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Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



Dipartimento
di Fisica
e Astronomia

UNIVERSITÀ DEGLI STUDI DI PADOVA

Agencia Spaziale Italiana **ExplorE!**

magnetar sources

Roberto Taverna (speaker)

Roberto Turolla, Silvia Zane, Jeremy Heyl, Fabio Muleri, Luca Baldini, Matteo Bachetti, Ilaria Caiazzo, Niccolò Di Lalla, Alessandro Di Marco, Ephraim Gau, Denis Gonzalez, Gian Luca Israel, Ruth Kelly, Demet Kirmızıbayrak, Henric Krawczynski, Fabio La Monaca, Michela Negro, Mason Ng, Nicola Omodei, Andrea Possenti, John Rankin, Toru Tamagawa, Keisuke Uchiyama, Martin C. Weisskopf
and the IXPE team

Congresso Nazionale Oggetti Compatti (CNOC XIII)

Magnetar e Stelle di Neutroni Isolate

Alghero, September 23–26, 2024

Polarization in strong B -fields

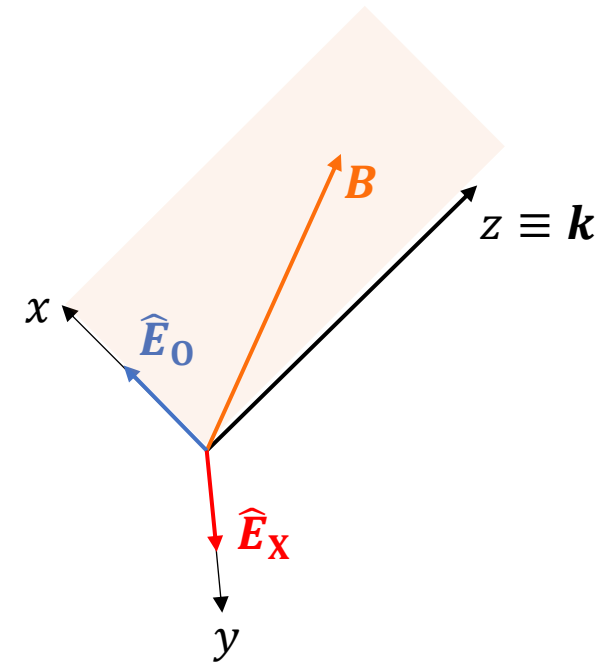
- The polarization state of photons can be studied solving the wave equation

$$\nabla \times (\bar{\mu} \cdot \nabla \times \mathbf{E}) = \frac{\omega^2}{c^2} \epsilon \cdot \mathbf{E}$$

$$B \gtrsim B_Q \Rightarrow \hat{\mathbf{E}} \approx \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

Ordinary mode Extraordinary mode

$B_Q \approx 4 \times 10^{13} \text{ G}$
 Quantum-critical field

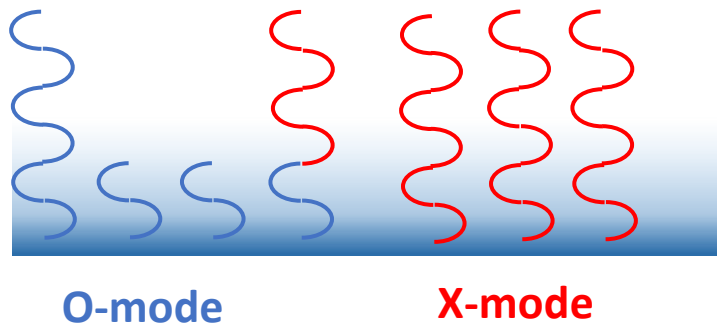


Dichroism in strongly-magnetized plasma

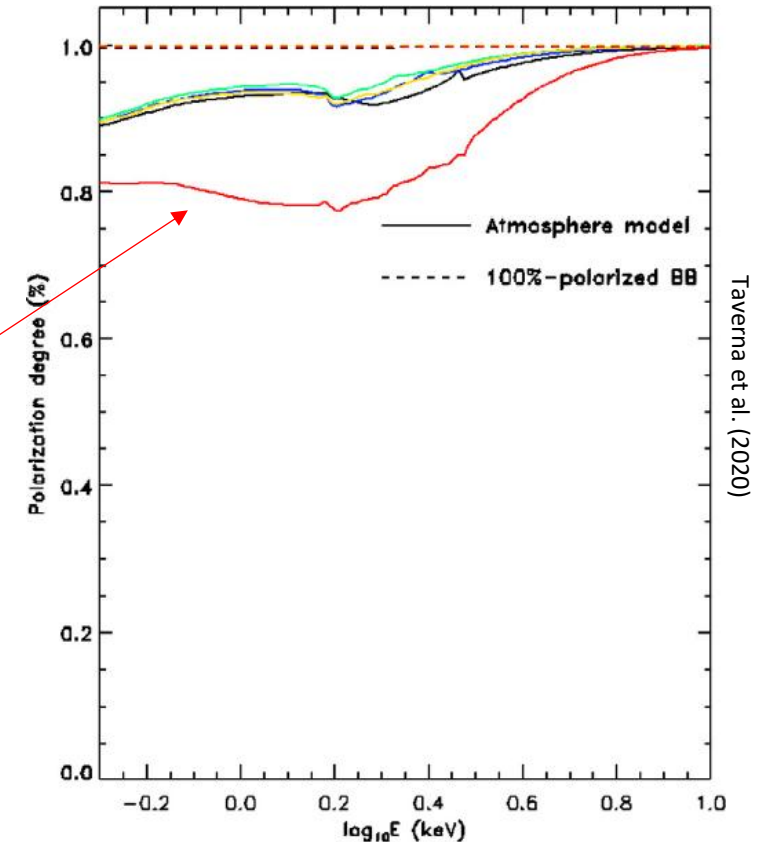
- In strong fields ($B \gtrsim B_Q$) and $E \ll \hbar\omega_B$ plasma is (generally) transparent for X-mode photons

$$\sigma_{OO} \sim \sigma_{\text{unmag}} \quad \sigma_{XO} \sim \left(\frac{B}{B_Q}\right)^{-2} \sigma_{OO}$$

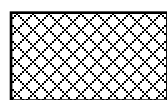
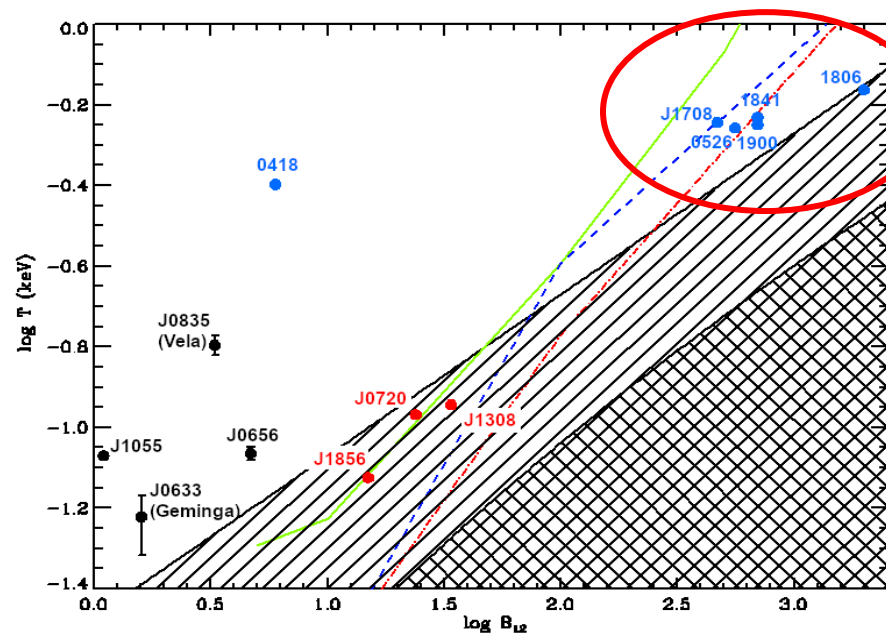
$$\sigma_{OX} \sim \left(\frac{B}{B_Q}\right)^{-2} \sigma_{OO} \quad \sigma_{XX} \sim \left(\frac{B}{B_Q}\right)^{-2} \sigma_{OO}$$



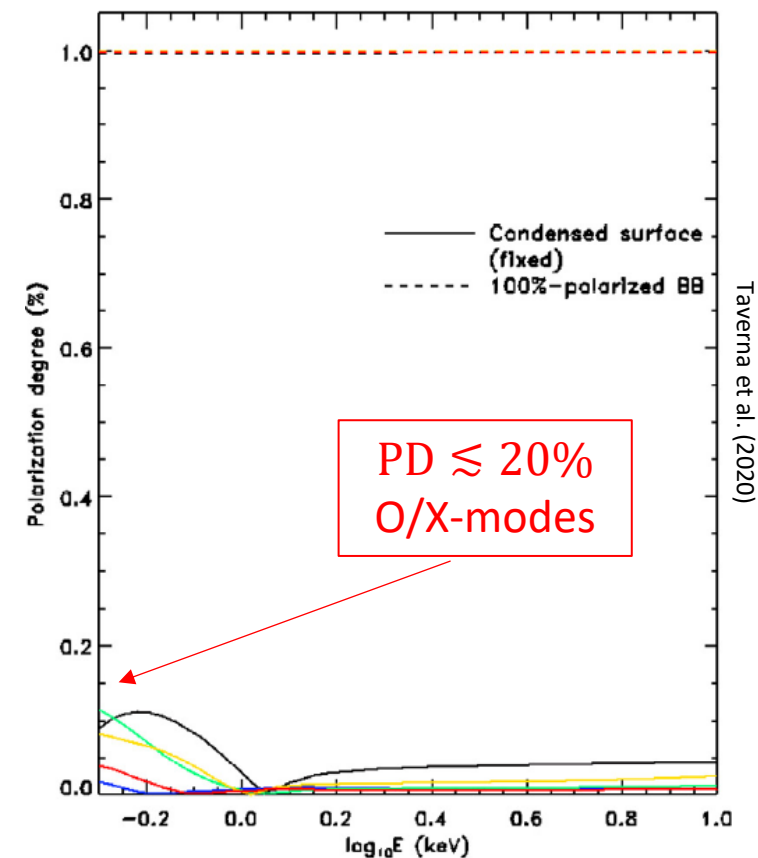
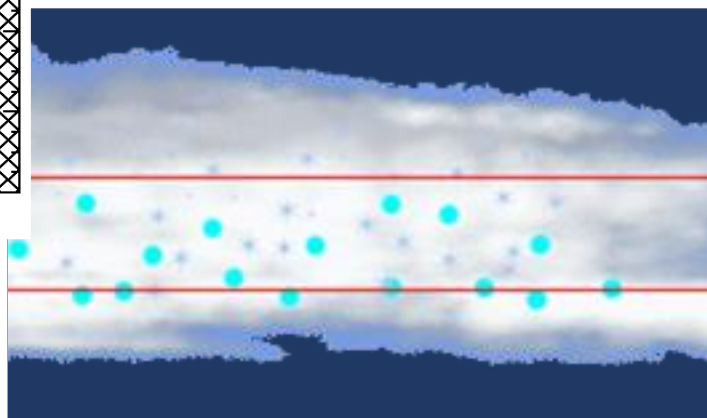
PD \gtrsim 80%
 X-mode



- In strong fields ($B \gtrsim B_Q$) and sufficiently low T magnetic condensation can occur



magnetic condensation



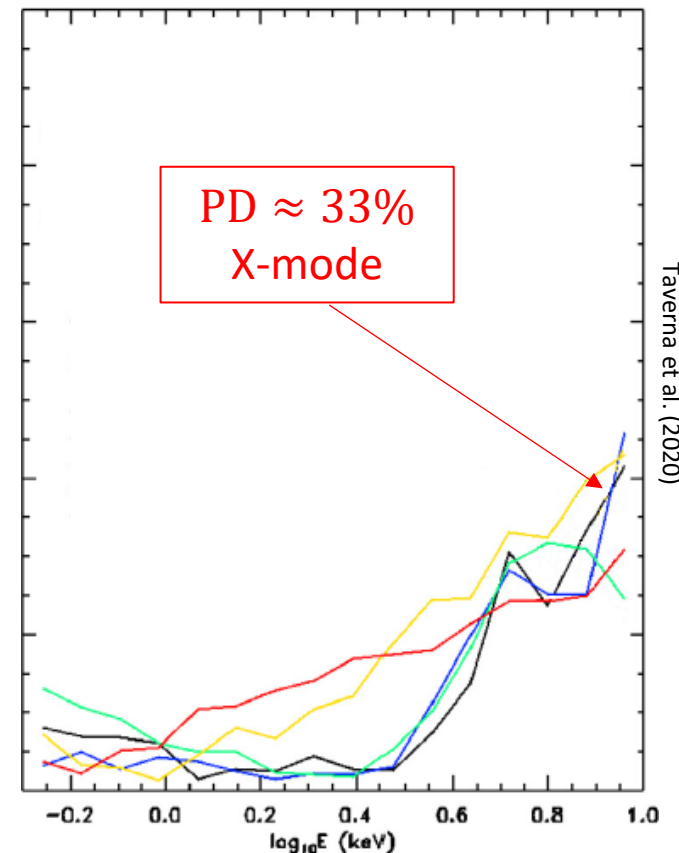
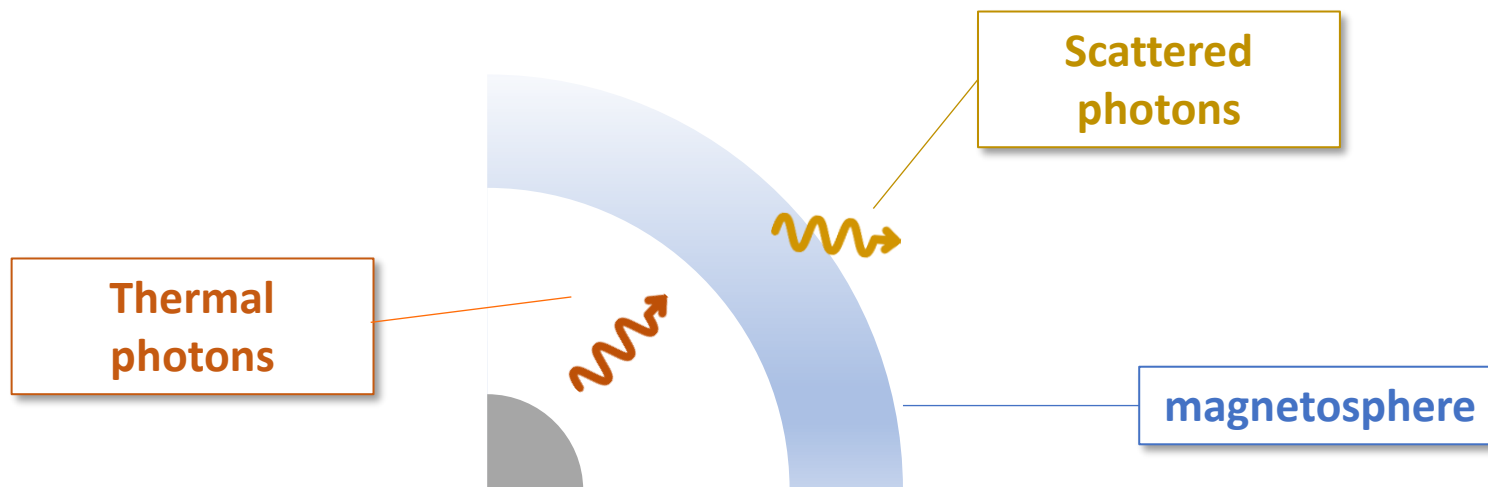
Taverna et al. (2020)

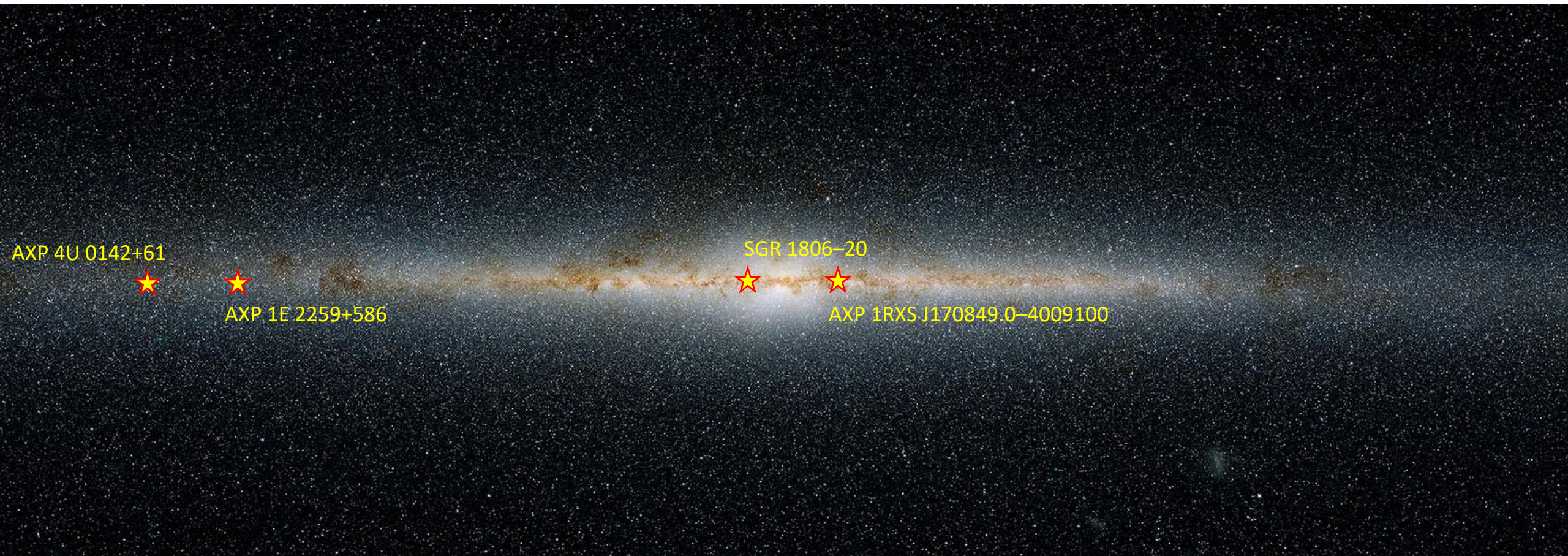
Reprocessing in the magnetosphere

- The magnetosphere is optically thick for RCS (at the cyclotron resonance, $\omega = \omega_B$)
- X-mode photons still favourite (but suppression factor $\approx 1/3$)

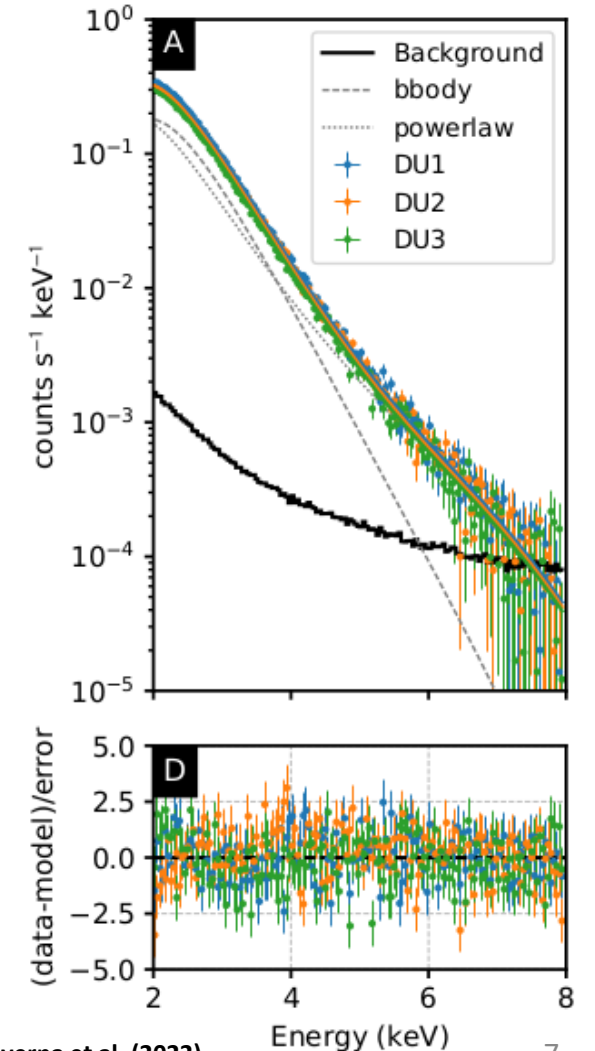
$$\sigma_{OO} = \frac{1}{3} \sigma_{OX}$$

$$\sigma_{XX} = 3\sigma_{XO}$$

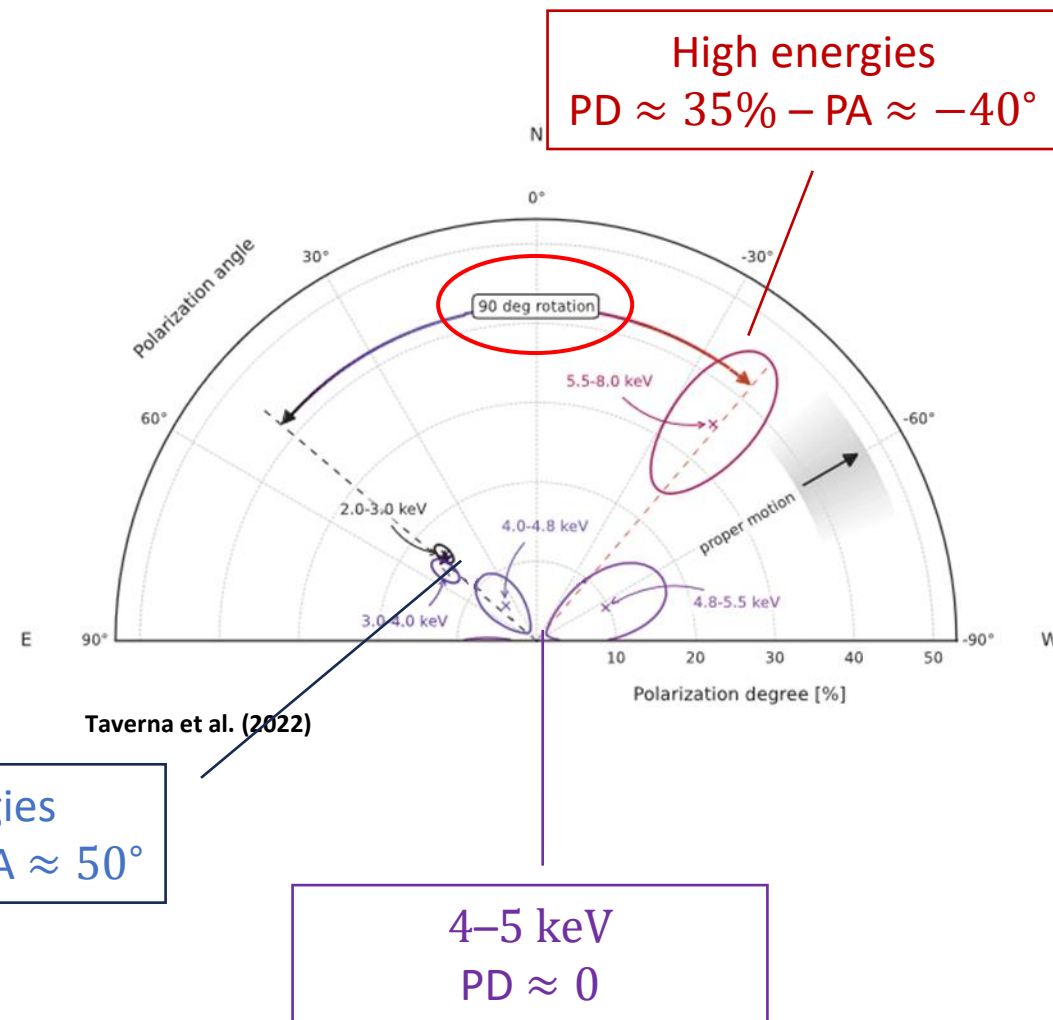




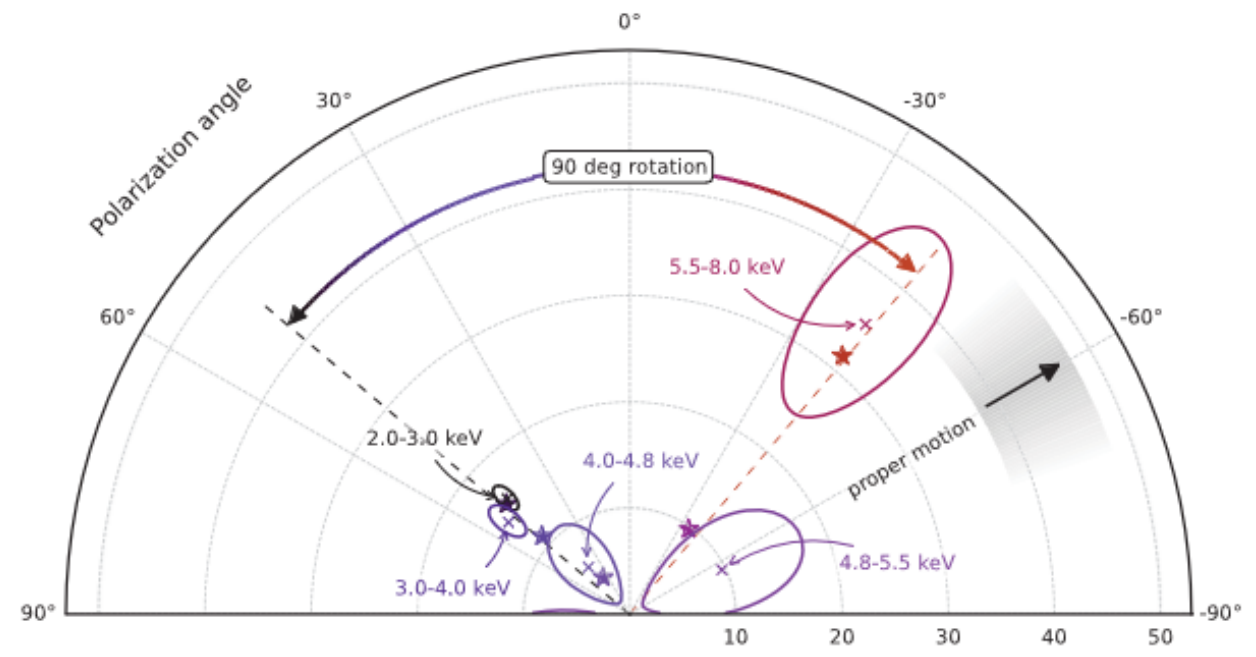
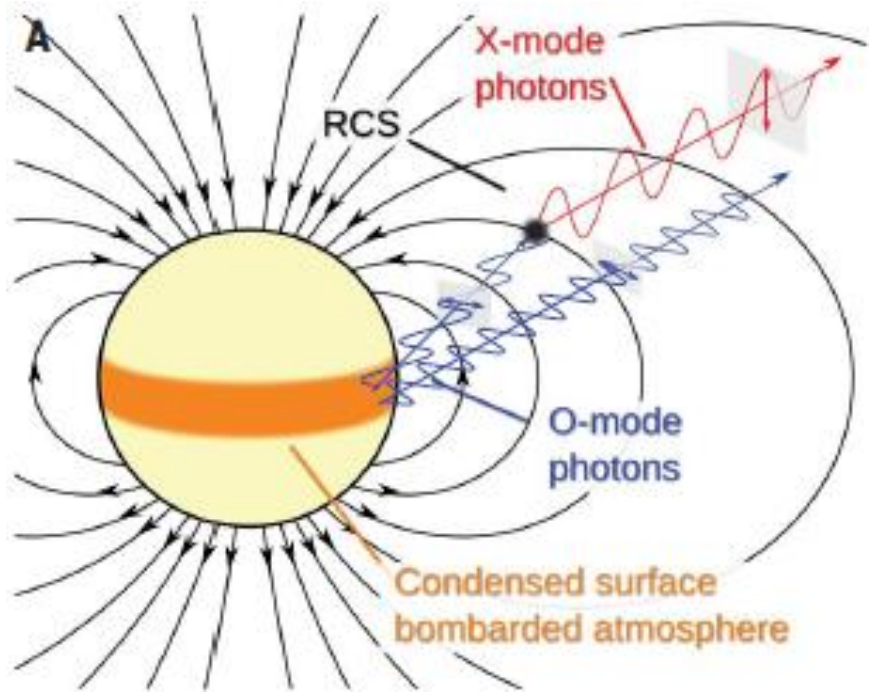
- Brightest among persistent magnetars
- $B_{p\dot{p}} \approx 1.5 \times 10^{14} \text{ G}$
- Spectrum BB+PL
 - $kT_{\text{BB}} = 0.471^{+0.004}_{-0.004} \text{ keV}$
 - $\Gamma = 3.69^{+0.05}_{-0.05}$
 - $\chi^2/\text{dof} = 511.5/441$



- Brightest among persistent magnetars
- $B_{p\dot{p}} \approx 1.5 \times 10^{14} \text{ G}$
- Spectrum BB+PL
- Polarization measurement (840 ks):
 - PD = 13.5% (17σ) – PA $\approx 50^\circ \text{ E}$ (MDP₉₉ $\approx 2\%$)
 - Complex behavior against photon energy



- 90°-swing → X- and O- modes ⇒ ***B*-field should be ultra-strong ($\gtrsim 10^{13}$ G)**
- PD at high energies $\approx 35\%$ ⇒ **PL tail populated by RCS photons ($\approx 33\%$)
Magnetar model reliable!**
- Low PD at low energies ⇒ **Condensed surface exposed**

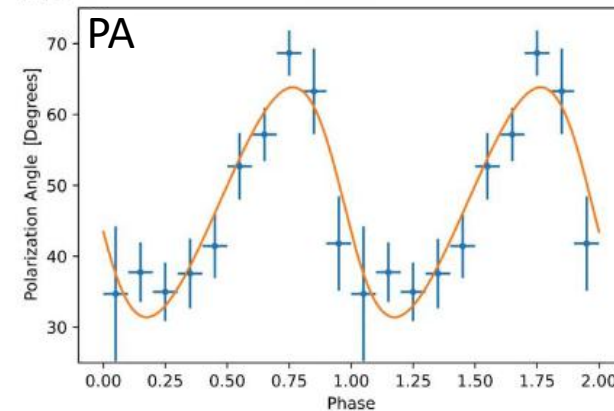
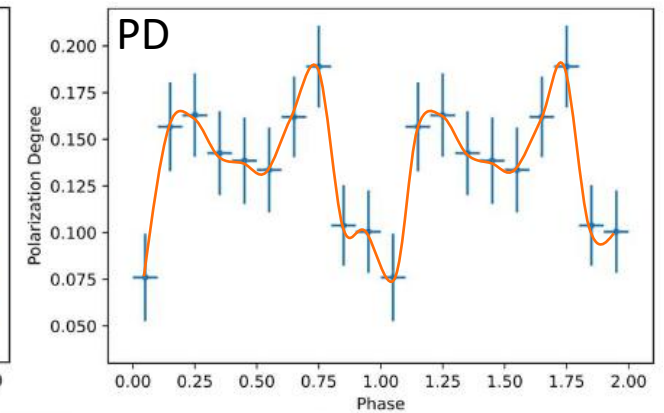
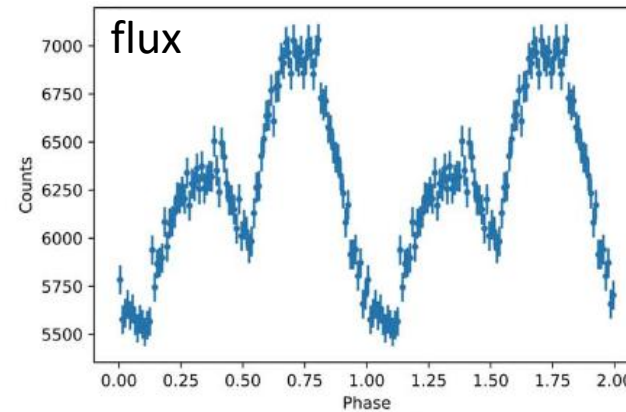


Taverna et al. (2022)

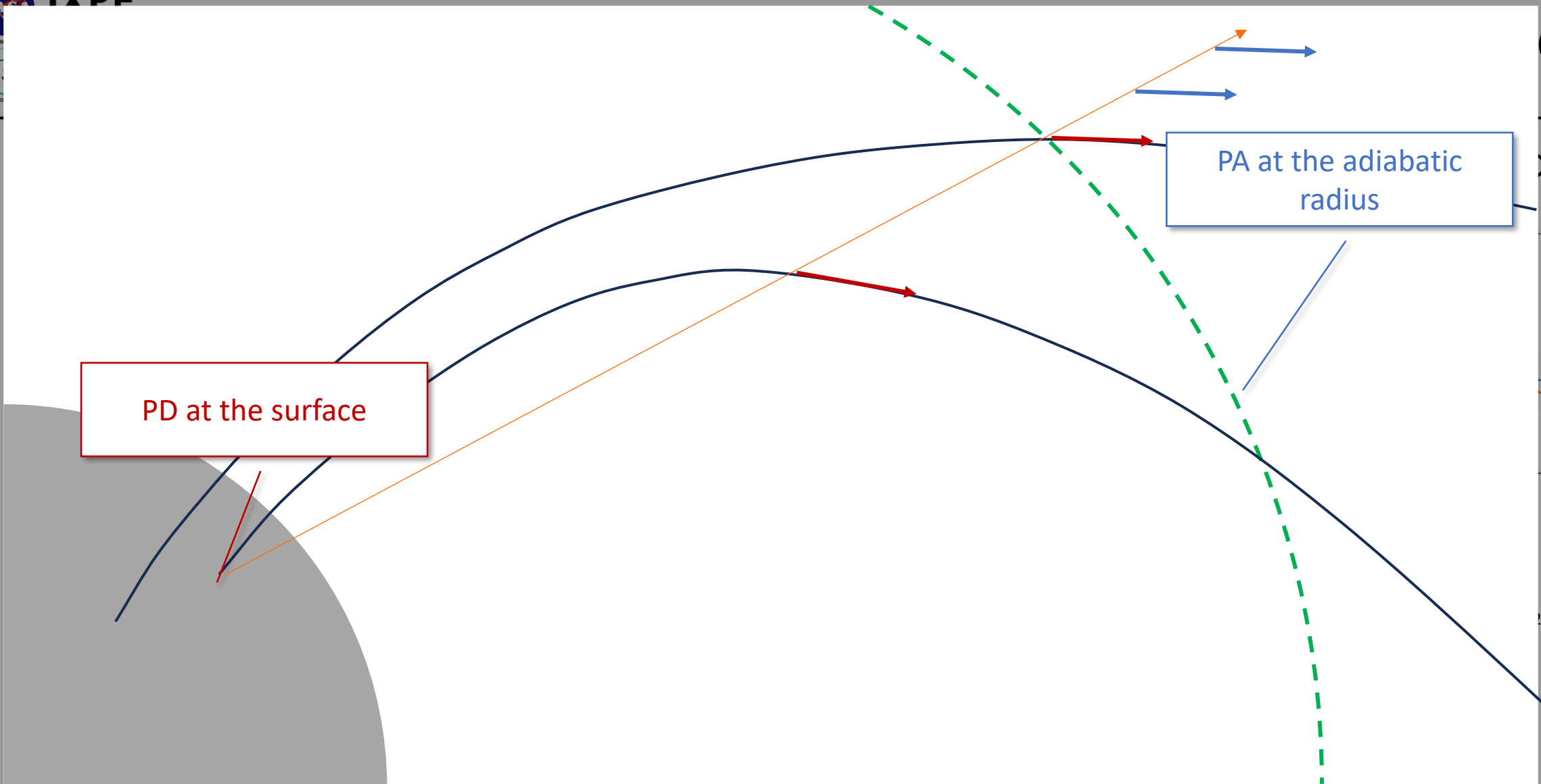
★ Numerical simulation

AXP 4U 0142+61 – Phase resolved

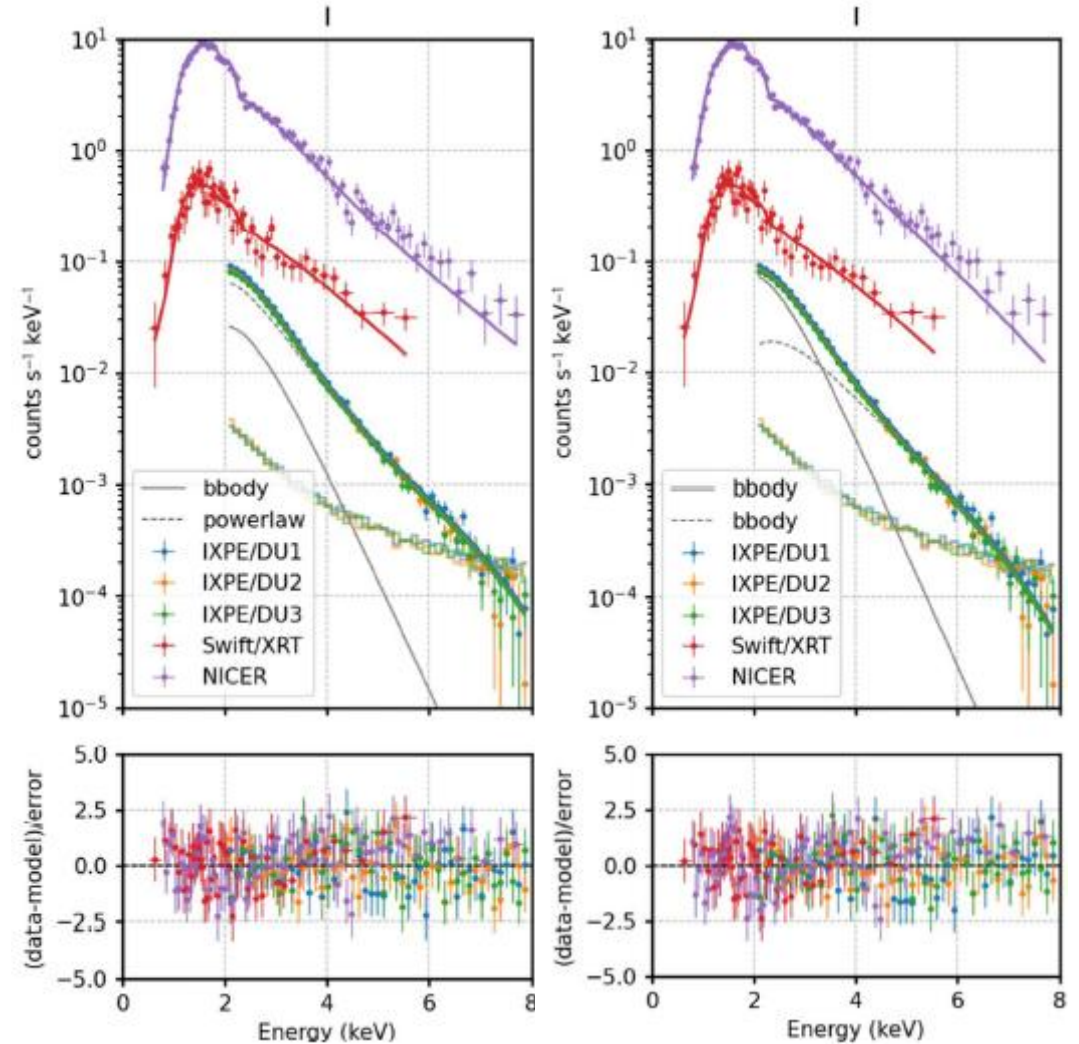
- Low phase-averaged PD ($< 40\%$) \Rightarrow Vacuum birefringence cannot be probed
- Phase dependent results
 - PD is in-phase with the LC (determined at the surface)
 - PA is sinusoidal (RVM)
- RVM for extended regions holds for dipolar fields only
 - In the magnetar model B is dipolar only far away from the surface



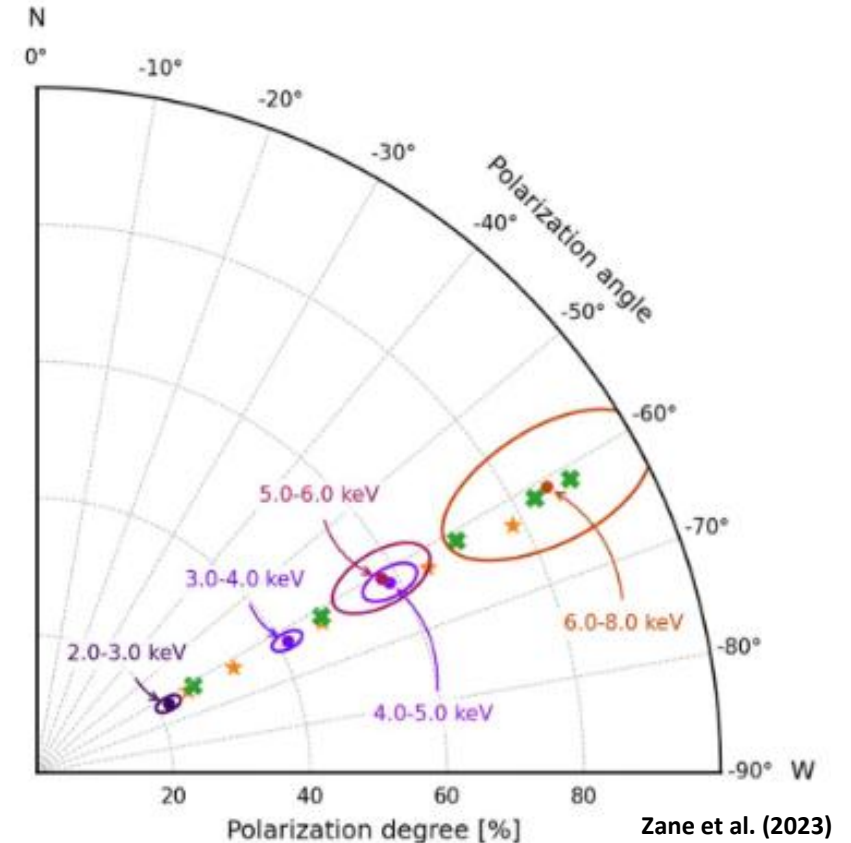
Taverna et al. (2022)



- 2nd brightest magnetar
- $B_{p\dot{p}} \approx 5 \times 10^{14}$ G
- Spectrum BB+PL or BB+BB?
 - BB+PL – $kT_{\text{BB}} = 0.454_{-0.006}^{+0.007}$ keV
 $\Gamma = 2.97_{-0.056}^{+0.009}$
 $\chi^2 = 410.8/408$ dof
 - BB+BB – $kT_{\text{BB}_1} = 0.435_{-0.007}^{+0.007}$ keV
 $kT_{\text{BB}_2} = 1.073_{-0.029}^{+0.031}$
 $\chi^2 = 405.8/408$ dof

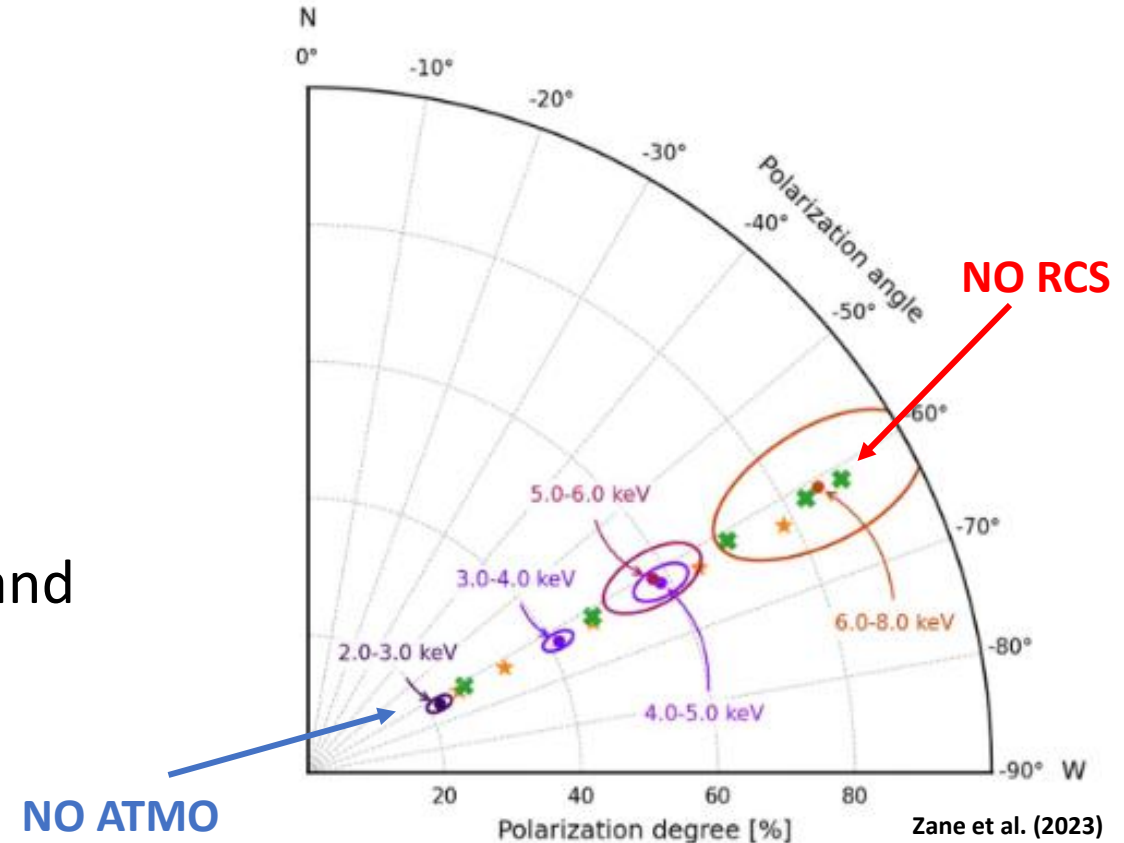


- 2nd brightest magnetar
- $B_{p\dot{p}} \approx 5 \times 10^{14}$ G
- Spectrum BB+PL or BB+BB?
- Polarization measurement (837 ks):
 - PD = 35% (22.5σ) – PA $\approx 60^\circ$ W
 - Polarization direction is constant in the IXPE band
 - PD at 6–8 keV: $\approx 85\%$ ($MDP_{99} = 50\%$)



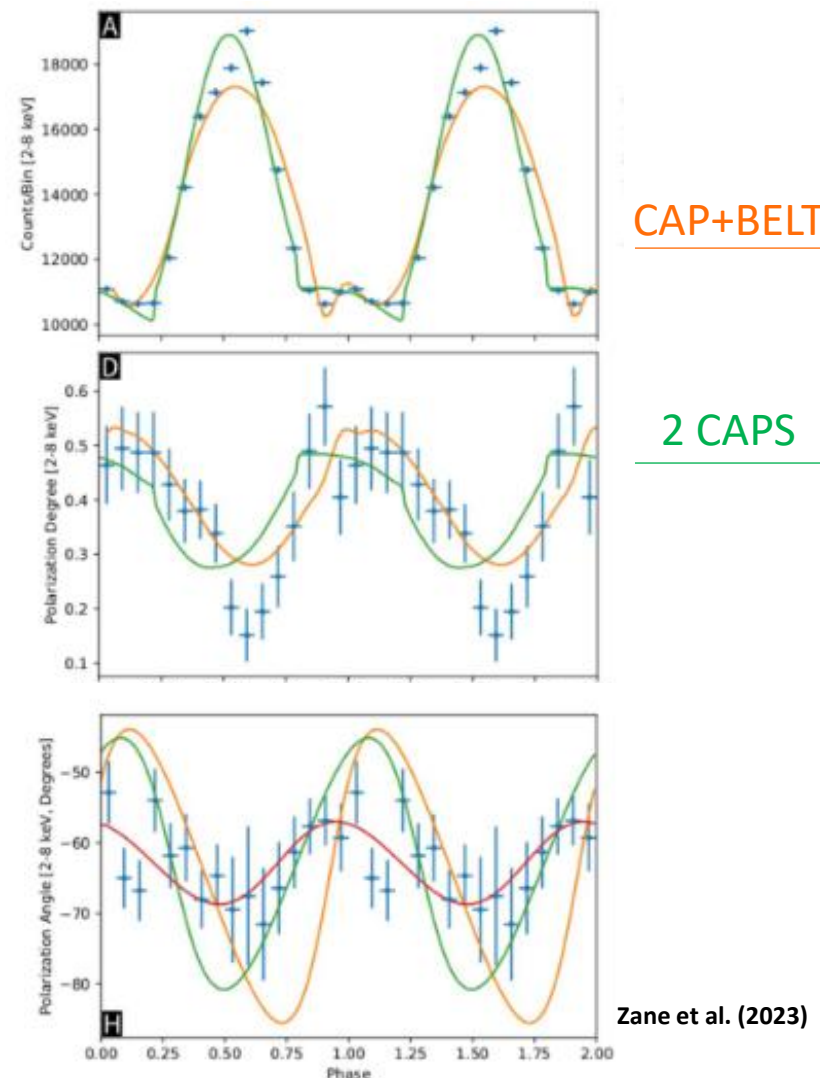
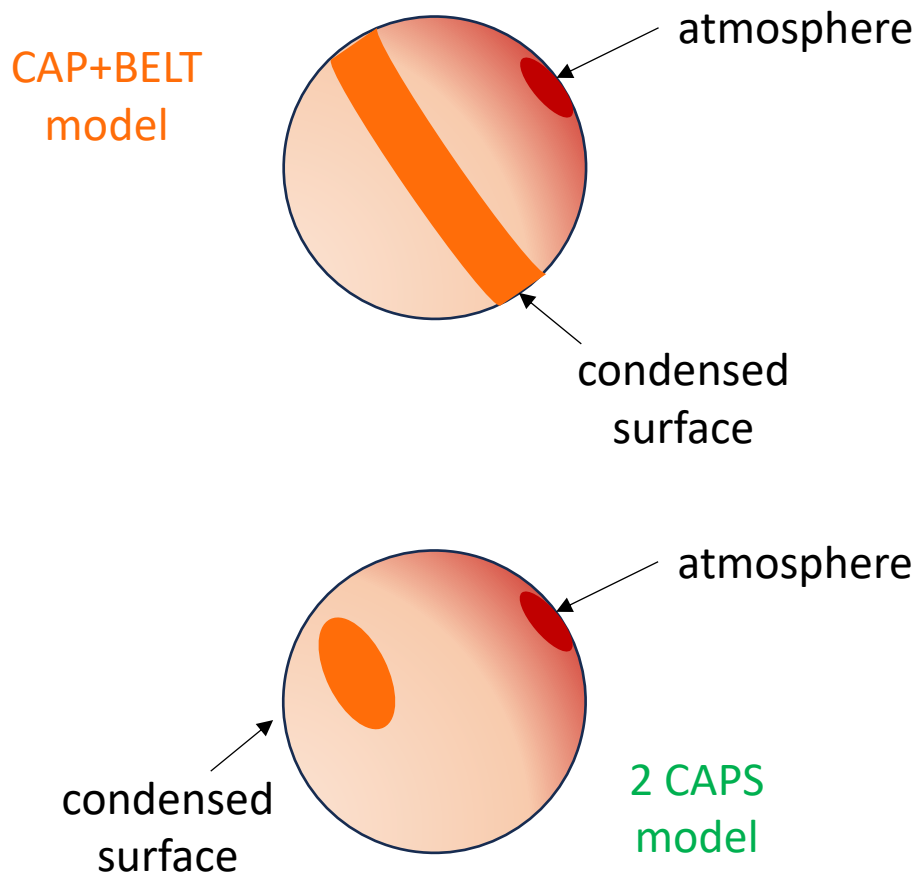
AXP 1RXS J170849.0–4009100

- 2nd brightest magnetar
- $B_{p\dot{p}} \approx 5 \times 10^{14}$ G
- Spectrum BB+PL or BB+BB?
- Polarization measurement (837 ks):
 - PD = 35% (22.5σ) – PA $\approx 60^\circ$ W
 - Polarization direction is constant in the IXPE band
 - PD at 6–8 keV: $\approx 85\%$ ($MDP_{99} = 50\%$)



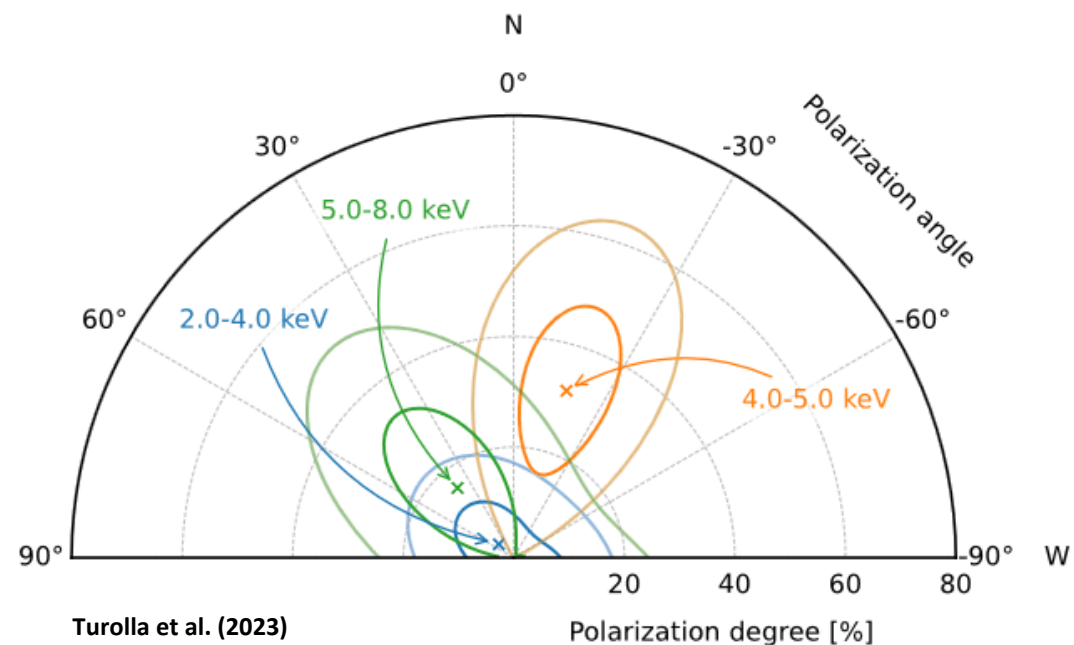
Interpretation (Zane et al. 2023)

- Phase transition across the surface



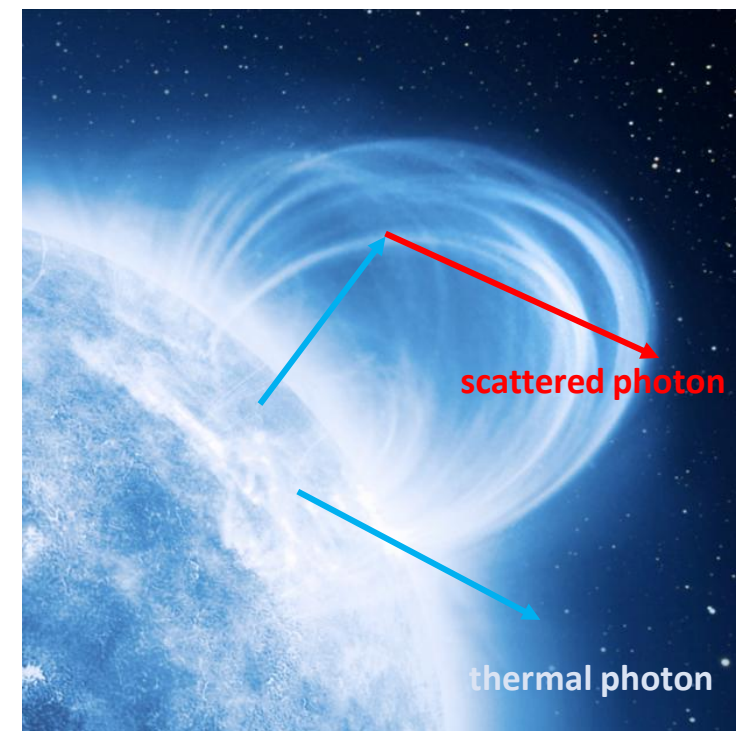
SGR 1806-20 (Turolla et al. 2023)

- XMM DDT observation
 - BB+PL spectral decomposition ($kT_{\text{BB}} = 0.59 \pm 0.04$ keV, $\Gamma = 1.7 \pm 0.1$)
 - Double-peaked pulse profile (P.F. $\approx 5\%$)
- IXPE observation (947 ks)
 - 2-8 keV – PD $\sim 6\%$ ($\text{MDP}_{99} \approx 20\%$)
 - Energy-dependent PD
 - $\lesssim 24\%$ (2–4 keV, 3σ u.l.)
 - $= 31.6 \pm 10.5\%$ (4–5 keV, 99% c.l. detection only «probable»)
 - $\lesssim 55\%$ (5–8 keV, 3σ u.l.)



- $B_{p\dot{p}} \approx 6 \times 10^{13}$ G (low- B)
- Spectral fit BB+PL is not good enough \rightarrow adding an **absorption line** (Pizzocaro+19) improves the fit
- XMM contemporary observation

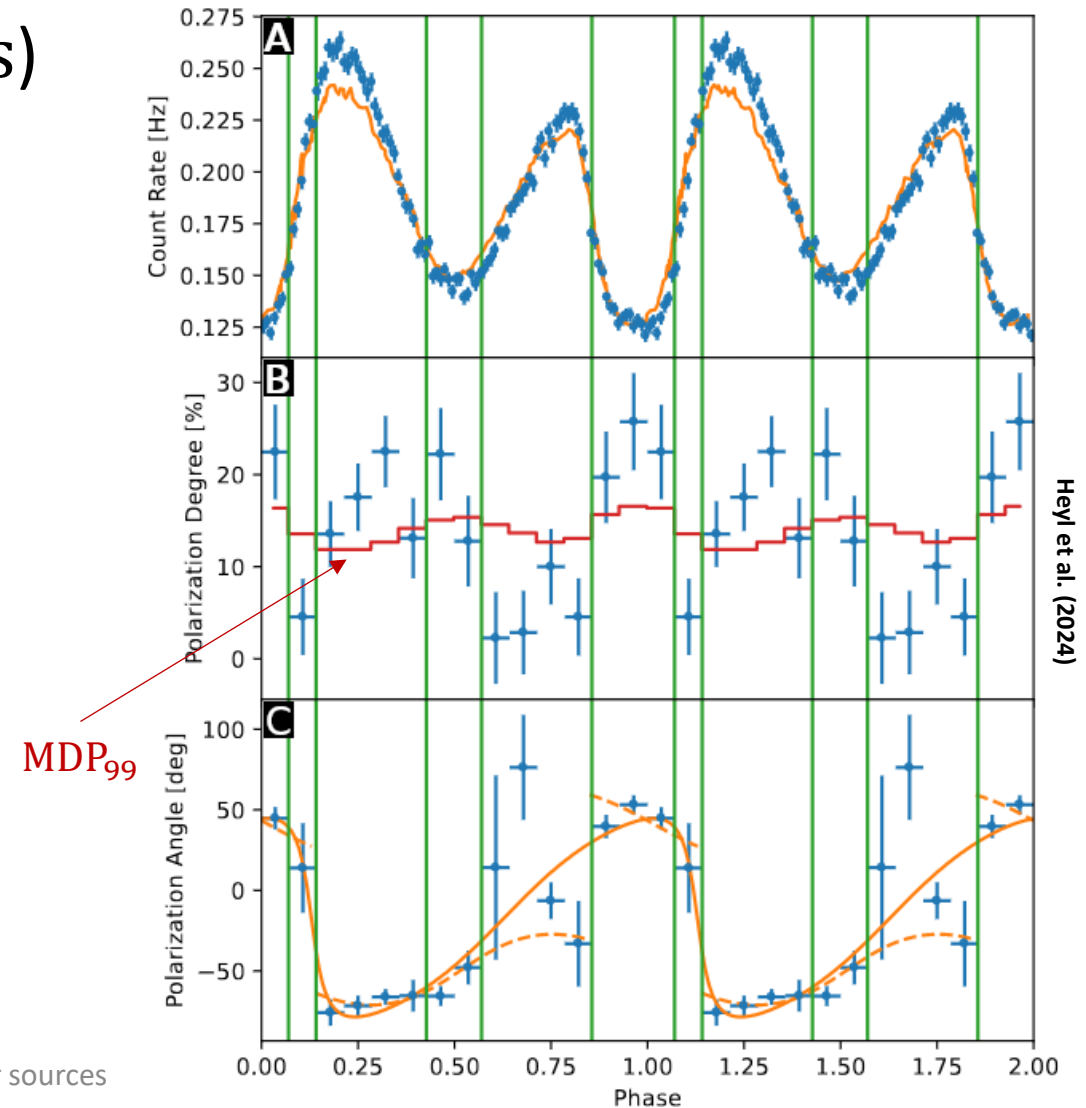
	kT_{BB} (keV)	Γ	E_{line} (keV)	σ_{line} (keV)	χ^2/dof
XMM	0.44 ± 0.01	4.09 ± 0.08	$0.96^{+0.07}_{-0.18}$	$0.23^{+0.10}_{-0.06}$	94.1/93
IXPE	0.43 ± 0.01	4.36 ± 0.09	frozen	frozen	138.0/147



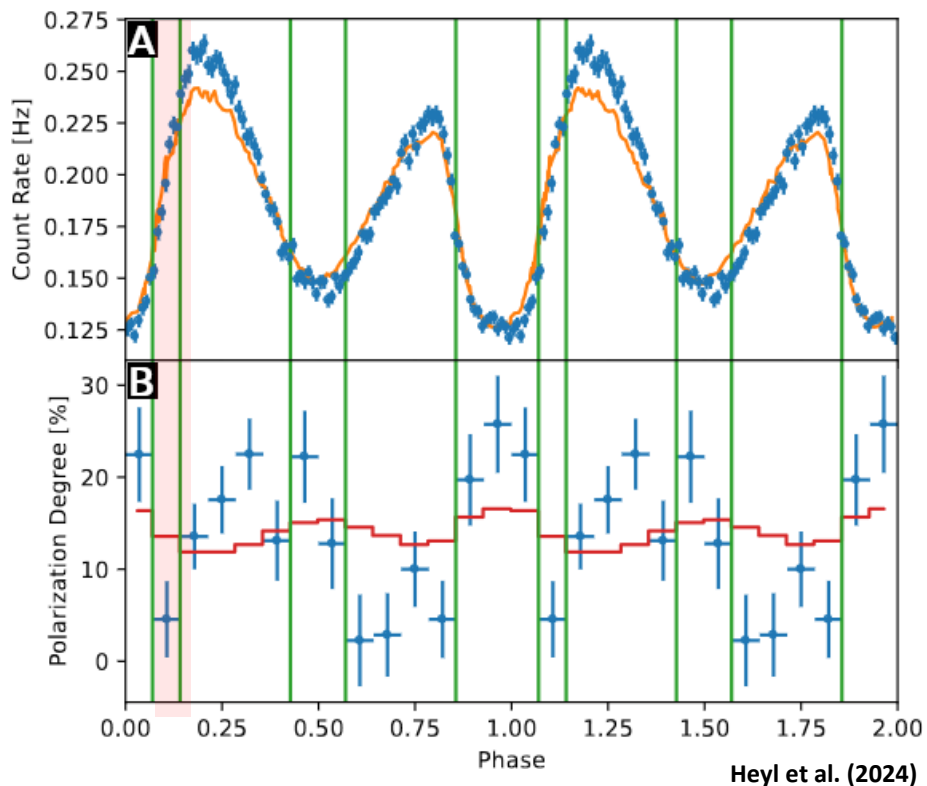
Credit: ESA Science & Technology

Observation (Heyl et al. 2024)

- IXPE phase-dependent observation (1.2 Ms)
 - Polarization up to $\approx 30\%$ (well above MDP_{99}) at particular phases (corresponding to the rise and maximum of the primary LC peak)
 - Secondary peak basically unpolarized
 - PA well fitted by a RVM in which photons are assumed to change mode (from O- to X- and vice versa)

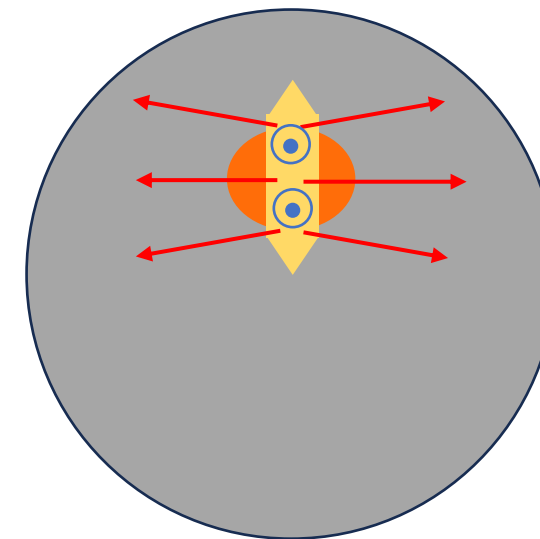


- Theoretical interpretation (in terms of the magnetic-loop model)

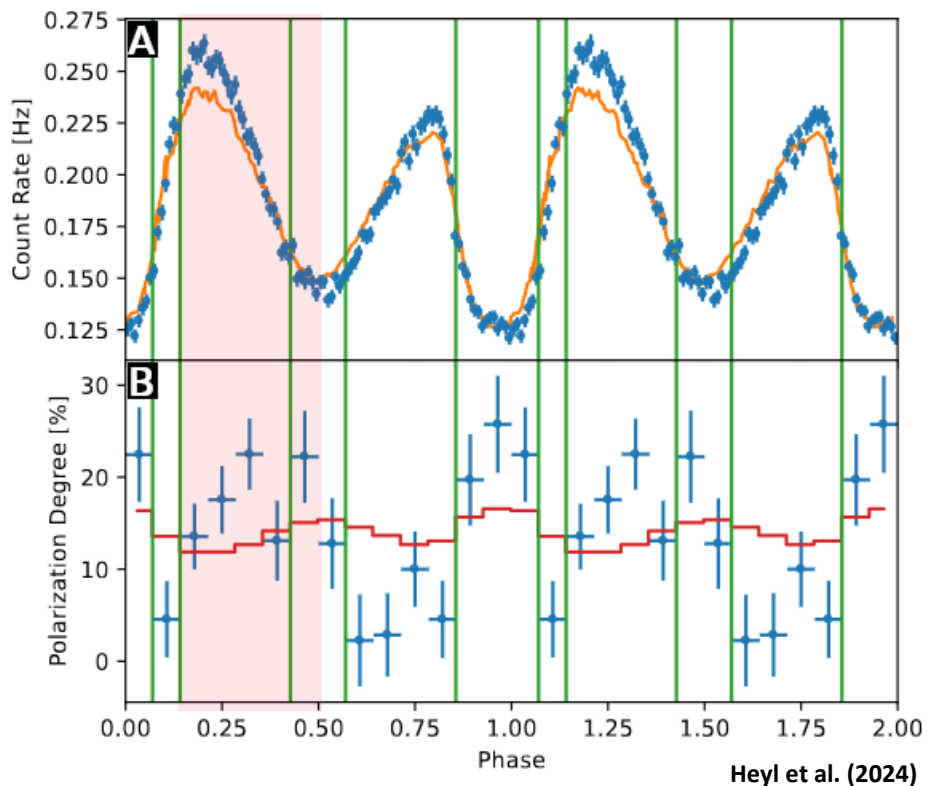


1st rise

- unscattered (O-mode) photons (lowly polarized) are directly intercepted
- scattered photons (at most 33% X-mode) are deviated away from the LOS

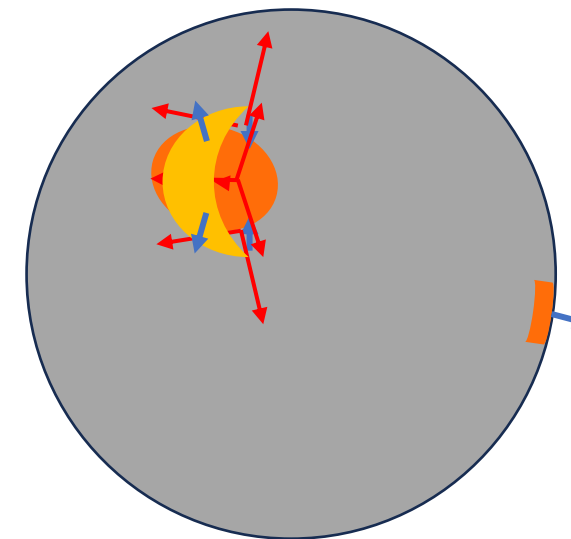


- Theoretical interpretation (in terms of the magnetic-loop model)

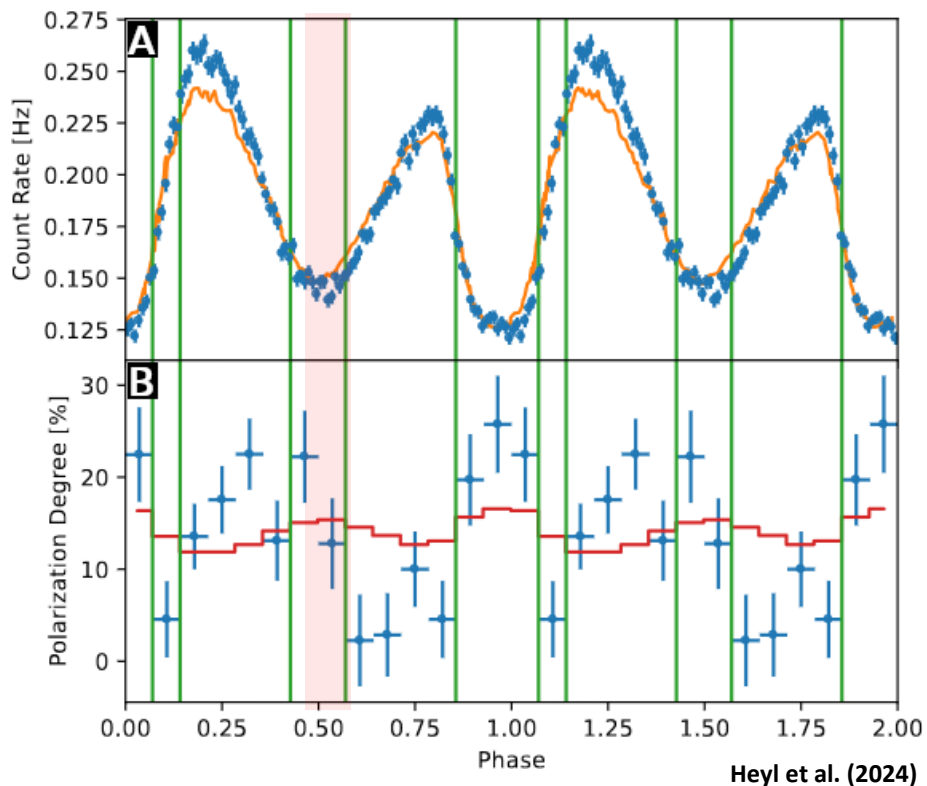


1st peak

- scattered X-mode photons are now intercepted (with also primary O-mode ones from the underlying spot → peak in the flux)
- polarization increases
- contamination from O-mode condensed-surface photons prevent PD to reach 33%

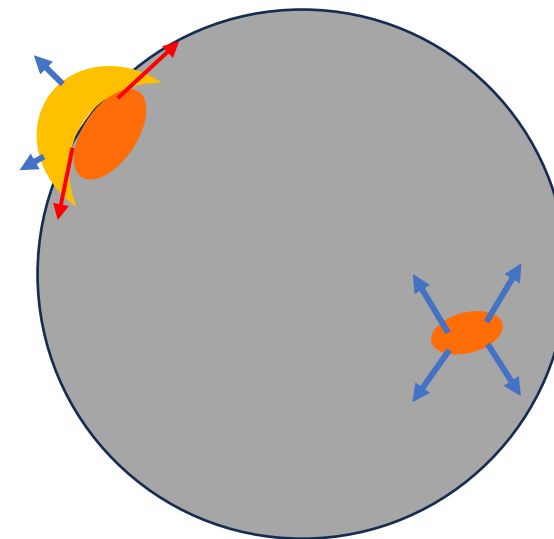


- Theoretical interpretation (in terms of the magnetic-loop model)

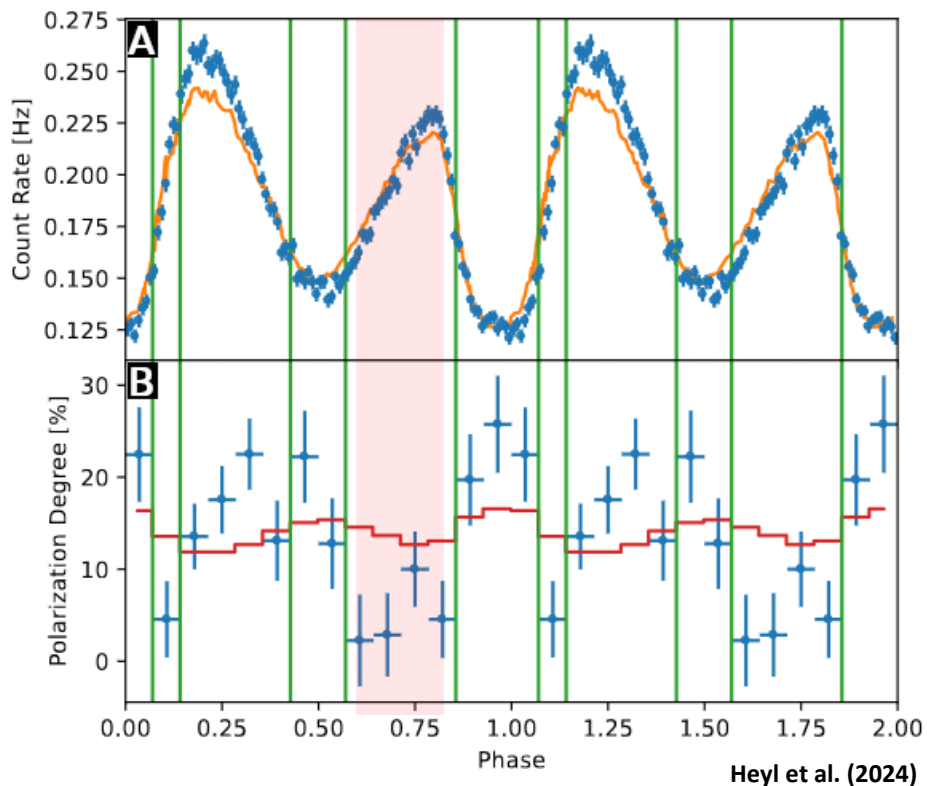


Little dip

- the larger spot starts to be hidden behind (only a fraction of mildly polarized photons are observed)
- the secondary spot (with no loop) enters in view (emitting low-polarized O-mode photons)

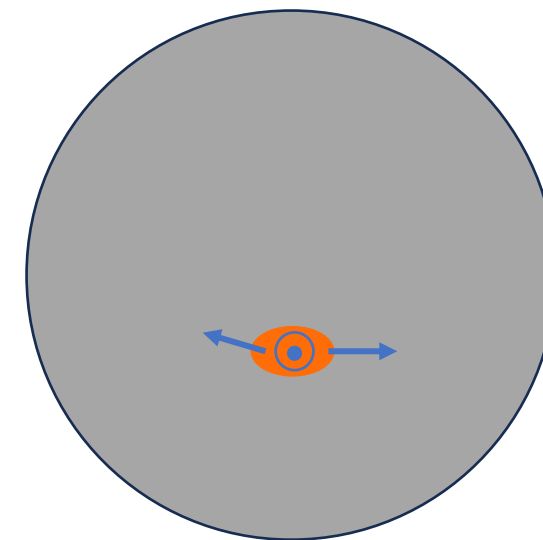


- Theoretical interpretation (in terms of the magnetic-loop model)

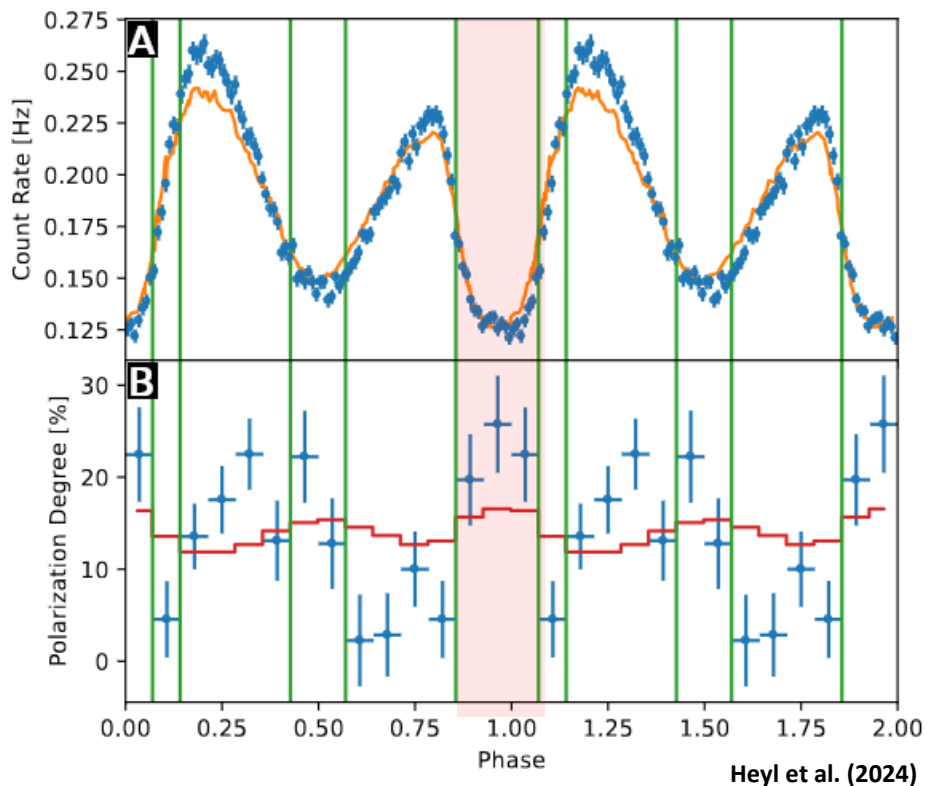


2nd peak

- the secondary spot is fully in view (peak in the flux)
- only condensed-surface photons collected (O-mode, polarized at no more than 10–15%)

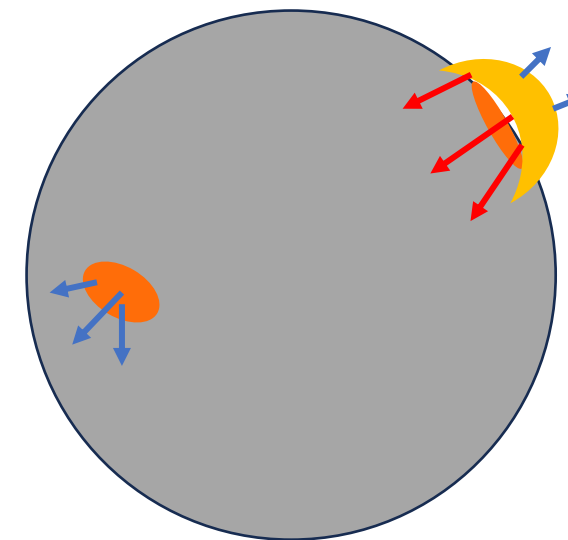


- Theoretical interpretation (in terms of the magnetic-loop model)



Big dip

- secondary spot photons are not in view
- the primary peak returns in view
- X-mode scattered photons along the LOS are intercepted first (minimum in the flux, maximum in PD)



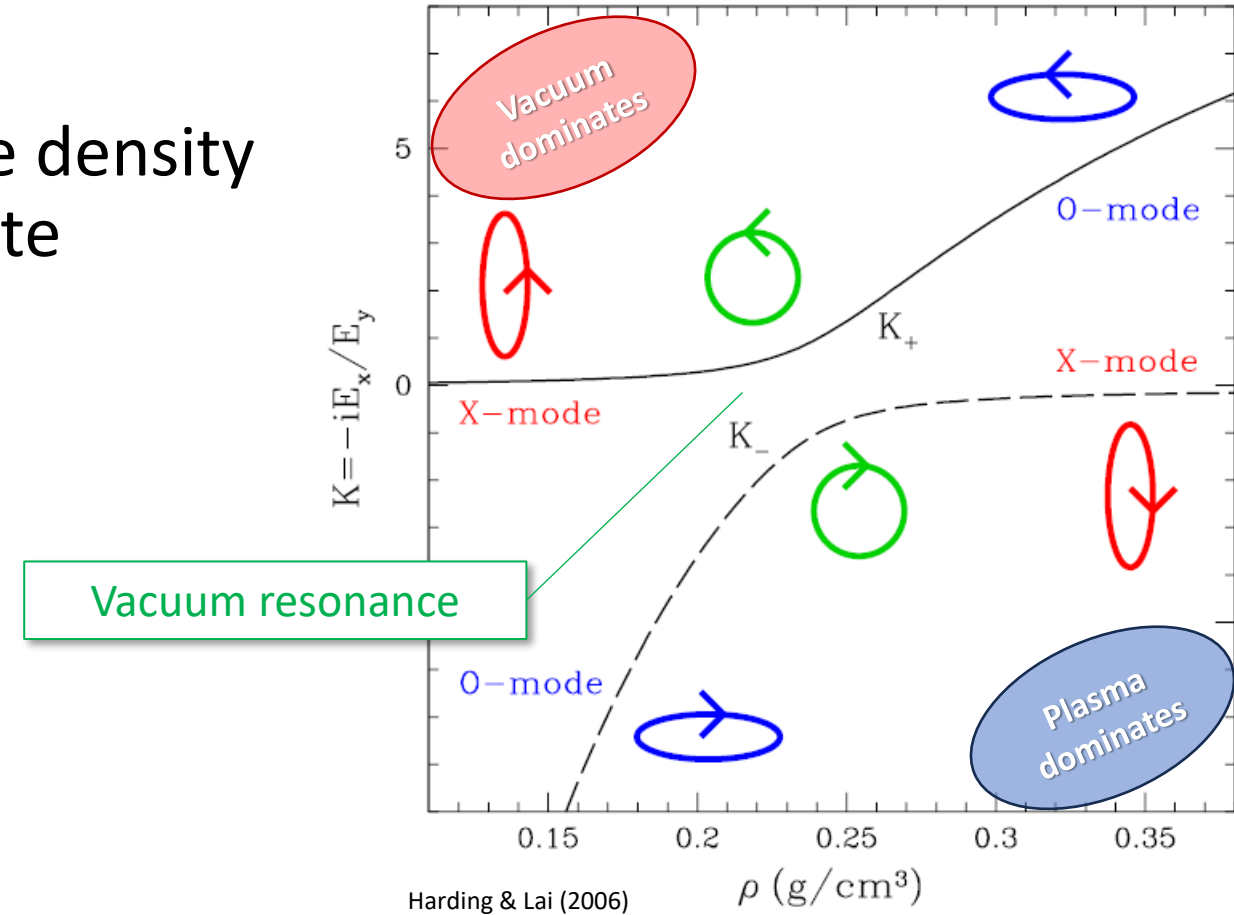
- X-ray polarimetry on magnetar sources complemented information from spectral and timing analysis
- Detection of photons polarized in two normal modes in 4U 0142 confirmed the presence of strong magnetic fields ($\gtrsim 5 \times 10^{13}$ G) independently of $P\dot{P}$
- Energy-dependent PD and PA allowed to confirm the expectations of the RCS model
- Phase-dependent PD and PA provided a first hint that vacuum birefringence effects are at work around magnetars
- Further magnetars should be explored in polarized X-rays (persistent and transient in outburst, softer X-ray energies)

Thanks!

Backup slides

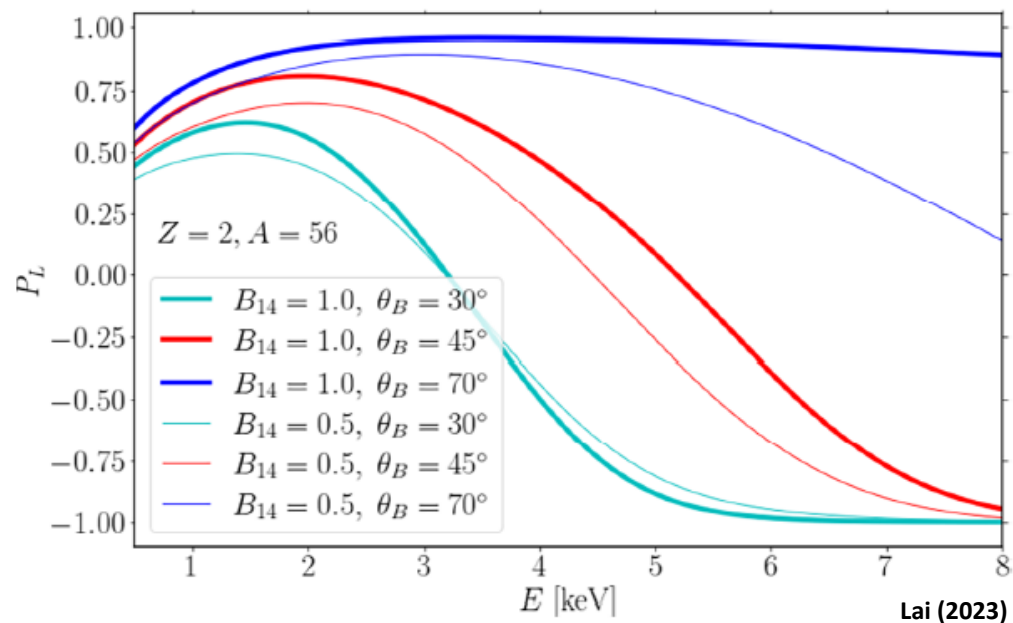
Normal modes of polarization

- For ultra strong B -fields ($\gtrsim B_Q$) photons at X-ray energies are linearly polarized in two normal modes
- Polarization evolution depends on the density of material in which photons propagate

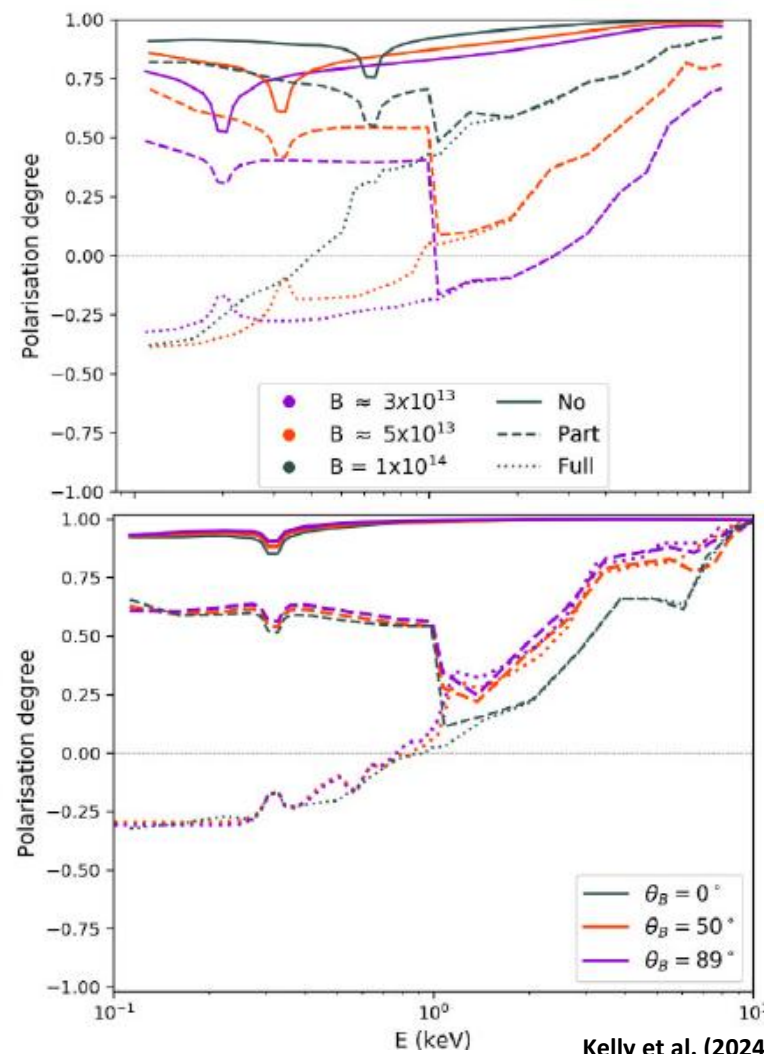


Harding & Lai (2006)

- Mode switching in 4U 0142+61 as a consequence of partial mode conversion at the vacuum resonance (Lai 2023)



- Not without problems (once scattering/free-free and integration over the whole surface are considered \Rightarrow no mode switching in the IXPE band)



Harding & Lai (2006)

ρ (g/cm^3)

Polarization transport in the magnetized vacuum

- Solving the wave equation accounting for vacuum effects only it reduces to

$$\frac{2}{k_0 \delta(B)} \frac{dE_x}{dz} = i[M E_x + P E_y] \quad \frac{2}{k_0 \delta(B)} \frac{dE_y}{dz} = i[P E_x + N E_y]$$

Polarization transport in the magnetized vacuum

- Solving the wave equation accounting for vacuum effects only it reduces to

$$\frac{2}{k_0 \delta(B)} \frac{dE_x}{dz} = i [ME_x + PE_y]$$

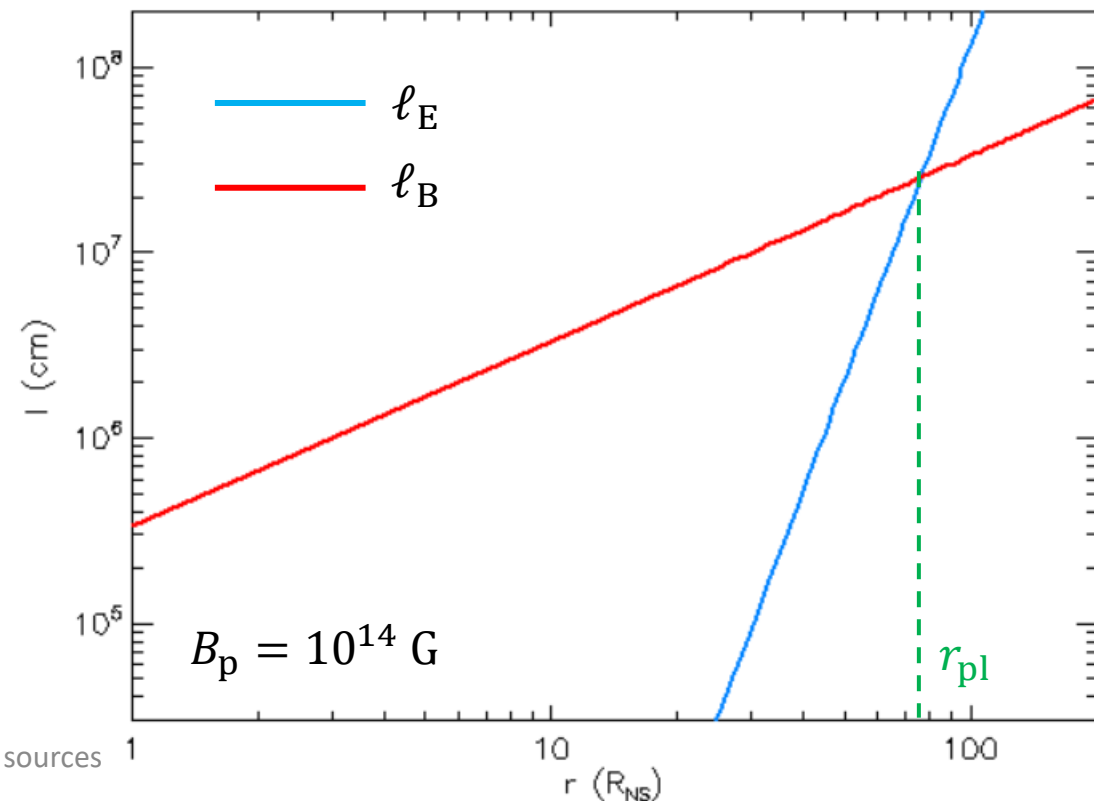
$$\frac{2}{k_0 \delta(B)} \frac{dE_y}{dz} = i [PE_x + NE_y]$$

E-field evolution length:

$$\ell_E = \frac{2}{k_0 \delta} \approx 130 \left(\frac{B}{10^{11} \text{ G}} \right)^{-2} \left(\frac{\hbar \omega}{1 \text{ keV}} \right)^{-1} \text{ cm}$$

(Dipolar) *B*-field evolution length:

$$\ell_B = \frac{B}{|\mathbf{k} \cdot \nabla B|} \approx \frac{r}{3}$$



Polarization transport in the magnetized vacuum

- Solving the wave equation accounting for vacuum effects only it reduces to

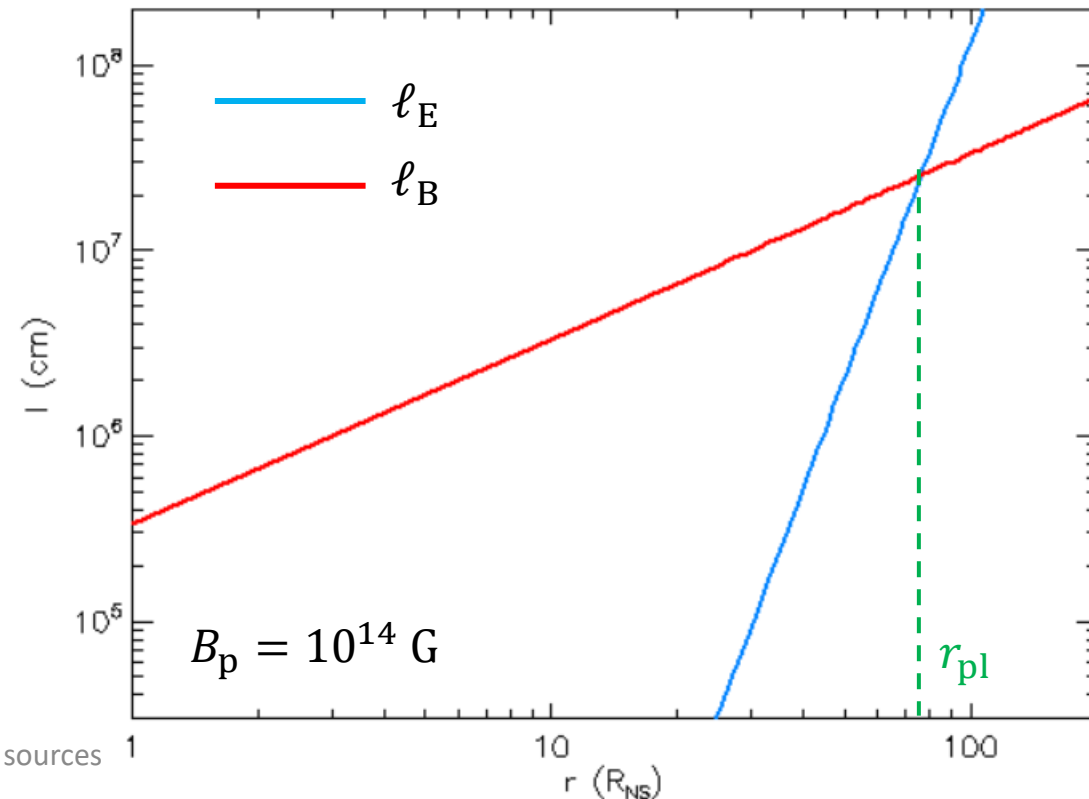
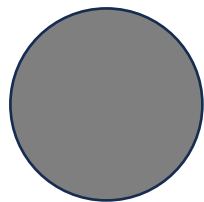
$$\frac{2}{k_0 \delta(B)} \frac{dE_x}{dz} = i [ME_x + PE_y]$$

$$\frac{2}{k_0 \delta(B)} \frac{dE_y}{dz} = i [PE_x + NE_y]$$

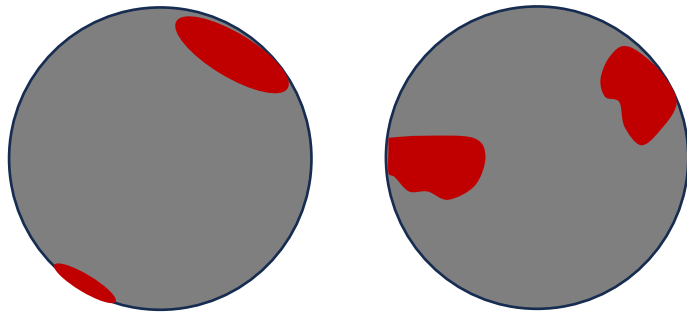
$\ell_E \gg \ell_B$: \mathbf{E} direction is frozen

$r_{pl} (\ell_E = \ell_B)$

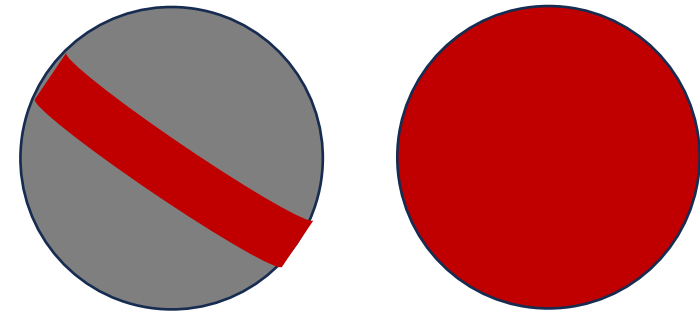
$\ell_E \ll \ell_B$: \mathbf{E} direction changes



Vacuum birefringence – Extension of emitting regions



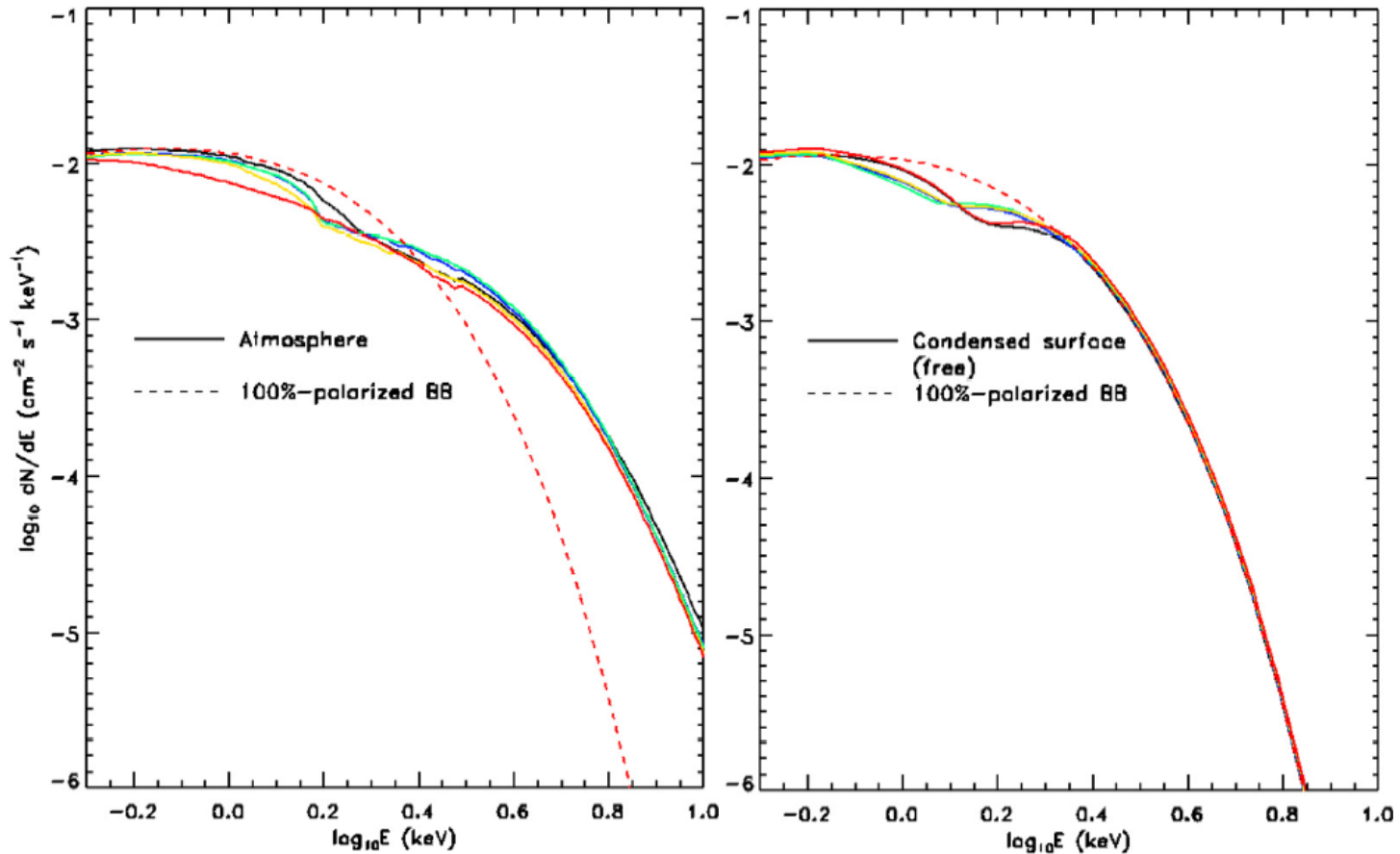
If emitting regions on the surface are small depolarization due to the tangled magnetic field is not much effective (van Adelsberg & Perna 09)



For large emitting regions (or the entire surface) geometrical depolarization may be much more important (surface 100% → 40% at infinity, Taverna+ 20)

CS vs ATMO – Removing spectral degeneracy

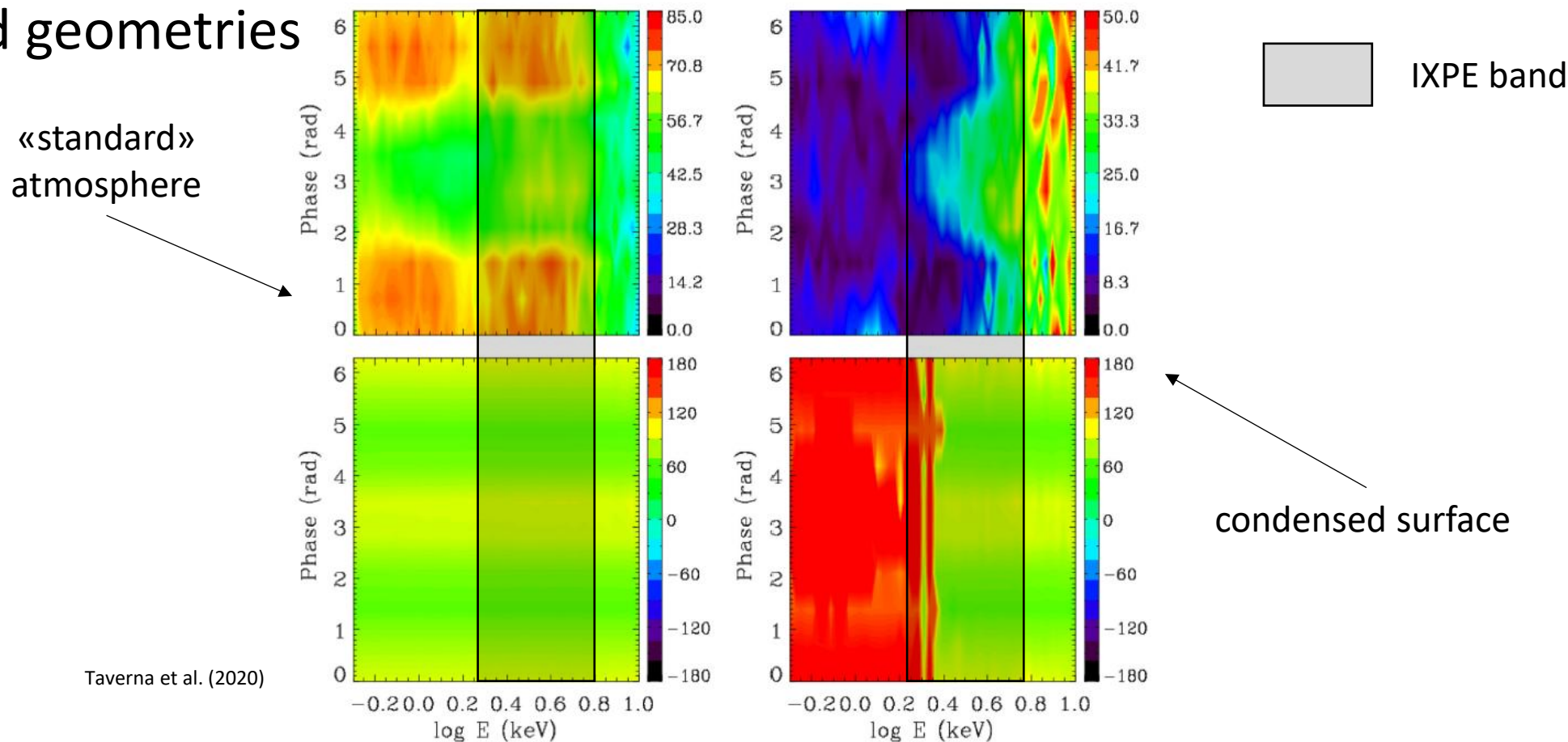
- Spectra for atmosphere and condensed-surface model are similar (BB-like)



Taverna et al. (2020)

CS vs ATMO – Removing spectral degeneracy

- Spectra for atmosphere and condensed-surface model are similar (BB-like)
- Different behaviors of PA with energy are expected for particular emission models and geometries

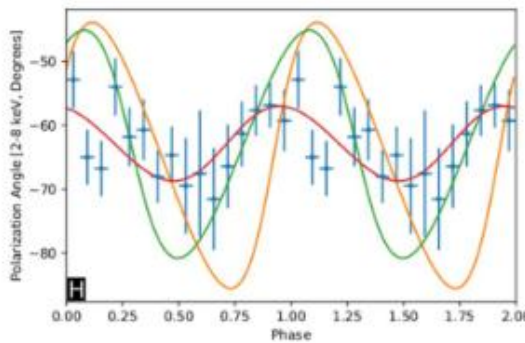
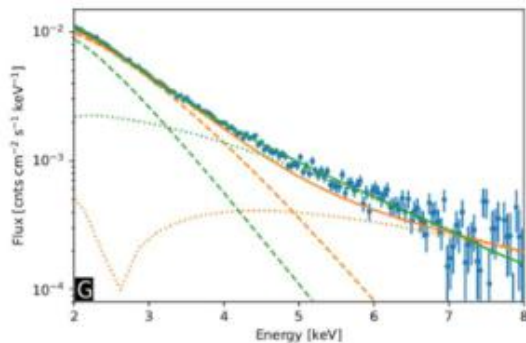
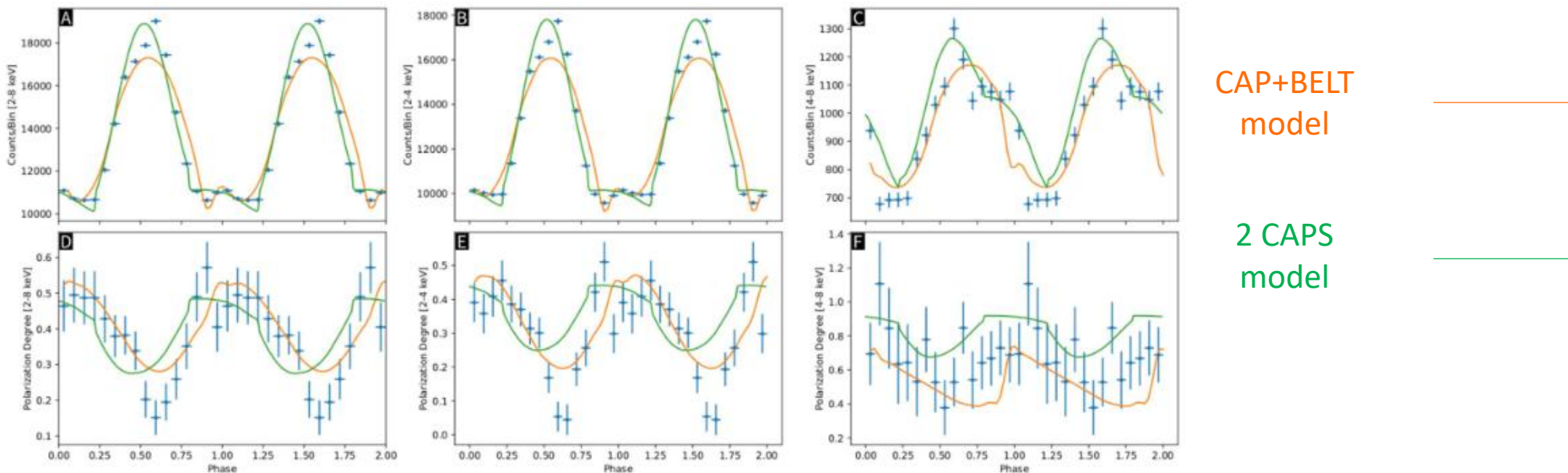


Taverna et al. (2020)

- **AXP 4U 0142+61** (R.A. 01:46:22.41, DEC. 61°45'03".2)
 - Cassiopeia – Distance: 3.6 kpc
 - January 31st – February 27th 2022 (840 ks)
 - Unabsorbed flux (2–10 keV): 6×10^{-11} erg cm⁻² s⁻¹
- **AXP 1RXS J170849.0–4009100** (R.A. 17:08:46.3, DEC. –40°08'44".6)
 - Scorpio – Distance: 5–10 kpc
 - September 19th – October 8th 2022 (837 ks)
 - Unabsorbed flux (2–10 keV): 2.4×10^{-11} erg cm⁻² s⁻¹
- **SGR 1806–20** (R.A. 18:08:39.8, DEC. –20°24'26".7)
 - Sagittarius – Distance: 8.7 kpc
 - March 22nd – April 13th 2023 (947 ks)
 - Unabsorbed flux (2–10 keV): 4×10^{-12} erg cm⁻² s⁻¹

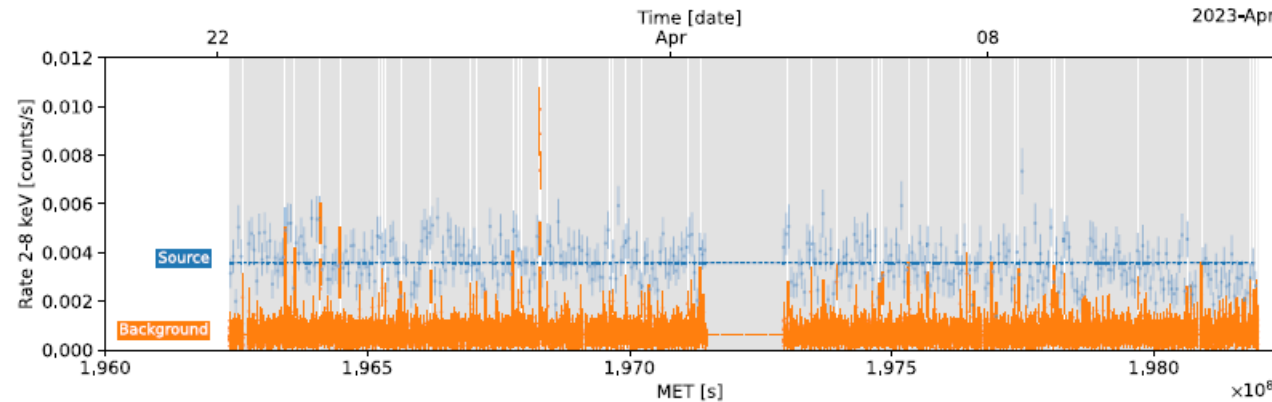
- **AXP 1E 2259+586** (R.A. 23:01:08.8, DEC. 58°52'20".8)
 - Cassiopeia – Distance: 3.2 kpc
 - June 2nd – July 6th 2023 (1.2 Ms)
 - Unabsorbed flux (2–10 keV): 1.4×10^{-11} erg cm⁻² s⁻¹

- Phase-dependent results



Zane et al. (2023)

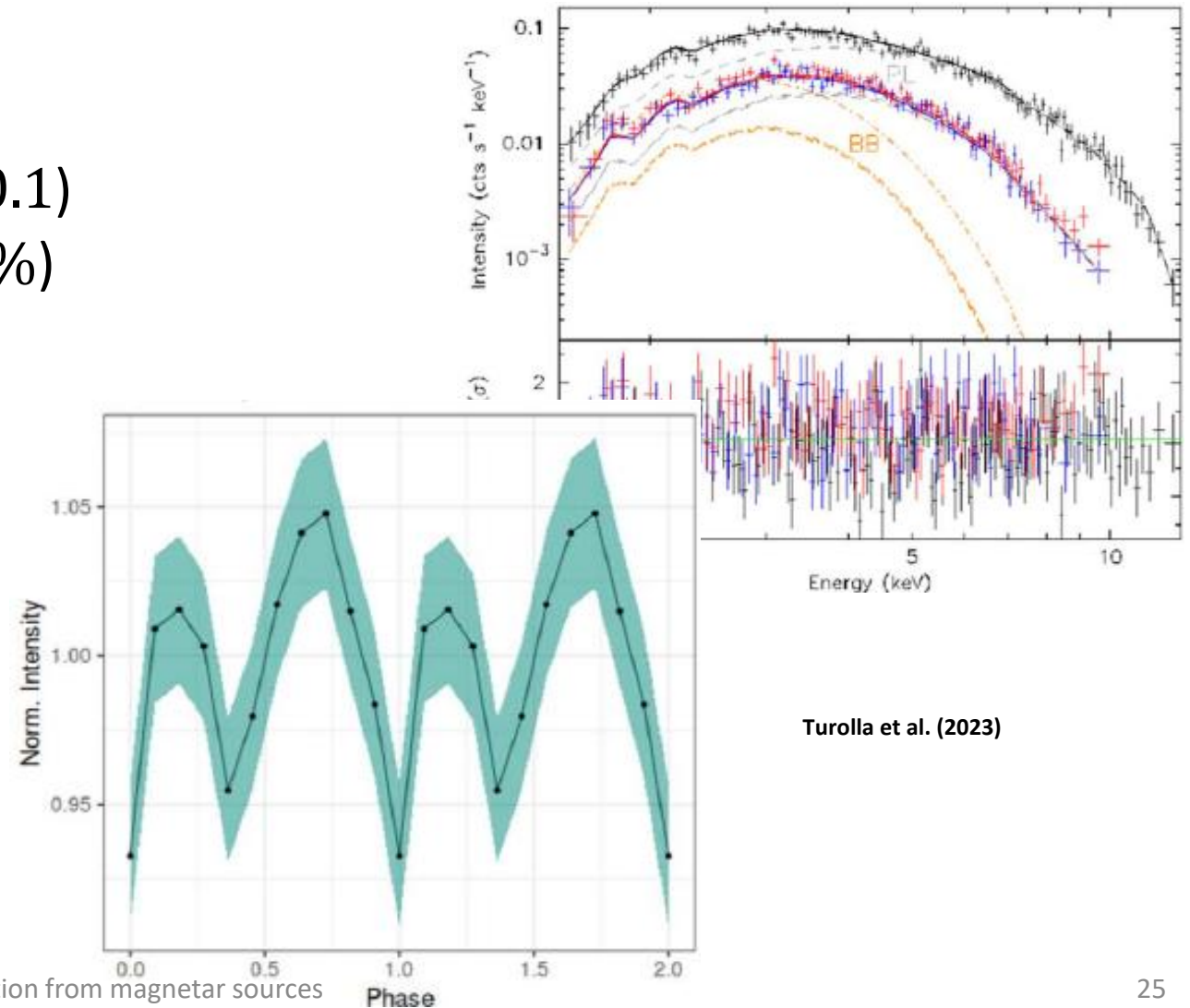
- Emitted the strongest giant flare ever detected (December 27, 2004)
- $B_{P\dot{P}} \approx 8 \times 10^{14}$ G (strongest B -field)
- Observed 1 month after an active phase (emission of a bunch of bursts)
- Flux lowered wrt quiescence ($\approx 10^{-12}$ erg cm $^{-2}$ s $^{-1}$, 1/10 than tabulated)
- Contamination by solar flares during IXPE observation



Turolla et al. (2023)

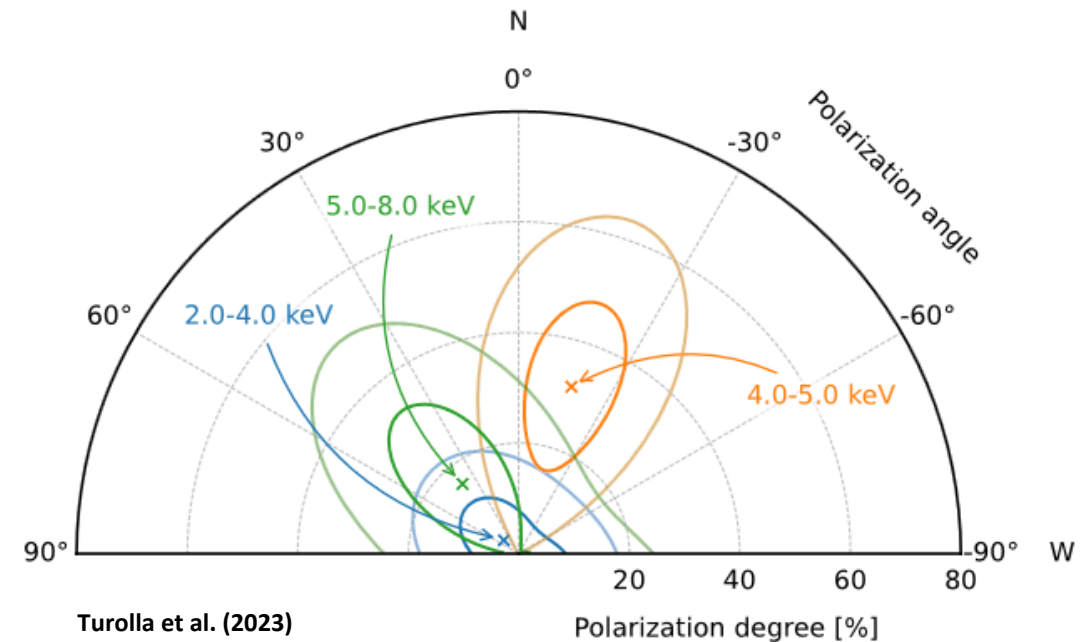
Observation (Turolla et al. 2023)

- XMM DDT observation
 - BB+PL spectral decomposition ($kT_{\text{BB}} = 0.59 \pm 0.04 \text{ keV}$, $\Gamma = 1.7 \pm 0.1$)
 - Double-peaked pulse profile (P.F. $\approx 5\%$)



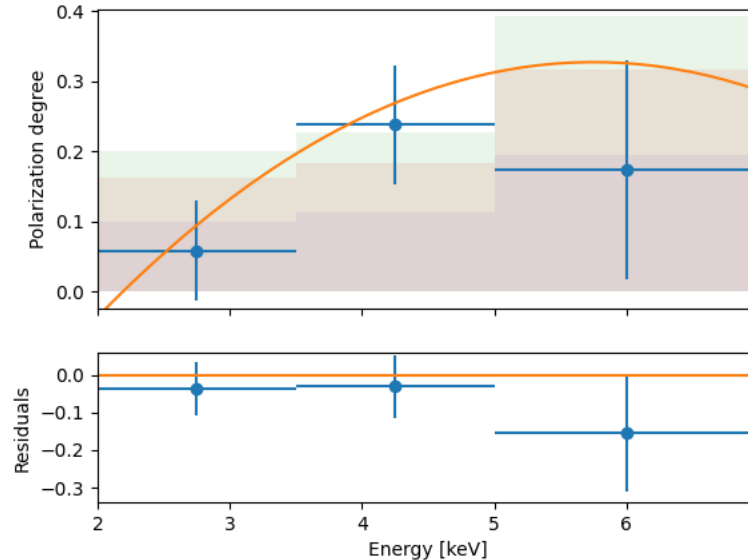
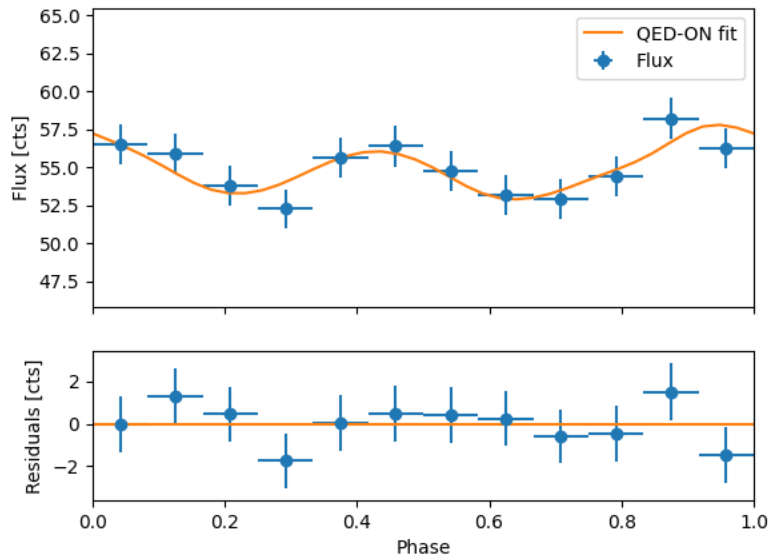
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- XMM DDT observation
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 - Double-peaked pulse profile (P.F. $\approx 5\%$)
- IXPE observation (947 ks)
 - 2-8 keV – PD $\sim 6\%$ ($\text{MDP}_{99} \approx 20\%$)
 - Energy-dependent PD
 - $\lesssim 24\%$ (2–4 keV, 3σ u.l.)
 - $= 31.6 \pm 10.5\%$ (4–5 keV, 99% c.l. detection only «probable»)
 - $\lesssim 55\%$ (5–8 keV, 3σ u.l.)



SGR 1806–20 – Theoretical interpretation

- Fitting the pulse profile with a condensed surface model + RCS (4U like) gives a energy-dependent PD not uncompatible with what IXPE found



— CS+RCS

