Chasing dark matter with pulsar experiments

Nataliya K. Porayko

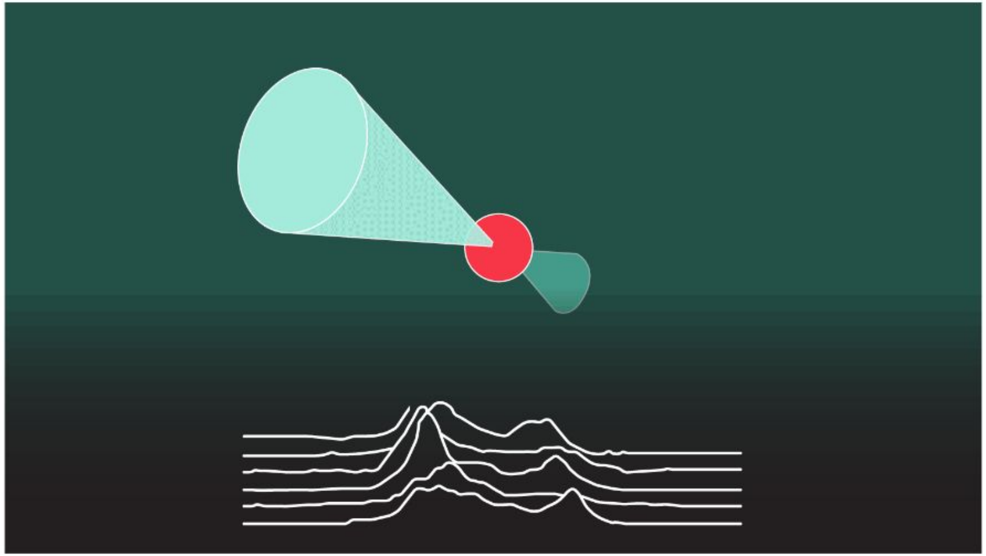
on behalf of the EPTA

Pulsars in a nutshell

Pulsars are neutron stars, which are:

- Rapidly spinning. Periods:

  from few ms to several seconds
- Highly magnetised $\sim 10^8 - 10^{15}\mathrm{G}$
- Extremely dense: $\rho > 10^{14}\mathrm{g/cm^3}$
- Linearly polarised synchrotron radiation
- Stable rotators ("Galactic clocks")



Credit: Jen Christiansen

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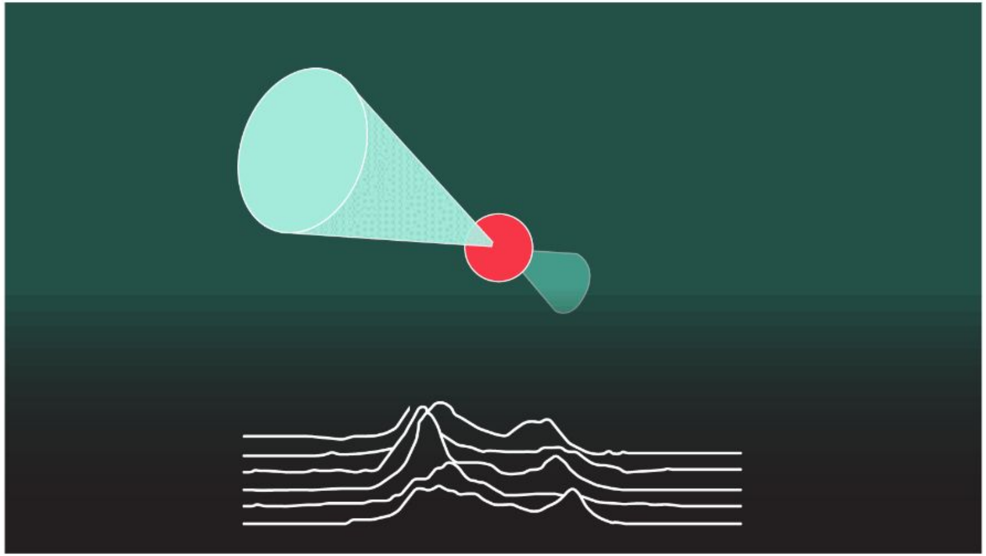
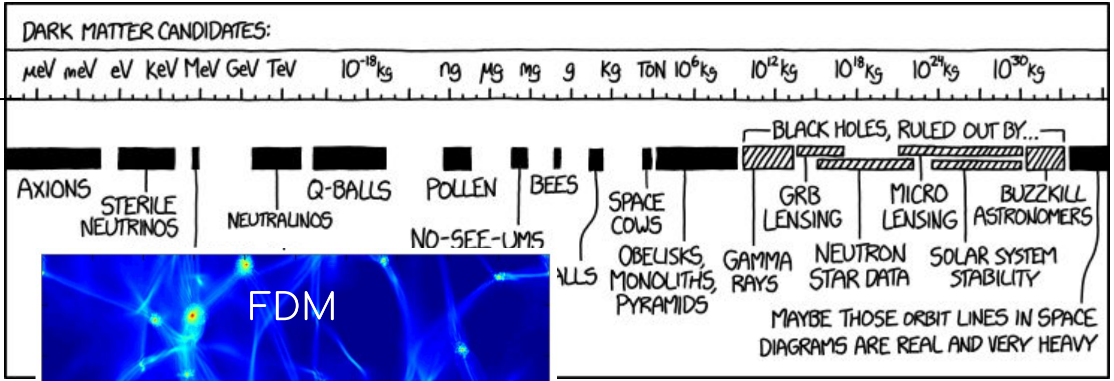


Credit: Jen Christiansen

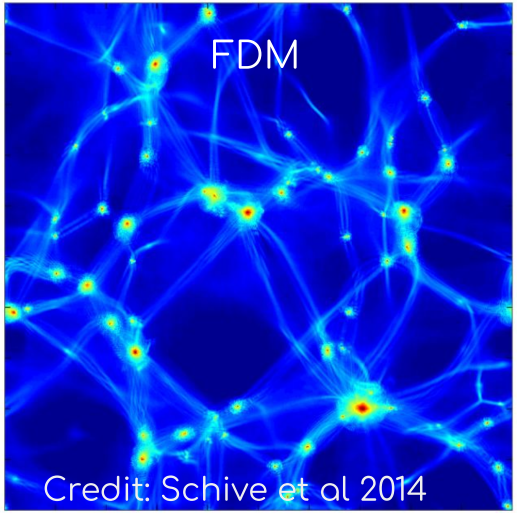
Many faces of dark matter

10^{-22}eV

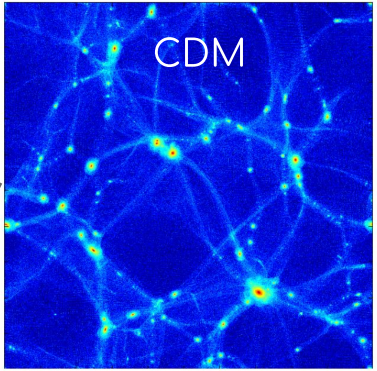


Fuzzy dark matter:

1. Formed by very light axions of masses 1e-23 - 1e-20 eV
2. Very large de Broigle length of ~10-100 pc
3. Solve some of the issues of CDM associated with overproduction of structures at galactic and sub-Galactic scales



Credit: Schive et al 2014



FDM coupled gravitationally with SM particles

Scalar field ansatz: *mass of bosons*

$$\varphi(x,t) = A(x)\cos(mt + \alpha(x))$$

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:

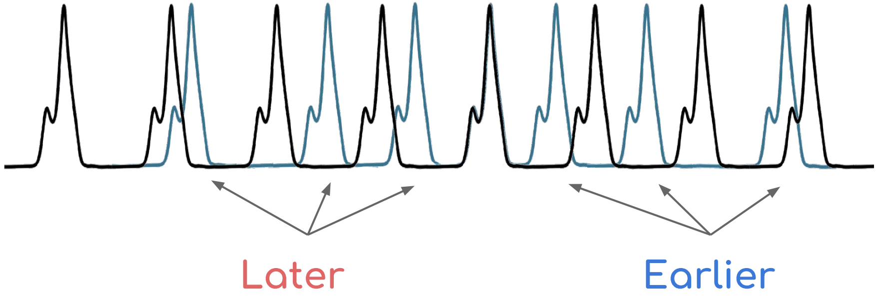
$$T_{\mu\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix} \qquad g_{\mu\nu}(t) = \begin{pmatrix} 2\Phi(t) & 0 & 0 & 0 \\ 0 & -2\Psi(t) & 0 & 0 \\ 0 & 0 & -2\Psi(t) & 0 \\ 0 & 0 & 0 & -2\Psi(t) \end{pmatrix}$$

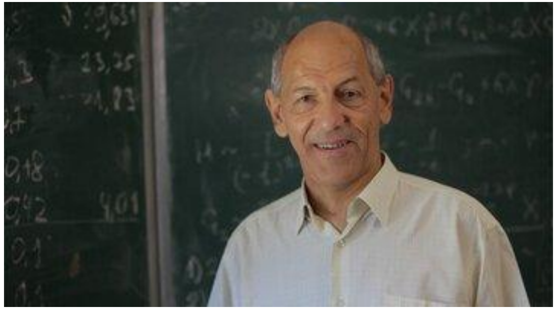
$8\pi G T_{\mu\nu} = G_{\mu\nu}$, *$p \sim \cos(2mt)$*, *$\Psi \sim \cos(2mt)$*

The final experssion of the signal in the residuals:

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

$\Psi(x_E) \sim \rho_{DM}$





Khmelnitsky, Rubakov 2014

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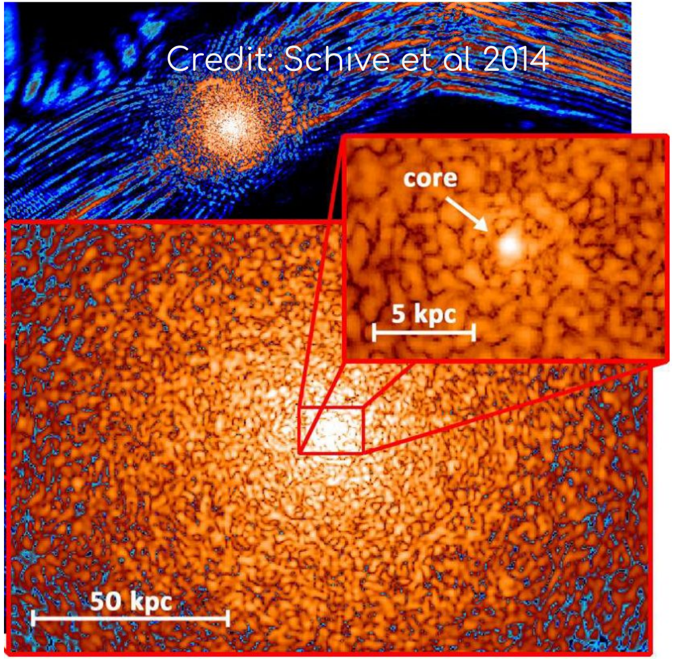
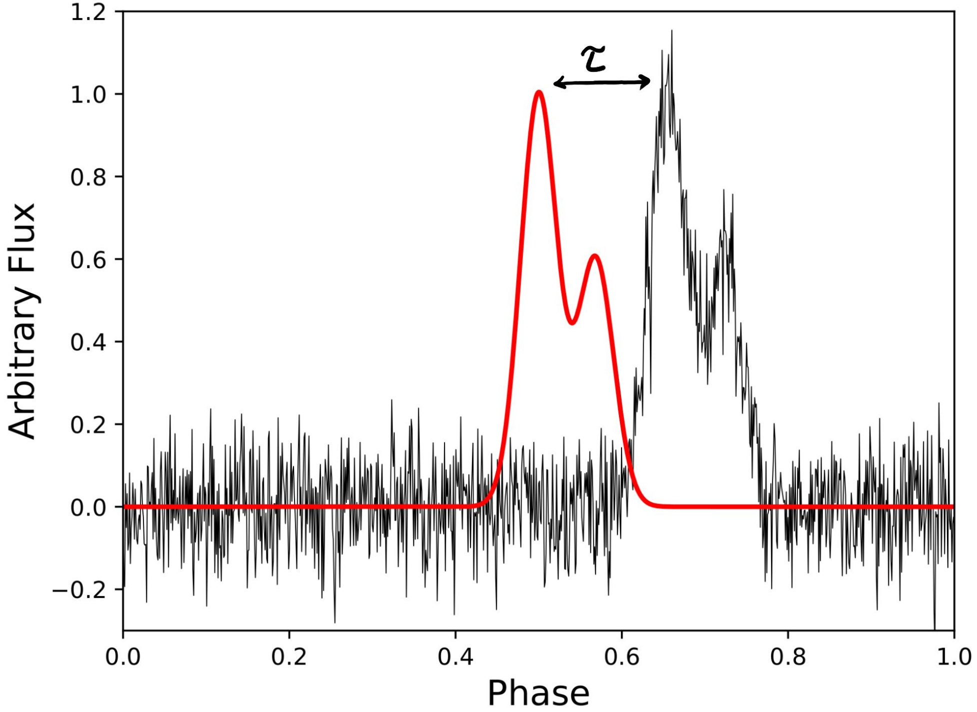
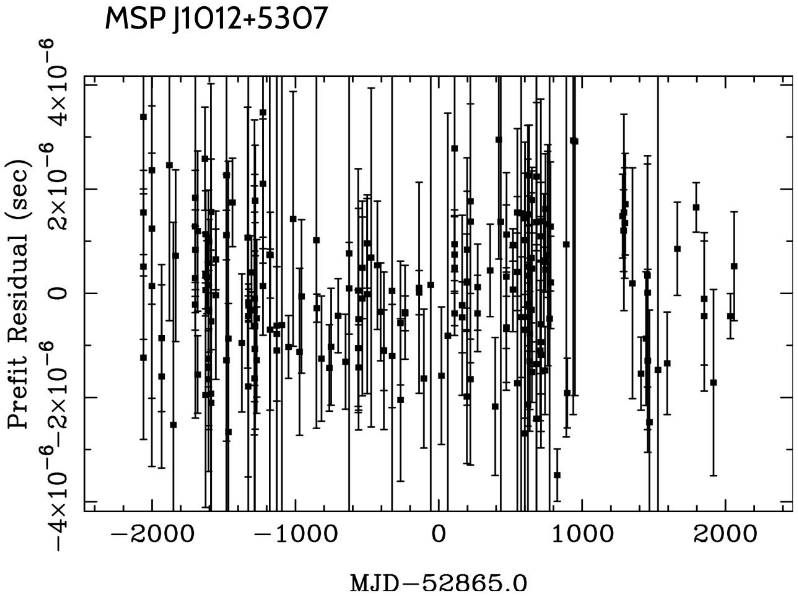
$\Psi(x_E) \sim \rho_{DM}$; $\mathcal{X}_E^2 : p(\mathcal{X}_E) = \mathcal{X}_E \exp(-\frac{\mathcal{X}_E^2}{2})$



Khmelnitsky, Rubakov 2014

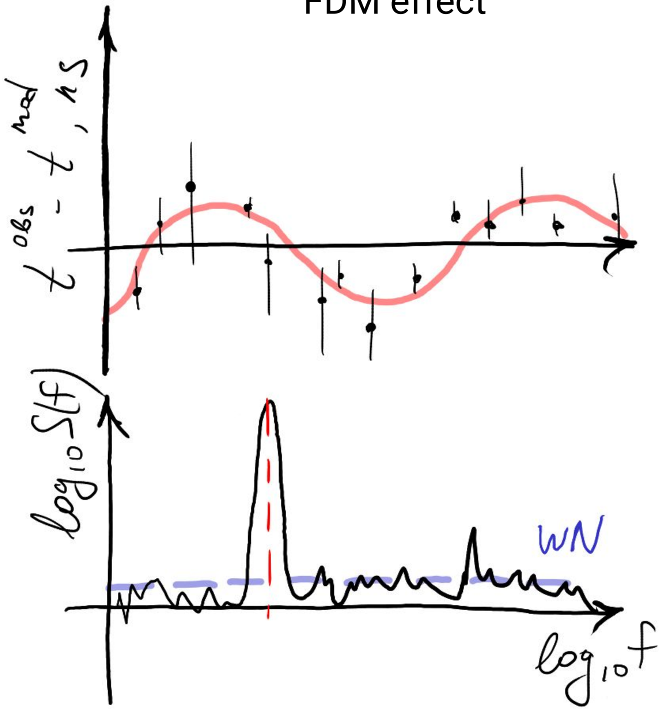
Pulsar timing and FDM



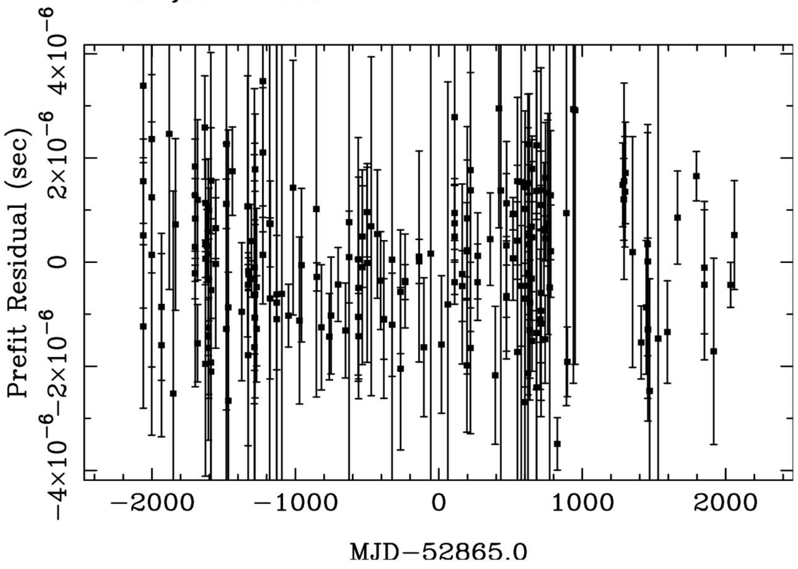


Pulsar timing and FDM

FDM effect



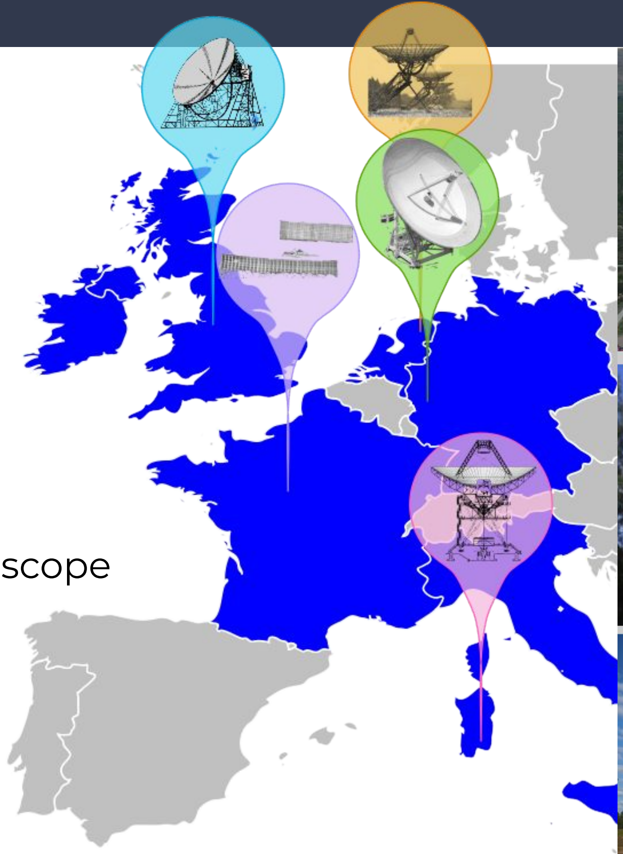
MSP J1012+5307



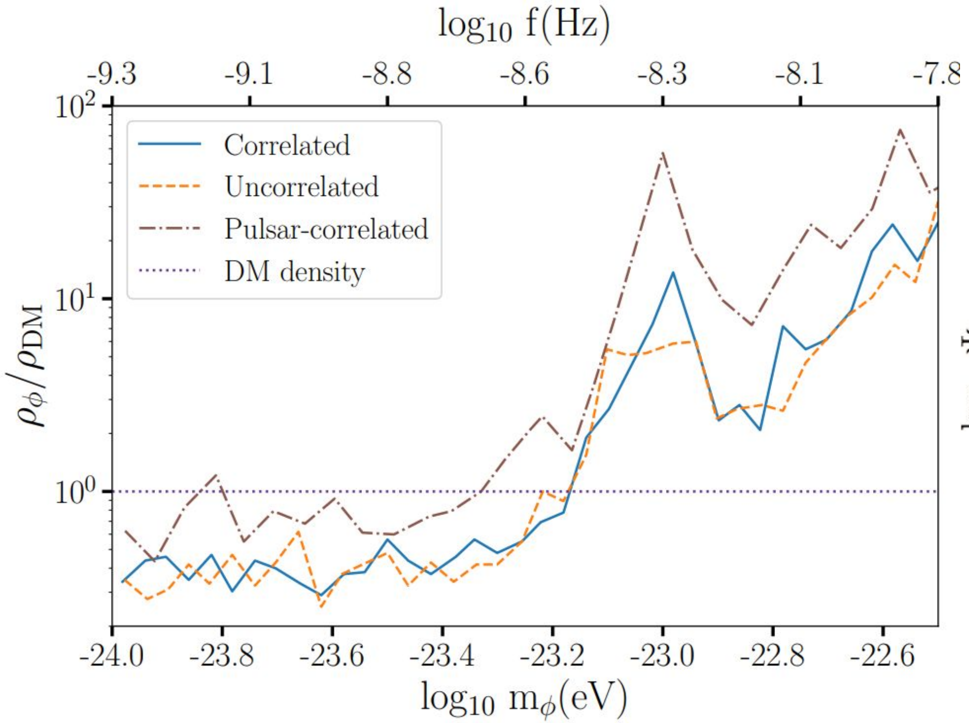
European Pulsar Timing Array

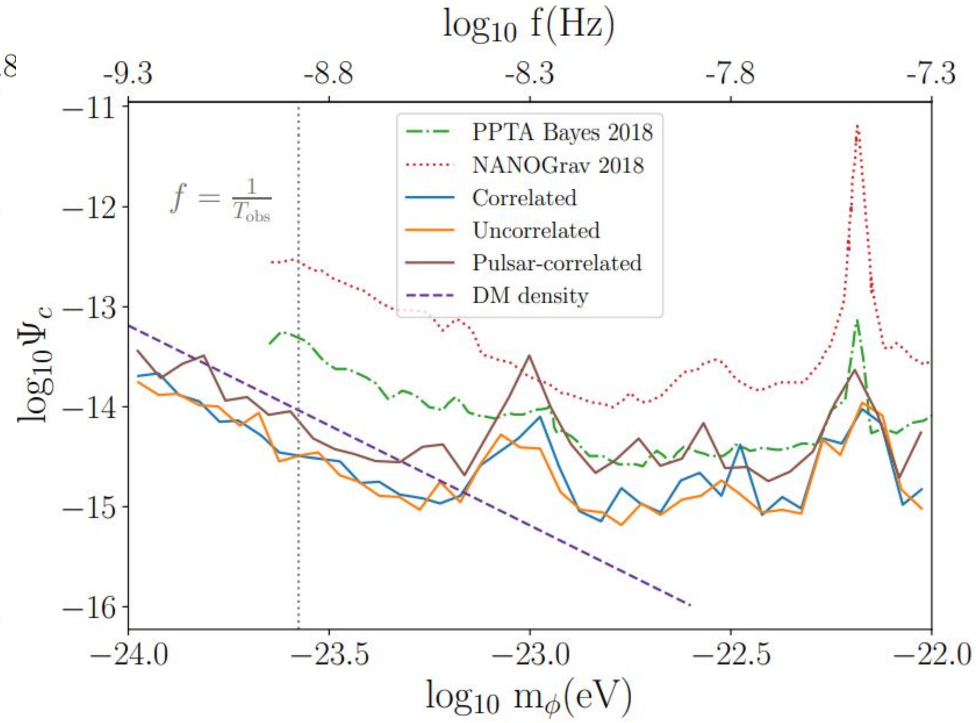
Partner telescopes:

- Effelsberg
- Lovell
- Nancay Radio Telescope
- Sardinia Radio Telescope
- Westerbork Synthesis Radio Telescope



FDM coupled gravitationally with SM particles





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

FDM coupled non-universally with photons

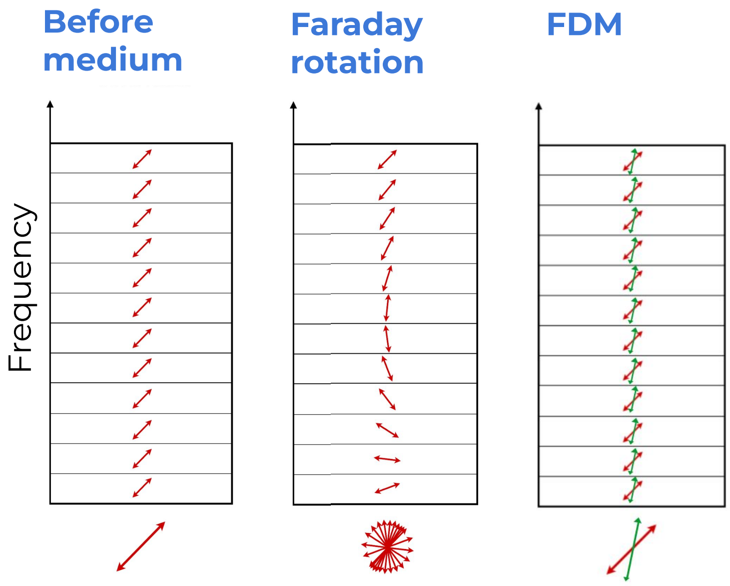
If assume non-renormolizable interaction between fuzzy DM particles and photons:

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

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

Polarization properties of light are altered

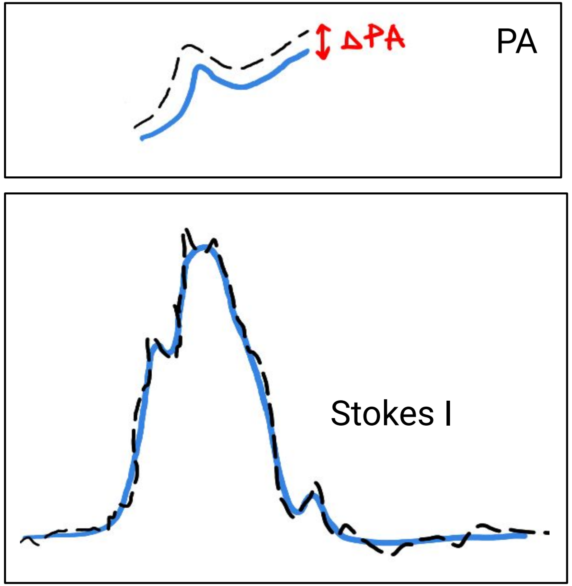
$$\omega_\pm = k\sqrt{1 \pm g_{a\gamma}\frac{\partial_0 a}{k}} \simeq k \pm \frac{1}{2}g_{a\gamma}\partial_0 a$$

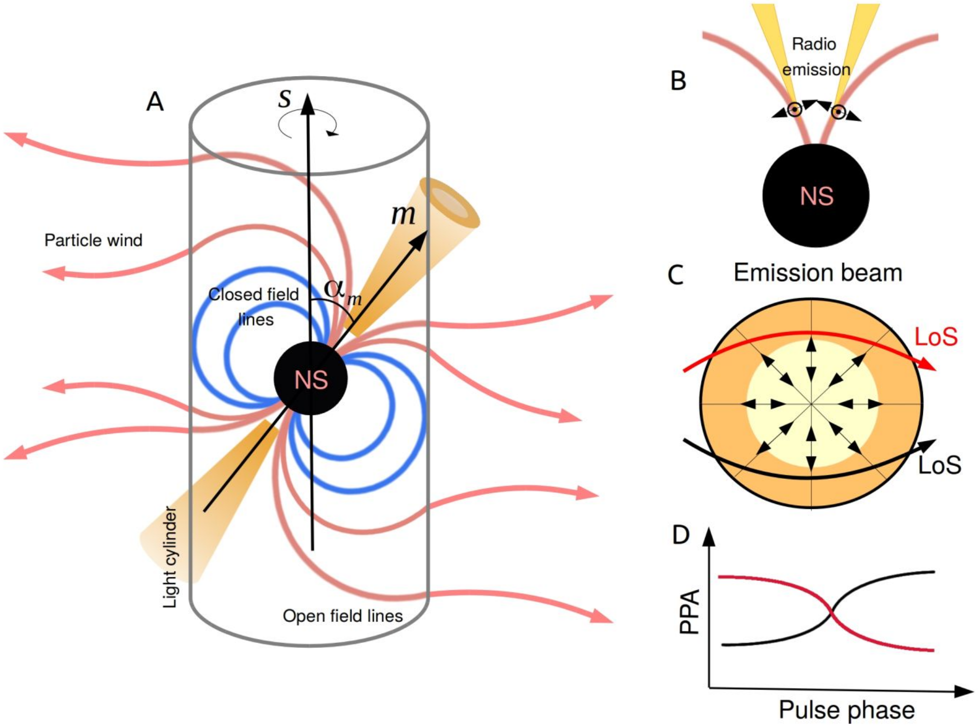


$$\Delta(\mathrm{PA}(t)) = \frac{g_{a\gamma}}{\sqrt{2}m}[\mathrm{p}(t_E, x_E) - \mathrm{p}(t_p, x_p)], \quad p(t_E, x_E) = \sqrt{\rho_{\mathrm{DM}}}\kappa_E \cos(mt + \phi(x_E))$$

See: Ivanov et al 2018, Castillo et al 2022

Searching for FDM: data processing





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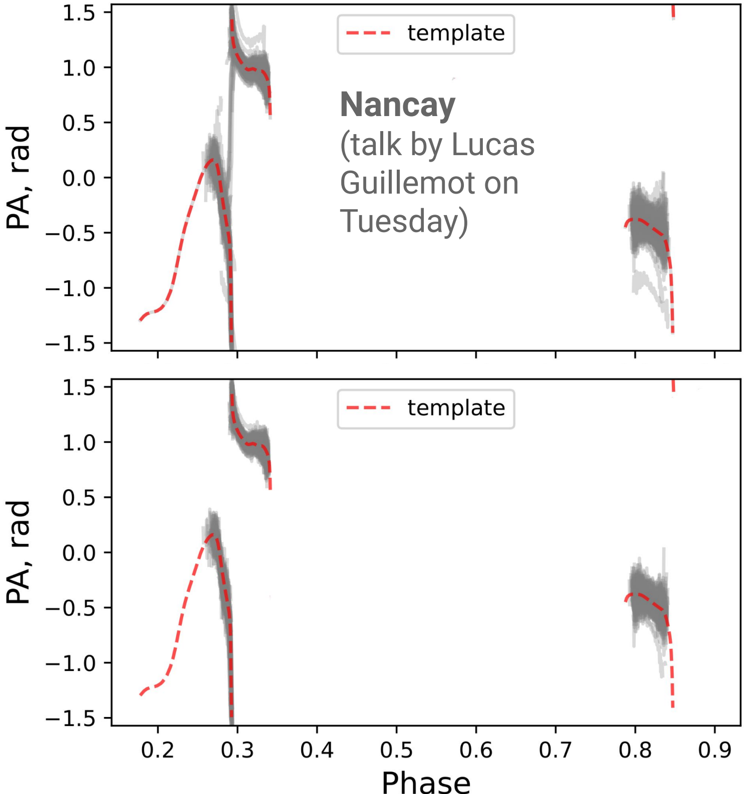
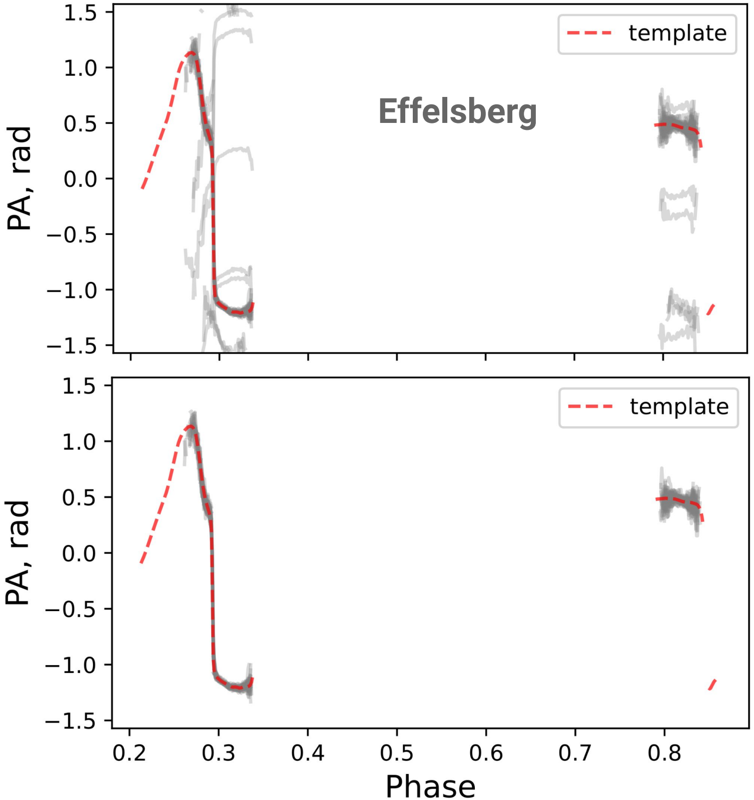


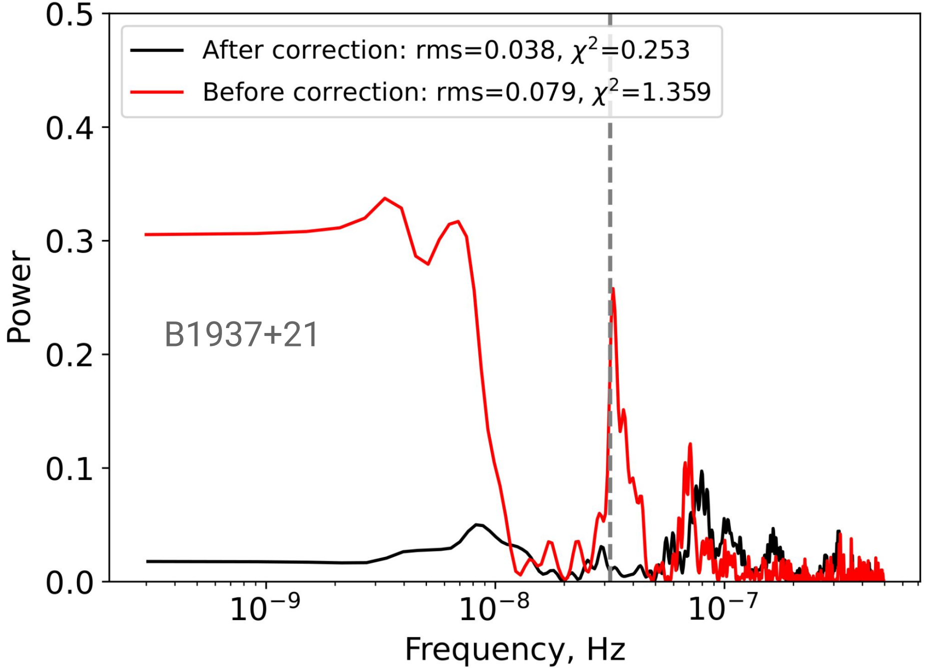
B1937+21

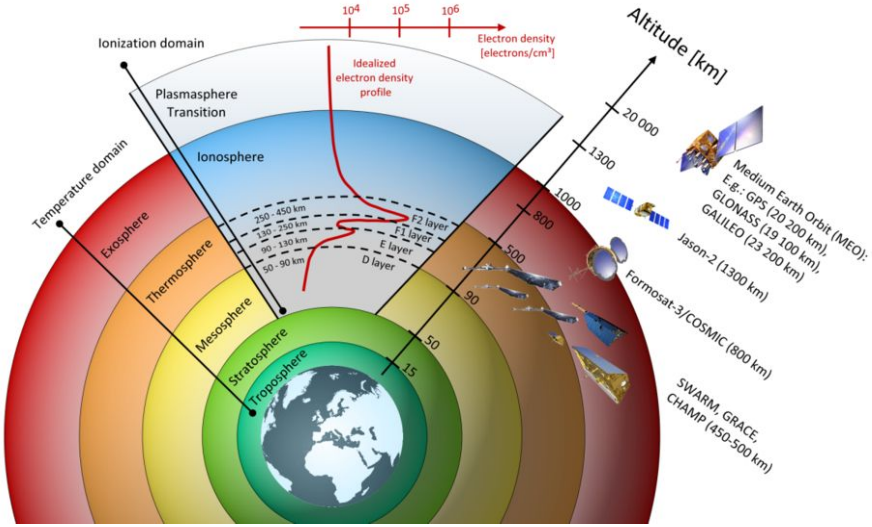
All PA profiles

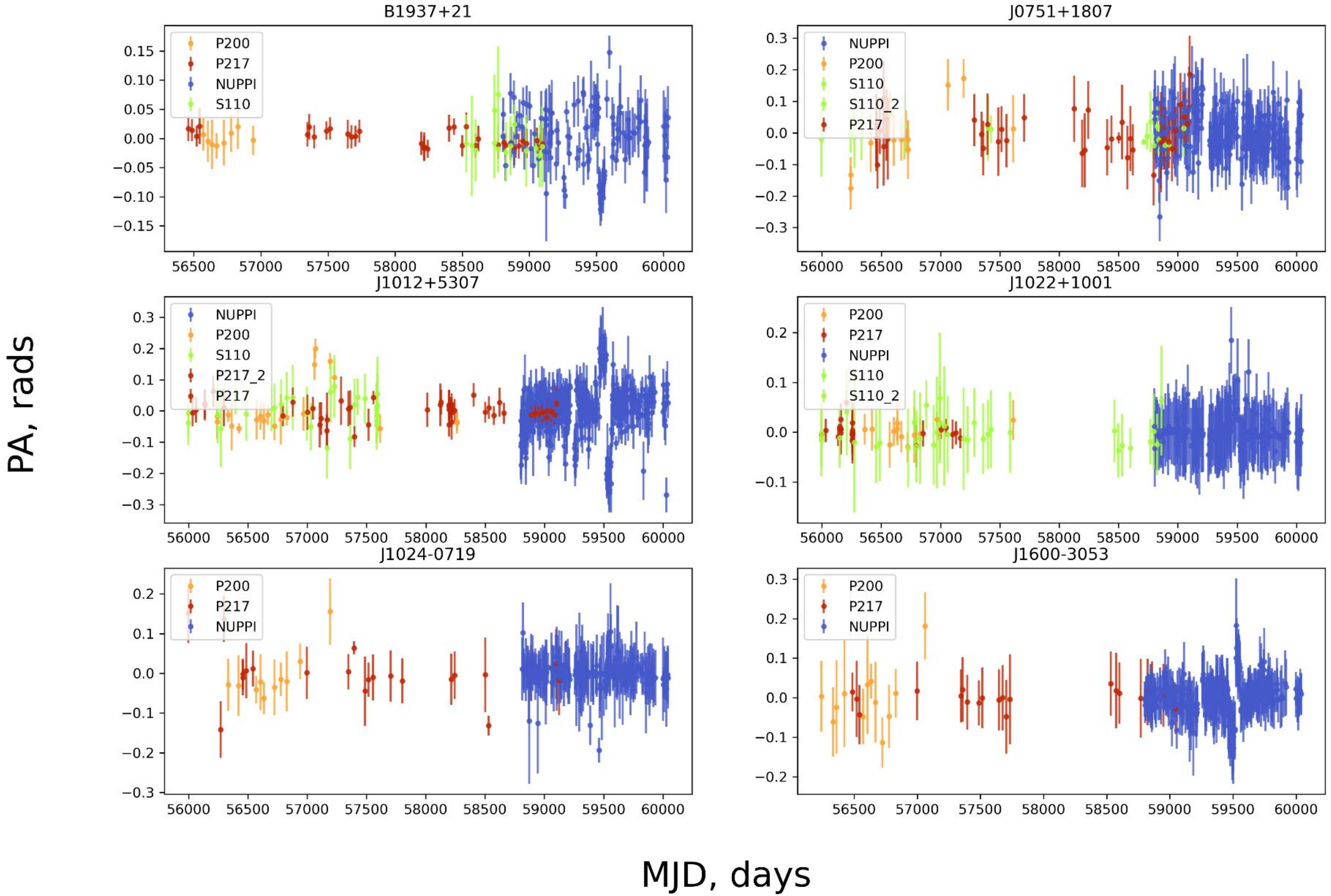
Manually selected PA profiles

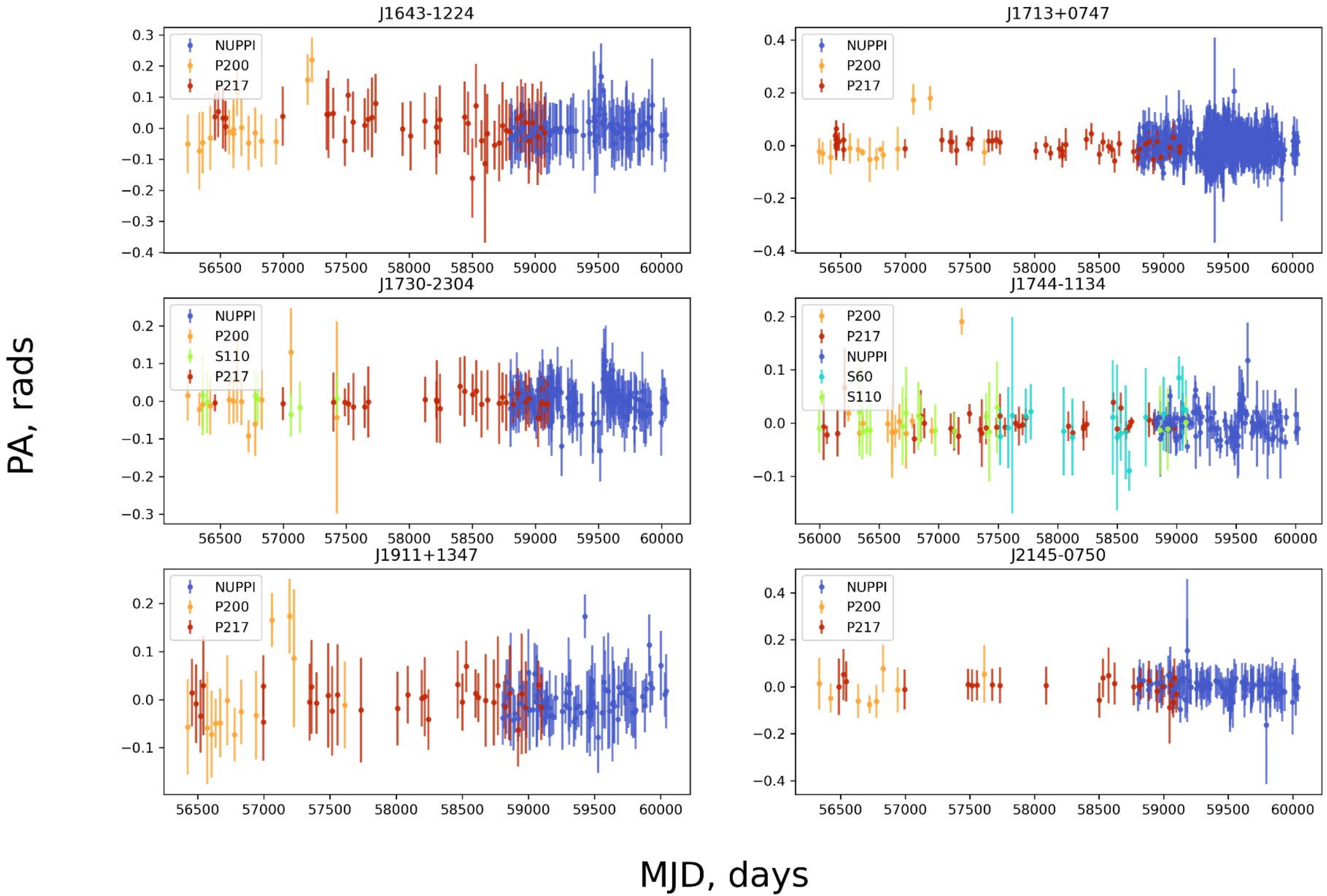


Searching for FDM: ionosphere

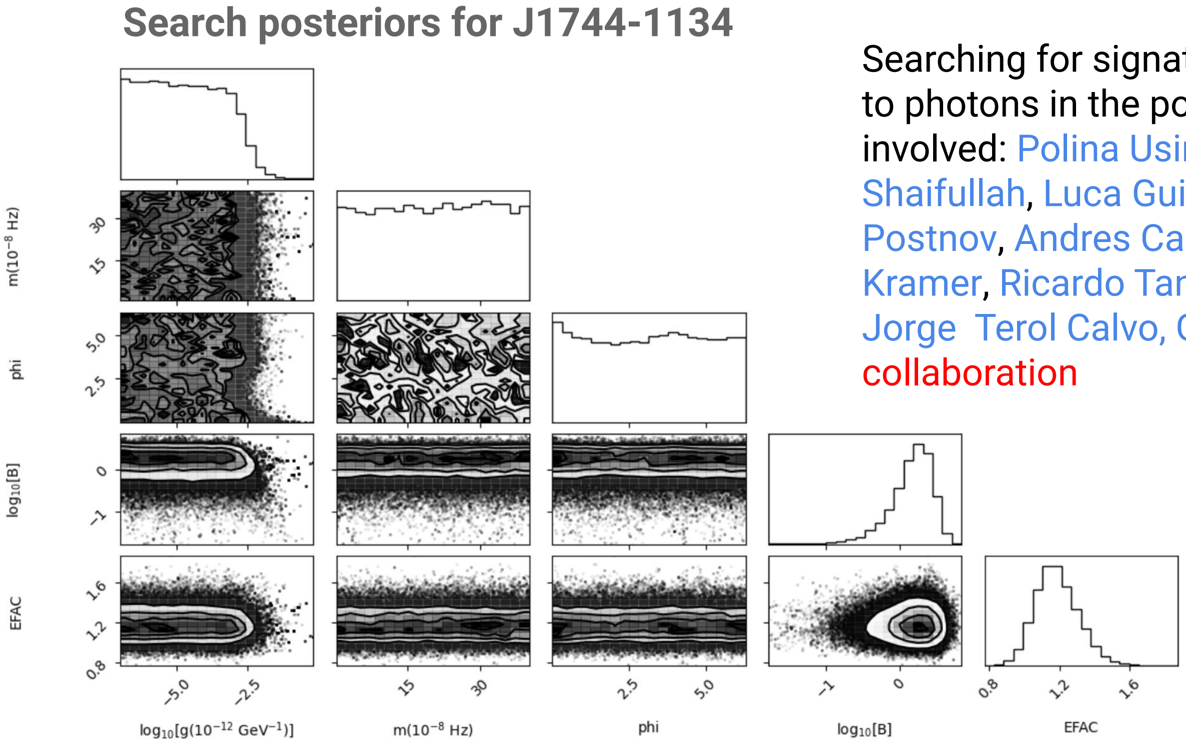





B1937+21
P200
P217
NUPPI
S110
J0751+1807
NUPPI
P200
S110
S110_2
P217
J1012+5307
NUPPI
P200
S110
P217_2
P217
J1022+1001
P200
P217
NUPPI
S110
S110_2
J1024-0719
P200
P217
NUPPI
J1600-3053
P200
P217
NUPPI
PA, rads
MJD, days


J1643-1224
J1713+0747
J1730-2304
J1744-1134
J1911+1347
J2145-0750
NUPPI
P200
P217
S110
S60
PA, rads
MJD, days

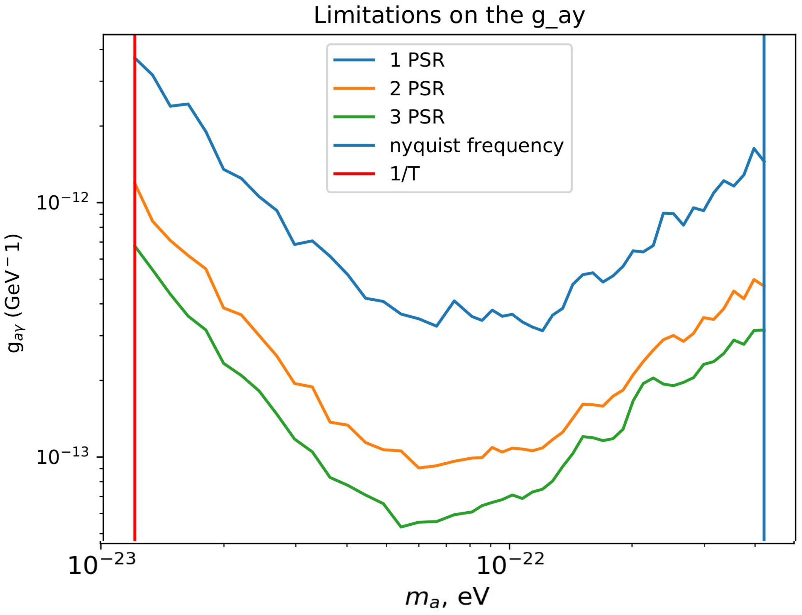
Searching for FDM in real data



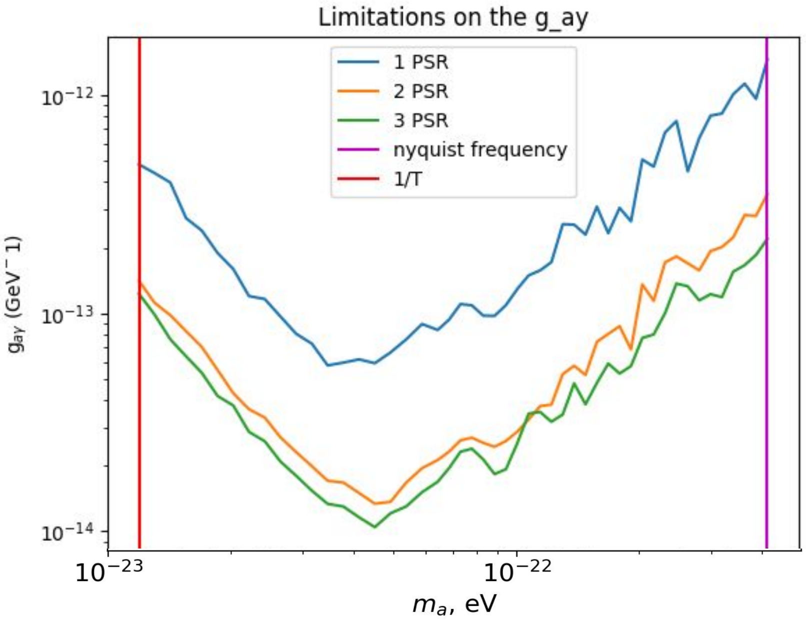
Searching for signatures of FDM non-universally coupled to photons in the polarization data of the EPTA. People involved: Polina Usinina, Andres Castillo, Golam Shaifullah, Luca Guillemot, Caterina Tiburzi, Konstantin Postnov, Andres Castillo, Jorge Martin Camalich, Michael Kramer, Ricardo Tanausu Genova, Santos, Mike Peel, Jorge Terol Calvo, Gregory Desvignes and EPTA collaboration

Searching for FDM: factorised upper limits

Simulated data:
all identical sets with rms=0.1 rad

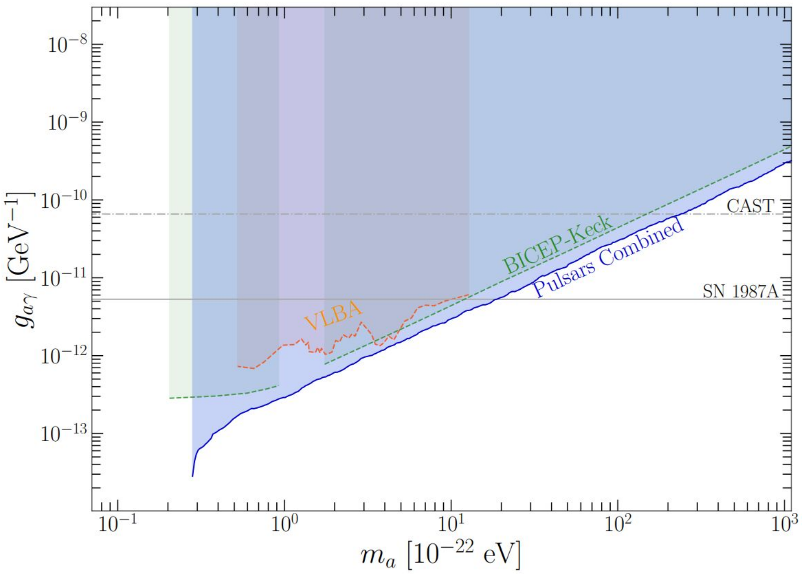


Real data for three pulsars:
J1022+1001, J1744-1134, J1713+0747

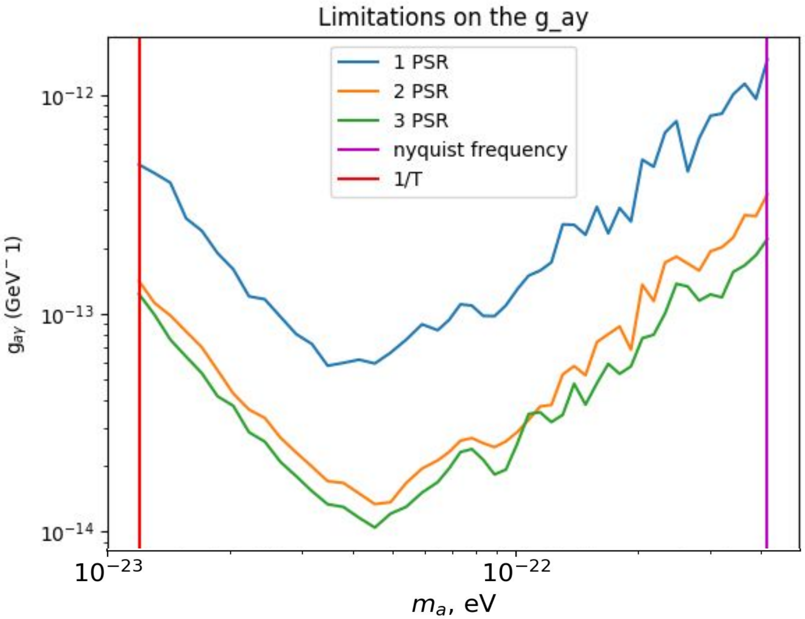


Searching for FDM: upper limits

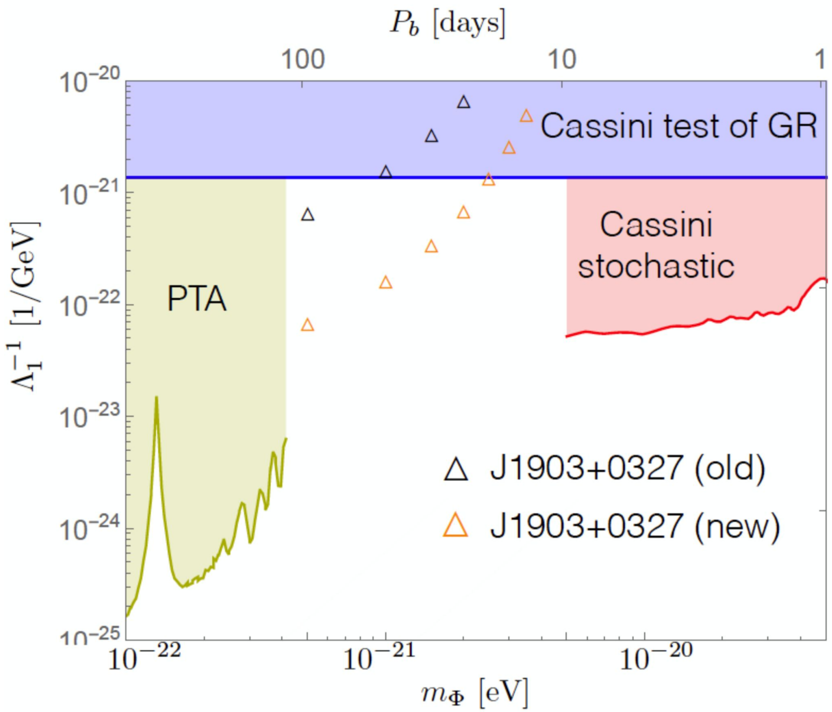
Previous study using PPTA polarisations (Castillo, Martin-Camalich, Terol-Calvo et al. 2023)



Real data for three pulsars: J1022+1001, J1744-1134, J1713+0747

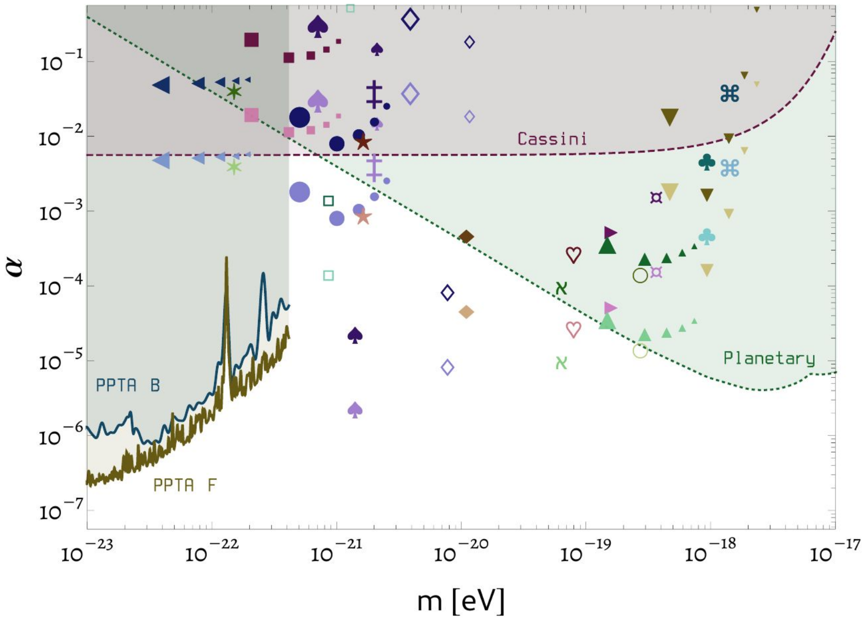


FDM: pulsar timing and beyond



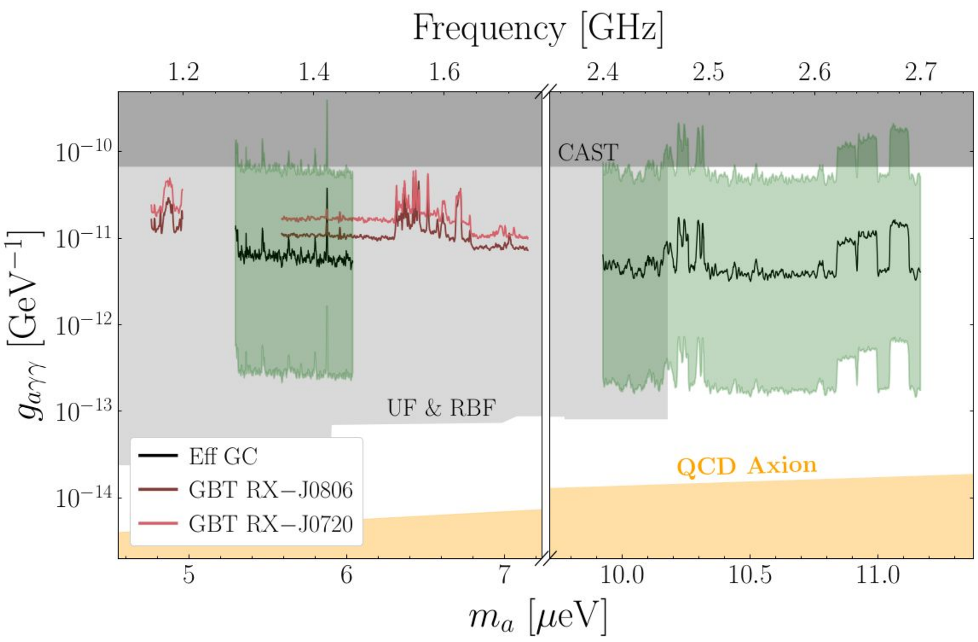
Credit: Blas et al 2020, Heusgen et al., in prep.

Spin-2 axionic DM

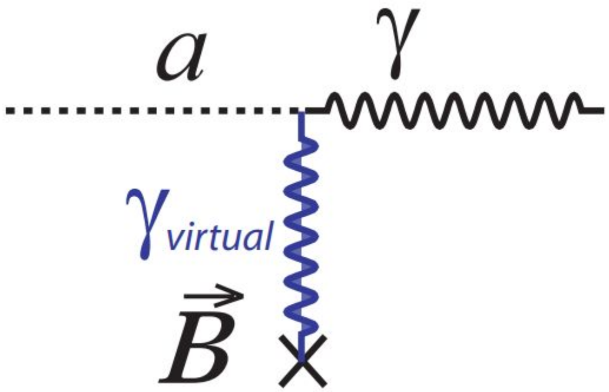


Credit: Armaleo et al., 2020

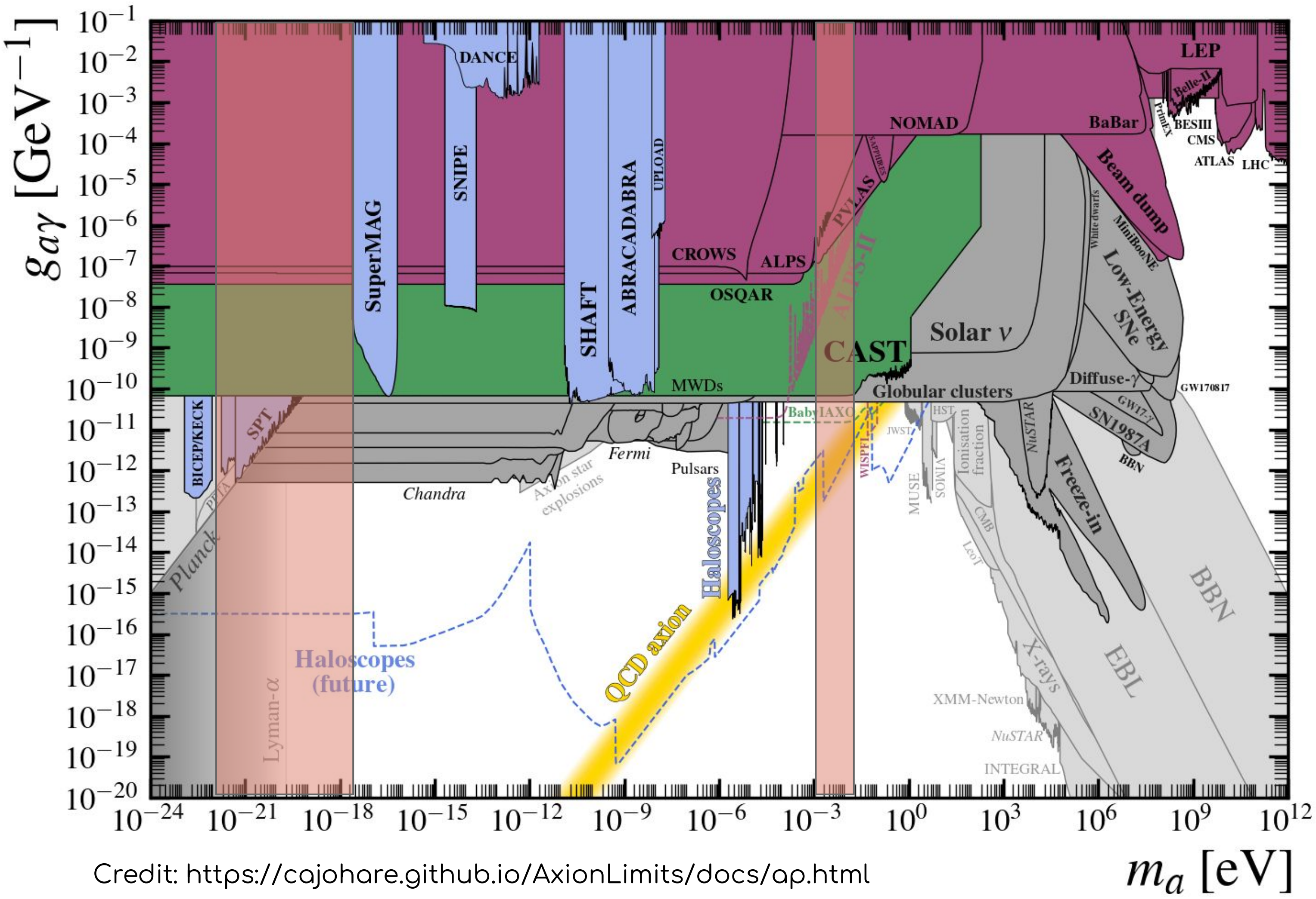
Searching for QCD axions with pulsar polarimetry



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



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



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