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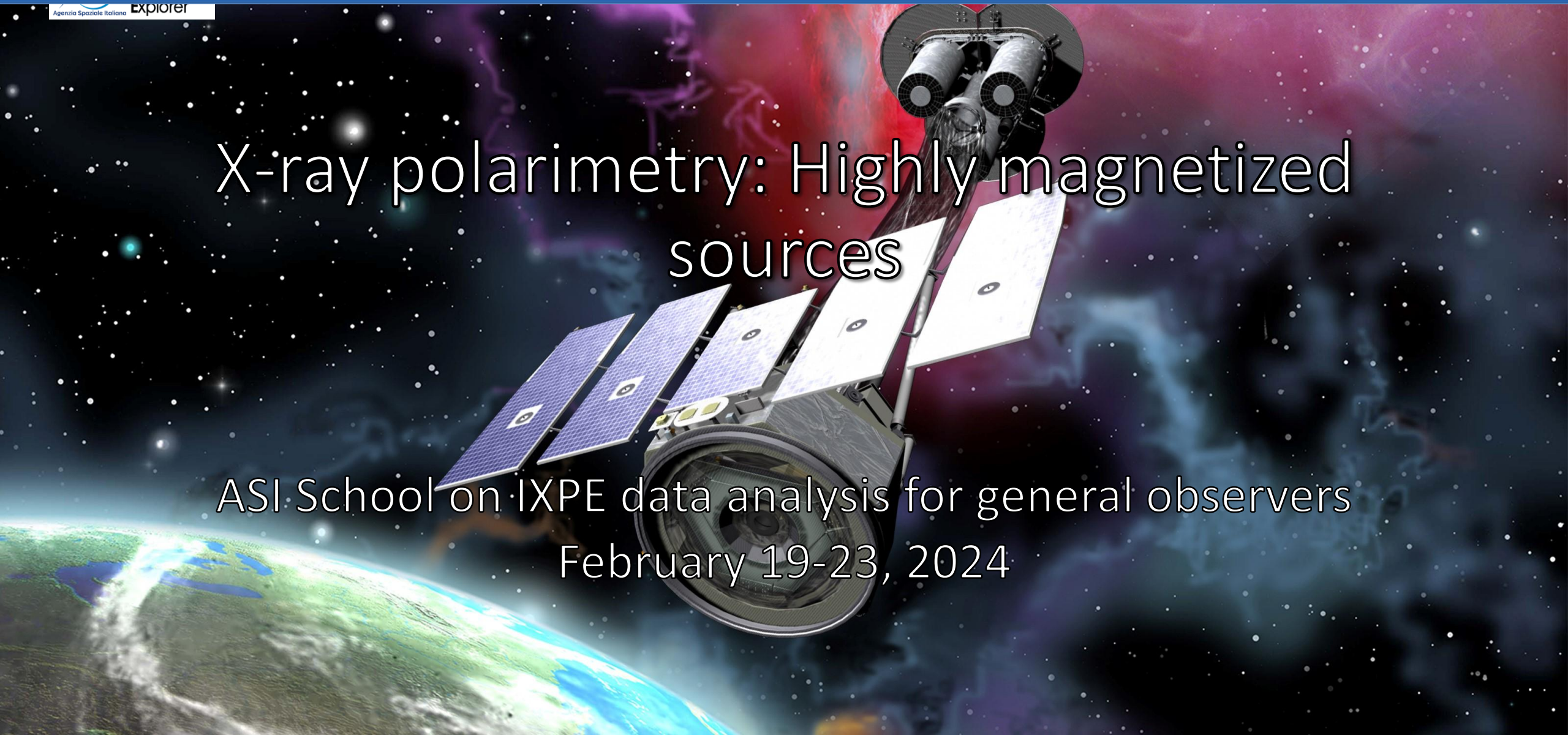
Agenzia Spaziale Italiana Explorer



X-ray polarimetry: Highly magnetized sources

ASI School on IXPE data analysis for general observers

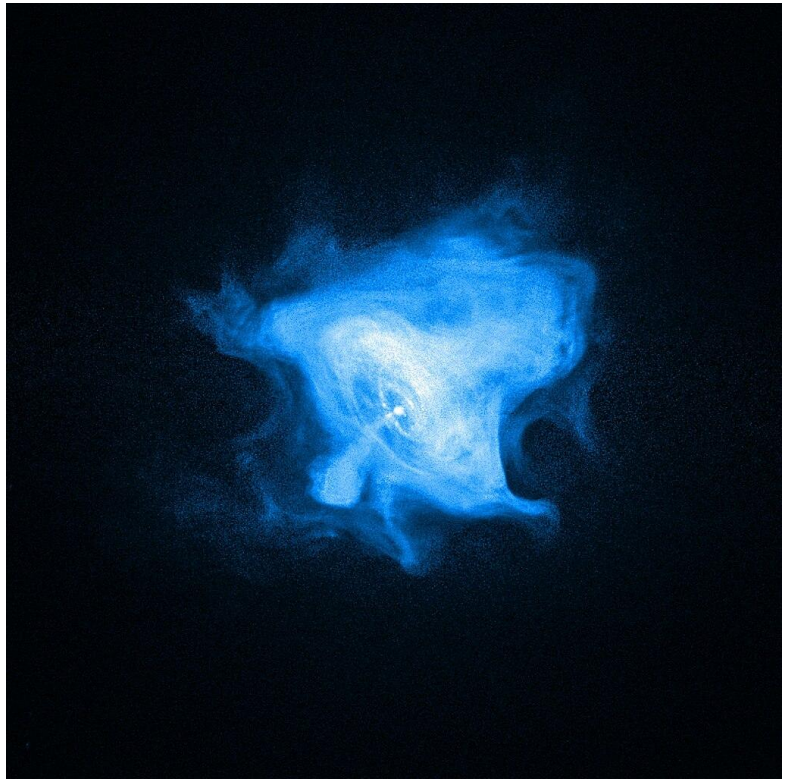
February 19-23, 2024

Neutron stars: general notions

- Neutron stars (NSs) are relics of massive stars ($M_{\rm prog} \approx 8 - 25\ M_\odot$)
- Masses $M_{\rm NS} \approx 1 - 2\ M_\odot$
- Radii $R_{\rm NS} \approx 10 - 15\ \rm km$

$\rho_{\rm m} \approx 10^{14} - 10^{15}\ \rm g/cm^3$

- Indeed made of neutrons (mostly, typically $8\ n$ every p^+/e^-) – sustained by the pressure of degenerate neutrons



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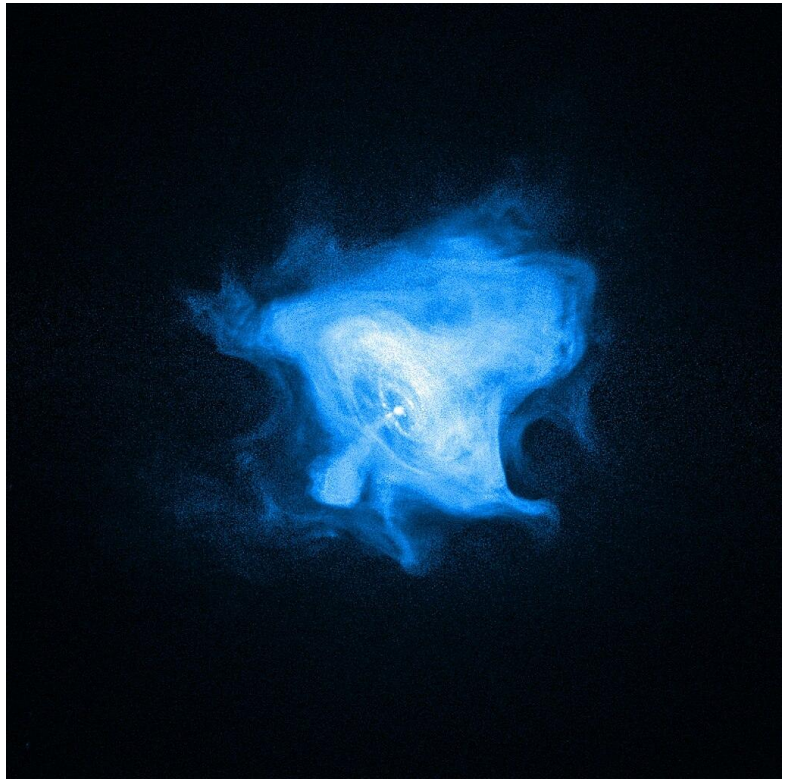
- Indeed made of neutrons (mostly, typically $8\ n$ every p^+/e^-) – sustained by the pressure of degenerate neutrons
- Fast rotators

$$P \approx 10^{-2} - 10\ \rm s$$

$$\dot{P} \approx 10^{-20} - 10^{-9}\ \rm s/s$$



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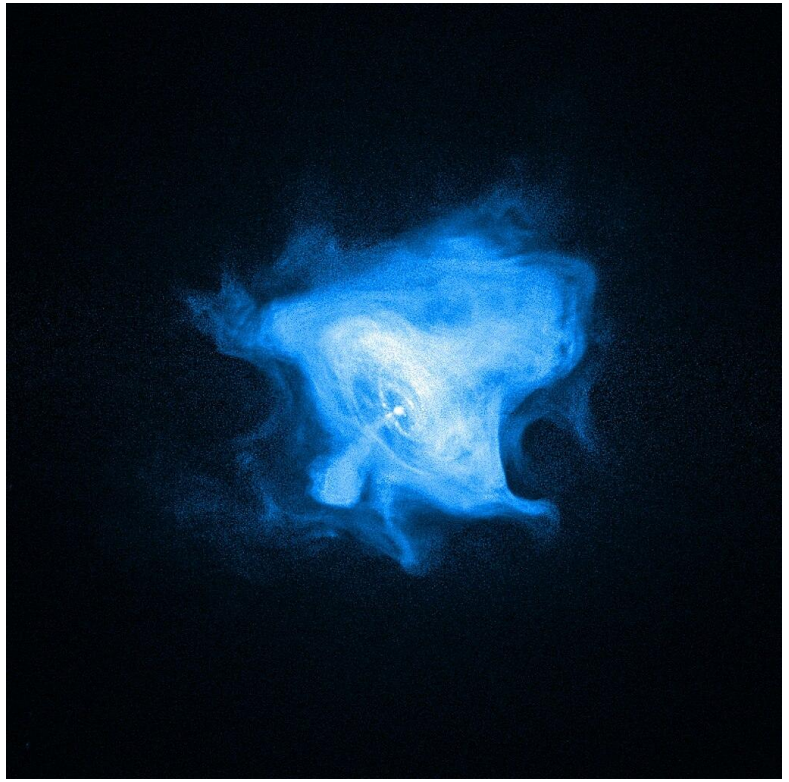
- Indeed made of neutrons (mostly, typically $8\ n$ every p^+/e^-) – sustained by the pressure of degenerate neutrons
- Fast rotators
- Powerful magnets



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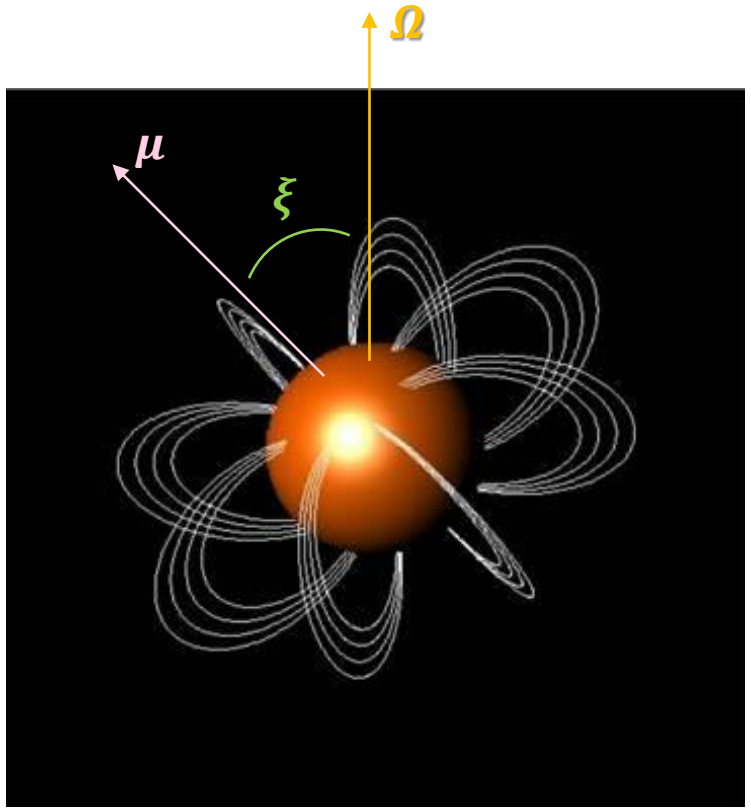
Magneto-rotational evolution

- A rotating dipole field emits EM radiation at the expenses of the rotational energy



Larmor formula

$$-\frac{2}{3c^3}\left(\frac{\partial^2\mu}{\partial t^2}\right)^2 = I\Omega\dot{\Omega}$$

Magnetic dipole moment

Rotation frequency ($\Omega = 2\pi/P$)

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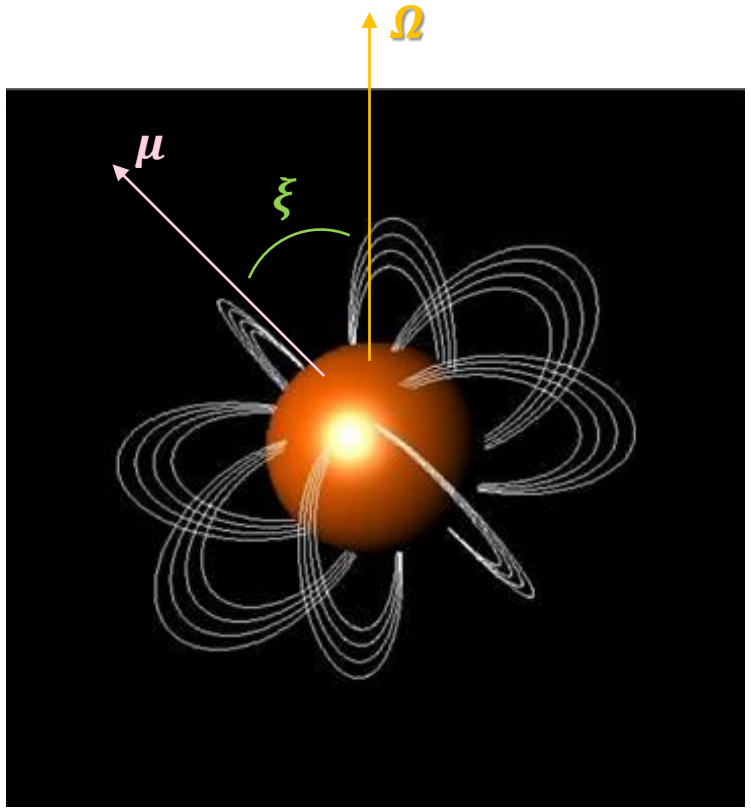

Solving for B

$$B \approx 3.2 \times 10^{19} \sqrt{P\dot{P}}\ \mathrm{G}$$

⚠ This holds for:

- purely dipolar magnetic field ($\boldsymbol{\mu}$ in the Larmor formula)
- all the rotation energy is converted into EM emission

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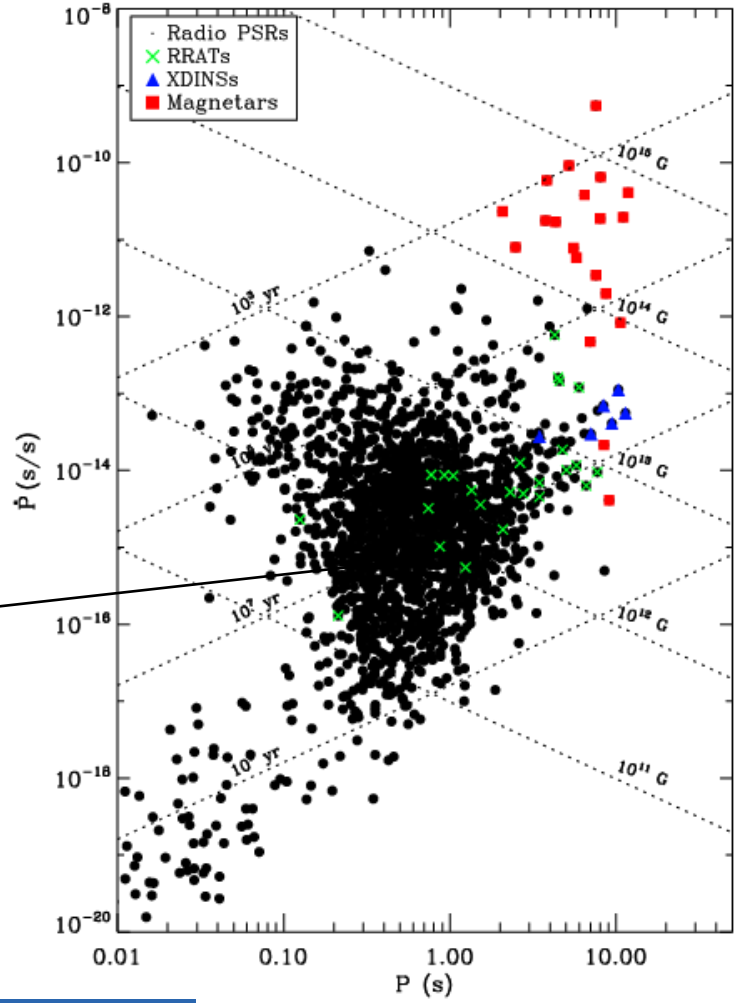
$P\dot{P}$ diagram

- Classification of NSs according to their values of P and $\dot{P}$

Rotation-Powered Pulsars (RPPs)



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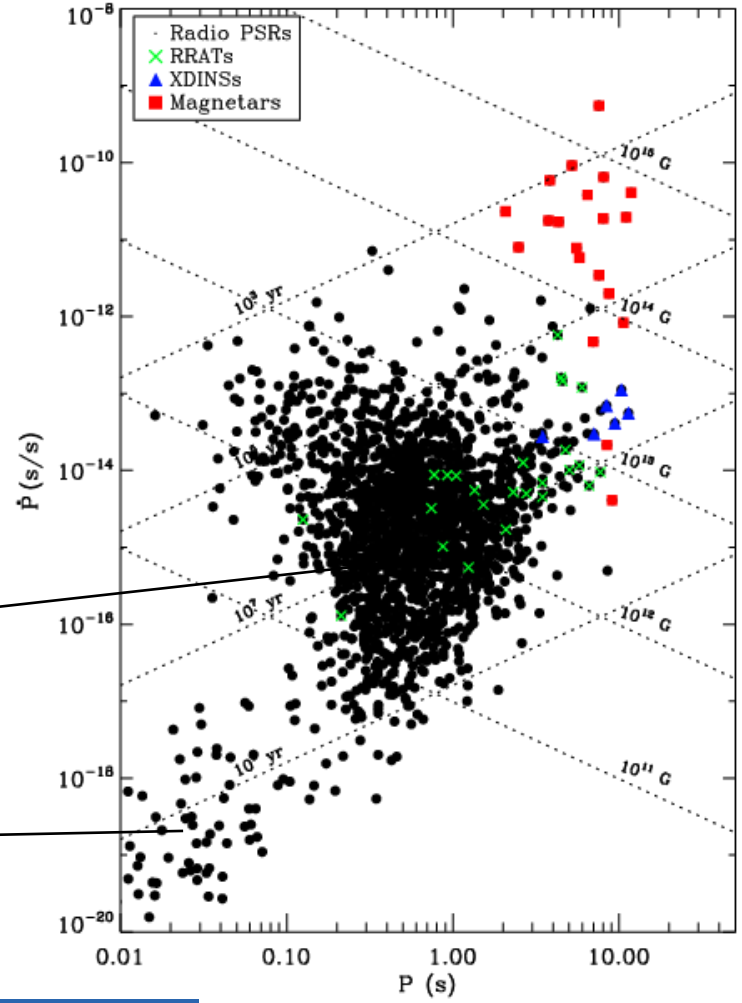

Rotation-Powered Pulsars (RPPs)

(Accreting) millisecond pulsars

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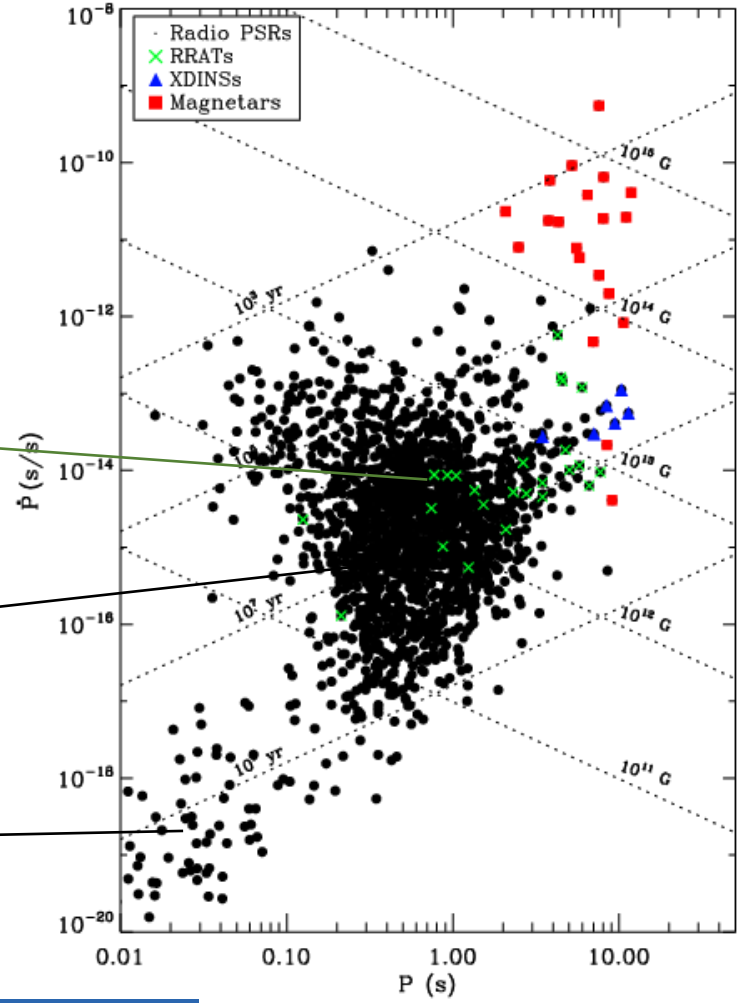

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$P\dot{P}$ diagram

- Classification of NSs according to their values of P and $\dot{P}$

X-ray Dim Isolated NSs (XDINSs)

Rotating Radio Transients (RRaTs)

Rotation-Powered Pulsars (RPPs)

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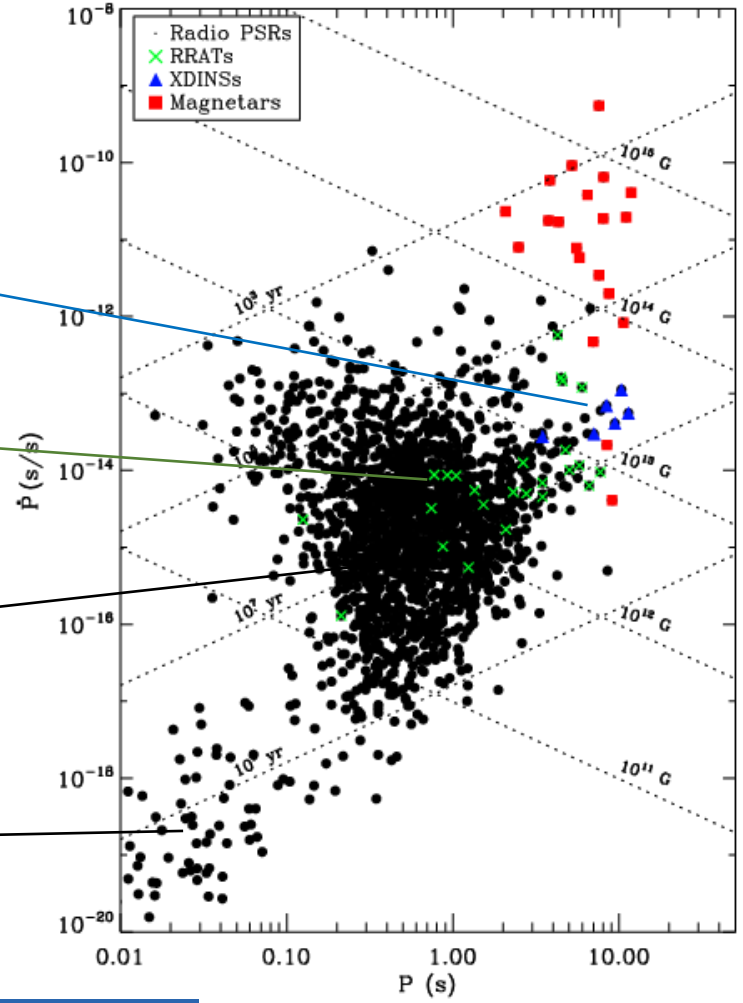

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X-ray Dim Isolated NSs (XDINSs)

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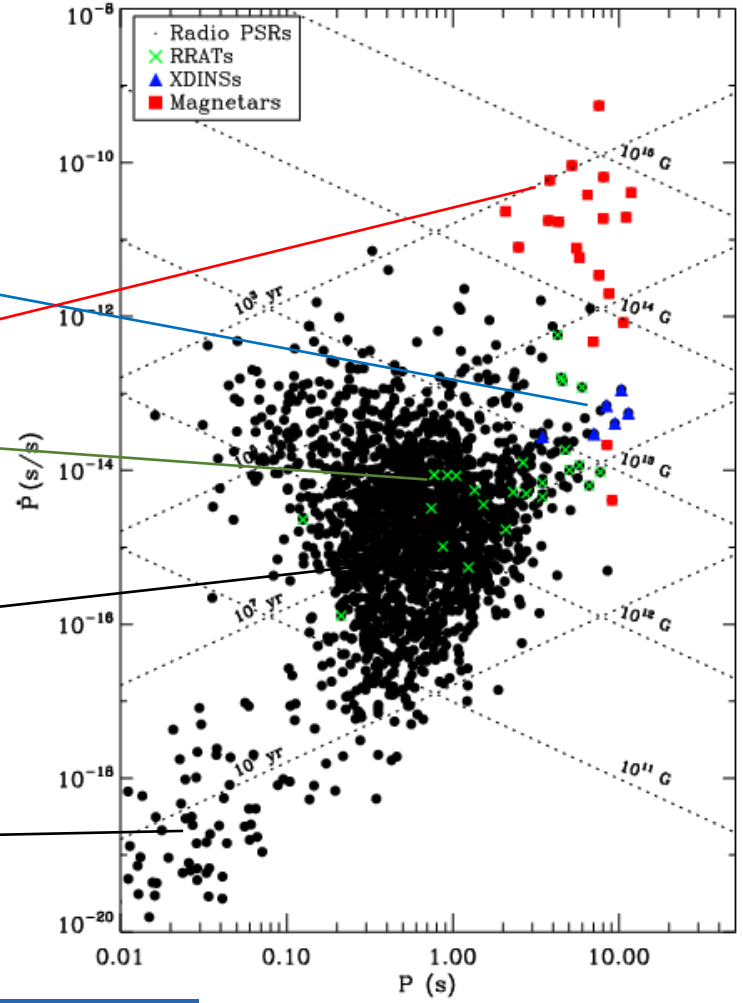
Magnetars (AXPs and SGRs)

Rotation-Powered Pulsars (RPPs)

(Accreting) millisecond pulsars



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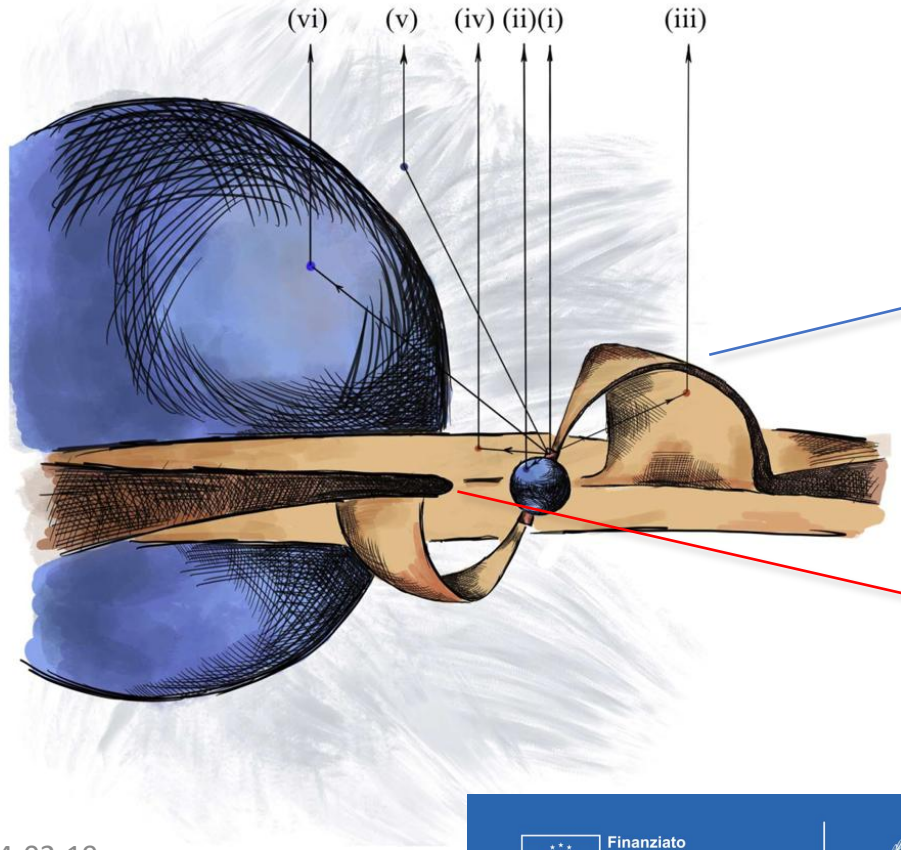
Accreting X-ray pulsars (XRPs)

- Strongly magnetized NSs ($B \approx 10^{12-13}$ G) in binary systems
- Emission determined by accretion geometry



Accretion flow funnelled along magnetic field lines

Accretion stopped ($P_{\mathrm{magn}} = P_{\mathrm{ram}}$)

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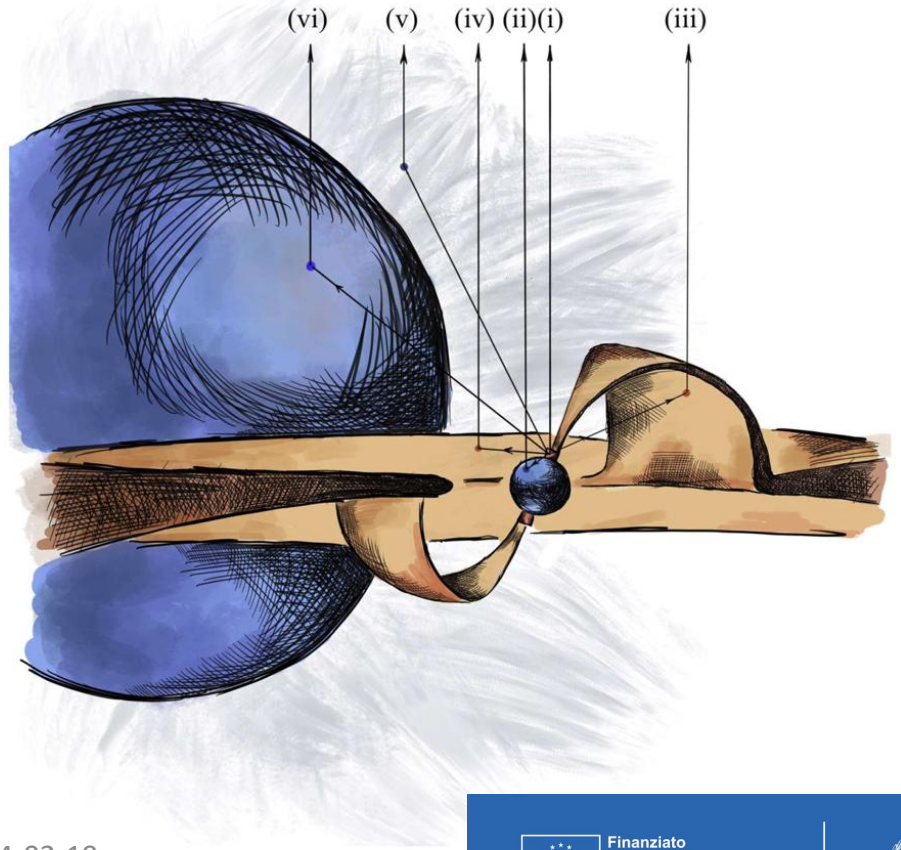
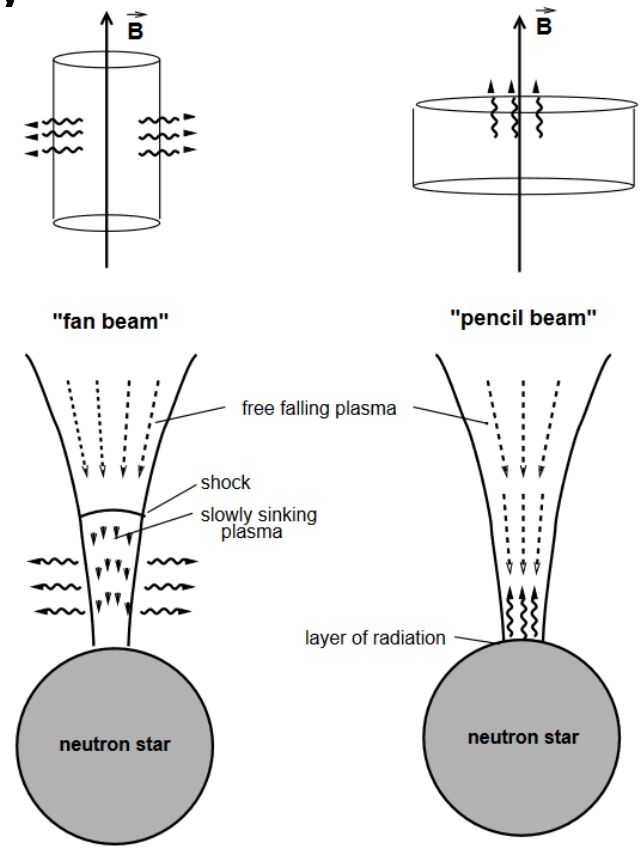


Fan beam
(large $\dot{M}$)



Pencil beam
(small $\dot{M}$)

önherr et al. 2007

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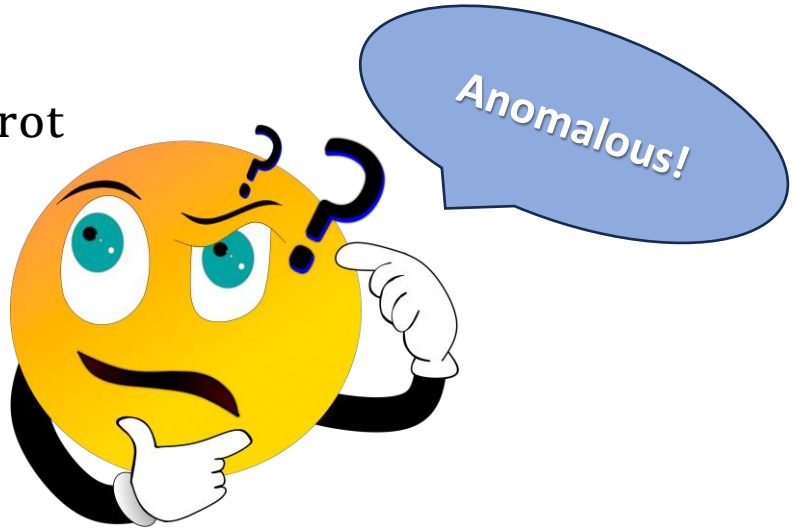
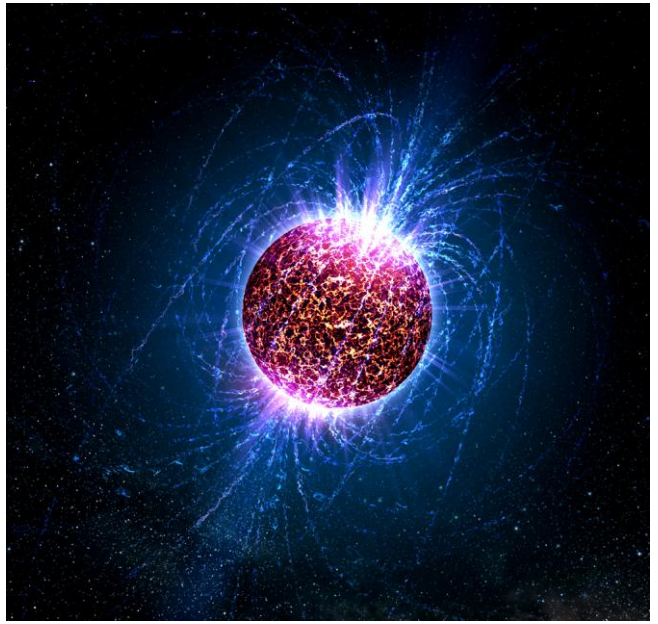
Anomalous X-ray pulsars (AXPs)

- Isolated NSs
- X-ray luminosity (usually) in excess of the rotational energy loss rate

$$L_X > \dot{E}_{\rm rot}$$





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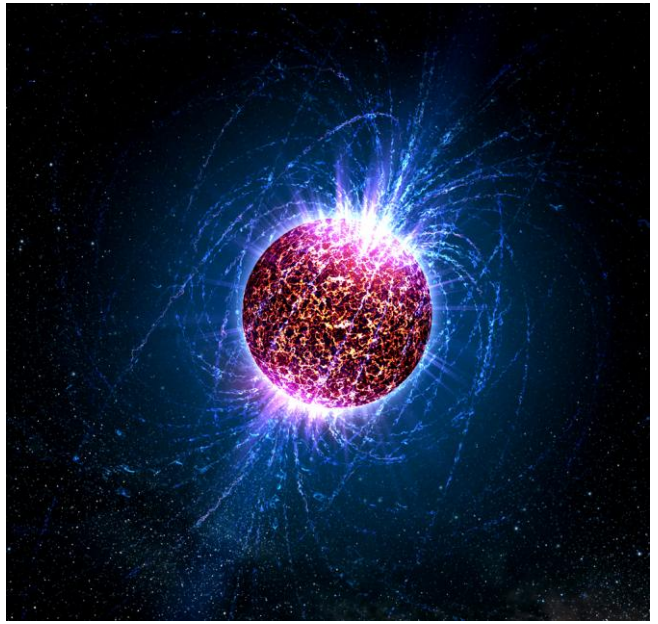
Anomalous X-ray pulsars (AXPs)

- Isolated NSs
- X-ray luminosity (usually) in excess of the rotational energy loss rate
- Large spin periods and spin-down rates

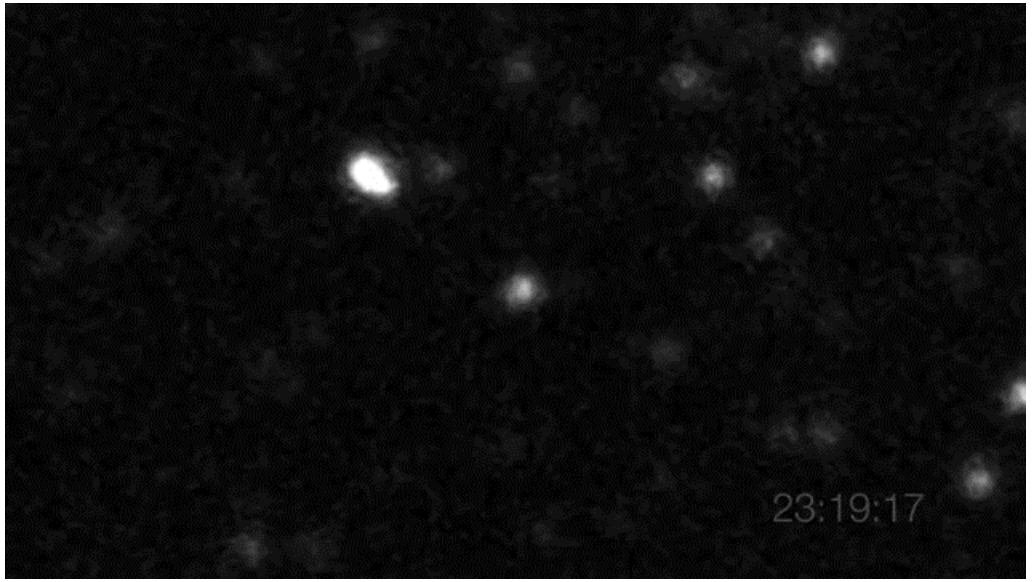
$$P \approx 2 - 12 \text{ s}$$
$$\dot{P} \approx 10^{-13} - 10^{-9} \text{ s/s} \quad \Rightarrow \quad B_{\text{sd}} \approx 10^{14} - 10^{15} \text{ G}$$



Ultra strong!

Soft-γ repeaters (SGRs)

- Sudden emission of a huge amount of X-ray energy (up to 10^{47} erg/s)
- Initially confused with GRBs (but then observed to repeat)
- Pulsations detected in the event afterglow ($\rightarrow$ NSs!)
- P and $\dot{P}$ compatible with those of AXPs (and so again $B_{\rm sd} \approx 10^{14-15}$ G)
- Still isolated objects



A.J. Castro-Tirado/IAC80/ESO

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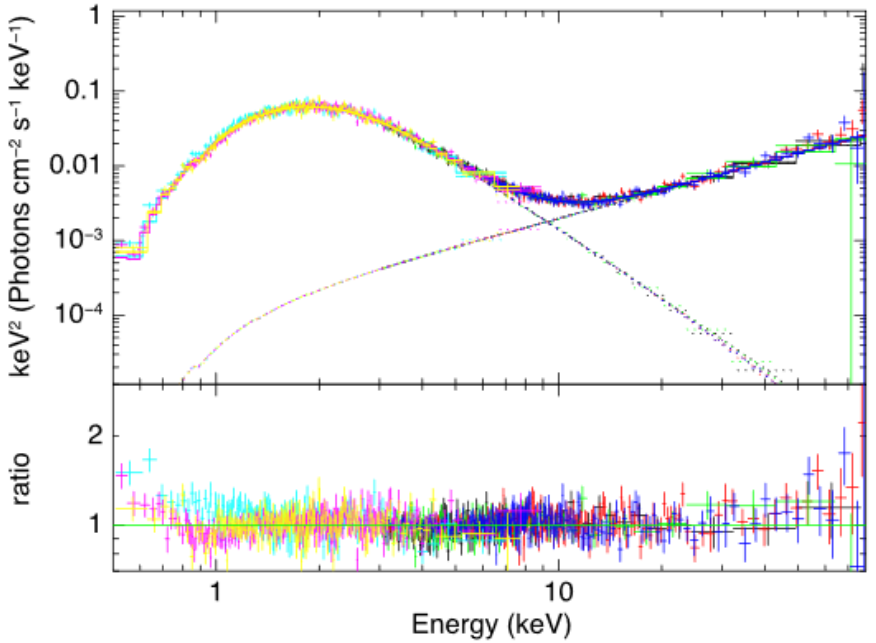
Magnetars – Persistent emission

- Properties of AXPs and SGRs are shared between the two classes
- Energy must be supplied by the ultra-strong magnetic field (MAGNEtic stARs)
- Persistent and transient sources
- Soft X-ray persistent spectra ($0.5 - 10$ keV) are usually fitted by a BB+PL decomposition (BB+BB for transients)
- Additional PL component at higher energies ($\gtrsim 20$ keV)



Tendulkar et al. (2015)

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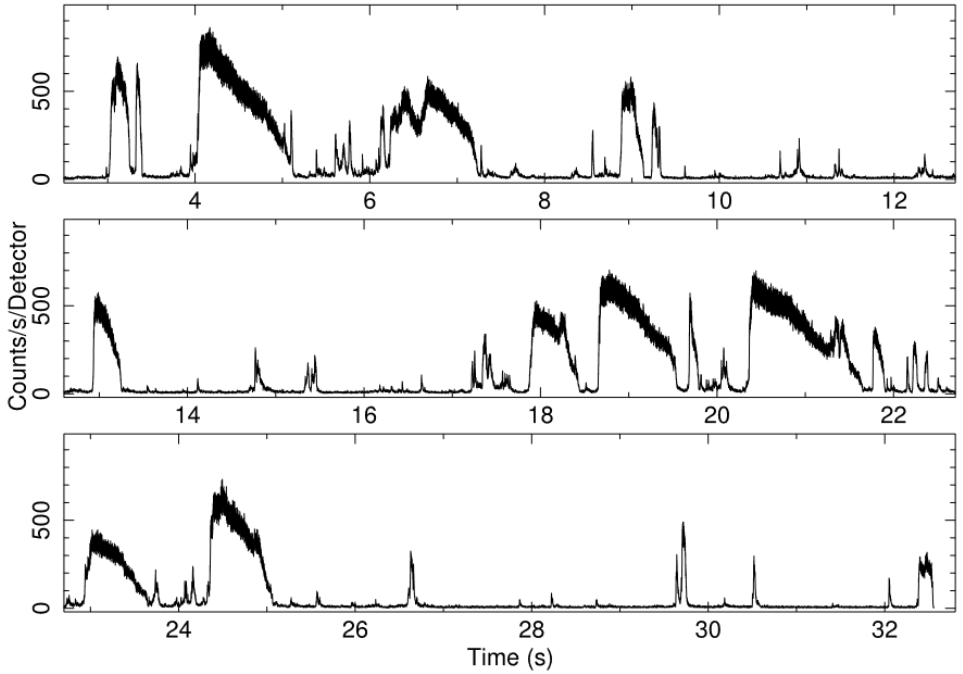
Magnetars – Bursting activity

- Short bursts
  - $\Delta t \approx 0.01 - 1$ s
  - $L_{\mathrm{X}} \approx 10^{36} - 10^{41}$ erg/s
- (Intermediate) flares
  - $\Delta t \approx 1 - 10$ s
  - $L_{\mathrm{X}} \approx 10^{41} - 10^{43}$ erg/s
- Giant flares
  - $\Delta t \approx 10^{2}$ s
  - $L_{\mathrm{X}} \approx 10^{44} - 10^{47}$ erg/s



Israel et al. (2008)

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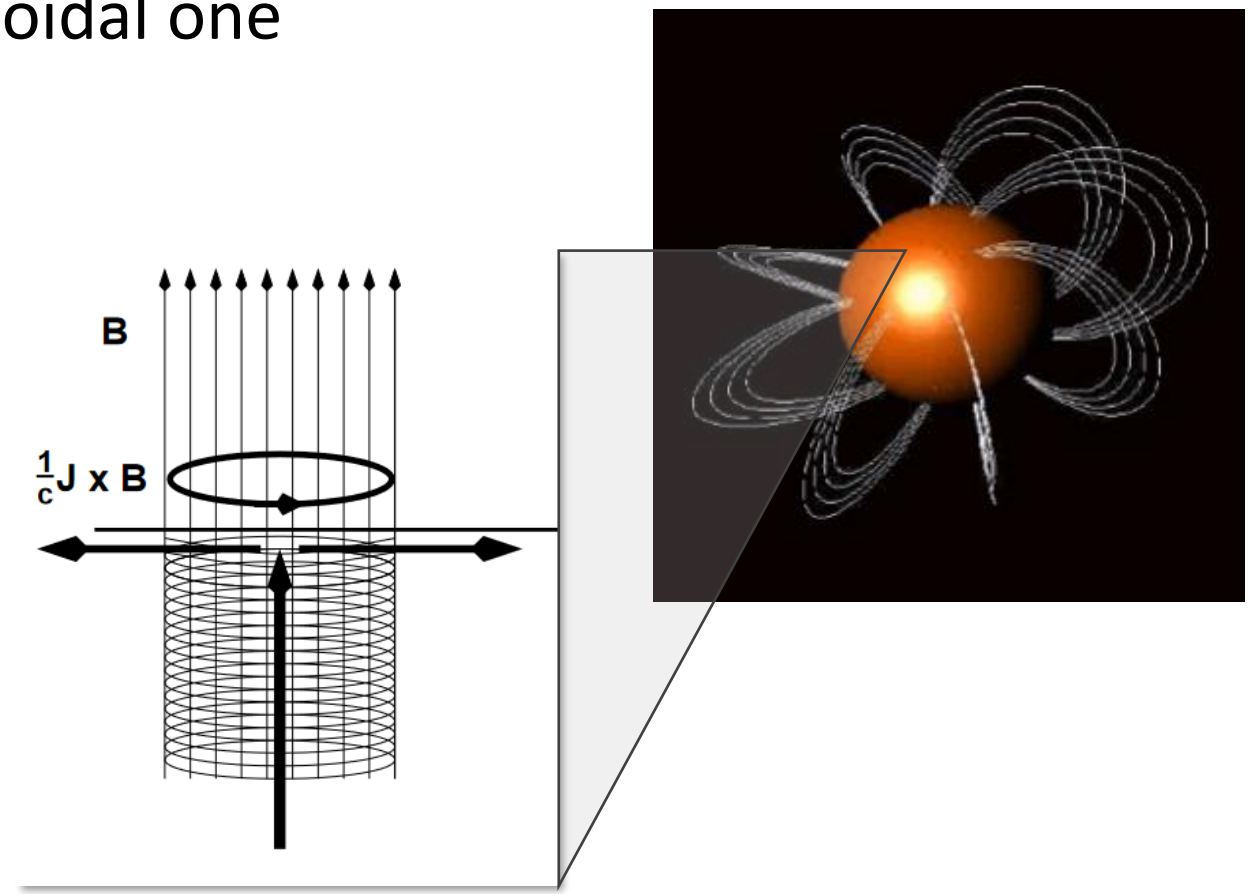
Twisted-magnetosphere scenario

- The strong internal field (up to 10^{16} G) must contain a toroidal component at least of the same order of the poloidal one



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Twisted-magnetosphere scenario

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

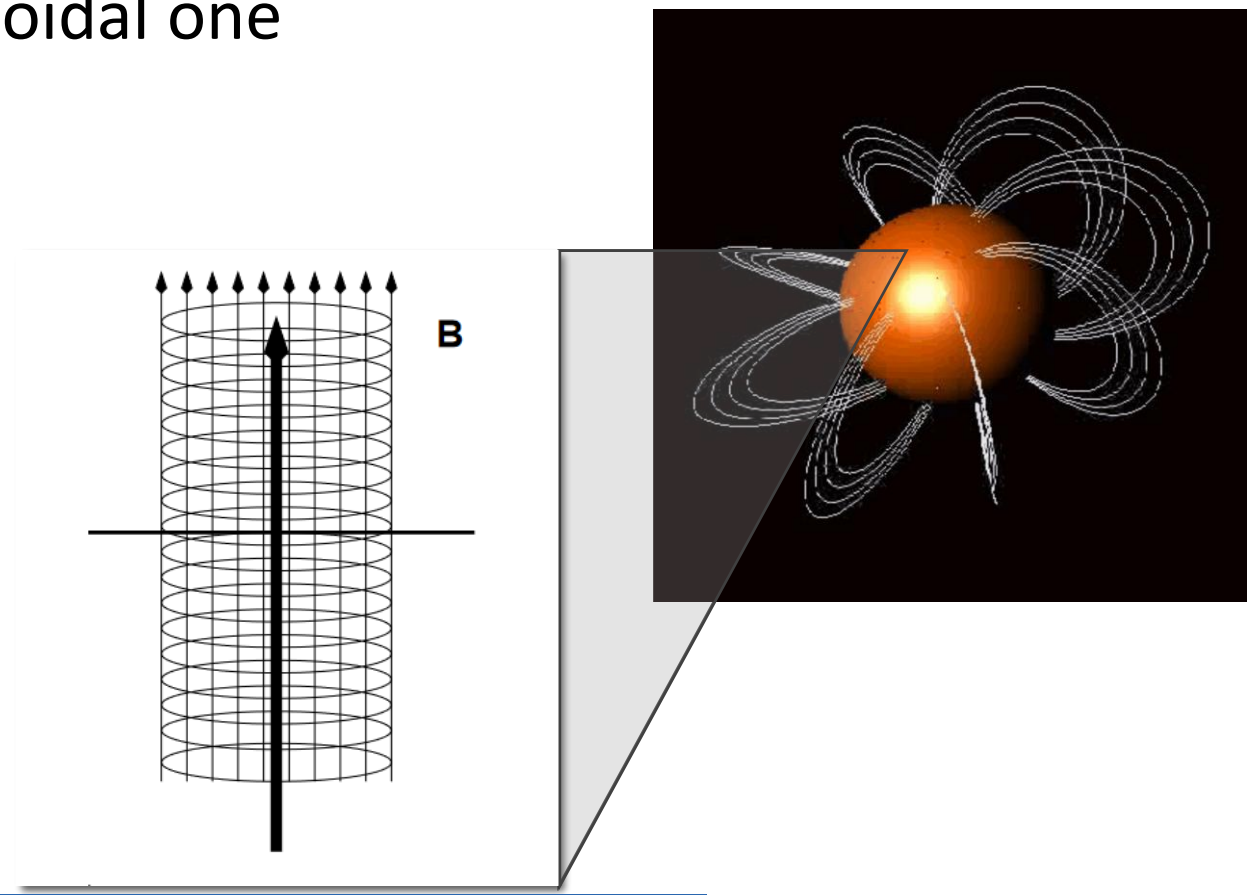
$$\boldsymbol{B} = [B_r, B_\theta . B_\phi] = \frac{B_\mathrm{p}}{2}\left(\frac{R_\mathrm{NS}}{r}\right)^3 [2\cos\theta\,, \sin\theta\,, 0]$$

dipole

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

twisted dipole

$$0 < p \leq 1$$



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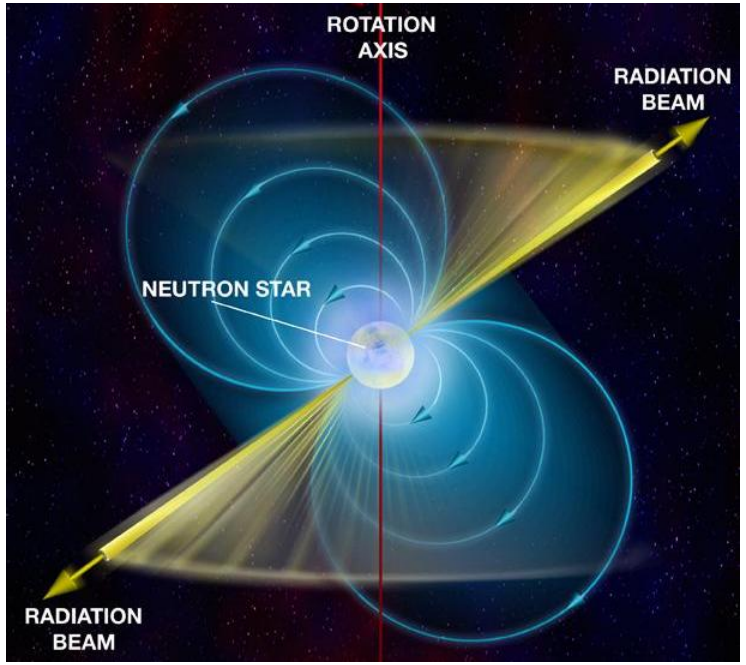
Twisted-magnetosphere scenario

$$\nabla \times \boldsymbol{B}_{\mathrm{dip}} = 4\pi \boldsymbol{j}/c$$
$$\| \qquad\qquad \Downarrow$$
$$0 \qquad \text{no currents}$$



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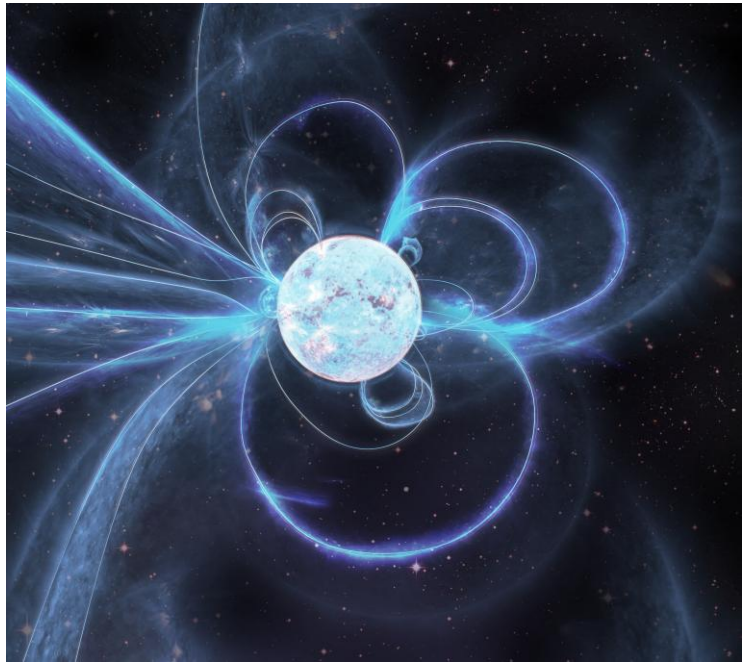
Twisted-magnetosphere scenario

$$\nabla \times \boldsymbol{B}_{\rm dip} = 4\pi \boldsymbol{j}/c \qquad \nabla \times \boldsymbol{B}_{\rm twist} = 4\pi \boldsymbol{j}/c$$

$$\| \qquad \Downarrow \qquad \nparallel \qquad \Downarrow$$

$$0 \qquad \text{no currents} \qquad 0 \qquad \text{currents}$$



- Magnetosphere is populated by charged particles:

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

not enough for photons to interact efficiently

Twisted-magnetosphere scenario

$$\nabla \times \boldsymbol{B}_{\rm dip} = 4\pi \boldsymbol{j}/c \qquad \nabla \times \boldsymbol{B}_{\rm twist} = 4\pi \boldsymbol{j}/c$$

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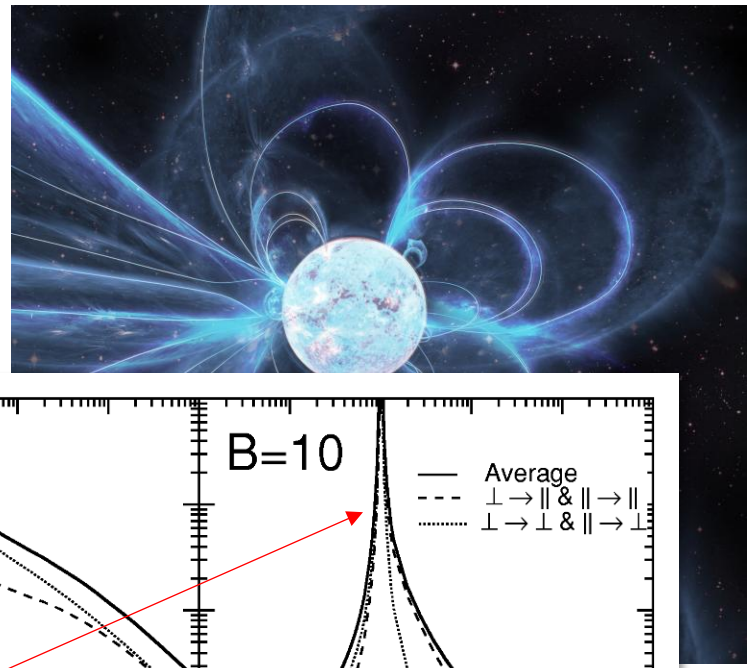

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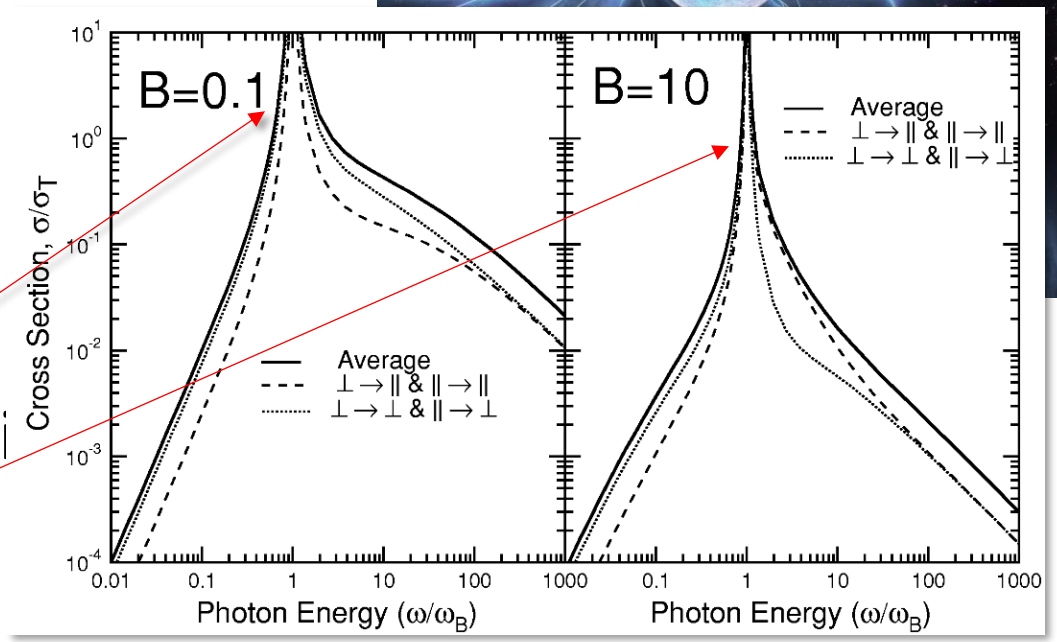
$$n_e \sim \frac{B}{r\beta}\left(\frac{B_\phi}{B_\theta}\right)$$

not enough for photons to interact effici

Scattering cross sections peak at the cyclotron energy



Gonthier et al. (2000)

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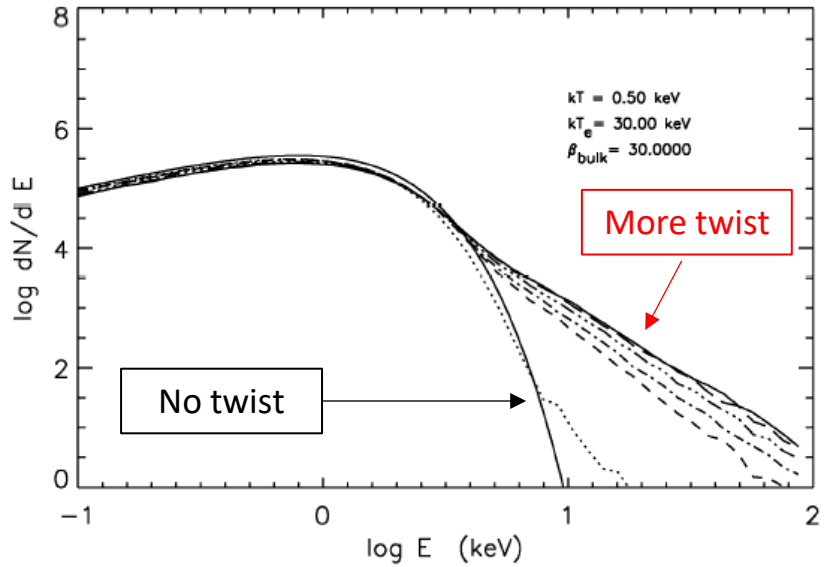
Magnetar model achievements (till IXPE)

- RCS of thermal photons onto magnetospheric particles generates PL tails at soft X-ray energies



Nobili et al. (2008)

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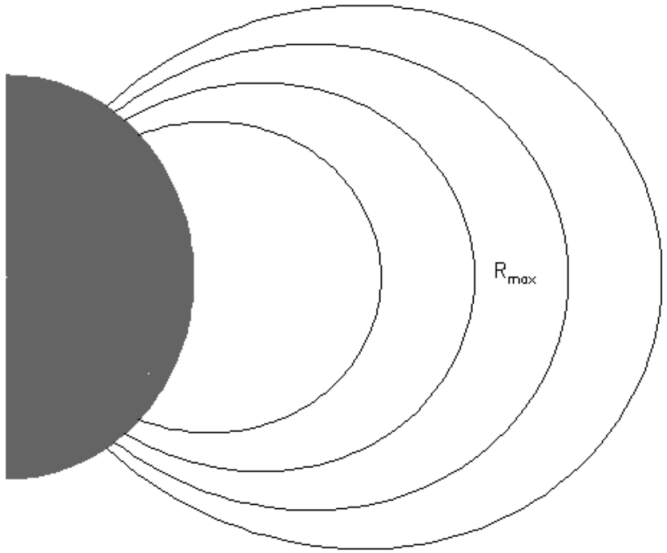
Magnetar model achievements (till IXPE)

- RCS of thermal photons onto magnetospheric particles generates PL tails at soft X-ray energies
- Internal magnetic stresses on the star crust induce injection of $e^- e^+$ magnetically confined fireball (at the base of burst emission)
- Magnetic scattering models can explain the observed spectral properties



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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)

- Magnetar phenomenology very different from other NSs
  - strongly-magnetized ($\approx 10^9$ G) white dwarfs?
  - disrupting events for SGRs?

May polarimetry provide new constraints?

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Polarization in strongly magnetized environments

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

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

magnetic permeability tensor (inverse)

dielectric tensor

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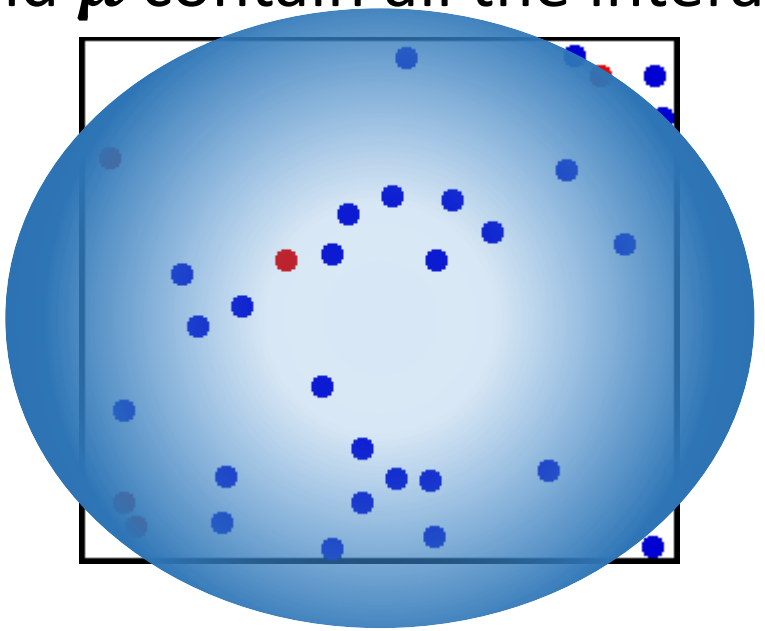
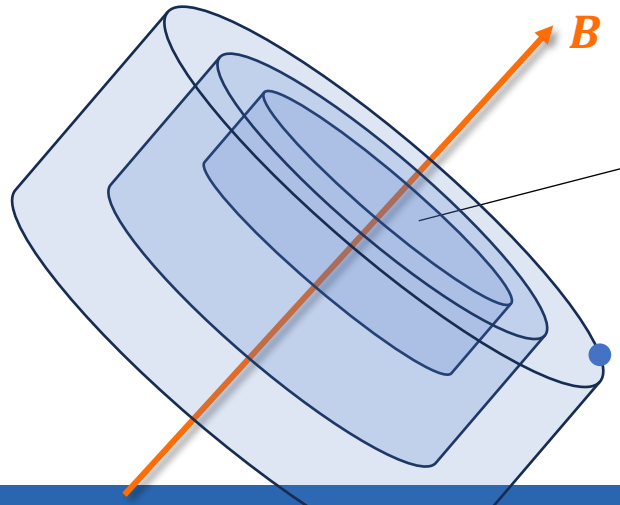
- $\boldsymbol{\epsilon}$ and $\bar{\boldsymbol{\mu}}$ contain all the interaction terms



magnetized plasma

In strong $\boldsymbol{B}$ fields the charge motion is quantized



1st Landau level energy

$$\hbar\omega_{\mathrm{B}} = \frac{\hbar e B_{\mathrm{Q}}}{m_{\mathrm{e}} c} = m_e c^2$$

$$\Downarrow$$

$$B_{\mathrm{Q}} = \frac{m_e^2 c^3}{\hbar e} = 4.414 \times 10^{13}\ \mathrm{G}$$

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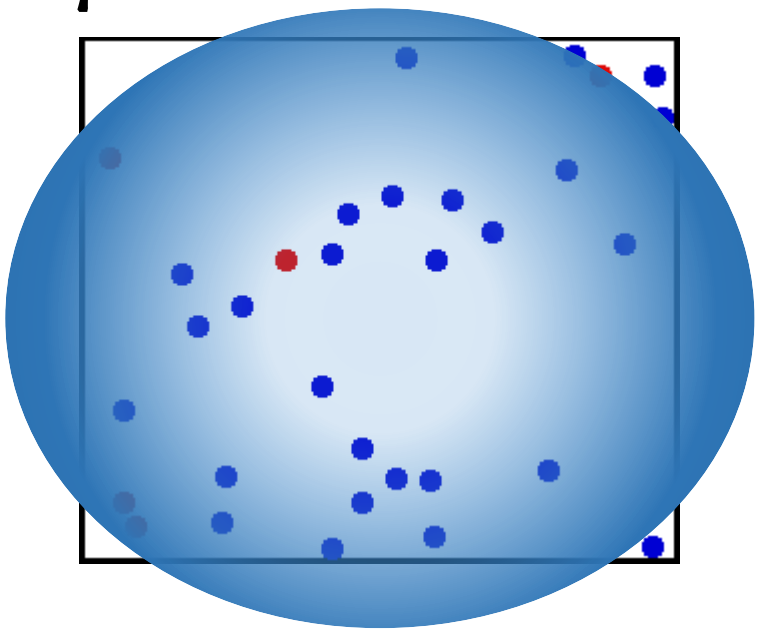
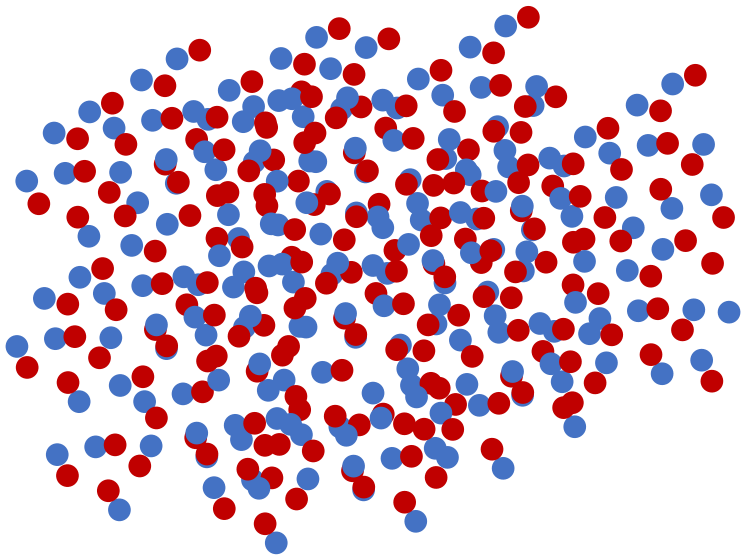


magnetized plasma



vacuum birefringence

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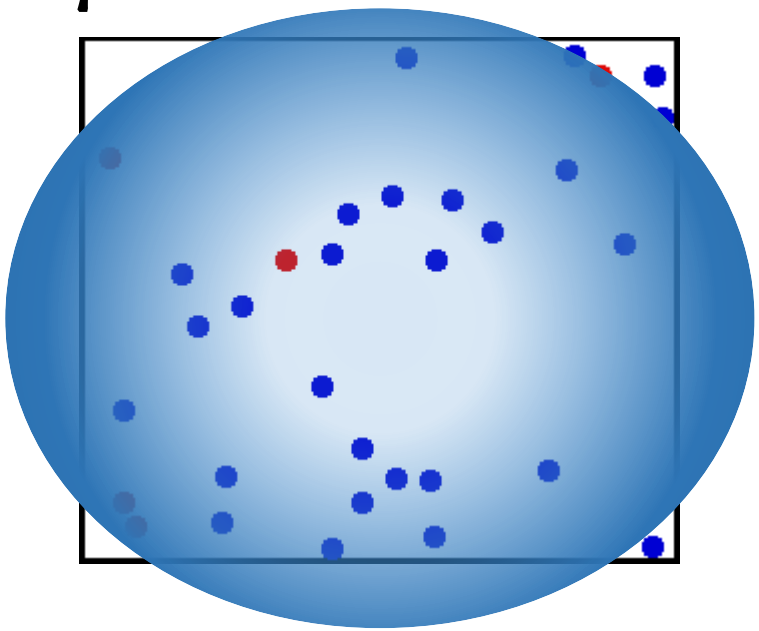
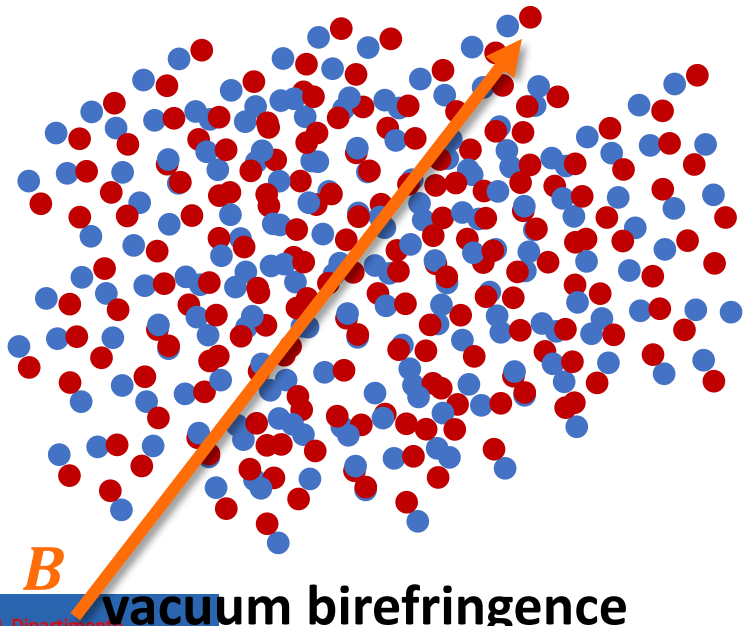


magnetized plasma



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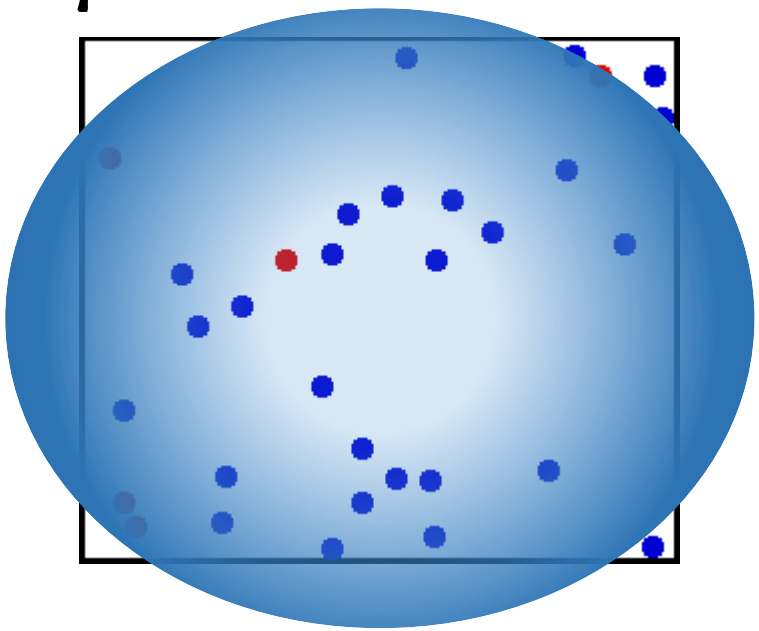

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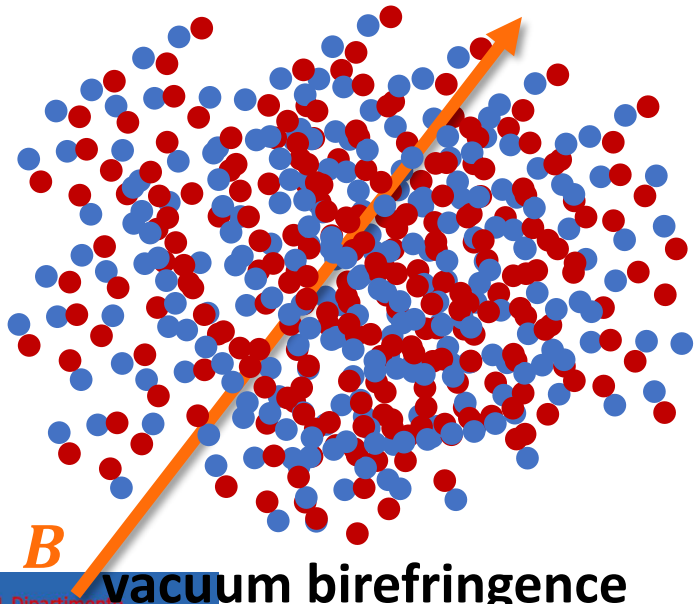

vacuum birefringence

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Polarization in strongly magnetized environments

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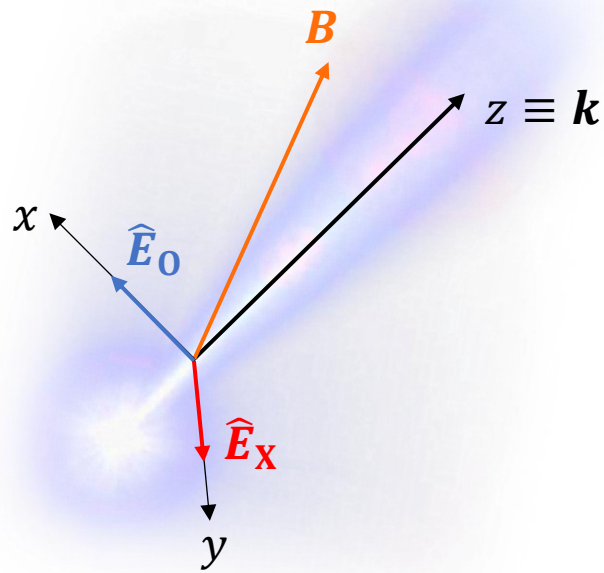
$$\boldsymbol{\nabla} \times (\bar{\boldsymbol{\mu}} \cdot \boldsymbol{\nabla} \times \boldsymbol{E}) = \frac{\omega^2}{c^2} \boldsymbol{\epsilon} \cdot \boldsymbol{E}$$

- $\boldsymbol{\epsilon}$ and $\bar{\boldsymbol{\mu}}$ contain all the interaction terms
- Either with plasma or vacuum dominating

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

Ordinary mode **Extraordinary mode**



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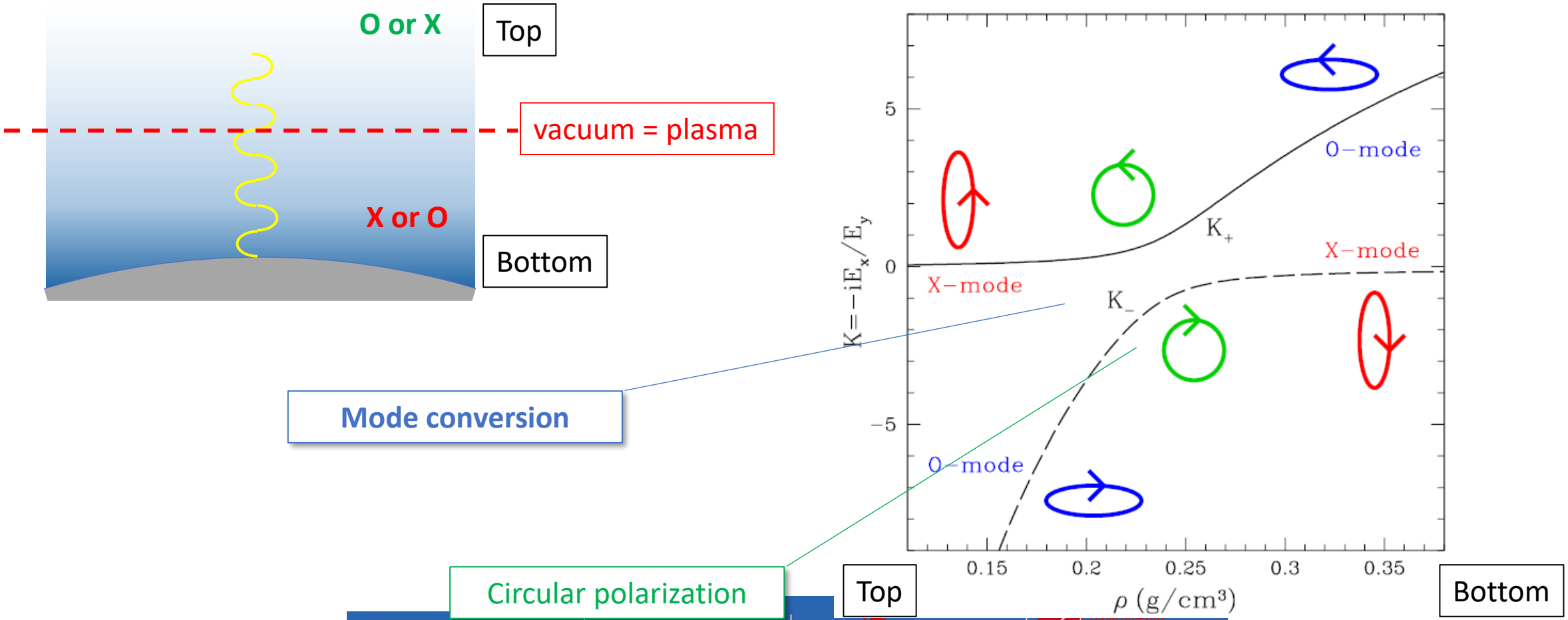
Vacuum resonance

- Plasma and vacuum contributions balance at a given density



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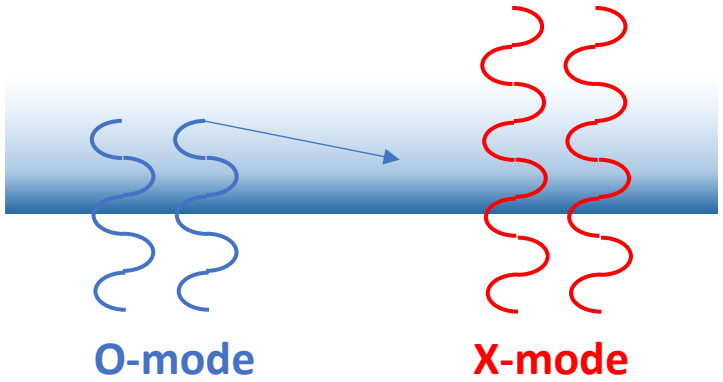
Dichroism in strongly-magnetized plasma

- In strong fields ($B \gtrsim B_{\rm Q}$) plasma is (generally) transparent for X-photons

$$\sigma_{\rm OO} \sim \sigma_{\rm unmag} \qquad \sigma_{\rm XO} \sim \left(\frac{B}{B_{\rm Q}}\right)^{-2} \sigma_{\rm OO}$$

$$\sigma_{\rm OX} \sim \left(\frac{B}{B_{\rm Q}}\right)^{-2} \sigma_{\rm OO} \qquad \sigma_{\rm XX} \sim \left(\frac{B}{B_{\rm Q}}\right)^{-2} \sigma_{\rm OO}$$



High polarization (in the X-mode)

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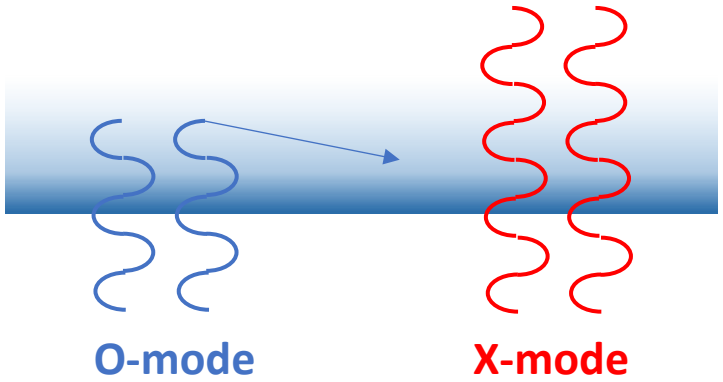

High polarization (in the X-mode)

- At the cyclotron resonance:

$$\sigma_{\rm OO} = \frac{1}{3}\sigma_{\rm OX} \qquad \sigma_{\rm XX} = 3\sigma_{\rm XO}$$

- X-mode photons are still preferred, but emerging radiation is only 33% polarized

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Propagation in the pure magnetized vacuum

- Solving the wave equation accounting for vacuum effects only yields

$$\frac{2}{k_0\delta}\frac{dE_x}{dz} = i\left[ME_x + PE_y\right] \qquad \frac{2}{k_0\delta}\frac{dE_y}{dz} = i\left[PE_x + NE_y\right]$$

$$\delta \sim \left(B/B_{\mathrm{Q}}\right)^2$$

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Propagation in the pure magnetized vacuum

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

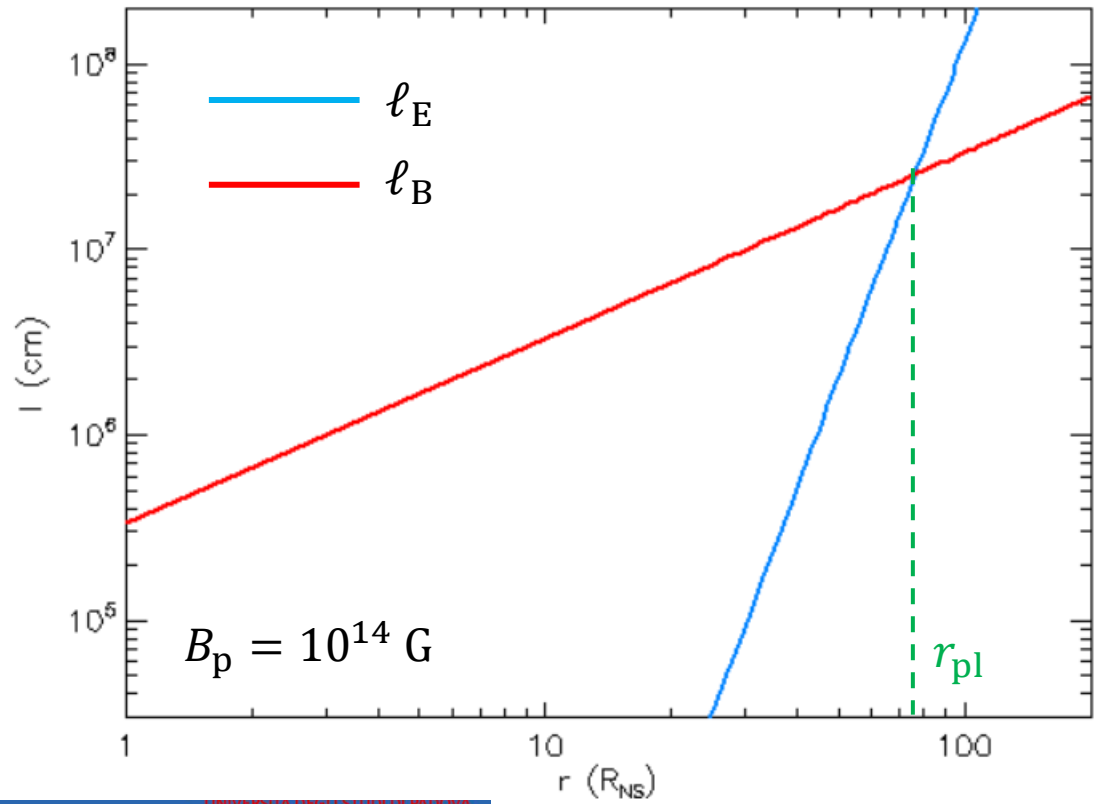
$$\frac{2}{k_0\delta}\frac{dE_x}{dz} = i\left[ME_x + PE_y\right] \qquad \frac{2}{k_0\delta}\frac{dE_y}{dz} = i\left[PE_x + NE_y\right]$$

E-field evolution length:

$$\ell_{\rm E} = \frac{2}{k_0\delta} \approx 130\left(\frac{B}{10^{11}\ {\rm G}}\right)^{-2}\left(\frac{\hbar\omega}{1\ {\rm keV}}\right)^{-1}\ {\rm cm}$$

(Dipolar) B-field evolution length:

$$\ell_{\rm B} = \frac{B}{|\boldsymbol{k}\cdot\boldsymbol{\nabla}B|} \approx \frac{r}{3}$$



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Propagation in the pure magnetized vacuum

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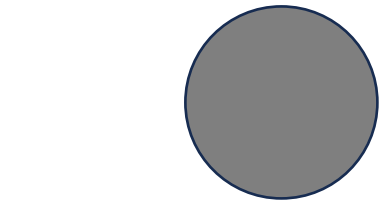
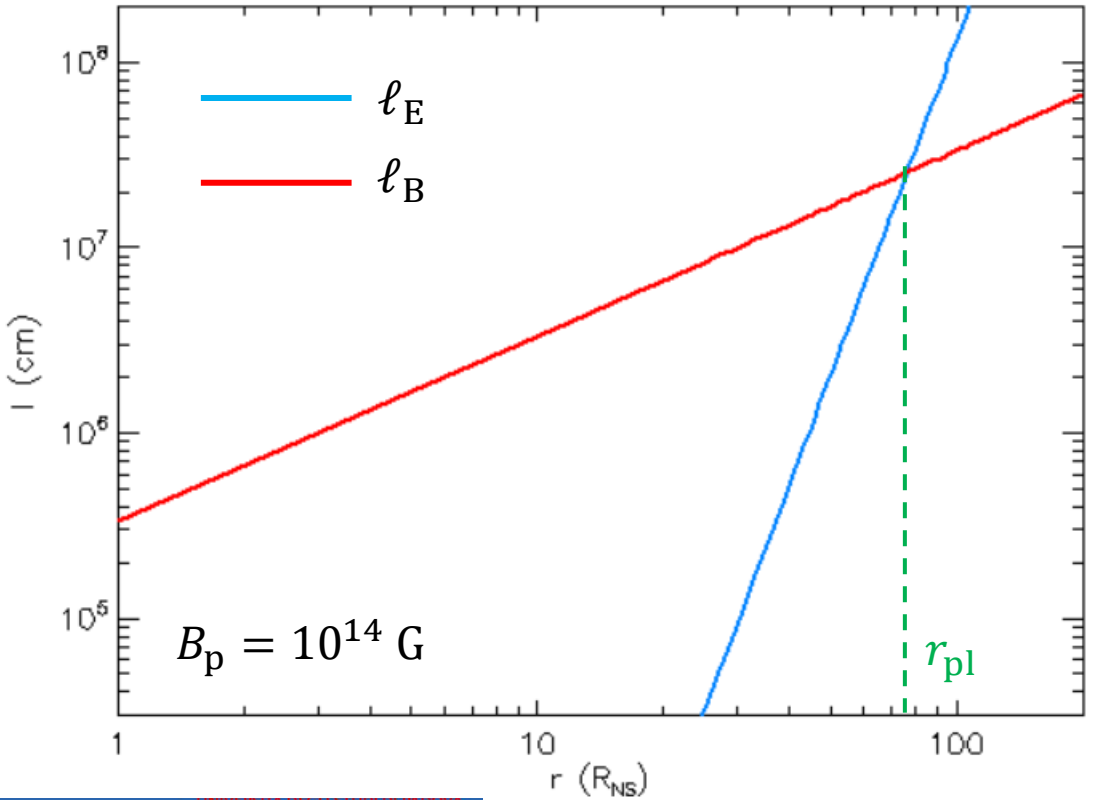
$$\frac{2}{k_0\delta}\frac{dE_x}{dz} = i\left[ME_x + PE_y\right] \qquad \frac{2}{k_0\delta}\frac{dE_y}{dz} = i\left[PE_x + NE_y\right]$$

$\ell_{\mathrm{E}} \gg \ell_{\mathrm{B}}$: $\boldsymbol{E}$ direction is frozen

r_{pl} $(\ell_{\mathrm{E}} = \ell_{\mathrm{B}})$

$\ell_{\mathrm{E}} \ll \ell_{\mathrm{B}}$: $\boldsymbol{E}$ adapts to $\boldsymbol{B}$





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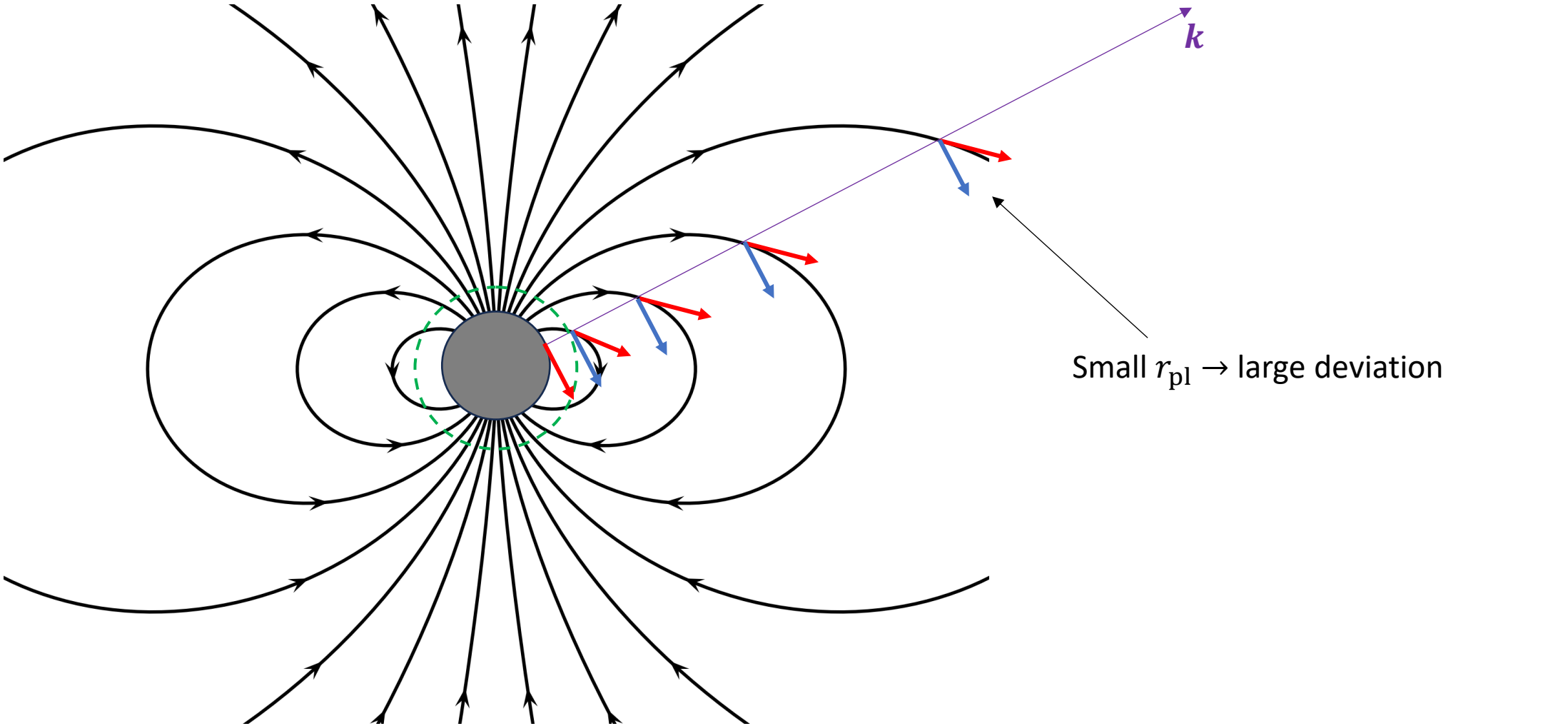

$\ell_{\rm E}$ <

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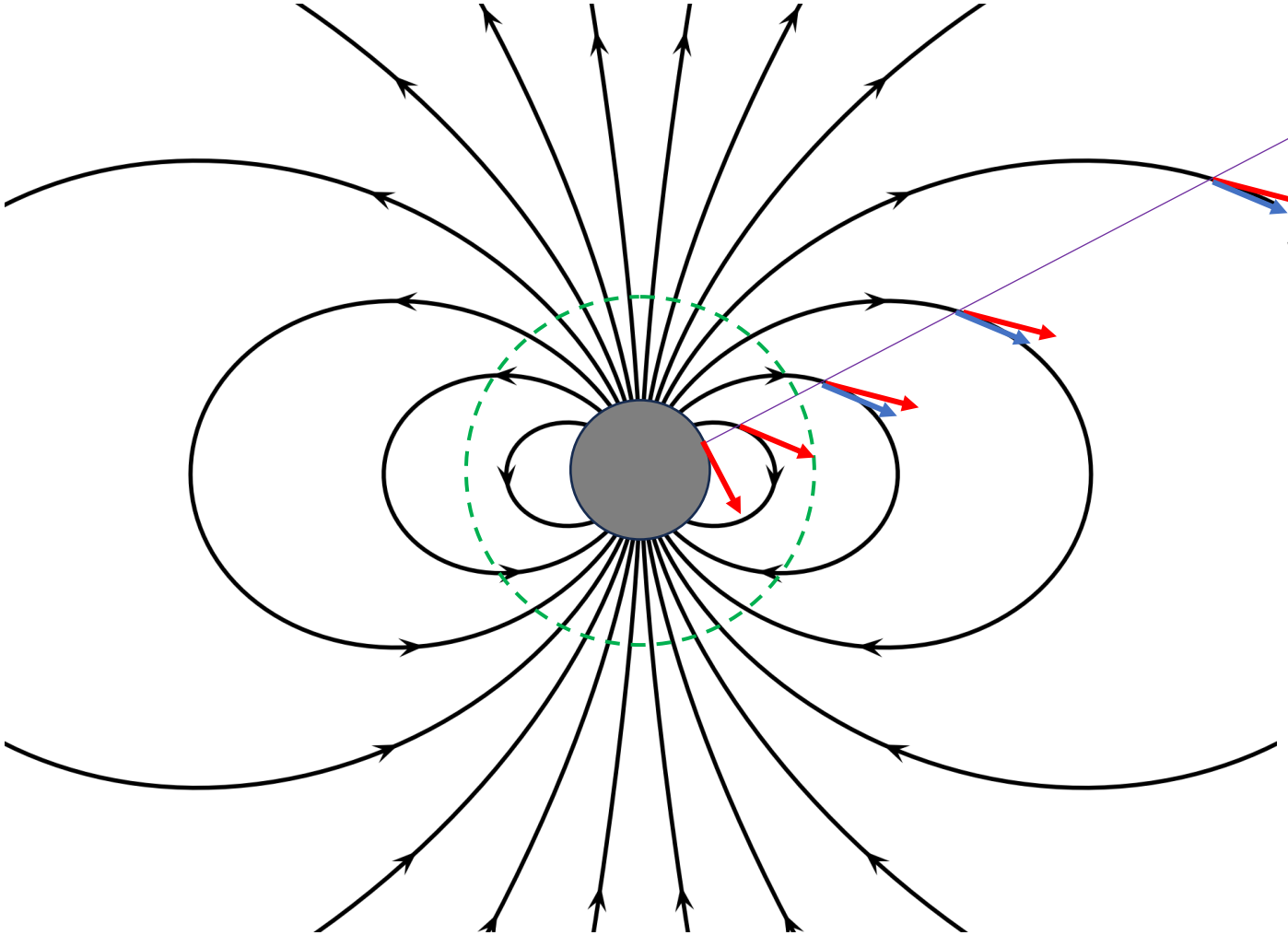

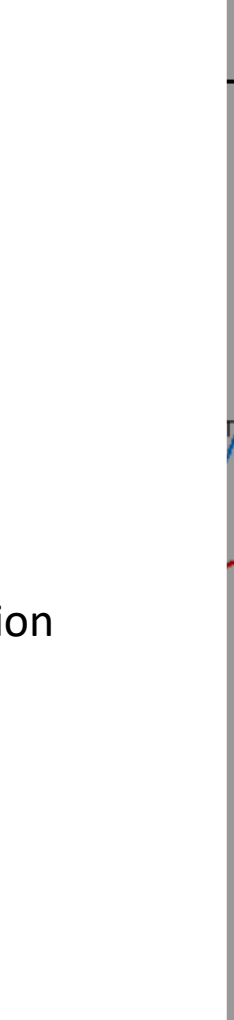

k

Large $r_{\rm pl} \rightarrow$ small deviation

$\ell_{\rm E} <$

$r_{\rm pl}$

1 10 100

r (R_{NS})

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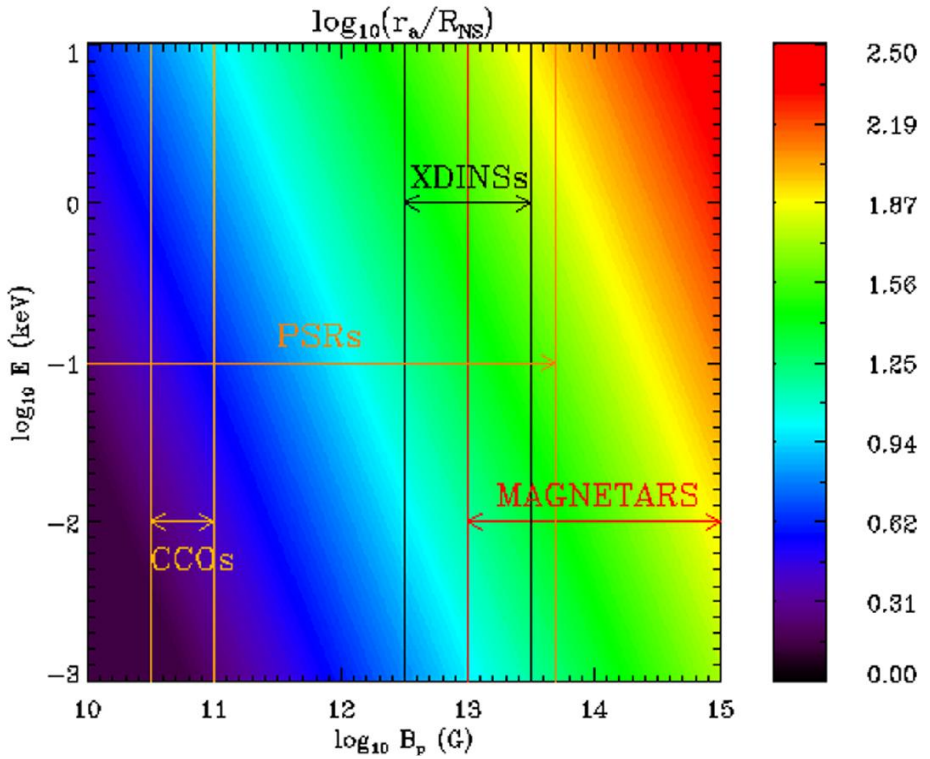

Taverna et al. (2015)

$$r_{\rm pl} \approx 5 \left(\frac{B_{\rm pol}}{10^{11}\ {\rm G}}\right)^{2/5} \left(\frac{\hbar\omega}{1\ {\rm keV}}\right)^{1/5} \left(\frac{R_{\rm NS}}{10\ {\rm km}}\right)^{1/5} R_{\rm NS}$$

Magnetars (with the strongest $\boldsymbol{B}$) have the largest $r_{\rm pl}$

⇓

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

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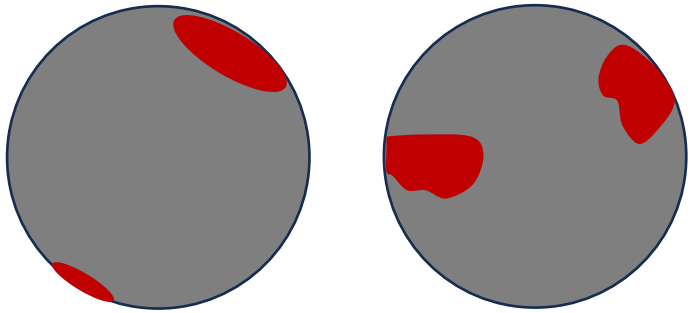
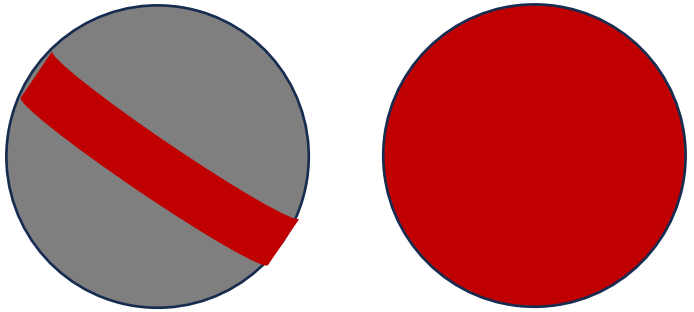
Test of vacuum birefringence depends as well on the size of the emitting region





Small (polar) emitting region ⇒
Small depolarization
(van Adelsberg & Perna 09)

Large emitting regions ⇒
Large depolarization
(Taverna+ 20)

Test of vacuum birefringence: high polarization from an extended region!

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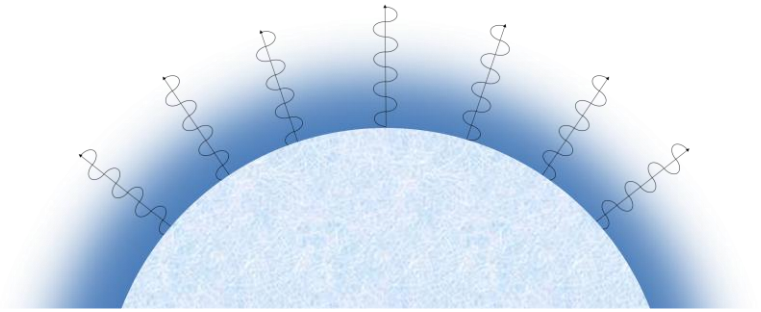
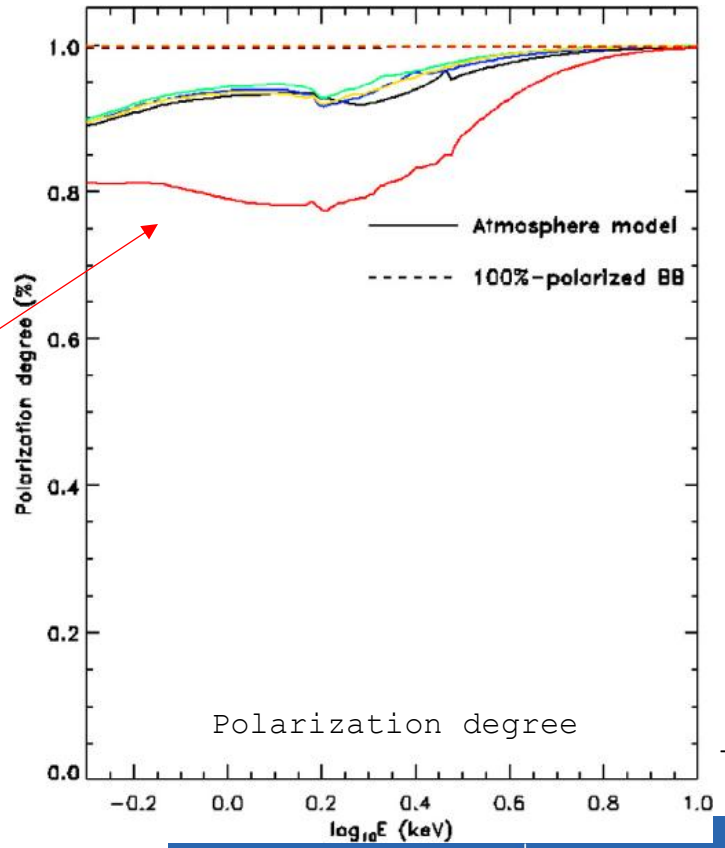
Surface emission models

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



PD ≳ 80%



Taverna et al. (2020)

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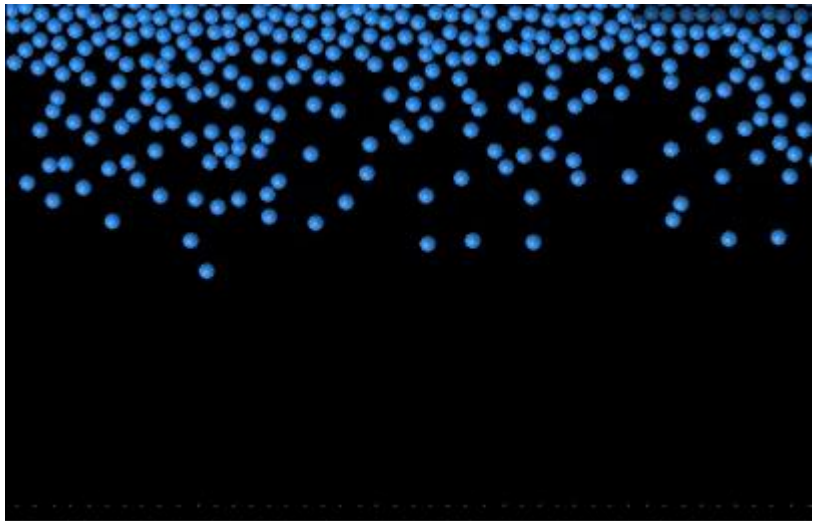
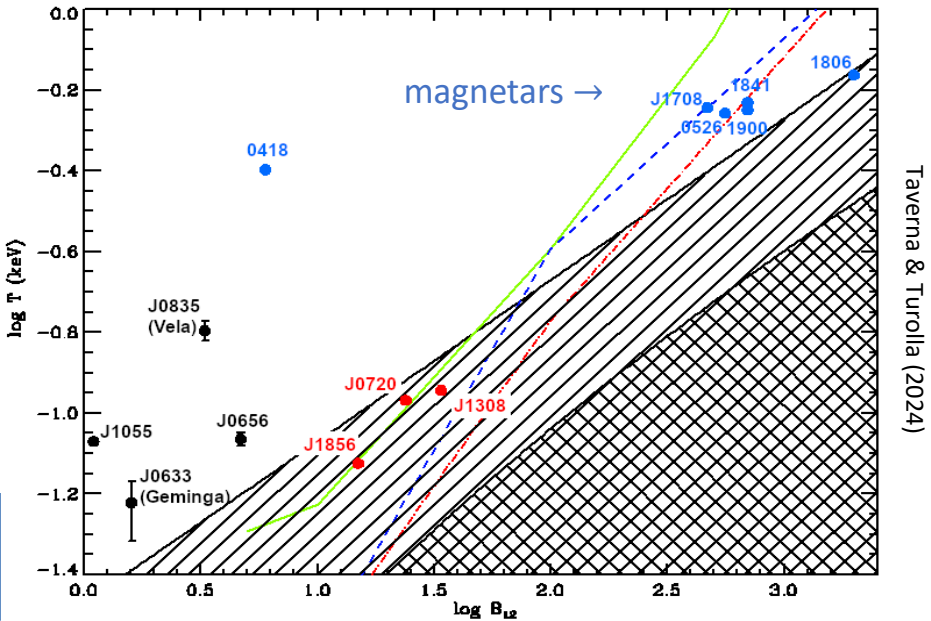
Surface emission models

- 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





Taverna & Turolla (2024)

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Surface emission models

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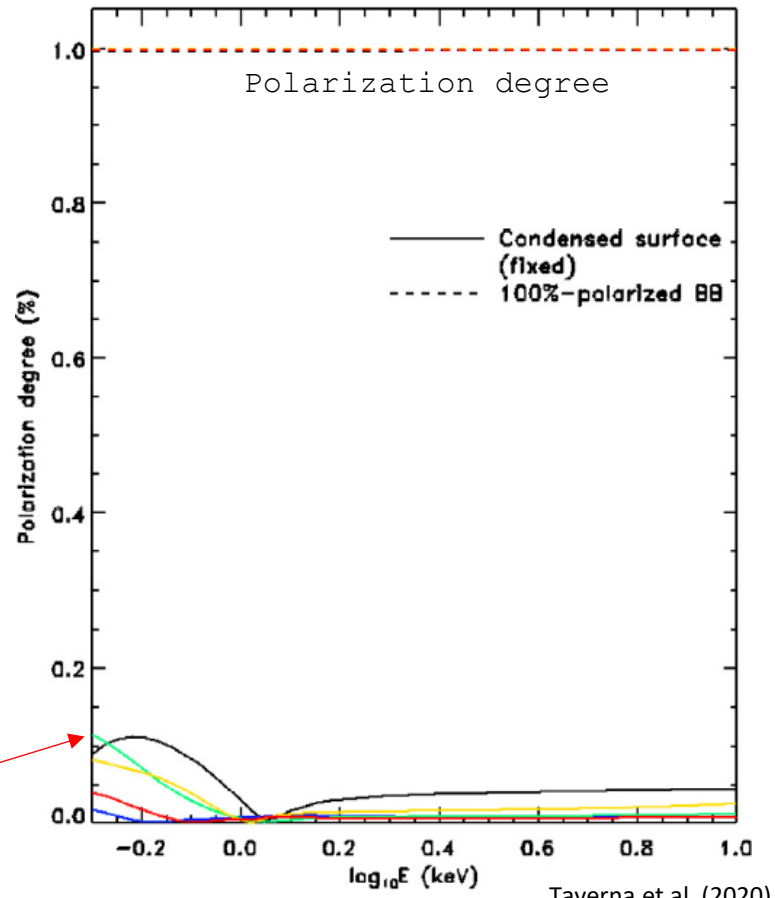
- Very strong B-fields elongate atoms along the field direction → molecular chains are formed for sufficiently low T
- The atmosphere settles onto the surface and the (condensed) crust is left exposed
- Much lower PD (both O- and X-)



$PD \lesssim 20\%$

Taverna et al. (2020)

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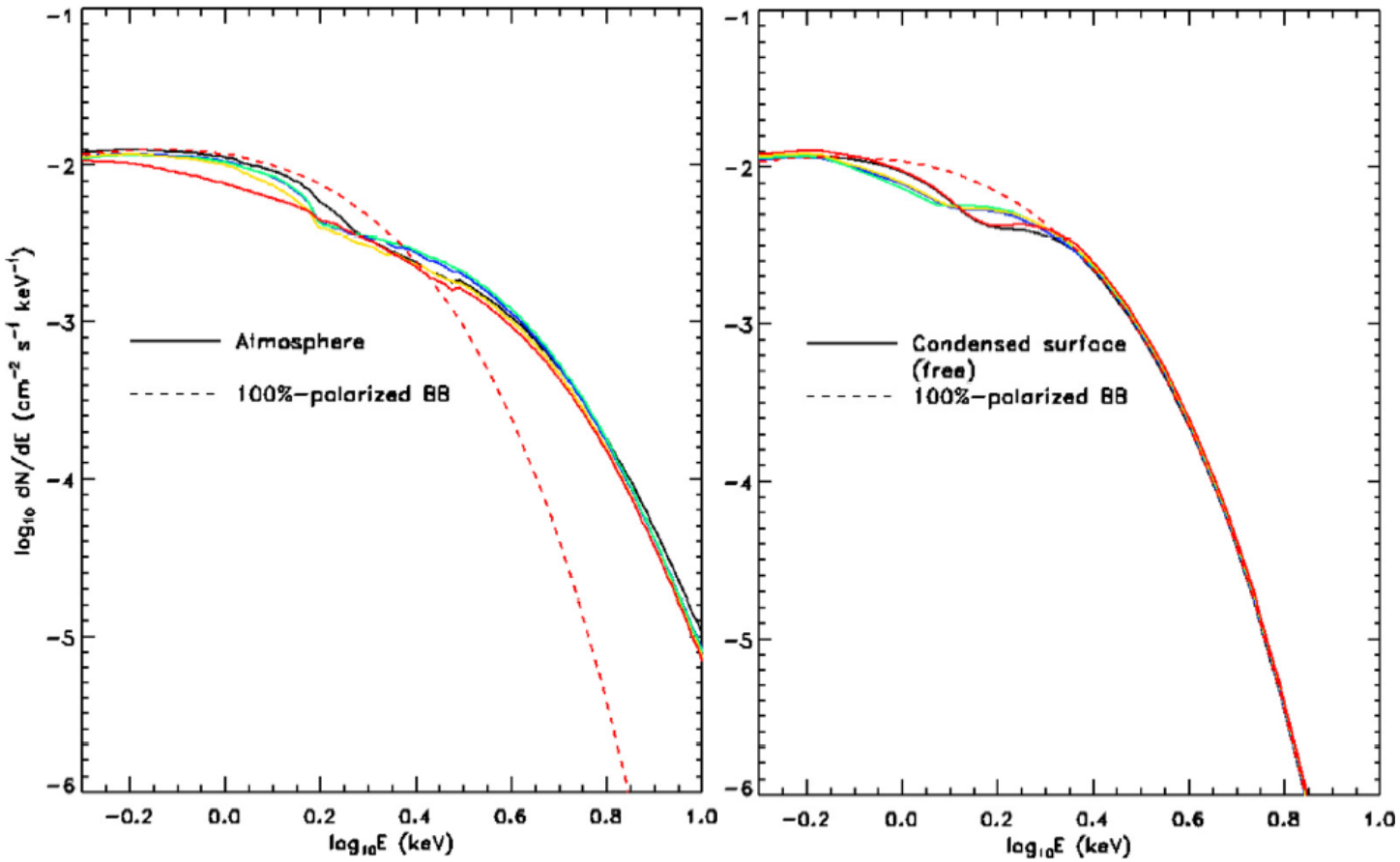


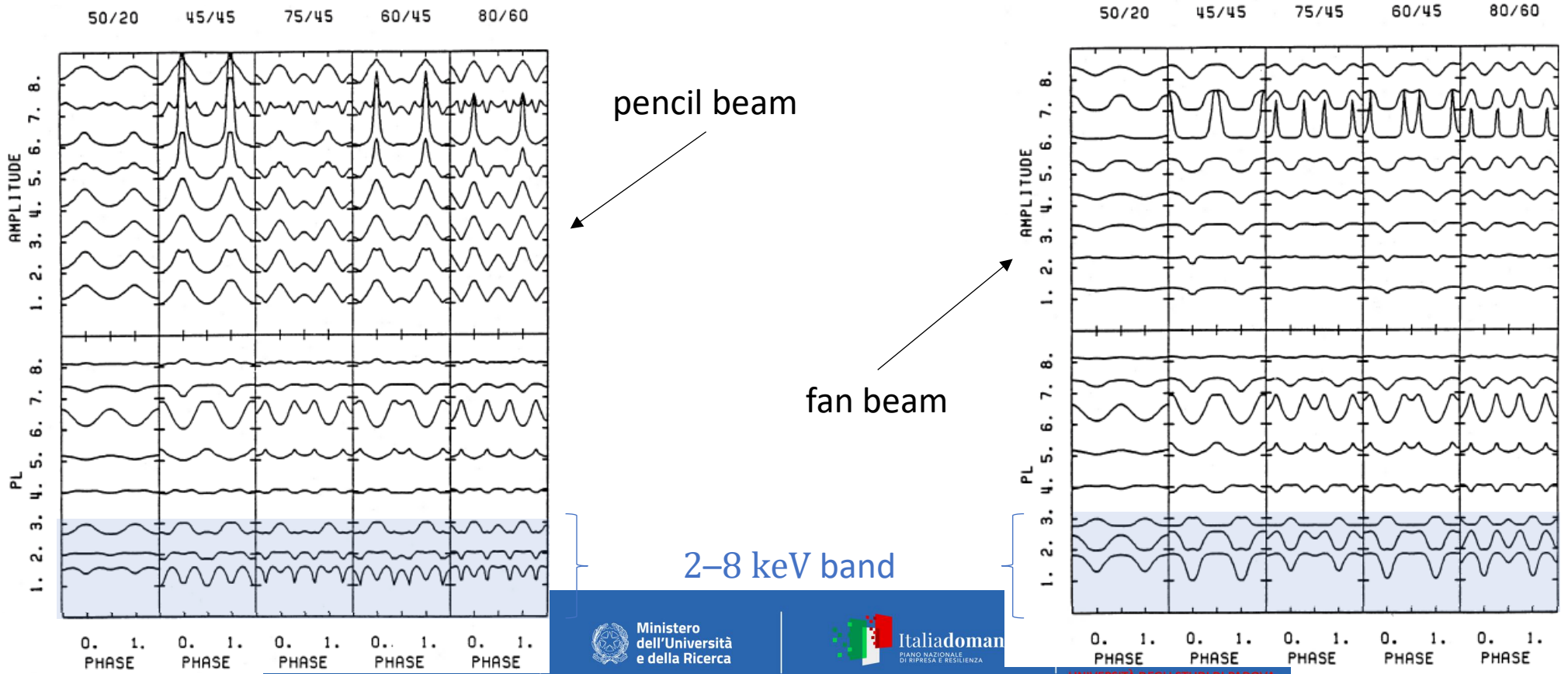
Spectra for atmosphere and condensed-surface model are similar (BB-like)

Polarization may help in disentangling the surface emission model

Taverna et al. (2020)

Theoretical expectations (XRPs)

- Model for X-ray polarization in accreting X-ray pulsars (Meszaros et al. 1988)
  - radiation reprocessed by a plasma over the hot-spots (atmosphere or column)
  - Bremsstrahlung and Comptonization (in high B-fields)



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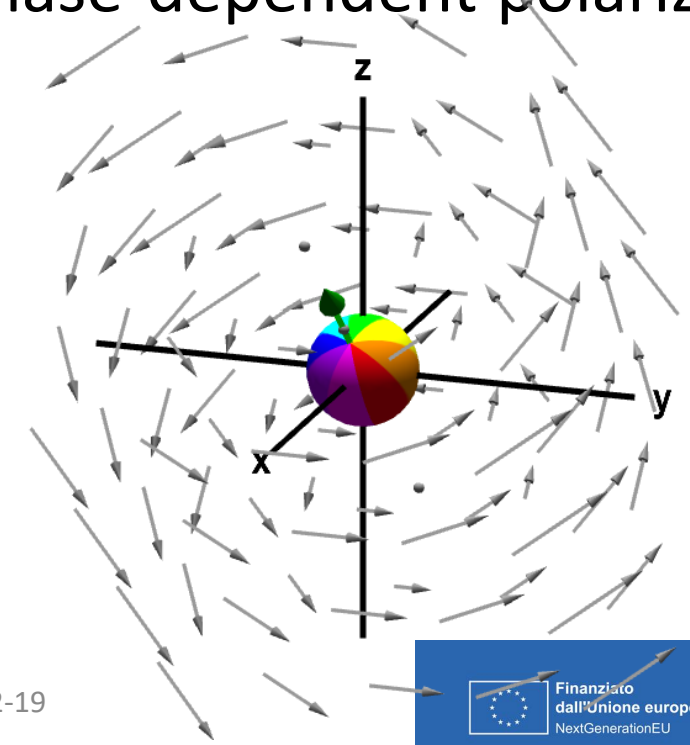
- Phase-dependent polarization angle → Rotating Vector Model (RVM)



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

  - dipolar magnetic field topology
  - small emitting regions (hot-spots)

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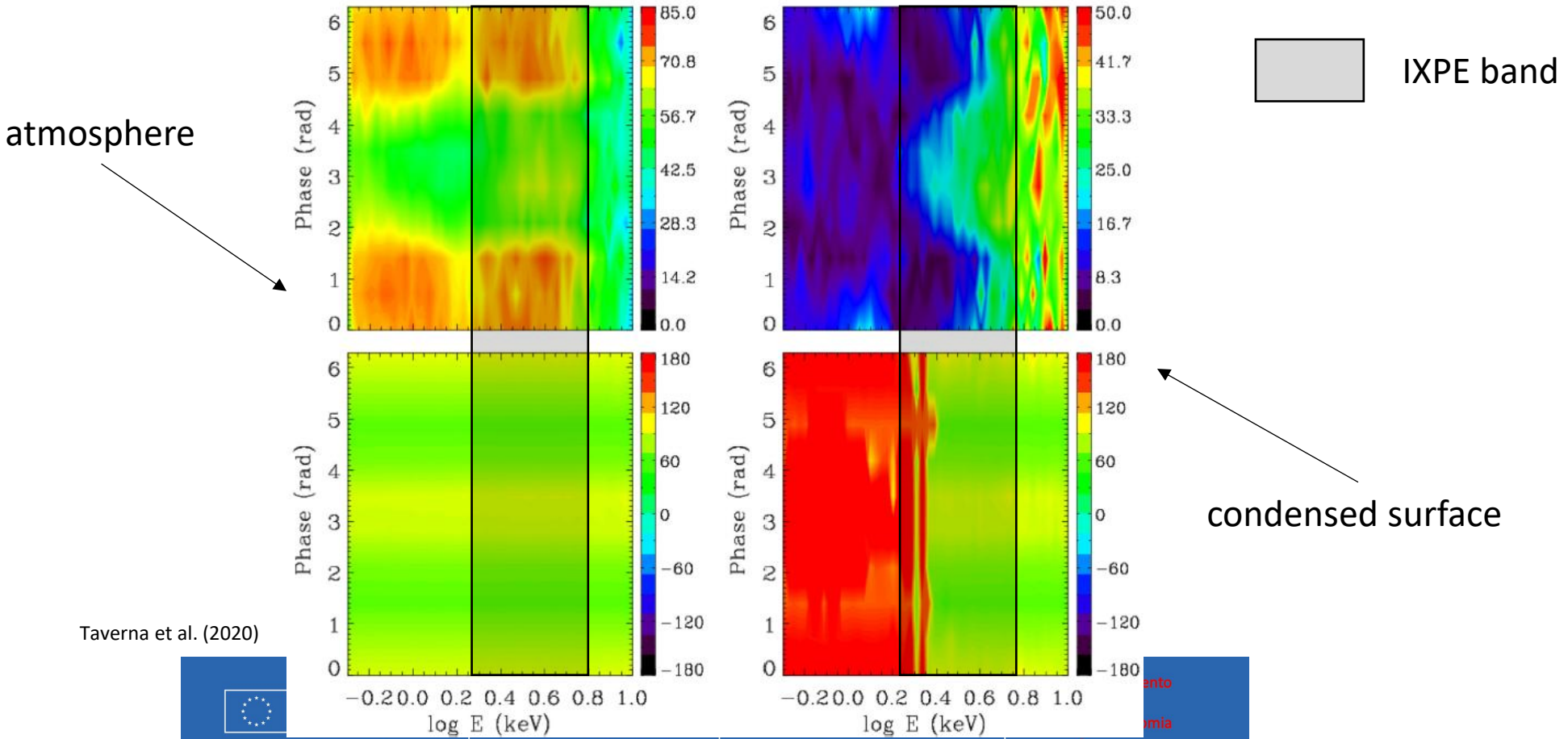
Theoretical expectations (magnetars)

- Emission coming from the whole star surface (covered by an atmosphere or with condensed surface exposed)



Taverna et al. (2020)

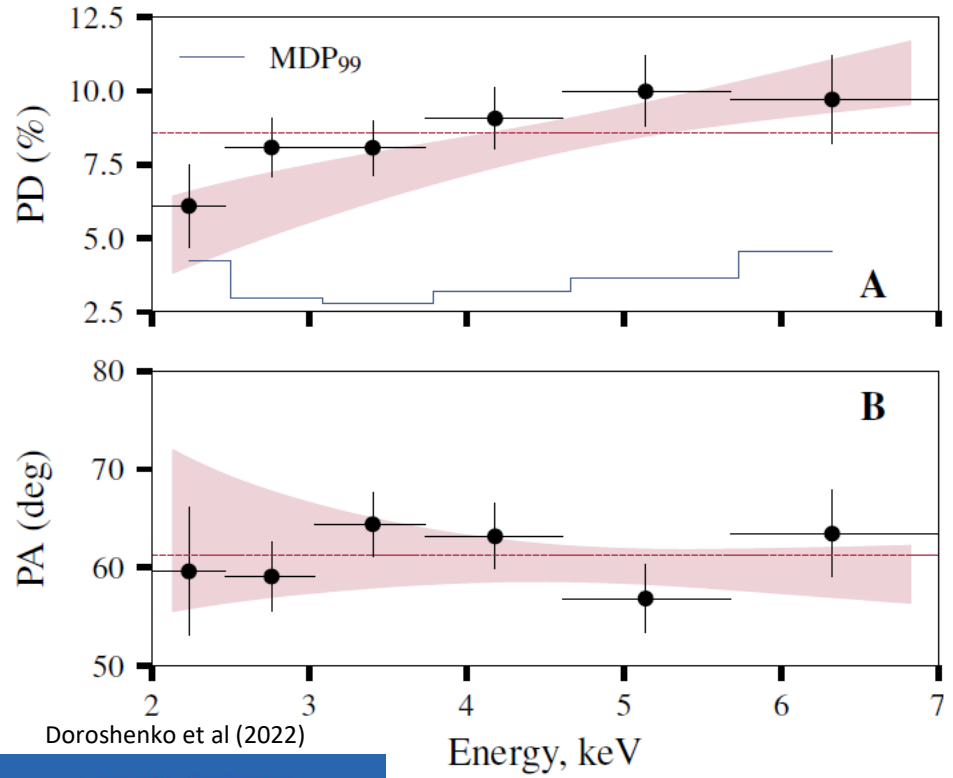
Her X-1

- Strongly magnetized NS ($B = 4.5 \times 10^{12}$ G) – intermediate-mass binary

- Two observations
  - February, 17–24 2022 (Doroshenko et al. 2022)
  - January 18–21, February 3–5 2023 (Heyl et al. 2023)

- Polarization detected:
  - PD $= 8.6\%$ – PA $\approx 60^\circ$ E (17σ)

- Well below the expectations (60–80%, Meszaros+88, Caiazzo & Heyl 21)



Doroshenko et al (2022)

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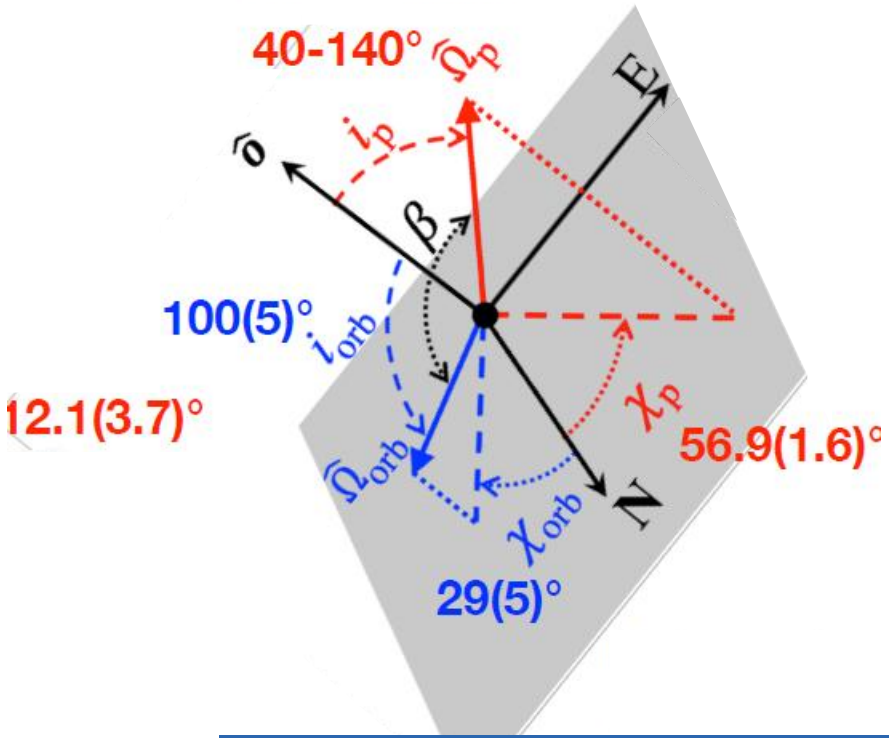
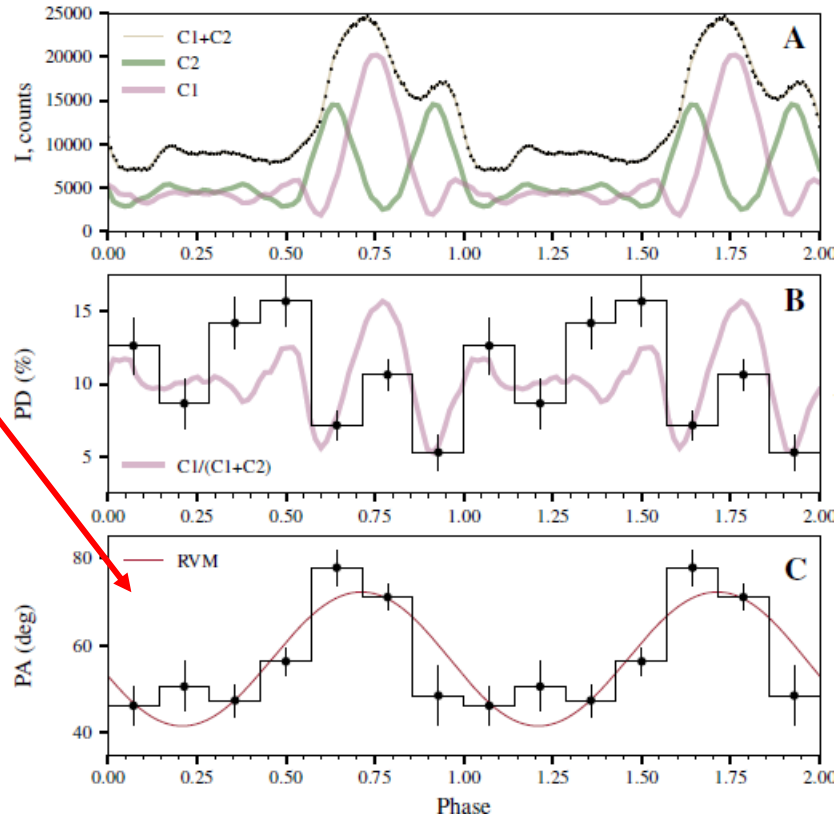
Her X-1

- RVM fit of the phase-dependent PA helped in constraining spin and magnetic axis inclinations for the first time for an XRP





Doroshenko et al (2022)

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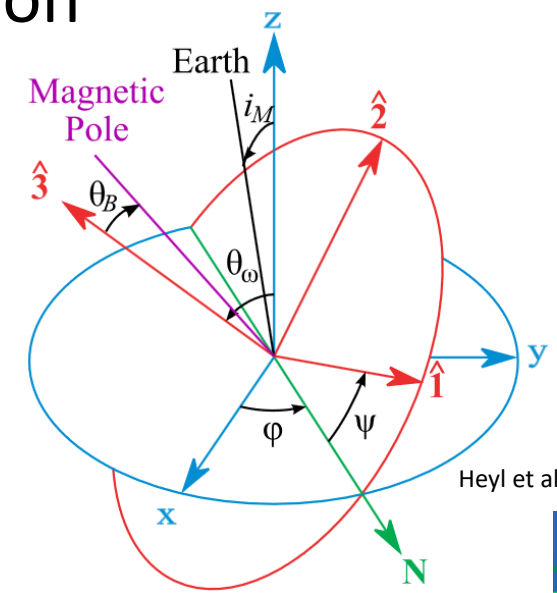
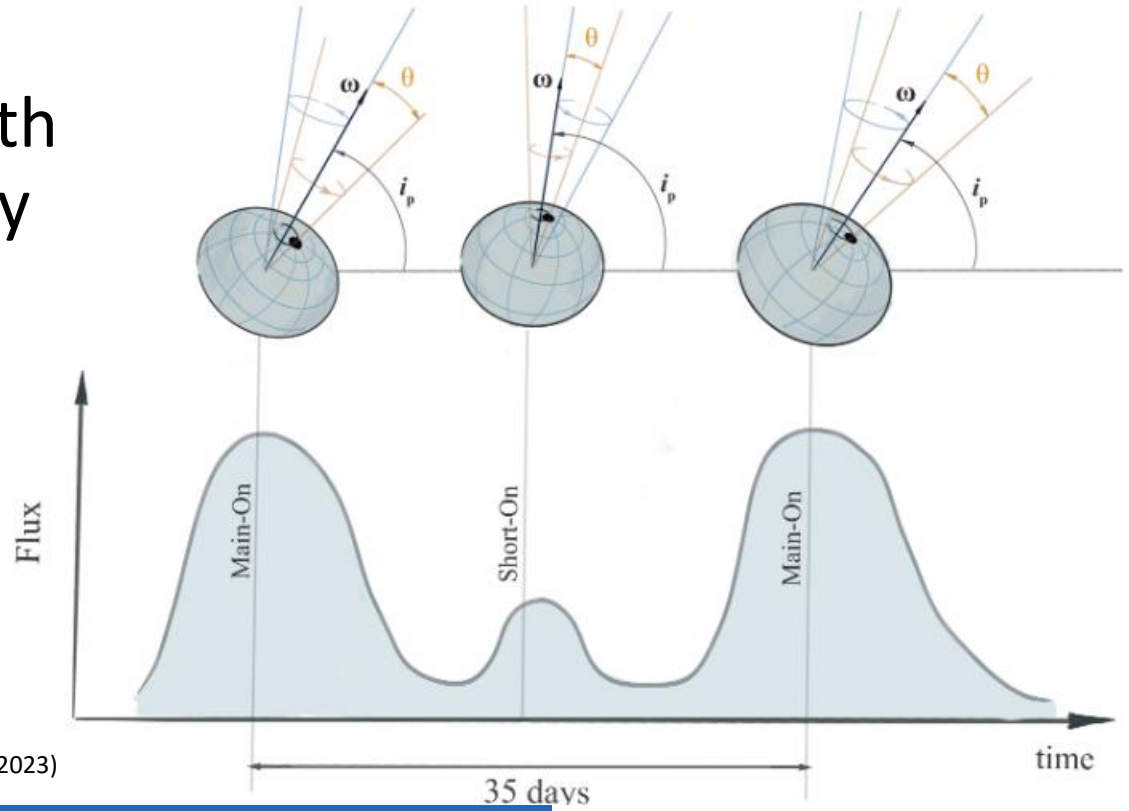
Her X-1

- RVM fit of the phase-dependent PA helped in constraining spin and magnetic axis inclinations for the first time for an XRP
- Second, time-dependent observation (with PA changing by ≈ 10°) allowed for a study of the source precession

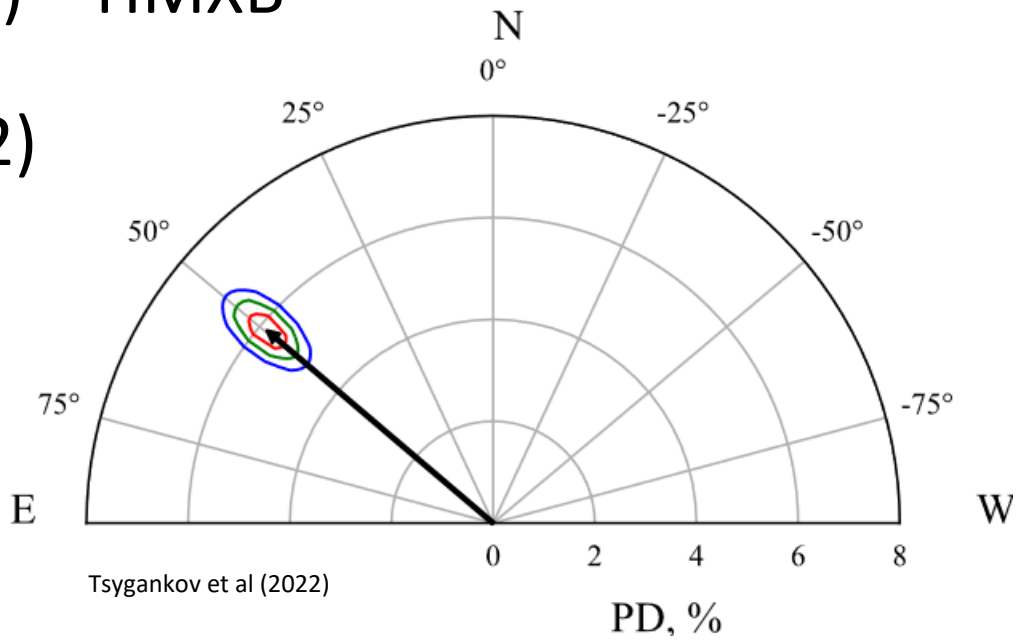


Heyl et al. (2023)



Cen X-3

- Strongly magnetized NS ($B = 3–4 \times 10^{12}$ G) – HMXB
- Observed in two slots (Tsygankov et al. 2022)
  - January, 29–31 2022 (low state)
  - July, 4–7 2022 (high state)
- Polarization detected:
  - Low state: Not significant
  - High state: PD $= 5.6\%$ – PA $= 47°$ E (15σ)
- Still below the expectations (60–80%, Meszaros+88) – to be understood



Tsygankov et al (2022)

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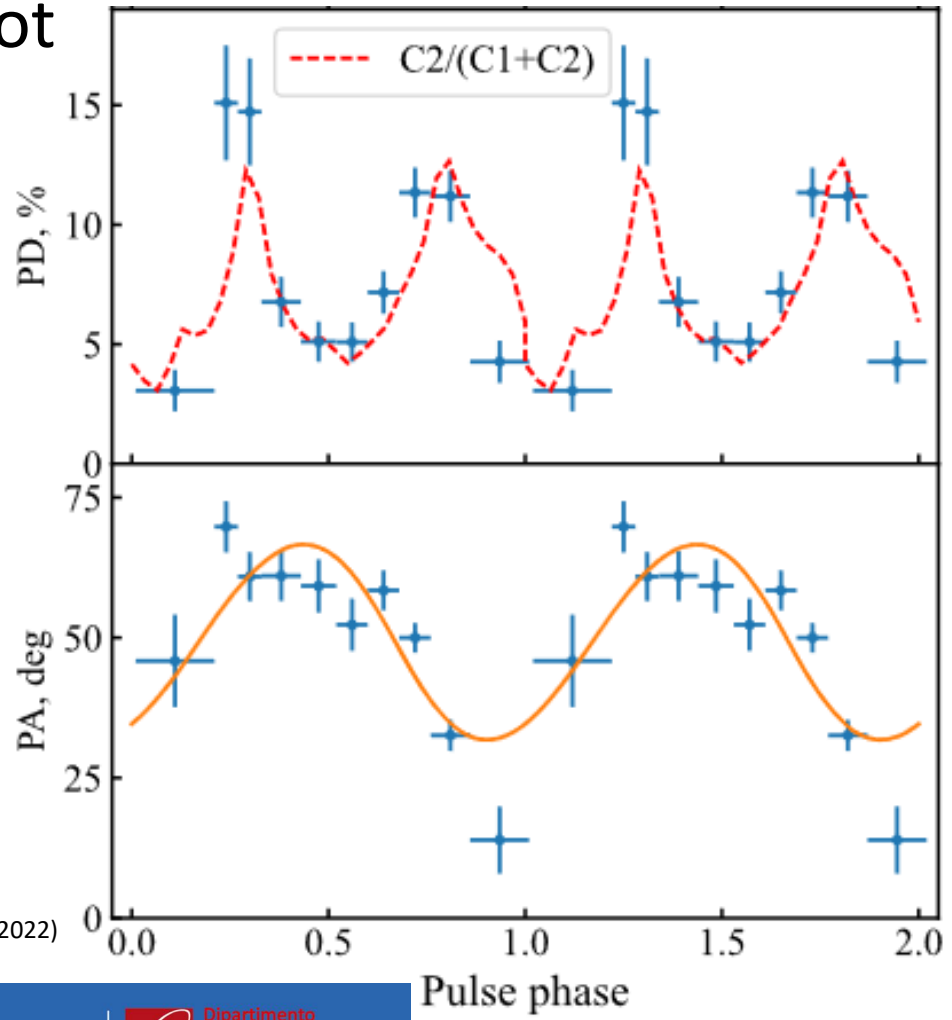
Cen X-3

- Phase-dependent PD well explained by a 2-spot model, slightly displaced from antipodal position (Kraus+ 96)
- PA still follows a sinusoidal behavior (RVM)
- Constraints on the spin/magnetic axis inclinations: $\chi \approx 70^\circ - \xi \approx 20^\circ$



Tsygankov et al (2022)

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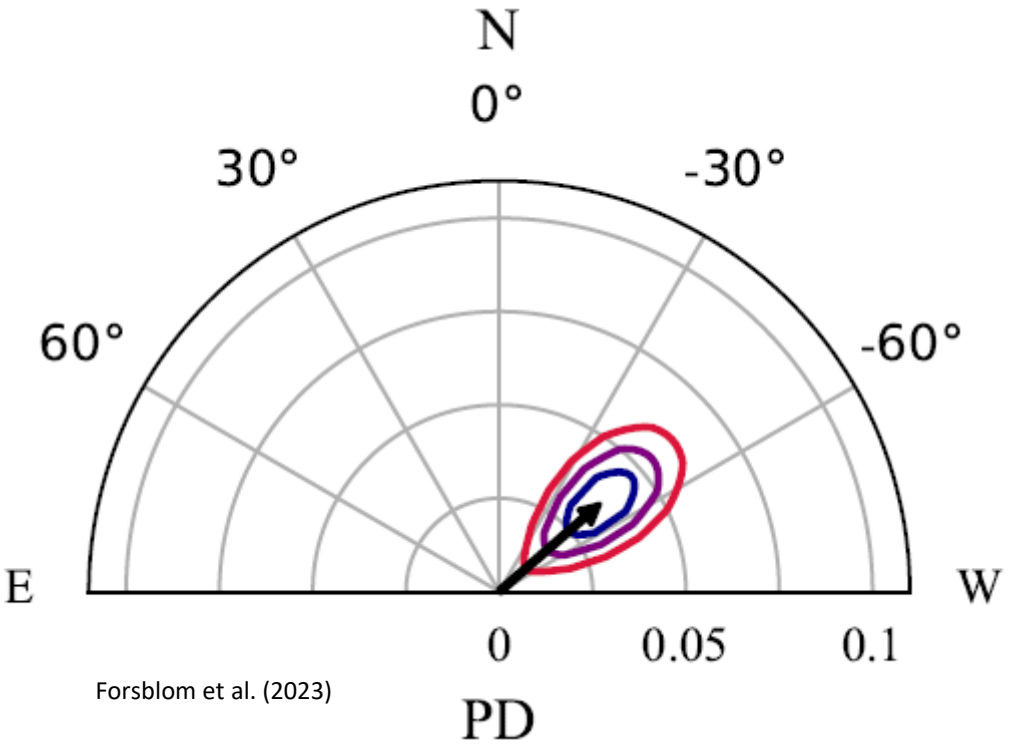
Vela X-1

- HMXB – Highly magnetized ($B \approx 3 \times 10^{12}$ G)
- Observation (Forsblom et al. 2023):
  - April, 15–21 2022 (low state)
- Measurement: PD $= 3.9\%$ ($\mathrm{MDP}_{99} = 2.6\%$)
  PA $= 52°$ W



Forsblom et al. (2023)

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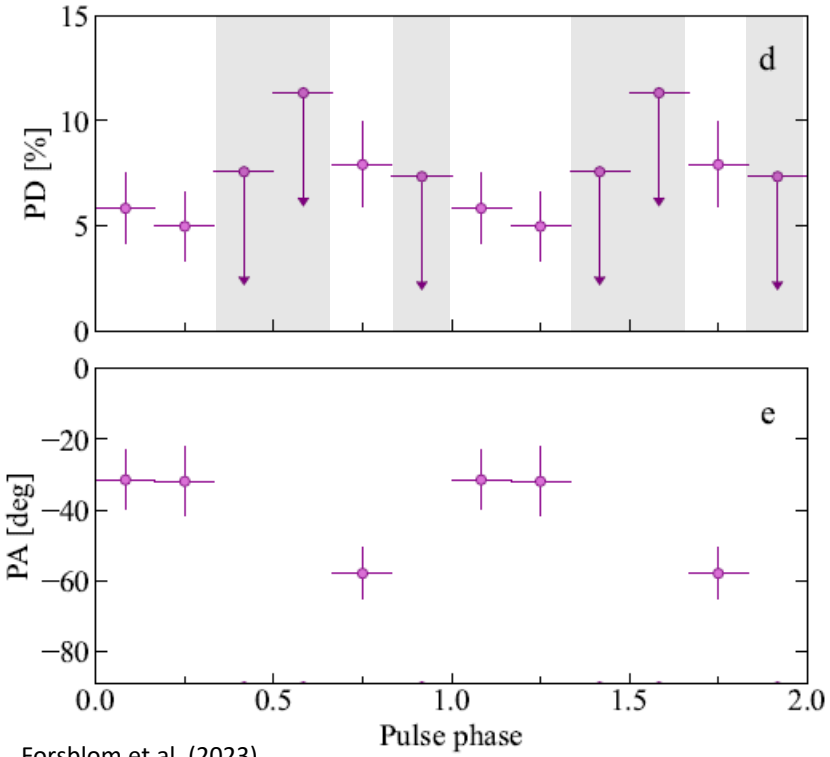
Vela X-1

- Phase-dependent PD only marginally above the MDP_{99}
- Correspondent PA is not significantly determined (but RVM oscillations seem to be plausible)



Forsblom et al. (2023)

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XRP low polarization

- In all the observed accreting XRPs, PD is much lower than expected (despite the strong magnetic field points to high PD and X-mode photons)
- New models are required
  - The atmosphere above the surface is not a «standard», cooling atmosphere (heating from the accretion flow)
  - Partial mode conversion at the vacuum resonance (inside the IXPE energy band) may determine a depolarization of the emitted radiation

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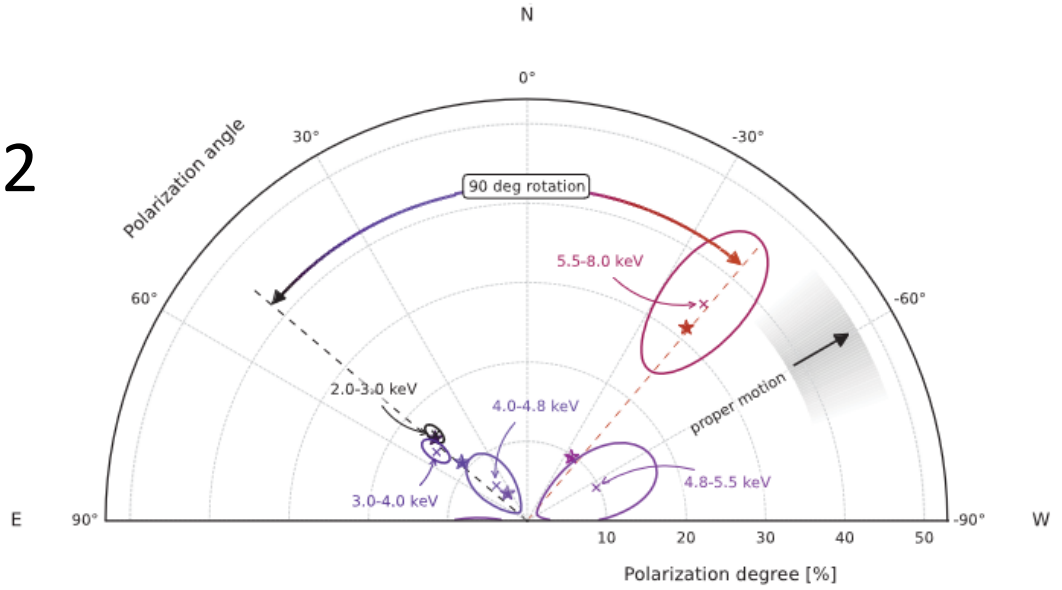
AXP 4U 0142+61

- Brightest among magnetars ($F_{2-10}^{\mathrm{unabs}} \approx 7 \times 10^{-11}$ cgs)
- $B_{P\dot{P}} \approx 1.5 \times 10^{14}$ G
- Observed once January 31–February 27, 2022
- Spectrum BB+PL
- Polarization measurement (2–8 keV):
  - PD $= 13.5\%$ (17σ) – PA $\approx 50°$ E
  - PD and PA change with energy in a non-trivial way



Taverna et al. (2022)

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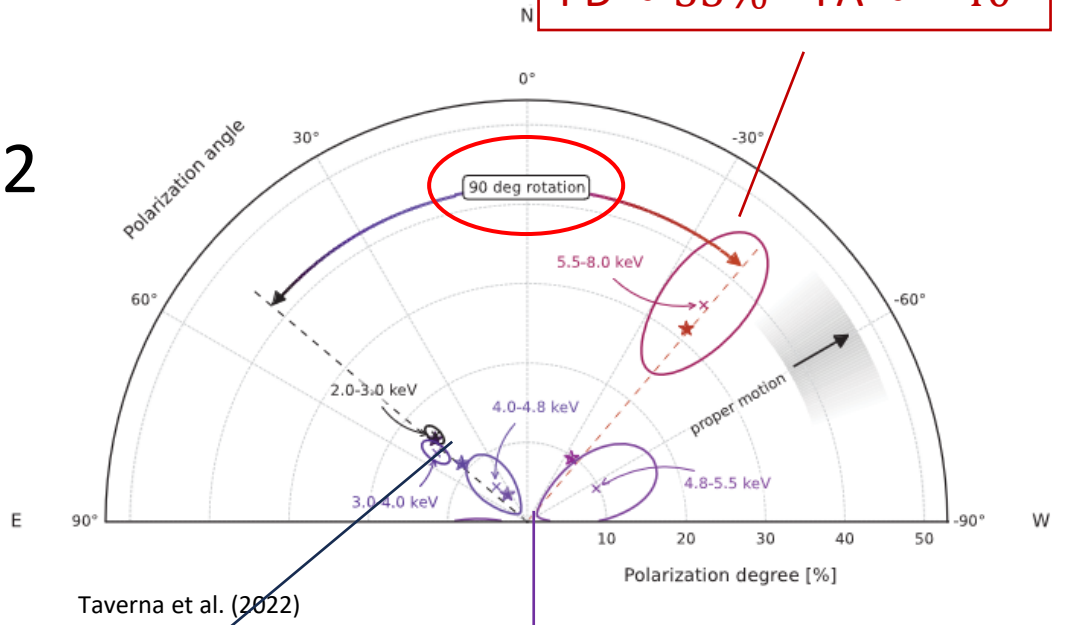
  - PD and PA change with energy in a non-trivial way

High energies
PD $\approx 35\%$ – PA $\approx -40°$



Taverna et al. (2022)

Low energies
PD $\approx 15\%$ – PA $\approx 50°$

4–5 keV
PD ≈ 0

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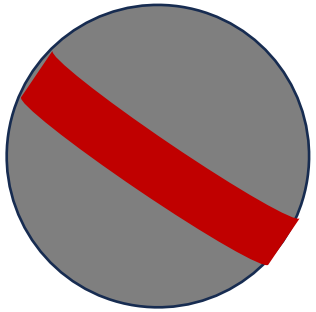
AXP 4U 0142+61

- Results are compatible with the magnetar model
  - $90°$-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)



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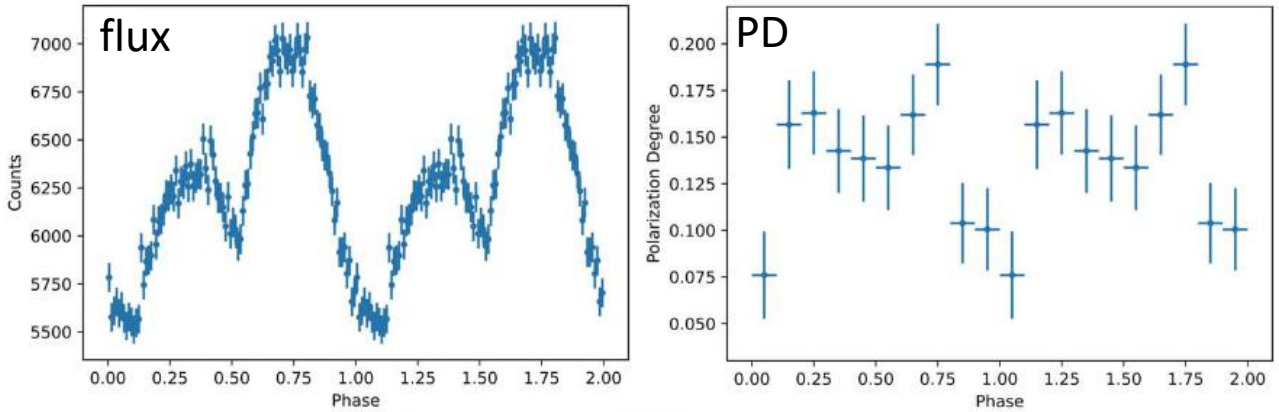
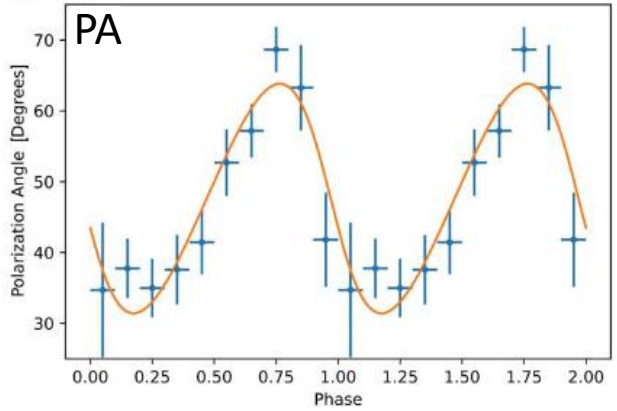
AXP 4U 0142+61

- Phase dependent results
  - PD is in-phase with the LC (determined at the surface)
  - PA is sinusoidal (RVM)



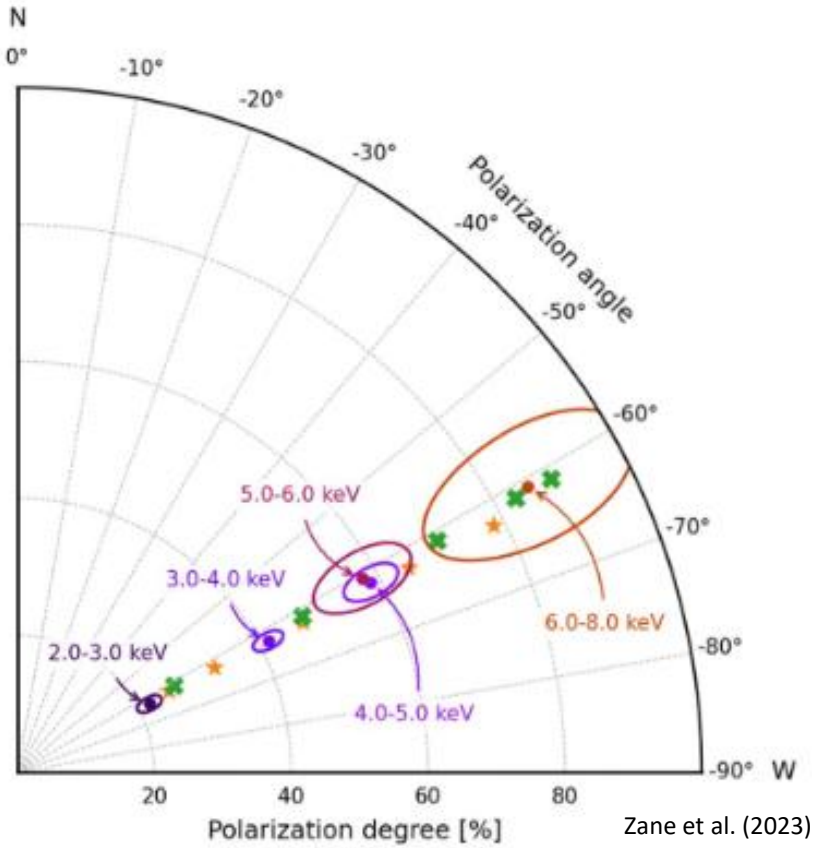


Taverna et al. (2022)

- RVM for extended regions holds for dipolar fields only
  - In the magnetar model B is dipolar only far away from the surface
- Effect explained if vacuum birefringence is at work!

AXP 1RXS J170849.0–4009100

- 2nd brightest magnetar ($F_{2-10}^{\mathrm{unabs}} \approx 3 \times 10^{-11}$ cgs)
- $B_{P\dot{P}} \approx 5 \times 10^{14}$ G
- Observed once September 19–October 8, 2022
- Spectrum BB+PL or BB+BB?
- Polarization measurement (2–8 keV):
  - PD = 35% (22.5σ) – PA $\approx 60°$ W
  - Polarization direction is constant within the IXPE band
  - PD at 6–8 keV: $\approx 85\%$ ($\mathrm{MDP}_{99} = 50\%$)
    <u>the highest measured so far!</u>



Zane et al. (2023)

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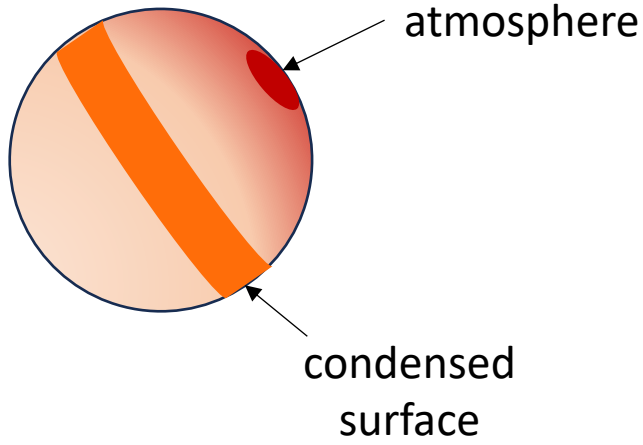
AXP 1RXS J170849.0–4009100

- 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

⇓

Phase transition across the surface



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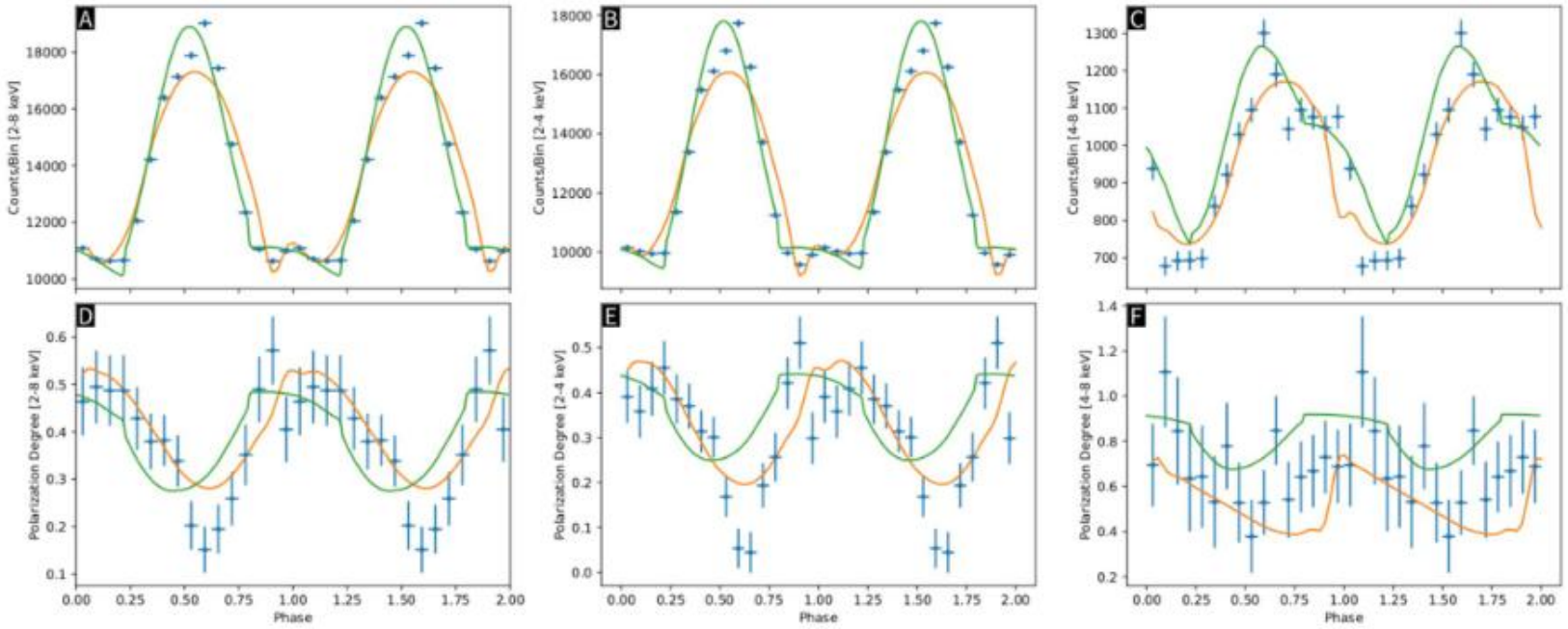
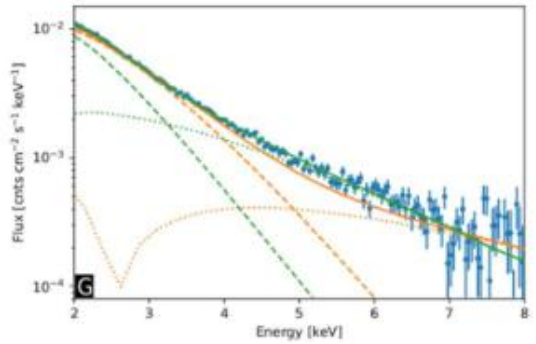
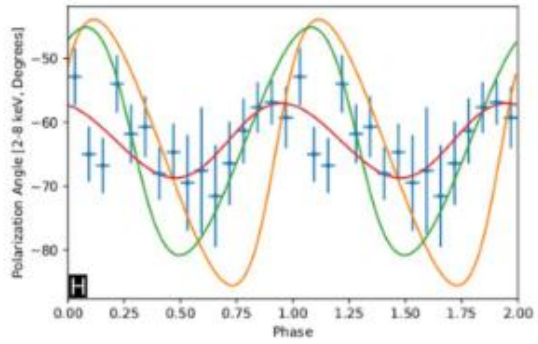
AXP 1RXS J170849.0–4009100

- Phase-dependent results are coherently explained by the model



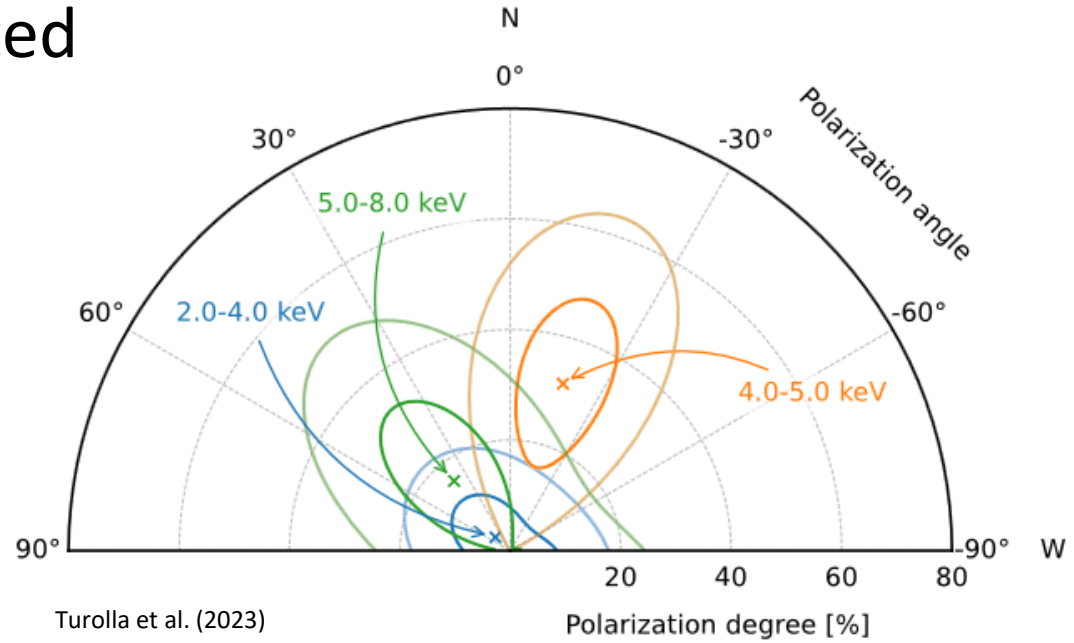
Spectral decomposition (atmo+CS)





SGR 1806–20

- Emitted the strongest giant flare ever detected (December 27, 2004)
- $B_{P\dot{P}} \approx 8 \times 10^{14}$ G (strongest B-field)
- Observed once March 22–April 13, 2023 (+ XMM contemporary campaign)
- Marginally significant IXPE measurement
  - Unexpectedly low flux (4×10^{-12} cgs, $\approx 1/10$ historical)
  - Occurrence of solar flares during observation
  - PD $\approx 32\%$ (4–5 keV, 99% c.l.)



Turolla et al. (2023)

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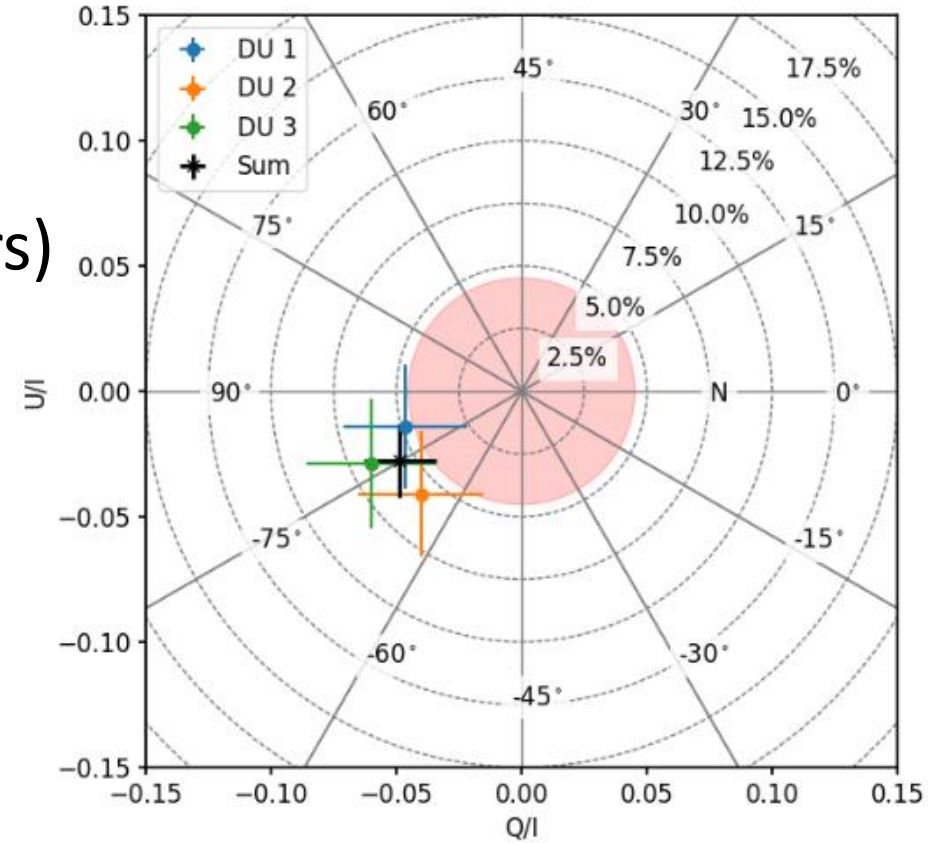
AXP 1E 2259+586

- Observed once, June 2–July 6, 2023 + XMM & NICER observations
- $B_{P\dot{P}} \approx 6 \times 10^{13}$ G (among low-field magnetars)
- Averaged (2–8 keV) PD $= 5.6\%$, only significant at low energies
- Spectral fit BB+PL is not good enough → adding an absorption line the fit improves
- Previous studies (Pizzocaro+ 19) invoked the presence of a magnetic loop where proton cyclotron scattering occurs (then $B \approx 10^{14}$ G)



Heyl et al. (2024)

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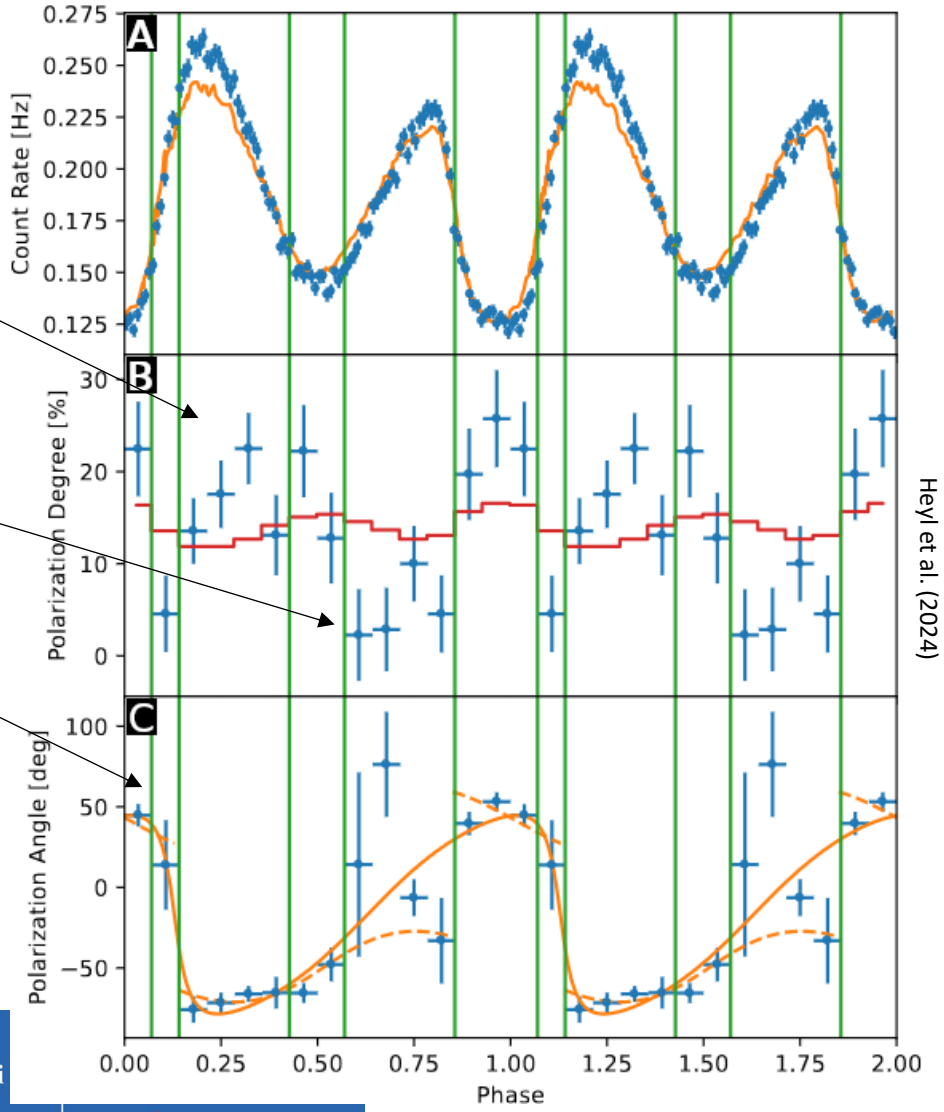
AXP 1E 2259+586

- Peculiar phase-dependent behavior
  - Polarization up to $\approx 25\%$ (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)



Heyl et al. (2024)

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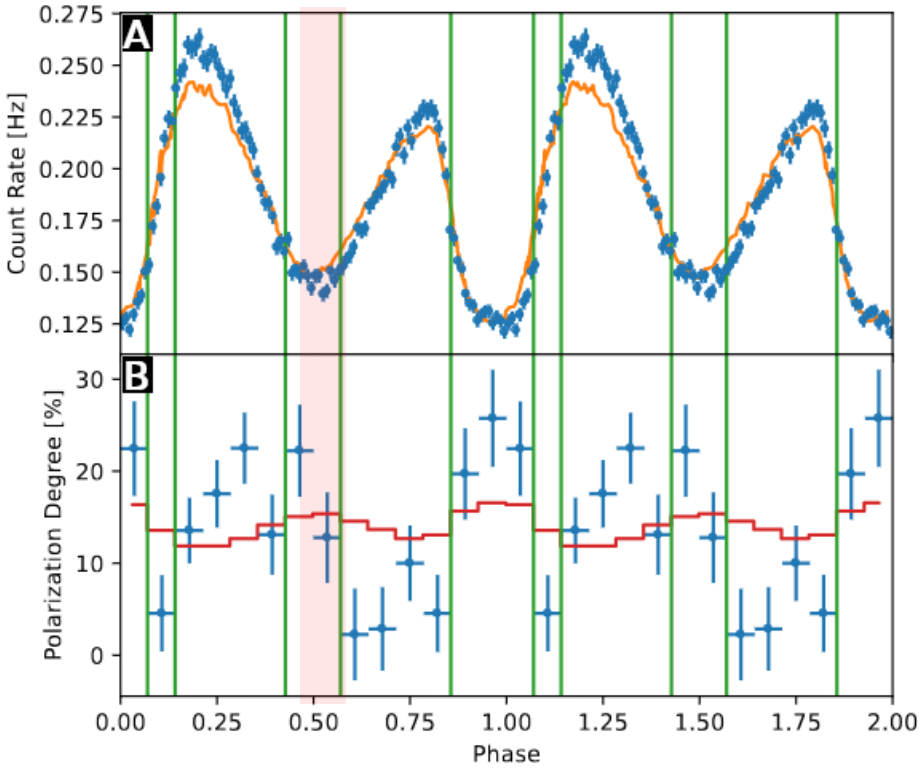
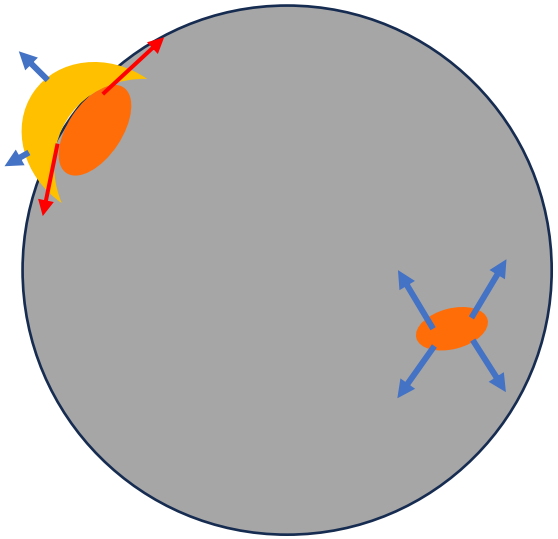
AXP 1E 2259+586

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



2 condensed-surface hotspots are present on the NS surface

The protons magnetic loop scatters away X-mode photons



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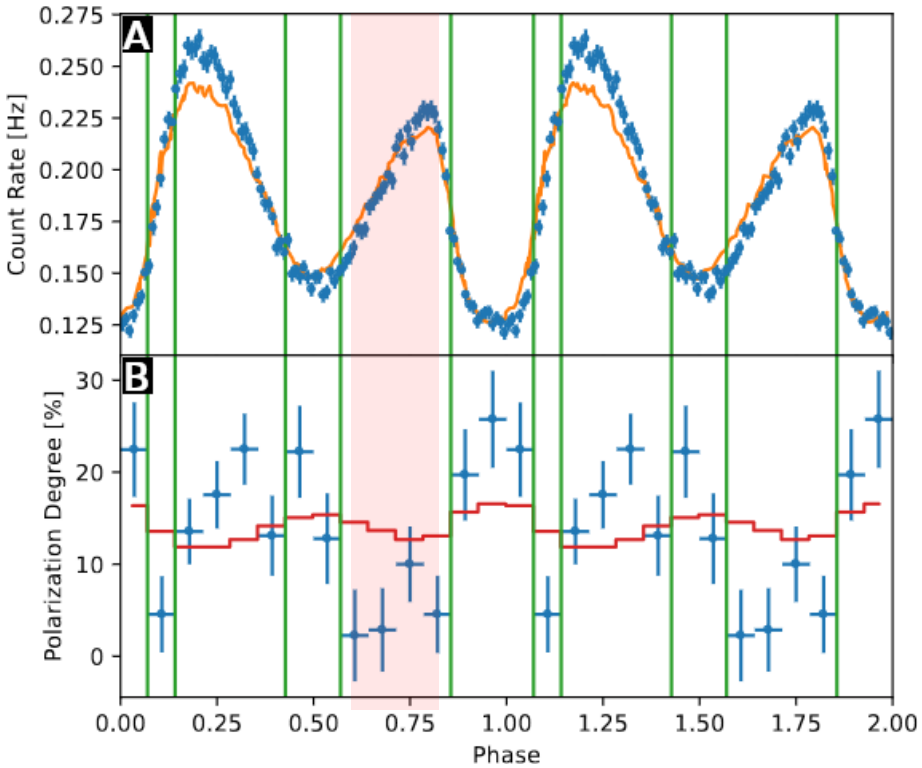

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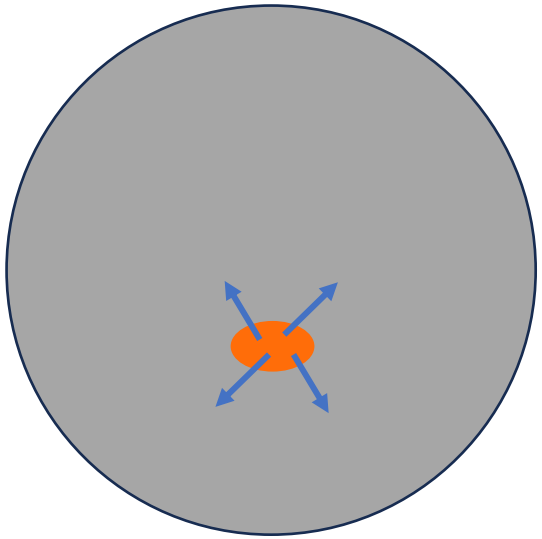

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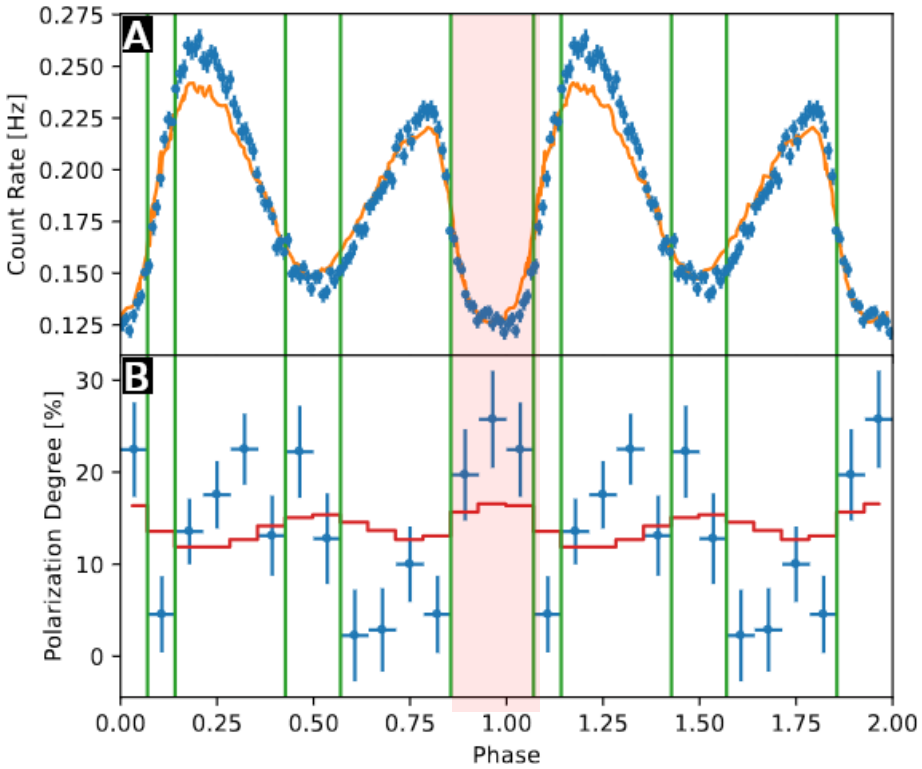

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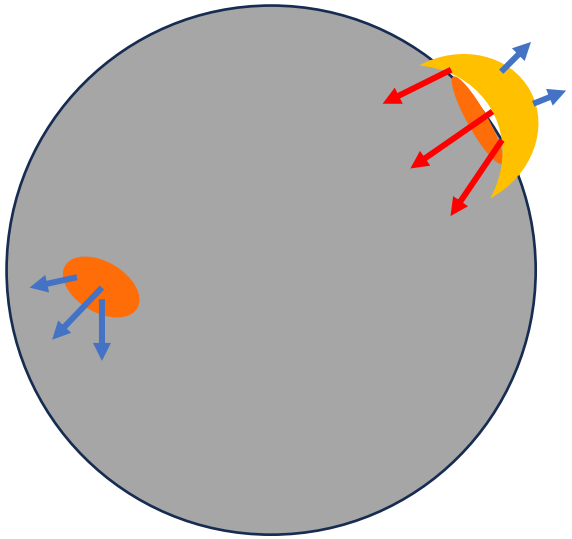

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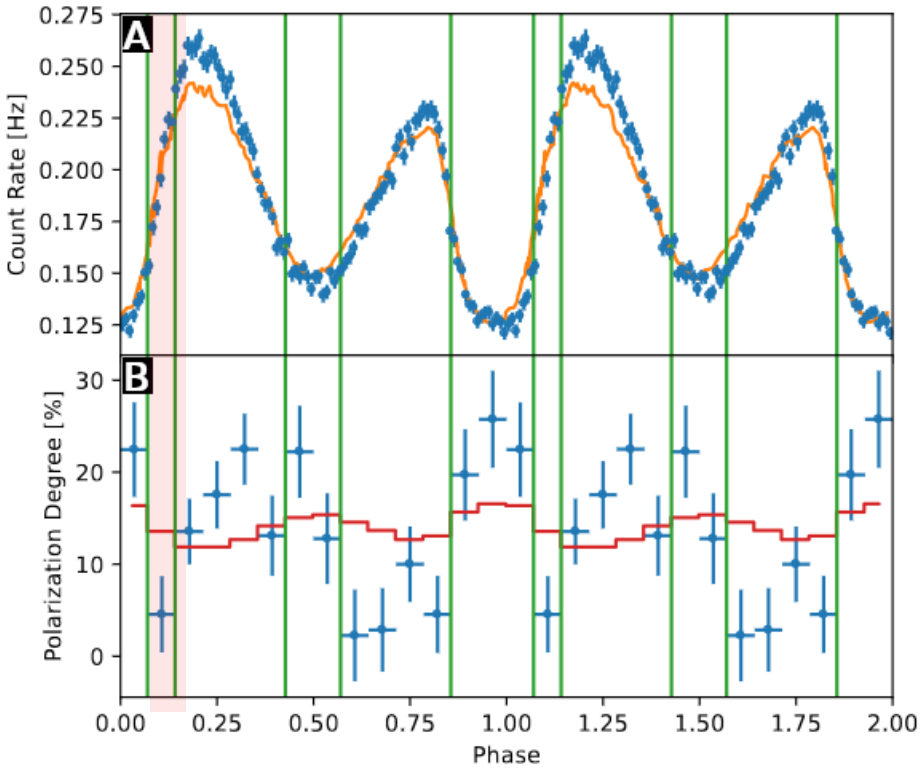

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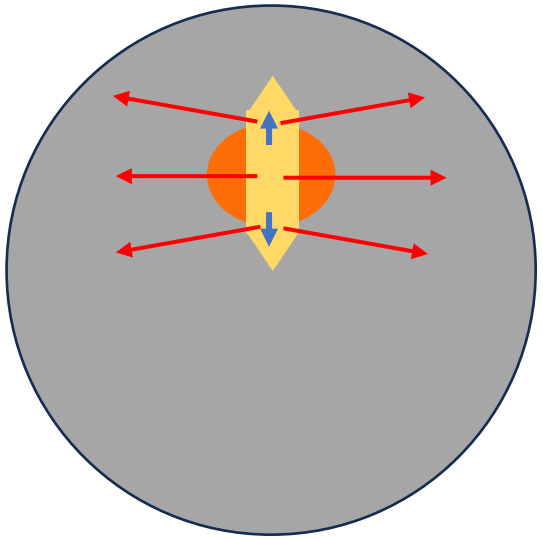

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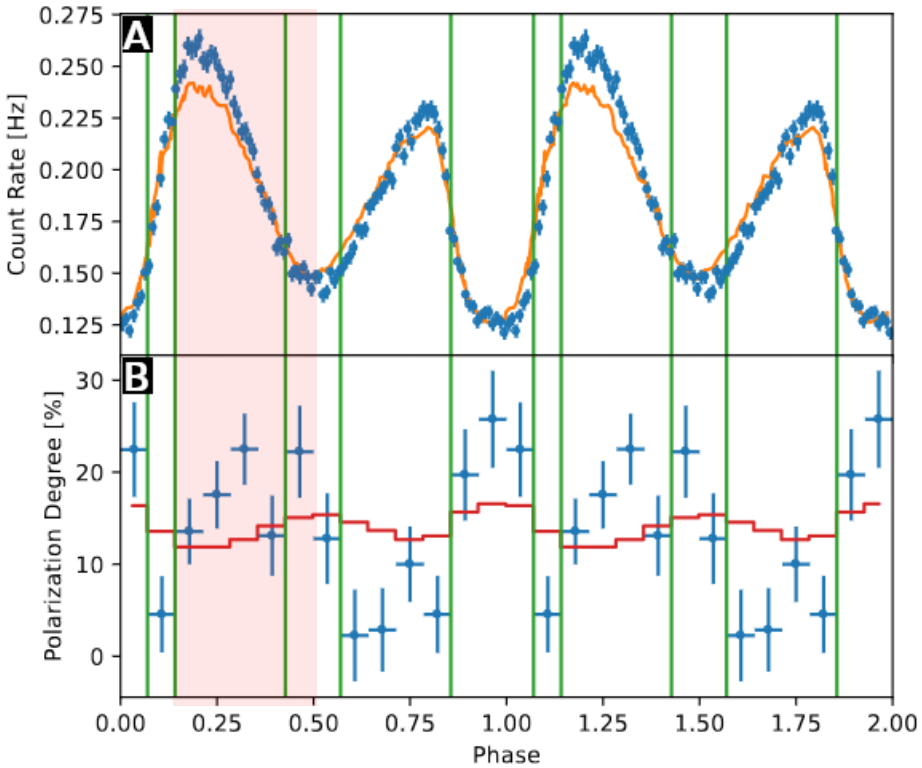

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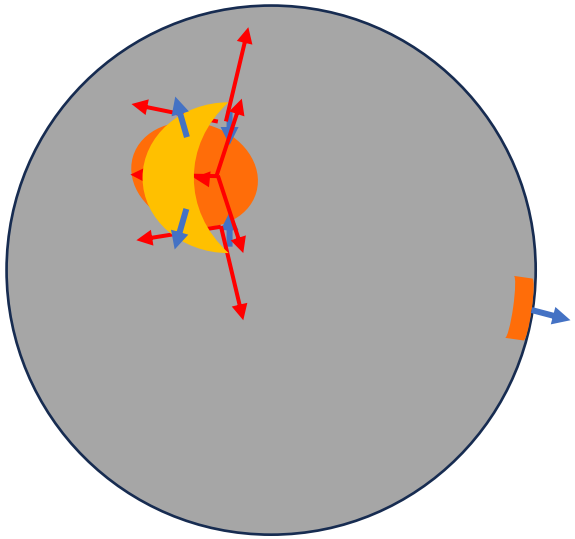

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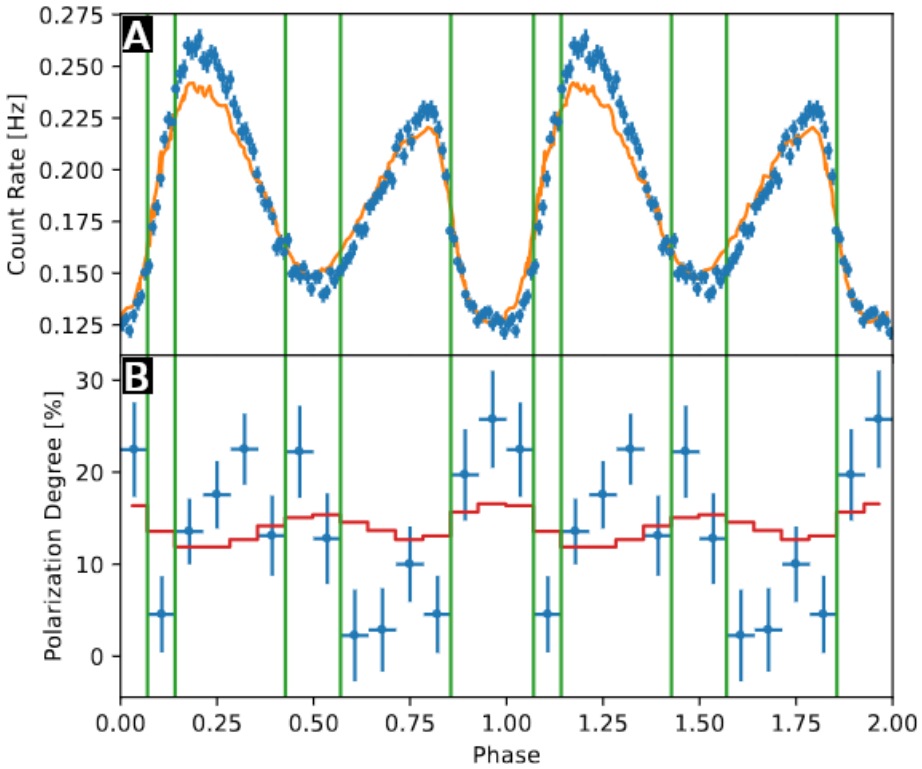
AXP 1E 2259+586

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



2 condensed-surface hotspots are present on the NS surface

The protons magnetic loop scatters away X-mode photons