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Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA



Dipartimento
di Fisica
e Astronomia

UNIVERSITÀ DEGLI STUDI DI PADOVA

Agenzia Spaziale Italiana **ExplorE!**

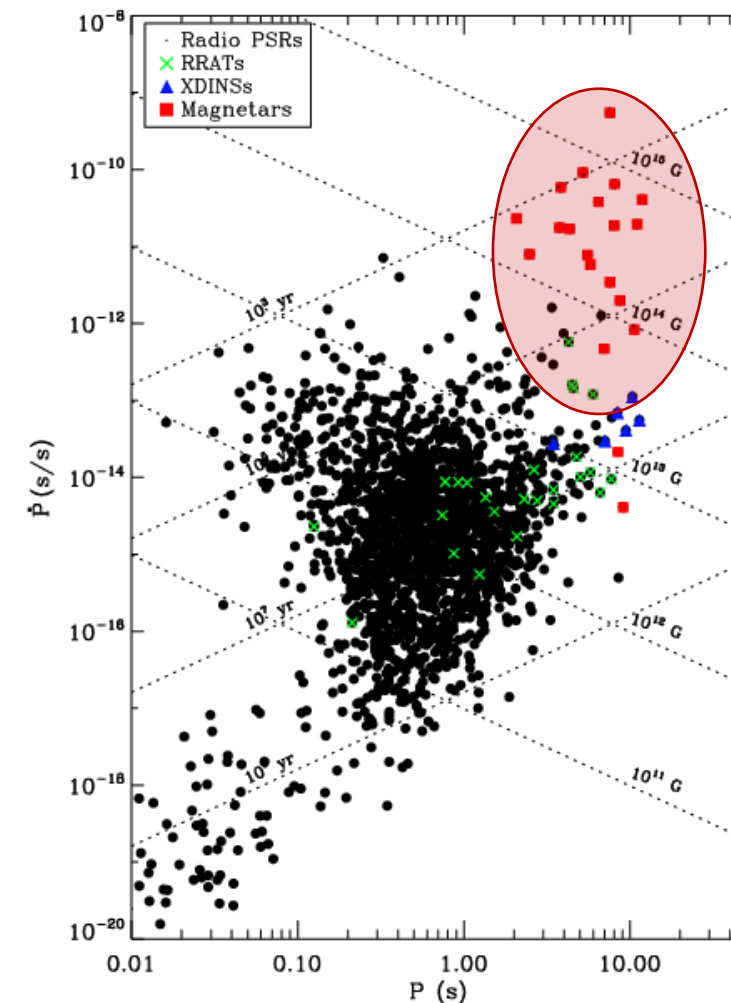
X-ray polarization from magnetar sources

17th Marcel Grossmann meeting

Galactic and extra-galactic magnetars: recent observations and
theoretical progress

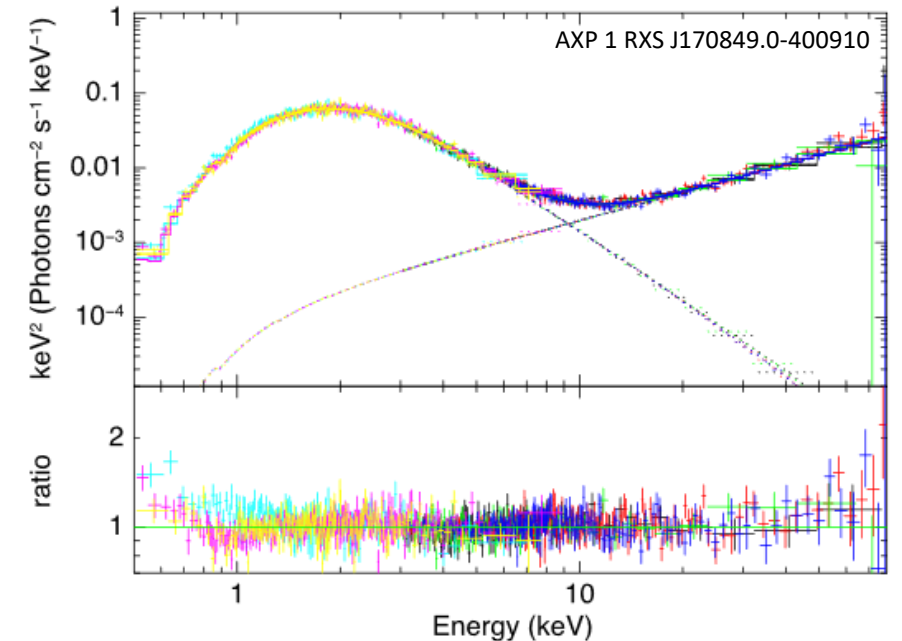
Pescara, July 12, 2024

- Persistent emission from 4 magnetar sources
 - 4U 0142+61
 - 1 RXS J170849.0–400910
 - SGR 1806–20
 - 1E 2259+586
- Strong B -fields in the range $6 \times 10^{13} - 10^{15}$ G (P - \dot{P} estimates)



Spectral properties

- Soft X-ray spectra (0.5–10 keV) usually fitted by BB+PL decomposition (alternative BB+BB, typical of transients in outburst)
- $kT_{\text{BB}} \approx 0.3\text{--}0.6$ keV and $\Gamma_{\text{PL}} \approx -(2\text{--}4)$ dominating above $\approx 3\text{--}4$ keV
- Additional PL component at higher energies ($\gtrsim 20$ keV)



Tendulkar et al. (2015)

Twisted-magnetosphere scenario

- The strong internal field (up to 10^{16} G) should develop a toroidal component at least of the same order
- Once the magnetic stress exceeds the crust mechanical yield, helicity is transferred to the external field

dipole

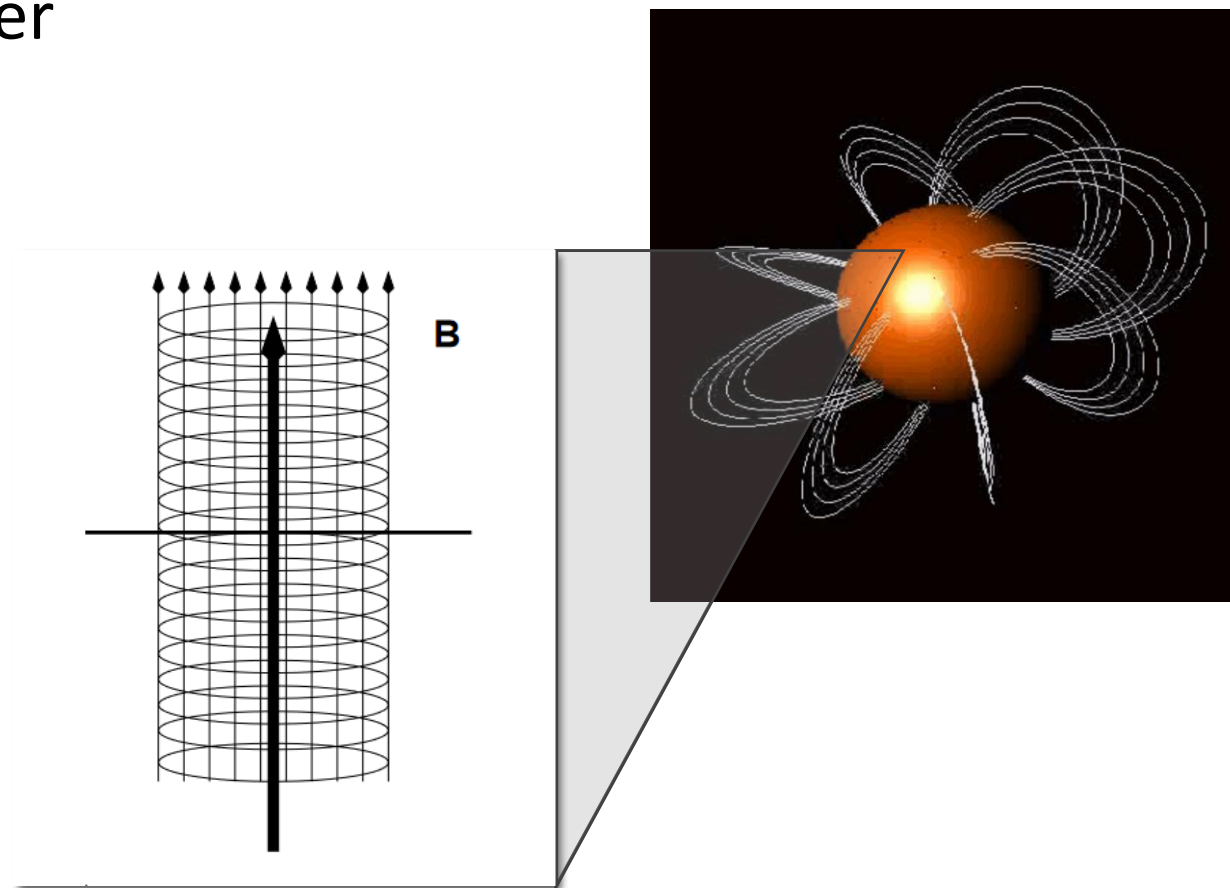
$$\mathbf{B} = [B_r, B_\theta, B_\phi] = \frac{B_p}{2} \left(\frac{R_{NS}}{r} \right)^3 [2 \cos \theta, \sin \theta, 0]$$



twisted dipole

$$\mathbf{B} = \frac{B_p}{2} \left(\frac{R_{NS}}{r} \right)^{2+p} \left[-\frac{df}{d \cos \theta}, \frac{pf}{\sin \theta}, \sqrt{\frac{pC(p) f^{1+1/p}}{p+1} \frac{1}{\sin \theta}} \right]$$

$$0 < p \leq 1$$



Twisted-magnetosphere scenario

$$\nabla \times \mathbf{B}_{\text{dip}} = 4\pi\mathbf{j}/c$$

||

0

no currents

↓

$$\nabla \times \mathbf{B}_{\text{twist}} = 4\pi\mathbf{j}/c$$

≠

0

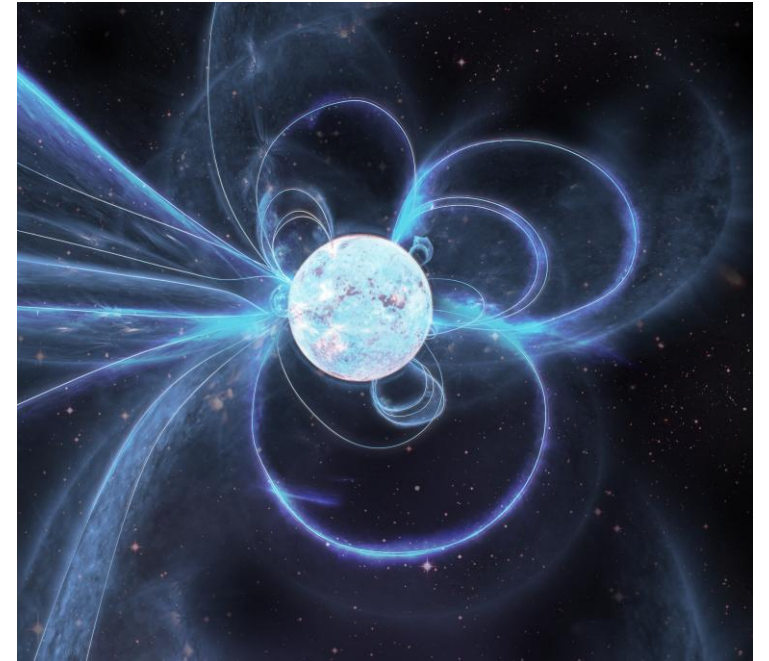
currents

↓

- Magnetosphere is populated by charged particles:

$$n_e \sim \frac{B}{r\beta} \left(\frac{B_\phi}{B_\theta} \right)$$

- The magnetosphere is optically thick for RCS



Magnetar model alternatives

- The $P-\dot{P}$ estimate of the magnetic field strength holds for:
 - dipolar fields (magnetar field topology not dipolar)
 - emission energy all supplied by rotation (need for another source of energy)
- Alternative models
 - strongly-magnetized ($\approx 10^9$ G) white dwarfs?
 - disrupting events for SGRs?

Polarimetry supports the magnetar model!

Polarization in strongly magnetized environments

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

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

magnetic permeability tensor (inverse)

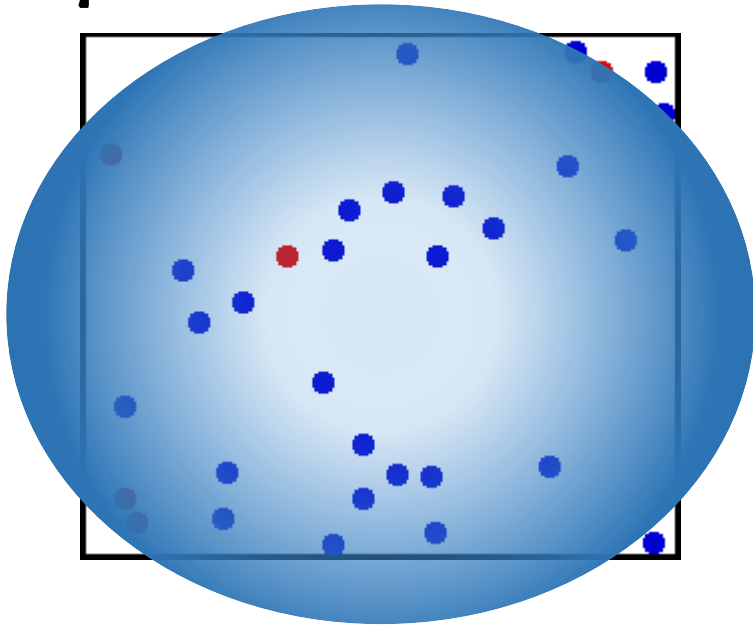
dielectric tensor

Polarization in strongly magnetized environments

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

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

- ϵ and $\bar{\mu}$ contain all the interaction terms



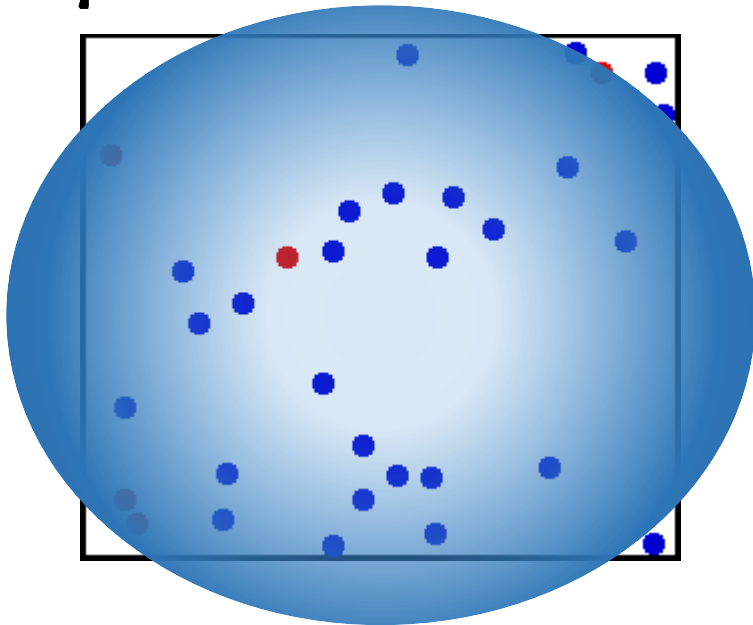
plasma

Polarization in strongly magnetized environments

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

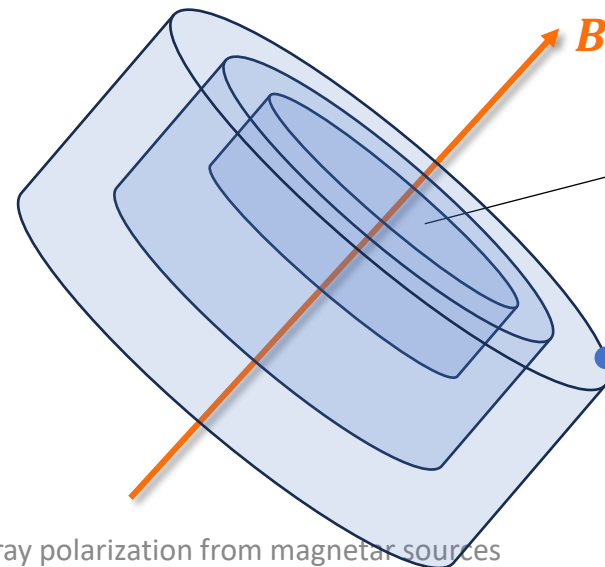
$$\nabla \times (\bar{\mu} \cdot \nabla \times \mathbf{E}) = \frac{\omega^2}{c^2} \epsilon \cdot \mathbf{E}$$

- ϵ and $\bar{\mu}$ contain all the interaction terms



plasma

In strong B fields the charge motion is quantized



1st Landau level energy

$$\hbar\omega_B = \frac{\hbar e B_Q}{m_e c} = m_e c^2$$

↓

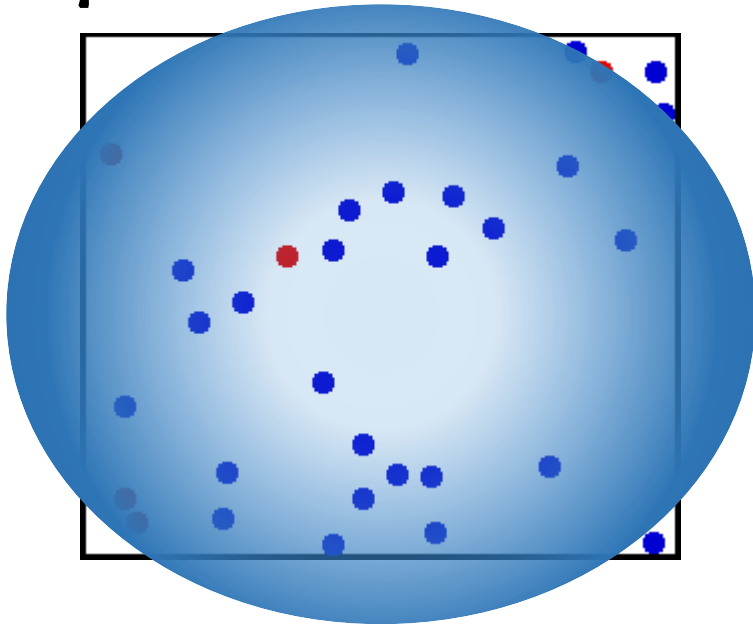
$$B_Q = \frac{m_e^2 c^3}{\hbar e} = 4.414 \times 10^{13} \text{ G}$$

Polarization in strongly magnetized environments

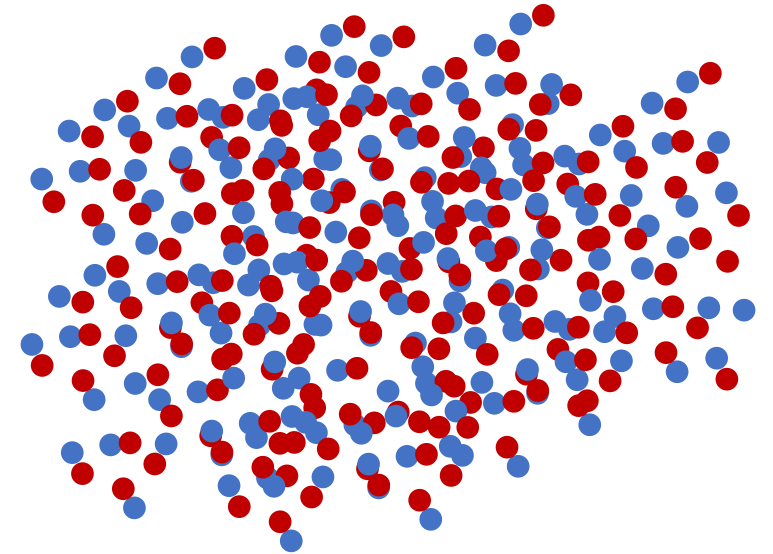
- The polarization state of photons can be studied solving the wave equation

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plasma



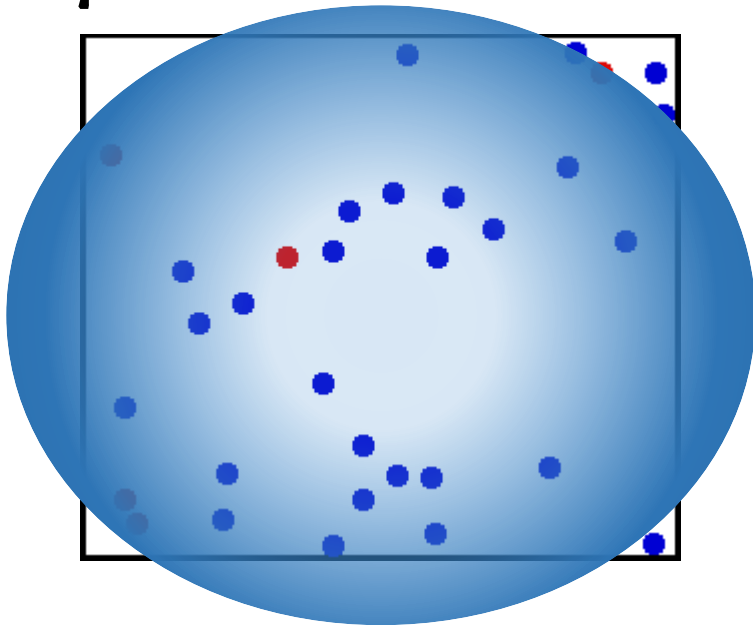
vacuum

Polarization in strongly magnetized environments

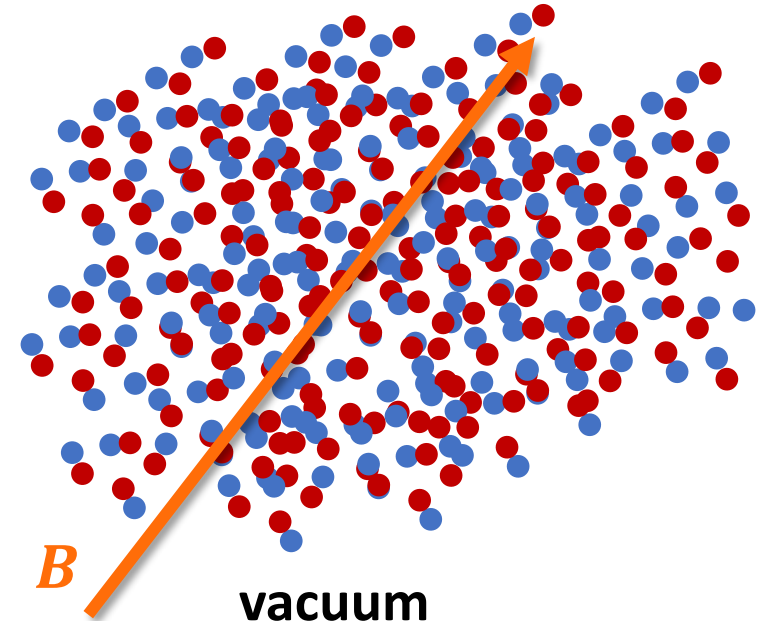
- The polarization state of photons can be studied solving the wave equation

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plasma



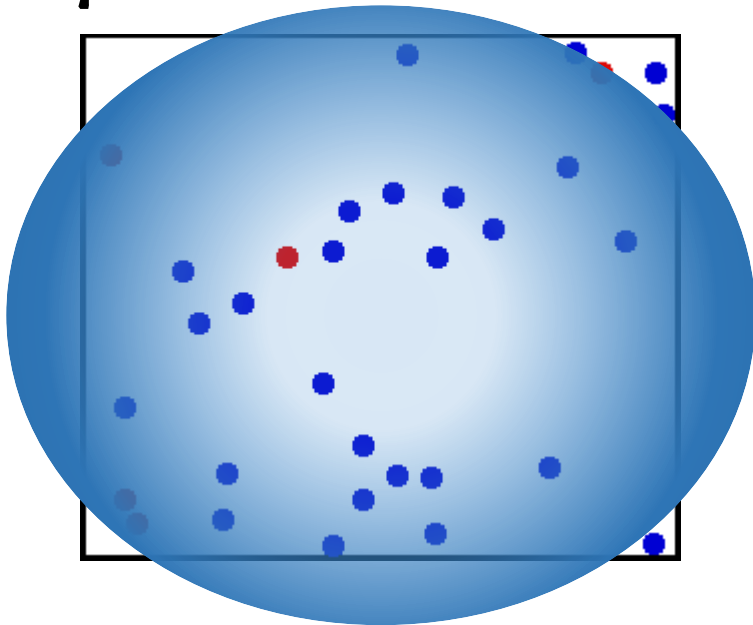
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Polarization in strongly magnetized environments

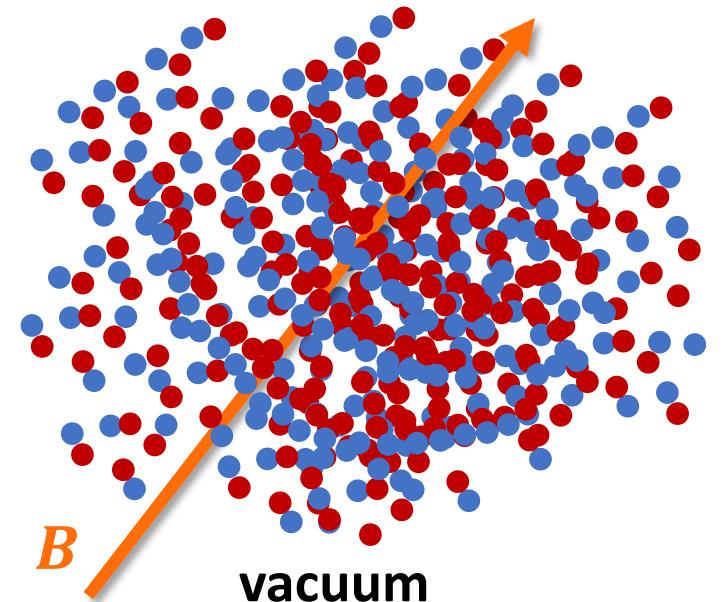
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plasma



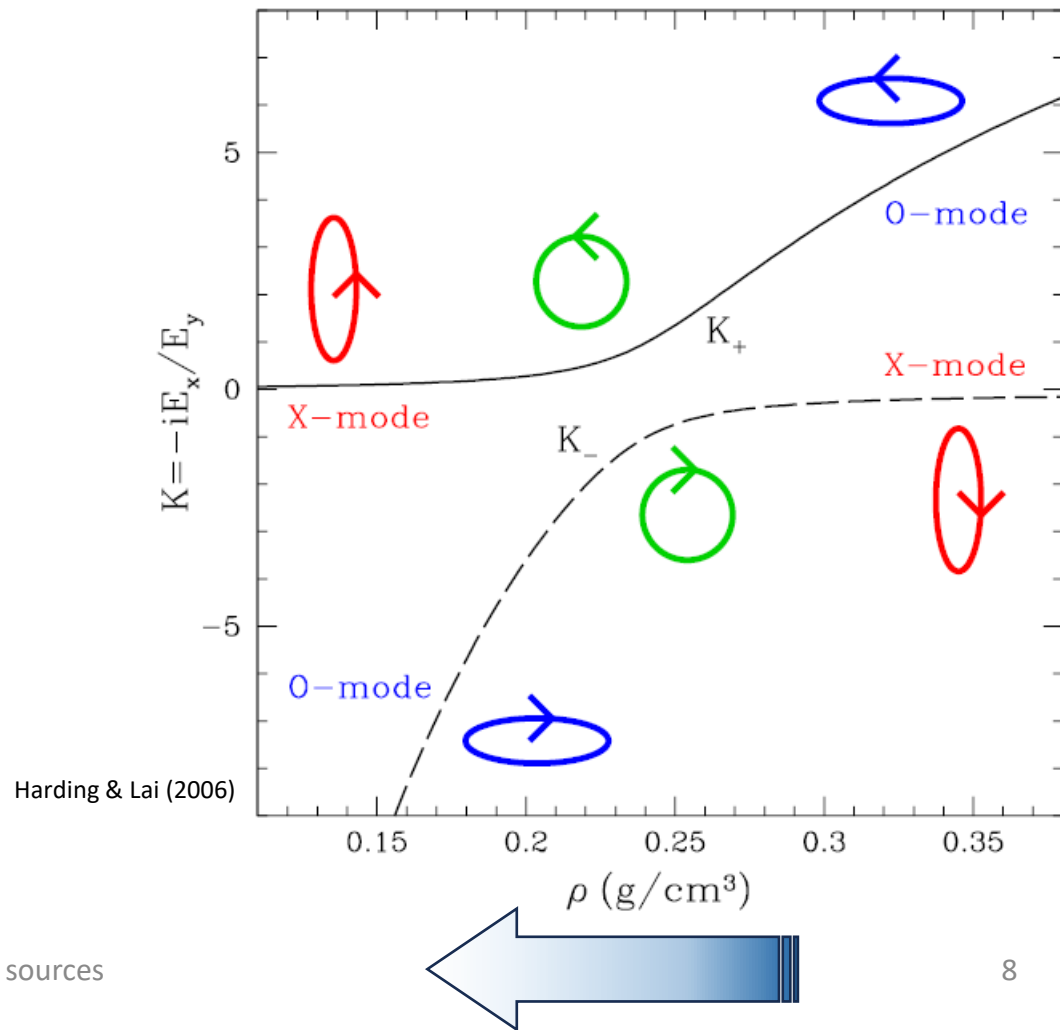
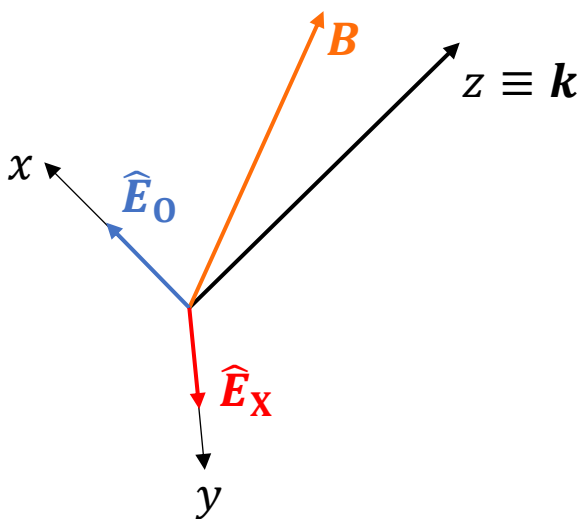
vacuum

Normal modes of polarization

- Where plasma or vacuum terms dominate in the dielectric tensor radiation is approximately linearly polarized

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

Ordinary mode Extraordinary mode

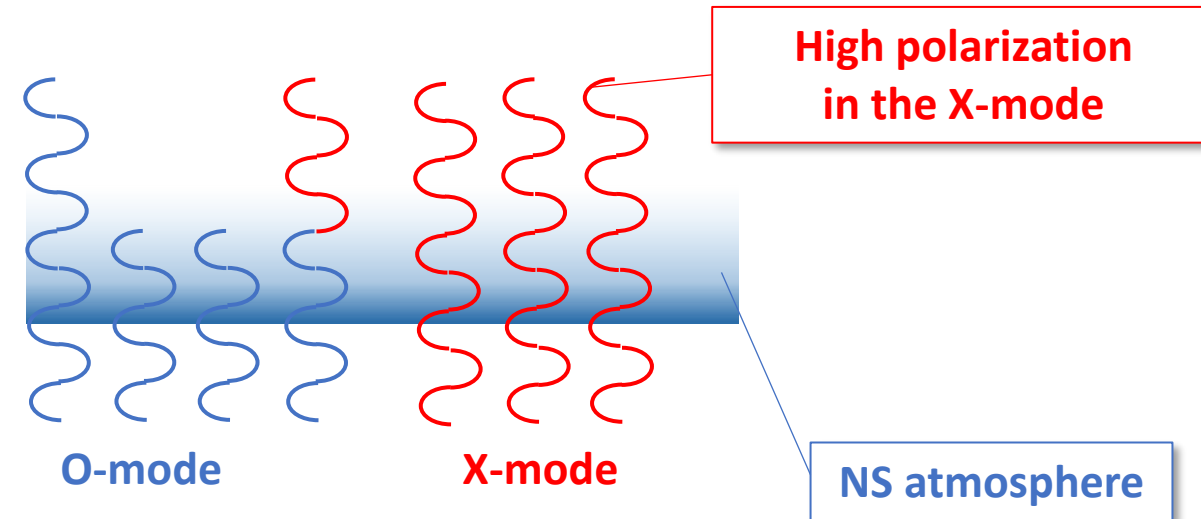


Dichroism in strongly-magnetized plasma

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

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

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

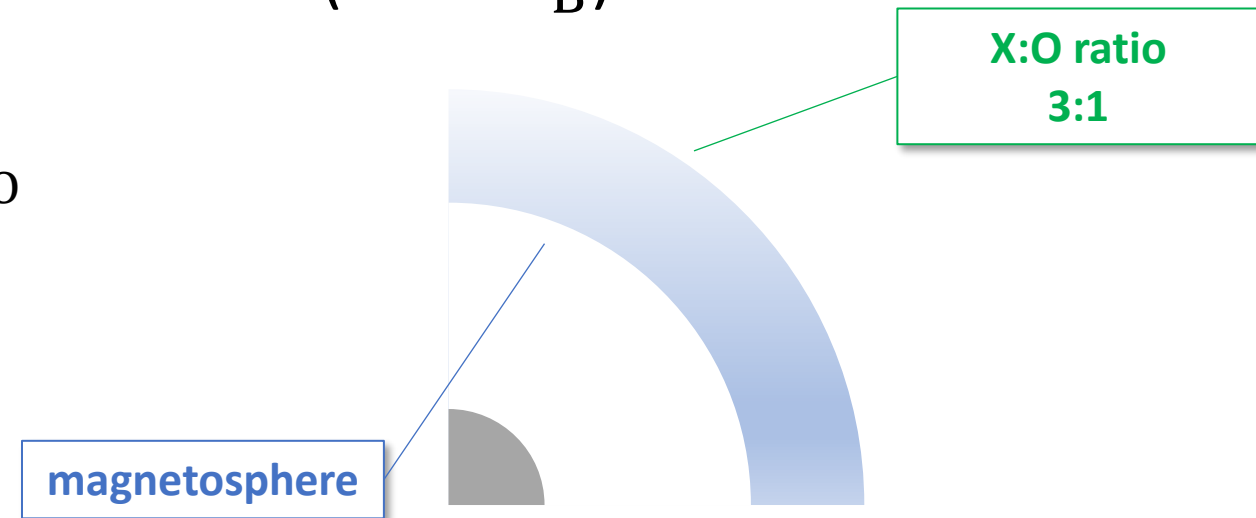


Dichroism in strongly-magnetized plasma

- In strong fields ($B \gtrsim B_Q$) and $E \ll \hbar\omega_B$ plasma is (generally) transparent for X-mode photons
- Things are different at the cyclotron resonance ($\omega = \omega_B$)

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

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



Polarization transport in the magnetized vacuum

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

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

Polarization transport in the magnetized vacuum

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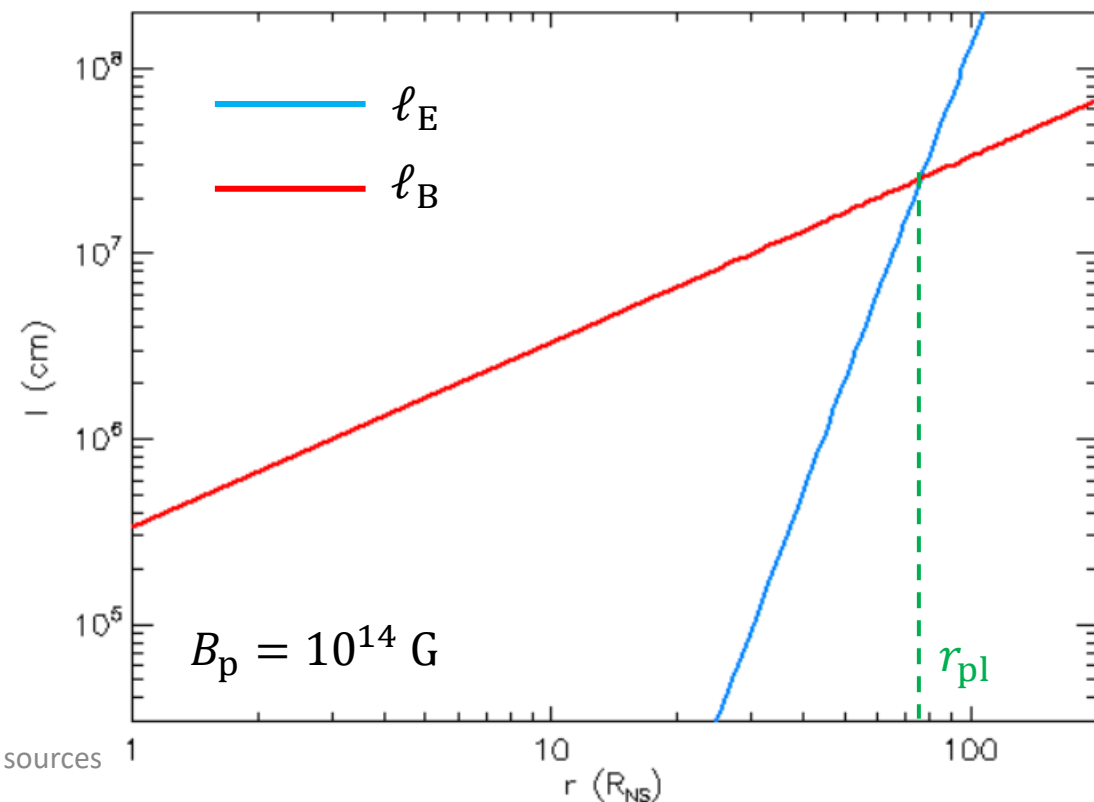
$$\frac{2}{k_0 \delta(B)} \frac{dE_y}{dz} = i [PE_x + NE_y]$$

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

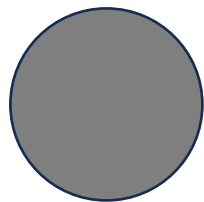
$$\frac{2}{k_0 \delta(B)} \frac{dE_x}{dz} = i [ME_x + PE_y]$$

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

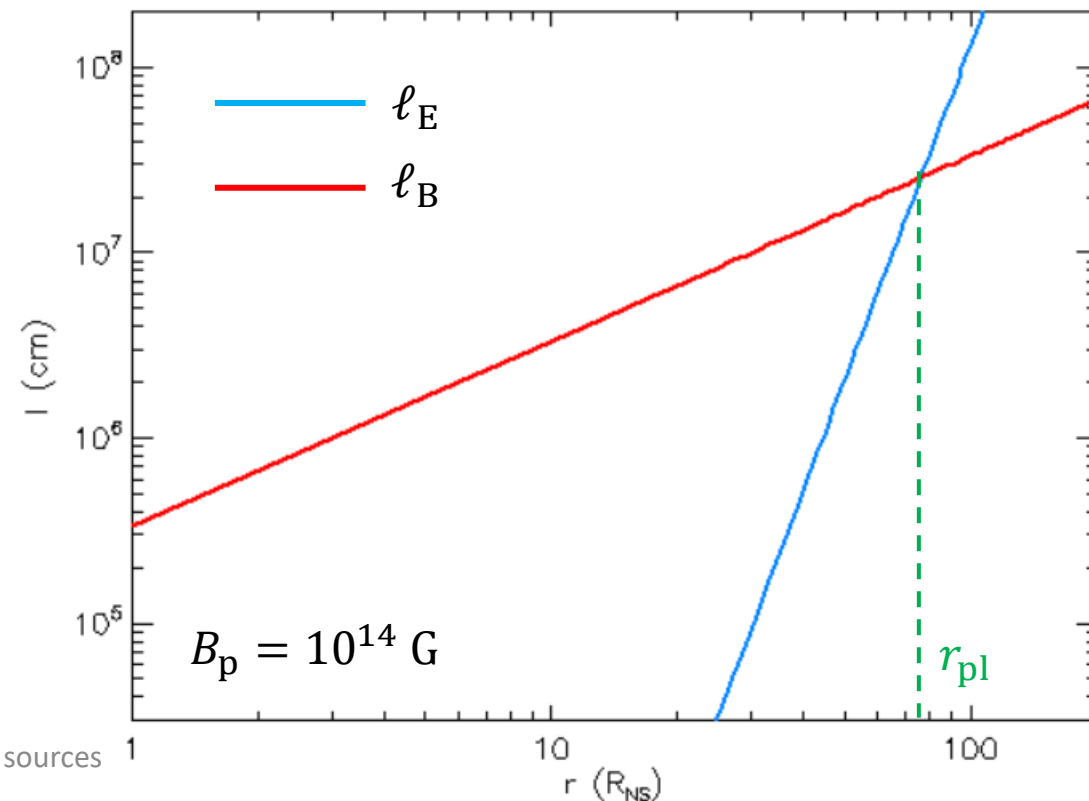
$\ell_E \gg \ell_B$: \mathbf{E} direction is frozen

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

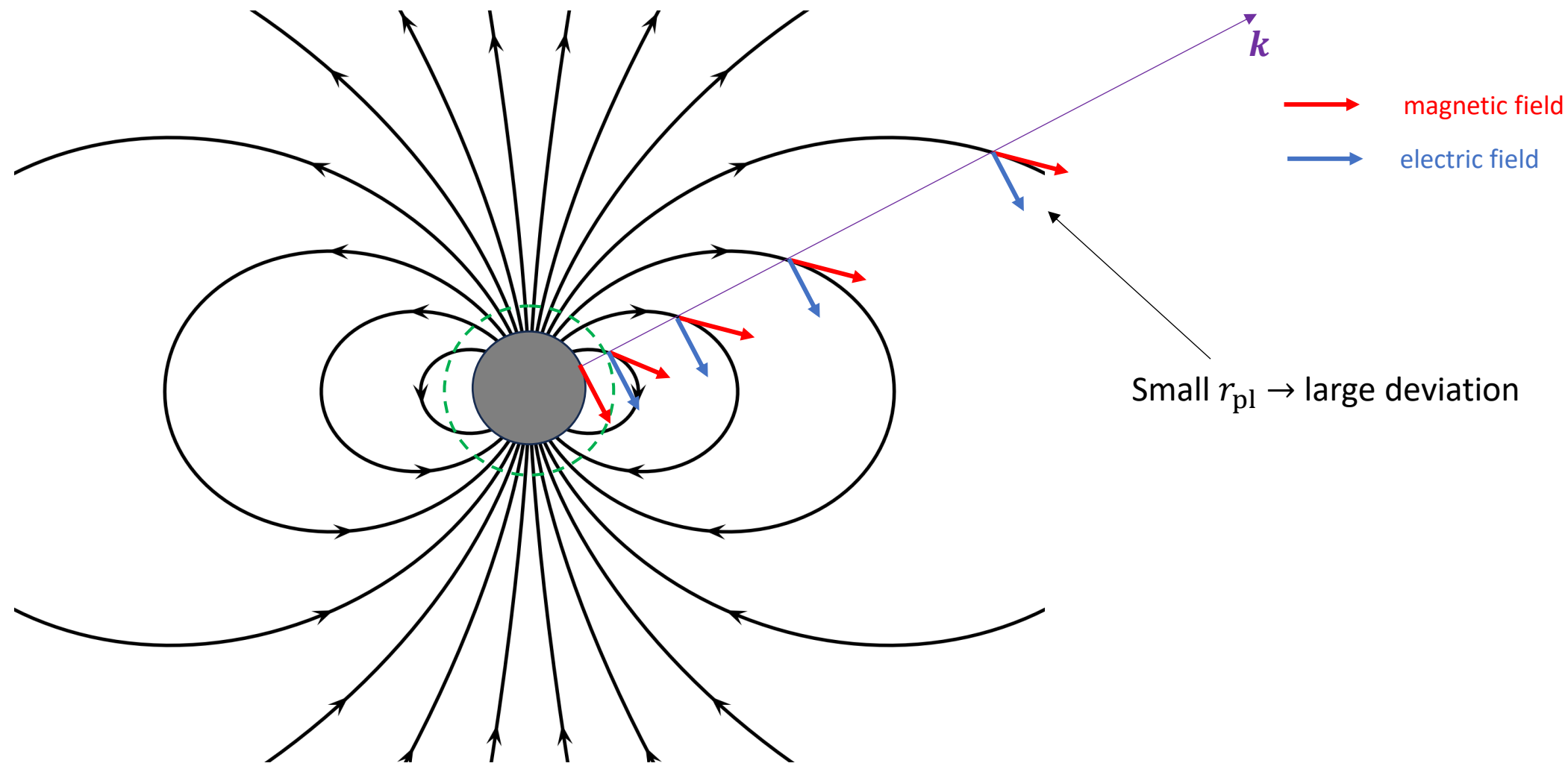
$\ell_E \ll \ell_B$: \mathbf{E} adapts to \mathbf{B}



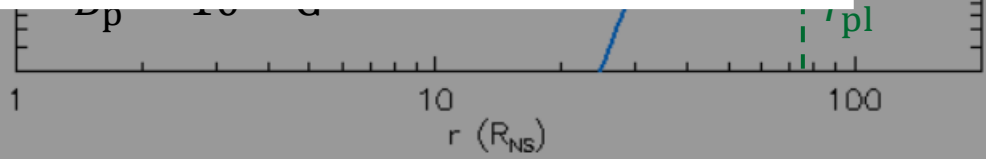
2024-07-12

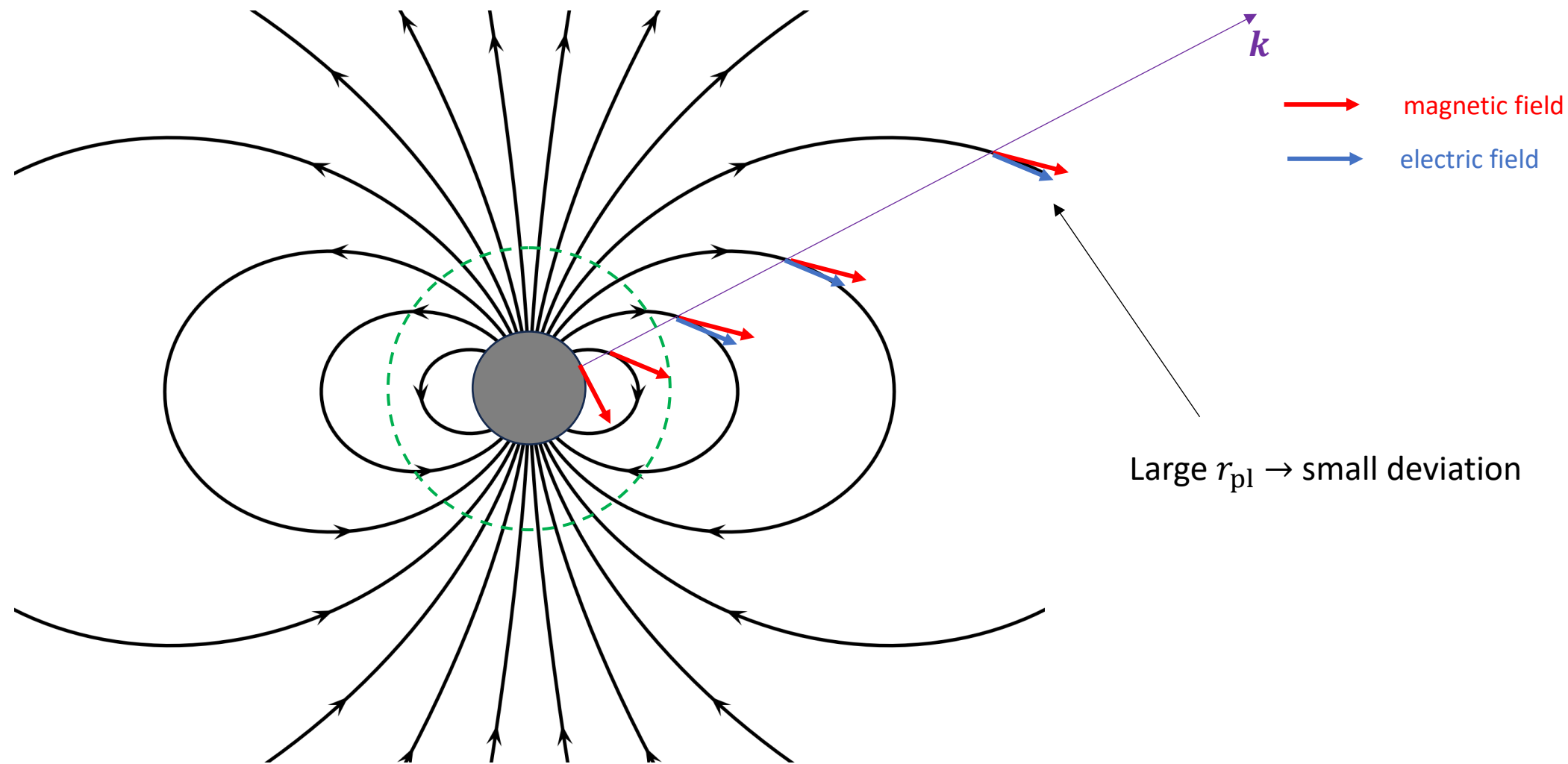


X-ray polarization from magnetar sources

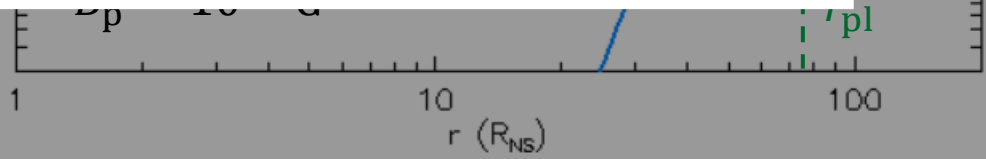


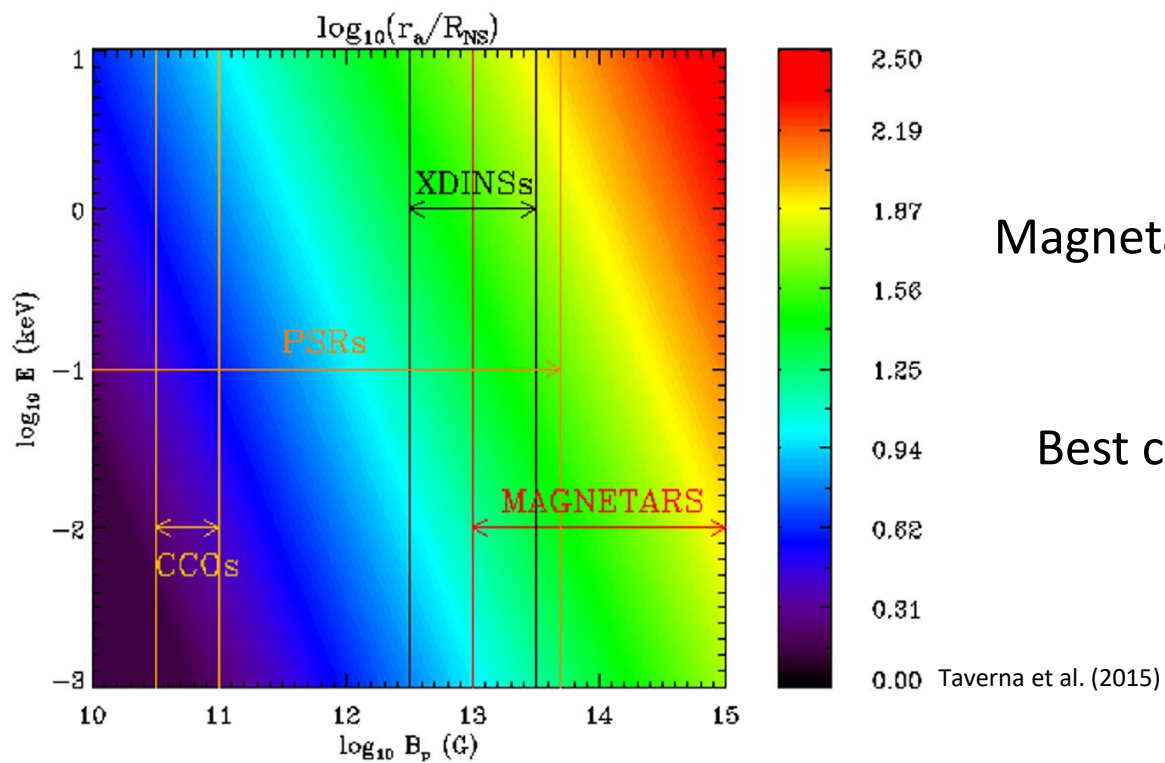
$\ell_E <$





$\ell_E <$

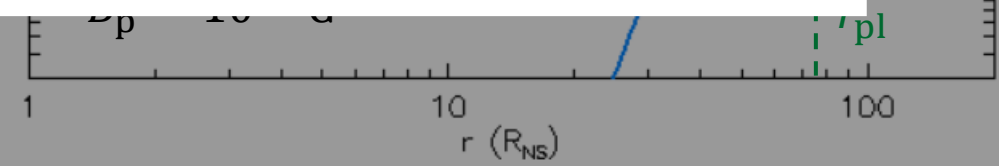




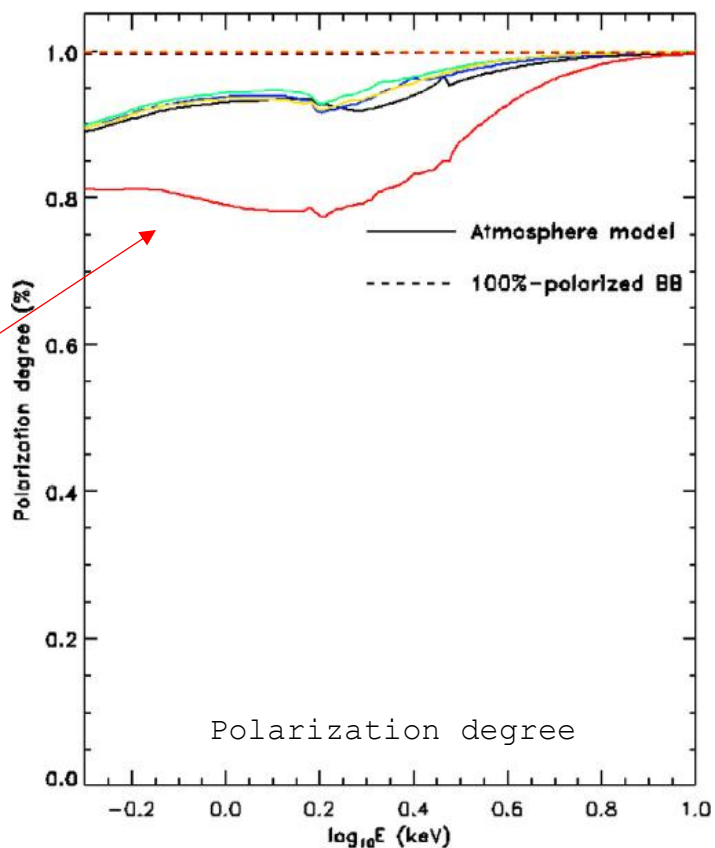
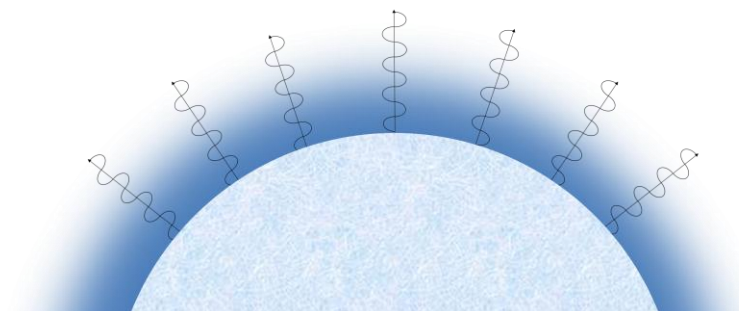
Magnetars (with the strongest B) have the largest r_{pl}



Best candidates to observe polarization of surface emission (potentially very high)



- Surface photons reprocessed by a standard, magnetized atmosphere → high PD (X-mode)

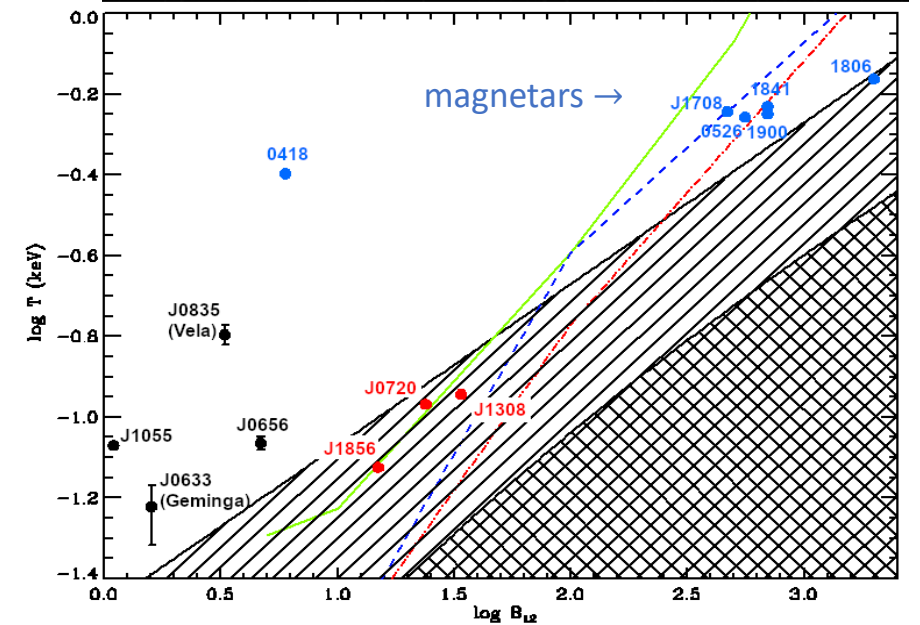
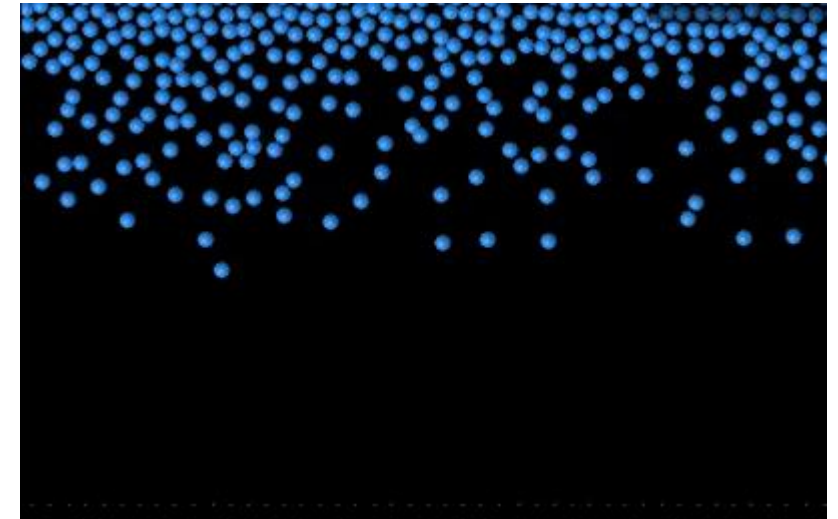


Taverna et al. (2020)

PD \gtrsim 80%

Surface emission models

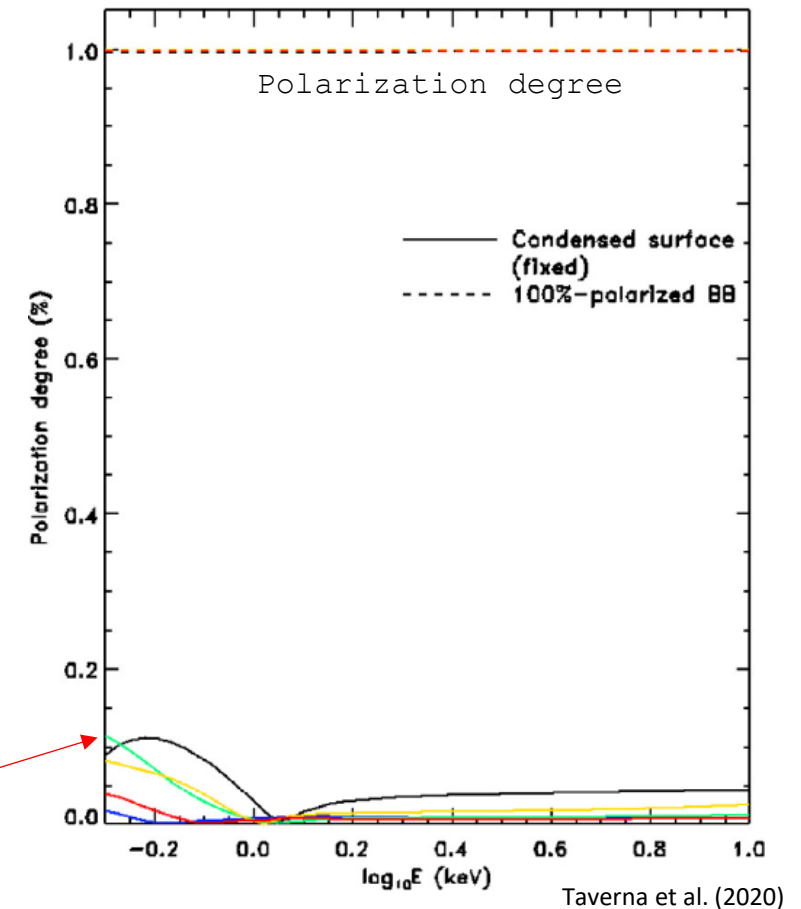
- Surface photons reprocessed by a standard, magnetized atmosphere → high PD (X-mode)
- Very strong B -fields elongate atoms along the field direction → molecular chains are formed for sufficiently low T



Taverna & Turolla (2024)

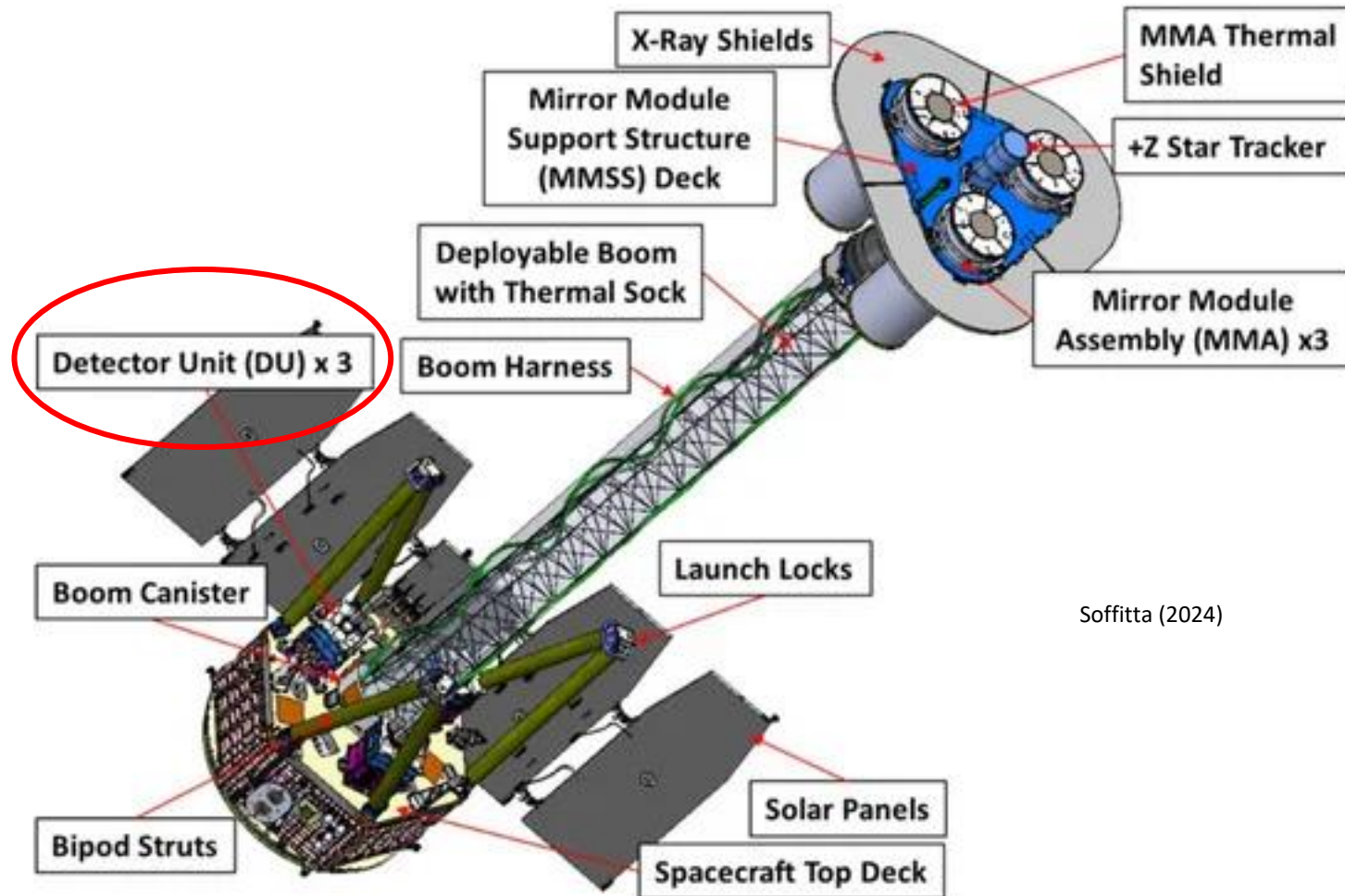
Surface emission models

- Surface photons reprocessed by a standard, magnetized atmosphere → high PD (X-mode)
- Very strong B -fields elongate atoms along the field direction → molecular chains are formed for sufficiently low T
- The atmosphere settles onto the surface and the (condensed) crust is left exposed
- Much lower PD (both O- and X-)



PD \lesssim 20%

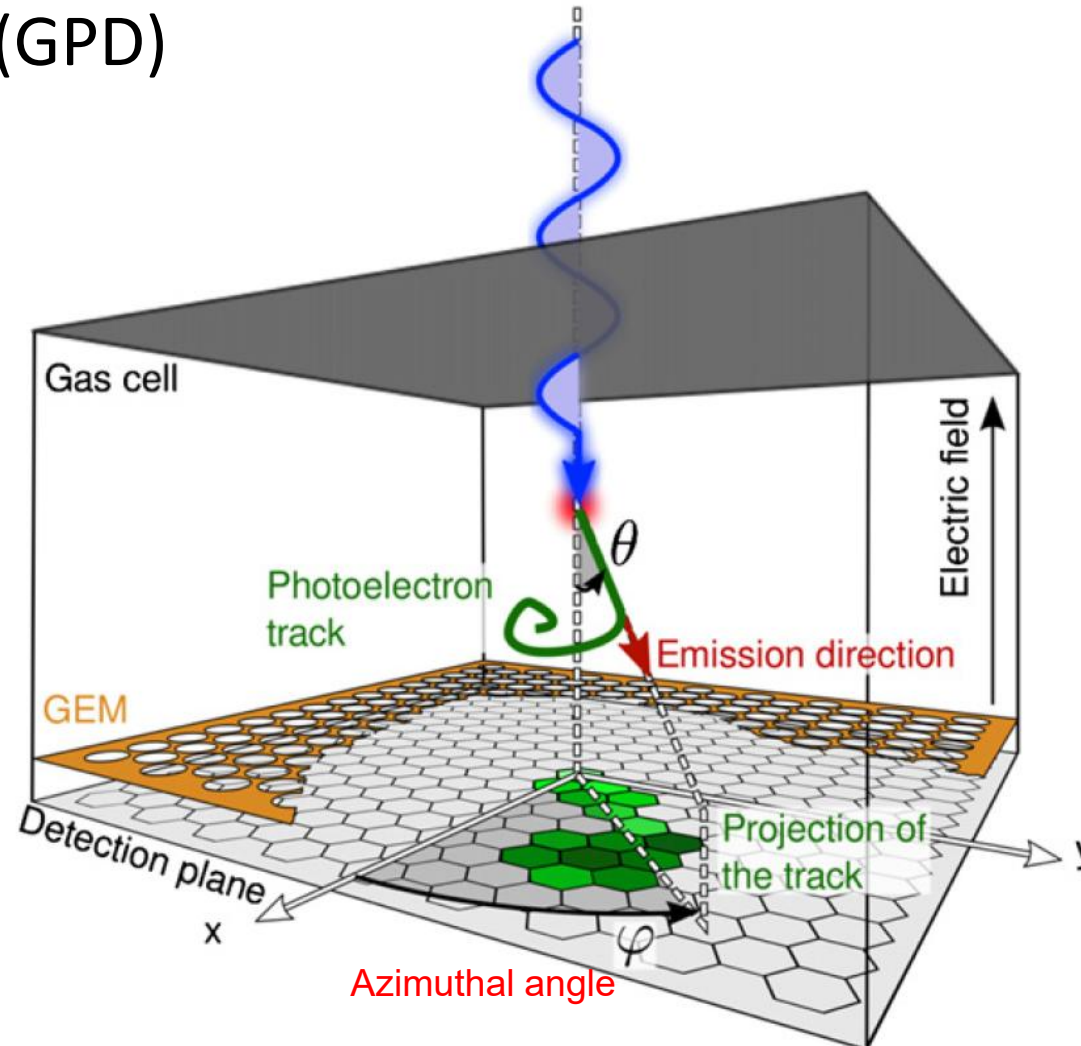
Imaging X-ray Polarimetry Explorer (IXPE)



Soffitta (2024)

Imaging X-ray Polarimetry Explorer (IXPE)

- Gas Pixel Detector (GPD)



Muleri (2014)

Imaging X-ray Polarimetry Explorer (IXPE)

- Gas Pixel Detector (GPD)
- Photoelectric cross section

$$\frac{d\sigma_{\text{Ph}}}{d\Omega} = r_0^2 \alpha^4 Z^5 \left(\frac{m_e c^2}{E} \right)^{\frac{7}{2}} \frac{4\sqrt{2} \sin^2 \theta}{(1 - \beta \cos \theta)^4} \cos^2 \phi$$

Photoelectrons most probably emitted in the direction of E

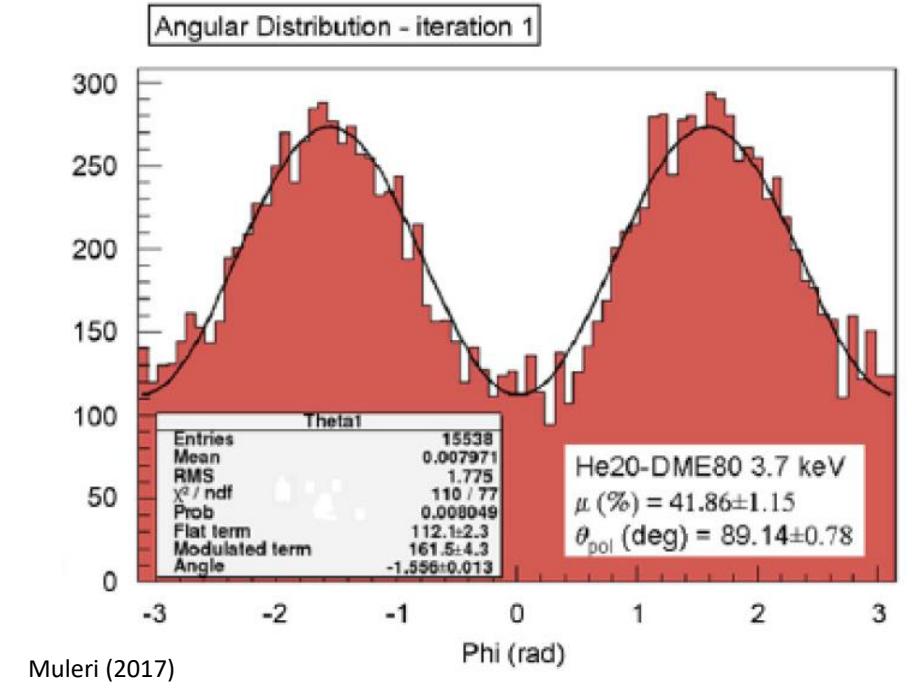
Imaging X-ray Polarimetry Explorer (IXPE)

- Gas Pixel Detector (GPD)
- Photoelectric cross section
- Modulation curve

$$\mathcal{M}(\varphi) = K + A \cos^2(\varphi - \varphi_0)$$

Modulation factor μ :

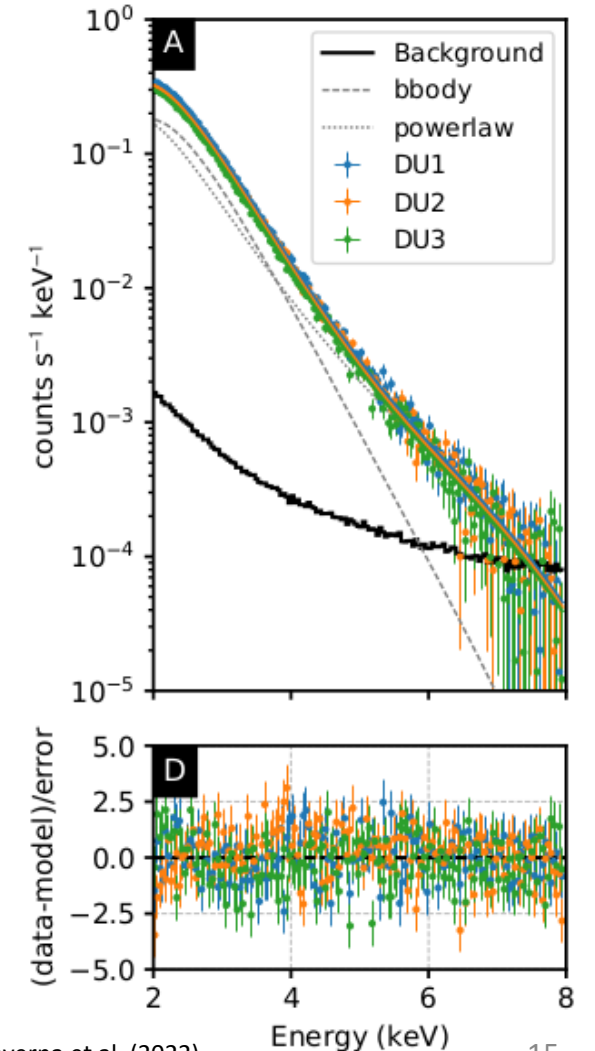
Amplitude for 100% polarized radiation



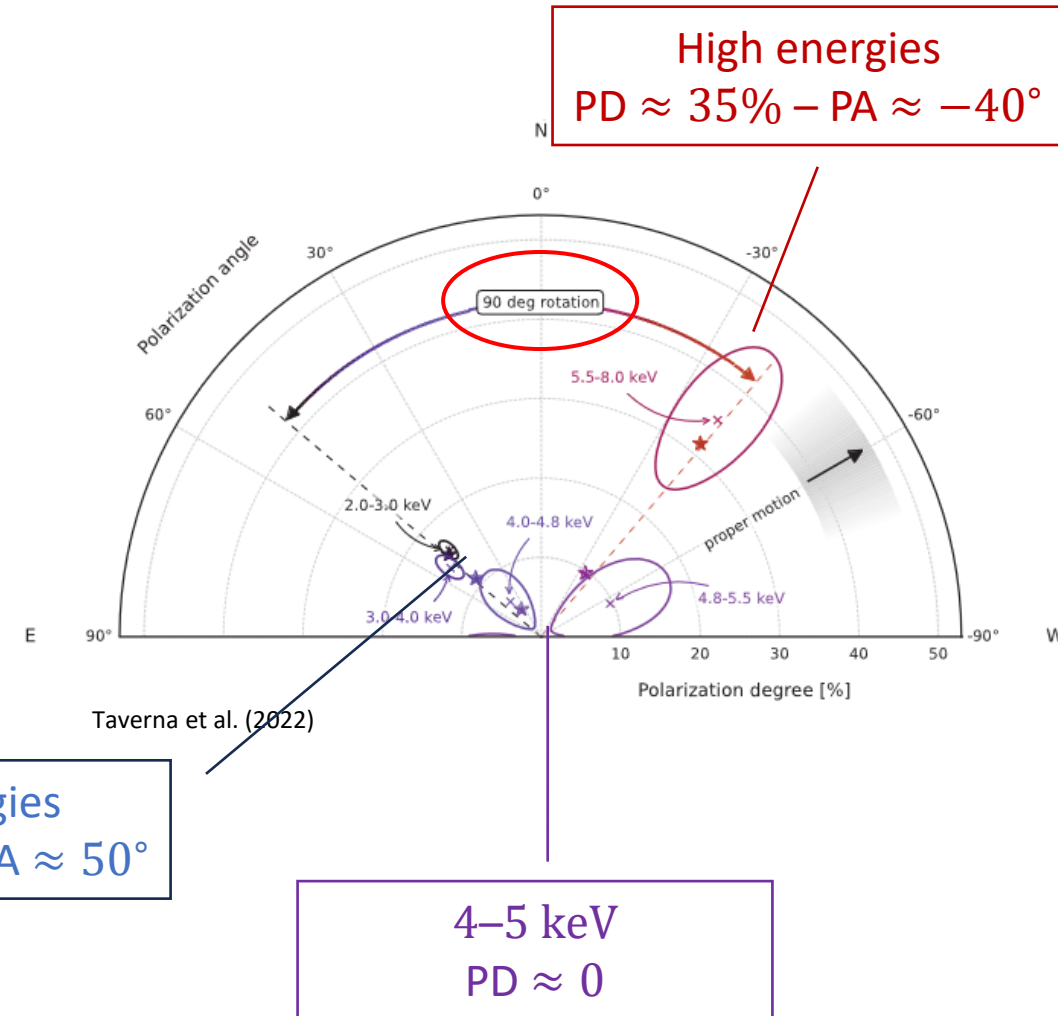
- **AXP 4U 0142+61** (R.A. 01:46:22.41, DEC. 61°45'03".2)
 - Cassiopeia – Distance: 3.6 kpc
 - January 31st – February 27th 2022 (840 ks)
 - Unabsorbed flux (2–10 keV): 6×10^{-11} erg cm⁻² s⁻¹
- **AXP 1RXS J170849.0–4009100** (R.A. 17:08:46.3, DEC. –40°08'44".6)
 - Scorpio – Distance: 5–10 kpc
 - September 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

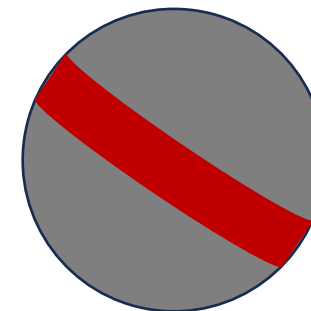
- Brightest among magnetars
- $B_{p\dot{p}} \approx 1.5 \times 10^{14} \text{ G}$
- Spectrum BB+PL
 - $kT_{\text{BB}} = 0.471^{+0.004}_{-0.004} \text{ keV}$
 - $\Gamma = 3.69^{+0.05}_{-0.05}$
 - $\chi^2/\text{dof} = 511.5/441$



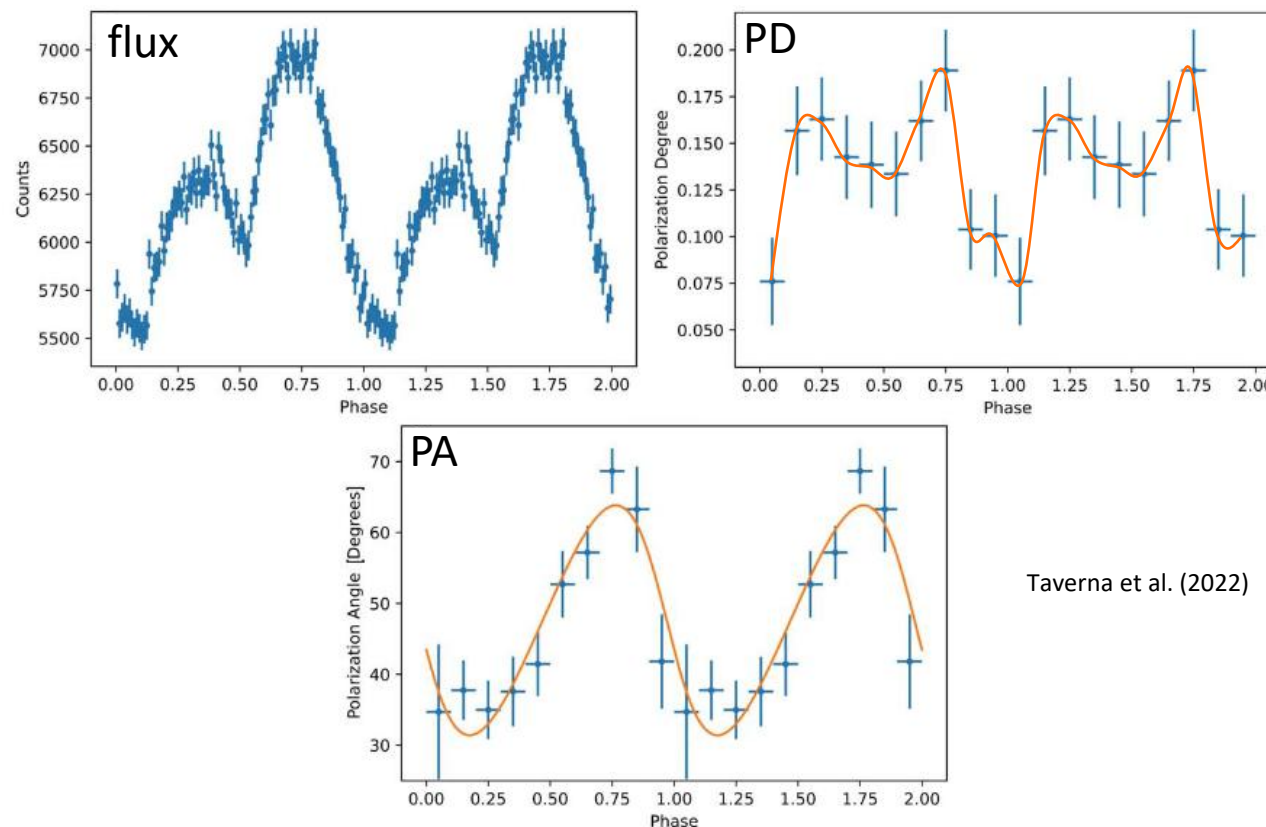
- Brightest among magnetars
- $B_{p\dot{p}} \approx 1.5 \times 10^{14}$ G
- Spectrum BB+PL
- Polarization measurement (2–8 keV):
 - PD = 13.5% (17σ) – PA $\approx 50^\circ$ E
 - Complex behavior against photon energy



- Results are compatible with the magnetar model (Taverna+22)
 - 90°-swing → X- and O-modes (ultra-strong B -fields $\gtrsim 10^{13}$ G independently from $P-\dot{P}$)
 - PD at high energies ($\approx 35\%$) → PL tail populated by RCS photons
 - According to the model RCS photons are X-mode → O-mode at low energies
 - Low PD + O-mode photons → **condensed surface exposed** (equatorial-belt emission geometry)



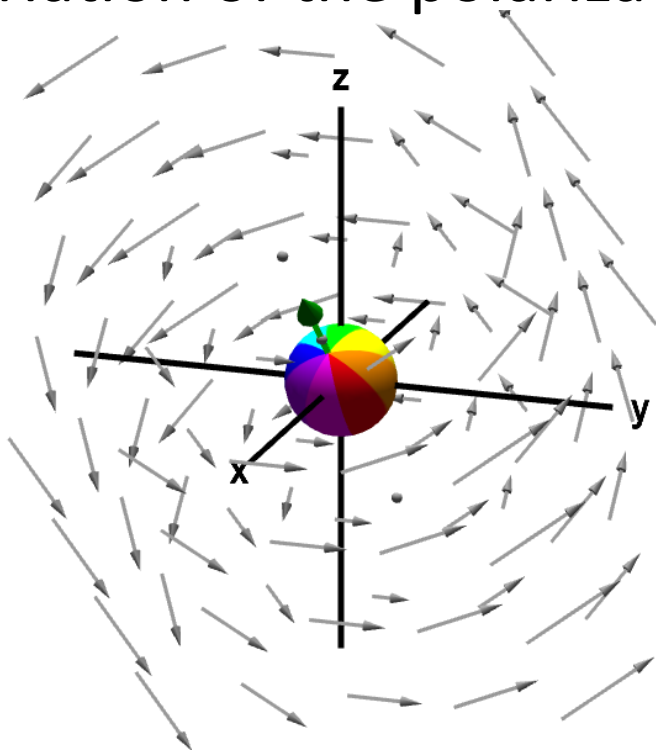
- Low phase-averaged PD ($< 40\%$) \Rightarrow Vacuum birefringence cannot be probed
- Phase dependent results
 - PD is in-phase with the LC (determined at the surface)
 - PA is sinusoidal (RVM)



Taverna et al. (2022)

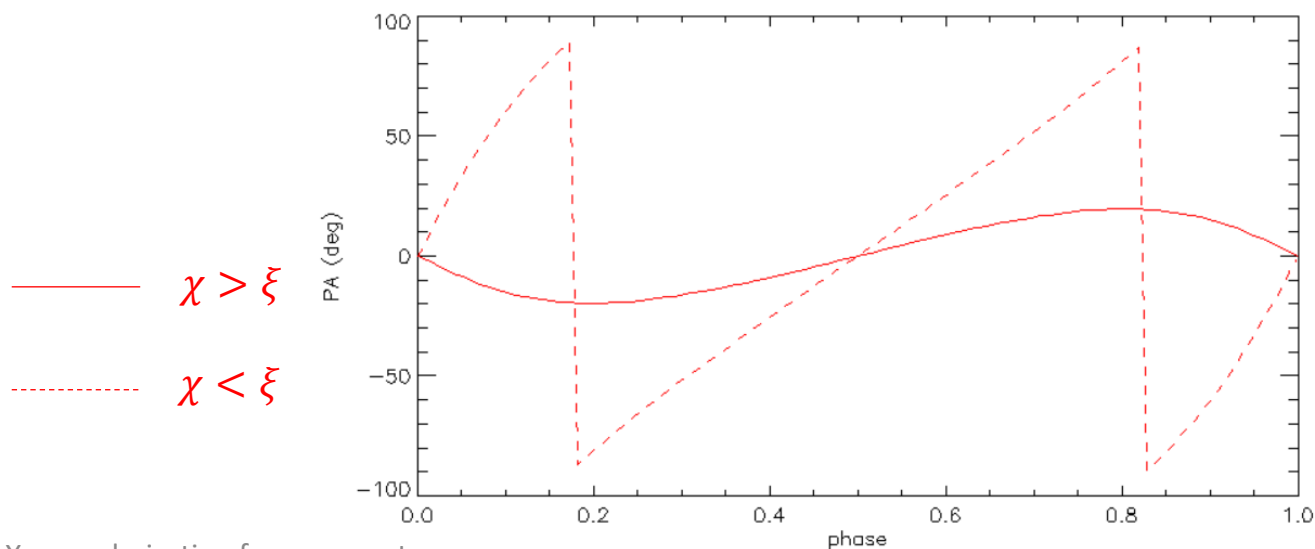
Rotating vector model (RVM)

- Variation of the polarization angle with rotational phase



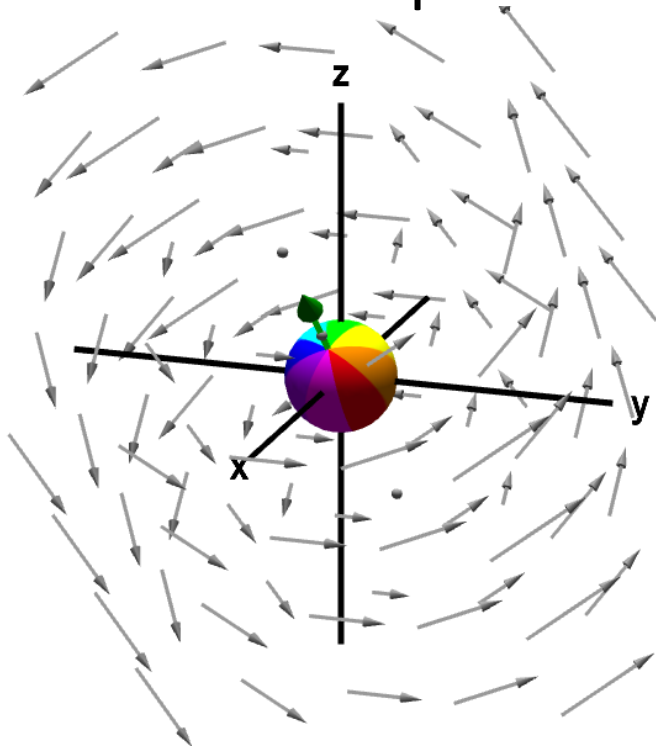
$$\tan(\text{PA}) = \frac{\sin \xi \sin \phi}{\cos \chi \sin \xi \cos \phi - \sin \chi \cos \xi}$$

- Emission from small caps (e.g. in radio pulsars or in accreting X-ray pulsars)



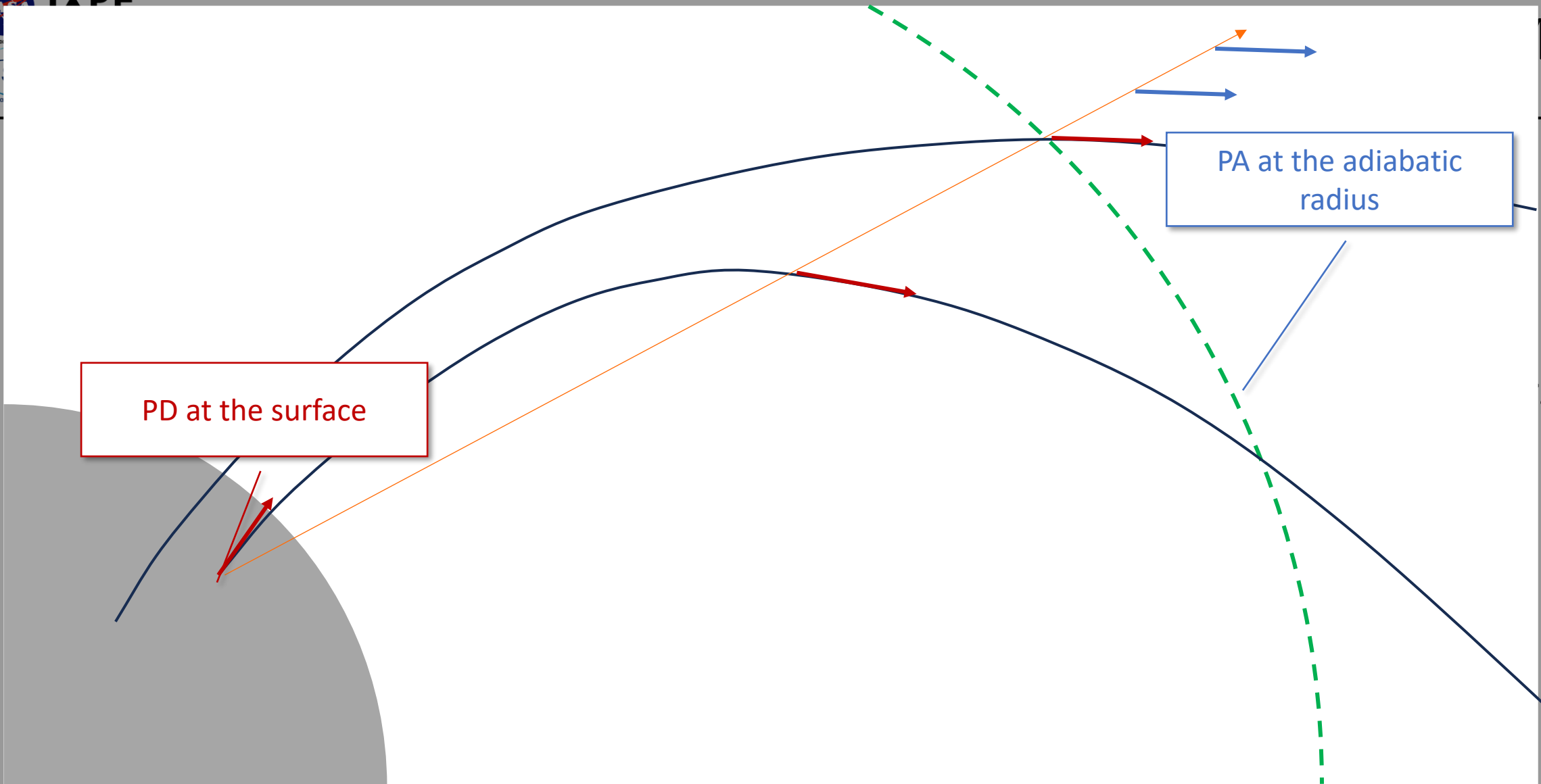
Rotating vector model (RVM)

- Variation of the polarization angle with rotational phase



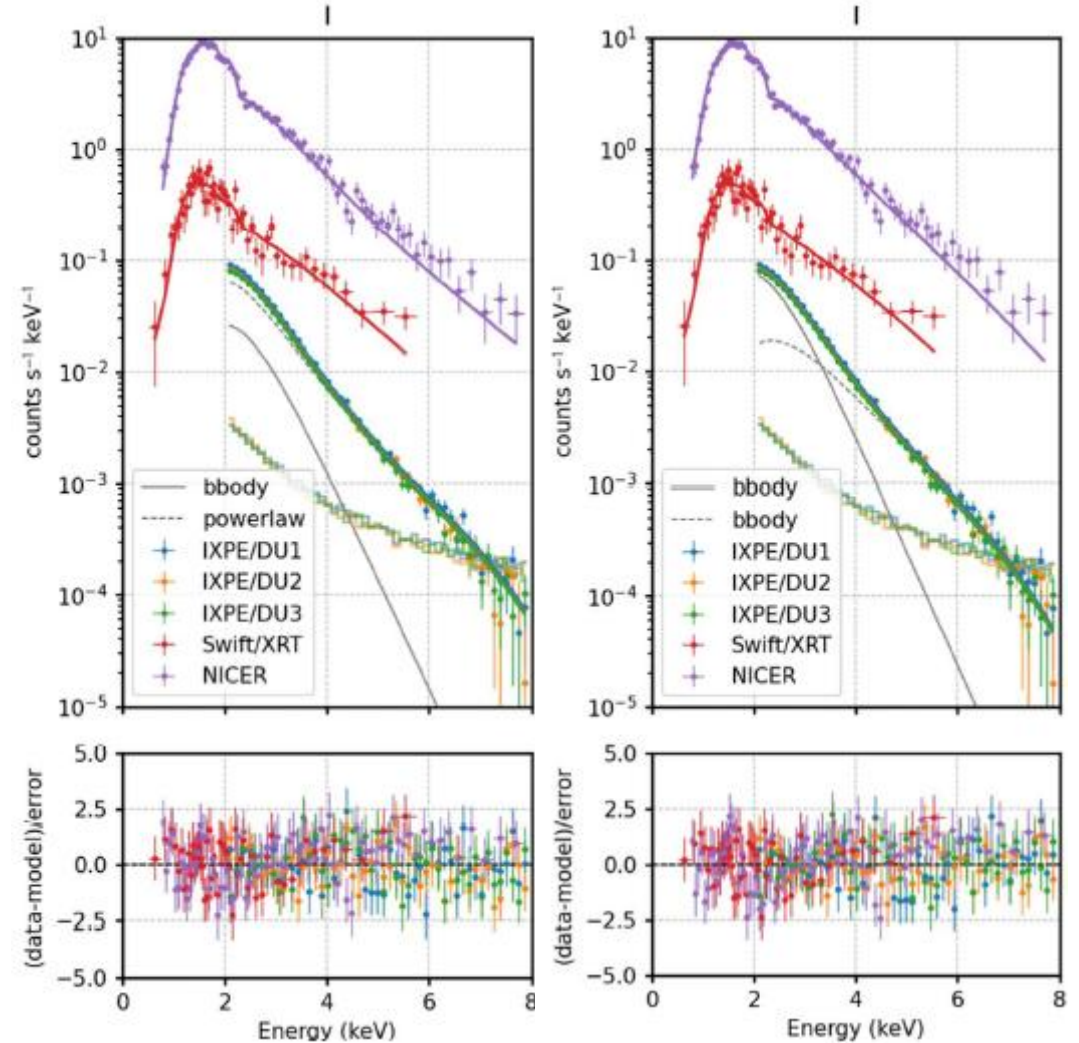
$$\tan(\text{PA}) = \frac{\sin \xi \sin \phi}{\cos \chi \sin \xi \cos \phi - \sin \chi \cos \xi}$$

- Emission from small caps (e.g. in radio pulsars or in accreting X-ray pulsars)
- RVM for extended regions holds for dipolar fields only
- In the magnetar model the field can be approximated as dipolar only far away from the surface

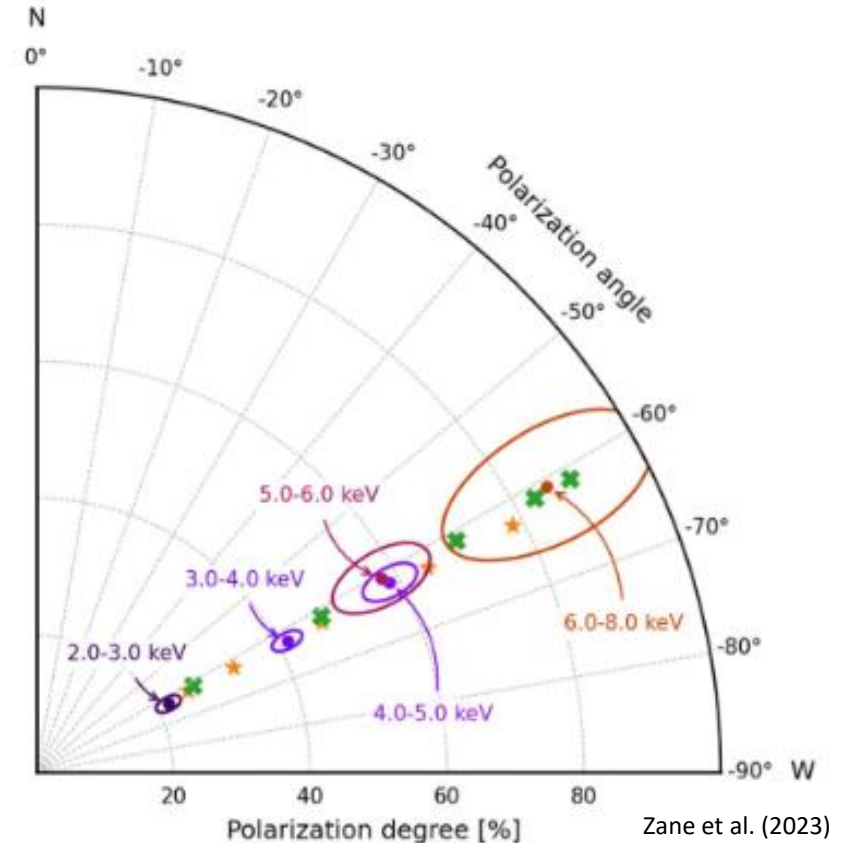


AXP 1RXS J170849.0–4009100

- 2nd brightest magnetar
- $B_{p\dot{p}} \approx 5 \times 10^{14}$ G
- Spectrum BB+PL or BB+BB?
 - BB+PL – $kT_{BB} = 0.454^{+0.007}_{-0.006}$ keV
 $\Gamma = 2.97^{+0.009}_{-0.056}$
 $\chi^2 = 410.8/408$ dof
 - BB+BB – $kT_{BB_1} = 0.435^{+0.007}_{-0.007}$ keV
 $kT_{BB_2} = 1.073^{+0.031}_{-0.029}$
 $\chi^2 = 405.8/408$ dof

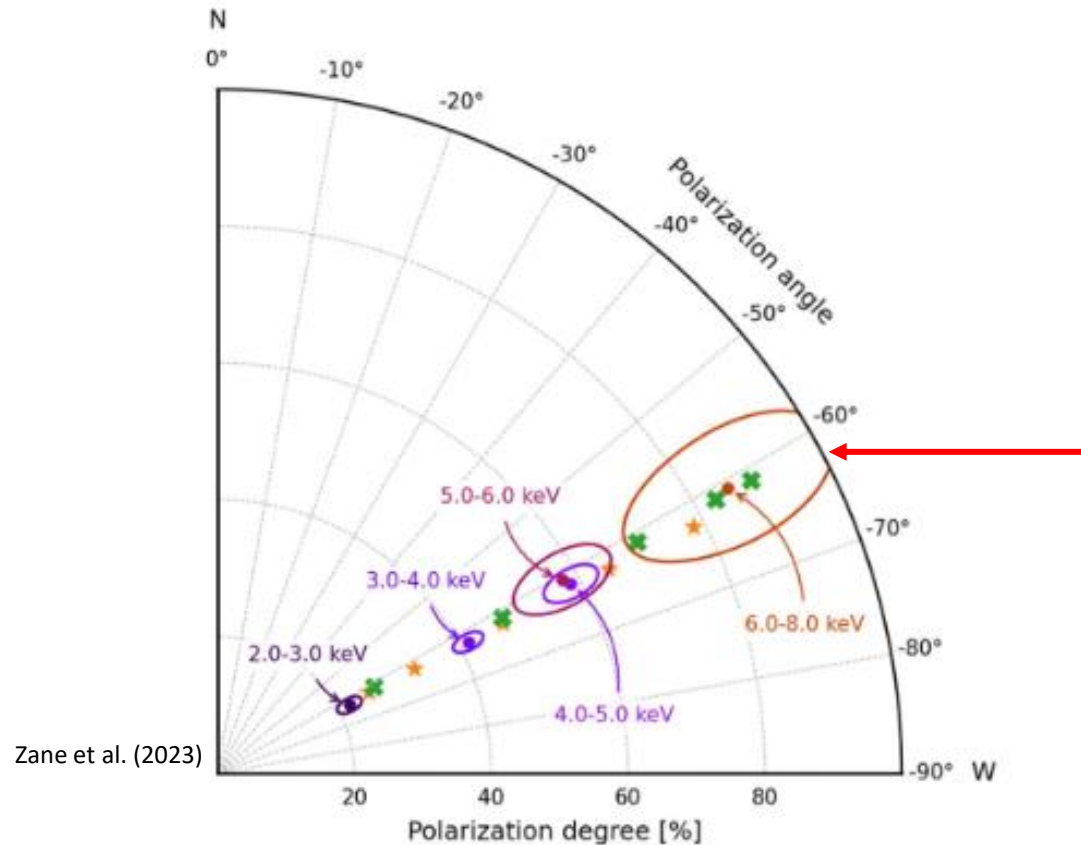


- 2nd brightest magnetar
- $B_{p\dot{p}} \approx 5 \times 10^{14}$ G
- Spectrum BB+PL or BB+BB?
- Polarization measurement (2–8 keV):
 - PD = 35% (22.5σ) – PA $\approx 60^\circ$ W
 - Polarization direction is kept in the IXPE band
 - PD at 6–8 keV: $\approx 85\%$ (MDP₉₉ = 50%)
the highest measured so far!



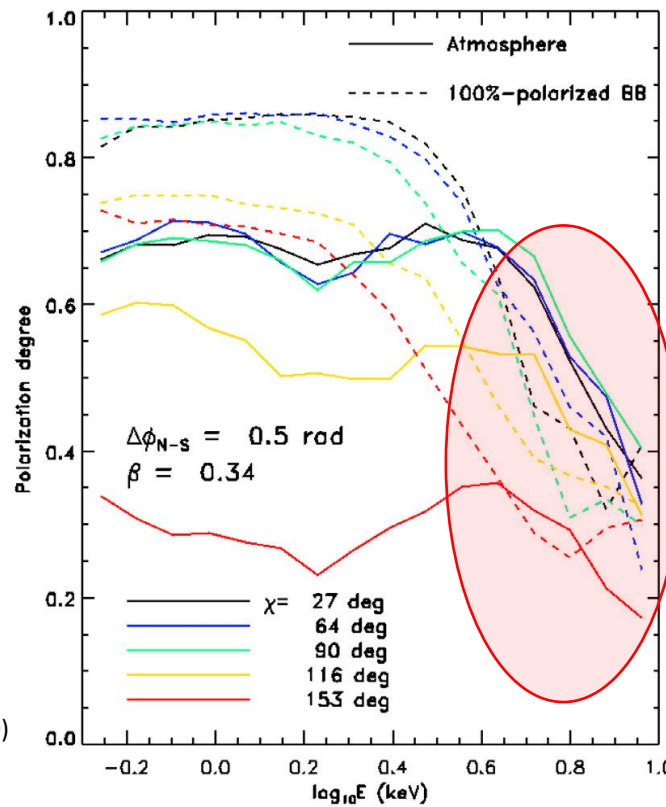
- Theoretical interpretation

- high PD points towards plasma reprocessing → NS atmosphere



- Theoretical interpretation

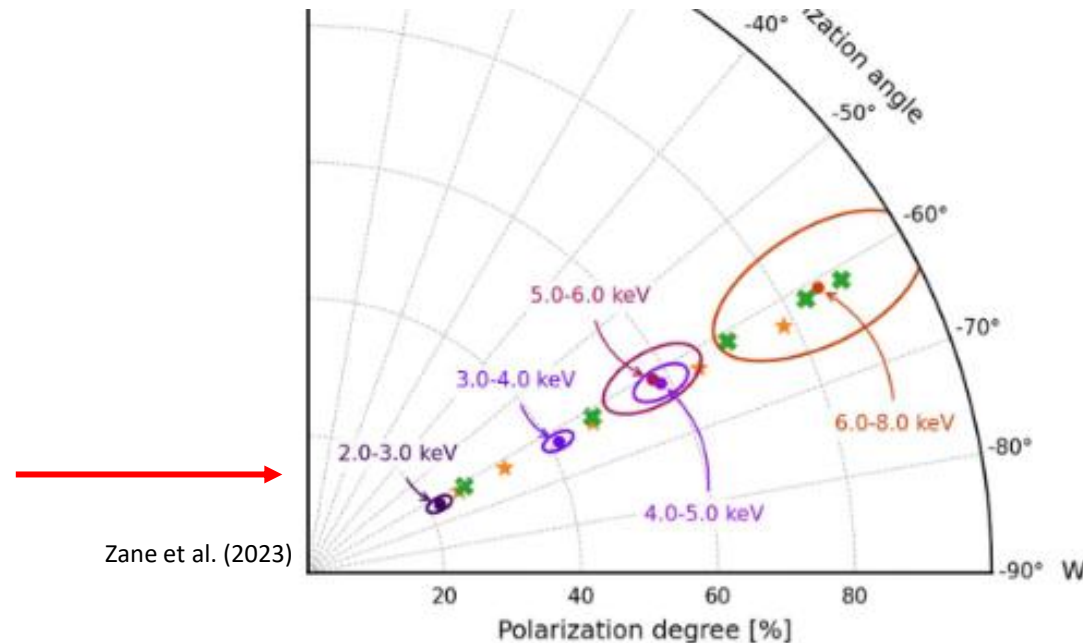
- high PD points towards plasma reprocessing → NS atmosphere
- PD at high energies too large for RCS ($\approx 33\%$) → BB+BB (2 distinct thermal regions)



Taverna et al. (2020)

- Theoretical interpretation

- high PD points towards plasma reprocessing → NS atmosphere
- PD at high energies too large for RCS ($\approx 33\%$) → BB+BB (2 distinct thermal regions)
- PD at low energies too small for atmosphere → condensed surface



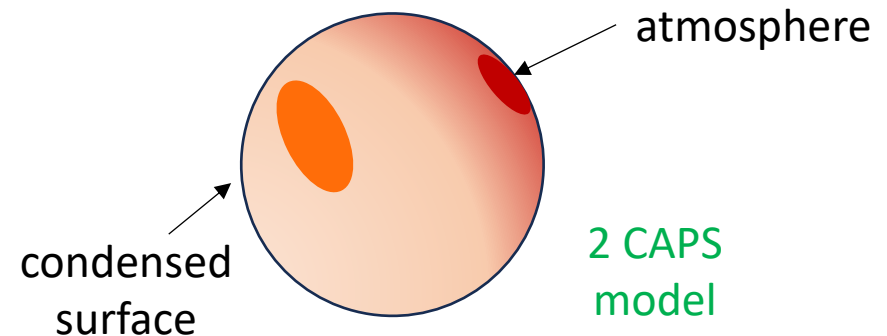
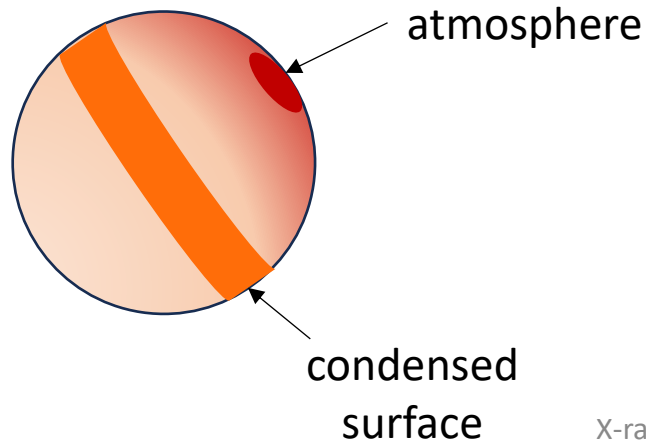
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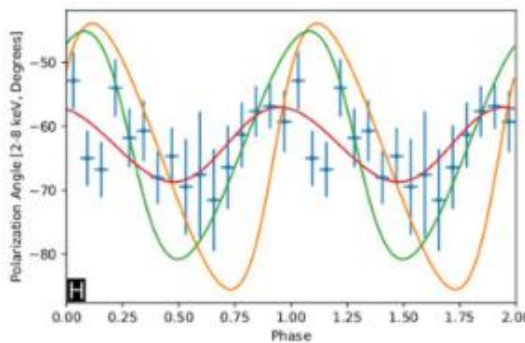
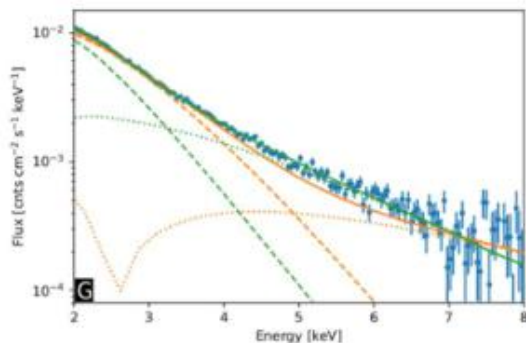
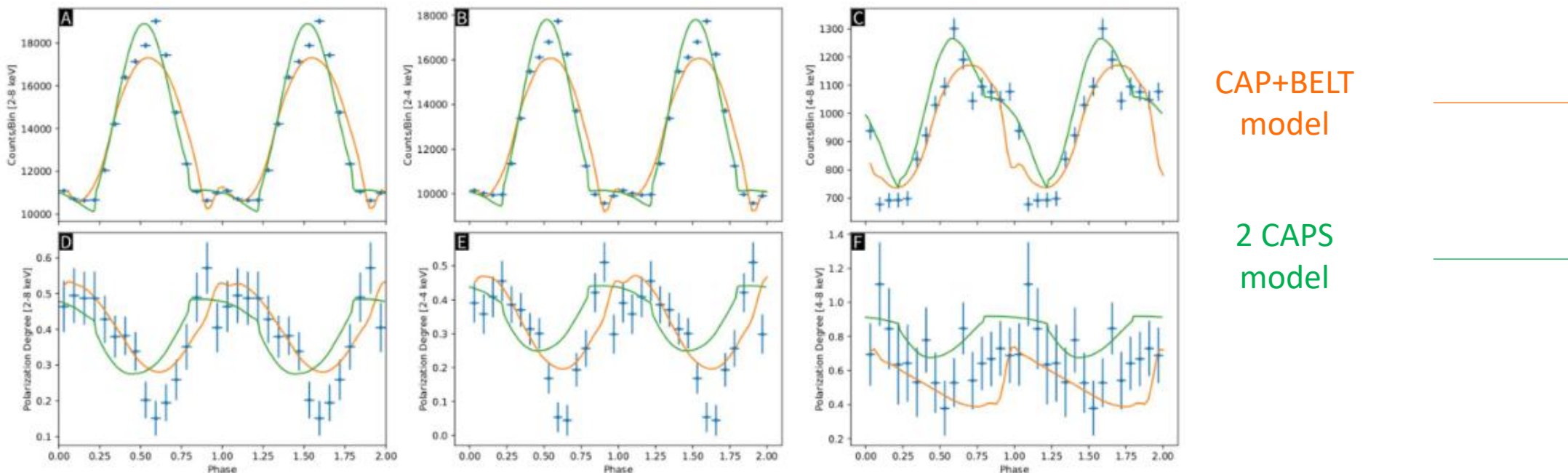


Phase transition across the surface

CAP+BELT
model

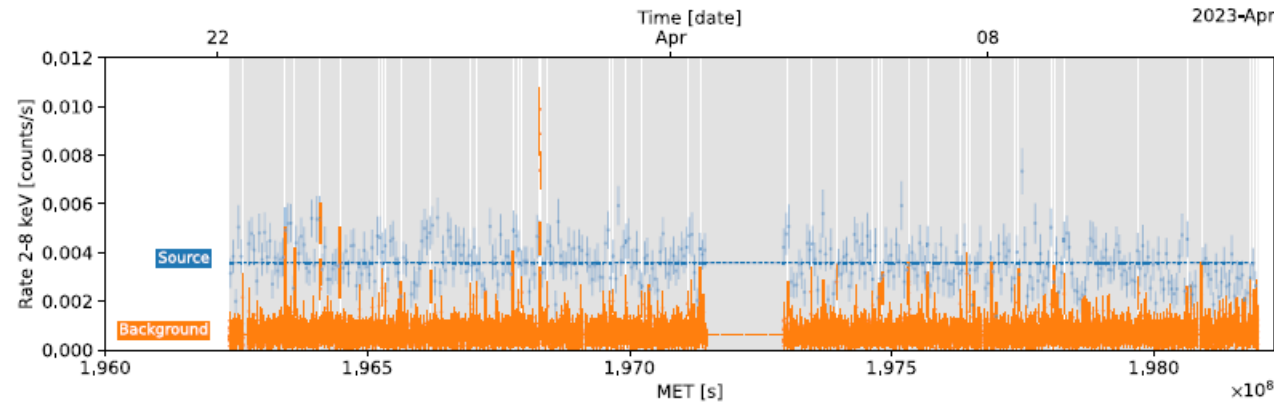


- Phase-dependent results are coherently explained by the models

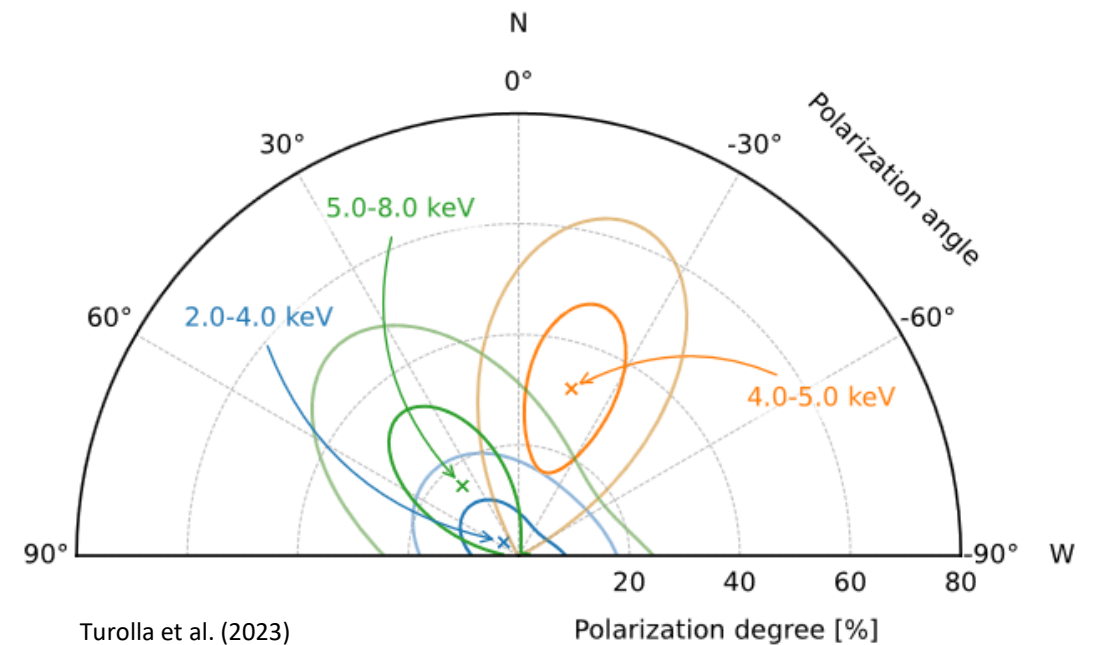


Zane et al. (2023)

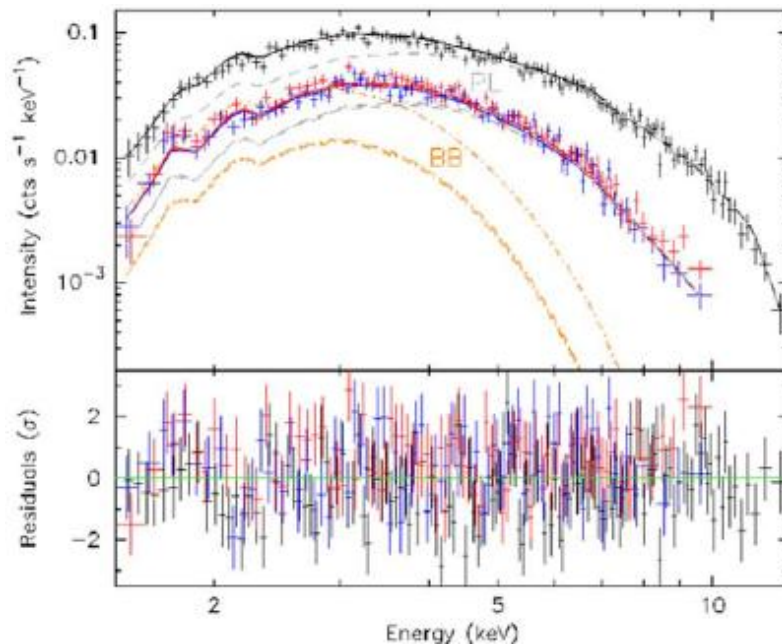
- Emitted the strongest giant flare ever detected (December 27, 2004)
- $B_{P\dot{P}} \approx 8 \times 10^{14}$ G (strongest B -field)
- Observed during an active phase
- Unexpectedly low flux level (1/10 than tabulated)
- Contamination by solar flares during IXPE observation



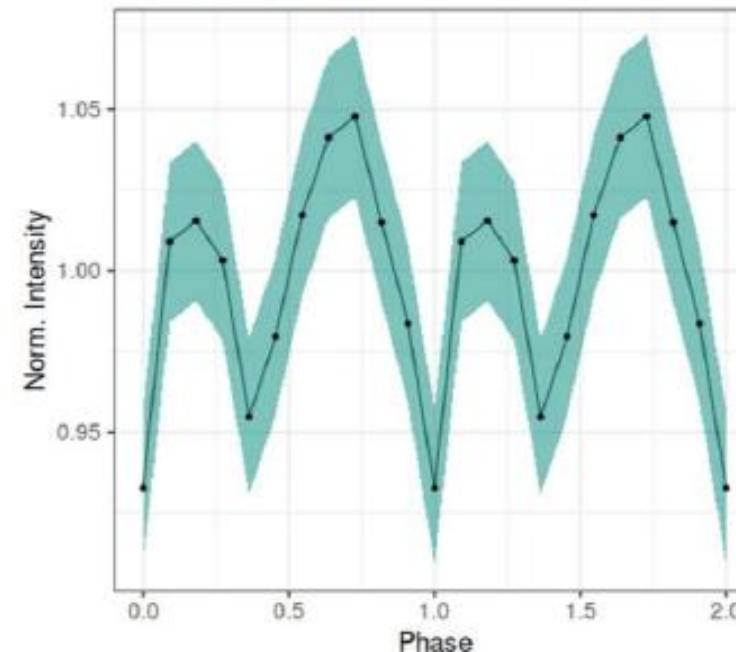
- Marginally significant IXPE measurement
 - Phase- and energy-integrated PD (5.7%) well below MDP_{99} ($\approx 20\%$)
 - Energy-dependent PD (99% c.l.)
 - (2–4 keV) $\approx 32\%$ (4–5 keV, 99% c.l.)
 - $\lesssim 55\%$ (5–8 keV)



- Marginally significant IXPE measurement
- Spectral and timing analysis from 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. $\approx 5\%$)



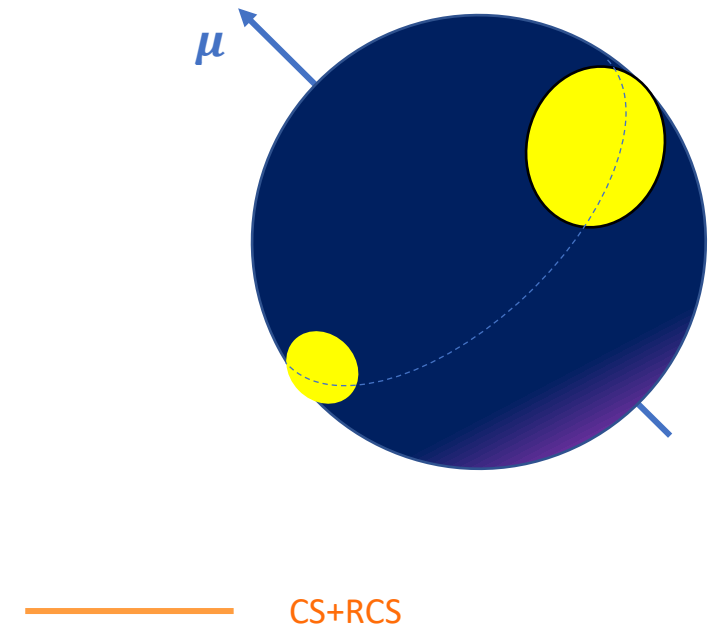
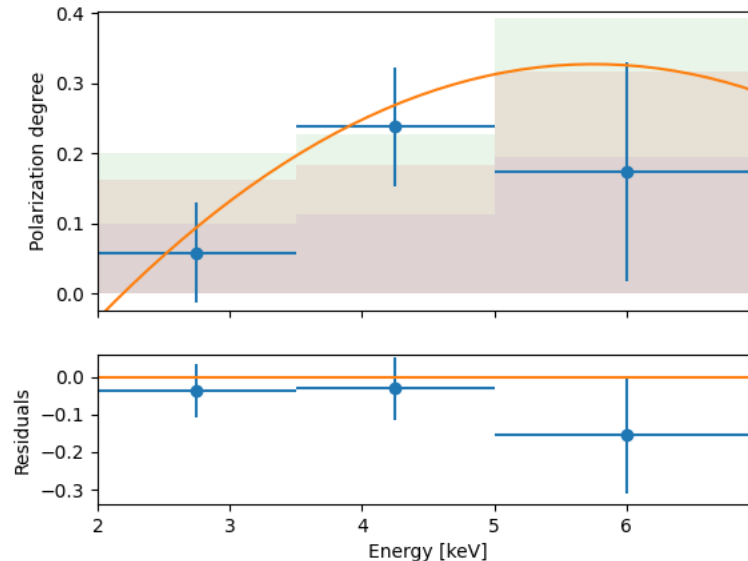
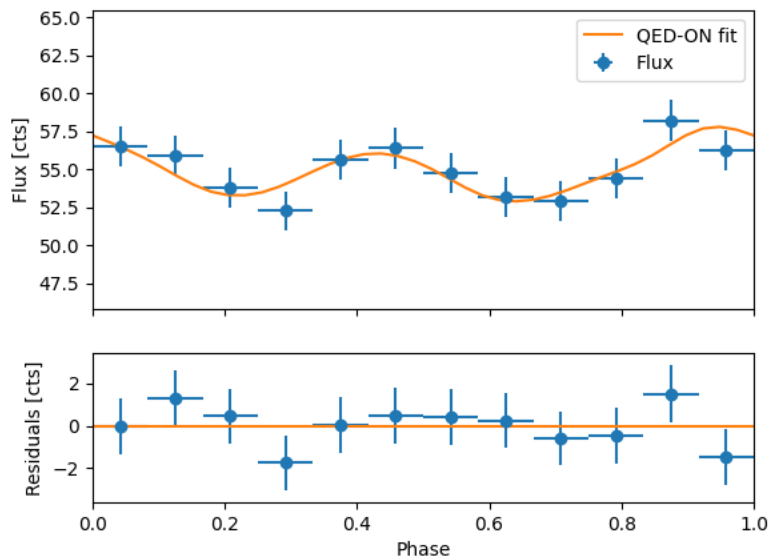
SGR1806-20 XMM
P = 7.7703 s, PF = 5%



Turolla et al. (2023)

• Theoretical interpretation

- Limited by the non-significant polarization measurement
- IXPE observations are not incompatible with emission from a condensed region of the surface reprocessed by RCS (4U like)



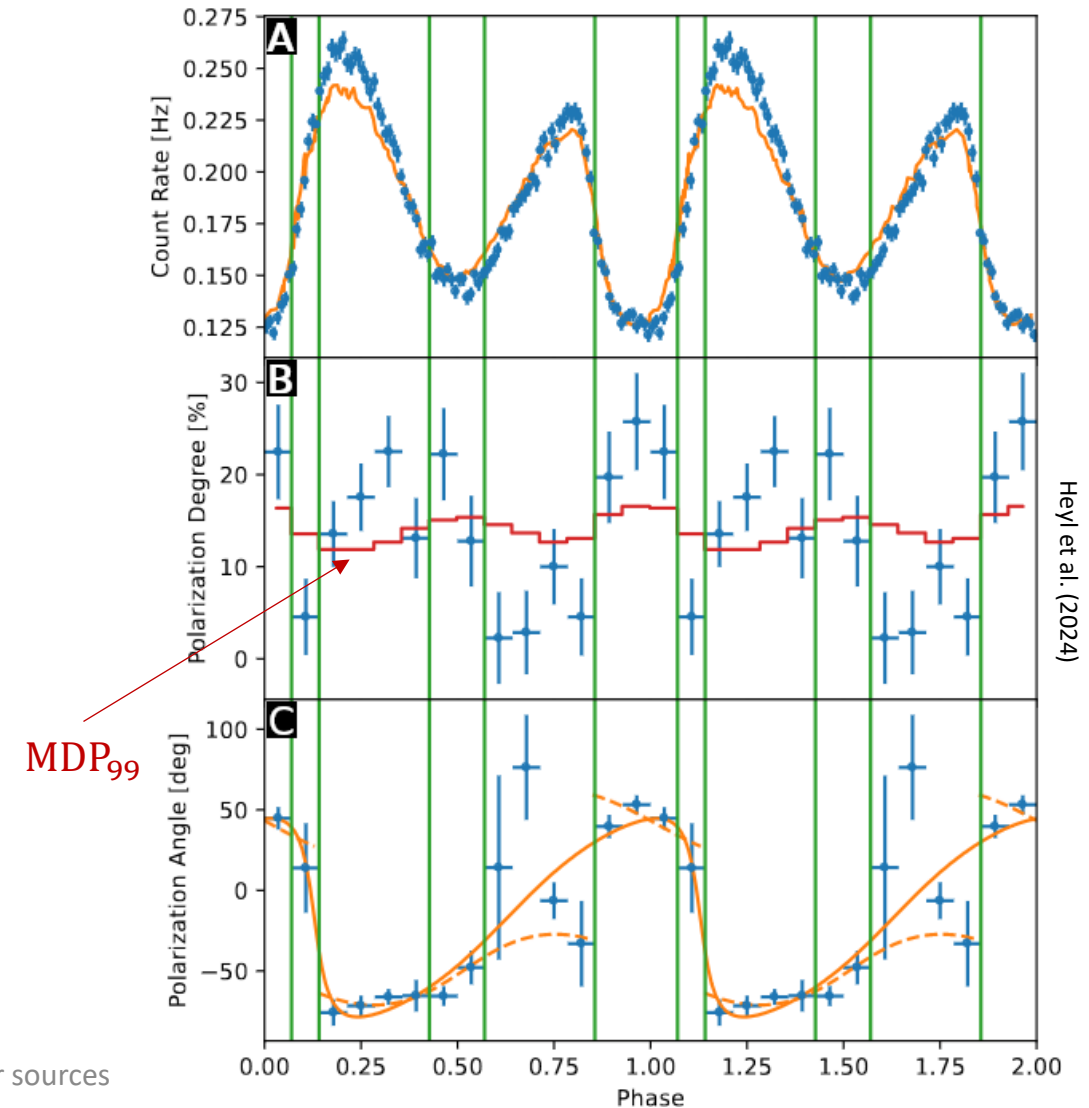
- XMM & NICER observations
- $B_{p\dot{p}} \approx 6 \times 10^{13}$ G (not so much)
- Spectral fit BB+PL is not good enough → adding an absorption line (Pizzocaro+19) improves the fit

	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

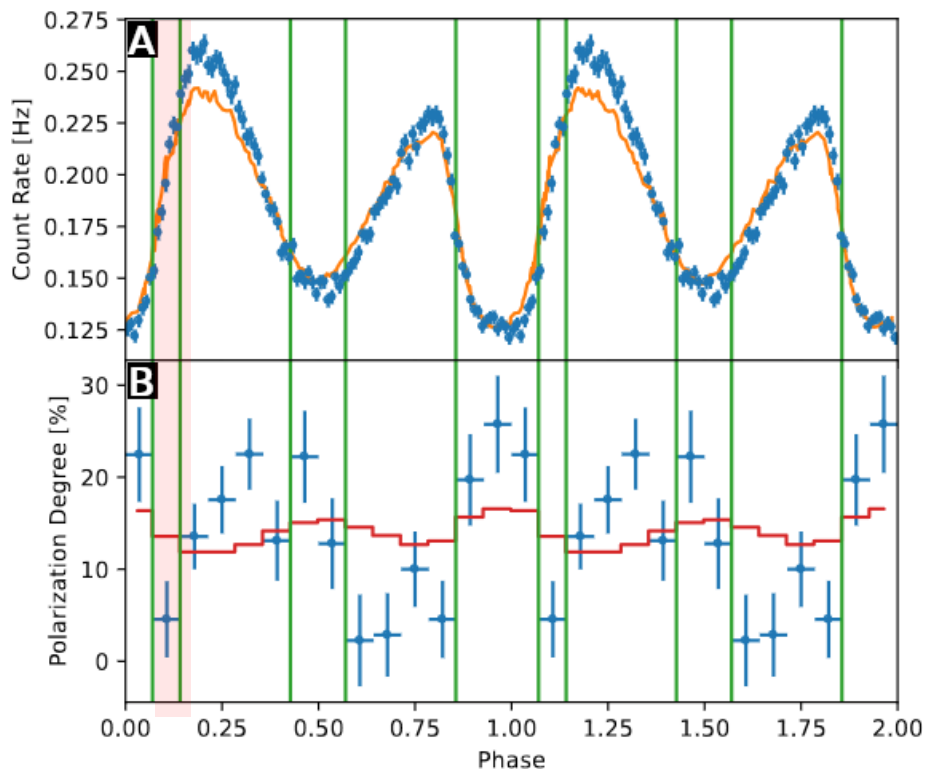


Credit: ESA Science & Technology

- Peculiar phase-dependent behavior
 - 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)

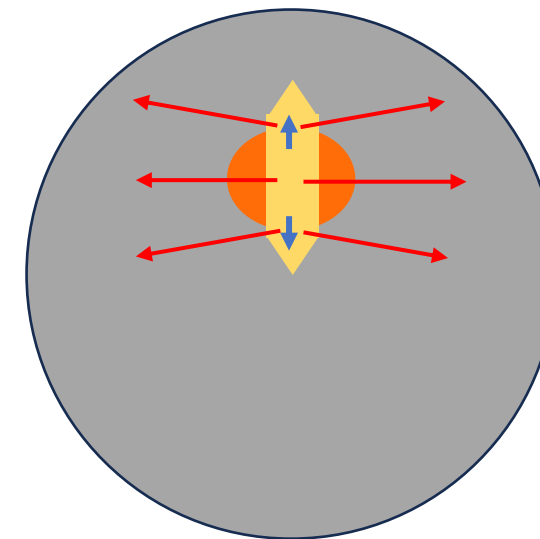


- Theoretical interpretation (in terms of the magnetic-loop model)

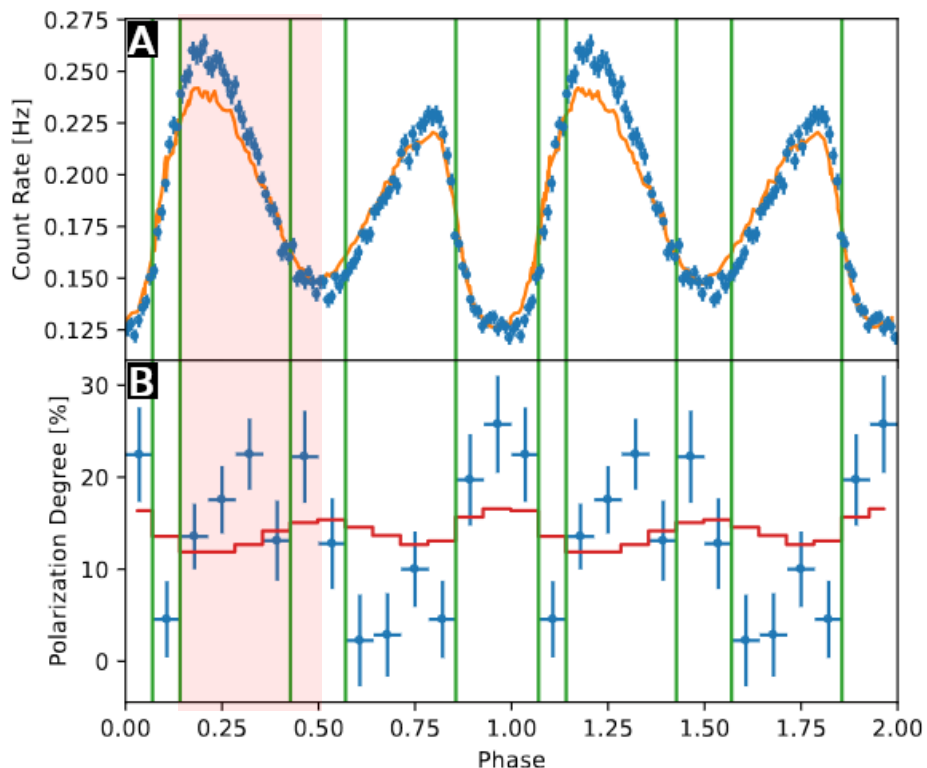


1st rise

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

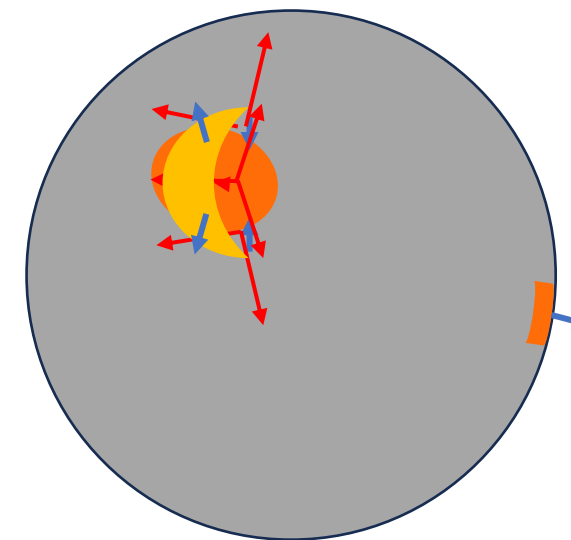


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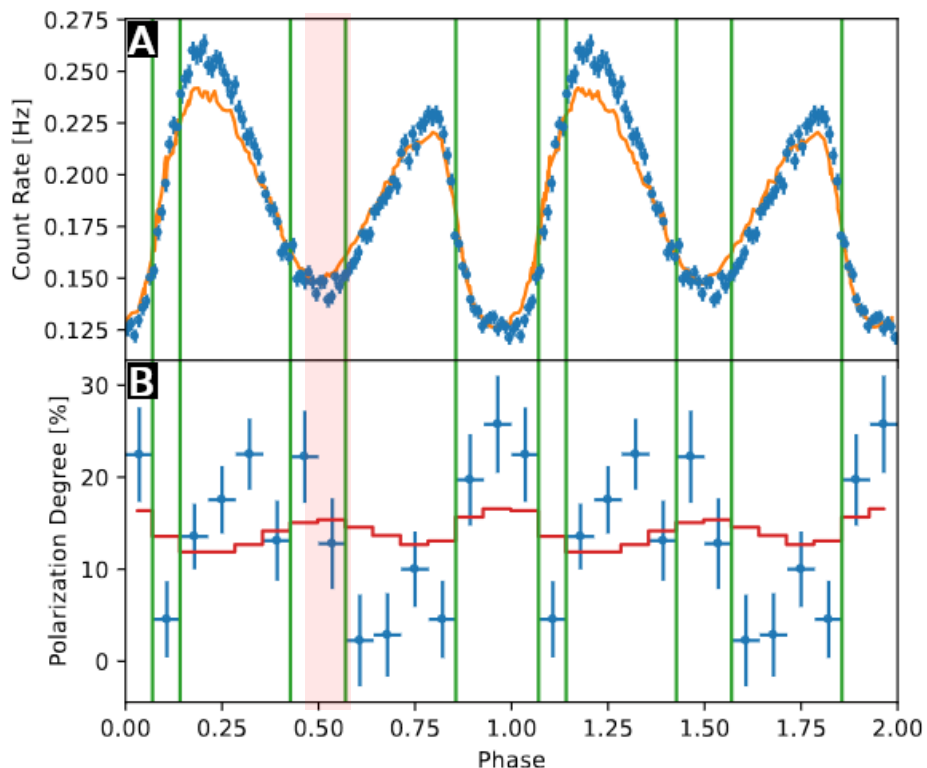


1st peak

- 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%

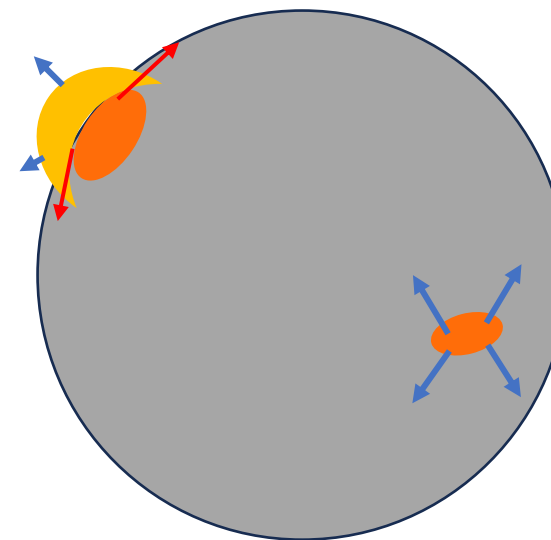


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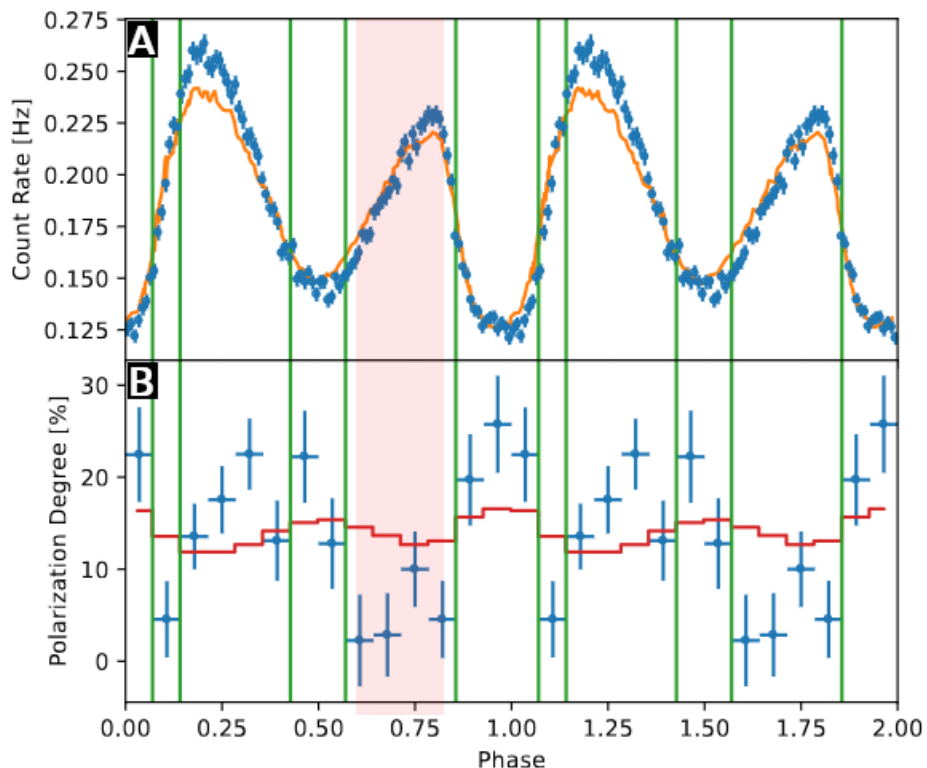


Little dip

- 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)

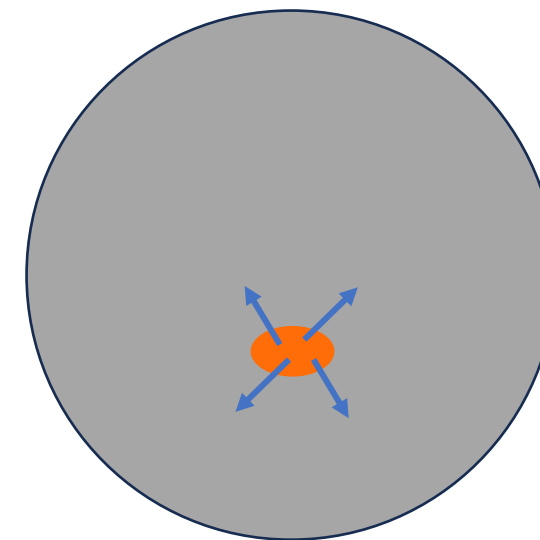


- Theoretical interpretation (in terms of the magnetic-loop model)

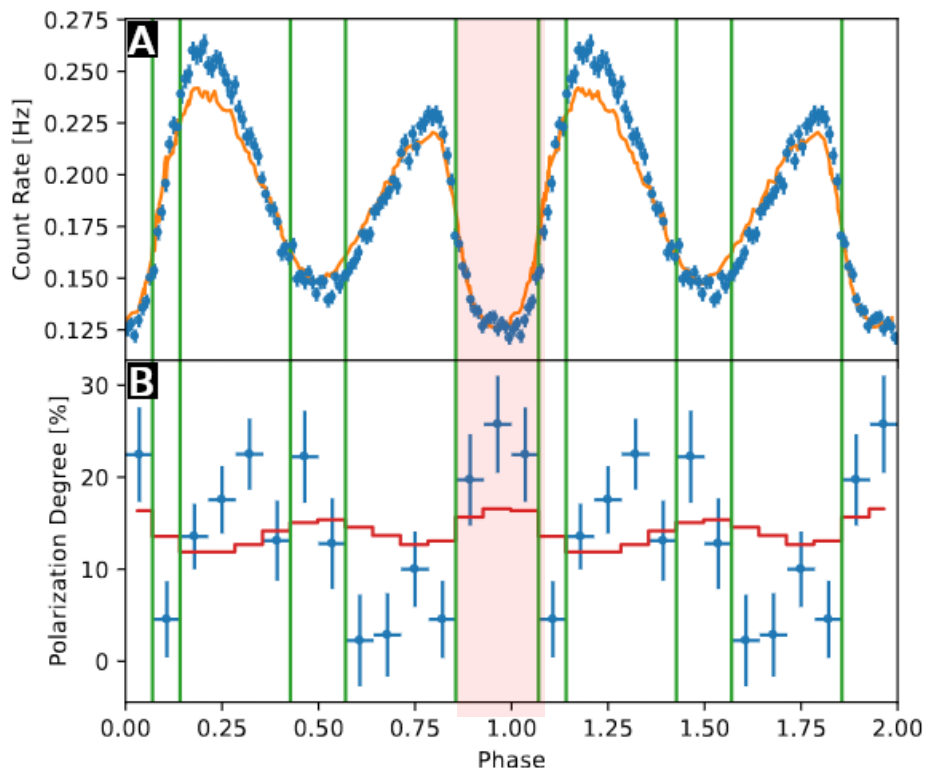


2nd peak

- 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%)

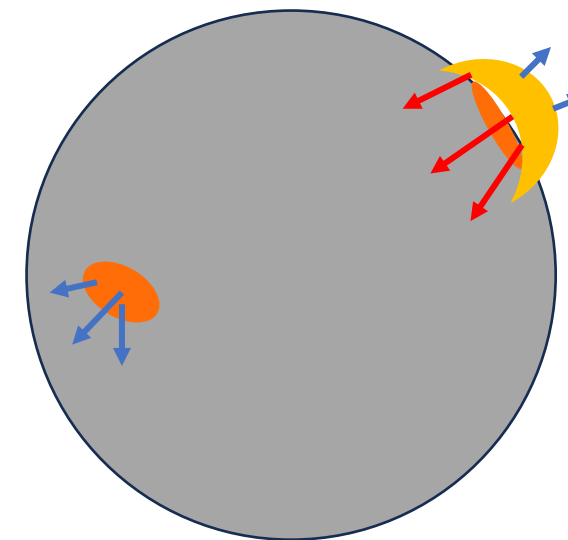


- Theoretical interpretation (in terms of the magnetic-loop model)



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 the same source (4U 0142) confirmed the presence of strong magnetic fields ($\gtrsim 5 \times 10^{13}$ G)
- Energy-dependent PD and PA allowed to confirm the expectations of the RCS model (at least in some persistent sources)
- 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)