

STRUCTURE OF ALP CONVERSION AT NEUTRON STARS

Polarization & Pulsation

Lingfeng Li

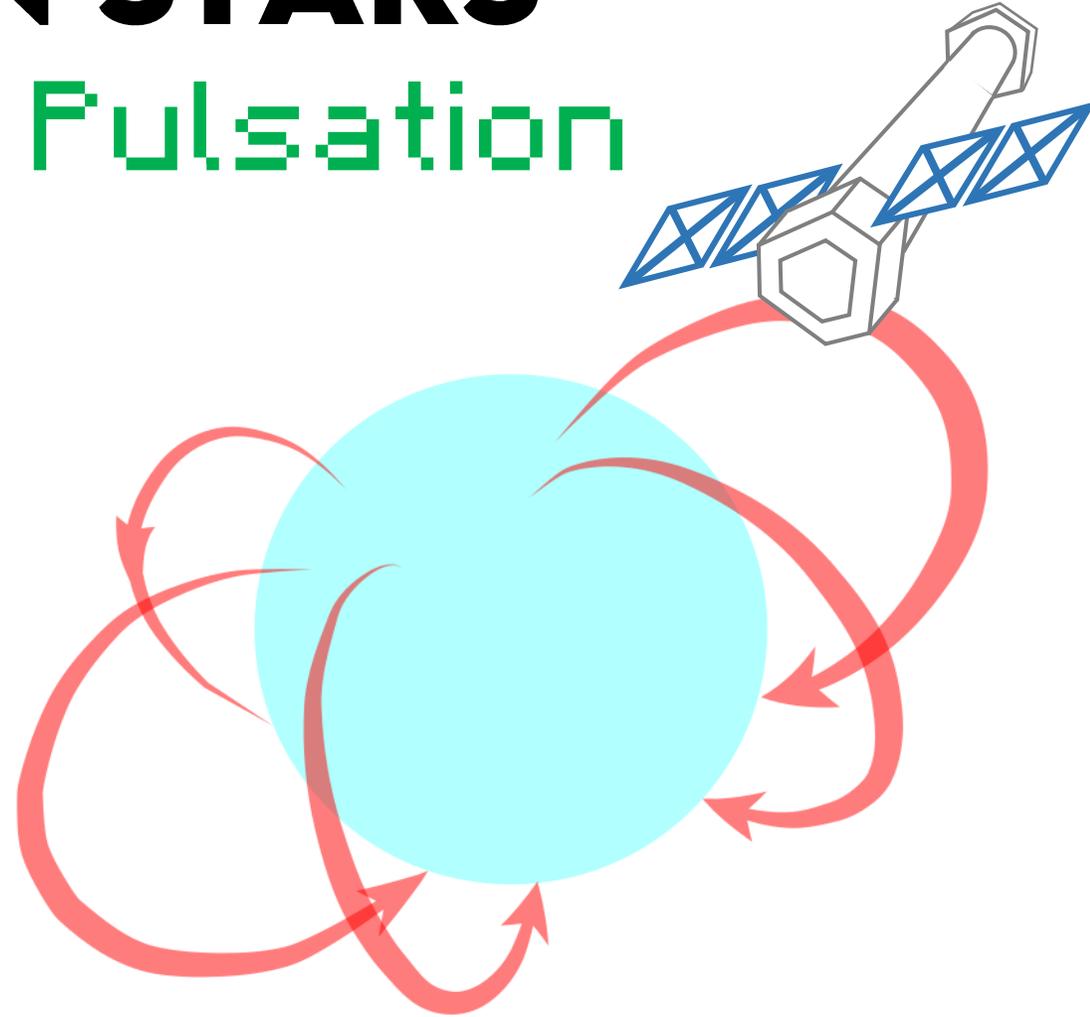
李凌风



arXiv:2501.12440

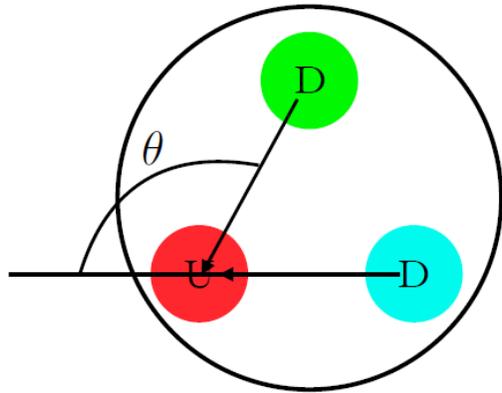
Ji Ji Fan, LFL, Chen Sun

PRL 135 (2025), 231801



PQ Symmetry and QCD Axion

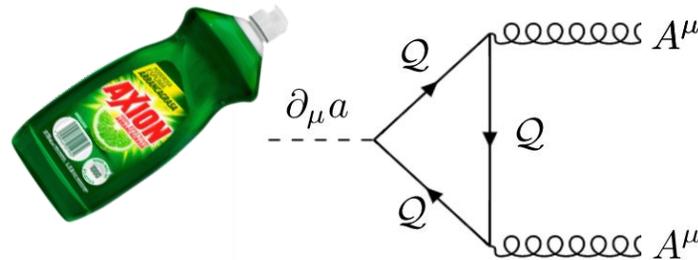
The extreme fine-tuning indicates the strong CP problem



$$\mathcal{L} \supset \theta \frac{g^2}{32\pi^2} G\tilde{G}$$

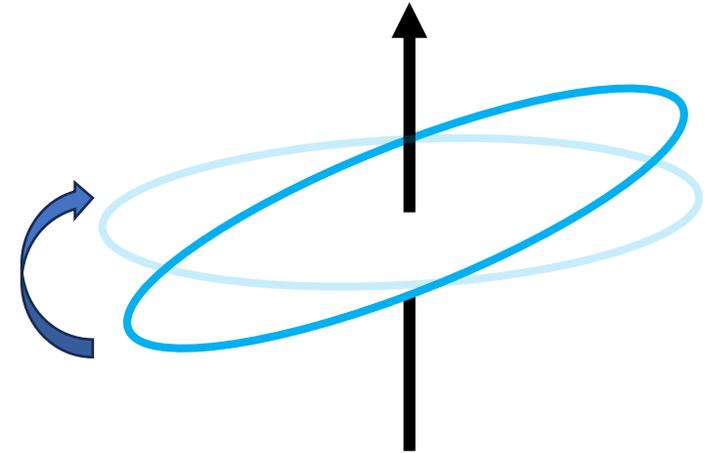
Experimental hints: neutron EDM
 Experimental result $\lesssim 10^{-26}$ e cm,
 $\theta \lesssim 10^{-10}$

QCD axion: A pseudo Nambu-Goldstone Boson (pNGB) of a the Peccei-Quinn symmetry



$$\mathcal{L} \supset \left(\frac{a}{f_a} + \theta \right) \frac{1}{32\pi^2} G\tilde{G}$$

Greater than $\sim 10^9$ GeV from data
 Suppressed interaction with SM



The strong CP θ angle are set to zero at the minima during the current universe

Peccei, Quinn; Weinberg;
 Wilczek; Kim; Shifman,
 Vainshtein, Zakharov;
 Zhitnitsky; Dine, Fischler,
 Srednicki, 1977-1981

The axion-like particle (ALP)

- Motivated by other theories in the UV (e.g. the string axiverse picture)

EFT coupling with the photon field

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

EFT coupling with the SM fermion (nucleon)

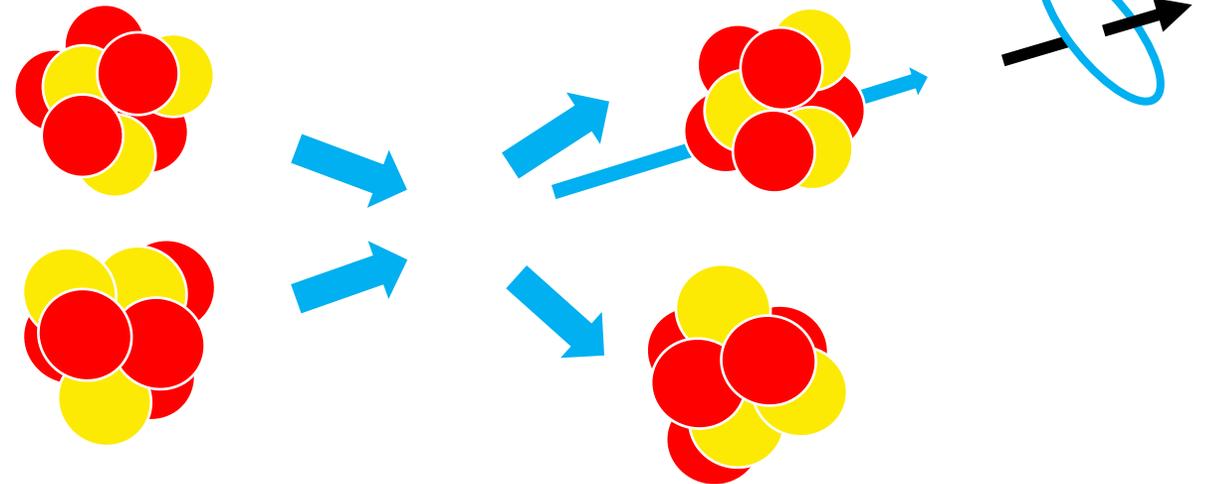
- Can be good wave-like DM candidate, either from misalignment or the decay of topological defects

Neutron Star(NS) as an ALP Source

The hot, dense core ($T \sim \text{keV}$) of NS could generate ALP through multiple mechanisms

- Nucleon scattering/emission processes
- Cooper pair-breaking-formation
-

$> 10^{30}$
ALP/s (?)

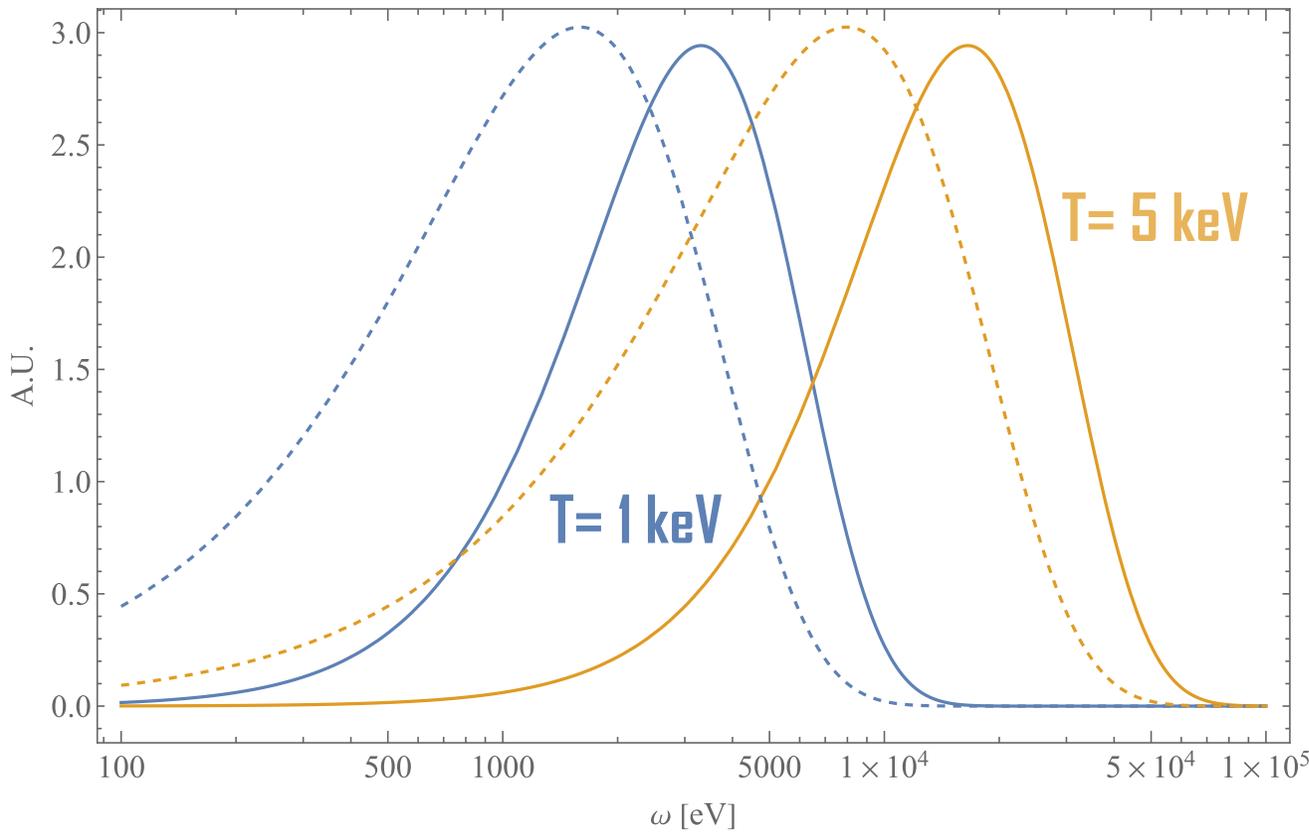


G. Raffelt, 1996; D. Yakovlev, K. Levenfish and Y. Shibano, 1999;
J. Keller and A. Sedrakian, 2012; A. Sedrakian, 2015; B.J. F.
Fortin, H. K. Guo, S.P. Harris, D. Kim, K. Sinha and C. Sun, 2021;

Production Rate

The axion production rate & spectrum

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

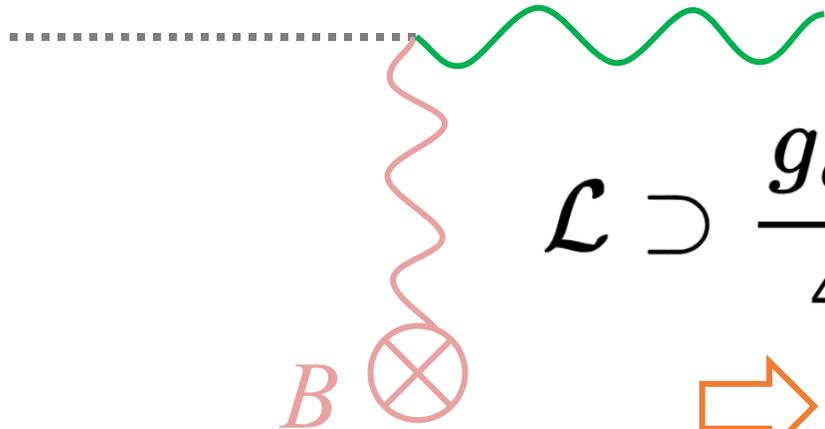


Significantly harder than a thermal (black body) component of the same temperature

ALP Conversion in Strong Magnetic Fields

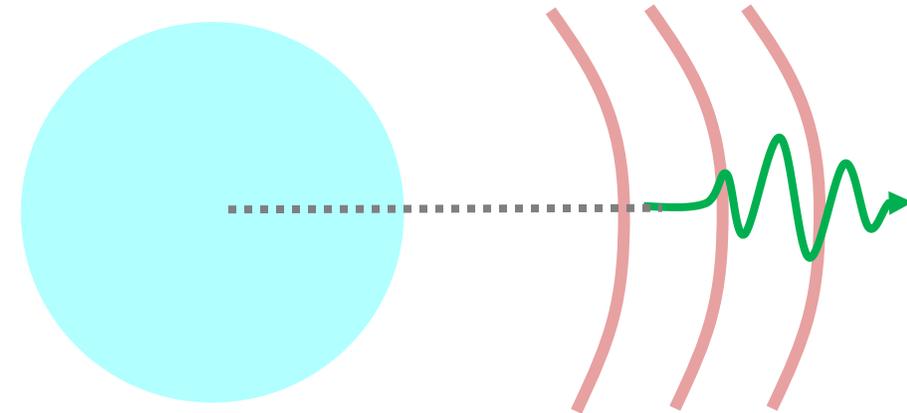
G. Raffelt and L. Stodolsky, 1988
D. Lai and J. Heyl, 2006;

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



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

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



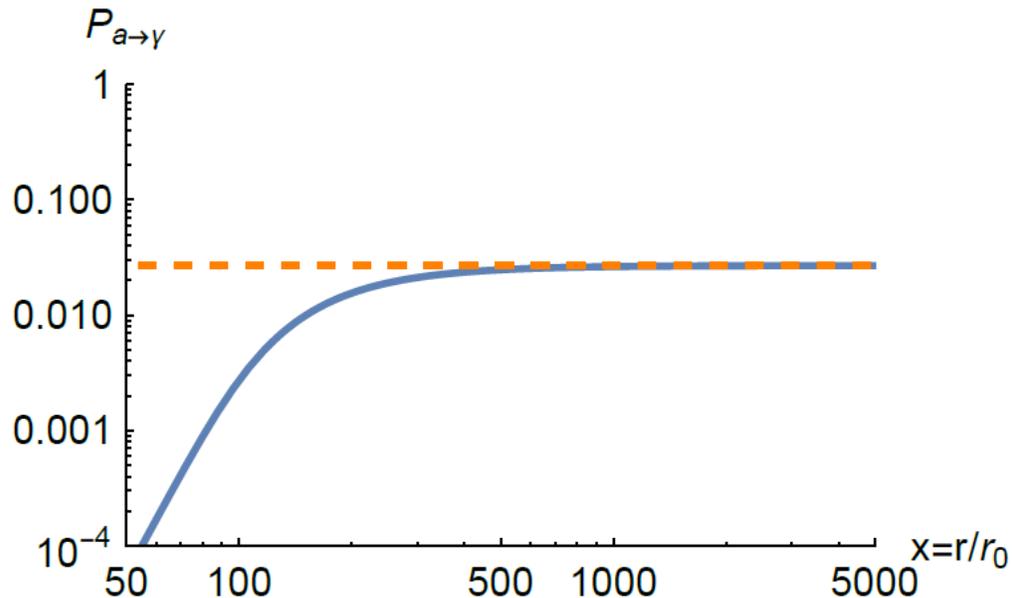
- The mixing matrix between axion, the O- and X-modes:

$$i \frac{d}{dx} \begin{pmatrix} a \\ E_{\parallel} \\ E_{\perp} \end{pmatrix} = \begin{pmatrix} \omega R + \Delta_a R & \Delta_M R & 0 \\ \Delta_M R & \omega R + \Delta_{\parallel} R & 0 \\ 0 & 0 & \omega R + \Delta_{\perp} R \end{pmatrix} \begin{pmatrix} a \\ E_{\parallel} \\ E_{\perp} \end{pmatrix}$$

ALP Conversion in Strong Magnetic Fields (II)

Near the NS, where the B field is extreme,
Mixing **only** happens far from the surface

$$\frac{r_{\text{con}}}{r_0} = 85 \left(\frac{\omega}{3 \text{ keV}} \right)^{\frac{1}{5}} \left(\frac{B_0}{10^{13} \text{ G}} \right)^{\frac{2}{5}} \left(\frac{r_0}{12 \text{ km}} \right)^{\frac{1}{5}} (\sin \theta)^{\frac{2}{5}}$$



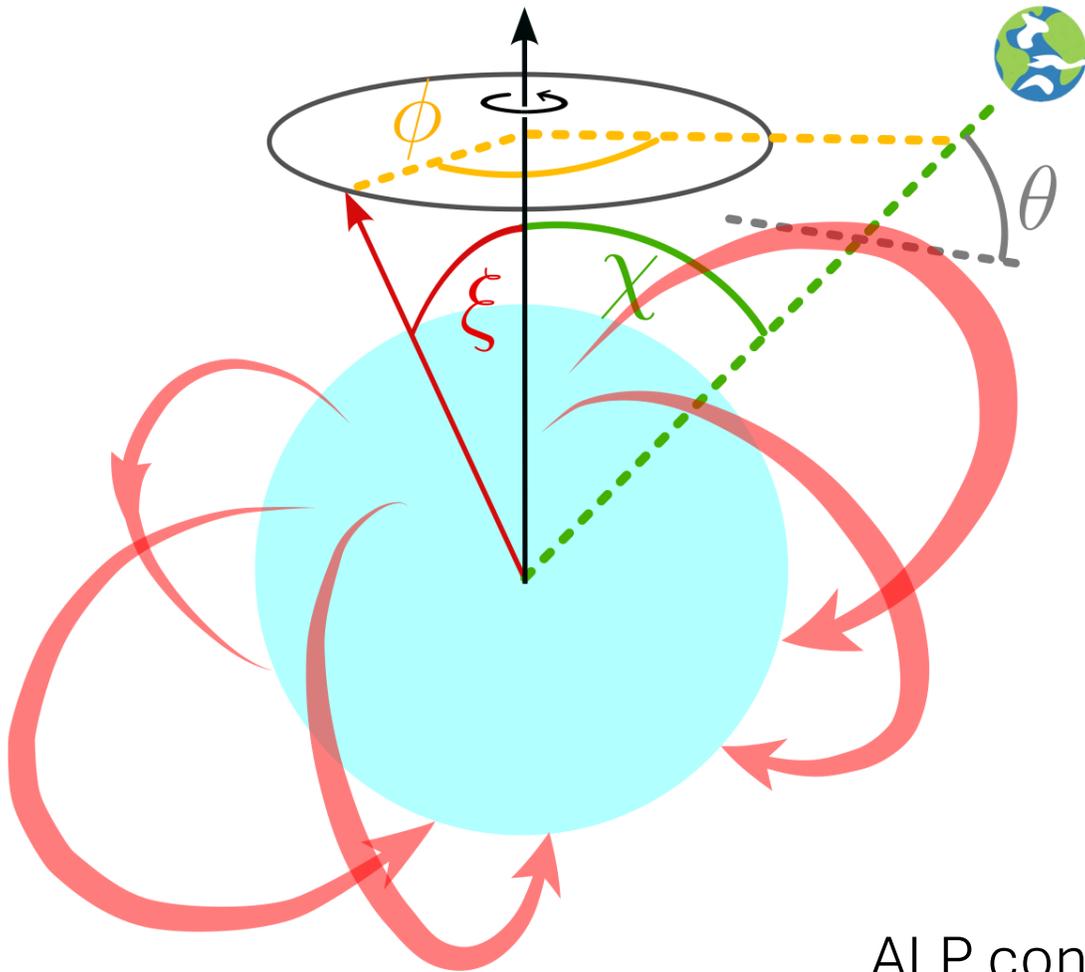
$$p_{a \rightarrow \gamma} \approx 1.5 \times 10^{-4} \left(\frac{g_{a\gamma\gamma}}{10^{-11} \text{ GeV}^{-1}} \right)^2 \left(\frac{1 \text{ keV}}{\omega} \right)^{4/5} \left(\frac{B_0}{10^{13} \text{ G}} \right)^{2/5} \left(\frac{R_{\text{NS}}}{10 \text{ km}} \right)^{6/5} \sin^{2/5} \theta,$$

Robust against non-dipole and GR corrections

See also:

C. Dessert, D. Dunsy 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



- Our line of sight (LOS) doesn't align with the NS's spin axis, leaving a non-zero χ
- The magnetic dipole is also not guaranteed to align with the spin axis, giving another angle ξ
- The phase ϕ



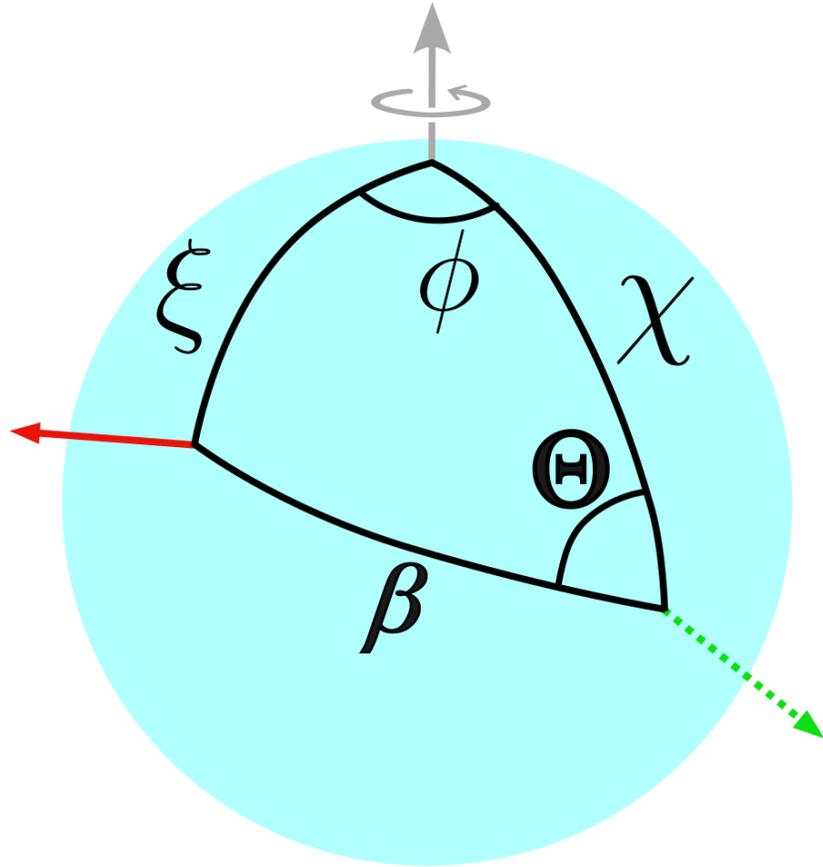
$$\xi \simeq 0.2$$

J. Fan, *LFL*, *JHEP* 10, 186 (2022);
S. Yan, *LFL*, J. Fan, *JHEP* 06,
028 (2024); P. Singh, S. Yan, I.
Allalil, *LFL*, J. Fan, *JCAP* 09,
019, (2024)

ALP conversion always gives the O mode, but the O mode needs to be defined “locally”

Spherical Trigonometry

The conversion only depend on the LOS angle relative to the dipole (β)



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

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

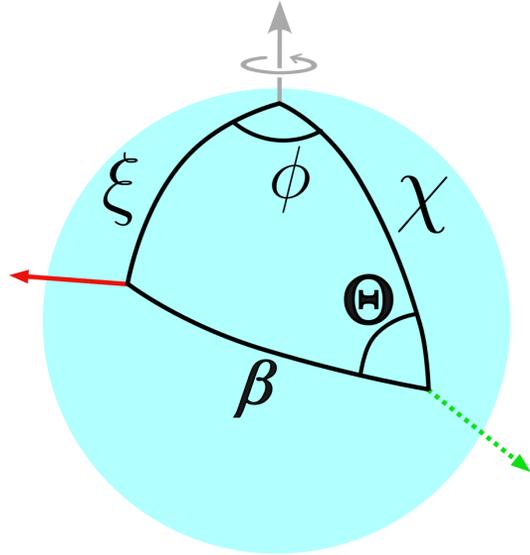
Modulated intensity: the pulse

$$P_{a \rightarrow \gamma} \propto (B_0 \sin \theta)^{2/5}$$

$$\propto \sin \beta^{2/5}$$

$$= [1 - (\cos \xi \cos \chi + \sin \xi \sin \chi \cos \phi)^2]^{1/5}$$

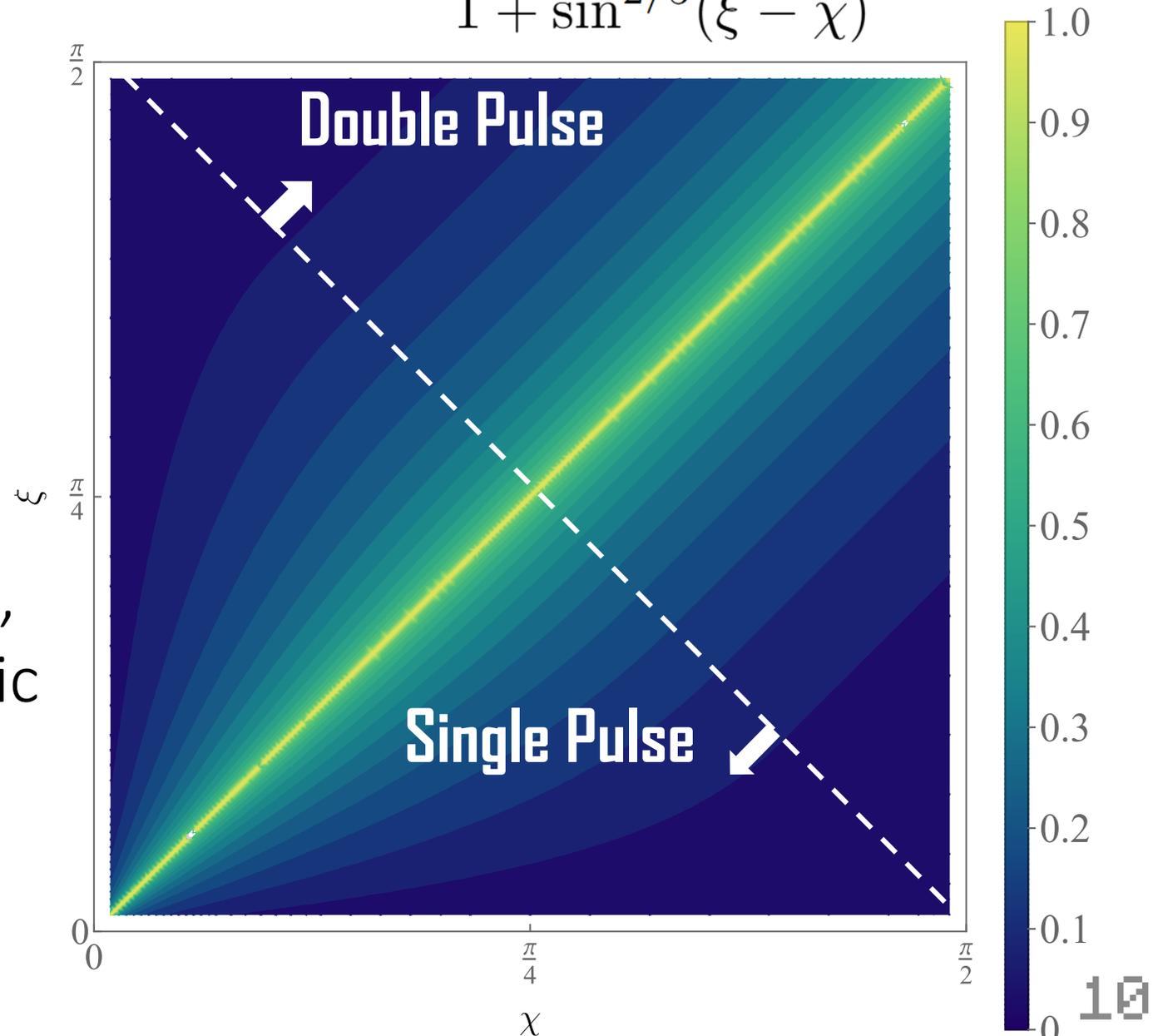
Pulse Fraction



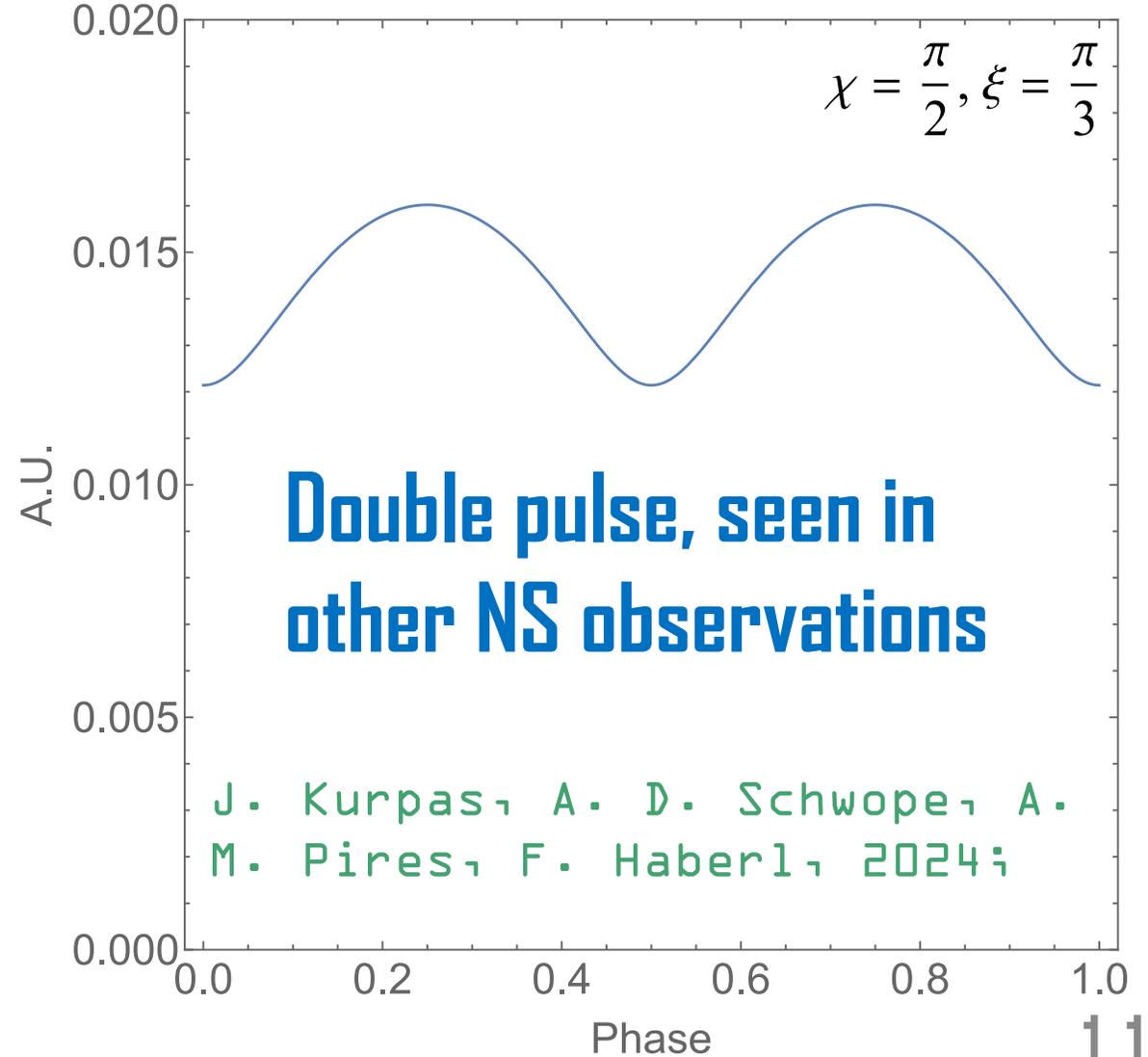
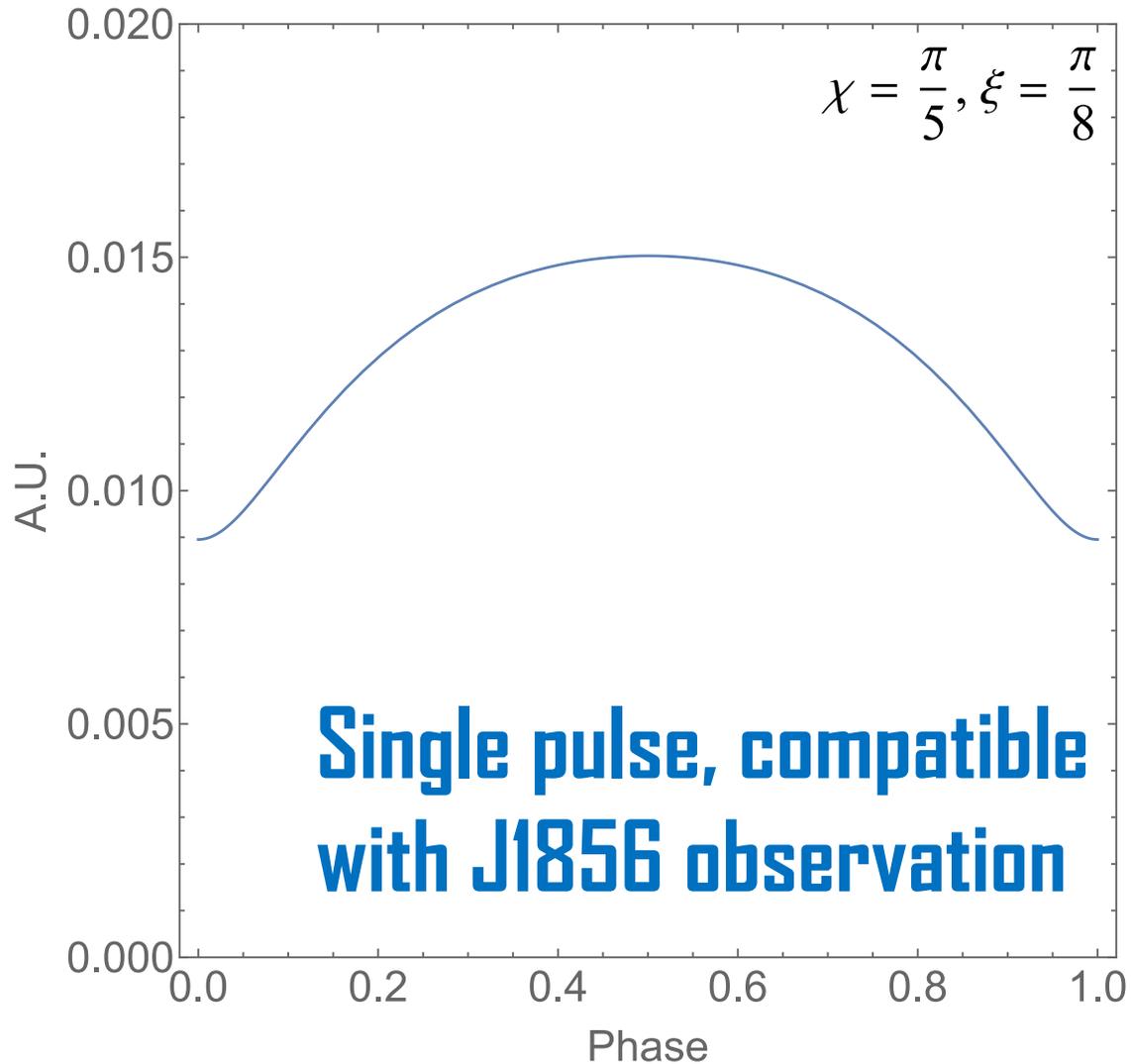
- Without polarization probes, the two angles are symmetric under exchange

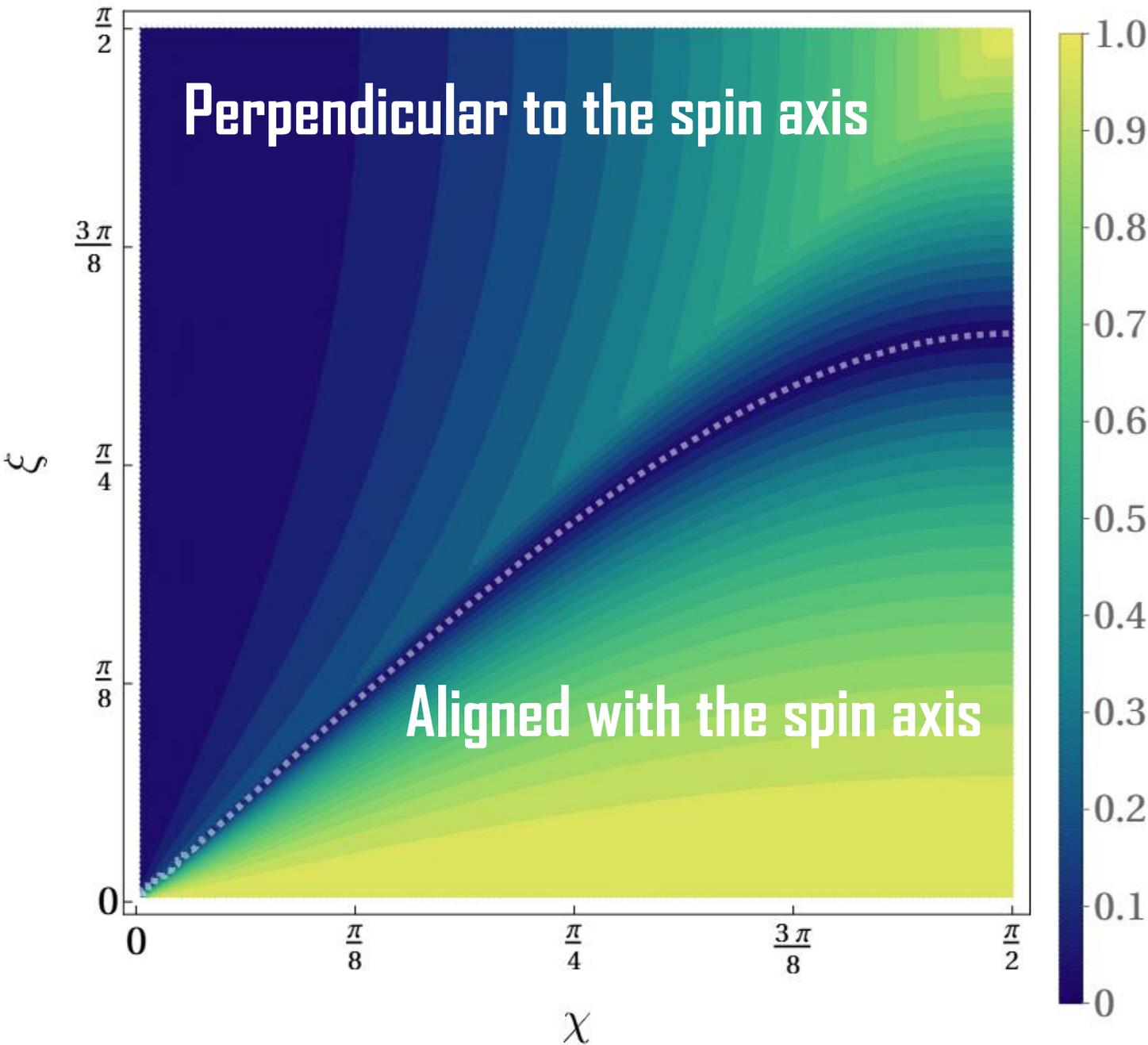
$$\text{PF} = \frac{\sin^{2/5}(\xi + \chi) - \sin^{2/5}(\xi - \chi)}{\sin^{2/5}(\xi + \chi) + \sin^{2/5}(\xi - \chi)}$$

$$\text{PF} = \frac{1 - \sin^{2/5}(\xi - \chi)}{1 + \sin^{2/5}(\xi - \chi)}$$



Theoretical Prediction





Phase-integrated Polarization

$$\begin{aligned}
 \text{PD} &= \frac{\sqrt{Q^2 + U^2}}{I} \\
 &= \left[\langle |\mathbf{A}|^2 \cos(2\Theta) \rangle^2 + \langle |\mathbf{A}|^2 \sin(2\Theta) \rangle^2 \right]^{1/2} / \langle |\mathbf{A}|^2 \rangle.
 \end{aligned}$$

Uniformly applied to NS conversions of light ALPs

- Energy independent
- ALP mass independent
- Magnetic field independent

X-ray (Must) in Space



eXTP



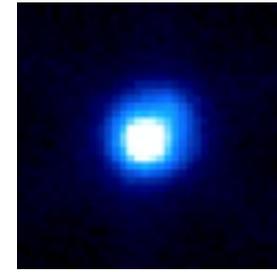
We hope so



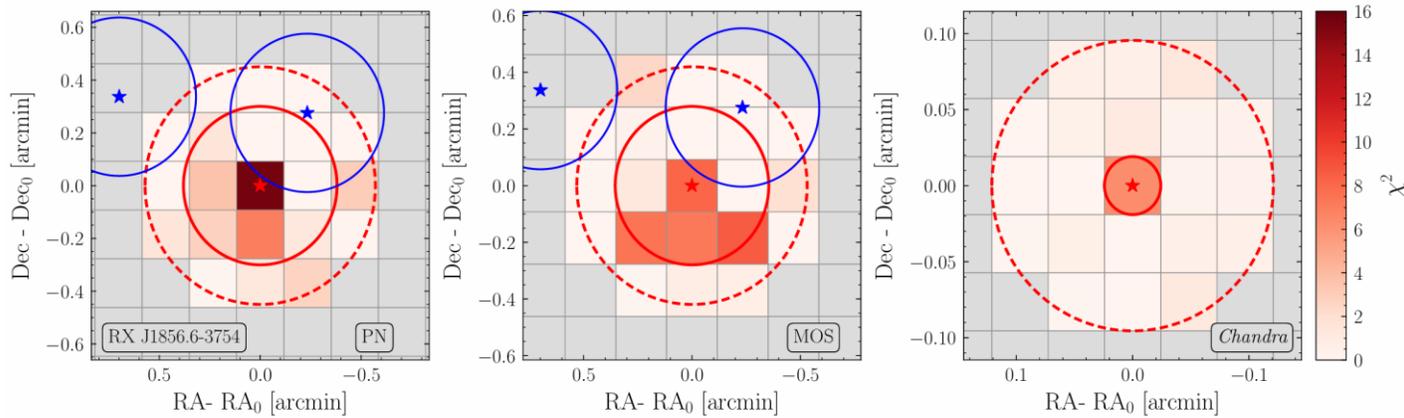
CATCH

In the future

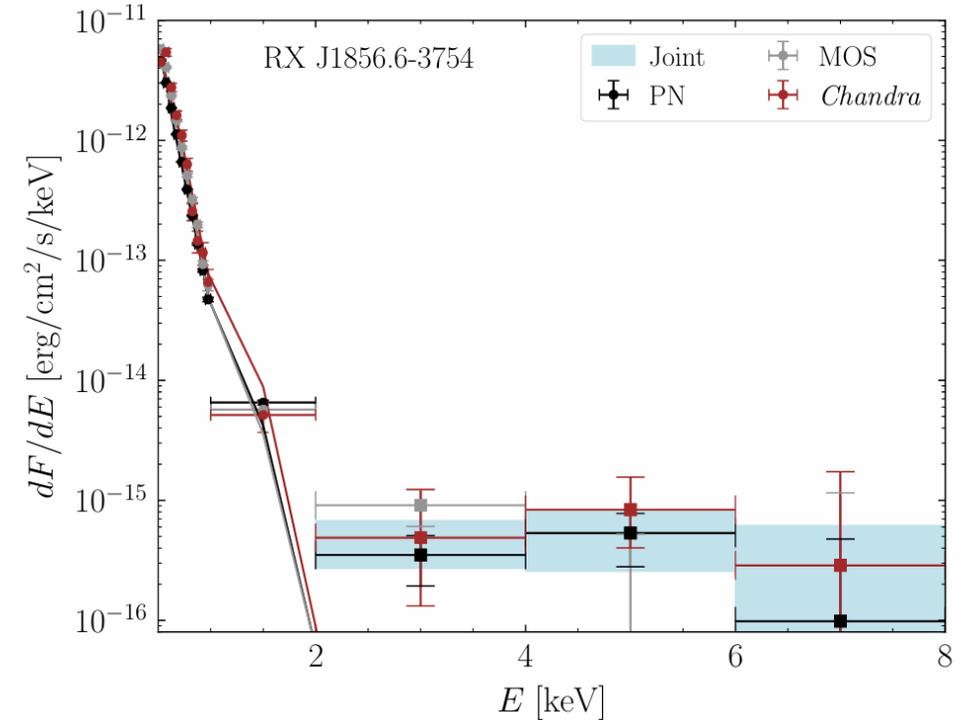
Hard X-ray Excess in RX J1856.6-3745



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



Observed in both XMM-Newton and Chandra, accumulated $\sim 5\sigma$ excess

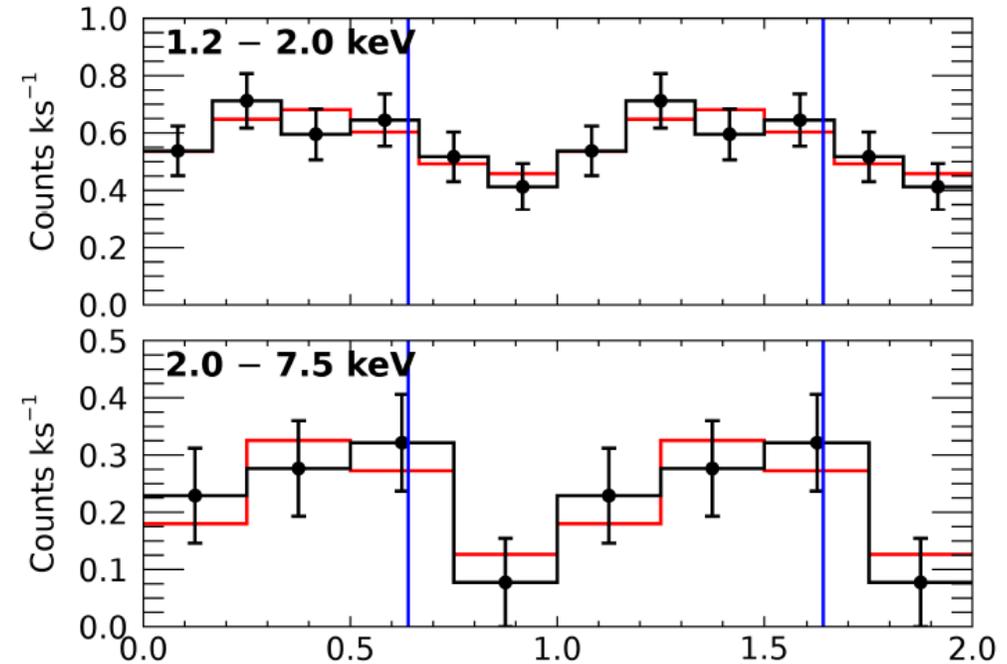
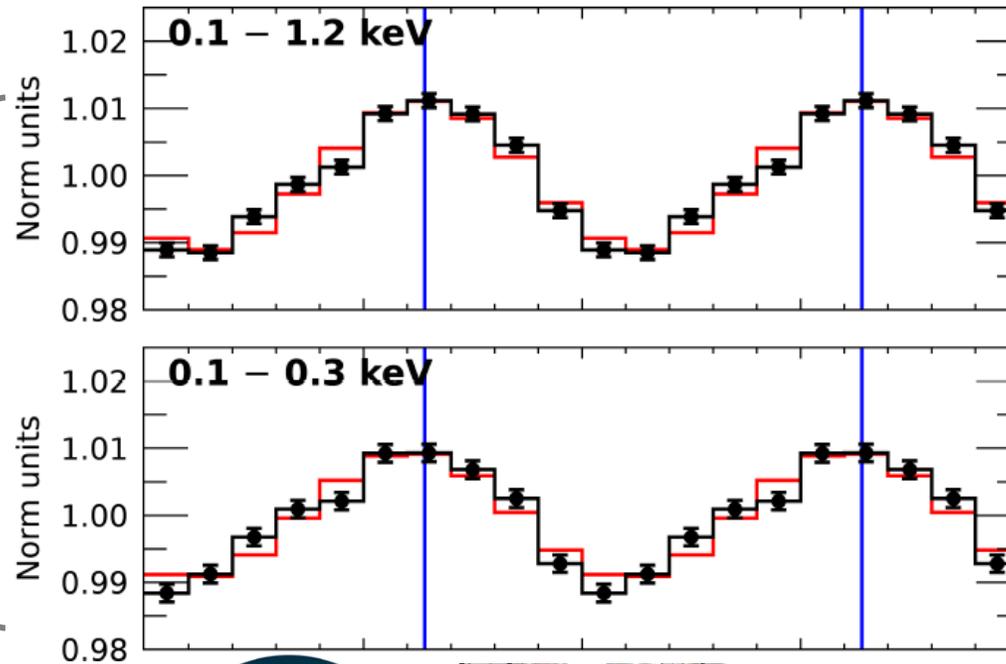


C. Dessert, J. W. Foster,
B. R. Safdi, 1910.02596

Pulse Structure, from XDINS RX-J1856.5-3754

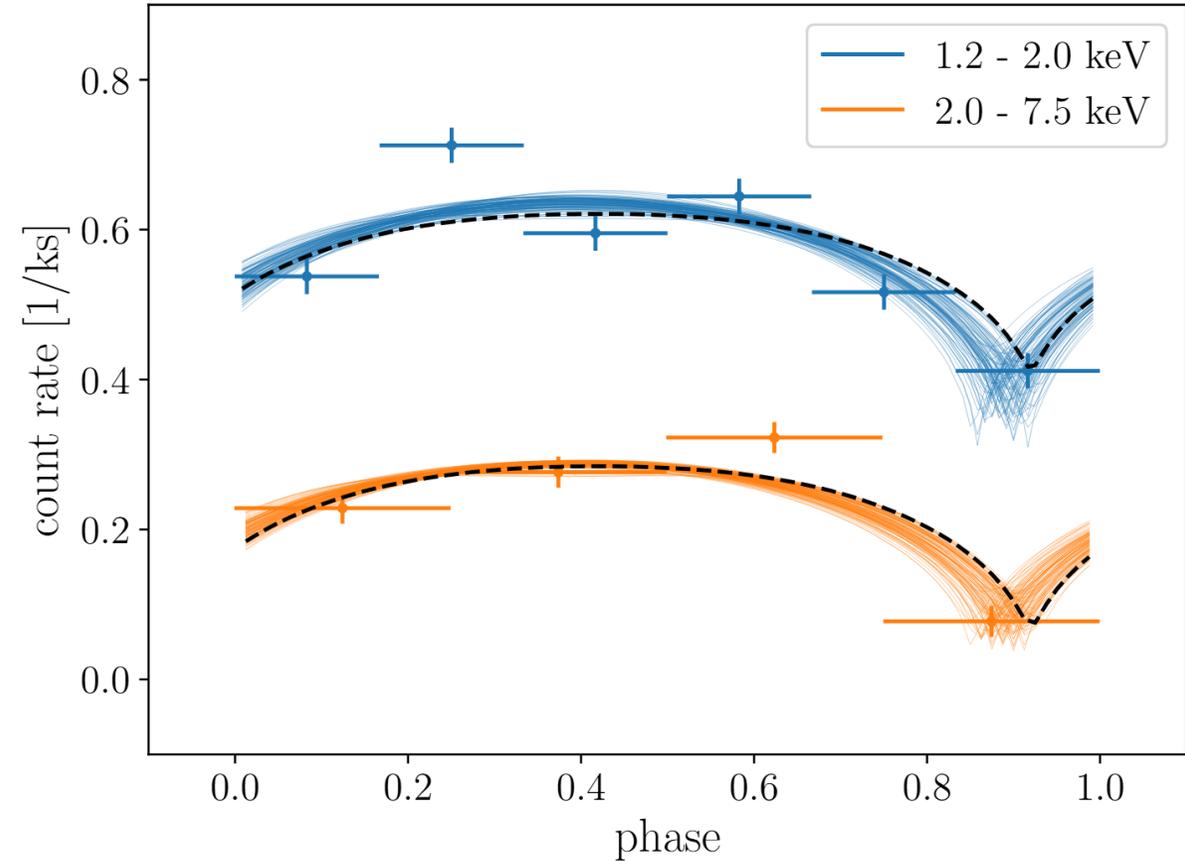
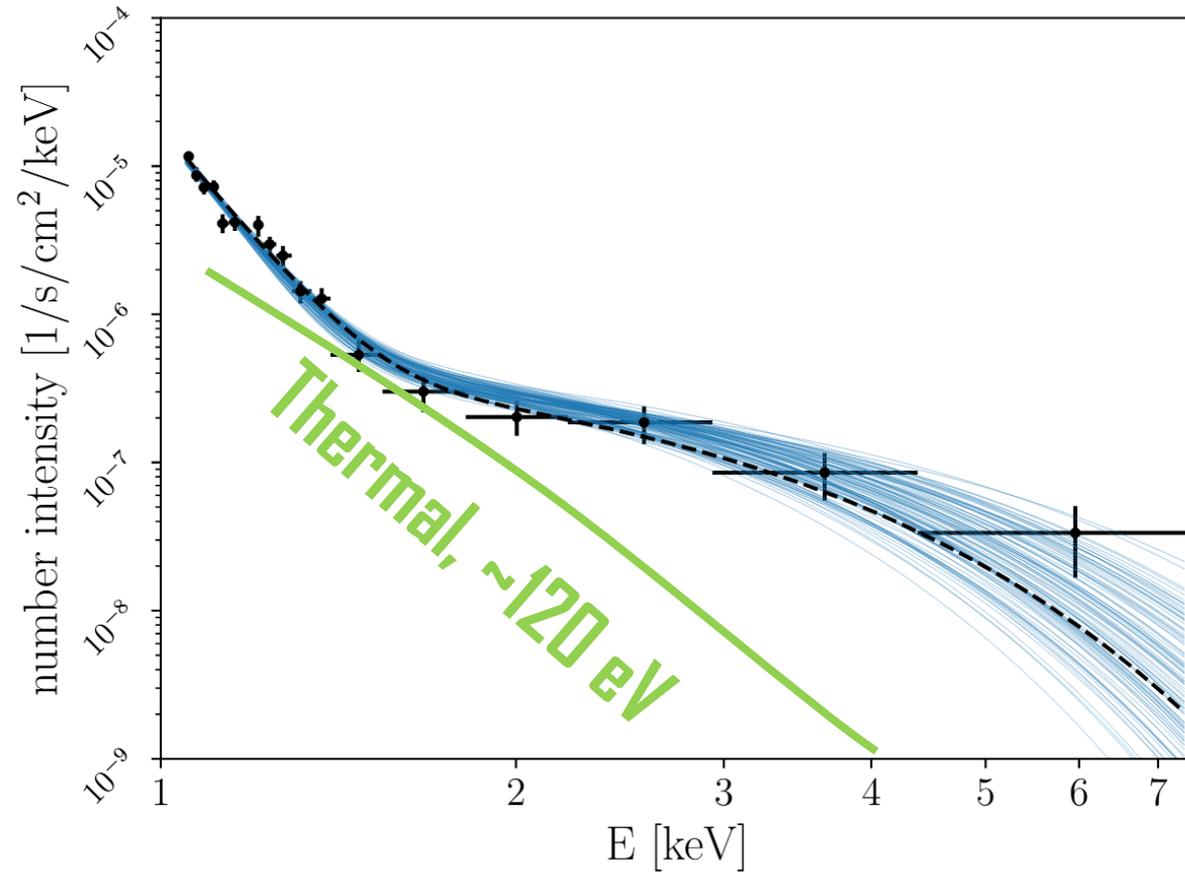
Pulse fraction goes up to
~50% at higher energies

1-2%
pulse
at low
energies



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

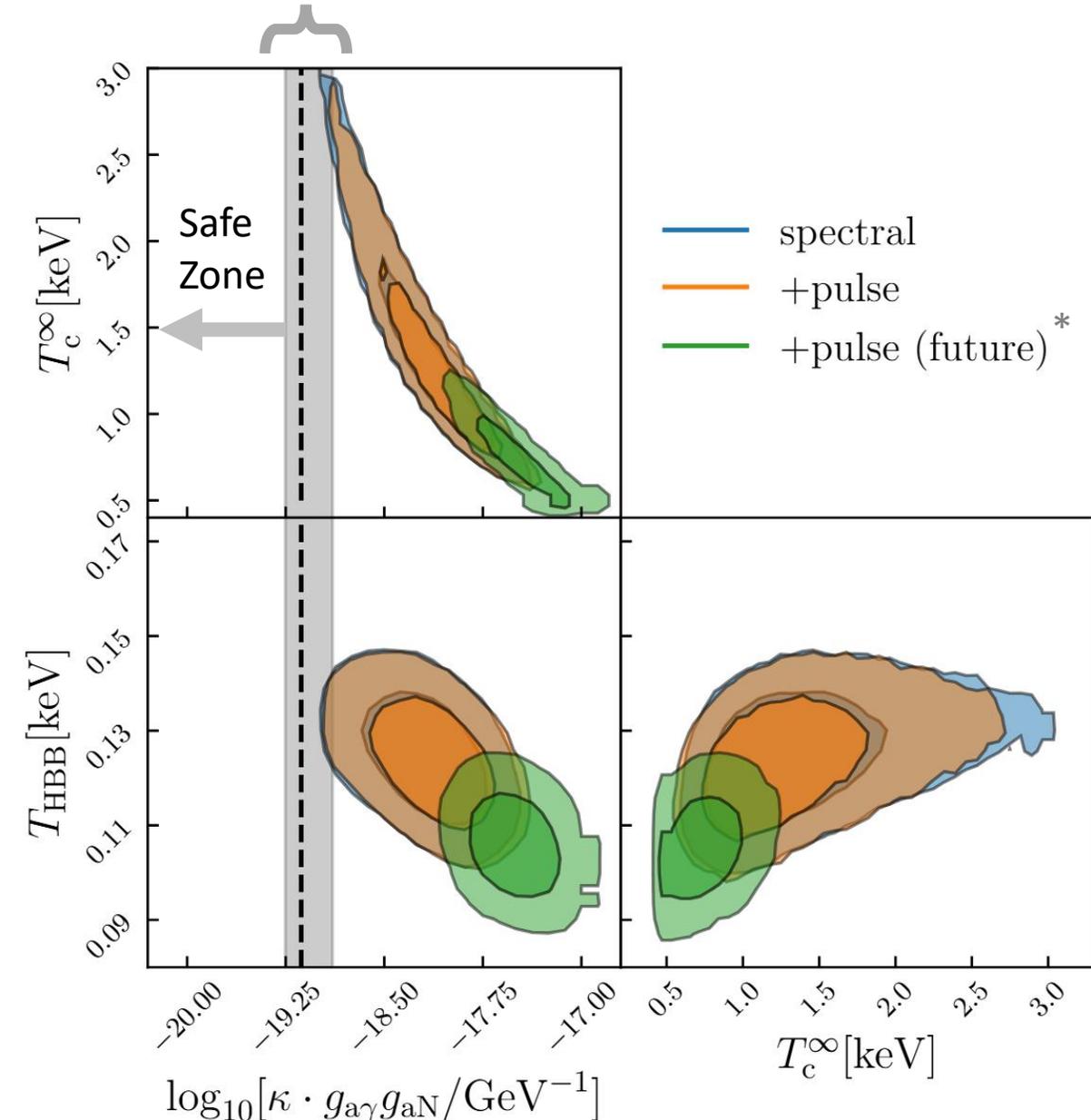
Limiting the Axion Param Space



Phase error bars shrunk to mimic potential progress

Systematic Uncertainties!

Fit Result



Systematic uncertainty mainly from the NS equation of states (EOS) and its unknown mass

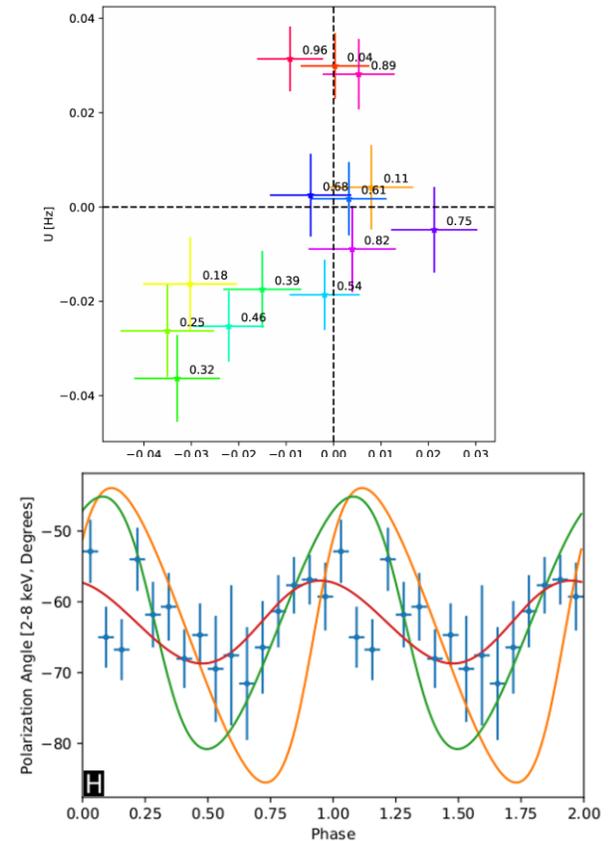
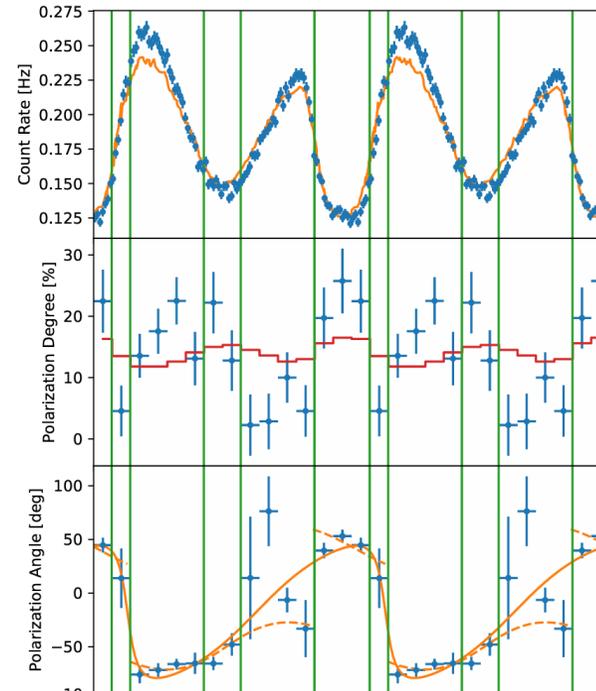
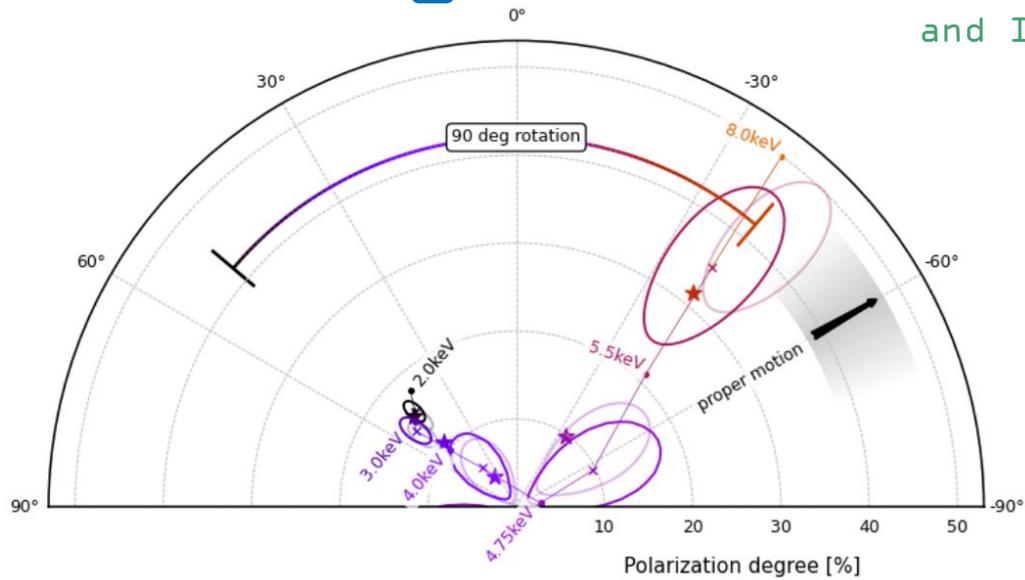
	$\text{Log}(g \cdot g)$	T_c^∞ [keV]	T_{HBB}^∞ [keV]	ξ	χ
Q_1	$-18.25^{+0.29}_{-0.33}$	$1.30^{+0.52}_{-0.32}$	$0.12^{+0.01}_{-0.01}$	$0.79^{+0.52}_{-0.53}$	$0.79^{+0.54}_{-0.53}$
Q_2	$-18.19^{+0.28}_{-0.33}$	$1.26^{+0.50}_{-0.31}$	$0.12^{+0.01}_{-0.01}$	$0.72^{+0.46}_{-0.41}$	$0.73^{+0.46}_{-0.42}$
Q_3	$-17.59^{+0.22}_{-0.22}$	$0.76^{+0.19}_{-0.15}$	$0.11^{+0.01}_{-0.01}$	$0.42^{+0.24}_{-0.20}$	$0.41^{+0.23}_{-0.20}$

* Future pulse is obtained by shrinking the current error bars by a factor of 4

Another Interesting Target

Magnetars

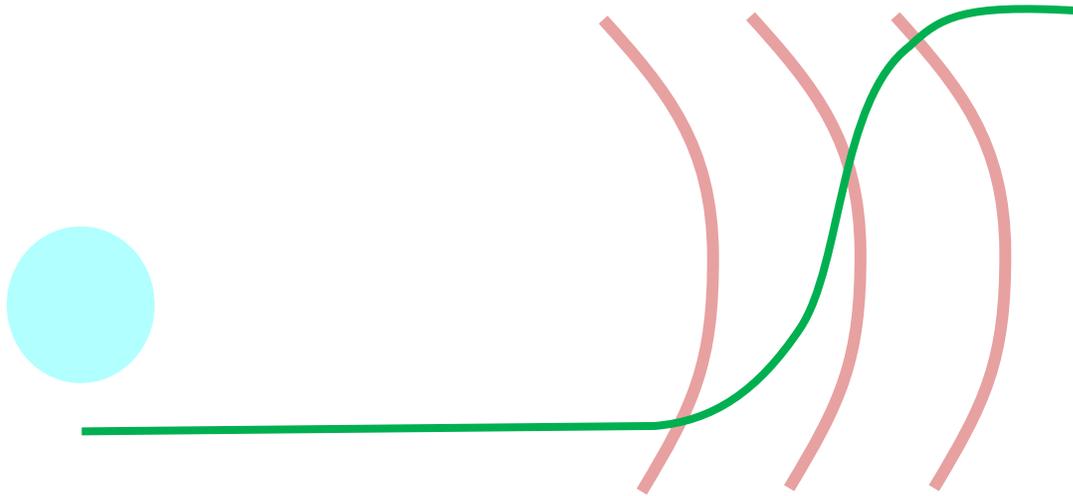
R. Taverna, R. Turolla, F. Muleri, J. Heyl, S. Zane, L. Baldini et al., 2022; S. Zane, R. Taverna, D. G. Caniulef, F. Muleri, R. Turolla, J. Heyl, K. Uchiyama, M. Ng, T. Tamagawa and I. Caiazzo et al., 2023



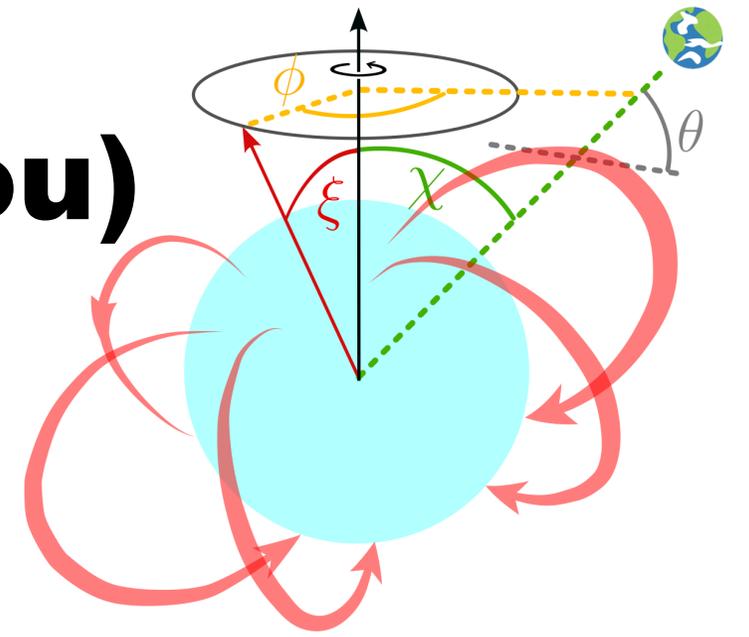
- ❑ Very bright sources, allowing to obtain structural information
- ❑ Significant astrophysical background

Summary (and Thank You)

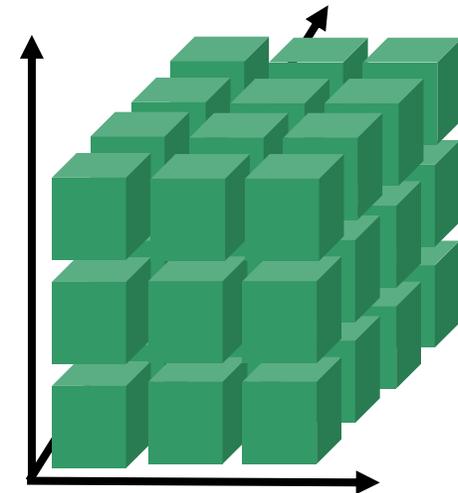
- Polarization and pulse structures naturally arises with moderate axial symmetry breaking



- Analyzing 3/4D info (energy, polarization, time) helps discriminate models and apply on other targets



- Geometric solution: insensitive to many corrections



Backup Slides

Why Neutron Star?

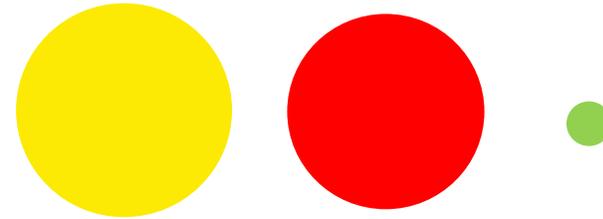


First discussed in public:
Lev Landau, 1932

First observation as radio pulsars in 1967

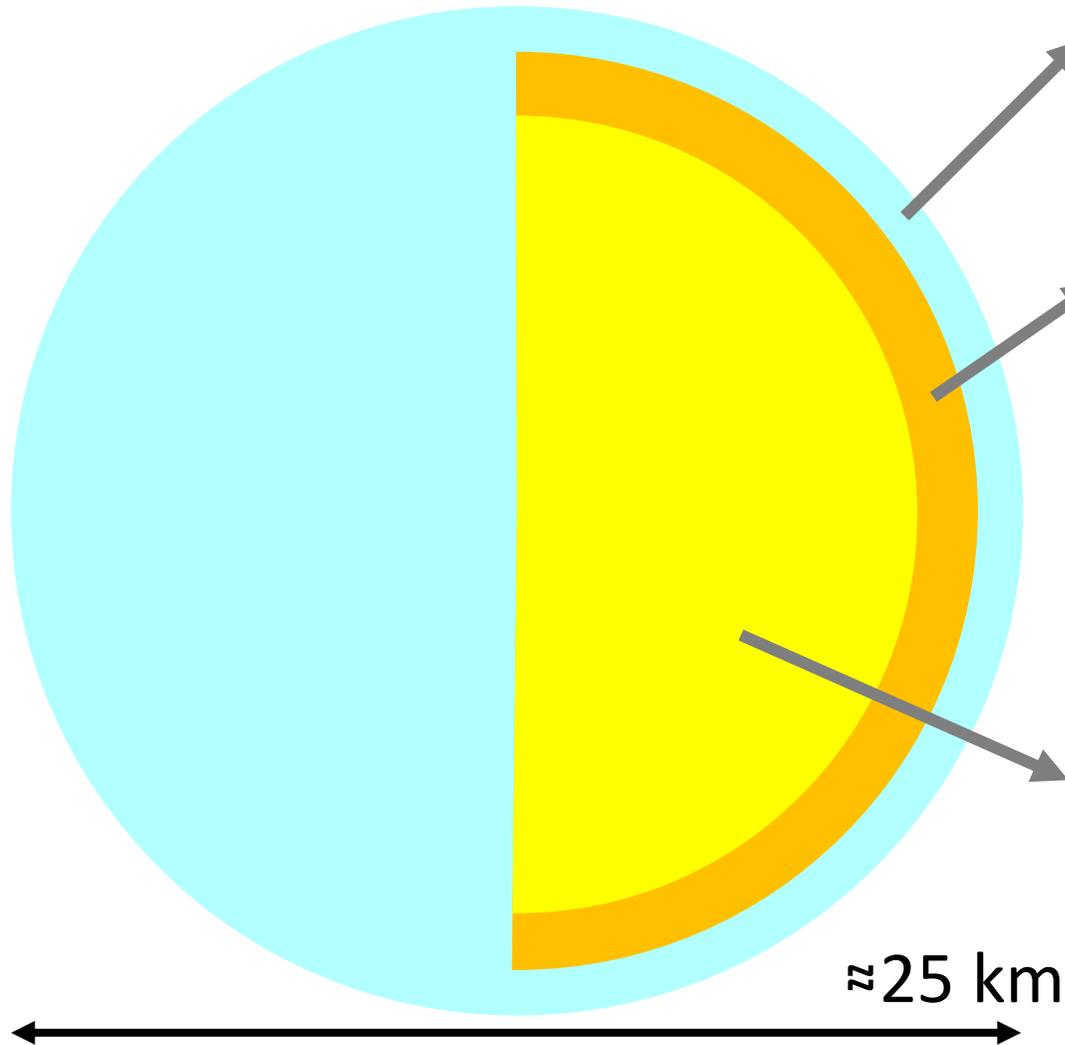
See also: D. G. Yakovlev¹, P. Haensel, G. Baym³, C. J. Pethick, 1210.0682

$$m_n > m_p + m_e$$



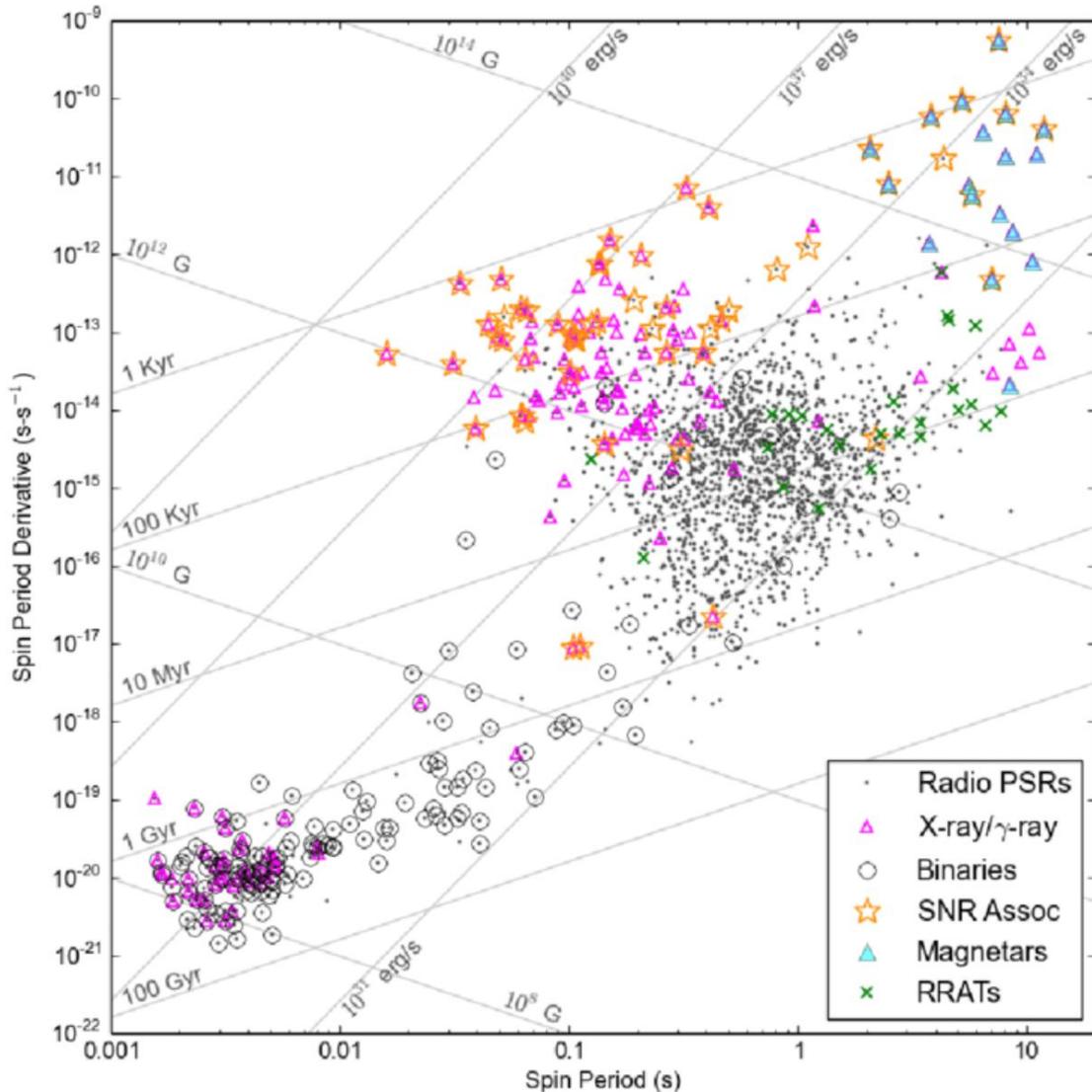
Free neutrons decay, need
HUGE pressure to compress
electrons and protons
→neutrons

Pulsar in a Nutshell



- ❑ Gaseous Iron Atmosphere (~cm) thick
- ❑ Degenerate Electron State Outer Surface (Fermi pressure provided by electrons)
- ❑ Neutron-Rich Core Region with Exotic Matter (Neutron Fermi pressure reach $\sim O(100)$ MeV)

Pulsar in a Nutshell (II)



- Spin period varies from 10s to milliseconds
- VERY strong magnetic field:
Critical B field: $\approx 10^{14}$ Gauss $\approx m_e^2$
- Surface feature also varies, leading to different electromagnetic signals
- Core temperature up to $O(100)$ KeV

Axion Conversion in Strong Magnetic Fields

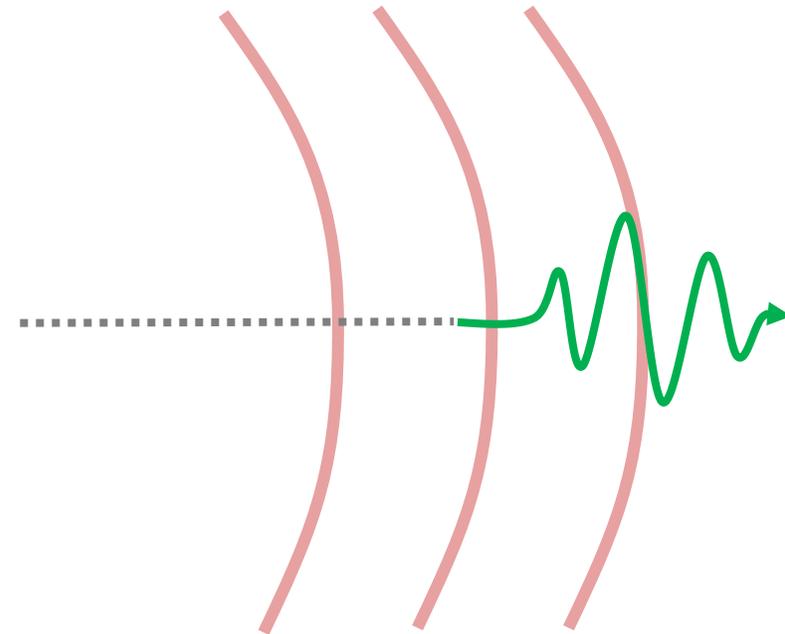
D. Lai and J. Heyl, 2006;
G. Raffelt and L. Stodolsky, 1988

$$i \frac{d}{dx} \begin{pmatrix} a \\ E_{\parallel} \\ E_{\perp} \end{pmatrix} = \begin{pmatrix} \omega R + \Delta_a R & \Delta_M R & 0 \\ \Delta_M R & \omega R + \Delta_{\parallel} R & 0 \\ 0 & 0 & \omega R + \Delta_{\perp} R \end{pmatrix} \begin{pmatrix} a \\ E_{\parallel} \\ E_{\perp} \end{pmatrix}$$

$$\Delta_a = -\frac{m_a^2}{2\omega} : \text{ALP mass term, negligible for now}$$

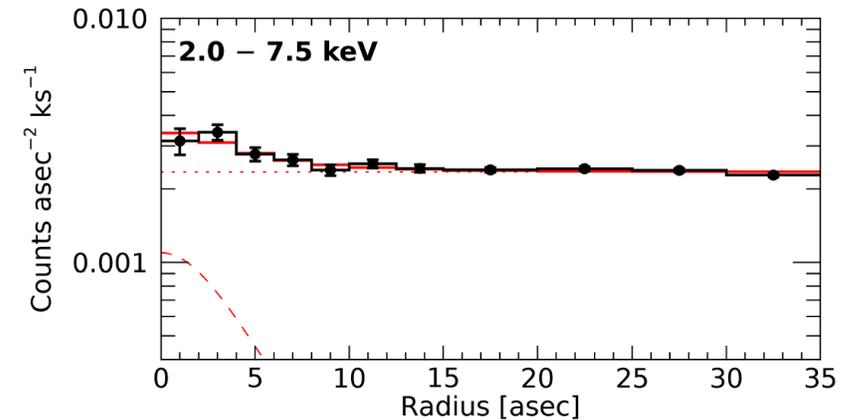
$$\Delta_{\parallel} \simeq \frac{7\alpha}{45\pi} \frac{B^2 \omega \sin^2 \theta}{B_c^2} : \text{from vacuum polarization, dominates near the NS}$$

$$\Delta_M = \frac{g_{a\gamma} B \sin \theta}{2} : \text{Mixing term, changes slowly}$$



About the Data Used

- ❑ Major data from XMM-Newton Epic-pn camera, across 2 decades with 1.43 Ms
- ❑ Phase information (time stamps) are obtained from NICER
- ❑ Background subtracted (short-term flare noise and permeating backgrounds, giving rise to systematics at high energy).
- ❑ A soft black body (~ 62 eV) and a hard black body (~ 120 eV) is found, not able to explain the excess.



Systematic Uncertainties

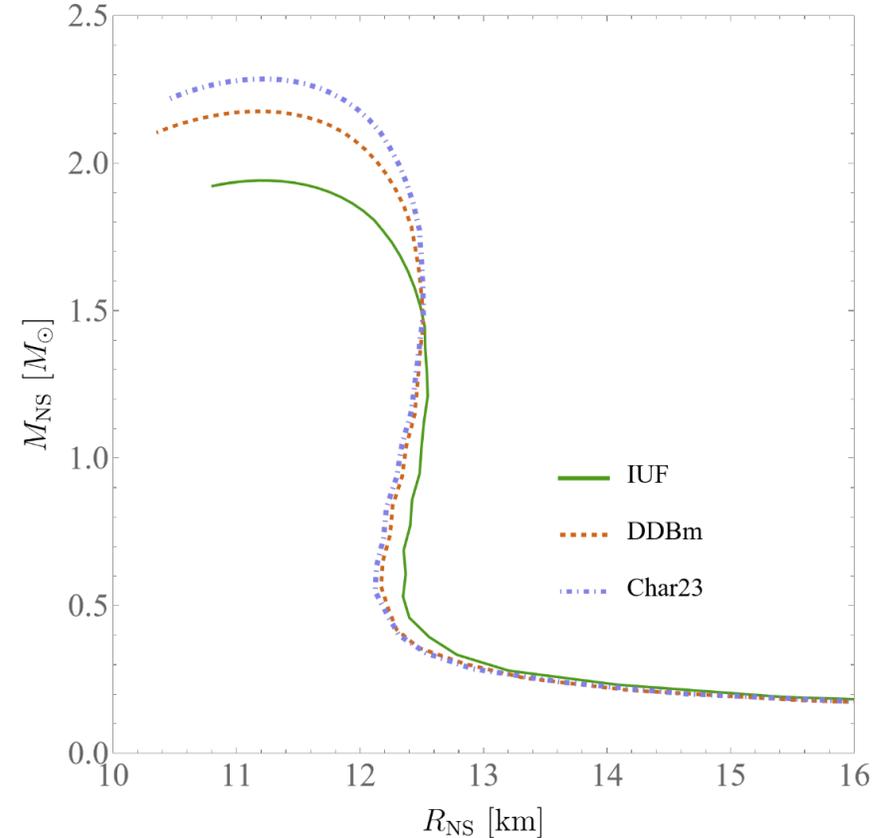
$$\frac{dL_{nn}^\infty}{d\omega_a^\infty} = \frac{1}{9\pi^6} C_\pi \left(\frac{m_N}{m_\pi}\right)^4 f^4 g_{aN}^2 \frac{\omega_a^{\infty,3} (\omega_a^{\infty,2} + 4\pi^2 T^{\infty,2})}{e^{\omega_a^\infty/T^\infty} - 1}$$

$$\times \int_0^{R_{\text{crust}}} dr \frac{r^2}{\sqrt{1 - \frac{2Gm(r)}{r}}} p_{Fn}(r) F[c(r)] e^{-4\phi(r)}$$

Integrating Tolman-Oppenheimer-Volkoff equation with EOS, large uncertainties

Other factors:

- B field: not very important as the 2/5 power suppression in conversion
- Distance: we got parallax
- Radius: not changing very much with mass



$M_{\text{NS}} [M_\odot]$	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	1.9
$L_a [L_{a,0}]$	1.70	2.05	2.48	2.98	3.58	4.32	5.29	6.62	8.91
$R_{\text{NS}} [\text{km}]$	12.8	12.8	12.8	12.7	12.7	12.6	12.4	12.2	11.8