Binary pulsars as fuzzy dark matter detectors

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Abstract

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We devise a method that enables us to compute the sensitivity limit to ULDM with binary pulsars and apply it to the case of a universal, linearly-coupled, scalar ultra-light dark matter.

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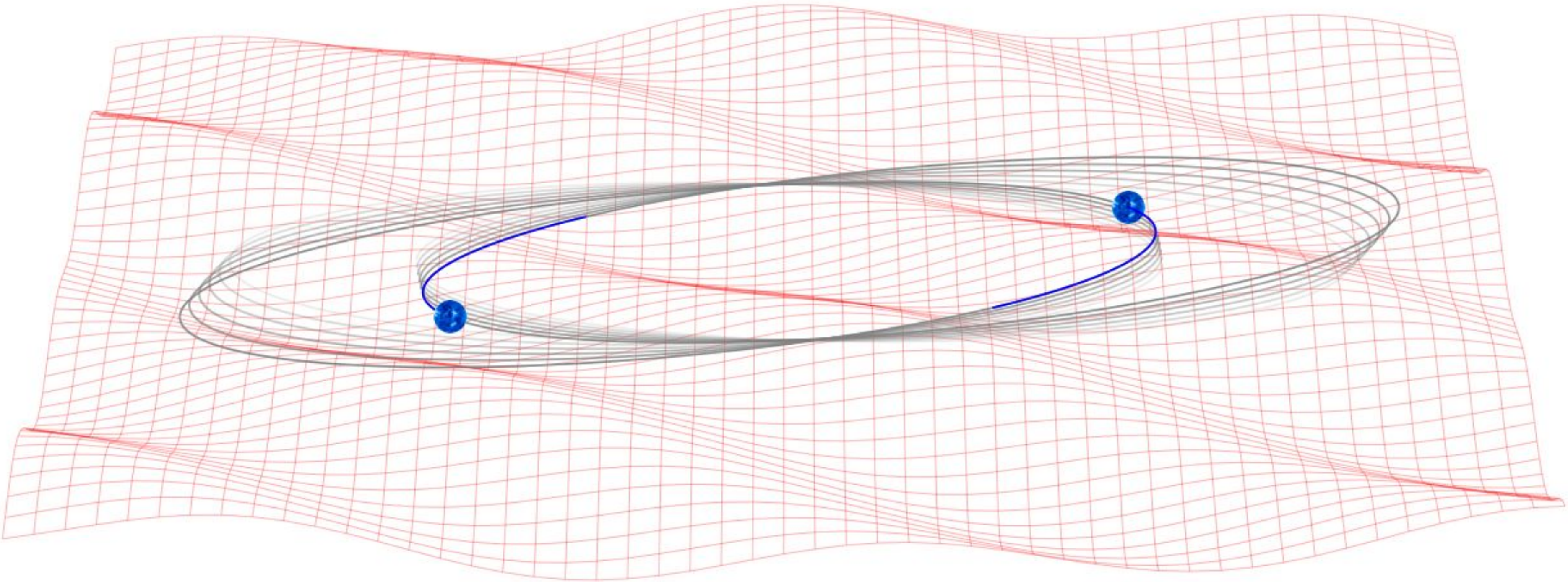
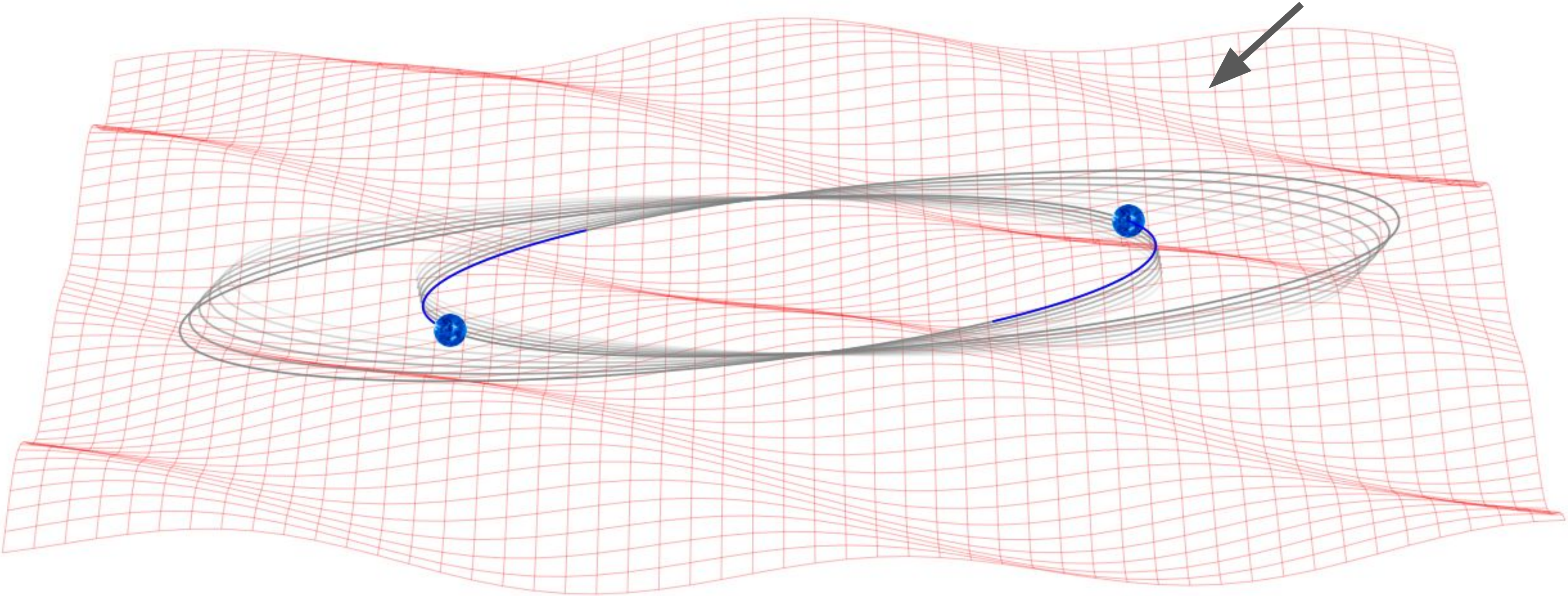


Figure comes from https://arxiv.org/pdf/2107.04063.pdf

1. Dark matter interaction



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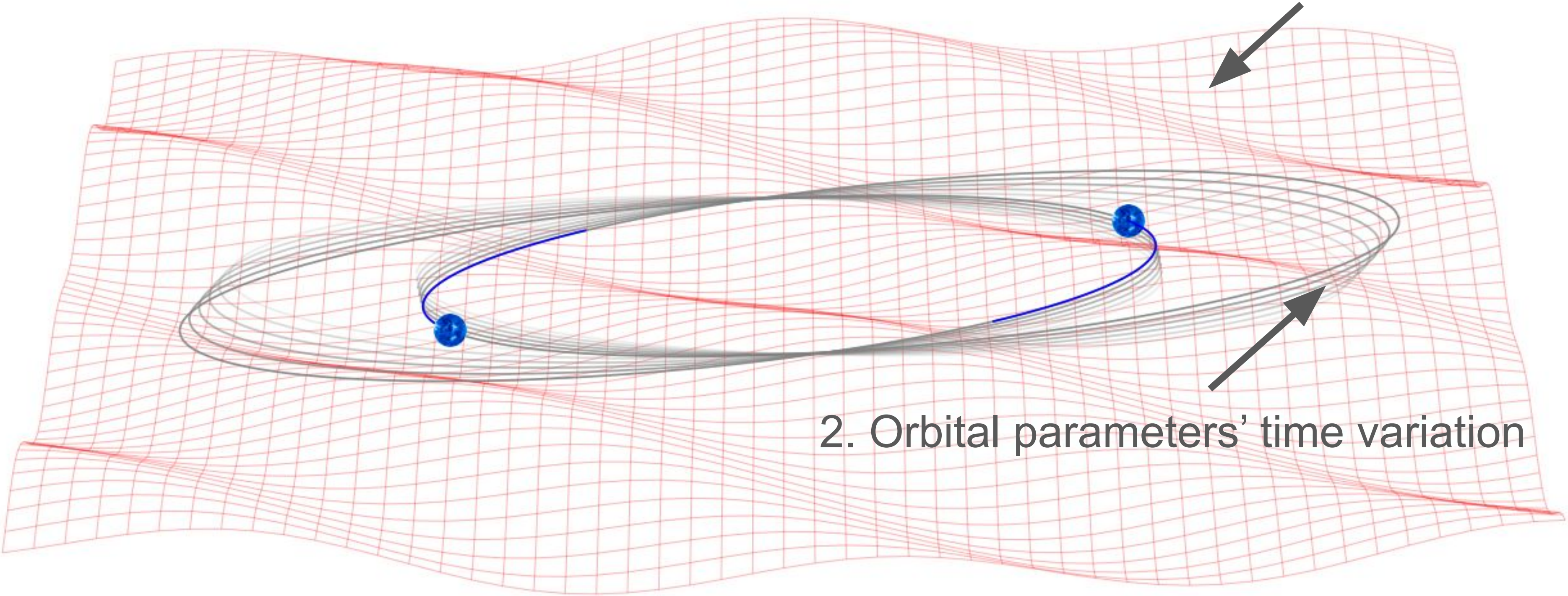

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ULDM models and Binaries

Interaction: gravitational and/or **direct**

Probed masses: $m = 10^{-23}\,\mathrm{eV} \div 10^{-18}\,\mathrm{eV}$ (back-reaction negligible)

Spin 0 Φ $$M_{1,2}^{(\alpha)}(\Phi) = M_{1,2}\,(1+\alpha\,\Phi) \quad \text{or} \quad M_{1,2}^{(\beta)}(\Phi) = M_{1,2}\left(1+\frac{\beta}{2}\,\Phi^2\right)$$ arXiv:1612.06789, arXiv:1910.08544

Spin 1 $\vec{A}$ $$L_{\rm int} = q_1\dot{\vec{r}}_1\cdot\vec{A} + q_2\dot{\vec{r}}_2\cdot\vec{A}\,,$$ arXiv:1807.10491

Spin 2 $M_{\mu\nu}$ $$S_{\rm int} = \lambda\int d^4x\sqrt{-g}M_{\mu\nu}T^{\mu\nu}$$ arXiv:1909.13814

coupling constant

energy-momentum tensor of the binary

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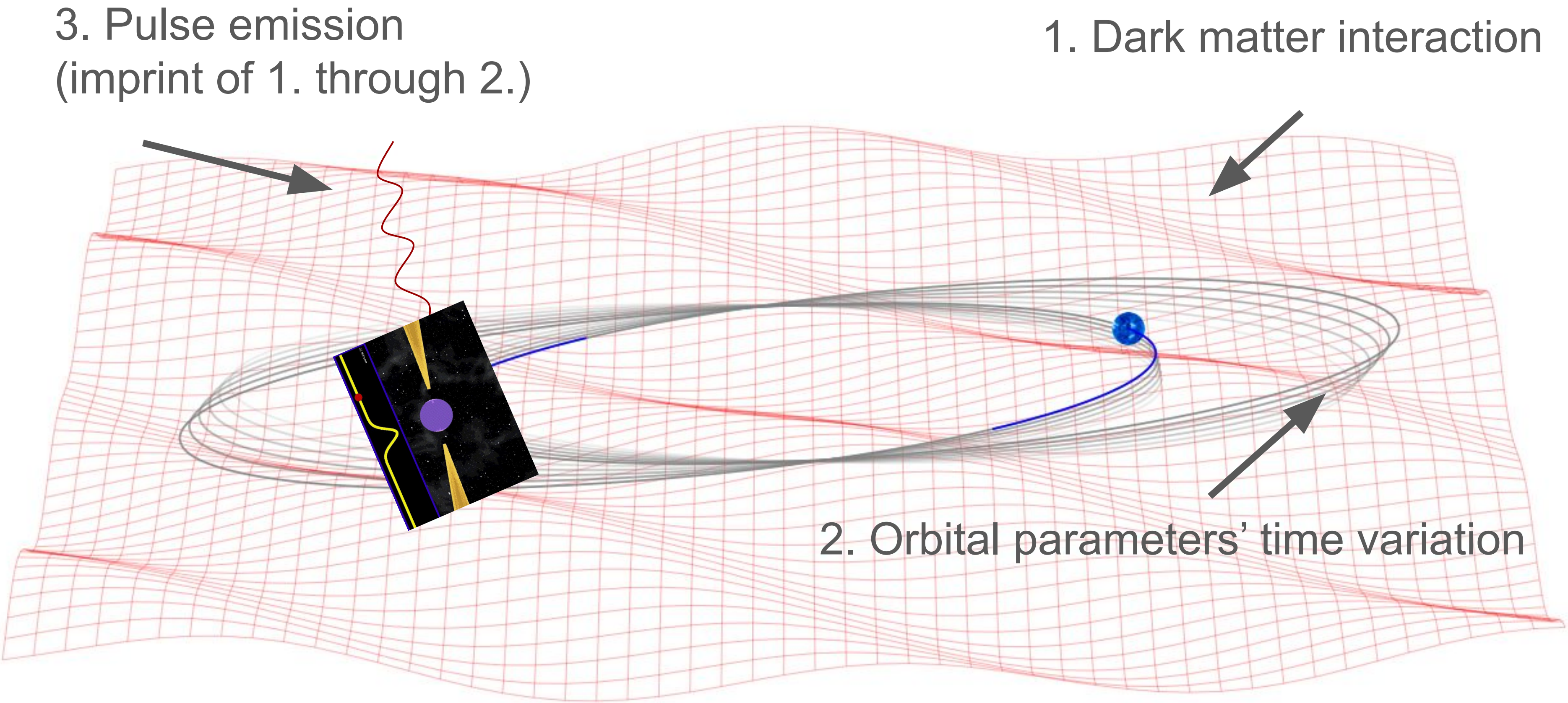

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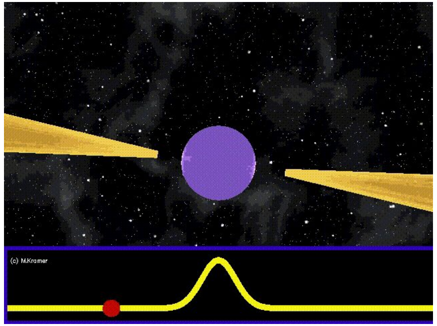
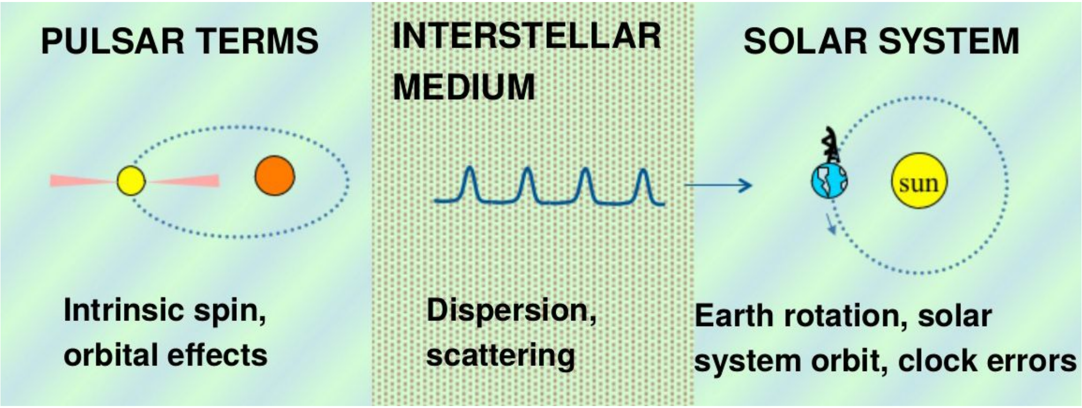
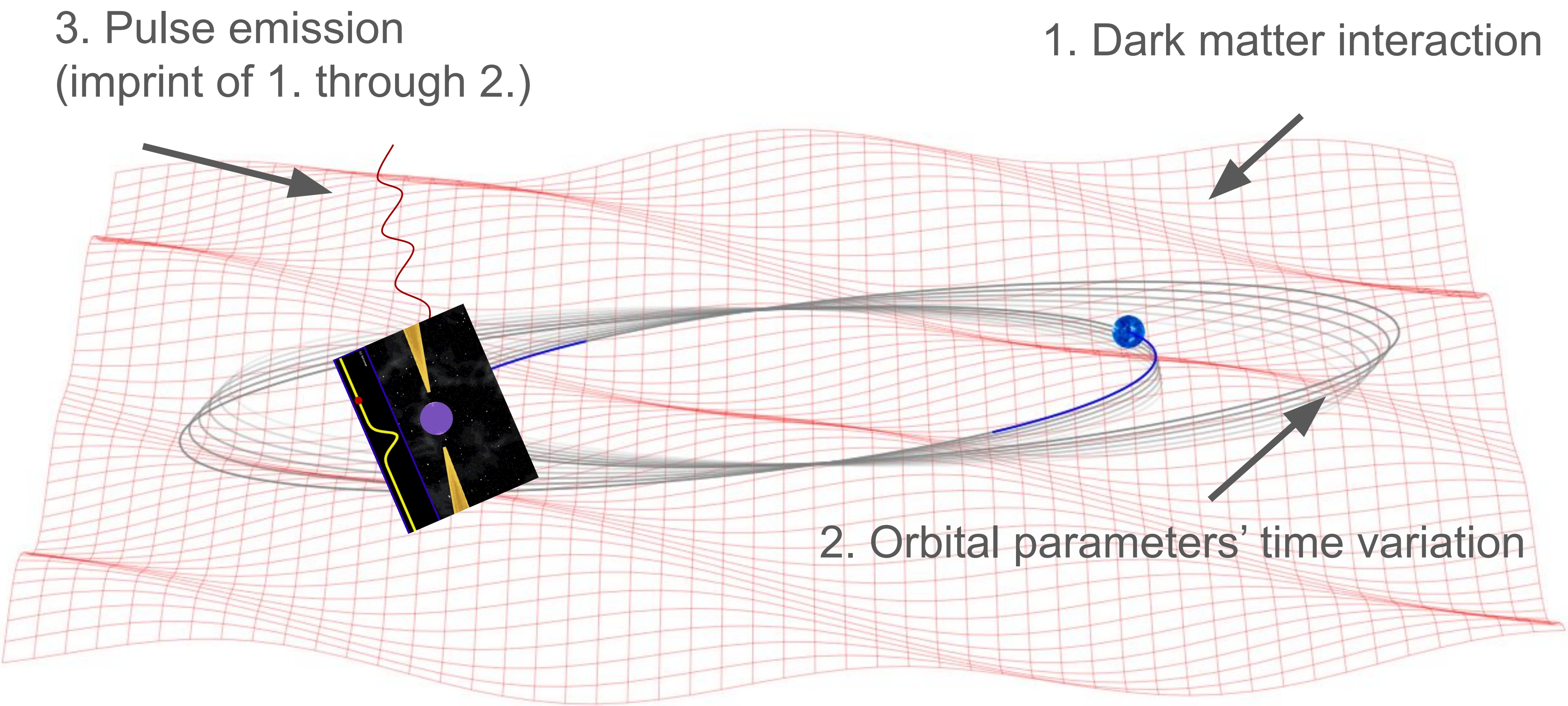
Pulsar timing



pulse propagation



Timing model = description of the propagation of pulses from the pulsar to the Earth *"binary pulsar"* = binary star with a pulsar as one component



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Bayes' Theorem

$$\overbrace{P(\theta \mid y)}^{\text{Posterior}} \propto \prod_{i}^{N} \underbrace{P(y_i \mid \theta)}_{\text{Data Likelihood}} \overbrace{P(\theta)}^{\text{Prior}}$$

A bit of theory

evidence for signal hypothesis

$$\mathcal{B} \equiv \frac{\mathcal{O}_h}{\mathcal{O}_n}$$

evidence for null hypothesis

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evidence for null hypothesis

nuisance parameters (errors, secular effects)

$$\mathcal{O}_n = \int \mathcal{L}(\Xi)\,\mathrm{d}\vec{\Xi}$$

$$\mathcal{O}_h = \int P(X,Y)P(\alpha,m)\mathcal{L}(\Xi,X,Y,\alpha,m)\,\mathrm{d}\vec{\Xi}\,\mathrm{d}X\,\mathrm{d}Y\,\mathrm{d}\alpha\,\mathrm{d}m\,,\, P(\alpha,m) = \delta(\alpha-\alpha_f)\delta(m-m_f)\,.$$

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$$\bar{\mathcal{B}} \equiv \int d\mathbf{n} P(\mathbf{n})\mathcal{B}$$

averaging over noise

$$\bar{\mathcal{B}}^C = \prod_{p=1}^{N_p} \bar{\mathcal{B}}_p = 1000$$ (depends on α)

combination of all pulsars

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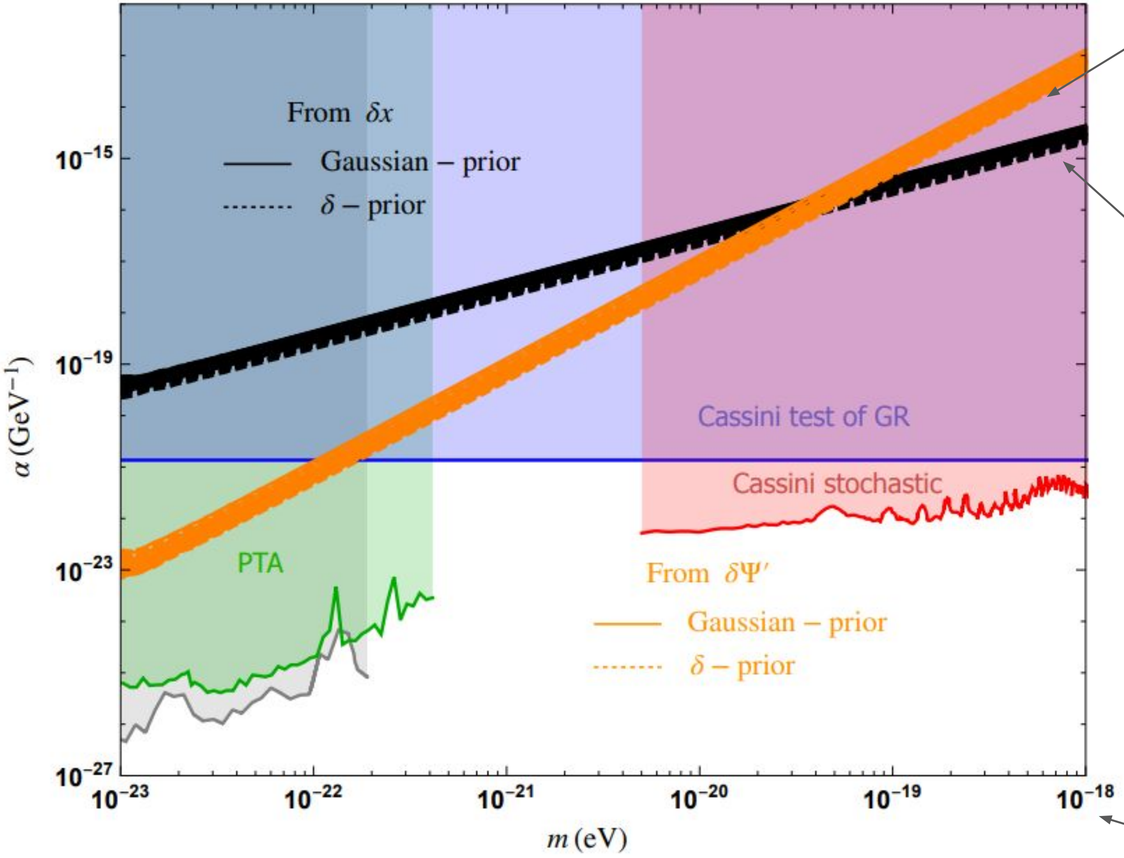
Limit on coupling constant of direct interaction

$$M_{1,2}^{(\alpha)}(\Phi) = M_{1,2}\,(1+\alpha\,\Phi)$$

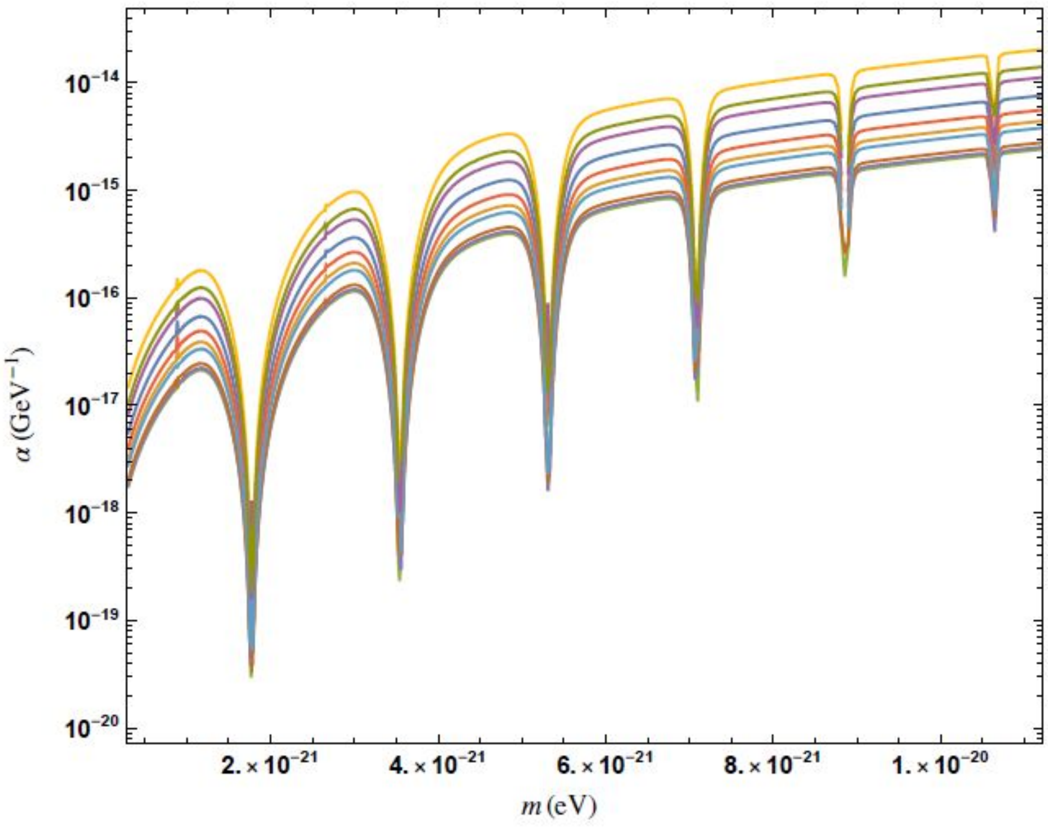


sensitivity line (from variation of $\Psi' = \int_{T_0}^{t} \omega_b dt'$)

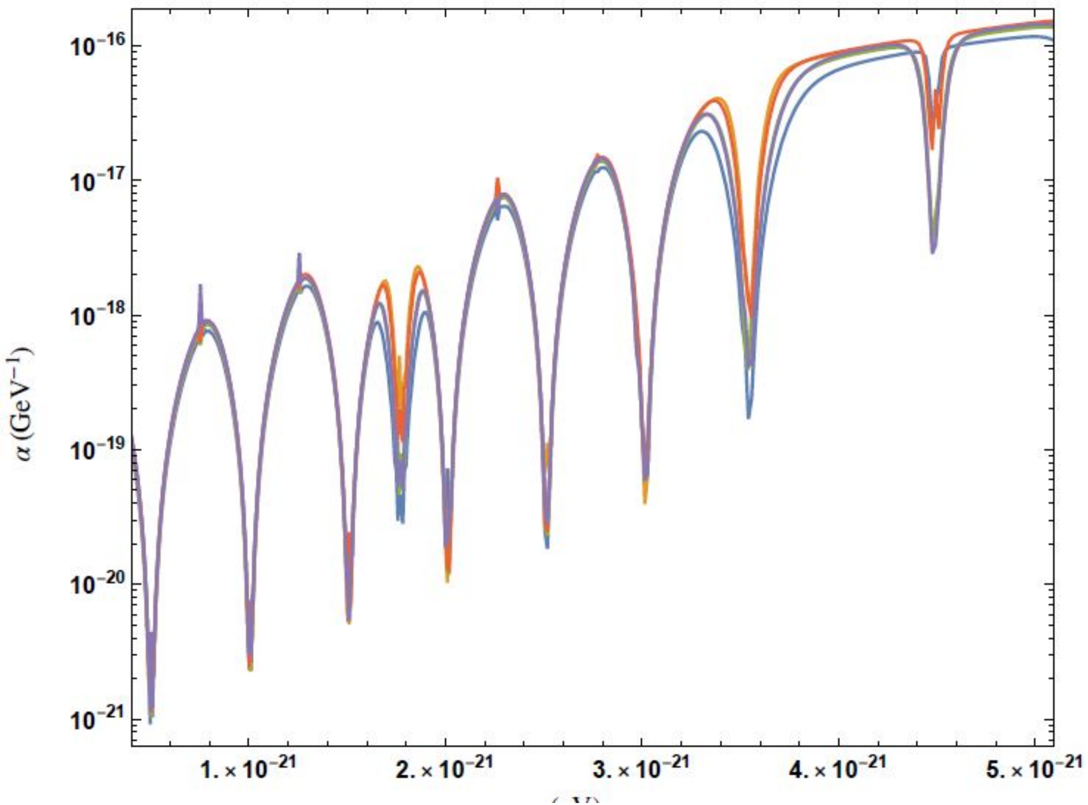
sensitivity line (from variation of $x = a_1 \sin\iota$)

Probed DM mass

111 binary pulsars from the ATNF catalogue and assuming next-generation radio-telescope precision (future SKA)



J1946+3417, NANOGrav



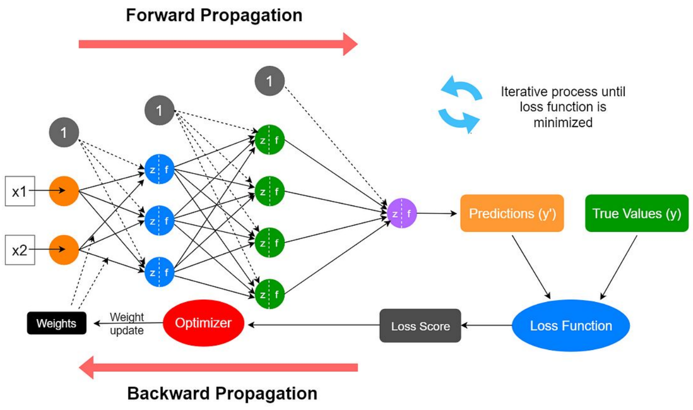
J1946+3417, J2234+0611, J1903+0327, NANOGrav

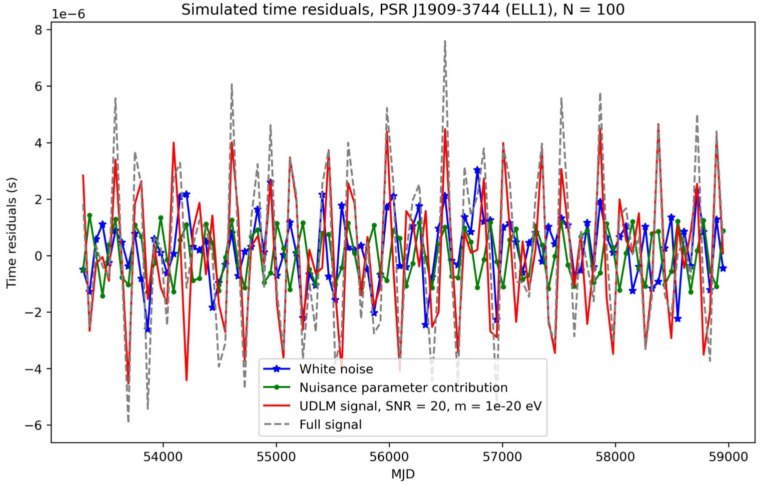
Summary

1. binary pulsars are *UDLM detectors*
2. new method → *Bayesian sensitivity lines*
3. applied to *scalar ULDM*, large portion of DM *phase space constrained*
4. *forecast* of the constraining power of data, not an actual data analysis
5. each orbital parameter has a *different constraining power* (main x, Ψ')
6. ELL1 binaries — even more restrictive than eccentric (BT) systems!

Outlook

1. Generalization to spin 1 and 2
2. Application of Machine learning to search for UDLM signals in data





Thank you for your attention!

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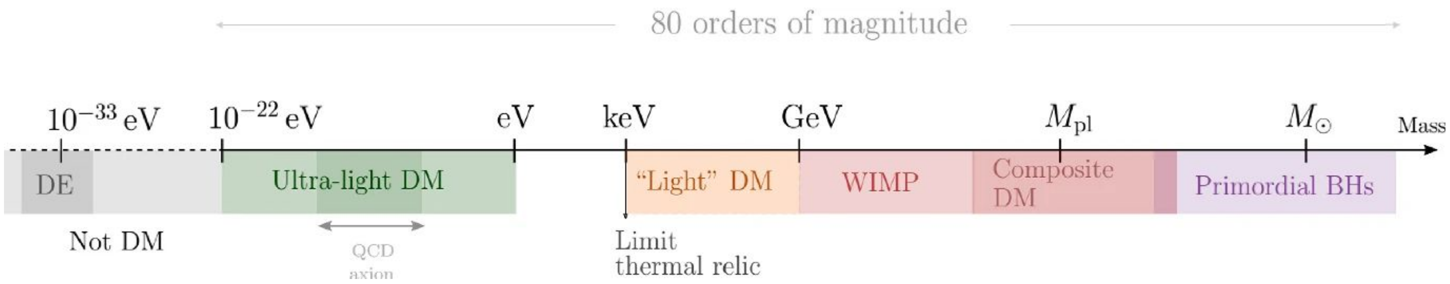
Backup slides

ULDM



Dark matter particle

$$m = 10^{-23}\,\mathrm{eV} \div 1\,\mathrm{eV}$$

very light bosons

de Broglie wavelength of astrophysical scale

$$\lambda_{\rm dB} \sim 1.3 \times 10^{12}\,\mathrm{km}\left(\frac{10^{-3}}{V_0}\right)\left(\frac{10^{-18}\,\mathrm{eV}}{m}\right)$$

typical DM velocity in the Milky Way halo

Within the halo of typical galaxy

classical field theory description applicable

Schrödinger–Poisson system of eqs

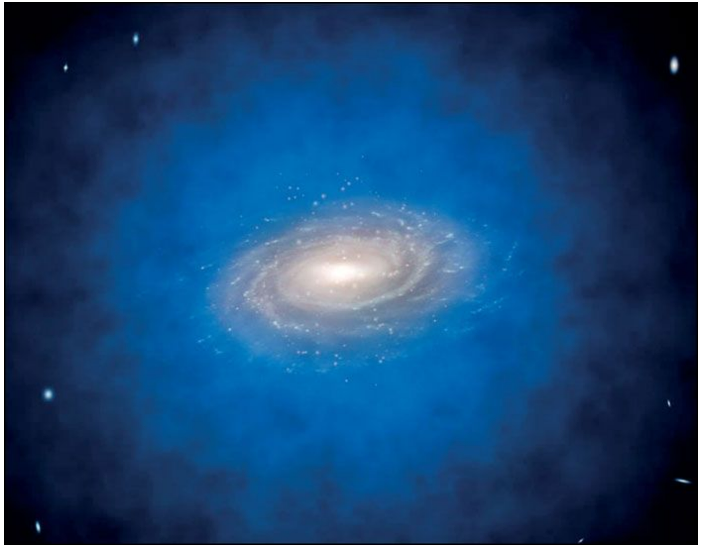
wave-like behavior, interference patterns

$$\Phi = \Phi_0 \varrho \cos(mt + \Upsilon) \qquad \Phi_0 \equiv \frac{\sqrt{2\rho_{\rm DM}}}{m}$$

Local DM amplitude

Local DM phase

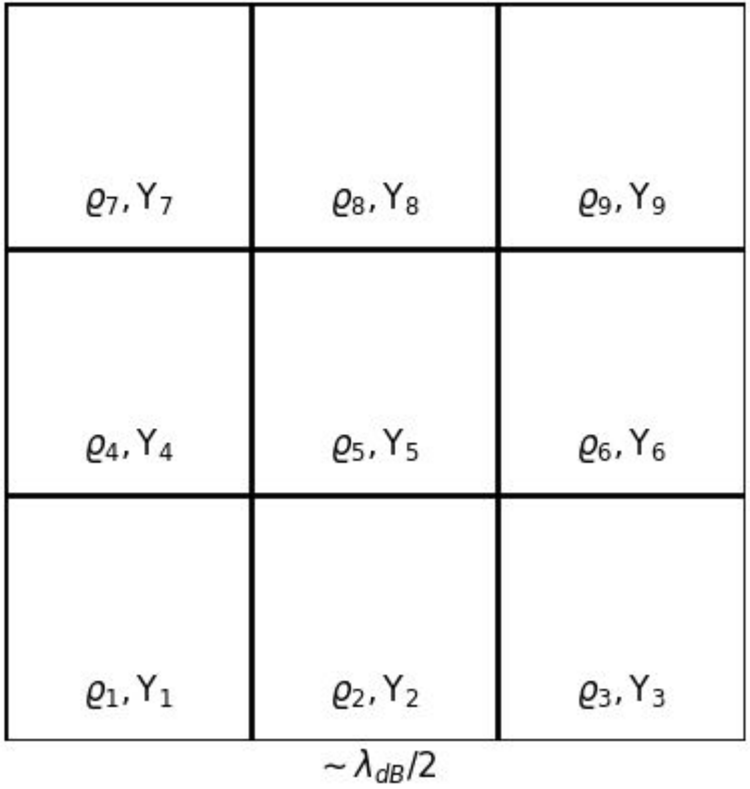
DM mass (= oscillation frequency)



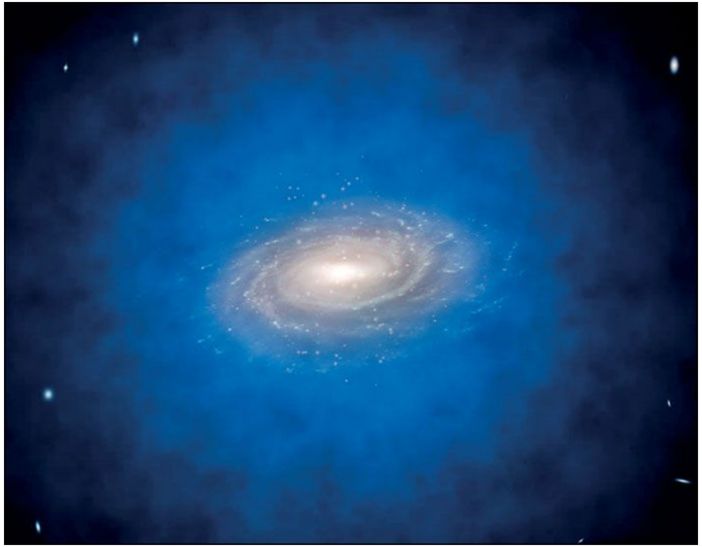
Granular structure

$\xrightarrow{\hspace{3em}}$

ULDM



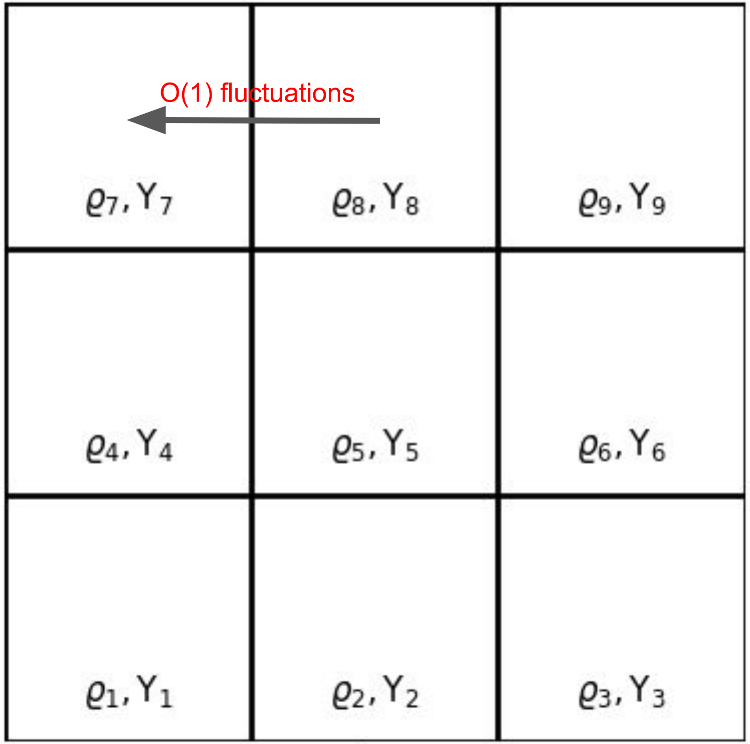
$$P(\varrho) = 2\varrho e^{-\varrho^2}, \; P(\Upsilon) = \frac{1}{2\pi}$$



Granular structure

ULDM

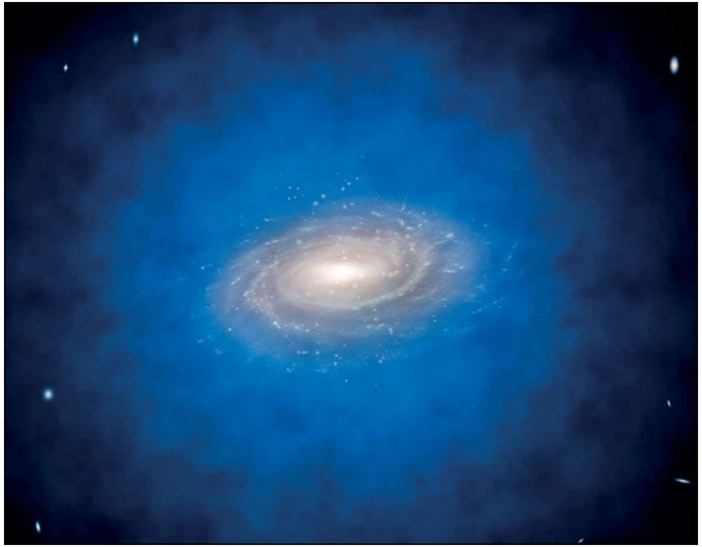
ULDM homogeneous
within one patch



$\sim \lambda_{dB}/2$

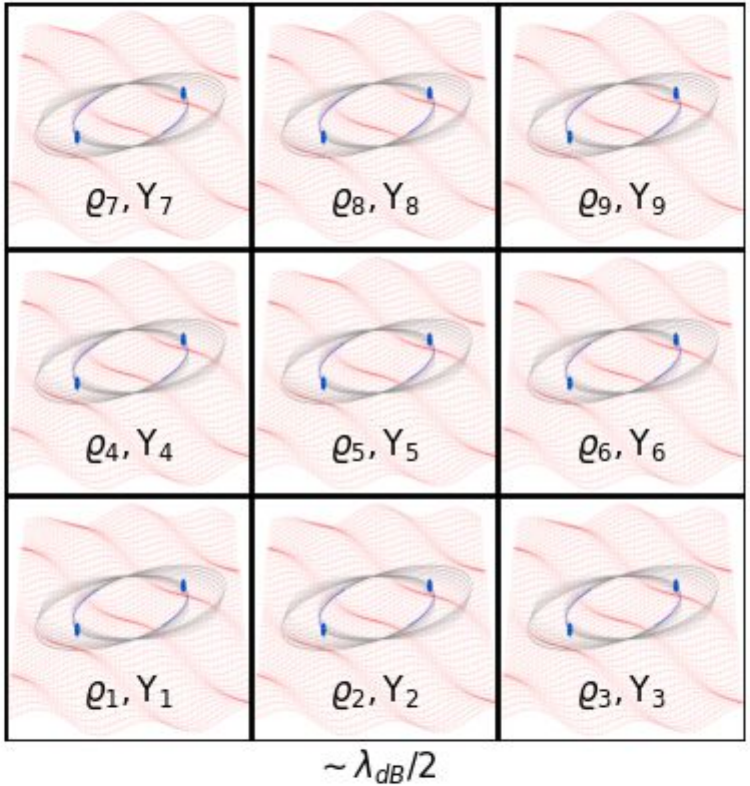
$$P(\varrho) = 2\varrho e^{-\varrho^2}, \ P(\Upsilon) = \frac{1}{2\pi}$$

arXiv:1711.10489



Granular structure

ULDM



Binary size << λ_{dB}

3 key assumptions

1. orbital resonance on P_b

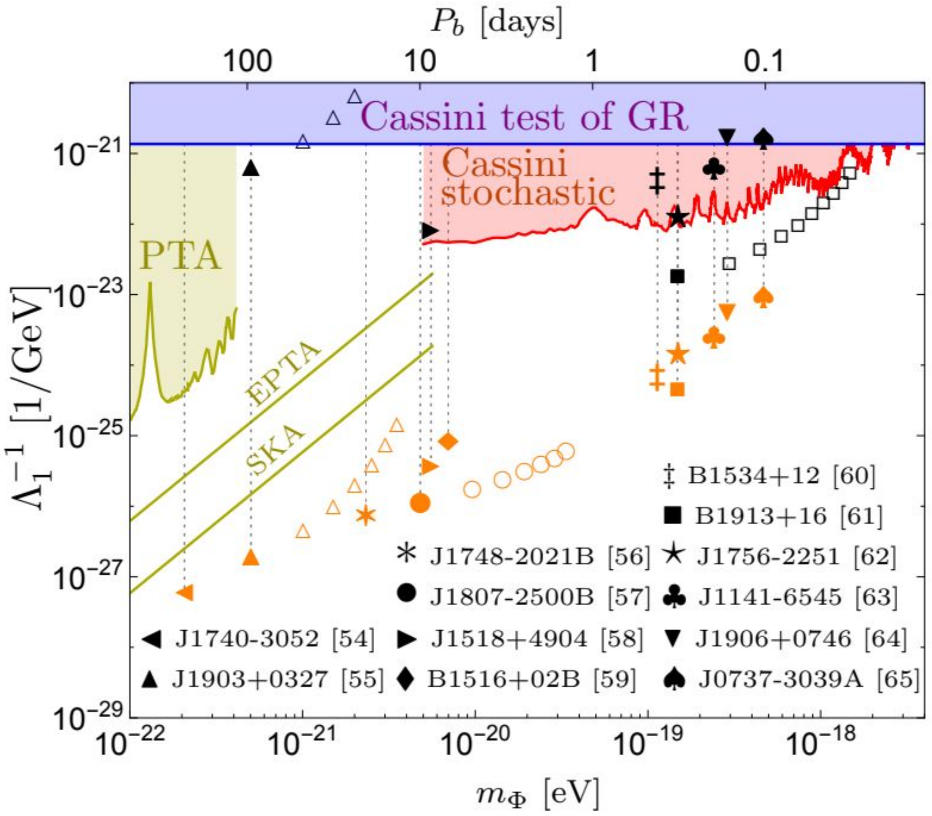
$$m = k\omega_b \, , \; k \in \mathbb{N}$$

2. $e \gg 0$

small subset of all pulsars

3. $\langle (\dot{P}_b)_{\mathrm{UDLM}} \rangle \leq (\dot{P}_b)_{\mathrm{error}}$

ignoring the time behaviour of the ULDM perturbations



New method:

1. beyond resonance (all masses)
2. any eccentricity
3. inclusion of the time behaviour of ULDM perturbations
4. combining all pulsars together to form one global sensitivity line.

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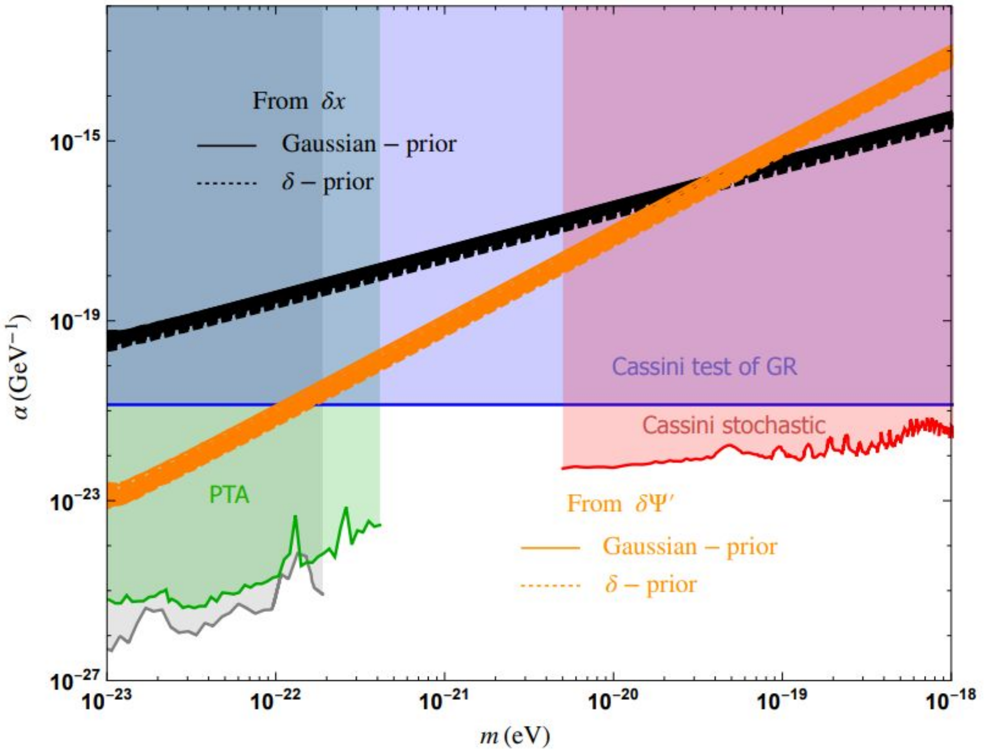

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Pulsar timing

$$N = N_0 + \nu T + \frac{1}{2}\frac{\mathrm{d}\nu}{\mathrm{d}T}T^2 + \frac{1}{6}\frac{\mathrm{d}^2\nu}{\mathrm{d}T^2}T^3$$

T … *proper time*
t … *infinite-frequency barycenter arrival time*
$T(t)$ … *timing model*

$$N = N_0 + \nu t + \frac{\dot\nu}{2}t^2 + \frac{\ddot\nu}{6}t^3 - \dot\nu x g(\Psi')t - \nu\, g(\Psi') + \nu\omega_b\, g(z)\frac{dg(z)}{dz}\bigg|_{z=\Psi'},$$

where $g(z) = -x\frac{\eta}{2}\cos 2z - x\frac{3\eta}{2} + x\frac{\kappa}{2}\sin 2z + x\sin z$ (binary terms)

ELL1, non-relativistic systems, low *e*

BT, non-relativistic systems, larger *e*

Time residuals

$\{N_0^{(1)}, \nu^{(1)}, \dots\}$ ... "first guess"

true values

estimated values

$$-\nu^{(1)} R(t) \equiv N(t, N_0, \nu, \dots) - N(t, N_0^{(1)}, \nu^{(1)}, \dots)\,,$$

definition of time residuals

variation of orbital parameters

$$R(t) = \delta K - \left.\frac{\partial N}{\partial x}\right|_1 \frac{\delta x}{\nu} - \left.\frac{\partial N}{\partial \eta}\right|_1 \frac{\delta \eta}{\nu} - \left.\frac{\partial N}{\partial \kappa}\right|_1 \frac{\delta \kappa}{\nu} - \left.\frac{\partial N}{\partial \Psi'}\right|_1 \frac{\delta \Psi'}{\nu}$$

$$\delta K \equiv -\frac{\delta N_0}{\nu} - \frac{\delta \nu}{\nu} t - \frac{\delta \dot{\nu}}{2\nu} t^2 - \frac{\delta \ddot{\nu}}{6\nu} t^3$$

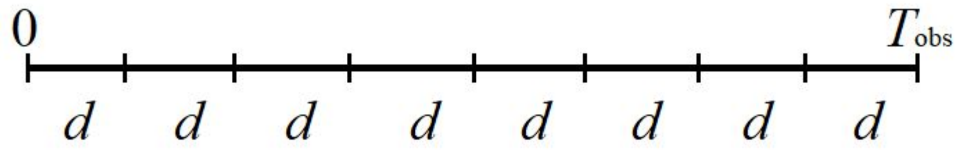
Post-Keplerian formalism:

Error Secular effect ULDM signal

$$\frac{\dot{x}}{x} = -2\alpha\dot{\Phi}\,, \quad \delta x(t) = \delta x_{\rm asc} + \dot{x}(t - T_{\rm asc}) - 2\alpha x \Phi_0 \varrho[\cos(mt + \Upsilon) - \cos(mT_{\rm asc} + \Upsilon)]$$

Two-step method

Step 1: variances $\quad \delta \mathsf{S}_{\mathrm{ELL1}} \equiv \{\delta K\,, \delta x\,, \delta\eta\,, \delta\kappa\,, \delta\Psi'\}$



n_c … cadence

$n_c d$ … number of observations

$$\frac{1}{\epsilon^2}\sum_{i=1}^{n_c d} \mathsf{M}^i \delta\mathsf{S} = \mathsf{D}$$

$$\sum_{i=1}^{n_c d} \mathsf{M}^i \simeq \frac{n_c d}{2\pi}\int_0^{2\pi} \mathsf{M}^i d\Theta' = n_c d \bar{\mathsf{M}}$$

$$\mathsf{C} = \frac{\epsilon^2}{n_c d}\bar{\mathsf{M}}^{-1}$$

Two-step method

Step 2: time-dependence

evidence for signal hypothesis

$$\mathcal{B} \equiv \frac{\mathcal{O}_h}{\mathcal{O}_n}$$

evidence for null hypothesis

nuisance parameters (errors, secular effects)

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(depends on α)

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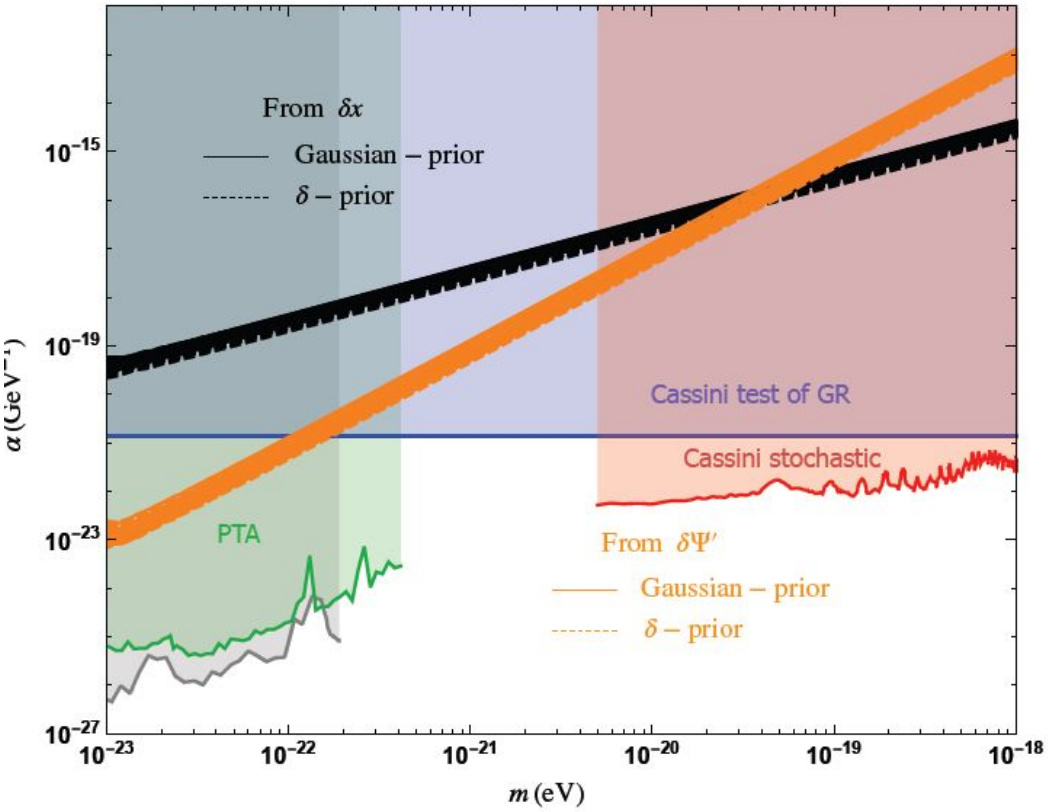

22 ELL1, NANOGrav