Probing Ultralight Dark Matter with Binary Pulsars

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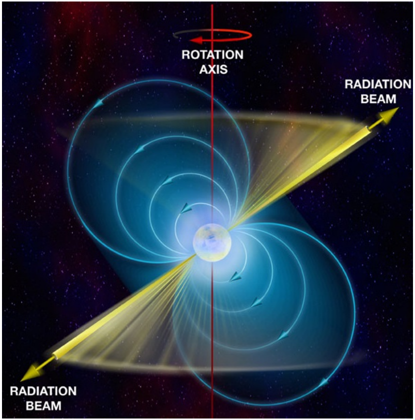
Outline

1. Binary pulsars
2. Pulsar timing
3. Ultralight dark matter and its effect on binary systems
4. Results
5. Conclusion

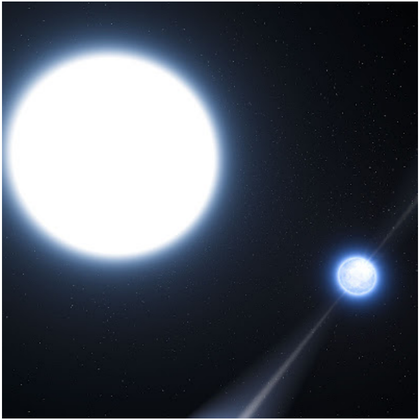
Outline

Binary pulsar

- pulsar = "pulse" + "star"
  = highly magnetised rotating neutron star which emits pulses of light, represents a very stable clock



(a) A pulsar



(b) A binary pulsar (it has 1 pulsar only)

Lighthouse effect

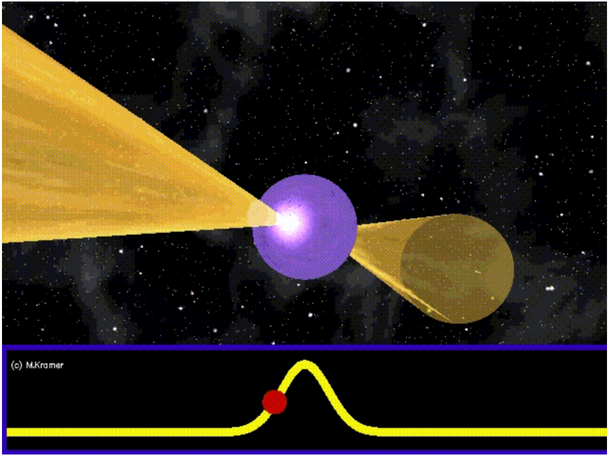


Figure 2: Lighthouse effect - idea

Keplerian formalism

- 6 orbital parameters, e.g.: a, e, i, Ω, ω, t_0

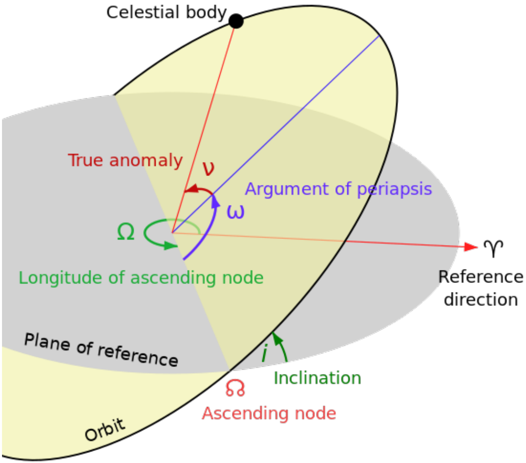


Figure 3: Orbital parameters

Perturbation of Keplerian orbits

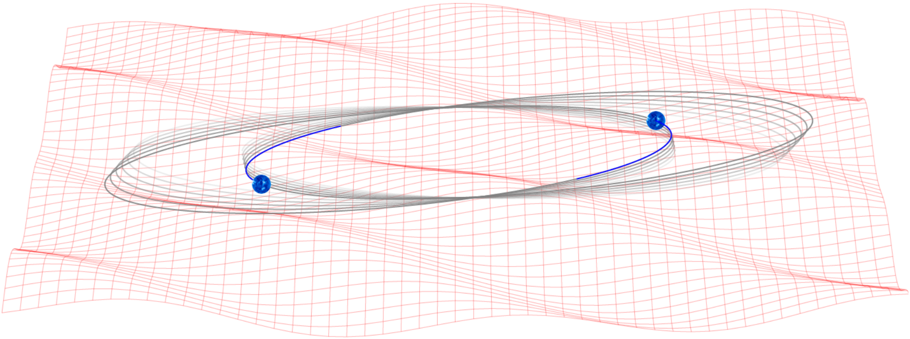


Figure 4: Perturbed Keplerian orbit

$\rightarrow$ Post-Keplerian formalism

$$\dot{a} = \frac{2}{\omega_b}\left(\frac{F_r e}{\sqrt{1-e^2}}\sin\theta + \frac{F_\theta}{r}a\sqrt{1-e^2}\right)$$

Outline

Timing model

- basic quantities:

$$
\begin{aligned}
N &\ \dots\ \text{phase of the pulsar when emitted a pulse} \\
t &\ \dots\ \text{pulse's time of arrival} \\
N_0 &\ \dots\ \text{reference phase} \\
t_0 &\ \dots\ \text{reference time}
\end{aligned}
$$

- "ideal"/trivial case:

$$N = N_0 + \nu(t - t_0)$$

- to describe reality is more difficult, N is a complicated function

Timing model

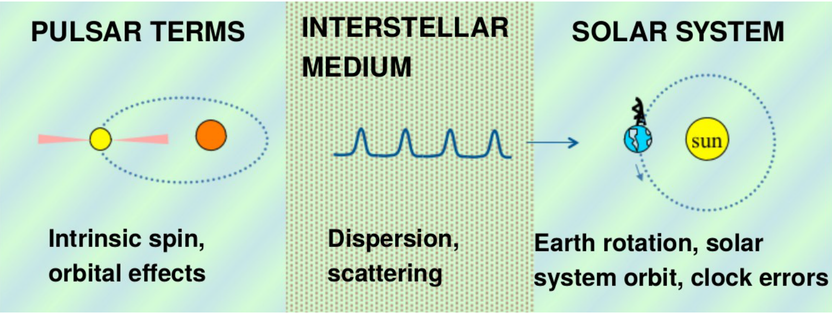


Figure 5: What makes N complicated in terms of t

Spoiler alert: We want to add one more effect to the picture, the interaction of ULDM with matter (components of the binary system)!

Timing model

- once we have a model for N and first parameter estimates, we can calculate the time residuals δt:

$$-\nu^{(1)}\delta t = \frac{\partial N}{\partial N_0}|_{(1)}\delta N_0 + \ldots ,$$

  where δN_0 is the difference between the actual and estimated value, etc.

- contributions to δt:
  1. inaccuracy in parameter determination
  2. oversimplified model
  3. noise

Timing model

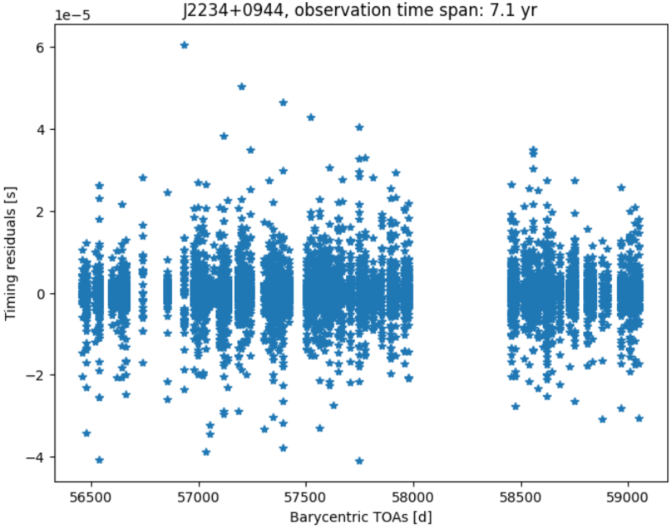


Figure 6: Example of time residuals calculated with PINT

Outline

(Ultralight) dark matter

- bosonic particles with $m \sim 10^{-22} \div 1$ eV
- huge phase space occupanion number
  $\rightarrow$ wave nature, creates interference patterns, locally described by a classical field (scalar, vector, tensor) $\Phi = \Phi_0 r \cos(m_\Phi t + B)$

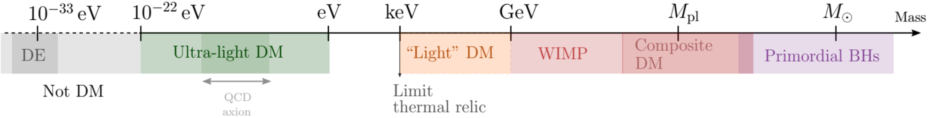


Figure 7: Dark matter models - range of masses

ULDM-binary system interaction

- if $m \sim 10^{-22} \div 10^{-18}$ eV, negligable backreaction
- for simplificity, scalar field and universal interaction with

$$M_A(\Phi) = \bar{M}_A(1 + \lambda\Phi),$$

- perturbation of binary dynamics by ULDM:

$$\ddot{\vec{r}} = -\,(1 + \lambda\Phi)\frac{G\bar{M}_T\vec{r}}{r^3} - \lambda\dot{\Phi}\,\dot{\vec{r}} = -\frac{G\bar{M}_T\vec{r}}{r^3} + \vec{F},$$

$$\rightarrow \frac{\dot{a}}{a} = -\,\frac{2\lambda\Phi e\omega_b}{\sqrt{1-e^2}}\frac{a^2}{r^2}\sin\theta - \frac{2\lambda\dot{\Phi}(1 + e^2 + 2e\cos\theta)}{(1-e^2)}$$

Outline

Constraining ULDM with NANOGrav data

1. constructing a probability distribution function for using Bayes' theorem
2. special assumption: δt comes from UDLM and noise (Gaussian, white) only:
$$\delta t = \delta t^{\mathrm{DM}} + \delta t^{\mathrm{PN}},$$
3. the present results cannot rule out/confirm the ULDM model, but place a stronger constraint on the value of the coupling constant α
$$\sigma_\alpha^a = 2.55 \times 10^{11} \frac{\sigma_a}{x(t_{0,a})} \frac{m_\Phi/\mathrm{eV}}{\sqrt{\rho_a/(\mathrm{GeV/cm^3})}} \frac{1}{\sqrt{\tilde{\vec{F}}_a^2 + \tilde{\vec{E}}_a^2}},$$

where $\tilde{\vec{F}}_a^2$ and $\tilde{\vec{E}}_a^2$ some complicated functions, σ is the noise level and $x \equiv a_{\mathrm{pulsar}} \sin i$.

Low-eccentric binary systems

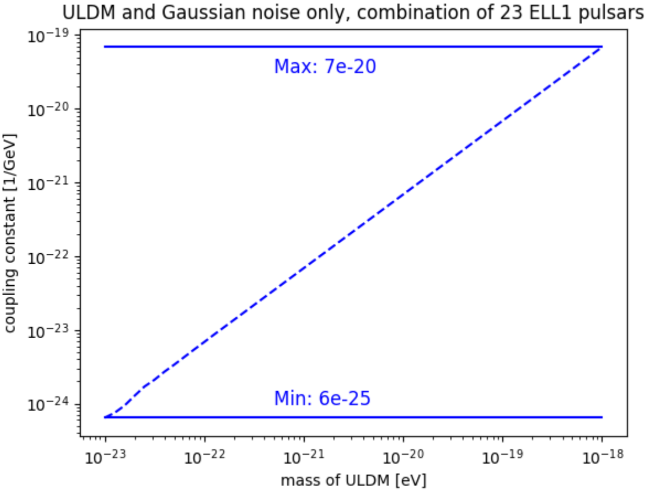


Figure 8: Blue line - constraint

High-eccentric binary systems

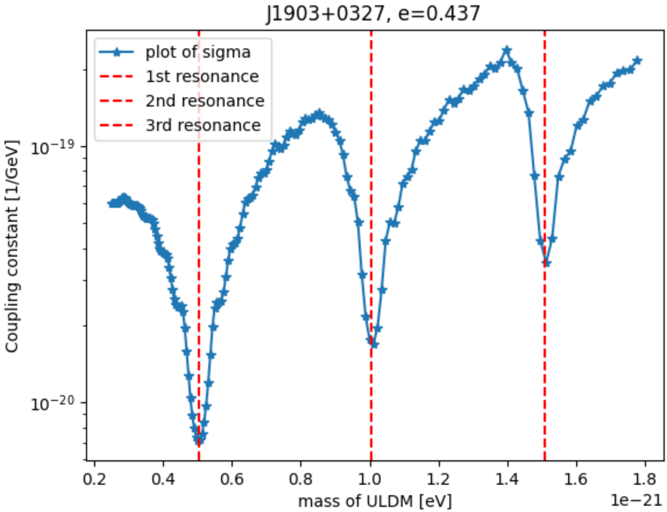


Figure 9: Blue line - constraint

Outline

Conclusion and Outlook

- We probe the particular model of ULDM, which includes interaction with ordinary matter via effective coupling constant λ, with binary pulsars.
- We achieve competing or even stronger constraints than those found in the literature.

- *It has not been shown here, but we have developed a procedure that can account for multiple contributions to δt, not just ULDM and noise.*
- *We will extend the work to vector and tensor ULDM.*

Thank you for your attention!

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