Search for Ultra-Light Dark Matter in Pulsar Observations

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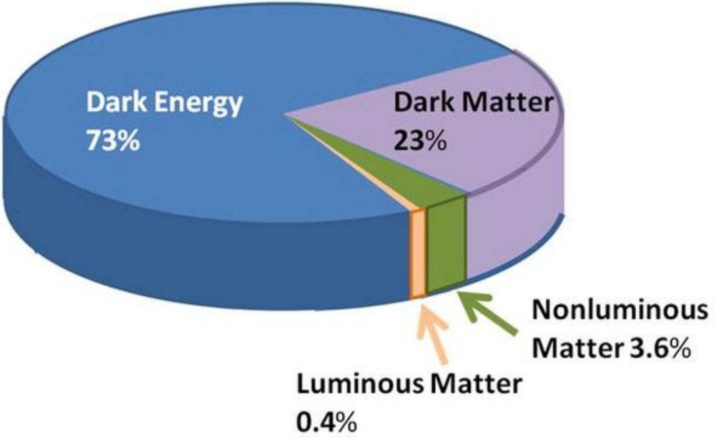
Oultline

- Dark matter
- Pulsar timing
- Ultralight pseudoscalar bosons as dark matter
- ULDM constraints from pulsar timing
- ULDM properties constraints from pulsar polarization
- Conclusion

Dark matter

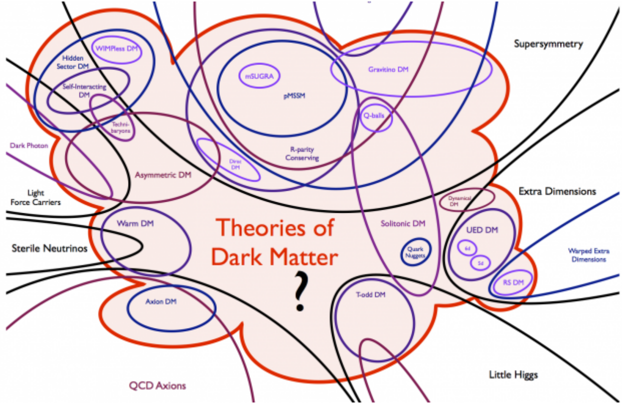
Matter in the Universe

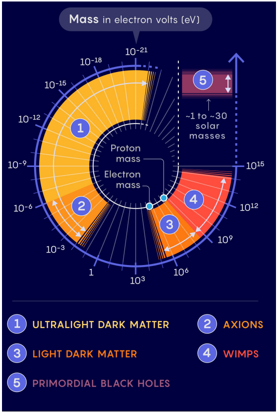


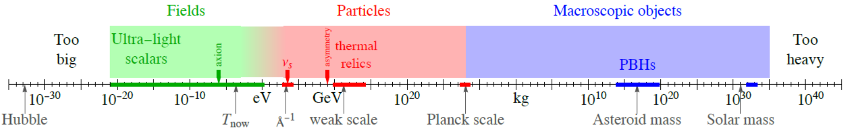
$$\Omega_{\rm DM}h^2 = 0.1200 \pm 0.0012,\ h \equiv H_0/100[\text{km/s/Mpc}]$$

Review: Cirelli et al, arXiv:2406.01705v2

Models and mass range







Ultralight DM (see Hu et al. PRL 85, 1158 (2000))

- Axion-like particles $10^{-22} \lesssim m \lesssim 1$ eV
  $\Box\varphi = m^2\varphi,\ \varphi = A\cos(mt-\alpha)$
- W.F. $\psi = Ae^{i\alpha} \Rightarrow$ Non-relativistic gravitating BE-condensate -- Shroedinger equation for particles in potential well +

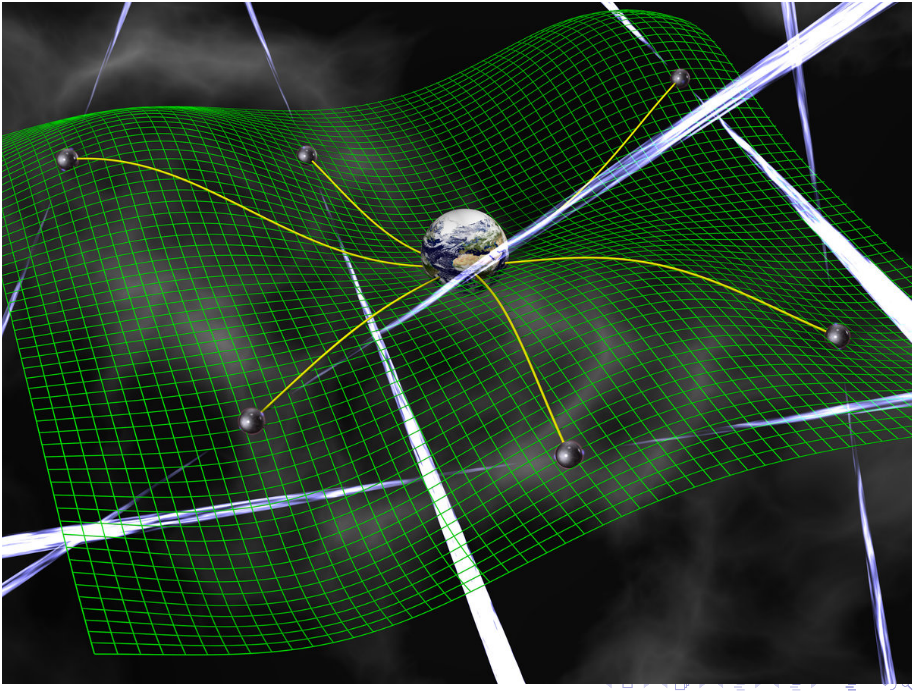
  Poisson equation
  $i\frac{\partial\psi}{\partial t} = (-\frac{1}{2m}\nabla^2 + m\Psi)\,\psi, \quad \nabla^2\Psi = 4\pi\delta\rho, \quad \delta\rho = m\delta|\psi|^2/2$
- Uncertainty principles: stability at scales smaller than Jeans length
  $\lambda_{dB} \sim 1/(mv) \sim$
  $1/(m \quad G\rho r) \Rightarrow r_J \approx 60[\mathrm{kpc}] \quad \frac{m}{10^{-22}\mathrm{eV}} \quad ^{-1/2} (\rho/\rho_b)^{-1/4}(\Omega_{\mathrm{DM}}h^2)^{-1/4}$
- Solves problem of overabundance of small-scale structures with masses $\lesssim 10^7 M_\odot$ in standard ΛCDM cosmology

- Predicts the absence of central density cusps

- Observable effects at pulsar timing frequencies

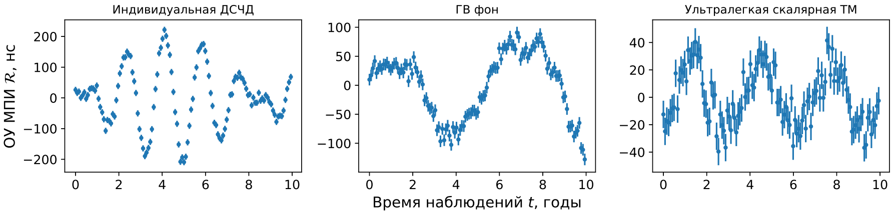
  $f = \omega/2\pi = \frac{m_a}{\pi} \approx 4.8\times10^{-8}\,\mathrm{Hz} \quad \frac{m_a}{10^{-22}\mathrm{eV}}$

Pulsar timing

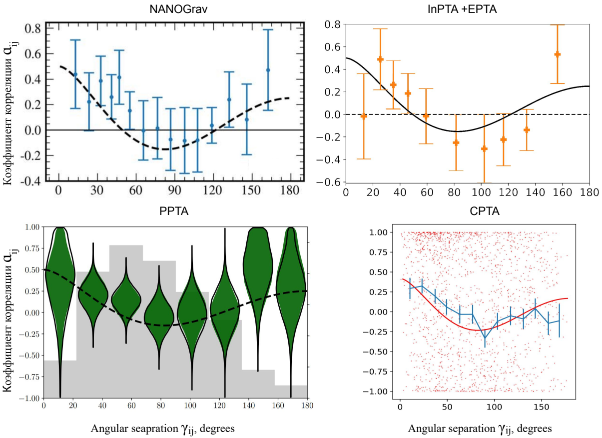


Pulsar timing residuals from different sources

$h_c \sim 10^{-15}, \omega \sim 1/T \sim 10^{-8}\,\mathrm{Hz}$
$\Rightarrow \sim \mathcal{O}(10\mathrm{ns})$ $\surd$ 2



Pulsar timing arrays: Hellings-Downs correlations



[2023ApJ...951L...8A], [2023A&A...678A..50E], [2023ApJ...951L...6R], [2023RAA....23g5024X].

Ultra-light pseudoscalar bosons as dark matter

ULDM as classical field

De Broglie wavelength : $\lambda_{\rm dB} = \frac{1}{m_a v} \sim 60\ \text{pc} \left(\frac{10^{-22}\text{эB}}{m_a}\right)\left(\frac{10^{-3}}{v}\right)$

Occupation number:

$$\mathcal{N} = \frac{N}{d^3x d^3k} \simeq n\lambda_{\rm dB}^3 \sim 10^{95}\left(\frac{\rho_{\rm DM}}{0.4\ \text{GeV}^{-3}}\right)\left(\frac{m_a}{10^{-22}\,\text{eV}}\right)^{-4}. \qquad (3)$$

- APL with masses $\mathcal{O}(10^{-22})$ eV coherently oscillate on scale $l_c \sim \lambda_{\rm dB}$ at frequency $\omega = m_a$: $\varphi = A\cos(\omega t + \alpha(t))$ (to within $\Delta\omega/\omega \sim v^2$)

- Time-independent part $T_{tt} = \rho_{\rm DM} = A^2 m_a^2/2$, oscillating part of energy-momentum tensor is small: $\rho_{\rm DM}^{osc} \sim (\nabla\varphi)^2 \sim k^2 m_a^2 = v^2\rho_{\rm DM}$. Small
- DM density oscillations $\boxed{\omega^{osc} = 2m_a,}$
  $T_{ij} = -\frac{1}{2}m^2 A^2(\cos 2m_a t + 2\alpha(t)) = p\delta_{ij}$
- Oscillating pressure $\rightarrow$ gravitational potential oscillations

Oscillating gravitational potential

$$ds^2 = (1 + 2\Phi(x,t))dt^2 - (1 - 2\Psi(x,t))dx^2 \,. \tag{4}$$

Newtonian potentials $\Psi_0 = \Phi_0$ from tt-component of Einstein equations:

$$\Delta\Psi_0 = 4\pi G T_{tt} = 4\pi G \rho_{\mathrm{DM}} \quad \Rightarrow \Psi_0 \sim \frac{G\rho_{\mathrm{DM}}}{k^2} \tag{5}$$

Variable gravitational potential:
$\Psi(x,t) \approx \Psi_s(x)\sin(\omega t + 2\alpha) + \Psi_c(x)\cos(\omega t + 2\alpha)$ as trace of ij-component of Einstein euations

$$-6\frac{\partial^2\Psi}{\partial t^2} + 2\Delta(\Psi - \Phi) = 8\pi G T^j{}_j = 24\pi G p(x,t)$$

oscillates at the same frequency $\omega = 2m_a$, as pressure $p(x,t)$. $\Psi_c(x) \sim v^2\Psi_0(x)$ (since $k^2 = m_a^2 v^2$)

ULDM constraints from pulsar timing by integral Sachs-Wolfe effect

Integral Sachs-Wolfe effect

EM signal propagating in metric (4)
$ds^2 = (1 + 2\Phi(x,t))dt^2 - (1 - 2\Psi(x,t))dx^2$

$$\frac{\Delta f}{f_0} = \frac{f - f_0}{f_0} = \underbrace{\Phi(t_0) - \Phi(t)}_{\text{grav. redshift}} + \underbrace{\int_{t_0}^{t} (\partial_t \Phi - \partial_t \Psi) dt}_{\text{инт. эф. Сакса-Вольфа}} \tag{6}$$

Change to total derivative $\partial_t = d/dt - n_i \partial_i$ and integrate:

$$\frac{f - f_0}{f_0} = \Psi(x,t) - \Psi(x_0,t_0) - \underbrace{\int_{t_0}^{t} n_i \partial_i (\Phi - \Psi) dt'}_{\text{oscillating f. } \sim k/\omega \Psi \sim v \Psi} . \tag{7}$$

$$\Rightarrow \frac{\Delta f(t)}{f_0} \approx \Psi(x,t) - \Psi(x_0,t_0) = \Psi_c(x) \cos(\omega t + 2\delta(x)) - \Psi_c(x_0) \cos(\omega(t - D) + 2\delta(x_0)) \tag{8}$$

Effect in pulsar timing (Khmelnitsky, Rubakov JCAP 2014)

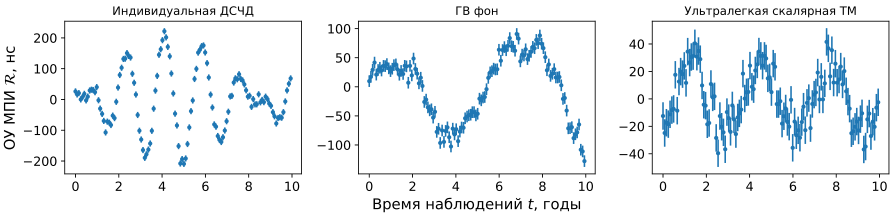
Grav. field oscillations:

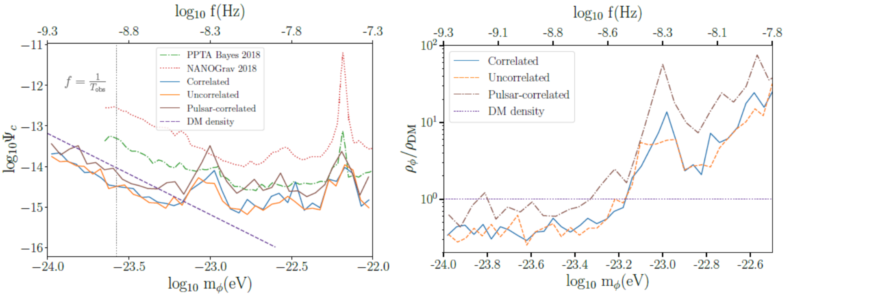
$$\Psi_c(f) = \frac{\pi G \rho_\varphi(x)}{m_a^2} = \frac{G\rho_\varphi(x)}{\pi f^2} \approx 6.5\times 10^{-18} \left(\frac{m_a}{10^{-22}\ \text{эВ}}\right)^{-2} \left(\frac{\rho_\varphi}{0.4\ \text{GeV/cm}^3}\right)$$

Timing residuals

$$\mathcal{R}(t) = \int_0^t \frac{\Delta f(t')}{f_0} dt' = \frac{\Psi_c(x_e)}{\omega} \sin(\omega t + 2\delta(x_e)) - \frac{\Psi_c(x_o)}{\omega} \sin(\omega(t-D) + 2\delta(x_p$$

$$\sigma_{\text{TOA}} = \sqrt{\langle \mathcal{R}^2(t) \rangle} = \frac{1}{2}\frac{\Psi_c}{2m_a} \boxed{\approx 0.02\ \text{ns} \left(\frac{m_a}{10^{-22}\ \text{эВ}}\right)^{-3} \left(\frac{\rho_\varphi}{0.4\ \text{GeV/cm}^3}\right)}$$





Верхние пределы у.з. 95% на безразмерную амплитуду осцилляций скалярного поля Ψ_c (слева) и на долю УЛТМ в локальной плотности ТМ $\rho_\varphi/\rho_{\rm DM}$ (справа) (Smarra et al. 2023 PRL 131, 171001). $f = \omega/2\pi = \frac{m_a}{\pi} \approx 4.8 \times 10^{-8}$ Гц $\left(\frac{m_a}{10^{-22}\text{эВ}}\right)$

ULDM constraints from pulsar polarization

Cosmic birefrigence

- Massive scalar field with non-renormalizable coupling to EM field

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{g_{a\gamma}}{4}\varphi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\left(\partial_\mu\varphi\partial^\mu a\varphi - m_a^2\varphi^2\right) . \quad (12)$$

- Equations of motion

$$\partial_t^2\mathbf{A} - \nabla^2\mathbf{A} = g_{a\gamma}(\partial_t\varphi\nabla\times\mathbf{A} + \partial_t\mathbf{A}\times\nabla\varphi) , \quad \Box\varphi + m_a^2\varphi = g_{a\gamma}\mathbf{EB} \quad (13)$$

- For $g_{a\gamma} \lesssim 10^{-12}\mathrm{GeV}^{-1}$ and $B \sim \mathcal{O}$ (mcG), $g_{a\gamma}\mathbf{EB} \ll m_a^2\varphi \Rightarrow$

$$\varphi(t,\mathbf{x}) = A(\mathbf{x})(\cos(m_a t + \delta(\mathbf{x})) \quad (14)$$

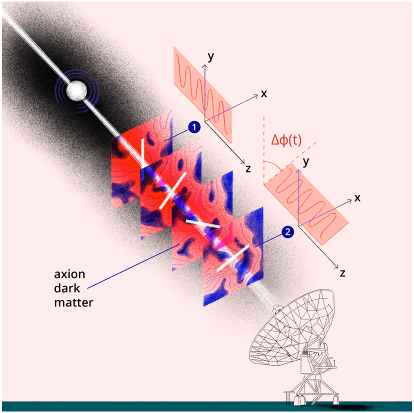
$$A = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a} \approx 2.5\times10^{10}\,\mathrm{GeV}\left(\frac{\rho_{\mathrm{DM}}}{0.4\,\mathrm{GeV/см}^3}\right)^{1/2}\left(\frac{10^{-22}\,\text{эВ}}{m_a}\right) \quad (15)$$

- For plane circularly polarized waves (Fujita et al. 2019)

$$\omega_\pm^2 \mp g_{a\gamma}(\partial_t\varphi + \widehat{\mathbf{k}}\cdot\nabla\varphi)|k| = 0 \quad k \gg m_a, \Rightarrow \boxed{\omega_\pm \simeq k \pm \frac{1}{2}g_{a\gamma}\left(\partial_t\varphi + \nabla\varphi\cdot\widehat{\mathbf{k}}\right)} \quad (16)$$

- Polarization angle rotation depends only on the field amplitude if $D < l_c \sim \lambda_{\mathrm{dB}} = 1/(m_a v) \sim 60\,\mathrm{pc}(10^{-22}\,\mathrm{eV}/m_a)$, $T < \tau_c = 1/(m_a v^2) \sim 10^{13}\,\mathrm{s}$

$$\Delta\theta = \frac{g_{a\gamma}}{2}\int_{t_p}^{t_e}\frac{d\varphi}{dt}dt = \frac{g_{a\gamma}}{2}[\varphi(t_e,x_e) - \varphi(t_p,x_p)] \equiv \frac{g_{a\gamma}}{2}\Delta\varphi \quad (17)$$



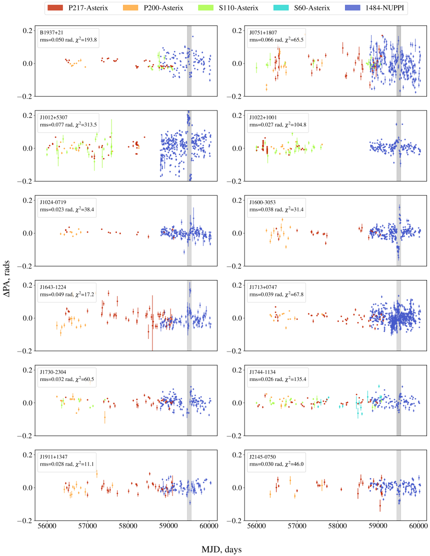
- Stochastic amplitudes due to inhomogeneities

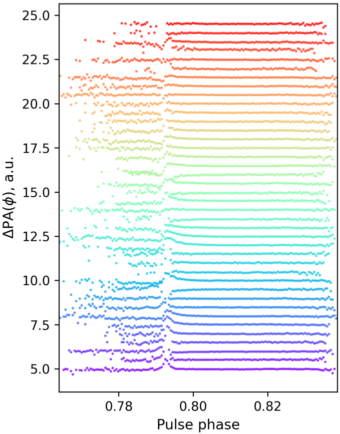
$$\Phi_a = \frac{g_{a\gamma}}{\sqrt{2}\, m_a}\left(\rho_e\alpha_e^2 + \rho_p\alpha_p^2 - 2\sqrt{\rho_e\rho_p}\,\alpha_e\alpha_p\cos\Delta\right)^{1/2}, \tag{18}$$

Typical values for phases $\Delta = \pi$, $\rho_e = \rho_p = \rho_{\rm DM}$ and $\alpha_e = \alpha_p = 1$

$$\Phi_a = g_{a\gamma} A \approx 0.025[\mathrm{rad}] \left(\frac{g_{a\gamma}}{10^{-12}\,\mathrm{GeV}^{-1}}\right)\left(\frac{\rho_{\rm DM}}{0.4\ \mathrm{GeV\ cm}^{-3}}\right)^{1/2}\left(\frac{10^{-22}\ \text{эВ}}{m_a}\right) \tag{19}$$

Pulsar observations (N.Porayko...KP... et al. 2025, PRD 111, id.062005, arXiv:2412.02232), Nançay Radio Obsevatory

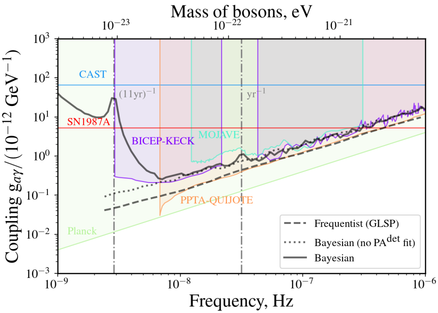




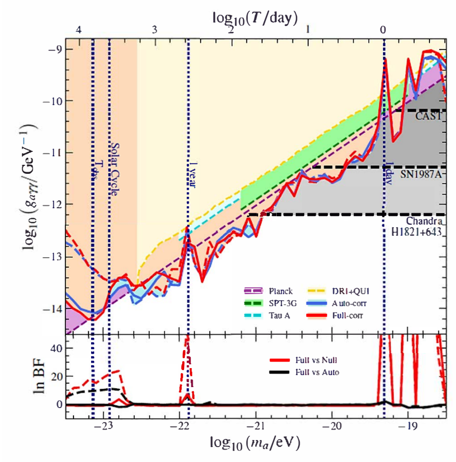
Residuals ΔPA from mean polarization profile in PSR 1937+21

Upper limits on $g_{a\gamma}$ coupling constant from pulsar polarization measurements

- Frequentist
- Bayesian



EPTA: N.Porayko...KP... et al. 2025, PRD 111(6), 0622005, arXiv:2412.02232

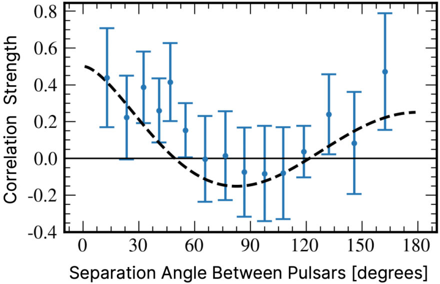


CPTA: Xiao Xue et al. arXiv:2412.02229

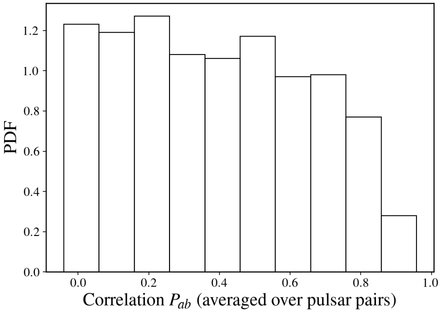
Discussion and conclusions

Difference ULTM from GW

- Monochromatic signal
- Correlation between pulsar pairs in not HD



Quadrupole Hellings-Downs correlation between pulsar pairs for isotropic stochastic GW background NANOGrav, 2023



Pair correlations between PA rotation (Porayko et al. 2025)

Caveat emptor

- Non-Gaussian noise in polarization measurements due to EM signal propagation effects (pulsar magnetosphere, Earth ionosphere...)
  $\Rightarrow$ underestimation of errors
- Timing has many systematic effects, especially stochastic, which may decrease sensitivity. Polarization measurements opens the way to search for such systematics that can mimic ULDM ==> need for combined analysis

Conclusion

- Parameters of ULDM (ALP with masses $m_a \sim 10^{-22} - 10^{-23}$ eV) are constrained by precise pulsar timing observations
- ULDM generates gravitational potential oscillations at frequency $2\pi f = 2m_a \Rightarrow$ (almost) monochromatic signal (Khmelnitsky, Rubakov 2014). Modern PTA constraints: for $10^{-24.0} \lesssim m_a \lesssim 10^{-23.3}$ eV $\rho_\varphi \lesssim 0.3$ GeV/cm^3 (Smarra et al. 2023). The method enables to set direct constraints on dark matter density.
- Pulsar polarization angle oscillations at frequency $2\pi f = m_a$ place independent constraints on axion coupling constant with gauge field $g_{a\gamma}$ in the APL mass range 6×10^{-24}–5×10^{-21} eV