Probing light dark matter with pulsar experiments

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**Pollica Workshop
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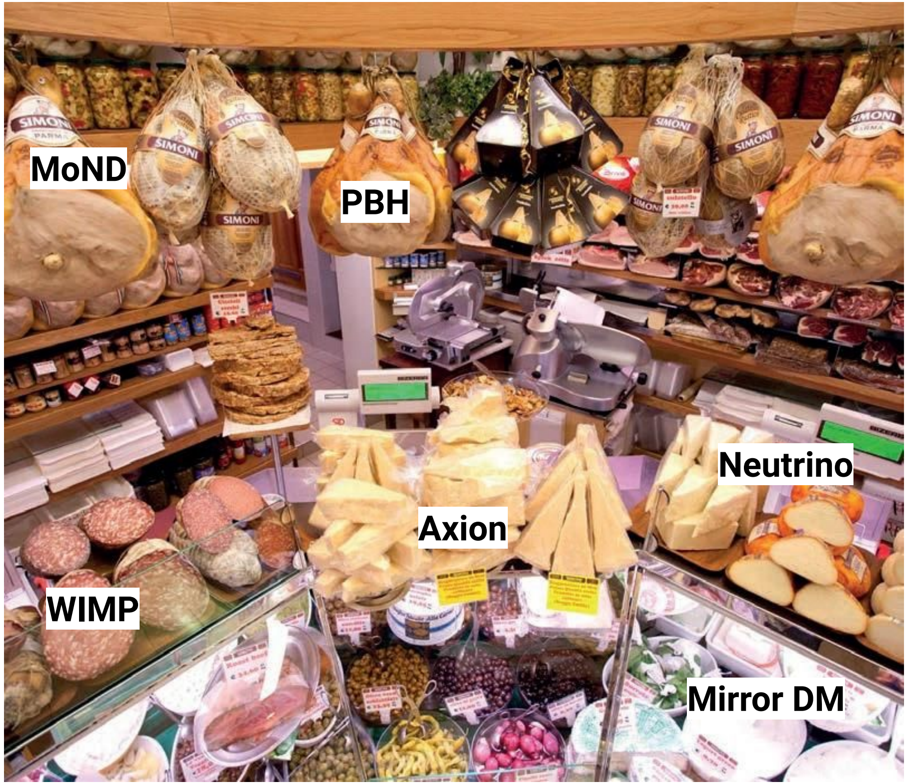
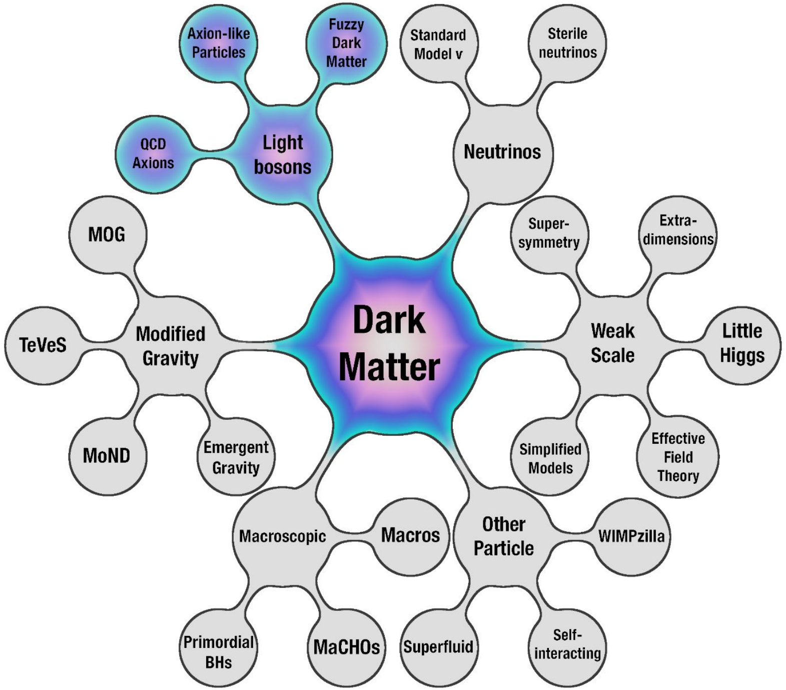
Dark Matter for every taste



Credit: https://www.paginegialle.it/



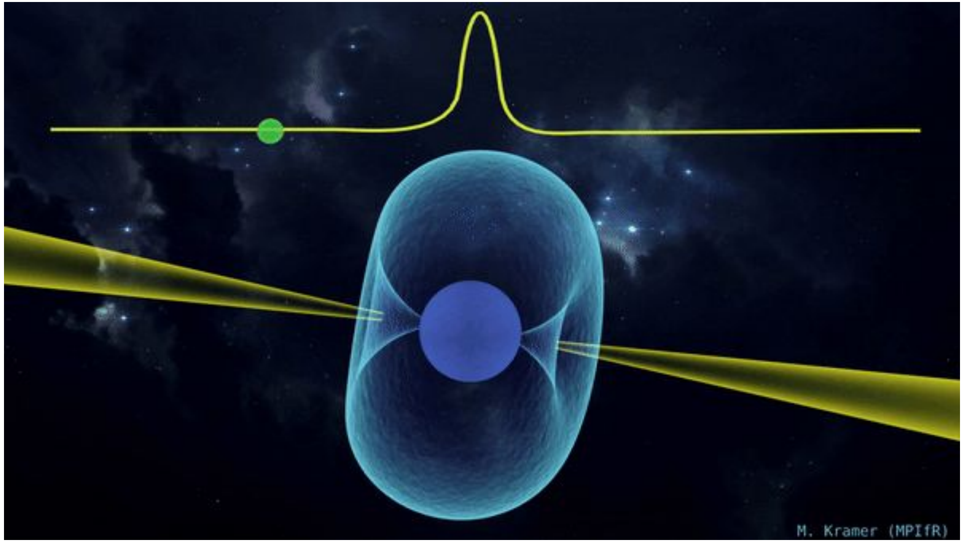
Credit: G. Bertone and T. Tait

Pulsars in a nutshell

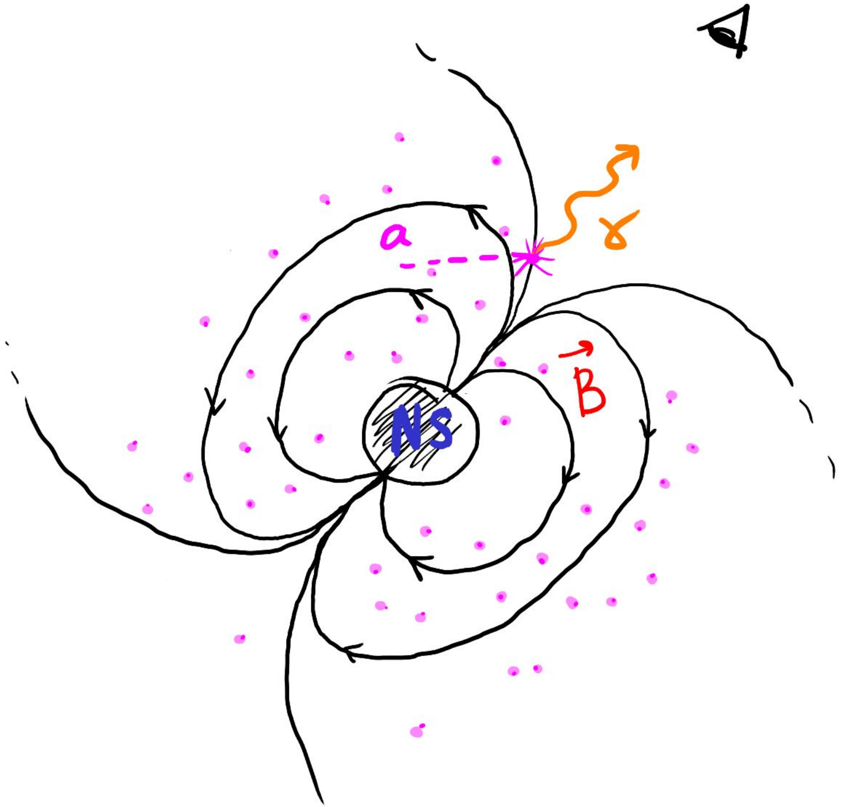
Pulsars are rapidly spinning neutron stars, which are:

- Stable rotators ("Galactic clocks")
- Highly magnetised $\sim 10^8 - 10^{15}\mathrm{G}$
- Broad-band and linearly polarised radiation

Credit: Michael Kramer



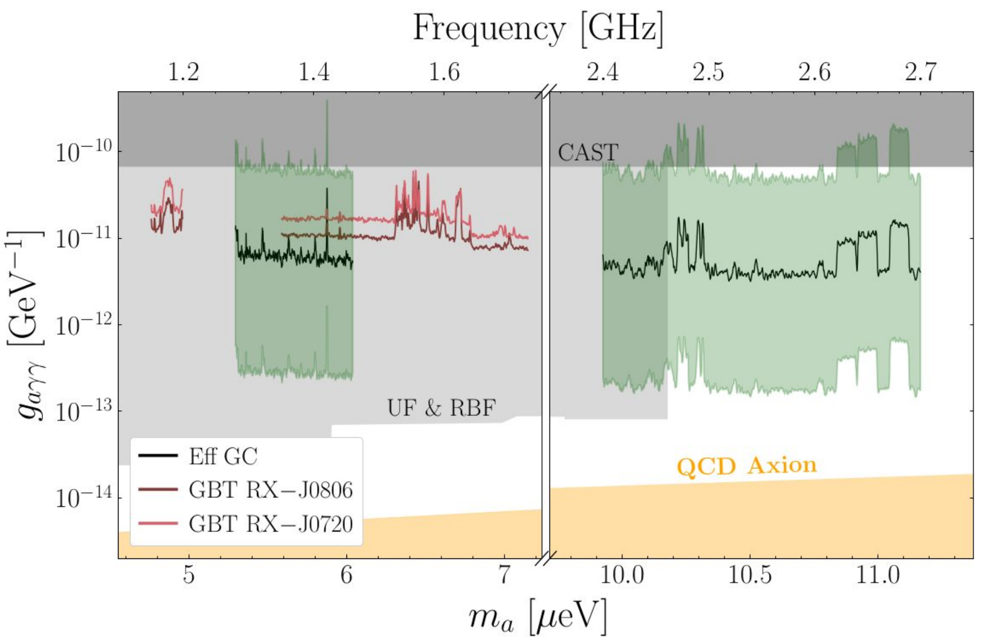
I. QCD axions with pulsar spectroscopy



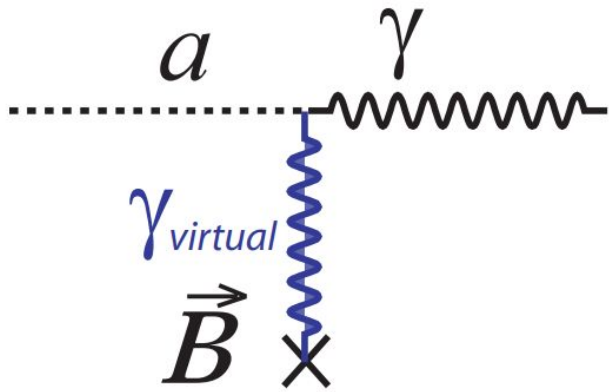
QCD axions in magnetosphere of pulsars:

1. **Primakoff effect (1951)**: axions are spontaneously converted to photons
2. **Frequency** of the resultant photon is unambiguously **defined by the mass** of the QCD axion
3. **Sharp line in the flux spectrum** of a pulsar

I. QCD axions with pulsar spectroscopy



$$\frac{d\mathcal{P}(\theta=\frac{\pi}{2},\theta_m=0)}{d\Omega} \approx 4.5\times 10^{8}\ \mathrm{W}\left(\frac{g_{a\gamma\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{r_0}{10\ \mathrm{km}}\right)^2 \left(\frac{m_a}{1\ \mathrm{GHz}}\right)^{5/3} \left(\frac{B_0}{10^{14}\ \mathrm{G}}\right)^{2/3} \left(\frac{P}{1\ \mathrm{sec}}\right)^{4/3} \left(\frac{\rho_\infty}{0.3\ \mathrm{GeV/cm^3}}\right) \left(\frac{M_{\mathrm{NS}}}{1\ M_\odot}\right) \left(\frac{200\ \mathrm{km/s}}{v_0}\right),$$



Pshirkov, Popov 2008, Foster et al. 2020, Zioutas et al. 2009

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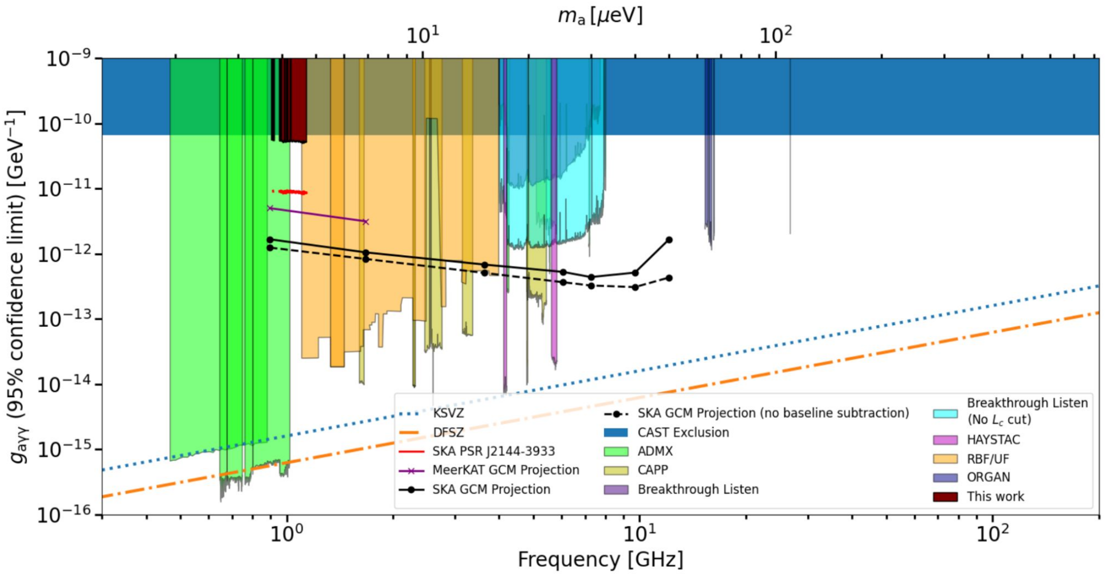
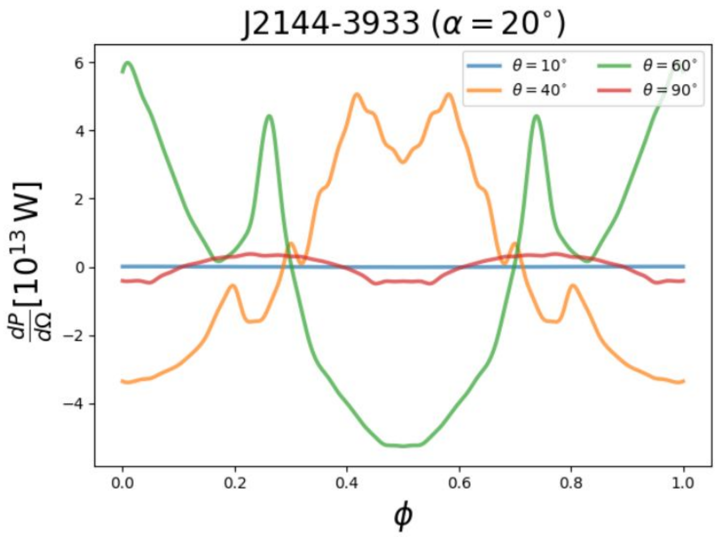




Battye et al. 2023

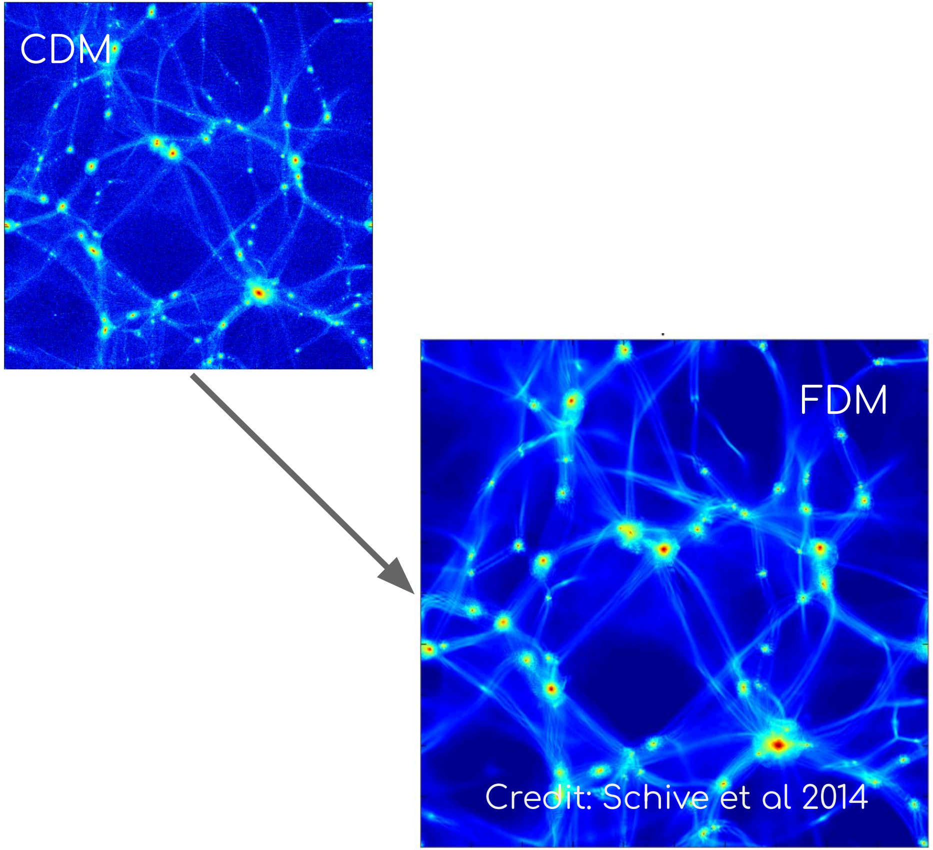
II. ULDM probes through timing data

Ultra-light axion dark matter:

1. **Very light axions** with masses ranging between 10^{-23} and 10^{-20} eV

2. **Solve some of the issues of CDM** associated with overproduction of structures at galactic and sub-Galactic scales

3. **Perturb the space-time**, so that the regular flow of pulses deviate from their regular flow



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Scalar field ansatz:
$\varphi(x,t) = A(x)\cos(mt + \alpha(x))$

Energy-momentum tesnsor:

$$T_{\mu\nu} = \partial_\mu\varphi\partial_\nu\varphi - \frac{1}{2}g_{\mu\nu}\left((\partial\varphi)^2 - m^2\varphi^2\right)$$

To the first order of v/c:

$$T_{\mu\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & \\ 0 & 0 & 0 & p \end{pmatrix} \quad g_{\mu\nu}(t) = \begin{pmatrix} 2\Phi(t) & 0 & 0 & 0 \\ 0 & -2\Psi(t) & 0 & 0 \\ 0 & 0 & -2\Psi(t) & 0 \\ 0 & 0 & 0 & -2\Psi(t) \end{pmatrix}$$

The final experssion of the signal in the residuals:

$$R(t) = r(x_E, t_E) - r(x_p, t_p), \quad r(x_E, t_E) = \frac{\Psi(x_E)}{2\pi f}\kappa(x_E)\sin(2\pi f t_E + \alpha(x_E))$$

Khmelnitsky, Rubakov 2014

II. ULDM probes through timing data

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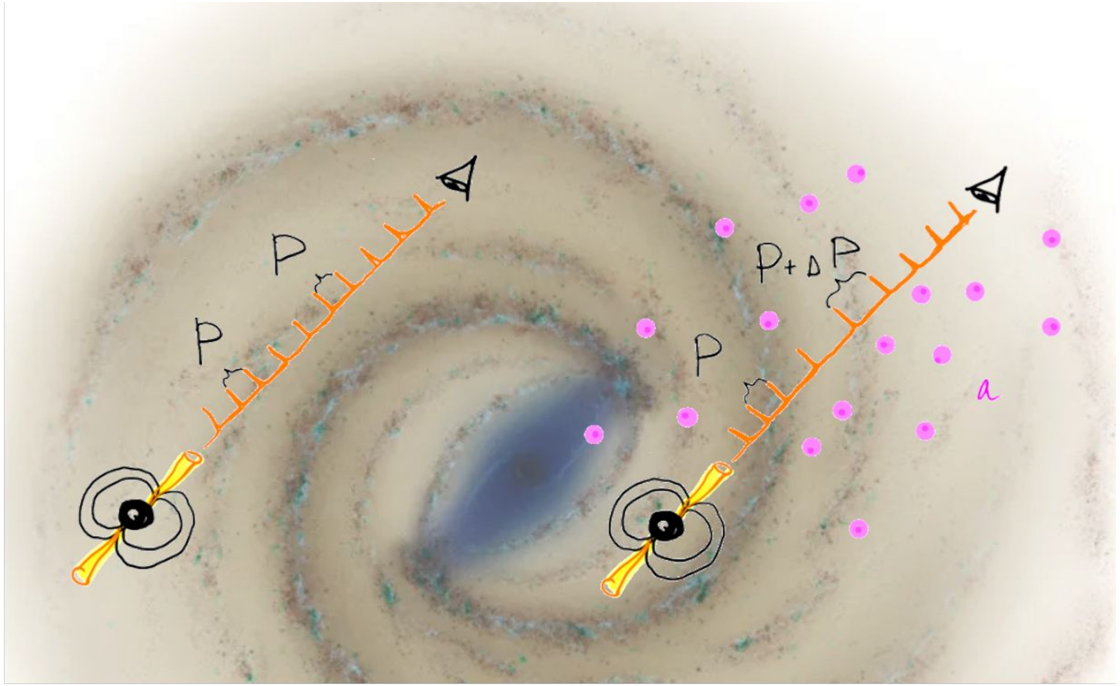

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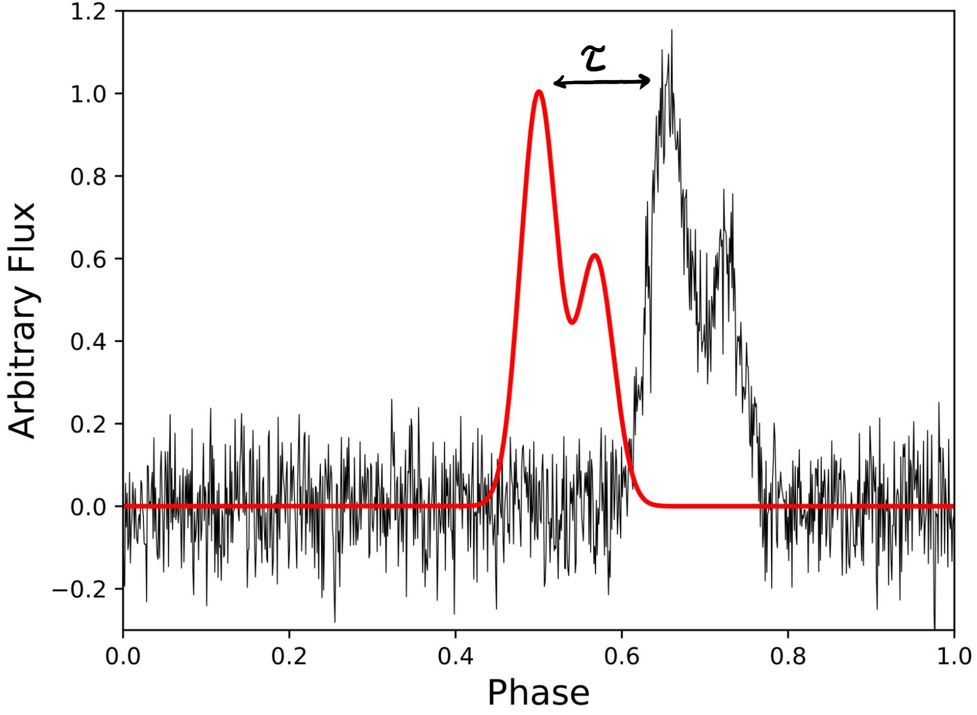

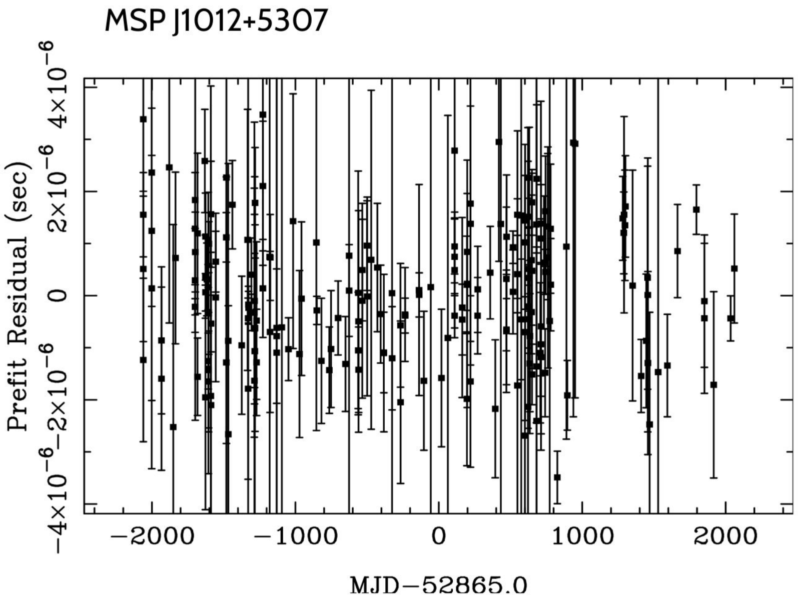

II. ULDM probes through timing data

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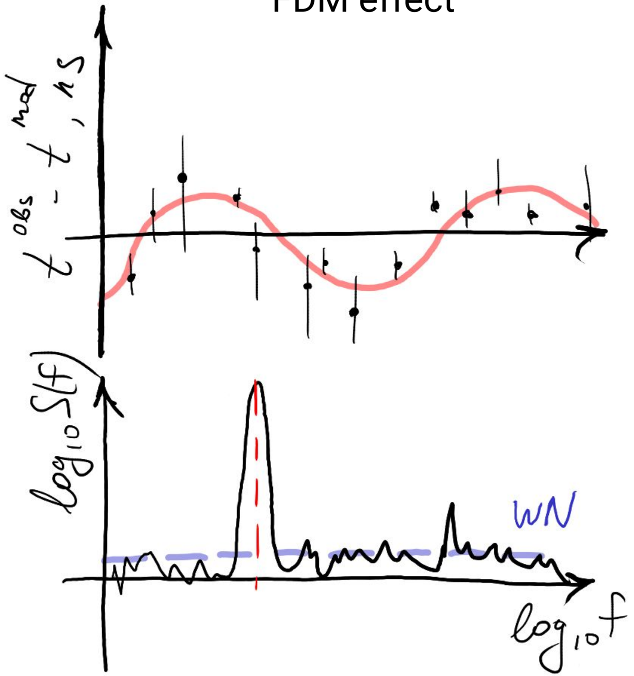
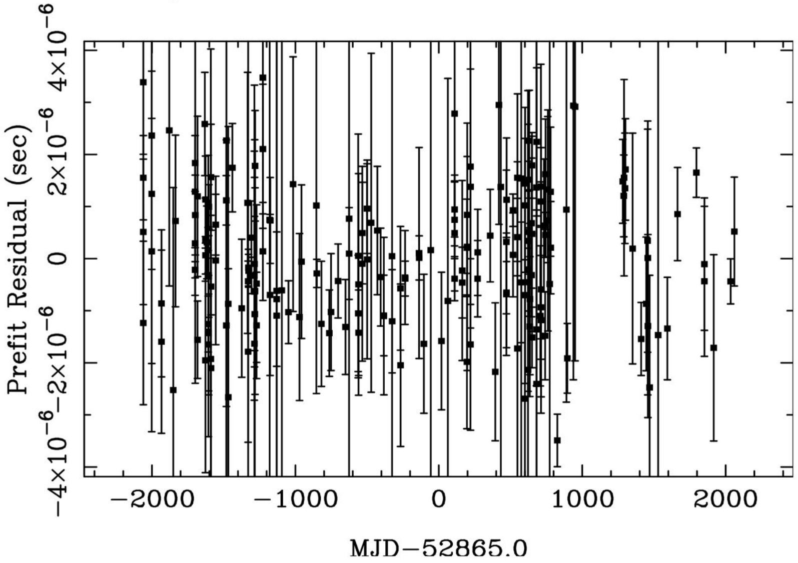
FDM effect



MSP J1012+5307



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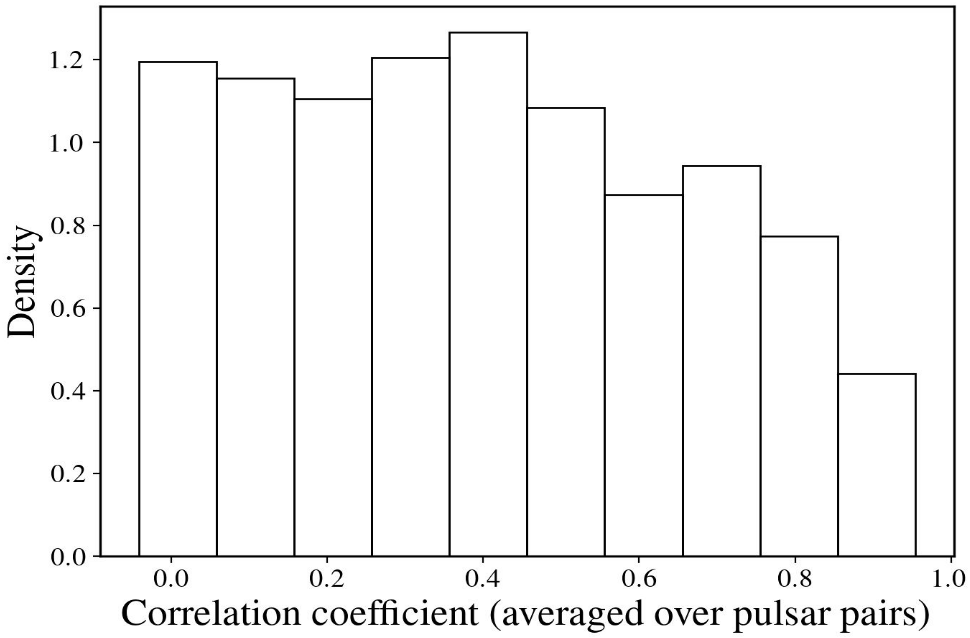

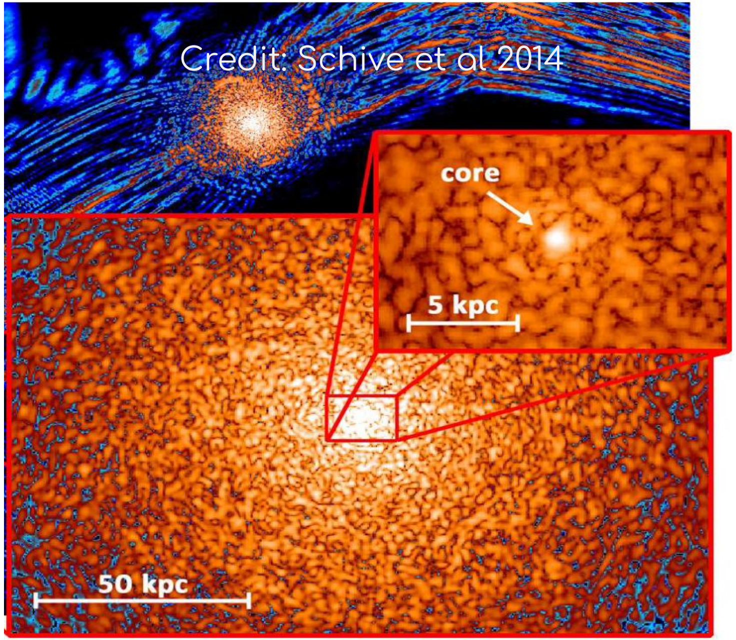

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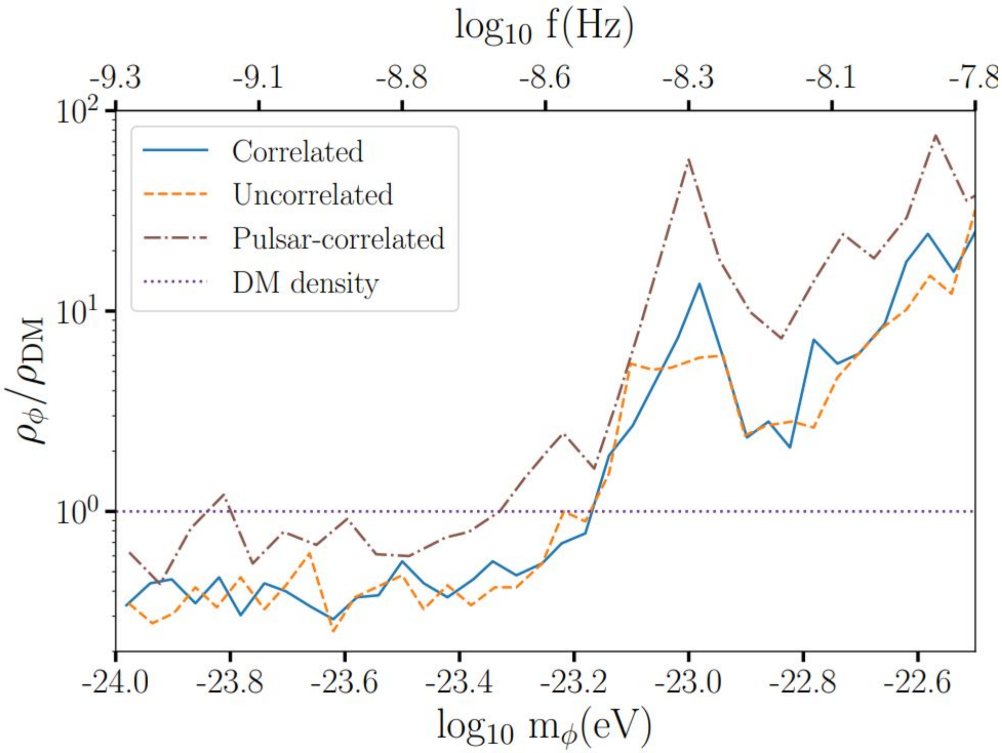
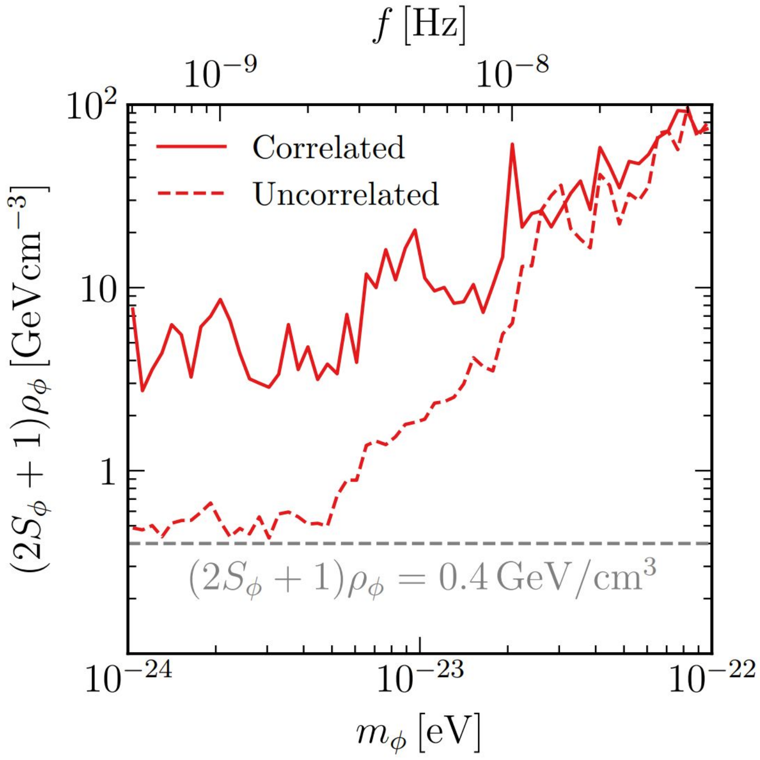
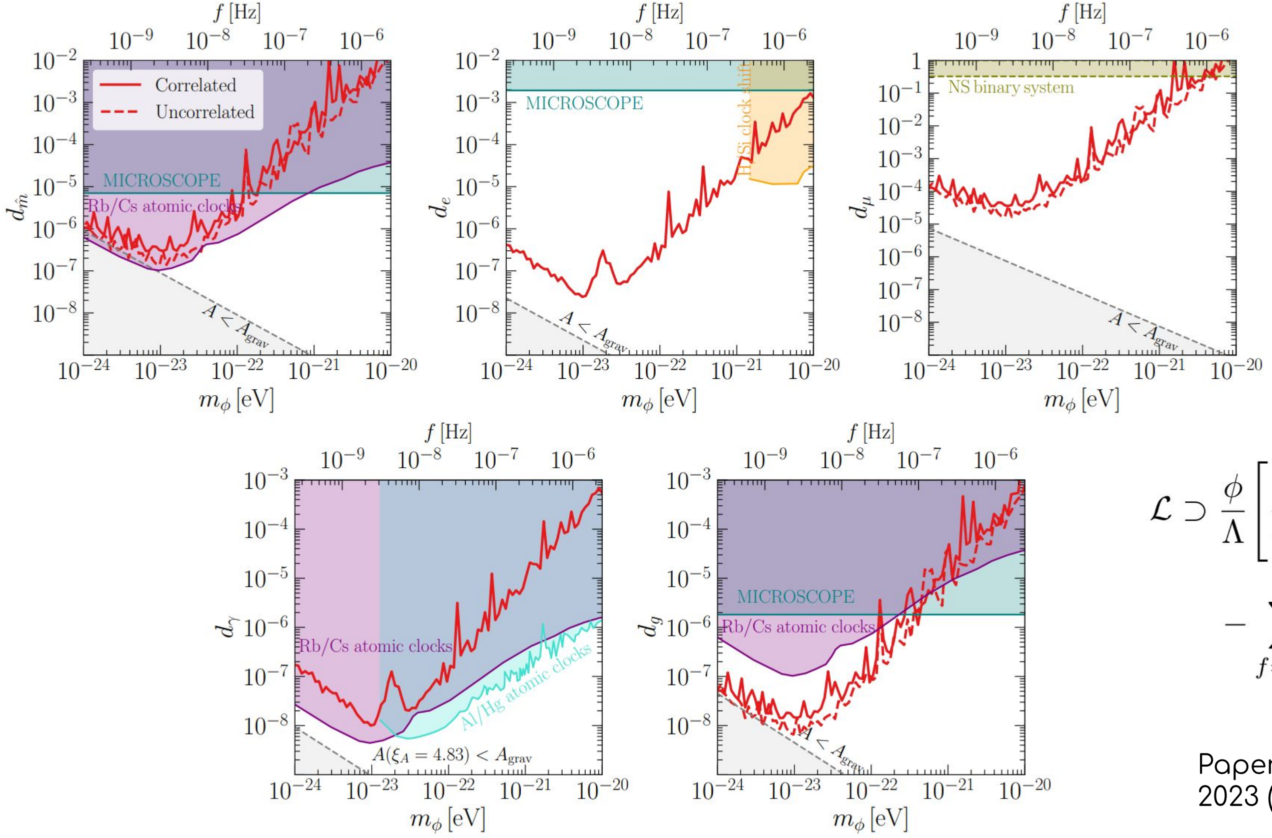


Paper VI: Smarra, Goncharov, Barausse and the EPTA Collaboration 2023



Paper V: NANOGrav Collaboration 2023 (new physics)

II. ULDM probes through timing data

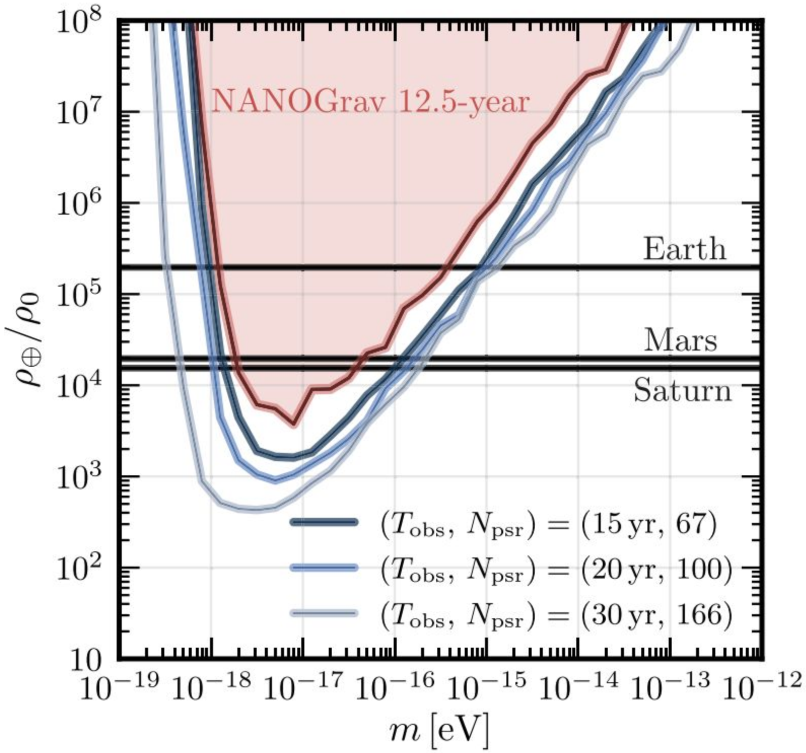


$$\mathcal{L} \supset \frac{\phi}{\Lambda}\left[\frac{d_\gamma}{4e^2}F_{\mu\nu}F^{\mu\nu} + \frac{d_g\beta_3}{2g_3}G^A_{\mu\nu}G^{\mu\nu}_A - \sum_{f=e,\mu} d_f m_f \bar{f}f - \sum_{q=u,d}(d_q + \gamma_q d_g)m_q\bar{q}q\right]$$

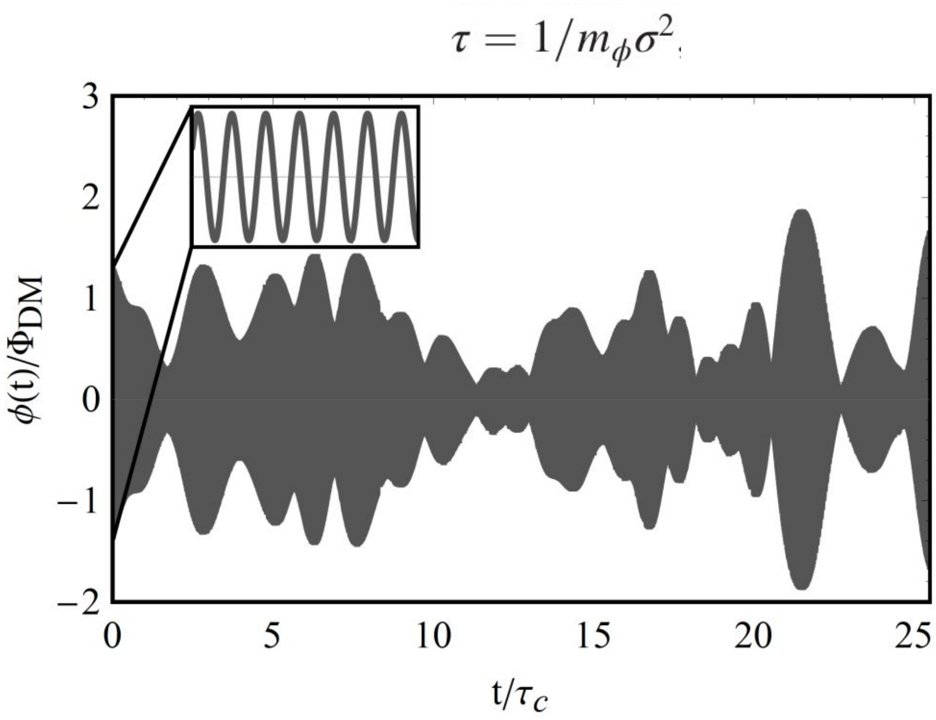
Paper V: NANOGrav Collaboration 2023 (new physics)

Extending limits to larger axion masses

Kim and Mitridate 2024



Centers et al. 2020



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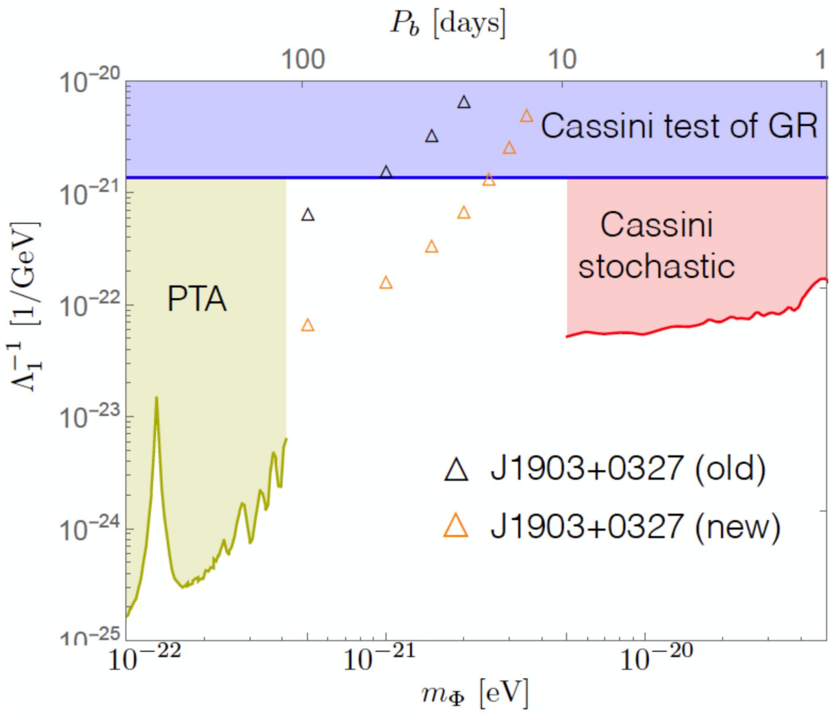
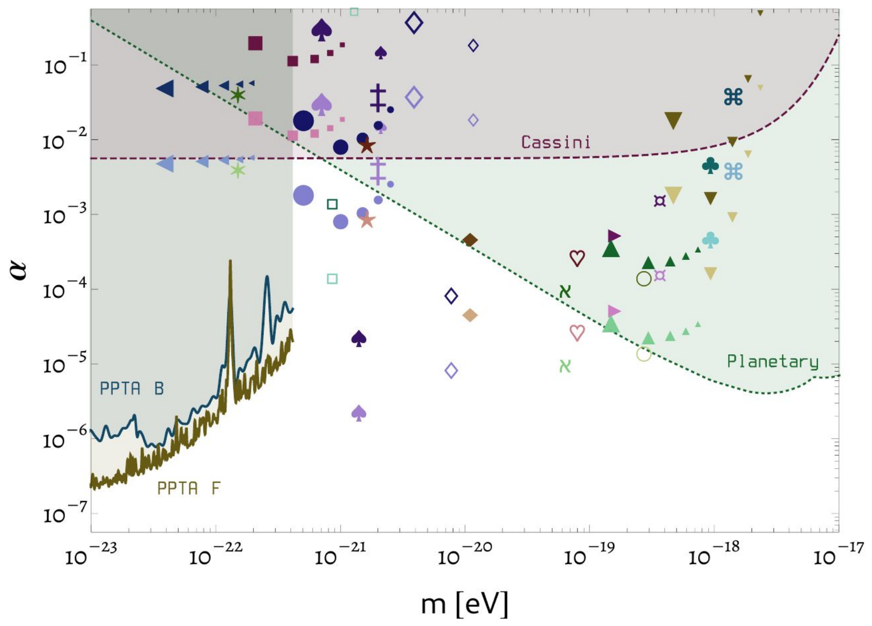


Credit: Blas et al 2020, Heusgen et al., in prep.

Spin-2 axionic DM



Credit: Armaleo et al., 2020

III. ULDM with pulsar polarimetry

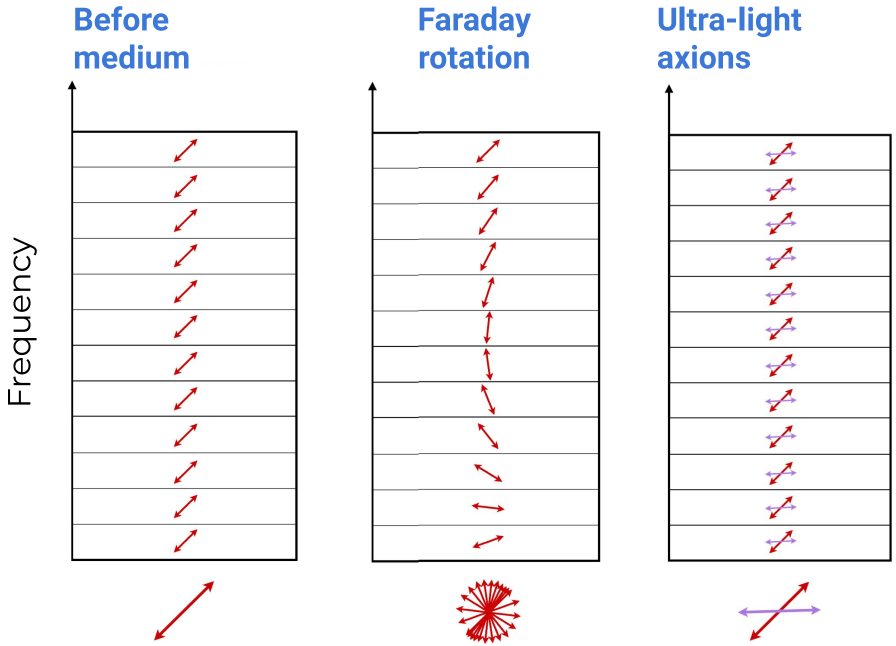
If assume non-renormolizable interaction between fuzzy DM particles and photons:

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

$$(\Box + m_a^2)a + \frac{g_{a\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} = 0$$

Polarization properties of light are altered

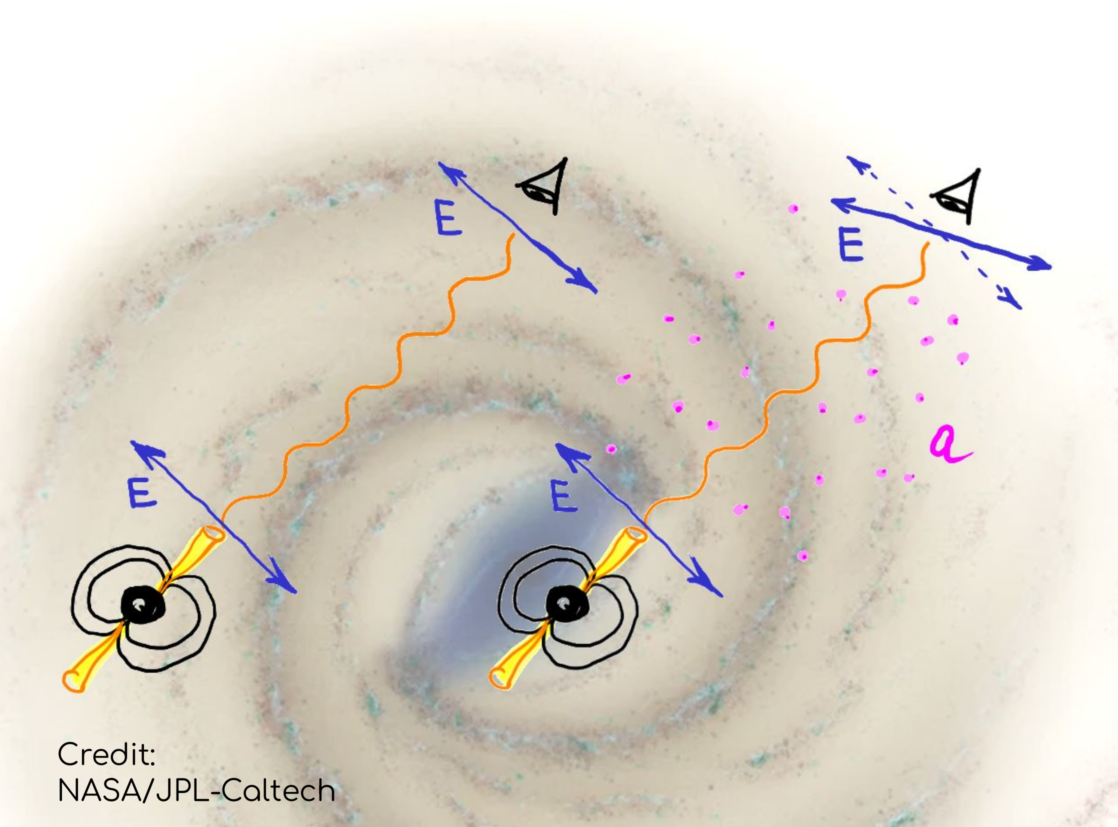
$$\omega_\pm = k\sqrt{1 \pm g_{a\gamma}\frac{\partial_0 a}{k}} \simeq k \pm \frac{1}{2}g_{a\gamma}\partial_0 a$$



$$\Delta(\mathrm{PA}(t)) = \frac{g_{a\gamma}}{\sqrt{2}m}[\mathrm{p}(t_E, x_E) - \mathrm{p}(t_p, x_p)], \quad p(t_E, x_E) = \sqrt{\rho_{\mathrm{DM}}}\kappa_E \cos(mt + \phi(x_E))$$

See: Ivanov et al 2018, Castillo et al 2022

III. ULDM with pulsar polarimetry



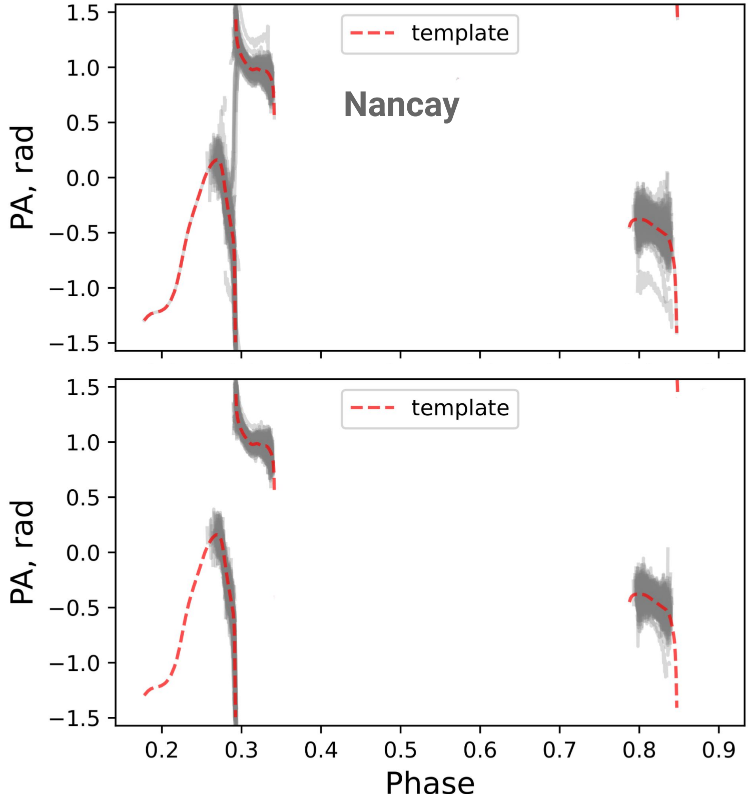
Ultra-light axions in the Milky Way:

1. **Very light axions** with masses ranging between 10^{-23} and 10^{-20} eV

2. When interacting weakly with photons, **rotate the plane** of linearly polarised pulsar light

3. Plane of linear polarisation **oscillates with periods of several years** due to varying pressure

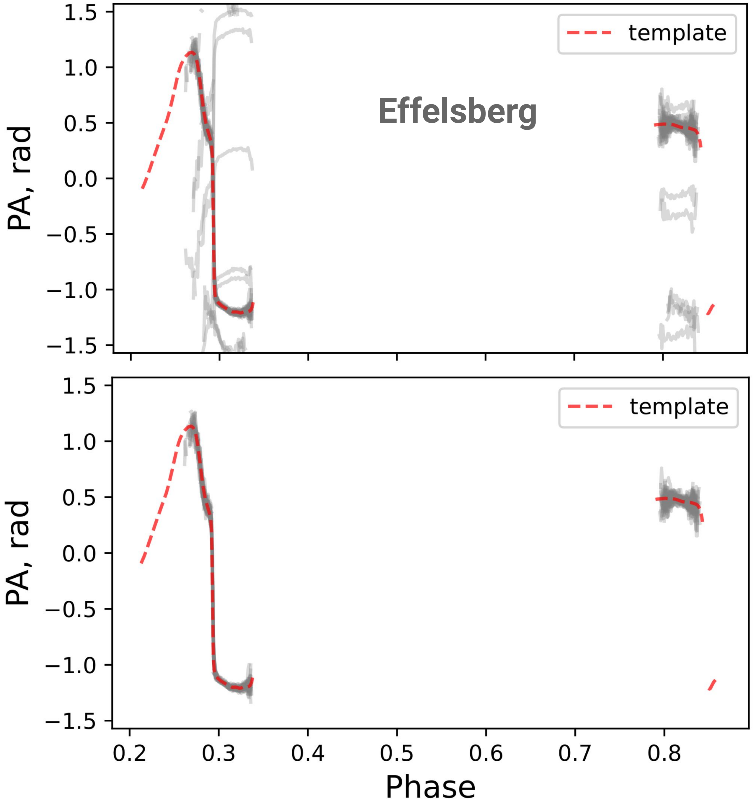
II. ULDM with pulsar polarimetry: challenges



B1937+21

All PA profiles

Manually selected PA profiles



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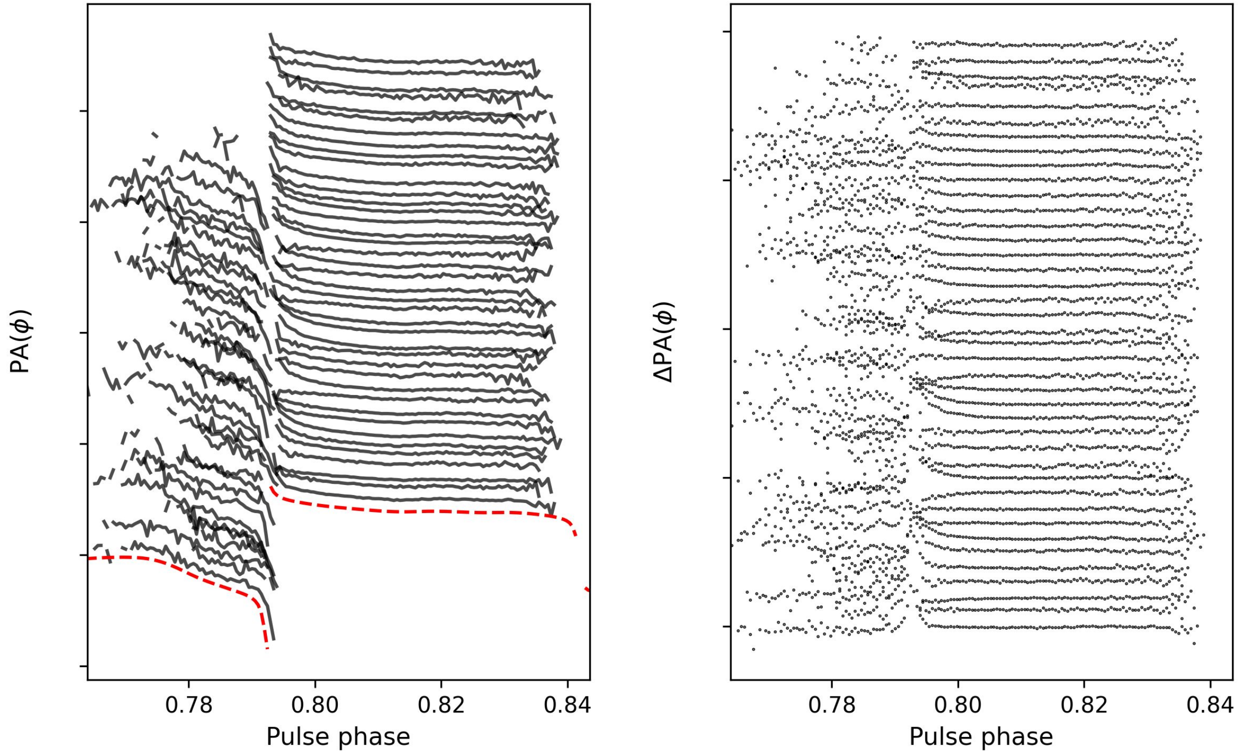
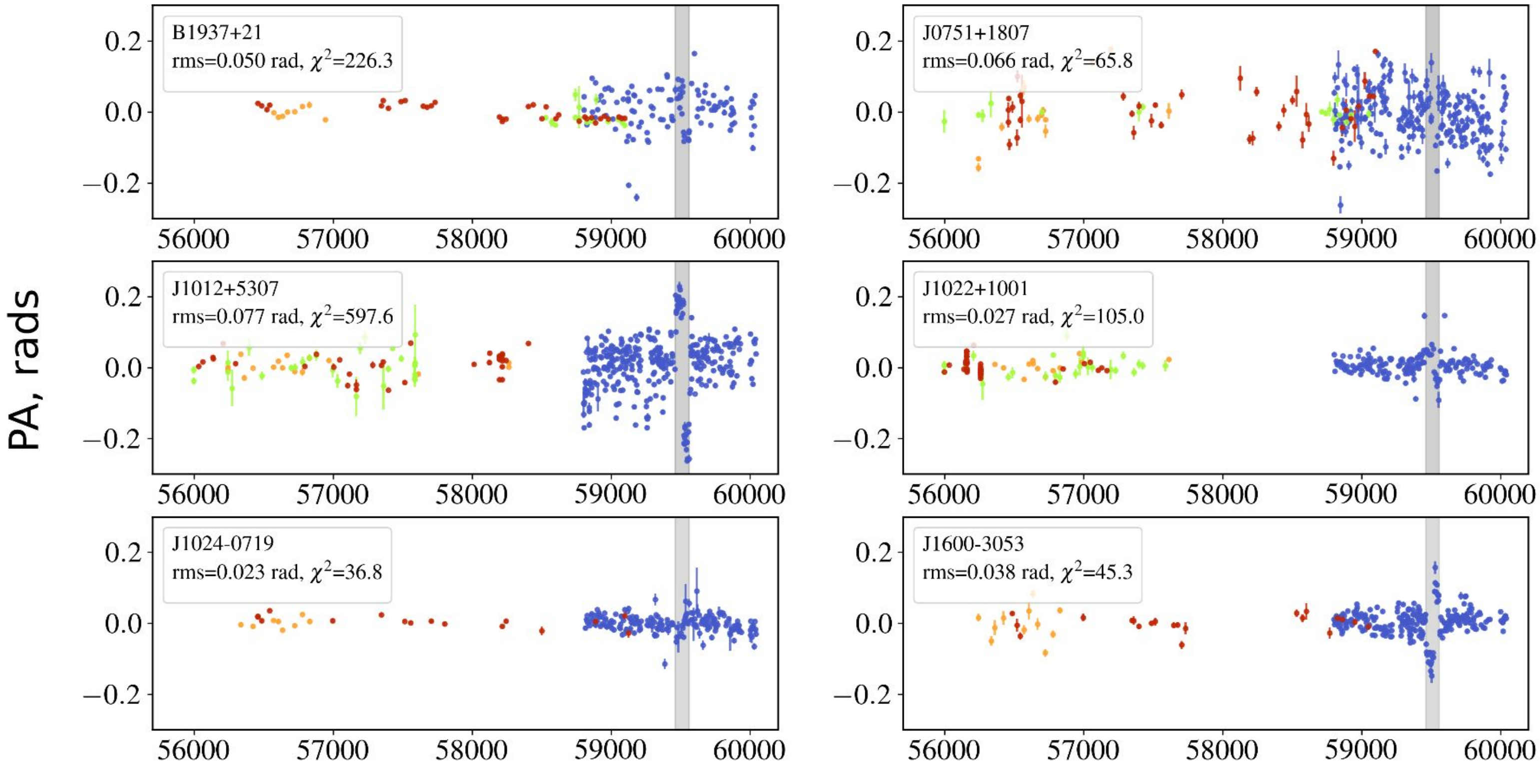


III. ULDM with pulsar polarimetry: dataset



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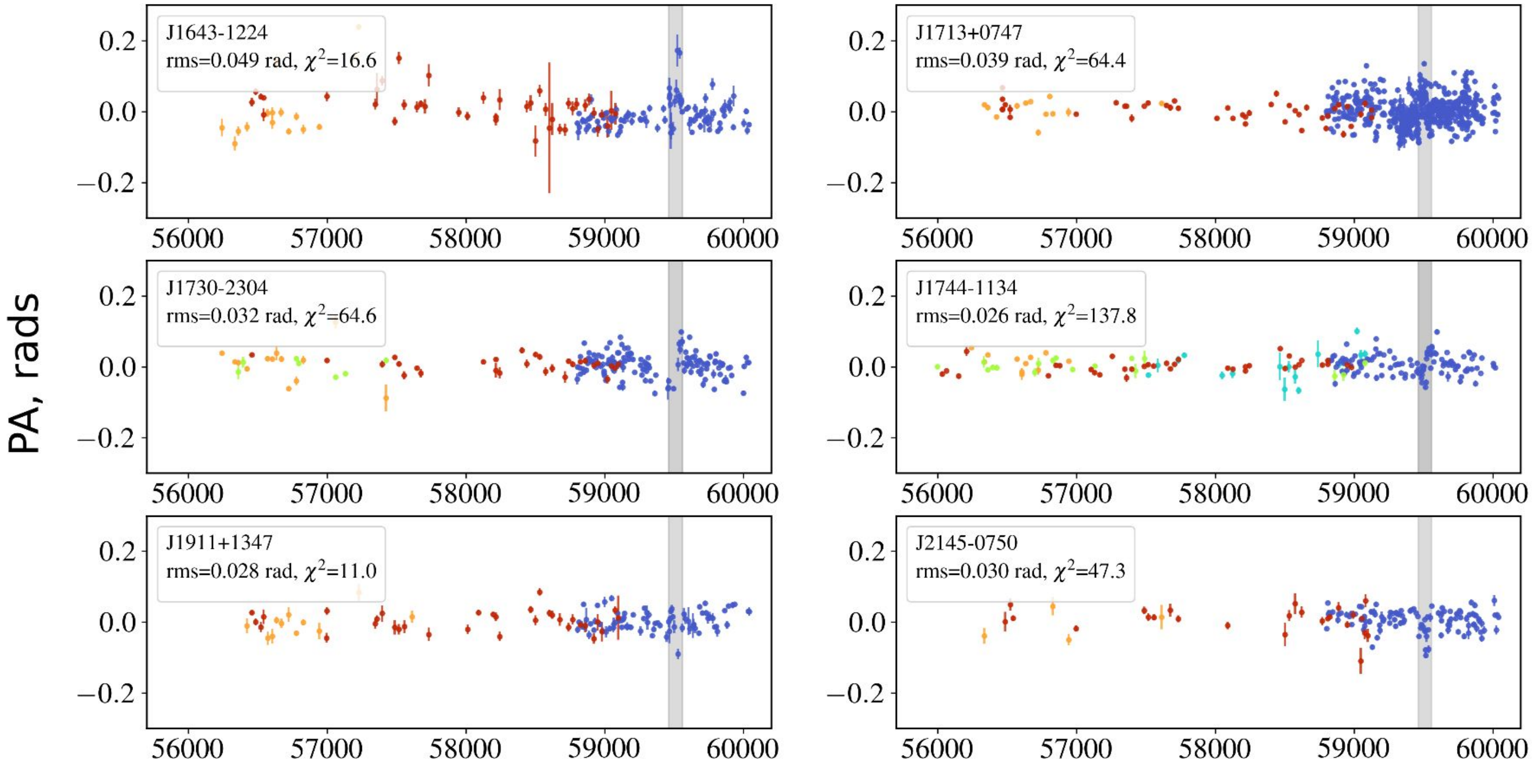
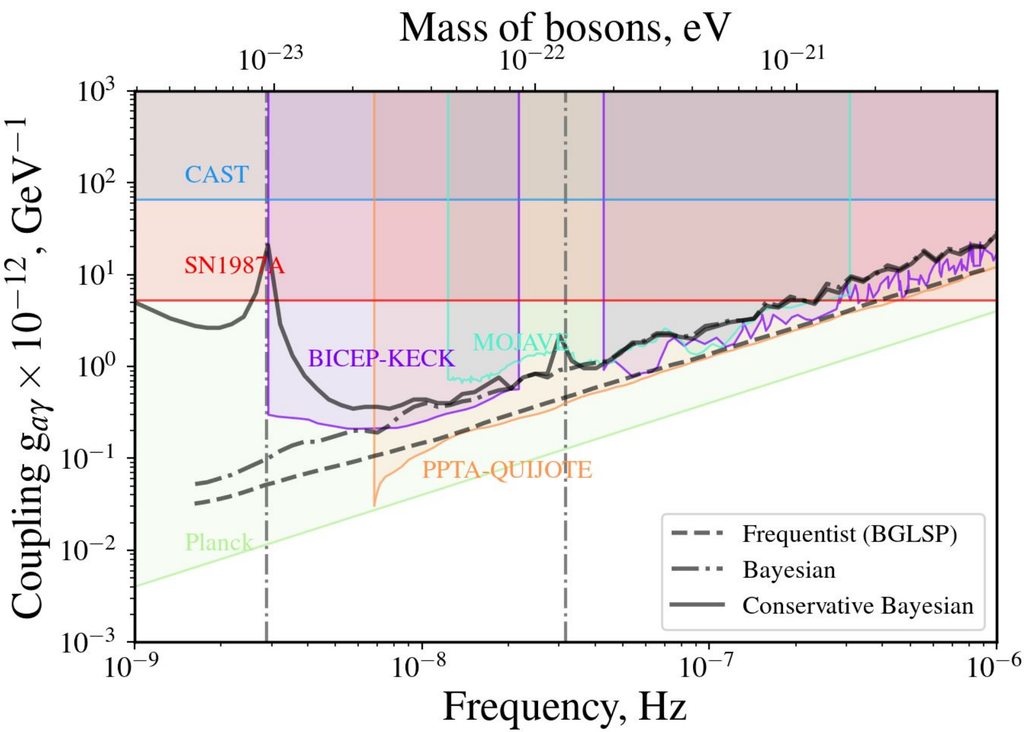


III. ULDM with pulsar polarimetry: first results



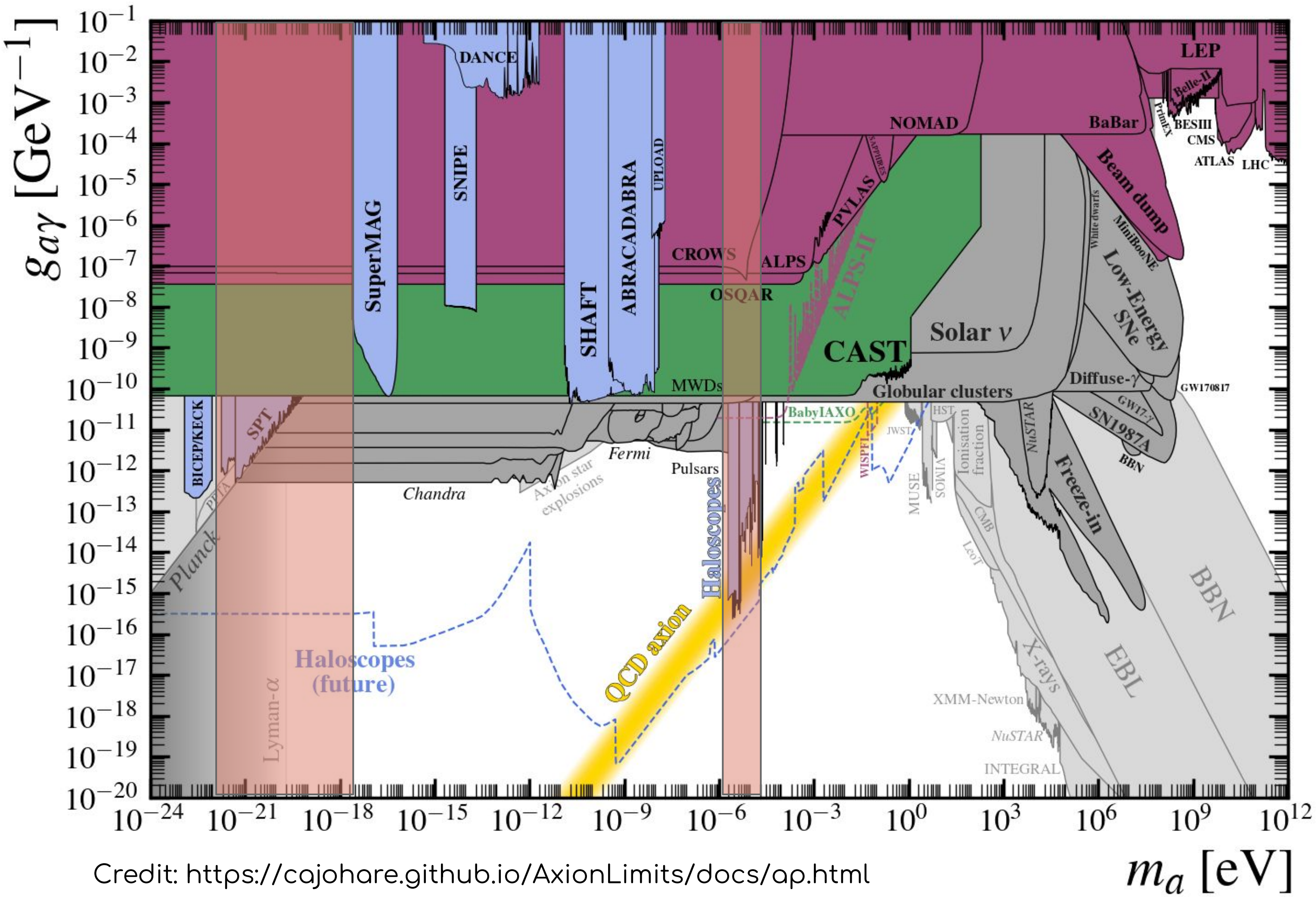
Porayko et al. (in prep.)

Ultra-light axions in the Milky Way:

3. The **effect is achromatic**, so can be distinguished from chromatic Faraday rotation

4. **Terrestrial ionosphere** is the main source of noise, when searching for ultra-light axions in pulsar polarimetry

5. We plan to incorporate **low-frequency data** from LOFAR(2.0) to independently mitigate ionospheric Faraday rotation



Credit: https://cajohare.github.io/AxionLimits/docs/ap.html