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Studying the importance of possible oscillations of photons into ALPs in pulsars

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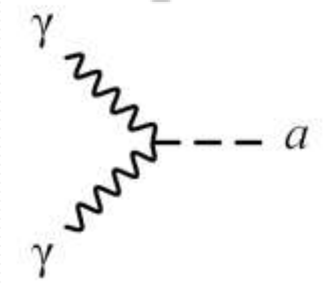
Axion-like particles (ALPs)

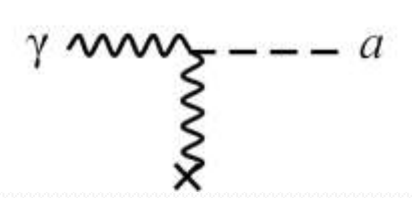
- Predicted by String Theory
- Very light particles ($m_a < 10^{-7}$ eV)
- Spin 0
- Interaction with two photons (coupling $g_{a\gamma\gamma}$)
- Interactions with other particles discarded
- Possible candidate for dark matter

Two photons



$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$

In an external B field



Photon-ALP oscillations

QUESTION:

Can pulsars tell us anything about axion-like particles (ALPs)?

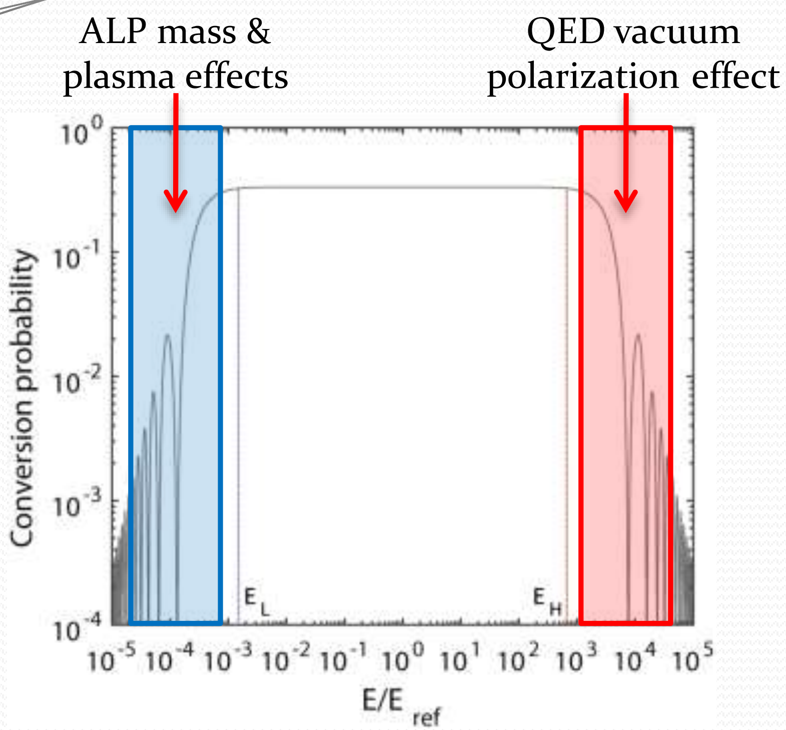
Possible photon-ALP conversion in the pulsar magnetic field[1] and/or in that of the Galaxy[2]?

Our plan (for the future):

- Evaluate ALP hints from pulsar comparison
- Extend existing studies to the largest possible sample
- Statistical analysis to constrain ALP parameter space
- Multi-frequency analysis

[1] Perna et al. 2012
[2] Majumdar et al. 2018

ALP-induced irregularities



- Photon-ALP conversion probability $P_{\gamma \rightarrow a}(E, m_a, g_{a\gamma\gamma}, B)$
- Effective photon absorption
- Highlighted zones predict spectral irregularities in observational data
- Constraints on $g_{a\gamma\gamma}$ and m_a

BLUE AREA:

- Modifications to pulsar spectra for photon-ALP conversion in the Galaxy

RED AREA:

- Modifications to pulsar spectra for photon-ALP conversion in the source

ALP-induced irregularities

- We can calculate the photon survival probability (in the presence of photon-ALP interactions) $P_{\gamma\to\gamma}$

- *Emitted* (intrinsic) flux F_{em} is not equal to the *observed* one F_{obs}

- photon-ALP interactions → $F_{obs} = P_{\gamma\to\gamma} F_{em}$

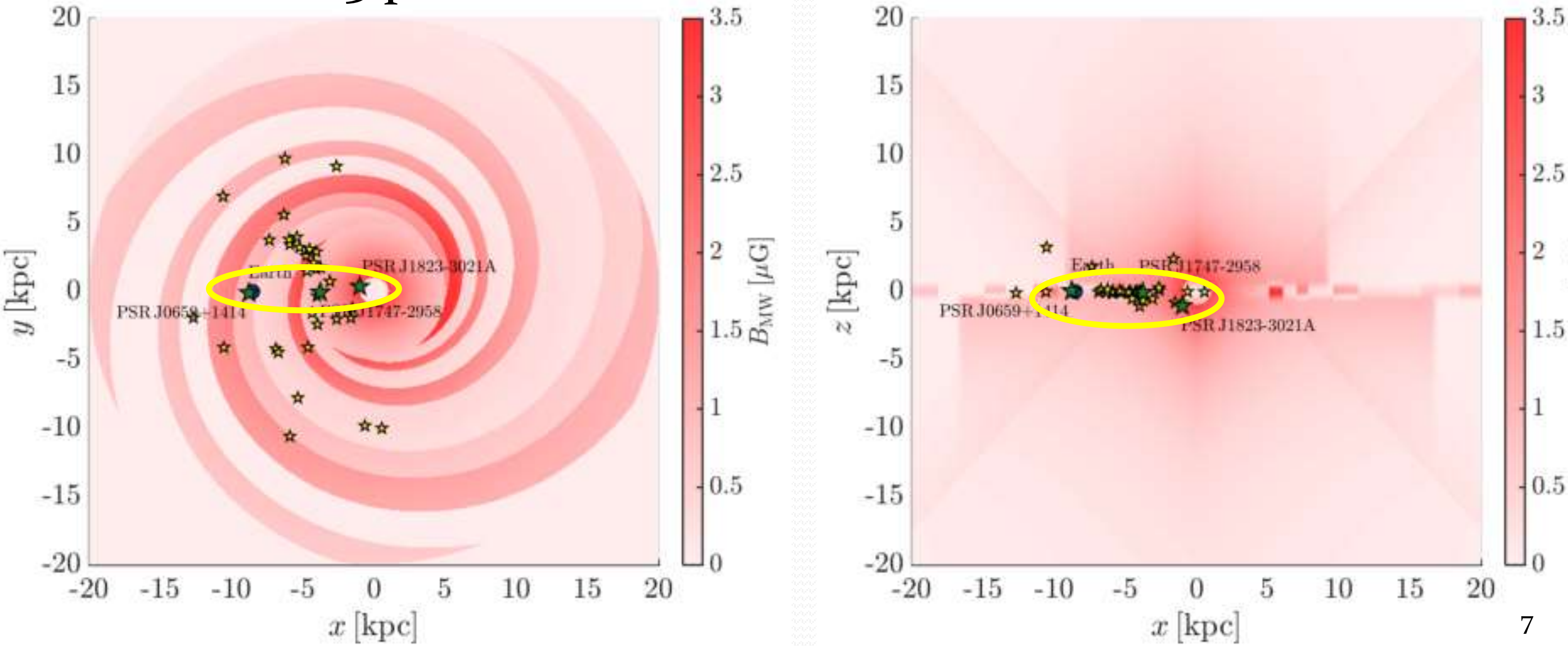
- No photon-ALP interactions → $P_{\gamma\to\gamma} = 1$, $F_{obs} = F_{em}$

Photon-ALP conversion **in the source**

- Photon-ALP mixing term: $\Delta_{a\gamma} = \frac{1}{2} g_{a\gamma\gamma} B_T$; B_T: **transverse** B
- QED term ∝ energy E: $\Delta_{xx}^{QED} = \frac{4}{2}\left(\frac{\alpha}{45\pi}\right)\left(\frac{B_T}{B_{cr}}\right)^2 E$ $\Delta_{zz}^{QED} = \frac{7}{2}\left(\frac{\alpha}{45\pi}\right)\left(\frac{B_T}{B_{cr}}\right)^2 E$
- Dipolar magnetic field B: $10^{11} - 10^{13}$ G in the centre
- By taking photon-ALP coupling $g_{a\gamma\gamma} = O(10^{-11}\ \mathrm{GeV}^{-1})$
- **GeV energy band**: $P_{\gamma \to a} < 10^{-6}$ → **no effects**
- X-ray energy band: $P_{\gamma \to a} = O(0.1)$ → effects on spectra and possible correlation with pulsar emission mechanisms

Photon-ALP conversion **in the Galaxy**

- Photon-ALP mixing term: $\Delta_{a\gamma} = \frac{1}{2} g_{a\gamma\gamma} B_T$; B_T: **transverse** B
- ALP mass term: $\Delta_{aa} = -m_a^2/(2E)$; m_a: ALP mass
- Galactic magnetic field B_{MW} by Jansson & Farrar 2012 maps
- **Select pulsars with distance > 4 kpc** for sizable ALP effects
- Focus on 3 pulsars for now

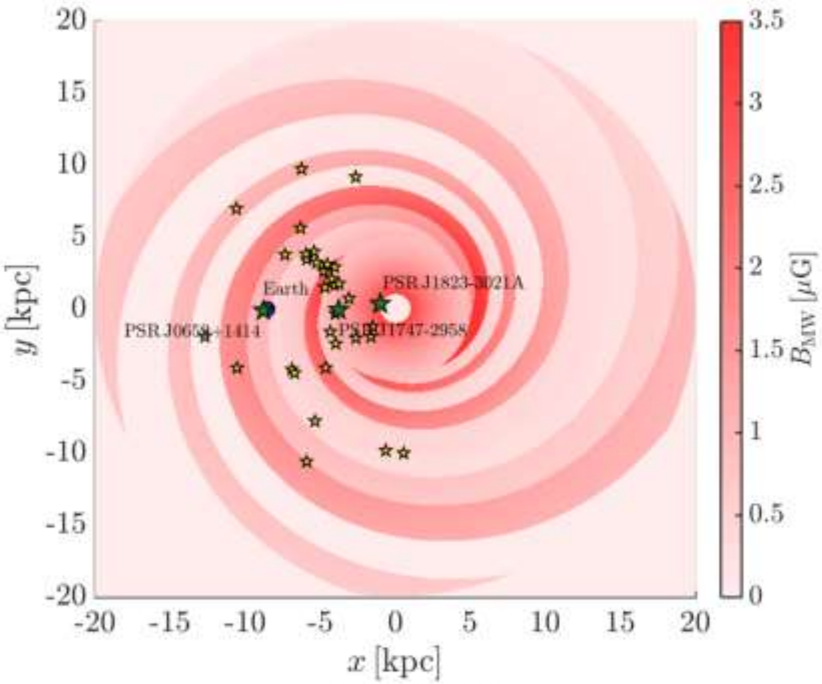


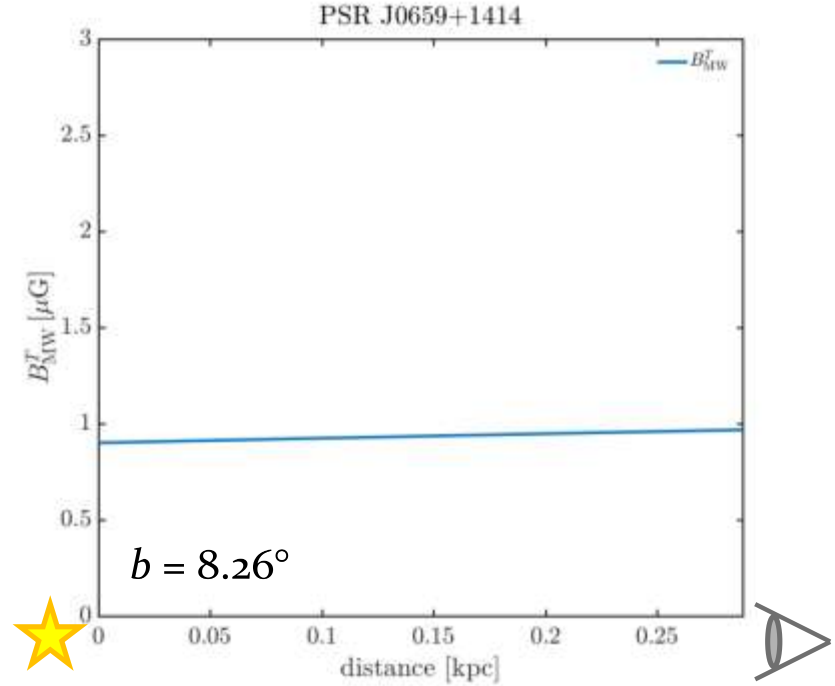
Photon-ALP conversion in the Galaxy

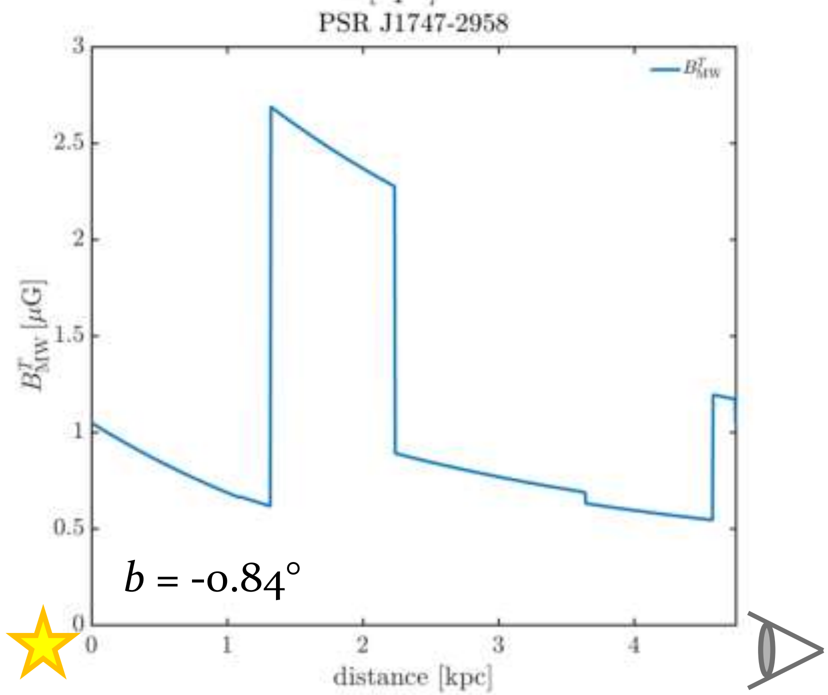
- **Best pulsars for ALP studies**:
  - distance > 4 kpc
  - in the Galactic plane (low Galactic latitude b)
  - located in zones where B_{MW} is high
  - better toward the centre for high **transverse** B_{MW}^T due to B_{MW} vector structure

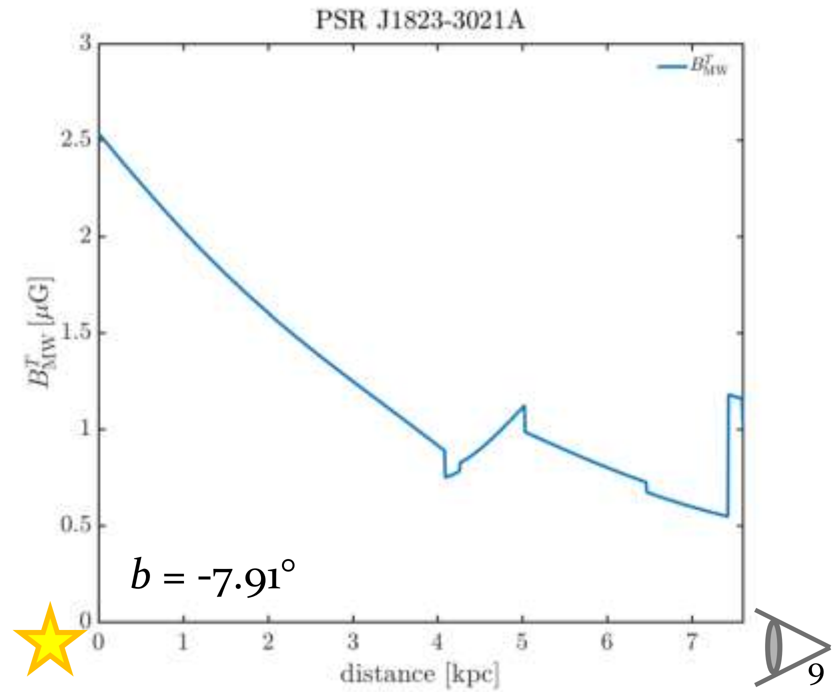
- Spectra modified by ALPs ($g_{a\gamma\gamma} = 0.7 \times 10^{-10}$ GeV^{-1}; $m_a = 2 \times 10^{-8}$ eV)

- Power law super exponential cutoff fit (PLECn models) in PLEC1 form $N \exp[\Gamma \ln(E/E_0) - (E/E_{cut})^b]$ applied to *emitted* spectra (modified by $P_{\gamma\rightarrow\gamma}$):
  - PSR J0659+1414 (very close, to crosscheck results)
  - PSR J1747-2958
  - PSR J1823-3021A

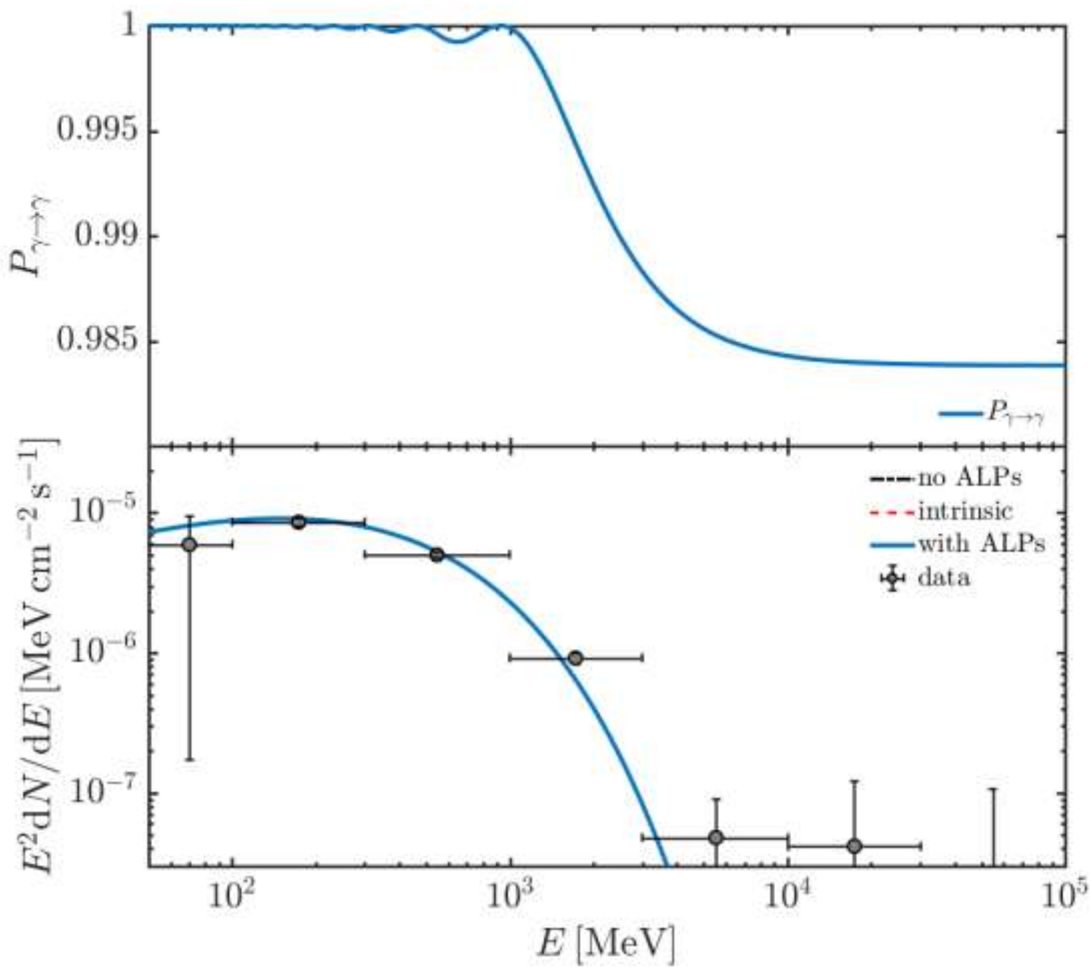

PSR J1823-3021A
Earth
PSR J0659+1414
PSR J1747-2958
y [kpc]
x [kpc]
B_{MW} [μG]


PSR J0659+1414
B^T_{MW}
B^T_{MW} [μG]
b = 8.26°
distance [kpc]


PSR J1747-2958
B^T_{MW}
B^T_{MW} [μG]
b = -0.84°
distance [kpc]

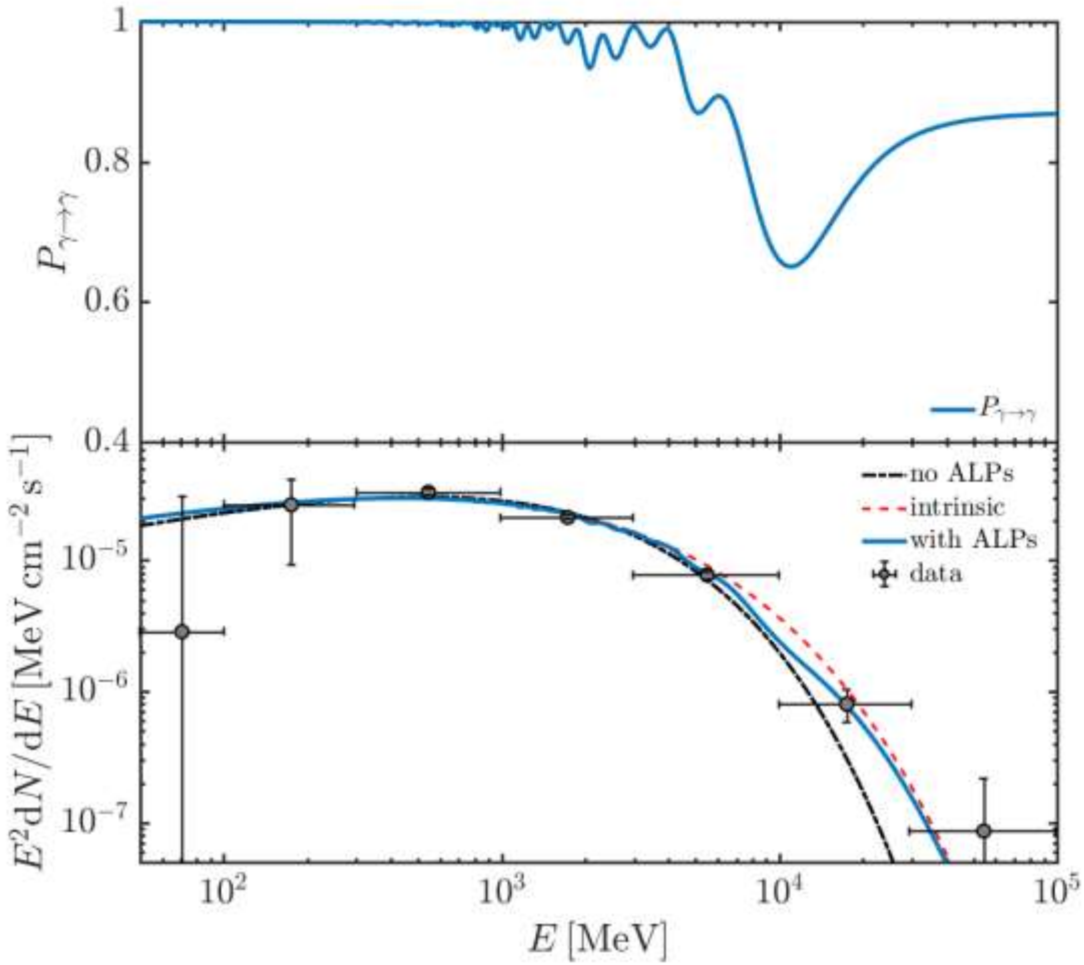

PSR J1823-3021A
B^T_{MW}
B^T_{MW} [μG]
b = -7.91°
distance [kpc]

PSR J0659+1414



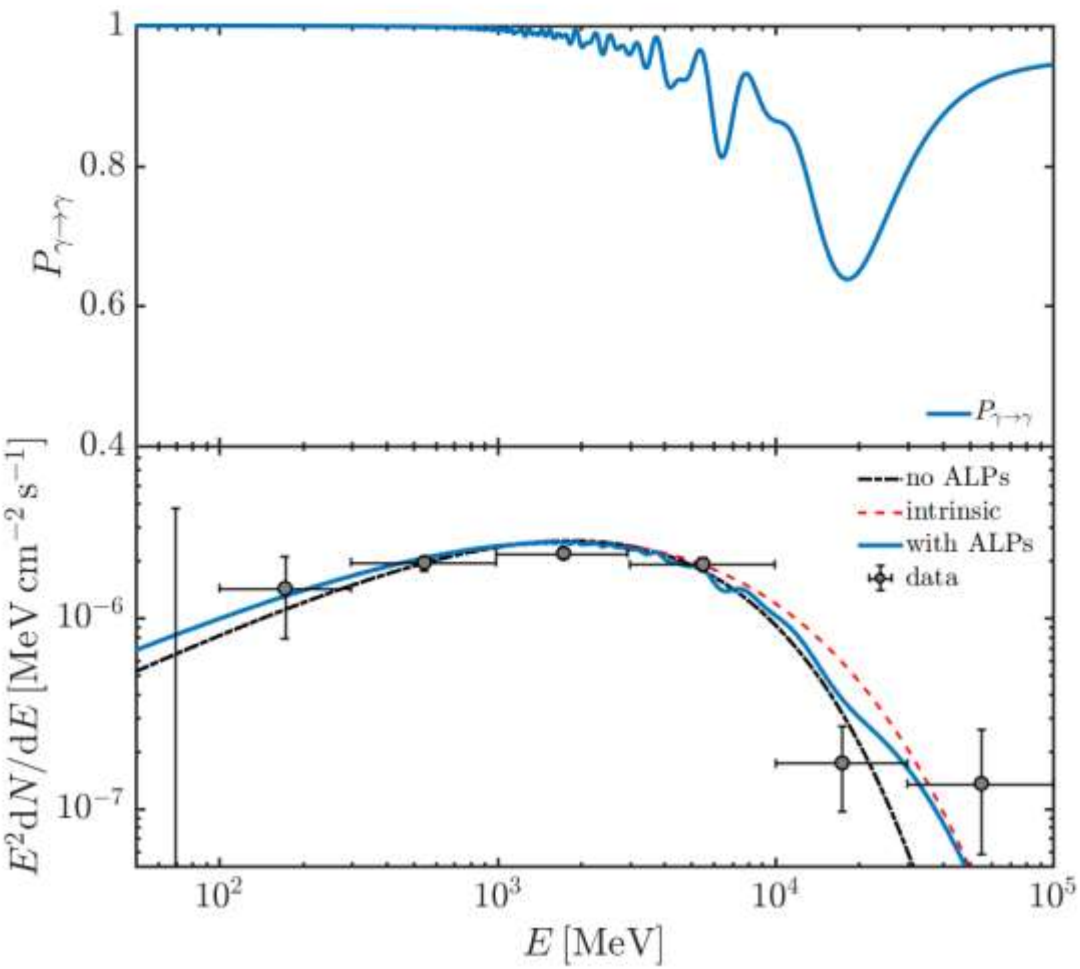
- No sizeable ALP effects (as expected)
- Fit unchanged
- Data and fits without ALPs → from *Fermi*-LAT repository

PSR J1747-2958



- ALP effects for $E > 1$ GeV
- Tentative new heuristic fit “with ALPs” resulting in
  - $\Gamma = 1.61$
  - $E_{cut} = 811.7$ MeV
  - $b = 0.56$
- Small increase of Γ, small decrease of E_{cut} and b

PSR J1823-3021A



- ALP effects for $E > 1$ GeV
- Tentative new heuristic fit "with ALPs" resulting in
  - $\Gamma = 1.33$
  - $E_{cut} = 1100.8$ MeV
  - $b = 0.53$
- Small increase of Γ, small decrease of E_{cut} and b

Photon-ALP conversion in the Galaxy

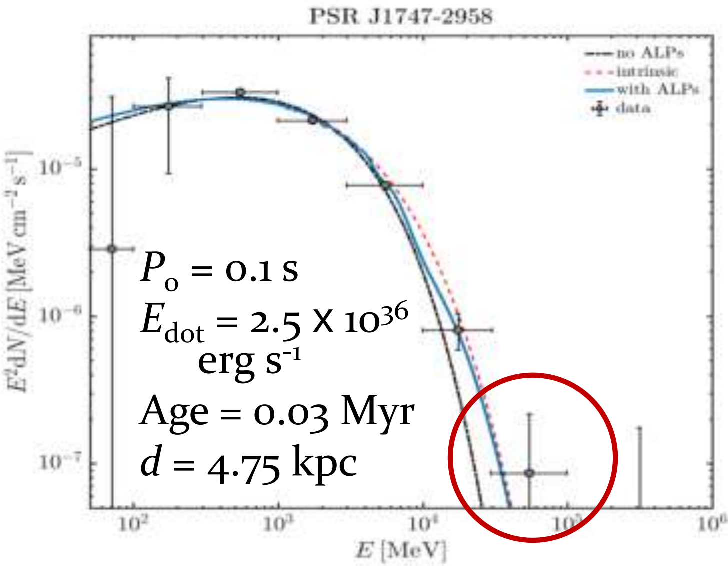
- **Distance is the key parameter**

- Comparison with pulsars similar to those considered but at *different distances* (similar *emitted* spectra are expected)

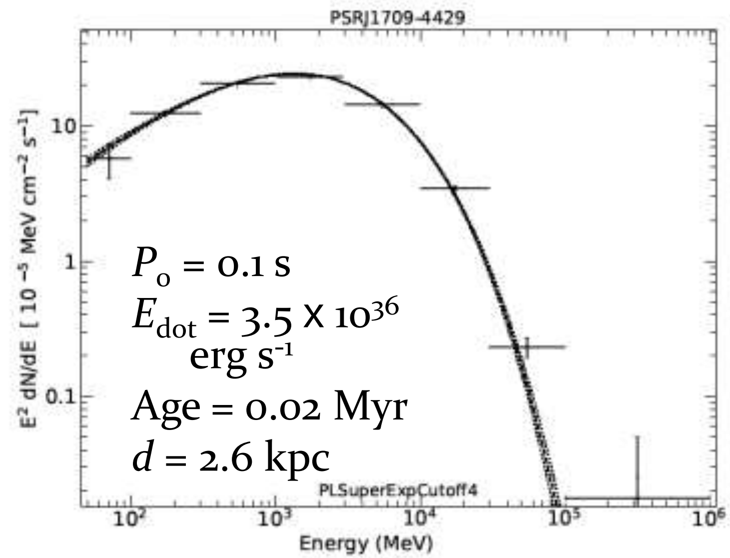
- **Hint on the presence of ALPs** if:
  - Comparing similar pulsars at different distances should yield different spectral shapes as a function of distance
  - **farther pulsars should have spectra more modified than closer ones**

- Without such correlation → hint against ALPs

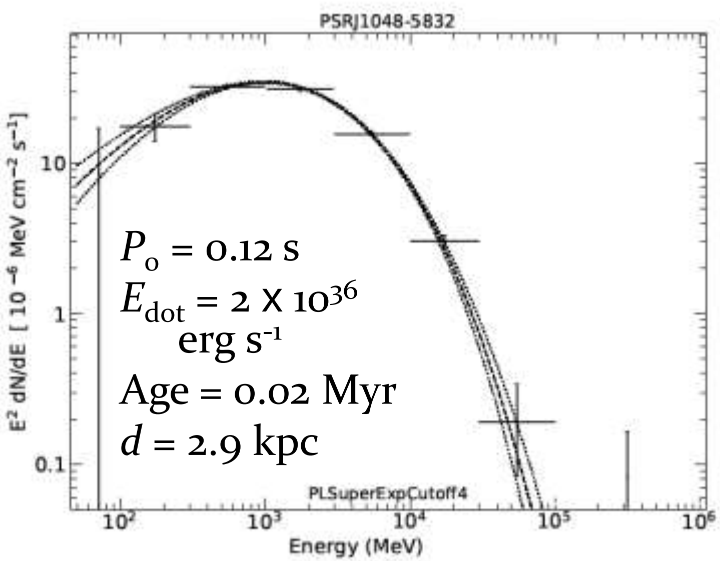
PSR J1747-2958



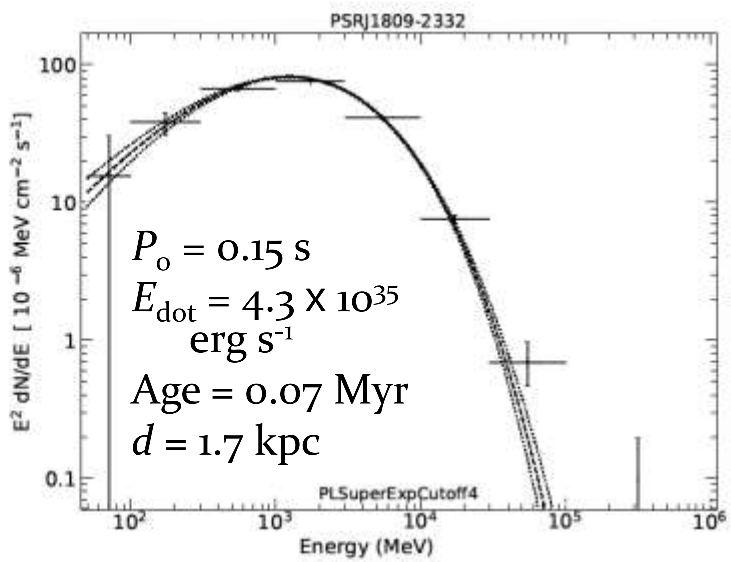
P_0 = 0.1 s
E_{dot} = 2.5 x 10^{36} erg s^{-1}
Age = 0.03 Myr
d = 4.75 kpc



P_0 = 0.1 s
E_{dot} = 3.5 x 10^{36} erg s^{-1}
Age = 0.02 Myr
d = 2.6 kpc

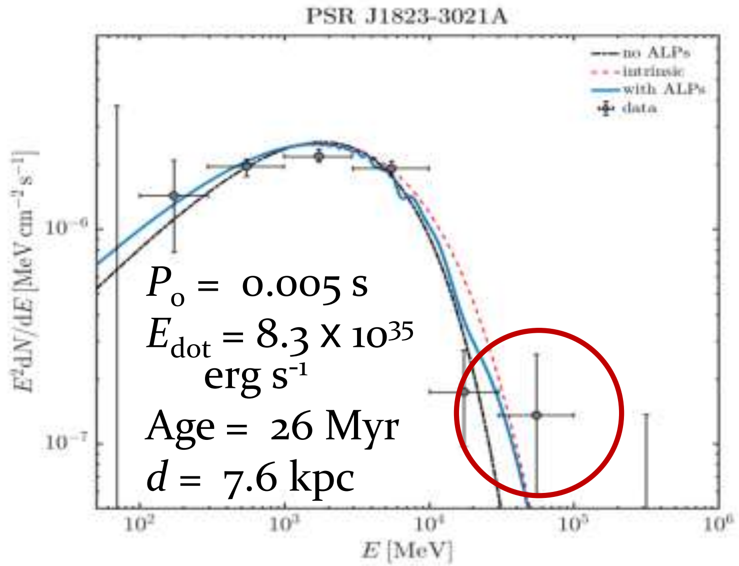


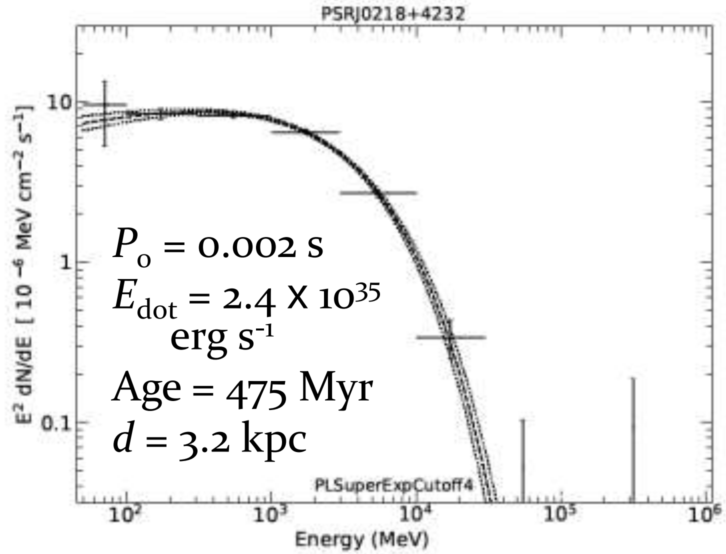
P_0 = 0.12 s
E_{dot} = 2 x 10^{36} erg s^{-1}
Age = 0.02 Myr
d = 2.9 kpc

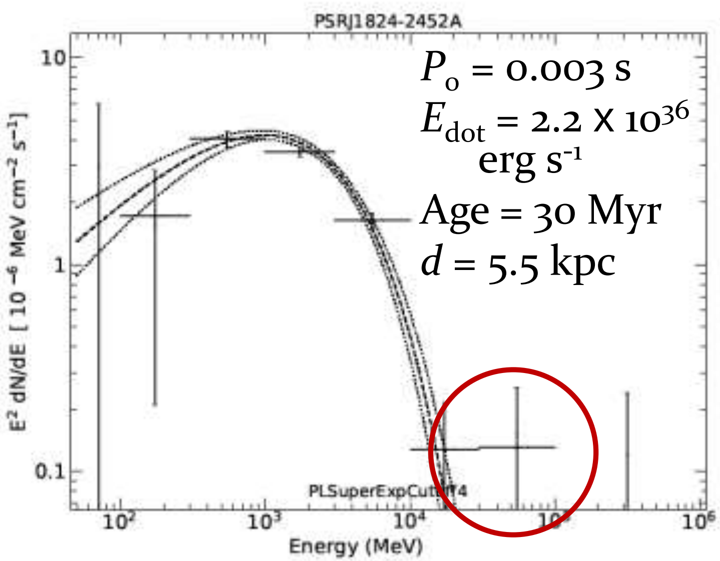


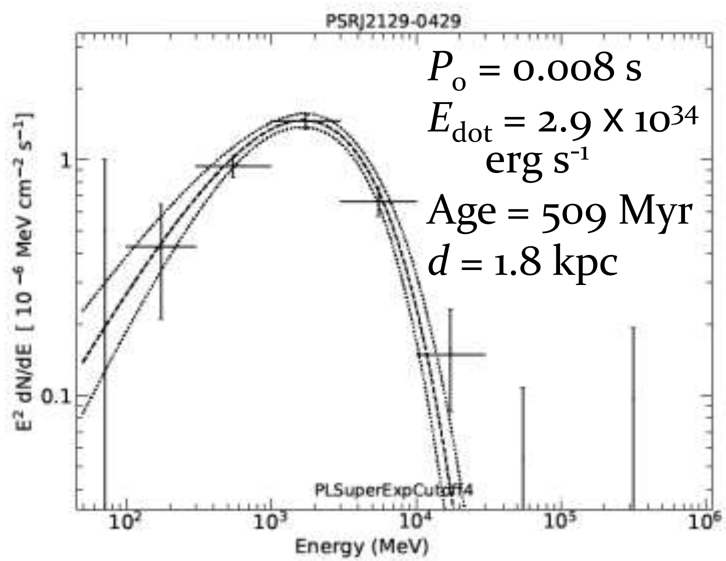
P_0 = 0.15 s
E_{dot} = 4.3 x 10^{35} erg s^{-1}
Age = 0.07 Myr
d = 1.7 kpc

PSR J1823-3021A









Conclusions (hints so far…)

- **In the GeV energy range what matters for photon-ALP conversion is the *transverse* component of B_{MW} only**

- **Best pulsars for ALP studies: distant, in the Galactic plane, towards the centre**

- Possible improvement of the spectral fits (to be confirmed with a more ROBUST analysis)

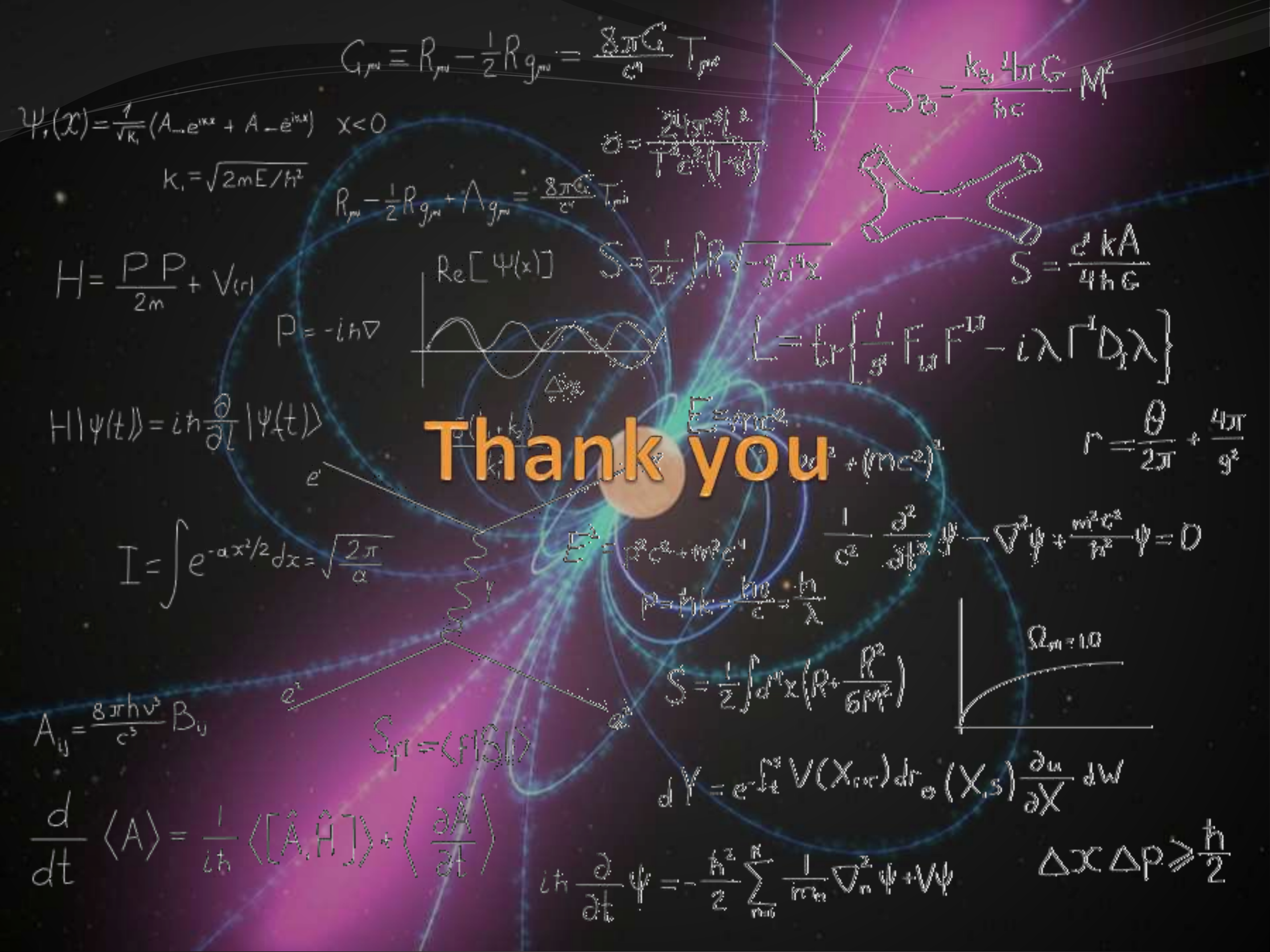
- Possible existence of ALP hint from the behavior of pulsar with similar properties but at different distances (to be investigated further)

- $g_{a\gamma\gamma} = O(10^{-10}\ \mathrm{GeV}^{-1})$ close to the upper limit of CAST, $m_a = O(10^{-8}\ \mathrm{eV})$

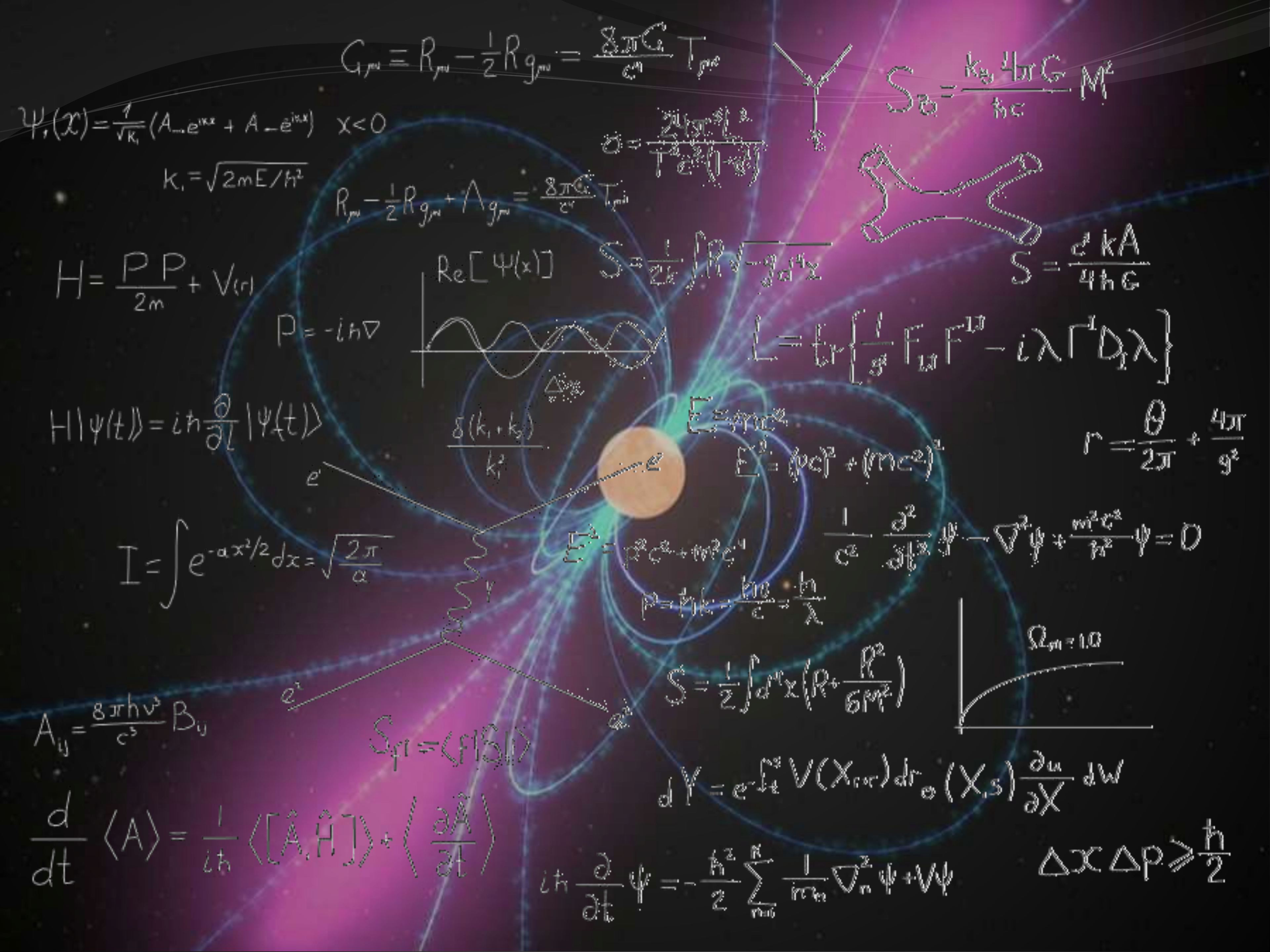
Future perspectives

- Possible ON-peak analysis to consider pulsar phase (thanks David)
- Perform a likelihood analysis to test the best ALP parameter space ($g_{a\gamma\gamma}$, m_a) and significance of the model
- Find hints for ALPs or constrain ALP parameter space by considering all known pulsars
- Continue analysis of the "ALP behavior" of similar pulsars
- Study the ALP effects in the X-ray band:
  - Modeling photon-ALP conversion in the source
  - Different pulsar B fields (dipolar, multipolar, …)
  - Different emission models
- Study of possible links between GeV and X-ray band

Thank you



$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$
$k_1 = \sqrt{2mE/\hbar^2}$
$H = \frac{P \cdot P}{2m} + V(r)$
$P = -i\hbar\nabla$
$Re[\Psi(x)]$
$H|\psi(t)\rangle = i\hbar \frac{\partial}{\partial t}|\psi(t)\rangle$
$I = \int e^{-ax^2/2} dx = \sqrt{\frac{2\pi}{a}}$
$A_{ij} = \frac{8\pi h \nu^3}{c^3} B_{ij}$
$\frac{d}{dt}\langle A \rangle = \frac{1}{i\hbar}\langle [\hat{A}, \hat{H}] \rangle + \left\langle \frac{\partial \hat{A}}{\partial t} \right\rangle$
$S = \frac{c^3 kA}{4\hbar G}$
$\Omega_m = 1.0$
$\Delta x \Delta p \geq \frac{\hbar}{2}$



H = PP/2m + V(r)
P = -iħ∇
Re[Ψ(x)]
k₁ = √(2mE/ħ²)
E = mc²
Ω_m = 1.0
ΔxΔp ≥ ħ/2