

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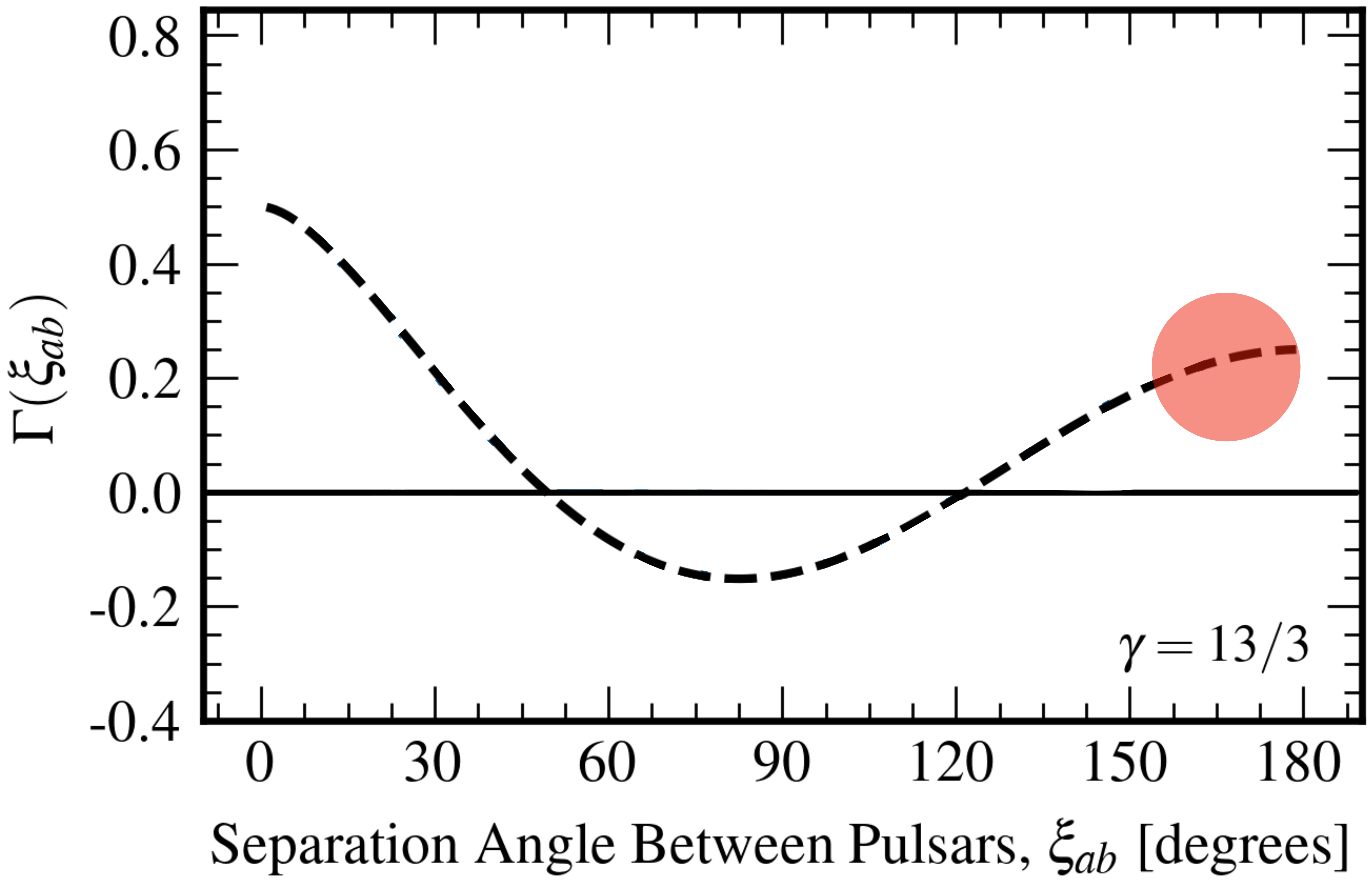
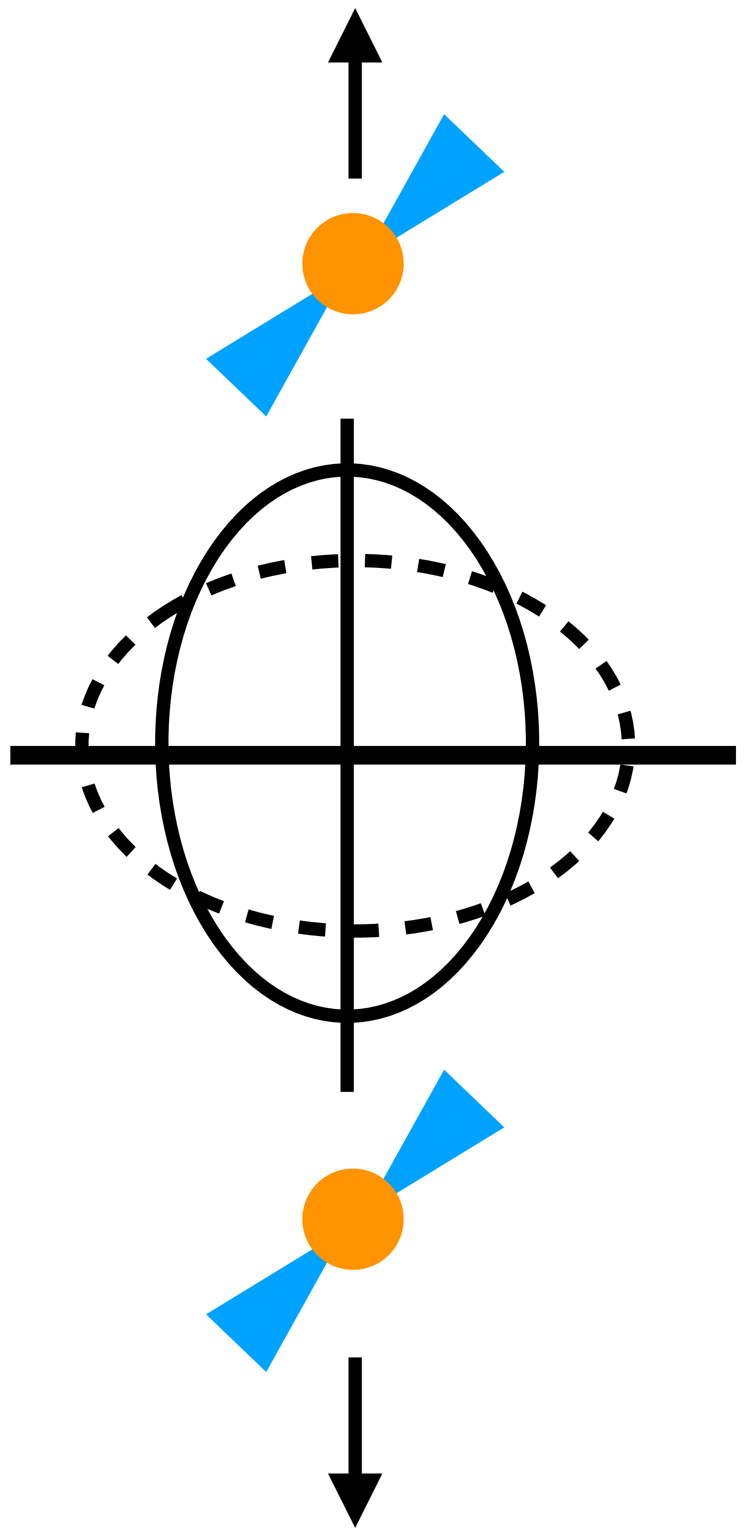
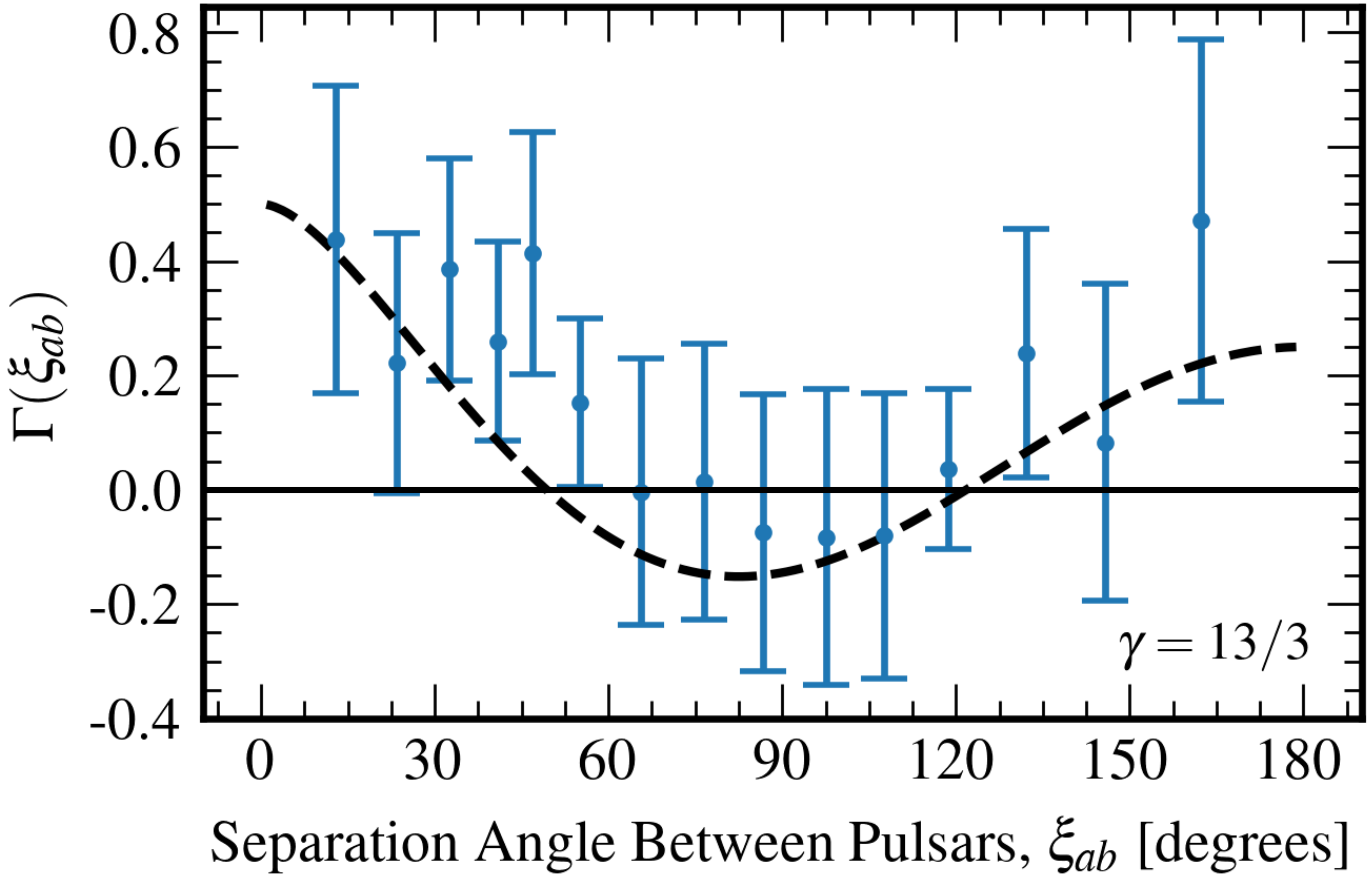




EVIDENCE FOR GWB

Agazie et al. [2306.16213]



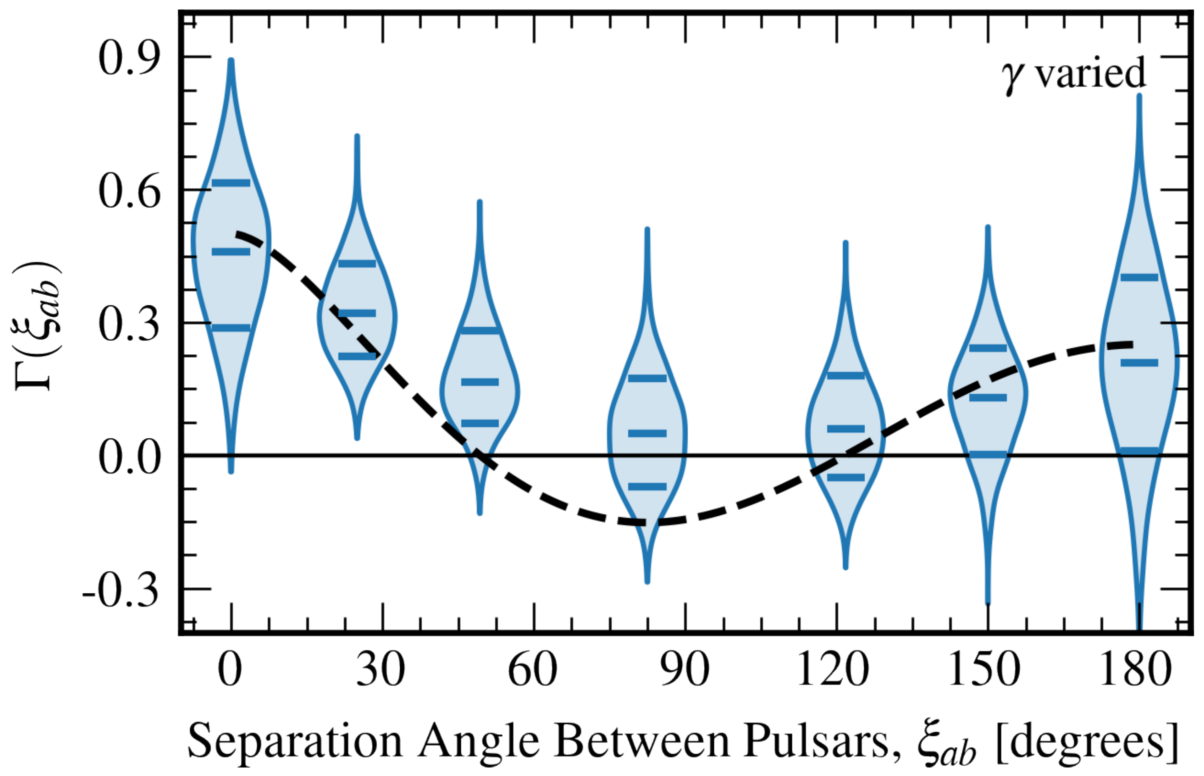
EVIDENCE FOR GWB

NANOGrav:

68 pulsars, 16yr of data

~3-4σ significance

Agazie et al. [2306.16213]

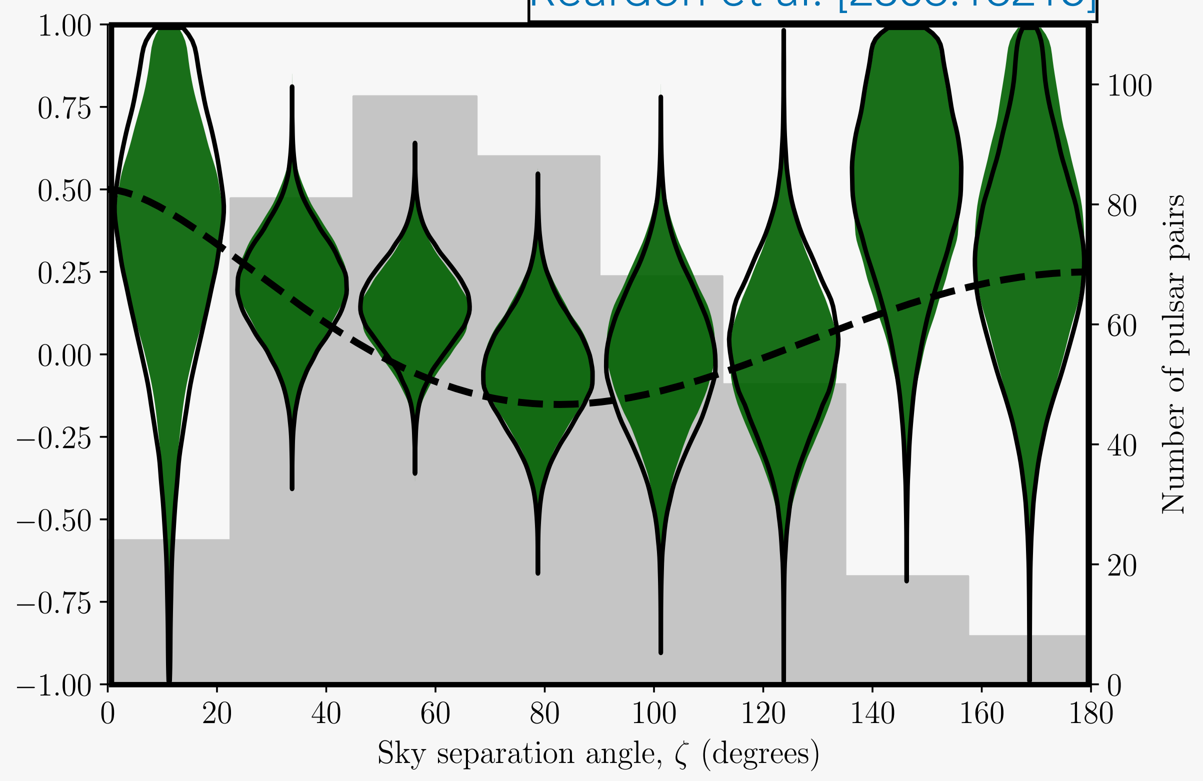


PPTA:

32 pulsars, 18yr of data

~2σ significance

Reardon et al. [2306.16215]

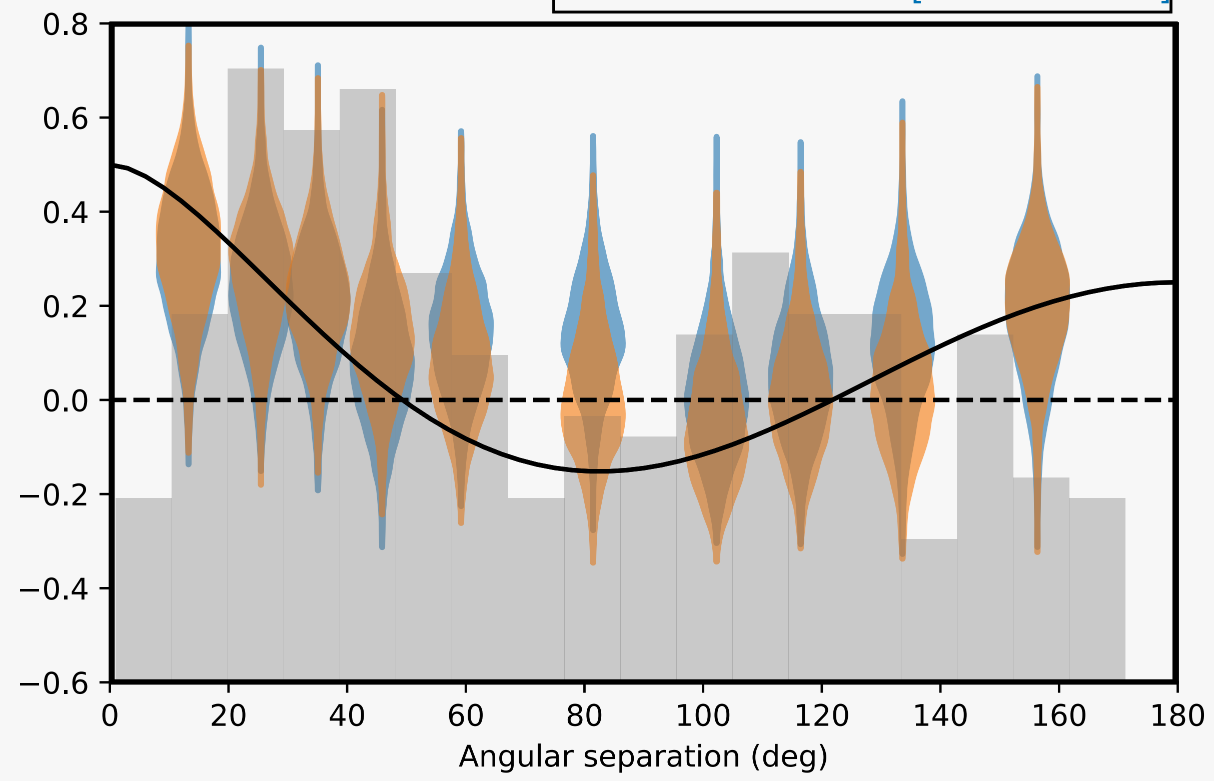


EPTA + InPTA:

25 pulsars, 24yr of data

~3σ significance

Antoniadis et al. [2306.16214]

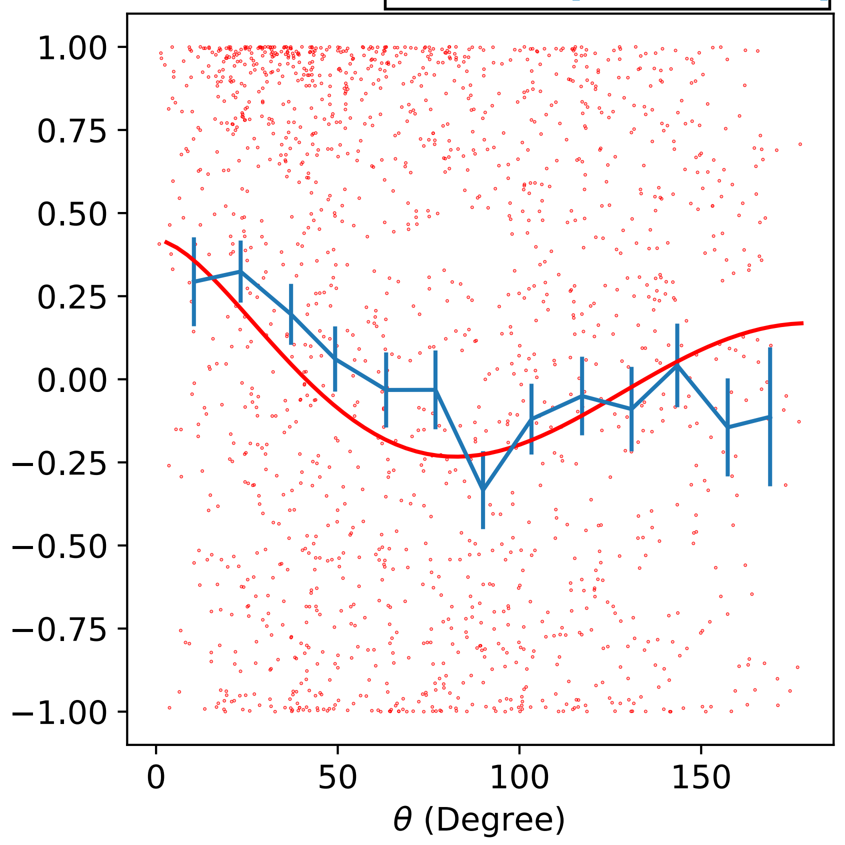


CPTA:

57 pulsars, 3yr of data

~4.6σ significance

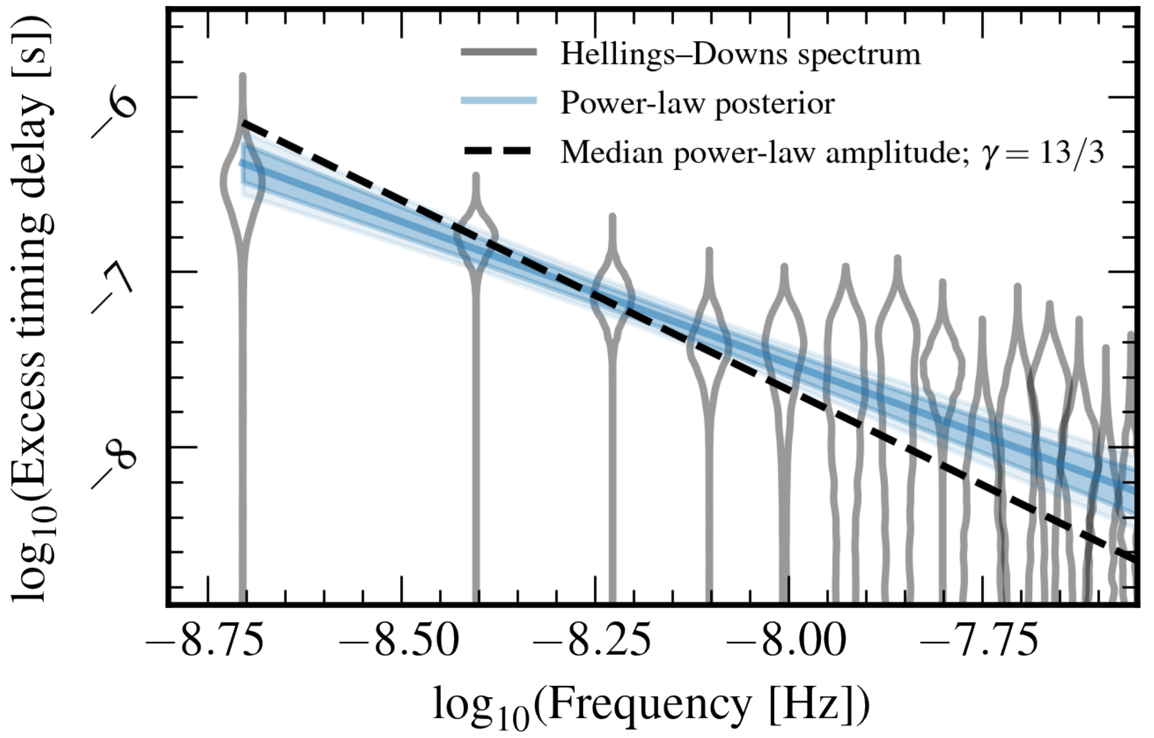
Xu et al. [2306.16216]

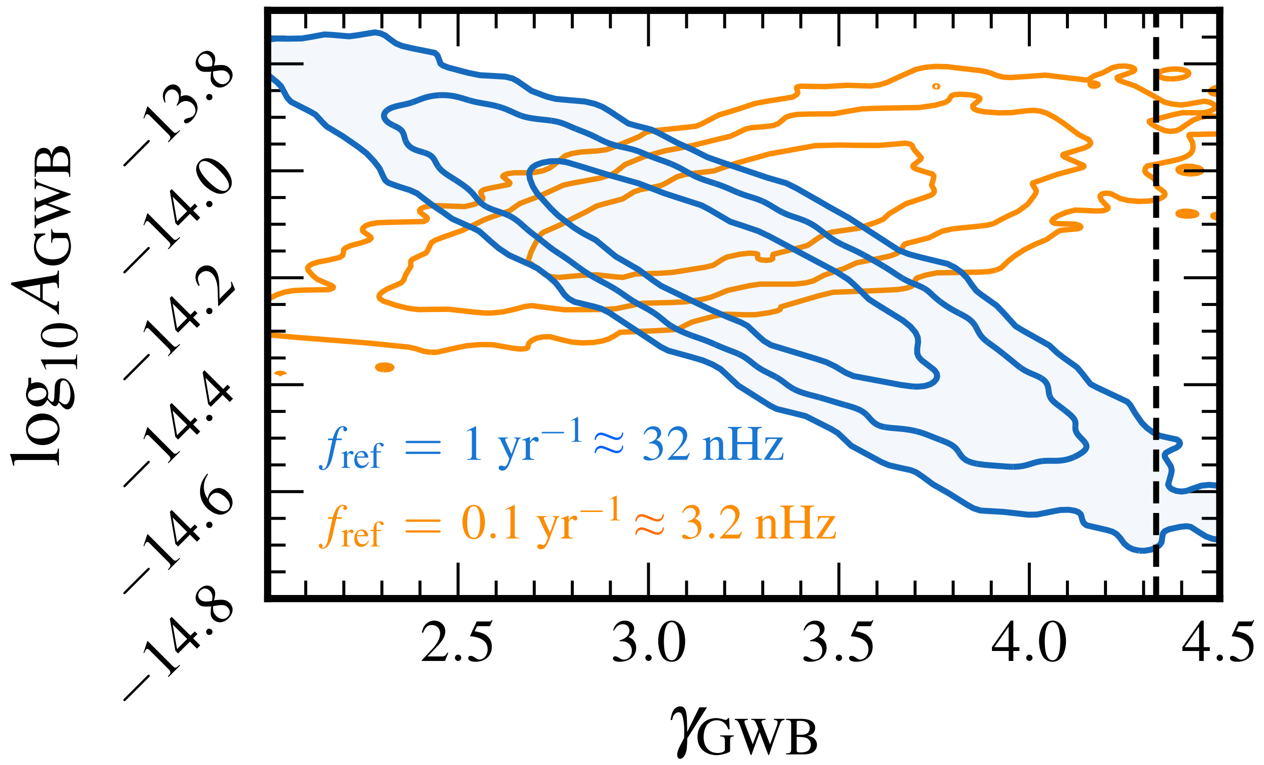


SPECTRUM

NANOGrav

Agazie et al. [2306.16213]





PPTA

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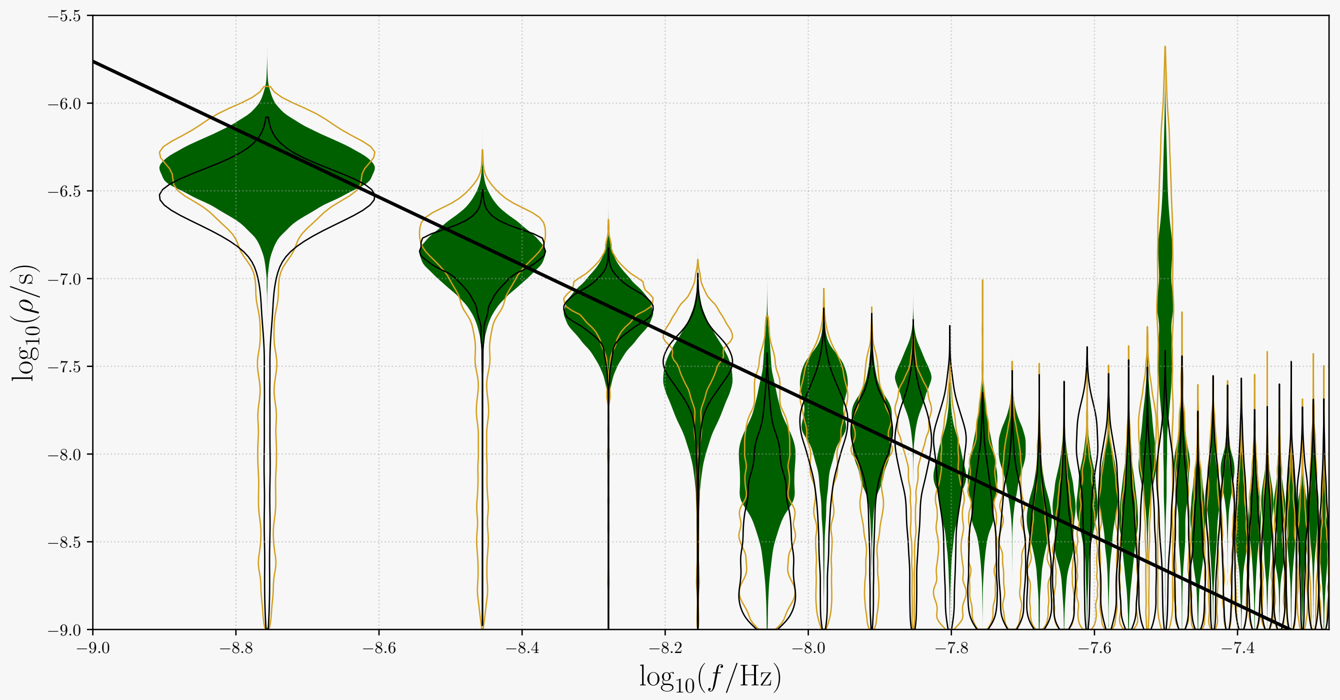

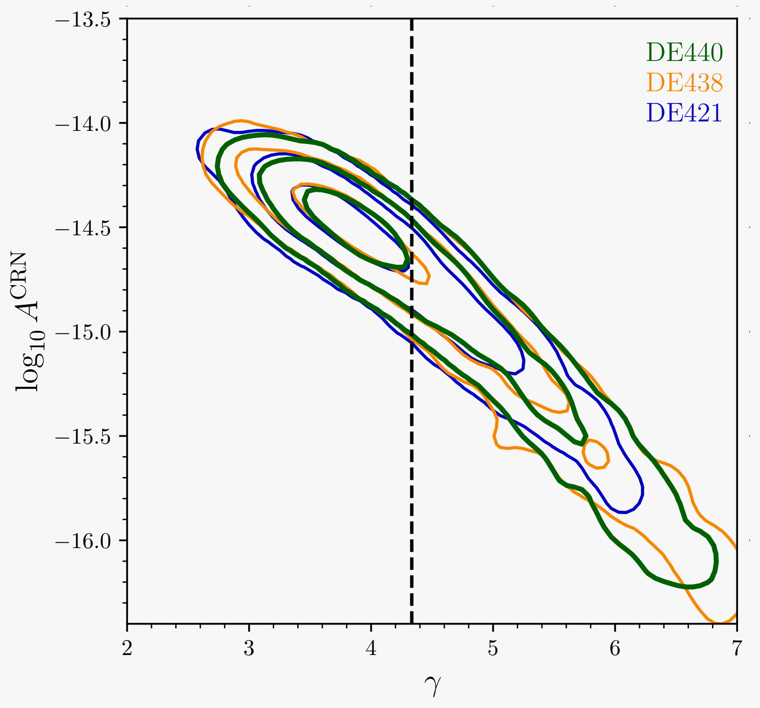

EPTA + InPTA

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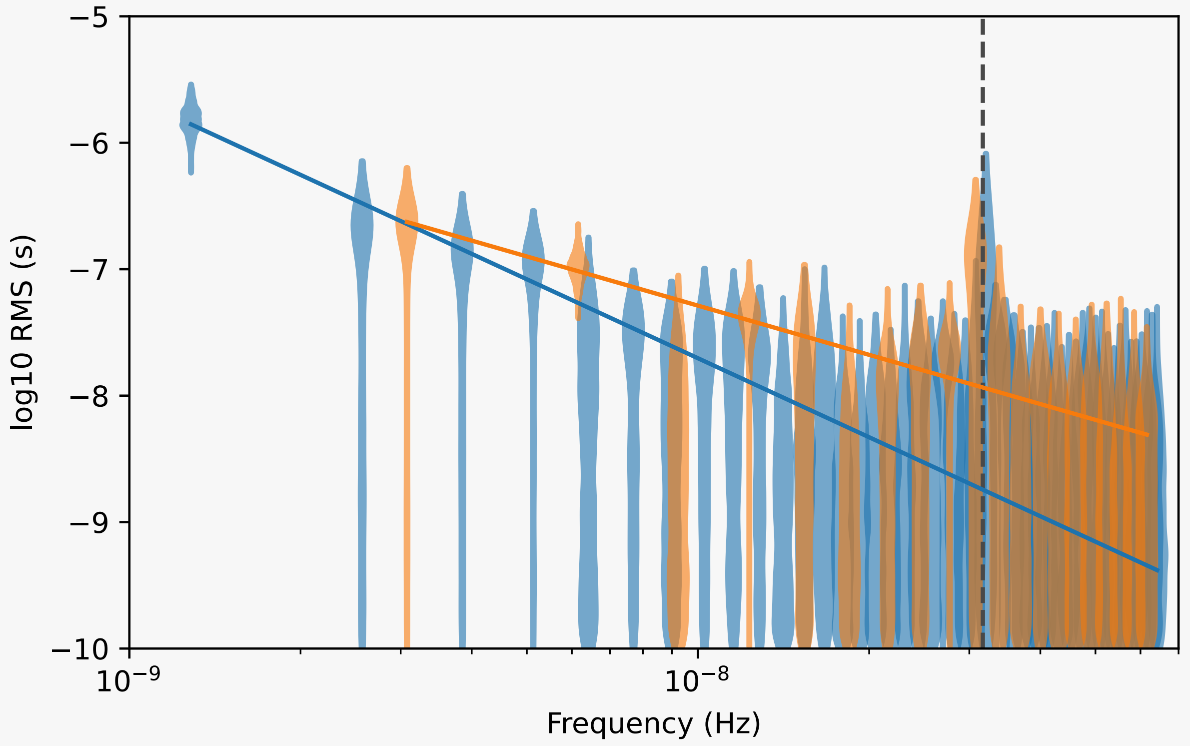
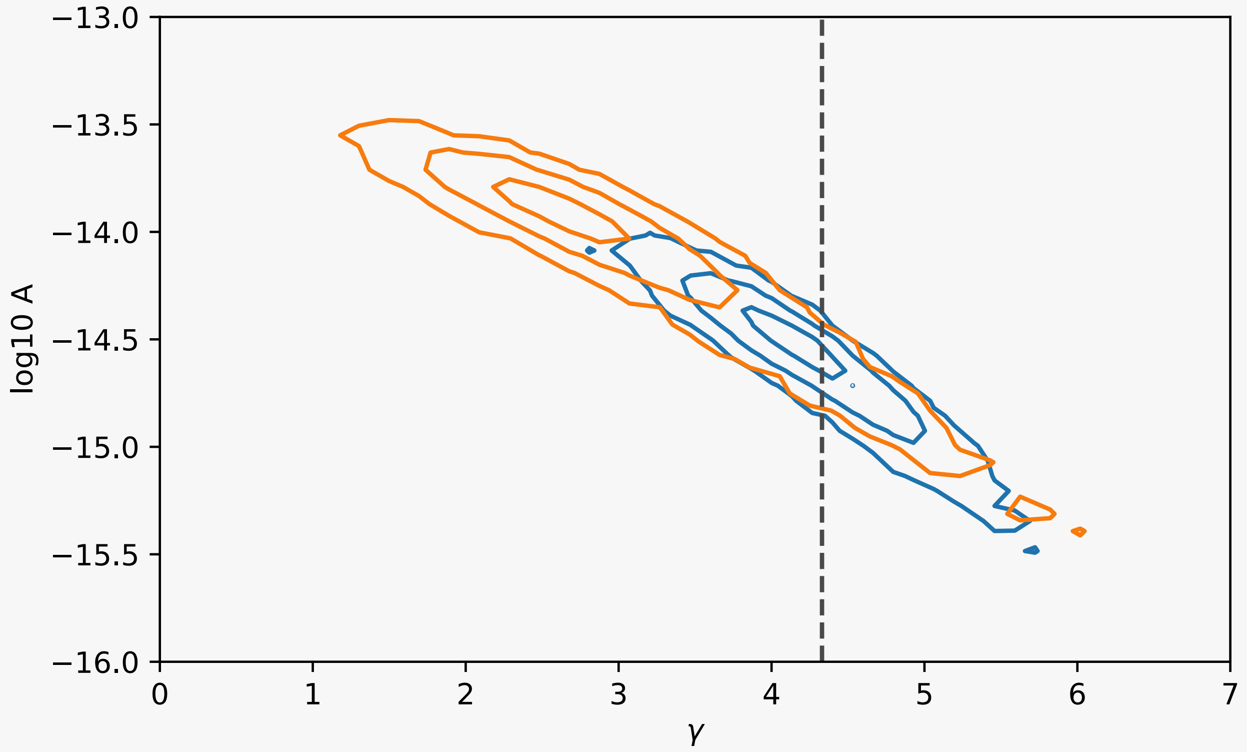
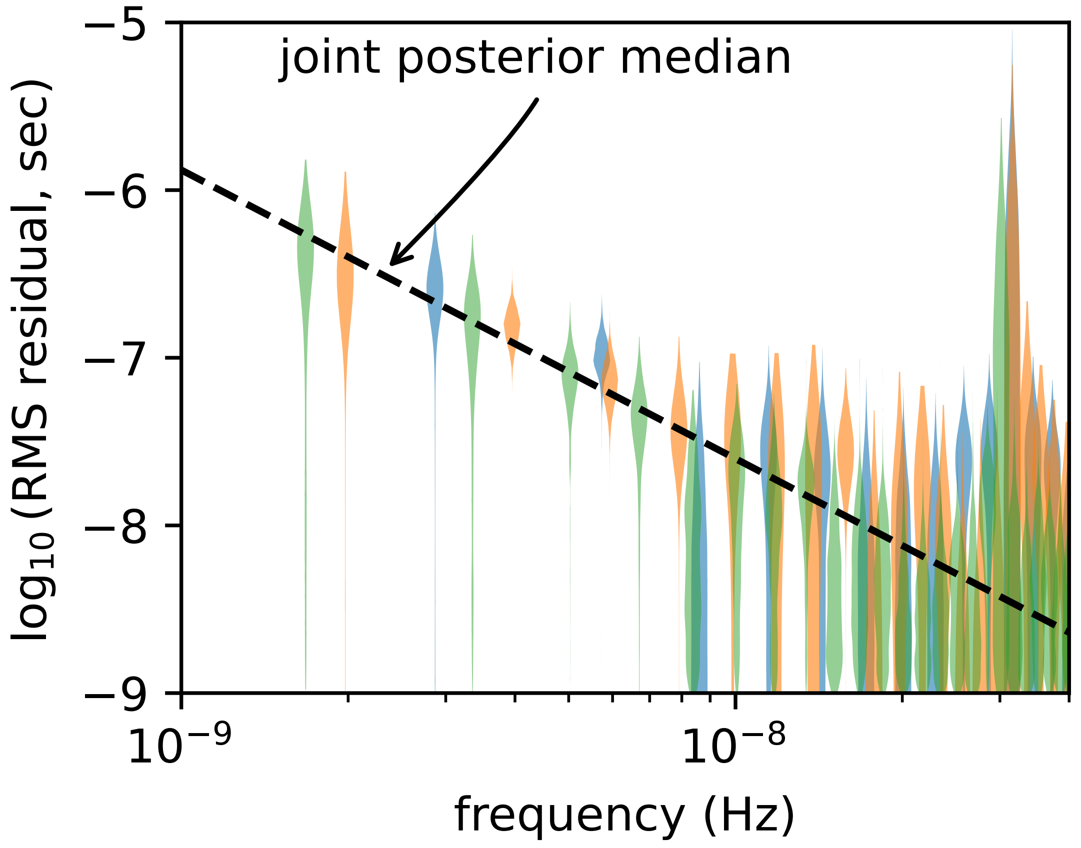
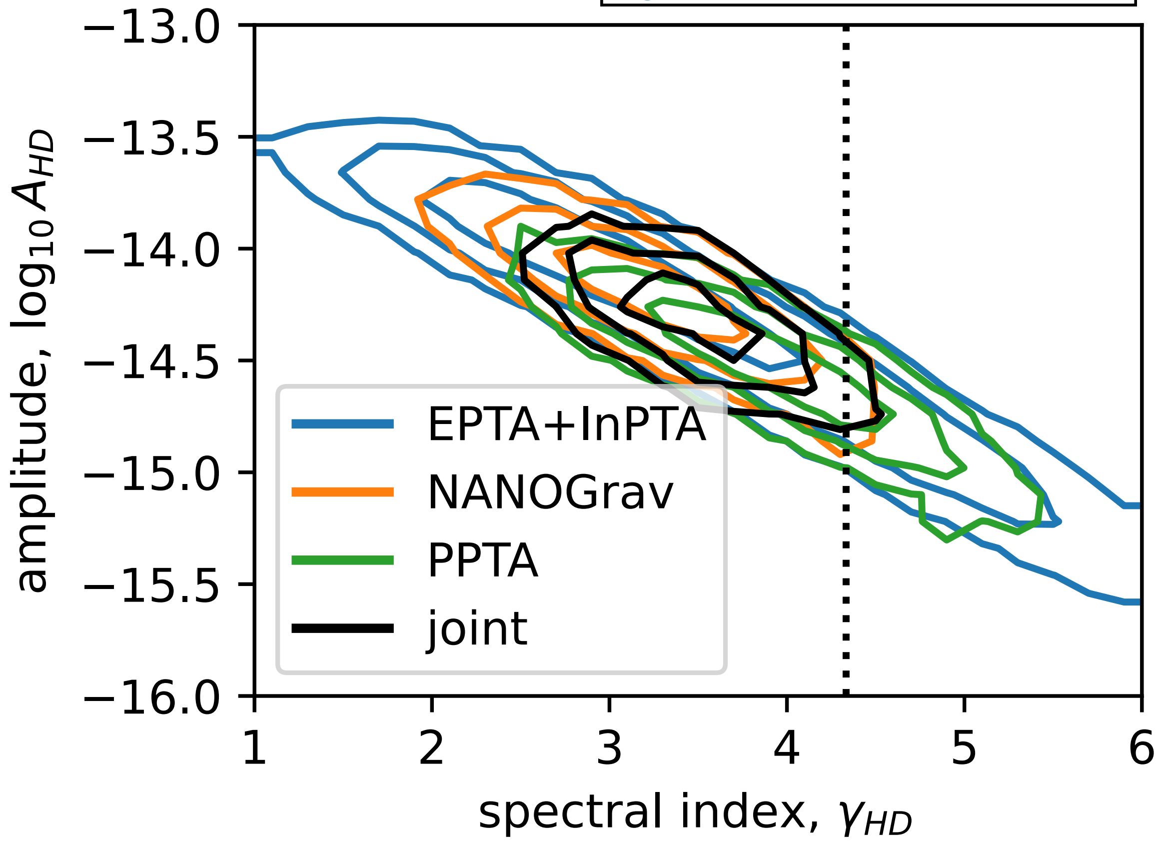




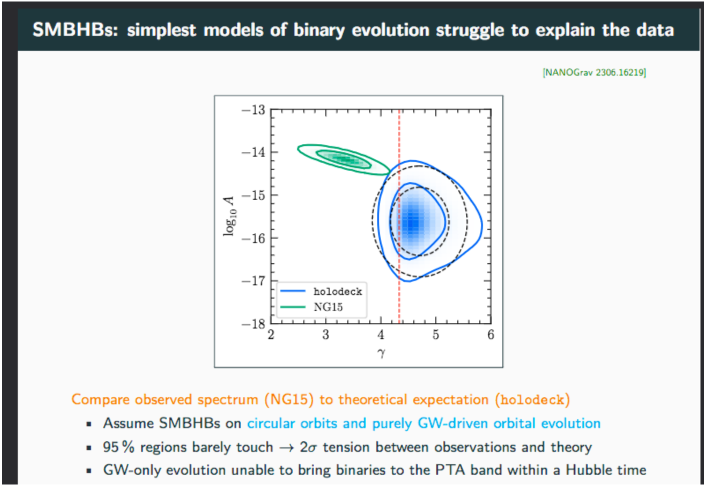
IPTA early data combination

Agazie et al. [2309.00693]





History of the Universe



History of the Universe

Probing the Dark Matter density with gravitational waves from super-massive binary black holes

Anish Ghoshal[a], **Alessandro Strumia**[b]

[a] *Institute of Theoretical Physics, Faculty of Physics, University of Warsaw, Poland*

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History of the Universe

Pulsar Timing Arrays observe gravitational waves. Assuming a power-law

$$\Omega_{\rm GW} \equiv \frac{1}{\rho_{\rm cr}} \frac{d\rho_{\rm GW}}{d\ln f} = \frac{\pi f^2 h_c^2}{4G}, \qquad h_c(f) = A_{\rm GW} \left(\frac{f}{f_{\rm PTA}}\right)^{\beta}.$$

they find $\beta \approx -0.1 \pm 0.3$ around $f_{\rm PTA} \equiv 1/10\,{\rm yr} \sim {\rm nHz}$ and $\Omega_{\rm GW} h^2 \sim 10^{-9-10}$.

Both roughly compatible with the astrophysical background, expected from in-spiralling super-massive black hole binaries (SMBH) with masses $M_{1,2} \sim 10^{8-9} M_\odot$ at red-shift $z \lesssim 0.3$, that predicts $\beta = -2/3$ when free.

Any fundamental implication?

New physics possible, but unicorns less plausible than horses.

Dark Matter can affect SMBH

History of the Universe

DM friction

Can approximate SMBH as Newtonian circular non-relativistic orbit,

$$\frac{v^2}{r} = \omega^2 r = \frac{G(M_1+M_2)}{r^2}.$$

- Power radiated via GW: $W_{\rm GW} = 32G\mu^2\omega^6 r^4/5$, $\mu = M_1M_2/(M_1+M_2)$.
- Power radiated via friction on (dark) matter: $W_{\rm DM} = 4\pi G^2\mu^2\rho_{\rm DM}\wp\ell/v$ where $\wp \sim 1/2$ is the fraction of DM slower than v, $\ell \sim 10$ is an IR log. It's just $W_{\rm DM} \sim \pi b^2\,\delta v\,\rho_{\rm DM}$ with $b \sim R_{\rm Sch}/|v - v_{\rm DM}|$ and $v \sim v_{\rm DM}$.

DM energy loss dominates at $\omega < \omega_{\rm cr}$ around the observed range

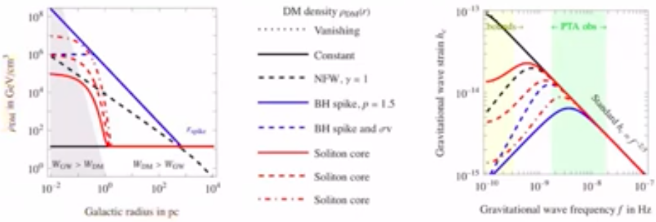
$$\omega_{\rm cr} \approx \frac{\rho_{\rm DM}^{3/11}}{G^{2/11}M^{5/11}} \approx 0.23\,{\rm nHz}\left(\frac{10^8 M_\odot}{M}\right)^{5/11}\left(\frac{\rho_{\rm DM}(r_{\rm cr})}{0.4\,{\rm GeV/cm^3}}\right)^{2/11}.$$

Imposing $\dot E = -W_{\rm GW} - W_{\rm DM}$, the spectral slope in $f = \omega/\pi(1+z)$ changes as:

$$\frac{dE_{\rm GW}}{d\omega} = \frac{W_{\rm GW}}{\dot\omega} = \begin{cases} \dfrac{M_1M_2G^{2/3}}{3(M_1+M_2)^{1/3}}\omega^{-1/3} & \text{GW-dominated,} \\[2ex] \dfrac{8G^{4/3}M_1M_2(M_1+M_2)^{4/3}\omega^{10/3}}{15\pi\wp\ell\,\rho_{\rm DM}(G^{1/3}(M_1+M_2)^{1/3}/\omega^{2/3})} & \text{DM-dominated.} \end{cases}$$

History of the Universe

Tomography of the DM density?



Expected DM dust density:

- From rotation curves at large r, e.g. $\rho_{DM}^{\odot} = 0.4\,\mathrm{GeV}/\mathrm{cm}^3$ in MW.
- $\rho_{DM\,GC} \approx \rho_{DM}^{\odot}(r_{\odot}/r_{spike})^{p'}$ with $p' = 1$ from NFW.
- Possibly an extra spike around BH, $\rho_{DM}(r) \approx \rho_{DM\,GC}(r_{spike}/r)^{p}$ at $r < r_{spike} \sim 0.2 r_{in}$ with $p = 1.5 - 2.5$, maybe $p \approx (9-2p')/(4-p')$.

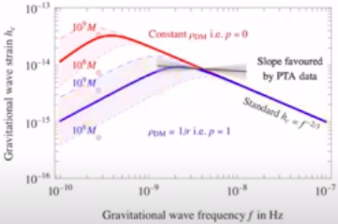
Fundamental physics effects:

- DM annihilations limit $\rho_{DM}(r) \lesssim m/\langle\sigma v\rangle \tau_{BH}$ with $\tau_{BH} \sim 10^{10}\,\mathrm{yr}$
- Ultra-light DM can give a soliton core $\rho_{DM} \propto e^{-r/\lambda_{DM}}$.

History of the Universe

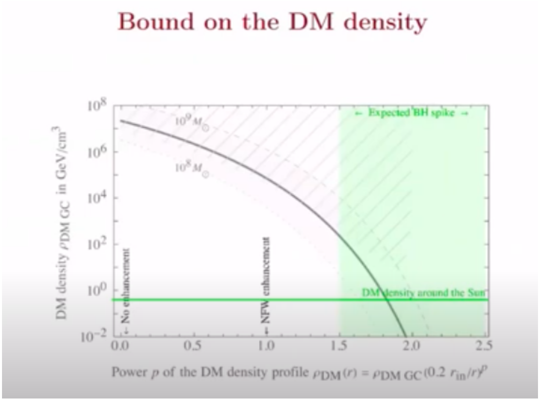
Astrophysical uncertainties

Some washing out with BH masses in the expected range $M \sim 10^{8-9} M_{\odot}$:



Additional friction from matter (star, gas), eccentricity go in the same direction, allowing to set a robust bound on ρ_{DM}.

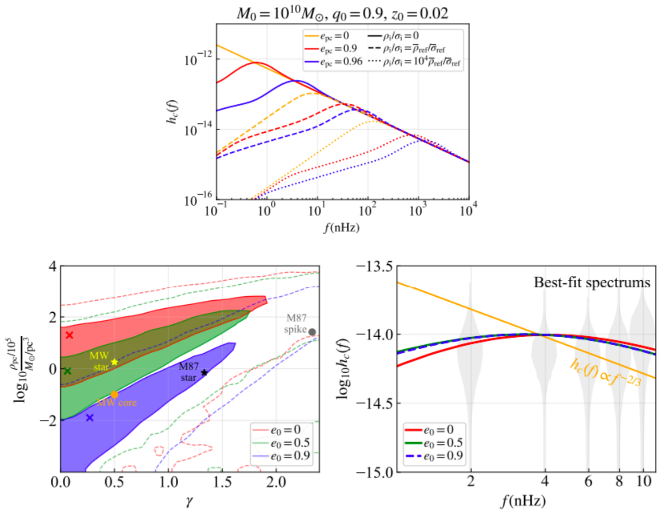
History of the Universe



DM density could be probes via measurements in pulsar timing arrays.

History of the Universe

Impact of eecentric orbits (Chen+ (2024)):



Summary:

- NANOGrav and other PTA data sees evidence of stochastic GW background (SGWB). They could arsie from supermassive black hole mergers but simple mergers does not match with the signal.
- astrophysical interpretation involves supermassive black holes with dynamical friction and dark matter density.
- Assumming presence of DM profiles, a galaxy tomography of DM can be performed by investigating the features in the SGWB.
- After our analysis NANOGrav carried out this investigation in more sophisticated manner in Ref: 2411.05906 and various constraints wee obtained on DM physics related to annihilation etc.