STRUCTURE OF ALP CONVERSION AT NEUTRON STARS

Polarization & Pulsation

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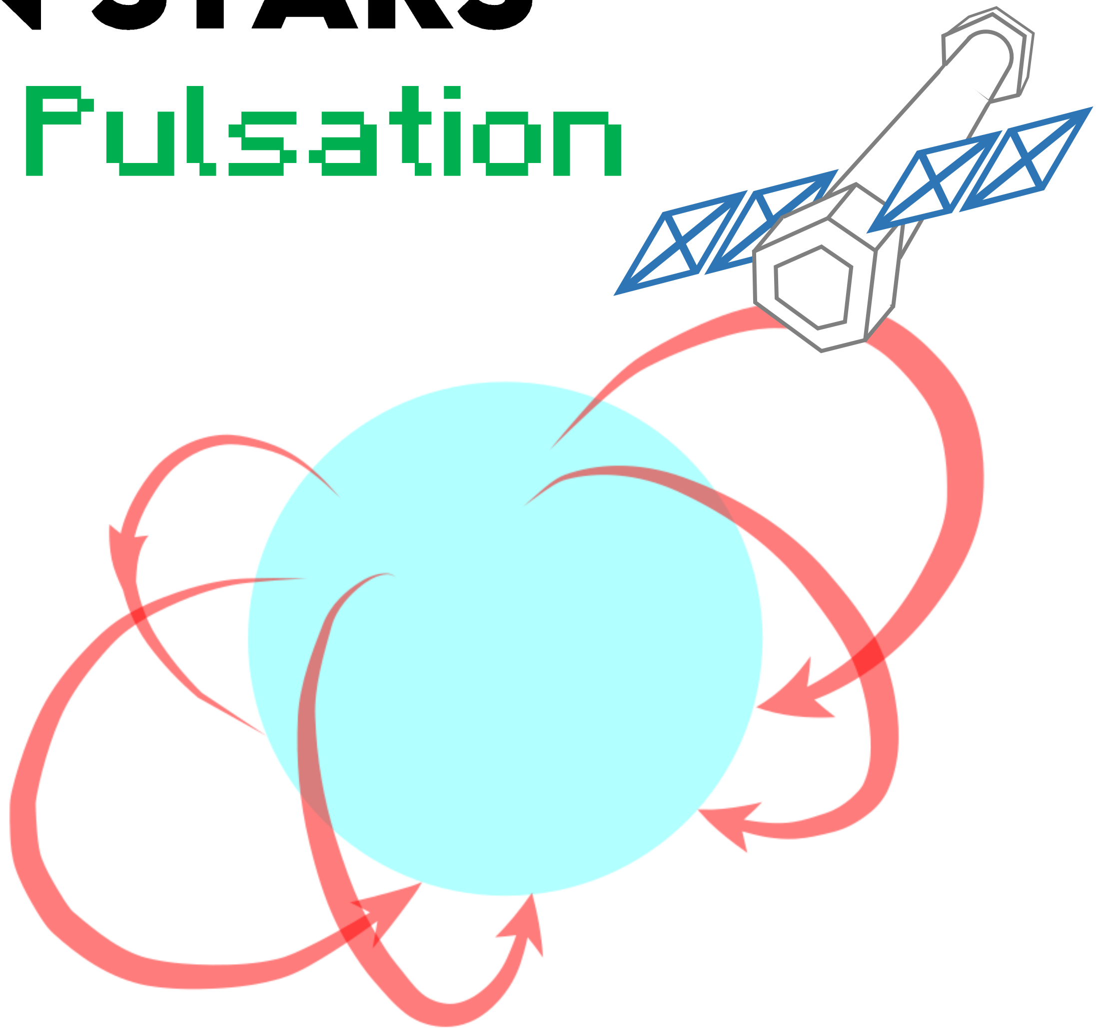


中国物理学会高能物理分会
第十二届全国会员代表大会暨学术年会

arXiv:2501.12440
JiJi Fan, LFL, Chen Sun
PRL 135 (2025), 231801

The axion-like particle (ALP)

- Motivated by other theories in the UV (e.g. the string axiverse picture), can be the QCD axion still

EFT coupling with the photon field

$$\mathcal{L} \supset \frac{g_{a\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} \qquad \frac{g_{af}}{2m_f} \partial^\mu a \, \bar{f}\gamma_\mu \gamma^5 f$$

EFT coupling with the SM fermion (nucleon)

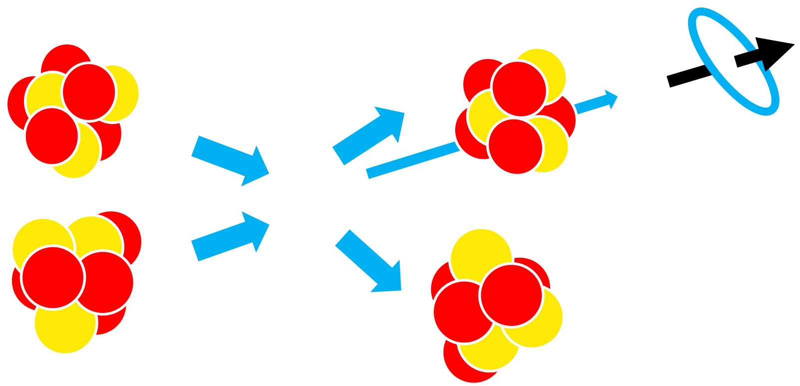
- Can be good wave-like DM candidate, either from misalignment or the decay of topological defects

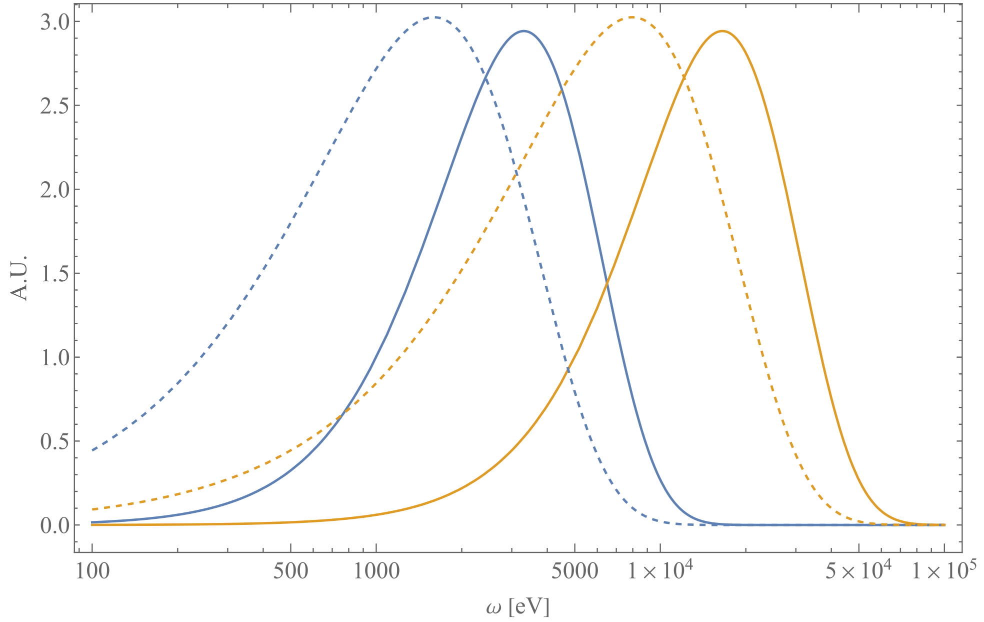
X. Chen, M. Braglia J. Fan, LFL, C. Preteti, P. Singh, In prep; X. Chen, J. Fan, LFL, 2303.03406; Y. Bao, J. Fan, LFL, 2209.09908;

Neutron Star(NS) as an ALP Source

The hot, dense core (T ~ keV) of NS could generate ALP through multiple mechanisms

G. Raffelt, 1996; D. Yakovlev, K. Levenfish and Y. Shibanov, 1999; J. Keller and A. Sedrakian, 2012; A. Sedrakian, 2015; B.J. F. Fortin, H. K. Guo, S.P. Harris, D. Kim, K. Sinha and C. Sun, 2021;





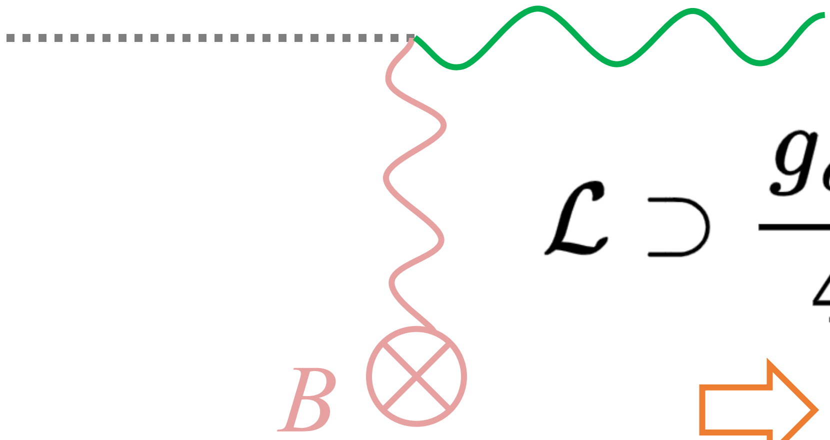
$$\frac{dL_{nn}^{\infty}}{d\omega_a^{\infty}} = \frac{1}{9\pi^6} C_\pi \left(\frac{m_N}{m_\pi}\right)^4 f^4 g_{aN}^2 \frac{\omega_a^{\infty,3}(\omega_a^{\infty,2} + 4\pi^2 T^{\infty,2})}{e^{\omega_a^\infty/T^\infty} - 1} \times \int_0^{R_{\rm crust}} dr \, \frac{r^2}{\sqrt{1 - \frac{2Gm(r)}{r}}} p_{Fn}(r) F[c(r)] e^{-4\phi(r)}$$

Significantly harder than a thermal (black body) component of the same temperature

ALP Conversion in Strong Magnetic Fields

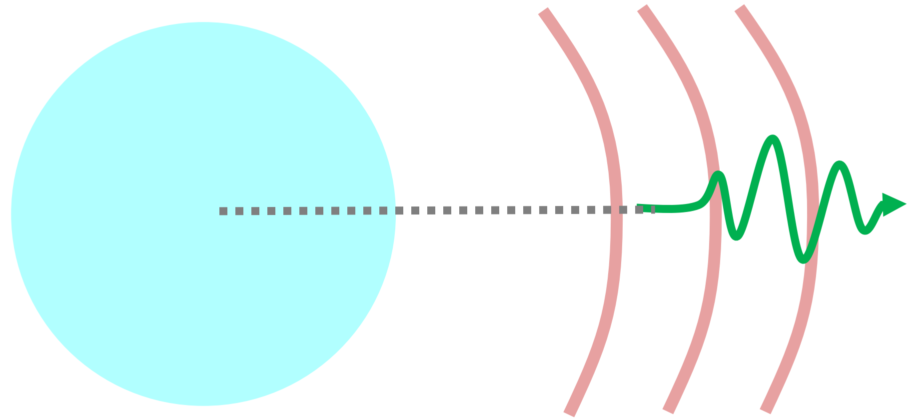
G. Raffelt and L. Stodolsky, 1988
D. Lai and J. Heyl, 2006;

- The strong magnetic field makes axion being converted to the Ordinary mode (O-mode) photon



$$\mathcal{L} \supset \frac{g_{a\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$$\Rightarrow \propto a\, \mathbf{E} \cdot \mathbf{B}$$

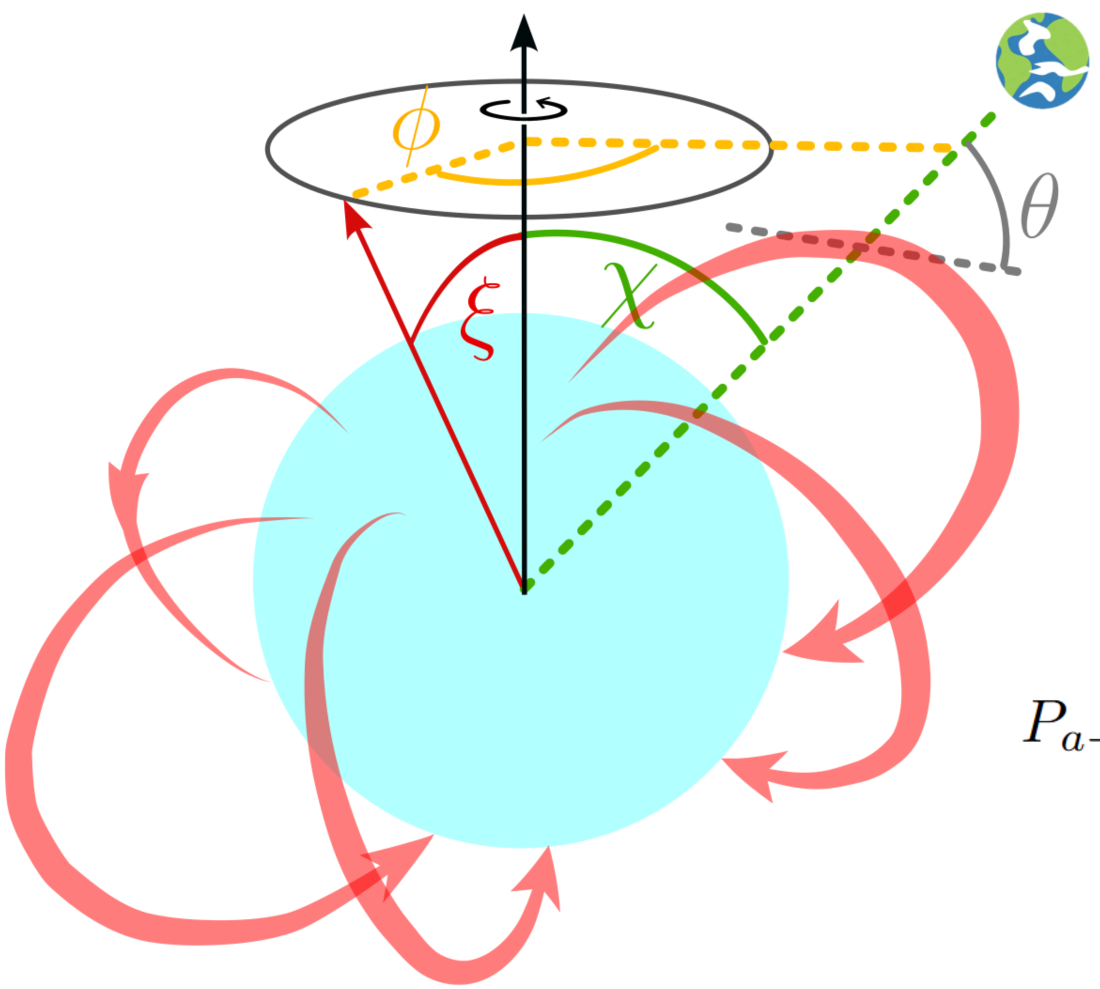


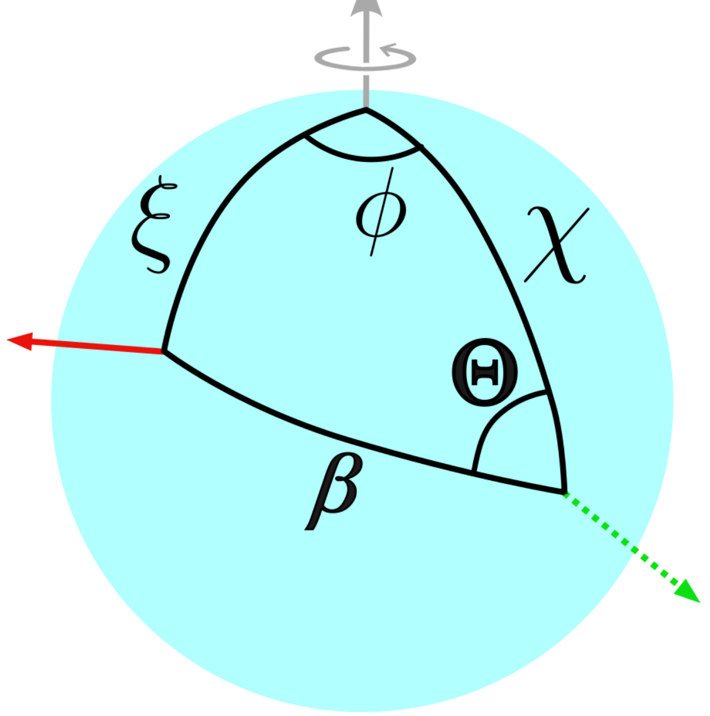
$$p_{a\to\gamma} \approx 1.5 \times 10^{-4} \left(\frac{g_{a\gamma\gamma}}{10^{-11}\ \mathrm{GeV}^{-1}}\right)^2 \left(\frac{1\ \mathrm{keV}}{\omega}\right)^{4/5} \left(\frac{B_0}{10^{13}\ \mathrm{G}}\right)^{2/5} \left(\frac{R_{\mathrm{NS}}}{10\ \mathrm{km}}\right)^{6/5} \sin^{2/5}\theta\,,$$

Conversion happens away from NS
Sensitive to dipole only

See also:
C. Dessert, D. Dunsky and B.R. Safdi, 2022; E. Gau, F. Hajkarim, S. P. Harris, P. S. B. Dev, J. F. Fortin, H. Krawczynski and K. Sinha, 2023

Geometry of the System





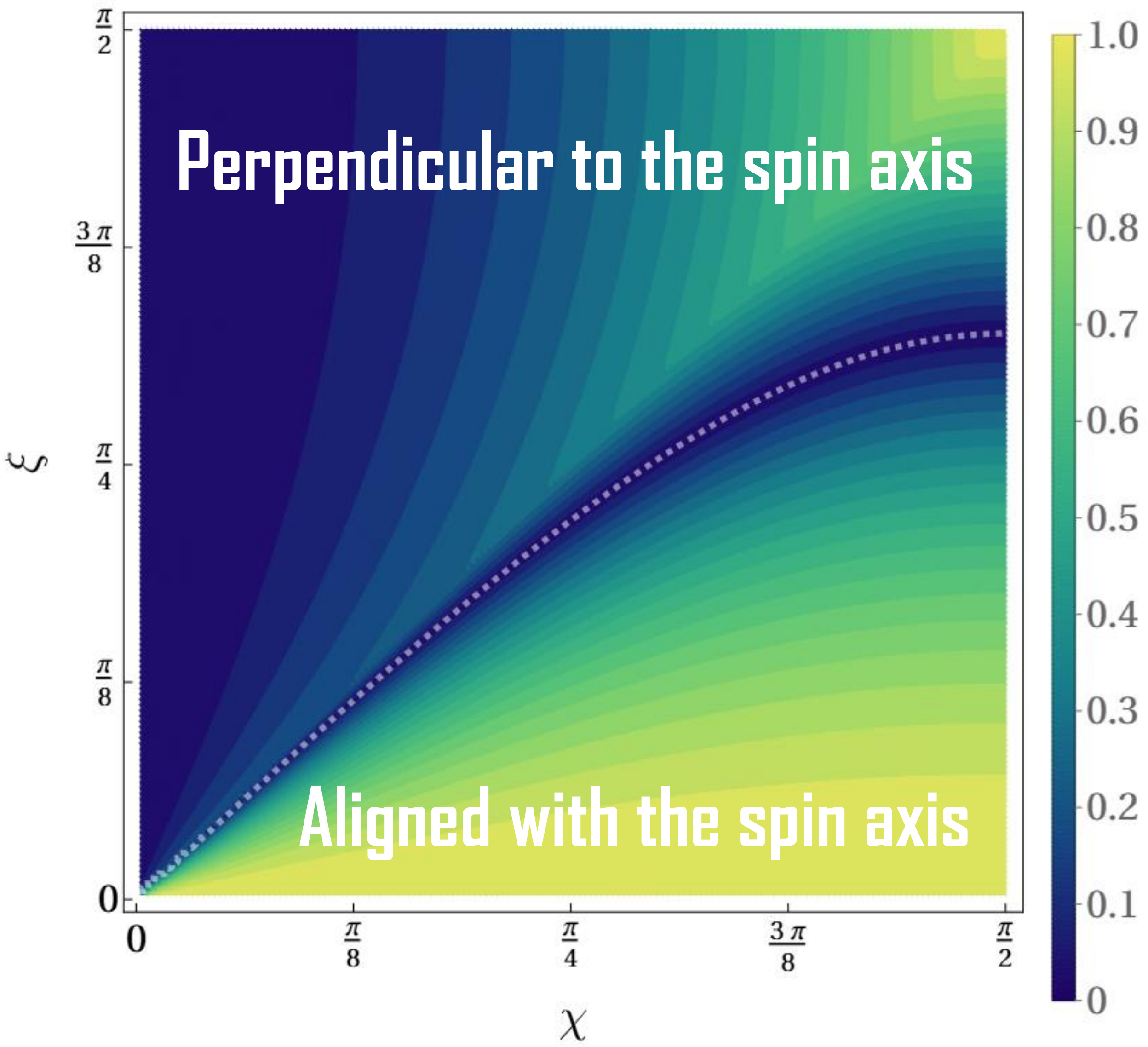
$$\cos\beta = \cos\xi\cos\chi + \sin\xi\sin\chi\cos\phi$$

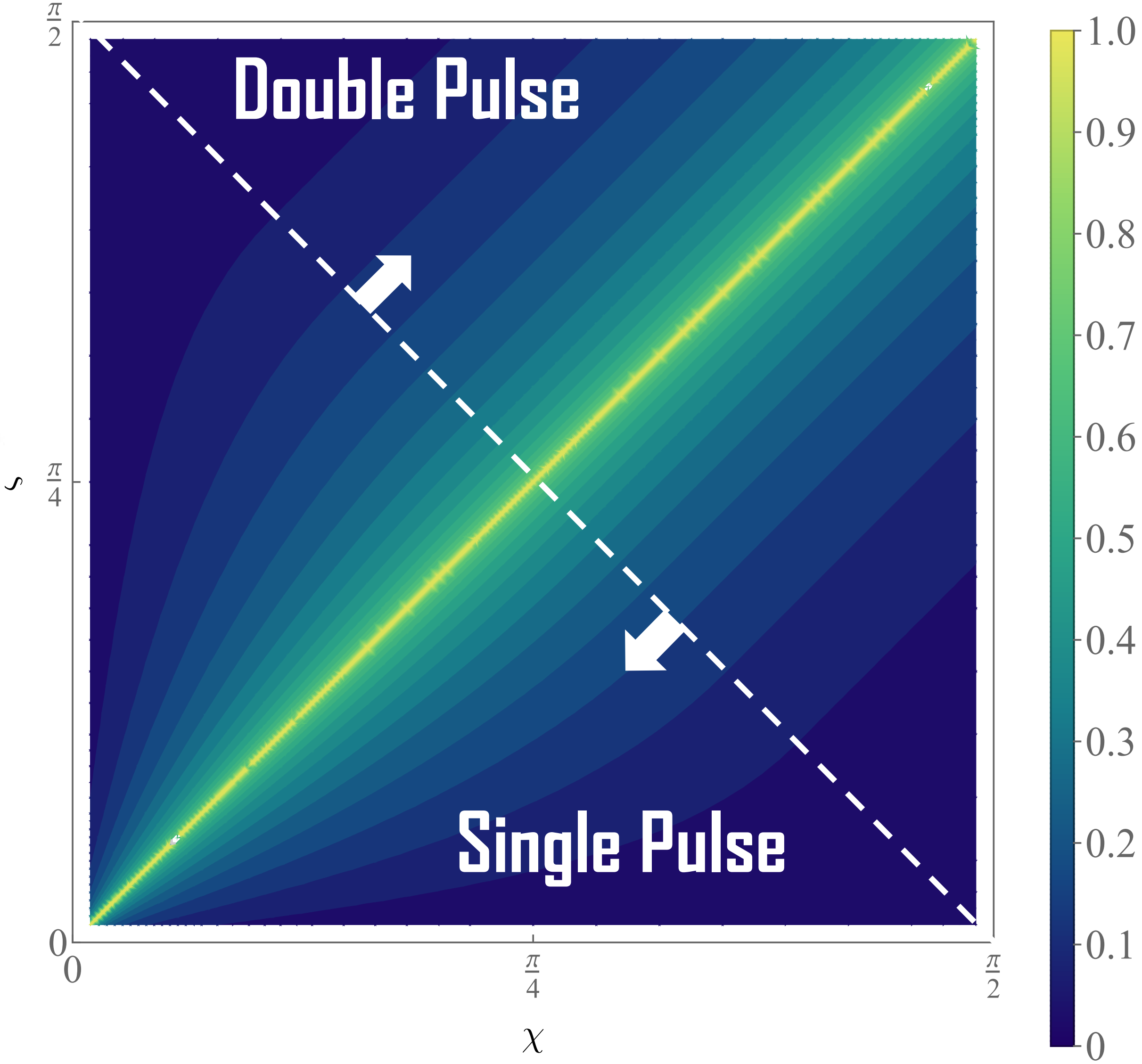
$$\tan\Theta = \frac{\sin\phi\sin\xi}{\cos\chi\sin\xi\cos\phi - \sin\chi\cos\xi}$$

$$\begin{aligned} P_{a\to\gamma} &\propto (B_0\sin\theta)^{2/5} \\ &\propto \sin\beta^{2/5} \\ &= [1-(\cos\xi\cos\chi+\sin\xi\sin\chi\cos\phi)^2]^{1/5} \end{aligned}$$

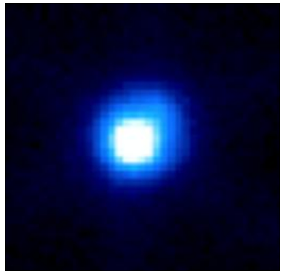
β gives pulse, Θ determines polarization

Pulse and Polarization Structure

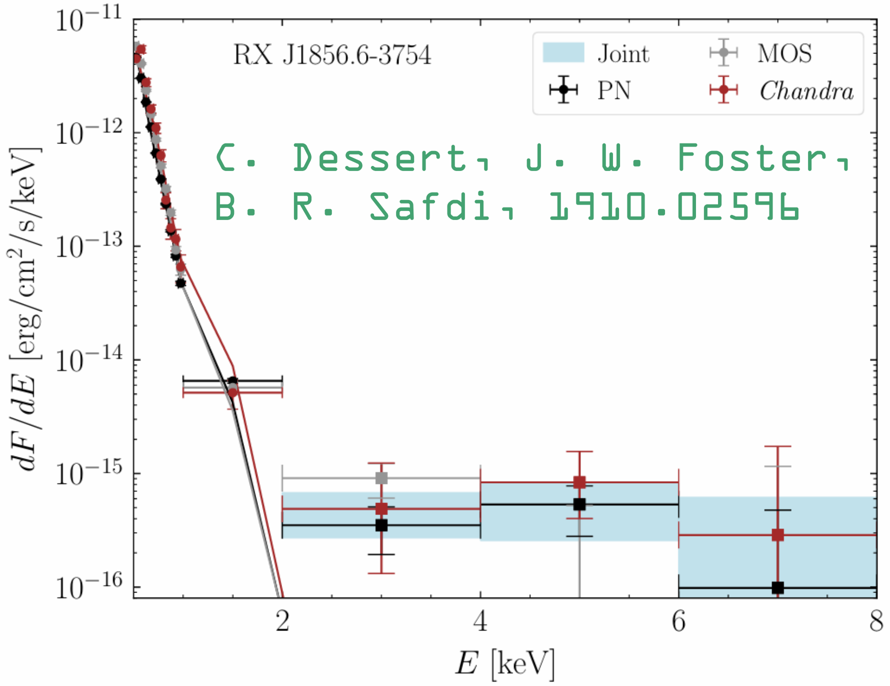




Hard X-ray Excess in RX J1856.6-3745

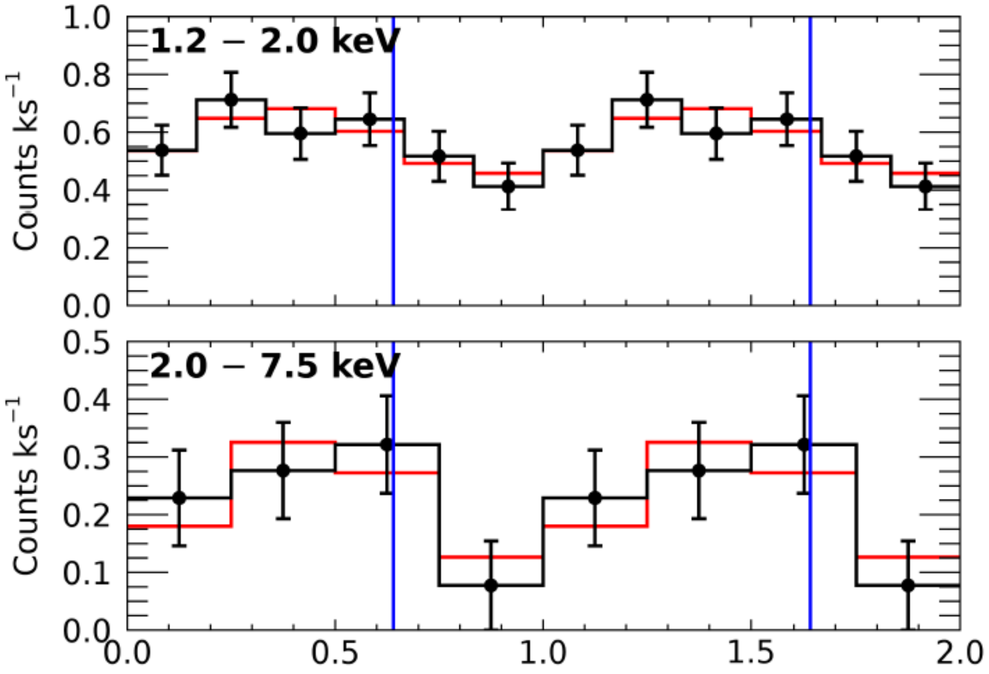


- Discovered in 1992
- One of the closest NS (~123 pc from us)



C. Dessert, J. W. Foster, B. R. Safdi, 1910.02596

Pulse fraction goes up to ~50% at higher energies

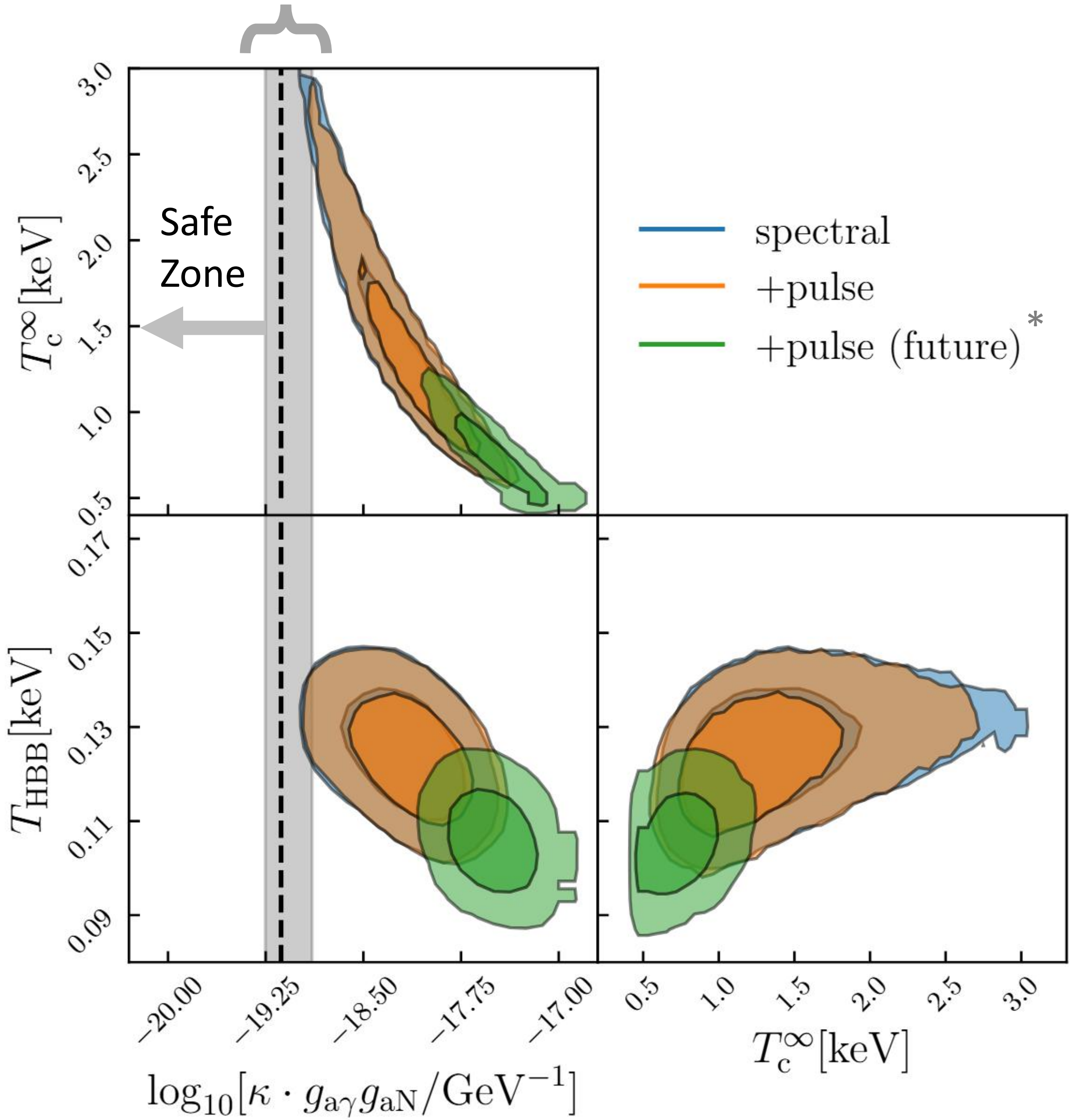


Observed in both XMM-Newton and Chandra, accumulated ~5σ excess

D. De Grandis, M. Rigoselli, S. Mereghetti, G. Younes, P. Pizzochero, R. Taverna, A. Tiengo, Rturolla, and S. Zane, 2022

Fit Result

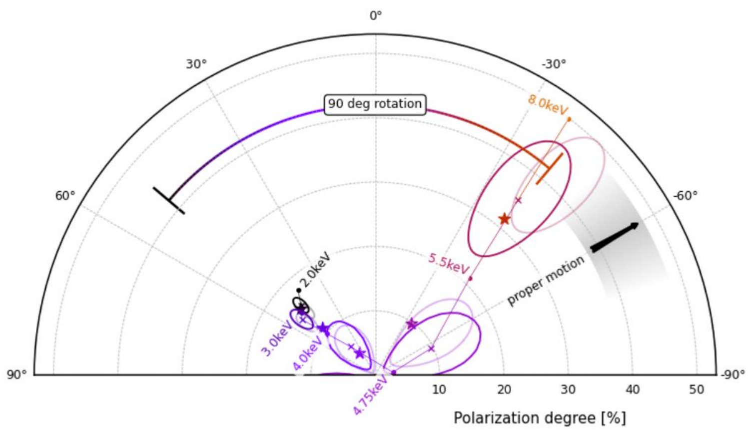
Systematic Uncertainties!

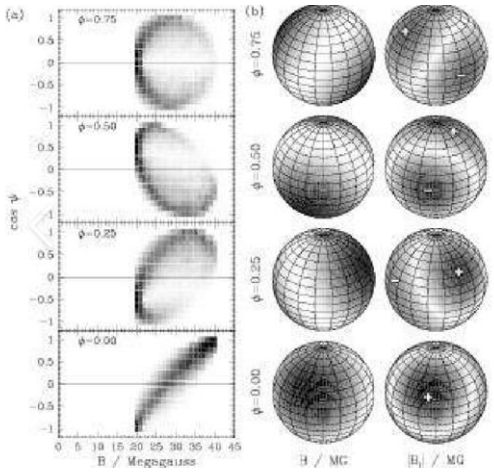


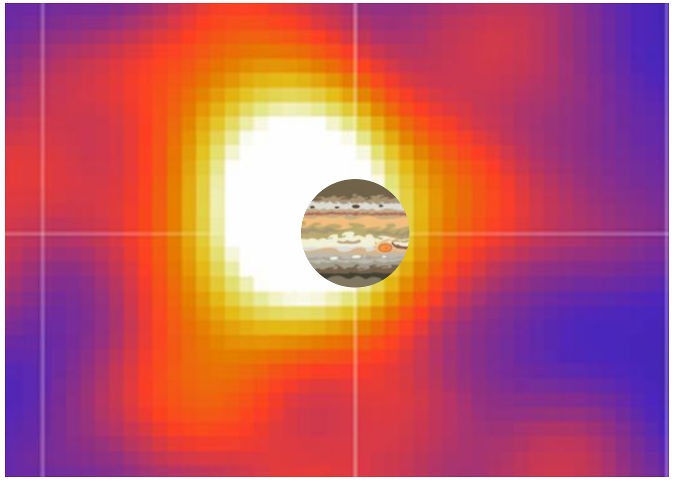
Future observations could constrain ALP parameter space efficiently

	$\mathrm{Log}(g \cdot g)$	T_c^∞ [keV]	T_{HBB}^∞ [keV]	ξ	χ
$\mathcal{Q}_1$	$-18.25^{+0.29}_{-0.33}$	$1.30^{+0.52}_{-0.32}$	$0.12^{+0.01}_{-0.01}$	$0.79^{+0.52}_{-0.53}$	$0.79^{+0.54}_{-0.53}$
$\mathcal{Q}_2$	$-18.19^{+0.28}_{-0.33}$	$1.26^{+0.50}_{-0.31}$	$0.12^{+0.01}_{-0.01}$	$0.72^{+0.46}_{-0.41}$	$0.73^{+0.46}_{-0.42}$
$\mathcal{Q}_3$	$-17.59^{+0.22}_{-0.22}$	$0.76^{+0.19}_{-0.15}$	$0.11^{+0.01}_{-0.01}$	$0.42^{+0.24}_{-0.20}$	$0.41^{+0.23}_{-0.20}$

What’s Next?







Magnetars

- ❑ Bright sources with abundant observations
- ❑ Interesting pulse-polarization pattern observed
- ❑ Significant systematic uncertainties

Magnetic White Dwarfs

- ❑ Lower systematic uncertainty
- ❑ Very different magnetic field and internal production

- ❑ **Jupiter (?!)**
- ❑ Not about ALP this time
- ❑ X-ray diffuse emission observed
- ❑ Need to predict the polarization property