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Dipartimento
di Fisica
e Astronomia

UNIVERSITÀ DEGLI STUDI DI PADOVA

Magnetars in the IXPE era



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di Fisica
e Astronomia

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Frascati Workshop 2025
Multifrequency Behaviour of
High Energy Cosmic sources – XV

X-ray polarimetry on magnetars - Expectations

- 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

X-ray polarimetry on magnetars - Expectations

- Wave equation

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

$$\bar{\mu} = \mathbb{1} + \bar{\mu}^{\text{vacuum}}$$

$$\epsilon = \epsilon^{\text{plasma}} + \epsilon^{\text{vacuum}}$$

Plasma effects: – collisions
– radiation damping

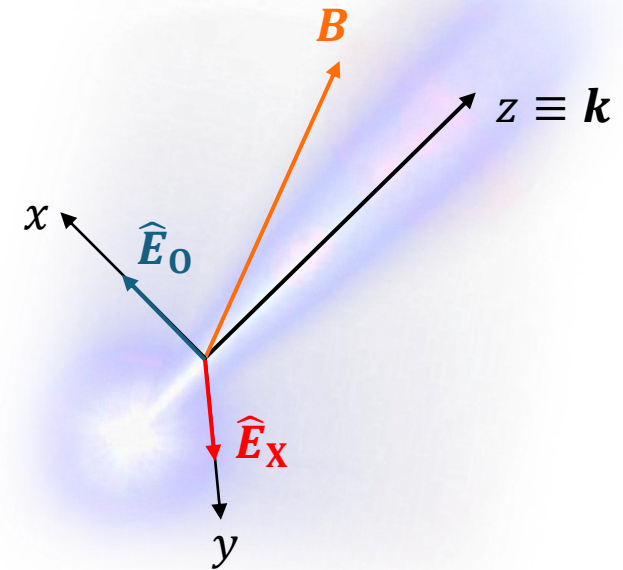
Vacuum effects: – vacuum birefringence
(relevant for $B \gtrsim B_{\text{QED}}$)
 $B_{\text{QED}} \approx 4 \times 10^{13} \text{ G}$

Normal polarization modes in strong B fields

- For B in excess of B_{QED} , when vacuum terms dominate in ϵ , photons turn out to be polarized linearly and only in two normal modes

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

Ordinary mode Extraordinary mode



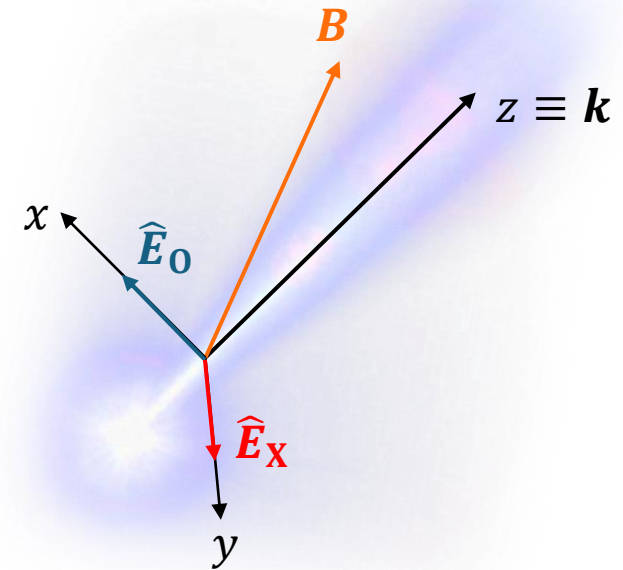
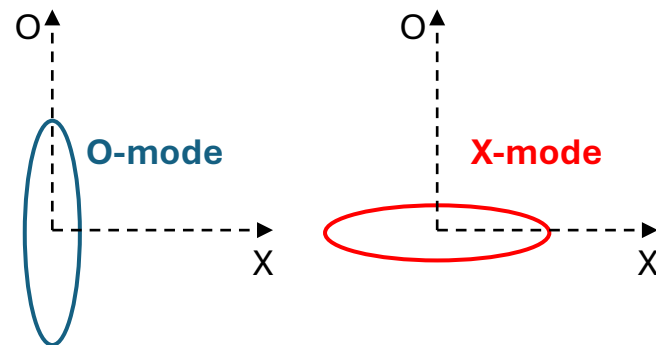
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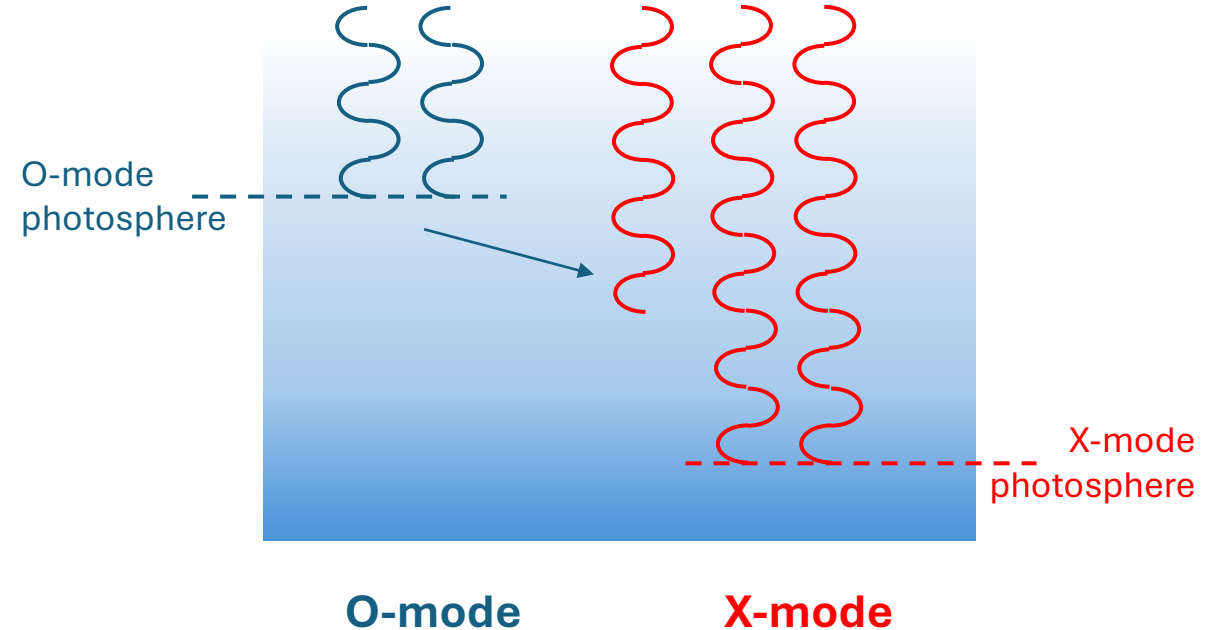
Normal modes in a plasma



Polarization of photons emerging from plasma

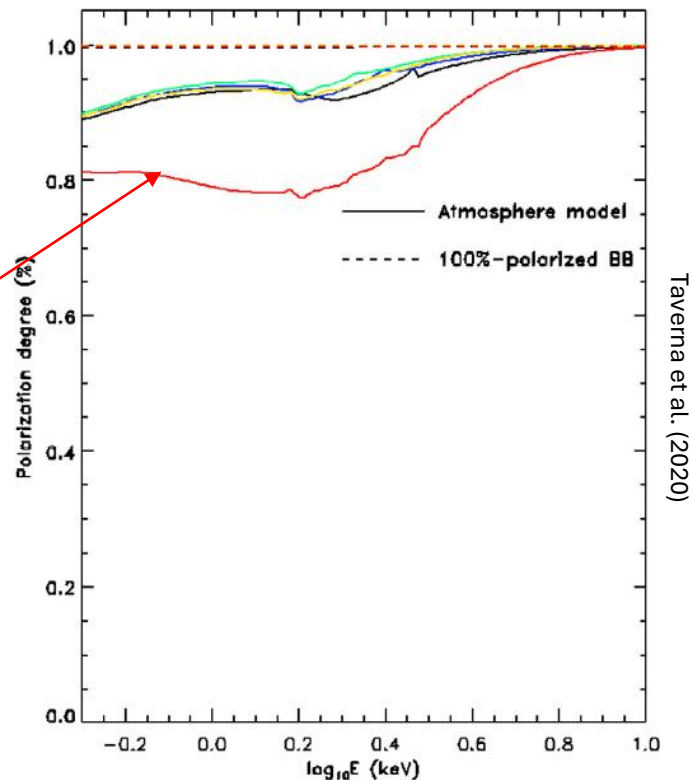
- In strong B fields radiative processes cross sections are different for O and X mode photons

$$\begin{aligned}\sigma_{OO} &\sim \sigma_{\text{unmag}} & \sigma_{XO} &\sim \left(\frac{B}{B_{\text{QED}}}\right)^{-2} \sigma_{OO} \\ \sigma_{OX} &\sim \left(\frac{B}{B_{\text{QED}}}\right)^{-2} \sigma_{OO} & \sigma_{XX} &\sim \left(\frac{B}{B_{\text{QED}}}\right)^{-2} \sigma_{OO}\end{aligned}$$



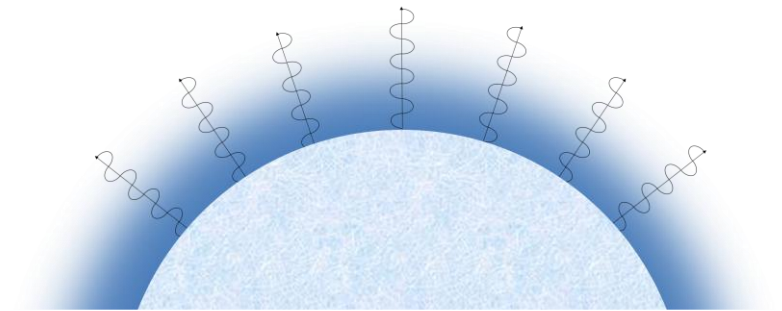
Polarization of photons emerging from plasma

- In strong B fields radiative processes cross sections are different for O and X mode photons
- If an atmosphere covers the NS surface high polarization is expected



High PD
 $\gtrsim 80\%$

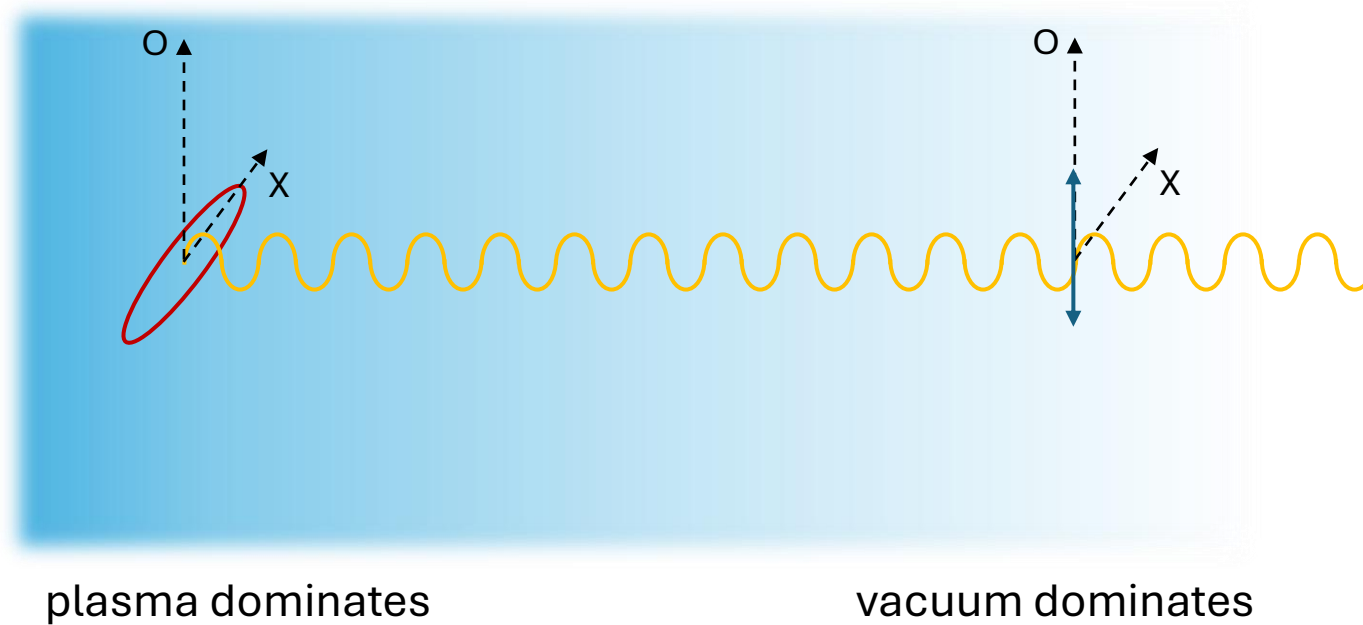
Taverna et al. (2020)



High polarization
(in the X-mode)

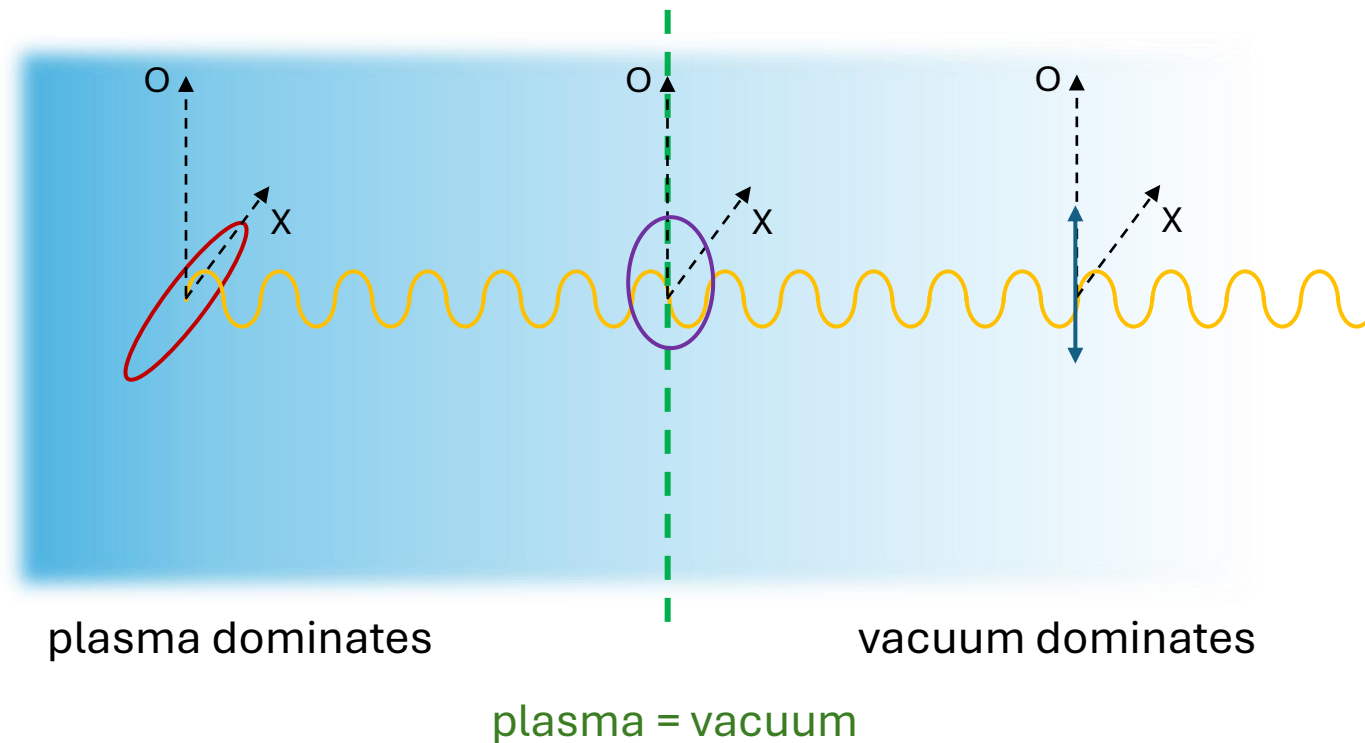
Vacuum resonance

- Plasma and vacuum «polarize» photons in opposite ways



Vacuum resonance

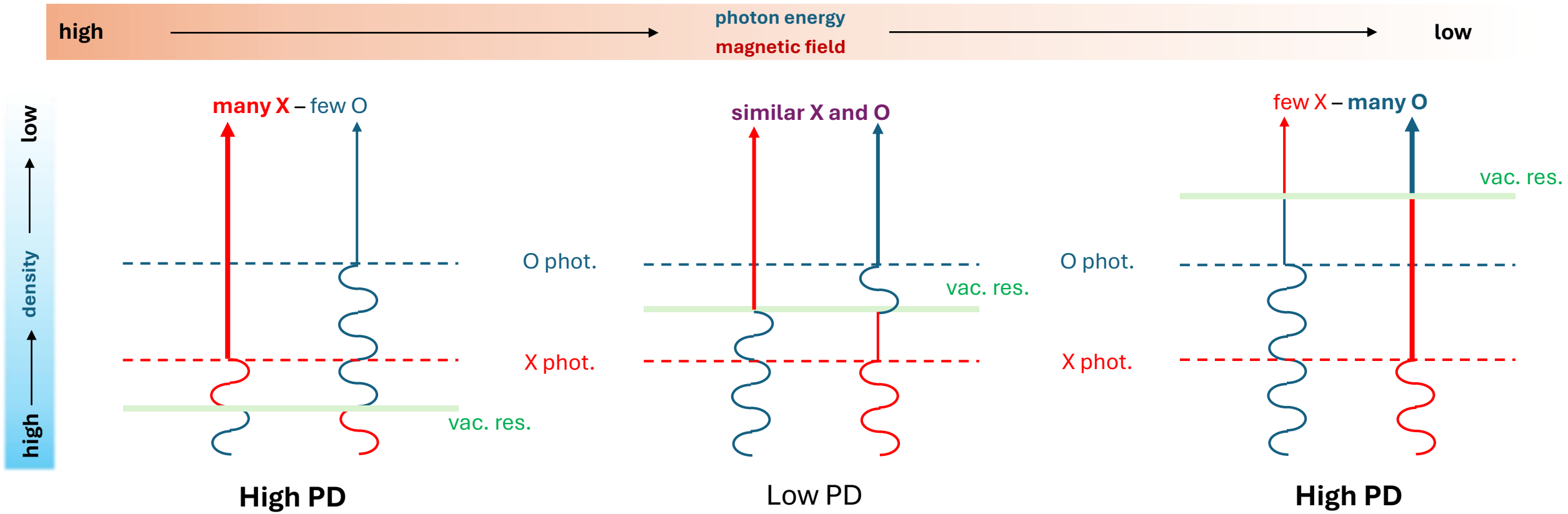
- Plasma and vacuum «polarize» photons in opposite ways



$$\rho_V \approx 50 Y_e^{-1} \left(\frac{B}{10^{14} \text{ G}} \right)^2 \left(\frac{\hbar\omega}{1 \text{ keV}} \right)^2 \left(\frac{q+m}{\alpha_F} \right) \left(\frac{B}{B_{\text{QED}}} \right)^{-1} \text{ gcm}^{-3}$$

Vacuum resonance

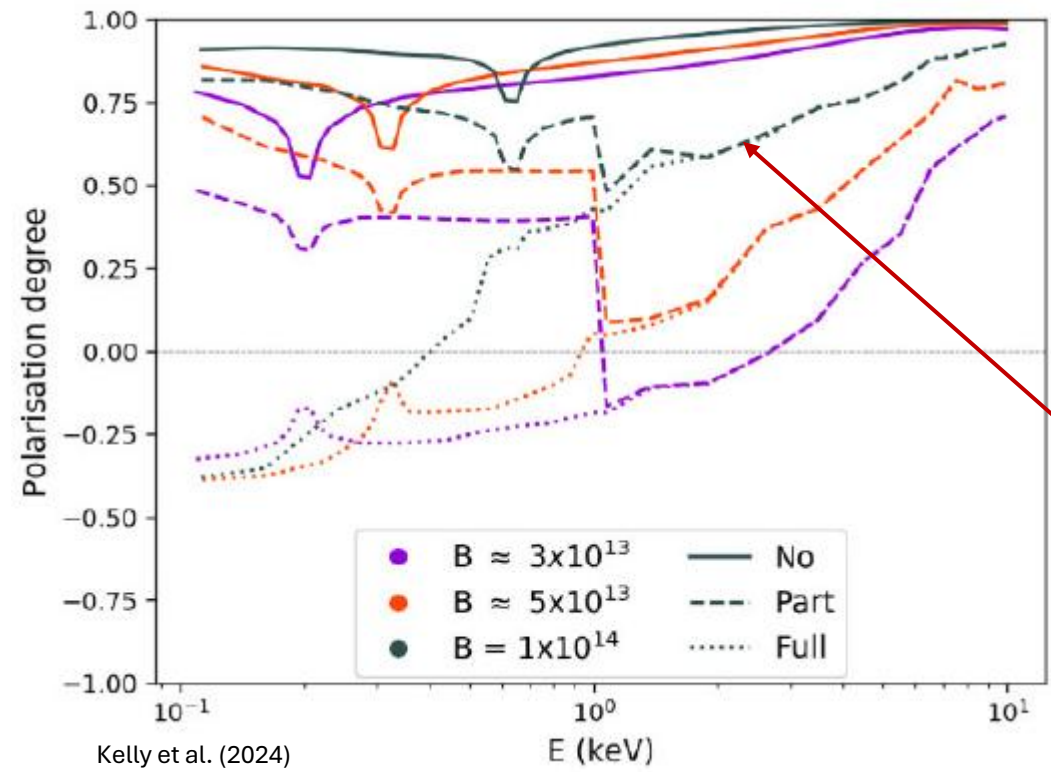
- Plasma and vacuum «polarize» photons in opposite ways
- Mode conversion at the vacuum resonance may modify the polarization pattern of photons emerging from plasma



• P
• M
• p

high

low
↑ density
↑ high



Kelly et al. (2024)

For magnetic fields $\gtrsim 10^{14}$ G (gray line), polarization above 1 keV is dominated by the X-mode, with a high polarization degree

High PD

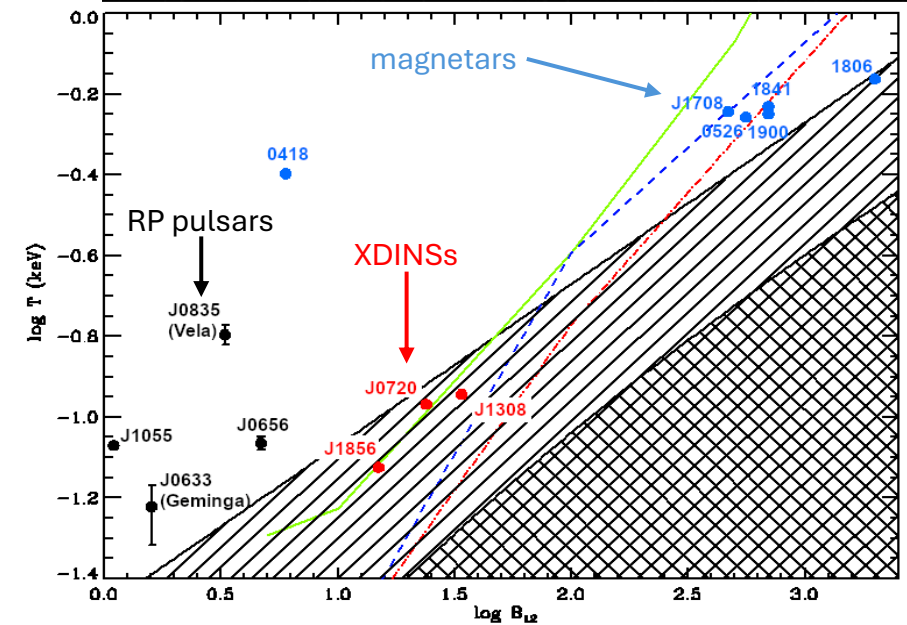
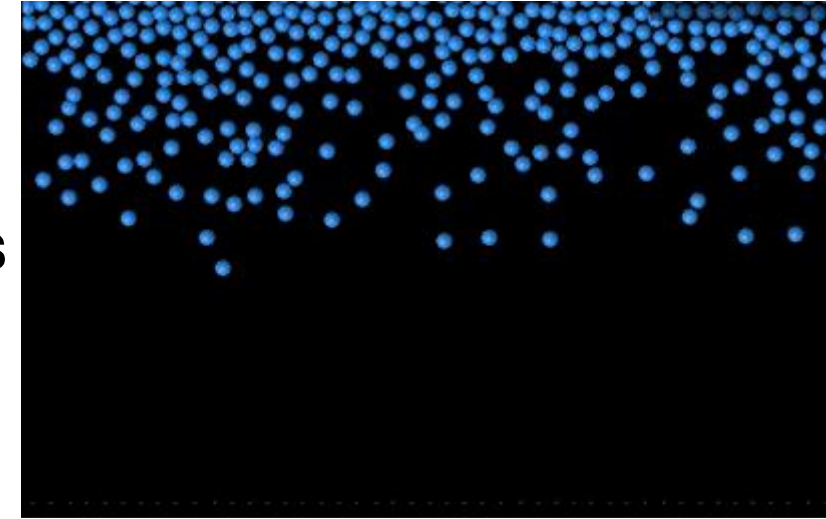
Low PD

High PD

vac. res.

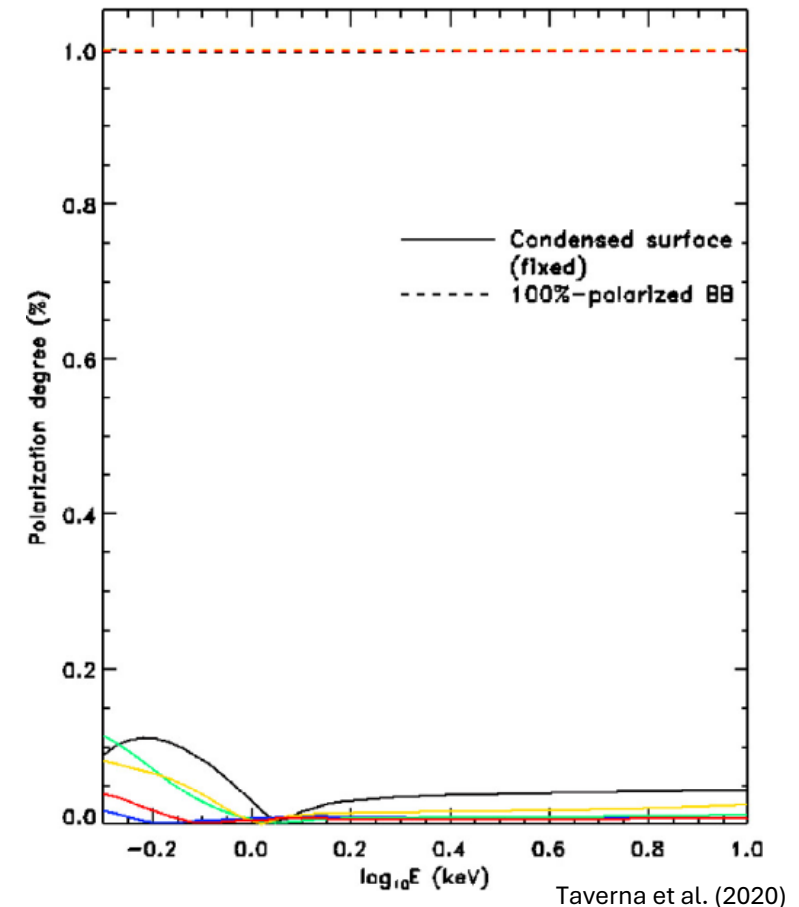
Magnetic condensation

- Atoms under strong B -fields are elongated along the field direction
- For sufficiently low temperatures molecular chains are formed
- This «condensed atmosphere» settles onto the surface, leaving the NS «bare»

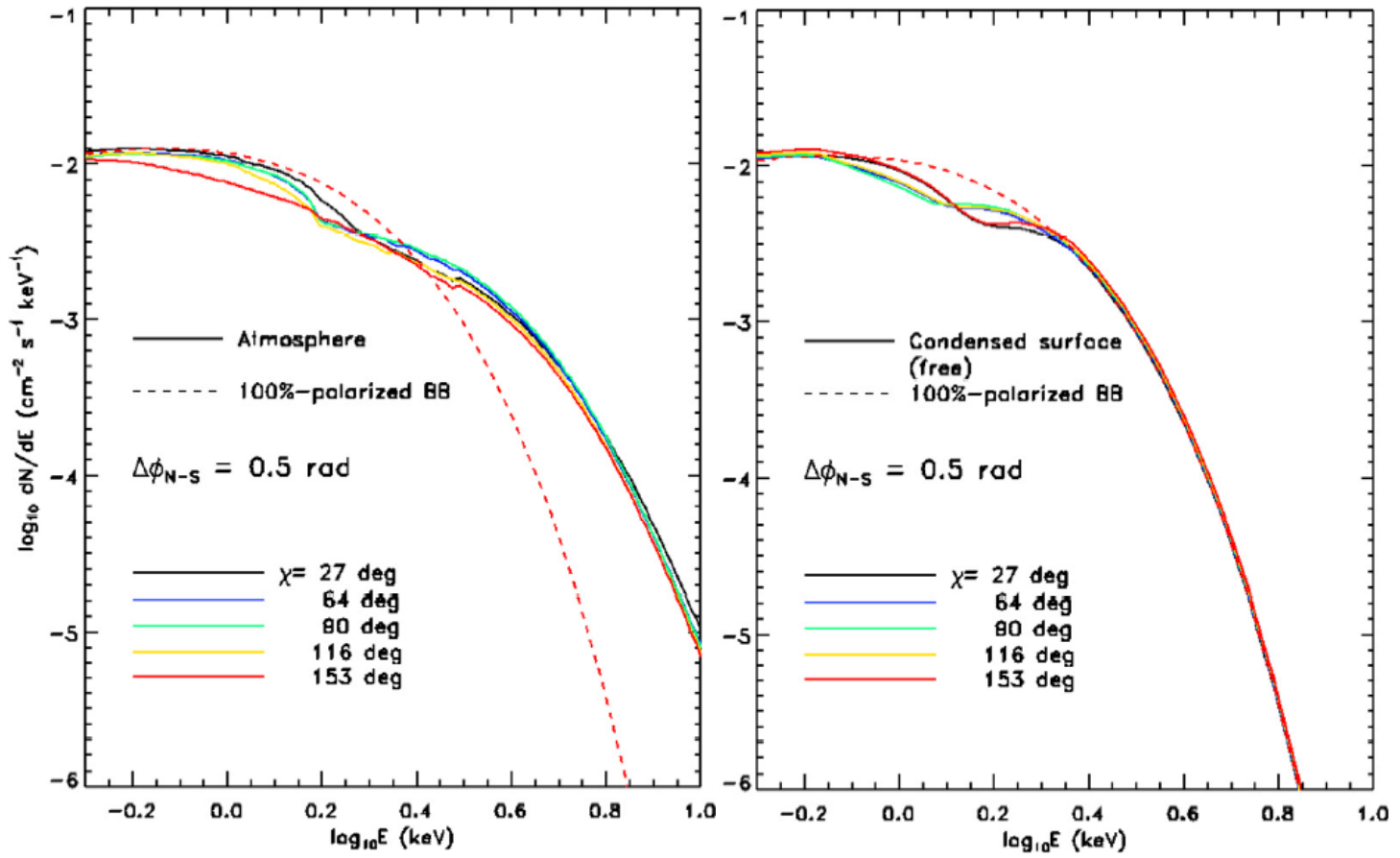


Magnetic condensation

- Atoms under strong B -fields are elongated along the field direction
- For sufficiently low temperatures molecular chains are formed
- This «condensed atmosphere» settles onto the surface, leaving the NS «bare»
- PD for condensed-surface emission is much lower than for atmospheric one (and both O- and X-mode photons can prevail)



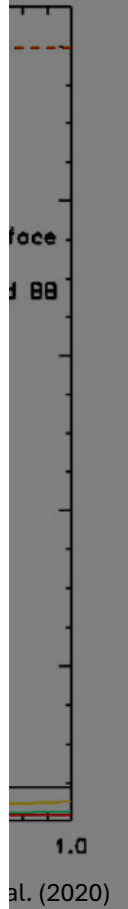
- A
- th
- F
- a
- T
- S
- P
- l
- a



Spectra for atmospheres and condensed-surfaces are similar (BB-like)

Polarization may help in disentangling the surface emission model

Taverna et al. (2020)



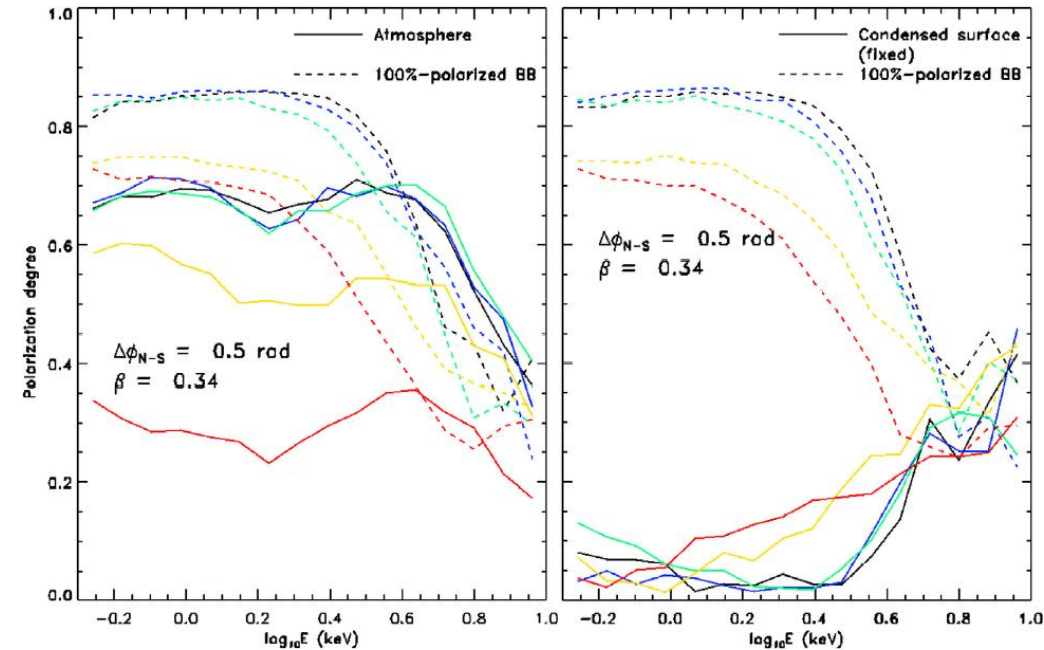
Magnetospheric RCS

- Charged particles flowing along the closed field lines make the magnetosphere optically thick for RCS
- RCS cross sections are also sensitive to the polarization mode

$$\sigma_{00} = \frac{1}{3} \sigma_{0X}$$

$$\sigma_{XX} = 3\sigma_{X0}$$

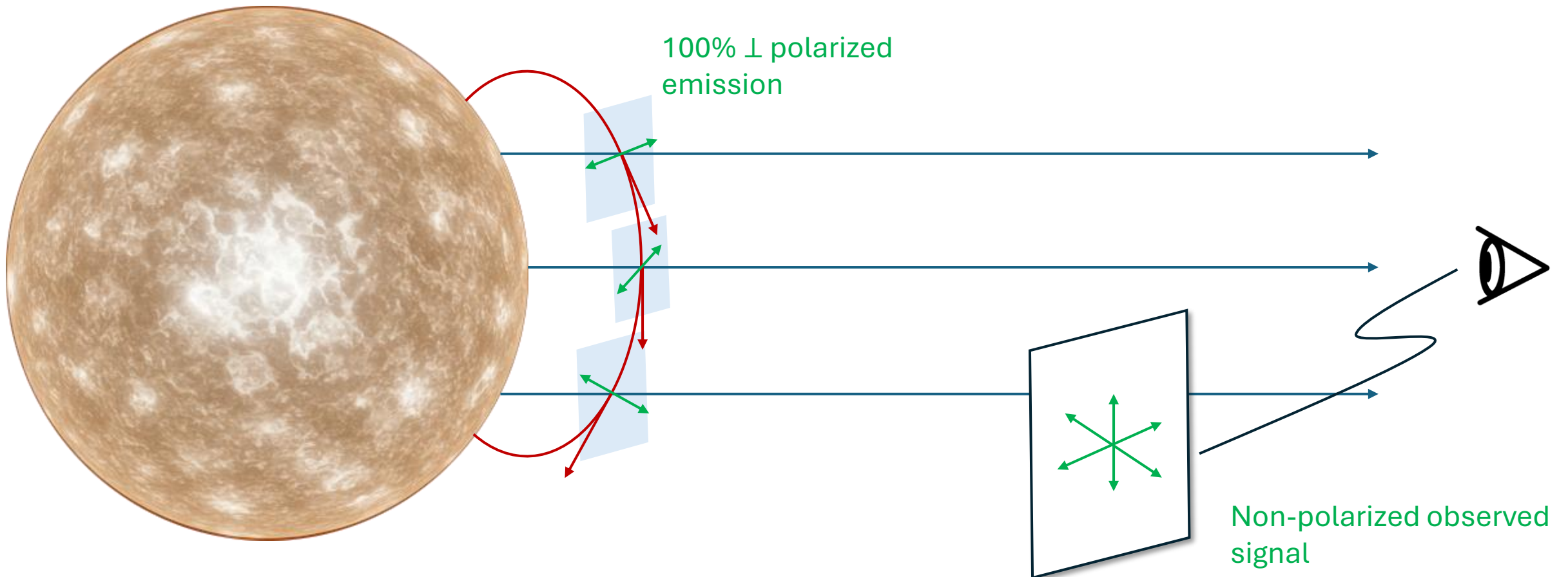
- Expected polarization in the soft PL tails of $\approx 33\%$ (X-mode dominated) for mildly relativistic charges



Taverna et al. (2020)

Transport of polarization at infinity

- In normal conditions, observed polarization is expected to be very low (due to tangled B -field topology close to the surface)



Magnetar IXPE observations

- AXP 4U 0142+61

- $F_{2-10}^{\text{unabs}} \approx 7 \times 10^{-11}$ cgs
- $B_{\text{pp}} \approx 2 \times 10^{14}$ G
- $t_{\text{exp}} = 840$ ks

- AXP 1RXS J170849.0–4009100

- $F_{2-10}^{\text{unabs}} \approx 3 \times 10^{-11}$ cgs
- $B_{\text{pp}} \approx 5 \times 10^{14}$ G
- $t_{\text{exp}} = 837$ ks

- SGR 1806–20

- $F_{0.5-10}^{\text{unabs}} \approx 1 \times 10^{-11}$ cgs
- $B_{\text{pp}} \approx 7 \times 10^{14}$ G
- $t_{\text{exp}} = 947$ ks

- AXP 1E 2259+586

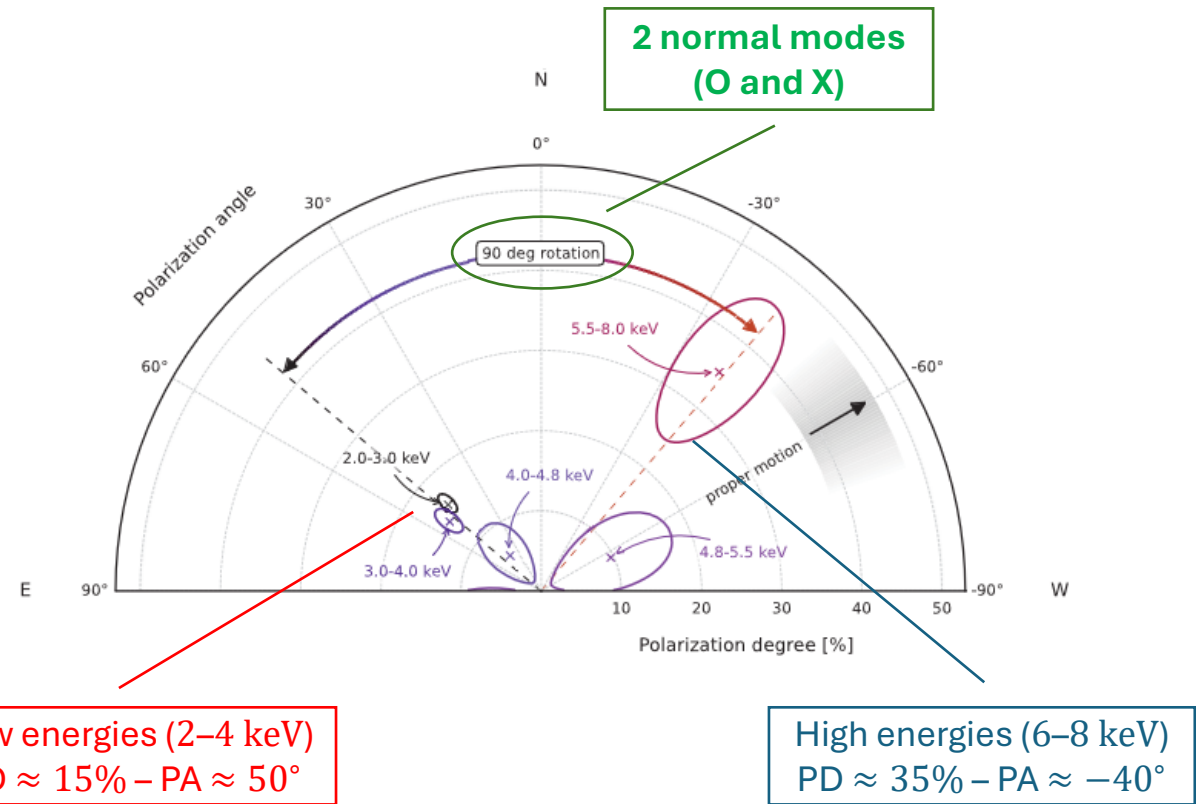
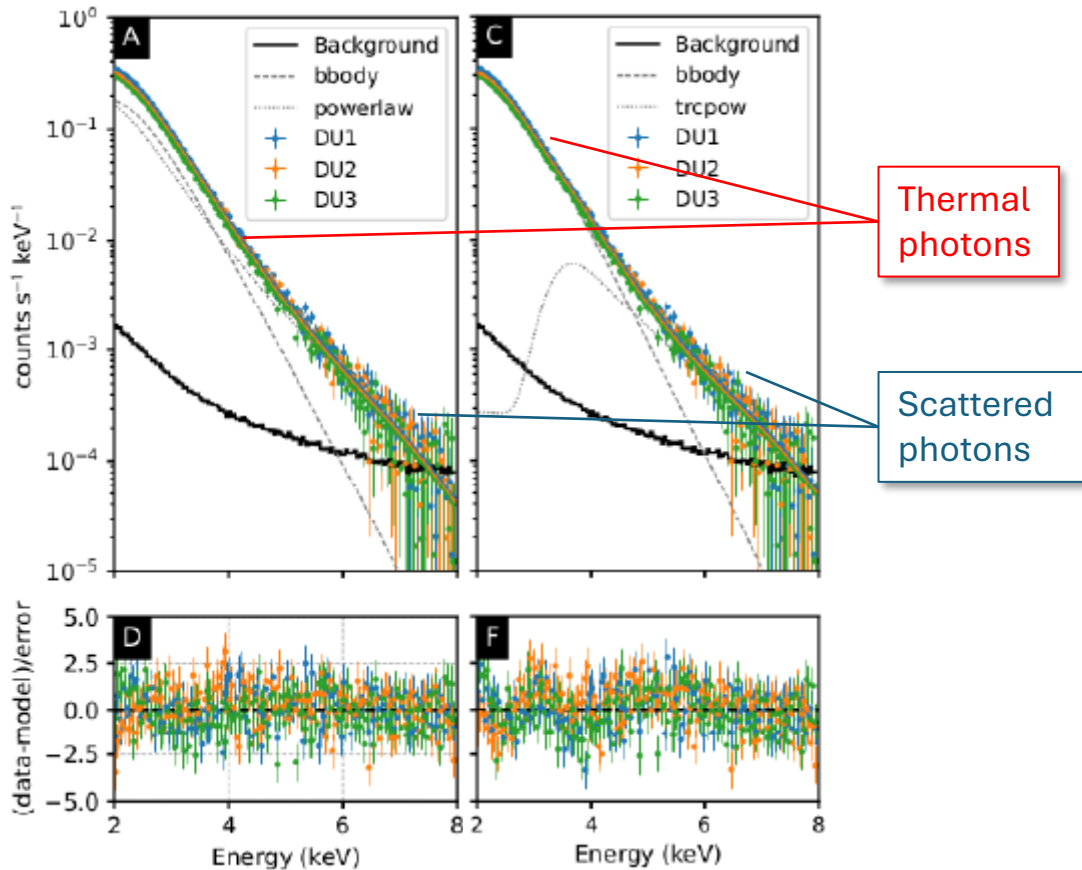
- $F_{2-10}^{\text{unabs}} \approx 1.5 \times 10^{-11}$ cgs
- $B_{\text{pp}} \approx 6 \times 10^{13}$ G
- $t_{\text{exp}} = 1200$ ks

- AXP 1E 1841–045

- $F_{2-8}^{\text{unabs}} \approx 2 \times 10^{-11}$ cgs
- $B_{\text{pp}} \approx 7 \times 10^{14}$ G
- $t_{\text{exp}} = 300$ ks

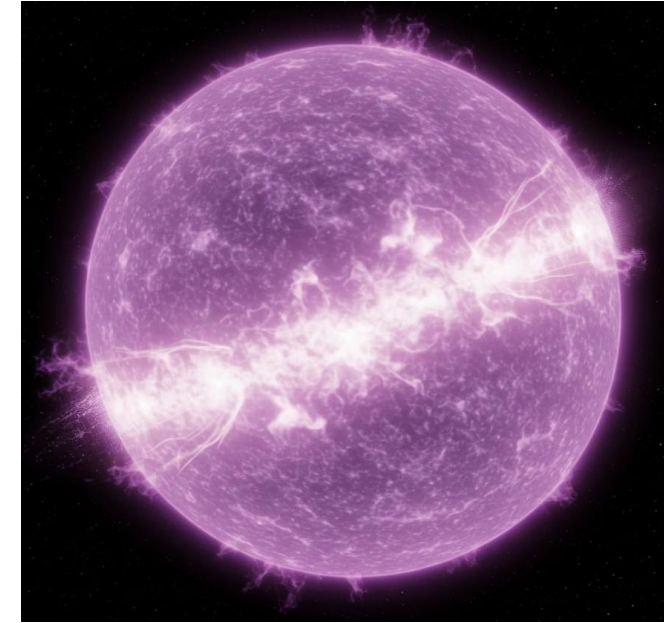
AXP 4U 0142+61

- Phase-integrated, spectro-polarization measurements



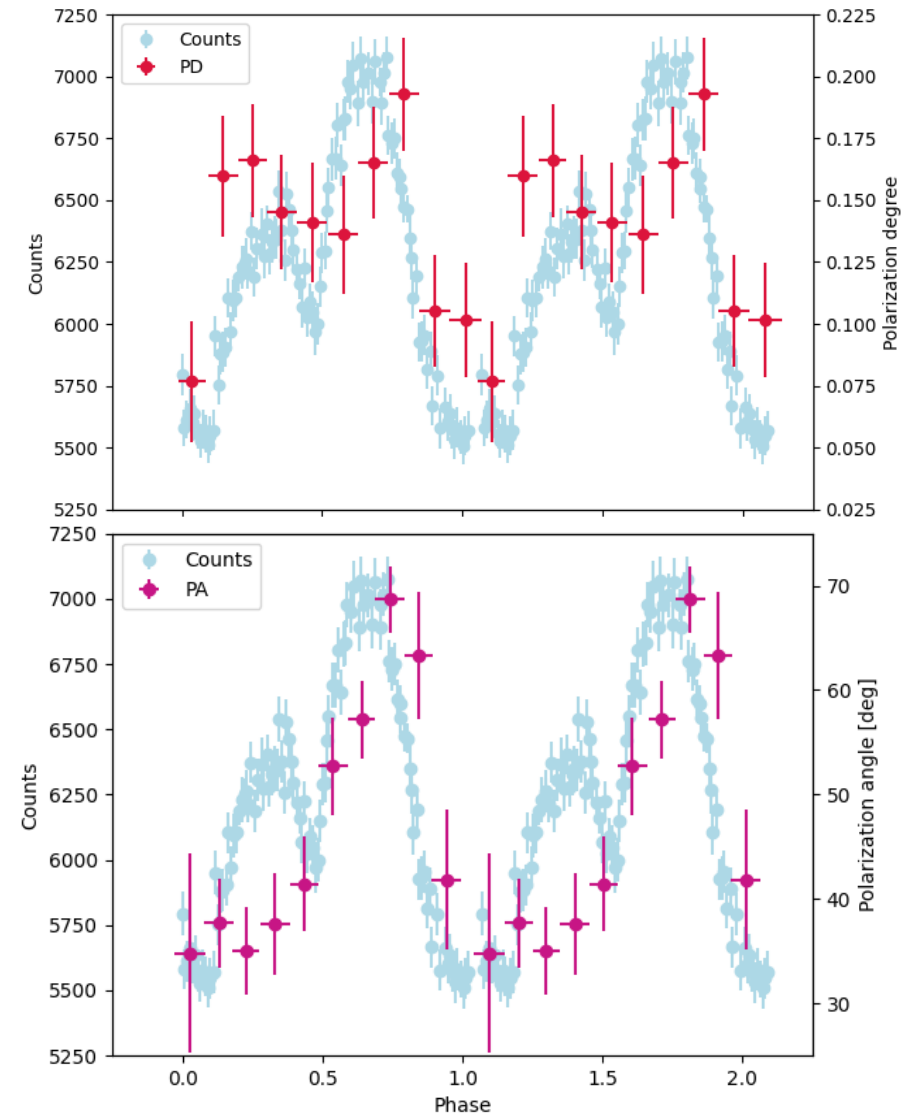
AXP 4U 0142+61

- Phase-integrated, spectro-polarization measurements
- 90° swing of PA points towards the presence of both O-mode and X-mode photons in the soft X-ray band
- Compatible with what expected from the RCS model
 - Low energy: thermal photons lowly polarized (condensed surface – O-mode)
 - Emission from an extended equatorial belt
 - High energy: resonantly scattered photons (33% – X-mode)



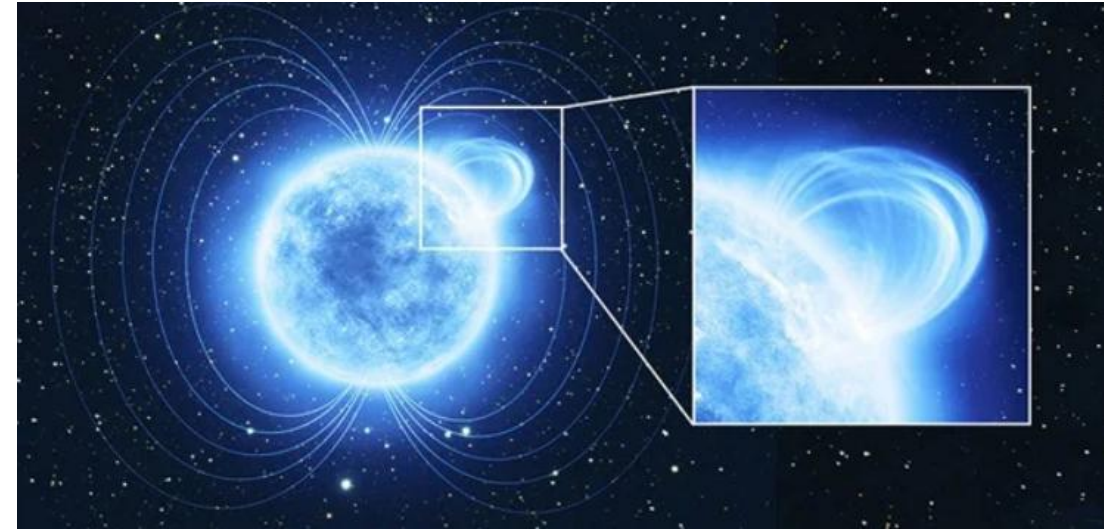
Indirect test of vacuum birefringence

- Phase-dependent PD coherent with the LC (double-peaked and in-phase)
→ determined at the surface
- Phase-dependent PA uncorrelated with the LC (single-peaked, quasi-sinusoidal – RVM)
→ determined far from the surface
- Vacuum birefringence naturally reconcile the contradiction

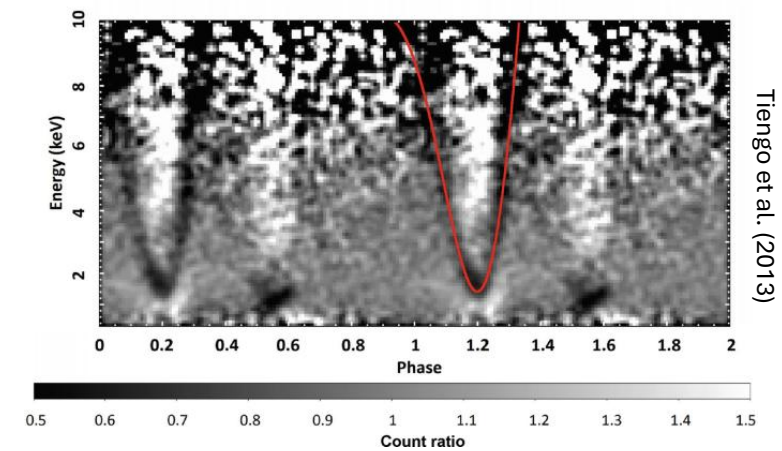


AXP 1E 2259+586

- Low- B magnetar ($B_{\text{sd}} \approx 6 \times 10^{13}$ G)
- Previous studies (Pizzoccaro et al. 2019) observed a (phase-dependent) spectral line at ≈ 1 keV
- Interpreted as a resonant Compton scattering feature
- Caused by photons intercepted by particles in a bundle of twisted field lines (like in SGR 0418+5729)



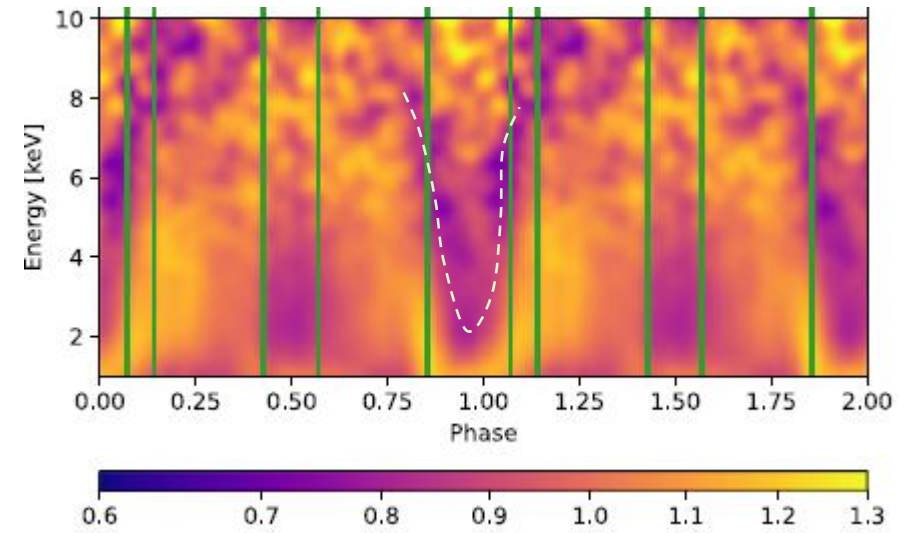
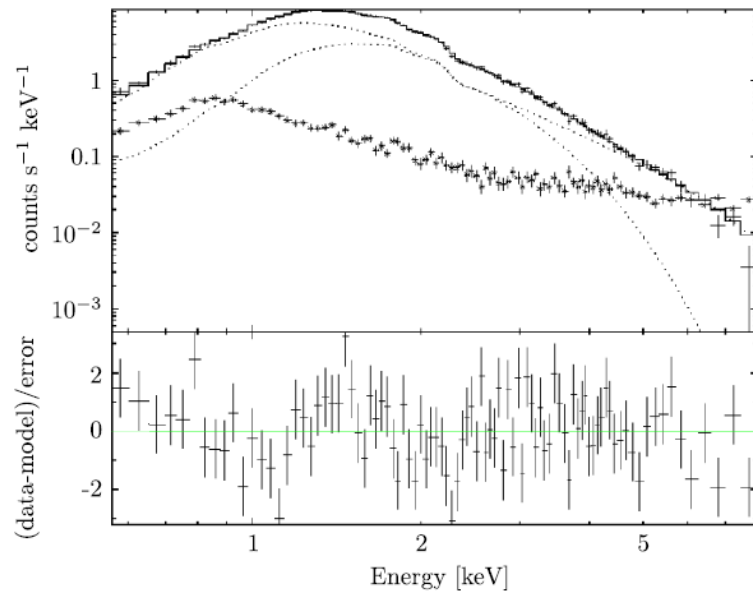
Credits: ESA



Tiengo et al. (2013)

AXP 1E 2259+586 – Spectral analysis

- Absorption line superimposed to the (usual) BB+PL decomposition

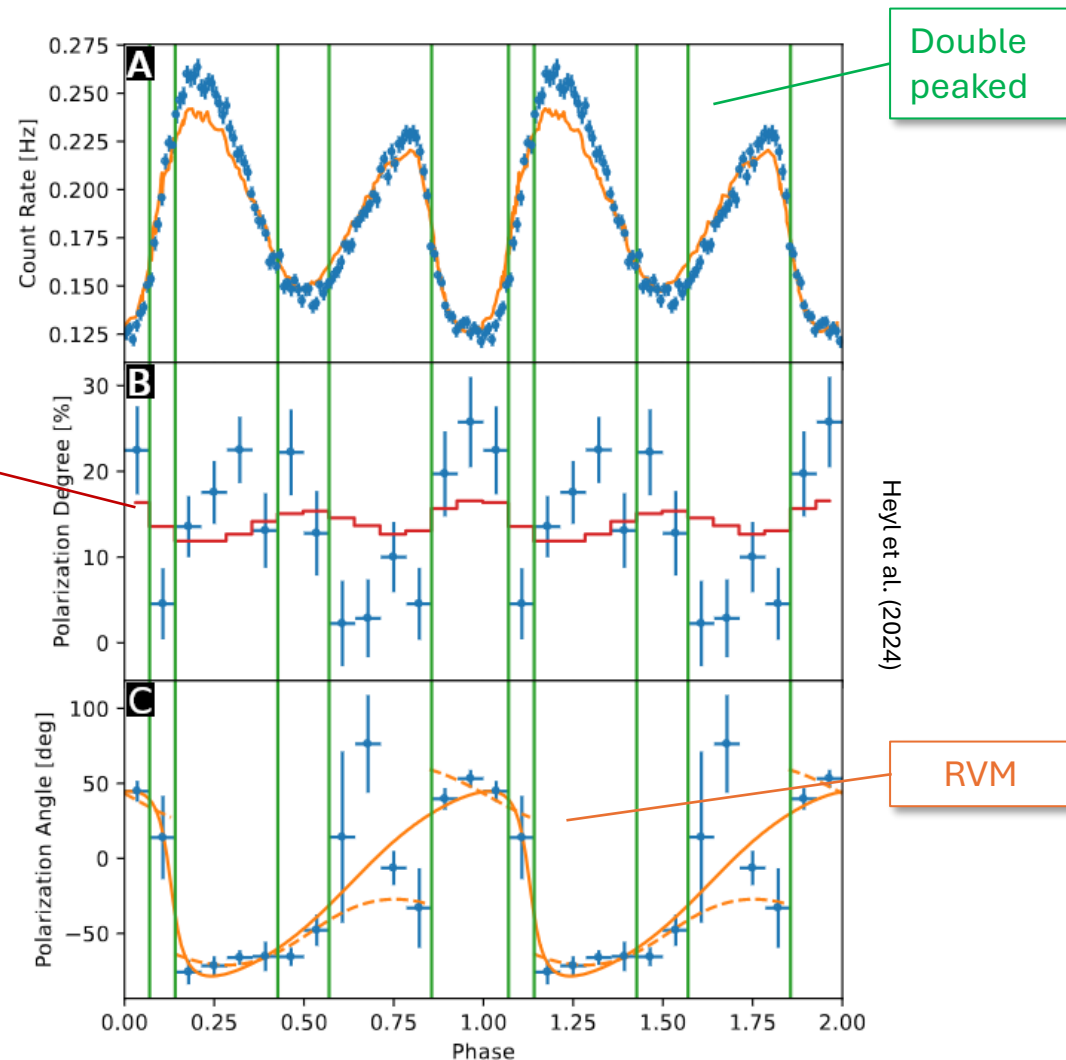
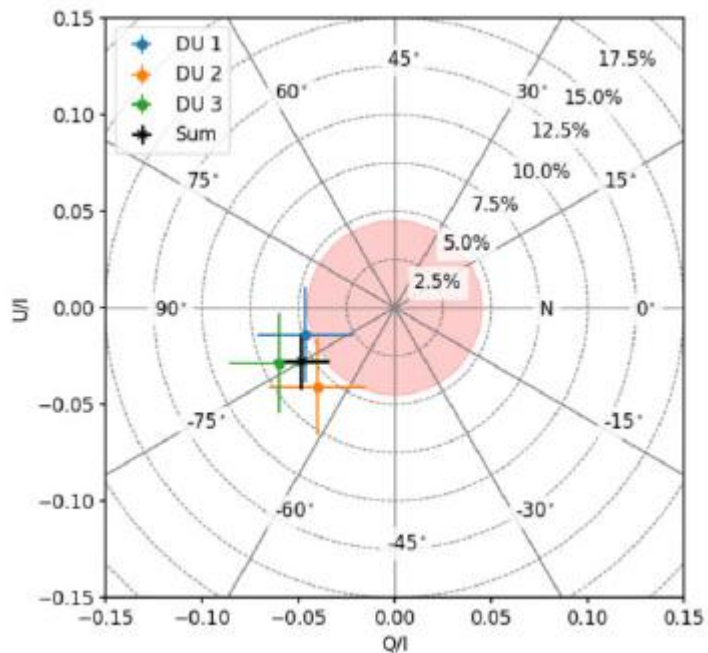


Heyl et al. (2024)

Data	N_{H} (10^{22} cm^{-2})	kT_{BB} (keV)	R_{BB}^a (km)	Γ_{PL}	Norm _{PL} at 1 keV ($10^{-3} \text{ s}^{-1} \text{ keV}^{-1} \text{ cm}^{-2}$)	E_{abs} (keV)	σ_{abs} (keV)	Depth _{abs} (keV)	χ^2/dof
PN + MOS	$0.91^{+0.08}_{-0.13}$	$0.446^{+0.008}_{-0.009}$	$2.24^{+0.13}_{-0.13}$	$3.93^{+0.08}_{-0.11}$	$50.72^{+6.87}_{-9.14}$	$0.71 \pm^{+0.17}_{-0.22}$	$0.30^{+0.09}_{-0.08}$	$0.30^{+0.63}_{-0.20}$	341.0/245
PN	$1.02^{+0.03}_{-0.07}$	$0.437^{+0.012}_{-0.011}$	$2.33^{+0.22}_{-0.21}$	$4.09^{+0.08}_{-0.08}$	$62.09^{+6.81}_{-6.41}$	$0.96^{+0.07}_{-0.18}$	$0.23^{+0.10}_{-0.06}$	$0.11^{+0.20}_{-0.05}$	94.1/93
IXPE ^b	1.02^c	$0.429^{+0.011}_{-0.010}$	$2.45^{+0.24}_{-0.20}$	$4.36^{+0.09}_{-0.09}$	$75.95^{+7.79}_{-7.80}$	0.96^c	0.23^c	0.11^c	138.0/147

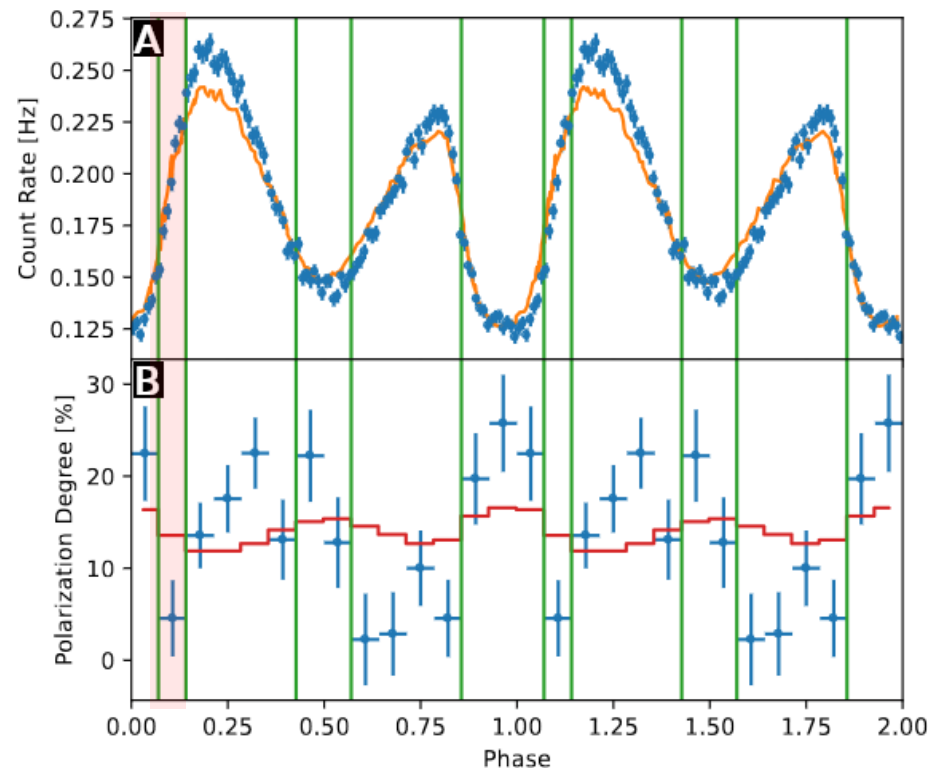
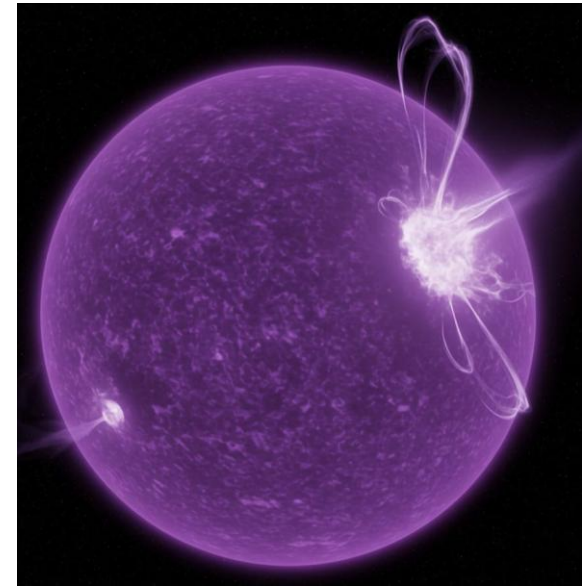
AXP 1E 2259+586 – Polarization analysis

- Low phase-/energy-integrated PD – Peculiar phase-dependent behavior

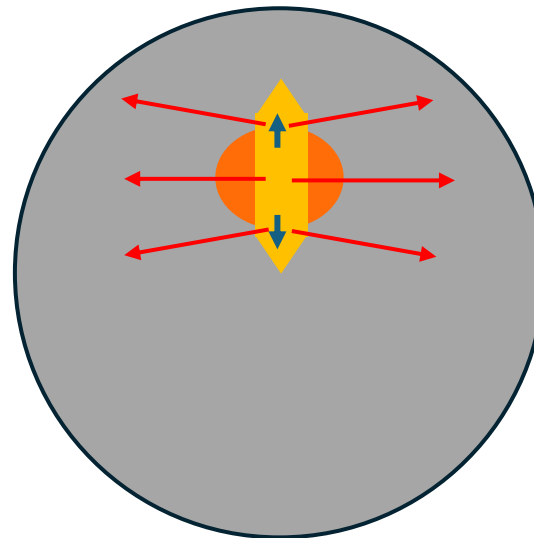


AXP 1E 2259+586 – Interpretation

- Two emitting hot-spots (with condensed surface exposed), the primary covered by a magnetic loop

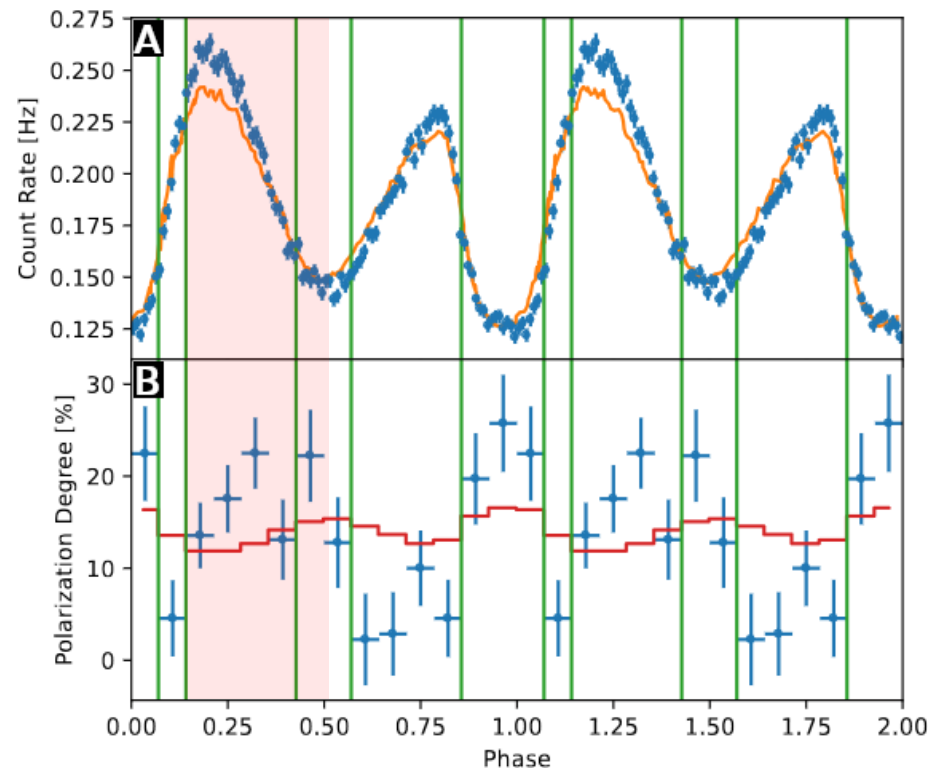
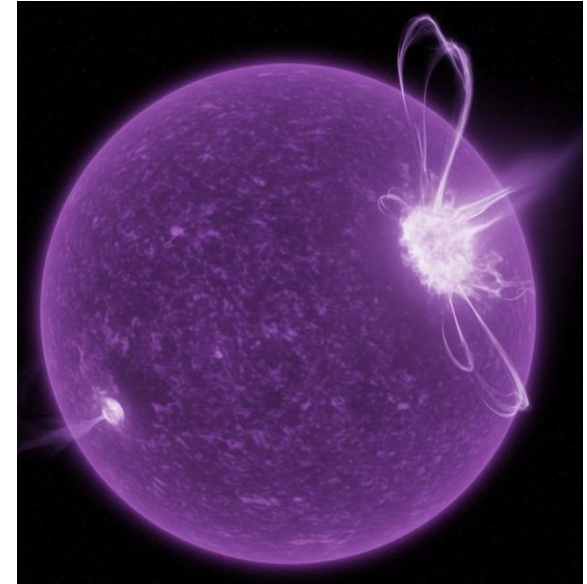


- **1st rise: primary spot face-on**
Thermal photons (low PD in O-mode) mostly scattered away from the LOS by RCS onto p^+

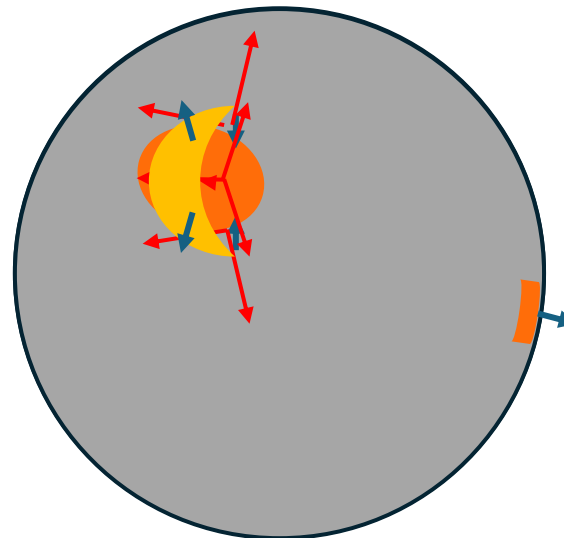


AXP 1E 2259+586 – Interpretation

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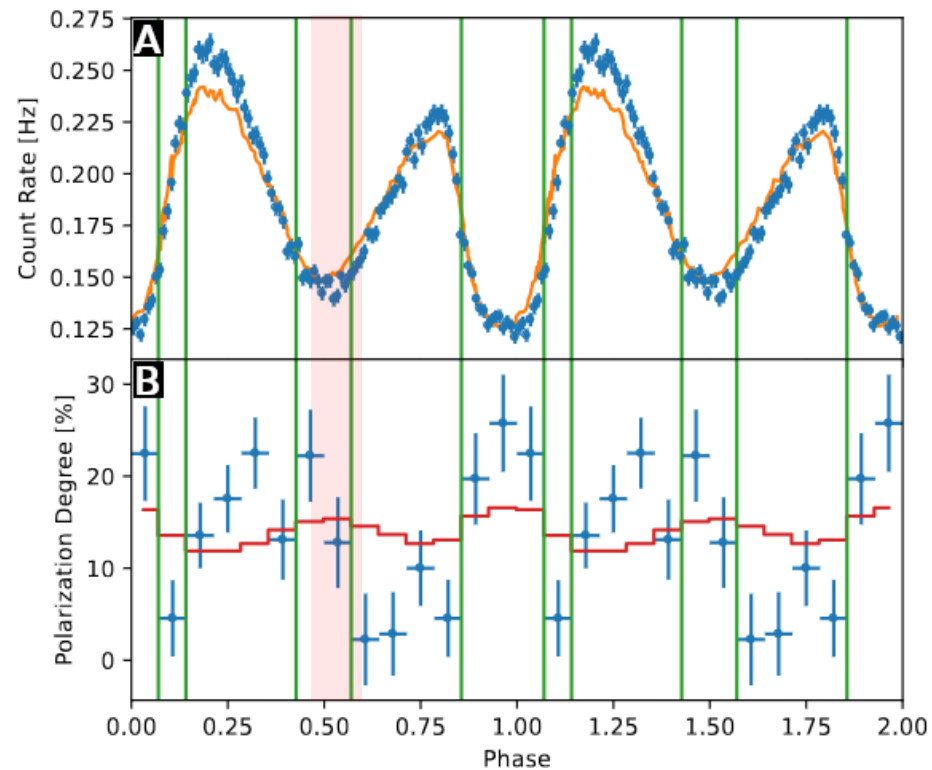
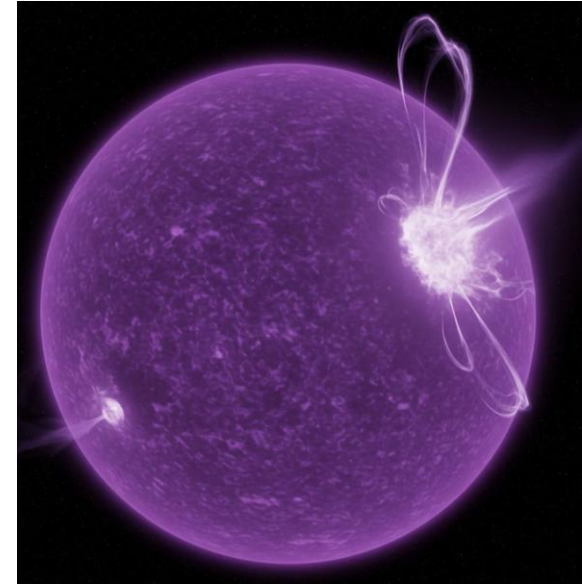


- **1st peak: primary spot off-axis**
Scattered photons enter in view (PD → 33%, mostly in the X-mode)

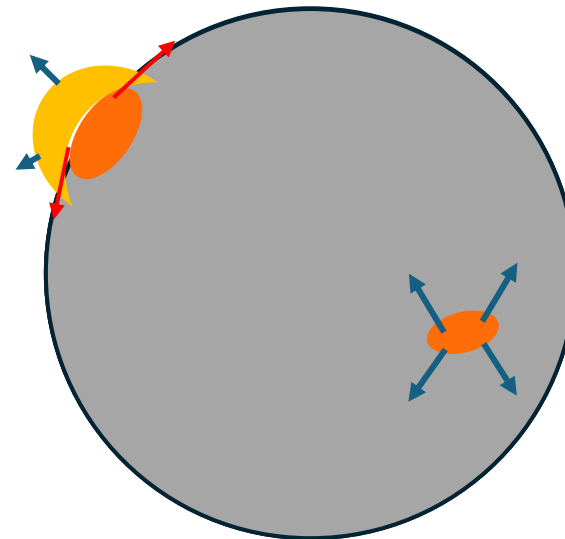


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- Two emitting hot-spots (with condensed surface exposed), the primary covered by a magnetic loop

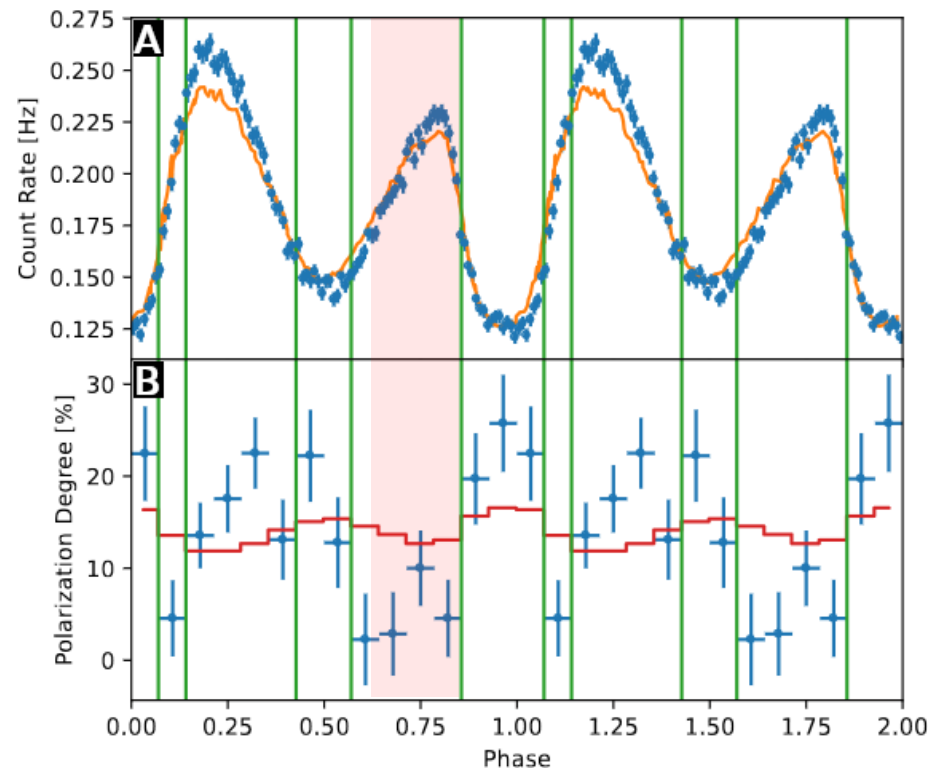
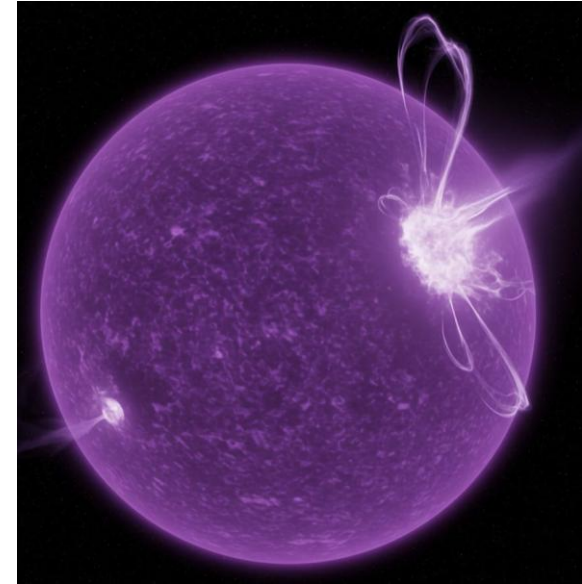


- **1st min: two spots are in view**
X-mode photons from the primary spot sum with O-mode (lowly polarized) from the secondary one

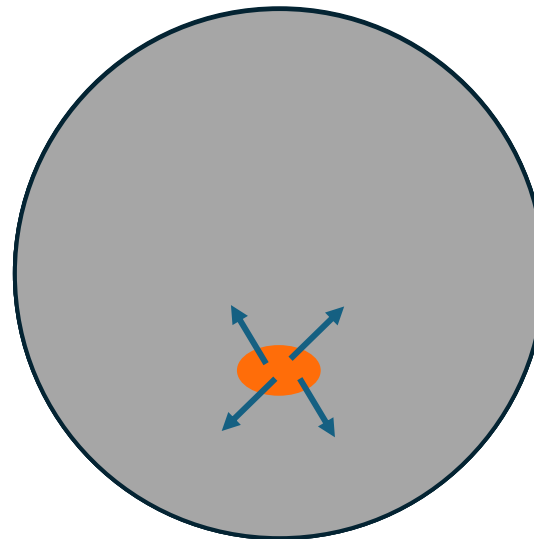


AXP 1E 2259+586 – Interpretation

- Two emitting hot-spots (with condensed surface exposed), the primary covered by a magnetic loop

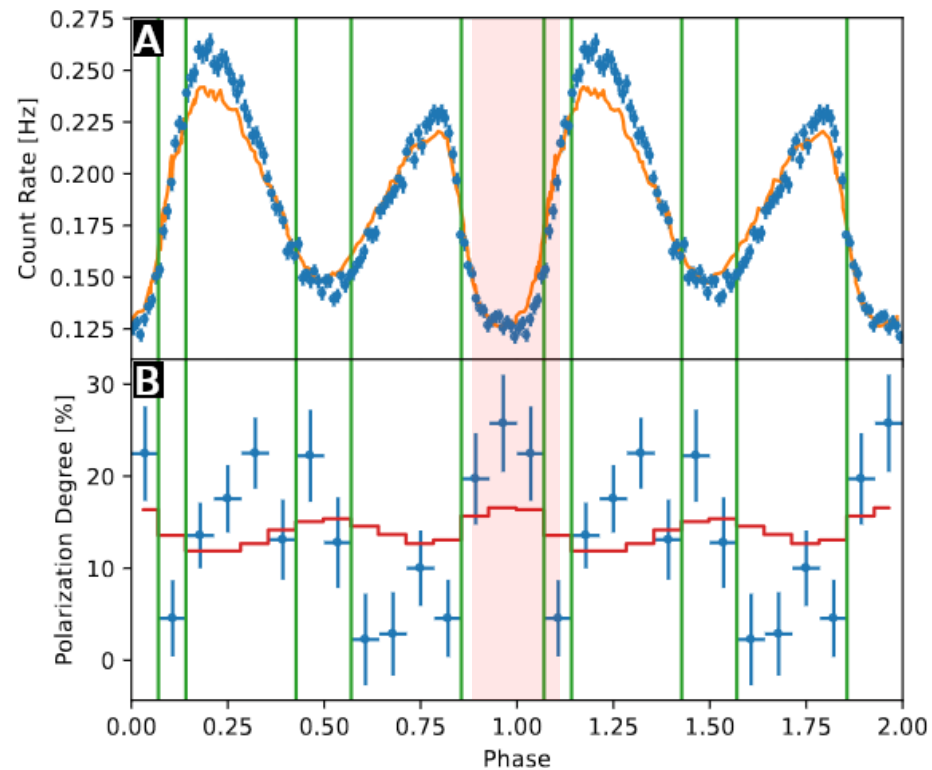
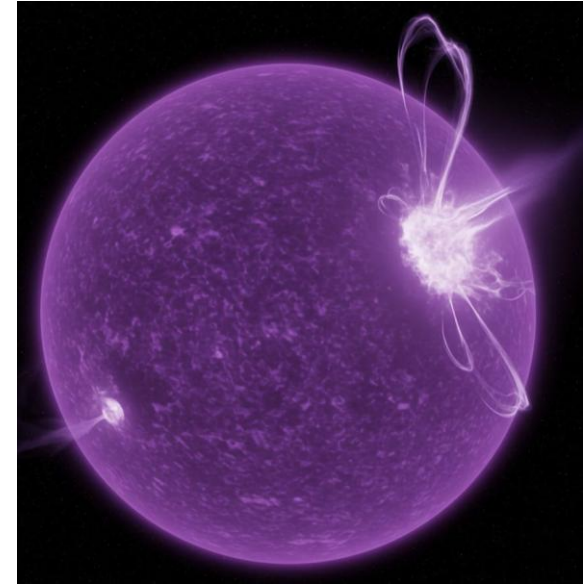


- **2nd peak: secondary spot only**
O-mode (lowly polarized) photons (not scattered) are observed directly from the condensed surface

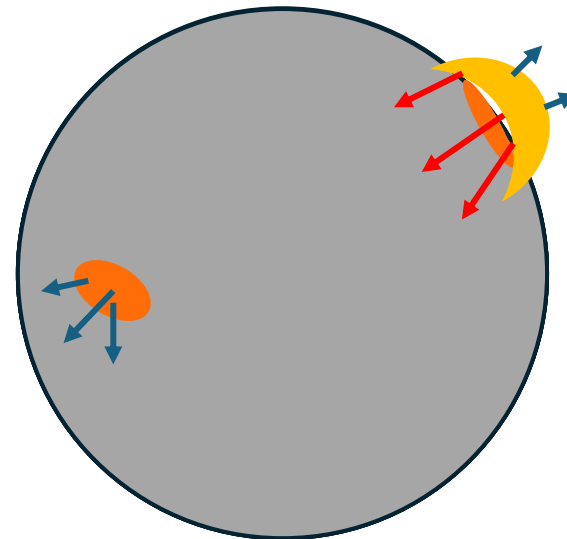


AXP 1E 2259+586 – Interpretation

- Two emitting hot-spots (with condensed surface exposed), the primary covered by a magnetic loop

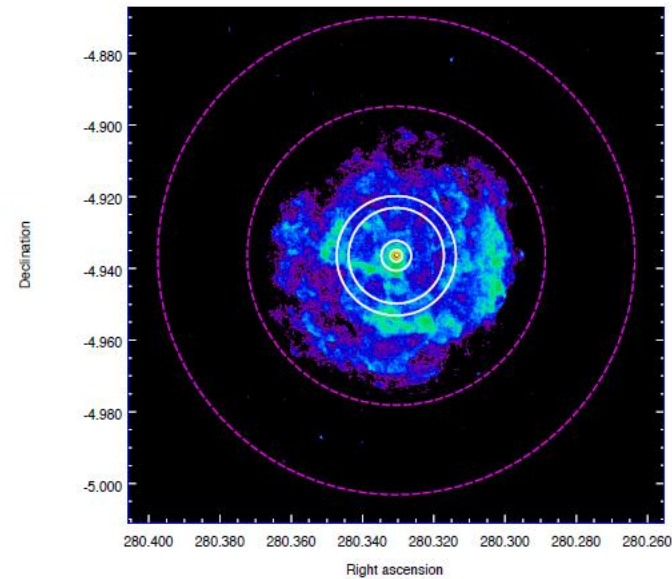
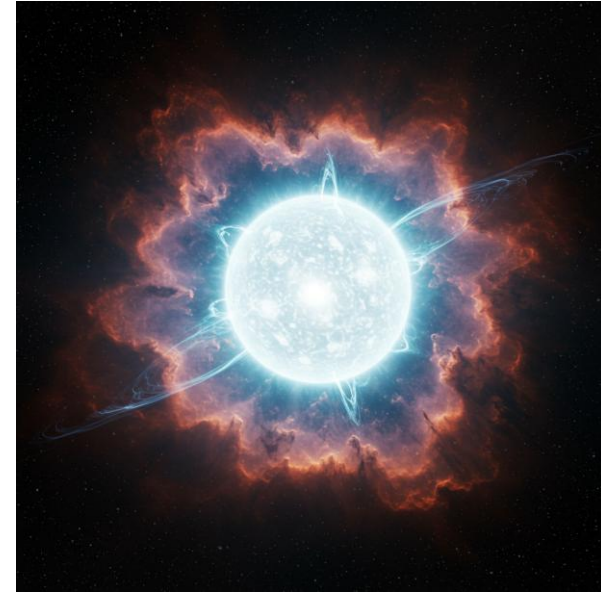


- **2nd min: primary spot returns**
The secondary spot exit from the FOV, while the primary one returns in view, firstly showing scattered photons



AXP 1E 1841–045

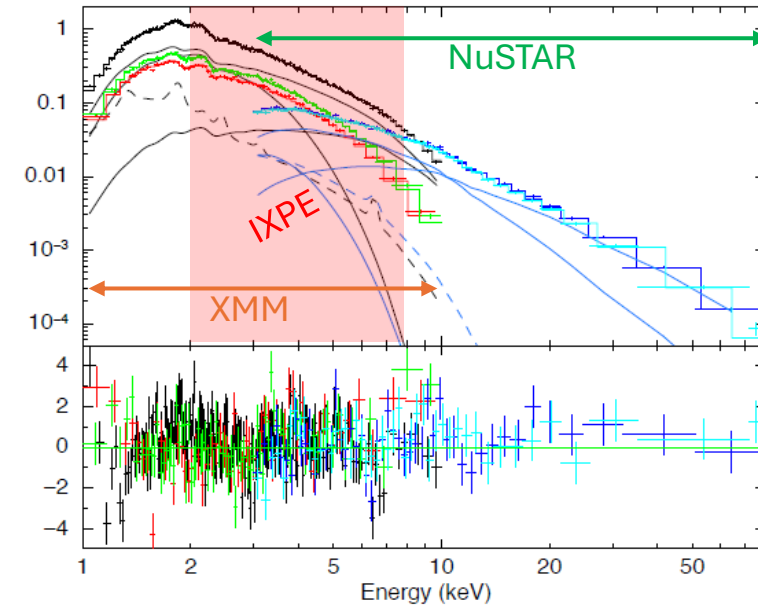
- Bright source at the center of Kes 73 SNR, entered in an active burst-emitting phase in August/ September 2024
- Two publications:
 - Rigoselli et al. (2025, ApJL 985, 34)
 - Stewart et al. (2025, ApJL 985, 35)



Rigoselli et al. (2025)

AXP 1E 1841–045 – Spectral analysis

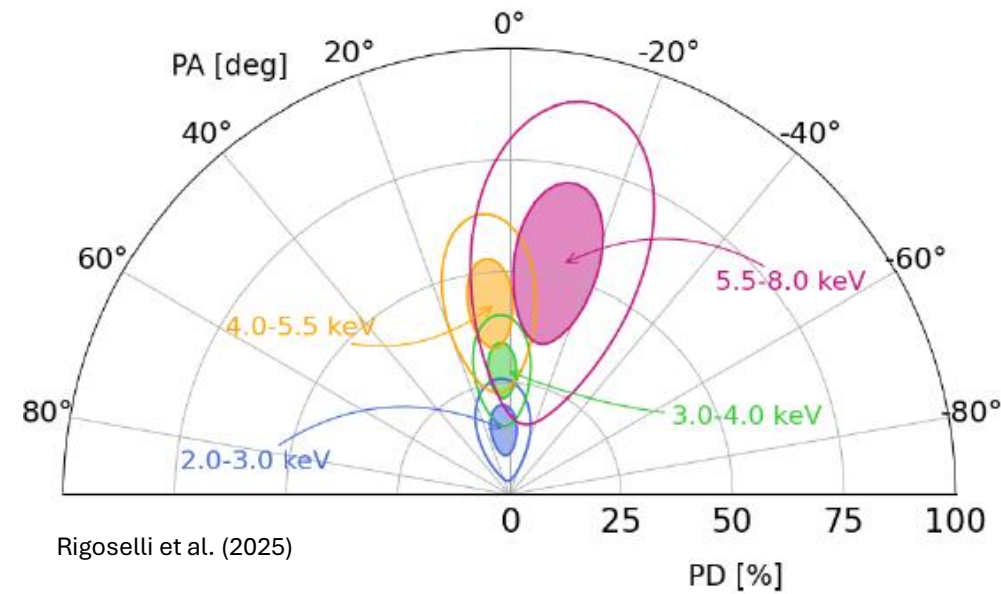
- Spectral analysis with IXPE+XMM+NuSTAR revealed the presence of 3 spectral components above 2 keV $BB+PL_s+PL_h$ (the latter already present at ≈ 6 keV)
- IXPE could assess the polarization PL_h photons (important to understand the origin of high-energy PL in magnetars)



Rigoselli et al. (2025)

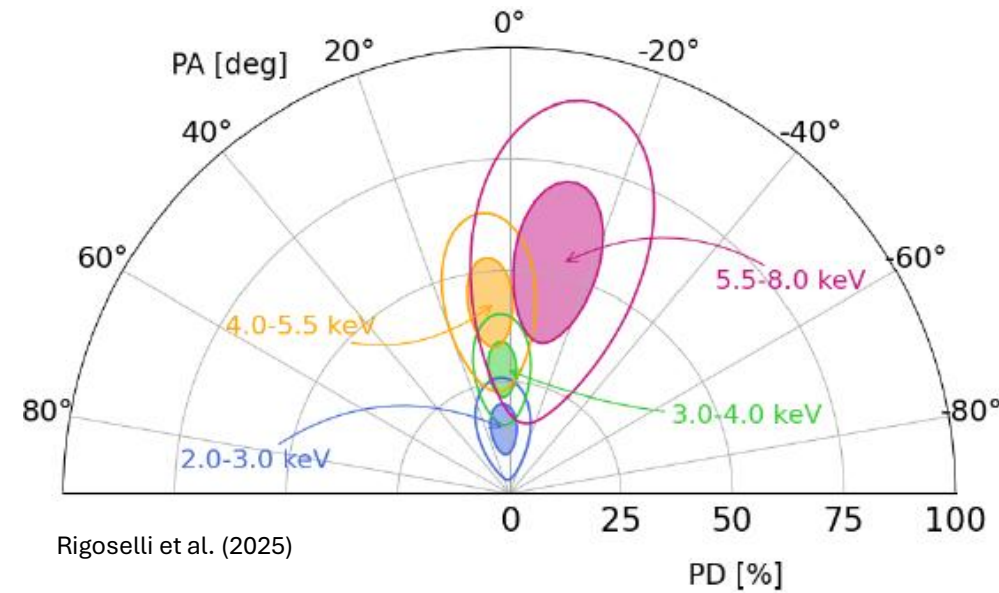
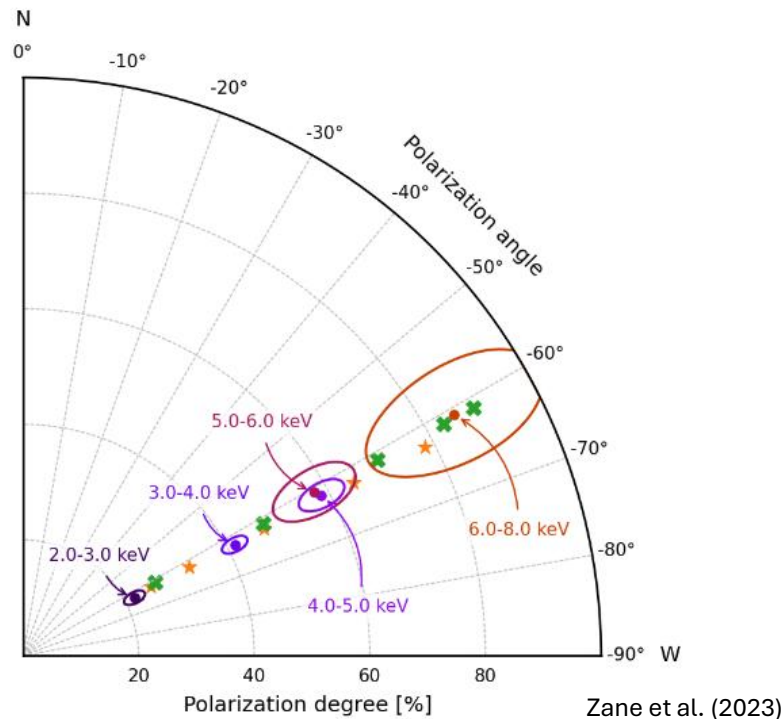
AXP 1E 1841–045 – Polarization

- Despite the short exposure (300 ks-ToO), polarization is detected at high significance ($\approx 26\%$ phase- and energy-integrated)
- Energy-dependent PD increasing with energy with a constant PA



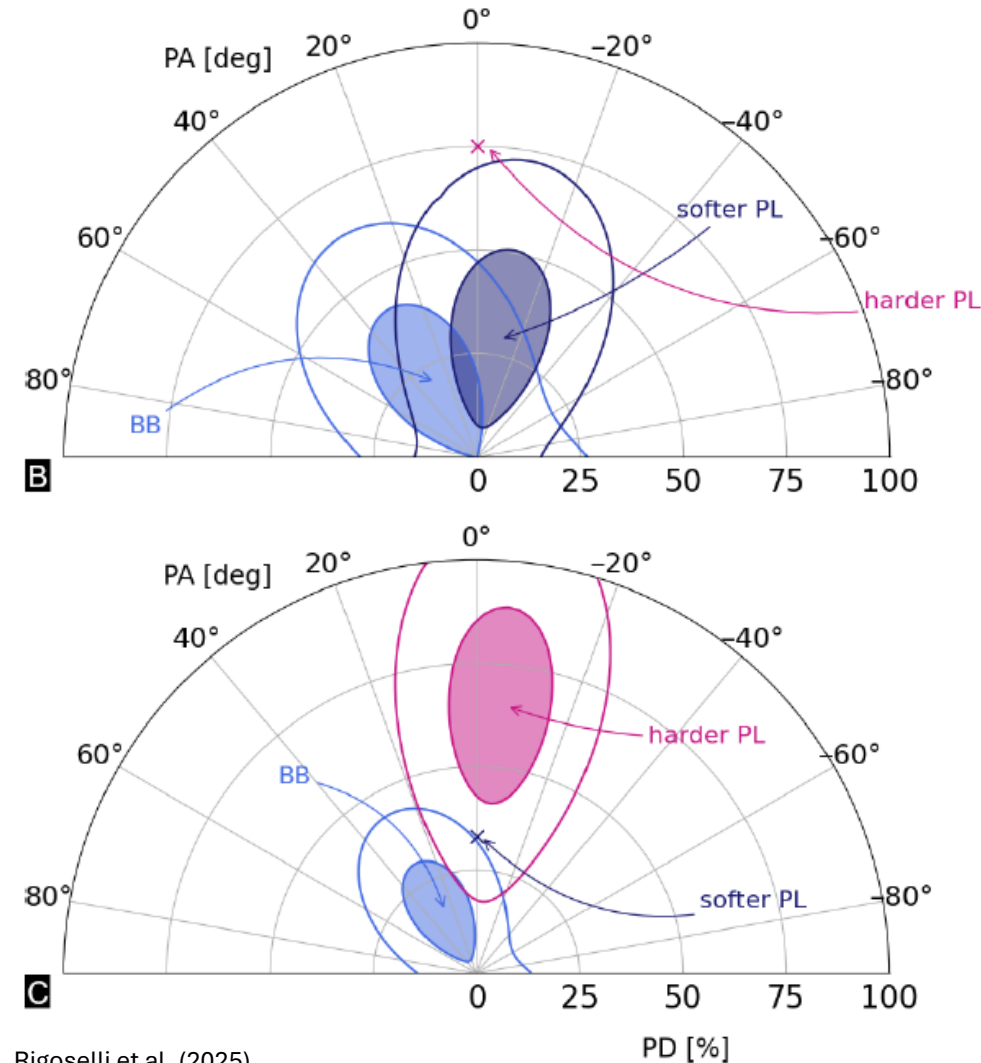
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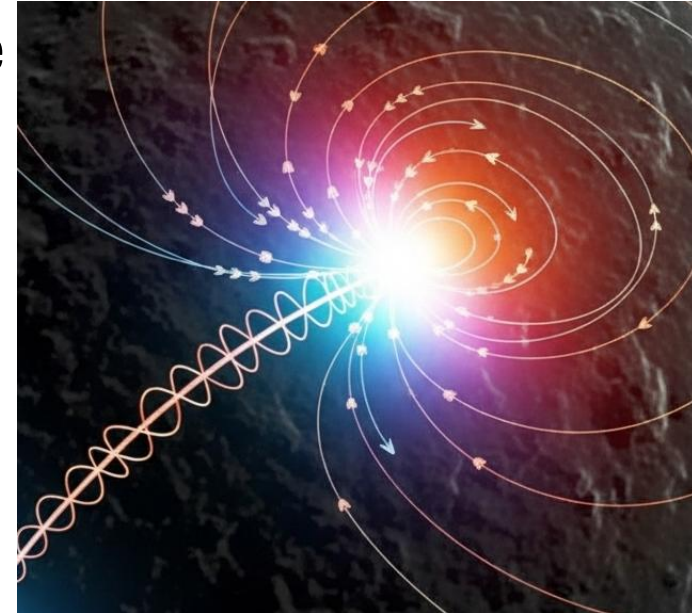
AXP 1E 1841–045 – Spectro-polarimetry

- SNR contribution (important at 2–4 keV) is unpolarized at high degree of significance
- Freezing the polarization of PL_s to 33% (in agreement with the RCS model) results in a well-constrained polarization $\approx 70\%$ for the PL_h component
- A low polarization for the BB component is suggested by this analysis



AXP 1E 1841–045 – Interpretation (1)

- Thermal radiation comes from the condensed surface of the neutron star (compatible with PD $\approx 15\%$ at low energy)
- Photons reprocessed by RCS in the magnetosphere form the PL_s component (polarized at $\approx 33\%$ in the X-mode)
- High-energy, PL_h photons are possibly generated by synchrotron emission from relativistic electrons



$$\Gamma_{\text{PL}_h} = 1.1^{+0.06}_{-0.07} \Rightarrow \text{PD} \approx 75\% \quad (\perp \text{ to } B \text{ in the plane of the sky})$$

- The constancy of PA with energy may be a further (indirect) test of QED vacuum birefringence

AXP 1E 1841–045 – Interpretation (2)

- Hard PL may originate via resonant scattering onto relativistic e^+/e^- pairs flowing in a (localized) j-bundle in the star magnetosphere (Beloborodov 2013)
- According to relativistic resonant scattering cross-sections $\approx 3/4$ of the emerging photons should be polarized in the X-mode (\Rightarrow PD $\approx 50\%$)
- This is coherent with what observed at high energies (5.5–8 keV)

