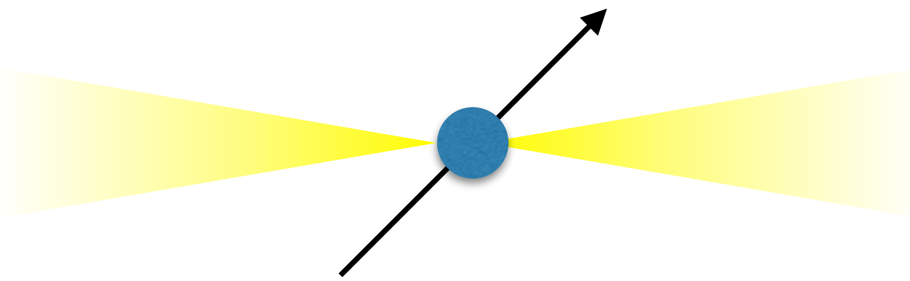
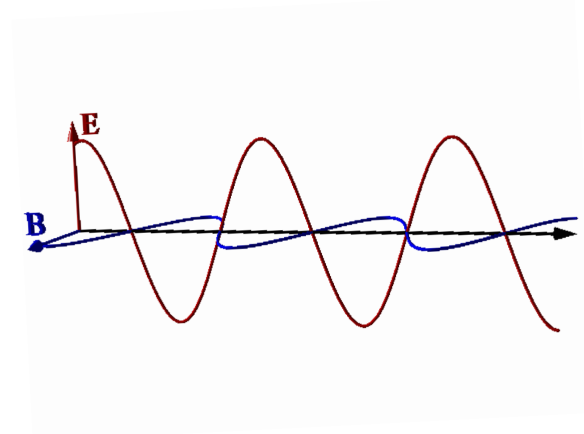
Probing light dark matter with pulsar observations

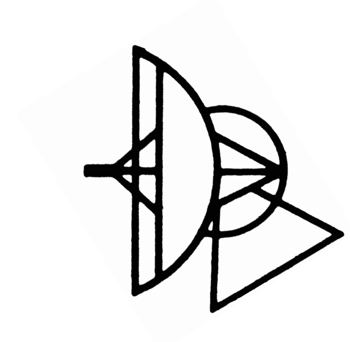
Diego Blas

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

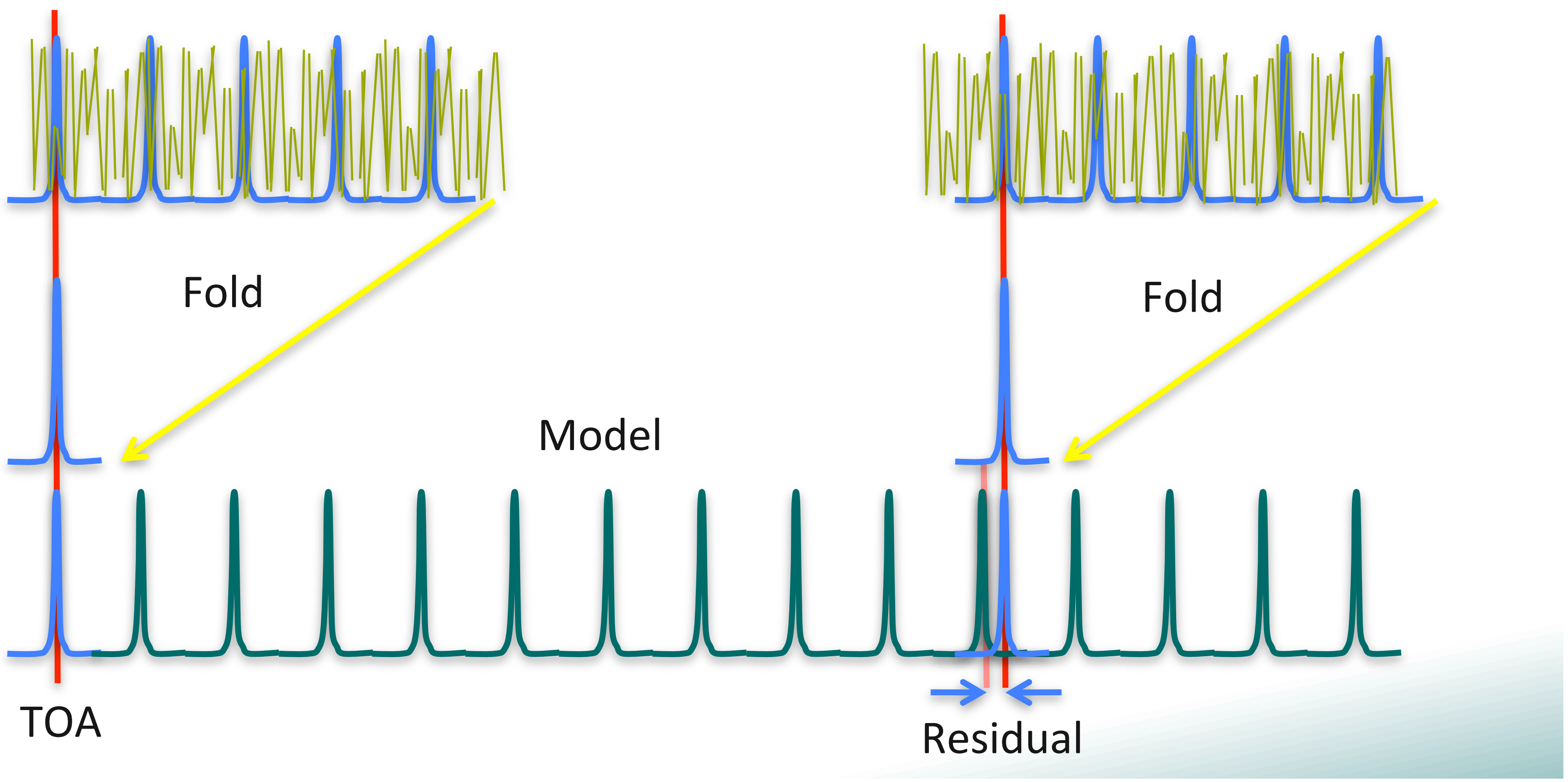
The beauty of the ToA signal







from P. Freire

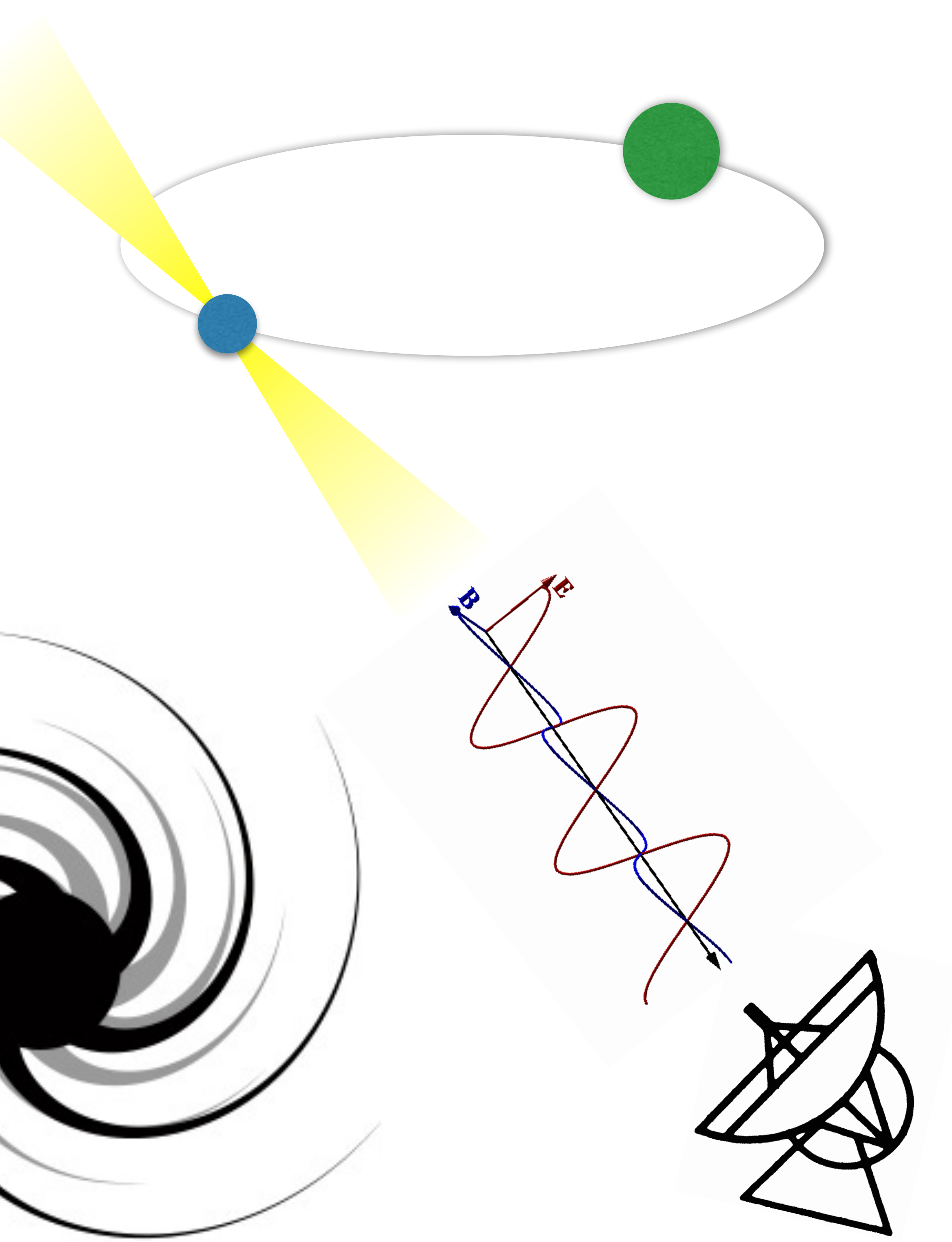


PSR J0437-4715

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

(for different frequencies and including polarization)

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

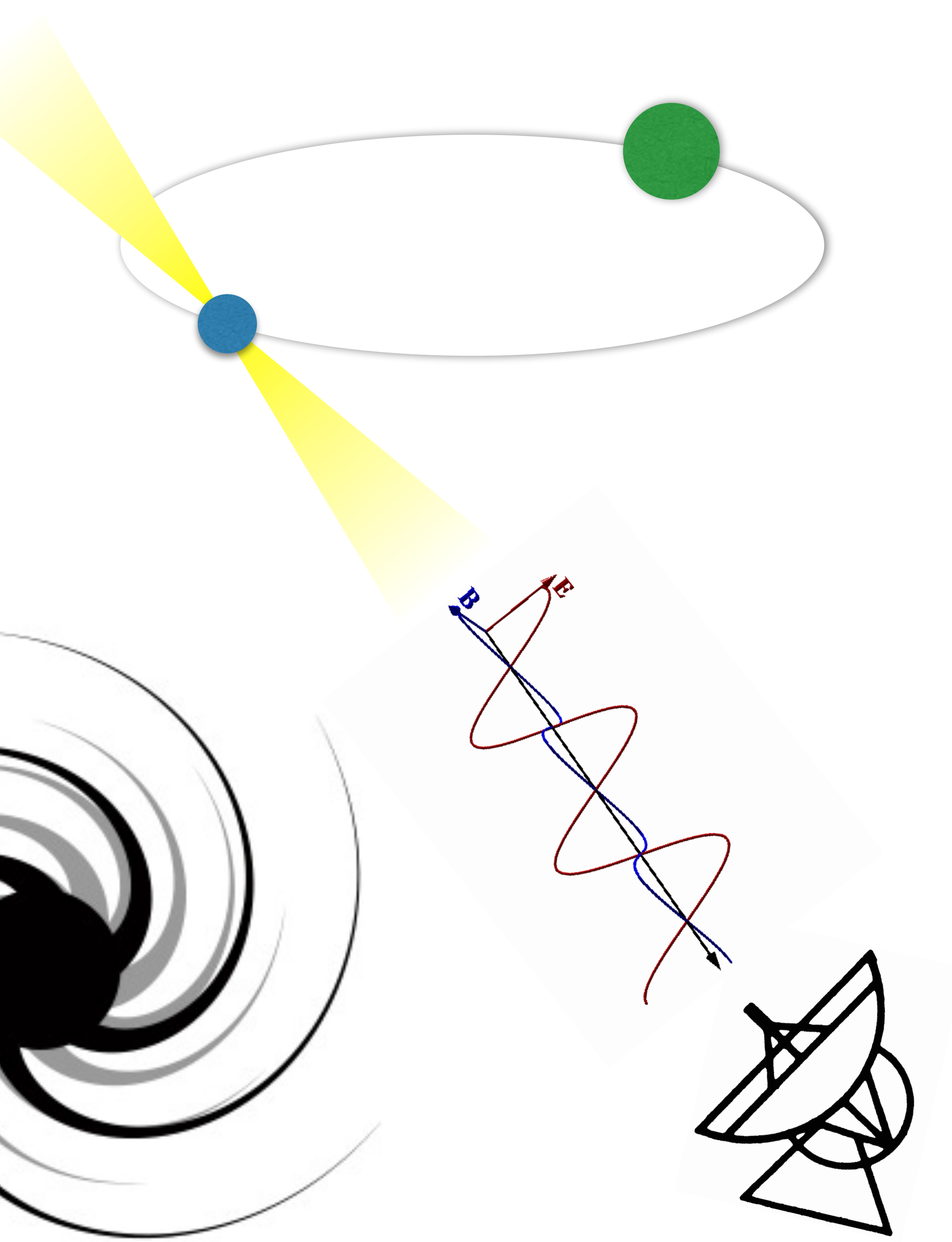
$$X = \mathcal{L}(\phi, F^{\mu\nu}) = \phi\, \vec{E} \cdot \vec{B}$$

- 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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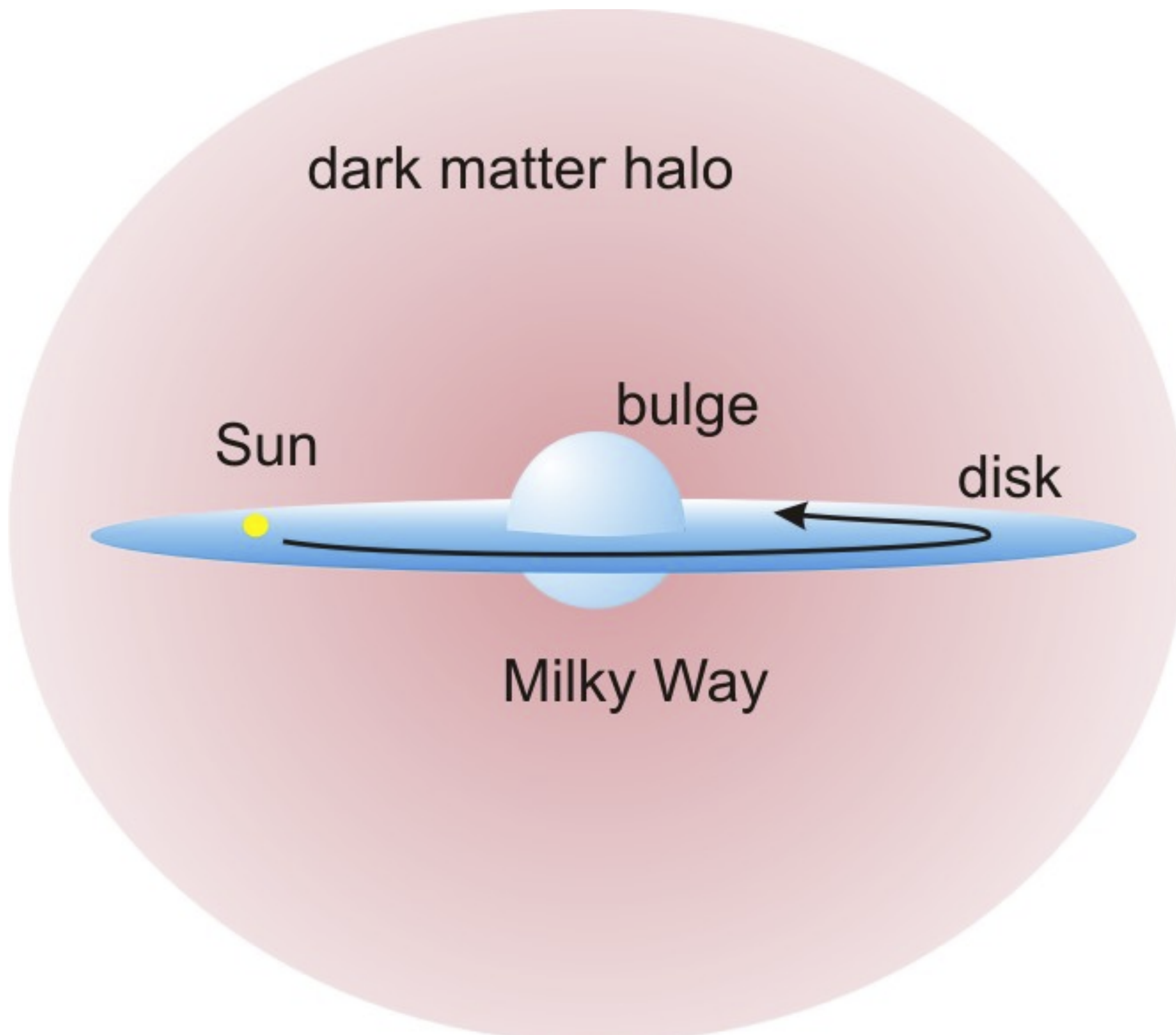
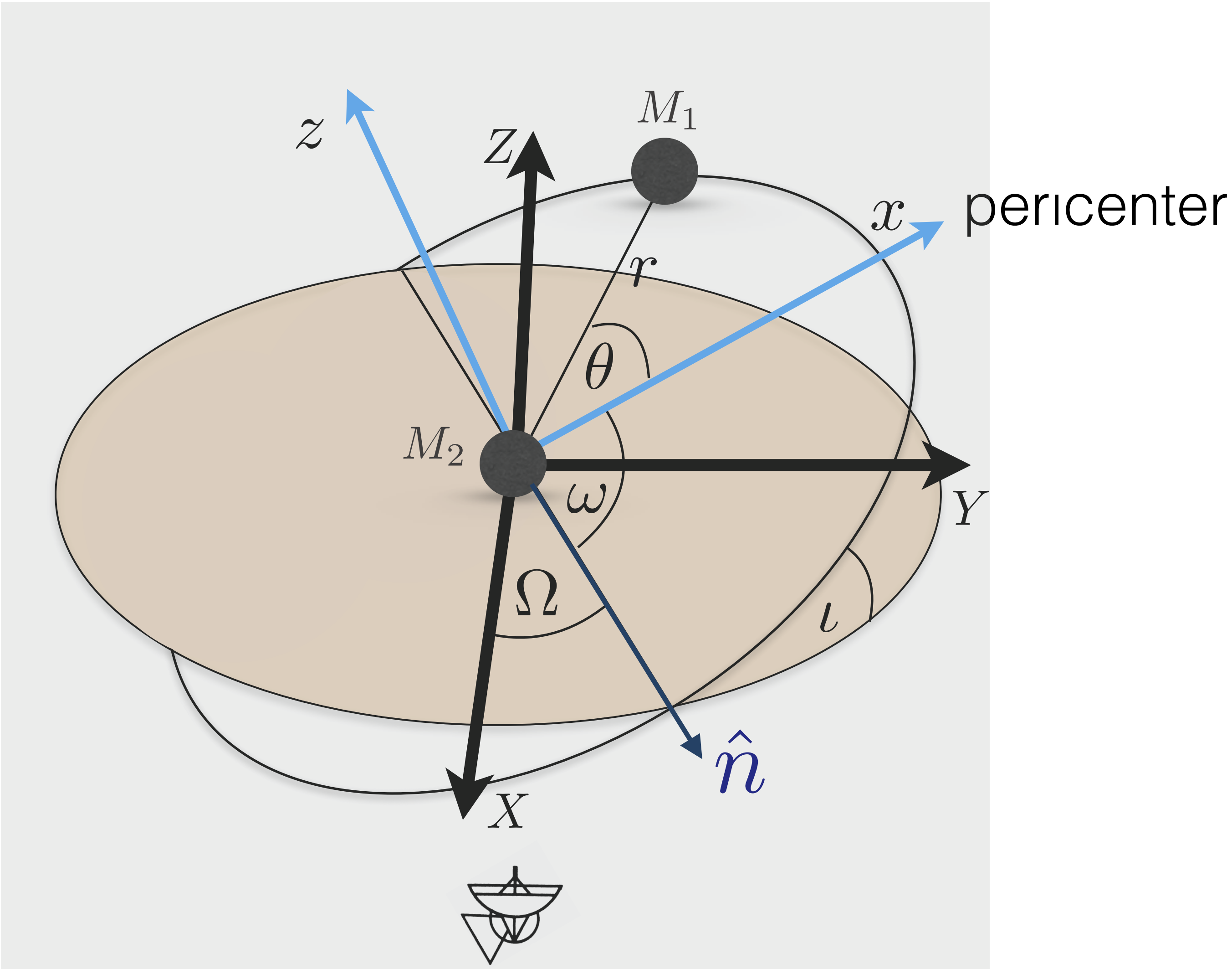
X= (Ultra) light DM

DM in galaxies (e.g. MW)



Orbital motion in the presence of WIMPS



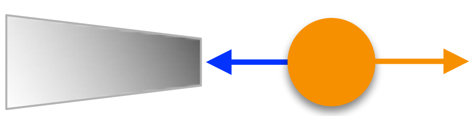
orbital parameters

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

(drift by any perturbation)

In a WIMP medium

dynamical friction in each object

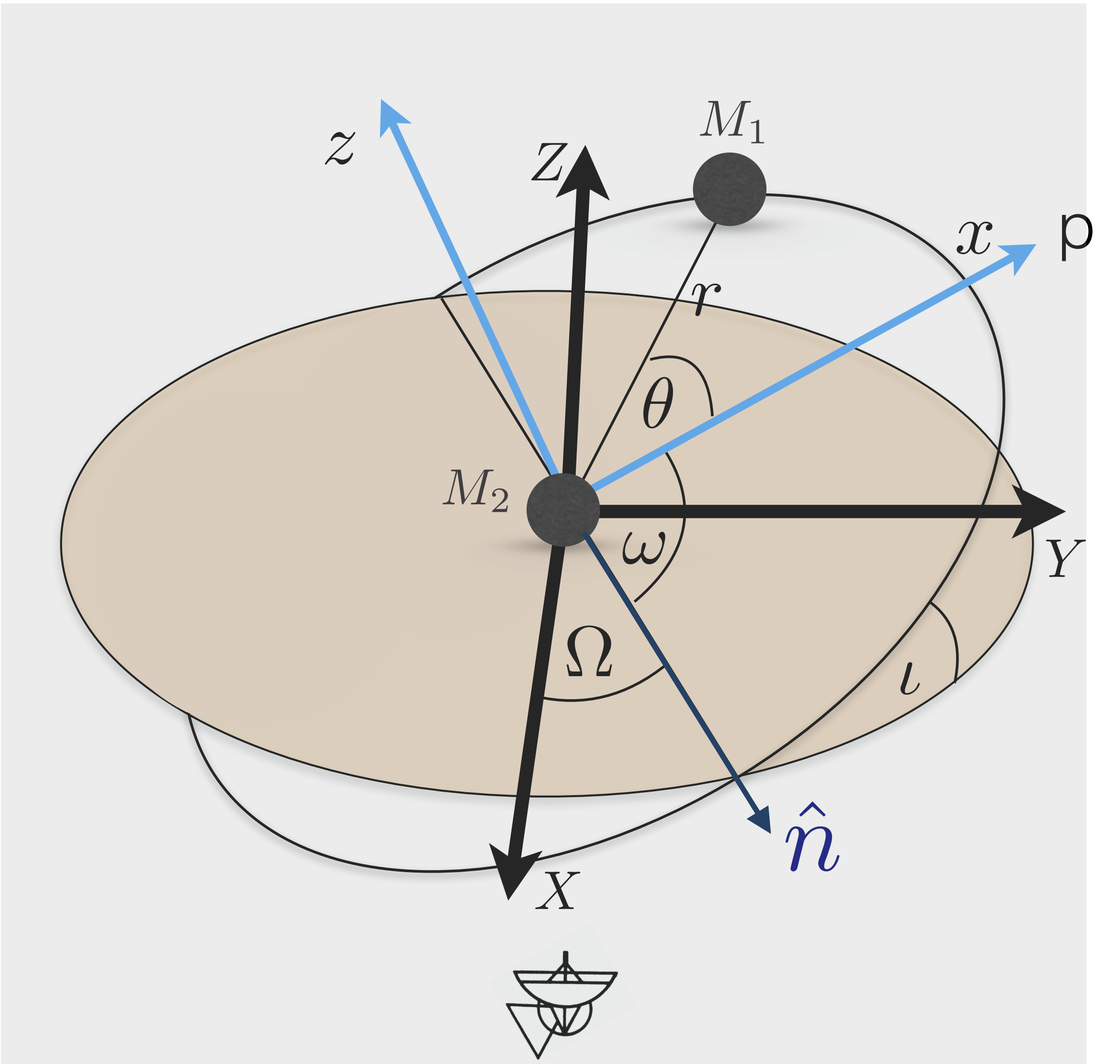


$v \ll \sigma$ (DM dispersion) Pani 2015

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

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

Orbital motion in the presence of WIMPS



pericenter

orbital parameters

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

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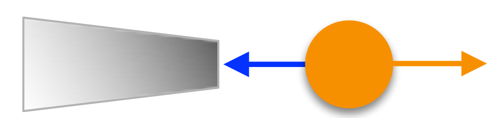

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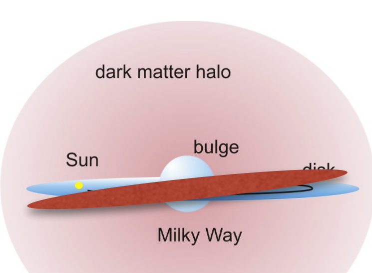


better prospects in other WIMP models

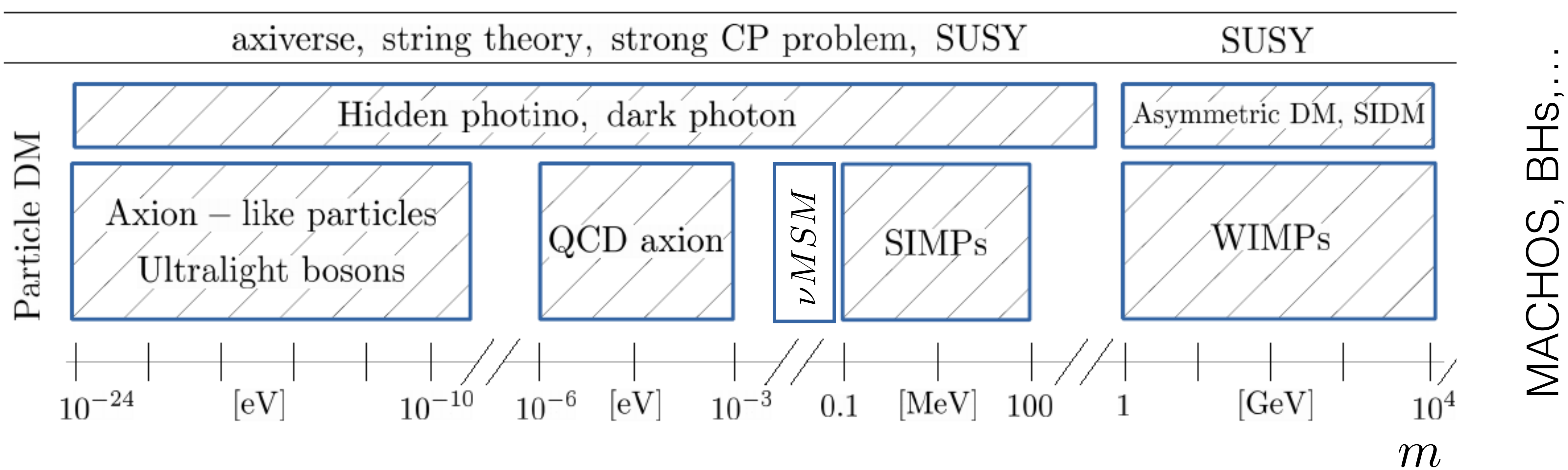
(Randall et al 2014)

Caputo, DB, Zavala 2017

*(cross section very small for SM-DM interactions unless UL mediator)

On the DM landscape

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

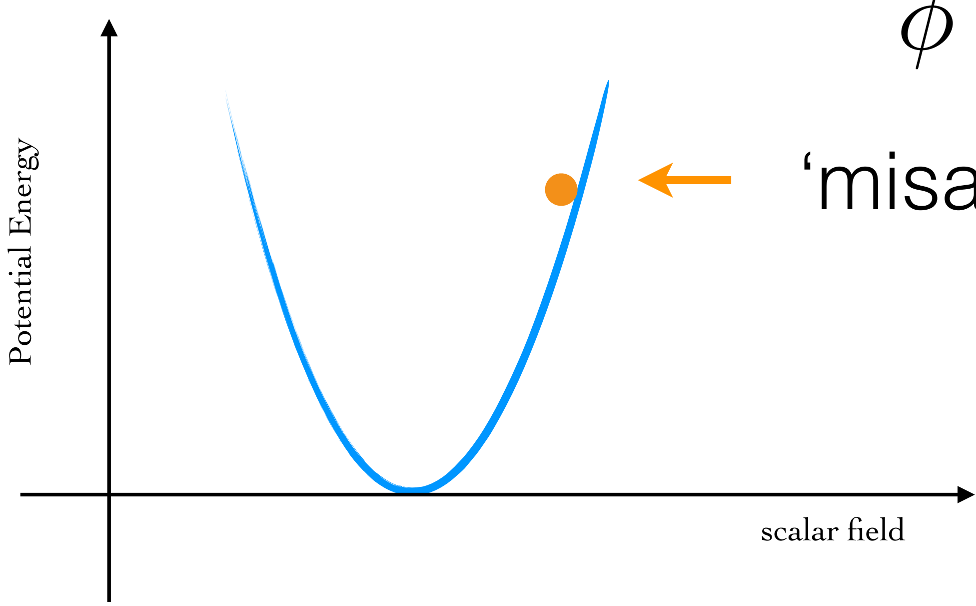


Ultra light (fuzzy) DM

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

homogeneous and isotropic evolution

$$\ddot{\phi} + H\dot{\phi} + m^2\phi = 0$$



'misaligned' conditions set by early universe

- $m \ll H \qquad \phi = ct.$
- $m \gg H \qquad \phi = \phi_0 \cos(mt + \alpha(x))$

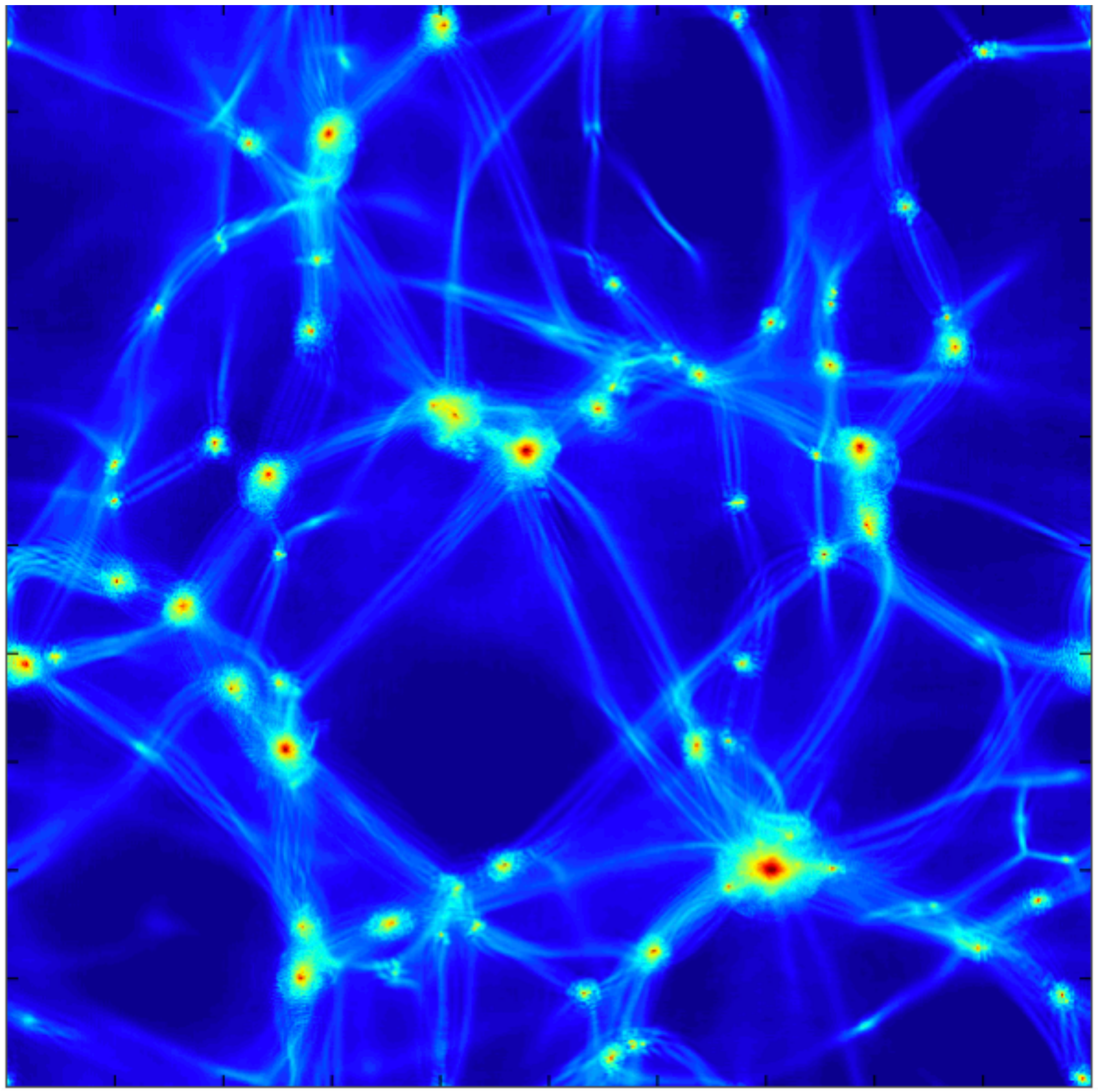
$$\rho_{DM} = \frac{m^2\phi_0^2(t)}{2} \sim a(t)^{-3}$$

$$p = -\rho_{DM}\cos(2mt + 2\alpha) \qquad \langle p \rangle_{mt \gg 1} = 0$$

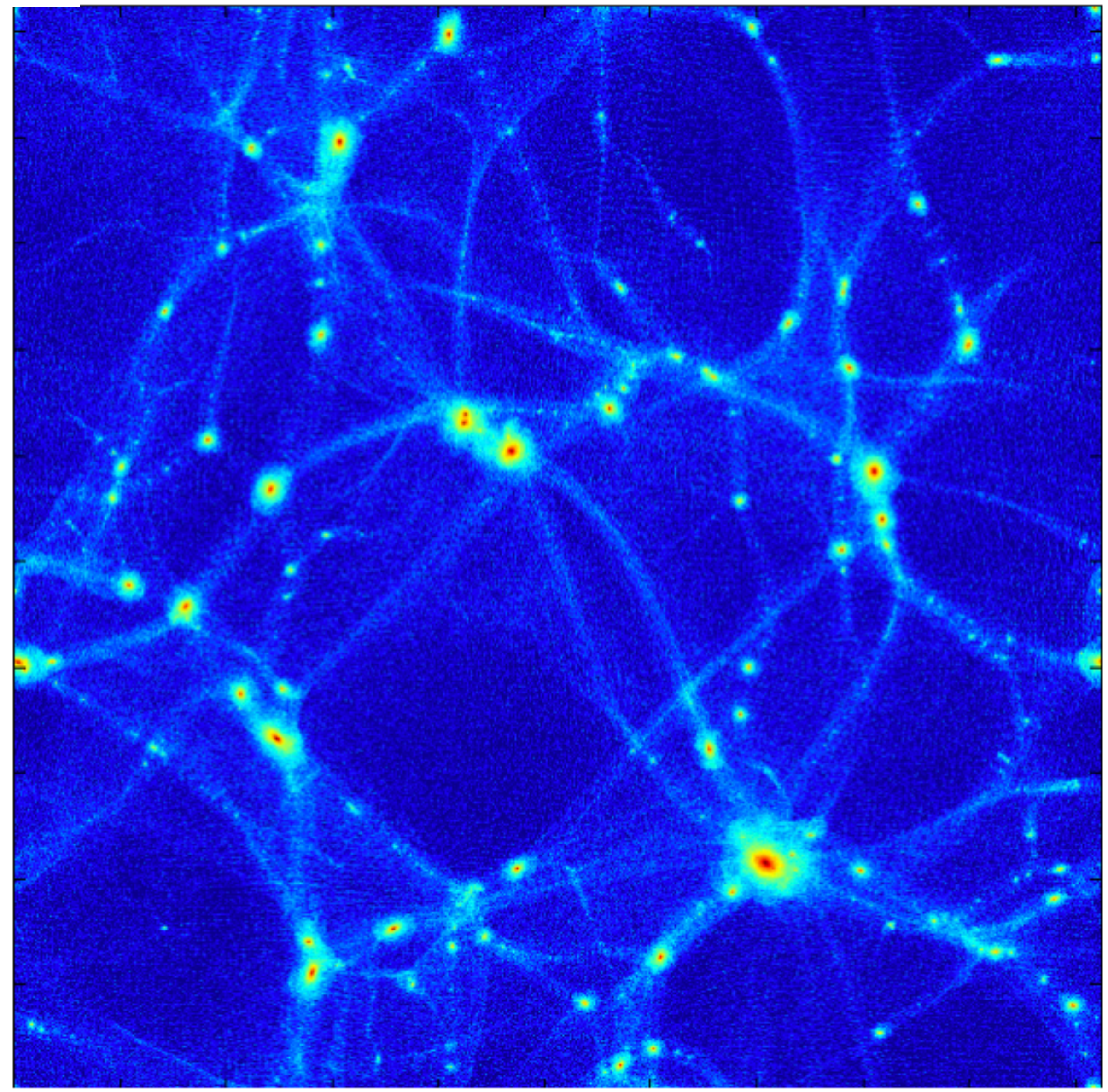
ULDM behaves like CDM at large-scales

Scale of ~30 Mpc, Schive et al. 1406.6586

ULDM

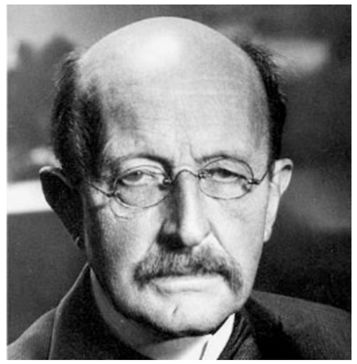


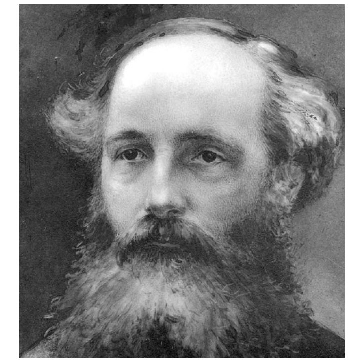
CDM



Ultra light DM in our Galaxy

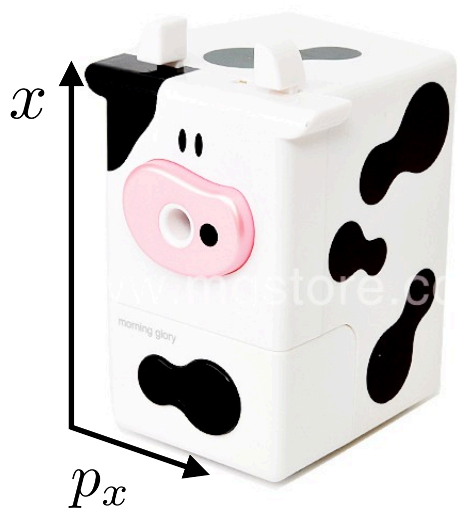
$\hbar\omega$





$F_{\mu\nu}$

The bosonic field has huge occupation numbers with random phases



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

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

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

For low masses it can be considered as a classical field

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

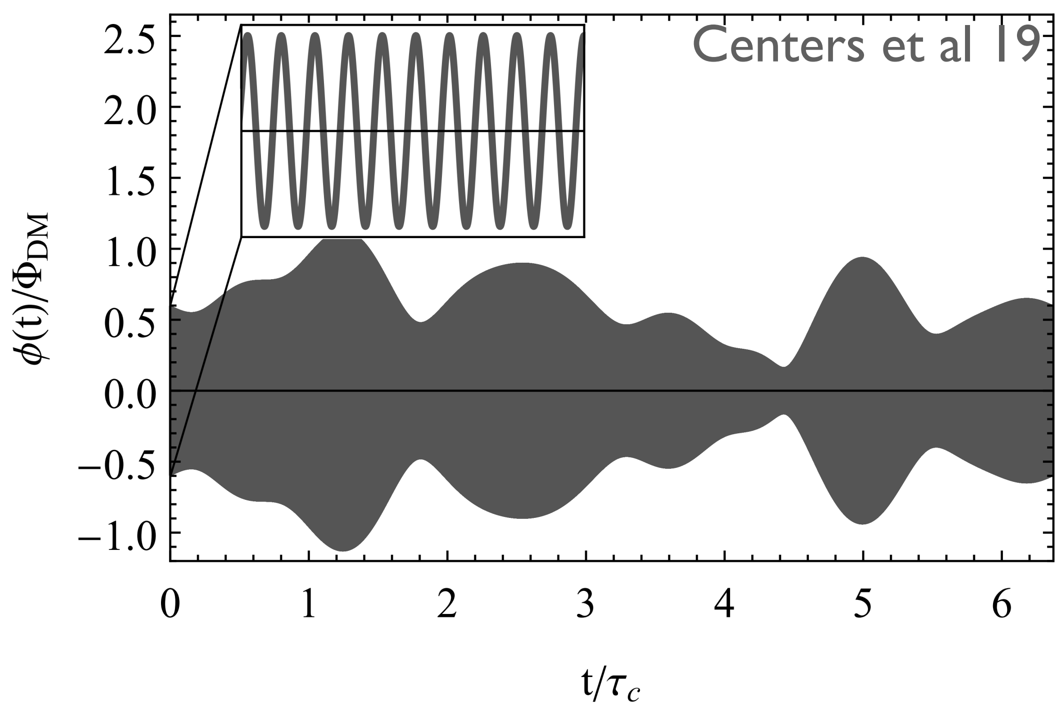
Ultra-light (fuzzy) DM in galactic halos

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

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

$(\vec{k} = m\vec{v})$ ϕ_k $\sigma_0 \sim 10^{-3} c$ in the MW

since $v \sim \sigma_0 \ll 1$ $\omega_v \approx m(1+v^2)$ $\tau_c \sim 65\ \text{years} \left(\frac{10^{-3}}{V_0}\right)^2 \left(\frac{10^{-18}\text{eV}}{m_\Phi}\right)$



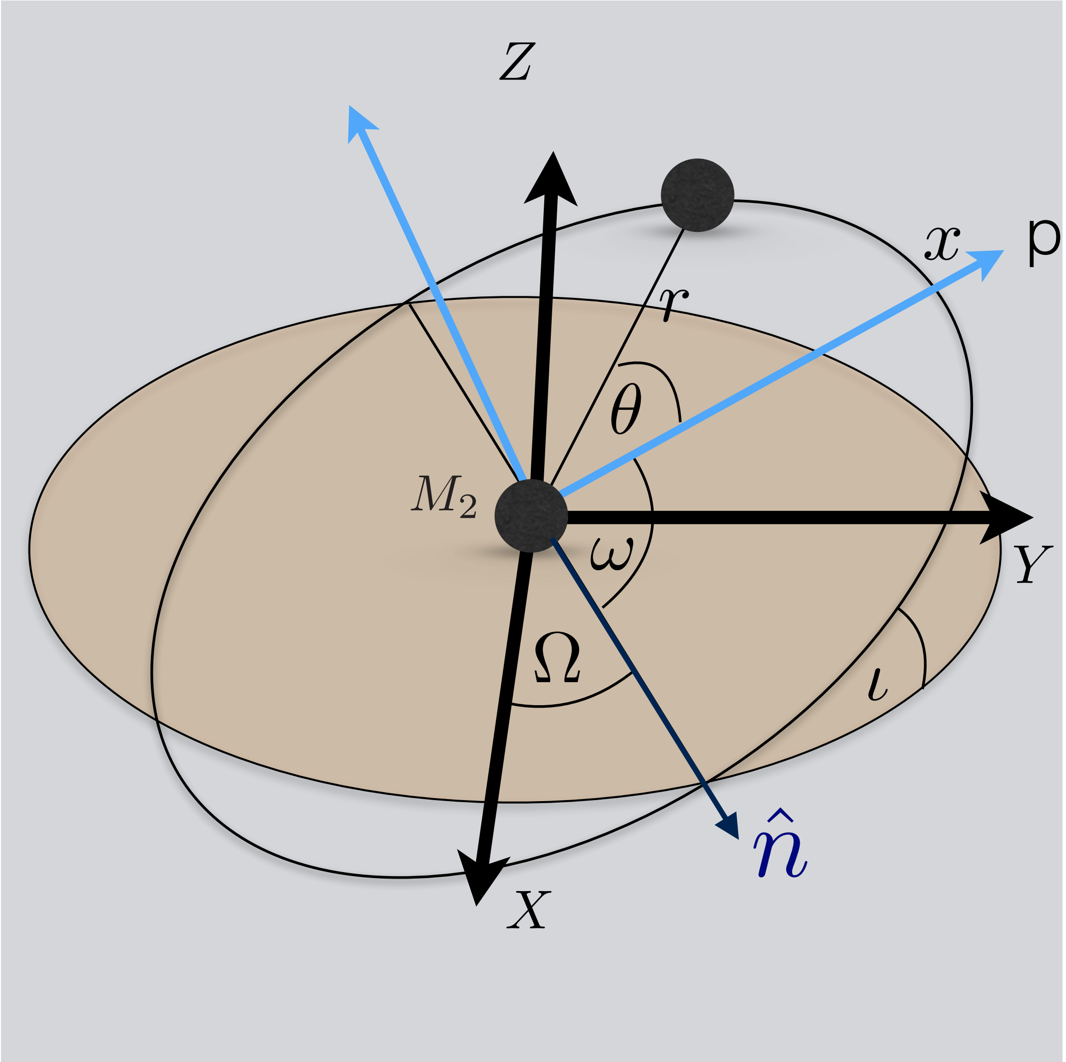
at shorter times $$\sum_i \phi_{0,i} \cos\left(mt + f_i\right) = \phi_0 \cos(mt + f)$$

It is also very homogenous

the field is homogeneous at scales

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

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



(stars should move)

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

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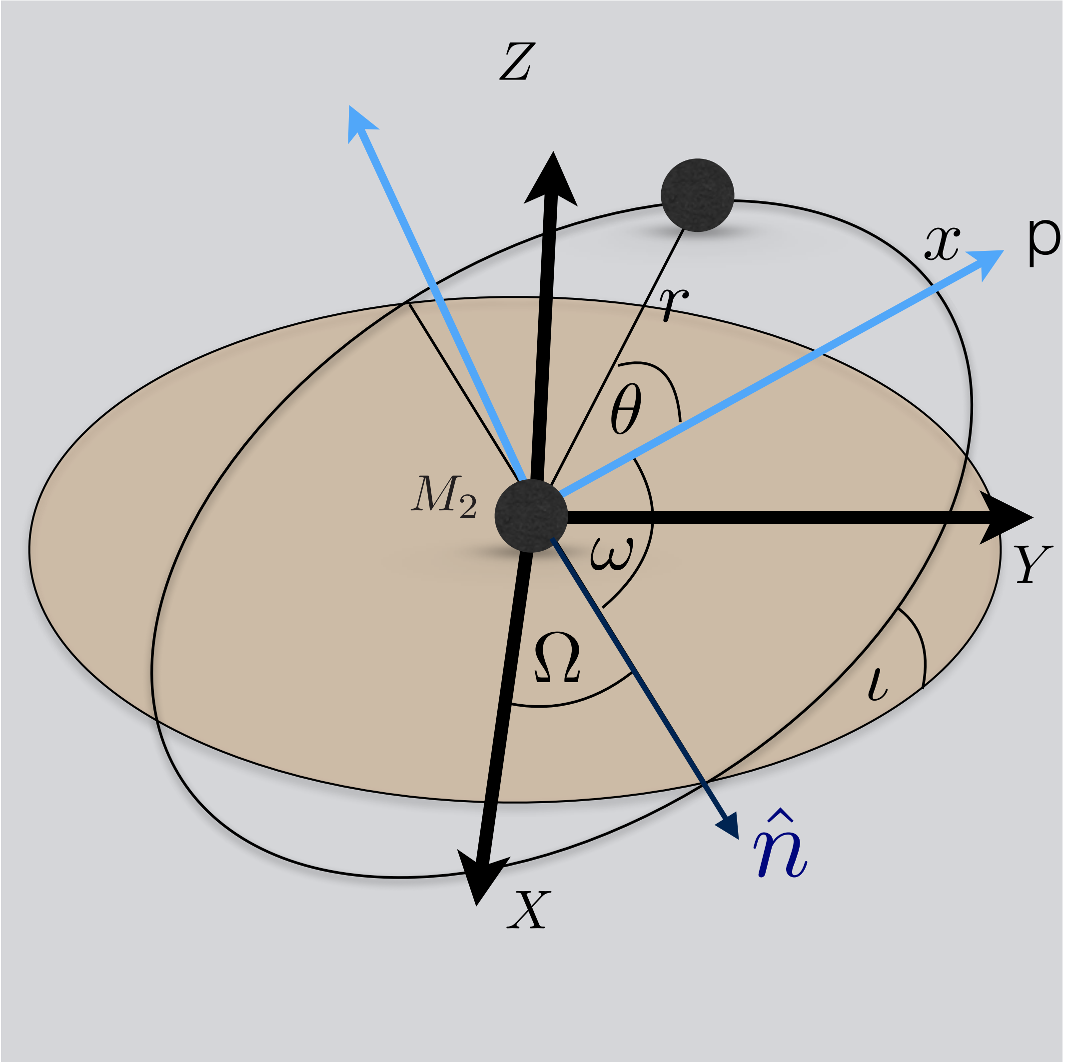

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$$\rho_{DM} = \frac{m^2\phi_0^2(t)}{2} \quad p = -\rho_{DM}\cos(2mt + 2\alpha) \rightarrow (\varphi_N^{\rm gal}(t), \psi_N^{\rm gal}(t))$$

Effects on binary system: pure gravity

DB, LopezNacir, Sibiryakov 16, 19

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

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

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

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

Can be expressed as modification of orbital parameters

e.g.

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

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

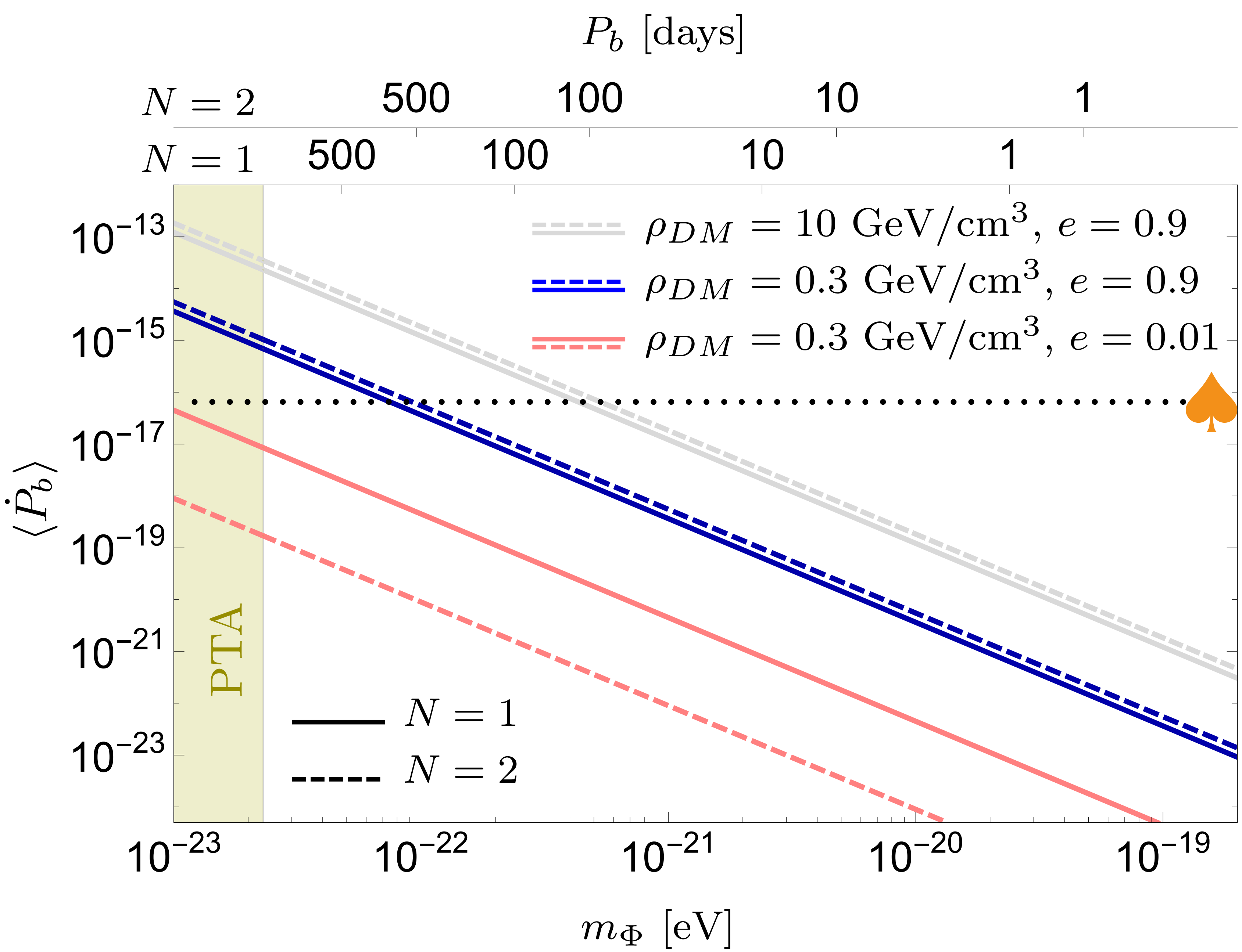
$\rightarrow$ if $\quad m \approx N\dfrac{2\pi}{P_b}$

the effect accumulates
in every orbit
(resonances appear)

Prospects of observation

DB, LopezNacir, Sibiryakov 16

This would be a pure gravitational test of this DM model
but it is beyond reach….



Effects on binary system: DM-matter interaction

DB, LopezNacir, Sibiryakov 16, 19

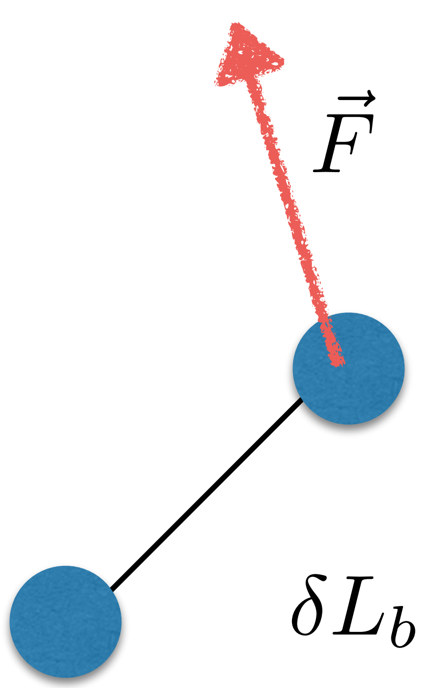
bosons can couple directly to matter

$$q \int A_\mu(x_{pp}) \mathrm{d}x^\mu$$

for scalars.

$$\alpha \int \phi(x_{pp}) \mathrm{d}s + \beta \int [\phi(x_{pp})]^2 \mathrm{d}s \ \cdots$$

(Armaleo, LopezNacir, Urban
for spin1 and spin 2 DM)



again

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

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

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

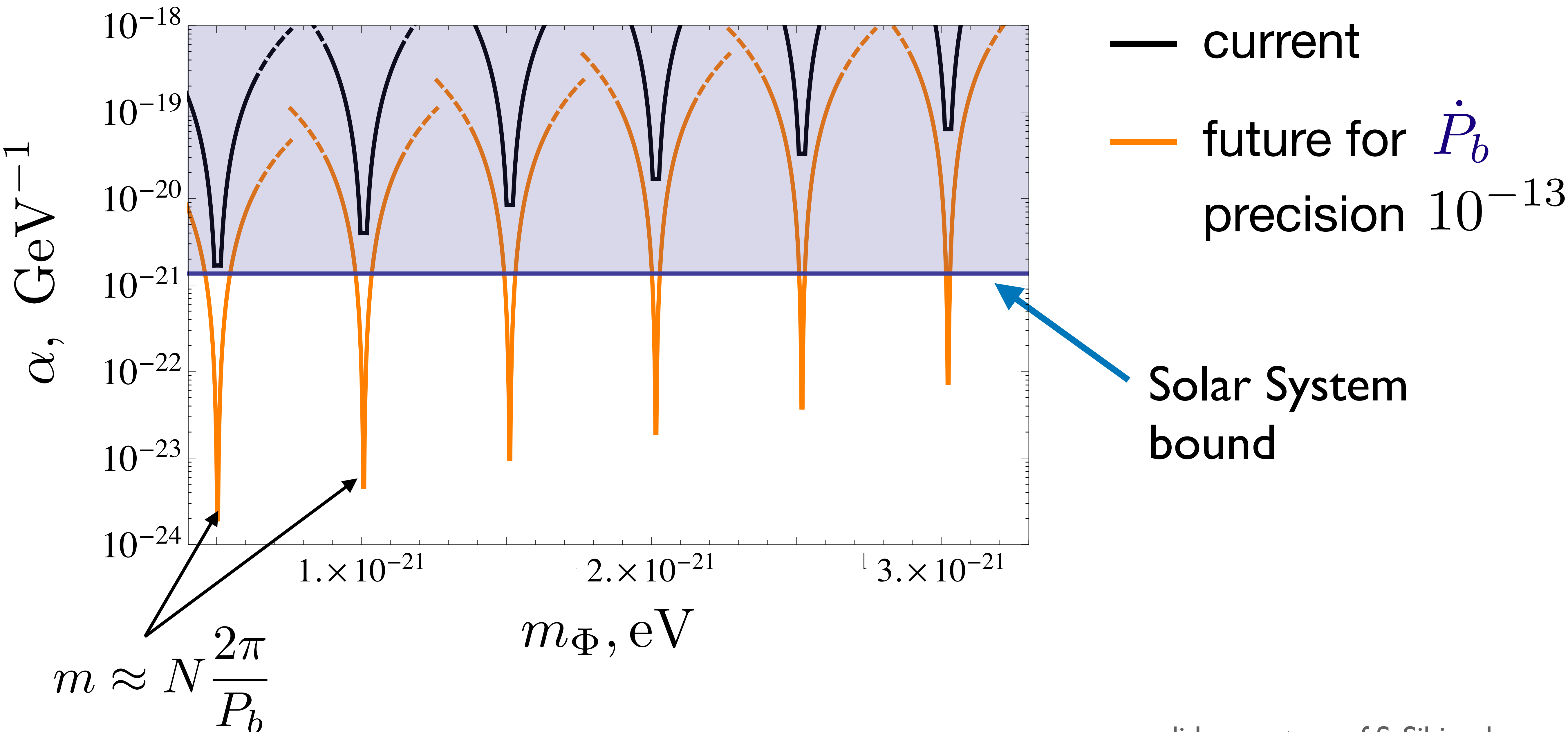
Secular effects at J1903+0327

Freire et al 2011

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

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

DB, LopezNacir, Sibiryakov 16, 19

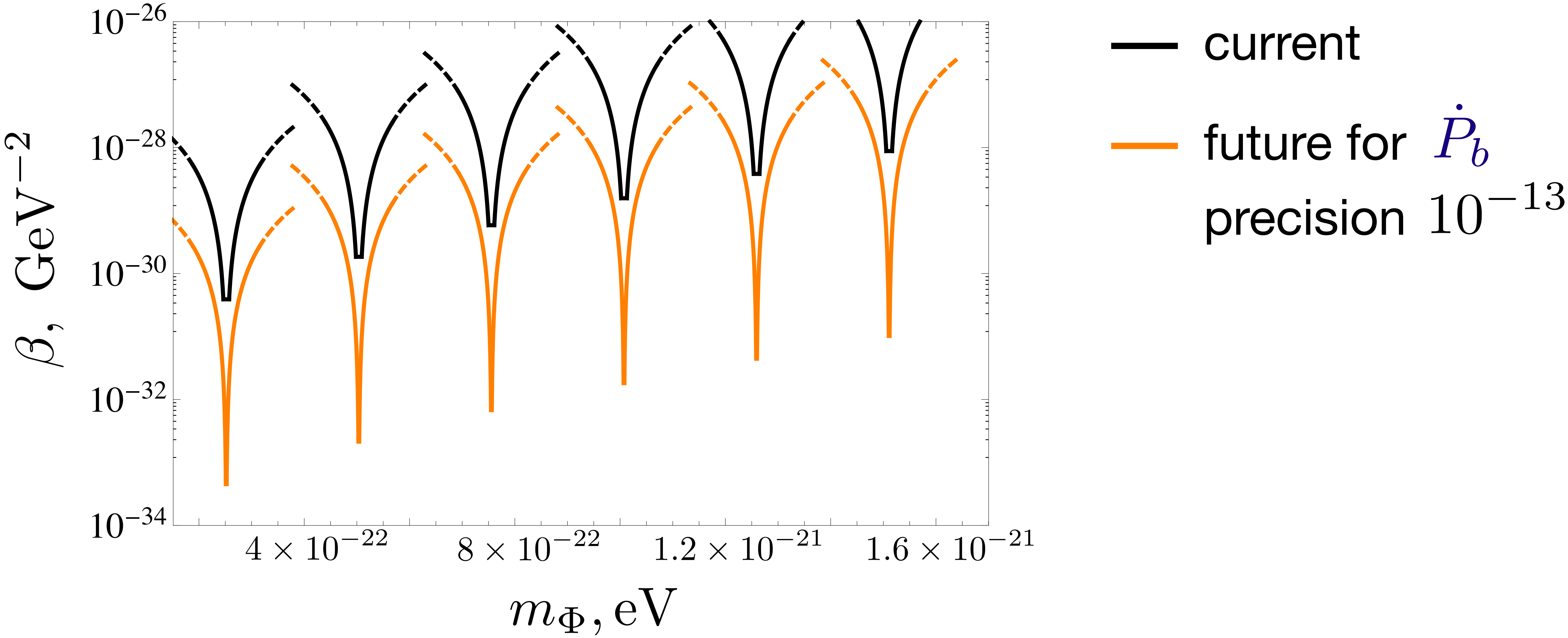


slide courtesy of S. Sibiryakov

Secular effects at J1903+0327

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

Limits on **quadratic** coupling

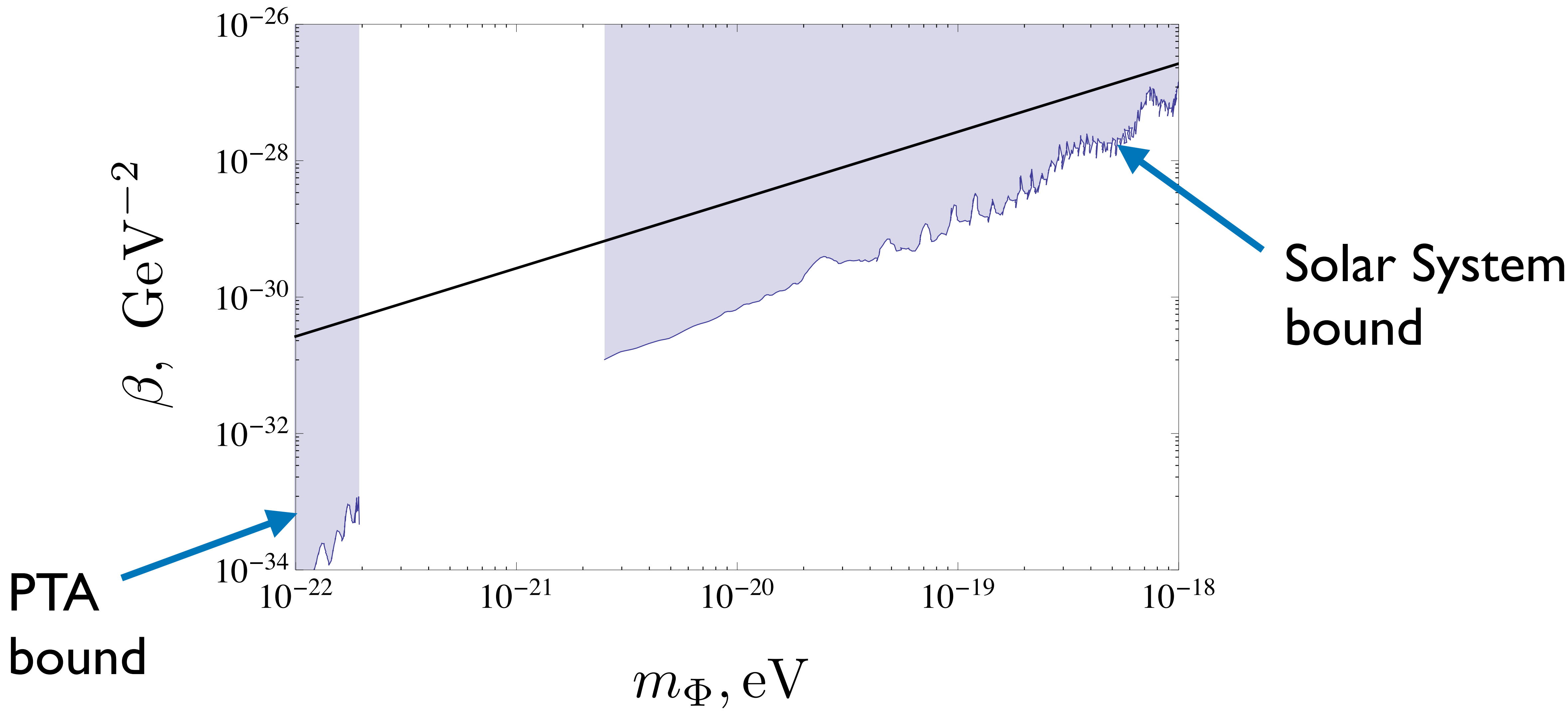


slide courtesy of S. Sibiryakov

Broadband limits

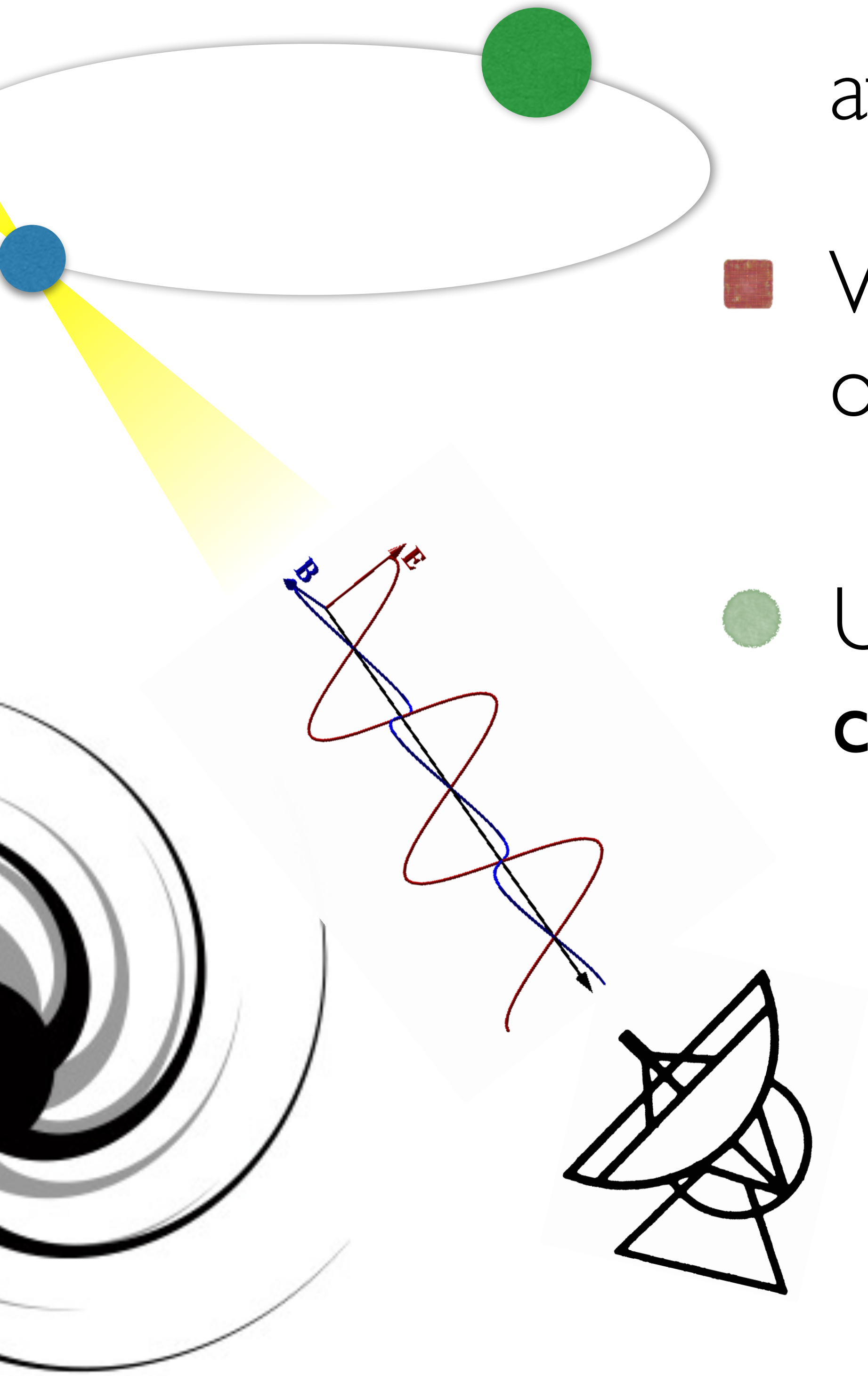
from J1713+0747 $\quad (P_b = 67.8\,\mathrm{days}\ ,\ e = 7 \times 10^{-5})$

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



slide courtesy of S. Sibiryakov

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 at for certain DM models

Future work

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

- Other effects related to propagation or at production

Future work

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- Other effects related to propagation or at production
- P. Freire: "Nature has always been good to us"

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

Propagation of EM waves in a DM medium

The DM may be also coupled to the photons

charged DM

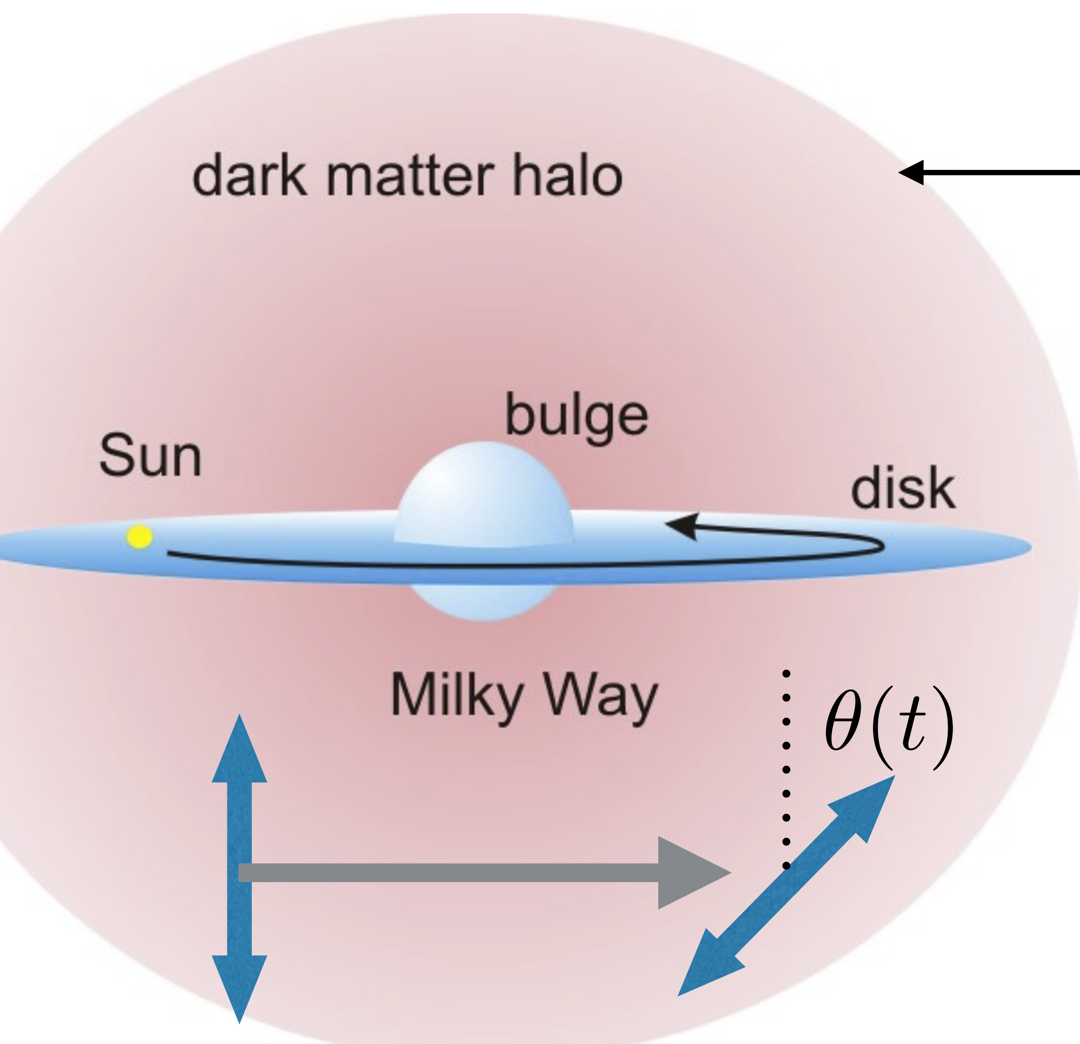
$$q_{\mathrm{DM}} \int A_\mu(x_{pp}) \mathrm{d}x^\mu_{\mathrm{DM}}$$

axions

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

modifies the dispersion relation of light

e.g. axions



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

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

time dependent birefringence

oscillating polarisation angle!

Constraints

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

using signals from pulsars