Department of Space and Climate Physics, Mullard Space Science Laboratory

Is Polarisation the Key to Understanding Magnetar Emission?

Mode Conversion in a Magnetar Atmosphere

Ruth M. E. Kelly

Prof. Silvia Zane

Prof. Roberto Turolla

Dr. Roberto Taverna

UNIVERSITÀ DEGLI STUDI DI PADOVA

05/06/2024

XMM NEWTON Workshop June 5-7th 2024


Monthly Notices of the Royal Astronomical Society

MNRAS 528, 3927–3940 (2024)

Advance Access publication 2024 January 13

https://doi.org/10.1093/mnras/stae159

X-ray polarization in magnetar atmospheres – effects of mode conversion

Ruth M. E. Kelly,[1★] Silvia Zane,[1] Roberto Turolla[1,2] and Roberto Taverna[2]

[1] Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey RH5 6NT, UK

[2] Dipartimento di Fisica e Astronomia, Università di Padova, via Marzolo 8, I-35131 Padova, Italy

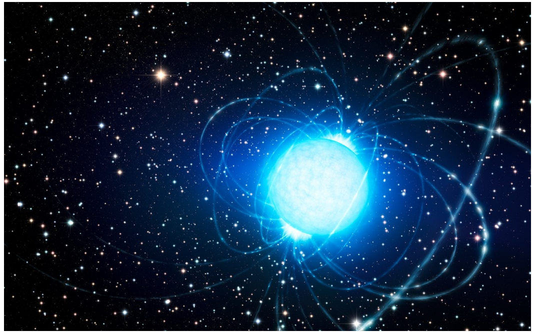
Accepted 2024 January 12. Received 2024 January 11; in original form 2023 December

ABSTRACT

Magnetars, the most strongly magnetized neutron stars, are an … X-ray Polarimetry Explorer (IXPE), the first satellite devot… magnetars to date. A proper interpretation of IXPE results r… into proper account the effects of the magnetized vacuum on… conversion at the vacuum resonance on the polarization pro… models under varying conditions of magnetic field stren… or partial adiabatic mode conversion. Complete mode… the extraordinary (X) to the ordinary (O) one, below… at ≈ 0.5 keV for a magnetic field strength of B =… degree when compared with a standard plasma at… two switches for lower fields of B = 3 × 10^13 G… expected polarization signal at infinity for differ… observability of quantum electrodynamics sig… Demonstration of a Soft X-ray Polarimeter i…

Key words: polarization – radiative trans…

Magnetars and Polarisation

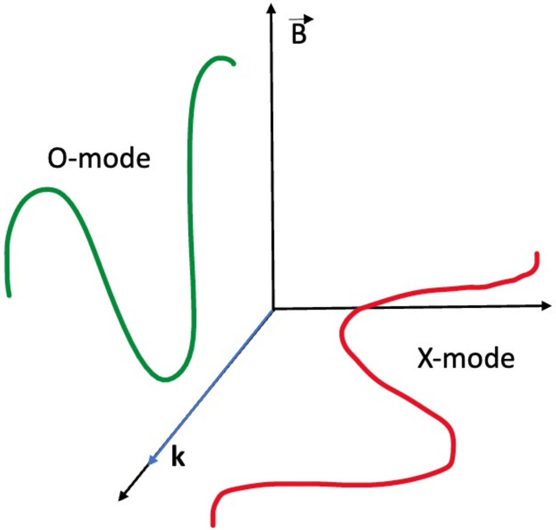


Magnetars:

- NS with magnetic field above $10^{13}G$
- Detected in X-ray range

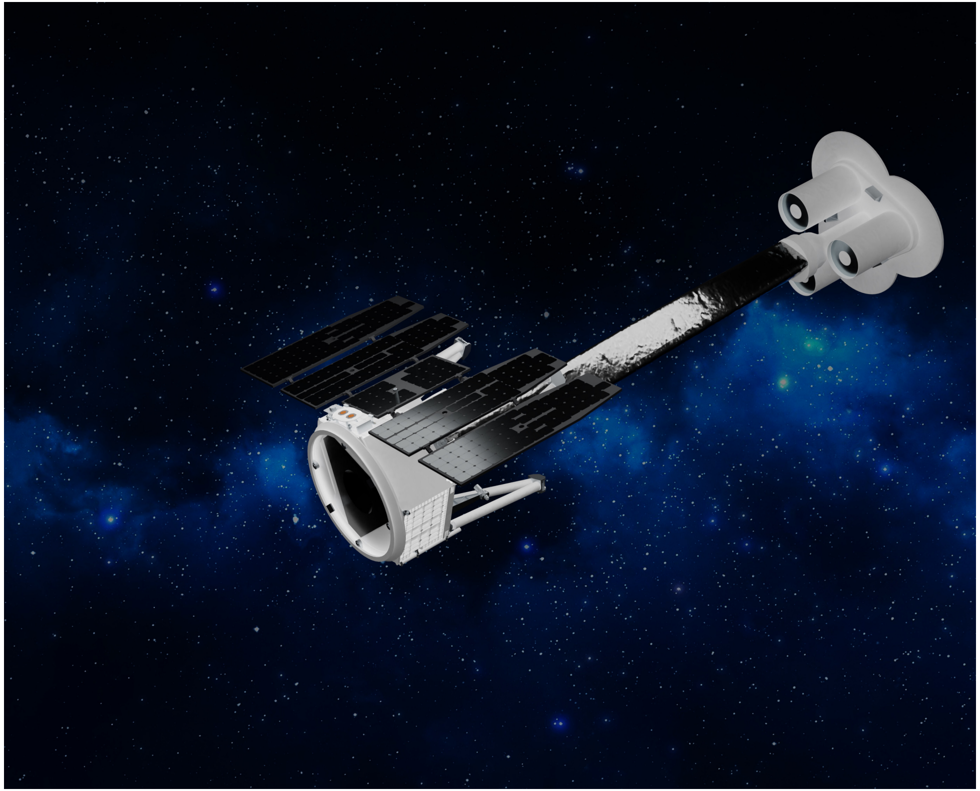
Polarisation:

- Anisotropic atmospheric medium
- Electromagnetic waves polarised in two normal modes
- X-mode has reduced refractive index
- Polarisation degree
- Polarisation angle



IXPE

- Exploit polarisation state of light to investigate X-ray production
- 2-8 keV
- Four magnetars to date:
  - 4U 0142+61
  - IRXS J1708
  - SGR 1806
  - IE 2259+586



4U 0142+61

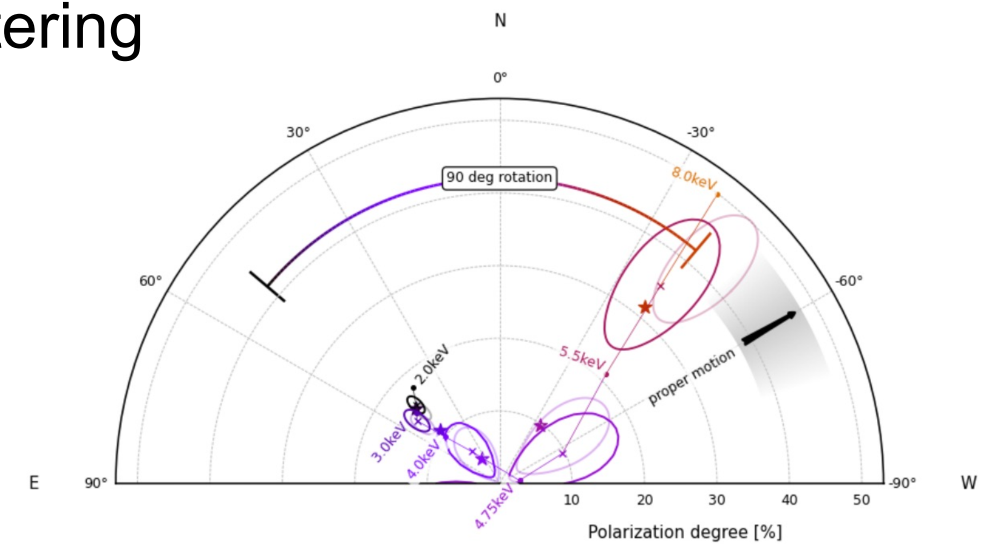
$B \approx 1.3 \times 10^{14} G$

Taverna et al 2022

- Resonant Compton Scattering
- Condensed surface

Lai 2023

- Partial mode conversion



IRXS J170849.0-400910

$B \approx 4 - 5 \times 10^{14}$G

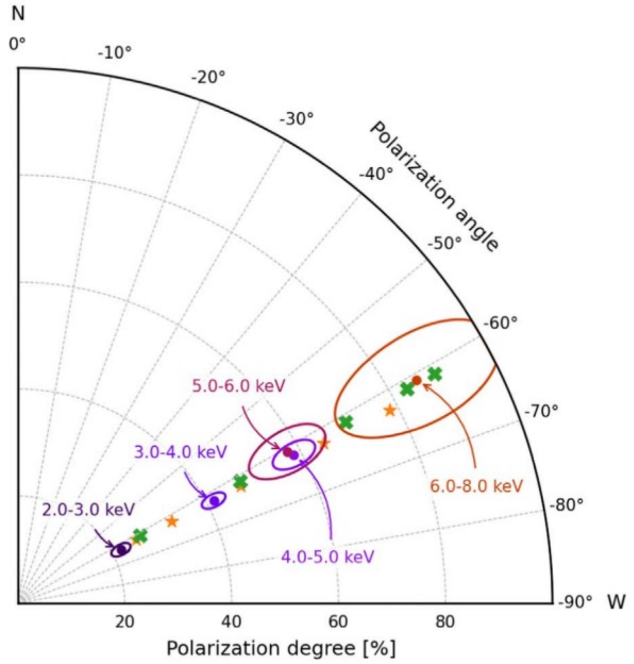
Zane et al 2023

High polarisation

➢ Standard atmosphere emission

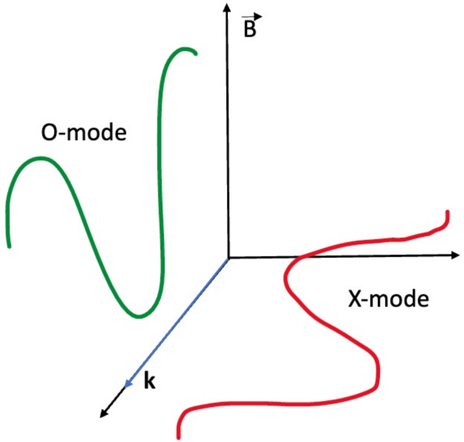
Low polarisation

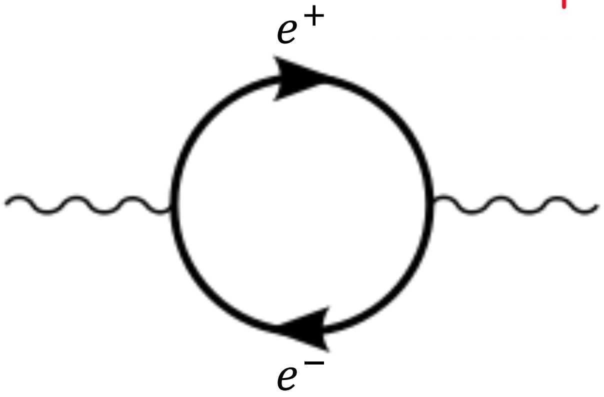
➢ Warm condensed region

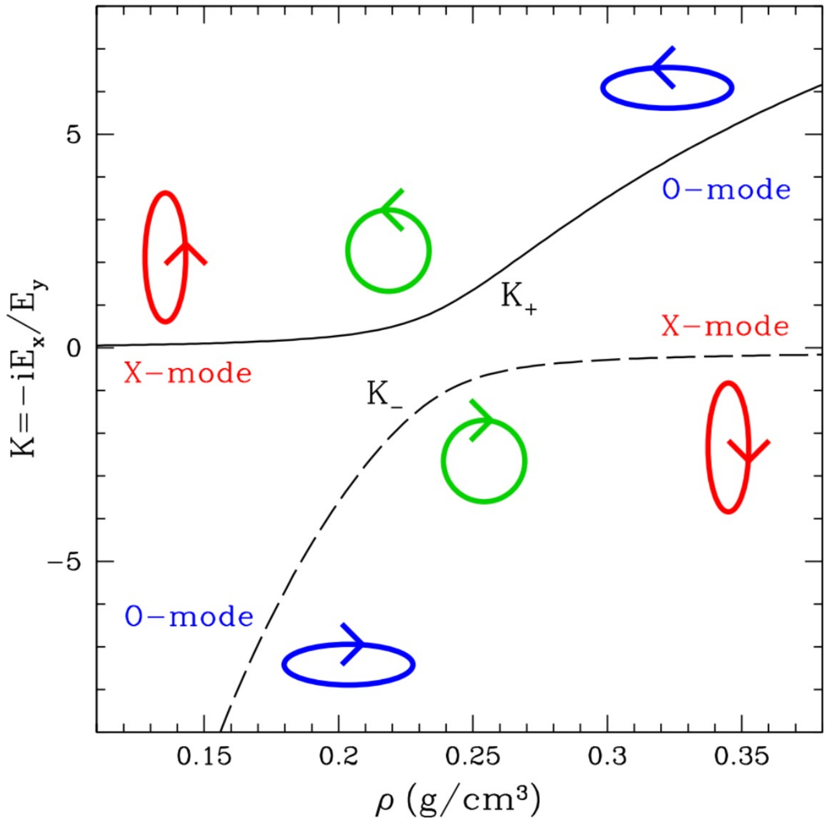


Mode Conversion

- Two polarisation modes
- High magnetic fields
- Vacuum birefringence (QED)
- Both plasma and vacuum contribute to dielectric tensor
- "Vacuum resonance"



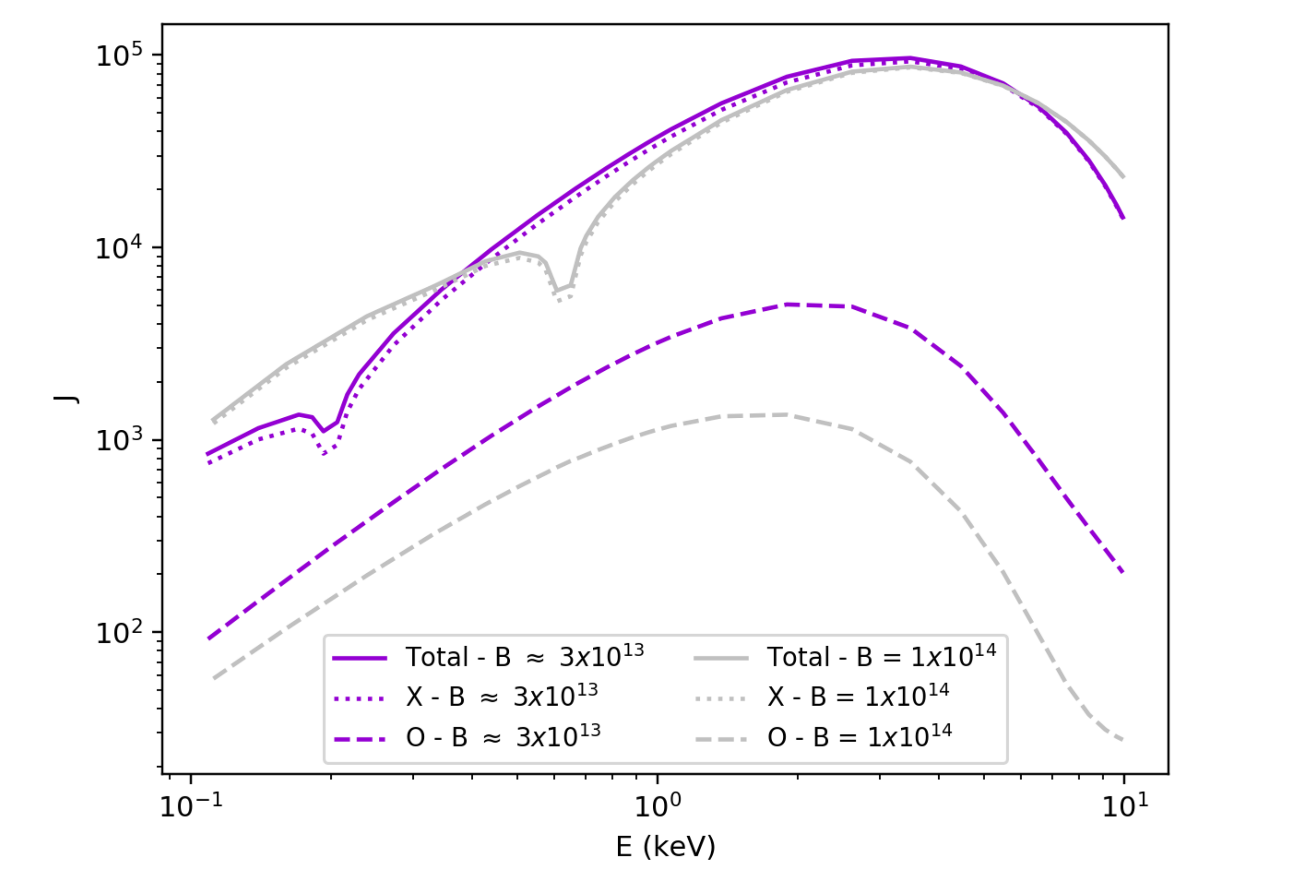




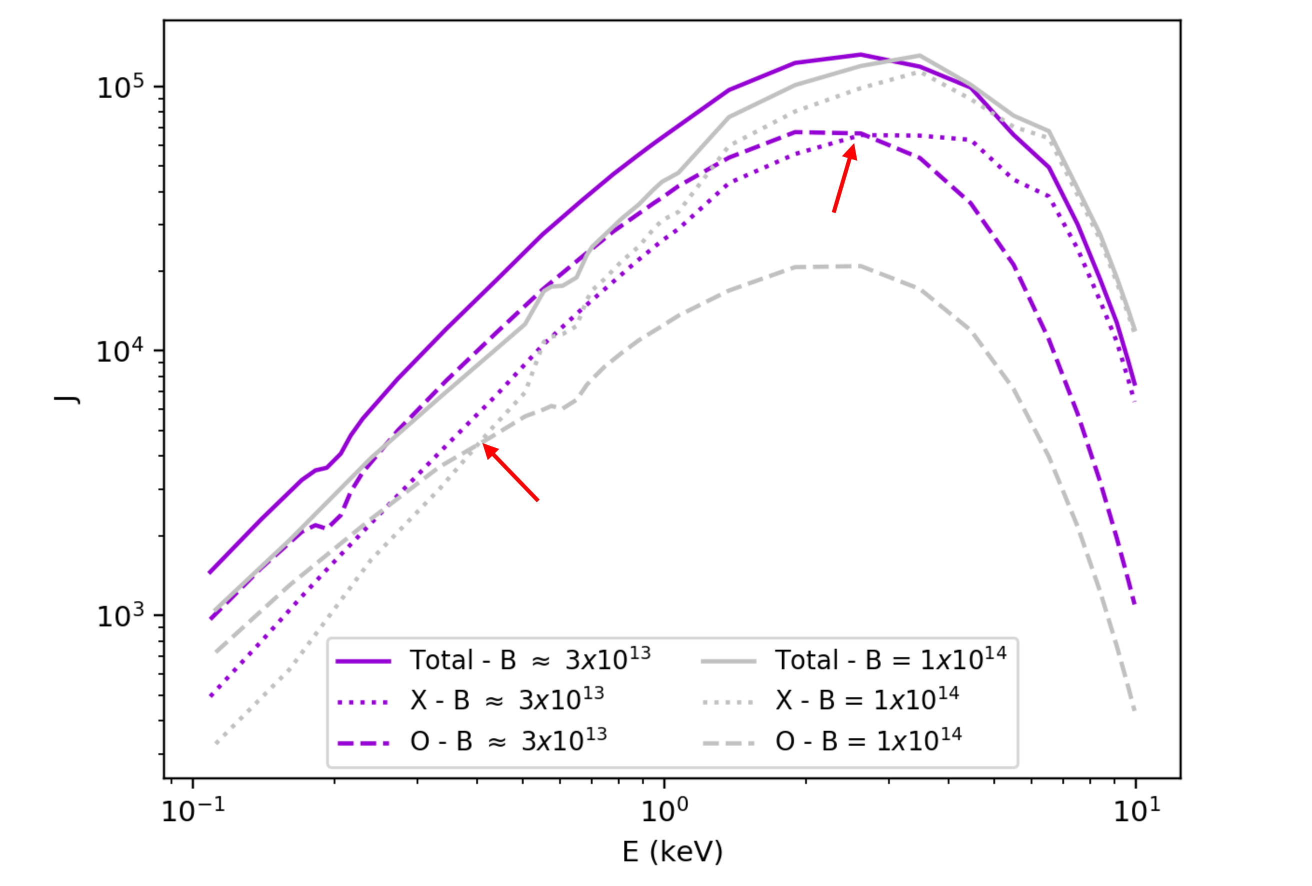
Harding and Lai, 2006

- No mode conversion
- Complete mode conversion
- Partial mode conversion
    - Adiabatic mode conversion

Standard Atmospheric Emission



Complete Mode Conversion



Probability of Mode Conversion

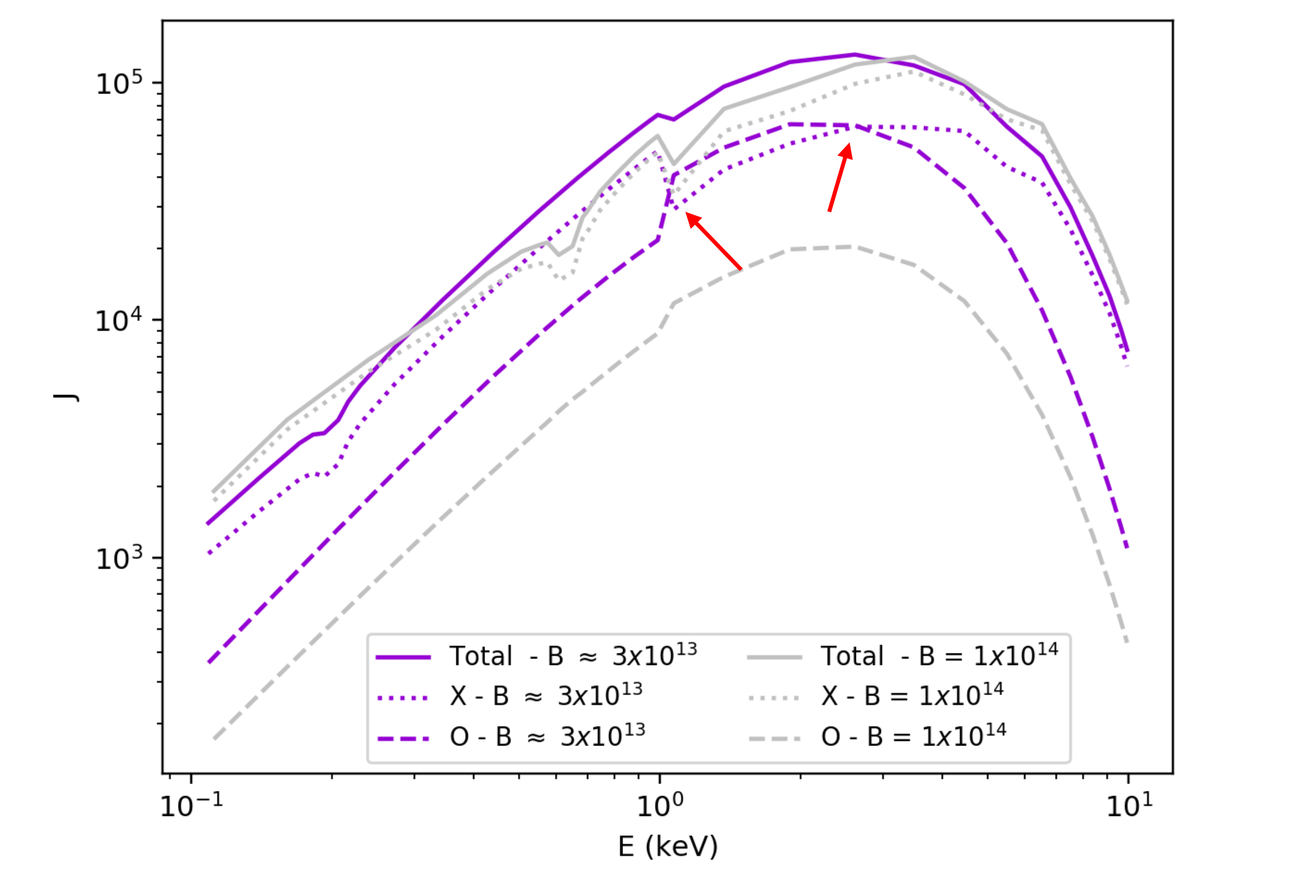
$$1 - exp\left[-\frac{\pi}{2}\left(\frac{E}{E_{ad}}\right)^3\right],$$

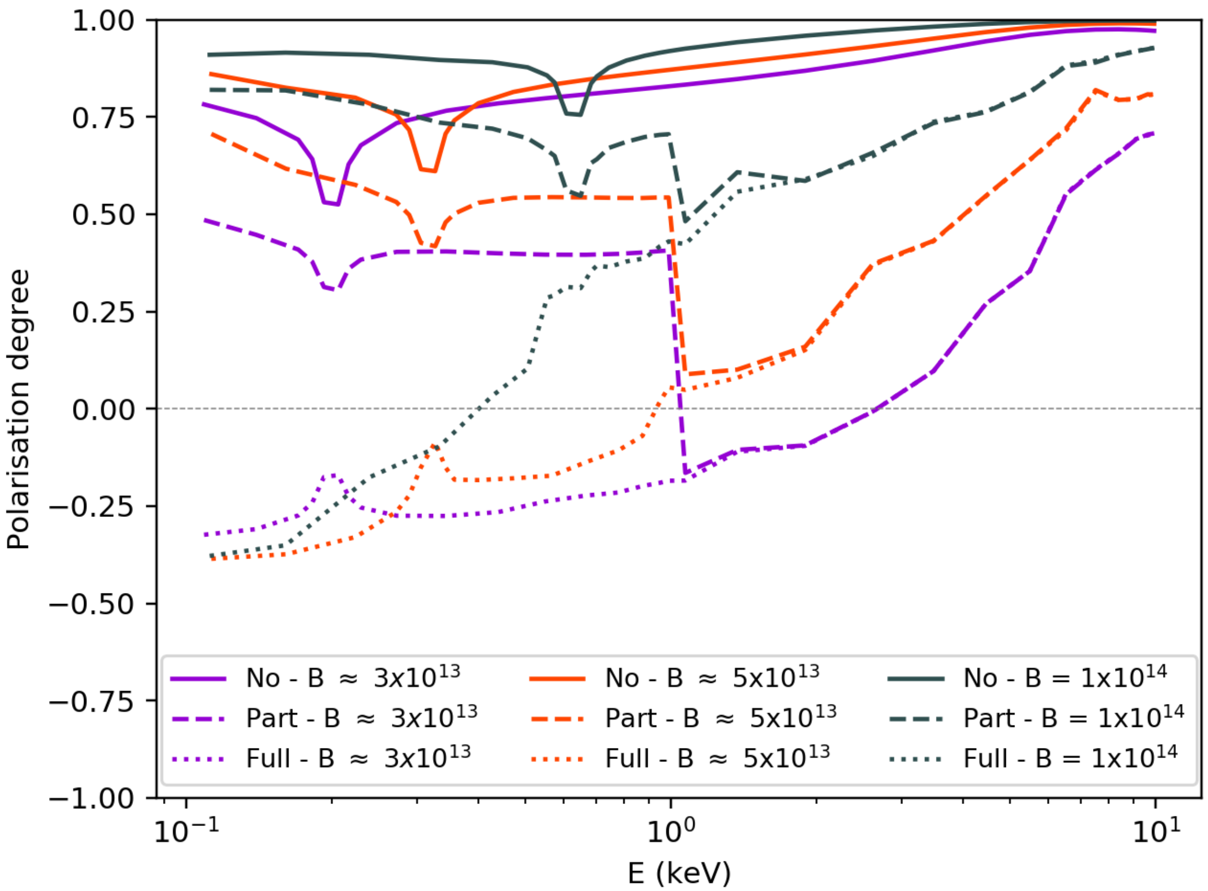
$$E_{ad} = 2.52(f\ tan\theta_B)^{\frac{2}{3}}\left(\frac{1cm}{H_p}\right)^{\frac{1}{3}}\text{keV}$$

Every photon with $\mathrm{P} > P_{con}$:
mode conversion occurs

$$f = 1$$
$$tan\theta_B = 1$$
$$H_p = 1$$

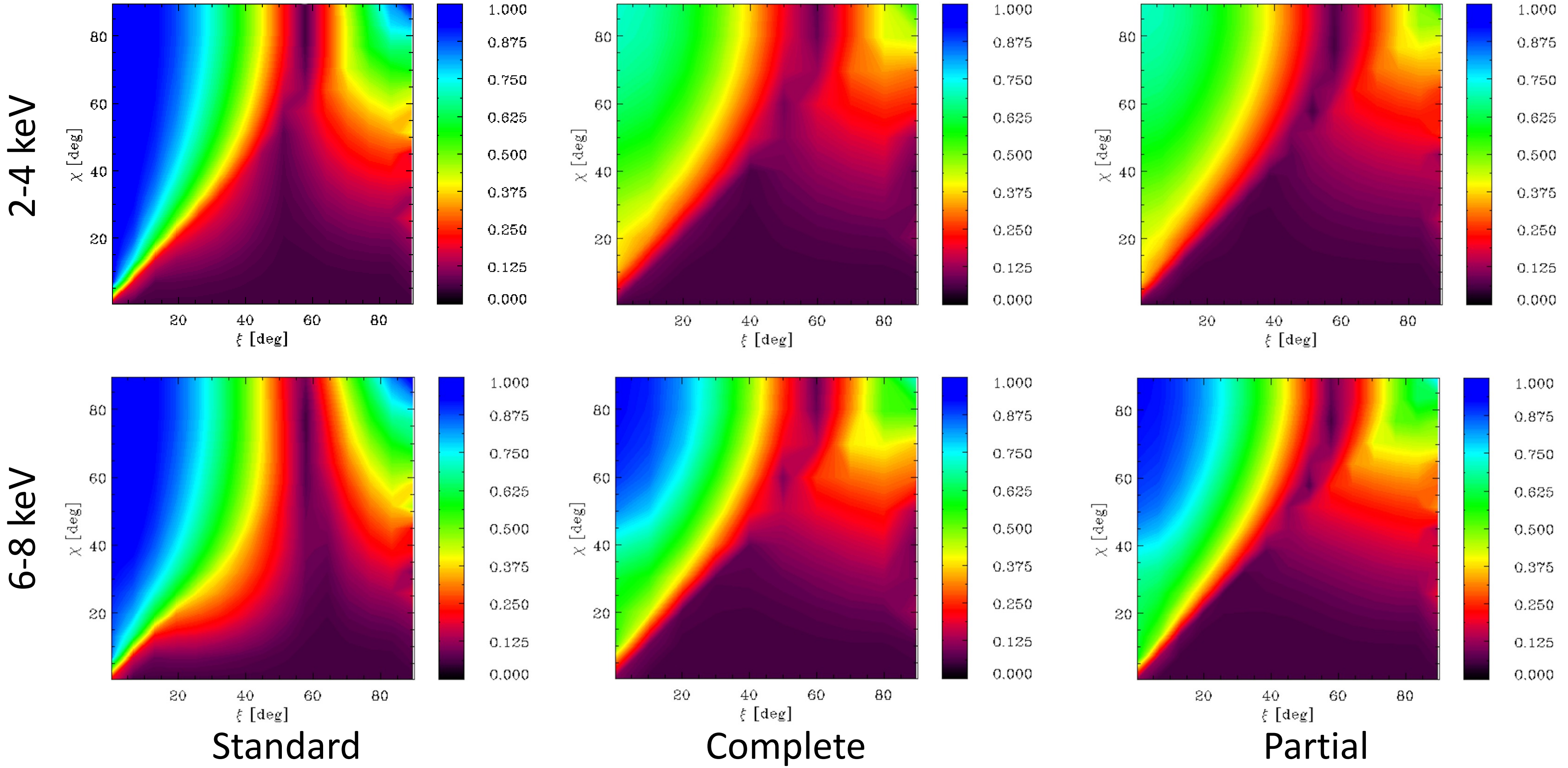
Partial Mode Conversion ($P_{con} = 0.1$)



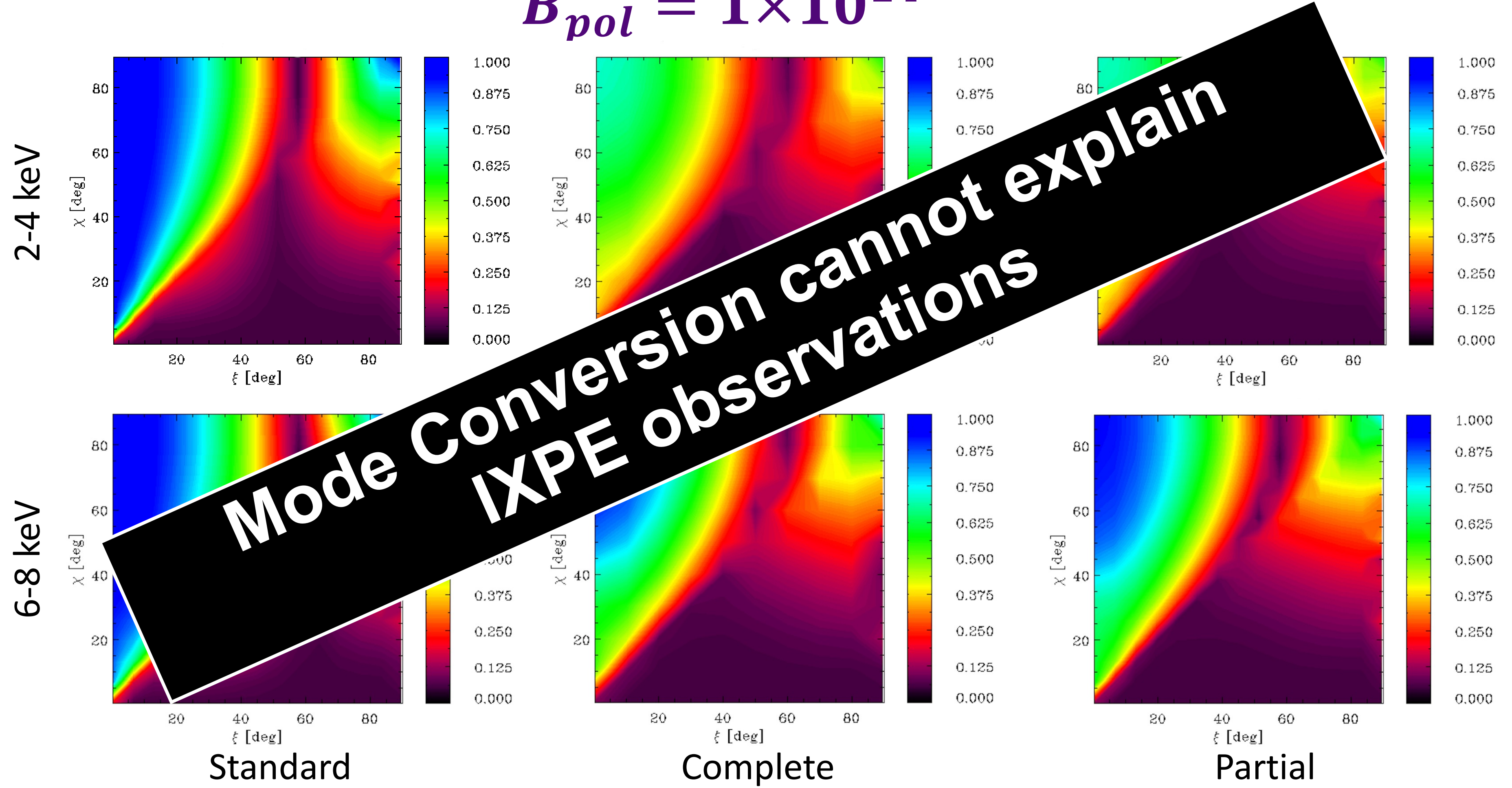


$$\mathrm{PD}_{\mathrm{em}} = \frac{J_\nu^{\mathrm{X}} - J_\nu^{\mathrm{O}}}{J_\nu^{\mathrm{X}} + J_\nu^{\mathrm{O}}}$$

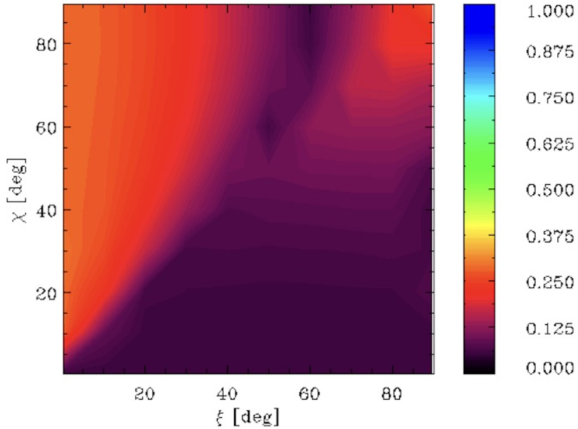
$B_{pol} = 1\times10^{14}$



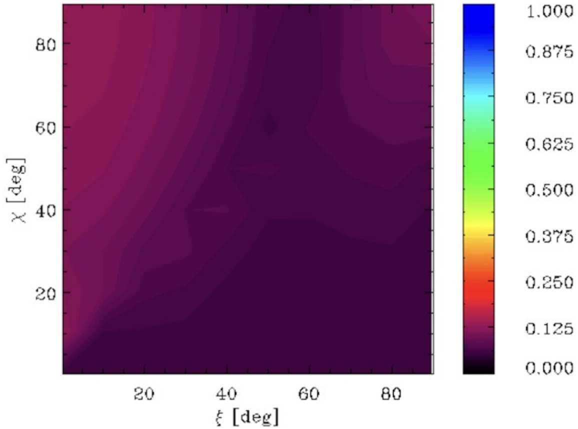
$B_{pol} = 1 \times 10^{14}$



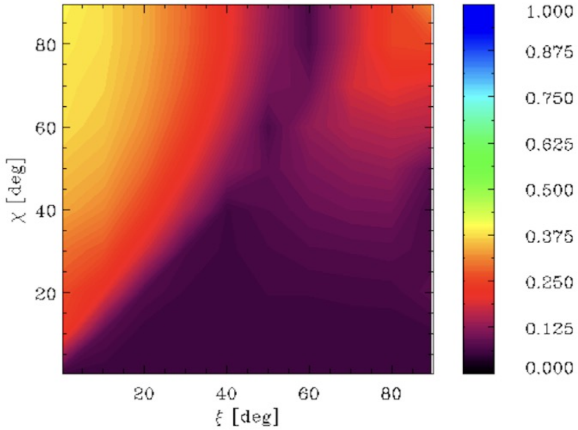
Complete Mode Conversion



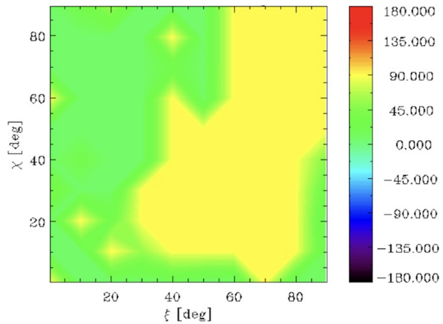
0.1-0.5 keV



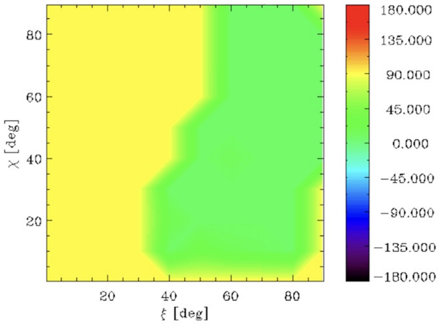
0.5-1 keV



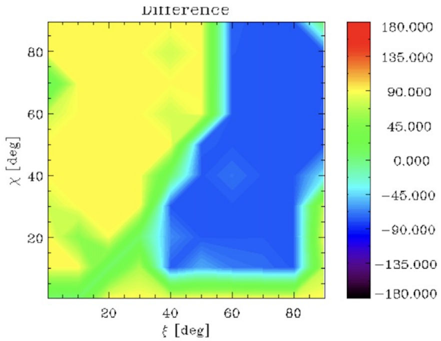
1-2 keV



0.1-0.5 keV

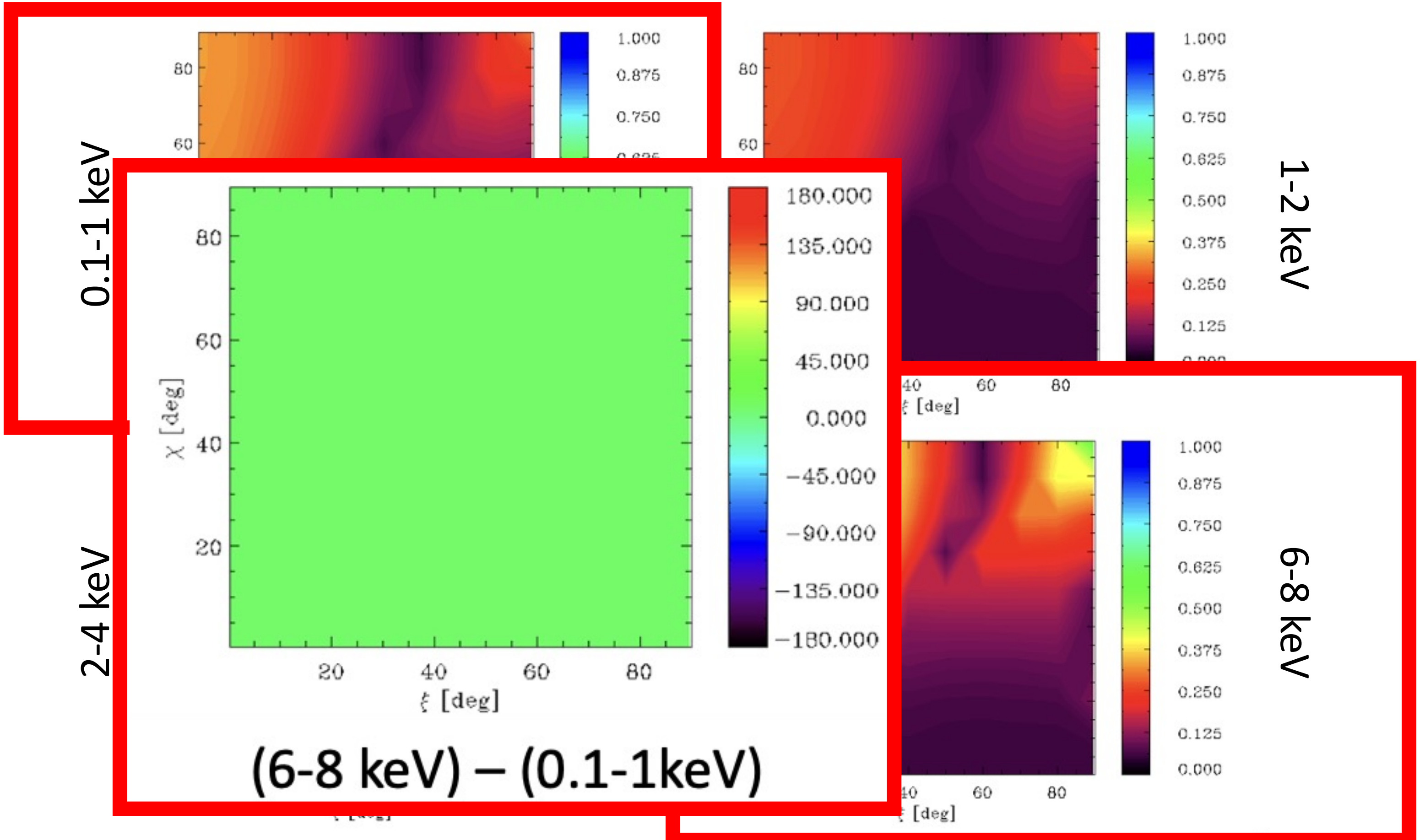


1-2 keV

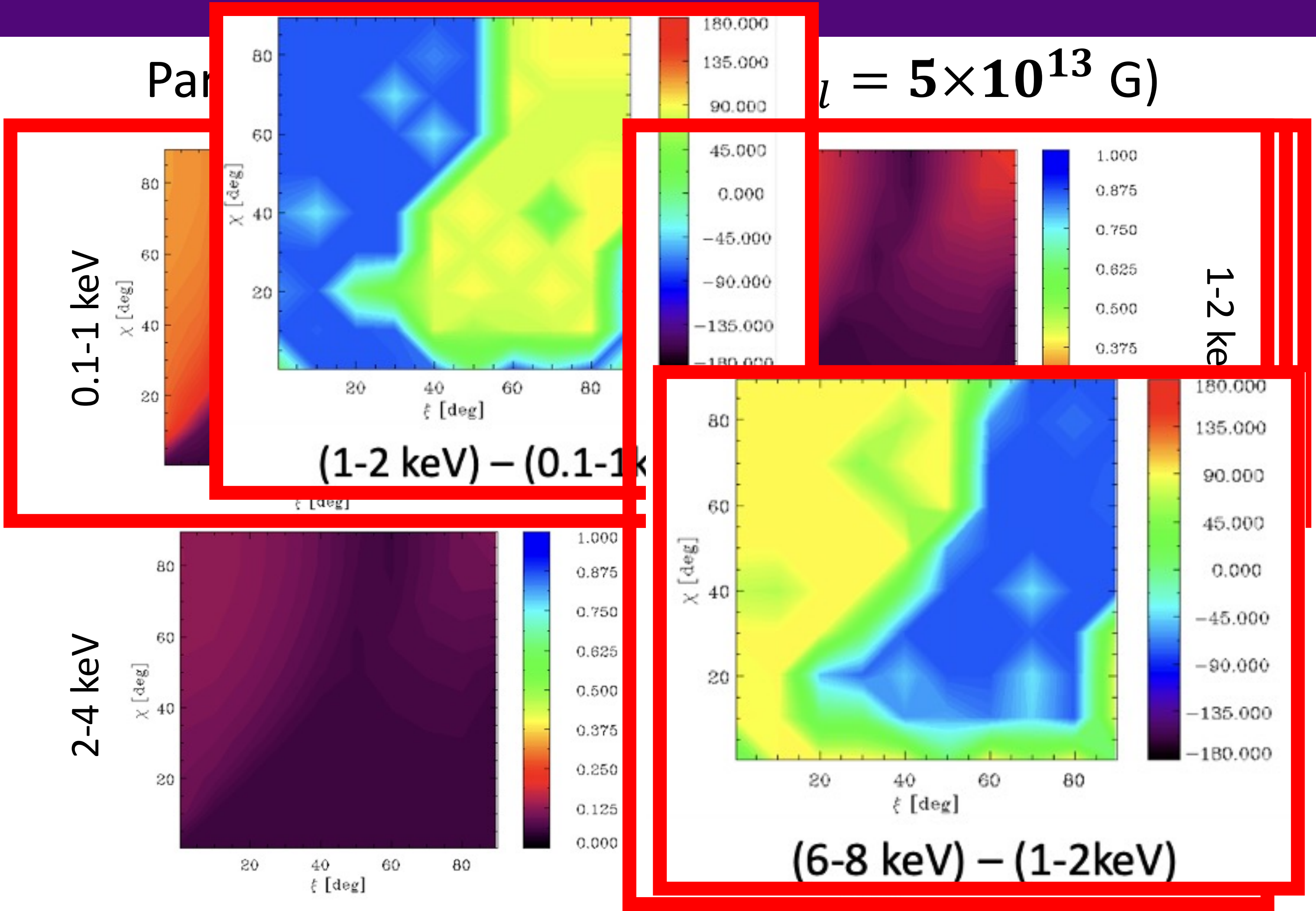


Difference

Partial Mode Conversion ($B_{pol} = 5\times10^{13}$ G)



Par… $_l = \mathbf{5\times10^{13}}$ G)



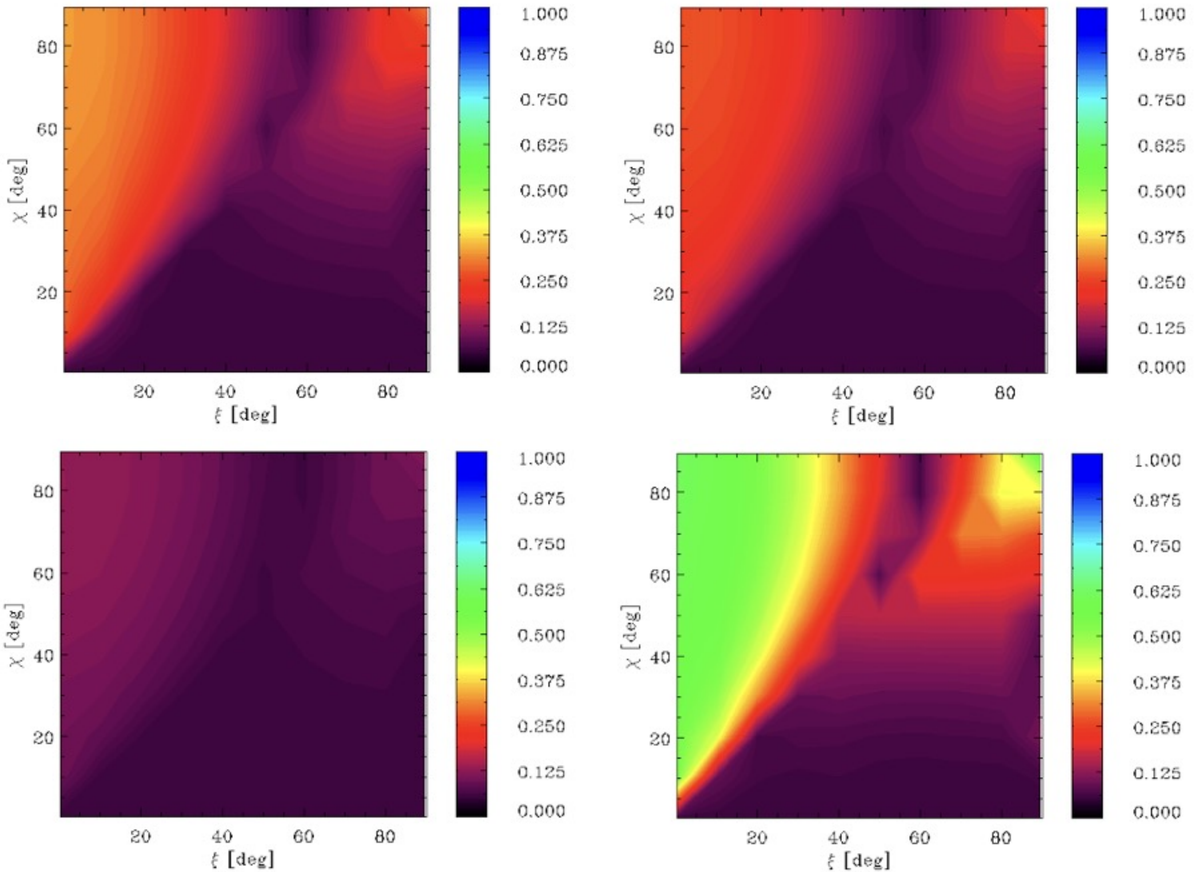
Partial Mode Conversion ($\boldsymbol{B_{pol} = 5 \times 10^{13}}$ G)

0.1-1 keV

1-2 keV

2-4 keV

6-8 keV



Conclusion

- Complete MC – switch in dominant polarisation mode (E ↑ as B ↓)
- Partial MC – reduced polarisation – two switches at low enough B
  - **In IXPE – XDINS ?**
  - **REDSoX (0.2-0.8 keV) ?**

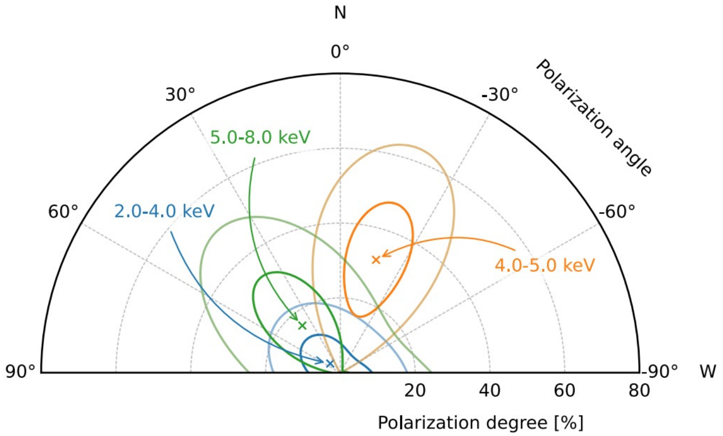
Future and Ongoing work

- Particle bombardment
- Partial ionization

Thank you!

SGR 1806-20

$B \approx 8 \times 10^{14} G$



Turolla et al 2023

- Resonant Compton Scattering
- Condensed surface

IE 2259+586

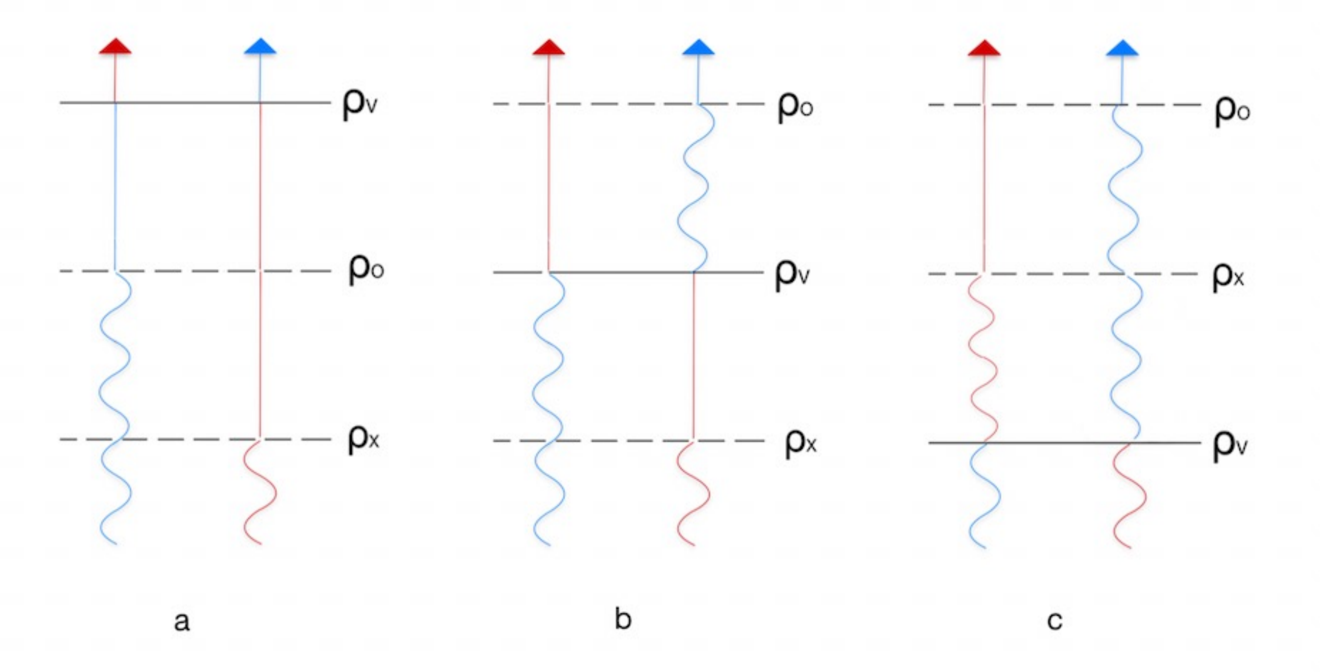
$B \approx 6 \times 10^{13} G$

Or

$B > 10^{15} G$

Heyl et al 2024

- mild, phase-dependent PD
- $\sim 0 - 25$ %
- a baryon-loaded magnetic loop



$$\rho_V \approx 0.96 Y_e^{-1} \left(\frac{E}{1\text{keV}}\right)^2 \left(\frac{B}{10^{14}}\right)^2 f(B)^{-2} \text{g cm}^{-3}$$

Ho and Lai, 2003

$$\tau_O = \rho \sigma z$$

$$\sigma_O = \sigma_T \left(\sin^2\theta + \frac{1}{2}\cos^2\theta \left[\frac{\epsilon^2}{(\epsilon+\epsilon_B)^2} + \frac{\epsilon^2}{(\epsilon-\epsilon_B)^2} \right] \right)$$

Harding and Lai, 2006