Secular effects of Ultralight Dark Matter on Binary Pulsars

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w/ D.Blas and D. Lopez Nacir

1612.06789, 1910.08544

BLV2019, IFT, Madrid

Ultralight Dark Matter

$$\mathcal{L} = \frac{1}{2}\left((\partial_\mu \Phi)^2 - m^2 \Phi^2\right)$$

For $m \lesssim 1\,\mathrm{eV}$ large occupation numbers $\Rightarrow$ classical field

focus on $m = (10^{-22} \div 10^{-18})\,\mathrm{eV}$

ALP
dilaton
relaxion …

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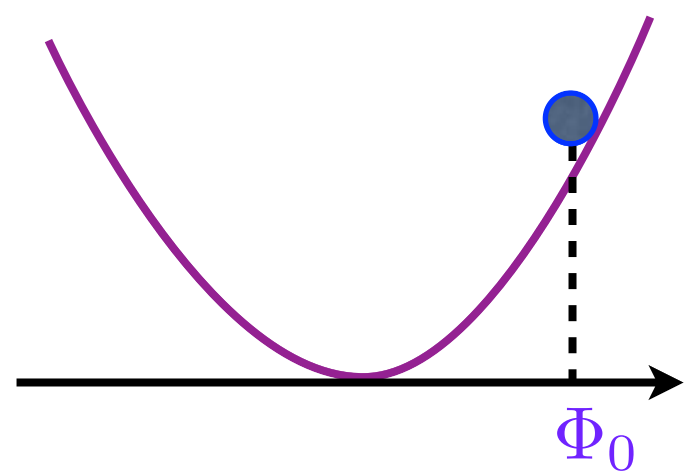
Production by misalignment:

- $H > m$ $\Rightarrow$ $\Phi = const$



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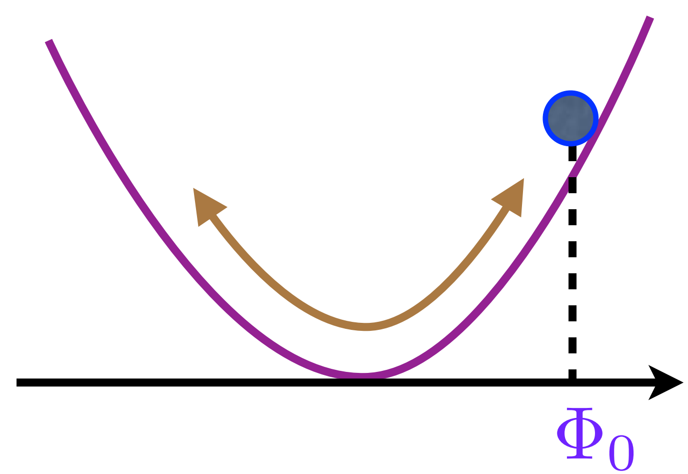
- $H > m$ $\Rightarrow$ $\Phi = const$
- $H < m$ $\Rightarrow$ $\Phi = \Phi_0 \cos(mt)$



density: $\rho = \frac{m^2\Phi_0^2}{2} \propto a^{-3}$

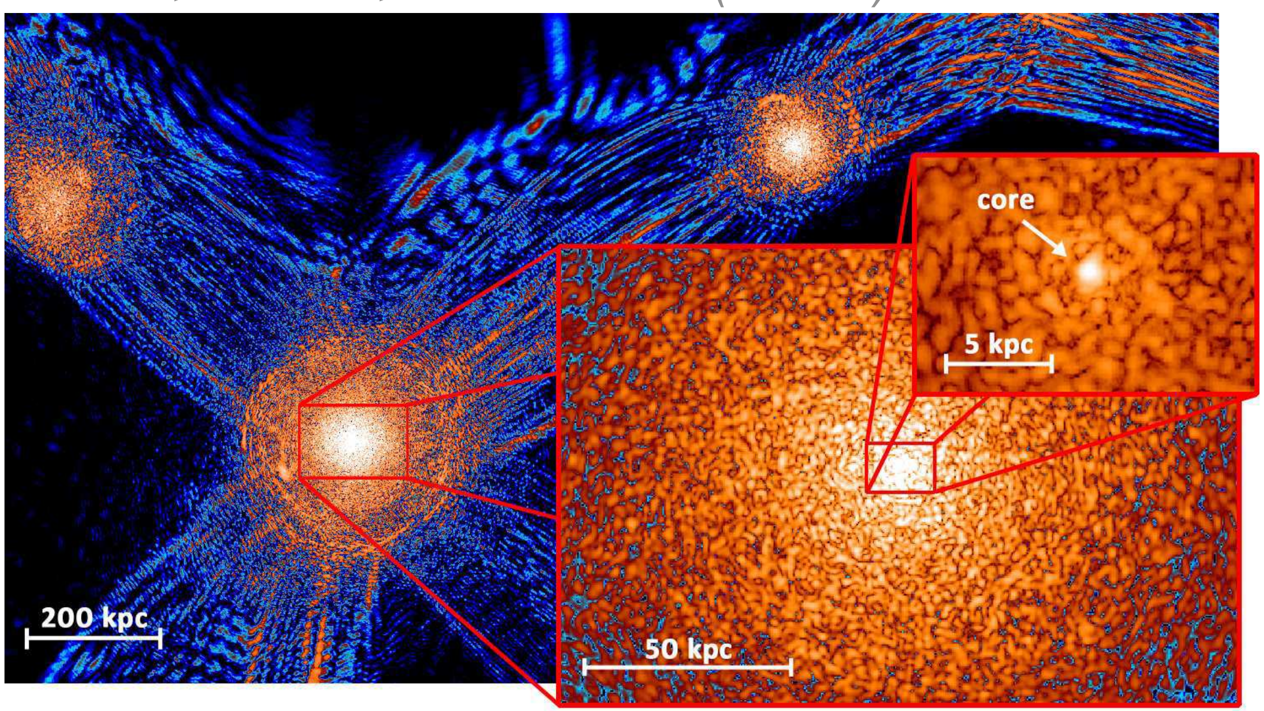
pressure: $p = -\rho\cos(2mt)$ averages to zero

ULDM in the halo

$$\Phi = \Phi_0(\mathbf{x}, t)\cos(mt + \Upsilon(\mathbf{x}, t))$$

slowly varying in space and time

Schive, Chiueh, Broadhurst (2014)



$$\Phi_0 = \frac{\sqrt{2\rho_{\rm DM}}}{m}$$

$$\nabla\Upsilon = -m\mathbf{V}$$

$$\nabla \log \Phi_0 \sim mV$$

- **coherent oscillations**
- **granular structure of the density**

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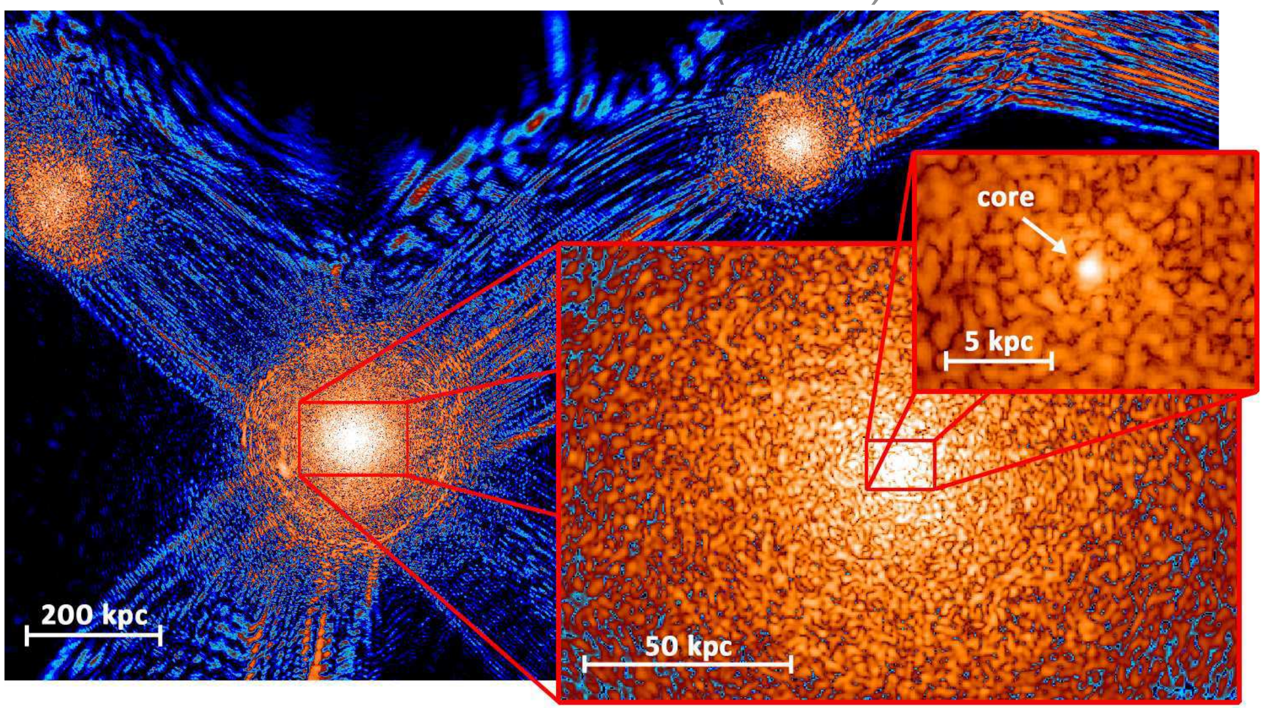

- **coherent oscillations**
- **granular structure of the density**

$$t_{\rm osc} \simeq 1.15\,\text{hours}\left(\frac{10^{-18}\text{eV}}{m_\Phi}\right)$$

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

$$t_{\rm coh} \sim 65\,\text{years}\left(\frac{10^{-3}}{V_0}\right)^2\left(\frac{10^{-18}\text{eV}}{m_\Phi}\right)$$

Cosmo/Astro probes

Pure gravity :

- Ly α forest, galactic rotation curves disfavour $m \lesssim 10^{-22}\,\mathrm{eV}$
- Eri II star cluster disfavours $10^{-20}\,\mathrm{eV} \lesssim m \lesssim 10^{-19}\,\mathrm{eV}$

Marsh, Niemeyer (2018)

Direct coupling — model dependent. **Universal :**

$$\mathcal{L}_{\mathrm{SM}}(g_{\mu\nu}, \psi) \mapsto \mathcal{L}_{\mathrm{SM}}(f(\Phi) g_{\mu\nu}, \psi)$$

preserves **Weak Equivalence Principle.**

Weak field constraints within Solar Systems (spacecraft tracking, planetary dynamics)

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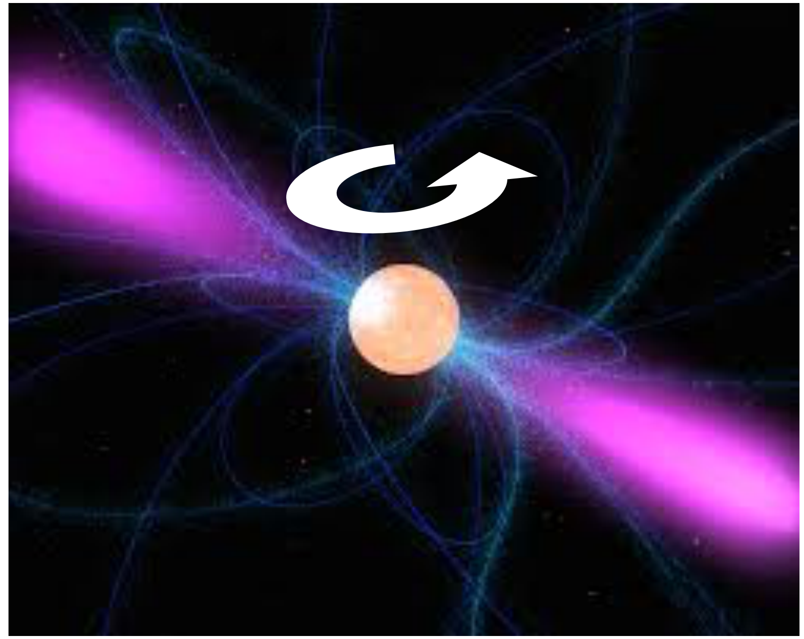
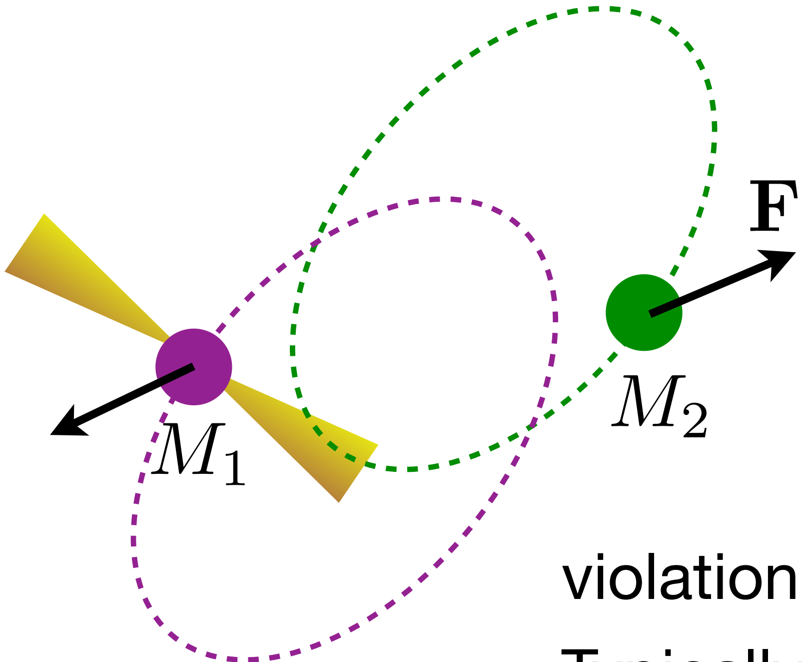
Millisecond pulsars



- Fast spinning Neutron Stars
- Very precise clocks at astronomical distances
- Majority in binary systems (with White Dwarfs, Main Sequence, other NS)
- Large fraction (~ 20%) of the mass from self-gravity

Orbital motion perturbed by ULDM



Extra force :

- Pure gravity: oscillating pressure
- Direct **linear** coupling: oscillating masses $M_A = \bar{M}_A(1 + \alpha_A \Phi)$

violation of Strong Equivalence Principle $\alpha_1 \neq \alpha_2$

Typically $\Delta\alpha \sim 0.2\,\alpha$ or bigger if spontaneous scalarization

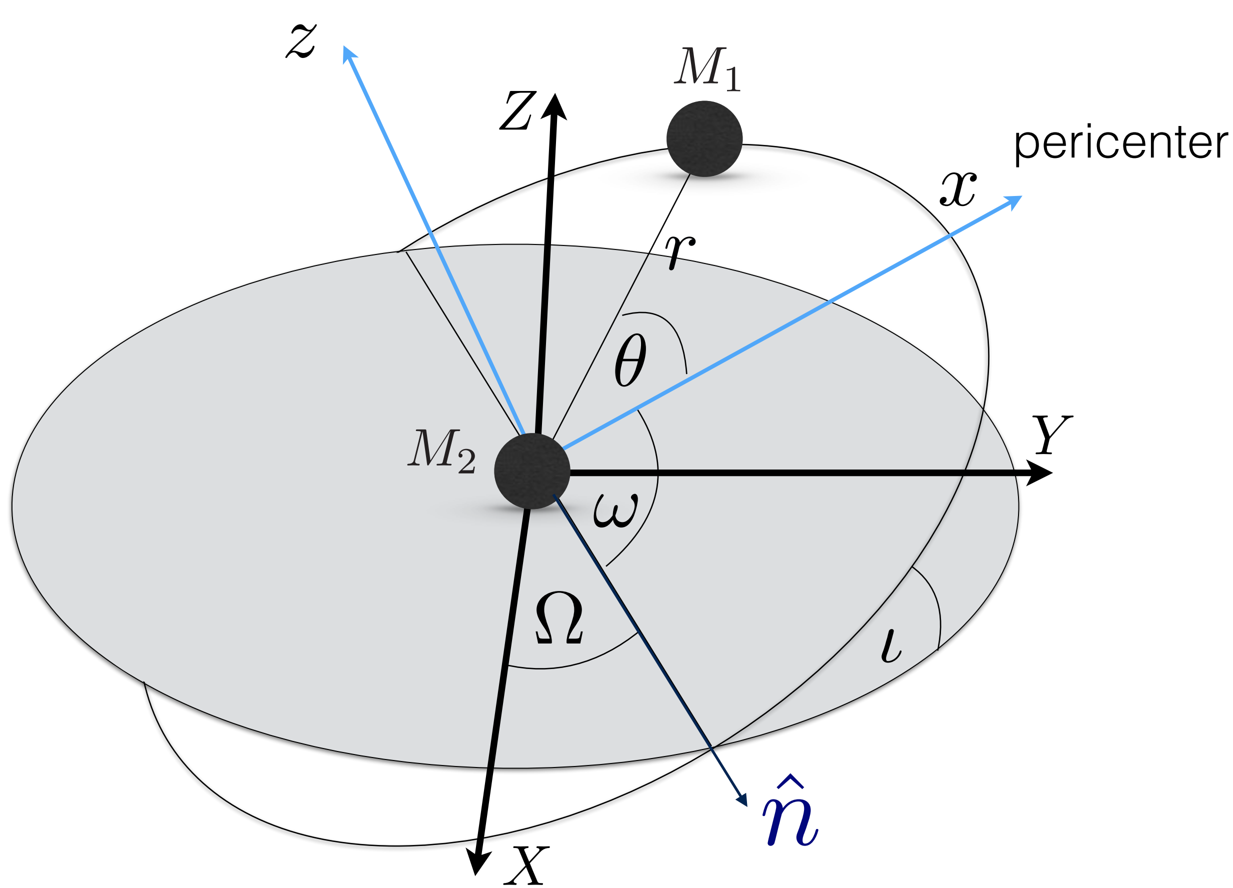
Damour, Esposito-Farese (1993)

- Direct **quadratic** coupling: masses depending on local DM density $M_A = \bar{M}_A\left(1 + \frac{\beta_A}{2}\Phi^2\right)$

$\langle \Phi^2 \rangle \propto \rho_{\mathrm{DM}}$

Osculating orbits

The orbit is determined by six parameters: $a,\ e,\ t_0,\ \Omega,\ \omega,\ \iota$



In general, all will drift under the influence of ULDM

Main effects

- **Resonant:** drift of the orbital period $\delta E_b = \mu \int_0^{P_b} \dot{\mathbf{r}}\, \mathbf{F}\, dt$

$$P_b \propto |E_b|^{-3/2} \quad \Rightarrow \quad \boxed{\dot{P}_b}$$

  + present in all cases, measured precisely

  – sizable only in narrow bands $m \simeq N\omega_b$ (or $m \simeq N\omega_b/2$), $N > 1$ requires eccentric orbits, contaminated by systematics

- **Non-resonant:** polarization of the orbit $\delta L_b = \mu \int_0^{P_b} \mathbf{r} \times \mathbf{F}\, dt$

$$L_b^2 \propto P_b^{2/3}(1 - e^2) \quad \Rightarrow \quad \boxed{\dot{e}}$$

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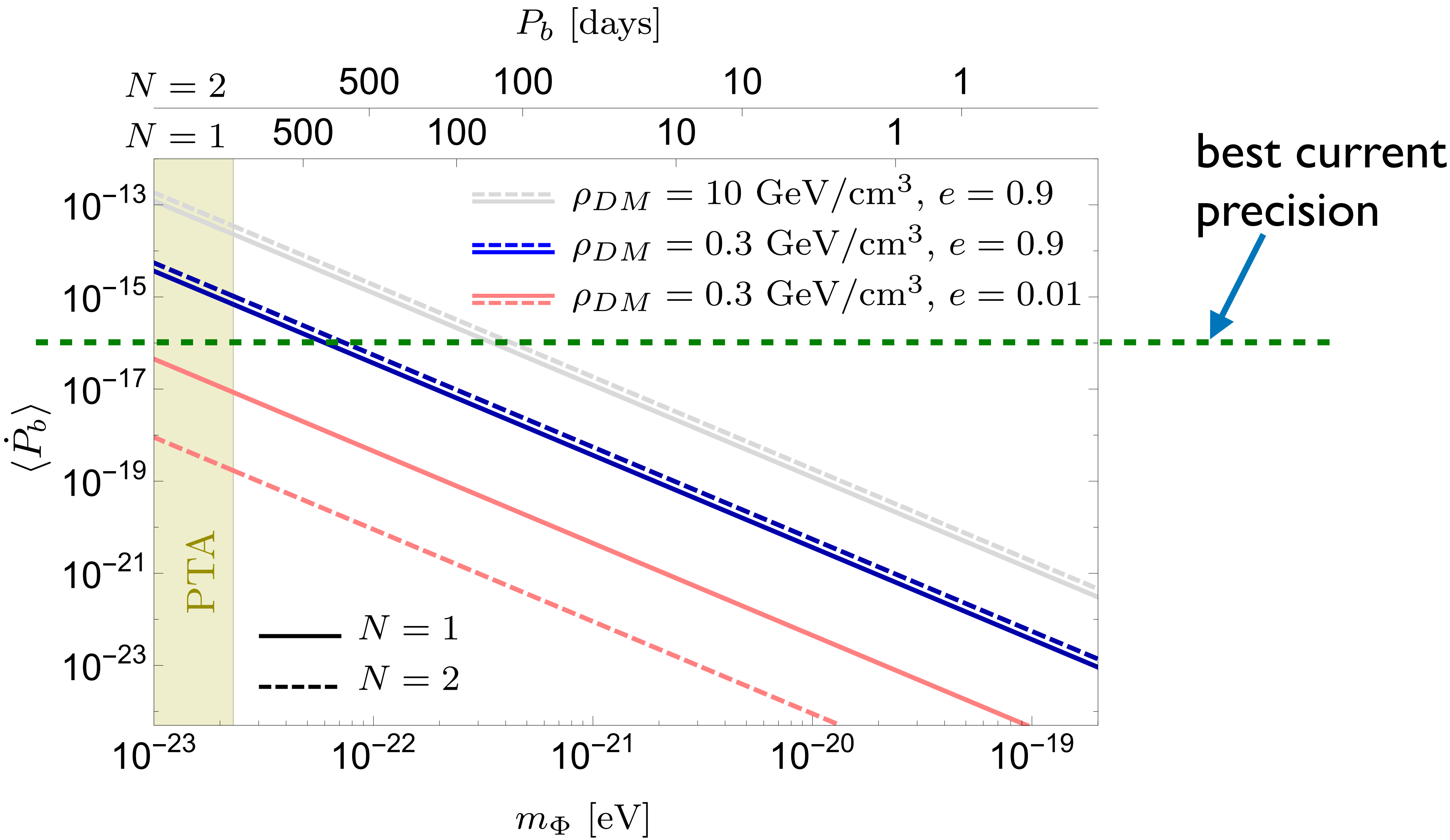

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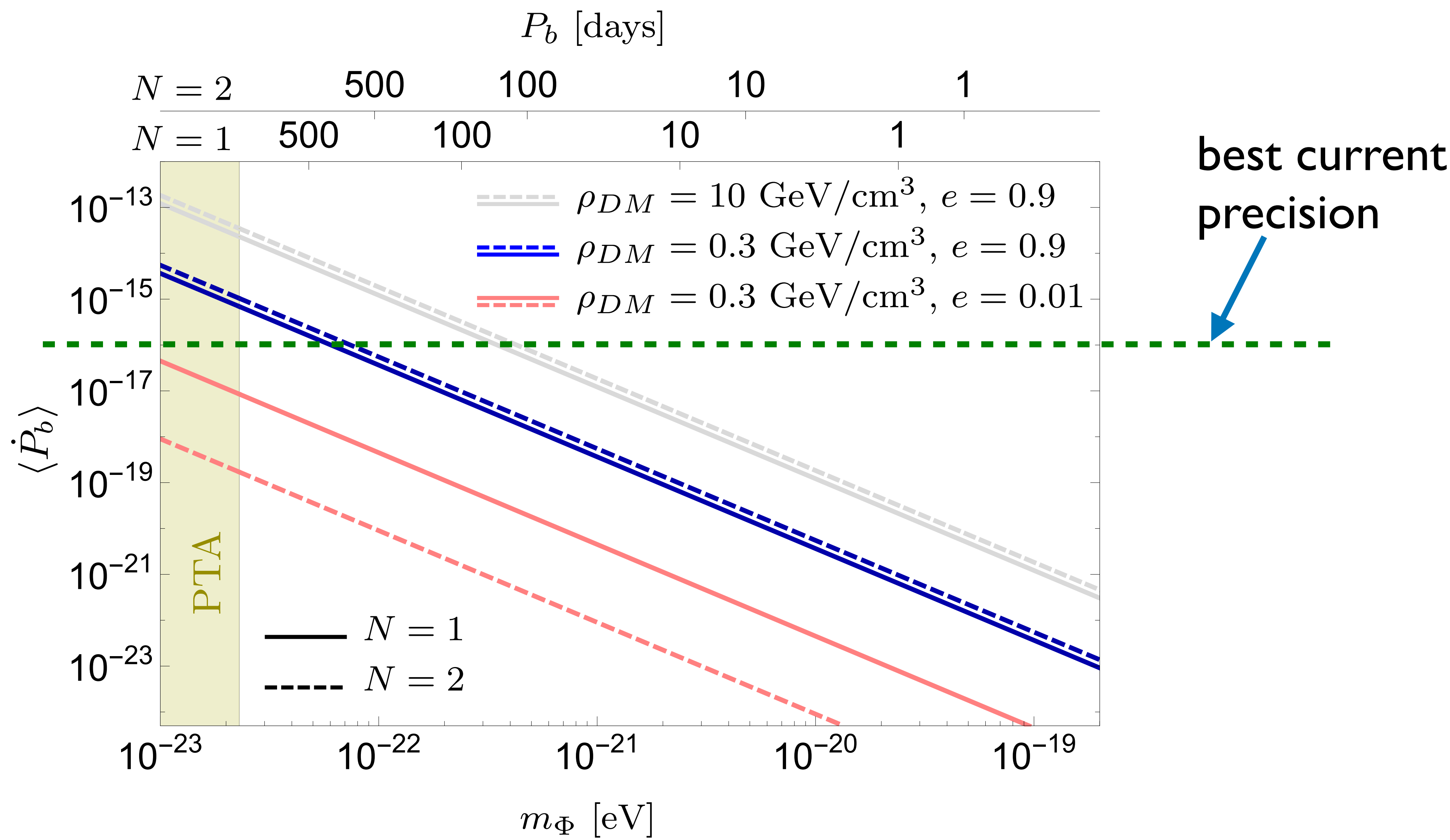


☹ for slow systems ($P_b >$ day) the precision is worse

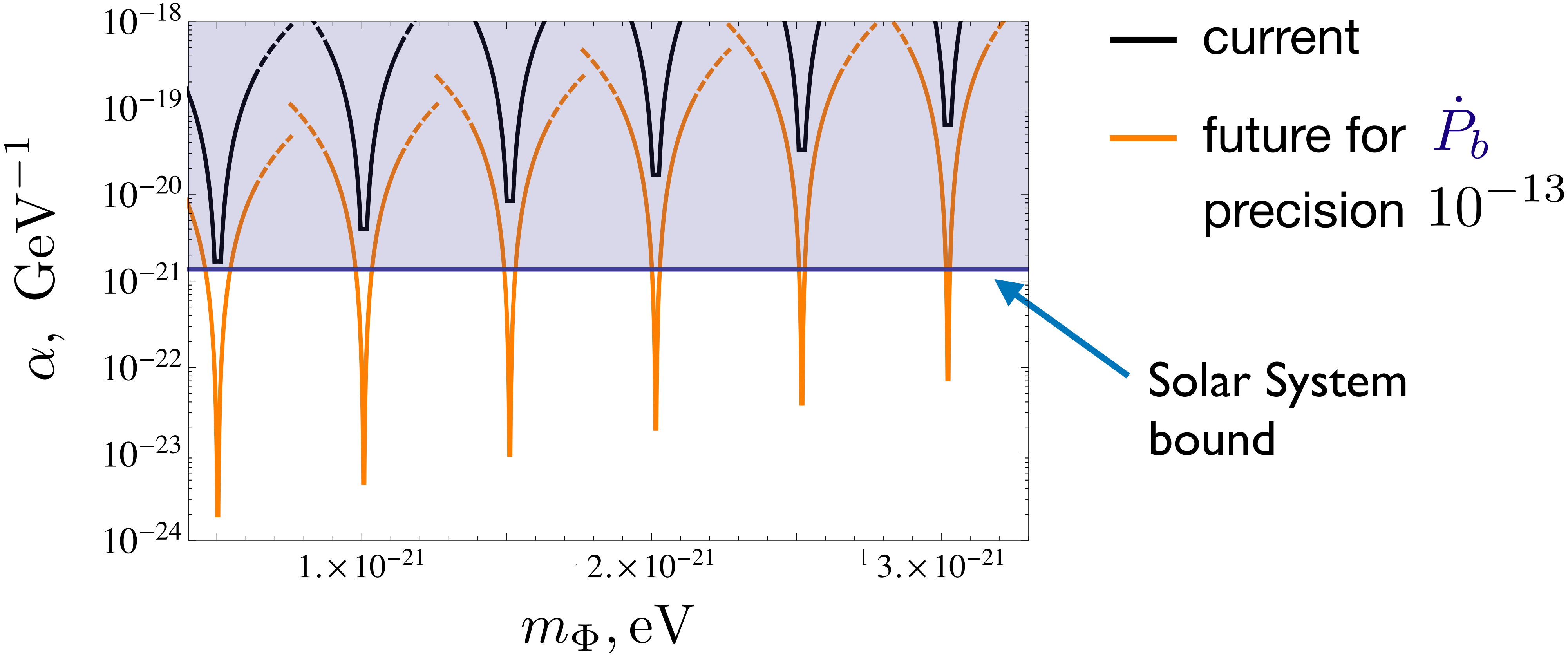
Need pulsars in regions with high DM overdensity

Direct coupling: Resonances

Example: system J1903+0327 ($P_b = 95\,\mathrm{days},\ e = 0.44$)

$$\dot{P}_b = (-52 \pm 33) \times 10^{-12}$$

Limits on **linear** coupling



NB. Pulsars probe strong gravity regime

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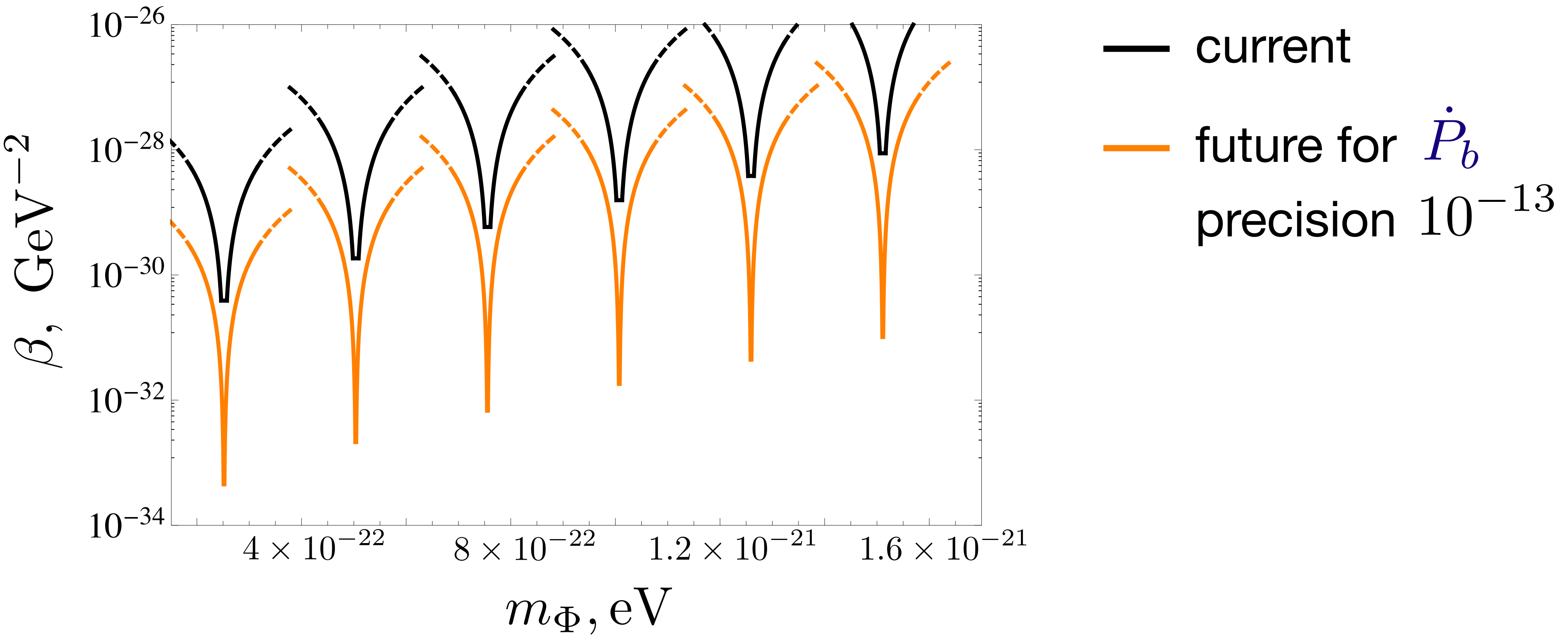


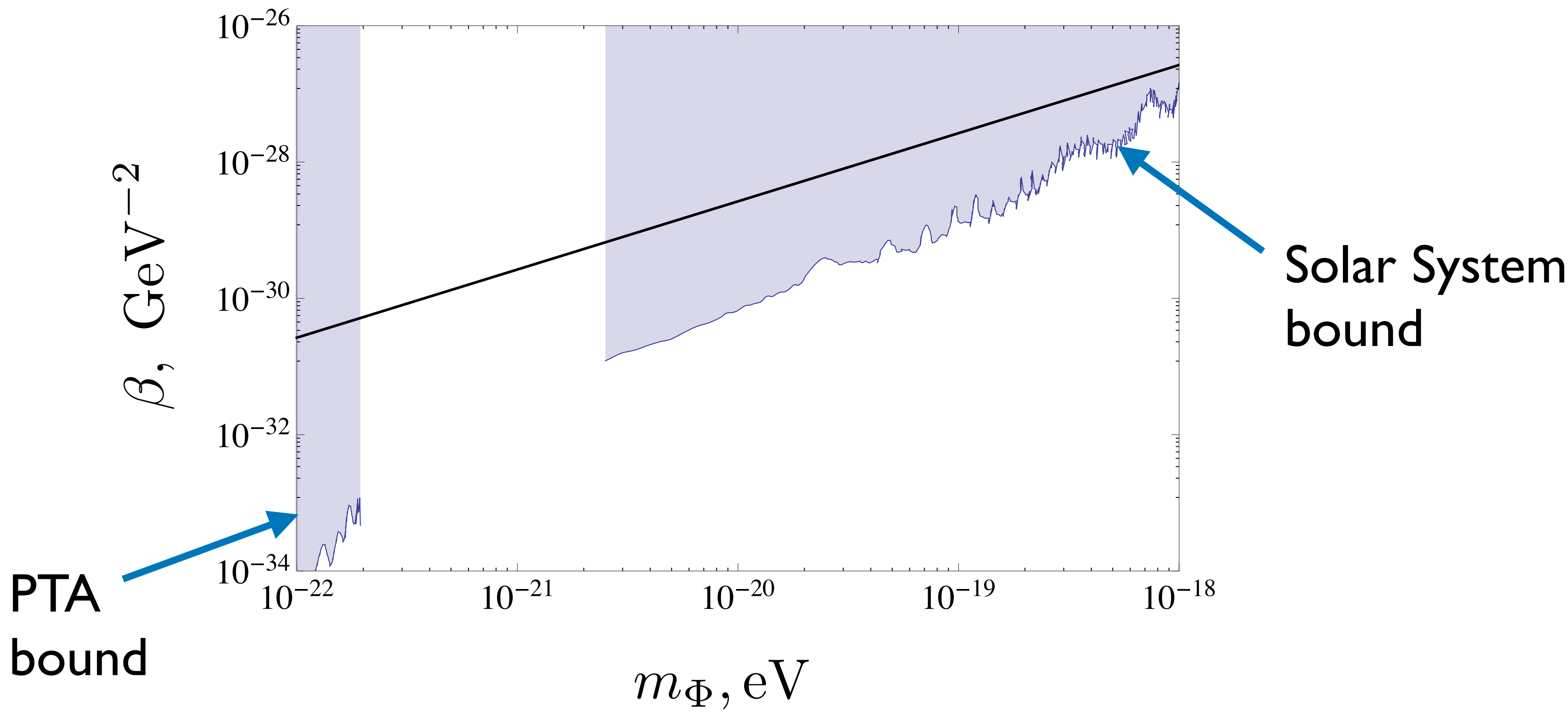
NB. Bigger coverage with multiple systems. Expected *O*(10) increase of statistics with Square Kilometer Array

Direct coupling: Broad-band

Example: system J1713+0747 ($P_b = 67.8\,\mathrm{days}$, $e = 7\times 10^{-5}$)

$$\dot{e} \lesssim 10^{-17}\,\mathrm{s}^{-1}$$

Limits on **quadratic** coupling



NB. Further limits can come from statistical analysis of binaries with low eccentricities

Summary and Outlook

- Ultralight Dark Matter: theoretically simple (simplest ?)
- Rich astrophysical phenomenology due to coherent oscillations, large density gradients
- Influences dynamics of binary systems $\Rightarrow$ Probe with pulsar timing
- Pure gravitational interaction outside reach (unless binaries in regions with large DM overdensity)
- Competitive constraints on non-minimal dilaton-like couplings
- Future: timing model for specific systems, statistical analysis of the population. Bright prospects with Square Kilometer Array