STRUCTURE OF ALP CONVERSION IN NEUTRON STARS

Polarization & Pulsation

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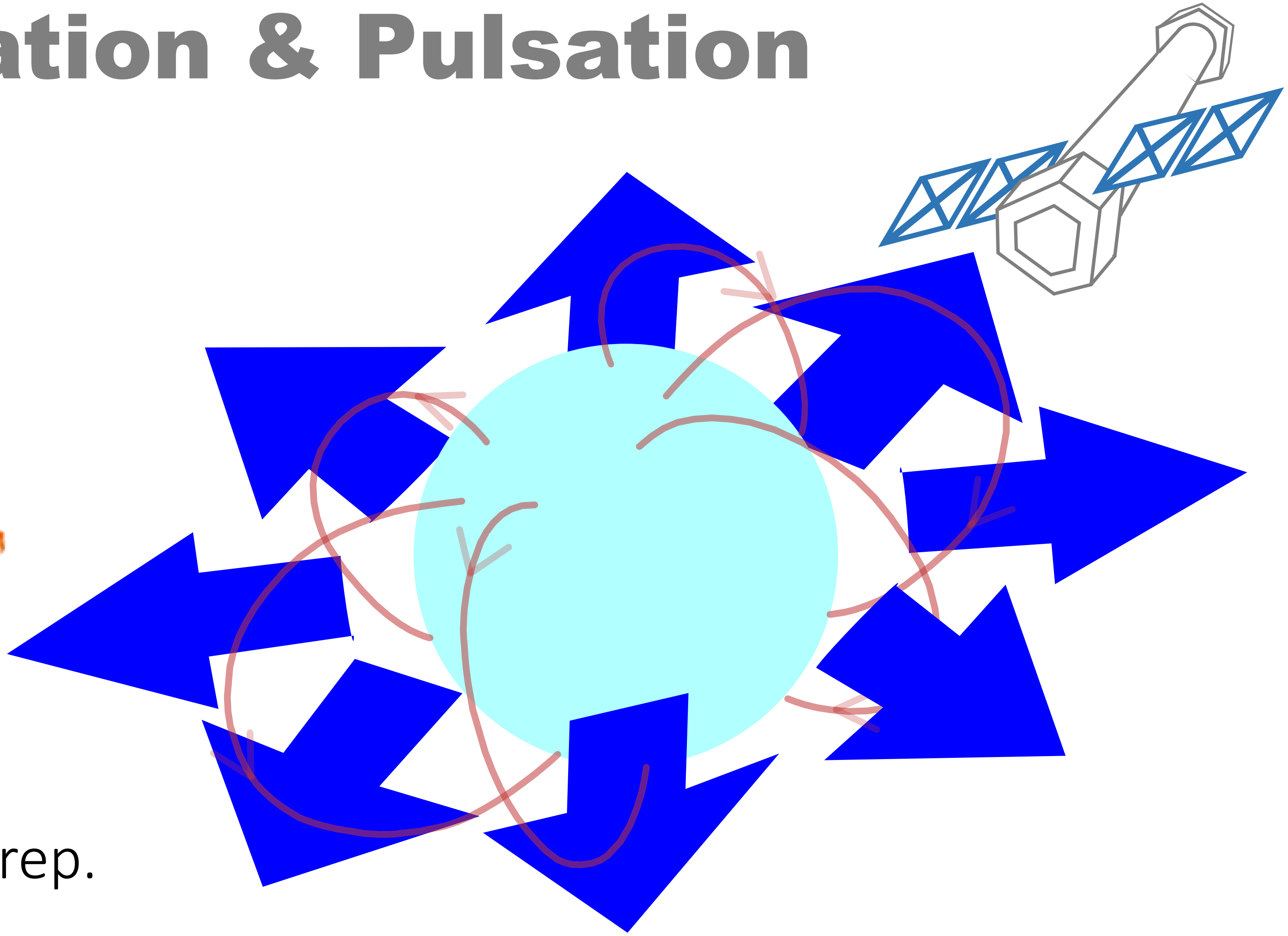
Chicago 2024



With JiJi Fan and Chen Sun, in prep.

Neutron Star(NS) as an ALP Source

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

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

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

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;
……

ALP Conversion in Strong Magnetic Fields

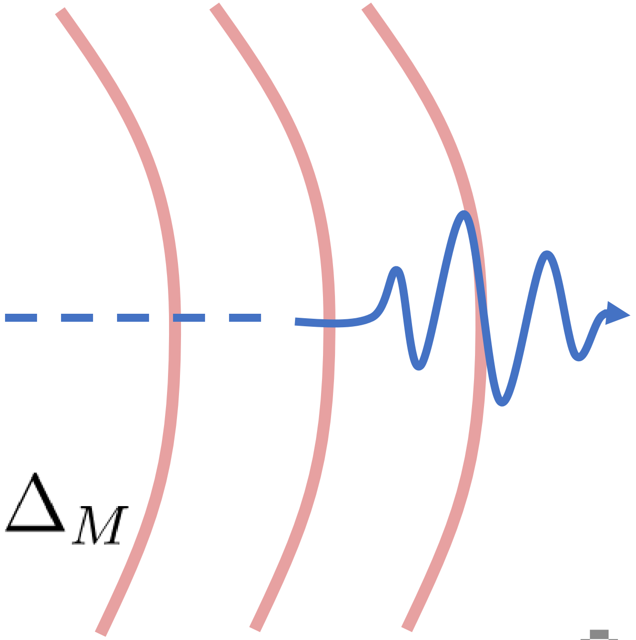
D. Lai and J. Heyl, 2006;
G. Raffelt and L. Stodolsky, 1988

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

Δ_a : ALP mass term, negligible for now

$\Delta_{\|}$: Eff. mass from vacuum polarization, dominates near the NS

Δ_M : Mixing term, changes slowly



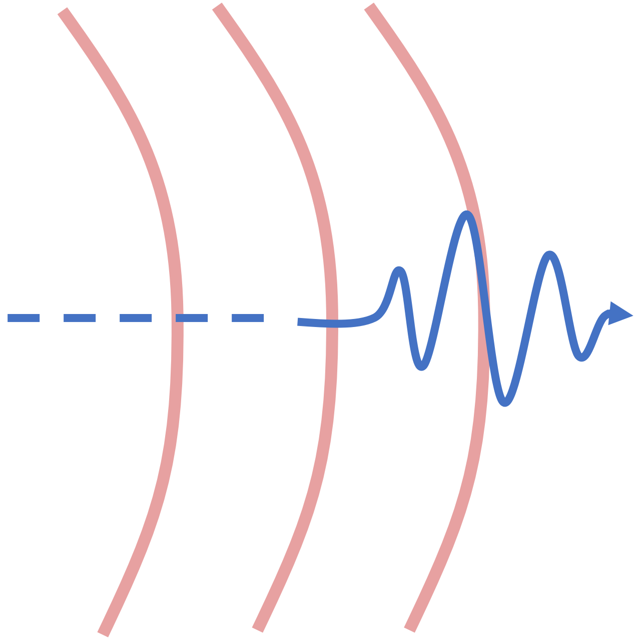
Near the NS, where the B field is extreme, $\Delta_{\|} \gg \Delta_M$

Mixing **only** happens when $r \gg r_0$

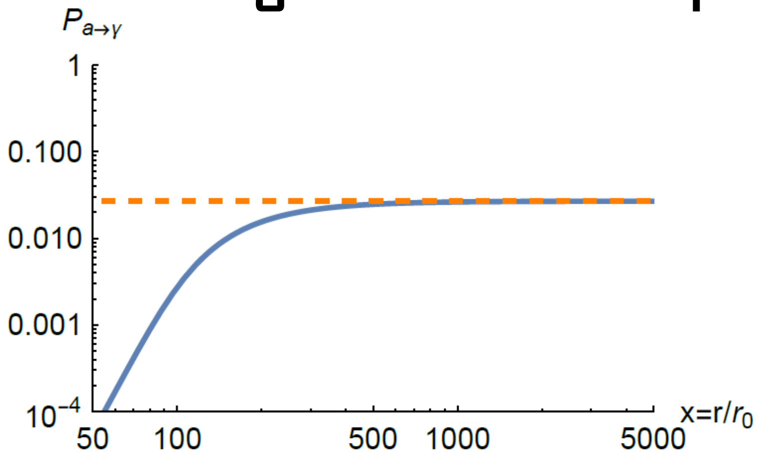
ALP Conversion in Strong Magnetic Fields (II)

$$\frac{r_{\rm con}}{r_0} \approx 1.05 \left(\frac{7\alpha}{45\pi}\right)^{1/5} \left(\frac{B_0 \sin\theta}{B_c}\right)^{2/5} (\omega r_0)^{1/5}$$

$$= 99 \left(\frac{\omega}{10\,\mathrm{keV}}\right)^{1/5} \left(\frac{r_0}{10\,\mathrm{km}}\right)^{1/5} \left(\frac{B_0}{10^{13}\,\mathrm{G}}\right)^{1/5} (\sin\theta)^{2/5}$$



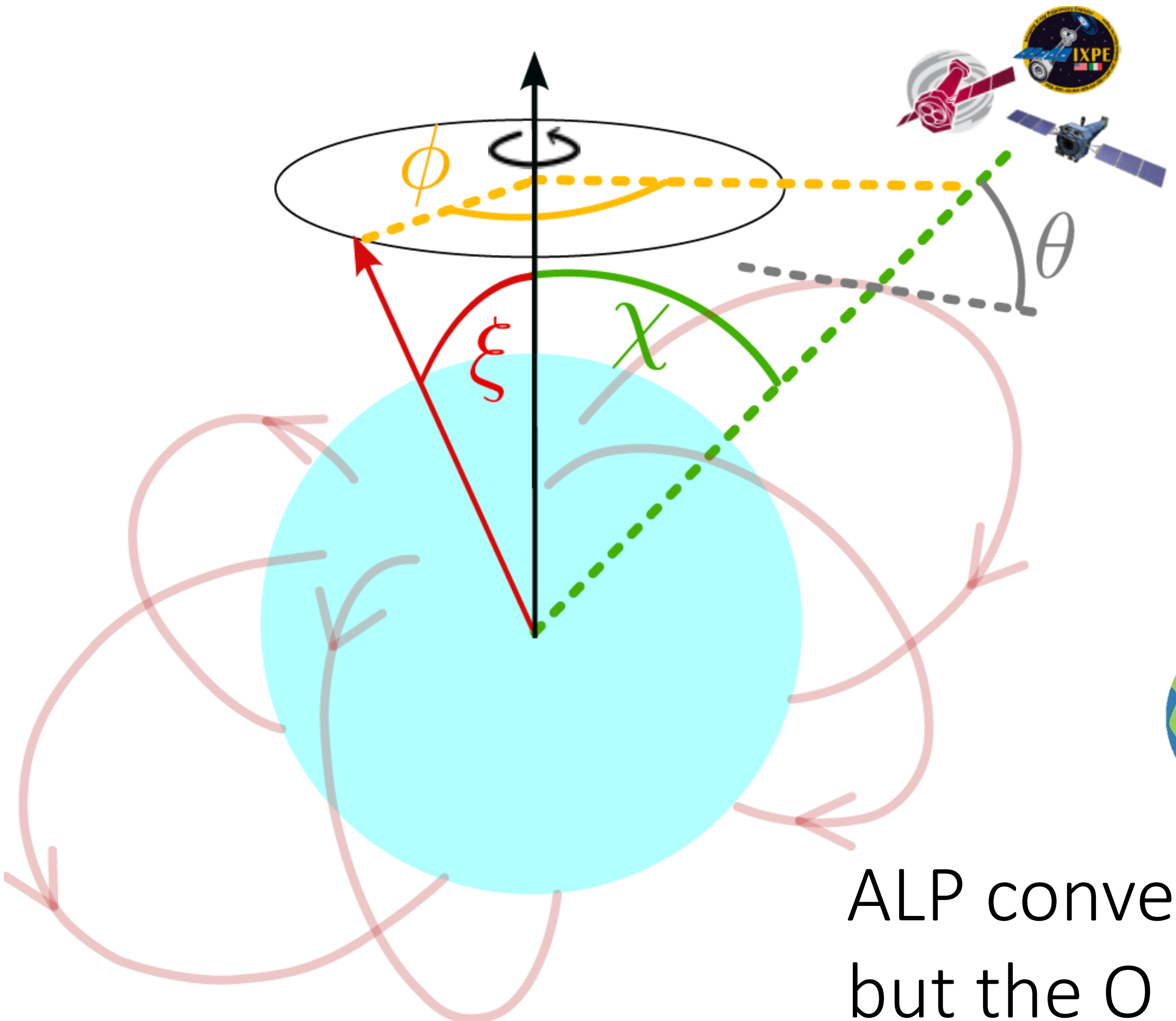
Robust against non-dipole and GR corrections



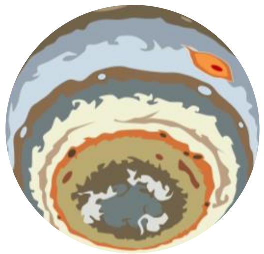
See also:

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



- 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

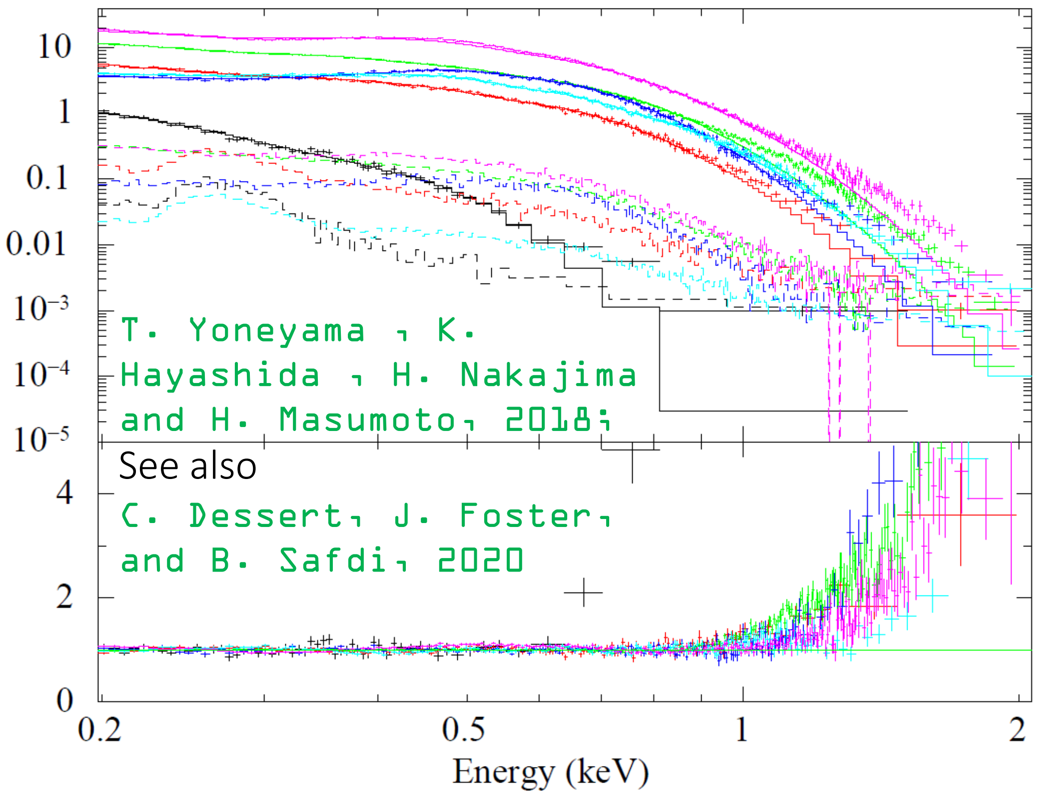


$$\xi \simeq 0.2$$

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

Interesting Targets

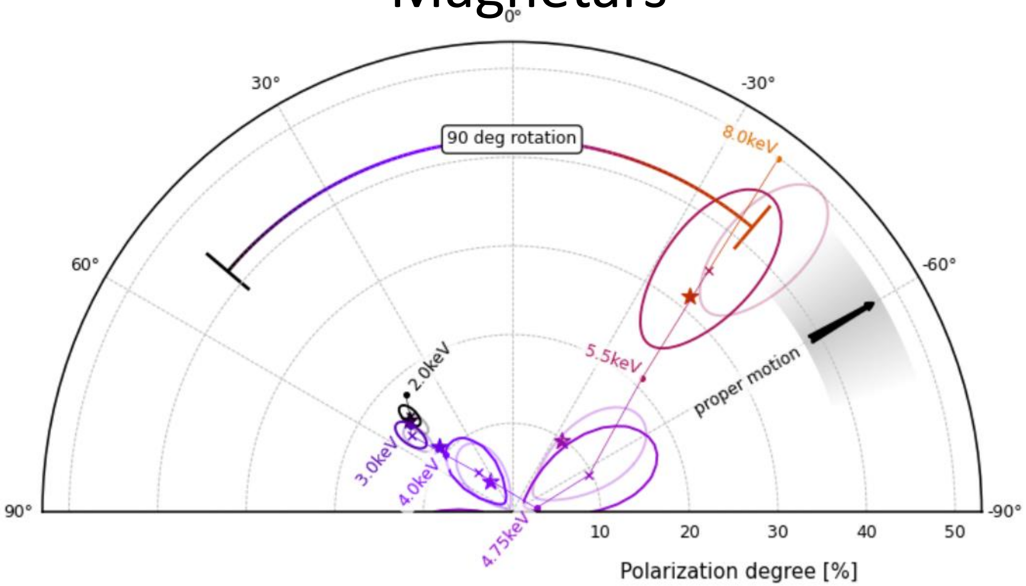
X-ray isolated Neutron Stars (XINS)



T. Yoneyama , K. Hayashida , H. Nakajima and H. Masumoto, 2018;

See also C. Dessert, J. Foster, and B. Safdi, 2020

Magnetars

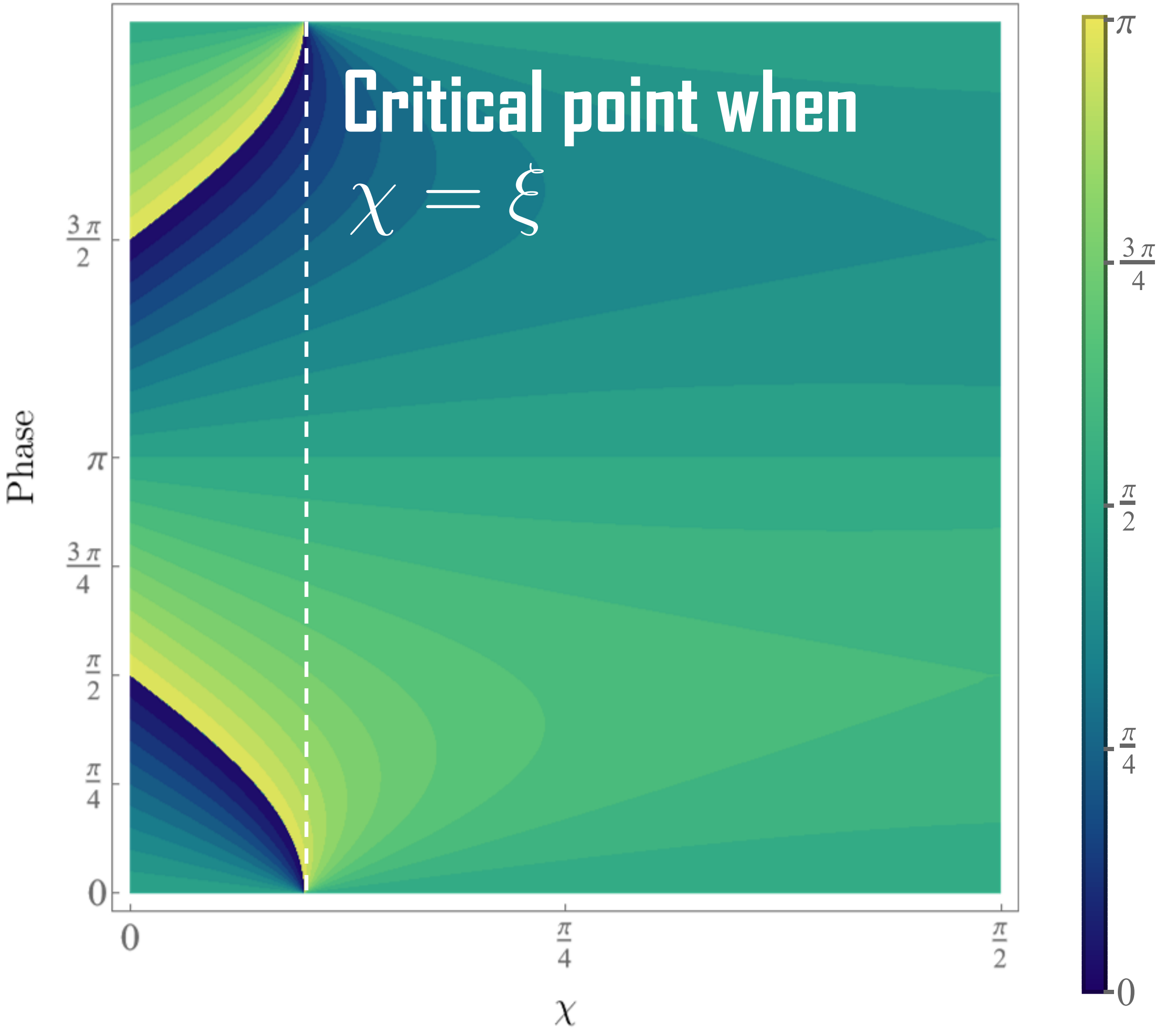


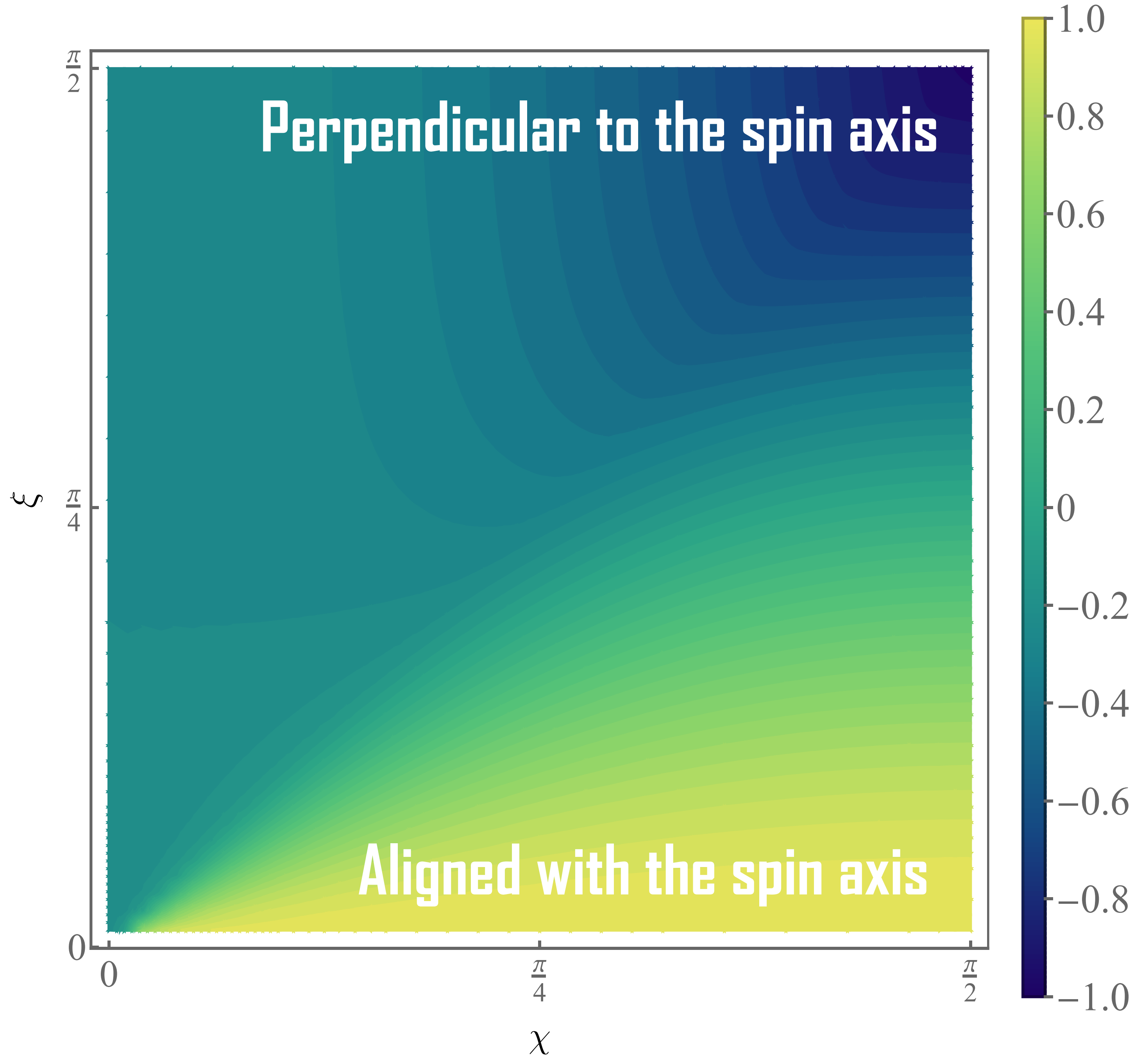
R. Taverna, R. Turolla, F. Muleri, J. Heyl, S. Zane, L. Baldini et al., 2022; S. Zane, R. Taverna, D. G. Caniulef, F. Muleri, R. Turolla, J. Heyl, K. Uchiyama, M. Ng, T. Tamagawa and I. Caiazzo et al., 2023

- (Universal) non-thermal X-ray excess
- Quiet in ratio band
- Rather dim sources (need 10^6 sec int. time)

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

Polarization Structure with Phase



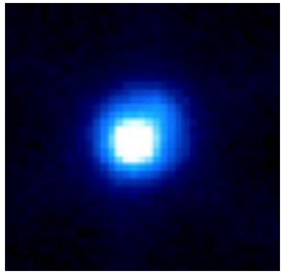


Phase-integrated Polarization (when there's not enough statistics)

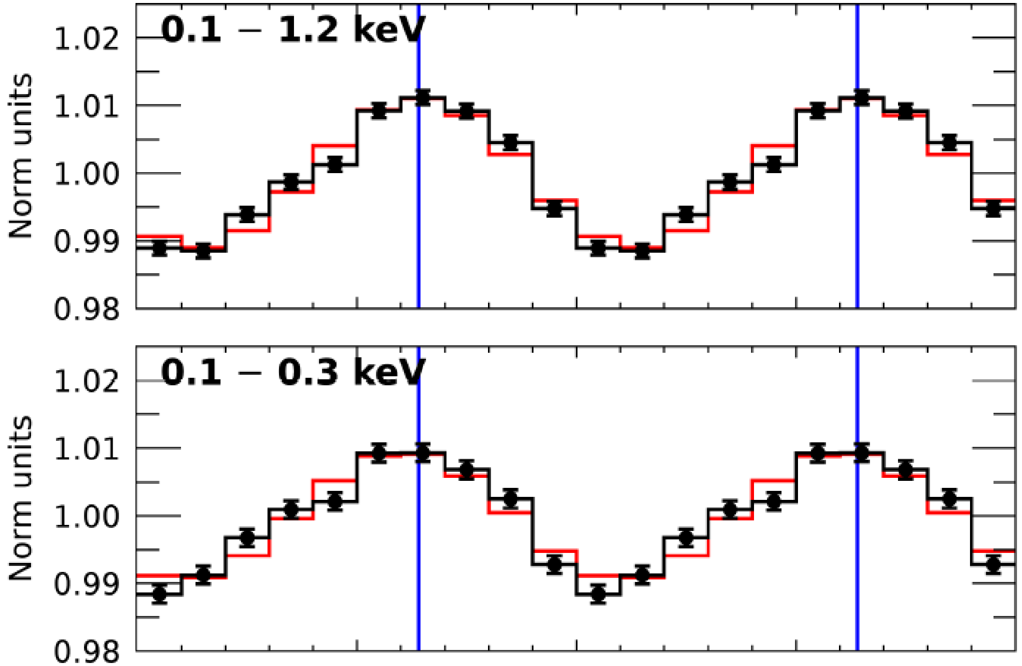
Uniformly applied to ALL NS conversions of light ALPs

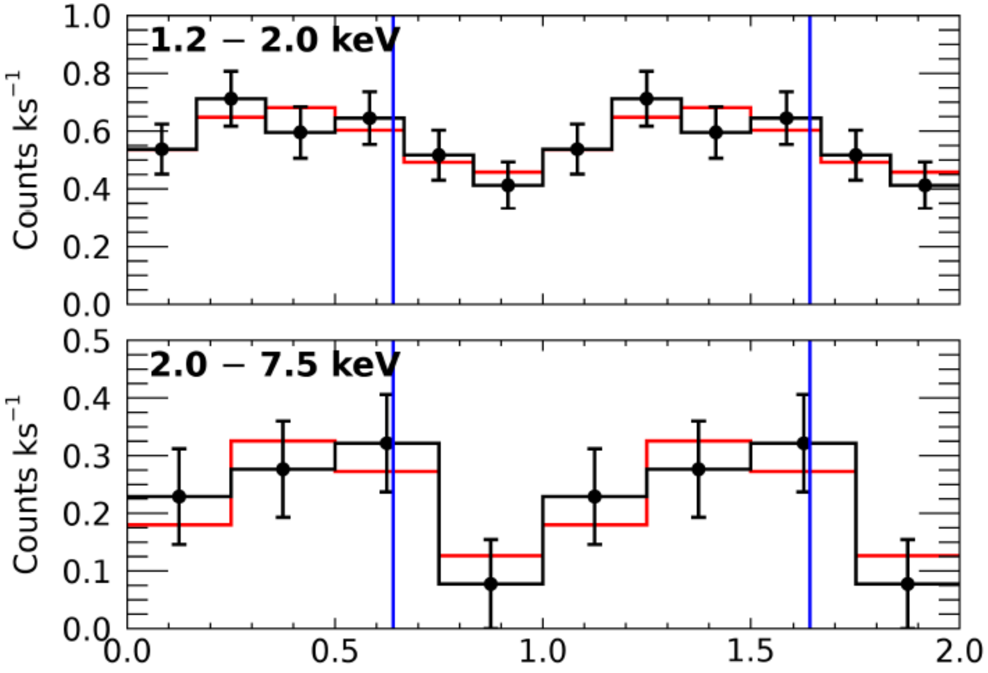
- Energy independent
- ALP mass independent
- Magnetic field independent

Pulse Structure, from XINS J1856.5-3754



Pulse fraction goes up to ~50% @ higher energies

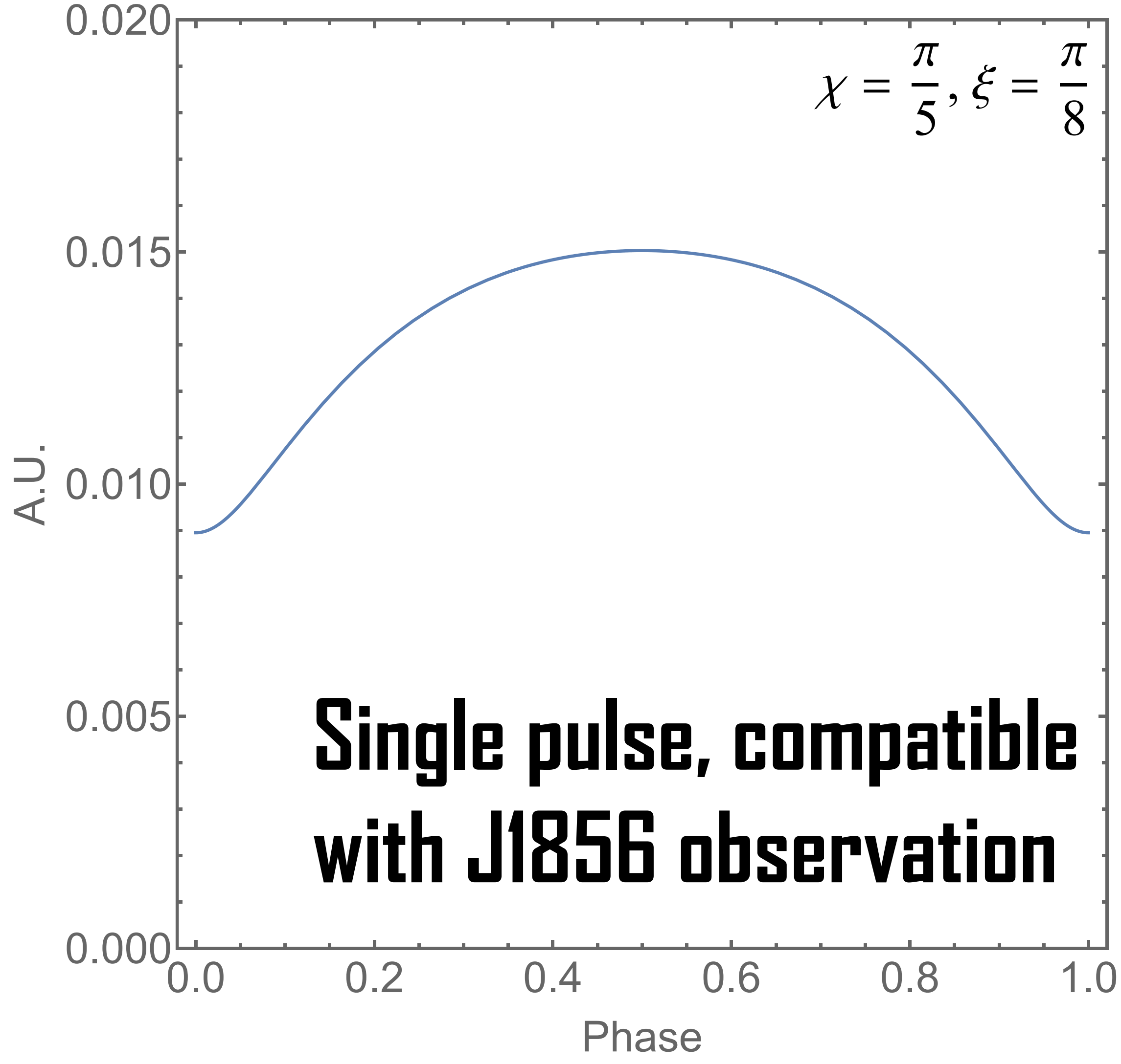


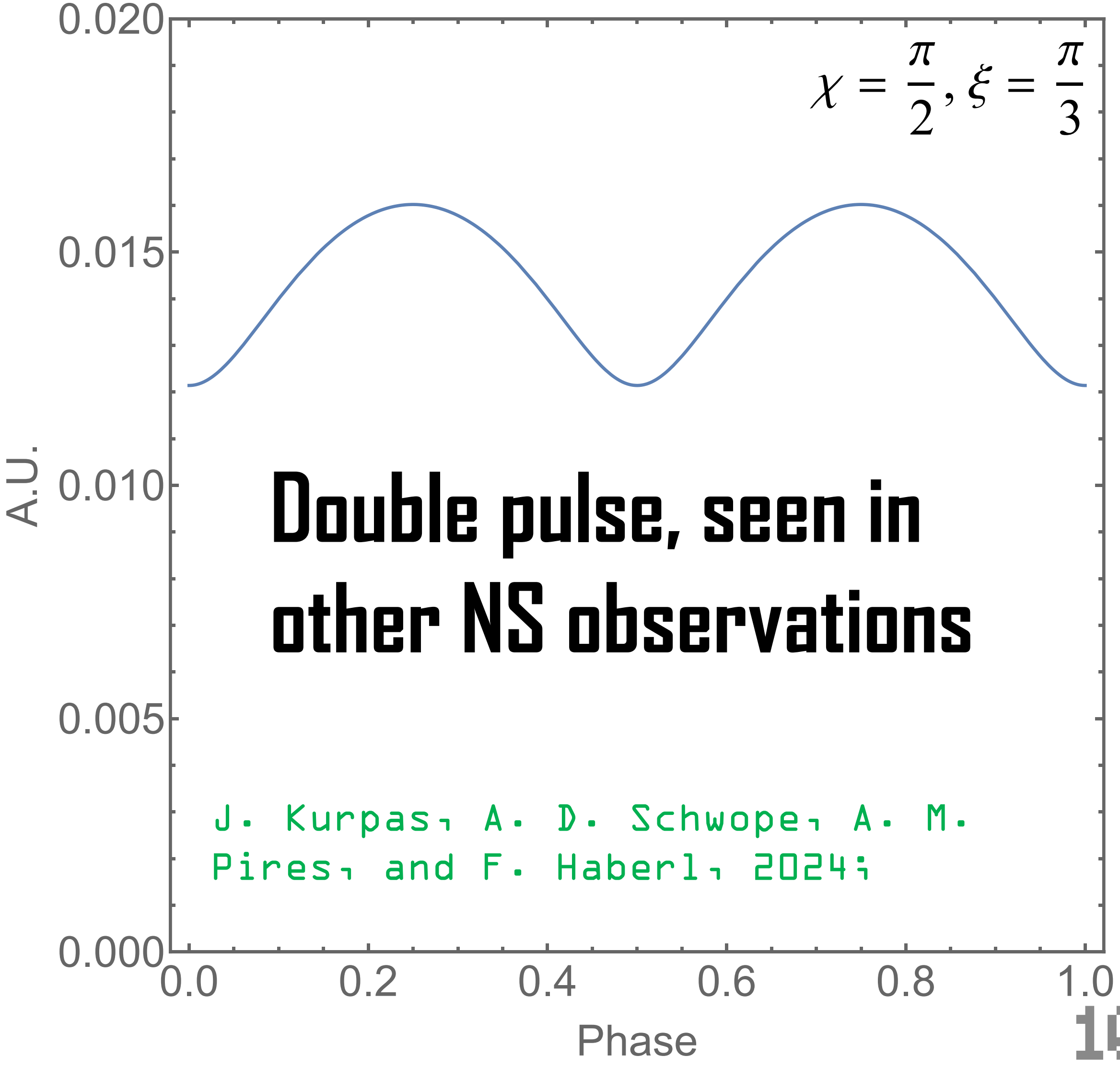


1-2% pulse @ low energies

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

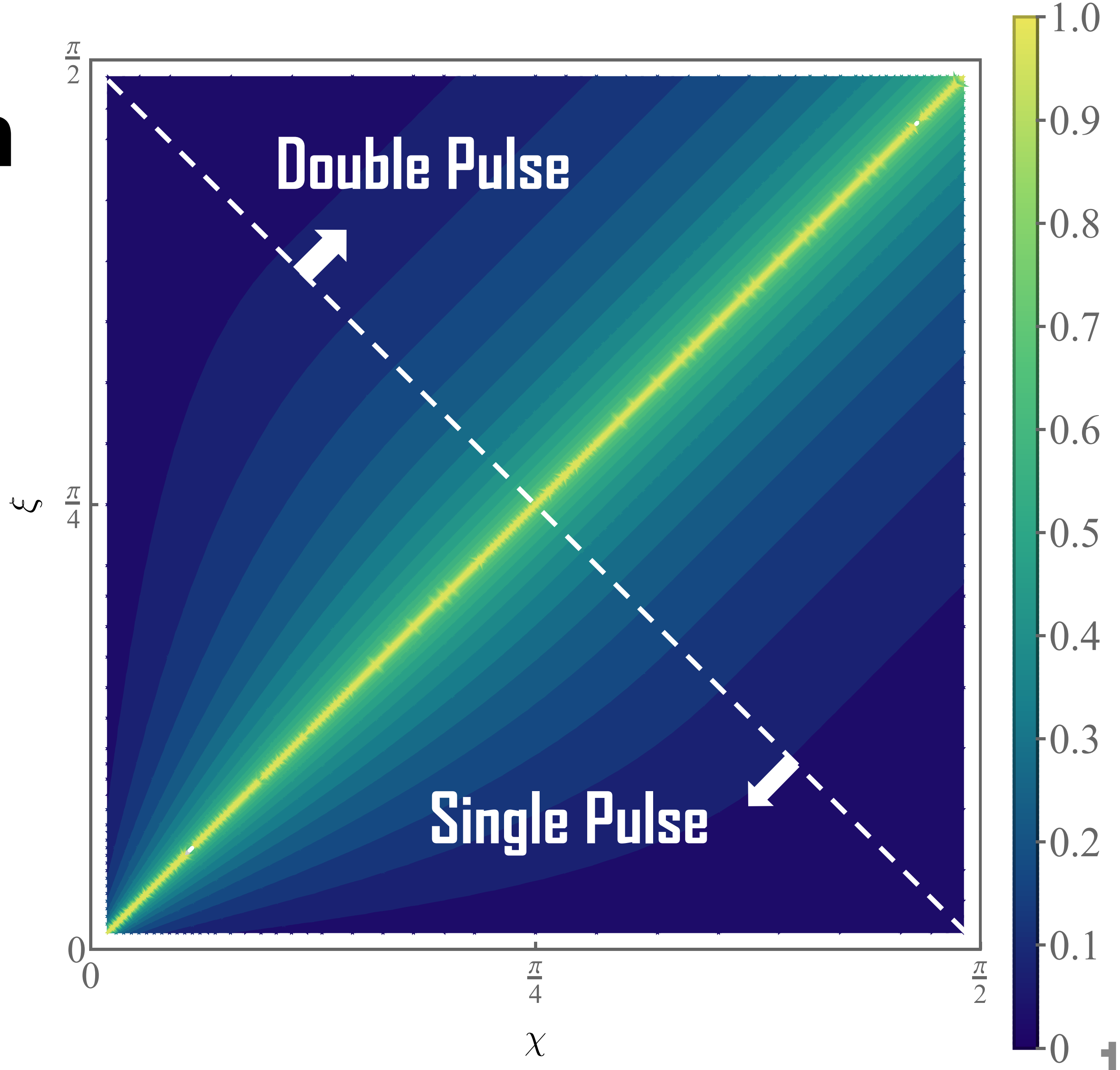
Theoretical Prediction



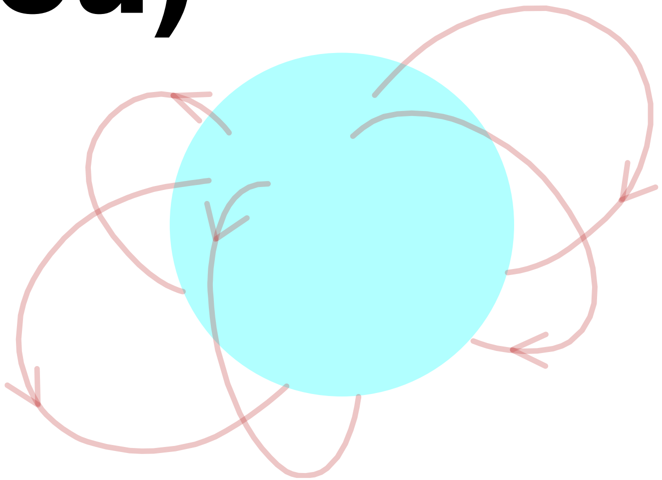


Pulse Fraction

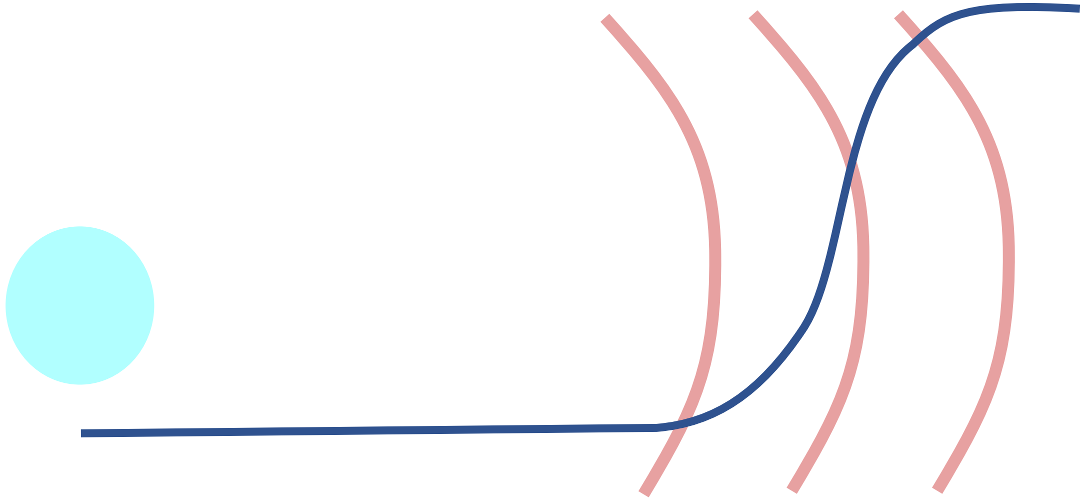
Without polarization probes, the two angles are equivalent



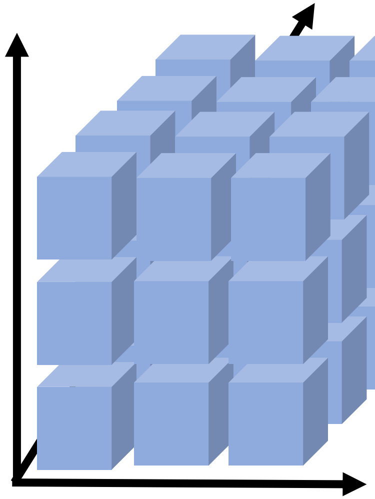
Summary (and Thank You)



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



- ❑Energy-independent & insensitive to detailed corrections



- ❑Analyzing 3D info (energy, polarization, time) helps discriminate models