Constraints on conformal ultralight dark matter couplings from the European Pulsar Timing Array

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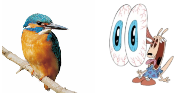
Dicette ‘o pappice vicino ‘a noce,
damme ‘o tiempo ca te spertose

Outline

- Ultra-Light Dark Matter (ULDM)
  -  view
- PTAs constraints on ULDM
  - Gravitationally coupled ULDM: CS+ (EPTA, 2023), Afzal+ (NANOGrav, 2023)
  - Conformally coupled ULDM: CS+ (2024)
  - Bonus: ULDM couplings with SM: Kaplan et al. (2022), Afzal+ (NANOGrav, 2023)
  - Bonus: constraining ULDM with pulsar polarization data

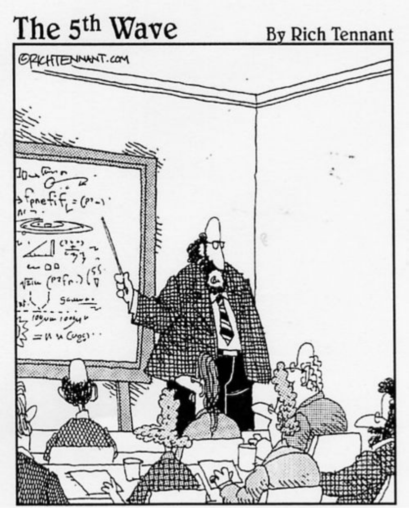
ULDM: where it stands

The CDM paradigm has some well-known issues, for example (Robles et al. 2018):

- *cusp/core problem*
- *Missing satellite problem*
- *Lower-than-expected central densities*

These problems might be alleviated invoking baryonic physics, *e.g.* gravitational stirring by SNe. But in dwarf spheroidal galaxies?

- Need to invoke another mechanism → ULDM



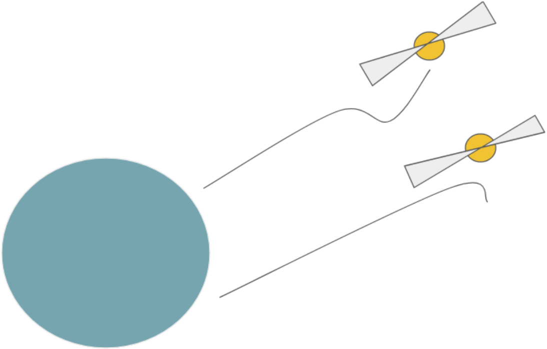
"After the discovery of 'antimatter' and 'dark matter', we have just confirmed the existence of 'doesn't matter', which does not have any influence on the Universe whatsoever."

ULDM: which one?

We focus on a scalar field with mass $m \sim 10^{-22}\mathrm{eV}$, whose de Broglie wavelength acts as a *quantum pressure* that suppresses power on very small scales. In formulae:

$$\frac{\lambda_{\mathrm{dB}}}{2\pi} = \frac{\hbar}{mv} \approx 60\mathrm{pc}\left(\frac{10^{-22}\mathrm{eV}}{m}\right)\left(\frac{10^{-3}c}{v}\right)$$

PTAs constraints on ULDM



PTAs: identikit!

- PTA experiments observe collections of pulsars and search for "special" signatures in their pulse time of arrivals (TOAs).
- They observe milli-second pulsars (MSPs), the most precise celestial clocks.
- Challenge: relate the observed time of arrivals (TOAs) at the observatory to the time of emission at the pulsar. (Edwards et al. 2006)

Convenient to single out three main contributions:

$$t_e^{psr} = t_a^{obs} - \Delta_\odot - \Delta_{IS} - \Delta_B$$

How to look for a signal in PTAs

The main observable in a PTA experiment is the timing residuals, $\vec{\delta t}$, which measure the discrepancy between the observed times of arrival (TOAs) and the ones predicted by the pulsar timing model. In general, each process will affect the timing residuals in a peculiar way. Qualitatively,

$$\vec{\delta t} = \mathbf{M}\vec{\epsilon} + \overrightarrow{W.N.} + \overrightarrow{R.N.} + \text{boh?...} \tag{1}$$

In order to look for a signal in PTAs, we should model how it affects the timing residuals!

ULDM: Classical Wave

In the following, we will think of ULDM as a free scalar field. Due to the huge occupation number (Khmelnitsky and Rubakov, 2013), the ULDM field can be thought as a collection of *classical waves*

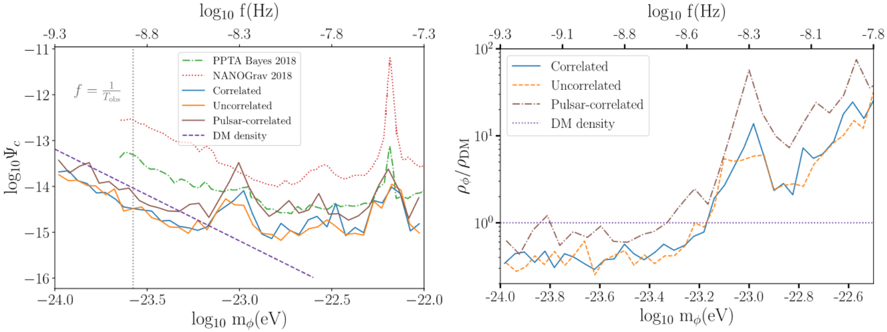
$$\phi(\mathbf{x}, t) = A(\mathbf{x})\cos(mt + \alpha(\mathbf{x}))$$

Skipping a little bit of details (Khmelnitsky and Rubakov, 2013), it turns out that(adapted from Porayko, 2018):

$$\Delta t(t) = \pi \frac{G\rho_{DM}}{2m_\phi^3}\left[\hat{\phi}_E^2 \sin\left[2m_\phi t + 2\alpha(x_e)\right] - \hat{\phi}_P^2 \sin\left[2m_\phi\left(t - \frac{d_p}{c}\right) + 2\alpha(x_p)\right]\right]$$

- *correlated limit*
- *pulsar-correlated limit*
- *uncorrelated limit*

ULDM: Gravitational interaction



EPTA paper VI, CS+ (2023) PRL

ULDM: Coupling to matter

- The previous results are based on the *gravitational* interaction of ULDM with matter.
- However, it might also happen that ULDM features some interaction with the Standard Model particles. Why? Why not? What will we be able to say in this case?

Qualitative understanding of the main point of this part: the coupling to matter modifies the moment of inertia of the pulsar. By conservation of angular momentum, this produces a change in the spin frequency of the pulsar.

Conformally coupled ULDM

We will consider here *universal* interactions of ULDM with the SM. To characterize the coupling we define a field-dependent function $\mathcal{A}(\phi)$ and assume ULDM couples universally with the SM through a Jordan-Fiertz metric $\tilde{g}_{\mu\nu} = \mathcal{A}^2\left(\phi\right) g_{\mu\nu}$.

$$S = M_{\mathrm{P}}^2 \int \mathrm{d}^4 x \sqrt{-g}\left[\frac{R}{2} - g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + m^2\phi^2\right] + S_m[\psi_m, \tilde{g}_{\mu\nu}]$$

- FJBD theory: $\mathcal{A}(\phi) = e^{\alpha\phi} \sim 1 + \alpha\,\phi$
- DEF theory: $\mathcal{A}(\phi) = e^{\beta\phi^2/2} \sim 1 + \frac{1}{2}\beta\phi^2$

Conformal ULDM: sensitivity

With the help of the code presented in (A.Kuntz, E.Barausse 2024), we compute the angular momentum sensitivity, defined as:

$$s_I = -\frac{1}{2\alpha(\phi)}\frac{d\ln I}{d\phi}\bigg|_{N,J} = \frac{1}{2\alpha(\phi)}\frac{d\ln\Omega_{\mathrm{obs}}}{d\phi}\bigg|_{N,J},$$

where $\alpha(\phi) = \mathcal{A}'(\phi)/\mathcal{A}(\phi)$, N is the pulsar's baryon number and J is the Einstein-frame angular momentum.

Conformal ULDM

In order to look for a signal in PTAs, we should model how it affects the timing residuals.

$$\text{FJBD:} \quad \Delta t(t) = \frac{\Psi}{m} s_I \hat{\phi}(\boldsymbol{x}) \sin(mt + \theta(\boldsymbol{x})) \qquad \Psi = 2\alpha \frac{\sqrt{\rho}}{M_{\text{P}} m}$$

$$\text{DEF:} \quad \Delta t(t) = \frac{\Psi}{2m} \beta s_I \hat{\phi}^2(\boldsymbol{x}) \sin(2mt + \theta(\boldsymbol{x})) \qquad \Psi = \frac{\rho}{M_{\text{P}}^2 m^2}$$

- *correlated limit*
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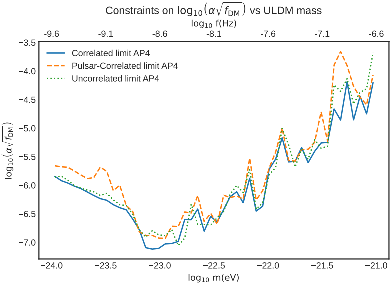
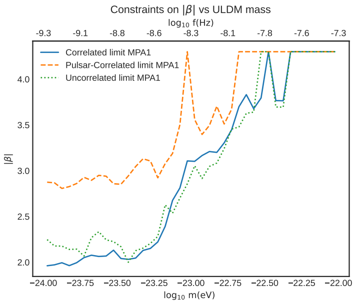
Conformal bounds vs ULDM mass

FJBD



Outcompete Cassini bounds in the relevant mass range!

DEF



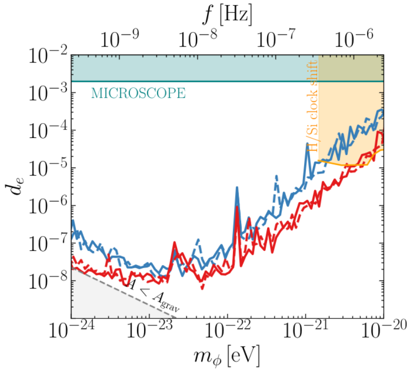
Improve on spontaneous scalarization bounds!

Bonus: Other ways to study ULDM

In the same way, one can also study ULDM couplings to the SM (Kaplan+ 2022).
The philosophy is the same:

- Define the Lagrangian
- Compute the induced timing residuals

$$\mathcal{L} \supset \frac{\phi}{M_{\rm pl}} \left(\frac{d_\gamma}{4e^2} F_{\mu\nu} F^{\mu\nu} - \sum_{f=e,\mu} d_f m_f \bar{f} f \right)$$



Bonus: Other ways to study ULDM

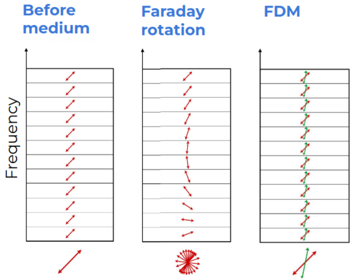
If assume non-renormolizable interaction between fuzzy DM particles and photons:

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

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

Polarization properties of light are altered

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

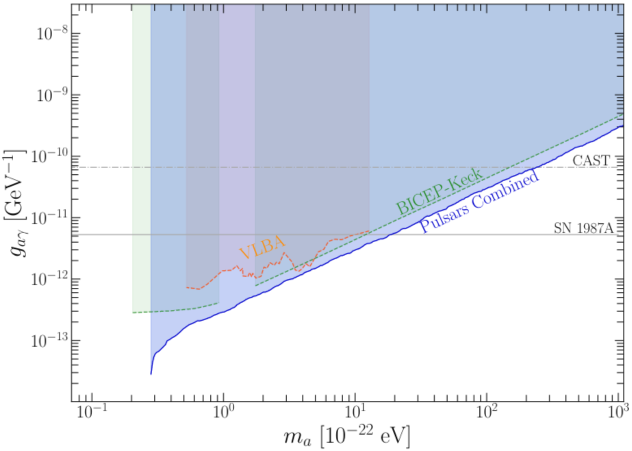


$$\Delta(\mathrm{PA}(t)) = \frac{g_{a\gamma}}{\sqrt{2}m}[\mathrm{p}(t_E, x_E) - \mathrm{p}(t_p, x_p)], \quad p(t_E, x_E) = \sqrt{\rho_{\mathrm{DM}}}\kappa_E\cos(mt + \phi(x_E))$$

See: Ivanov et al 2018, Castillo et al 2022

Courtesy of N. Porayko

Bonus: Other ways to study ULDM



Castillo+ (2022)

A few concluding remarks

- PTAs are wonderful laboratories to test signatures in signals coming from pulsars;
- It is possible to constrain ULDM density below the predicted abundance;
- If ULDM is non-minimally coupled to the SM, PTA searches can outcompete previous bounds (*e.g.* Cassini GR bounds or spontaneous scalarization) by several orders of magnitude in the relevant mass range;
- It is in general possible to set competitive constraints on ULDM couplings to the SM.

Final Considerations

"Physics is not stressful"
Tullio Levi Civita, 27 years old.

APPENDIX

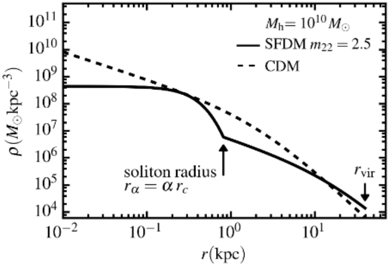
ULDM: some formulae

This behaviour can be easily seen by solving the relevant set of equations, namely the *Schrödinger-Poisson* system:

$$
\begin{aligned}
i\hbar\frac{\partial\psi}{\partial t} &= -\frac{\hbar^2}{2m}\nabla^2\psi + mV\psi \\
\nabla^2 V &= 4\pi G(\rho - \bar{\rho})
\end{aligned}
$$

Solving this numerically, we have a soliton-like behaviour at the centre and a NFW-like behaviour in the outskirts.

Robles et al. (2018)



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$$\phi(\mathbf{x}, t) = A(\mathbf{x}) \cos(mt + \alpha(\mathbf{x}))$$

Energy momentum tensor:

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

from which

$$\rho_{DM} \equiv T_{00} = \frac{1}{2} m^2 A^2$$

ULDM: Gravitational interaction

To find the gravitational field produced by ULDM, we can write (Newtonian gauge)

$$ds^2 = (1 + 2\Phi(\mathbf{x}, t))dt^2 - (1 - 2\Psi(\mathbf{x}, t))\delta_{ij}dx^i dx^j$$

We can split the potentials in t-independent and t-dependent part

$$\Psi(\mathbf{x}, t) \simeq \Psi_0(\mathbf{x}) + \Psi_c(\mathbf{x}) \cos(\omega t + 2\alpha(\mathbf{x})) + \Psi_s(\mathbf{x}) \sin(\omega t + 2\alpha(\mathbf{x}))$$

From the trace of the ij components of Einstein equations

$$-6\ddot{\Psi} + 2\Delta(\Psi - \Phi) = 8\pi G T_{kk}$$

we get:

- $\Psi_0 = \Phi_0$;
- $\Psi_c = \frac{1}{2}\pi G A(\mathbf{x})^2 = \pi \frac{G\rho_{DM}(\mathbf{x})}{m_\phi^2}$
- $\Psi_s = 0$

ULDM: Gravitational delay

Now, remember what we wrote before:

"In order to look for a signal in PTAs, we should model how it affects the timing residuals!"

$$\Delta t(t) = -\int_0^t \frac{\Omega\left(t'\right) - \Omega_0}{\Omega_0} dt'$$

Skipping a little bit of details (Khmelnitsky and Rubakov, 2013), it turns out that(adapted from Porayko, 2018):

$$\Delta t(t) = \frac{\Psi_c}{2m_\phi}\left[\hat{\phi}_E^2 \sin\left[2m_\phi t + 2\alpha(x_e)\right] - \hat{\phi}_P^2 \sin\left[2m_\phi\left(t - \frac{d_p}{c}\right) + 2\alpha(x_p)\right]\right] \tag{2}$$

- *correlated limit*
- *pulsar-correlated limit*
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