KING'S College LONDON

Probing light dark matter with pulsar observations

Diego Blas

based on DB, D. Lopez-Nacir, S. Sibiryakov 1612.06789 + 1910.08544

A. Caputo, L. Sberna, M. Frias, DB, P. Pani, L. Shao, W. Yan 1902.02695

A. Caputo, DB, J. Zavala 1709.03991

The extreme numbers of pulsars

Pulsars are neutron stars with strong magnetic fields
and a significant magnetosphere

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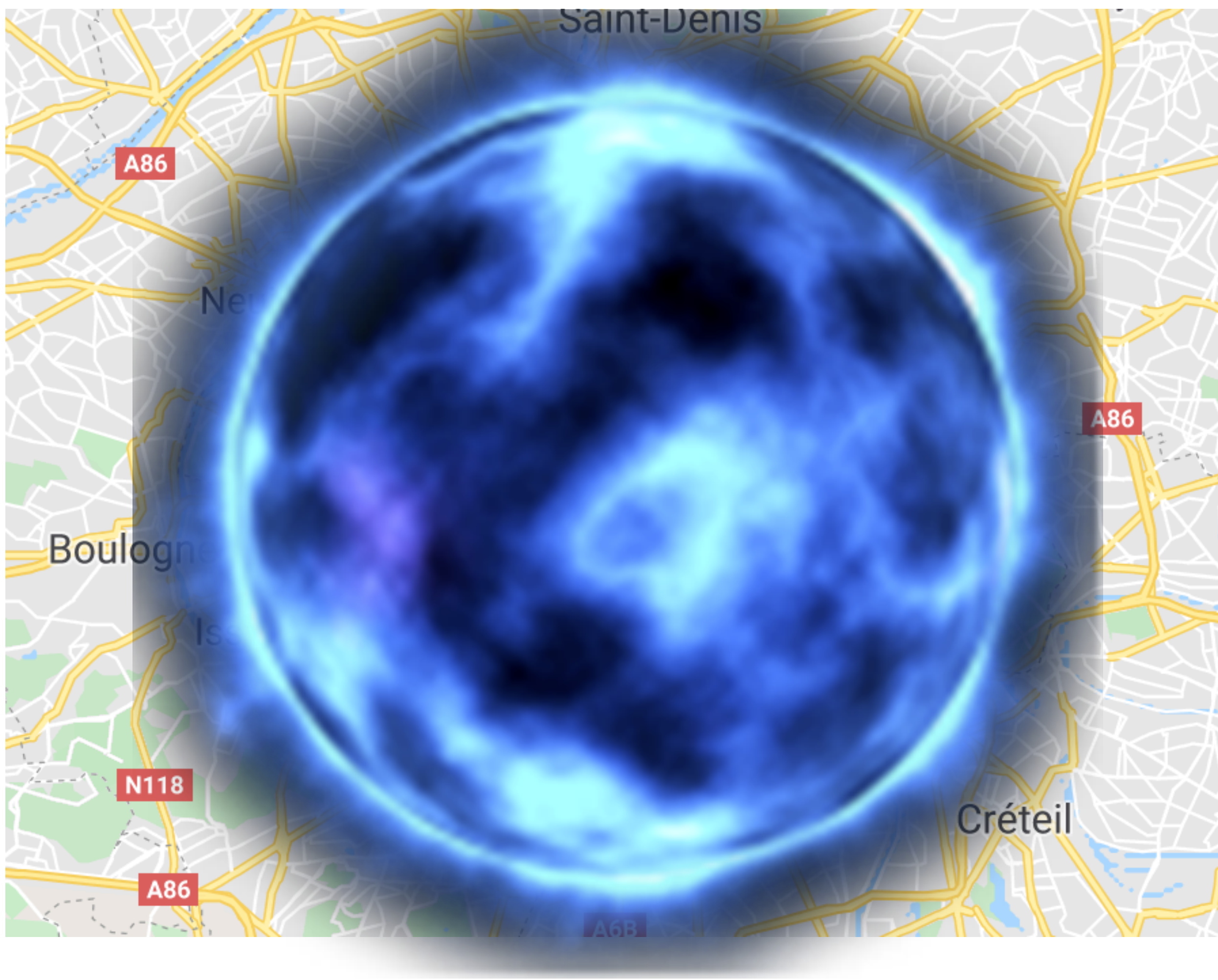

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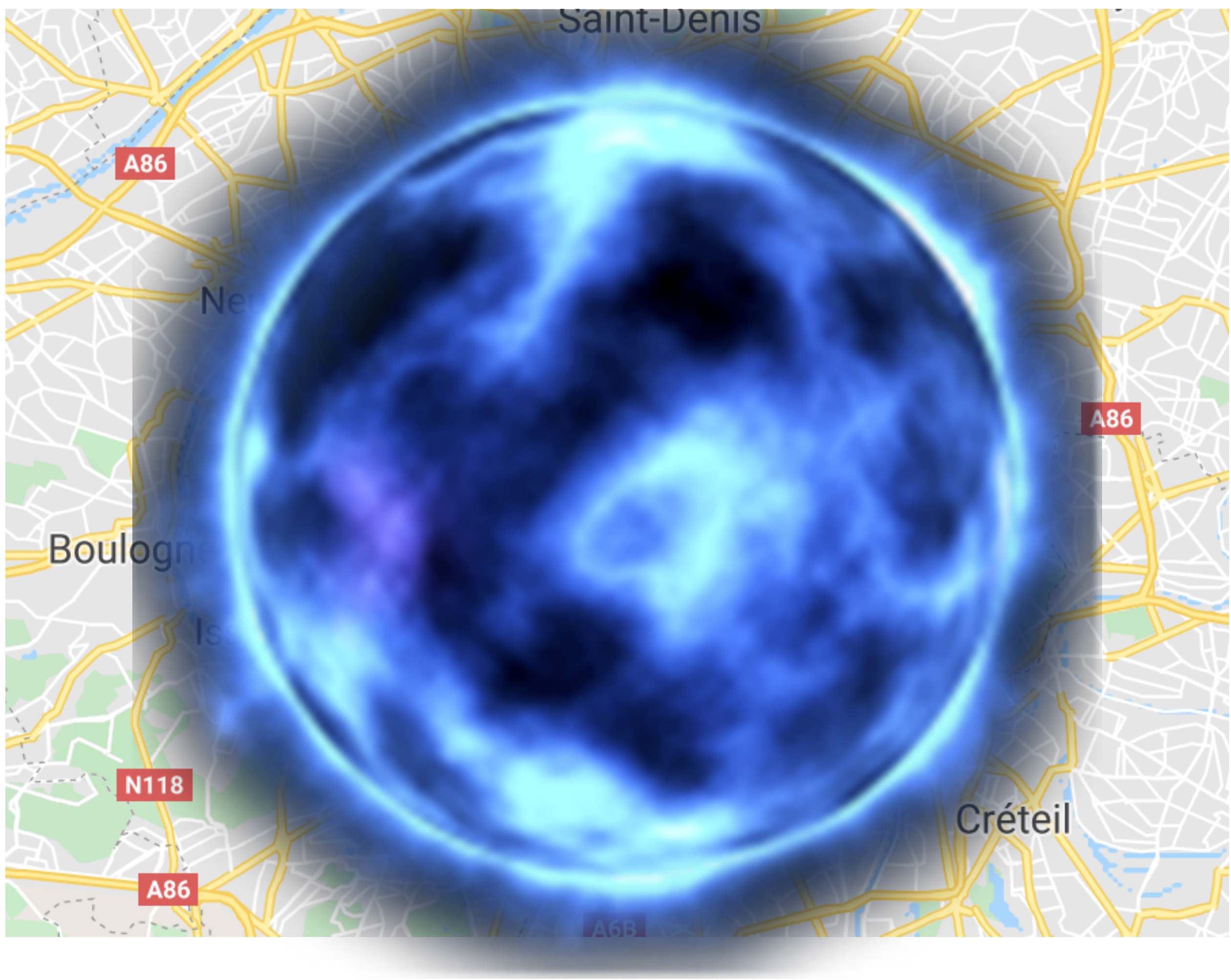

Some properties

$r \sim 10 \text{ km}$

$\mathcal{M} \sim \# \, \mathcal{M}_{\odot}$

$\rho_c >$ nuclear $\sim 10^{17} \text{ kg/cm}^3$

$B \sim 10^{14} \; G$

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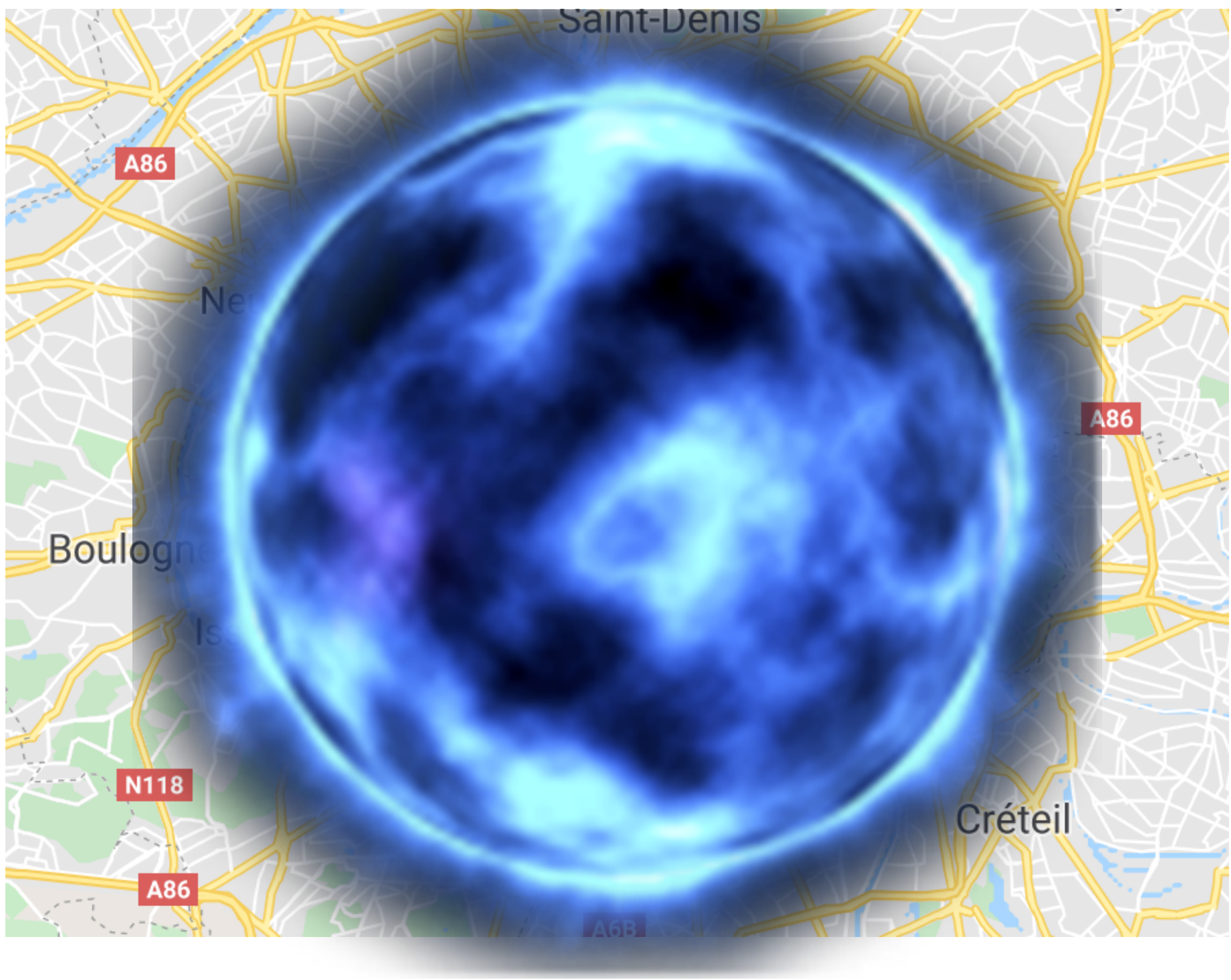

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But there is more…

The extreme numbers of pulsars

pulsars can spin very fast!

	J1748-2446ad	Vela Pulsar	PSR B0329+54	J2144-3933
Period	$1.4\ ms$	$89\ ms$	0.7 s	8.5 s

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speed at equator: $10^{-3}\ c$

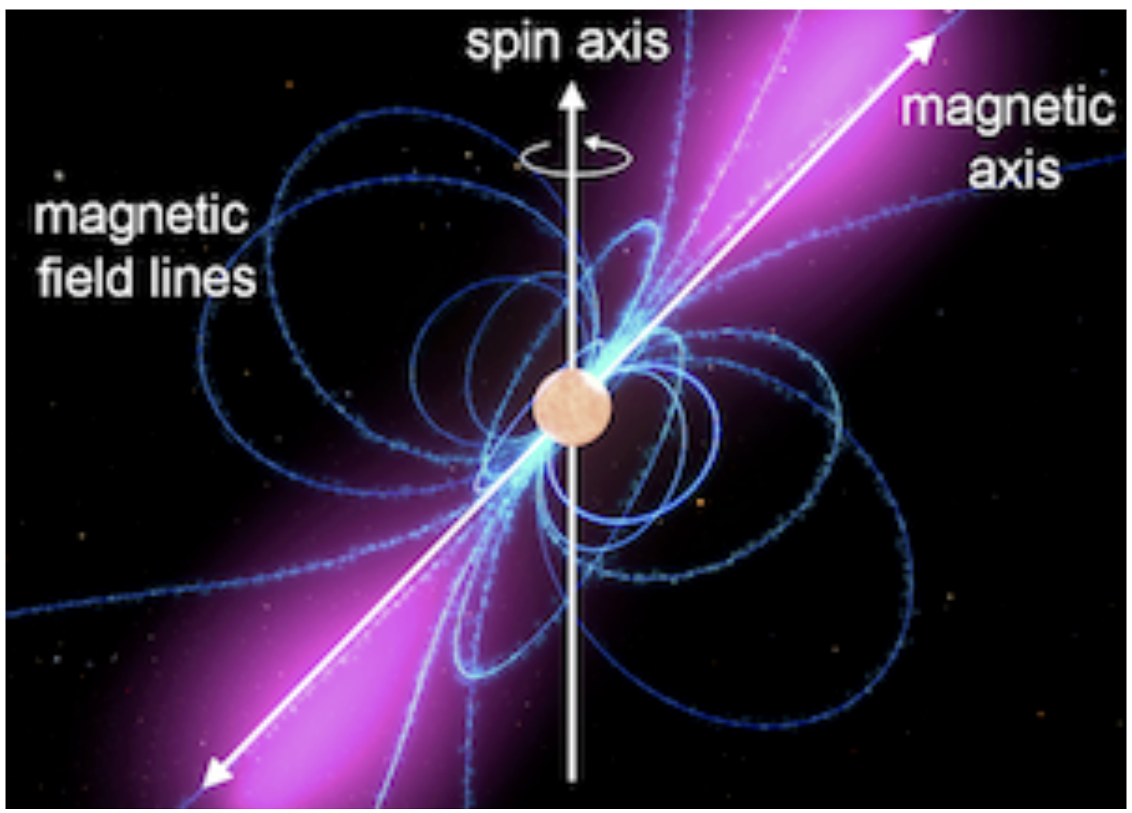
gravity at the equator: $10^{11}\ g$

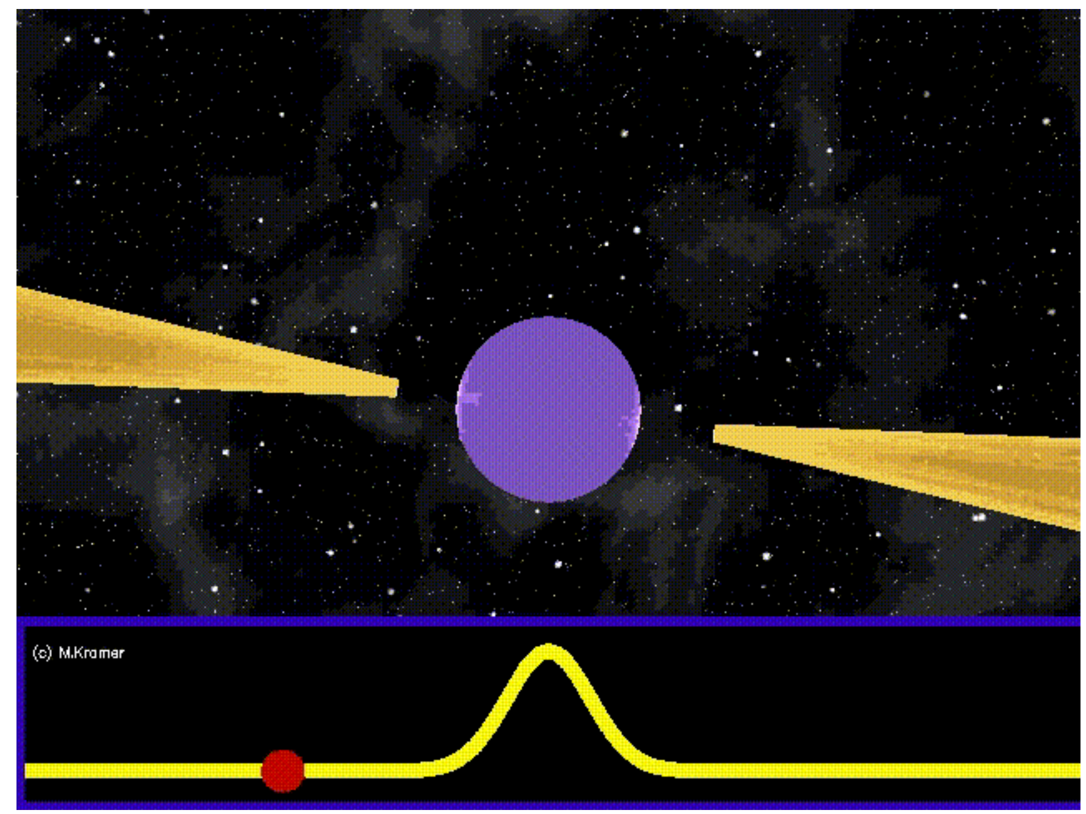
Pulsars are gigantic fly wheels!

Very precise clocks!

Beacons in the sky

pulsars have radio beams along the magnetic axes
(related to the physics of the magnetosphere)





a main observable is the ToA (time of arrival) at different ν

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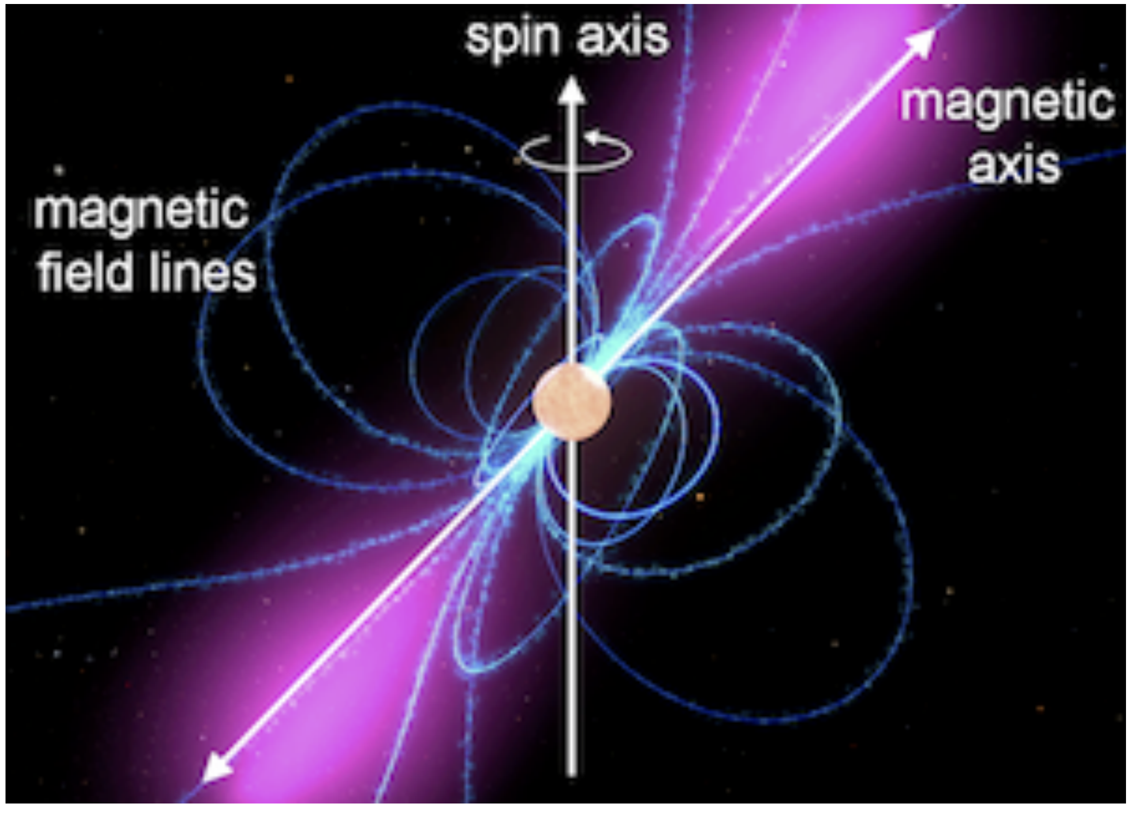
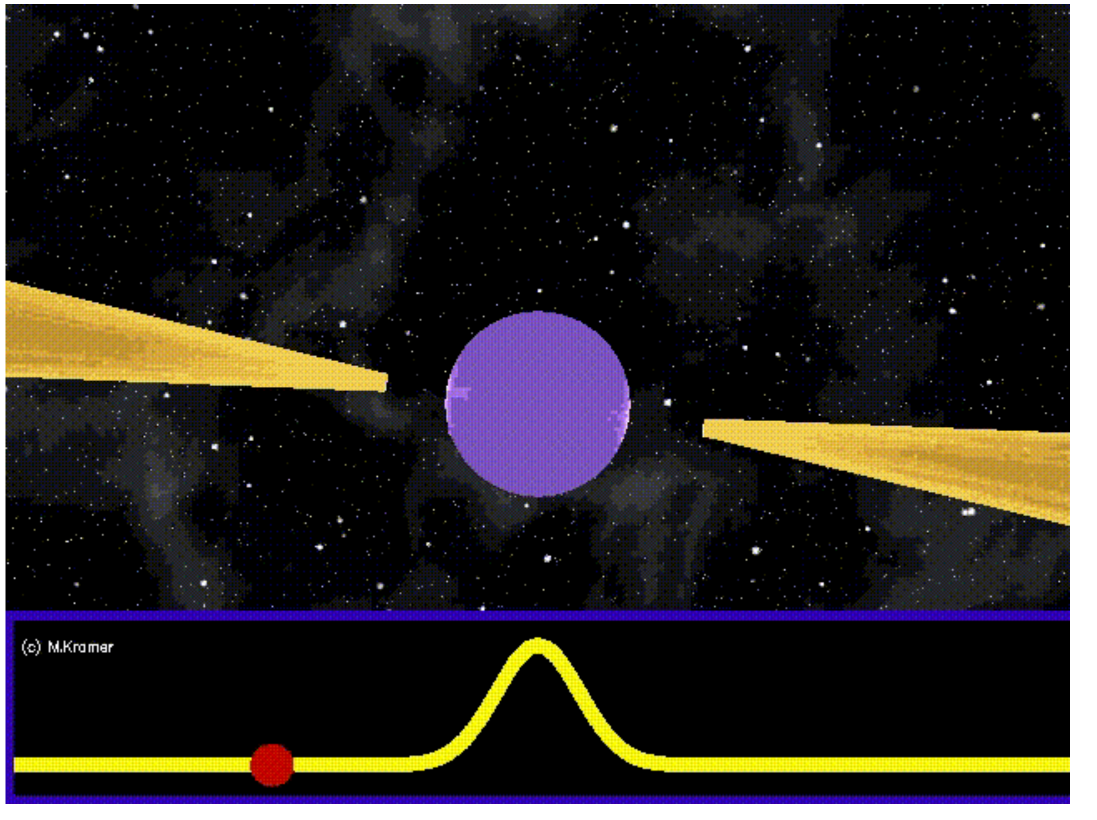
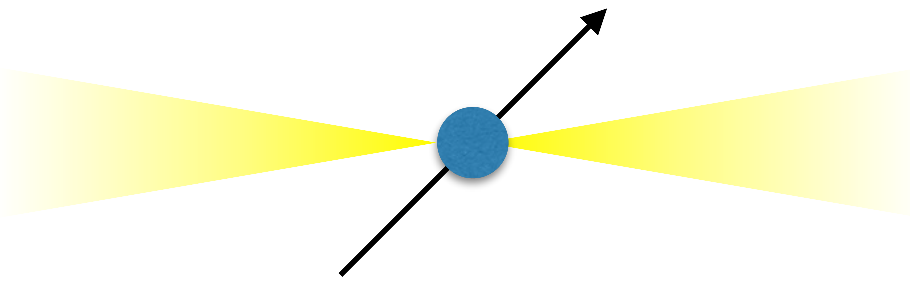
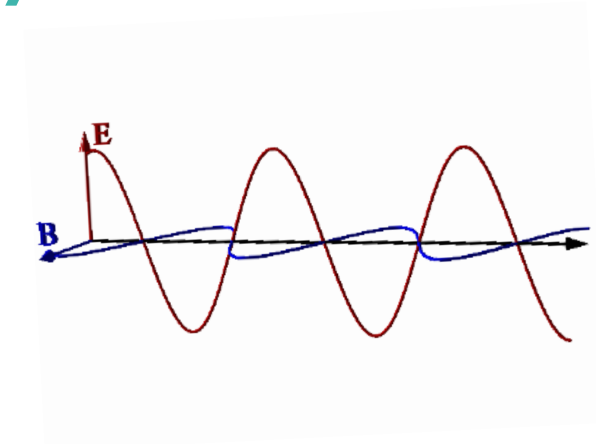


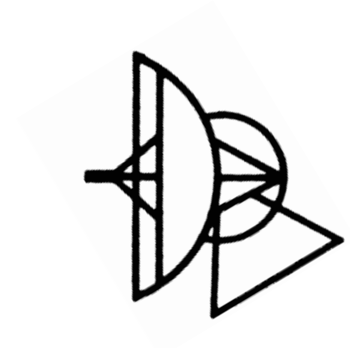


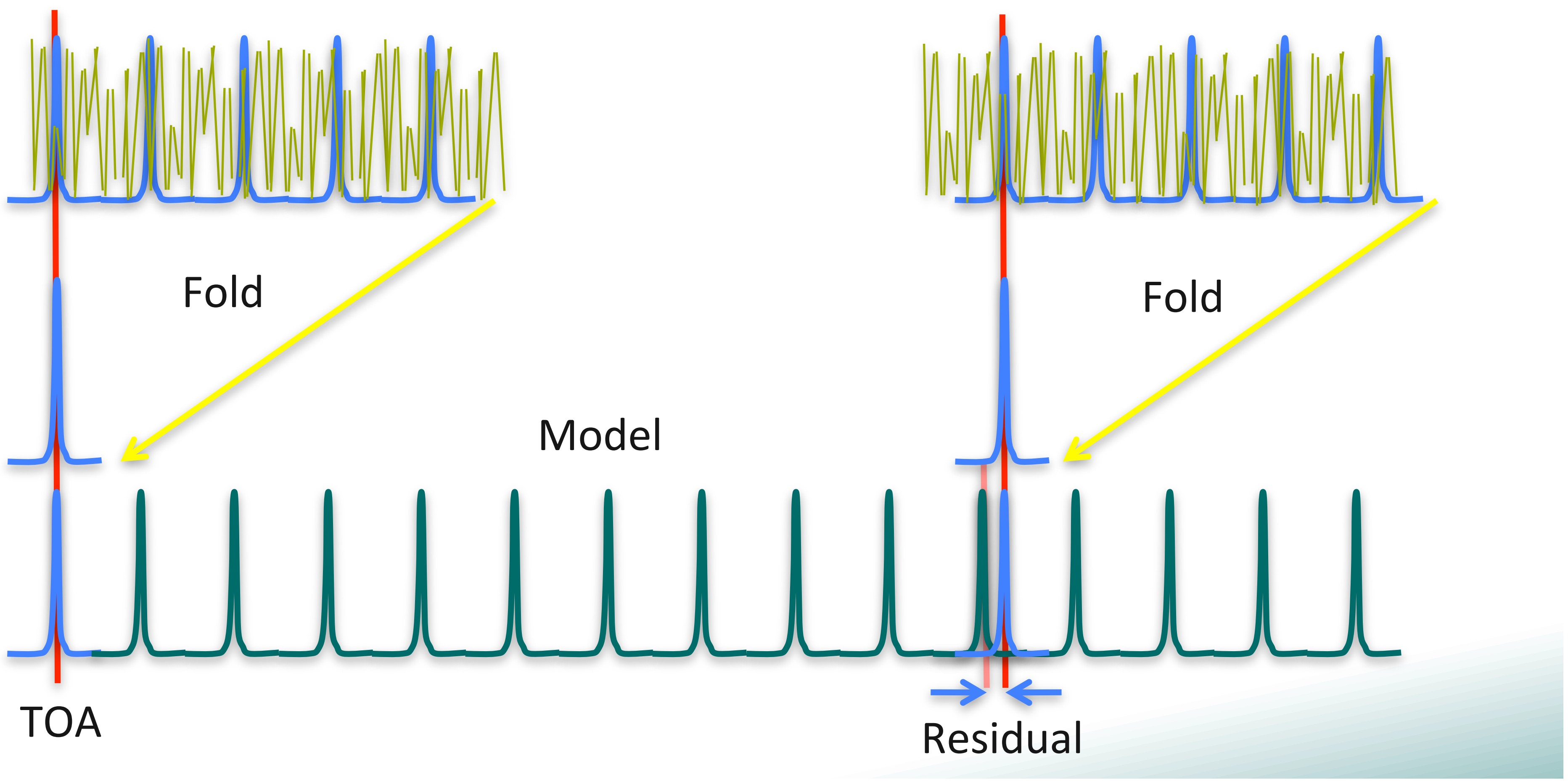
a main observable is the ToA (time of arrival) at different ν

The beauty of the ToA signal







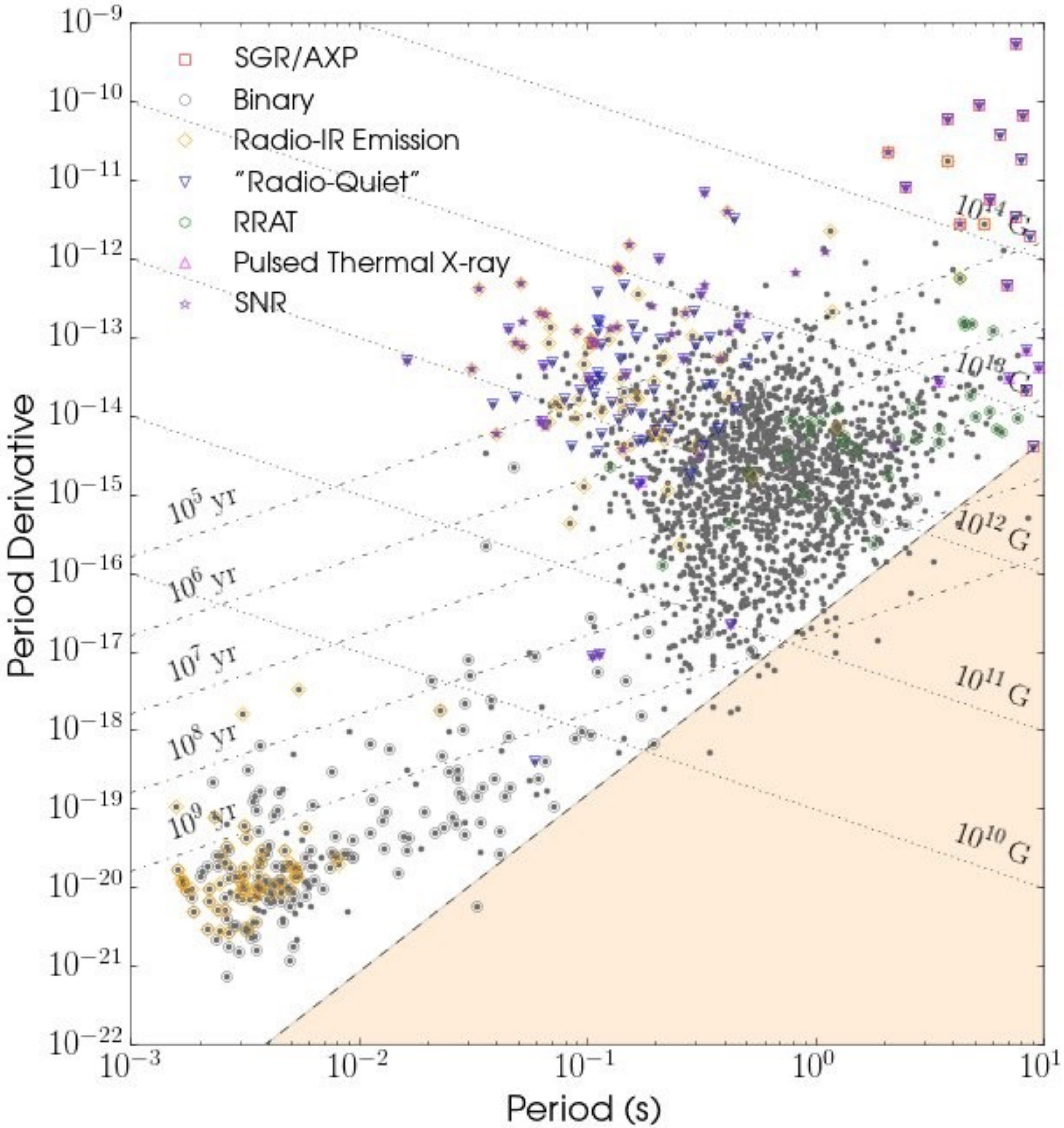


PSR J0437-4715

$P_s =$ 5.757451924362137(2) *ms* (2 atto seconds uncertainty)

(for different frequencies and including polarization)

Pulsars in binaries

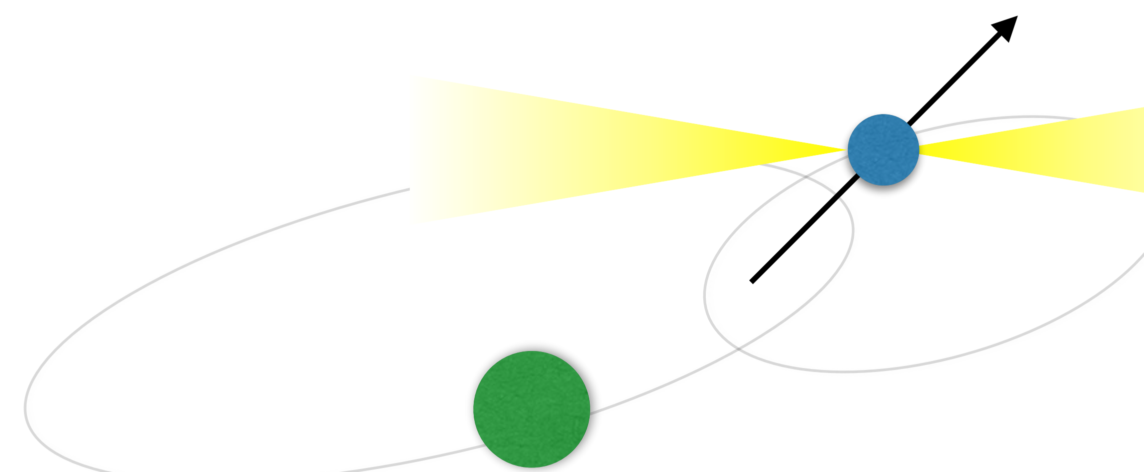


~ 2800 radio pulsars

$10\ \%$ are in binaries (MSS, WD, NS, planets)!

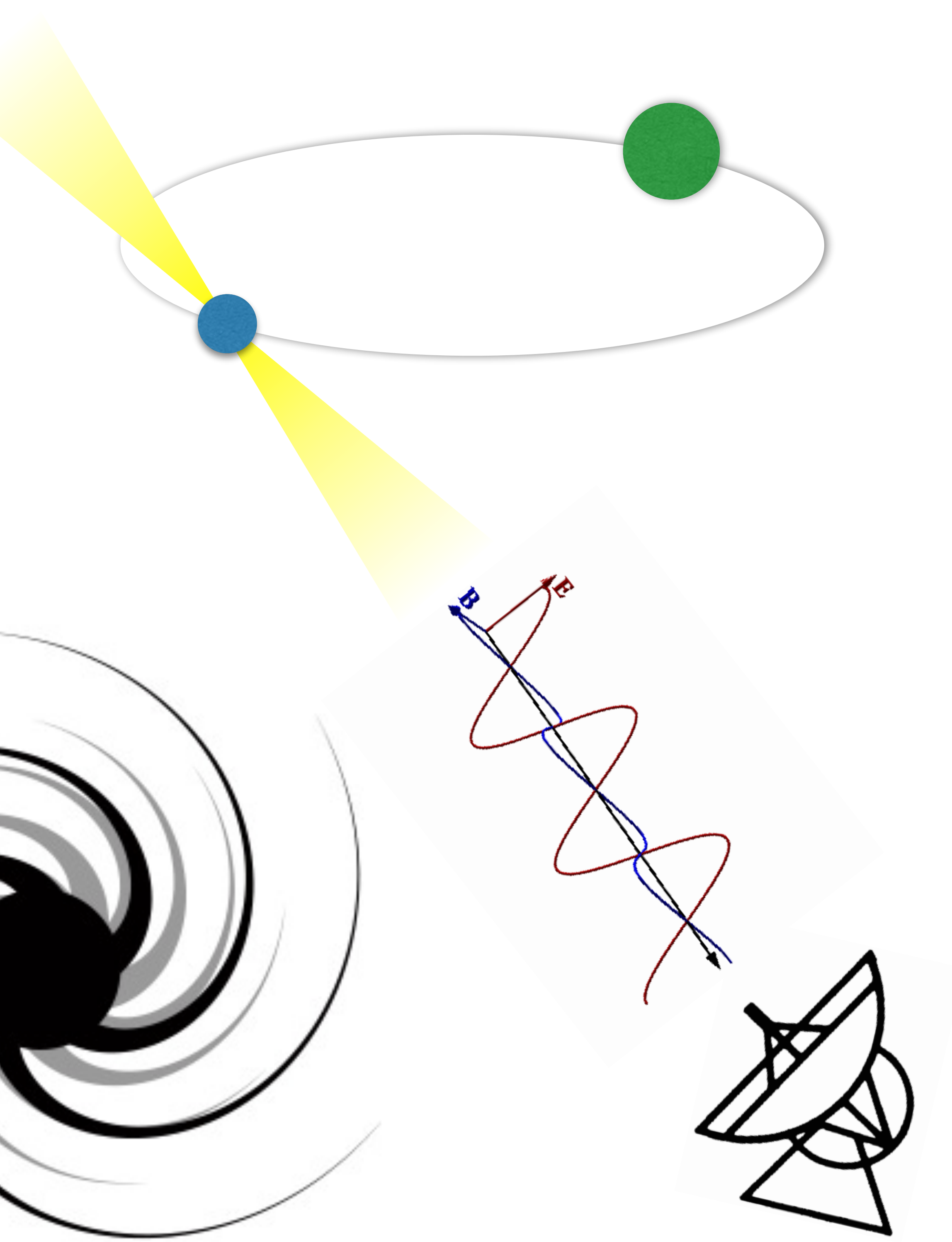
1 known double pulsar

$$P_b = 94 \text{ min} - 5 \text{ yr}$$



the **ToA** of the signal is sensitive to the orbit:
a precise clock falling in the potential

Pulsar timing for fundamental physiX



At emission

- Properties of NSs (dense matter, B, **X**)
- Dynamics of the system: binary (GR, **X**) and external (**X**, matter) interactions

Propagation

- Propagation in the magnetosphere

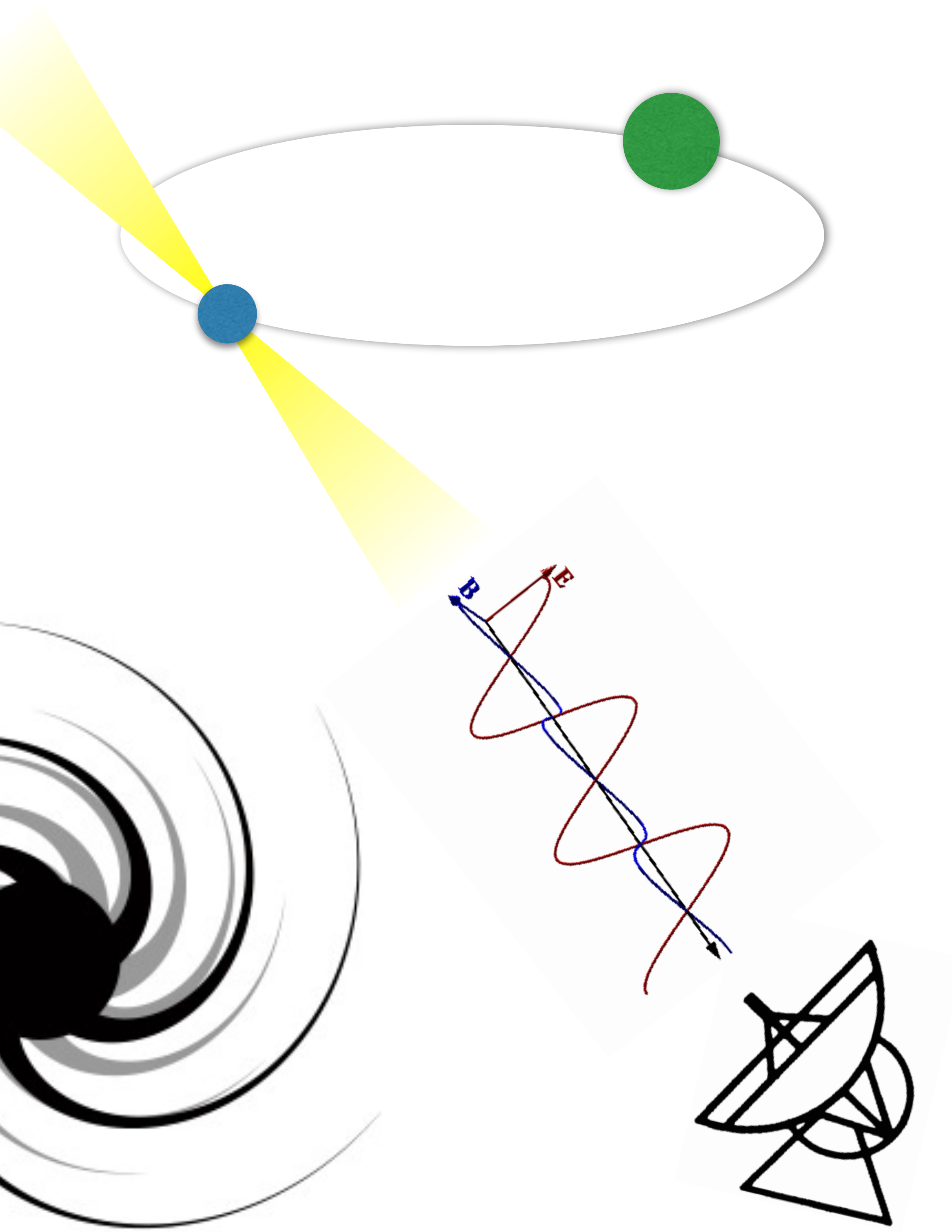
$$X = \mathcal{L}(\phi, F^{\mu\nu}) = \phi\, \vec{E} \cdot \vec{B}$$

- Propagation of signal in the interstellar medium: ions, e, GWs, **X**

At detection

- Fundamental ‘constants’ (**X**)

Pulsar timing for fundamental physiX



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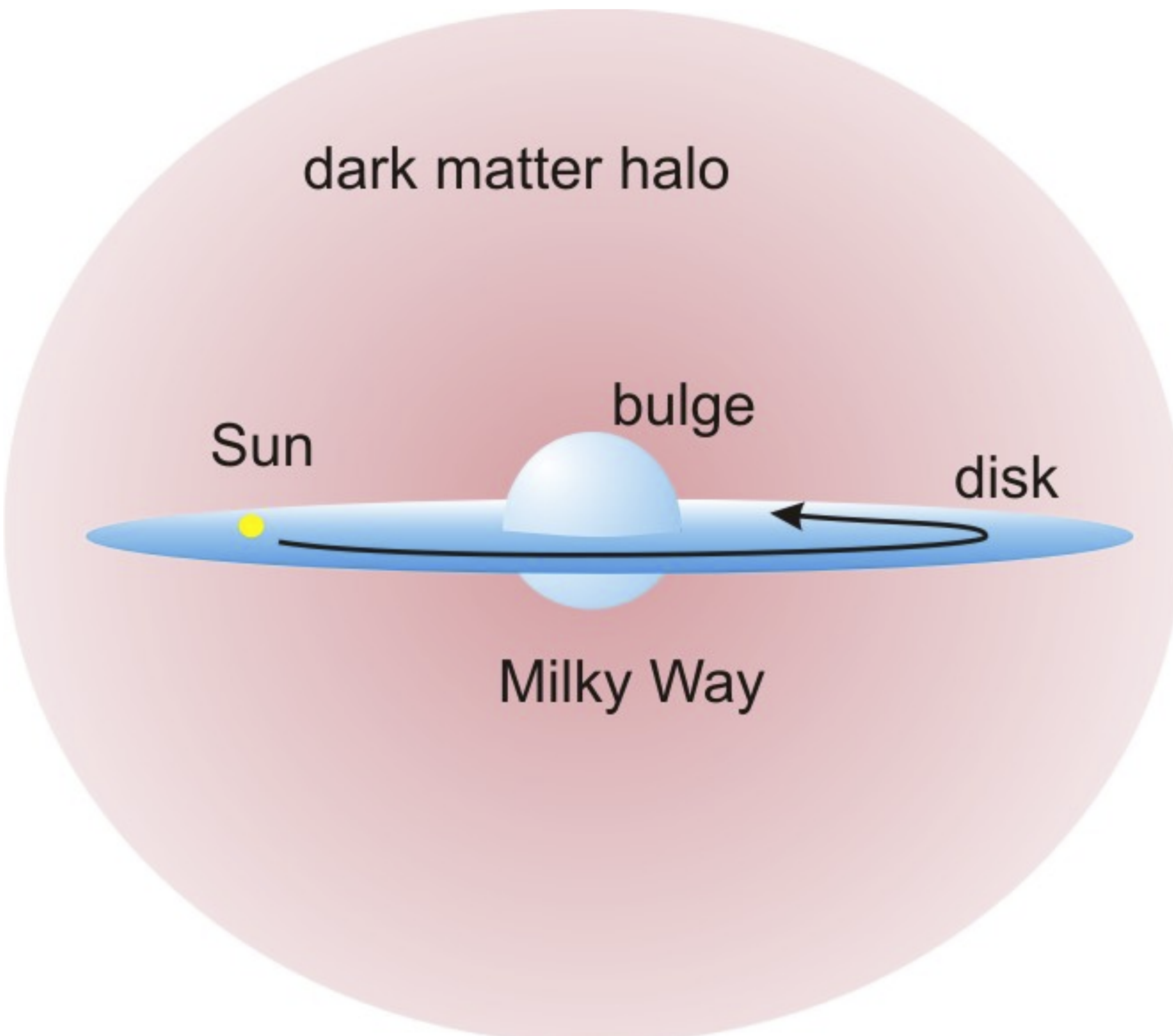
X= (Ultra) light DM

DM in galaxies (e.g. MW)



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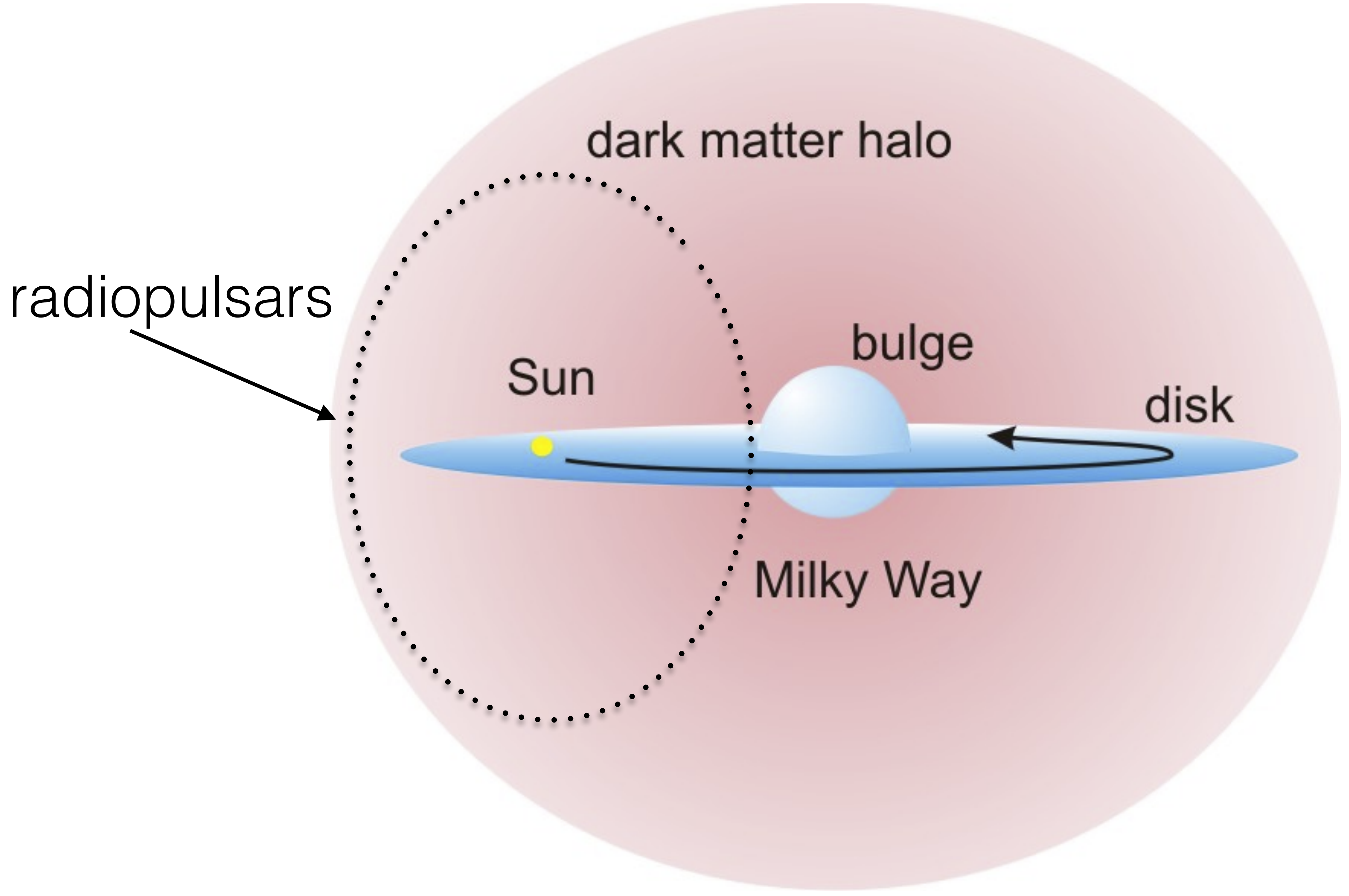
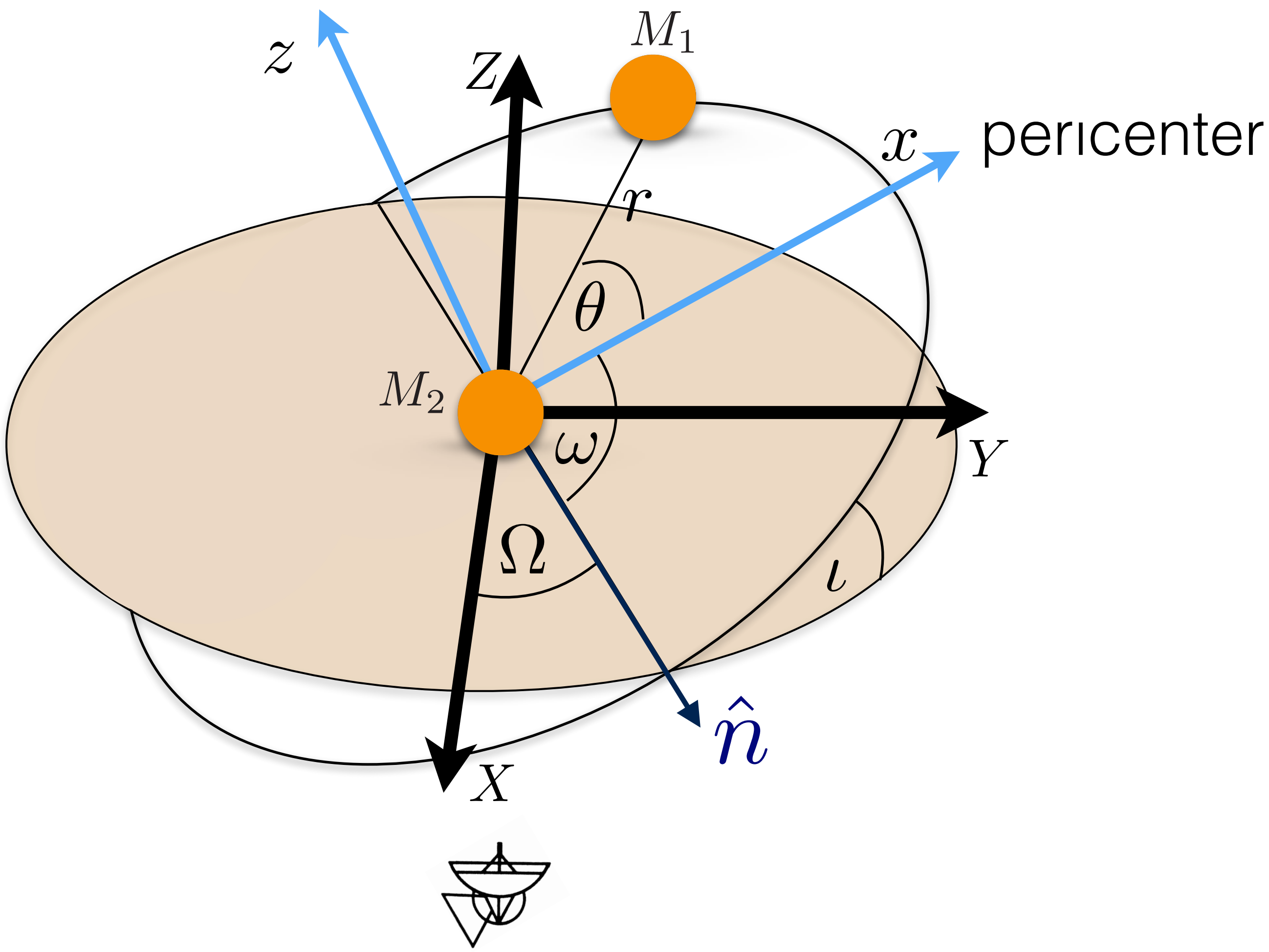


Orbital motion in the presence of WIMPS

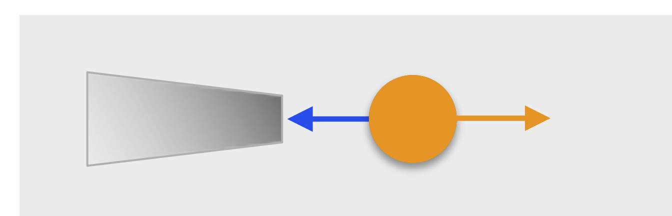


fixed orbital parameters

$a,\ e,\ \varpi,\ \Omega,\ \epsilon_1,\ \iota$

In a WIMP medium

dynamical friction in each object



$$m_i \ddot{\mathbf{r}}_i = \pm \frac{G m_1 m_2}{r^3} \mathbf{r} + \mathbf{F}_i^{\rm ext}$$

(drift of orbital parameters! method of *osculating orbits*)

e.g. $\dot{a} = 2\sqrt{\frac{r_0^3}{GM}}\, \mathbf{F}_i^{\rm ext} \cdot \mathbf{e}_\theta$

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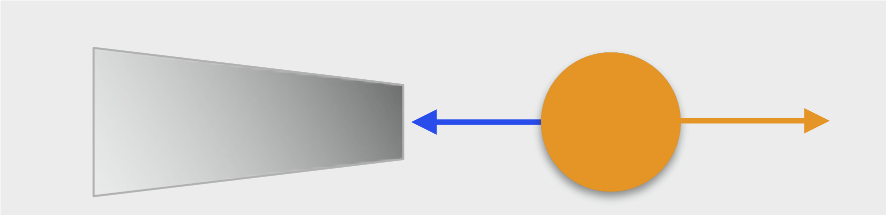
Chandrasekhar, 1940s, Binney & Tremaine, "Galactic Dynamics", 1987



σ : DM dispersion

$$x \equiv v/(\sqrt{2}\sigma) \ll 1$$

Dynamical friction:

$$\mathbf{F}_i^{\mathrm{DF}} = -4\pi\rho_{\mathrm{DM}}\lambda\frac{G^2 m_i^2}{v_i^3}\left(\frac{4x^3}{3\sqrt{\pi}} - \frac{4x^5}{5\sqrt{\pi}} + O\left(x^7\right)\right)\mathbf{v}_i$$

Pani 2015

$$\langle \dot{P}_b^{\mathrm{DF}} \rangle \approx -3\times 10^{-14}\left(\frac{\lambda}{20}\right)\left(\frac{\mu}{M_\odot}\right)\left(\frac{\rho_{\mathrm{DM}}}{2\times 10^3\,\mathrm{GeV/cm}^3}\right)\left(\frac{P_b}{100\,\mathrm{day}}\right)\left(\frac{150\,\mathrm{km/s}}{\sigma}\right)^3$$

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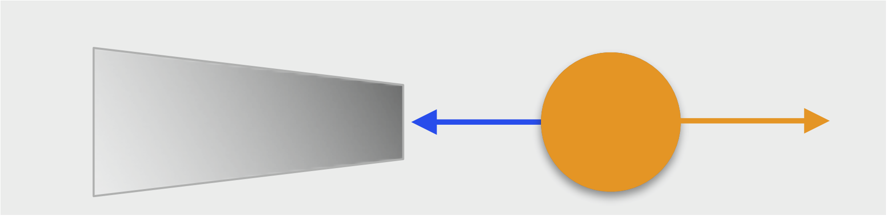

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$$\rho_\odot \sim 0.3\ \mathrm{GeV/cm^3}$$

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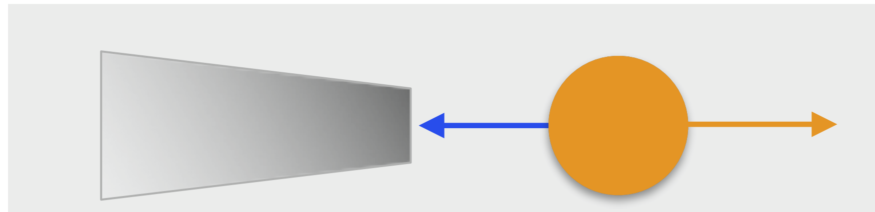

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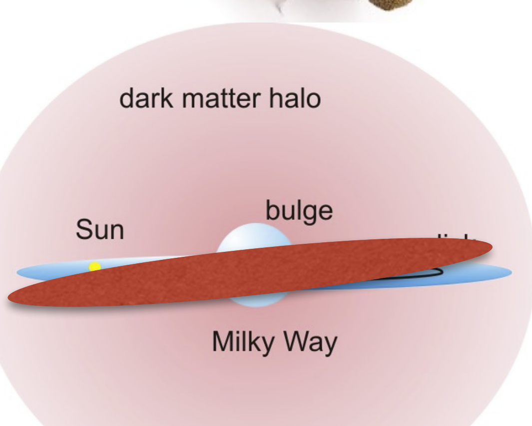
better prospects for other WIMP models Caputo, DB, Zavala 2017

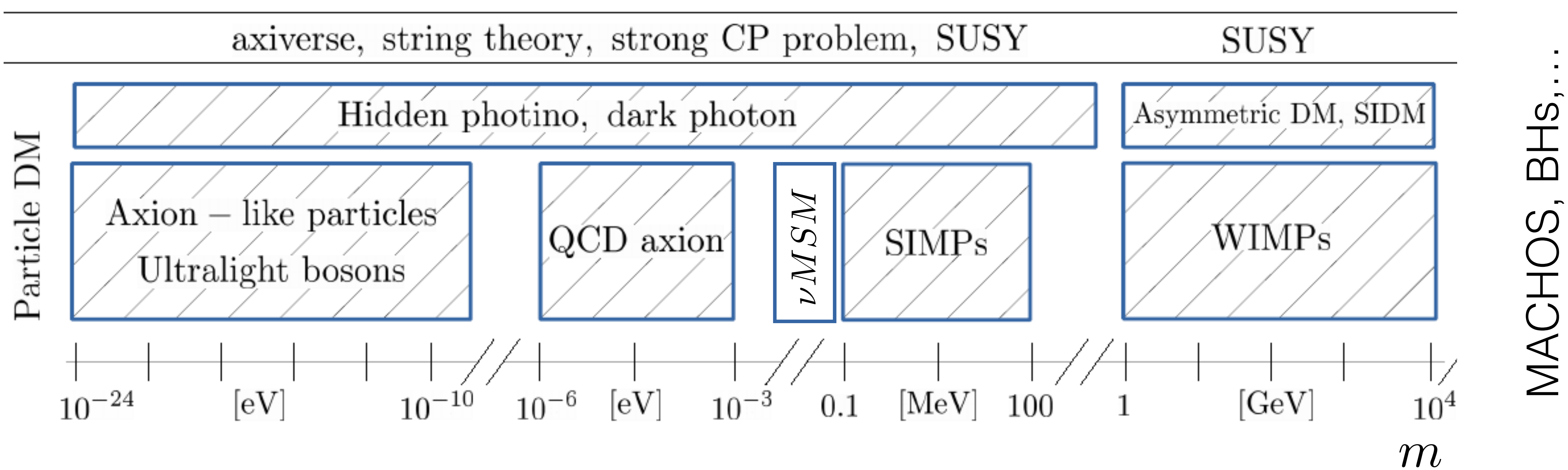


(Randall et al 2014)

* Double disk models have higher ρ and lower σ
* Maybe SM-DM interacting through a light mediator?

Ultra light DM models

- ☑ DM candidate should be a cold gravitating medium
- ☑ Production mechanism and viable cosmology
- ☑ Motivation from fundamental physics
- ☑ Possibility of (direct or indirect) detection

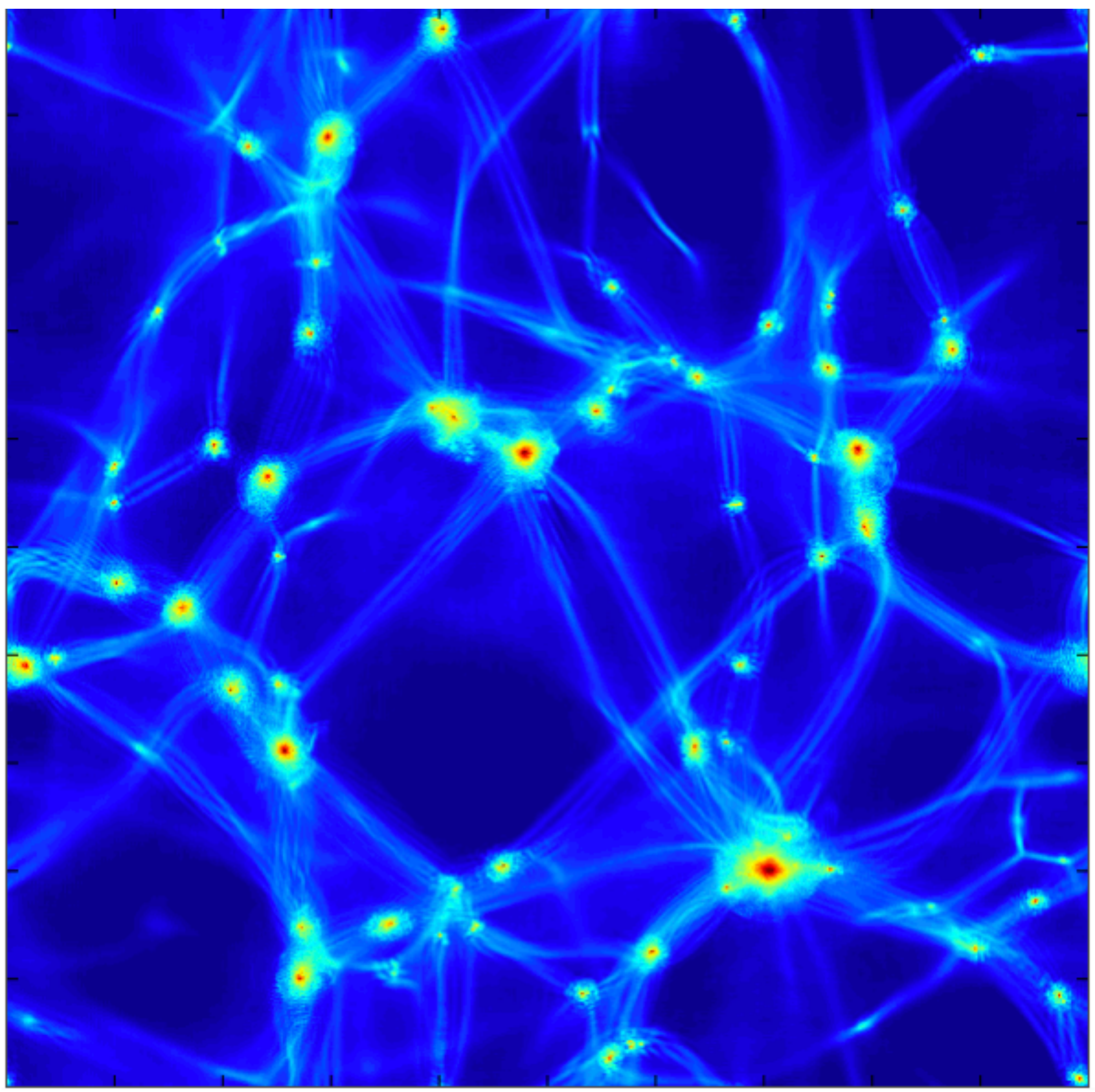


ULDM behaves like CDM at large-scales

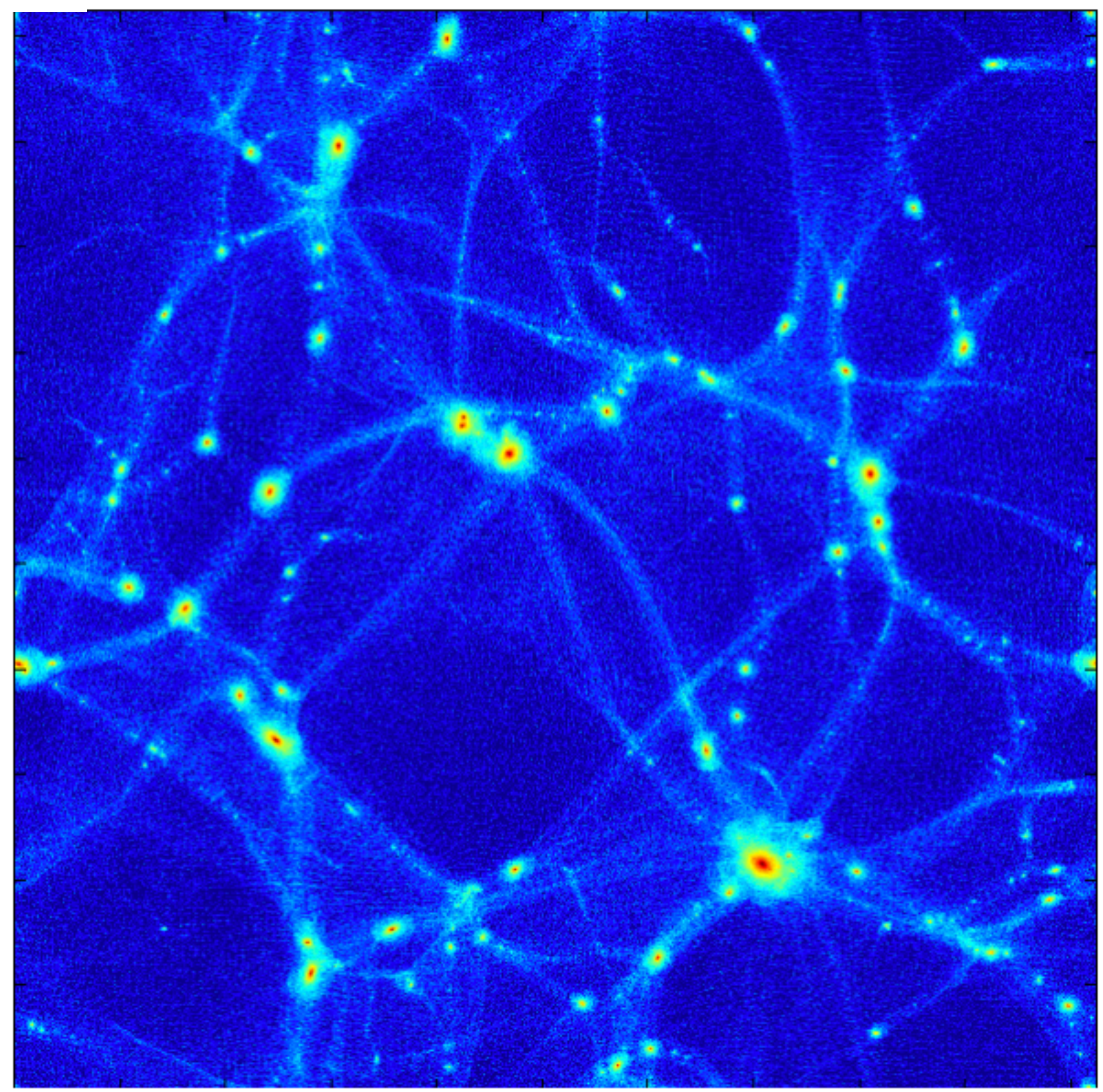
$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right] \quad + \text{gravity}$$

Scale of ~30 Mpc, Schive et al. 1406.6586

ULDM

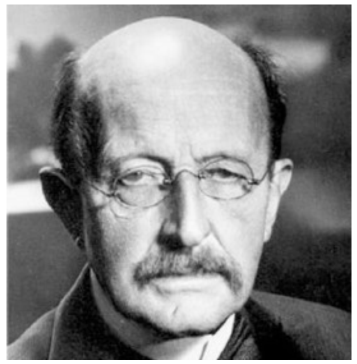


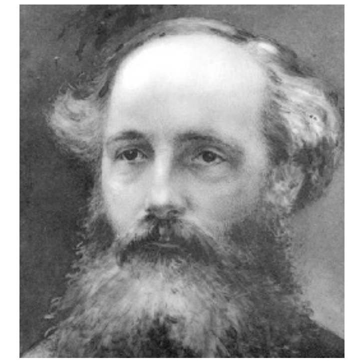
CDM



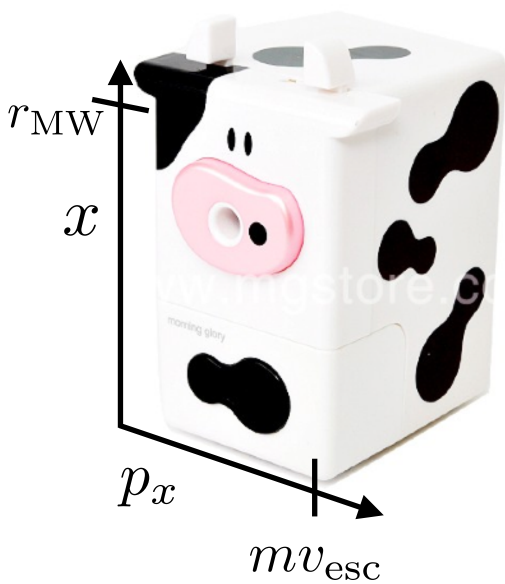
Ultra light DM in our Galaxy

$\hbar\omega$





$F_{\mu\nu}$



i) escape velocity $\sim 2 \times 10^{-3} c$ ii) size 100 kpc

$$\Delta x \Delta p \gtrsim \hbar \rightarrow N_s \sim 10^{75} \left(\frac{m}{\rm eV}\right)^3$$

$$N_p = \frac{M_{MW}}{N_s m} \sim 10^3 \left(\frac{\rm eV}{m}\right)^4$$

For ULDM, field has huge occupation numbers with random phases:

it can be treated as a classical field

$$\mathcal{L} = \frac{1}{2}\left[(\partial_\mu \phi)^2 - m^2\phi^2\right] \rightarrow \phi_k \sim e^{i(\omega t - kx)}$$

in a virialized halo

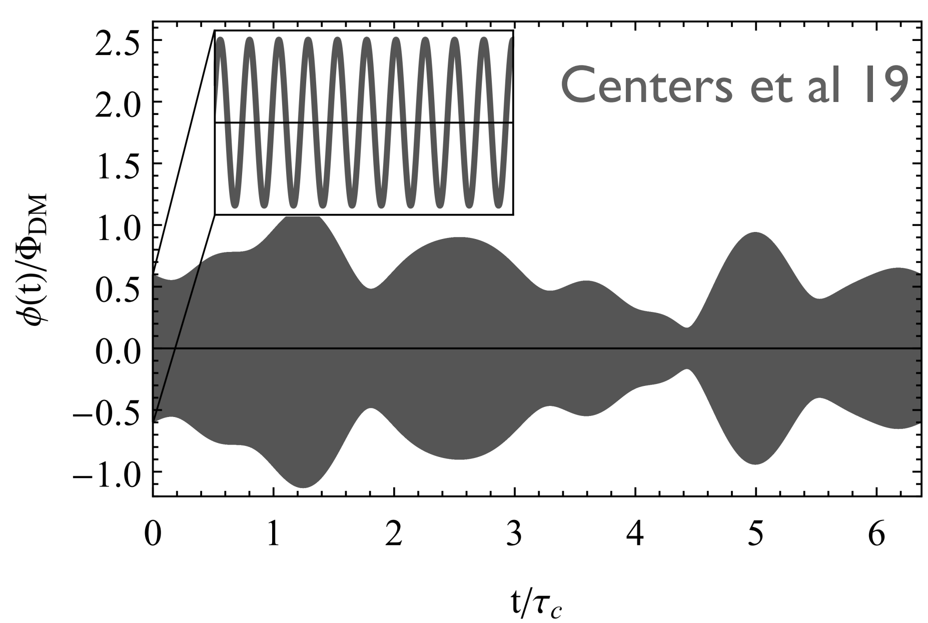
'Coherent' effects of ULDM in the MW

Virialized configuration: collection of waves
with distribution determined by properties from the galaxy

$$\phi \propto \int_0^{v_{max}} \mathrm{d}^3v\, e^{-v^2/\sigma_0^2} e^{i\omega_v t} e^{-im\vec{v}\cdot\vec{x}} e^{if_{\vec{v}}} + c.c.$$

distribution: $\sigma_0 \sim 10^{-3}c$ in the MW

since $v \sim \sigma_0 \ll 1$ ➔ $\omega_v \approx m(1+v^2)$ ➔ $\phi \propto \phi_0 \cos(mt + f)$



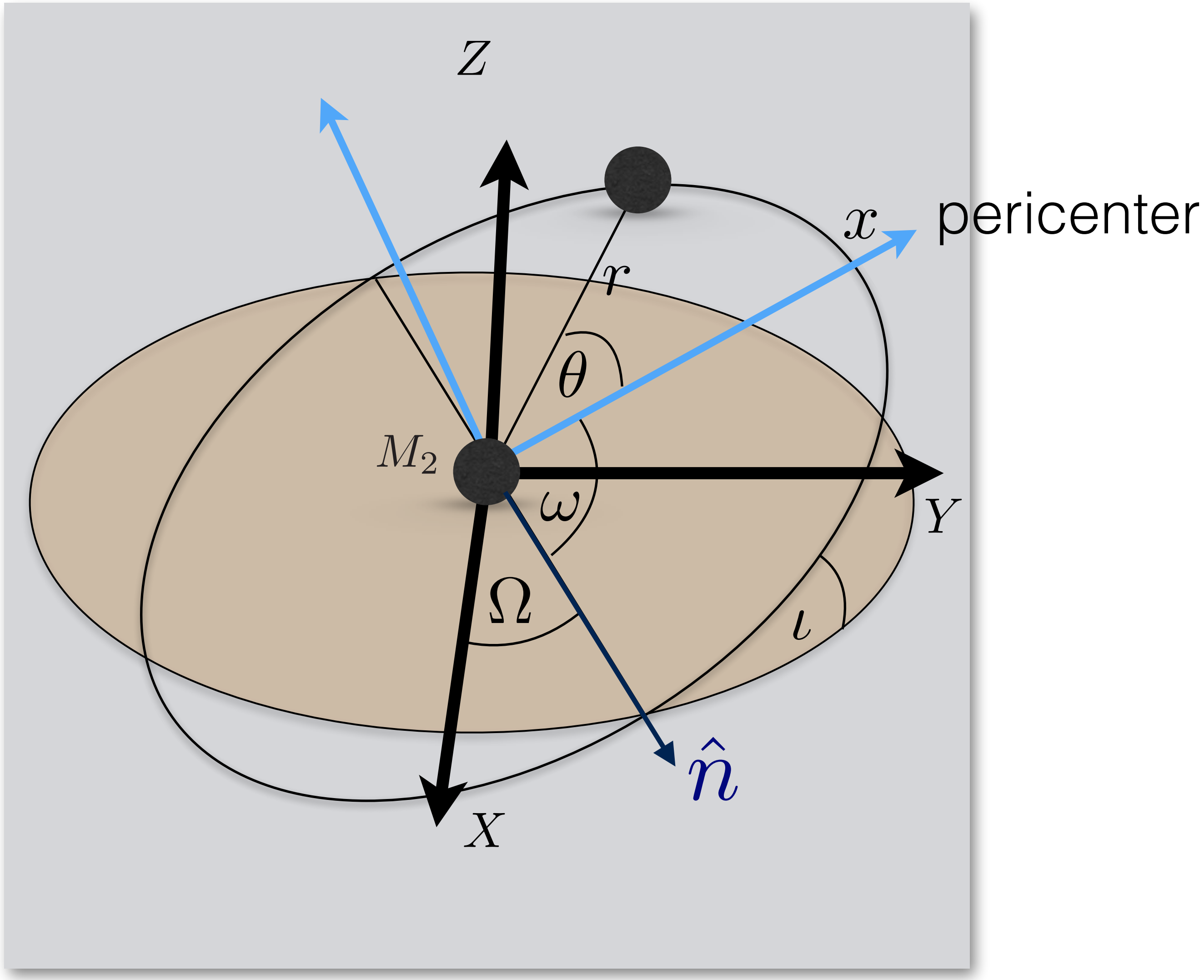
$$\tau_c \sim 65 \text{ years} \left(\frac{10^{-3}}{V_0}\right)^2 \left(\frac{10^{-18}\text{eV}}{m_\Phi}\right)$$

It is also very homogenous

the field is homogeneous at scales

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

$$\phi_0 \cos(mt + f)$$



$$\rho_{DM} = \frac{m^2 \phi_0^2(t)}{2} \qquad p = -\rho_{DM} \cos(2mt + 2\alpha) \quad \rightarrow \quad (\varphi_N^{\rm gal}(t), \psi_N^{\rm gal}(t))$$

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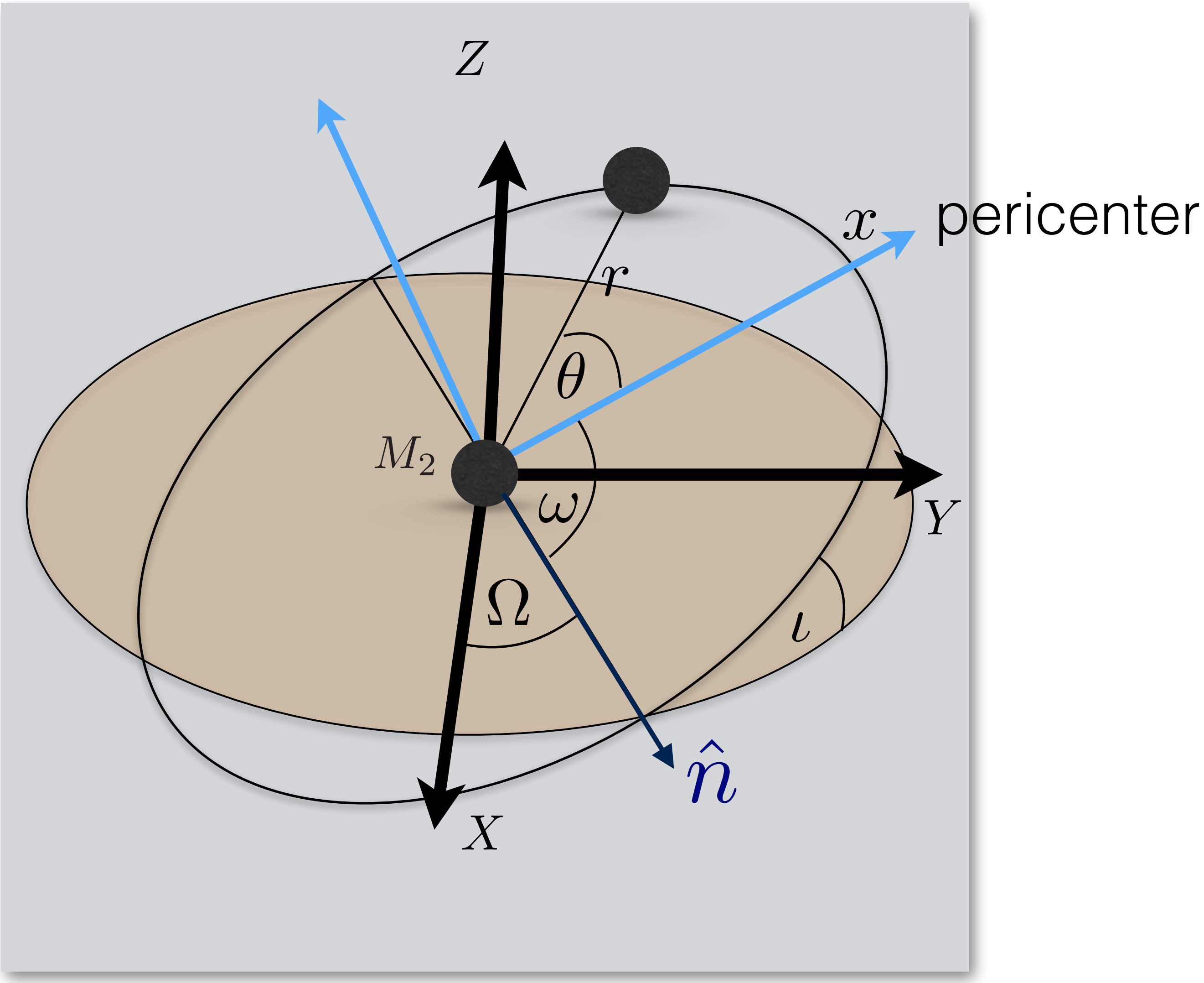

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Effects on binary system: pure gravity

DB, LopezNacir, Sibiryakov 16, 19

$$\ddot{\vec{R}}_{CM} = 0$$

$$\mu\,\ddot{\vec{r}} = \vec{F}_{\rm GR} + \vec{F}_{\rm DM,halo} \propto \vec{r}$$

$$\delta E_b = \mu \int_0^{P_b} \mathrm{d}t\, \dot{\vec{r}} \cdot \vec{F} \quad \rightarrow \quad \dot{P}_b$$

$$P_b \propto |E_b|^{-3/2}$$

Can also be found from the osculating method

$$\frac{\dot{a}}{a} = -\frac{2e}{\omega_b\sqrt{1-e^2}}\ddot{\psi}\frac{r}{a}\sin\theta$$

$$\dot{e} = -\frac{\sqrt{1-e^2}}{\omega_b}\ddot{\psi}\frac{r}{a}\sin\theta$$

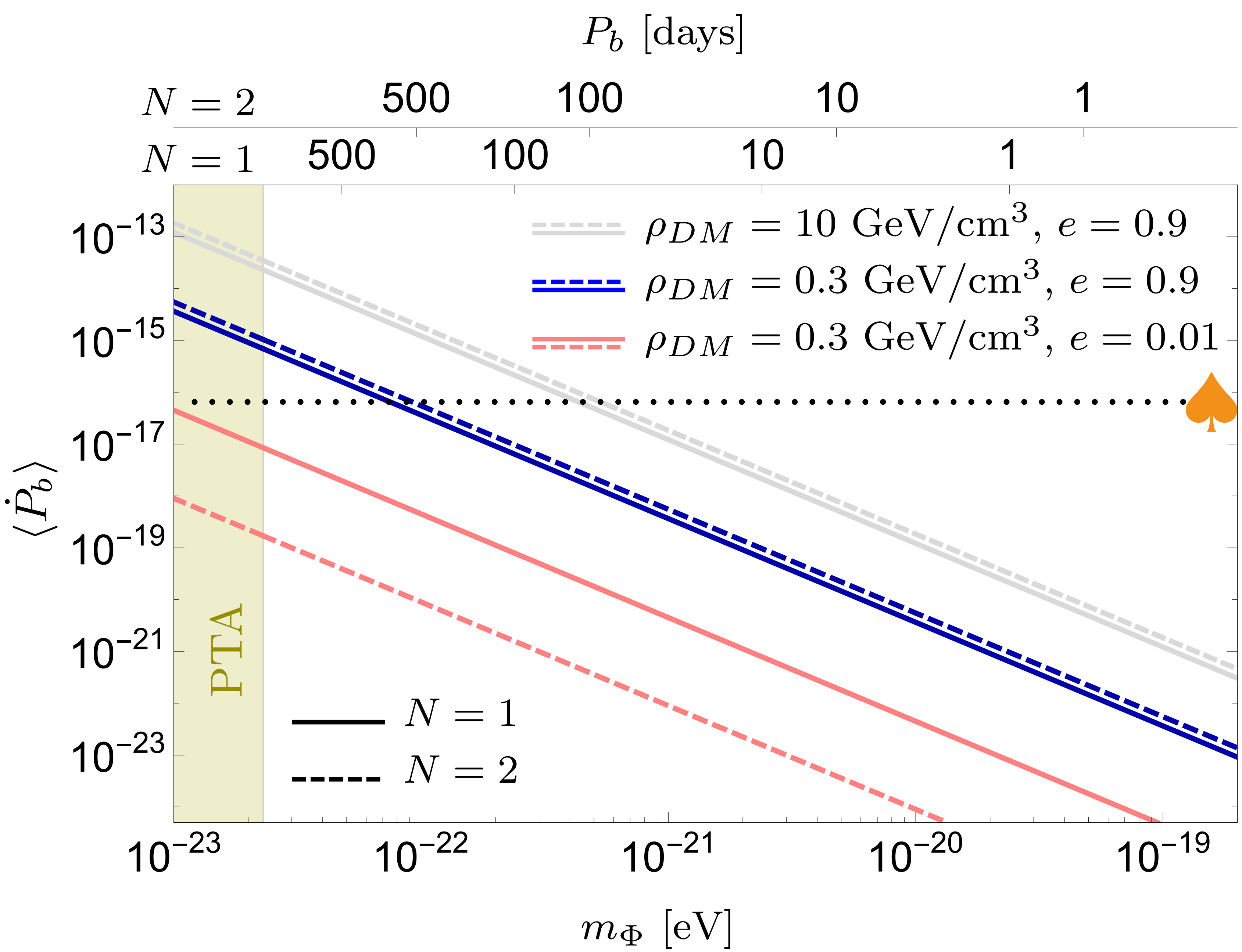
→ if $m \approx N\dfrac{2\pi}{P_b}$

the effect accumulates in every orbit (**resonant effect**)

Prospects of observation

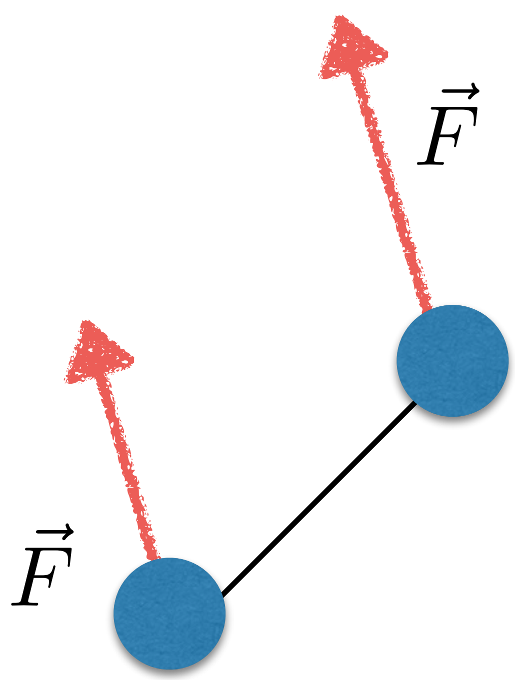
DB, LopezNacir, Sibiryakov 16

This pure gravitational test of ULDM
is beyond reach….



Effects on binary system: DM-matter interaction

DB, LopezNacir, Sibiryakov 16, 19



DM can couple directly to matter

$$m_i \alpha \int \phi\left(x_{pp}\right) \mathrm{d}s_i + m_i \beta \int \left[\phi\left(x_{pp}\right)\right]^2 \mathrm{d}s_i \ \ldots$$

again $$m_i \ddot{\mathbf{r}}_i = \pm \frac{G m_1 m_2}{r^3} \mathbf{r} + \mathbf{F}_i^{\text{ext}}$$

$$\ddot{\vec{R}}_{CM} \neq 0$$ (swamped by systematics)

$$\mu \, \ddot{\vec{r}} = \vec{F}_{\text{GR}} + \vec{F}_{\text{DM,halo}}(\phi(t))$$

$$\delta L_b = \mu \int_0^{P_b} \mathrm{d}t \, \vec{r} \times \vec{F} \rightarrow L_b^2 \propto P_b^{2/3} \left(1 - e^2\right) \rightarrow \dot{e}$$

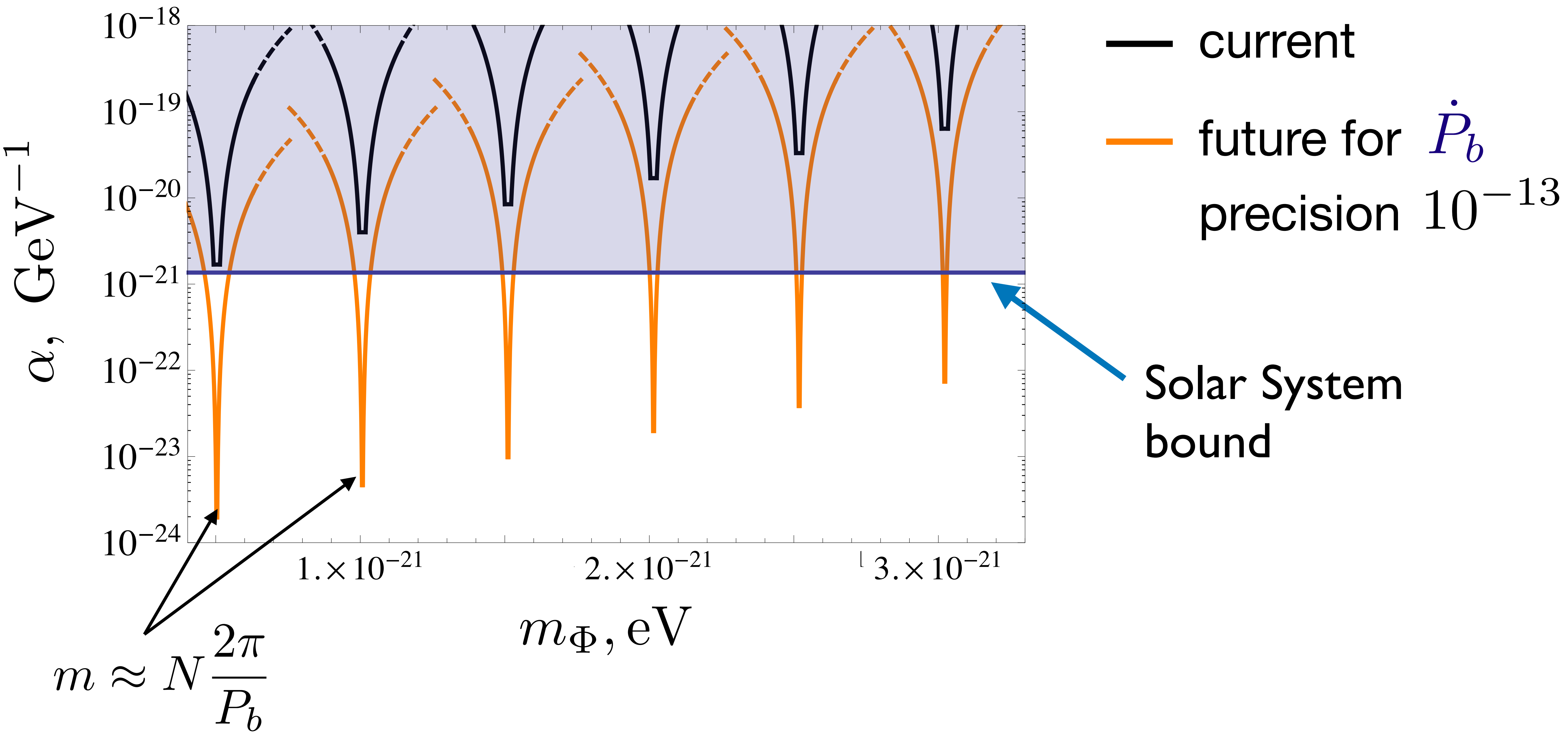
Secular effects at J1903+0327

$$P_b = 95 \text{ days} \ , e = 0.44$$

Freire et al 2011

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

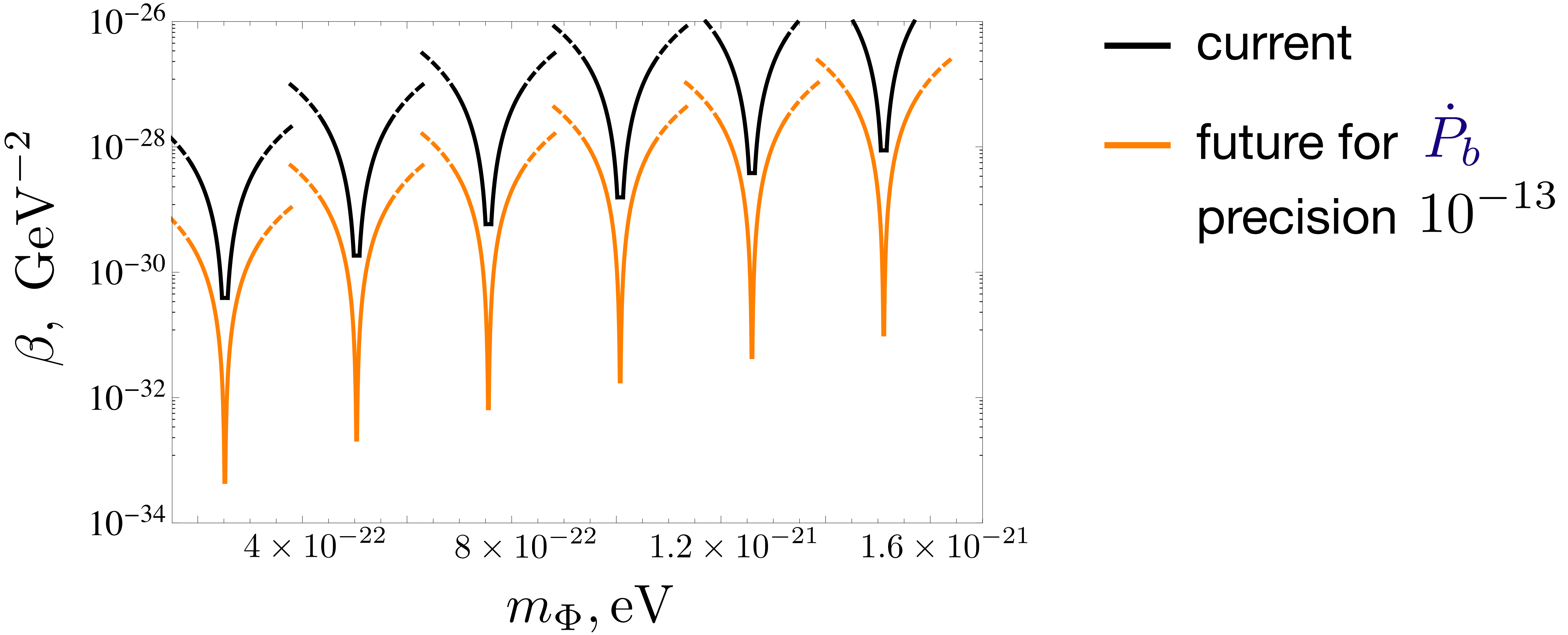
DB, LopezNacir, Sibiryakov 16, 19



Secular effects at J1903+0327

$$\cancel{m_i \alpha \int \phi\left(x_{pp}\right) \mathrm{d}s_i} + m_i \beta \int \left[\phi\left(x_{pp}\right)\right]^2 \mathrm{d}s_i$$

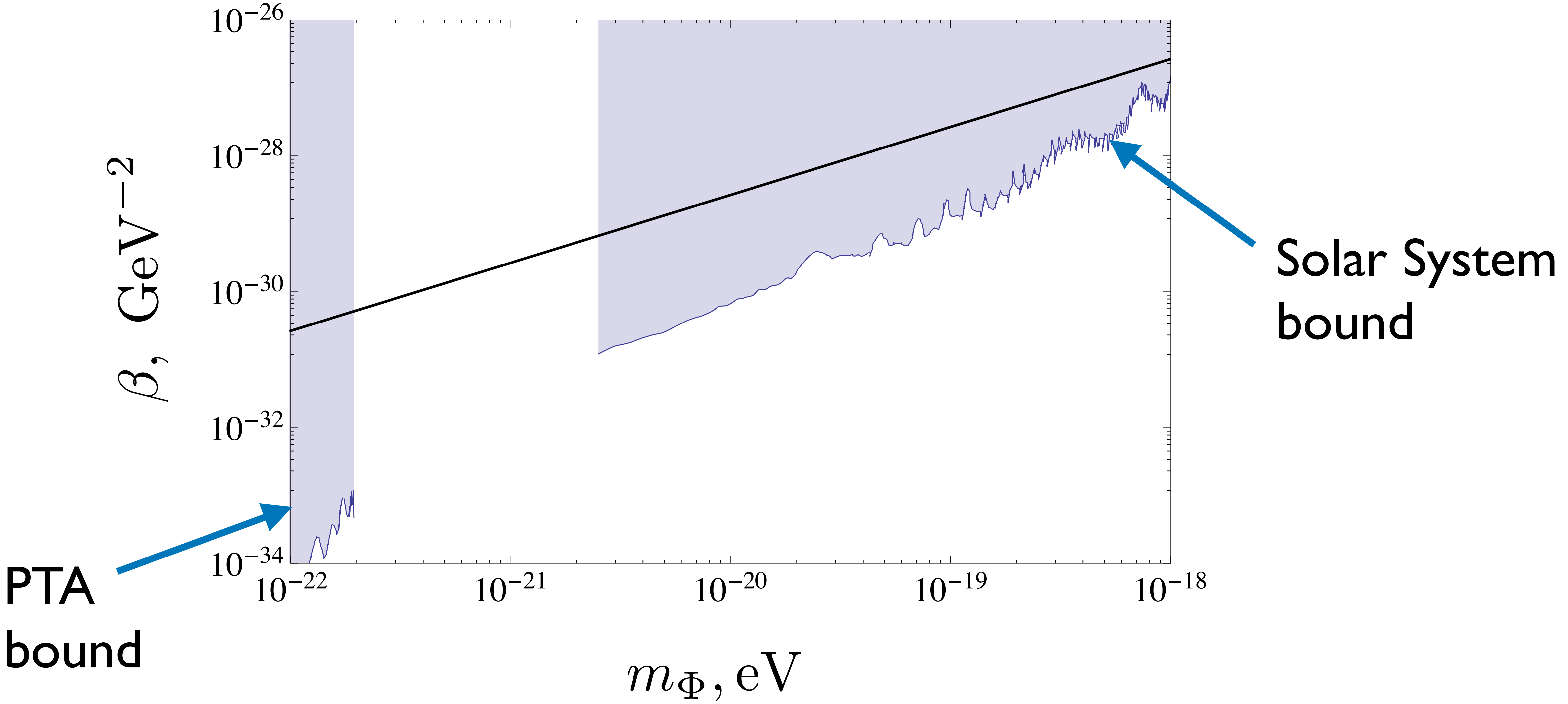
Limits on **quadratic** coupling



Broadband limits

from J1713+0747 ($P_b = 67.8\,\mathrm{days}$, $e = 7\times10^{-5}$)

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



Propagation of EM waves in a DM medium

Caputo, Sberna, Frias, DB, Pani, Shao, Yan 19

The DM may be also coupled to photons

charged DM

$$q_{\rm DM}\int A_\mu(x_{pp})\mathrm{d}x^\mu_{\rm DM}$$

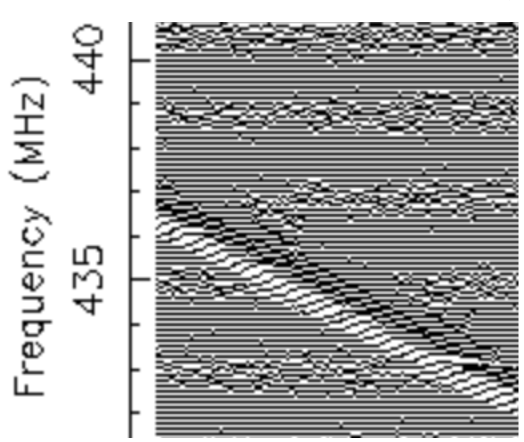
axions

$$g\,\phi\,F_{\mu\nu}\tilde{F}^{\mu\nu} = g\,\phi\,\vec{E}\cdot\vec{B}$$

modify the dispersion relation of light

$$\omega^2 = k^2 + \sum_\chi \frac{4\pi n_\chi q_\chi^2}{m_\chi}$$

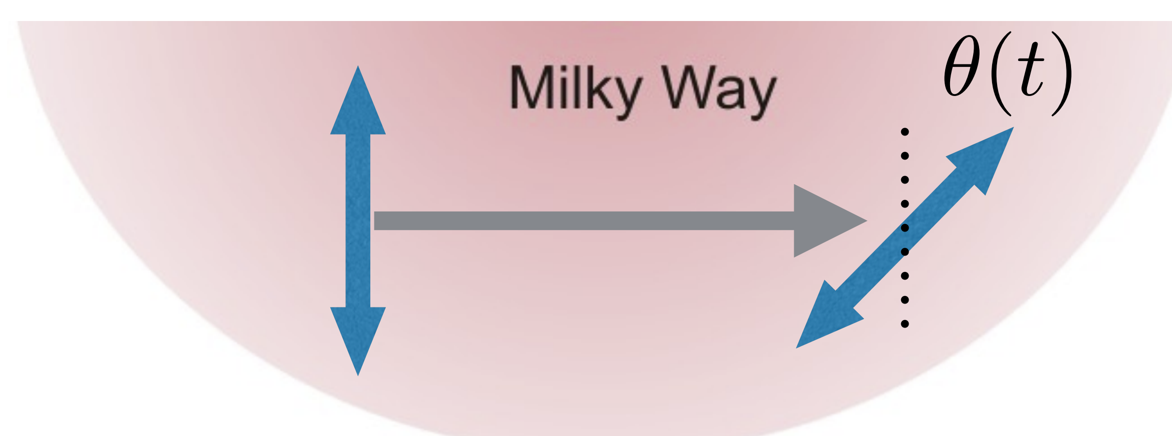
$$\Delta T(\omega) \propto \frac{q_\chi^2}{m_\chi^2\omega^2}$$



$$\phi = \phi_0\cos(mt + \alpha(x))$$

$$\omega^2 = k^2 \pm 2\dot{\phi}(t)\,k$$

oscillating polarisation angle!



Constraints on DM charge

Caputo, Sberna, Frias, DB, Pani, Shao, Yan 1902.02695

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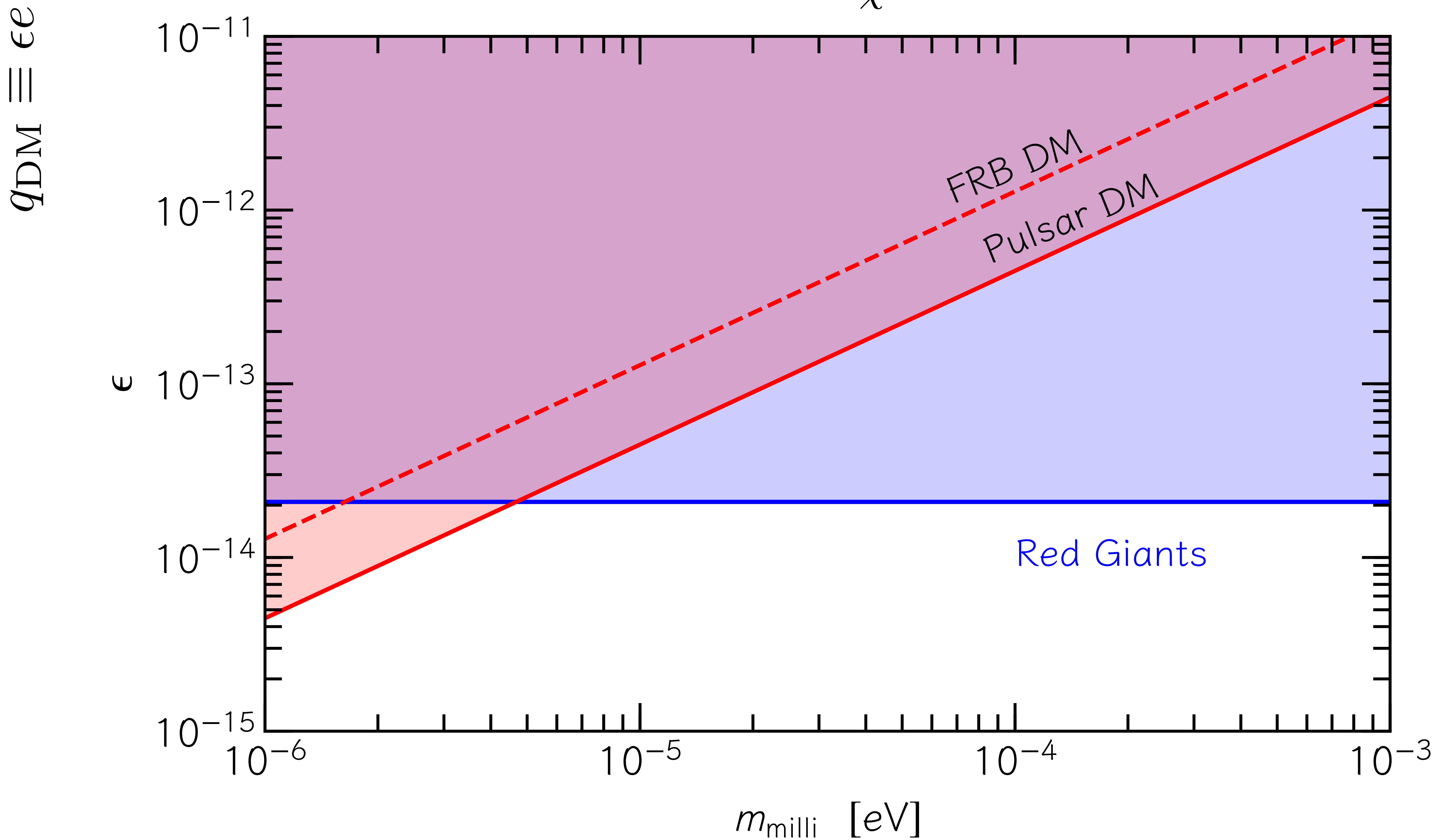
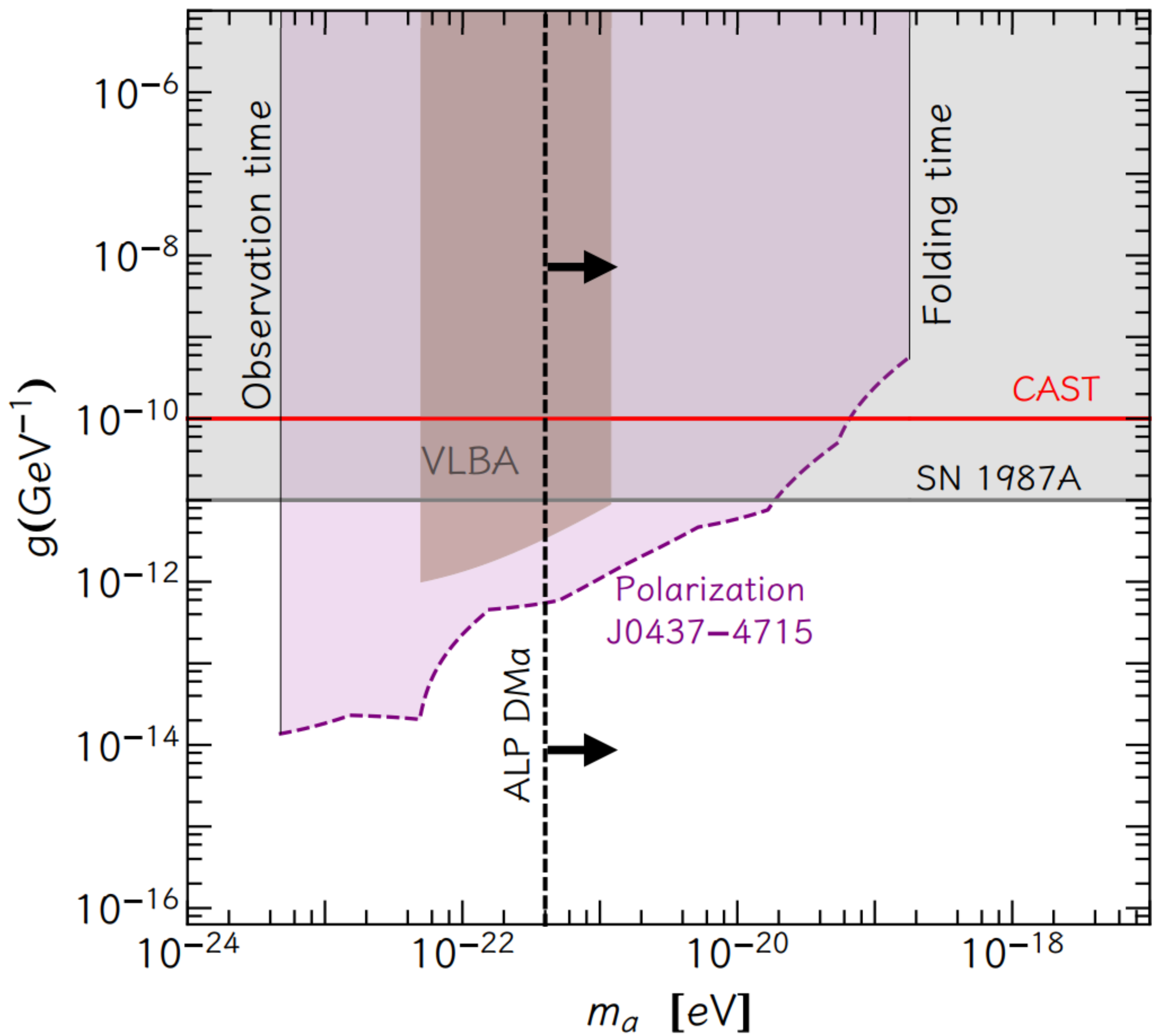


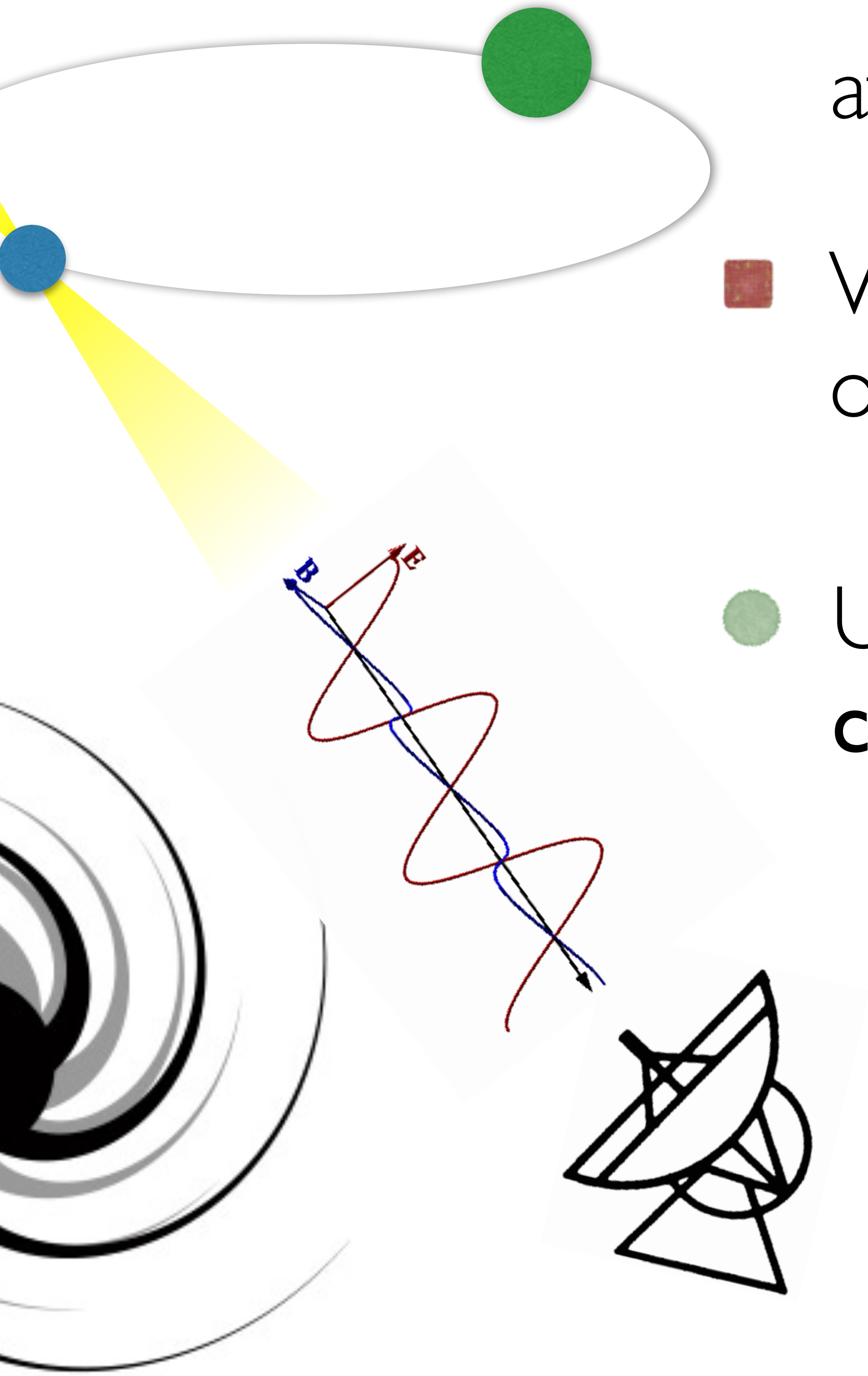
Constraints on axion-EM coupling

Caputo, Sberna, Frias, DB, Pani, Shao, Yan 1902.02695

using signals from pulsars



Conclusions



- The signals from pulsars can test new physics at production, propagation, detection
- WIMPS at the binary location modifies the orbits but hard to measure
- ULDM has better chances: rich phenomenology **coherent oscillations, large density gradients**
    - Pure gravity case out of reach
    - Case of DM-Matter interaction generates best constraints for certain DM models

Future work

- Detailed analysis of specific systems
- Study the effects in populations (not instantaneously)
- DM substructure with large over-densities
- Other interactions (torques?)

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- P. Freire: "Nature has always been good pulsar timing"

SKA, MeerKAT, FAST,…: new observations may bring new surprises!