Ultra-Light Dark Matter models and some observational probes

(Pulsar timing and gravitational waves interferometers)

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IFIBA
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Based on

- Spin=2: JM Armaleo, DLN and F. Urban, JCAP04 (2021), JCAP09 (2020), JCAP01 (2020)
- Spin=1: DLN and F. Urban, JCAP (2018)
- Spin=0: D. Blas, DLN and S. Sibiryakov, PRD (2020), PRL (2017)

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Motivations

Dark Matter (DM) remains a mysterious component of our Universe!

- **An alternative to CDM**: ultralight DM (ULDM) (standard candidates are axion- like particles and dilatons, but can also be vectors, spin 2 tensors).

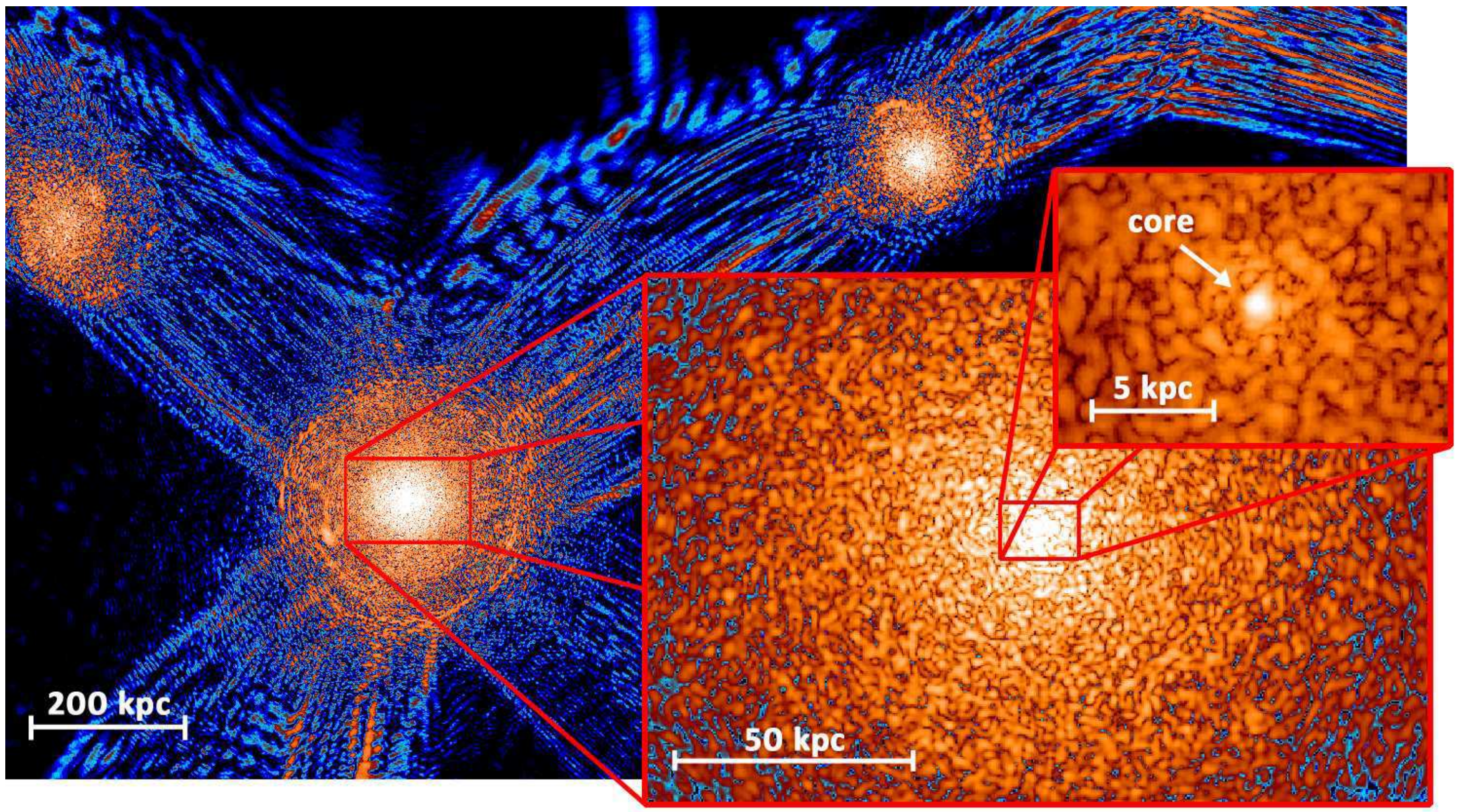
Ultralight $m \lesssim 1\mathrm{eV}$ $\longrightarrow$ Large occupation number: $n = \rho_{\mathrm{DM}}/m$

Classical field approximation

`Small-scale' properties: DM as a classical field

- **Spin 0: Halos structure (simulations)**

Schive, Chiueh, Broadhurst (2014)



$(\hbar = c = 1)$

Granular structure and coherence patches

$$\lambda_{coh} \sim \frac{1}{mV_0} \sim 1.3 \times 10^{12}\text{km}\left(\frac{10^{-3}}{V_0}\right)\left(\frac{10^{-18}\text{eV}}{m}\right)$$

$$t_{coh} \sim \frac{\lambda_{coh}}{2V_0} \sim 65\text{ years}\left(\frac{10^{-3}}{V_0}\right)^2\left(\frac{10^{-18}\text{eV}}{m}\right)$$

Coherent oscillations in each patch

$$t_{osc} \simeq \frac{2\pi}{m} \simeq 1.15\,\text{hours}\left(\frac{10^{-18}\text{eV}}{m}\right)$$

$$\Phi = \frac{\sqrt{2\rho_{\text{DM}}}}{m}\cos(mt + \Upsilon(\vec{x}, t))$$

$$\vec{\nabla}\Upsilon = -m\vec{V} \qquad \vec{\nabla}\log\rho_{\text{DM}} \sim m\vec{V}$$

‘Small-scale’ properties: DM as a classical field

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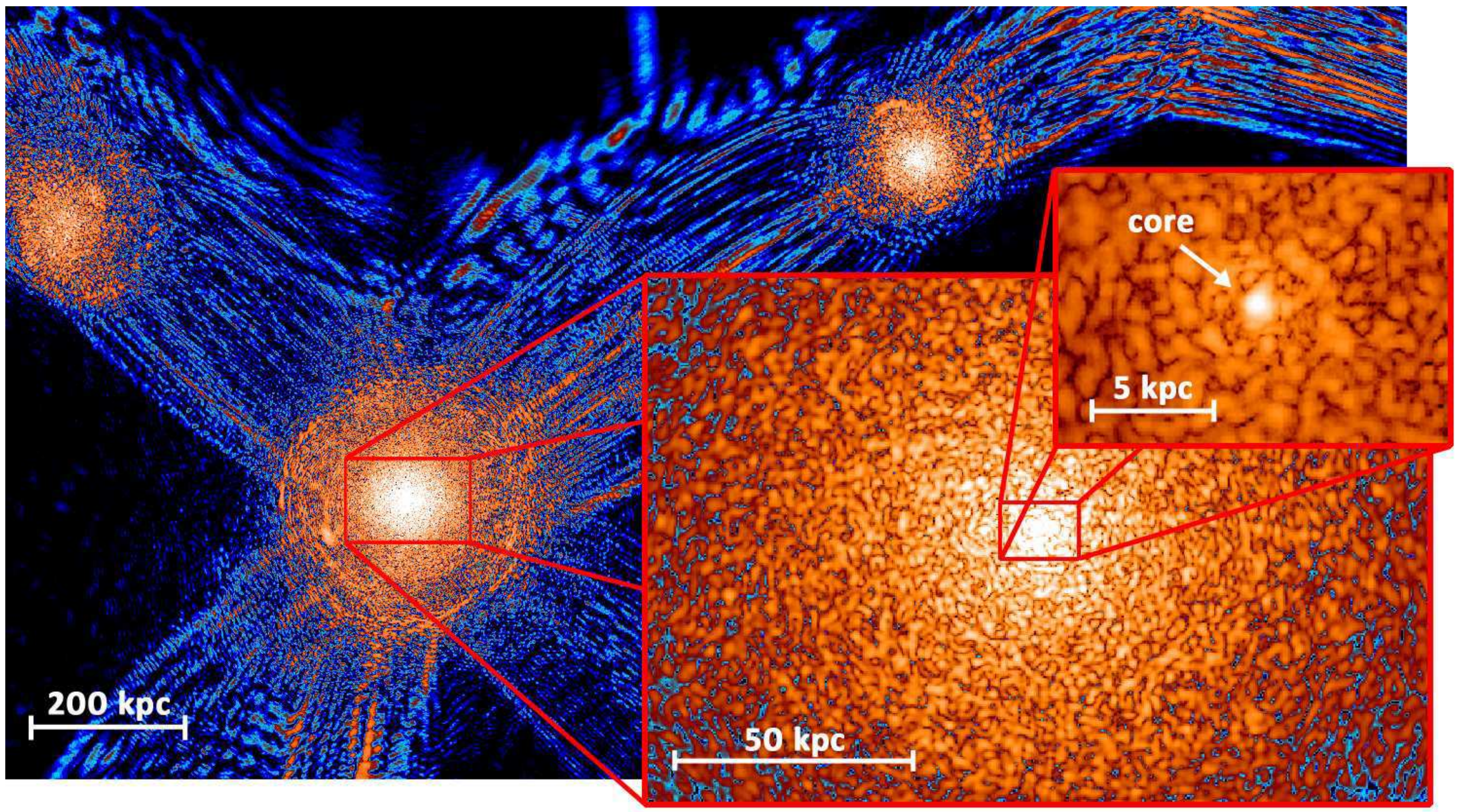

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- **Generalizations to spin 1 and 2:**

$$s = 1 \rightarrow A_i = \frac{\sqrt{2\rho_{\rm DM}}}{m}\cos(mt + \Upsilon(\vec{x}, t))\,\varepsilon_i, \qquad \varepsilon_i = \{\sin\vartheta\cos\phi, \sin\vartheta\sin\phi, \cos\vartheta\}\,.$$

$$s = 2 \rightarrow M_{ij} = \frac{\sqrt{2\rho_{\rm DM}}}{m}\cos(mt + \Upsilon(\vec{x}, t))\,\varepsilon_{ij}, \quad \varepsilon_{ij} = \frac{1}{\sqrt{2}}\begin{pmatrix} \varepsilon_{\rm T}\cos\chi - \varepsilon_{\rm S}/\sqrt{3} & \varepsilon_{\rm T}\sin\chi & \varepsilon_{\rm V}\cos\eta \\ \varepsilon_{\rm T}\sin\chi & -\varepsilon_{\rm T}\cos\chi - \varepsilon_{\rm S}/\sqrt{3} & \varepsilon_{\rm V}\sin\eta \\ \varepsilon_{\rm V}\cos\eta & \varepsilon_{\rm V}\sin\eta & 2\varepsilon_{\rm S}/\sqrt{3} \end{pmatrix}$$

$$\sum_{i,j=1}^{3}\varepsilon_{ij}\varepsilon_{ij} = 1 \rightarrow \varepsilon_S^2 + \varepsilon_V^2 + \varepsilon_T^2 = 1$$

E. g spin 2 (direct interaction)

[Marzola, Raidal & Urban (2018)]

$$S = S_{\rm free}[g, M_{\mu\nu}, \Psi] + S_{\rm int}[g, M_{\mu\nu}, \Psi]\,,$$

$\supset$ Fierz-Pauli for the spin 2 massive field

$$S_{\rm int}[g, M_{\mu\nu}, \Psi] = -\frac{\alpha}{2M_{pl}} \int d^4x \sqrt{-g} M_{\mu\nu} T^{\mu\nu}_{\Psi}$$

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Changing frame, $\tilde{g}_{\mu\nu} := g_{\mu\nu} + \frac{\alpha}{M_{pl}}M_{\mu\nu}\,,$ at leading order in α: $S \simeq S_{\text{free}}[\tilde{g}, M_{\mu\nu}, \Psi]$

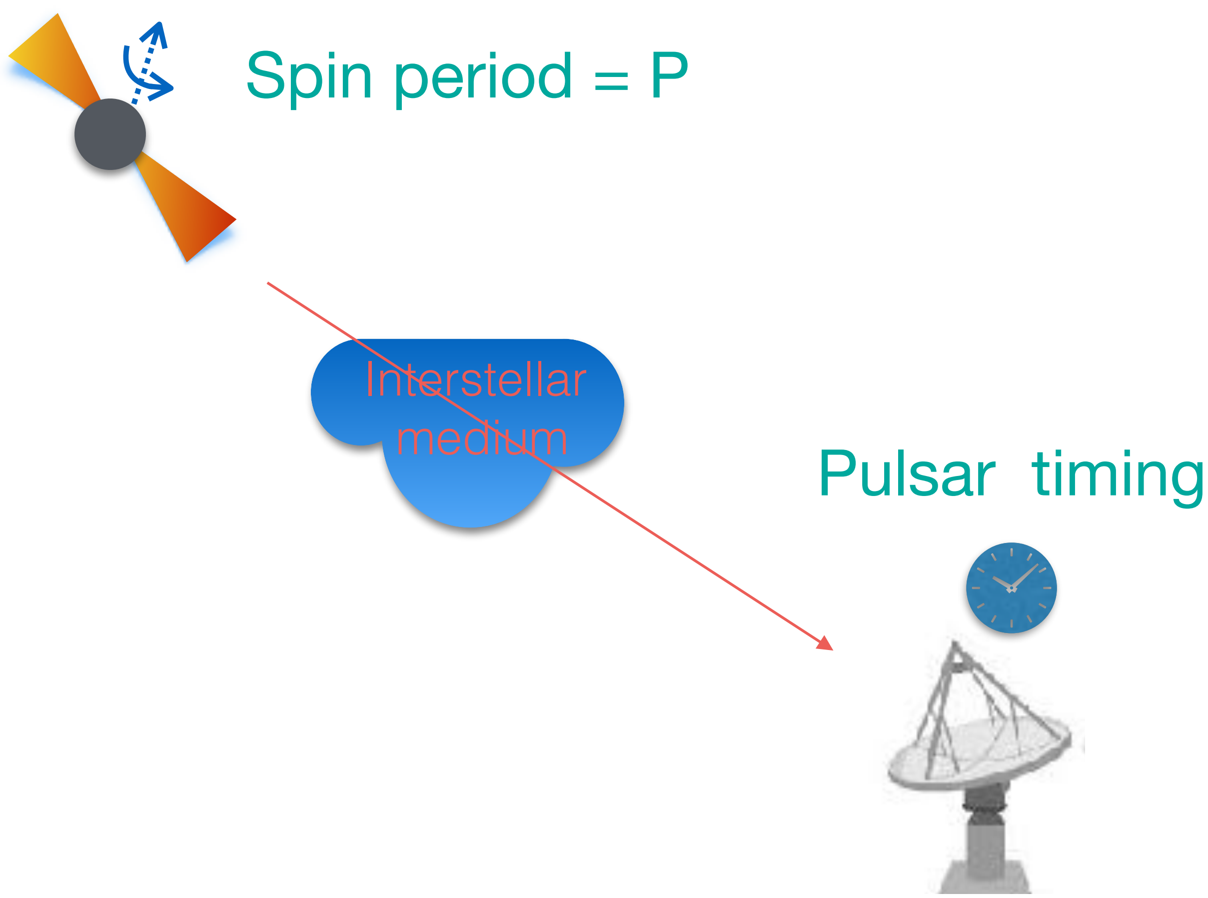
- Equivalent to a GW perturbation:

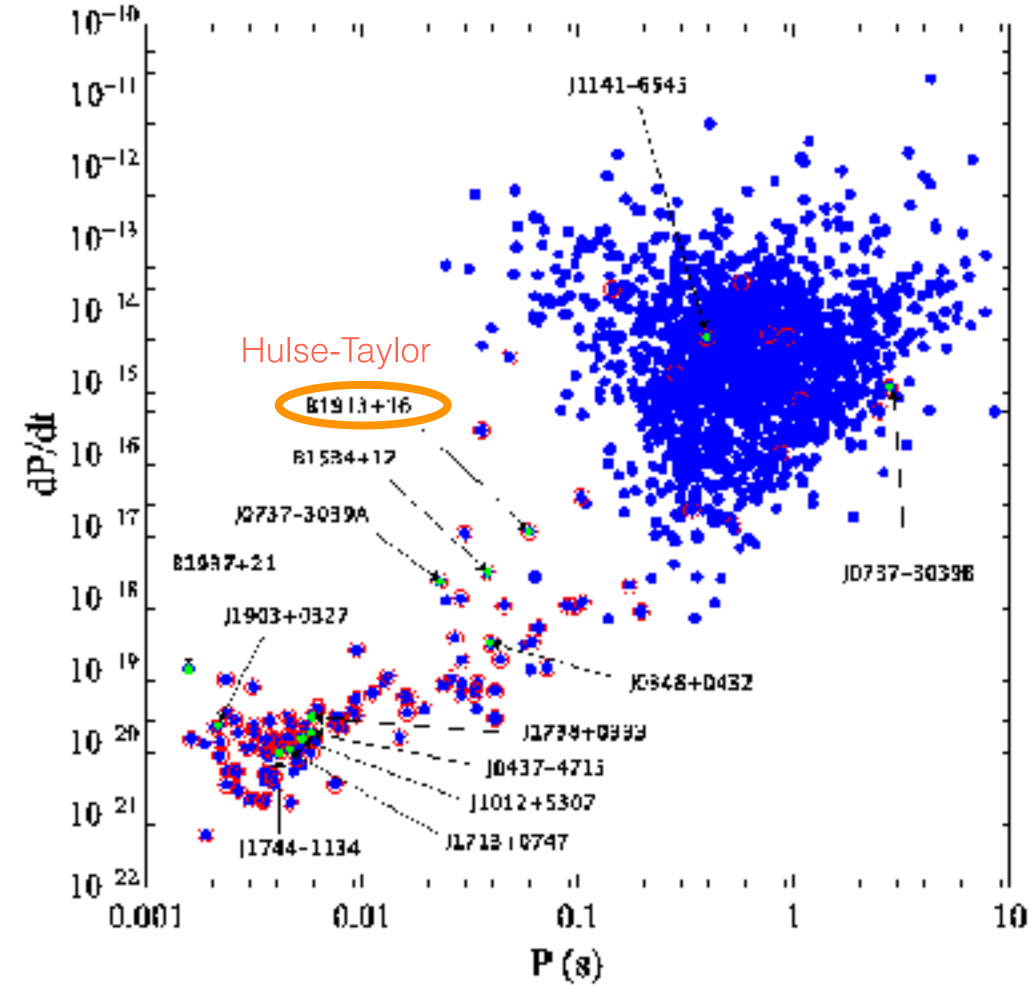
$$h_{ij} = \frac{\alpha}{M_{pl}}M_{ij} = \frac{\alpha\sqrt{2\rho_{DM}(\vec{x})}}{mM_{pl}}\cos\left(mt + \Upsilon(\vec{x})\right)\varepsilon_{ij}(\vec{x})$$

We assume $\rho_{\text{DM}} = 0.3\,\frac{\text{GeV}}{\text{cm}^3}$

Signal decreases as $m^{-1} = (2\pi f)^{-1}$

Why 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 its motion
- Ideal systems to constraint alternative theories of gravity, the presence of gravitational waves, and also ULDM!

Estimating the limits:

[Armaleo, DLN & Urban (2020)]

Dominant contribution (evaluated at the earth position)

$$t_r(t) \simeq -\frac{\alpha}{\sqrt{2}m^2 M_{pl}}\sqrt{\rho_{DM}}_{\oplus}\varepsilon_{ij,\oplus}n^i n^j \,\sin\left(mt + \Upsilon_{\oplus}\right)$$

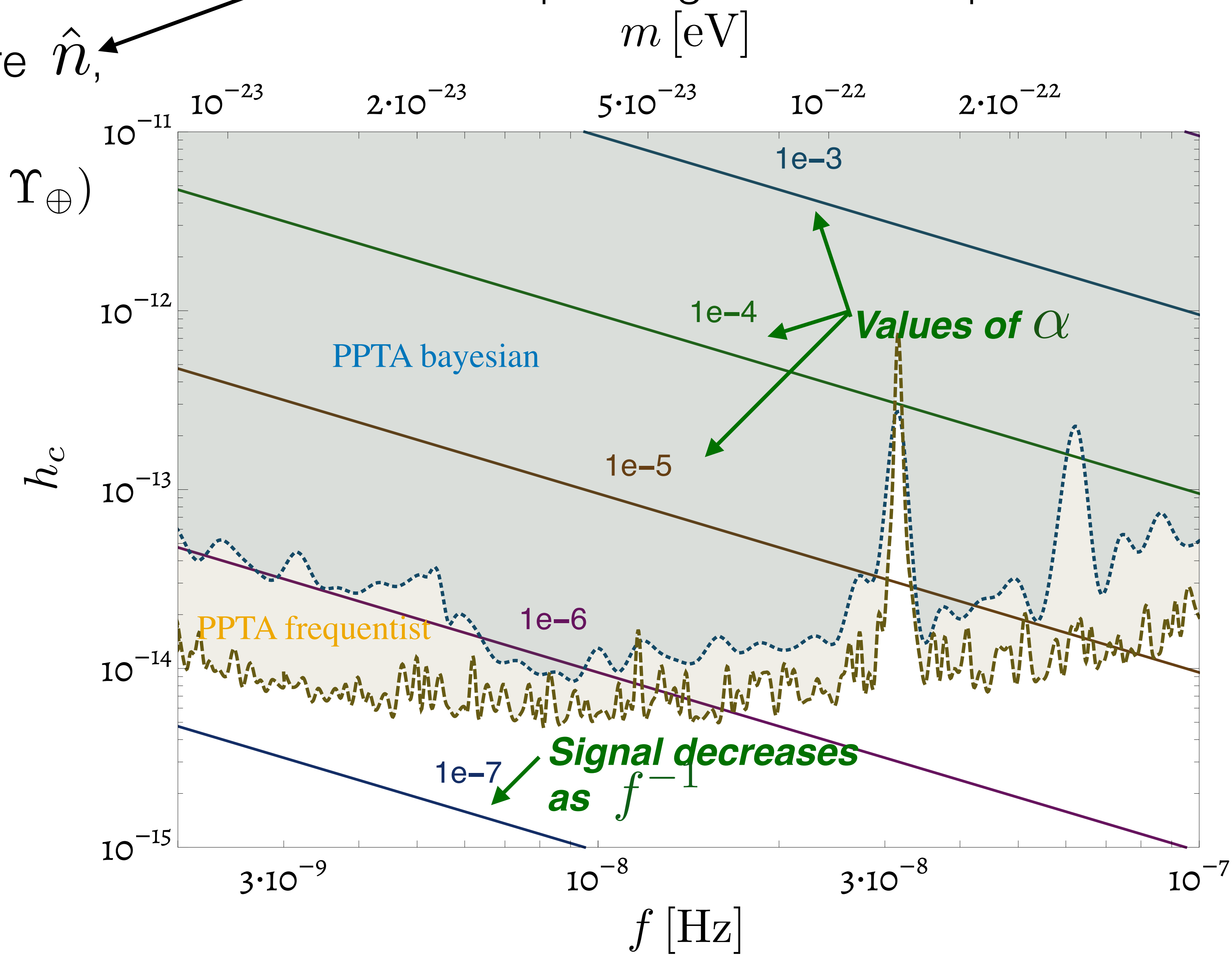
Unit vector pointing towards the pulsar

Averaging over the celestial sphere $\hat{n}$,

$$\sqrt{\langle t_r(t)^2\rangle} = \frac{\alpha\sqrt{\rho_{DM}}_{\oplus}}{\sqrt{15}m^2 M_{pl}}\sin\left(mt + \Upsilon_{\oplus}\right)$$

we obtain the same as a GW with:

$$h_c \simeq \frac{\alpha\sqrt{2\rho_{DM}}}{\sqrt{5}mM_{pl}}$$



Bounds on the equivalent gravitational wave strain as a function of frequency, reproduced with permission from [Porayko et al. 2018]

An improvement of $\sim 10^2$ is expected with SKA (15yrs, 5K pulsars) [$\ddot{U}$nal, Urban, Kovetz, arXiv:2209.02741]

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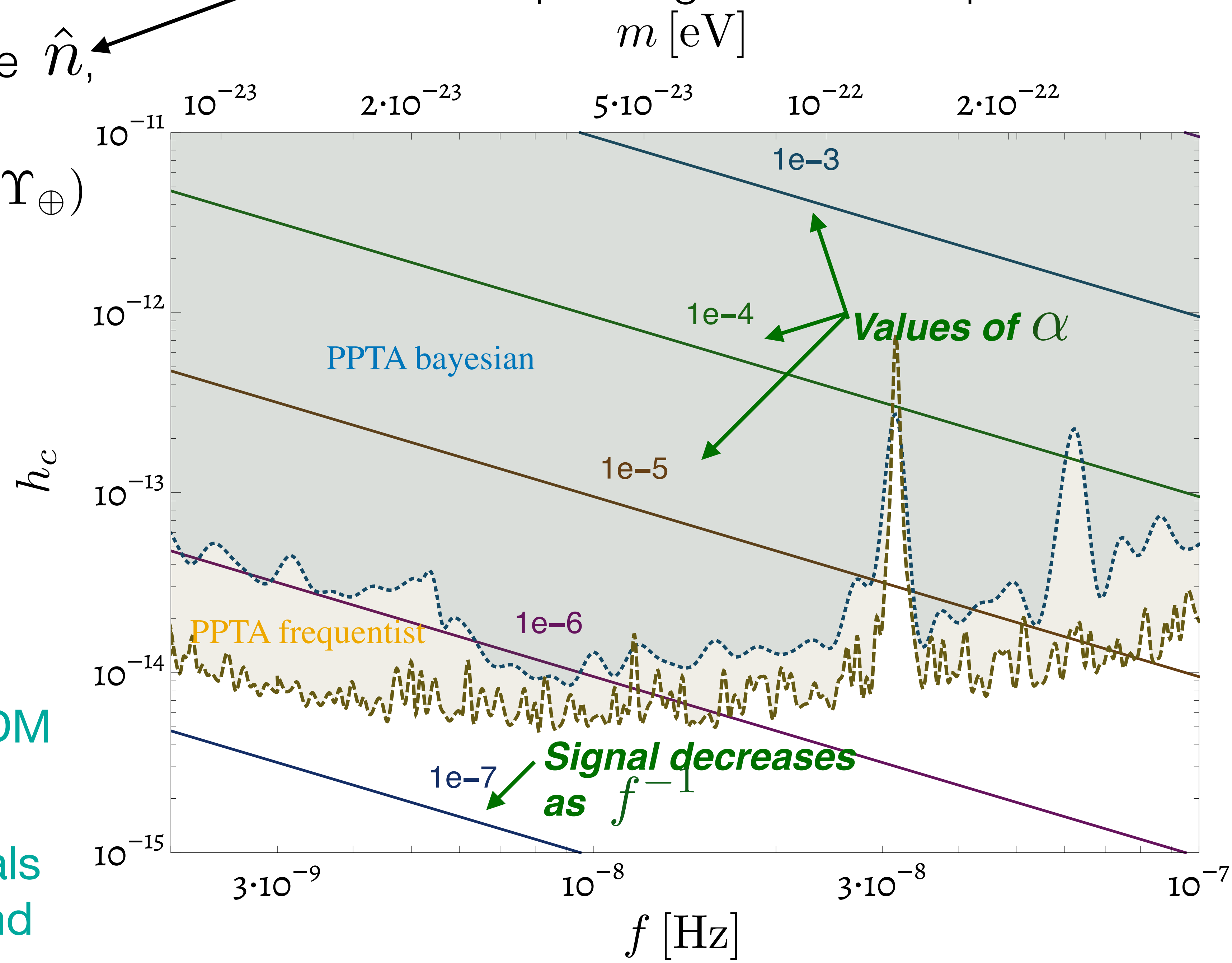
Quadrupolar nature of spin 2 ULDM

Correlation between time residuals can be useful to separate this and systematic errors



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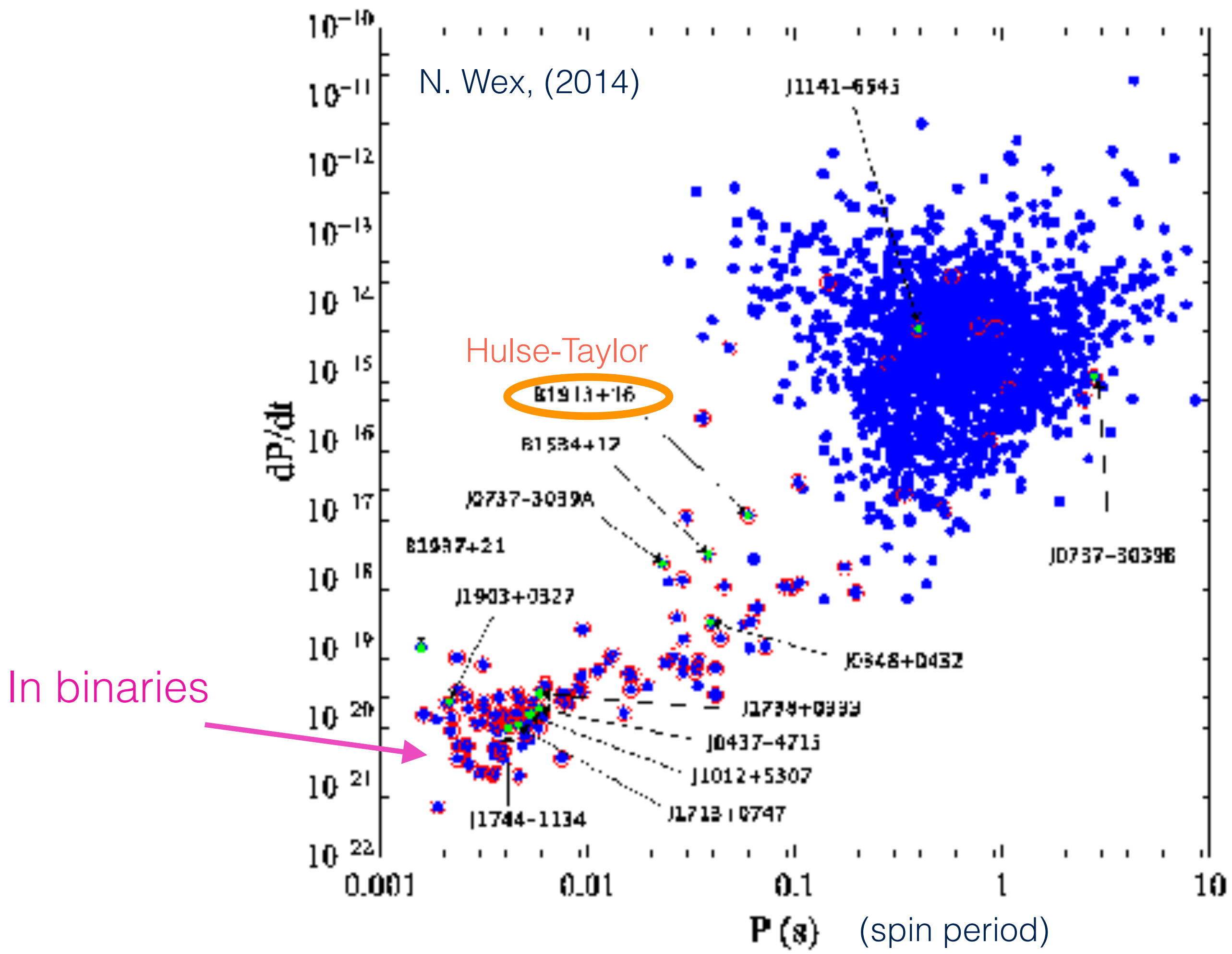
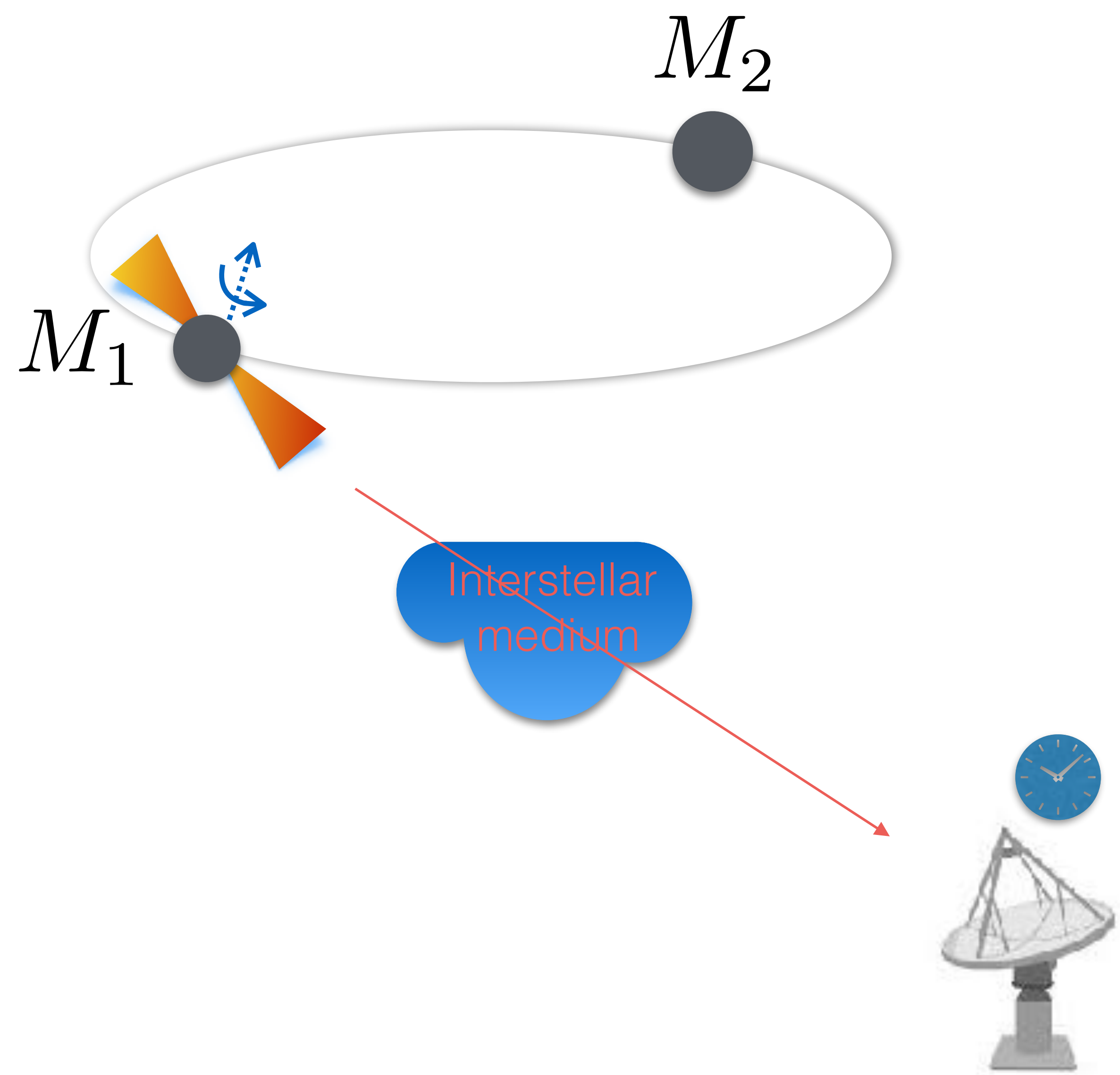
Why Binary Pulsars (BPs)?





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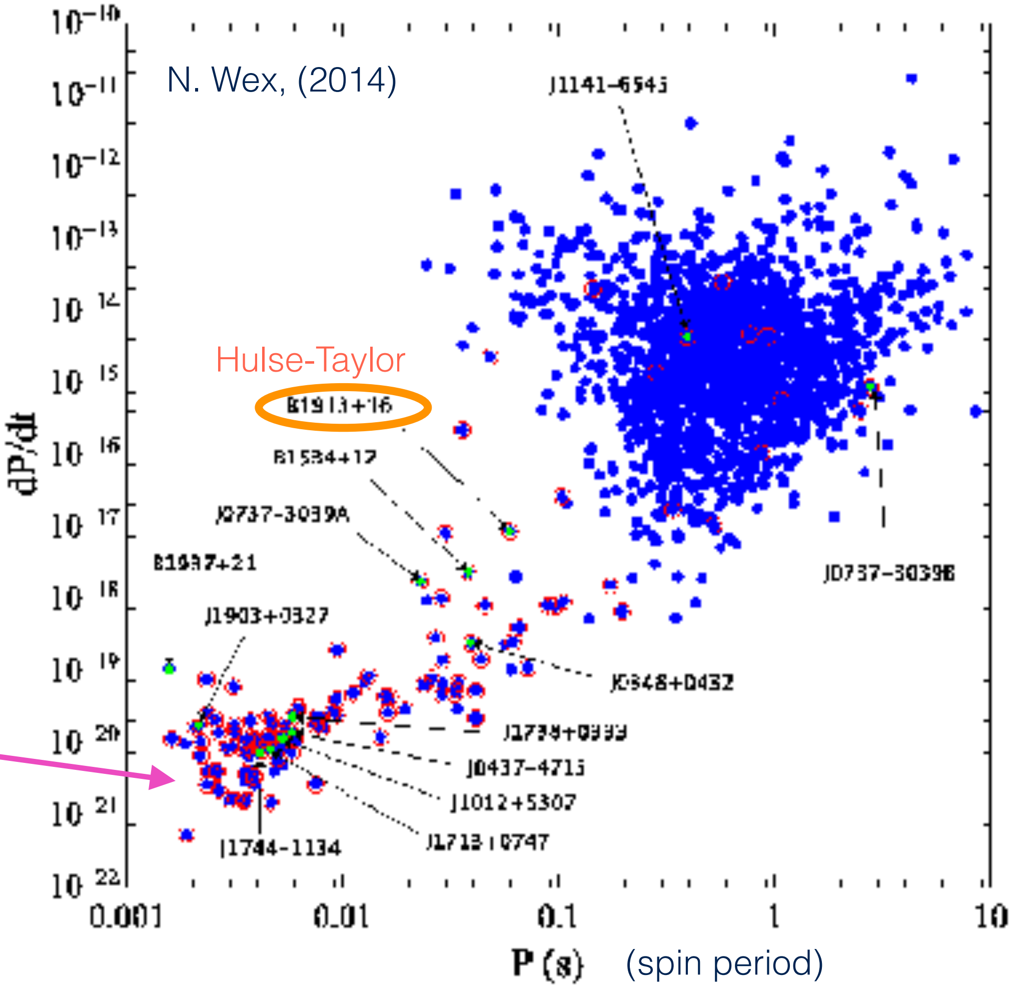
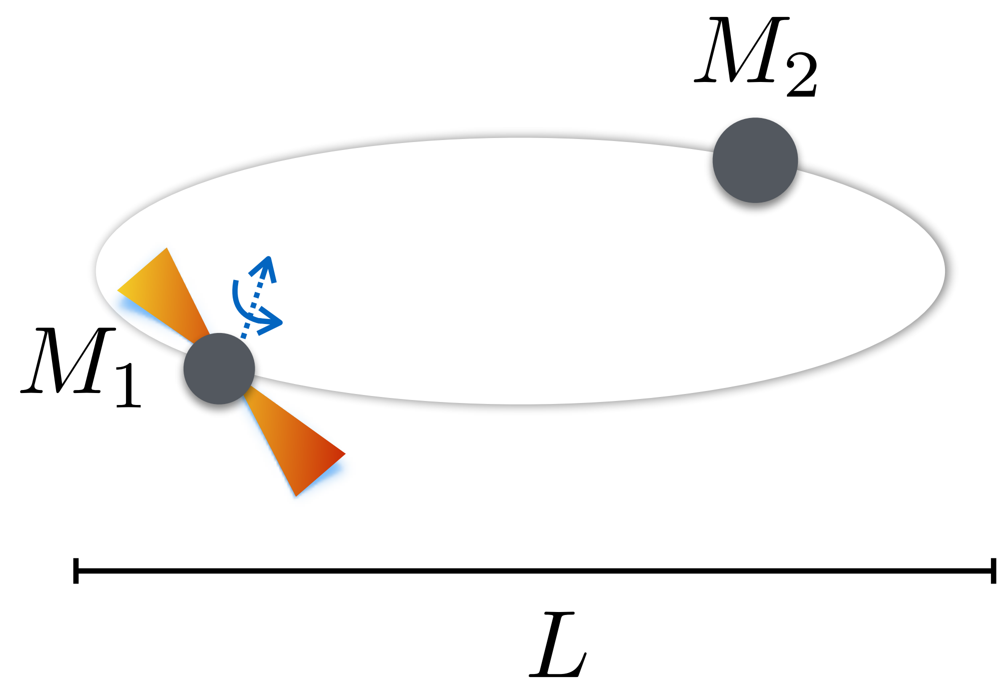




$$L \sim 10^8\,\mathrm{km}\left(\frac{P_b}{100\mathrm{days}}\right)^{2/3}\left(\frac{M_1+M_2}{M_\odot}\right)^{1/3}$$

Numbers:

$$v \sim 10^{-3},\ m \sim 10^{-18} \div 10^{-22}\mathrm{eV}$$

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

$$t_{osc} \simeq 100\ \mathrm{days}\left(\frac{10^{-22}\mathrm{eV}}{m}\right)$$

- Non relativistic: $v^2 \ll 1$ ✓
- Homogeneous: $\lambda_{coh} \gg L$ ✓
- Osc. are relevant!

Secular effects of DM on the binary pulsar orbits

- Oscillations of the DM field produce periodic perturbations to the PB orbits:

$$\mathrm{Force} \sim \cos(mt + \Upsilon)$$

- The unperturbed orbits can be expressed as Fourier series

$$\sum_n Q_n \cos(n\,2\pi/P_b + \Upsilon) \;\; (n \in \mathbb{N})$$

- In *resonance*

$$m \simeq N 2\pi/P_b \;\; (N \in \mathbb{N})$$

there is a *secular effect* on the orbital parameters;

for instance,

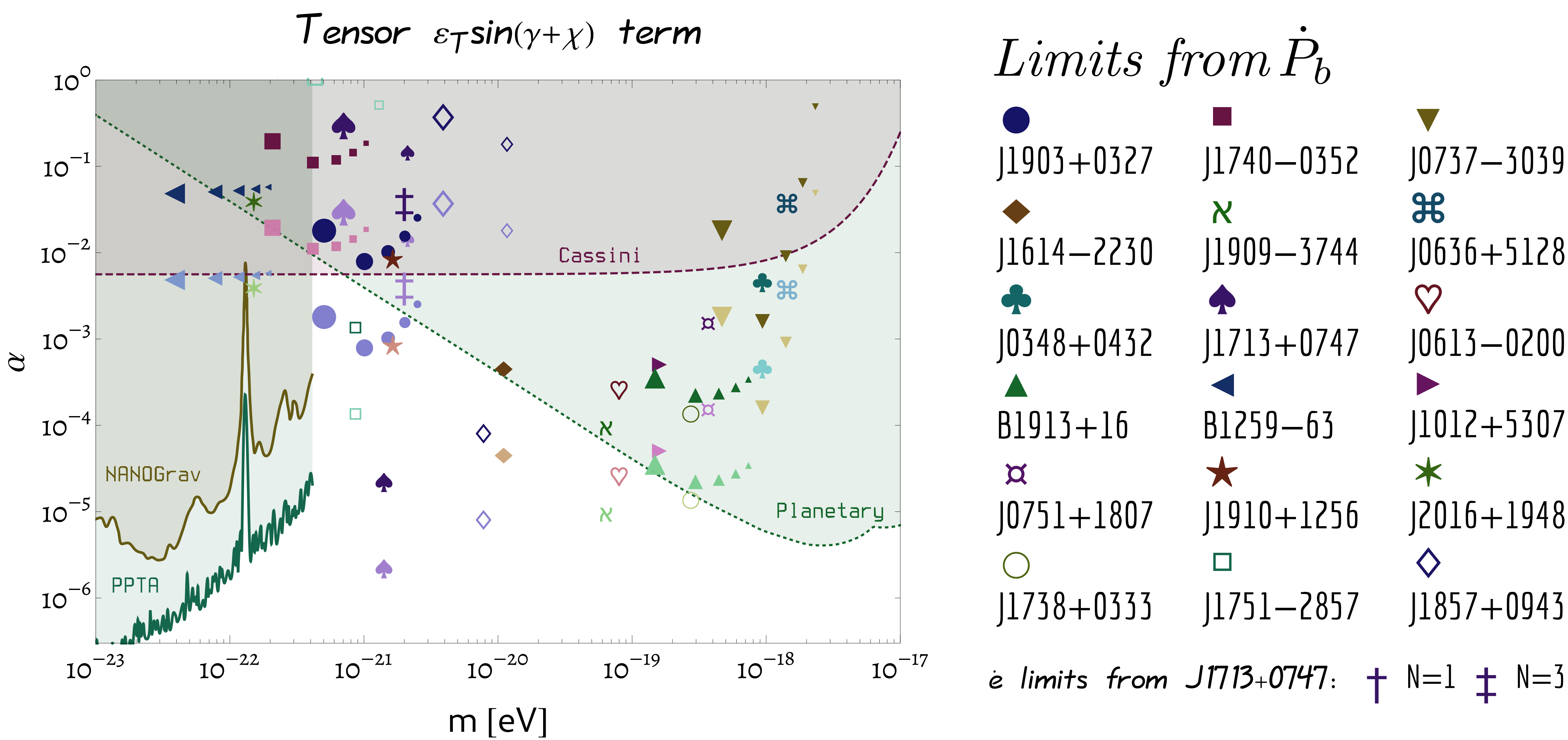
$$P_b \to P_b + \dot{P}_b(T - T_0),$$
$$e \to e + \dot{e}(T - T_0) \quad \ldots$$

Bounds on models with direct couplings

[Armaleo, DLN & Urban (2020)]

E.g. with s=2: **Tensor M_{ij}, universally coupled, with effective interaction**

$$L_I = \alpha M_{ij}(M_1 v_1^i v_1^j + M_2 v_2^i v_2^j)/M_{Pl}$$



Symbols corresponds to resonances:
- **Dark symbols (actual precision)**
- **Light symbols (a factor 10 better)**

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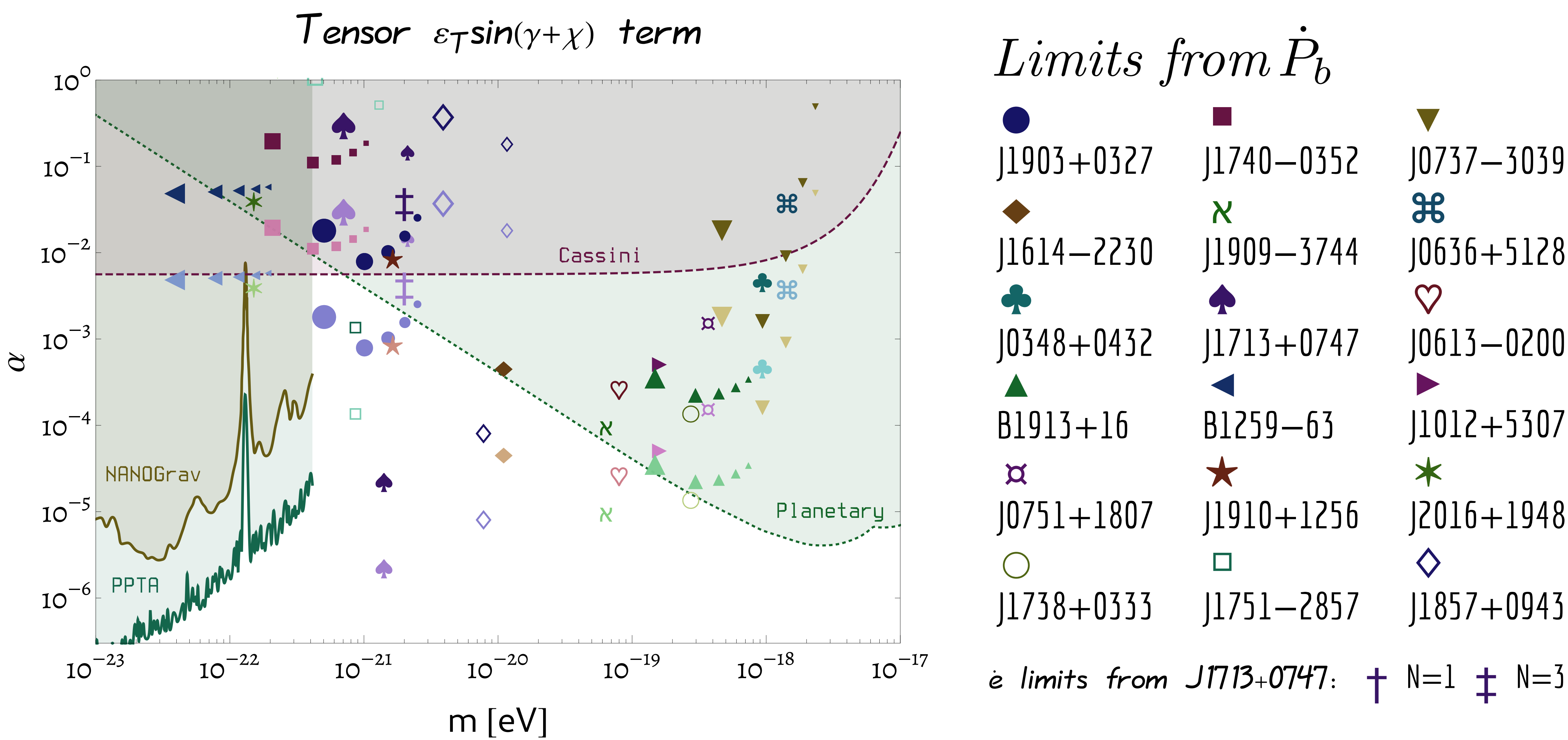

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Work in progress: What is the sensitivity beyond the resonant points?

Why Gravitational Wave Interferometers (GWIs)?

- Current facilities can detect transient events with $h = 10^{-21}$ (e.g. binary BHs)

- Weaker signals could be detected if they are coherent over a longer time (e.g. continuous GWs (CWs) emitted by rapidly spinning neutron stars)

- Currently there are upper limits on the maximum strain for CWs.
  E.g. $h \lesssim 10^{-25}$ for $f \sim 10^2\,\mathrm{Hz}$

- The ULDM field may not be coherent over the entire observation campaign.

- Semi-coherent techniques to analyze CWs can be adapted and optimized, taking into account the coherence time of the ULDM [Miller el al 2020]

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E.g. with s=2:

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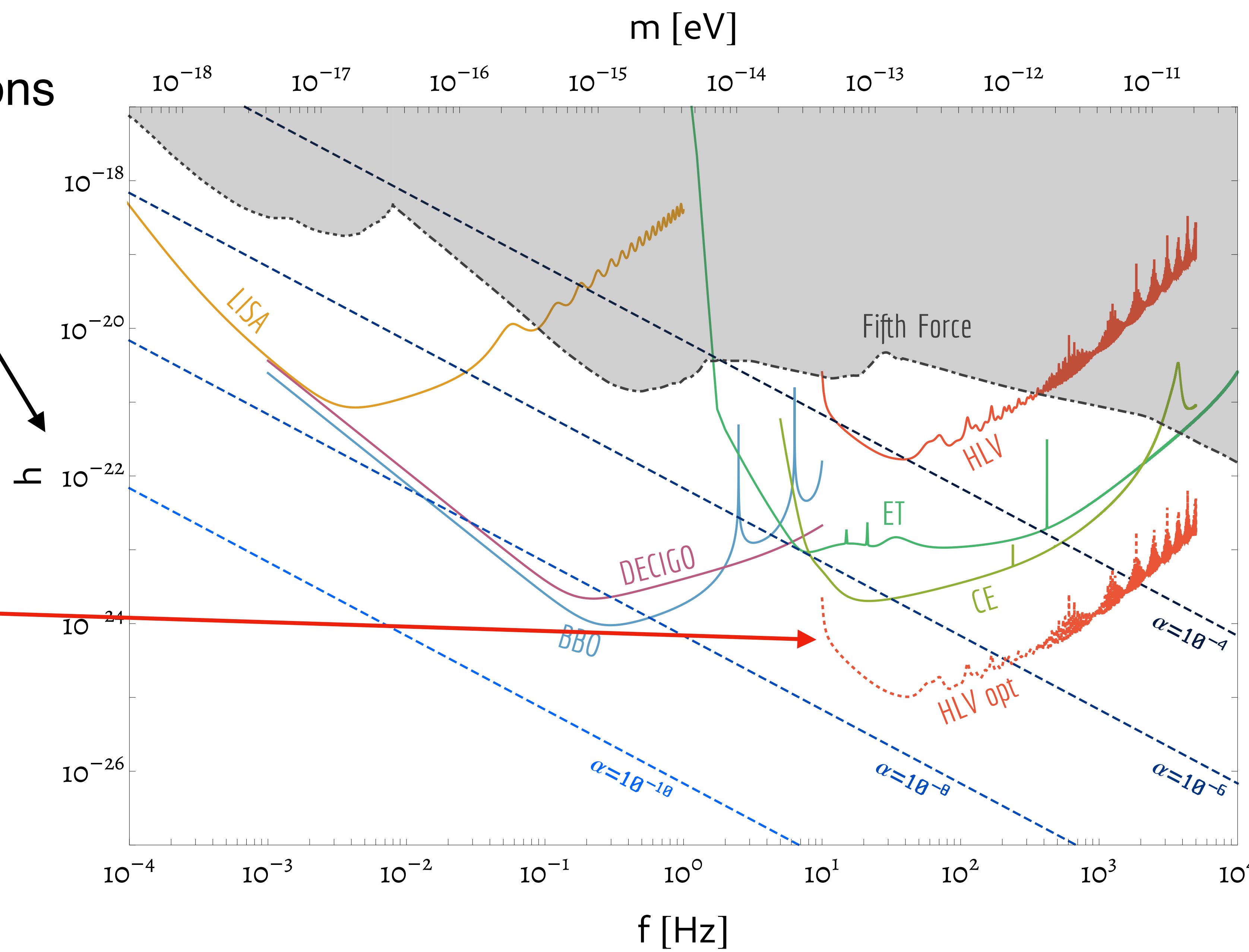
Using the response function of the detector with arms along $\hat{n}$ and $\hat{m}$ in the detector frame,

$$D^{ij} = (n^i n^j - m^i m^j)/2 \longrightarrow h(t) \equiv D^{ij} h_{ij}(t) \equiv h_s \sin(mt) + h_c \cos(mt)$$

Taking the average over polarizations

$$h \equiv \langle h_s^2 + h_c^2 \rangle^{1/2} = \frac{\alpha\sqrt{\rho_{\rm DM}}}{\sqrt{5} m M_{pl}} \,.$$

Optimized using Semi-coherent techniques



Conclusions

- ULDM can produce potentially observable effects on pulsars and GWIs
- Precise timing measurements are already ongoing for many pulsars
- A given BP is sensitive to ULDM only in a few narrow resonant bands
- New (~1000) BPs are expected to be discovered by SKA -> significant coverage
- PTA is sensitive to lighter fields and can provide complementary bounds
- To take advantage of the large number of systems it is necessary to develop new statistical approaches and techniques for the extraction of the constraints on the ULDM field -> Work in progress
- GWIs are useful to probe direct interactions between ULDM and the SM providing complementary bounds for heavier fields
- Both for pulsars and GWIs, it would be worth performing a dedicated data analysis!

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Thanks!