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Bridging the Gap: The Need for Precise Polarization Models in the Era of Magnetar Hard X-ray Observations

Roberto Turolla

Department of Physics and Astronomy, University of Padova, Italy

MSSL, University College London, UK

Roberto Taverna, Jeremy Heyl, Silvia Zane, Fabio Muleri, Michela Rigoselli, Denis González Caniulef, Ruth Kelly, Lorenzo Marra, Gianluca Israel, Sandro Mereghetti, Alice Borghese, Valery Suleimanov, Alexander Potekhin

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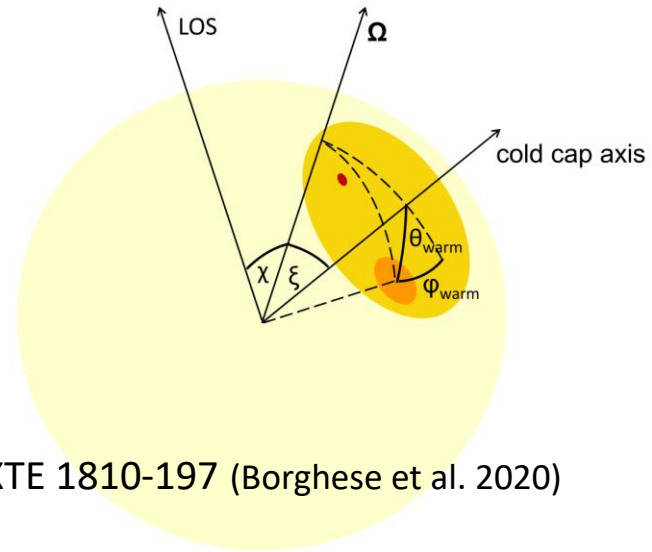
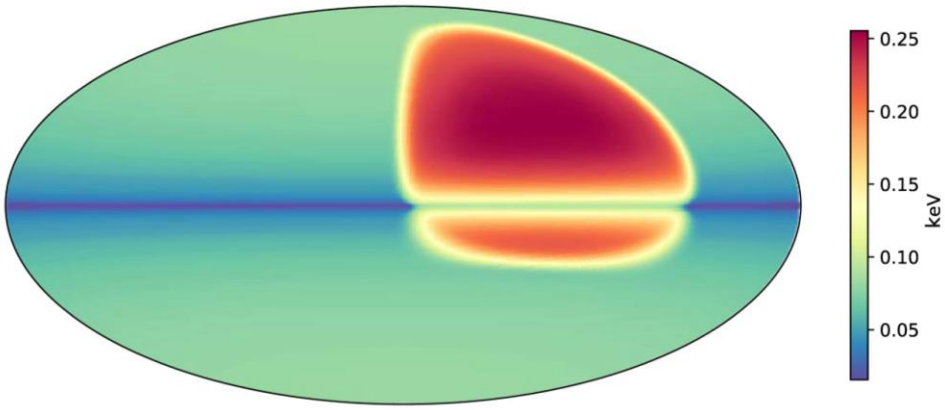
SOFT X-RAY EMISSION FROM MAGNETARS - I

- Soft → 0.1 -10 keV
- Variable, $L_X \approx 10^{33}$ -10^{35} erg/s
- Spectra well represented by a blackbody plus a power law (sometimes BB+BB)
- $kT_{BB} \sim 0.5$ keV, does not change much in different sources
- Photon index $\Gamma \approx 1 - 4$
- Many transient sources visible only during outbursts ($L_X \approx 10 - 1000\ L_{quies}$)
- Transient spectra typically BB+BB (+BB+…), T_{BB} and R_{BB} decrease in time



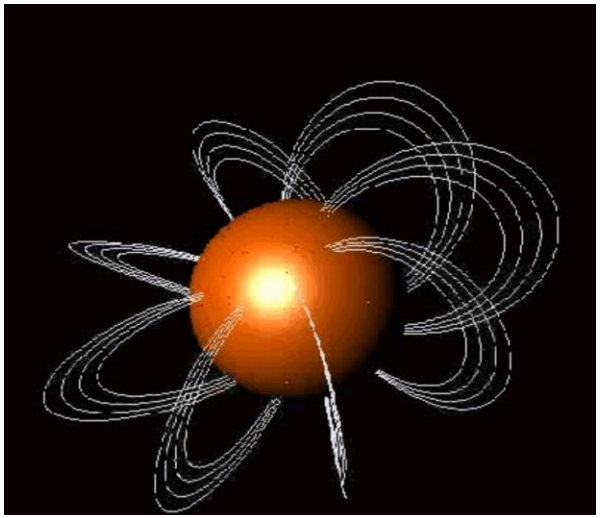
XTE 1810-197 (Borghese et al. 2020)

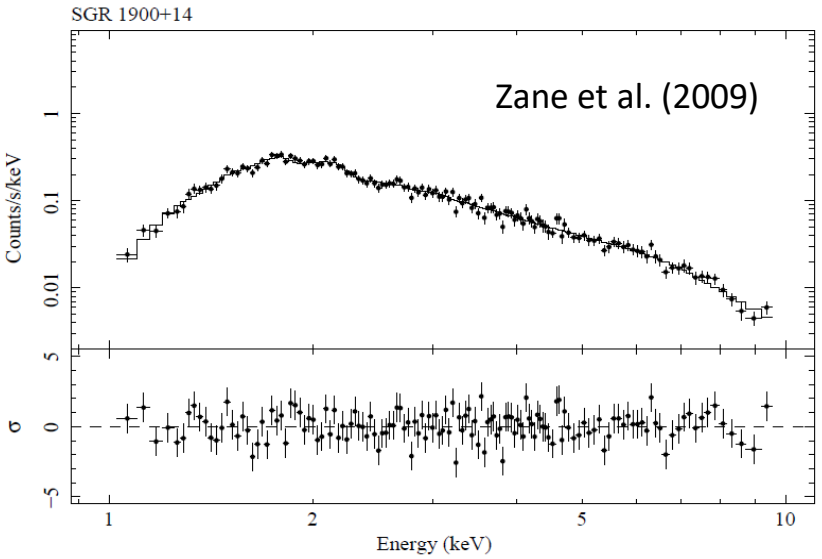


De Grandis et al. (2022)

SOFT X-RAY EMISSION FROM MAGNETARS - II

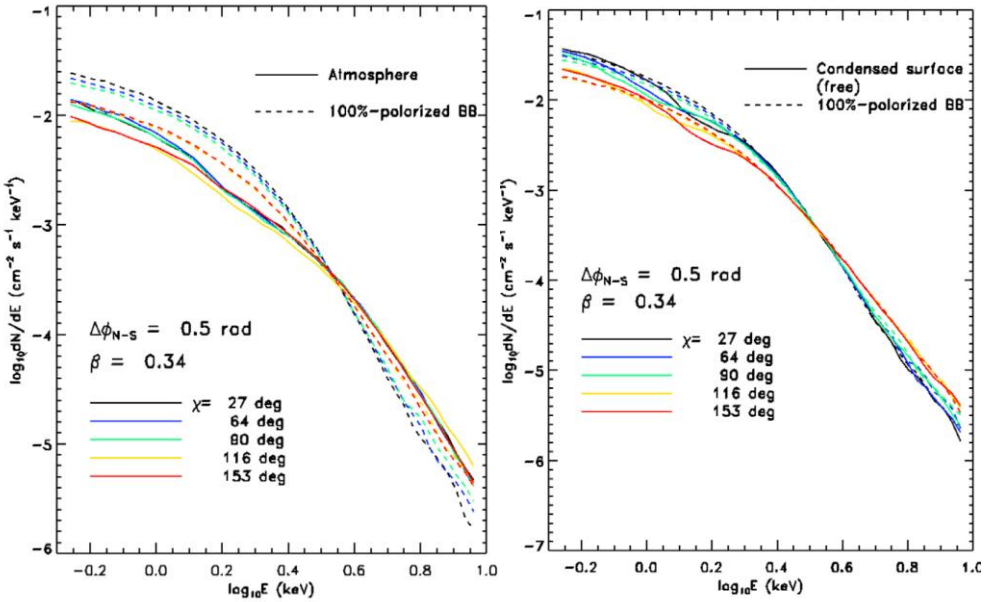
- **Twisted-magnetosphere**
  - Internal toroidal field produces magnetic stresses on the crust
  - The external field becomes «twisted»
- **Resonant Compton Scattering (RCS)**
  - Non-potential field → currents flowing along closed field lines ($\nabla \times \boldsymbol{B} = \frac{4\pi}{c}\boldsymbol{j}$)
  - Thermal surface photons are (resonan up-scattered onto moving charges
  - Formation of a power-law tail at high energies
  - Spectrum is “BB+PL”





SOFT X-RAY EMISSION FROM MAGNETARS - III

- Radiation in a strongly magnetized vacuum is polarized into two normal modes, the extraordinary (X) and ordinary (O) one
- Thermal radiation either from an atmosphere or a magnetic condensate → similar spectra but very different polarization properties
  - Atmosphere: PD ≈ 50-80% in the X mode
  - Condensate: PD ≈ 10-20% either in the X or O mode
- The PL is always polarized at about 30% in the X mode



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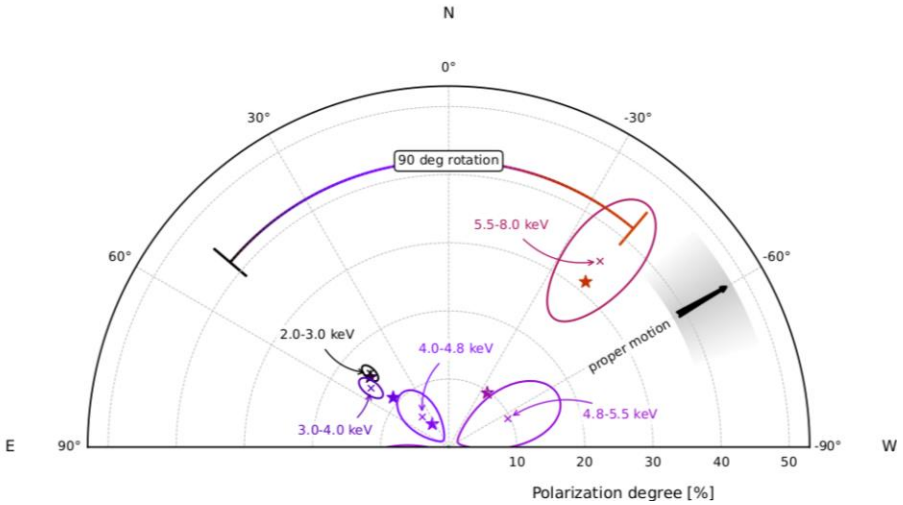
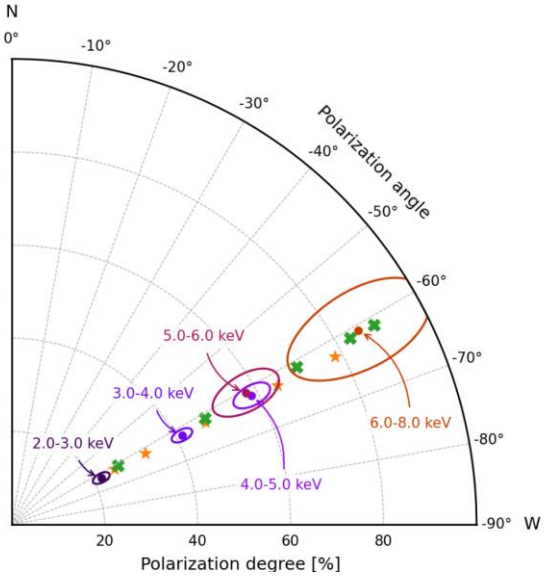
IXPE Observations of Magnetars - I

- Up to now IXPE targeted 6 magnetar sources:
  - AXP 4U 0142+61 (Taverna et al. 2022)
  - AXP 1RXS J170849.0-4009100 (Zane at al. 2023)
  - SGR 1806-20 (Turolla et al. 2023)
  - AXP 1E 2259+586 (Heyl et al. 2024)
  - AXP 1E 1841-045 (Rigoselli et al. 2025; Stewart et al. 2025)
  - AXP 1E 1547.0-5408 (Taverna et al. 2026; Stewart et al. 2025)
- Polarization clearly detected in all sources, with the exception of SGR 1806-20
- Polarization properties rather different in different sources

IXPE Observations of Magnetars - II





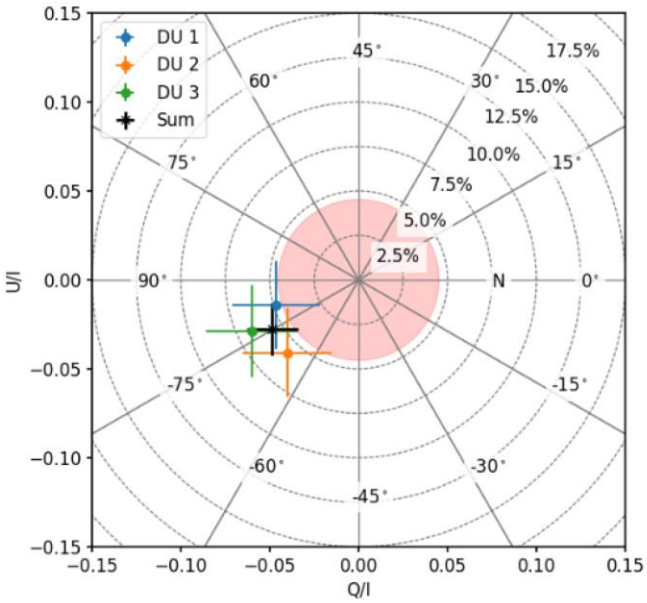
4U 0142+61

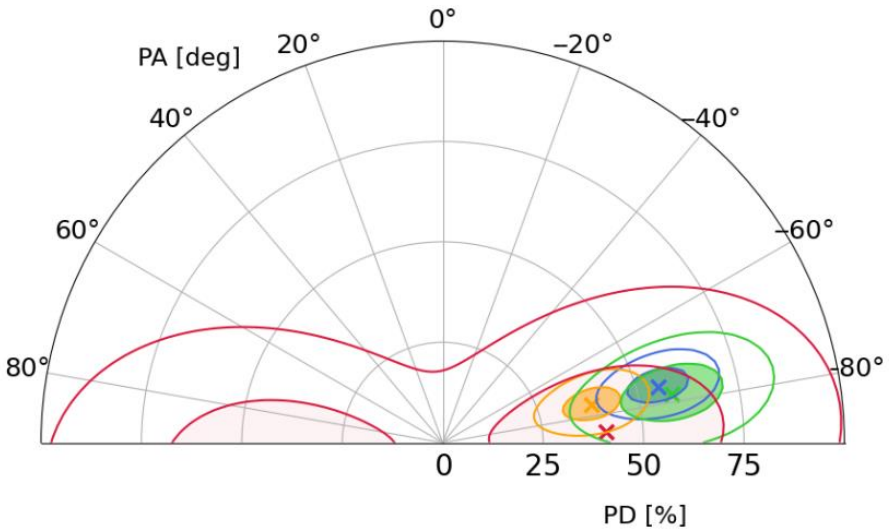
- Spectrum BB+PL
- PD ≤ 20% @ 2-4 keV, ~ 0% @ 5 keV, ~ 30% @ 6-8 keV
- 90° swing in PA
- Thermal emission from condensed surface (O mode) + RCS (X mode)

1RXS J1708

- Spectrum BB+BB or BB+PL ?
- PD increases from 20% @ 2-3 keV up to ~ 80% @ 6-8 keV
- Constant PA
- Thermal emission from condensed surface (X mode) + atmosphere (X mode)

IXPE Observations of Magnetars - III





1E 2259+586

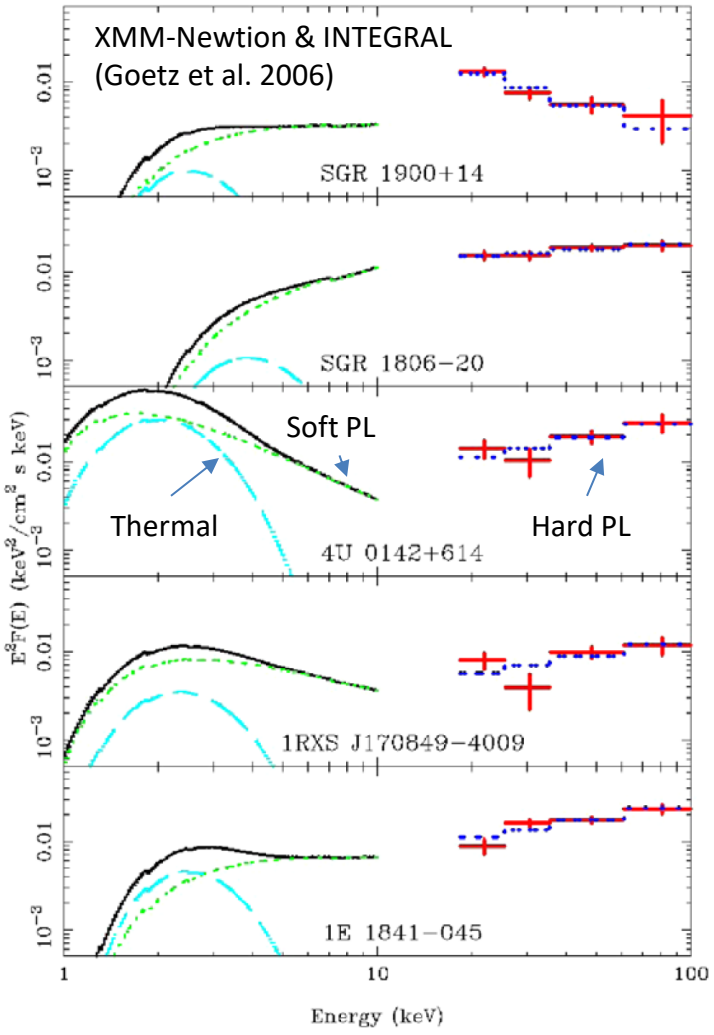
- Spectrum BB+PL+a
- PD ~ 6% @ 2-3 keV, < 15% @ 3-5 keV, < 70% @ 5-8 keV
- Thermal emission from condensed surface (O mode) + RCS (X mode) ?

What about 1E 1841-045 ?

- PD ~ 55% @ 2-3 keV, ~ 38% @ 3-4 keV, ~ 58% @ 4-5 keV, ~ (40%) @ 5-6 keV; constant PA
- Atmosphere (partial mode conversion ?)

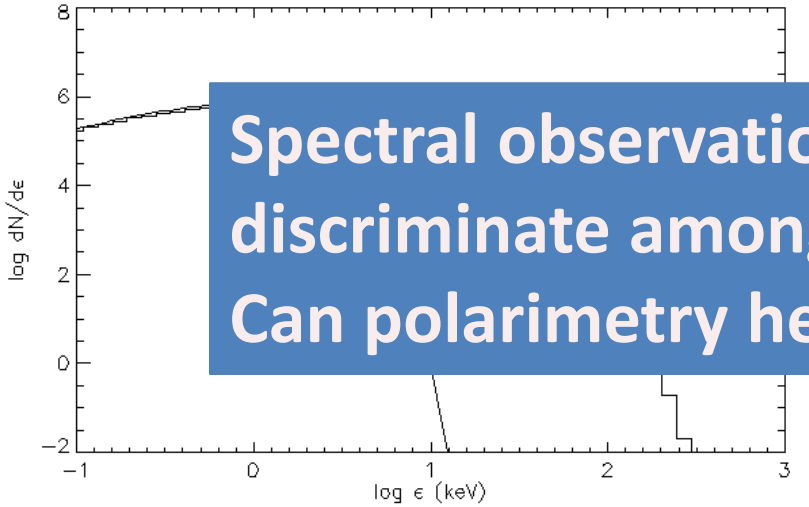
HARD X-RAY EMISSION FROM MAGNETARS - I

- Hard tails detected in about 10 sources by INTEGRAL, Suzako, RXTE and NuSTAR
- Rather flat PLs, with $\Gamma \sim 0.5 - 1$, extending in the ~ 20 - 200 keV range
- Emission strongly pulsed
- No detections with Fermi-LAT, spectral break expected at ~ 500 keV
- $L_{0.5\text{-}10\ keV} \sim L_{20\text{-}200\ keV}$
- Soft and hard PLs different, broadband X-ray spectrum is BB+PL+PL



HARD X-RAY EMISSION FROM MAGNETARS - II

- No definite model exists
- Proposed explanations fall into 3 broad groups:
  - thermal bremsstrahlung in the surface layers heated by returning currents (Thompson & Beloborodov 2005)
  - synchrotron/curvature radiation from relativistic pairs in the magnetosphere (Thompson & Beloborodov 2005; Rigoselli et al. 2025)
  - (resonant) upscattering by (relativistic) charges (Baring & Harding 2005, 2008; Zane et al. 2011; Beloborodov 2013; Hascoët et al. 2014; Wadiasingh et al. 2018)

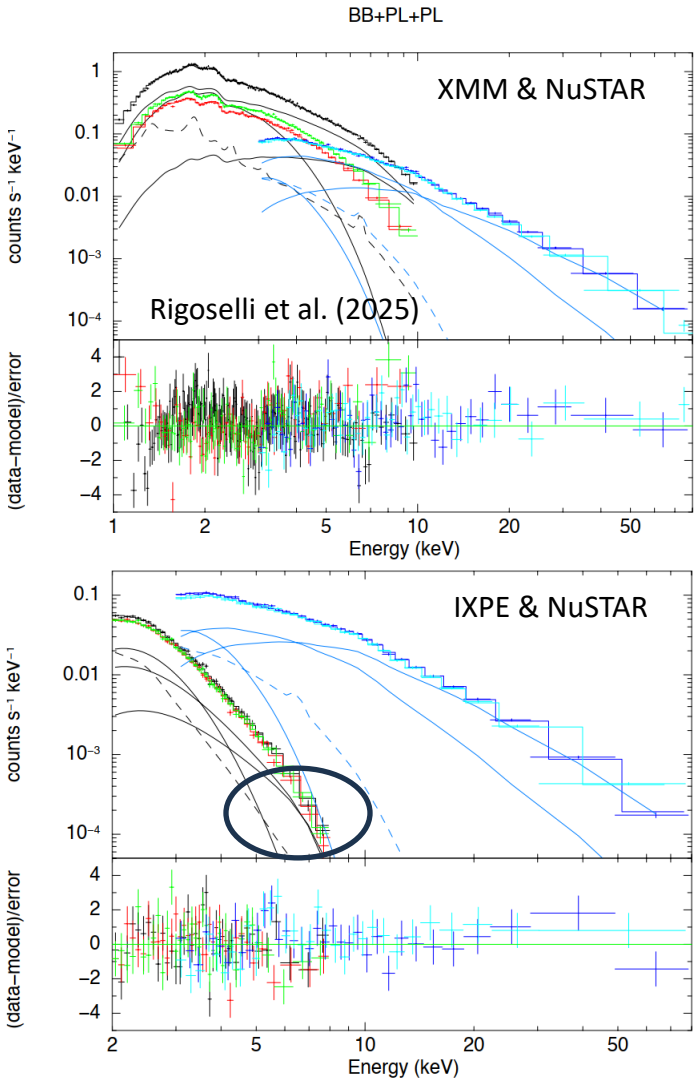


Spectral observations alone cannot discriminate among different scenarios
Can polarimetry help ?

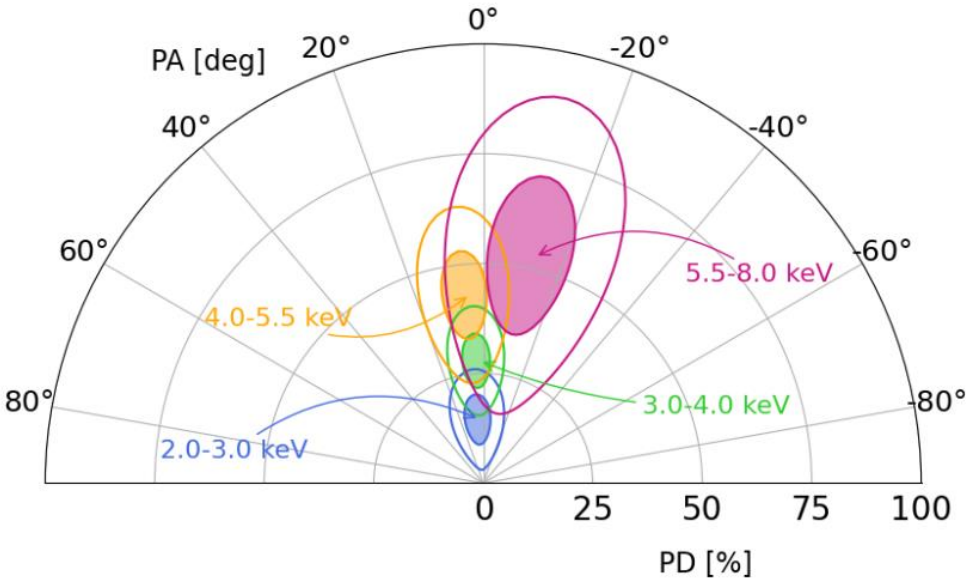
o
PLs

IXPE Observation of 1E 1841–045 - I

- Simultaneous fit of XMM-Newton + NuSTAR and IXPE + NuSTAR data
- Three spectral components statistically required: best fitting model BB+PL+PL
- $\Gamma_{soft} \sim 2.5$, $\Gamma_{hard} \sim 0.9$
- Hard PL contributes also below 8 kV



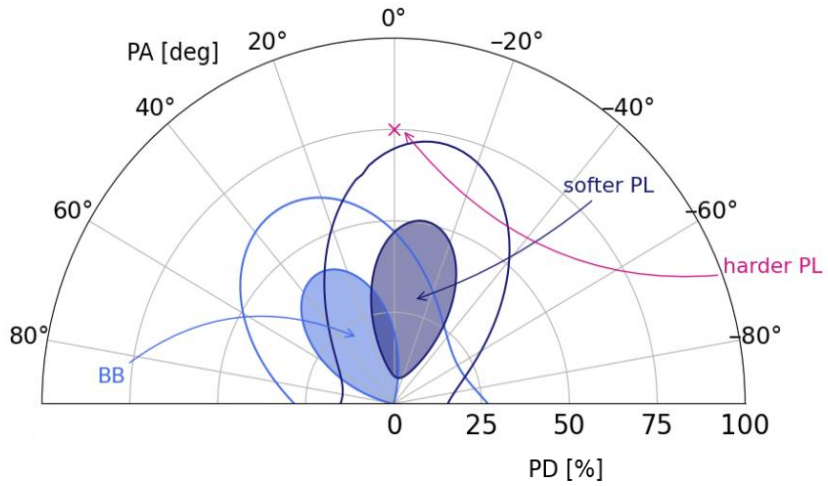
IXPE Observation of 1E 1841–045 - II

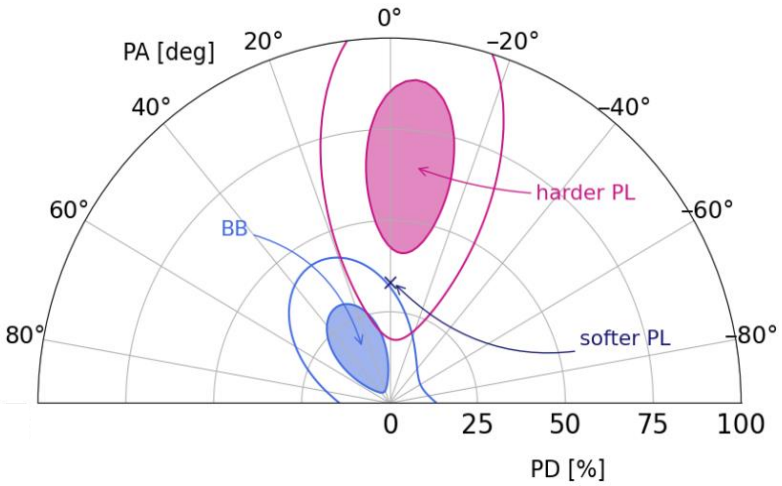


- PD monotonically increasing from ~ 15% @ 2-3 keV, up ~ 55% @ 5.5-8 keV, at constant PA ~ 0°
- No single spectral component dominates the spectrum in any energy range
- None of them can be associated a priori with the polarization measured by IXPE in a given energy interval

IXPE Observation of 1E 1841–045 - III

- Fit with tbabs × (polconst × bbodyrad + polconst × powerlaw + polconst × powerlaw) with all parameters free is unconstrained
- Fix PD = 75% and PA = 0° for the hard PL
- The fit returns PD_{BB} ~ 20%, PD_{PLsoft} ~ 33%, both with PA ~ 0°
- Fix PD = 33% and PA = 0° for the soft PL
- The fit returns PD_{BB} ~ 20%, PA_{BB} ~ 30°, PD_{PLhard} ~ 65%, PA_{PLhard} ~ -6°





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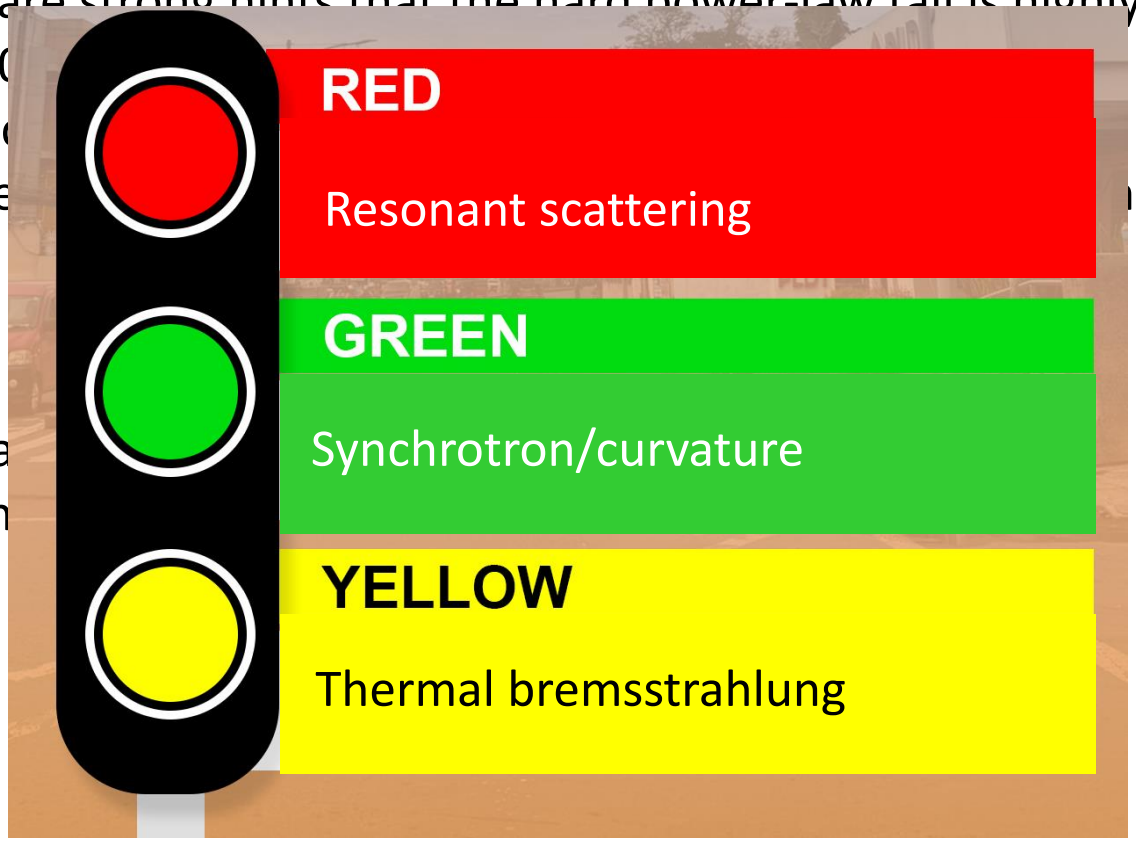
Inferences

- There are strong hints that the hard power-law tail is highly polarized, PD ~ 60
- Hardly c ratio of the cross se e relativistic regime
- Therma
- A synch



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TOWARDS BRIDGING THE GAP

- Extensive exploration of RCS polarization in the relativistic regime with MC codes (e.g. Nobili et al. 2008)
- Quantitative modeling of synchrotron/curvature emission and of emission from returning currents
- Next generation polarimetric missions (EXPO, currently proposed to ESA) will cover a wider energy band (up to 70 keV) with an effective area ~ 5 times larger than IXPE (same for eXTP)
- Detailed study of the polarization in magnetar hard tails for many sources, including 1 RXS J1708 which already exhibited a 70% PD at high energies

Understanding of the current structure in the magnetosphere (not an easy task; e.g. Beloborodov & Thompson 2007; Beloborodov 2013; Parfrey et al. 2013)