Binary pulsars as resonant detectors of Ultra-Light Dark Matter

Diana L. López Nacir

Based on work with Diego Blas and Sergey Sibiryakov

[PRL118, 261102 (2017)]

13th Rencontres du Vietnam: Cosmology 2017

Outline of the talk

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- Motivations and brief overview of ULDM

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- Why binary pulsars could be useful to constraint ULDM models?

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- Why binary pulsars could be useful to constraint ULDM models?
- Our results, and comparison with other constraints
- Conclusions and future prospects

Motivations

Standard cosmological model: ΛCDM $\rightarrow$ Dark contributions

Dark Matter (DM):

- DM could consist of some ``cold'' (small velocity dispersion) undiscovered particles
- An alternative model: DM consist of very light bosons or axion-like particles with high occupation numbers $n = \rho_{DM}/m$

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To what extend is it possible to discriminate among the different models?

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We need

- to identify and characterize observable signatures
- to confront with data all calculable predictions (on diverse scales)

Ultra-Light Dark Matter as a classical scalar field

Very light DM with large $n = \rho_{DM}/m_\Phi$

Classical solution to the Klein-Gordon equation $[-\Box + m_\Phi^2]\Phi(\vec{x}, t) = 0$

$$ds^2 = -(1+2\phi)c^2dt^2 + a^2(1-2\psi)\delta_{ij}dx^i dx^j$$

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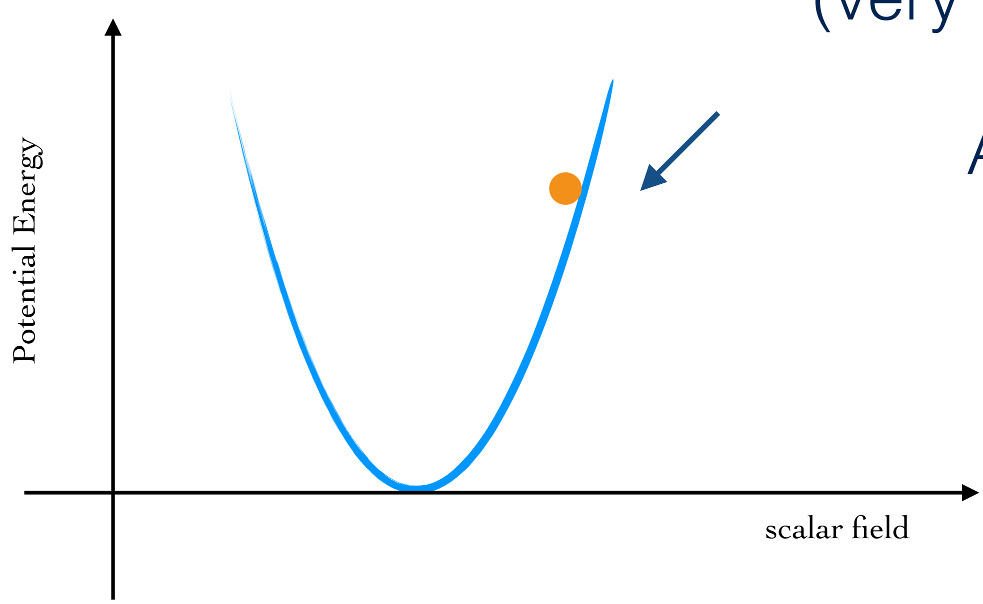
Initial conditions set by inflation
(very homogeneous)



After $H < m_\Phi \longrightarrow \Phi \sim \Phi_0 \cos(m_\Phi t + \Upsilon)$

$$T_{\mu\nu} \to \rho_{DM} = \frac{m_\Phi^2 \Phi_0^2}{2} + \text{oscillations}$$

$$p_{DM} = -\rho_{DM}\cos(2m_\Phi t + 2\Upsilon)$$

(oscillations are irrelevant on long time scales)

All DM $\rightarrow m_\Phi > H(a_{eq}) \sim 10^{-28}\text{eV}$

CMB + LSS $\longrightarrow m_\Phi \gtrsim 10^{-24}\text{eV}$ $(\times 10 \text{ in the future})$

ULDM as a classical scalar field (on shorter scales)

$$a\partial_t \rho_{DM} \ll c|\nabla \rho_{DM}|$$

Collection of plane waves: $\Phi = e^{-ict/\lambda_c}\Psi + e^{ict/\lambda_c}\Psi^*$

$$\left(\lambda_c = \frac{\hbar}{m_\Phi c}\right)$$

Compton wavelength

$$\Psi = \sqrt{\frac{c\rho_{DM}(\vec{x},t)}{2}}\lambda_c \exp\left\{-i\frac{\pi(\vec{x},t)}{c\lambda_c}\right\}$$

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$$t_c = \lambda_c/c$$

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$T_{\mu\nu}$

<…> "Fast" oscillations
+ leading order in 1/c
$(a = 1)$

$$\langle T_{00}\rangle \simeq c^2 \rho_{DM}$$

$$\langle T_{0i}\rangle \simeq c\rho_{DM}\partial_i \pi \quad \longrightarrow \quad v = |\nabla \pi|$$

$$\langle T_{ij}\rangle \simeq \rho_{DM}\partial_i\pi\partial_j\pi + \frac{\hbar^2}{m^2}\partial_i\sqrt{\rho_{DM}}\partial_j\sqrt{\rho_{DM}} - \frac{\delta_{ij}}{2}\left[\frac{\hbar^2}{m^2}\partial_i\sqrt{\rho_{DM}}\partial_i\sqrt{\rho_{DM}} + \rho_{DM}\partial_i\pi\partial_i\pi + \rho_{DM}\phi_N - \rho_{DM}\dot{\pi}\right]$$

$$(\phi_N = c^2\phi)$$

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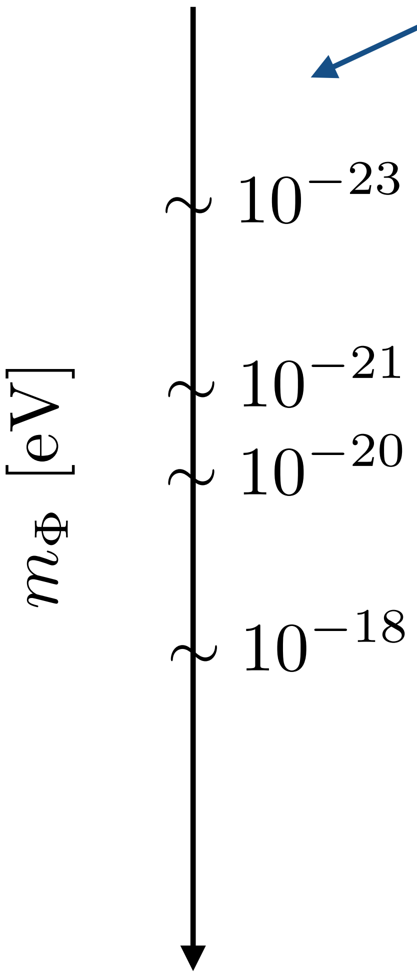
Gradients are relevant at length scales ~ De Broglie length

$$\lambda_{db} = \lambda_c\frac{c}{v} = \frac{\hbar}{m_\Phi v}$$

Observation on diverse scales can probe different mass ranges

Linear dynamics

Cosmic Microwave Background, Large Scale Structure



Lyman-alpha forest, Galaxy formation history, structure of galactic halos, Pulsar-Timing-Arrays (PTA)

21cm surveys

Black Hole physics

(not necessary DM)

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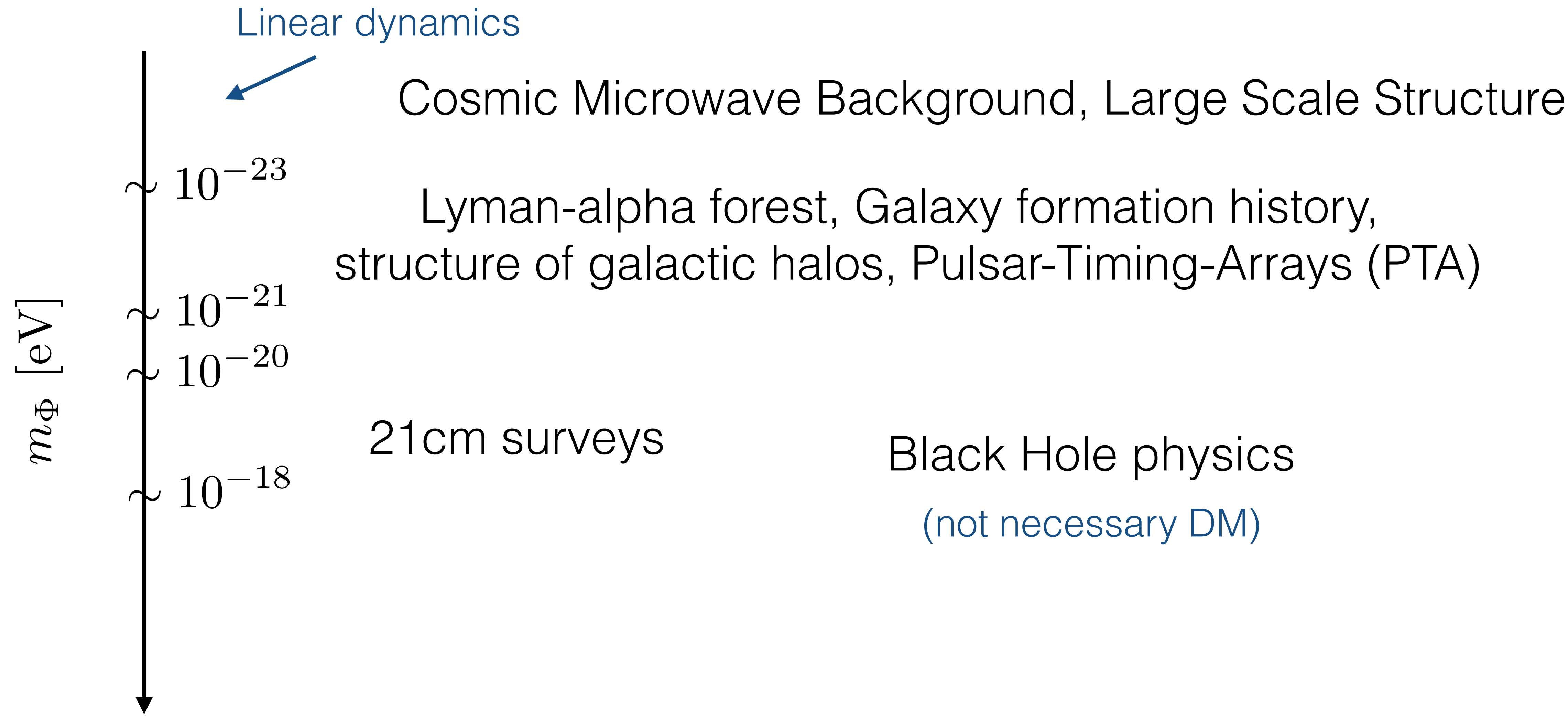

Goal: To add more observables to this list, both to constraint other mass ranges and to have complementary tests for same masses

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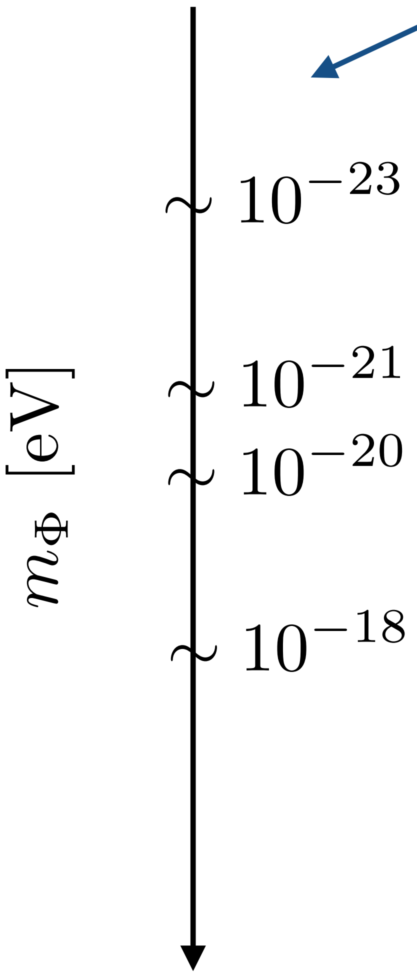

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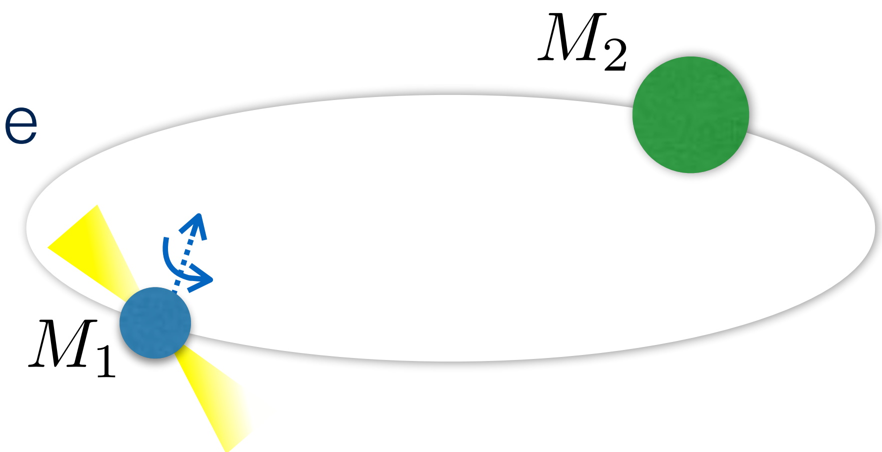
- These observations can probe ULDM *interacting only through gravity*
- If ULDM is *directly coupled to the Standard Model* -> many other (but *model-dependent*) possibilities: atomic clocks, accelerometers, resonant-mass detectors, laser and atom interferometry

Binary pulsars

- Radio pulsar: rapidly rotating neutron star (NS) with coherent radio emission along their magnetic poles and highly stable spin frequency

- Pulsar timing techniques provide very precise measurements of the orbital motion



- Ideal systems to constraint alternatives theories of gravity and the presence of gravity waves

- Are they also useful to explore the nature of DM?

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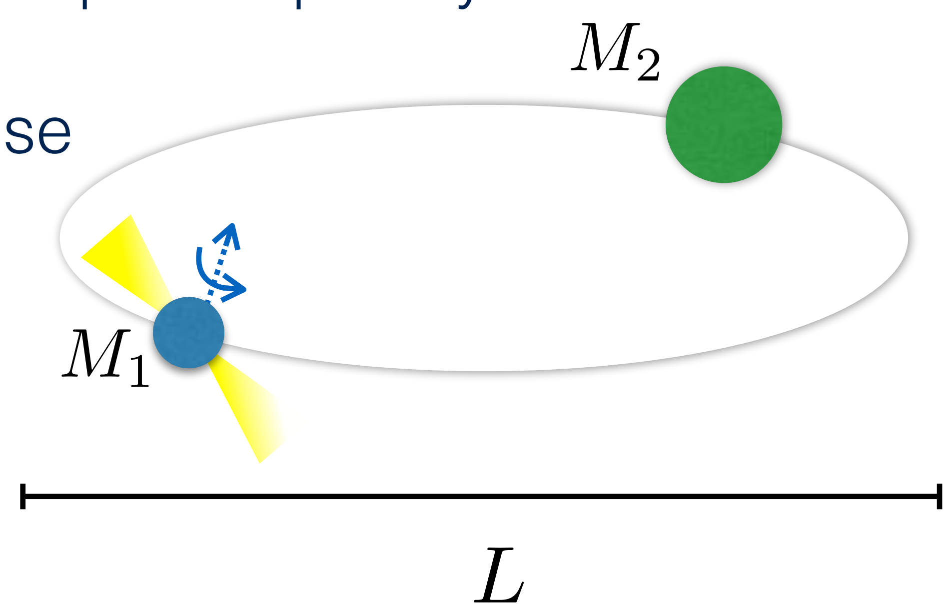

Some numbers:

$$L \sim 10^8\text{km}\left(\frac{\mathrm{P_b}}{100\,\text{days}}\right)^{2/3}\left(\frac{\mathrm{M_1+M_2}}{\mathrm{M_{sun}}}\right)^{1/3}$$

$$v \sim 10^{-3}c\,,\; c\,m_\Phi \sim 10^{-18} \div 10^{-22}\text{eV}$$

$$\lambda_{db} \sim 10^{12}\text{km}\left(\frac{10^{-3}c}{v}\right)\left(\frac{10^{-18}\text{eV}}{c\,m_\Phi}\right)$$

$$t_c \sim 100\,\text{days}\left(\frac{10^{-22}\text{eV}}{c\,m_\Phi}\right)$$

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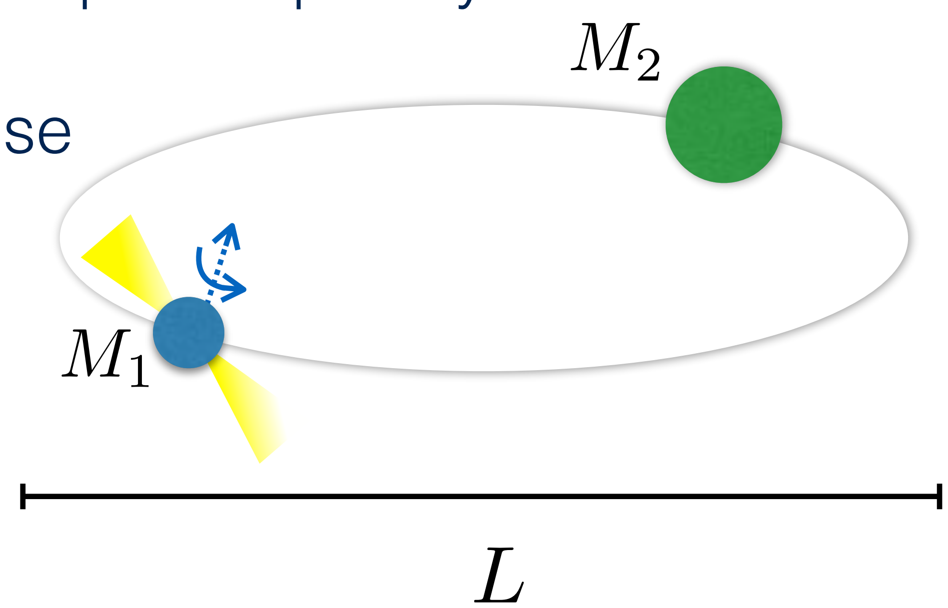

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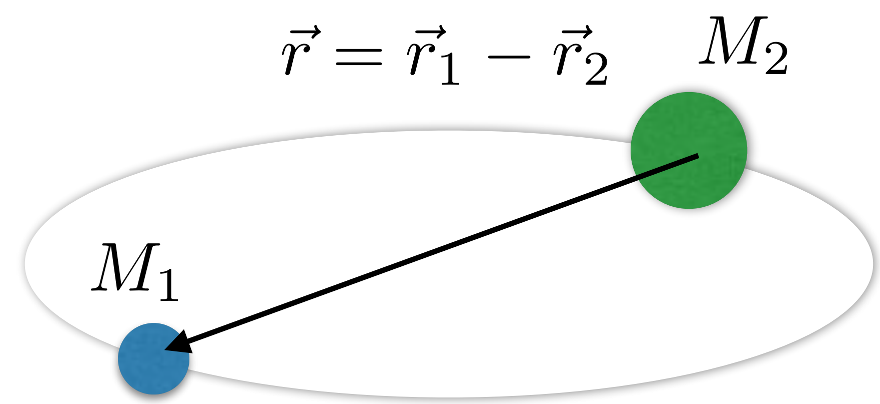
- Coherence: $v^2 \ll c^2$ ✓
- Homogeneity: $\lambda_{db} \gg L$ ✓
- Fast oscillations: $t_c \ll P_b$???

ULDM interacting only through gravity

$\hbar = c = 1$



$$\Phi(\vec{x}, t) = \Phi_0 \cos(m_\Phi t + \Upsilon(\vec{x}))$$

$$\rho_{DM} = \frac{m_\Phi \Phi_0^2}{2}$$

Only gravity!

$$p_{DM} = -\rho_{DM} \cos(2m_\Phi t + 2\Upsilon) \;\Longrightarrow\; h_{ij} \sim -\frac{2\pi G \rho_{DM}}{m_\Phi^2} \delta_{ij} \cos(2m_\Phi t + 2\Upsilon)$$

[PRL118, 261102 (2017)]

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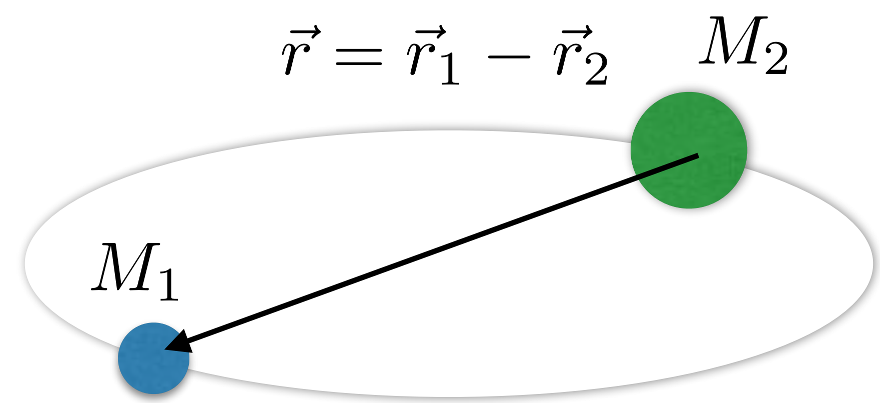

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Geodesic deviation eq.

$$\delta \ddot{r}^i = -\delta R^i{}_{0j0} r^j \quad \Rightarrow \quad \delta E_b = \mu \int_0^{P_b} \dot{r}^i \delta \ddot{r}^i dt \qquad (P_b \propto |E_b|^{-3/2})$$

$$\mu = M_1 M_2/(M_1 + M_2) \qquad = 4\pi G \rho_{DM} \mu \int_0^{P_b} \dot{r}(t) r(t) \cos(2m_\Phi t + 2\Upsilon) dt$$

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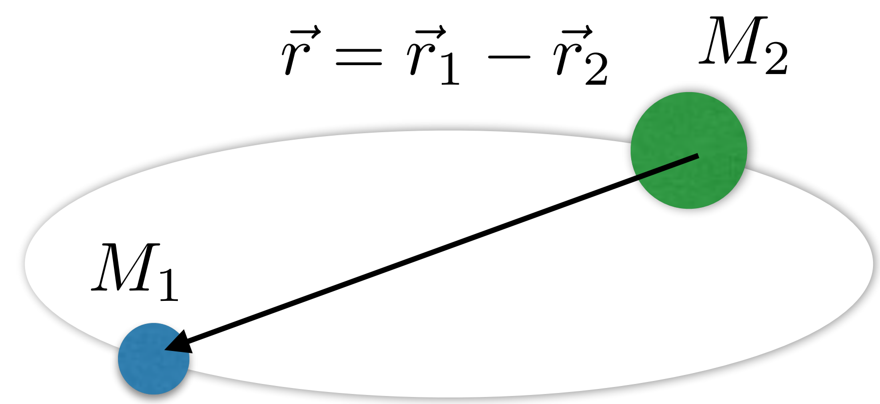

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Resonances: $\delta\omega = 2m_\Phi - 2\pi N/P_b, \;\; |\delta\omega| \ll 2m_\Phi \;\; (N \in \mathbb{N})$

$$\boxed{\langle \dot{P}_b \rangle \simeq -1.6 \times 10^{-17} \left(\frac{\rho_{DM}}{0.3 \, \frac{\text{GeV}}{\text{cm}^3}} \right) \left(\frac{P_b}{100\,\text{d}} \right)^2 \frac{J_N(Ne)}{N} \sin \gamma_g(t)}$$

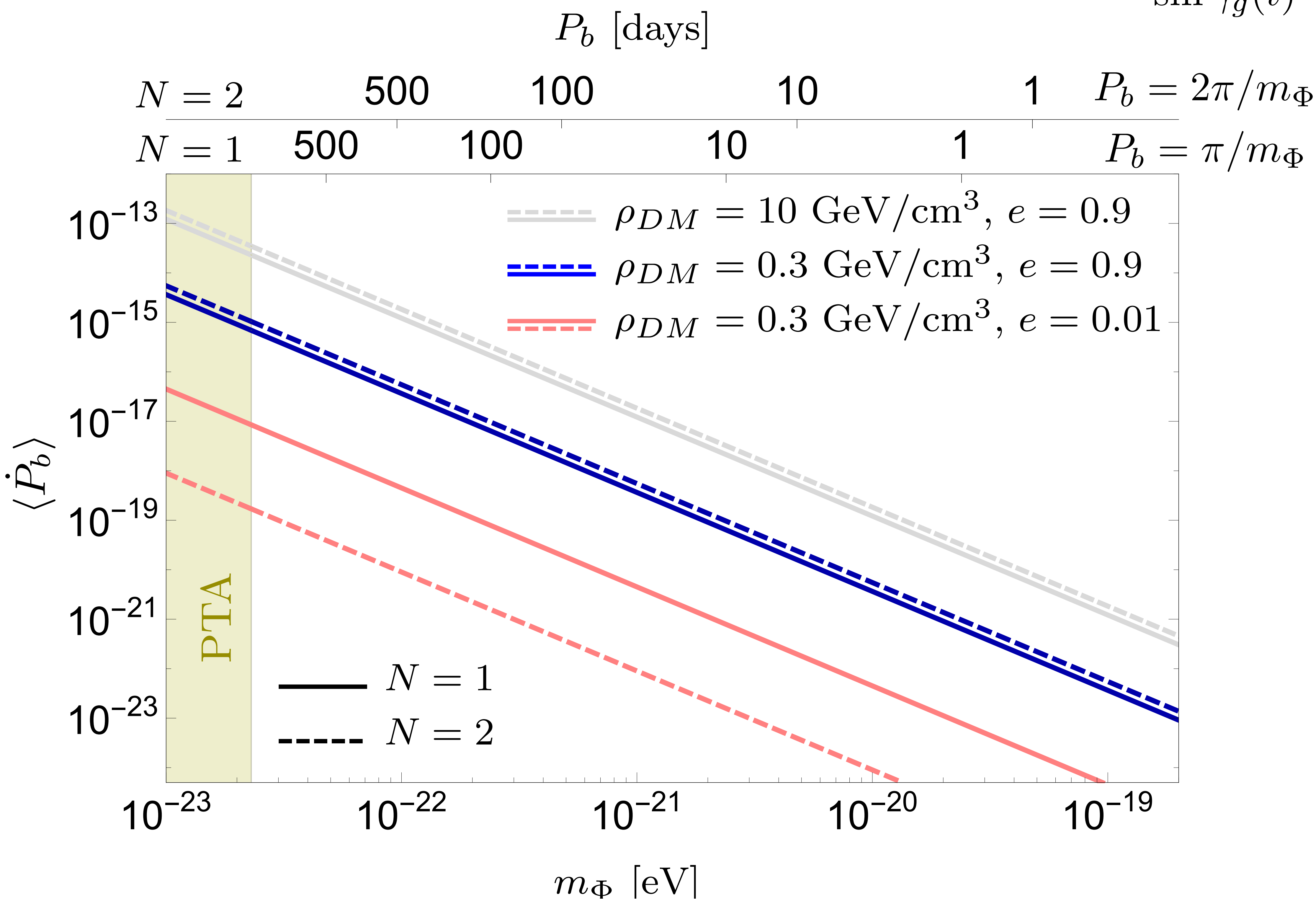
$(P_b/N \ll \Delta t \ll 2\pi/\delta\omega)$

$$\gamma_g(t) = \delta\omega\,(t - t_0) + 2m_\Phi\, t_0 + 2\Upsilon$$

For $e \ll 1, \;\; J_N(Ne) \sim \frac{\left(\frac{Ne}{2}\right)^N}{\Gamma[N+1]}$

[PRL118, 261102 (2017)]

$\sin\gamma_g(t) \to -1$



E. g. Double Pulsar (PSR J0737-3039) $\langle \Delta \dot{P}_b \rangle \sim \mathcal{O}(10^{-16})$, but $P_b \simeq 0.1\,\mathrm{days}$

[PRL118, 261102 (2017)]

Pulsar Timing Array (PTA)

[Khmelnitsky & Rubakov (2014)]

ULDM affects the propagation of the signal

$$h_{ij} \sim -\frac{2\pi G\rho_{DM}}{m_\Phi^2}\delta_{ij}\cos(2m_\Phi t + 2\Upsilon)$$

Distance to the pulsar

$$\Delta t(t) = \pi\frac{G\rho_{DM}}{m_\Phi^3}\sin(m_\Phi D + \Upsilon(x) - \Upsilon(x_p))\cos(2m_\Phi t + \Upsilon(x) + \Upsilon(x_p) - m_\Phi D)$$

Oscillations

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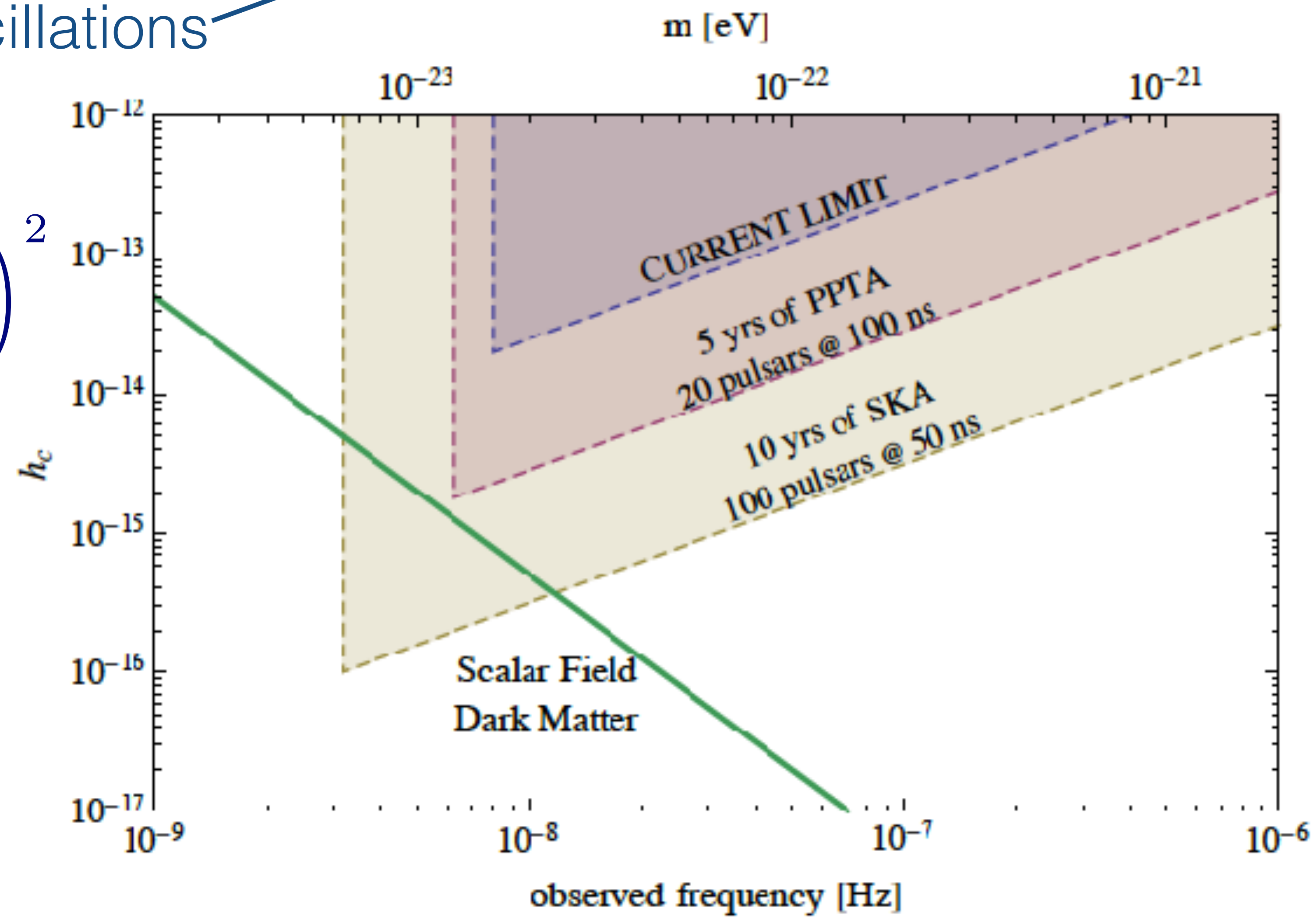
Oscillations

Same as a GW with

$$h_c = 2\times 10^{-15}\left(\frac{\rho_{DM}}{0.3\,\frac{\text{GeV}}{\text{cm}^3}}\right)\left(\frac{10^{-23}\text{eV}}{m_\Phi}\right)^2$$

$$f = 5\times 10^{-9}\text{Hz}\left(\frac{m_\Phi}{10^{-23}\text{eV}}\right)$$



ULDM interacting directly coupled to matter

$$L = M_1(\Phi)\left(1+\frac{v_1^2}{2}\right) + M_2(\Phi)\left(1+\frac{v_2^2}{2}\right) + \frac{GM_1(\Phi)M_2(\Phi)}{r}$$

Universal coupling: $$M_{1,2}(\Phi) = M_{1,2}(1+\alpha(\Phi)), \quad |\alpha(\Phi)| \ll 1$$

$$\delta\ddot{\vec{r}} = -\frac{d\alpha}{d\Phi}\dot{\Phi}\dot{\vec{r}} - \alpha(\Phi)\frac{G(M_1+M_2)}{r^3}\vec{r}$$

[PRL118, 261102 (2017)]

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Linear coupling $\alpha(\Phi) = \Phi/\Lambda_1$

Quadratic coupling $\alpha(\Phi) = \Phi^2/(2\Lambda_2^2)$

Different resonance conditions

Linear coupling:

$$\delta\omega = m_\Phi - 2\pi N/P_b, \quad |\delta\omega| \ll m_\Phi \quad (N \in \mathbb{N})$$

$$\langle \dot{P}_b \rangle \simeq 2.5\times 10^{-12} J_N(Ne)\sin\gamma_l(t) \times \left(\frac{\rho_{DM}}{0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}}\right)^{\frac{1}{2}}\left(\frac{P_b}{100\,\mathrm{d}}\right)\left(\frac{10^{23}\mathrm{GeV}}{\Lambda_1}\right)$$

$$\gamma_l(t) = \delta\omega\,(t-t_0) + m_\Phi\,t_0 + \Upsilon$$

Quadratic coupling:

$$\delta\omega = 2m_\Phi - 2\pi N/P_b, \quad |\delta\omega| \ll 2m_\Phi \quad (N \in \mathbb{N})$$

$$\langle \dot{P}_b \rangle \simeq 1.1\times 10^{-11}\frac{J_N(Ne)}{N}\sin\gamma_q(t) \times \left(\frac{\rho_{DM}}{0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}}\right)\left(\frac{P_b}{100\,\mathrm{d}}\right)^2\left(\frac{10^{16}\mathrm{GeV}}{\Lambda_2}\right)^2$$

$$\gamma_q(t) = \delta\omega\,(t-t_0) + 2m_\Phi\,t_0 + 2\Upsilon$$

[PRL118, 261102 (2017)]

Universal coupling

Jordan metric

$g_{\mu\nu} \mapsto \bar{g}_{\mu\nu} = g_{\mu\nu}\big(1 + 2\alpha(\Phi)\big)$ ⟶ *Scalar wave* ⟶ *Previous constraints on GWs can be easily translated*

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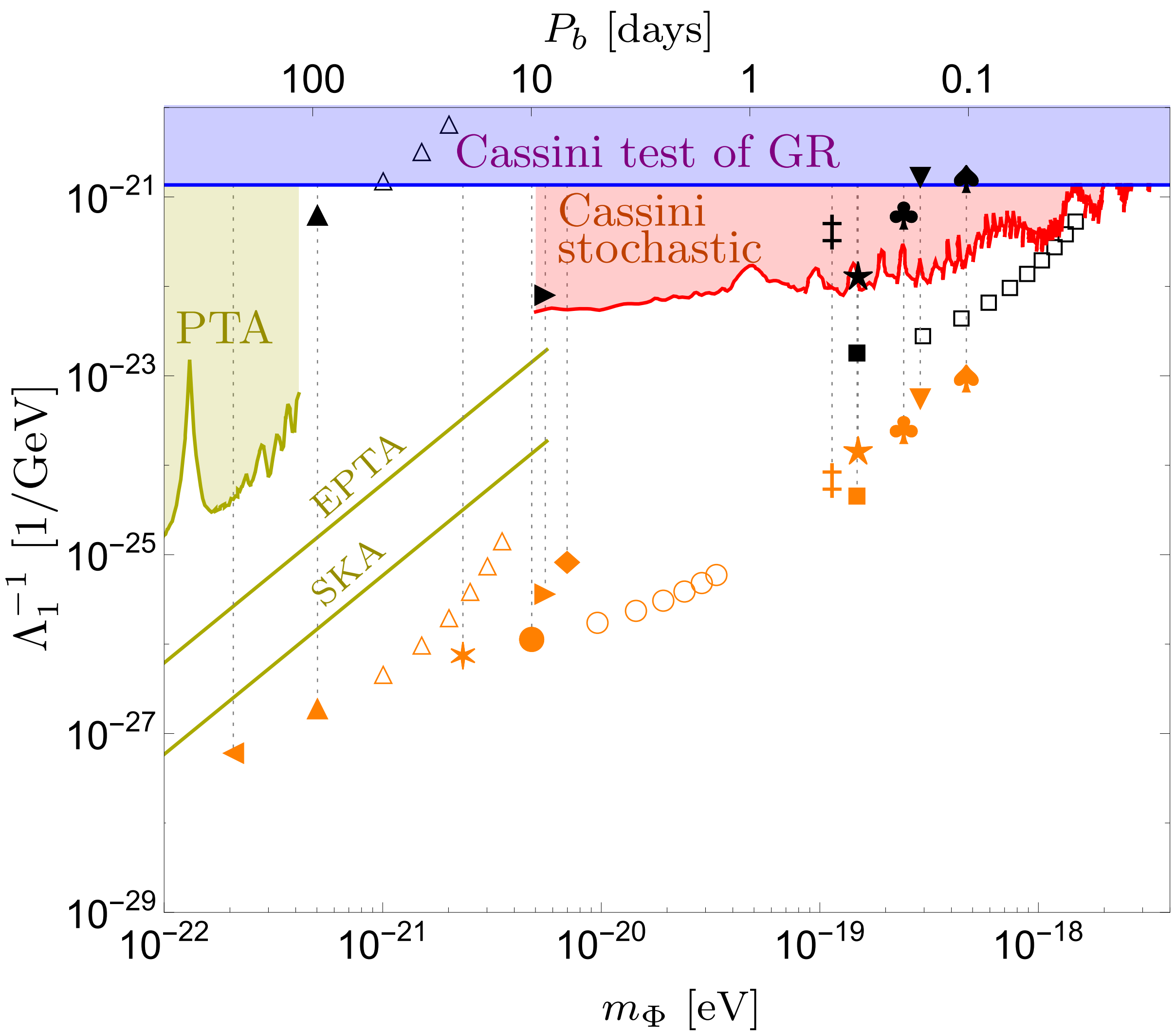
$$g_{\mu\nu} \mapsto \bar{g}_{\mu\nu} = g_{\mu\nu}\left(1 + 2\alpha(\Phi)\right) \longrightarrow \textit{Scalar wave} \longrightarrow$$

Previous constraints on GWs can be easily translated

Linear coupling $\alpha(\Phi) = \Phi/\Lambda_1$



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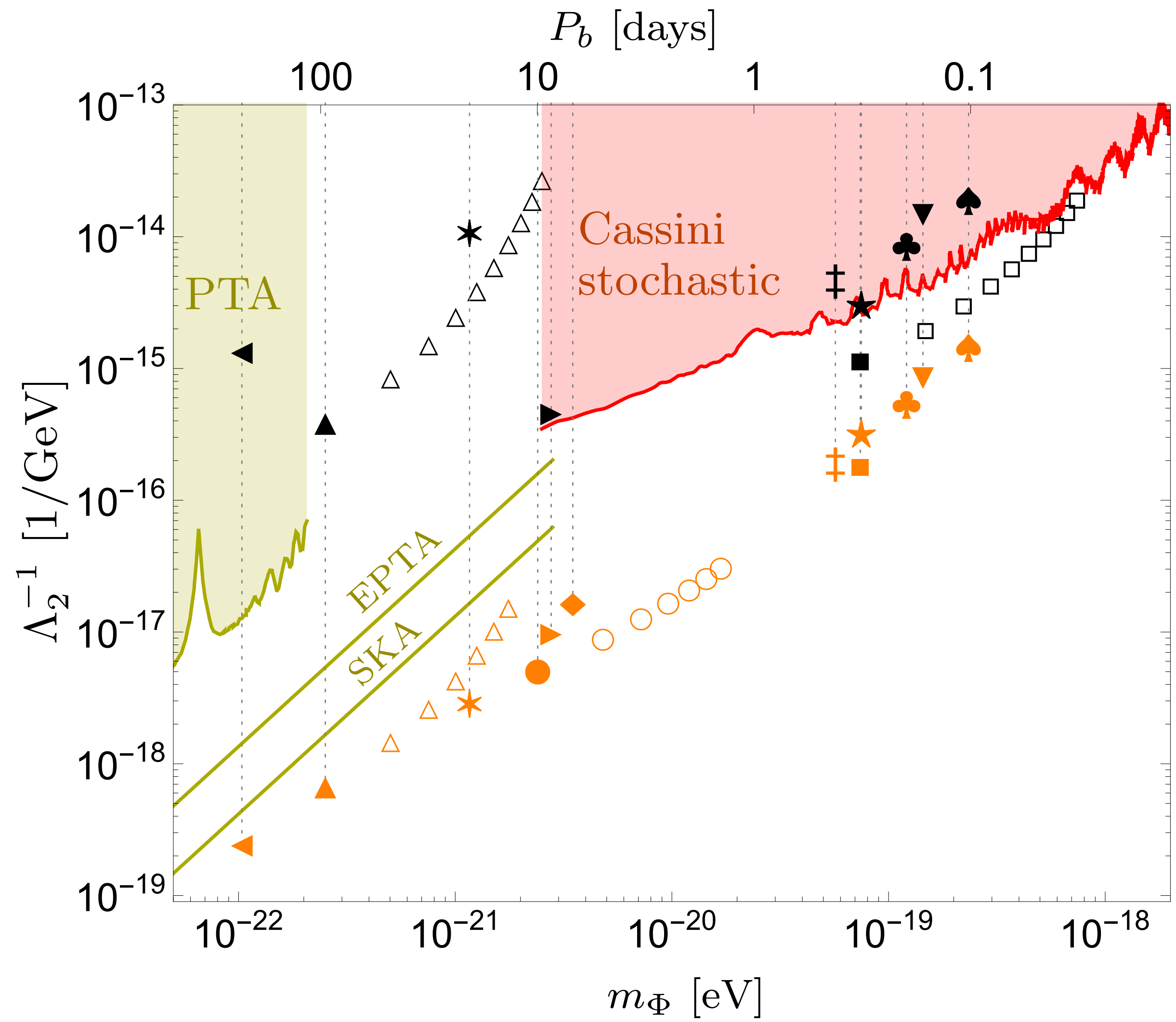

Binary pulsars

◀ J1740-3052	▶ J1518+4904	★ J1756-2251
▲ J1903+0327	◆ B1516+02B	♣ J1141-6545
∗ J1748-2021B	‡ B1534+12	▼ J1906+0746
● J1807-2500B	■ B1913+16	♠ J0737-3039A

Solid (empty) symbols $\rightarrow N = 1\ (N \geq 2)$

Black symbols $\rightarrow$ Current data

Orange symbols $\rightarrow \langle \Delta \dot{P}_b \rangle = 10^{-16}$

[PRL118, 261102 (2017)]

Universal coupling

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$g_{\mu\nu} \mapsto \bar{g}_{\mu\nu} = g_{\mu\nu}\left(1 + 2\alpha(\Phi)\right) \longrightarrow$ *Scalar wave* $\longrightarrow$ *Previous constraints on GWs can be easily translated*

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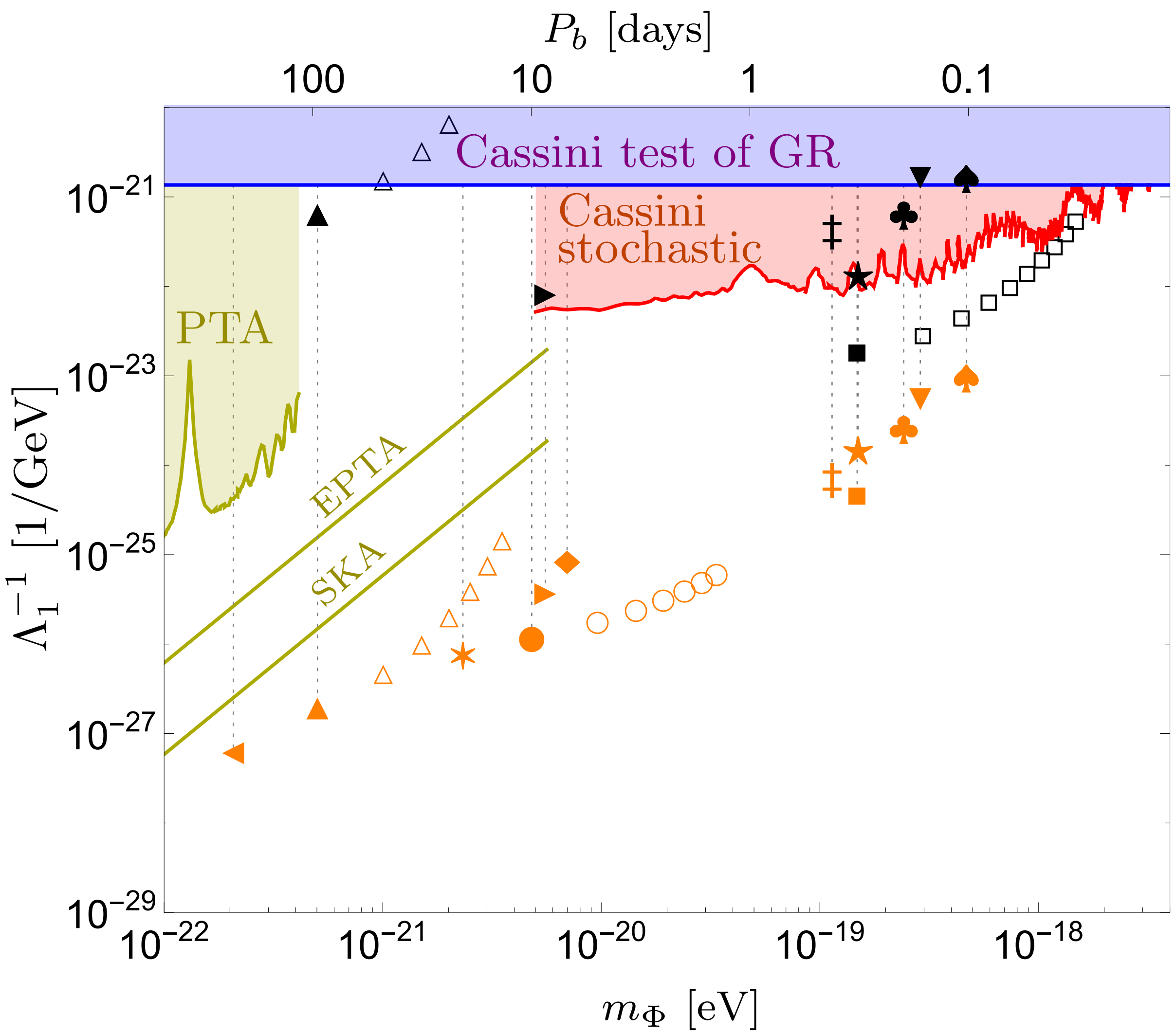

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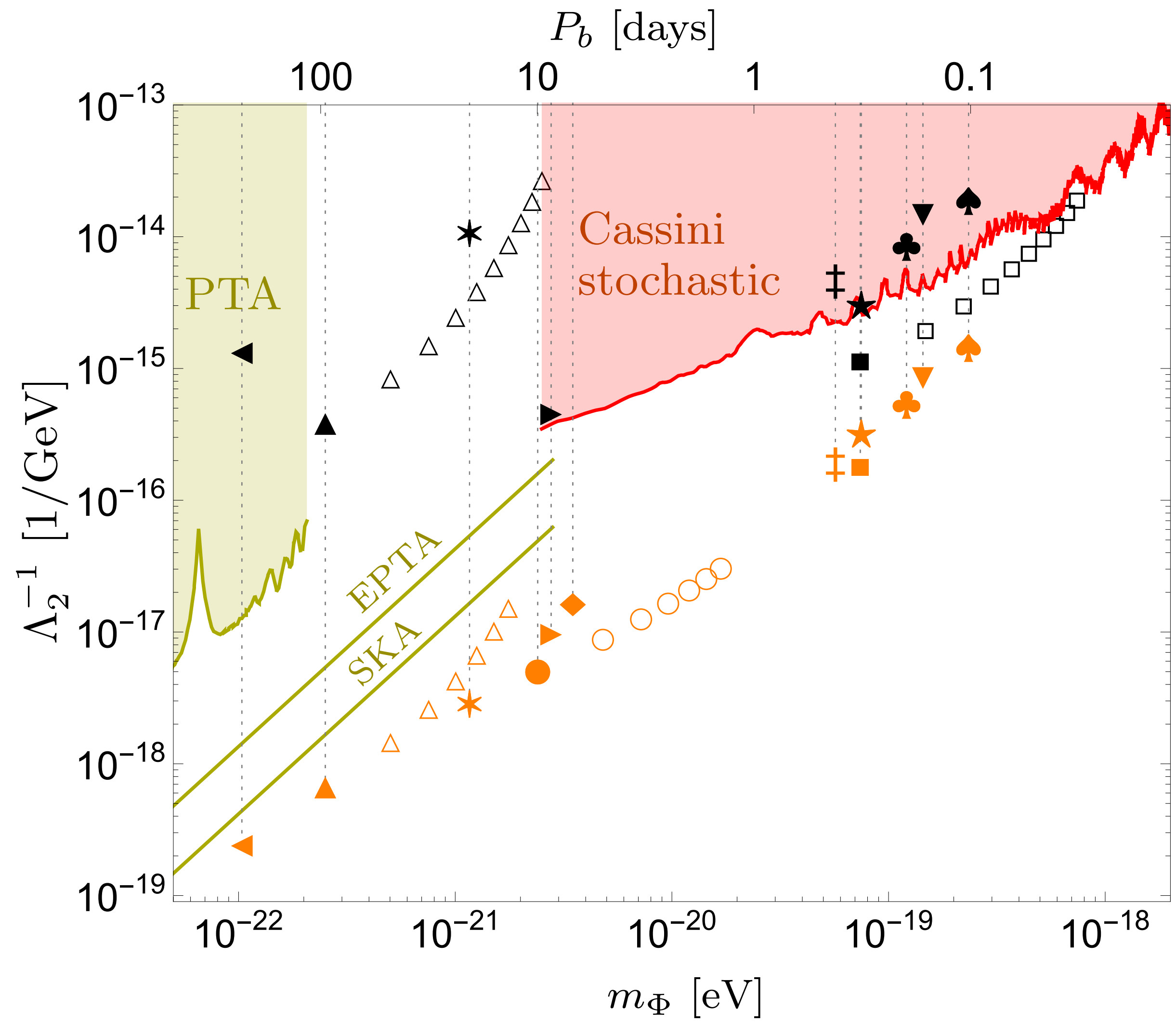

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$\delta m_\Phi \sim 5 \times 10^{-23}\,\mathrm{eV}/(\text{years of observation})$

[PRL118, 261102 (2017)]

Conclusions & future prospects

- ULDM could yield secular variations of the orbital parameters of Binary Pulsars (BPs):
  - because its stress-energy tensor modifies the spacetime metric
  - if it is directly coupled to the Standard Model

- The secular effect leads to potentially observable signatures in high precision timing measurements of pulsars in binaries

- Exquisitely precise measurements are already ongoing for many systems

- For the system to stay in resonance during the whole observational campaign, we estimate

$$\delta m_\Phi \sim 5 \times 10^{-23}\,\mathrm{eV}/(\text{years of observation})$$

  So, a given BP is sensitive to ULDM masses only in a few narrow bands

- New (~1000) BPs are expected to be discovered by SKA -> significant coverage

- Beyond the orbital period derivative: there will also be secular variations of other orbital parameters (D.Blas, DLN, and S. Sibiryakov, to appear) …

- Other resonant effects? Dipolar radiation? …

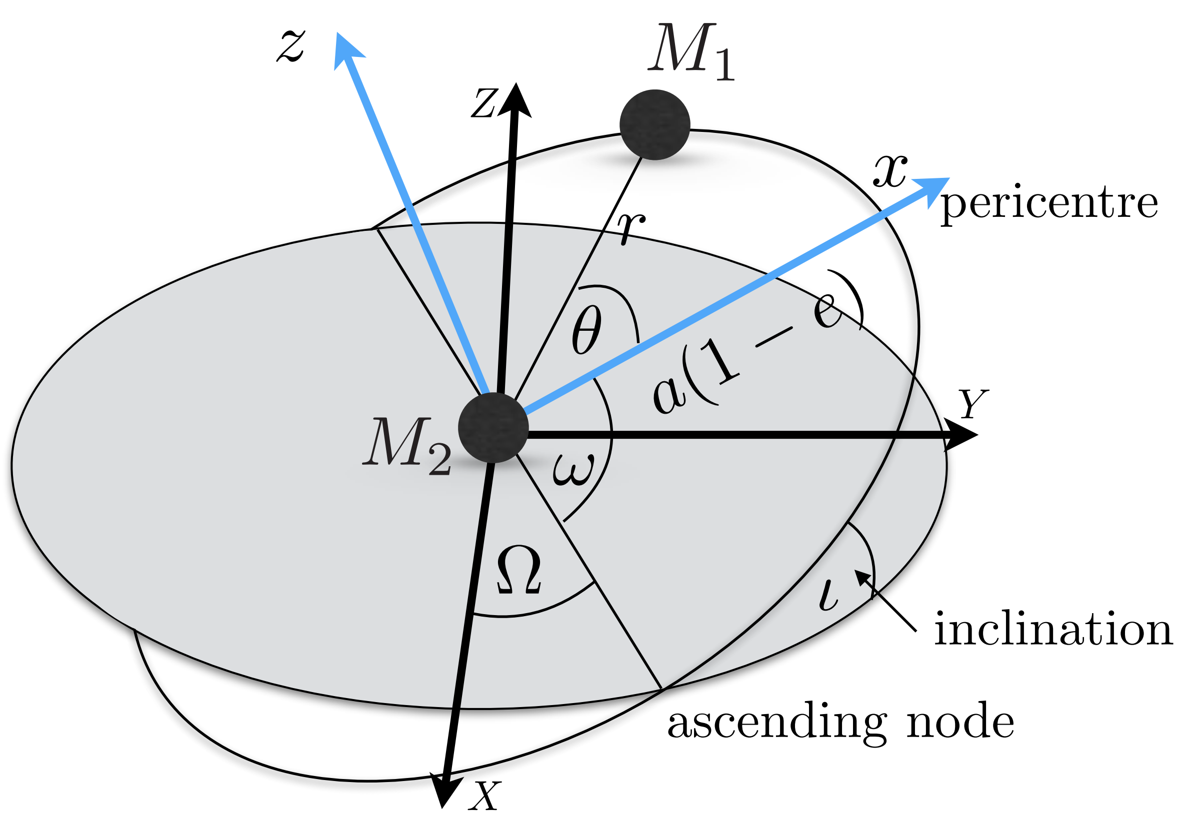
THANKS!

Beyond the orbital period derivative?

Phenomenological Timing model $\supset$ secular change of orbital parameters

[Blandford & Teukolsky (1976), Damour & Daruelle (1986)]

$$P_b \to P_b + \dot{P}_b(T - T_0),\ e \to e + \dot{e}(T - T_0),\ \omega \to \omega + \dot{\omega}(T - T_0),\ \ldots$$



$$\omega_0 = \frac{2\pi}{P_b} = \sqrt{\frac{G M_T}{a^3}}$$

semi-major axis

$$a_1 = a\, M_2/M_T,\ \ (M_T = M_1 + M_2)$$

E.g. Hulse-Taylor [B1913+16]
[from Weisberg & Huang (2016)]

T_0 (MJD)	52144.90097849(3)
P_b (d)	0.322997448918(3)
e	0.6171340(4)
ω (deg)	292.54450(8)
$x = a_1 \sin\iota$ (s)	2.341776(2)
$\dot{P}_b^{obs}$	$-2.423(1) \times 10^{-12}$
$\dot{\omega}$ (deg / yr)	4.226585(4)
$\dot{e}^{obs}$ (s^{-1})	$0.0006(7) \times 10^{-12}$
$\dot{x}^{obs}$	$-0.014(9) \times 10^{-12}$

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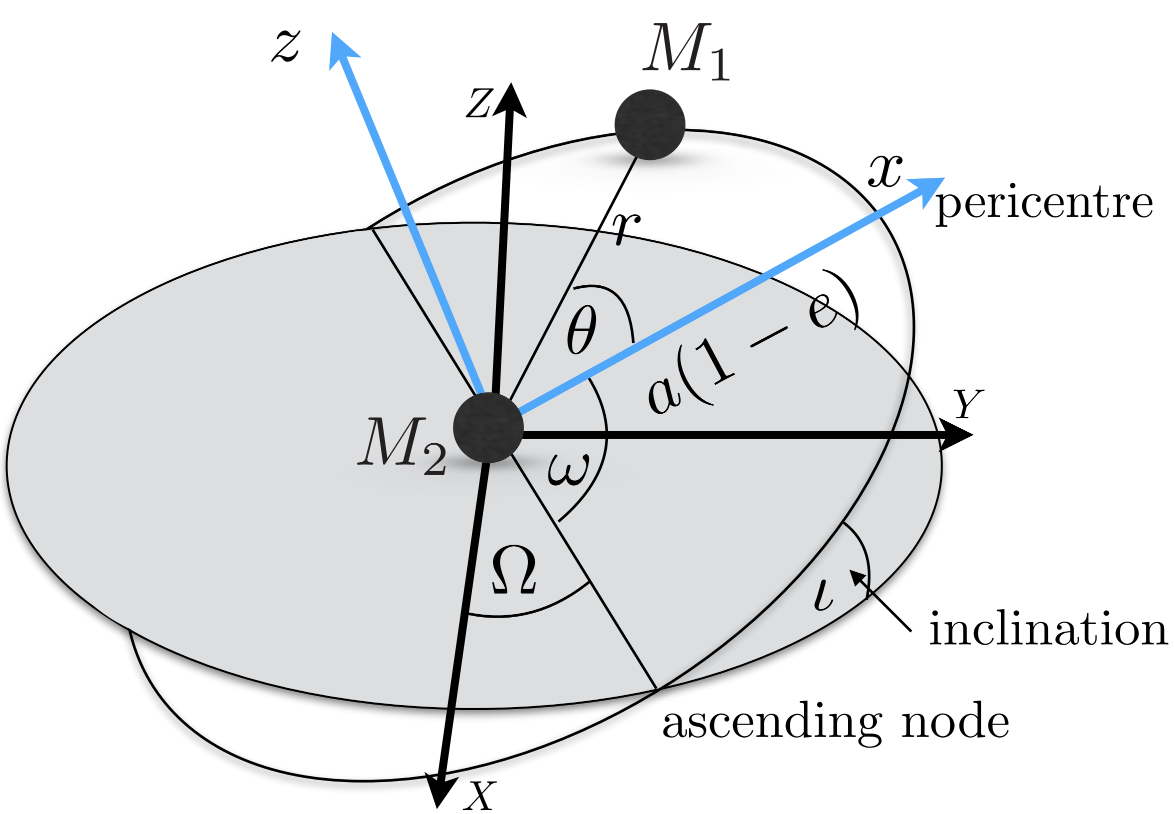

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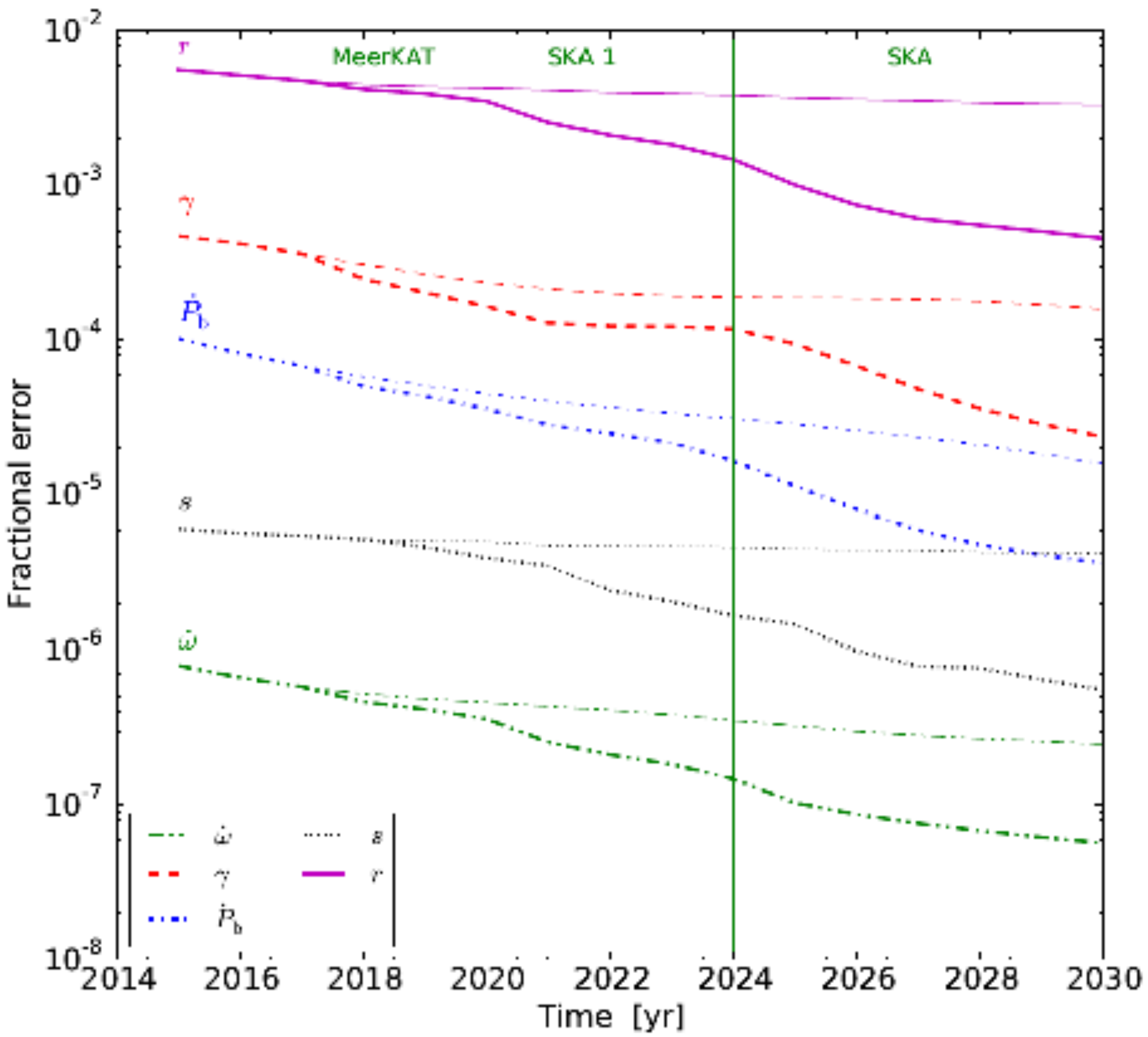
$$\dot{P}_b^{intr} = \dot{P}_b^{obs} - \dot{P}_b^{gal} = -(2.398 \pm 0.004) \times 10^{-12}$$

$$\dot{P}_b^{gal} = -(0.025 \pm 0.004) \times 10^{-12}$$

$$\dot{P}_b^{GW} = -(2.40263 \pm 0.00005) \times 10^{-12}$$

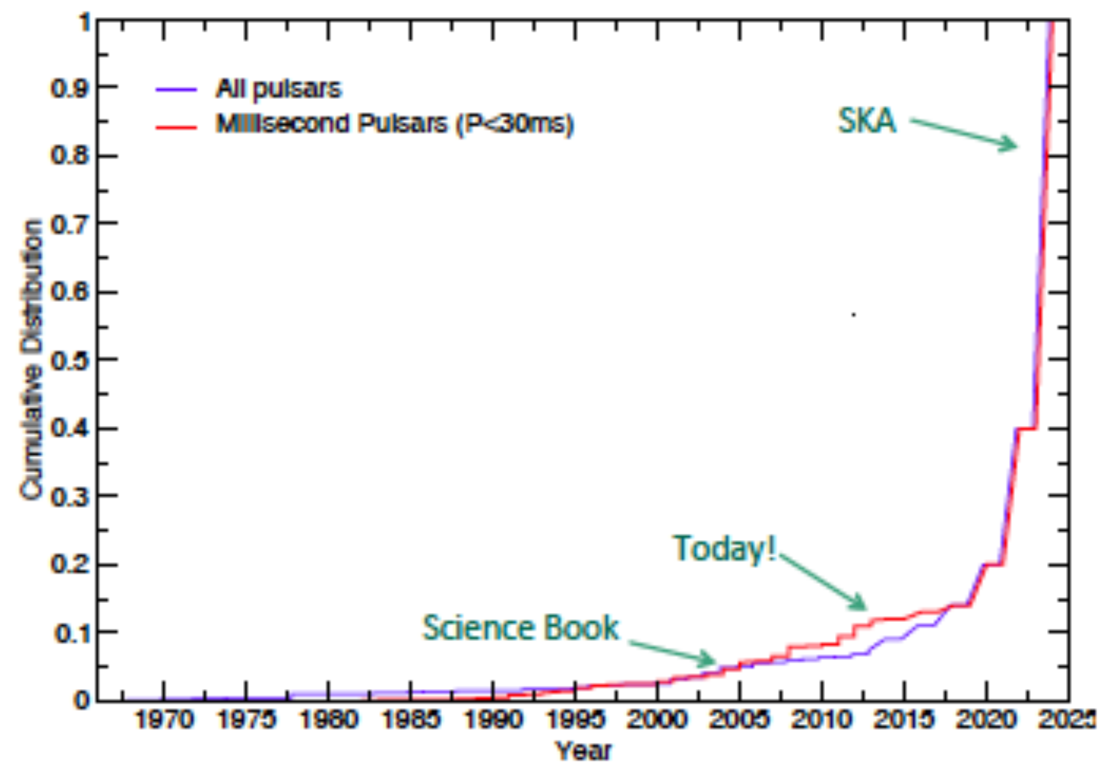
Beyond the orbital period derivative?

E.g. Double pulsar



[Kehl, et.al. (2016)]

Pulsar-related discoveries vs time



[Kramer& Ben Stappers (2014)]

Periodic modulations?

A rough estimation:

- If secular drift $\sim$ constant → accuracy increases with $T_{\rm obs}$

$$(\text{E.g., } \delta\dot{P}_b \sim T_{\rm obs}^{-5/2},\ \delta\dot{e} \sim T_{\rm obs}^{-3/2})$$

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Large $T_{\rm mod}$ ***but with*** $T_{\rm mod} \lesssim 2T_{\rm obs}$