Searching for Ultra-Light Axion-Like Particles Using Pulsars Polarimetry Measurements from PPTA and QUIJOTE

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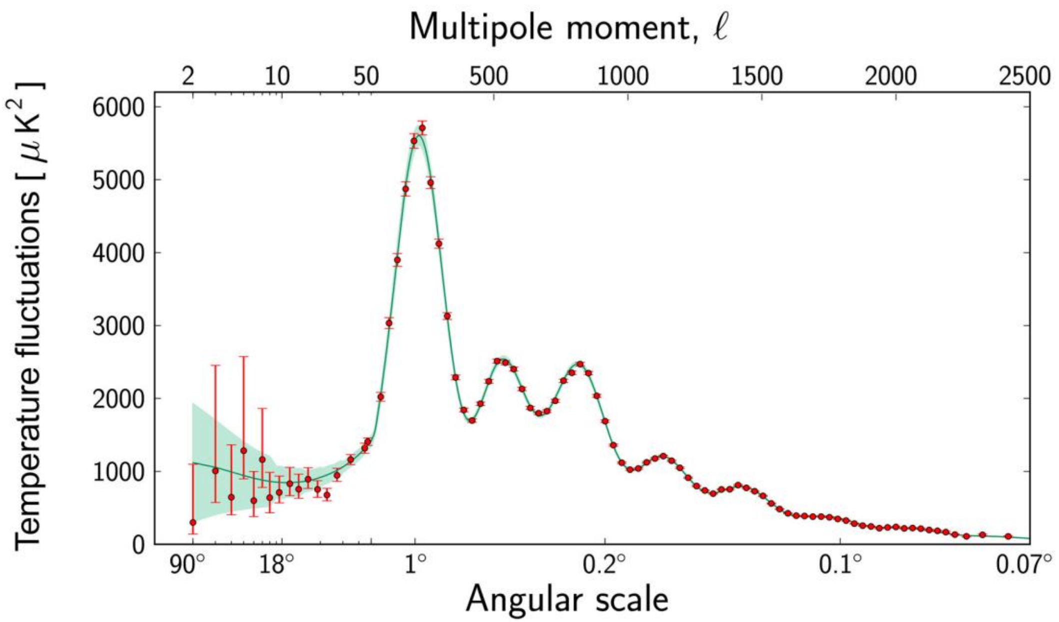
Based on JCAP 06 014 & arXiv:Astro-ph: 2412.02232

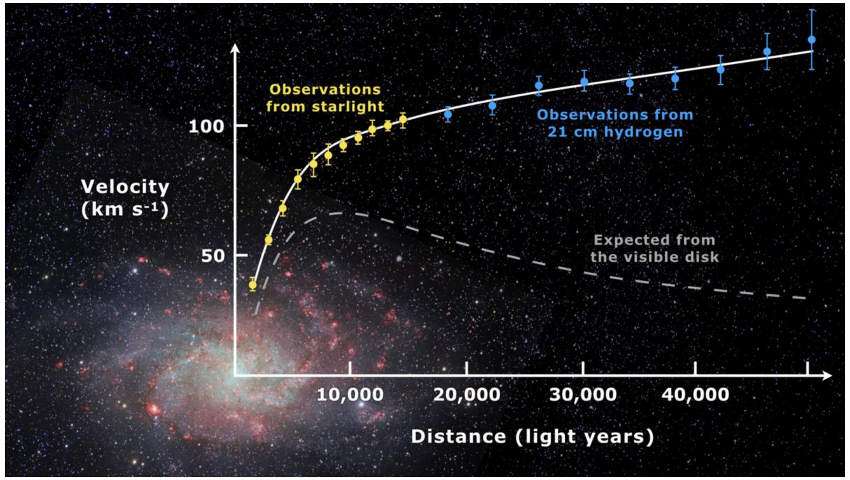
Outline

- Motivation to Ultra-Light Dark Matter (ULDM)
- Electromagnetic effects of ULDM
- Pulsars as laboratories of Electromagnetic effects ULDM
- Exclusion bounds of EM-ULDM using Pulsars Polarimetry
- Updates of the Bounds using EPTAs

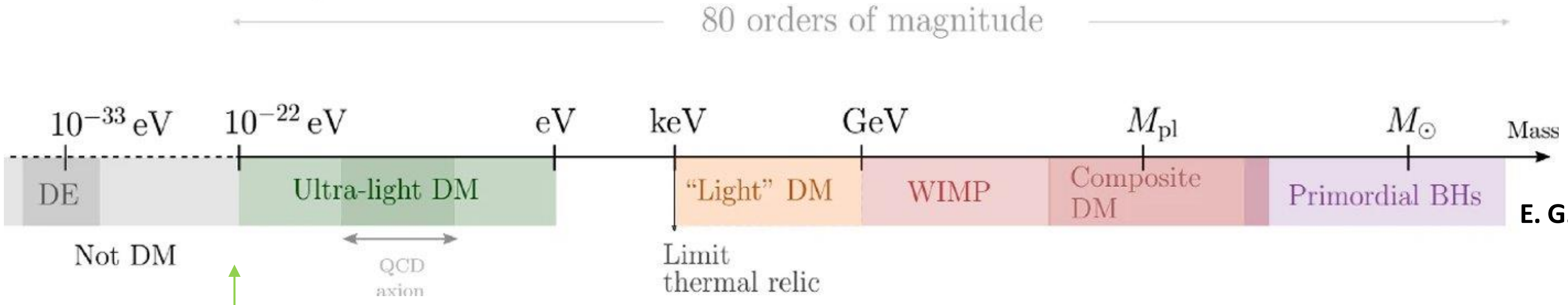
Why ULDM (Axion Like Particles)?

Observational evidence DM





CMB anisotropies, X-rays, gravitational lensing on clusters, Large Scale Structures, Galaxies (velocity curves)



E. G. M. Ferreira (2021)

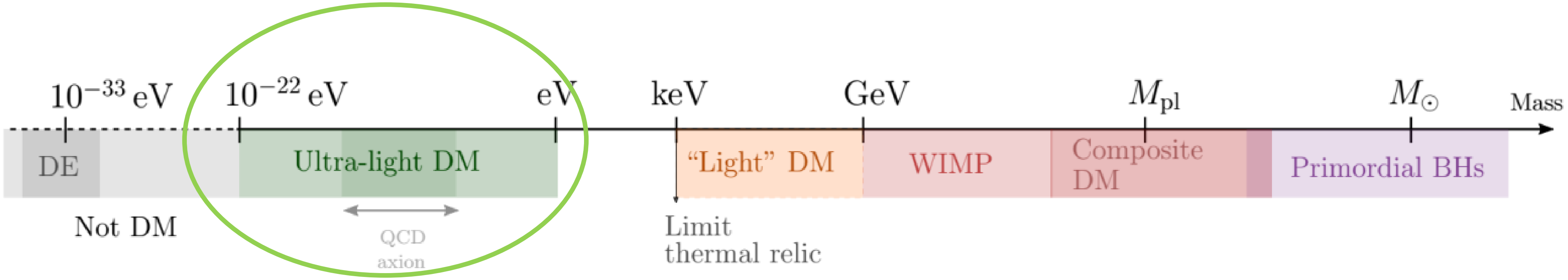
$a(x)$

Pseudoscalar field with a high occupancy number (BE condensate)

Axion like particles

- Originally proposed to solve the strong CP problem in QCD
- Axions also naturally arise in string theory
- In the range ~ 10^-22 – 10^-21 eV predicted relic abundances are consistent with observed DM abundance

$$\Omega_{\text{axion}} \sim 0.1 \left(\frac{f}{10^{17}\,\text{GeV}}\right)^2 \left(\frac{m}{10^{-22}\,\text{eV}}\right)^{1/2}$$



Wave like behavior

Ferreira+21

- Low masses mean a high de Broglie wavelength

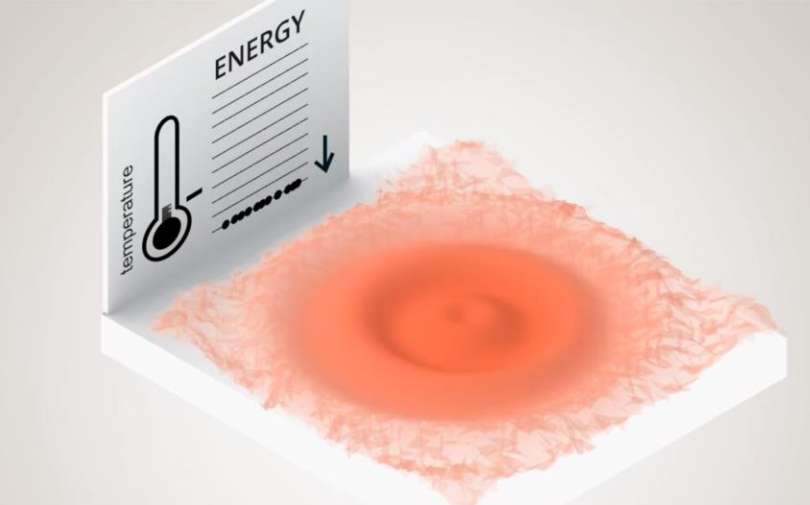
$$x_{dB} \approx 190 \left(\frac{v}{100\ \mathrm{km/s}}\right)^{-1} \left(\frac{m}{10^{-22}\ \mathrm{eV}}\right)^{-1}\ \mathrm{pc}.$$

Hui+16 and Bar+18

- Structure below the de Broglie wavelength is suppressed (wave-like behavior)

- In the high-particle density limit, forming cored structures analogous to BECs

$$(N/V)_{dB} \approx 10^{89} \left(\frac{\rho_{\rm halo}}{100\rho_c}\right) \left(\frac{x_{dB}}{100\ \mathrm{pc}}\right)^3 \left(\frac{m}{10^{-22}\ \mathrm{eV}}\right)^{-1}$$



They all form a single collective quantum wave called a Bose-Einstein condensate.

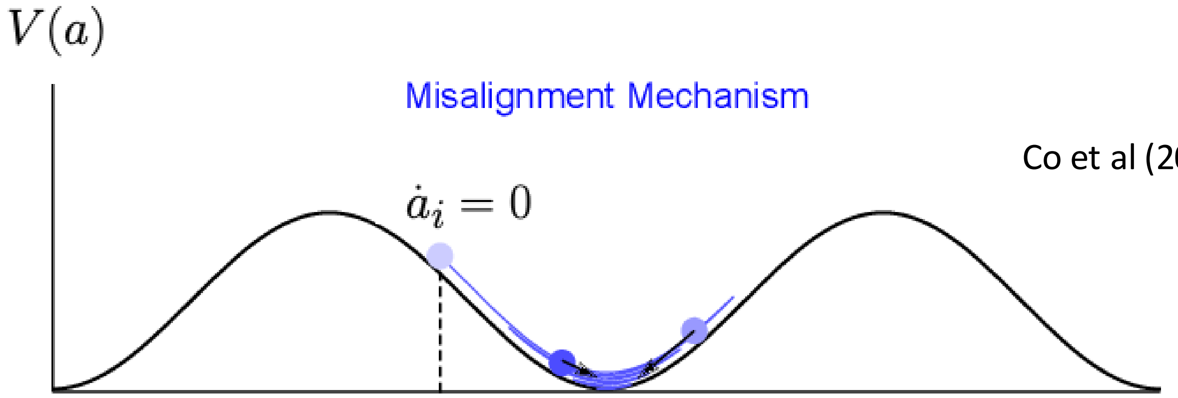
ULDM Motivations

- Isotropic and homogeneous expanding universe

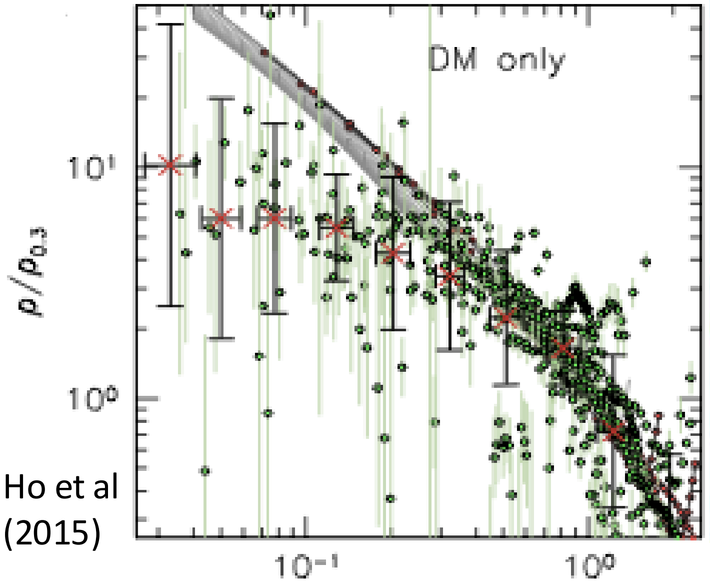
$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

$$m_a > H$$

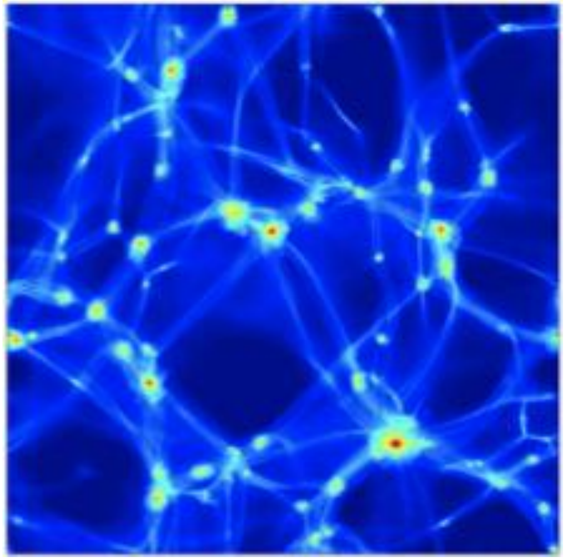
ULDM starts to oscillate with a frequency equal to its mass



Co et al (2019)



Ho et al (2015)



Schive et al (2014)

- Correct relic density: Misalignment Mechanism
- Core-cusp problem solution
- Large scale structure: CDM like behavior

Electromagnetic interactions for ULDM

Birefringence effect between ULDM and EM waves

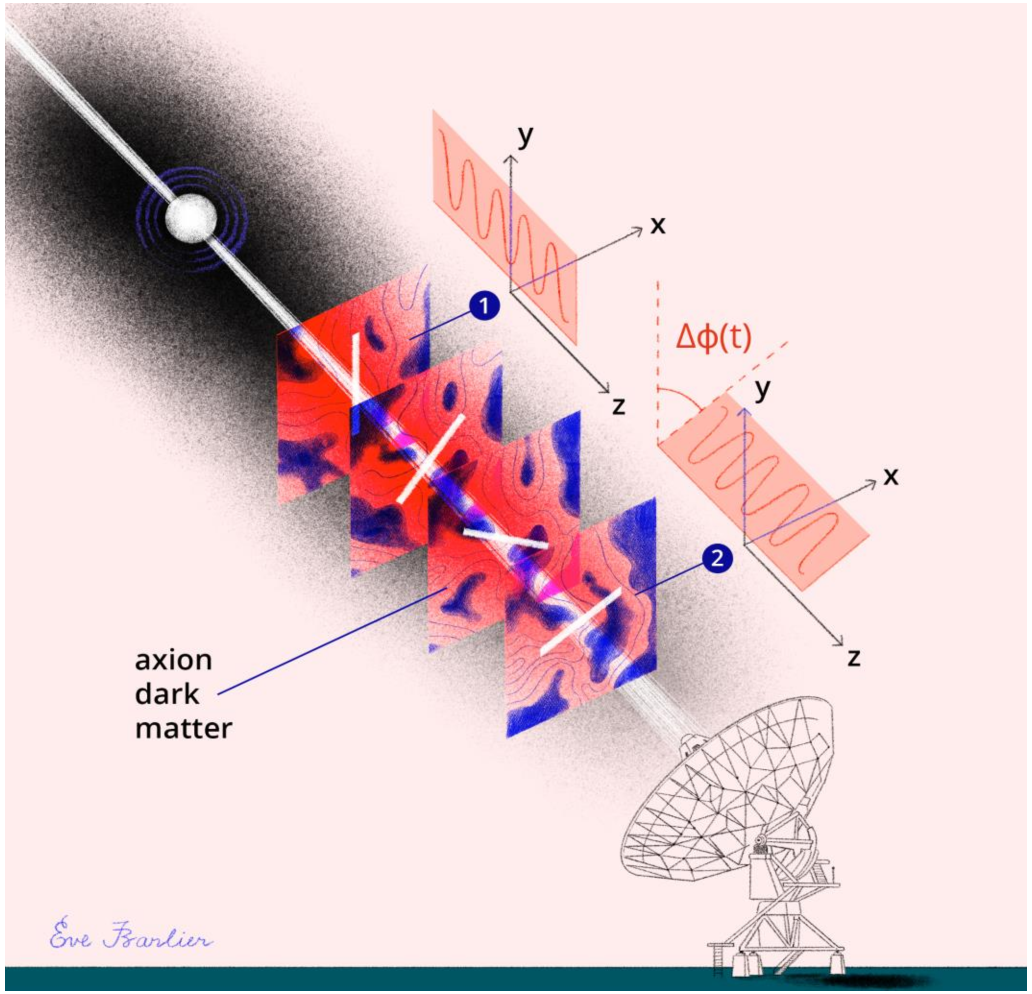
Effective picture of the axionic field

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{g_{a\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\left(\partial_\mu a\partial^\mu a - m_a^2 a^2\right)$$

EM interaction with ULDM

$$g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} \to g_{a\gamma}a\mathbf{E}\cdot\mathbf{B}$$

Axion field behaves as chiral medium via the P-violation term



Birefringence effect between ULDM and EM waves

EM interaction with ULDM

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

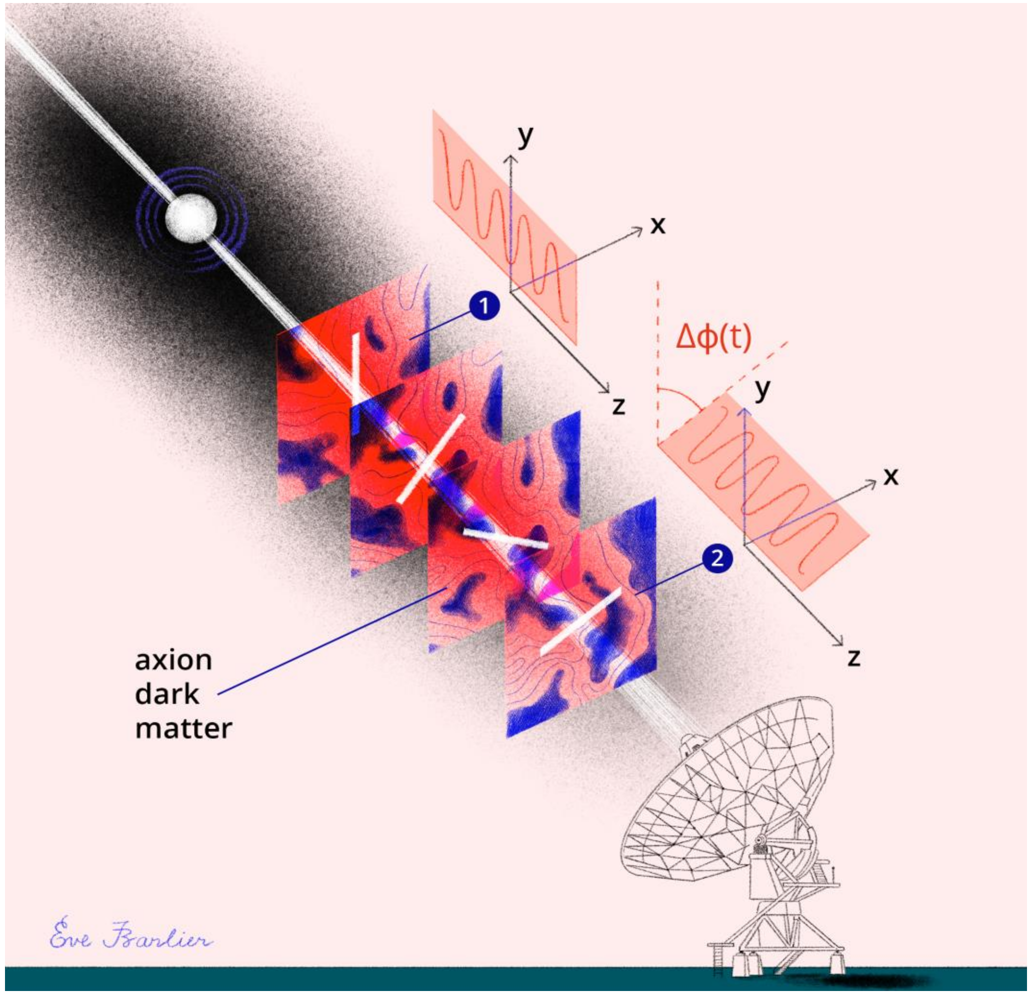
Dispersion relation

Harari and Sikivie (1991)

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

Change of the polarization plane

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



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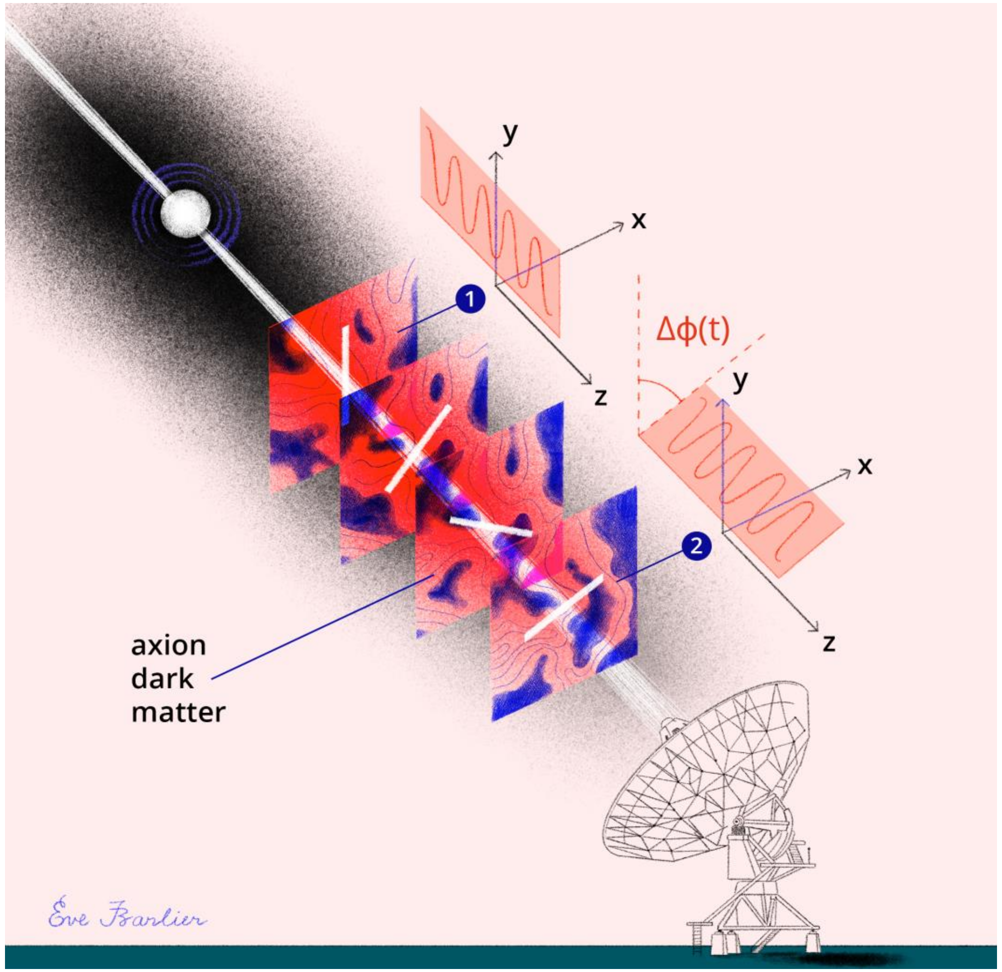
Change of the polarization plane:

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



Stochasticity effects

- Coherence time

$$\tau_c = (m_a\sigma^2)^{-1} \simeq 2\times10^5 \left(\frac{m_a}{10^{-22}\ \mathrm{eV}}\right)^{-1} \left(\frac{\sigma}{10^{-3}}\right)^{-2}\ \mathrm{yr}$$

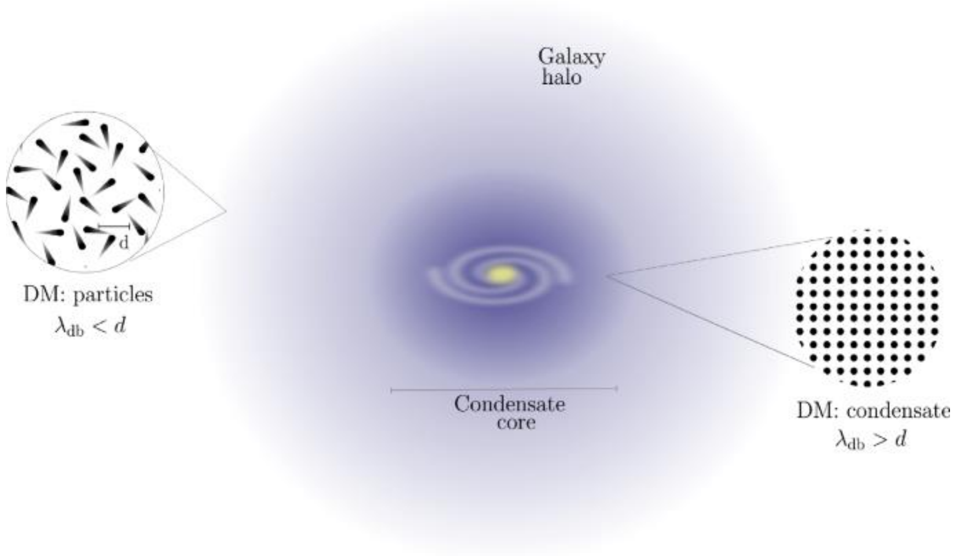
- Coherence length:

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

- The coherence of the oscillations is set by local DM velocity distribution.

$$\rho_{DM} = \frac{1}{2} m_a^2 \langle a_0^2 \rangle$$

- The connection between the ALP field amplitude and DM density acquires a stochastic nature

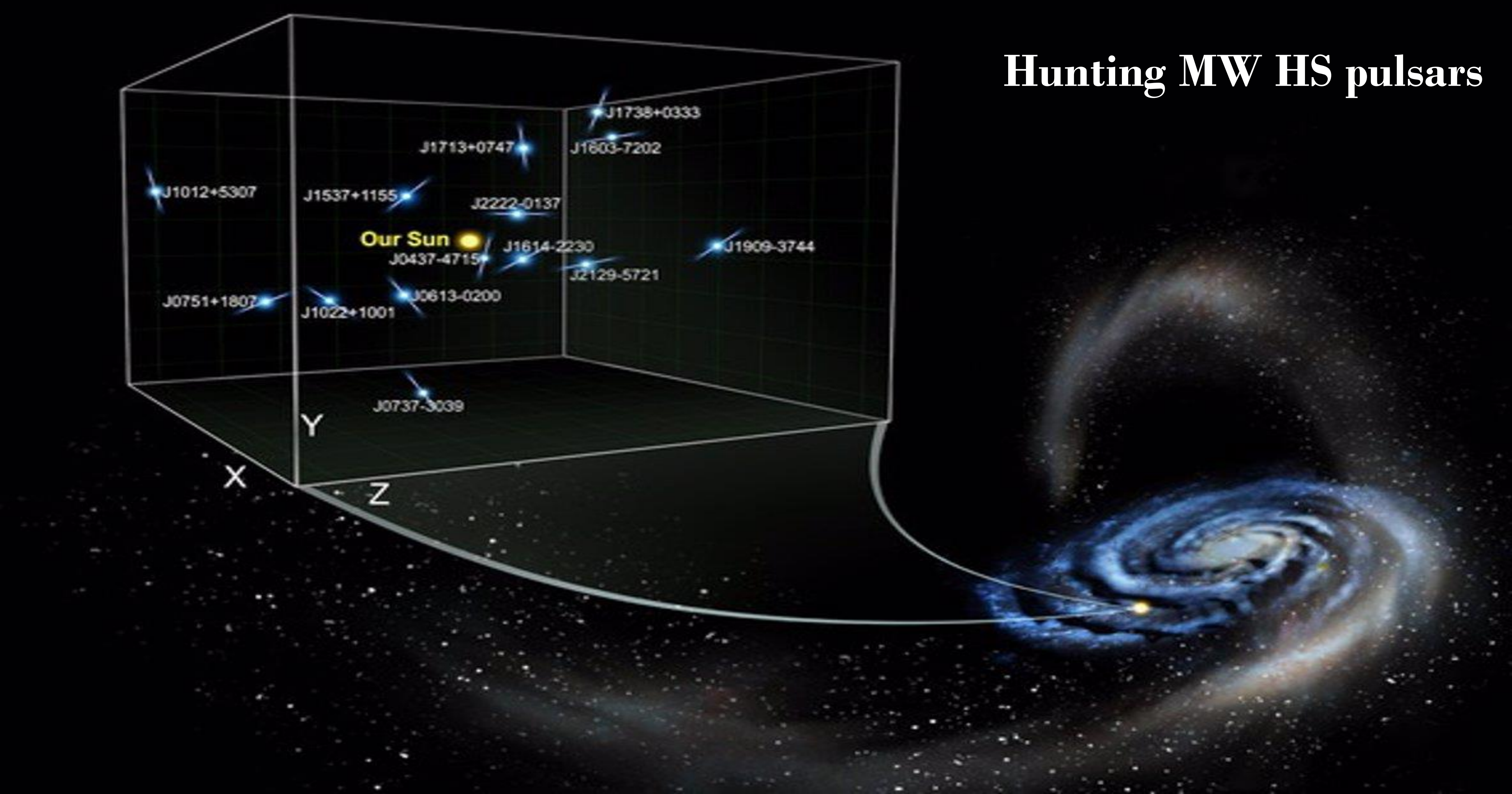


$$\phi_a = \frac{g_{a\gamma}}{\sqrt{2}m_a} \left(\rho_o\alpha_o^2 + \rho_s\alpha_s^2 - 2\sqrt{\rho_o\rho_s}\alpha_o\alpha_s \cos\Delta\right)^{1/2}$$

Rayleigh distributions

How to measure EM effects of ULDM?

Hunting MW HS pulsars



PARKES Pulsars Timing Array

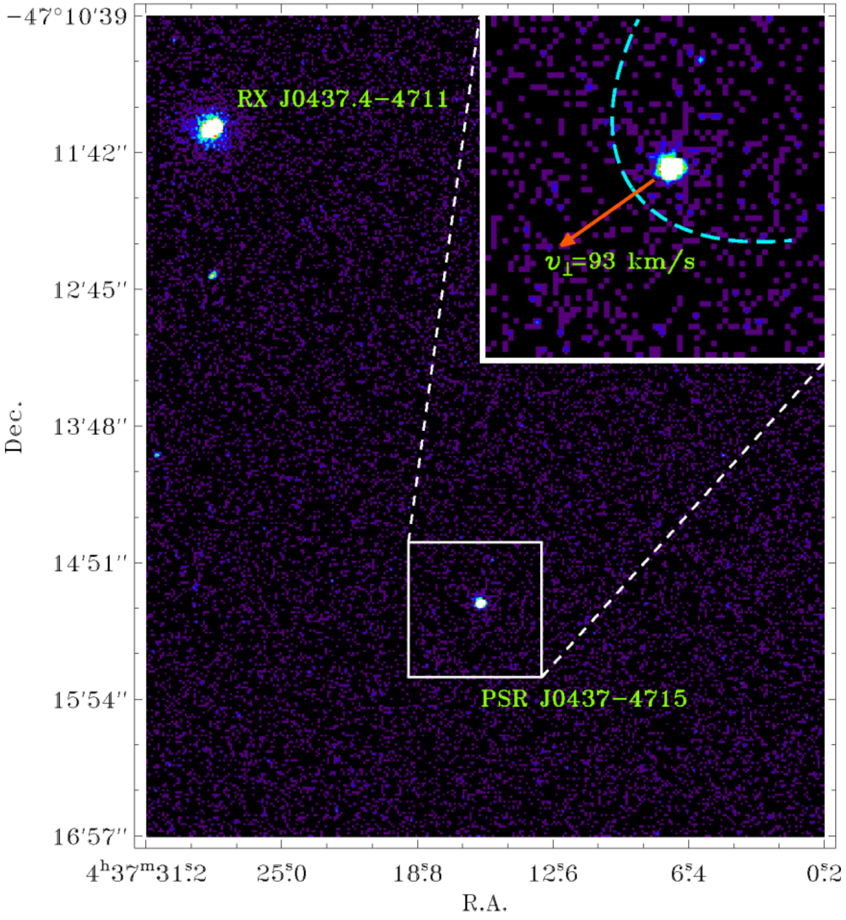
- The scientific goal of the Parkes Pulsar Timing Array (PPTA) is to detect low-frequency gravitational waves using millisecond pulsars as precise cosmic clocks.

- Observations of the polarization angle (PA) of 20 galactic pulsars measured by the Parkes Pulsar Time Array (PPTA) at about 1.4 GHz

- PA Observation windows between ~4.0-4.5 years (DR1)

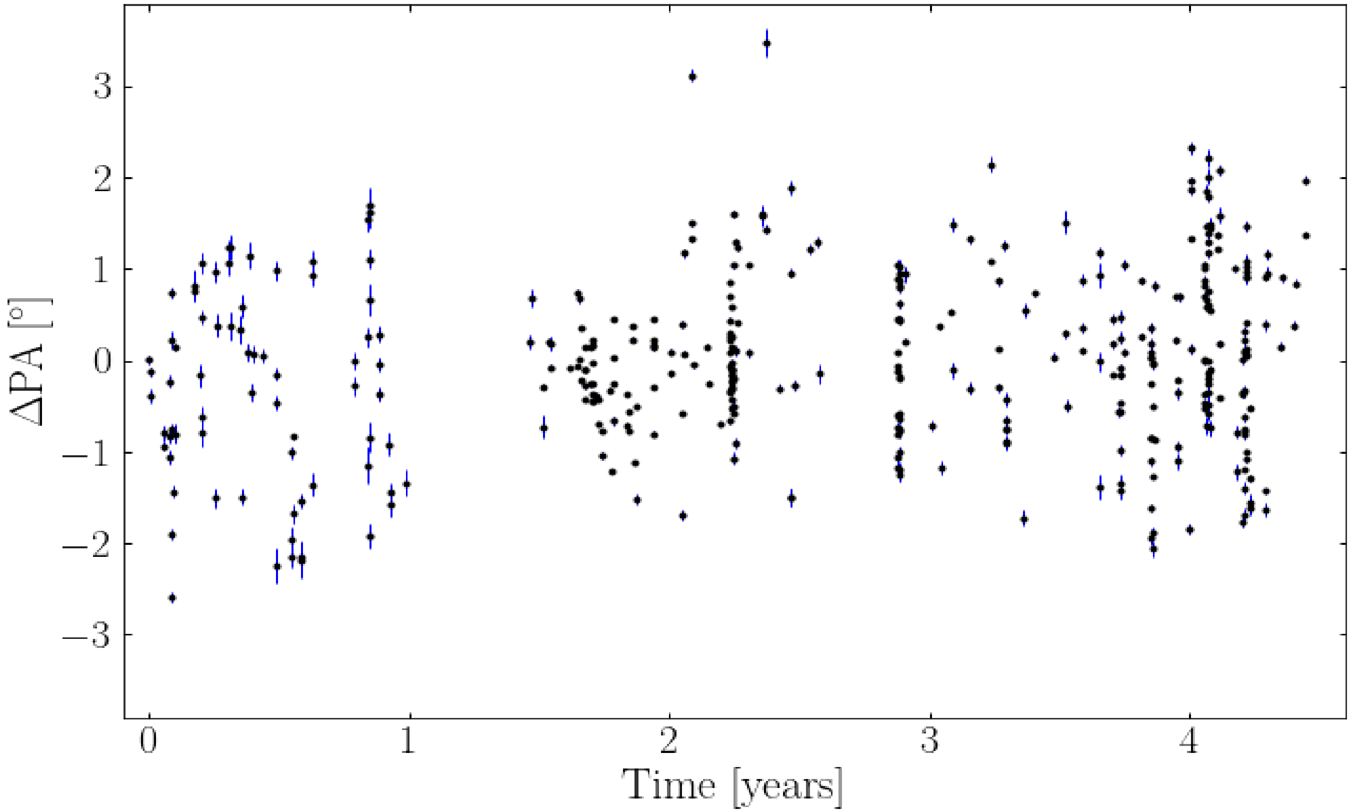
- Seasonal effects are treated with International Reference Ionosphere (IRI) model.

Pulsars Polarimetry from Parkes Pulsars Timing Array



Avlin+06

J0437-4715 IRI



PPTA + 11 DR1

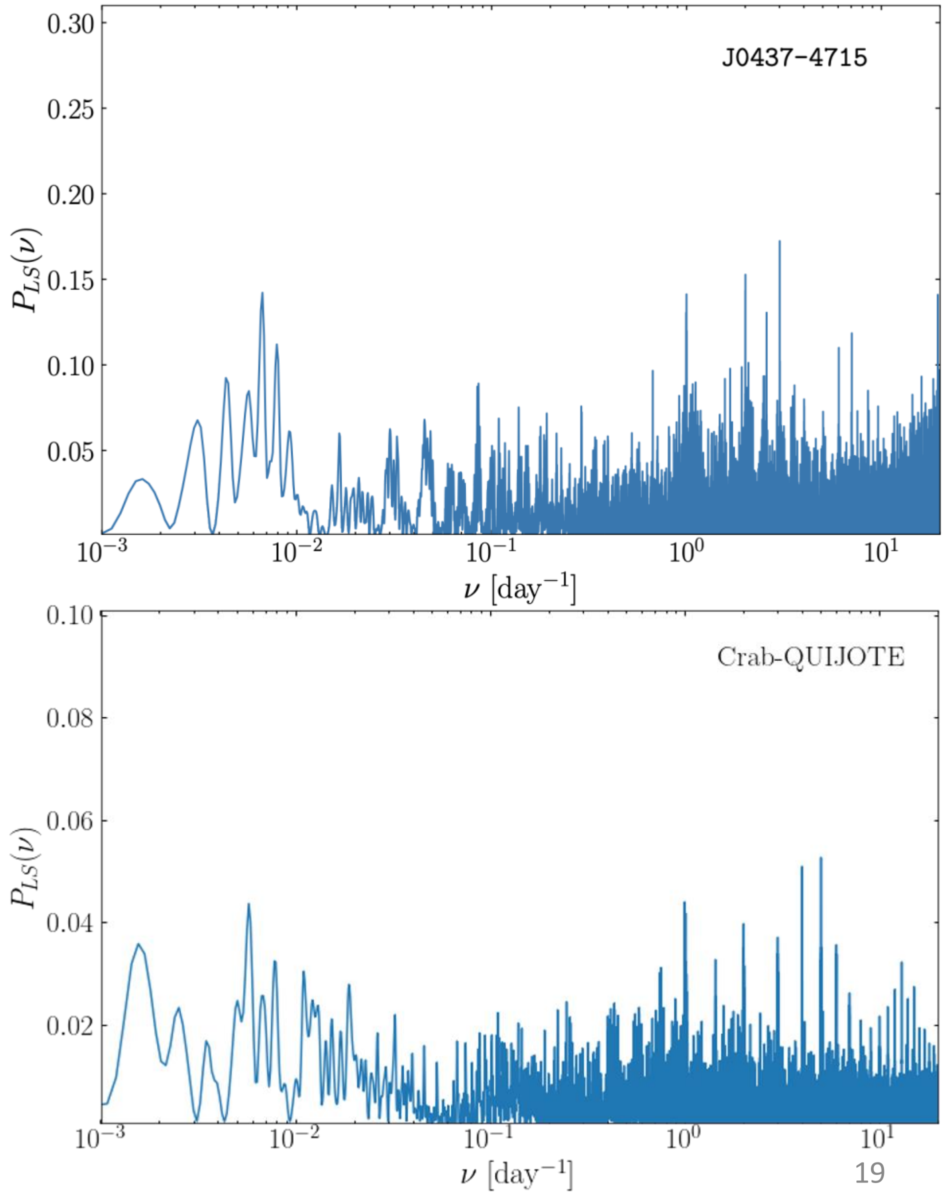
QUIJOTE (Q U I JOint TEnerife)-MFI

- QUIJOTE-MFI aims to unveil the polarization properties of the CMB and galactic emissions, providing key insights into the early Universe and astrophysical processes (10-40 GHz).
- QUIJOTE-MFI for Tau –A (Crab) at frequencies in the range 11-19 GHz
- Tau A is the main reference calibrator of QUIJOTE-MFI, due it is the brightest polarised compact source on the sky in the range 11-19 GHz
- Observation period of ~4.5 years for polarization measurements with an uncertainty of O(1◦).

How to search ULDM periodic signals in PM ?

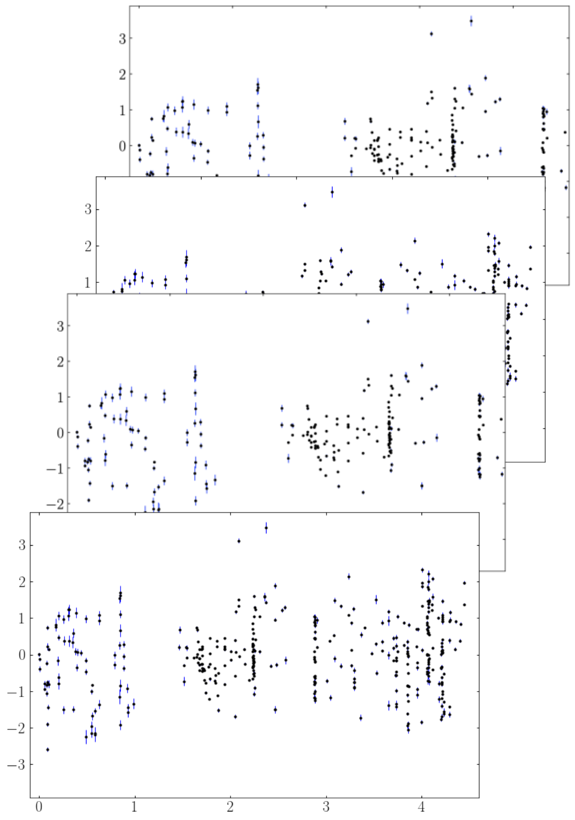
Lomb-Scargle Periodograms (LS)

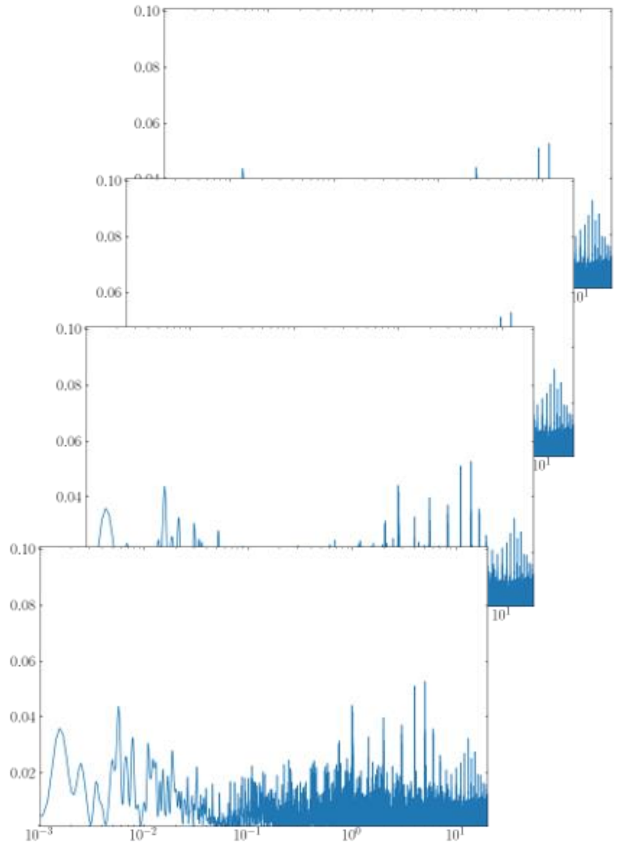
- LS can be regarded as the analog of the power spectrum in continuous Fourier analysis
- LS can also be understood as the result of a least-square minimization process (including data uncertainties)
- False Alarm Probability (FAP) quantifies the probability that a data set with no periodic signal leads to such peak by coincidental alignment of random fluctuations

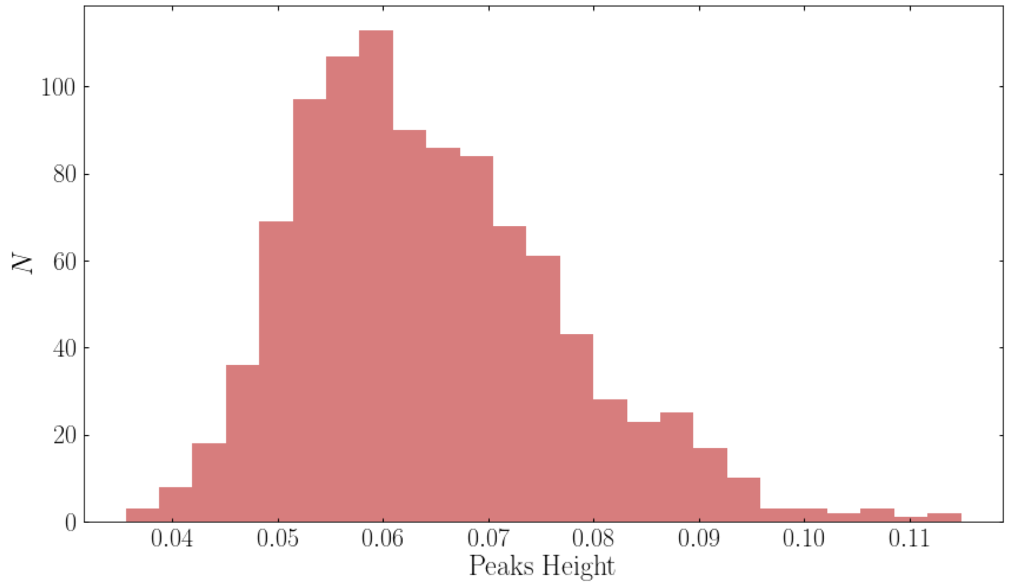


False Alarm Probability: Bootstrapping Method

N MCs ΔPA → $N\ P_{LS}(\nu)$ → Peaks → $\mathcal{P}(\max)$

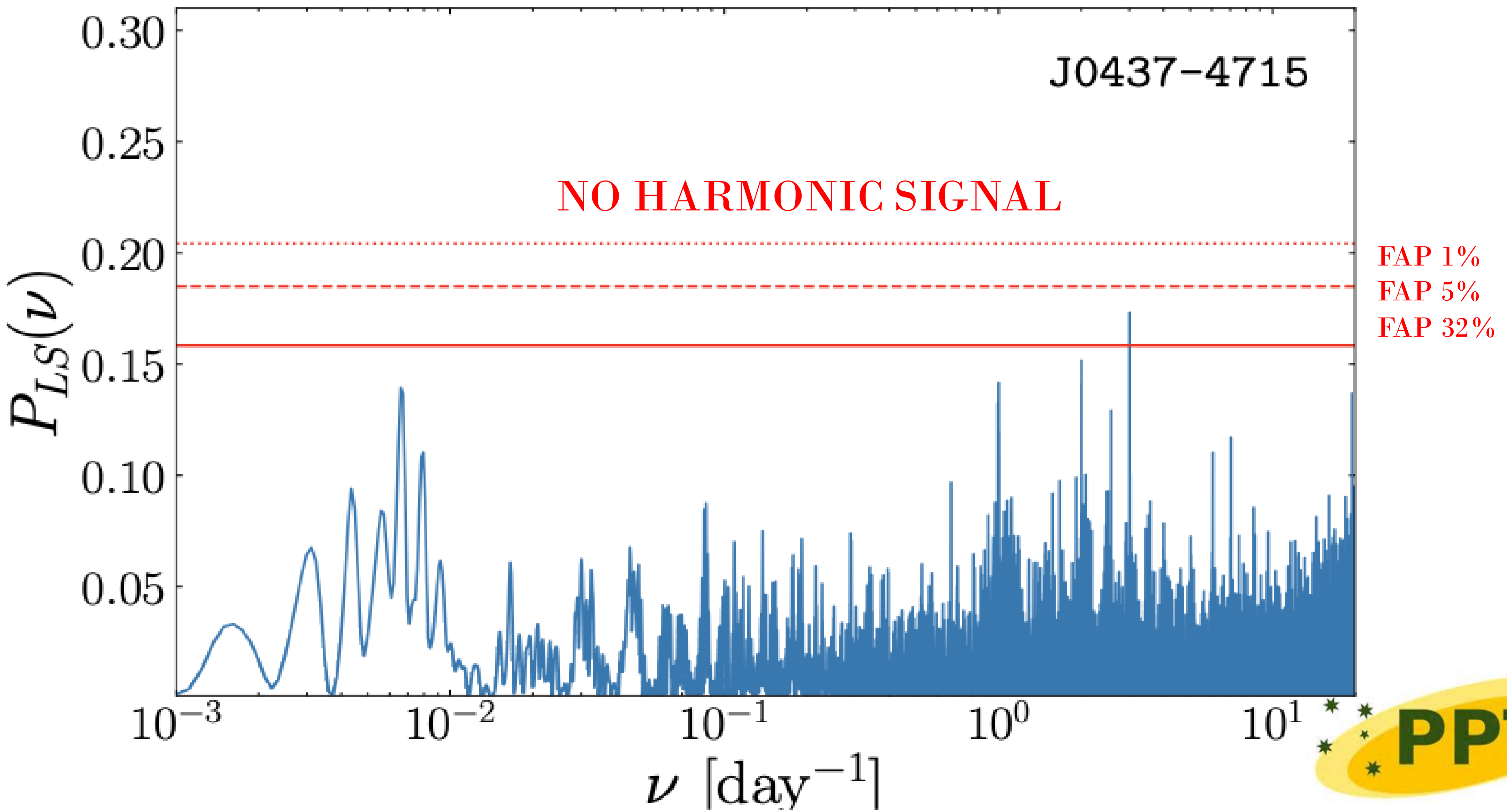




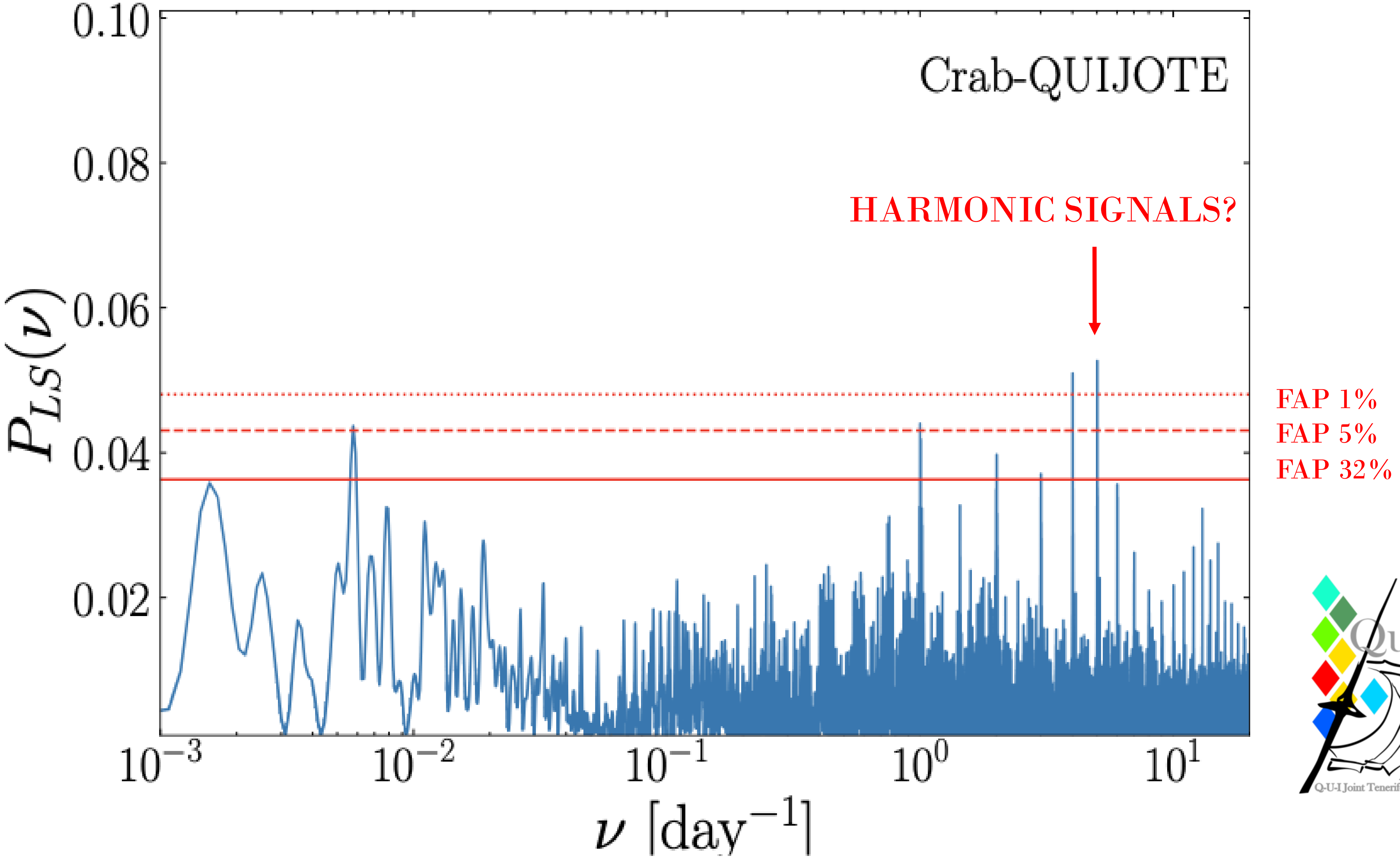


Confidence levels

FAPS and Harmonic signals

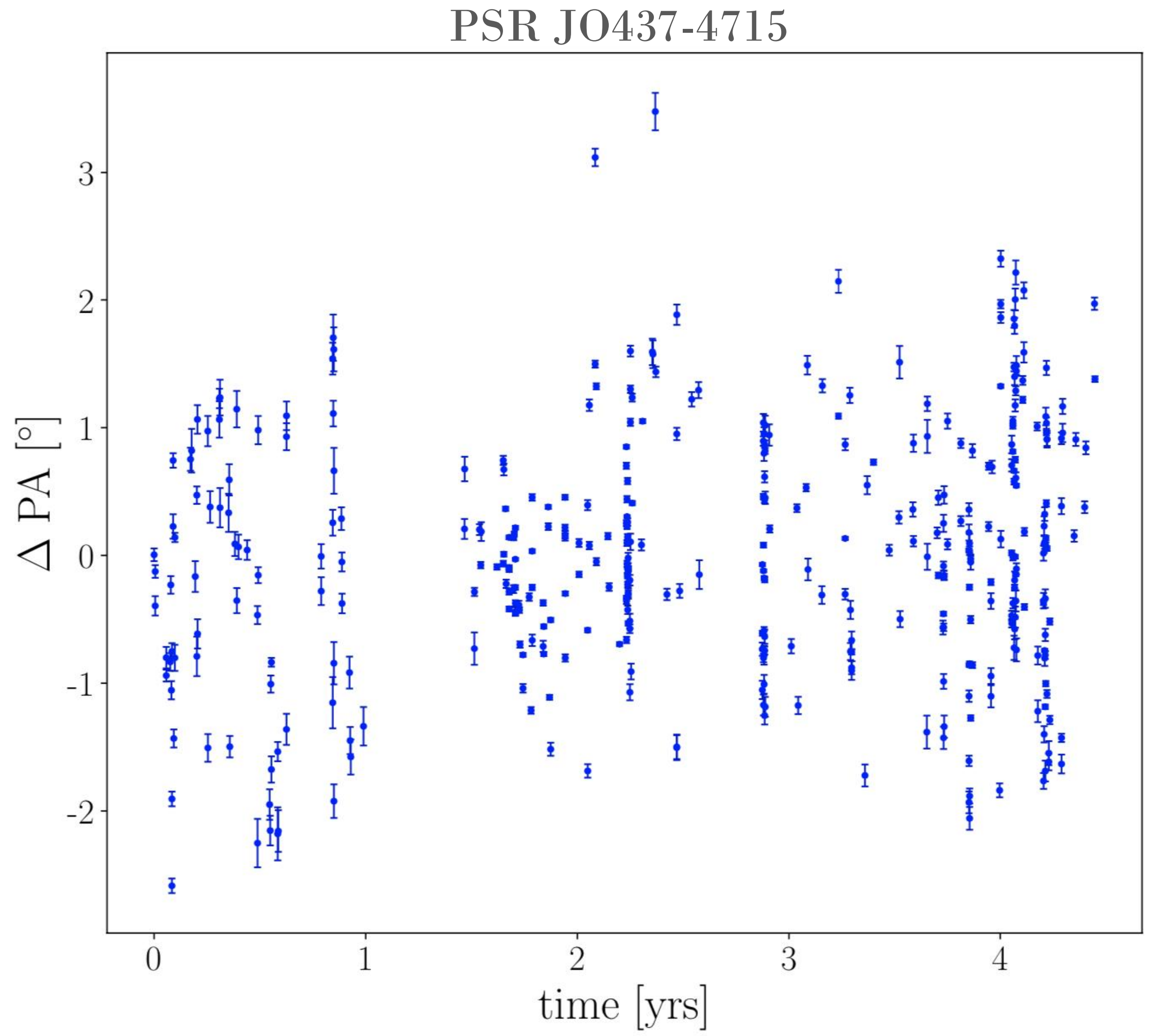


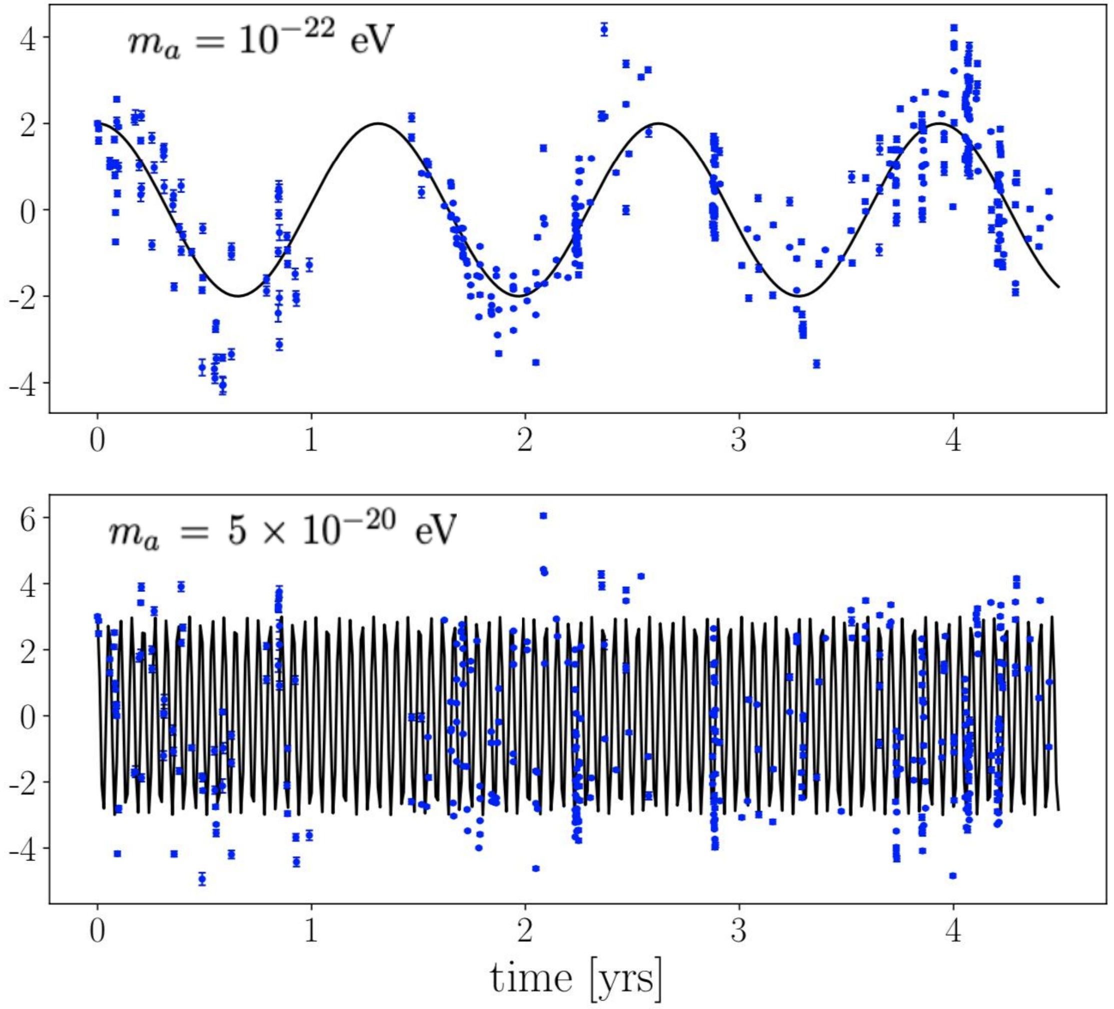
FAPS and Harmonic signals



How to obtain bounds on EM couplings and axion mass?

Time series vs ALP Birefringence effect

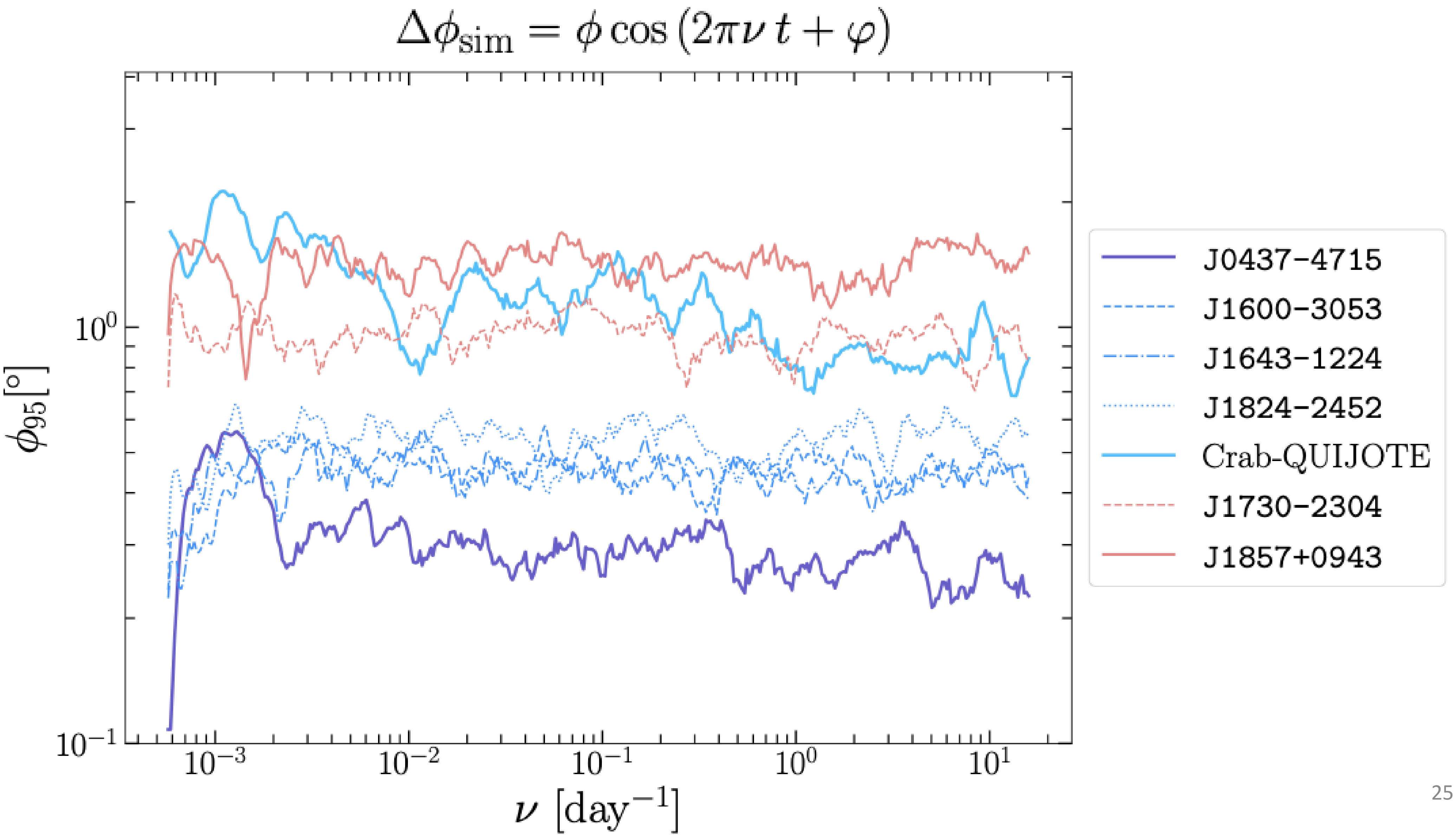




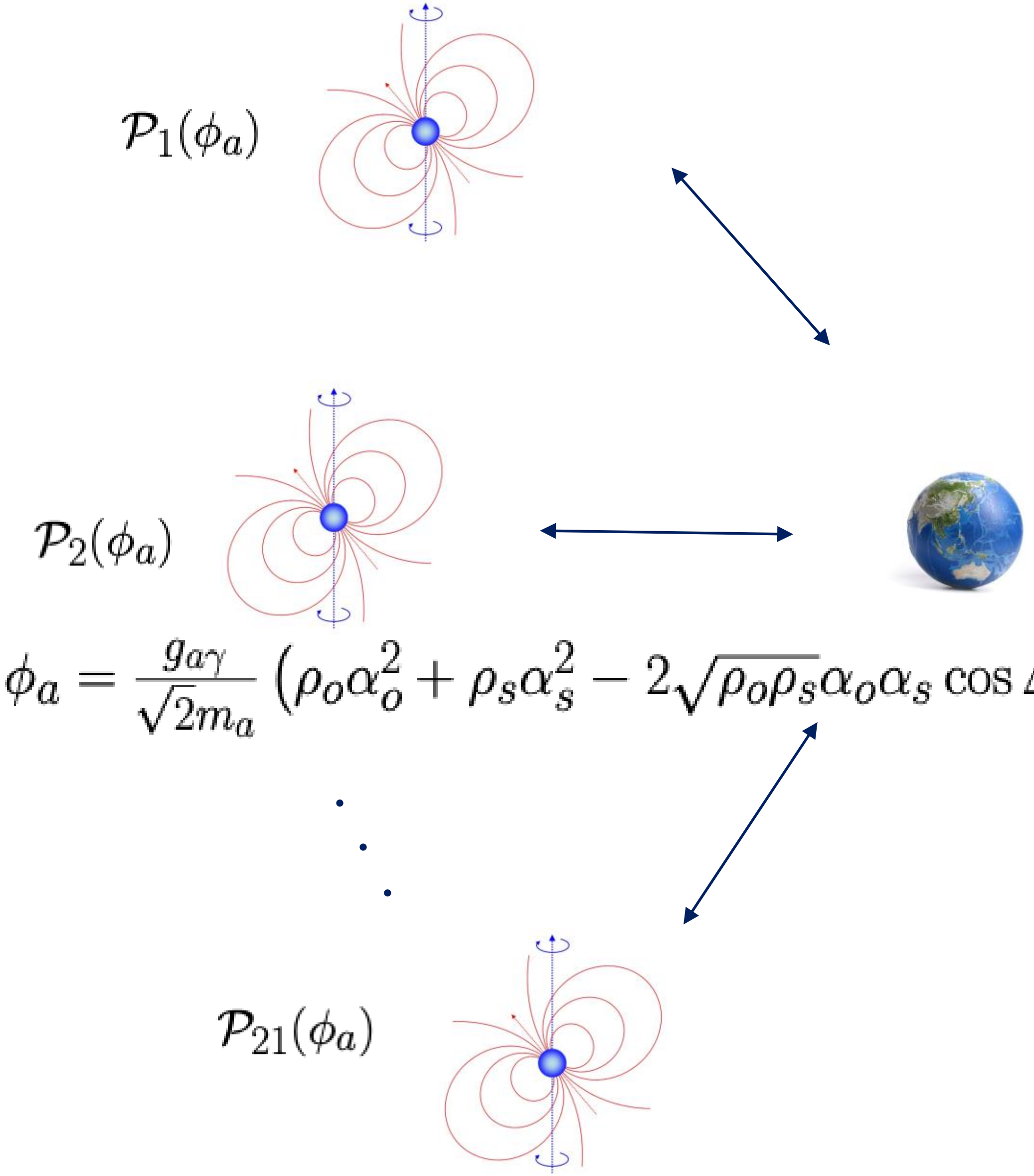
Real time series (with systematic corrections)

Expected time series with ALP effect

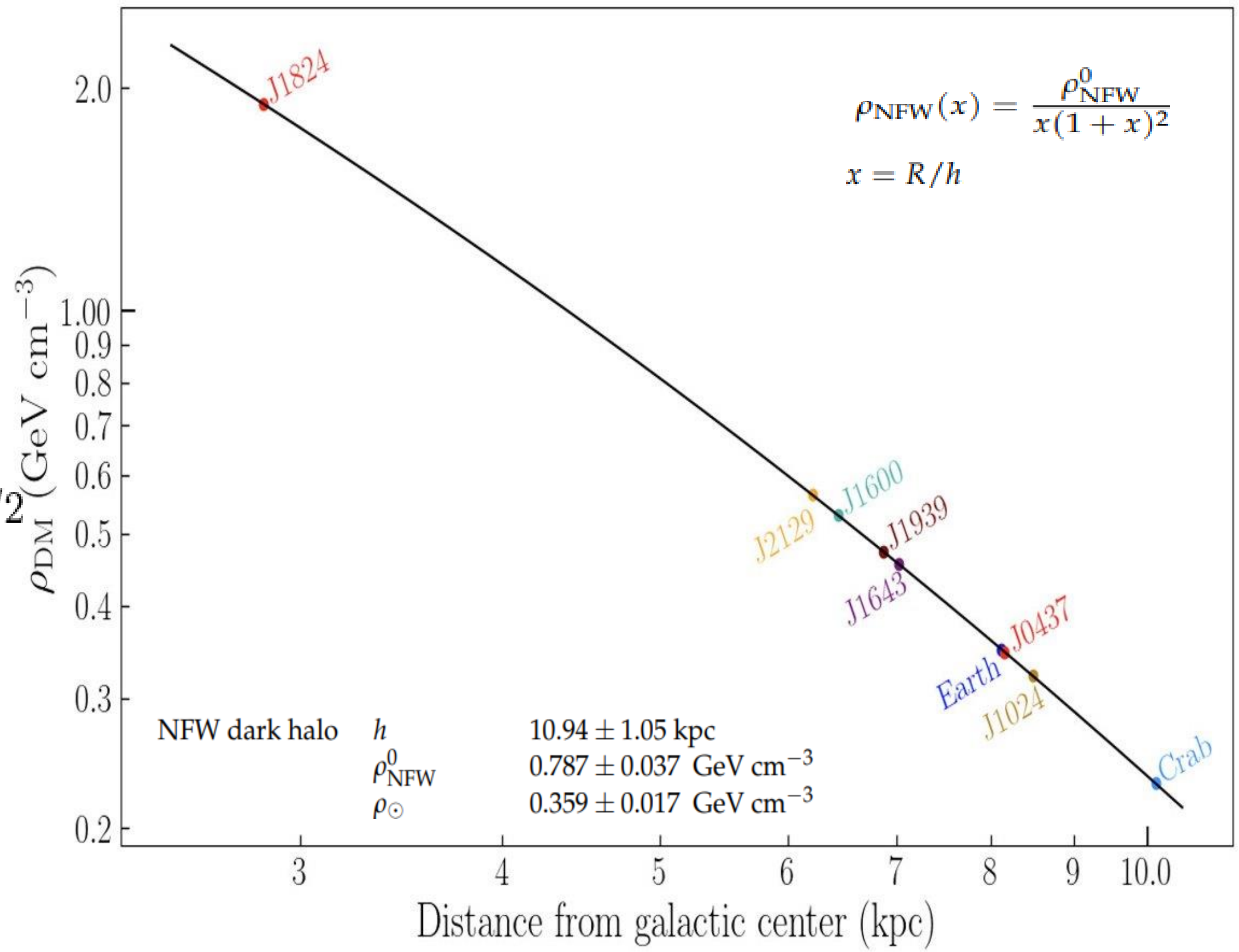
Individual Bounds



Stochasticity and correlation effects



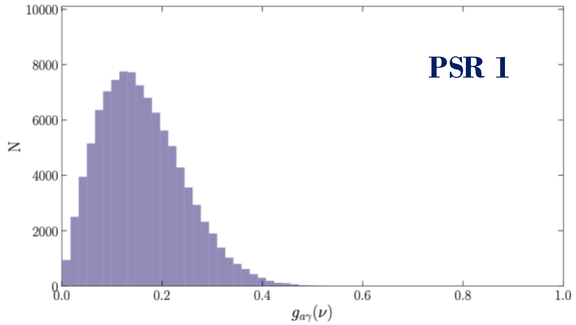
$$\phi_a = \frac{g_{a\gamma}}{\sqrt{2}m_a}\left(\rho_o\alpha_o^2 + \rho_s\alpha_s^2 - 2\sqrt{\rho_o\rho_s}\alpha_o\alpha_s\cos\Delta\right)^{1/2}$$



Stochastic effects: MC treatment

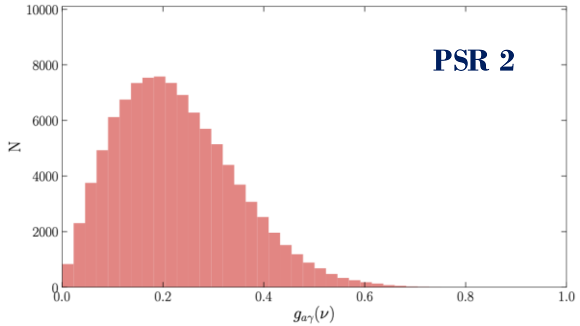
$$\phi_a = \frac{g_{a\gamma}}{\sqrt{2}m_a}\left(\rho_o\alpha_o^2 + \rho_s\alpha_s^2 - 2\sqrt{\rho_o\rho_s}\alpha_o\alpha_s\cos\Delta\right)^{1/2}$$

$\mathcal{P}_1(\phi_a)$



$(g_{a\gamma}, \Delta g_{a\gamma})_1$

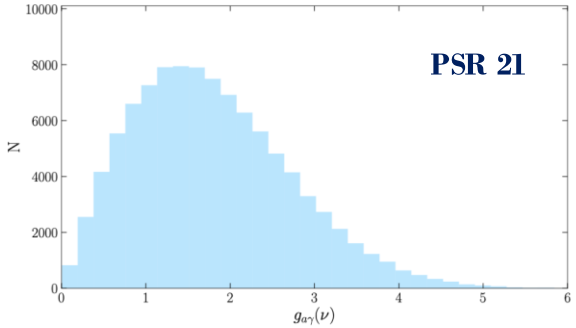
$\mathcal{P}_2(\phi_a)$



$(g_{a\gamma}, \Delta g_{a\gamma})_2$

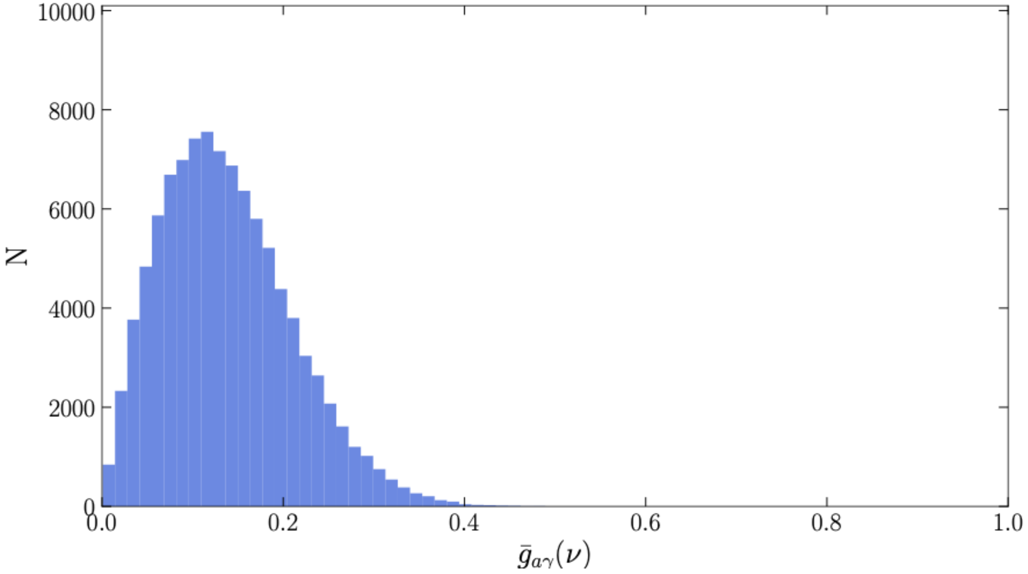
⋮

$\mathcal{P}_{21}(\phi_a)$



$(g_{a\gamma}, \Delta g_{a\gamma})_{21}$

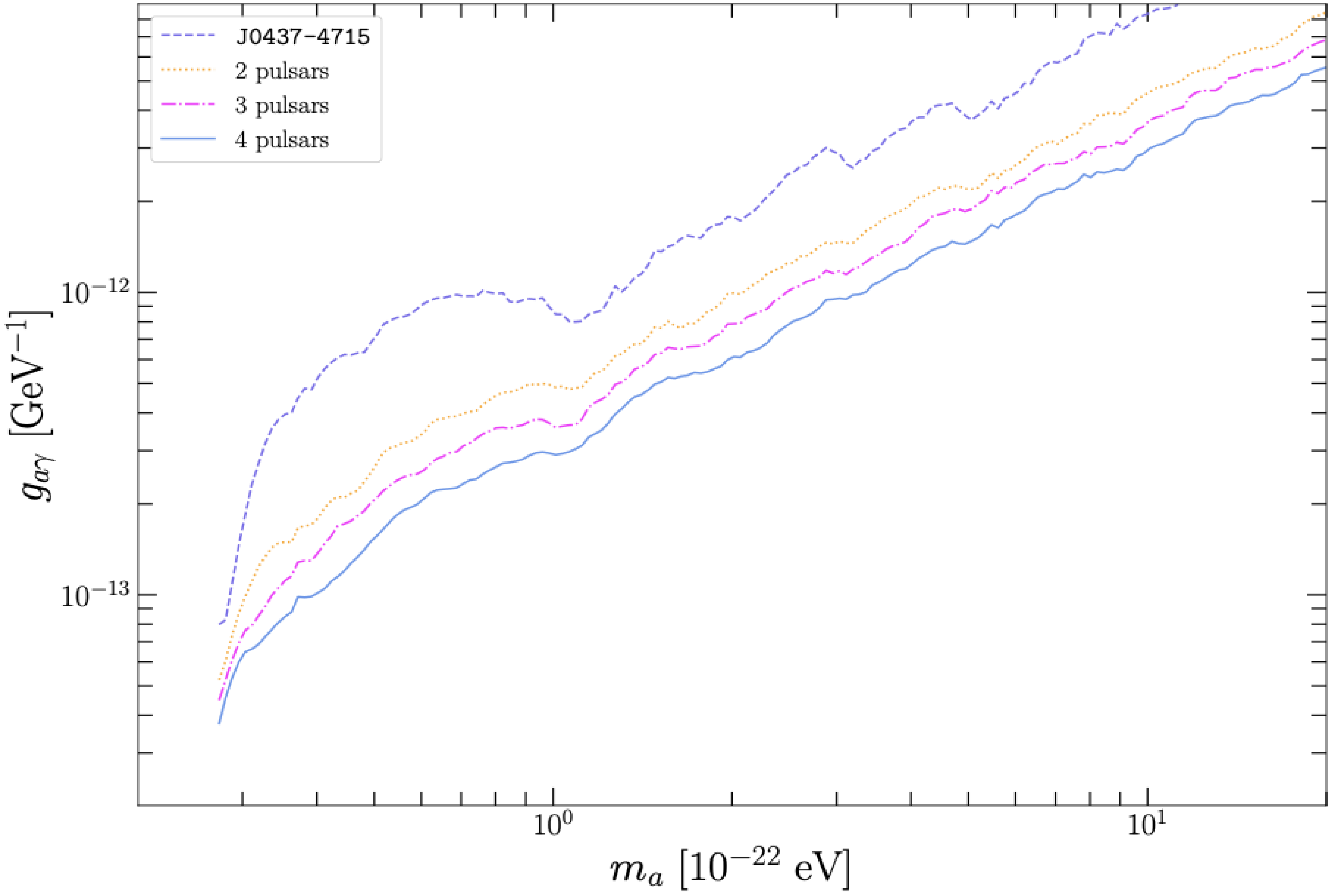
Weighted mean $\bar{g}_{a\gamma}$



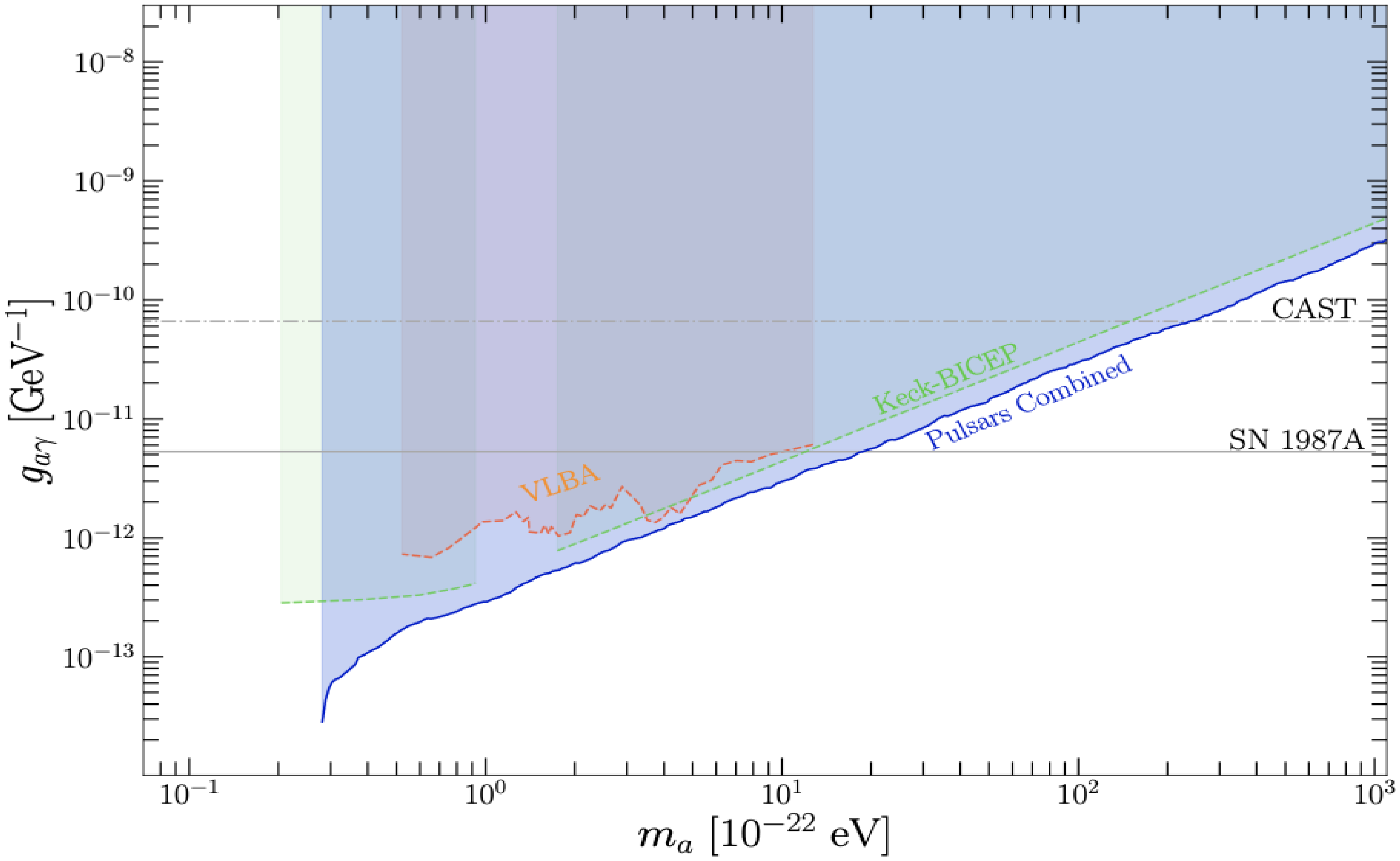
Confidence levels-Bounds

Combined bounds on g-ma plane

Bounds pulsar by pulsar (individual bounds)



Exclusion limits 95% CL for ULDM signals



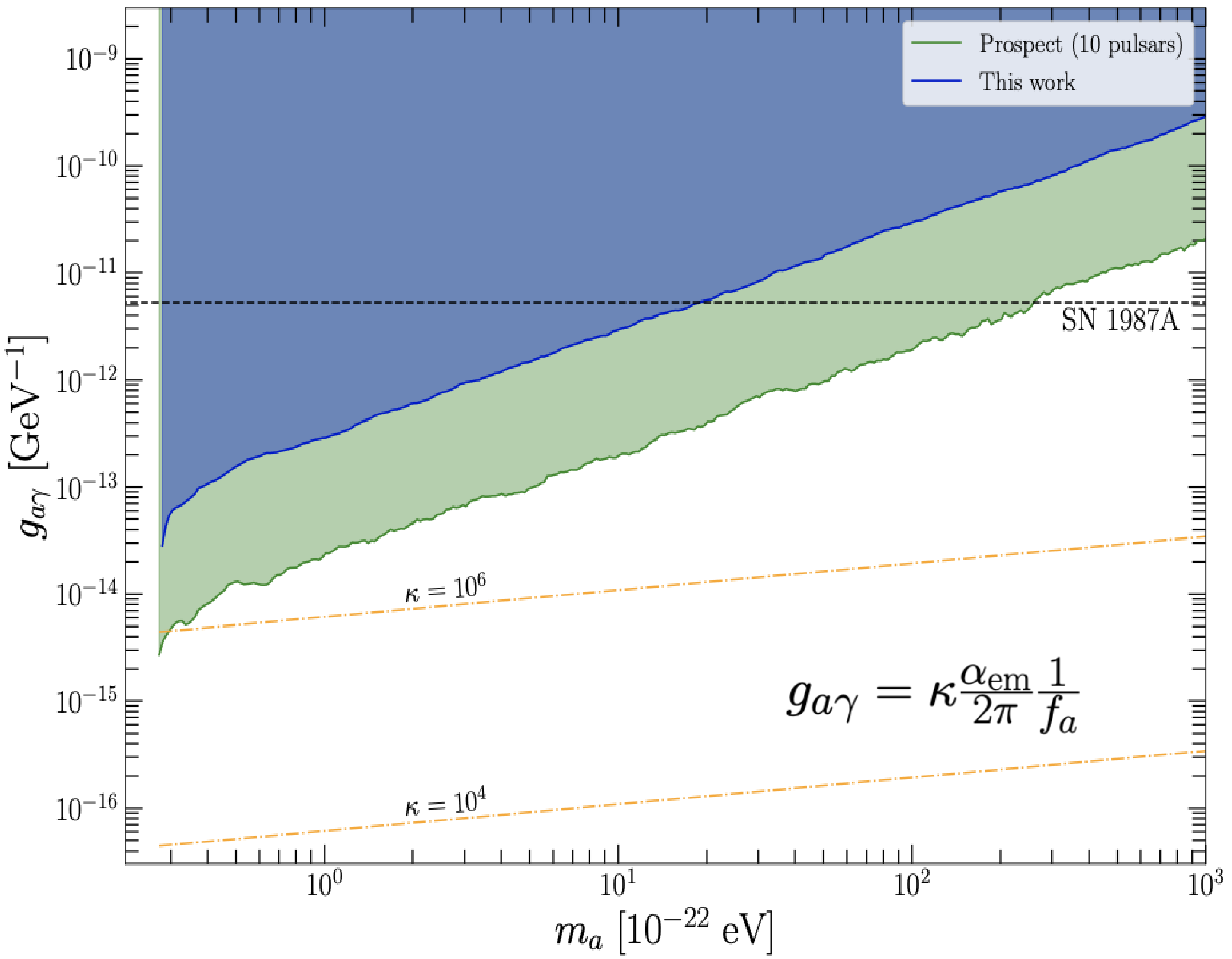
Future prospects

- FP with 10 pulsars near to the Galactic center with simulated data (5 years)

$$\rho_{DM} \simeq 50 \text{ GeV cm}^{-3}$$

- Overdense scenario inspired in the SGR J1745–2900

Kennea et al (2013)



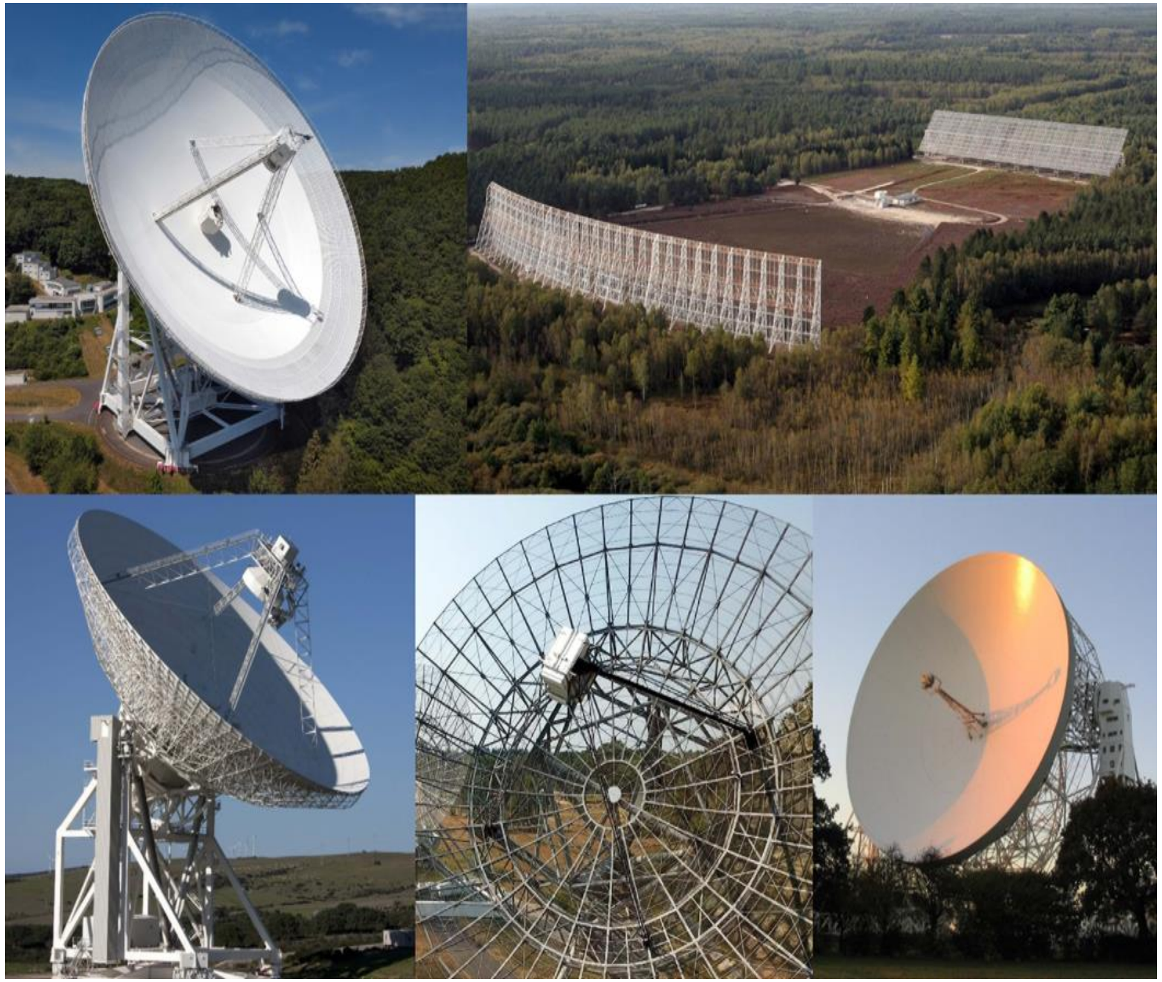
New results using European Pulsars timing Array (EPTA)

Based on arXiv/astro-ph: 2412.02232

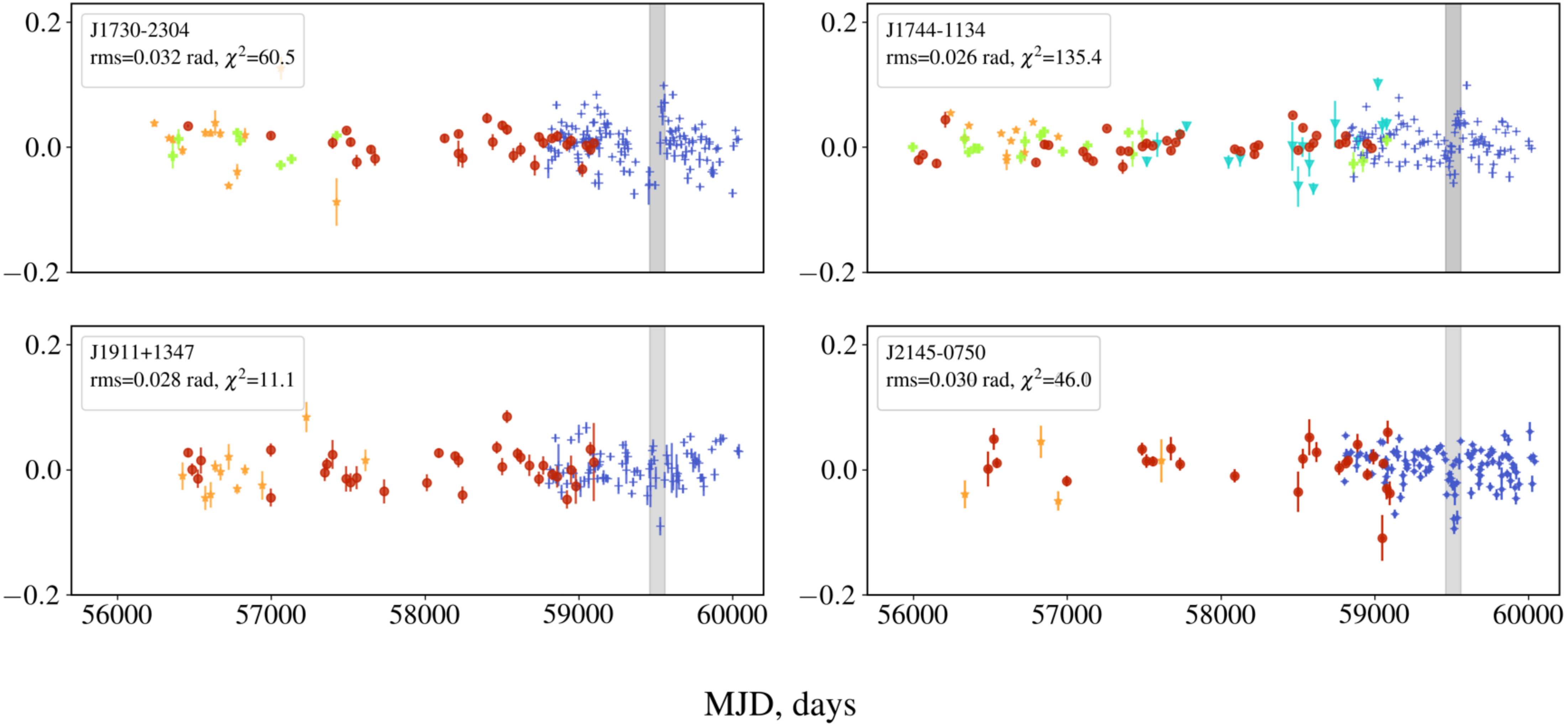
The European Pulsar Timing Array

- The aim of the **European Pulsar Timing Array (EPTA)** is to detect and study low-frequency gravitational waves using millisecond pulsars as highly precise cosmic clocks.

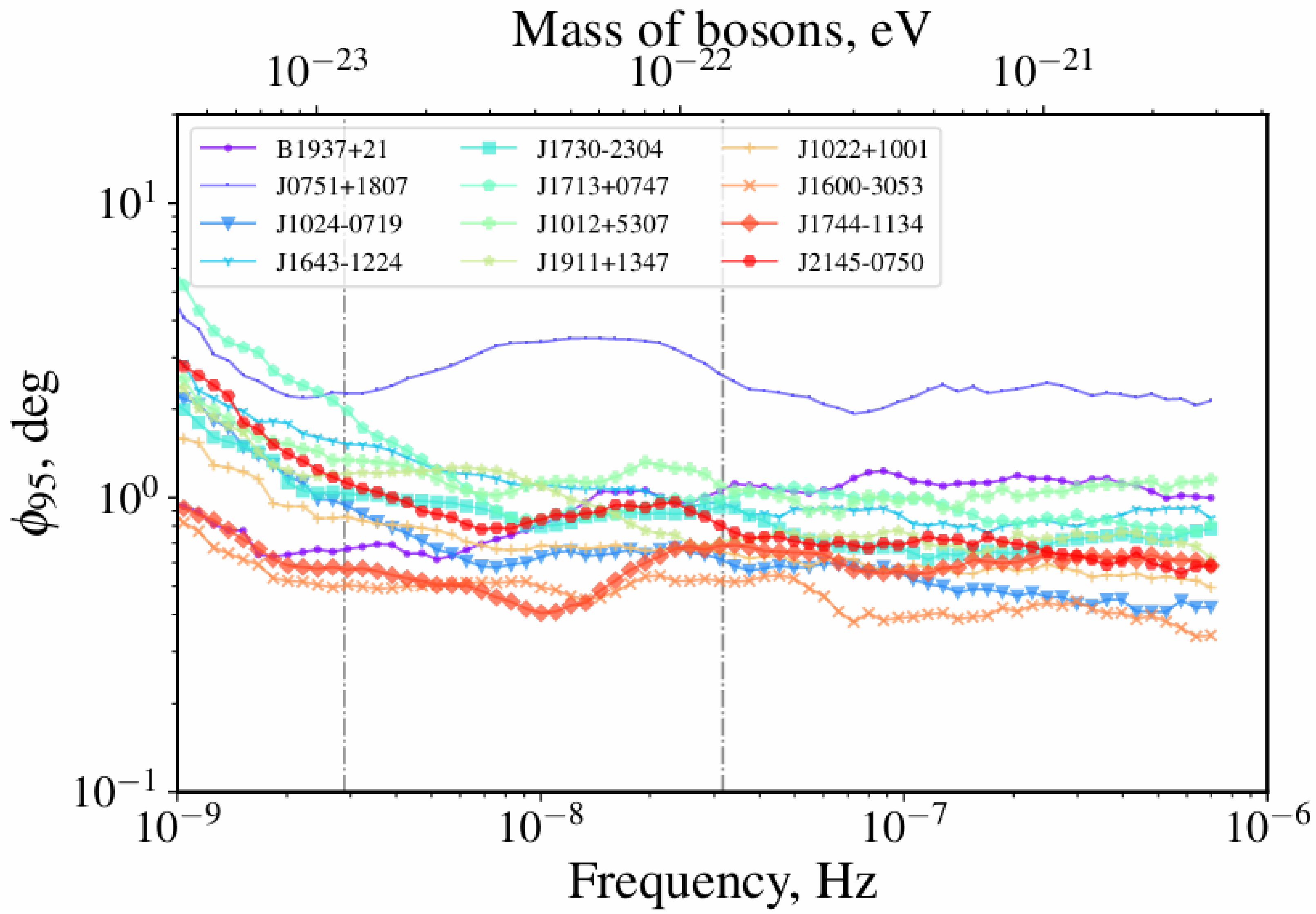
- We investigated for an astrophysical signal from axions using both frequentist (based on LS periodograms) and Bayesian statistical frameworks for 12 brightest Pulsars.



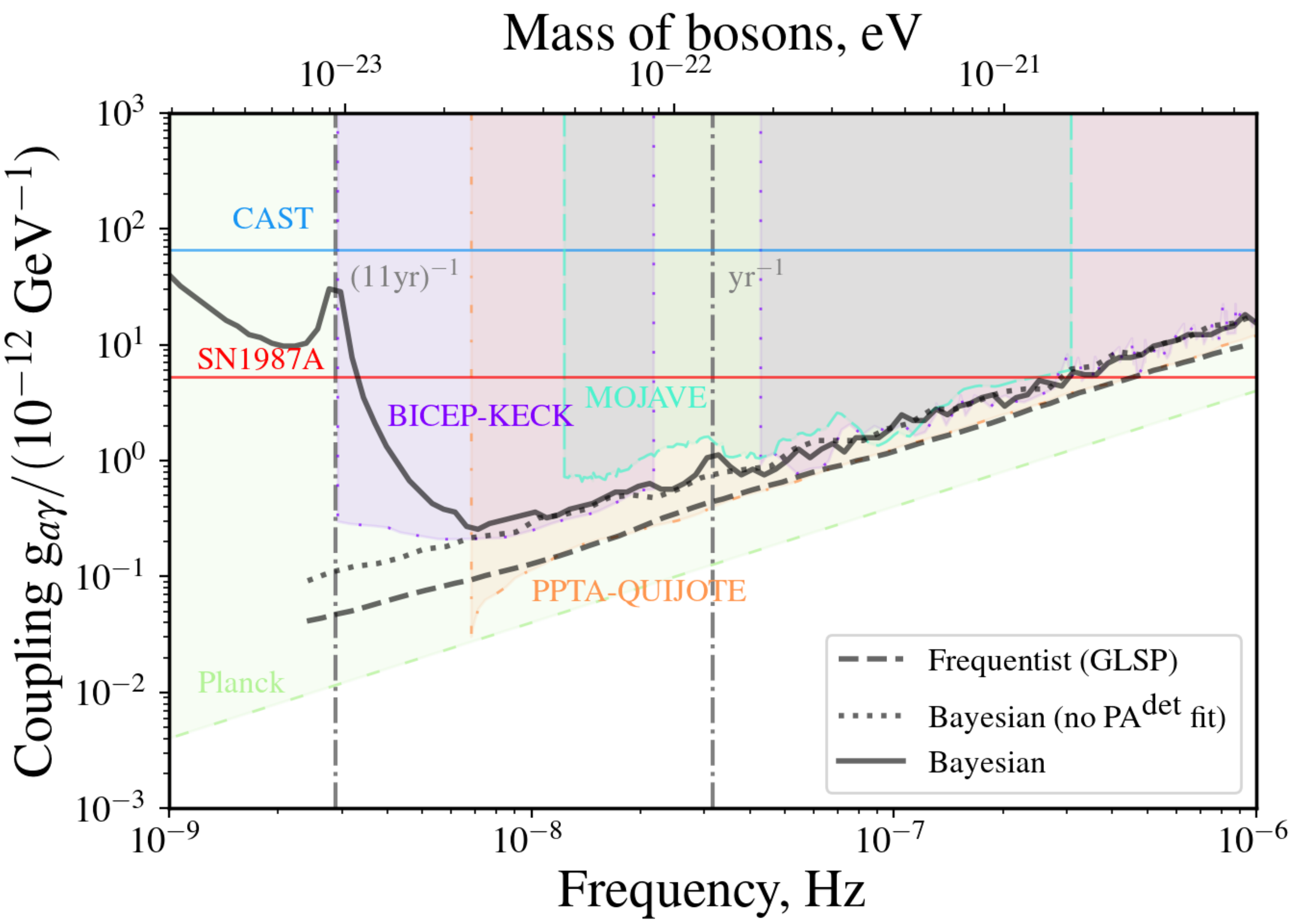
Polarization angle in brightest EPTA pulsars



Exclusion limits 95% CL on amplitude for ULDM signals (EPTA)



Exclusion limits 95% CL for ULDM signals (EPTA)



Concluding remarks

- We carefully considered the intrinsic degree of stochasticity of the axion signal interacting with radio EM waves from pulsars, arising from the virialized state of ULDM in the Milky Way's dark matter halo.

- Use of high-performance techniques based on Lomb-Scargle periodograms to extract a periodic signal in the polarization angle-time series measured by PPTA, QUIJOTE and, very recently for EPTA.

- With the complete dataset from PPTA and Crab-QUIJOTE, our analyses lead to a strong combined constraint in the ALP ULDM scenario for a wide range of masses. We enhanced the sensitivity of the experiments with pulsars to search ALPs.

- Our frequentist method was leveared to search Harmonic signals due to ALPs with EM signals in other catalogs, finding an agreement in sensitivity with PPTA+QUIJOTE

GRACIAS!

Backup slides

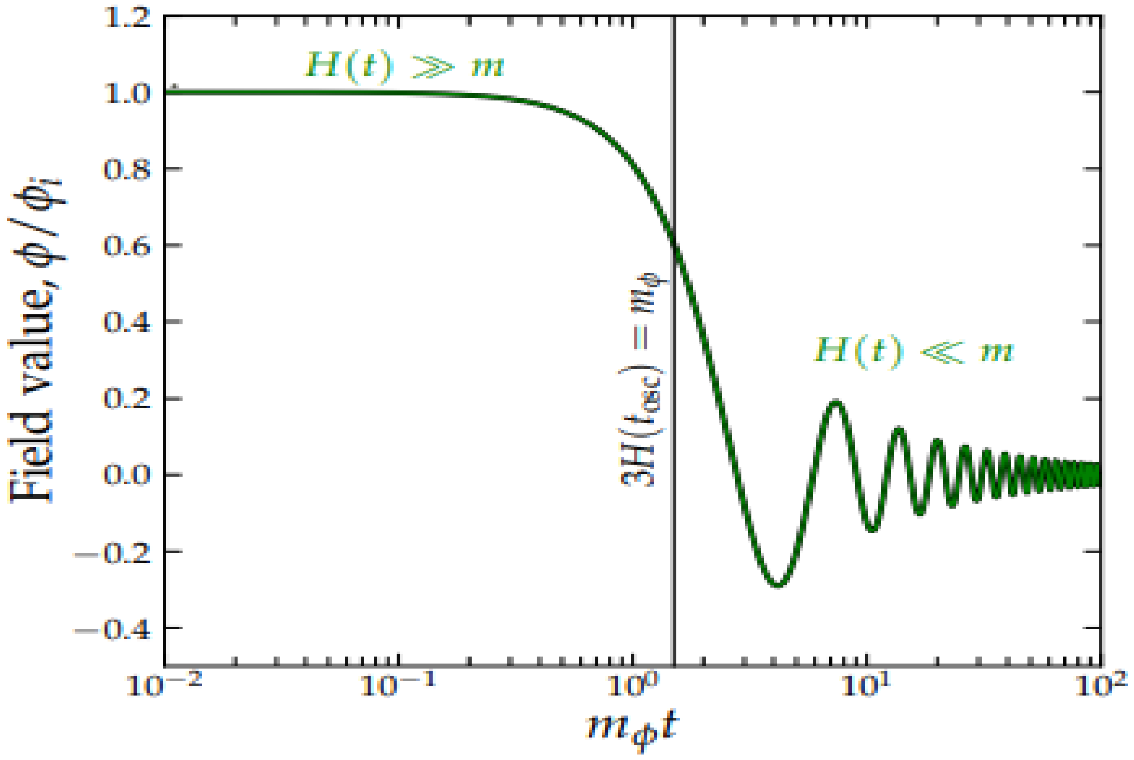
ULDM Motivations

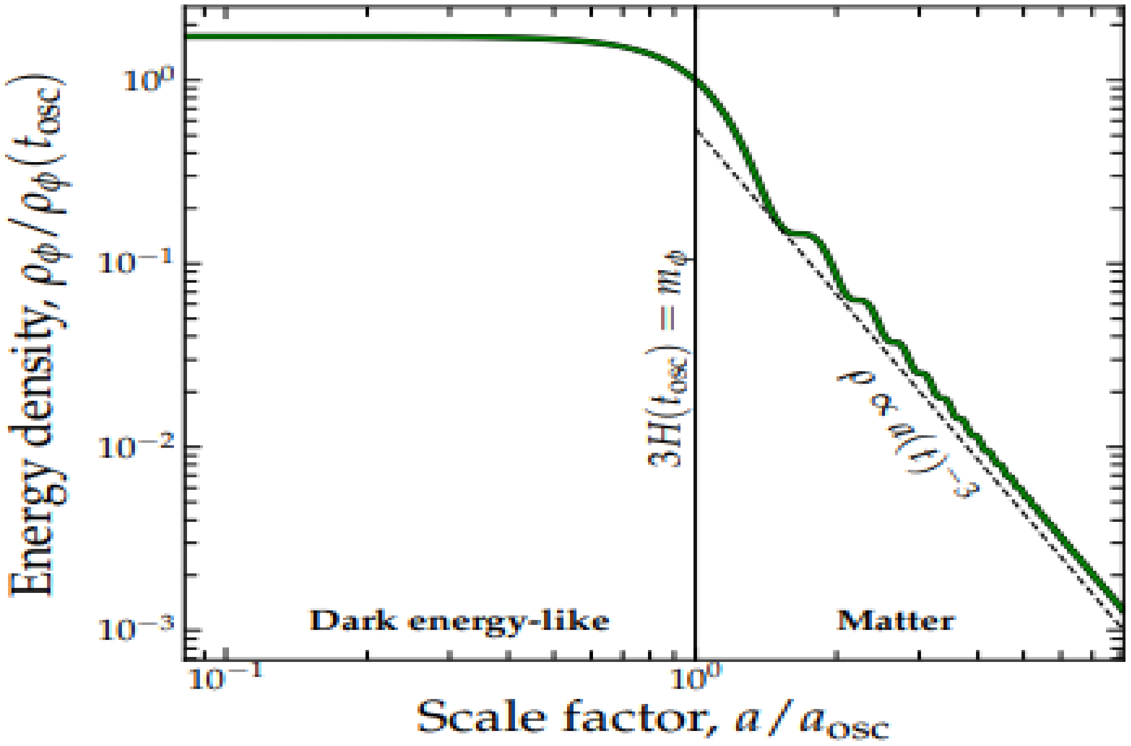
- Isotropic and homogeneous expanding universe

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

$$m_a > H$$

ULDM starts to oscillate with a frequency equal to its mass

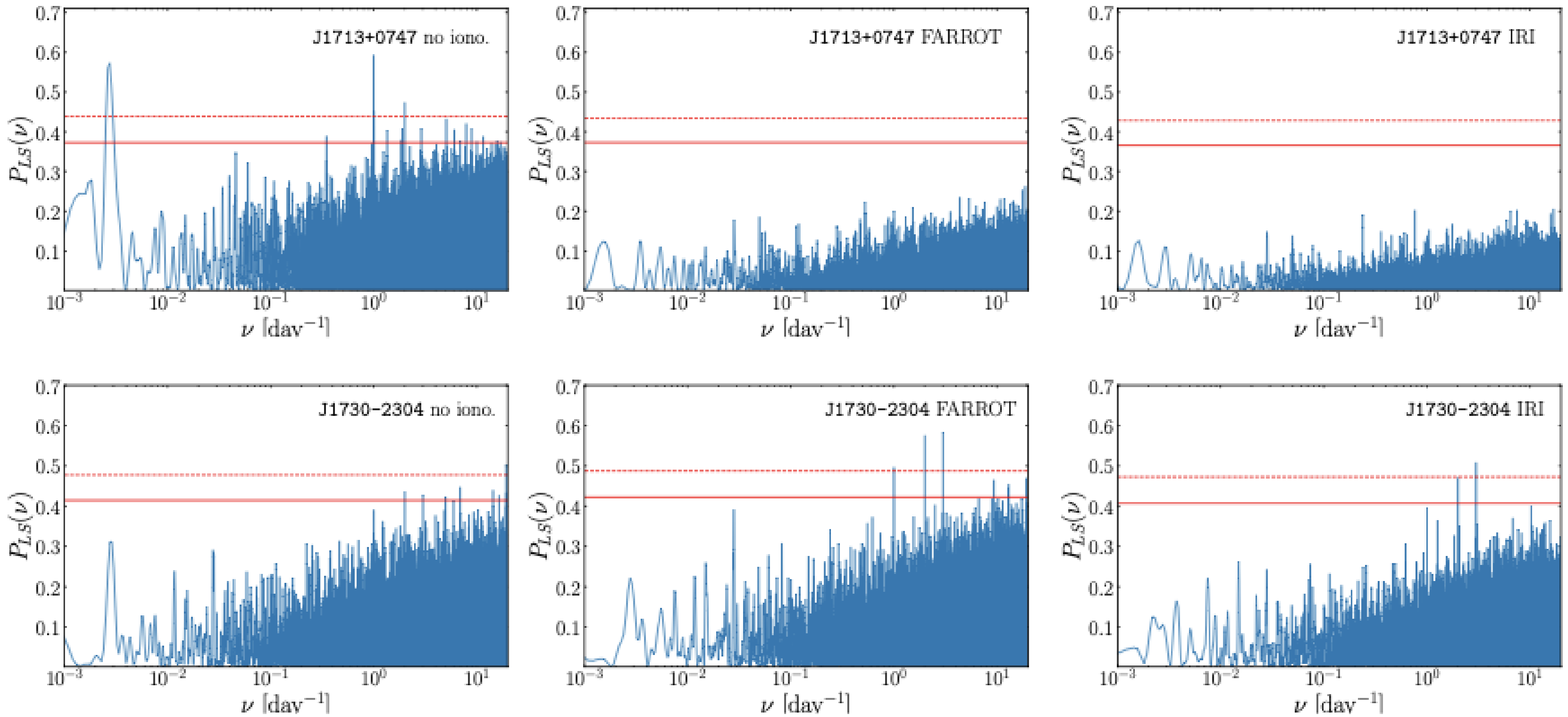




Ionospheric corrections

FARROT: 3 Chapmann Layers
Solar flux from DRAO

IRI: URSI model, F2 ionospheric layer, geomagnetic Ap index



*Both use Field2 to include the effects from Earth's magnetic field

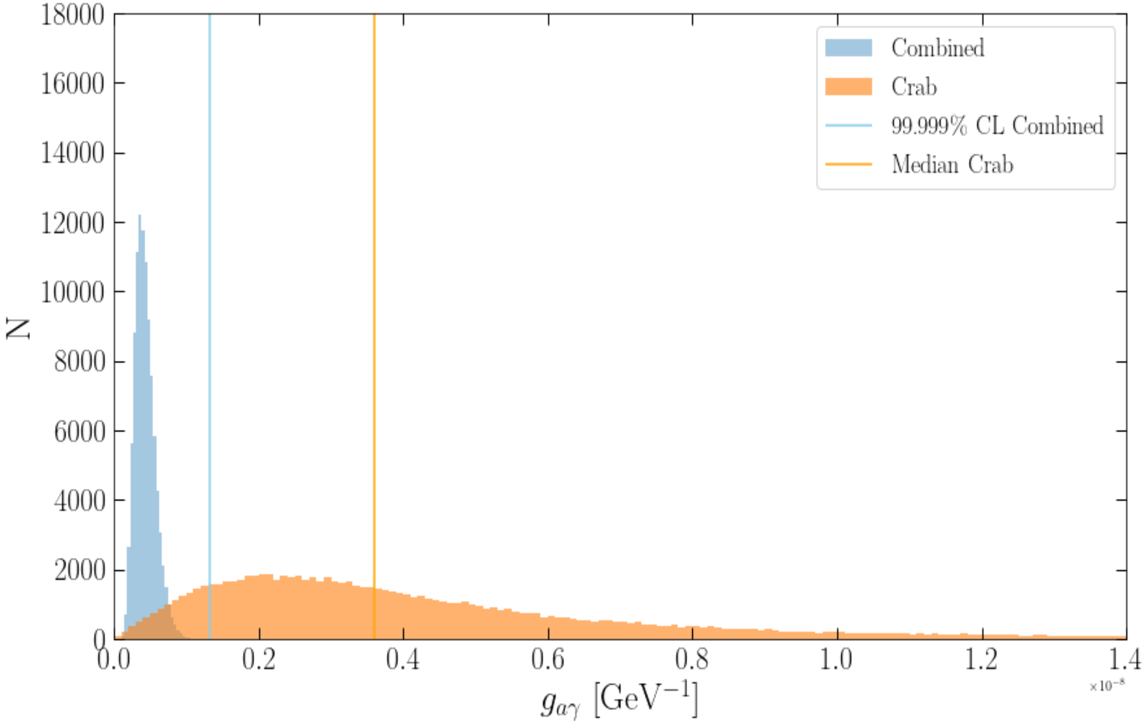
Stochastic vs deterministic: Toy MCs

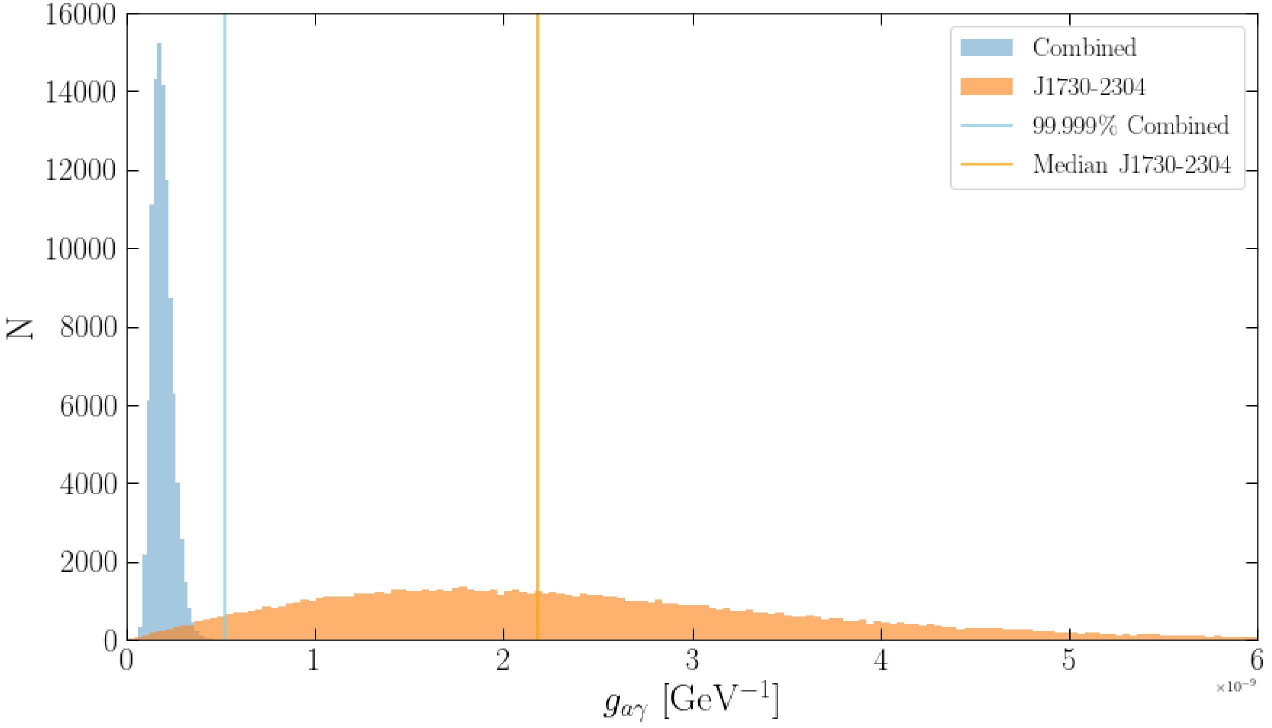
	Stochastic scenario	Deterministic scenario
Homogeneous	$\phi_a^{\rm hom} = \frac{g_{a\gamma}}{\sqrt{2}m_a}\rho_{\rm DM}^{1/2}\left(\alpha_o^2 + \alpha_s^2 - 2\alpha_o\alpha_s\cos\Delta\right)^{1/2}$	$\phi_a^{\rm hom} = \frac{g_{a\gamma}}{m_a}\rho_{\rm DM}^{1/2}\left(1 - \cos\Delta\right)^{1/2}$
Overdense	$\phi_a^{\rm over} = \frac{g_{a\gamma}}{\sqrt{2}m_a}\rho_{\rm DM}^{1/2}\alpha_s.$	$\phi_a^{\rm over} = \frac{g_{a\gamma}}{\sqrt{2}m_a}\rho_{\rm DM}^{1/2}.$

N_s	1	2	3	4	5	10	25	100
Homogeneous	2.60	1.30	1.16	1.13	1.12	1.12	1.12	1.11
Overdense	0.56	0.91	1.05	1.14	1.19	1.33	1.44	1.52

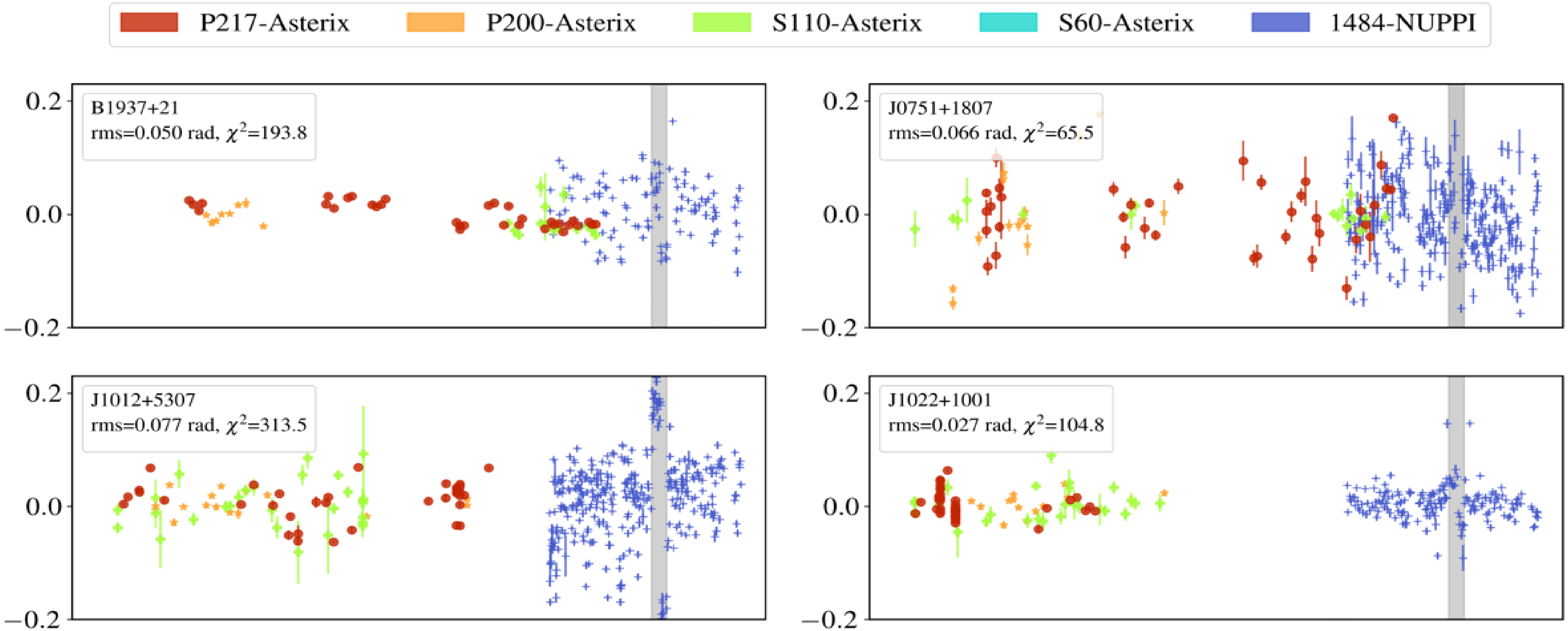
95% CL $g_{a\gamma}^{det}/g_{a\gamma}^{sto}$

Limits over possible axionic-harmonic signals





Polarization angle in brightest EPTA pulsars



Polarization angle in brightest EPTA pulsars