Searching for Ultralight Axions with pulsar polarimetry

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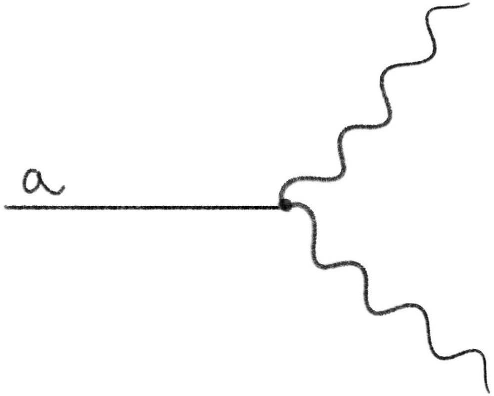
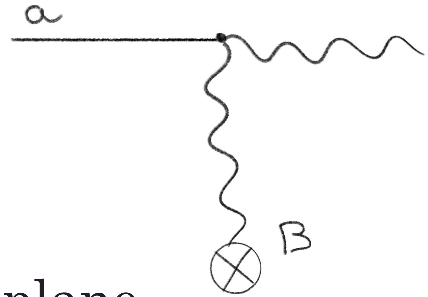
ALP-photon interaction

- Decay

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma}^2 m_a^3}{64\,\pi}$$

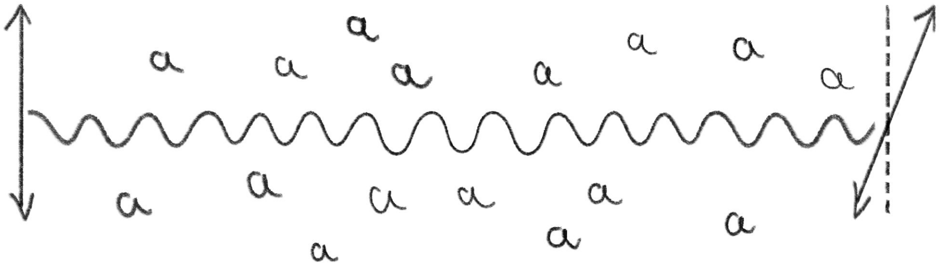


- Conversion a←→photon



- Change of the polarisation plane

$$\Delta\phi = \frac{g_{a\gamma}}{2}\Delta a$$



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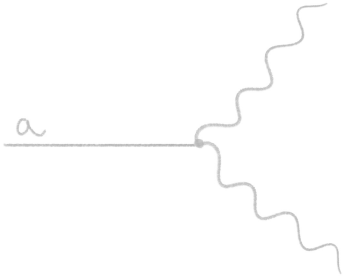

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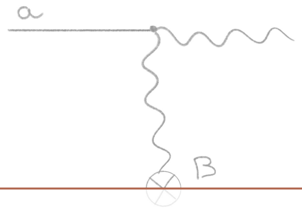

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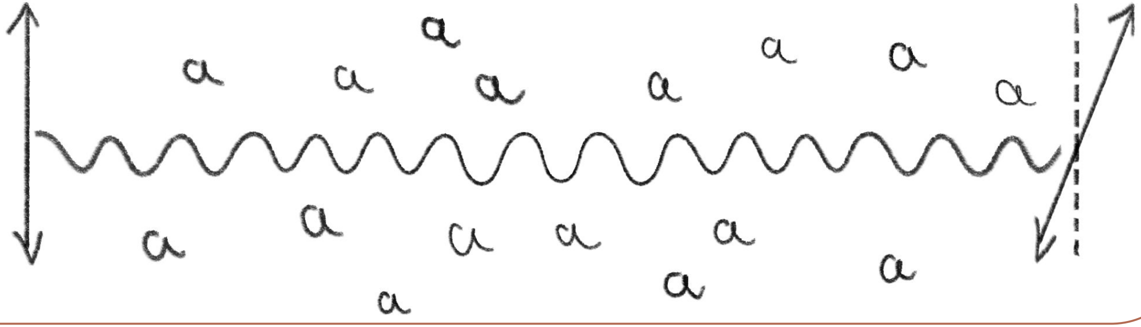
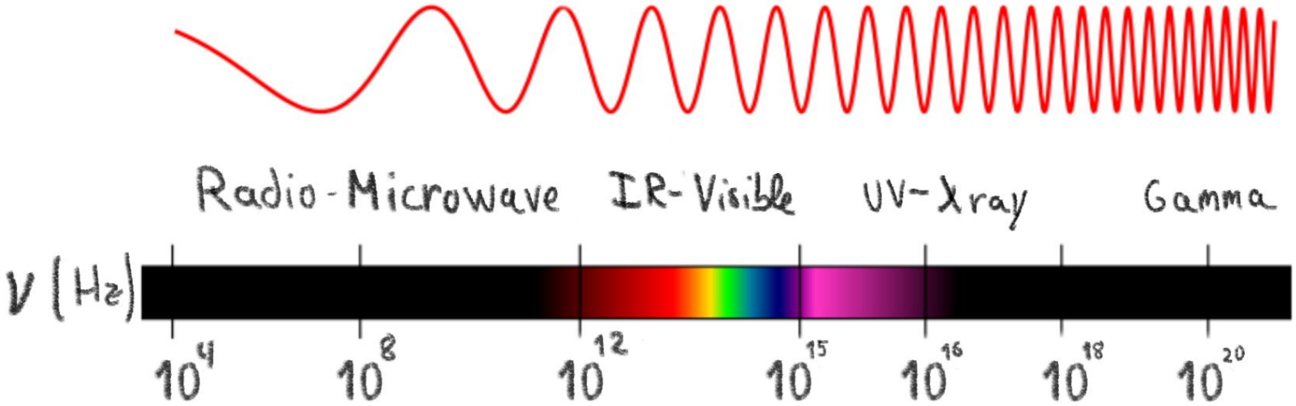


ALP birefringence across the spectrum



ALP birefringence across the spectrum

- Birefringence of pulsar radio waves

  M. Ivanonv et al. [1811.10997]

  A. Castillo et al. (**JTC**) [2201.03422]

  N. Porayko et al. (**JTC**) [2412.02232]

  PPTA Collaboration. [2412.02229]

- Birefringence of protoplanetary disk light

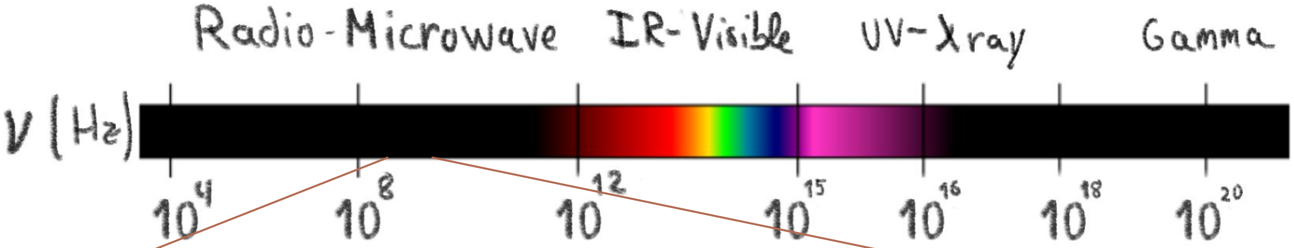
  T. Fujita, R. Tazaki and K. Toma. [1811.03525]

- Birefringence of distant galaxies UV light

  S. di Serego Alighieri, F. Finelli and M. Galaverni. [1003.4823]

ALP birefringence across the spectrum

Search of birefringence in radio-microwave polarisation



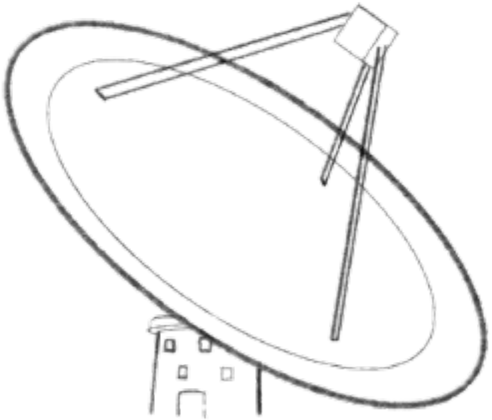
A. Castillo, J. Martin-Camalich, **JTC**, D. Blas, A. Caputo, R. T. Génova Santos, L. Sberna.,M. Peel, J. A. Rubiño-Martín. arXiv:2201.03422

N. K. Porayko, P. Usynina, **JTC**, J. Martin Camalich, A. Castillo, D. Blas, G. Shaifullah, L. Guillemot, C. Tiburzi, M. Peel, K. Postnov and EPTA Collaboration. arXiv:2412.02232

2201.03422: PPTA and QUIJOTE

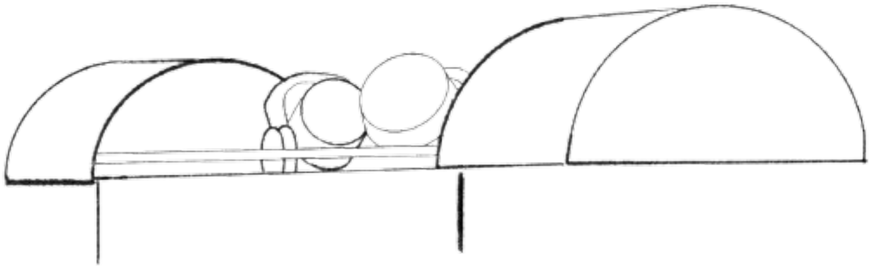
Parkes (64m Murriyang telescope)

- Obs. at 1.4 GHz
- 4.5 yr polarisation measurements of 20 different galactic pulsars



QUIJOTE-MFI

- Obs. at 11, 13, 17 and 19 GHz
- 4.5 yr polarisation measurements of Tau A

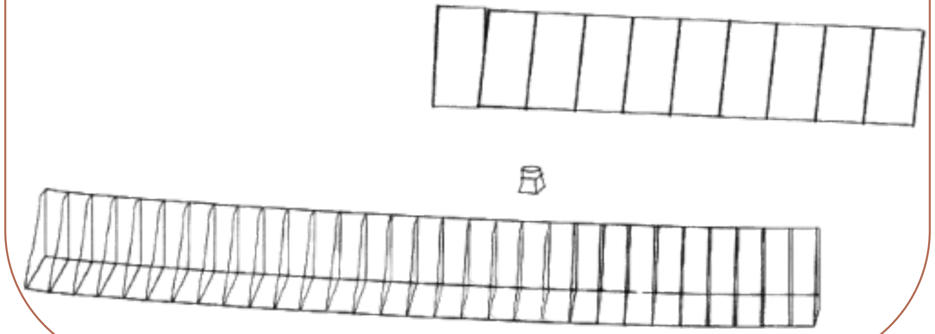


Search for birefringence

2412.02232: EPTA

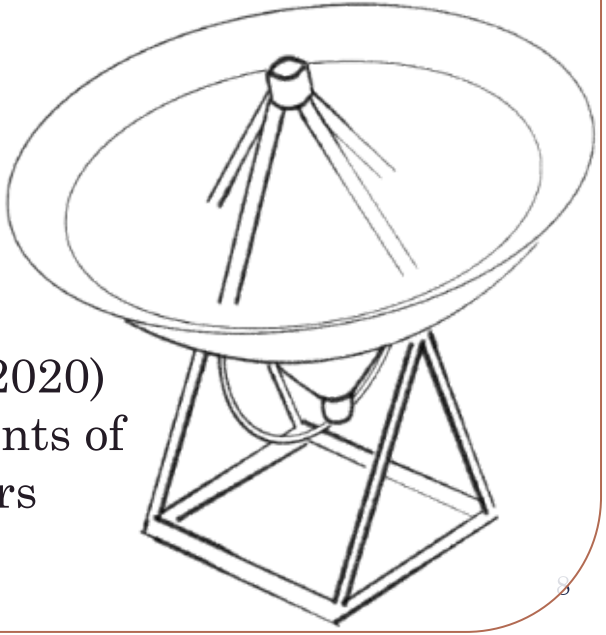
Nançay 94m telescope

- Obs. at 1.4 GHz
- 4 yr (2019-2023) polarisation measurements of 12 galactic pulsars



Effelsberg 100m telescope

- Obs. at 1.4, 2.6 and 4.85 GHz
- 7 yr (2013-2020) measurements of same pulsars



ALP birefringence

- Modified Maxwell equations

Harari & Sikivie, Phys. Lett. B 289 (1992) 67–72

$$\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} \rightarrow \frac{g_{a\gamma}}{4} a \mathbf{E} \cdot \mathbf{B}$$

$$\partial_\mu F^{\mu\nu} + g_{a\gamma} \partial_\mu \left(\tilde{F}^{\mu\nu} a \right) = 0$$

$$\partial_\mu \tilde{F}^{\mu\nu} = 0$$

- Dispersion relation is affected

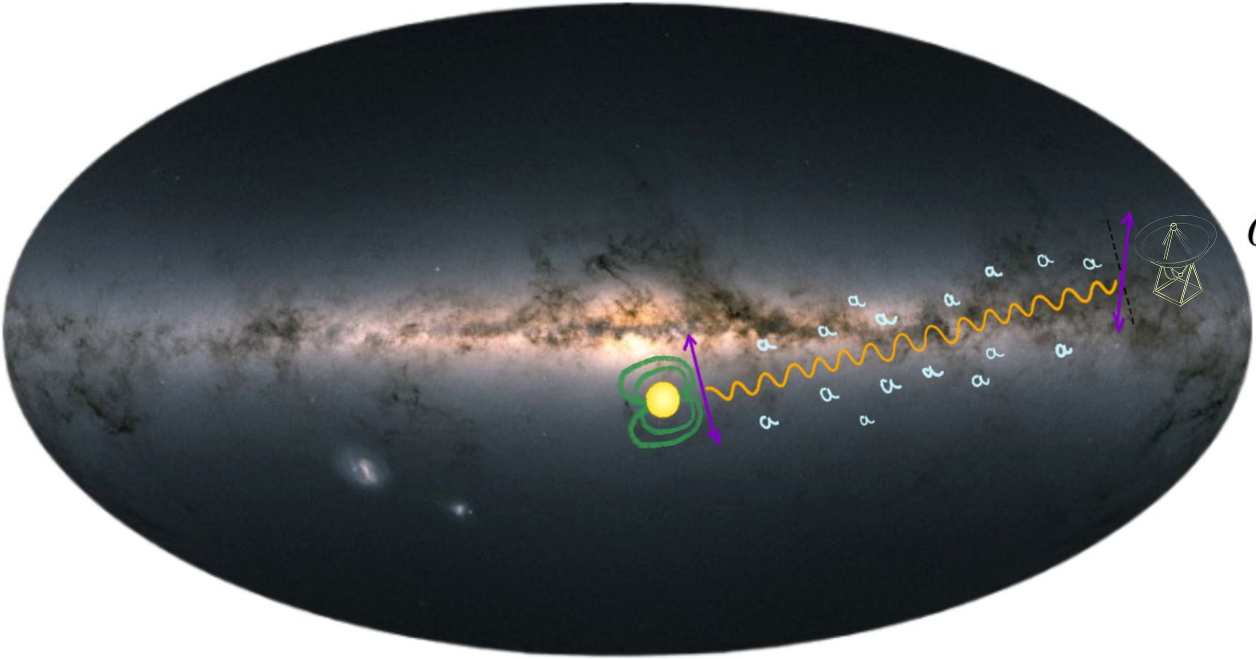
$$\omega_\pm \simeq k \pm \frac{1}{2} g_{a\gamma} \left(\partial_t a + \nabla a \cdot \widehat{\mathbf{k}} \right)$$

- Change of the polarisation plane

$$\Delta\phi = \frac{g_{a\gamma}}{2} \int_{t_s}^{t_o} \frac{da}{dt} dt = \frac{g_{a\gamma}}{2} \Delta a$$

ALP birefringence

- ALP wave behavior makes the polarisation change periodic



$$\Delta\phi = \frac{g_{a\gamma}}{2}\int_{t_s}^{t_o}\frac{da}{dt}dt = \frac{g_{a\gamma}}{2}\Delta a$$

$$a(t) = a_0 \cos\left(m_a t + \delta\right)$$

$$a_{0,i} = \sqrt{2\rho_i} m_a^{-1}\alpha_i$$

ALP birefringence

- ALP wave behavior makes the polarisation change periodic

$$\Delta\phi(t) = \phi_a \cos(m_a t + \varphi_a)$$

$$\nu_c = \frac{m_a}{2\pi}$$

$$\phi_a = 2.24^\circ \left(\frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right)\left(\frac{m_a}{10^{-22}\ \mathrm{eV}}\right)^{-1}\left(\frac{\rho_{DM}}{1\ \mathrm{GeV\ cm}^{-3}}\right)^{1/2}$$

Stochasticity

- Stochastic nature of ultralight dark matter affects field amplitude

J. Foster, N. Rodd, B. Safdi. [1711.10489]
G. Centers et al. [1905.13650]
M. Lisanti, M. Moschella, W. Terrano. [2107.10260]

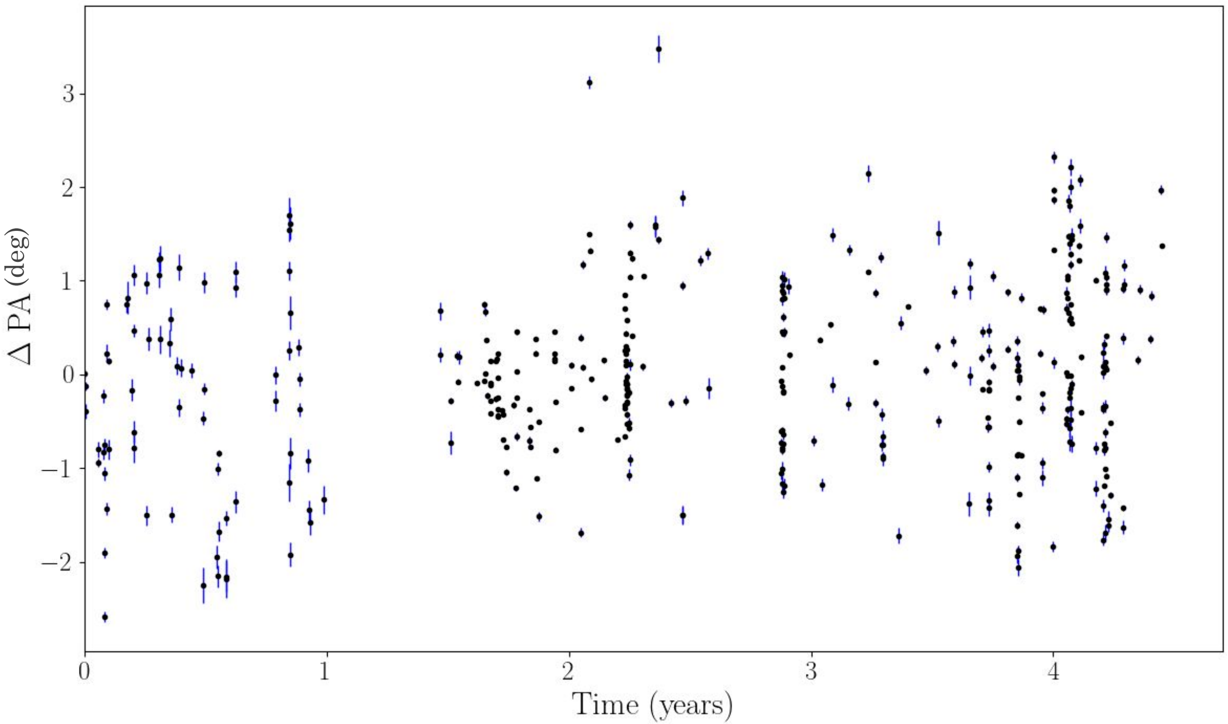
$$\phi_a = \frac{g_{a\gamma}}{\sqrt{2}m_a}\left(\rho_o\alpha_o^2 + \rho_s\alpha_s^2 - 2\sqrt{\rho_o\rho_s}\alpha_o\alpha_s\cos\Delta\right)^{1/2}$$

$$p(\alpha) = \alpha\exp\left(-\frac{\alpha^2}{2}\right)$$

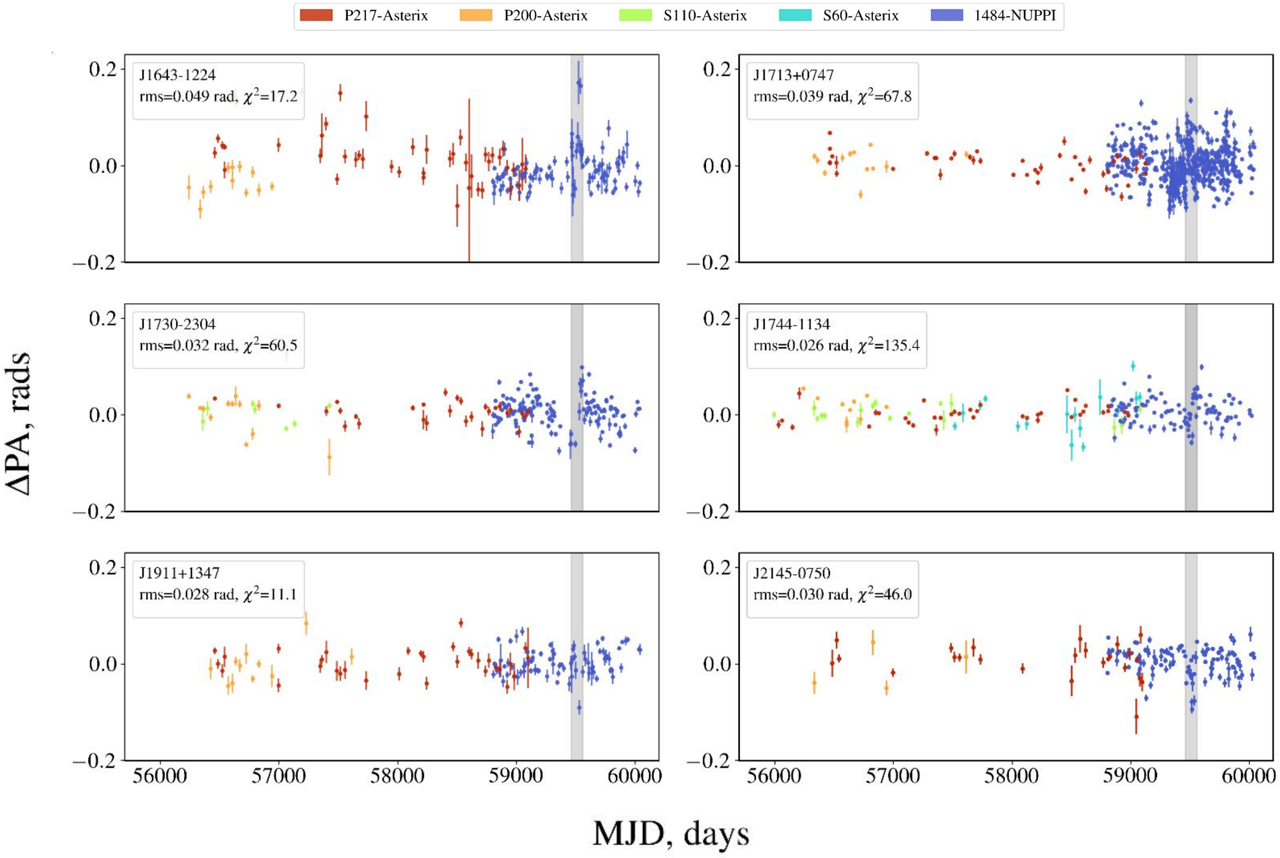
$$l_c = (m_a\sigma)^{-1} \simeq 65\left(\frac{m_a}{10^{-22}\ \mathrm{eV}}\right)^{-1}\left(\frac{\sigma}{10^{-3}}\right)^{-1}\ \mathrm{pc}$$

The data (PPTA)

- J0437-4715



The data (EPTA)



Search for polarisation oscillations

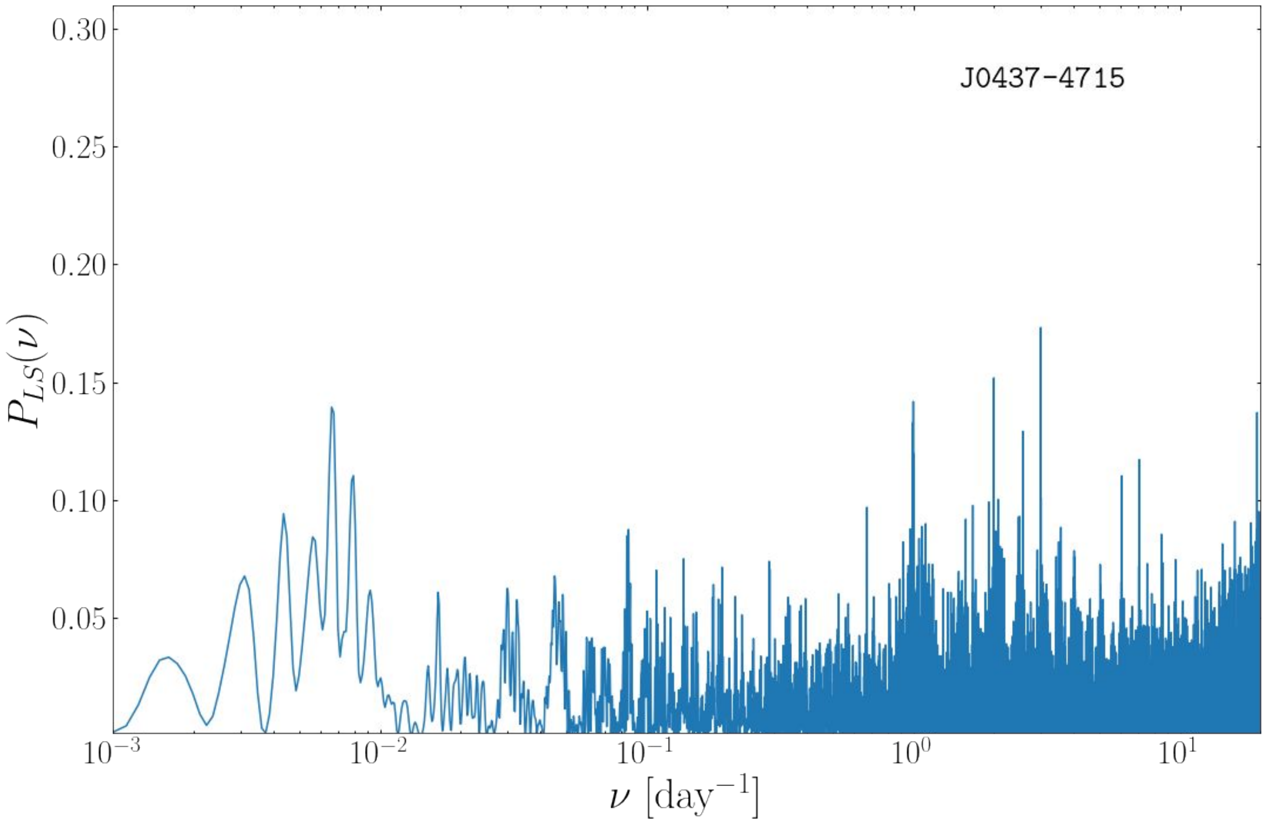
- Analysis with Generalised Lomb-Scargle Periodograms

$$y = a_\nu \cos(2\pi\nu t) + b_\nu \sin(2\pi\nu t) + c_\nu$$

$$P_{LS}(\nu) = \frac{1}{2}\left(\hat{\chi}_0^2 - \hat{\chi}_\nu^2\right)$$

N. R. Lomb. Astrophys. Space Sci. 39, 447 (1976)
J. D. Scargle. Astrophys. J. 263, 835 (1982)
M. Zechmeister, M. Kurster. [0901.2573]
J. T. VanderPlas. [1703.09824]

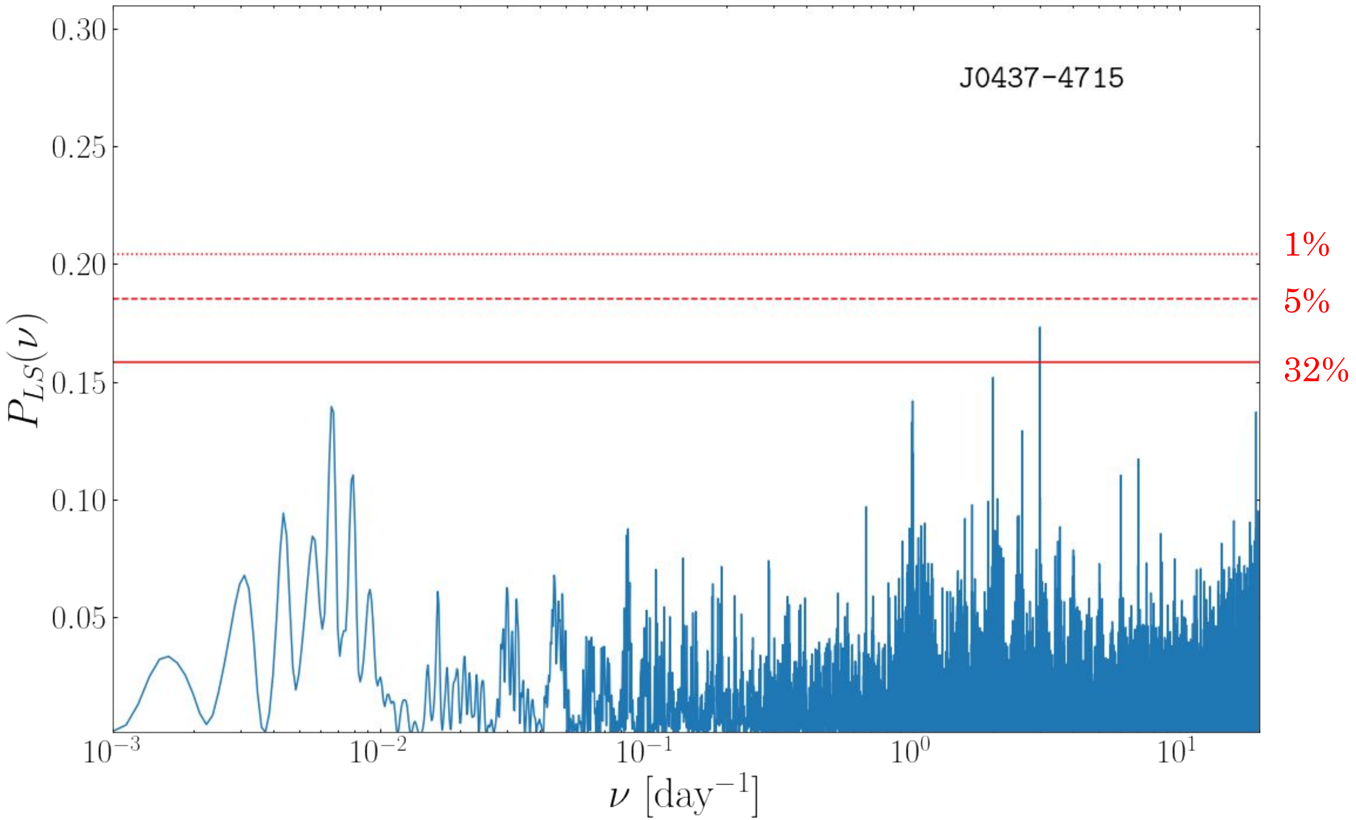
- Analysis with Generalised Lomb-Scargle Periodograms



False Alarm Probability

- Get distribution of data points
- Simulate new data maintaining time series
- Fill histogram with highest peak
- Repeat 10^3 times and calculate 99%, 95% and 68% quantiles

False Alarm Probability: NO SIGNAL



Bounds on polarisation oscillations

Individual bounds on a generic signal

- Perform a set of MC adding an artificial signal

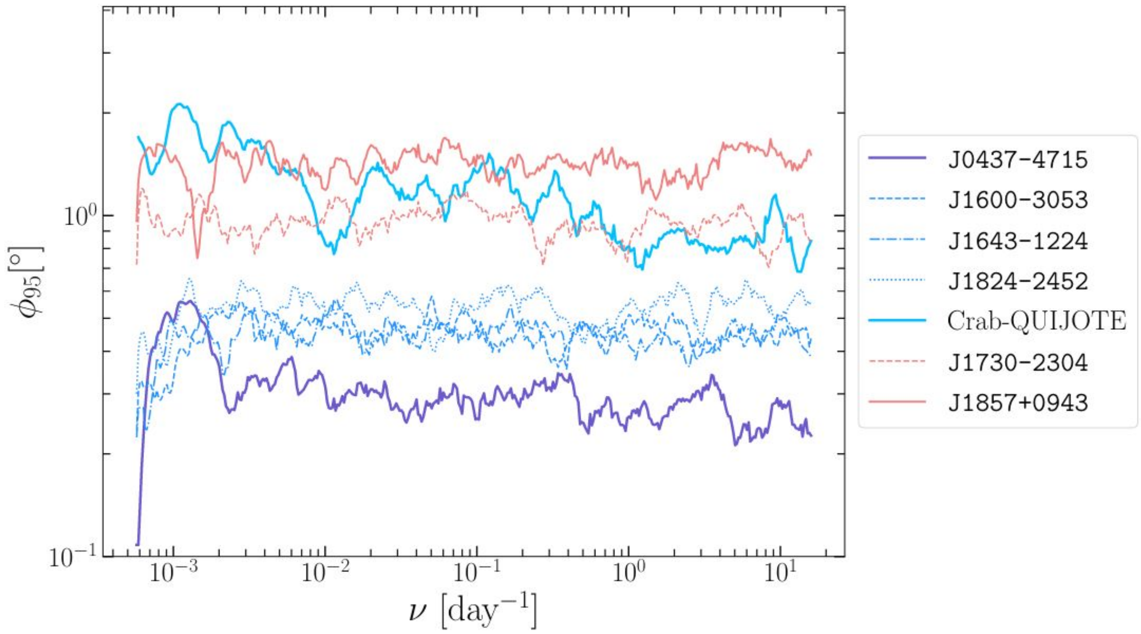
$$\Delta\phi_{\mathrm{sim}} = \phi \cos\left(2\pi\nu\, t + \varphi\right)$$

- Compute the PDF and identify the lower 5% tail of the distribution

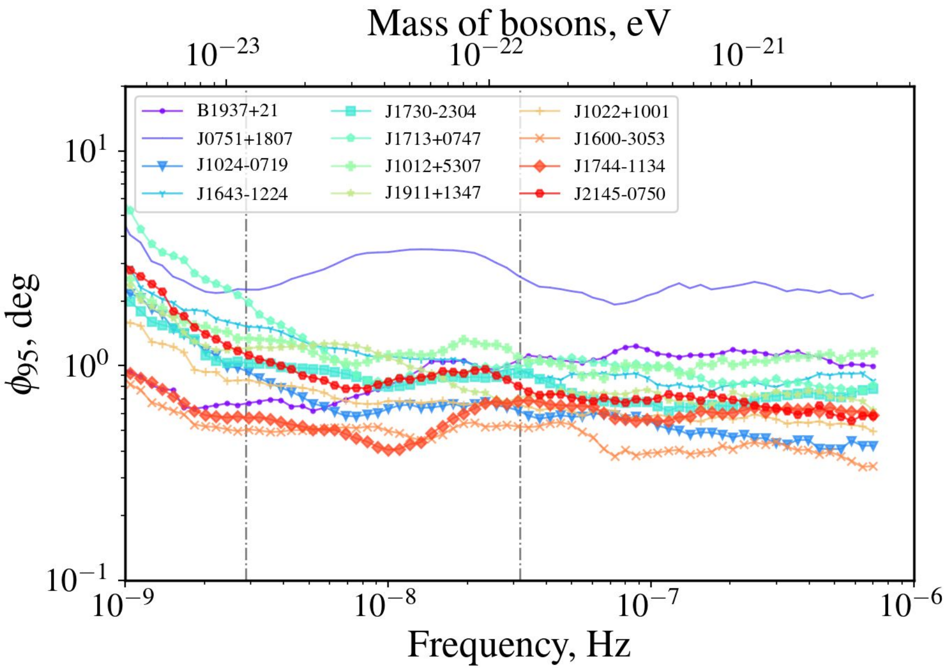
- Solve such that the 95% quantile corresponds to the data.

Individual bounds on a generic signal PPTA + QUIJOTE

$$\Delta\phi_{\text{sim}} = \phi \cos\left(2\pi\nu\, t + \varphi\right)$$



Individual bounds on a generic signal EPTA



$$\Delta\phi_{\rm sim} = \phi\cos\left(2\pi\nu t + \varphi\right)$$

Bounds on ALP induced polarisation oscillations

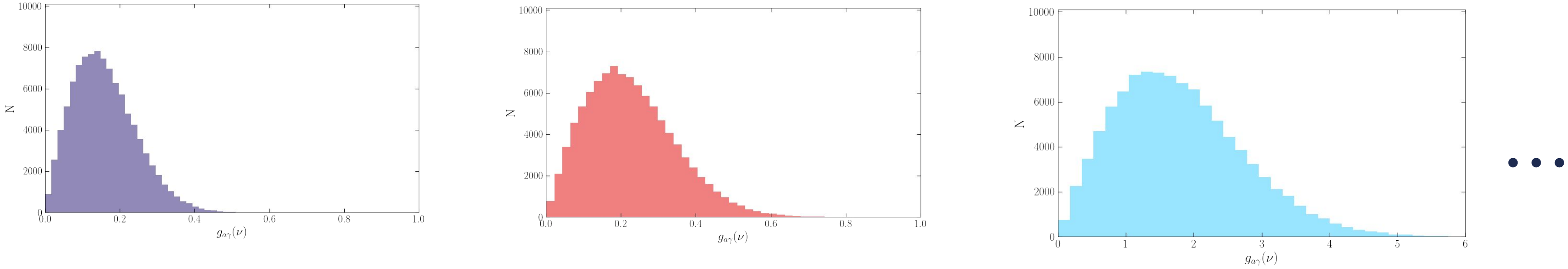
$$\Delta\phi_{\rm sim} = \phi\cos\left(2\pi\nu\, t + \varphi\right) \longrightarrow \Delta\phi(t) = \phi_a \cos(m_a t + \varphi_a)$$

$$\phi_a = \frac{g_{a\gamma}}{\sqrt{2}m_a}\left(\rho_o\alpha_o^2 + \rho_s\alpha_s^2 - 2\sqrt{\rho_o\rho_s}\alpha_o\alpha_s\cos\Delta\right)^{1/2}$$

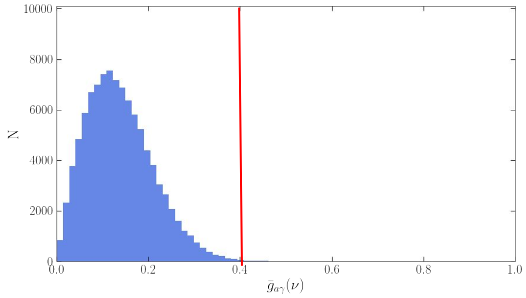
Bounds on ALP induced polarisation oscillations

$$\Delta\phi_{\text{sim}} = \phi\cos\left(2\pi\nu\, t + \varphi\right) \longrightarrow \Delta\phi(t) = \phi_a \cos(m_a t + \varphi_a)$$

- Need to do a combined analysis



- Weighted mean distribution, 95% C.L.



Bounds on ALP induced polarisation oscillations: Bayesian

Bayesian analysis (Nataliya K. Porayko, **Polina Usynina**)

- Modelling of the signal

$$\Delta\mathrm{PA}^{\mathrm{obs}}(t_i) = \delta\phi^{\mathrm{ULDM}}(\boldsymbol{\Theta}, t_i) + \mathrm{PA}^{\mathrm{det}}(\boldsymbol{\Psi}, t_i) + n(t_i)$$

- Multivariate Gaussian likelihood

$$\mathcal{L}(\boldsymbol{\Delta\mathrm{PA}}|\boldsymbol{\Theta}, \boldsymbol{\Psi}) = \frac{1}{\sqrt{|\det 2\pi \mathbf{C}|}} \times \exp\{-\frac{1}{2}(\boldsymbol{\Delta\mathrm{PA}}^{\mathrm{obs}} - \boldsymbol{\delta\phi}^{\mathrm{ULDM}} - \mathbf{PA}^{\mathrm{det}})^T \mathbf{C}^{-1} (\boldsymbol{\Delta\mathrm{PA}}^{\mathrm{obs}} - \boldsymbol{\delta\phi}^{\mathrm{ULDM}} - \mathbf{PA}^{\mathrm{det}})\},$$

Bounds on ALP induced polarisation oscillations: Bayesian

- Factorise likelihood

$$\mathcal{L}(\mathbf{\Delta PA}|g_{a\gamma}, m_a, \mathbf{A}_1, \mathbf{A}_2, ..., \mathbf{A}_N) = \prod_{k=1}^{N} \mathcal{L}(\mathbf{\Delta PA}|g_{a\gamma}, m_a, \mathbf{A}_k),$$

- Bayes factor

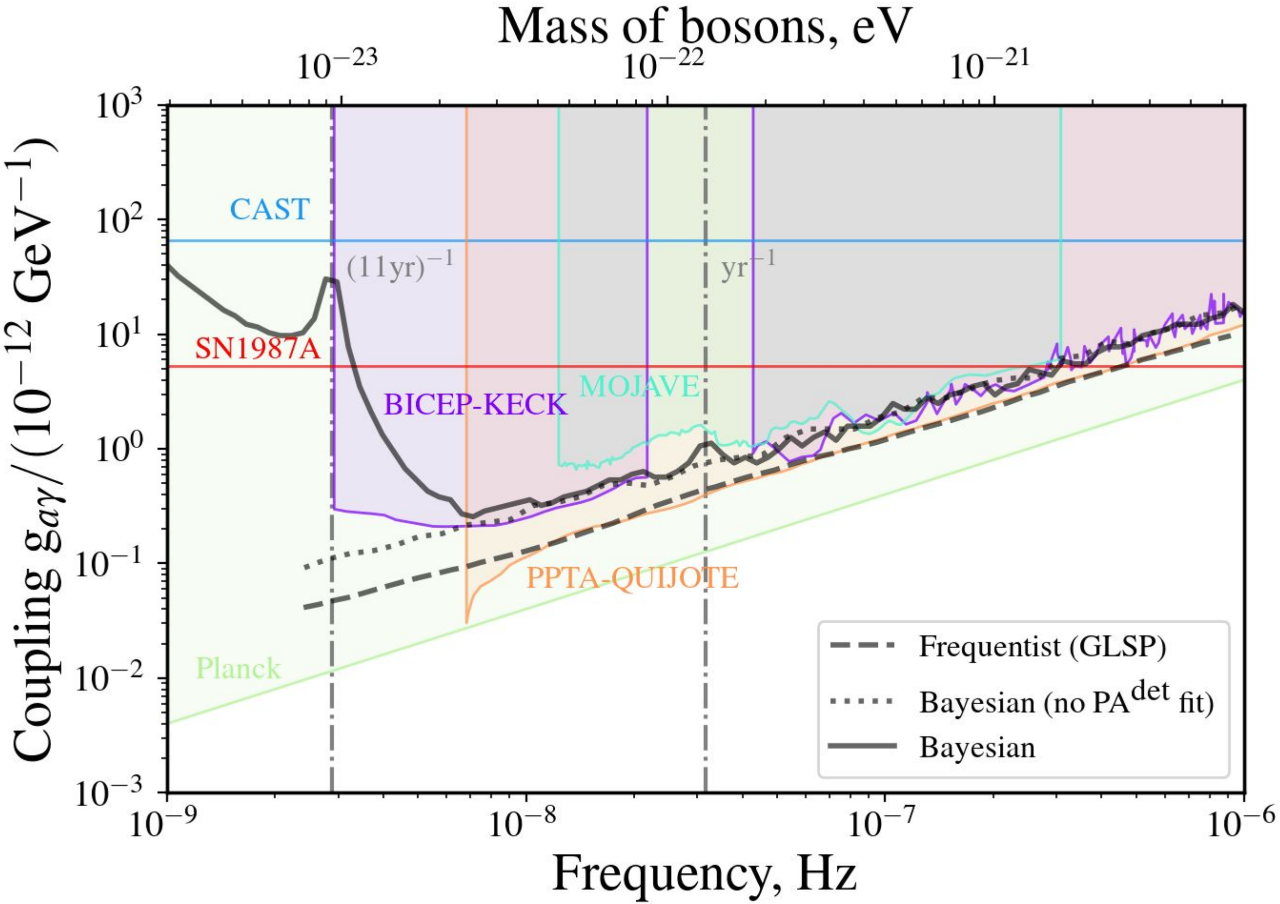
$$B_{21} = \frac{p^{\text{post}}(\mathbf{\Theta_0}|\mathbf{\Delta PA})}{p^{\text{prior}}(\mathbf{\Theta_0})}$$

Bounds on ALP induced polarisation oscillations: Bayesian

MCMC

Parameter	Description	Prior	Comments
Noise parameters			
EFAC	White-noise modifier per backend	Uniform [0, 4]	One parameter per backend
EQUAD	Additive white noise per backend	$\log_{10}$-Uniform [-8, 3]	One parameter per backend
OFFSET	An offset between observing systems	Uniform [-2, 2]	One parameter per backend
Signal parameters			
$g_{a\gamma}$	photon-axion coupling constant	$\log_{10}$-Uniform [-6, 5] (search) Linear-Exp [-7, 6] (upper limits)	One parameter per PTA
f(Hz)	Oscillation frequency	$\log_{10}$-Uniform [1/T, 10^{-6}]	Fixed, regular grid in log-scale
ϕ_a	Oscillation phase	Uniform$[0, 2\pi]$	
B	$B = \sqrt{\alpha_o^2 + \alpha_s^2 - 2\alpha_o\alpha_s \cos\chi}$	Estimated numerically using KDE (see Fig. 5)	
Additional parameters			
α_0	Stochastic amplitude on Earth	Rayleigh distribution	$p(\alpha) = \alpha \exp\left(-\frac{\alpha^2}{2}\right)$
α_s	Stochastic amplitude on a pulsar	Rayleigh distribution	$p(\alpha) = \alpha \exp\left(-\frac{\alpha^2}{2}\right)$
χ	Phase	Uniform$[0, 2\pi]$	$\chi = m_a T + \delta_o - \delta_s$

Bounds on ALP induced polarisation oscillations: Results



Take away

- Astrophysical polarisation data allows us to search for ALP Dark Matter in the lower end of the mass range

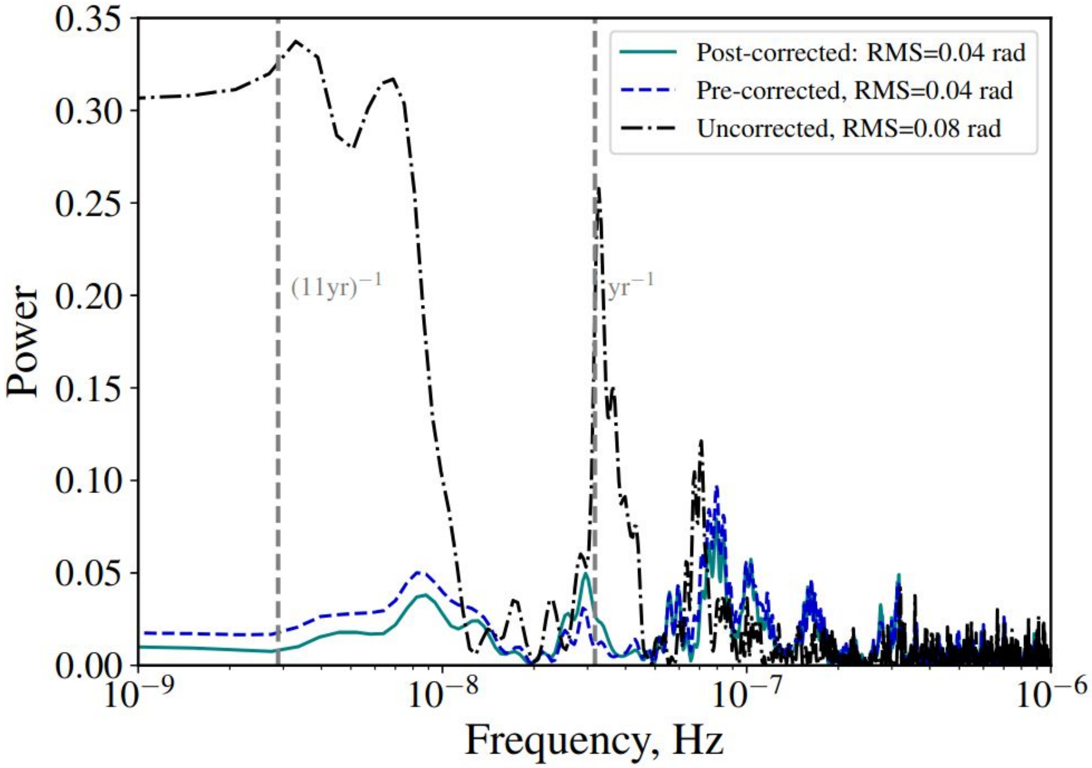
- No signs of ultralight dark matter in PPTA-QUIJOTE-EPTA data… Yet!


AXIONS IN STOCKHOLM
NORDITA, STOCKHOLM, SWEDEN
23 JUNE — 11 JULY 2025
TACK


AXIONS IN STOCKHOLM
NORDITA, STOCKHOLM, SWEDEN
23 JUNE — 11 JULY 2025

Back Up

Atmospheric corrections



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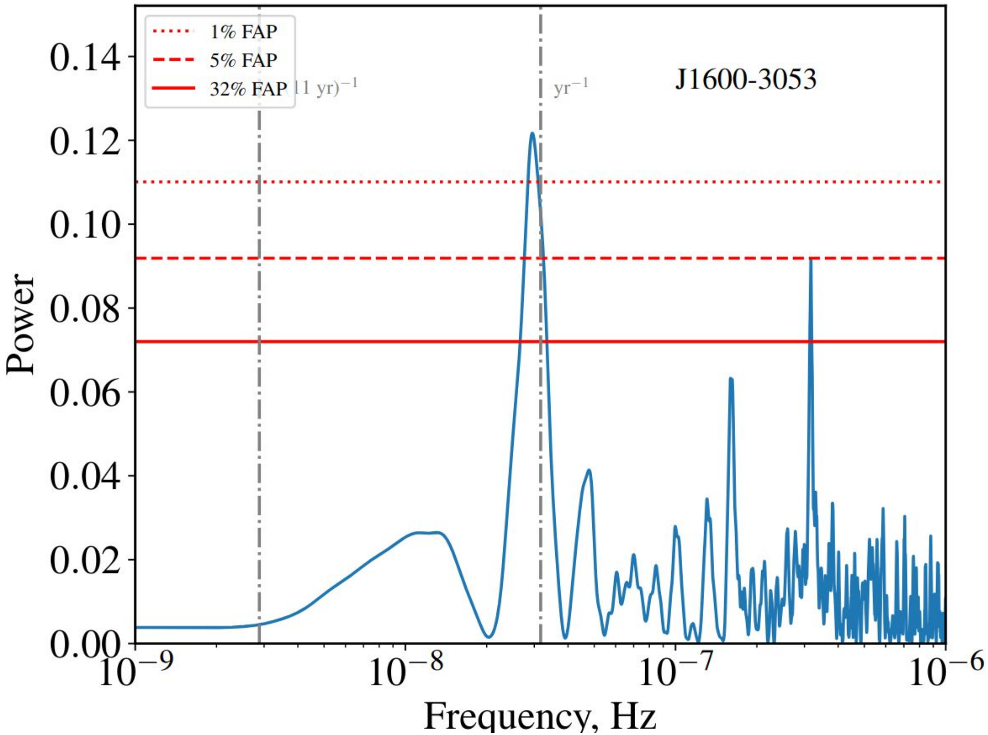

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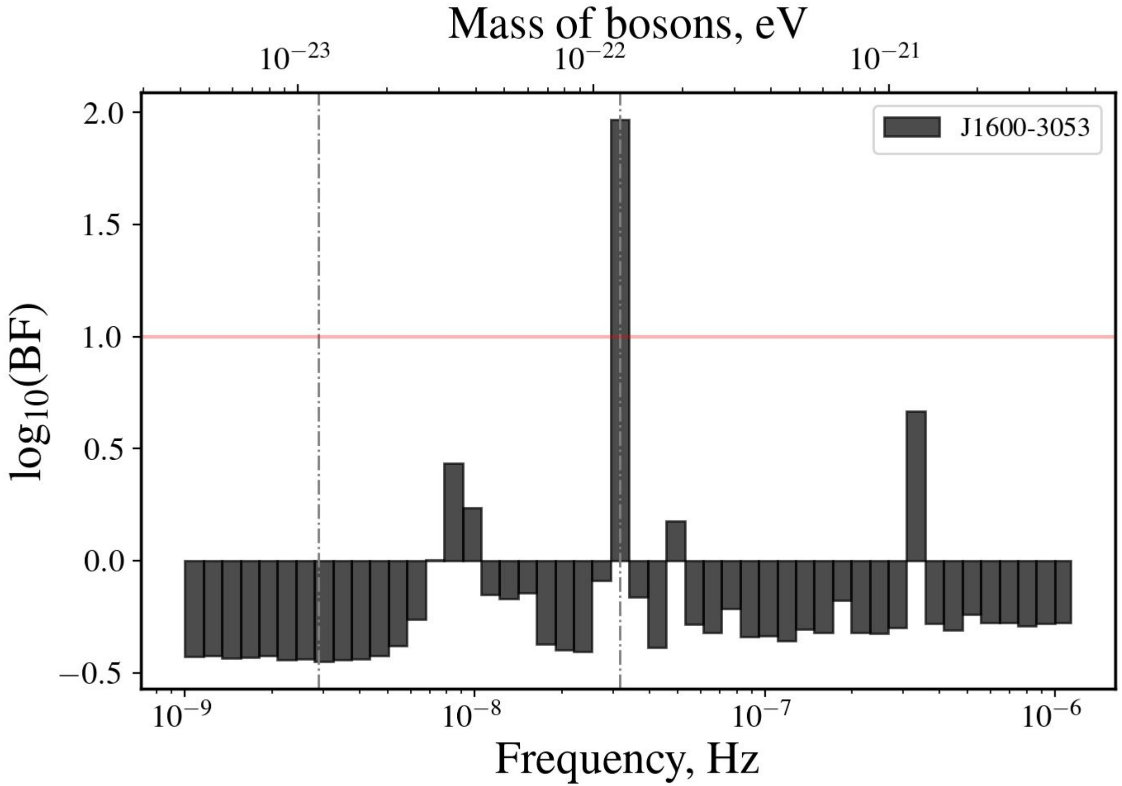
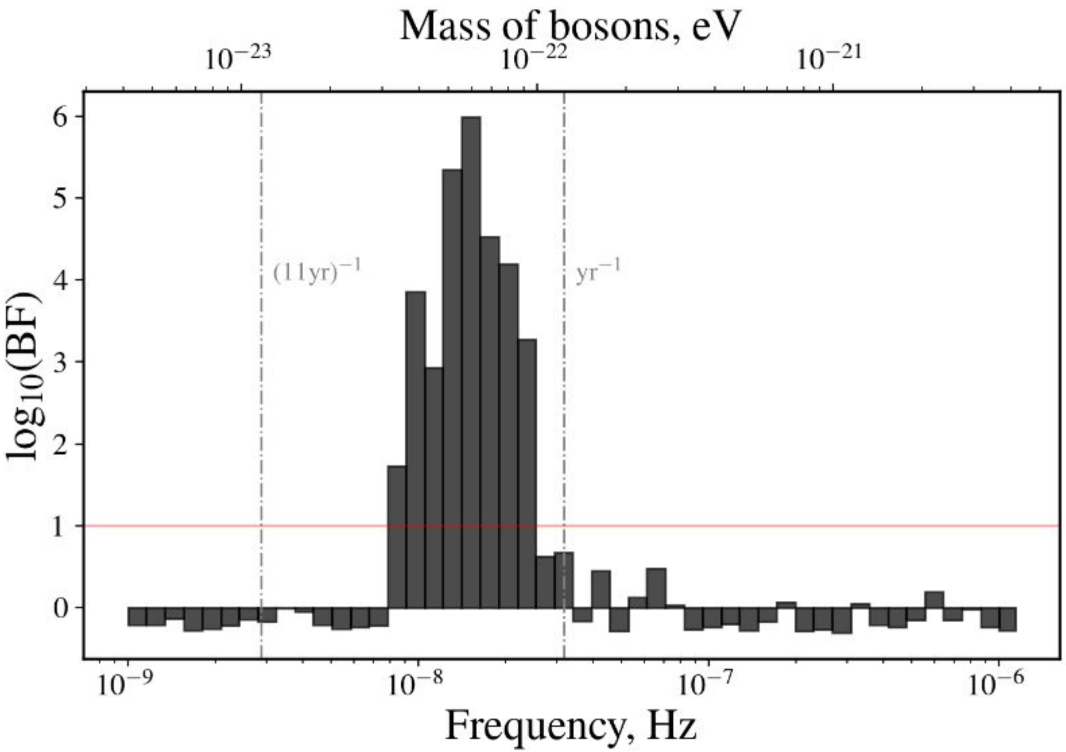


A signal? Only visible in the Bayesian analysis



Search for polarisation oscillations

A signal?