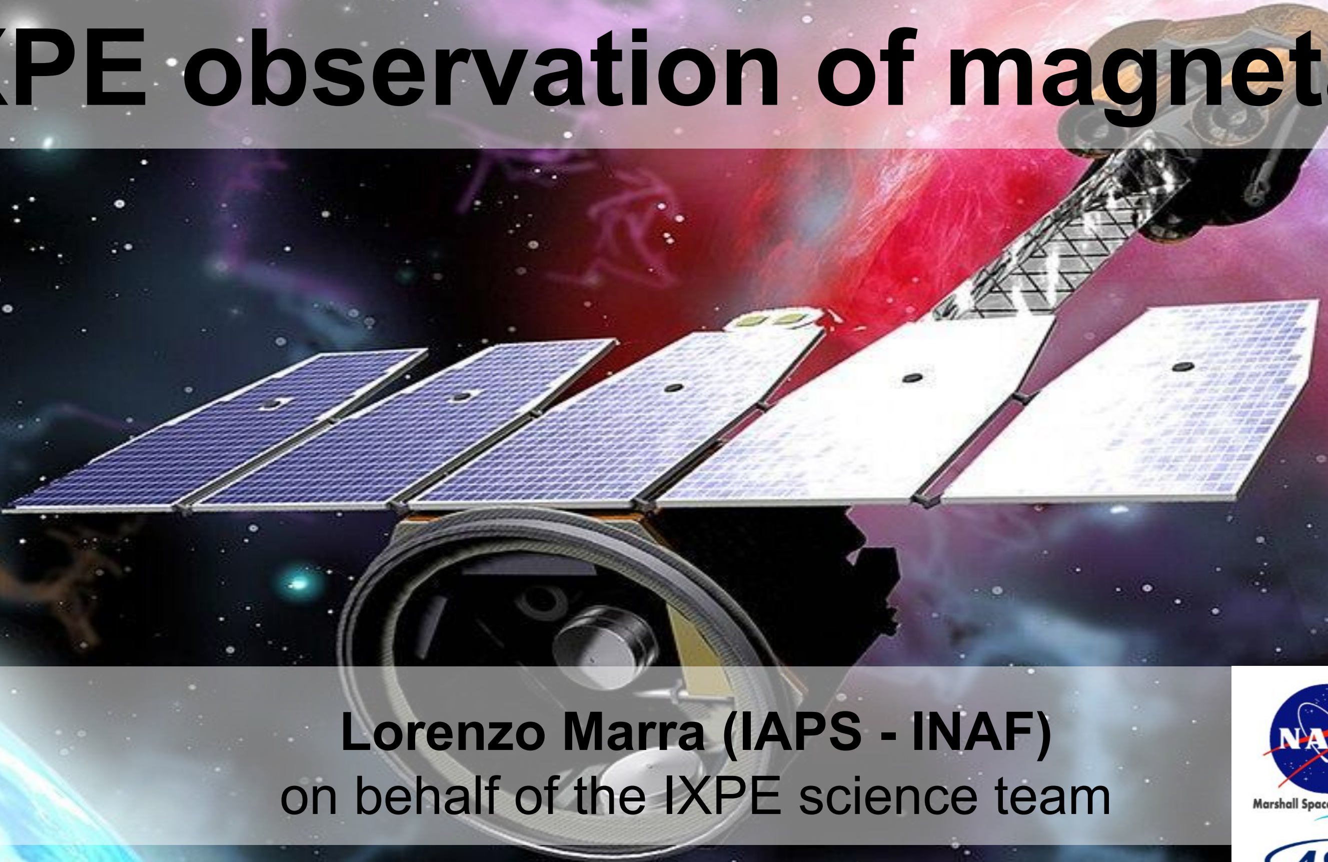
IXPE observation of magnetars



Lorenzo Marra (IAPS - INAF)
on behalf of the IXPE science team

October 28, 2025 - ASI

NASA
Marshall Space Flight Center
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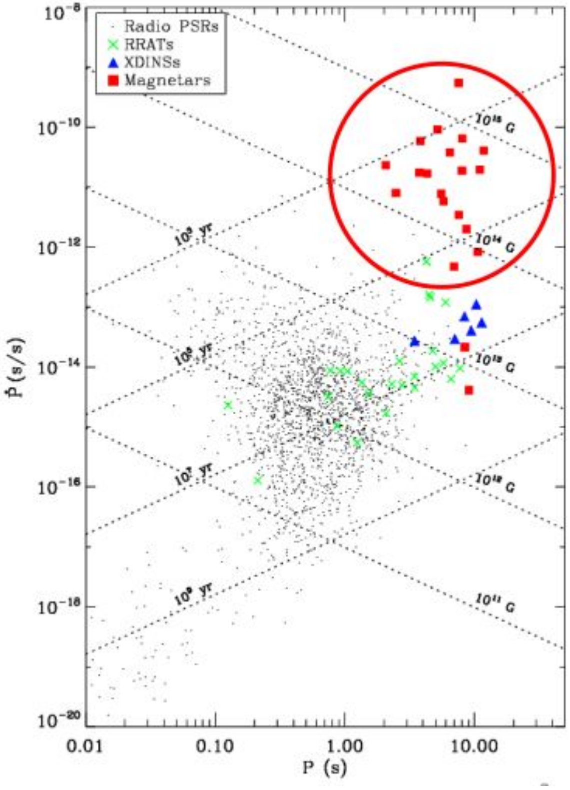
Agenzia Spaziale Italiana
IXPE
Imaging X-Ray Polarimetry Explorer

Introduction

Magnetar properties

- A class of neutron stars (NSs), initially classified into two separate groups:
  - Anomalous X-ray pulsars (AXPs)
  - Soft-Gamma Repeaters (SGRs)
- $P \approx 1 - 12$ s
- $\dot{P} \approx 10^{-10} - 10^{-14}$ s/s
- **Strong magnetic fields**
  - Dipolar $B \approx 10^{14} - 10^{15}$ G
- $L_X > \dot{E}_{rot}$ (anomalous)
- Bursting activity (short burst – giant flares)



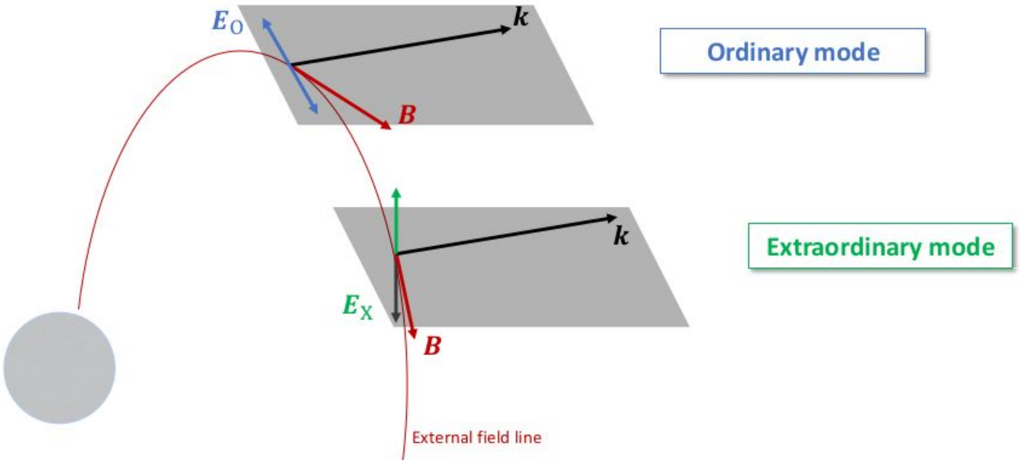
Introduction
Magnetar properties

Strong $\boldsymbol{B}$-fields can polarize photons (vacuum birefringence)

- For $B \sim B_Q = 4.4 \times 10^{13}$ G photons are likely linearly polarized in two normal modes:

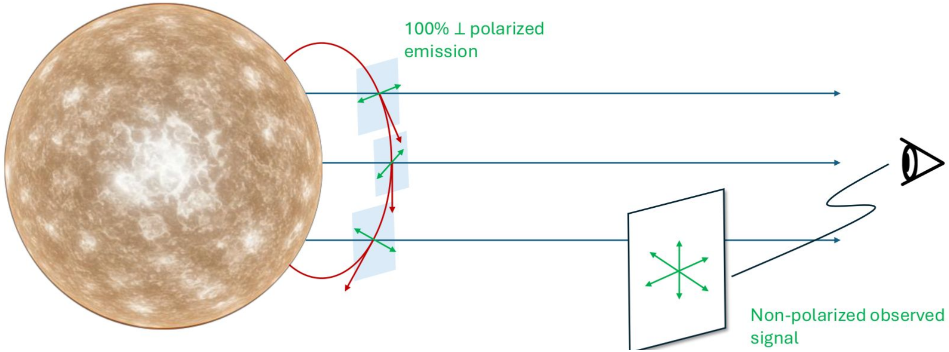
$$\hat{\boldsymbol{E}} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad \text{or} \quad \begin{pmatrix} 0 \\ 1 \\ 0 \end{pmatrix}$$

Ordinary mode   Extraordinary mode

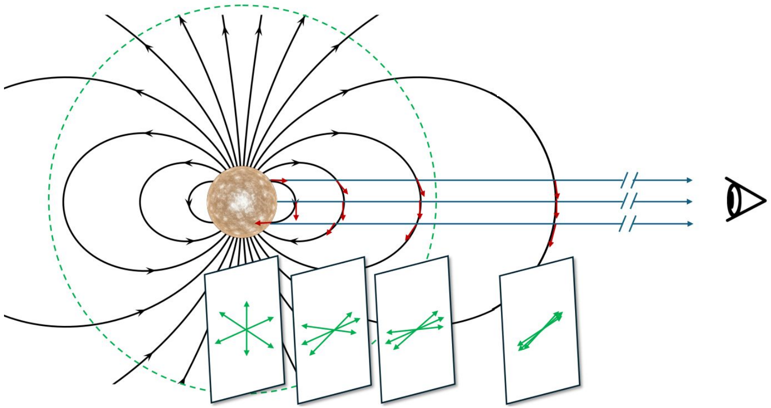


Introduction
Polarization Modes

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



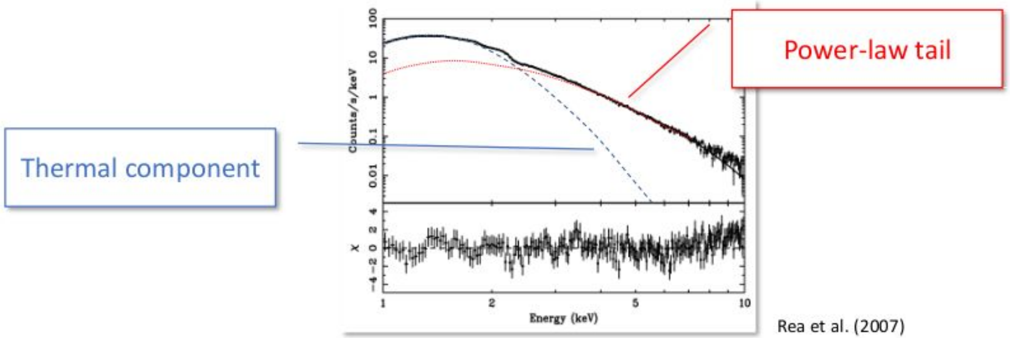
- In strong B-fields the photon $\boldsymbol{E}$ adapts to the star $\boldsymbol{B}$ close to the surface
  - **High Polarization expected**



Introduction
Magnetars X-ray Spectra

X-ray spectra

- Thermal component (BB) at low energies (0.5 − 3 keV)
- A “soft” Power-law tail (Γ ≈ 2–4) sometimes observed at higher energies (3 − 10 keV).
    - Additional BB in place of the PL (sometimes)
- A “hard”, distinct, much **flatter power law** (Γ ≈ 0.5–1.5) extending to **tens or hundreds of keV** sometimes observed.



Rea et al. (2007)

Introduction
Spectral components polarization

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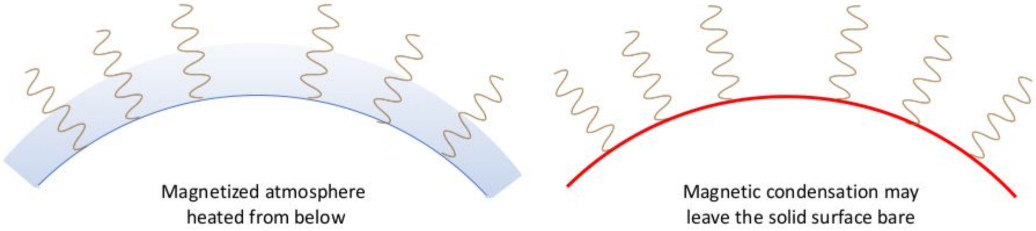

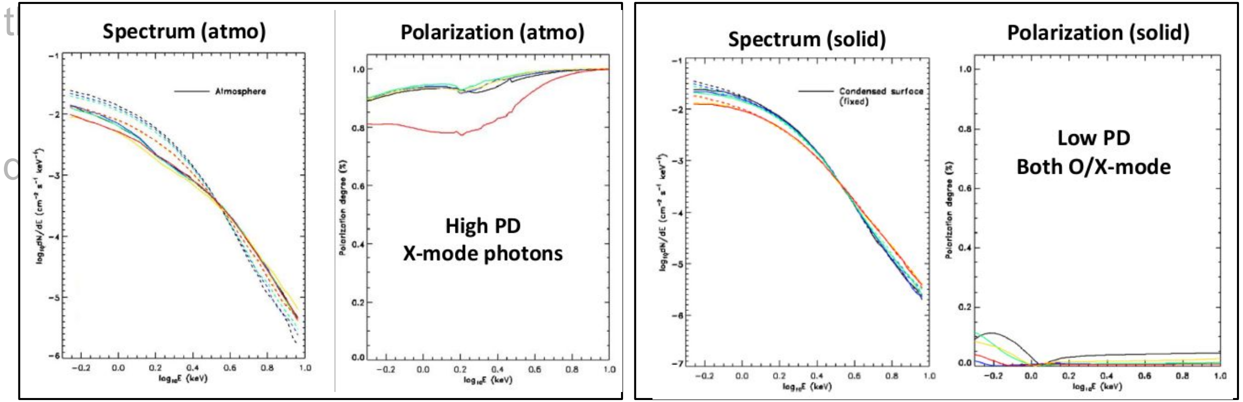

Taverna et al. (2020)

Introduction

Spectral components polarization

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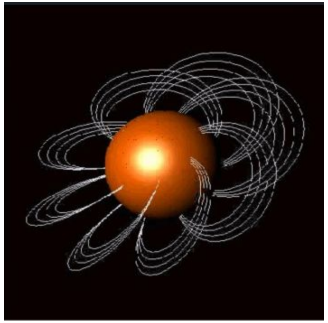
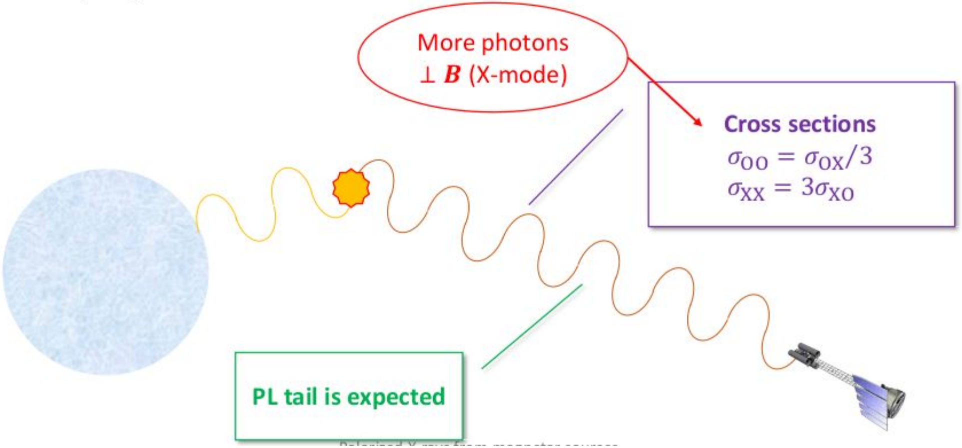
Magnetar magnetosphere

- Charged particles must flow along the external field lines
- Photons are scattered unto these particles via Resonant Compton Scattering (RCS)





Previous IXPE observations

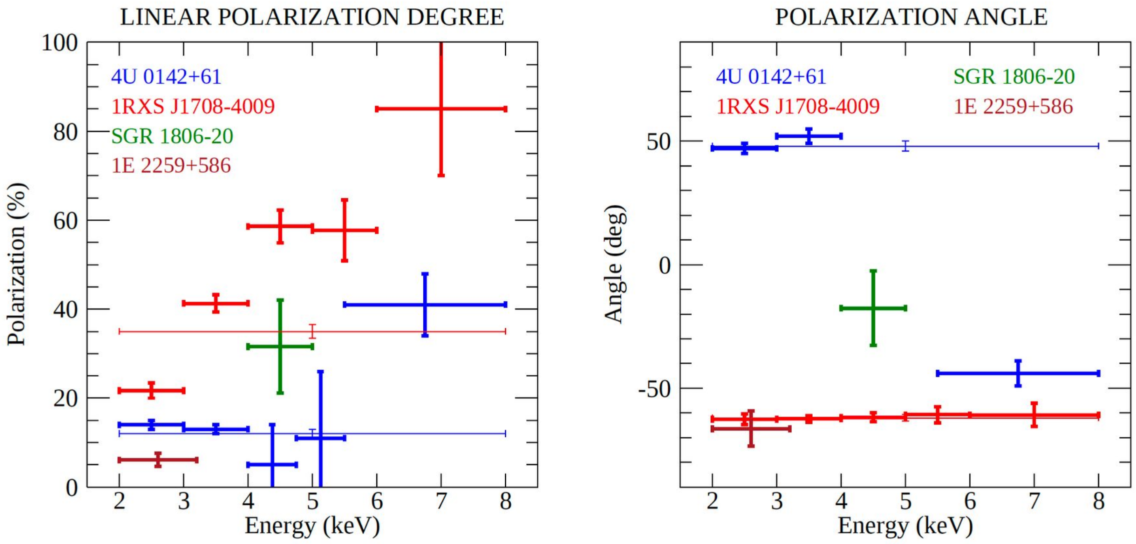
AXP 4U 0142+61
(Taverna, R. et al. Science, 2022, 378, 646.)
- $F_{2-10} \approx 7 \times 10^{-11}$ cgs
- $B \approx 2 \times 10^{14}$ G

AXP 1RXS J170849.0−4009100
(Zane, S. et al. ApJL, 2023, 944, L27)
- $F_{2-10} \approx 3 \times 10^{-11}$ cgs
- $B \approx 5 \times 10^{14}$ G

SGR 1806−20
(Turolla, R. et al. ApJ, 2023, 954, 88.)
- $F_{2-10} \approx 1 \times 10^{-11}$ cgs
- $B \approx 7 \times 10^{14}$ G

AXP 1E 2259+586 (Heyl, J. S. et al. MNRAS, 2024, 527, 12219.)
- $F_{2-10} \approx 1.5 \times 10^{-11}$ cgs
- $B \approx 6 \times 10^{13}$ G

Rigoselli et al. (2025)



AXP 1E 1841-045

Source properties

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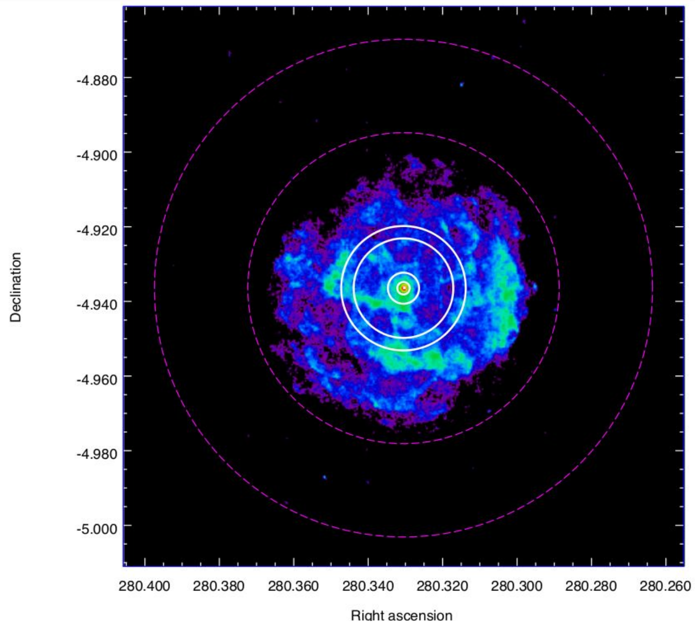
Bright source at the center of Kes 73 SNR, entered in an active burst-emitting phase in August/ September 2024

First Magnetar observed by IXPE during an active phase

- $F_{2-10} \approx 2 \times 10^{-11}$ cgs
- $B \approx 7 \times 10^{14}$ G

Two publications:

- Rigoselli et al. (2025, ApJL 985, 34)
- Stewart et al. (2025, ApJL 985, 35)

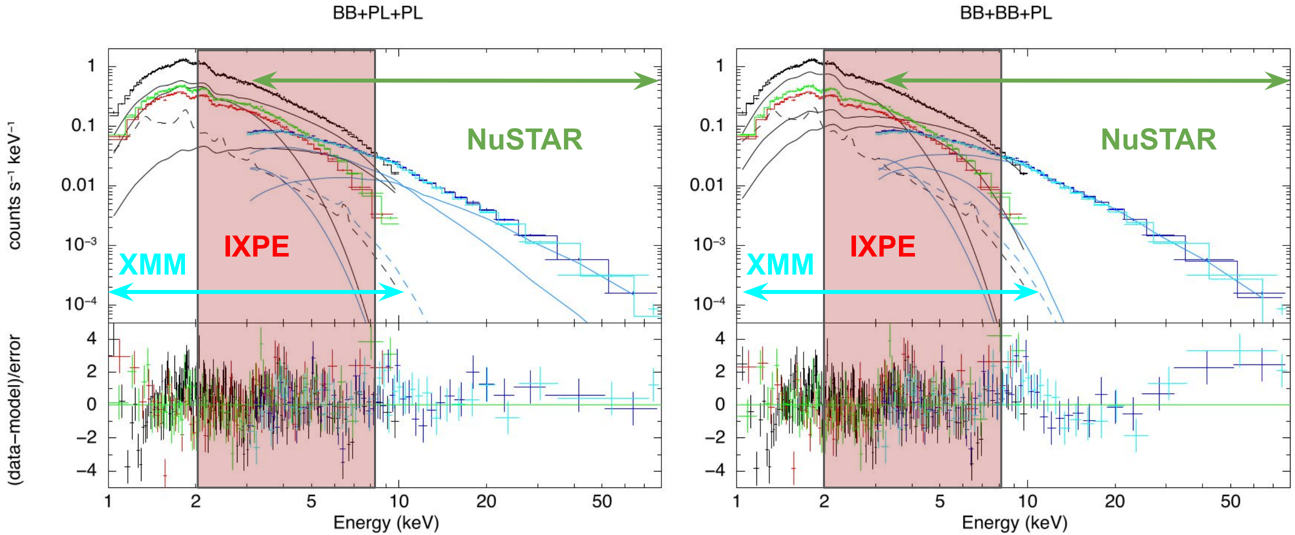


Rigoselli et al. (2025)

AXP 1E 1841-045

Spectral analysis

- Spectral analysis with IXPE+XMM+NuSTAR:
  - SNRs contribution below 4 keV
  - 3 spectral components (BB_{COLD}+BB_{HOT}+PL or BB+PL_{SOFT} +PL_{HARD})
- **First IXPE polarimetric measurement of the high-energy PL in magnetars**

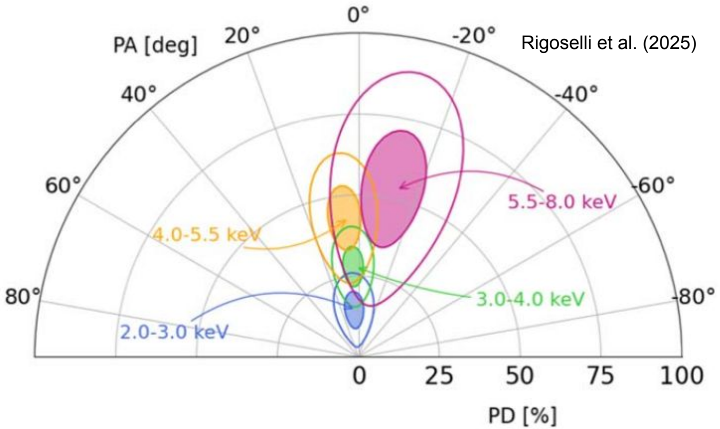


Rigoselli et al. (2025)

AXP 1E 1841-045
Polarimetric analysis

- Despite the short exposure (300 ks-ToO), polarization is detected at high significance
    - **PD ≈ 26% phase- and energy-integrated**

- Energy-dependent PD increasing with energy with a constant PA



Rigoselli et al. (2025)

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Polarimetric analysis

- Despite the short exposure (300 ks-ToO), polarization is detected at high significance
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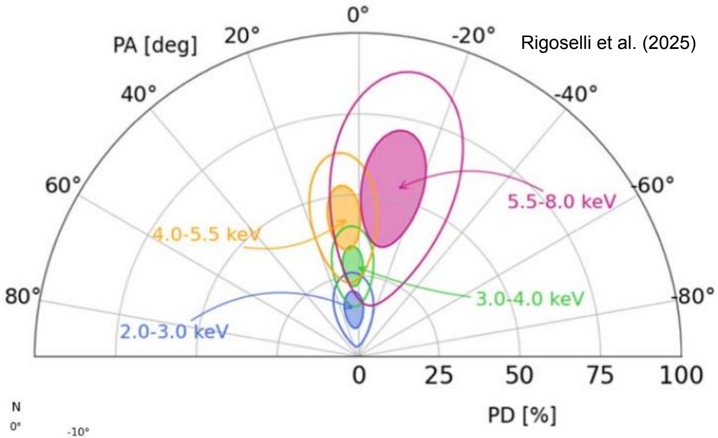
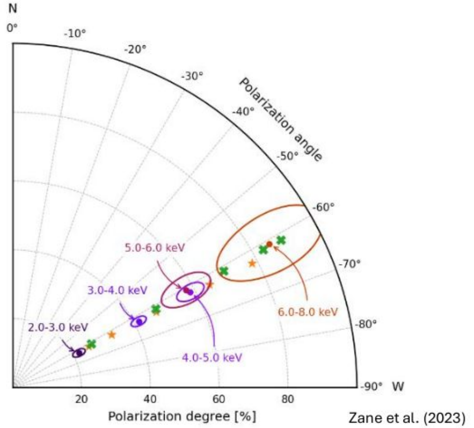
  - Similar polarization properties to **1RXS J170849.0−4009100**



Rigoseli et al. (2025)



Zane et al. (2023)

AXP 1E 1841-045

Polarimetric analysis

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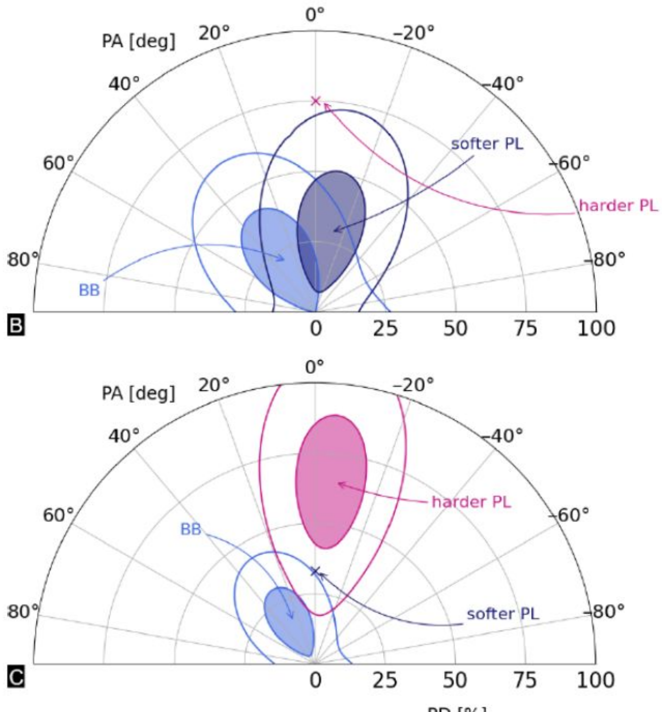
- SNR contribution is unpolarized at high degree of significance

- Freezing the polarization of PL_{SOFT} to 33% (in agreement with the RCS model) results in a well-constrained polarization ≈ 70% for the PL_{HARD} component

- A low polarization for the BB component is suggested by this analysis



Rigoselli et al. (2025)

AXP 1E 1841-045

Theoretical interpretations

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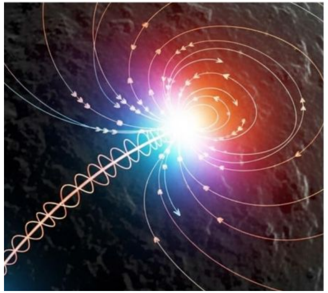
- **Thermal radiation comes from the condensed surface of the neutron star** (compatible with PD ≈ 15% at low energy)

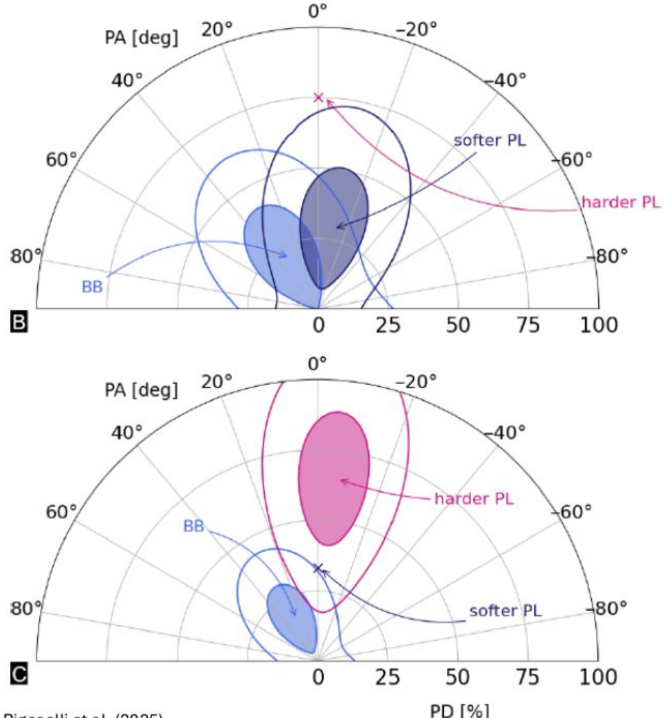
- **Photons reprocessed by RCS in the magnetosphere form the PLs component** (polarized at ≈ 33% in the X-mode)

- **High-energy, PLh photons are possibly generated by synchrotron emission from relativistic electrons**

  $\Gamma_{PLh} \approx 1.1 \Rightarrow$ PD ≈ 75% (⊥ to B in the plane of the sky)

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





Rigoselli et al. (2025)

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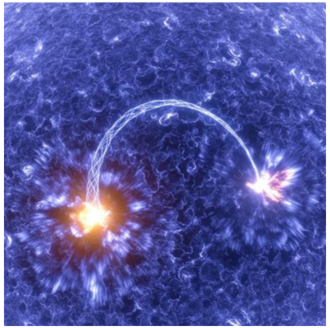

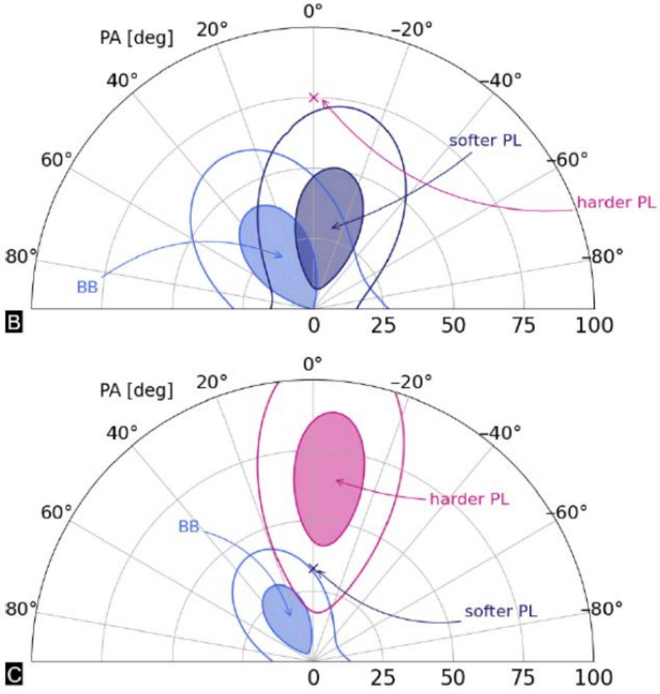

Rigoselli et al. (2025)

- 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 ≈ 3/4 of the emerging photons should be polarized in the X-mode (⇒ PD ≈ 50%)

- This is coherent with what observed at high energies (5.5–8 keV)

Conclusions

- Magnetars are (almost all) strongly polarized astrophysical sources
- All sources show low polarization at thermal energies ⇒ Condensed surface emission
- Observed sources provided hints that vacuum birefringence effects are at work but smoking gun has still to be found
- Large PD value observed for the hard X-ray PL tail in 1E 1841-045 (synchrotron emission?)
- Broad-band spectro-polarimetry may help in understanding the physical nature of hard-X PL tails in magnetars

Conclusions
THANK YOU FOR YOUR ATTENTION!

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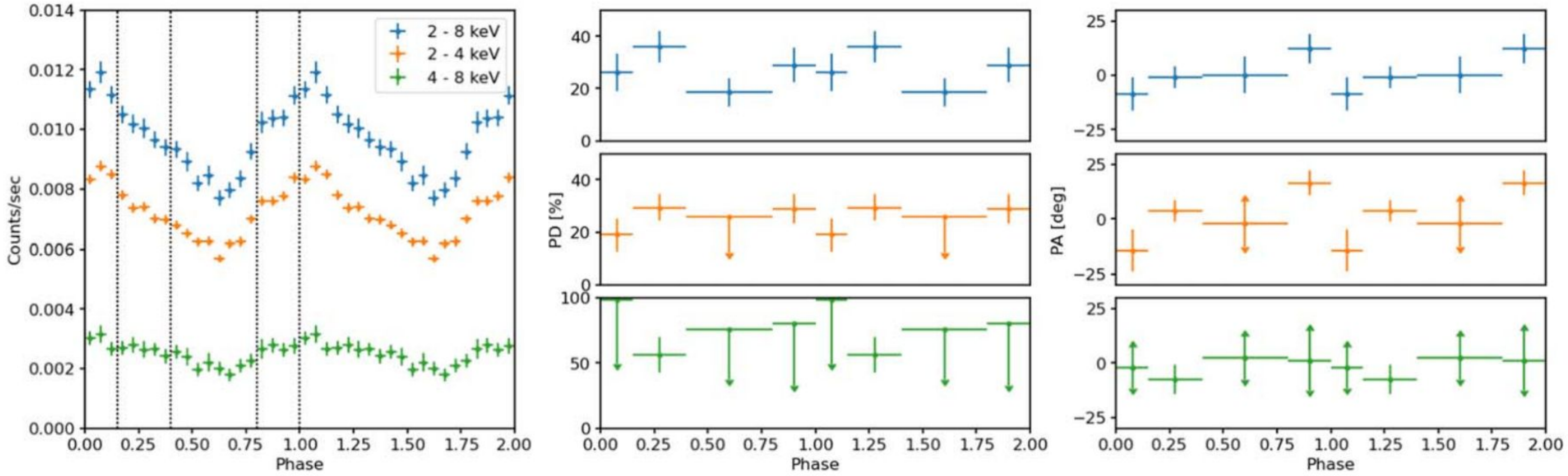
Extra

Extra
AXP 1E 1841-045 - Phase Dependent



Rigoselli et al. (2025)

Extra
AXP 4U 0142+61

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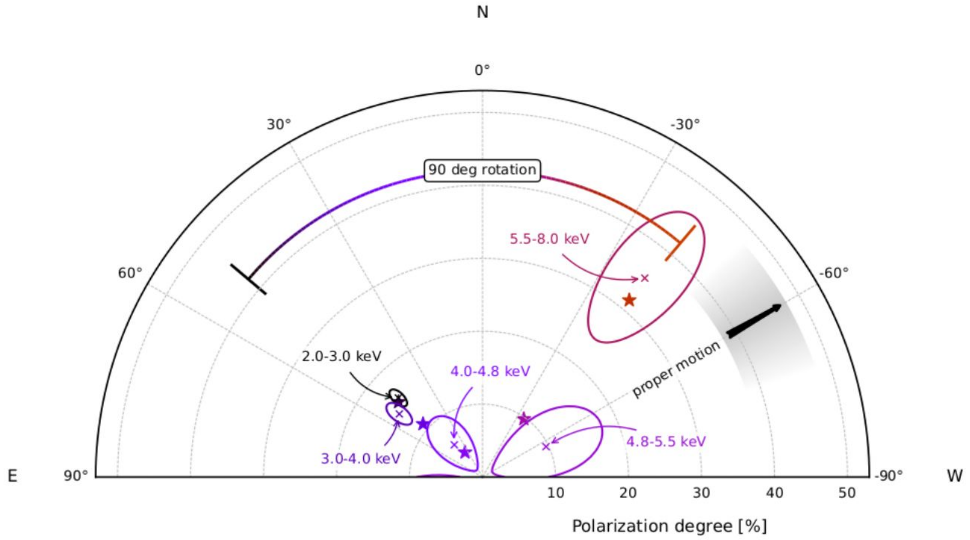
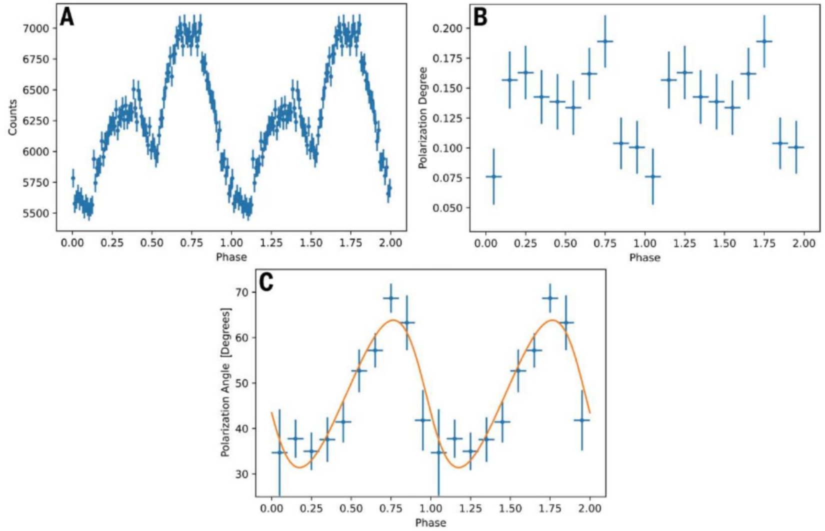
Taverna et al. (2022)





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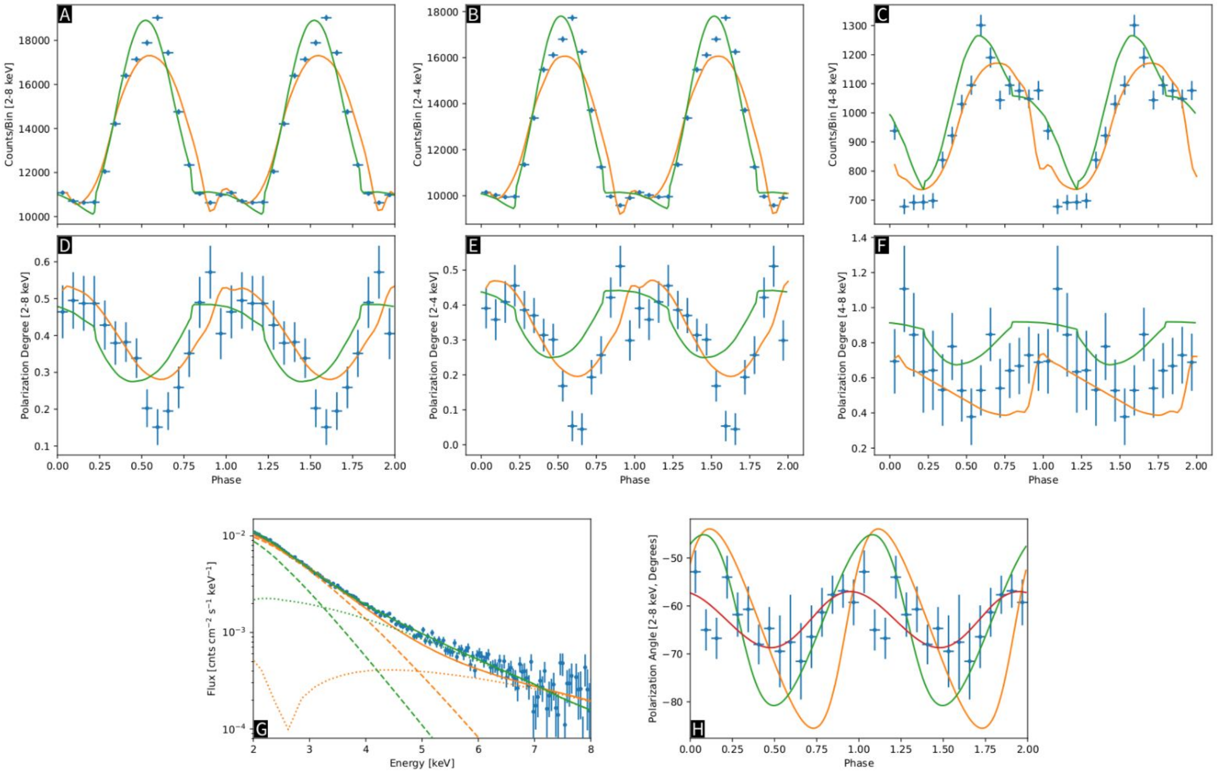
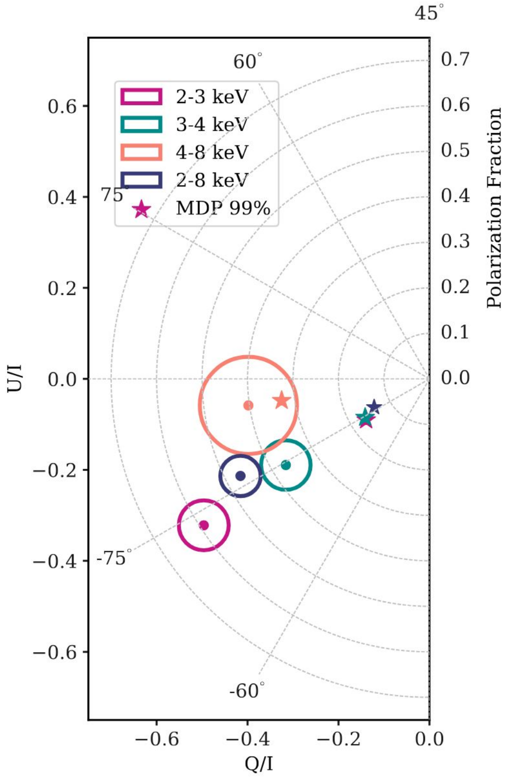
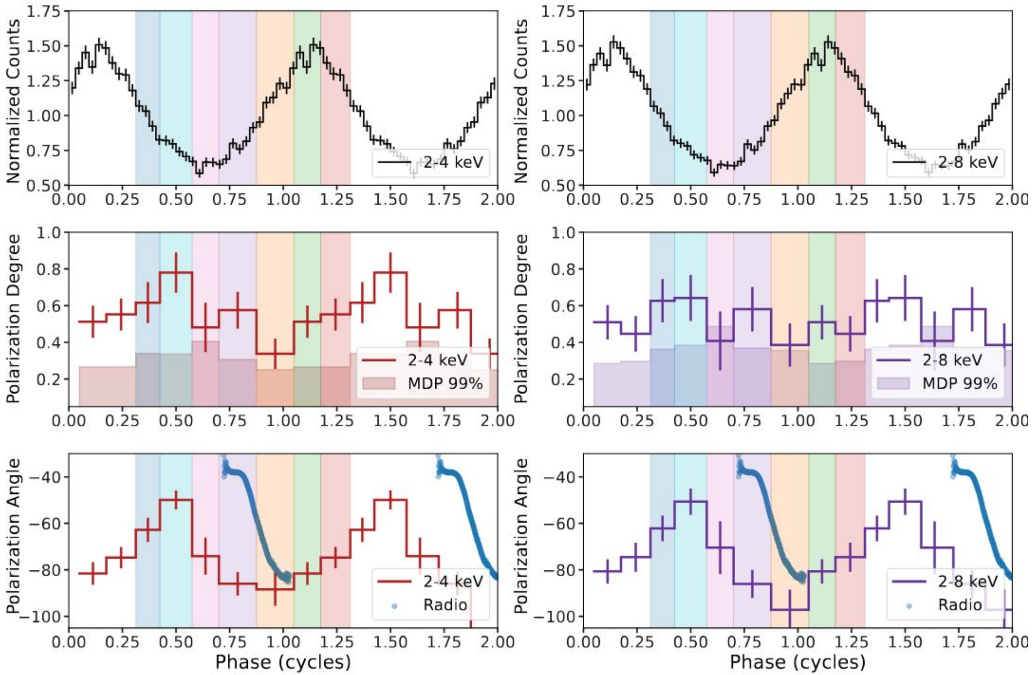


Extra
1E 1547.0−5408





Stewart et al Submitted