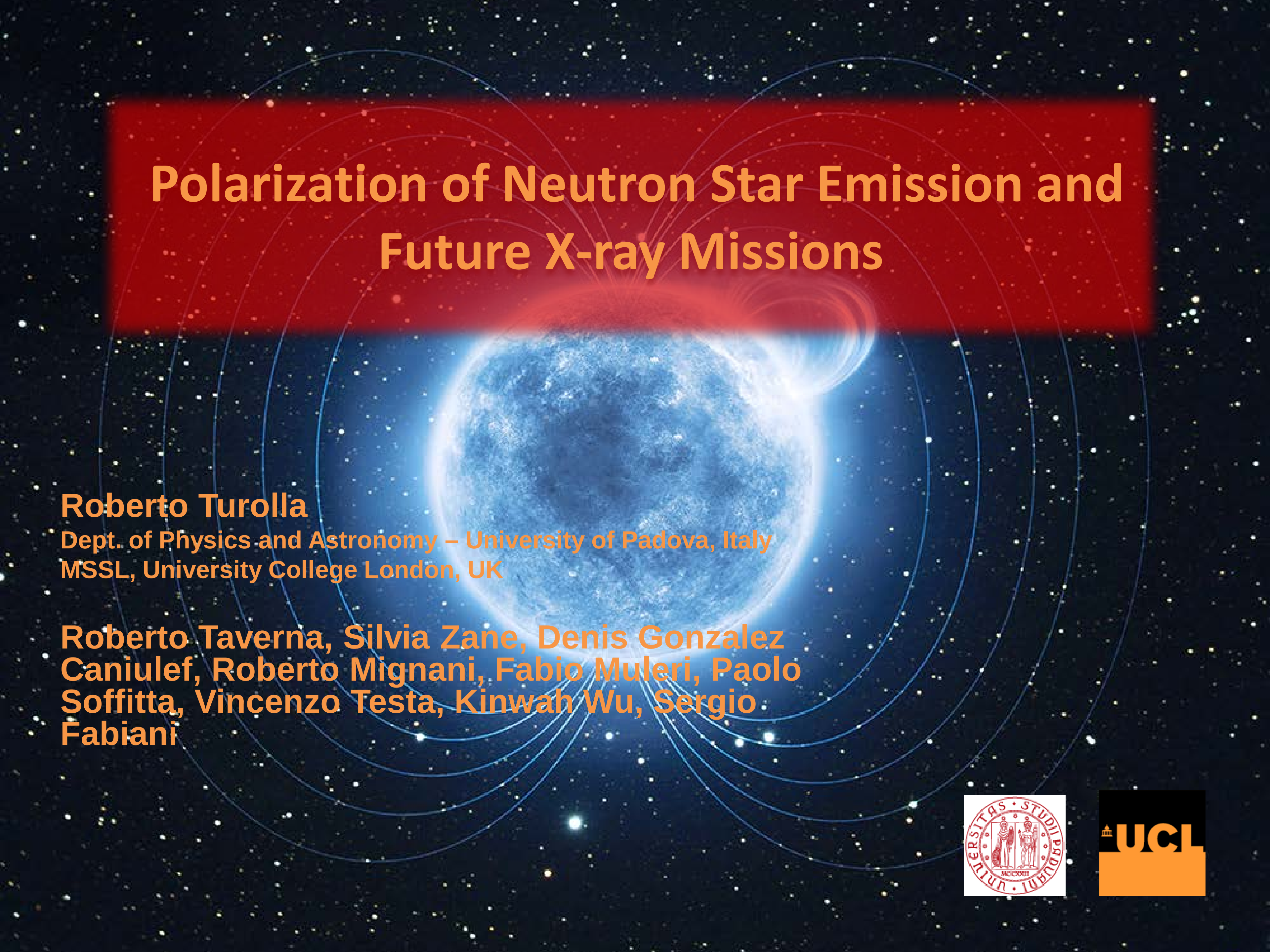

Polarization of Neutron Star Emission and Future X-ray Missions

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Outline

☐ The intrinsic polarization

☐ The observed polarization signal: QED (vacuum birefringence) and geometrical effects

☐ Predictions for magnetars and isolated neutron stars

☐ Upcoming X-ray polarimetry missions

☐ What we will measure (and what we have already measured)

Intrinsic polarization

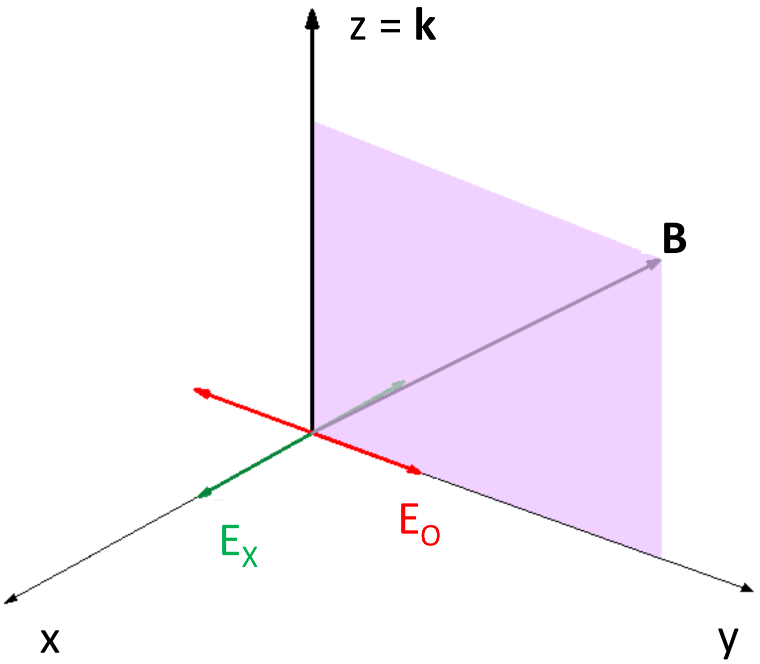
Photon polarization modes

- Radiation emitted by the star surface layers is expected to be polarized because the strong magnetic field
  - Changes the cross-sections and hence the way photons interact with matter
  - Alters the dielectric and (inverse) magnetic permeability tensors and hence affects the way photons propagate

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

- In general radiation in a magnetized cold plasma+vacuum is elliptically polarized
- However, for $\epsilon \ll E_{\rm ce}$ the two normal modes are almost linearly polarized: the extraordinary (X) and ordinary (O) modes

Photon polarization modes



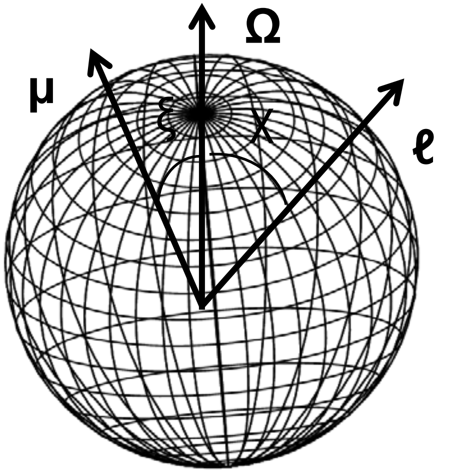
- O-mode opacity almost unaffected by the magnetic field
- X-mode opacity strongly reduced by a factor ≈ $\omega^2/\omega_{\rm ce}^2$
- Intrinsic polarization depends on the surface emission model (and on the possible reprocessing in the magnetosphere)
- Either an atmosphere or a condensed surface (bare NS), maybe covered by a thin H layer (e.g. Potekhin 2014)

Intrinsic polarization of surface emission

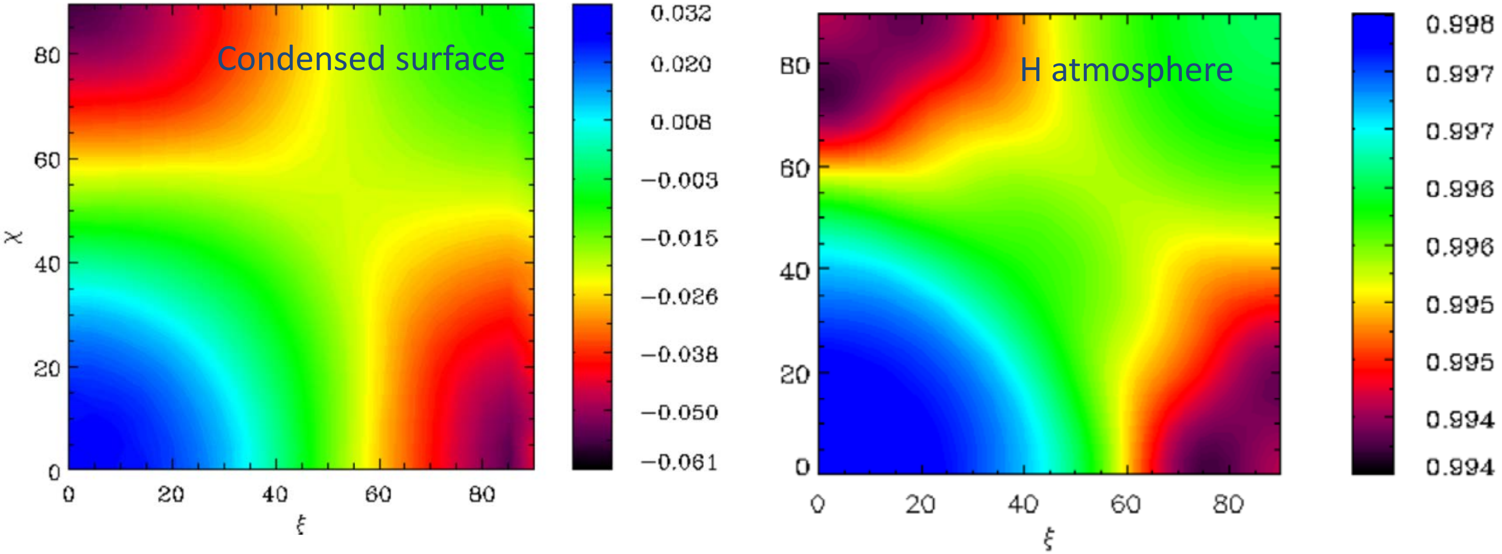
Emission properties depend on local **B** and T

Intrinsic polarization $\Pi_{\mathrm{L}}^{\mathrm{EM}} = \dfrac{F_{\mathrm{X}} - F_{\mathrm{O}}}{F_{\mathrm{X}} + F_{\mathrm{O}}}$

Divide the surface into patches and add up those which are in view at a certain phase



Phase-averaged intrinsic polarization (soft X-rays; Gonzalez Canjulef et al. 2016)

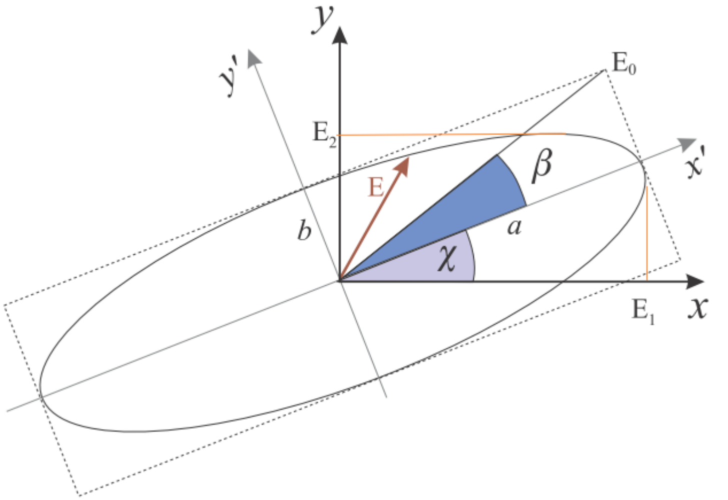


Observed polarization

Stokes parameters

- Wave electric field

$$E_x = A_x\,\mathrm{e}^{-i(kz-\omega t)} = a_x\,\mathrm{e}^{-i\varphi_x}\mathrm{e}^{-i(kz-\omega t)}$$
$$E_y = A_y\,\mathrm{e}^{-i(kz-\omega t)} = a_y\,\mathrm{e}^{-i\varphi_y}\mathrm{e}^{-i(kz-\omega t)}$$



- Polarized radiation convently described through the Stokes parameters (that are additive):

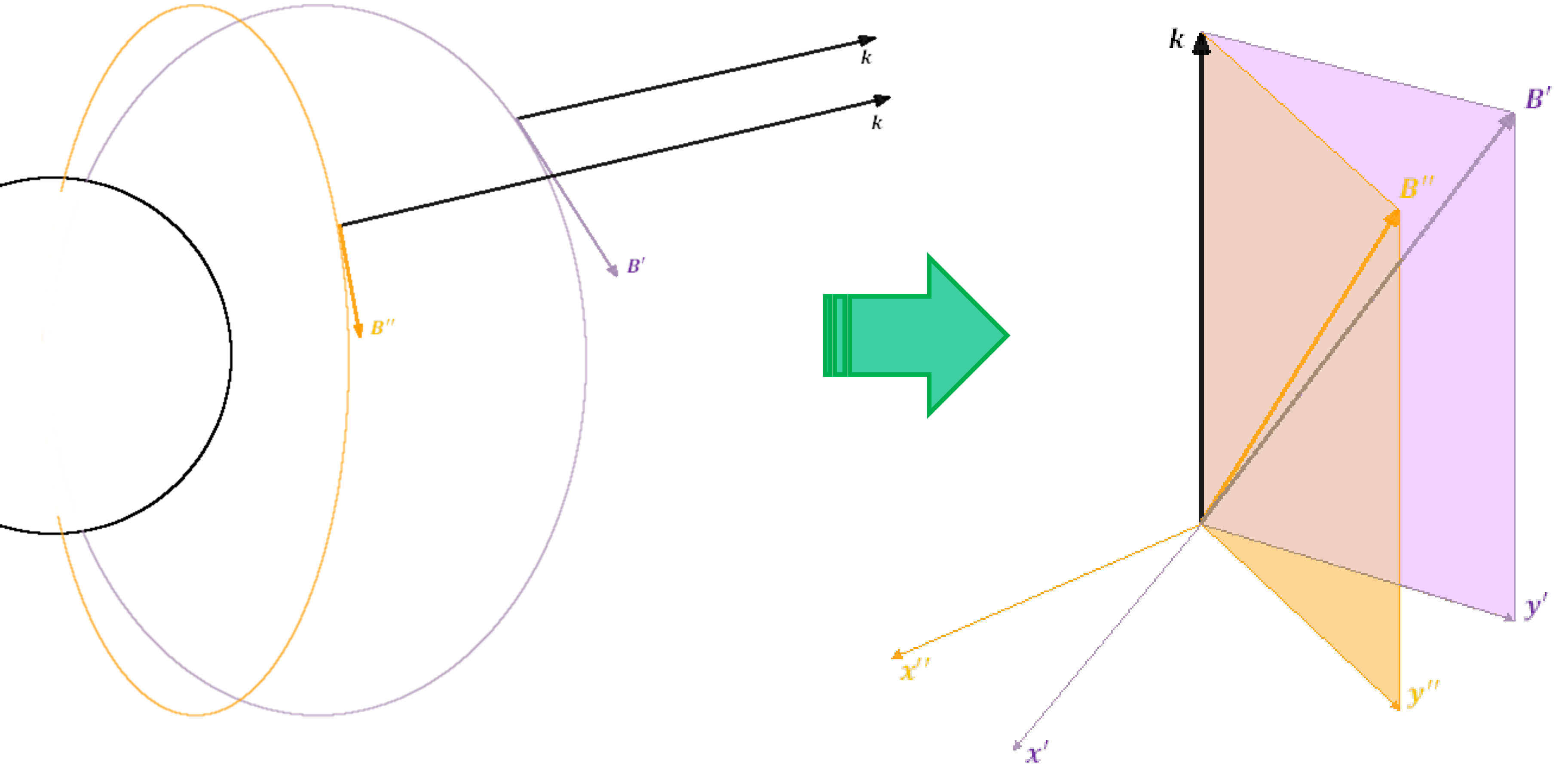
$$I = S_x + S_y = S = a_x^2 + a_y^2$$
$$Q = S_x - S_y = A_x A_x^* - A_y A_y^* = S\cos 2\beta\cos 2\chi = a_x^2 - a_y^2$$
$$U = A_x A_y^* + A_y A_x^* = 2\Re(A_x A_y^*) = S\cos 2\beta\sin 2\chi = 2a_x\,a_y\cos(\varphi_x - \varphi_y)$$
$$V = i\,(A_x A_y^* - A_y A_x^*) = 2\Im(A_x A_y^*) = S\sin 2\beta = 2a_x\,a_y\sin(\varphi_x - \varphi_y)$$

- Nomalized Stokes vector for linearly polarized radiation: $(1,0,0)_X$, $(-1,0,0)_O$

Stokes parameters rotation

- Each photon is polarized either in the X or O mode wrt the frame (x, y, z) defined by the propagation vector **k** and the local direction of **B**
- The local frame (x, y, z) changes if **B** varies
- Before the Stokes parameters for the entire radiation are computed they must be referred to the same frame, the polarimeter frame $(u, v, w = z)$

Stokes parameters rotation



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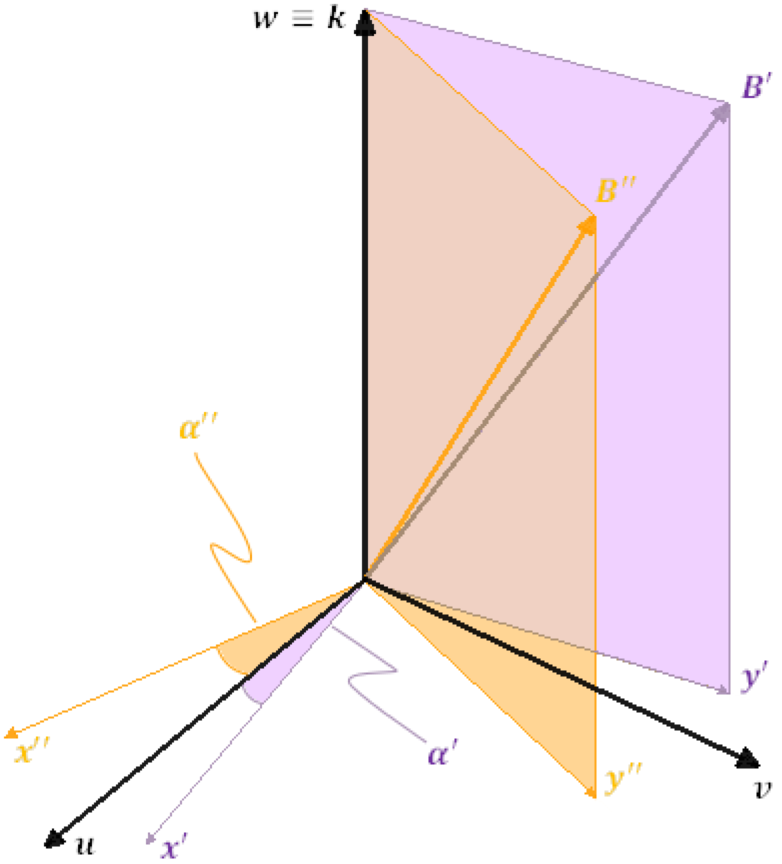


Stokes parameters rotation

- Under a rotation by an angle α_i the Stokes parameters transform as:

$$I_i = \bar{\mathcal{I}}_i \qquad Q_i = \bar{\mathcal{Q}}_i \cos(2\alpha_i) + \cancel{\bar{\mathcal{U}}_i \sin(2\alpha_i)}$$

$$V_i = \bar{\mathcal{V}}_i \qquad U_i = \cancel{\bar{\mathcal{U}}_i \cos(2\alpha_i)} - \bar{\mathcal{Q}}_i \sin(2\alpha_i)$$

- The Stokes parameters associated to the whole radiation are given by:

$$Q = \Sigma_i^{Nx} \cos(2\alpha_i) - \Sigma_i^{No} \cos(2\alpha_i) \qquad U = \Sigma_i^{No} \sin(2\alpha_i) - \Sigma_i^{Nx} \sin(2\alpha_i)$$

Polarization observables

- The polarization properties of NS emission are described by the polarization fraction and polarization angle

$$\Pi_{\mathrm{L}} = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\chi_{\mathrm{p}} = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)$$

- Only in the case $\alpha_i = const$ the observed Π_{L} and χ_{p} coincide with the intrinsic ones

Vacuum polarization

- According to QED, a (strong) magnetic field polarizes the vacuum (virtual $e^{\pm}$ pairs)

- This modifies the $\boldsymbol{\varepsilon}$ and $\boldsymbol{\mu}$ tensors of the vacuum which behaves like a birefringent medium

- By linearizing the wave equation (geometric optics approximation), one obtains a set of ODEs governing the evolution of the complex amplitude of **E**, **A** = (A_x, A_y, A_z)

Vacuum polarization

- Evolution of the Stokes parameters for photons propagating in vacuo (Heyl & Shaviv, 2002; Fernández & Davis, 2011; Taverna et al. 2014))

$$\frac{d\bar{Q}}{dz} = -\frac{k_0\delta}{2}(2P\bar{V})$$

$k_0 = \omega/c$

Two lengthscales

$$\frac{d\bar{U}}{dz} = -\frac{k_0\delta}{2}(N-M)\bar{V}$$

$$\ell_A = \frac{2}{k_0\delta} \sim B^{-2}E^{-1}$$

$\delta \propto B^2$

$$\frac{d\bar{V}}{dz} = \frac{k_0\delta}{2}[2P\bar{Q} + (N-M)\bar{V}]$$

z coordinate along the ray

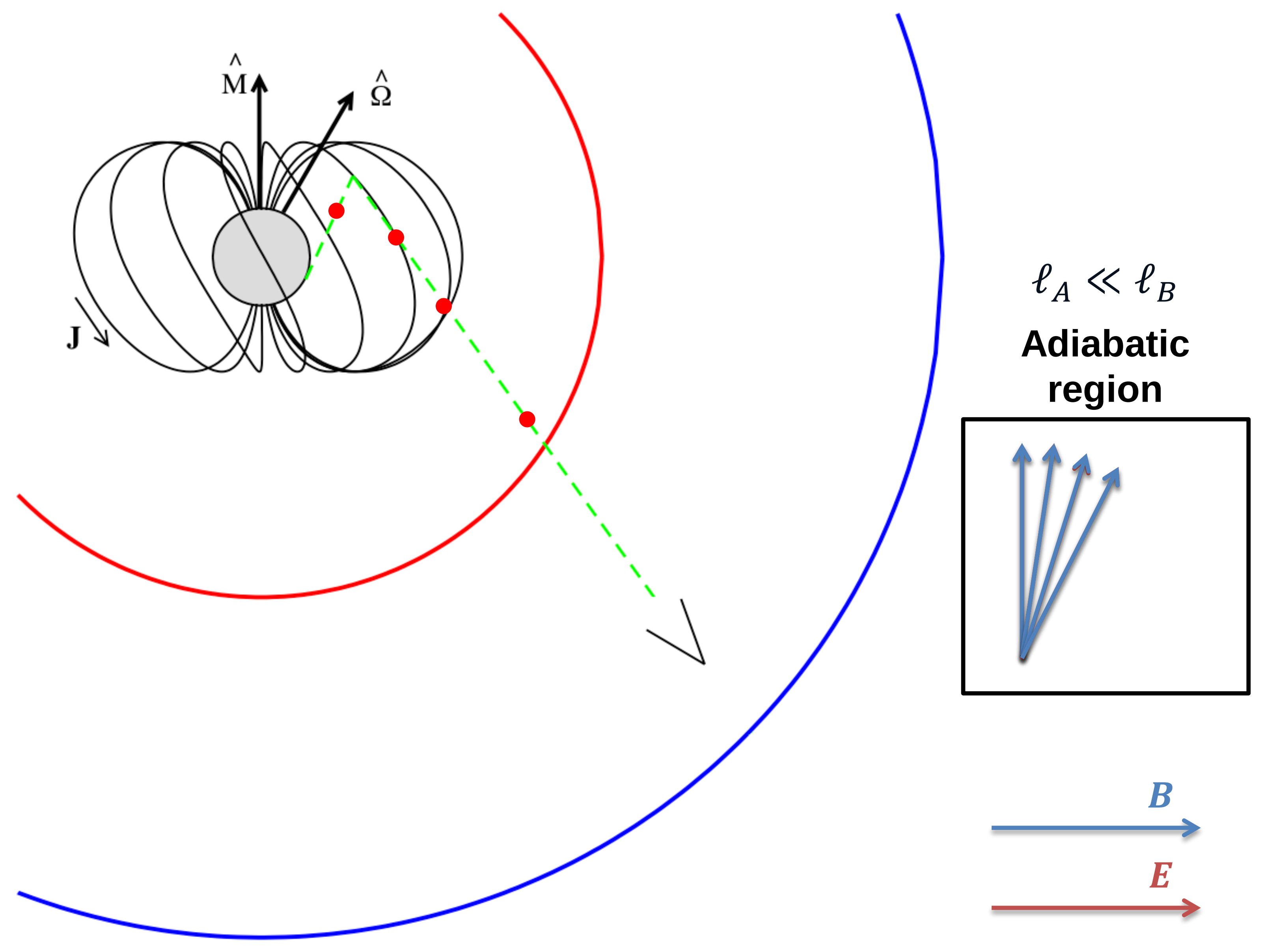
$$\ell_B = \frac{B}{|\hat{k}\cdot\nabla B|} \sim r$$

$$\ell_A = \ell_B \quad\Rightarrow\quad r_a \simeq 4.8\left(\frac{B_p}{10^{11}\ \mathrm{G}}\right)^{2/5}\left(\frac{E}{1\ \mathrm{keV}}\right)^{1/5} R_{NS}$$

Polarization limiting radius

Vac

- E g
  in

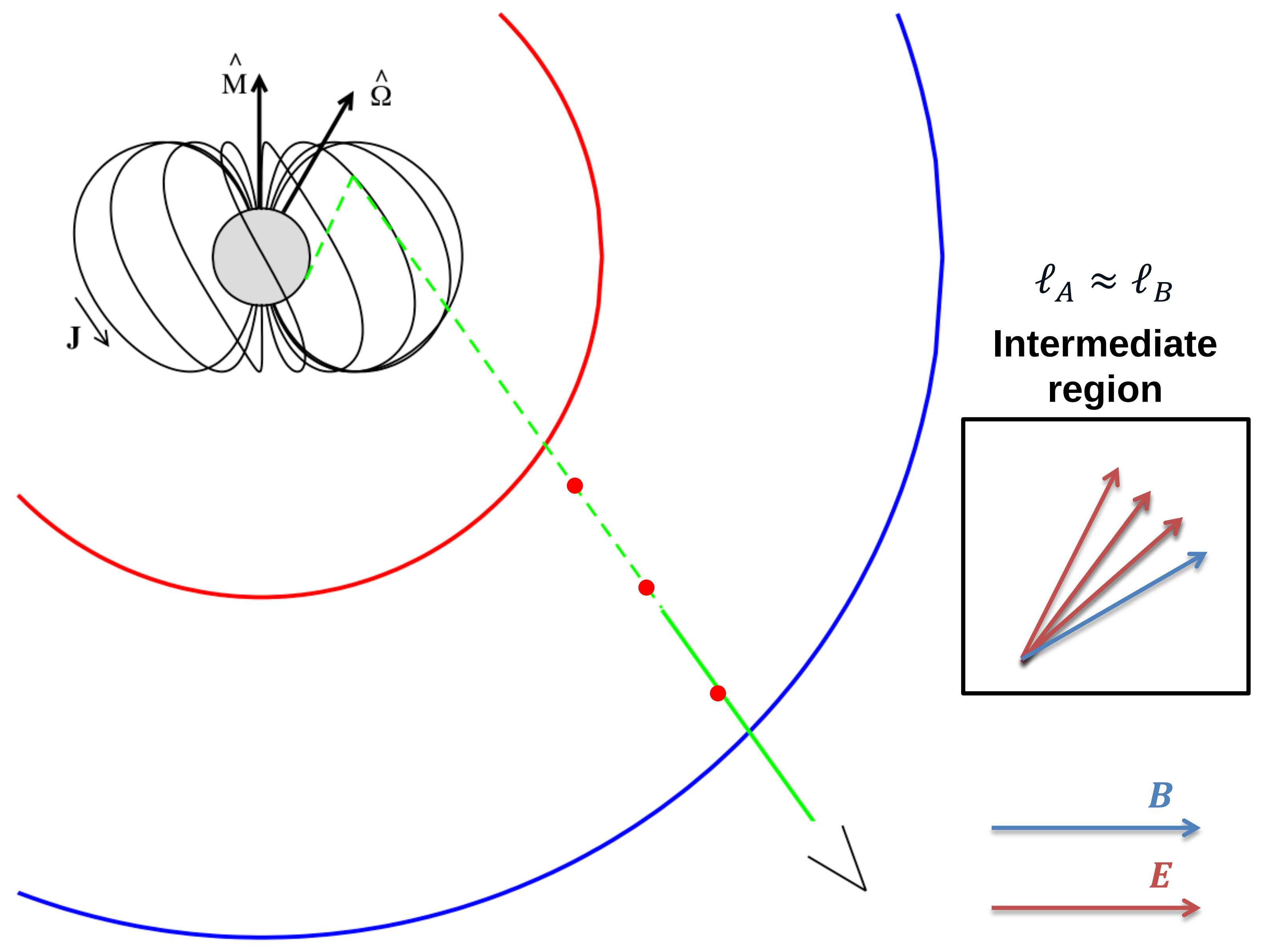


$\ell_A \ll \ell_B$

Adiabatic region

Vac

- E g
  in

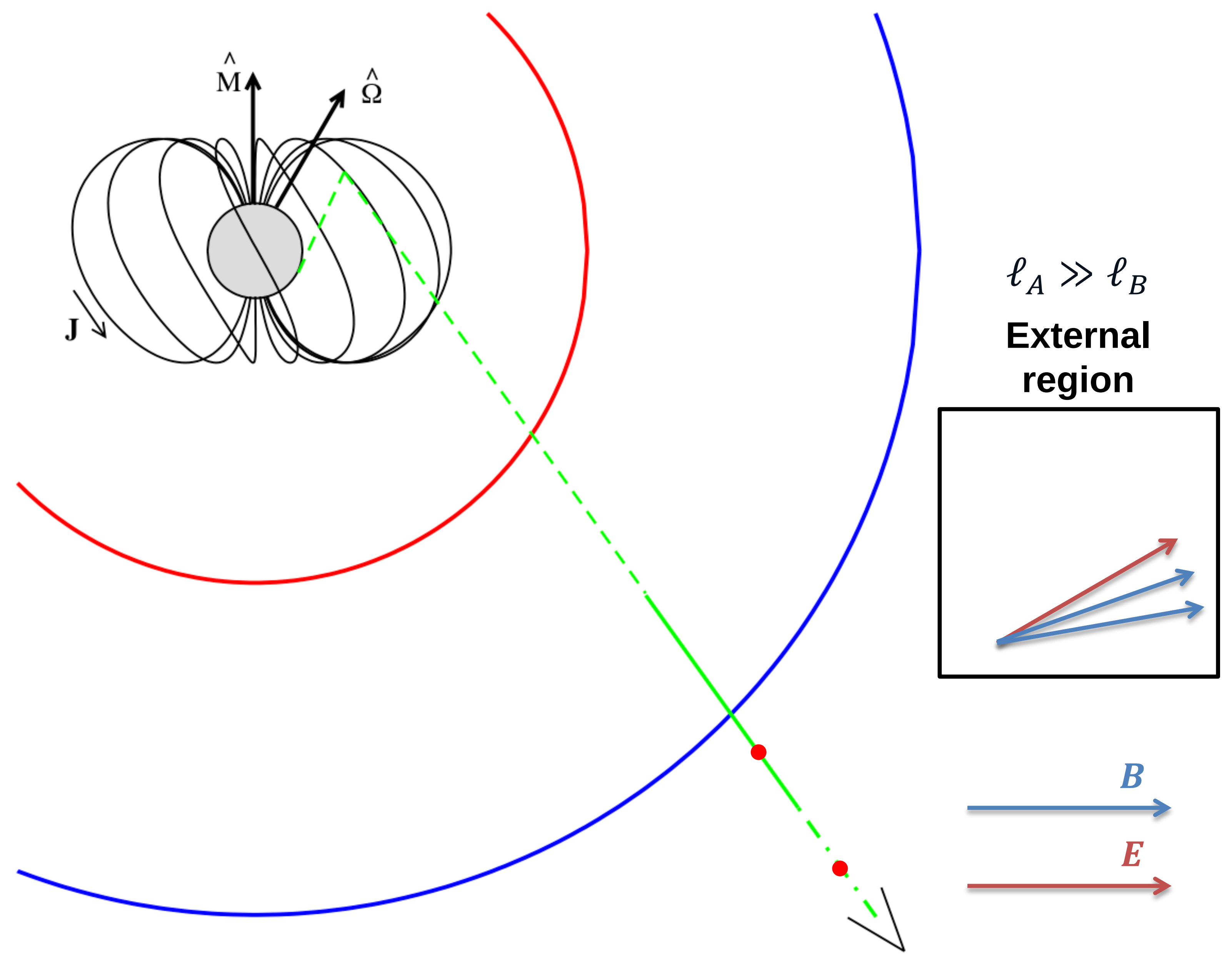


$\ell_A \approx \ell_B$

Intermediate region

Vac

- E g
ir



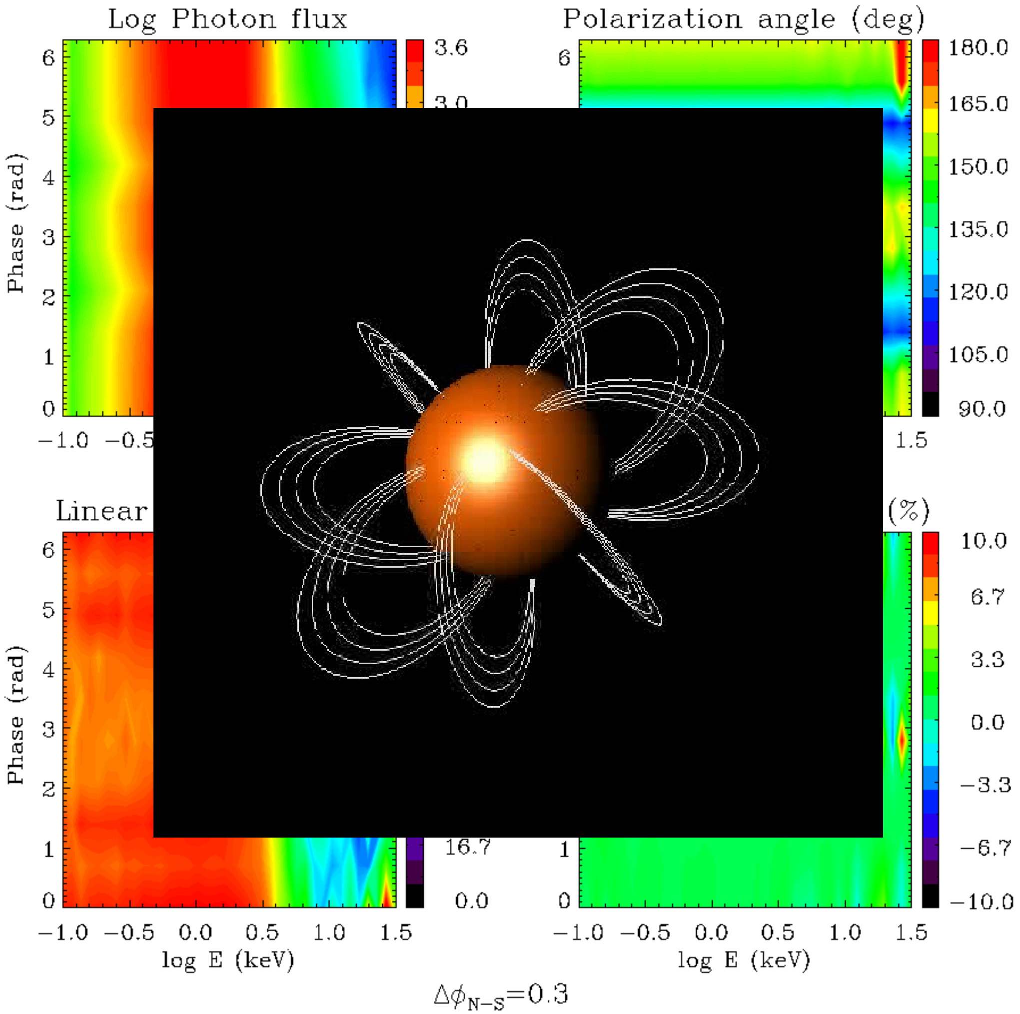
$\ell_A \gg \ell_B$

External region

Predictions for magnetars and isolated neutron star

Magnetars: persistent

- Magnetar persistent emission: reprocessing of surface thermal radiation by resonant compton scattering onto charges flowing into the twisted magnetosphere
- Scattering changes photon polarization state: $\sigma_{O-O} = \frac{1}{3}\sigma_{O-X}$, $\sigma_{X-X} = 3\sigma_{X-O}$
- PD and PA depend on twist angle, charge speed and geometrical angles (Fernandez & Davis 2011; Taverna et al. 2014)

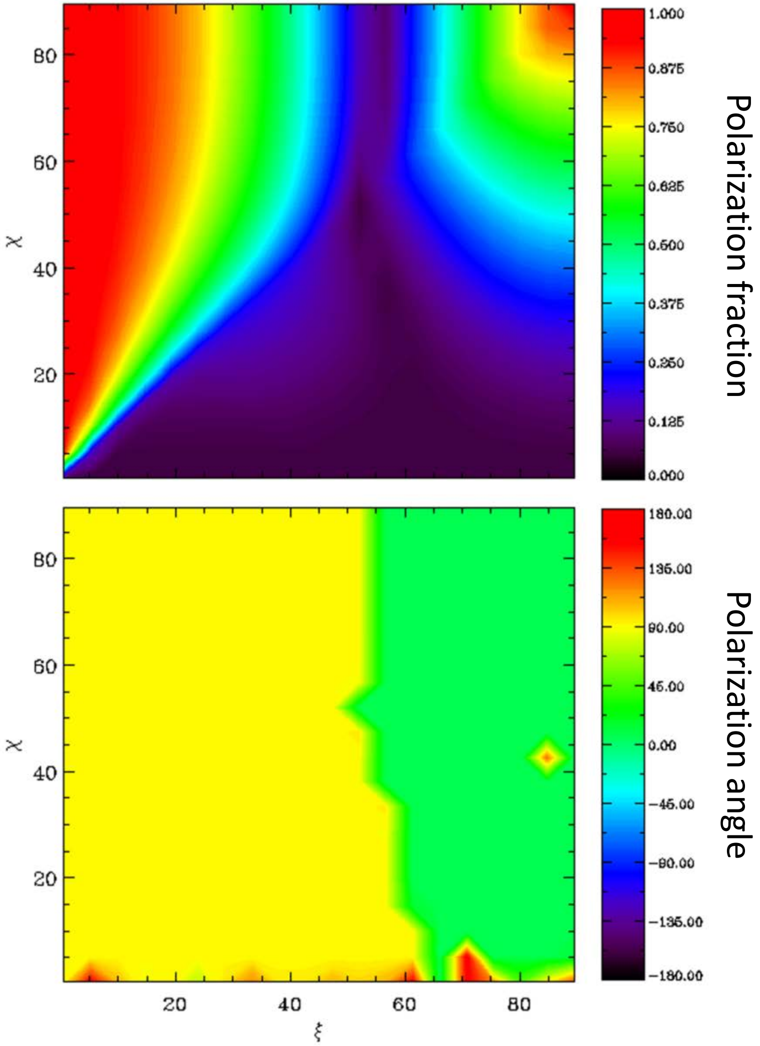


Adapted from Taverna et al. (2014)

Magnetars: bursts & flares

- Magnetar bursts/flares originate in a hot, magnetically-confined pair fireball (Thompson & Duncan 1995)
- Solve the radiative transfer for the two modes in the surface fireball layers (Lyubarsky 2002; Taverna & Turolla 2017)
- Because the scattering depth for the O-mode is >> than that for the E-mode, radiation is highly polarized. Spectrum ‘BB+BB’-like (Israel et al. 2007)

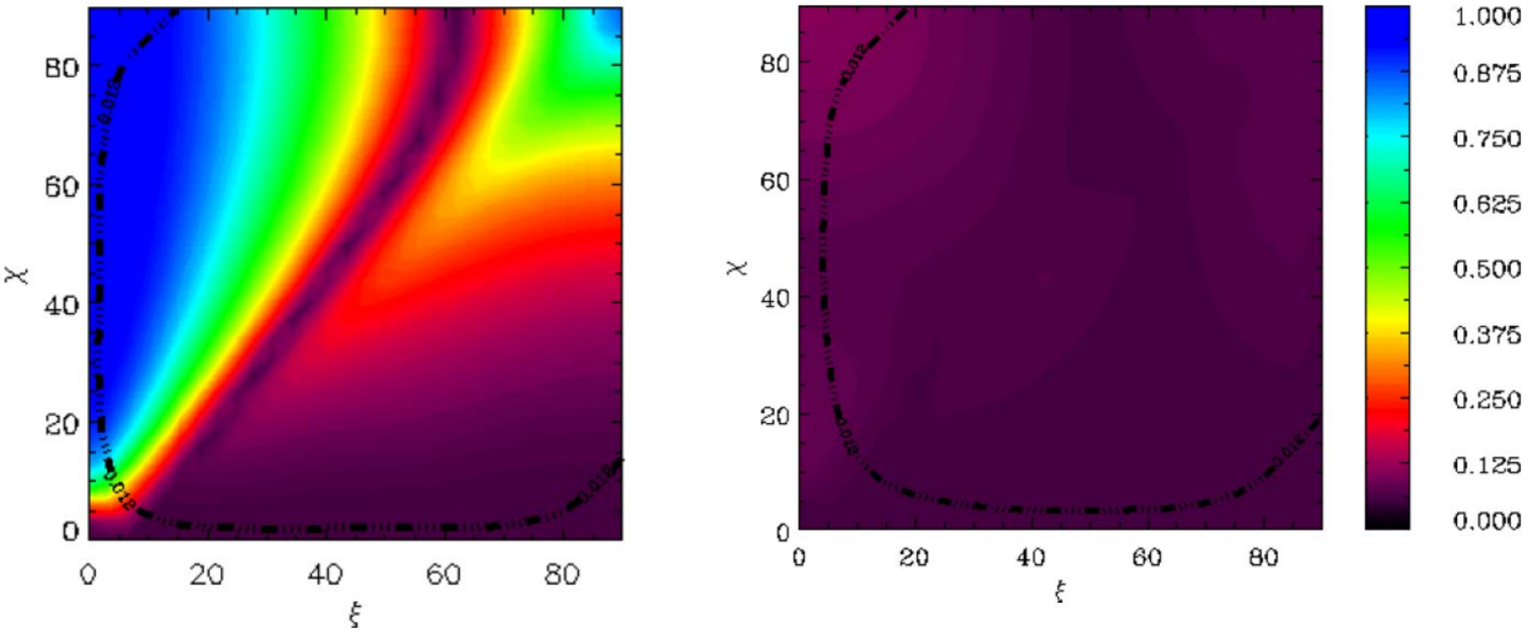
More in Roberto Taverna’s talk !



Thermally emitting isolated NSs

- The XDINSs: seven close-by sources with soft thermal spectrum, kT ≈ 50-100 eV, and period P ≈ 3-12 s (e.g. T
- E
  i
  l
- F
  a

Phase-averaged polarization fraction (González Caniulef et al. 2016)



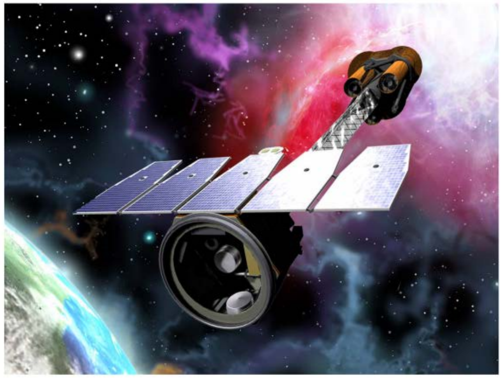
H atmosphere

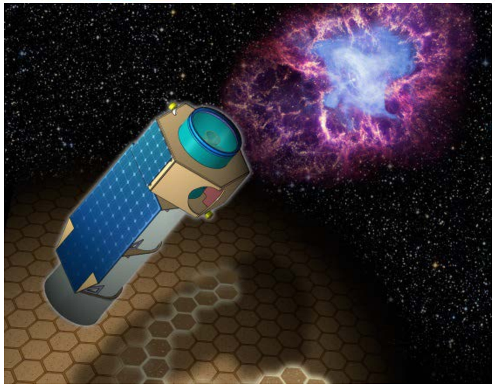
Condensed surface (fixed ions)

X-ray missions

X-ray polarimetric missions

- IXPE (Imaging X-ray Polarimetry Explorer), selected as NASA SMEX mission (launch expected late 2020)
- XIPE (X-ray Imaging Polarimeter Explorer), competing for ESA M4 (if selected launch expected late 2020)
- eXTP (enhanced X-ray Timing and Polarimetry mission), Strategic Priority Space Science Program of the Chinese Academy of Sciences (launch expected within 2025)





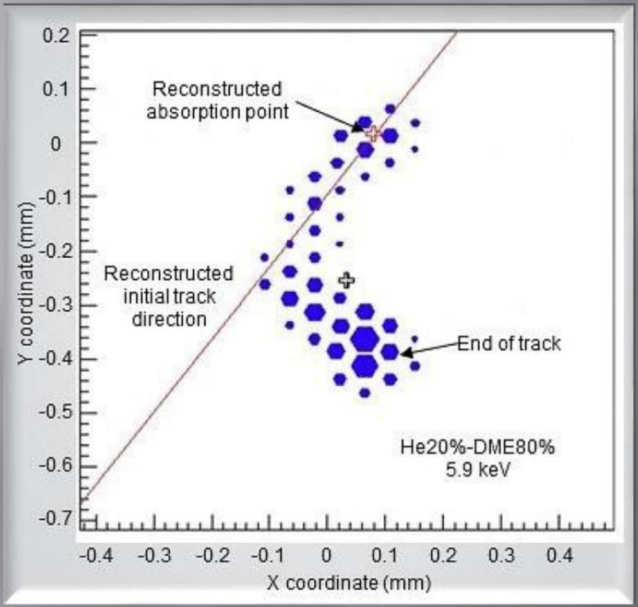
X-ray polarimetric missions

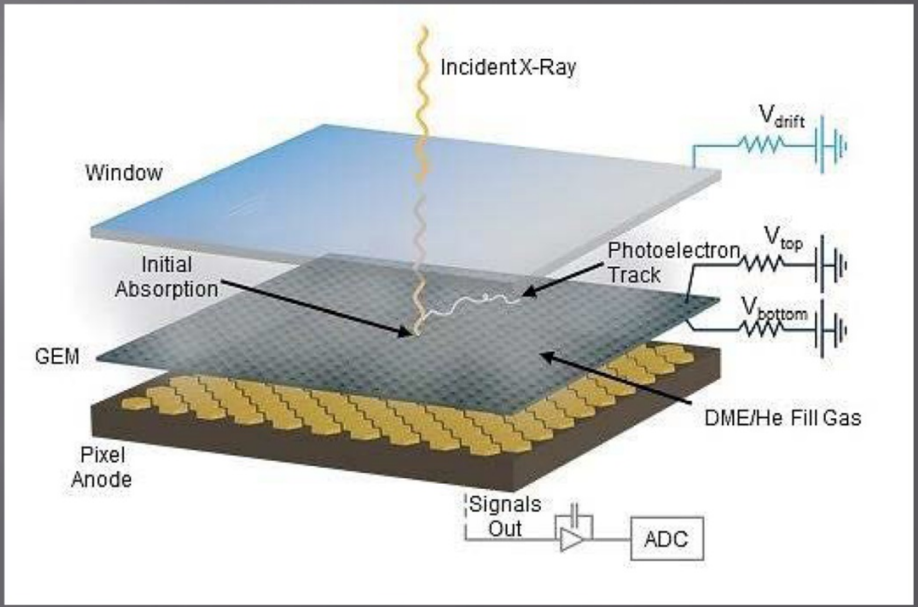
Mission	Effective area (cm^2)	Energy range (keV)	Angular resolution (arcsec)	Polarimeter
IXPE	690@2.3keV 3 units	2-8	< 25	GPD
XIPE	> 1100@3keV 3 units	2-8	< 30	GPD
eXTP	900@2keV 4 units	2-10	< 30	GPD

The three missions use the same Gas Pixel Detector polarimeter developed by INAF-IAPS (GPD; Costa et al. 2001; Bellazzini et al. 2005; Fabiani et al. 2014)

Gas pixel detector

- Detection uses photoelectric effect
- X-rays absorbed in detector fill gas
- Photoelectron emission aligned with X-ray polarization vector
- Electron multiplier with pixelated detector
- Analysis of the distribution of the initial directions of the tracks gives the degree of polarization and the position angle for the incident X ray



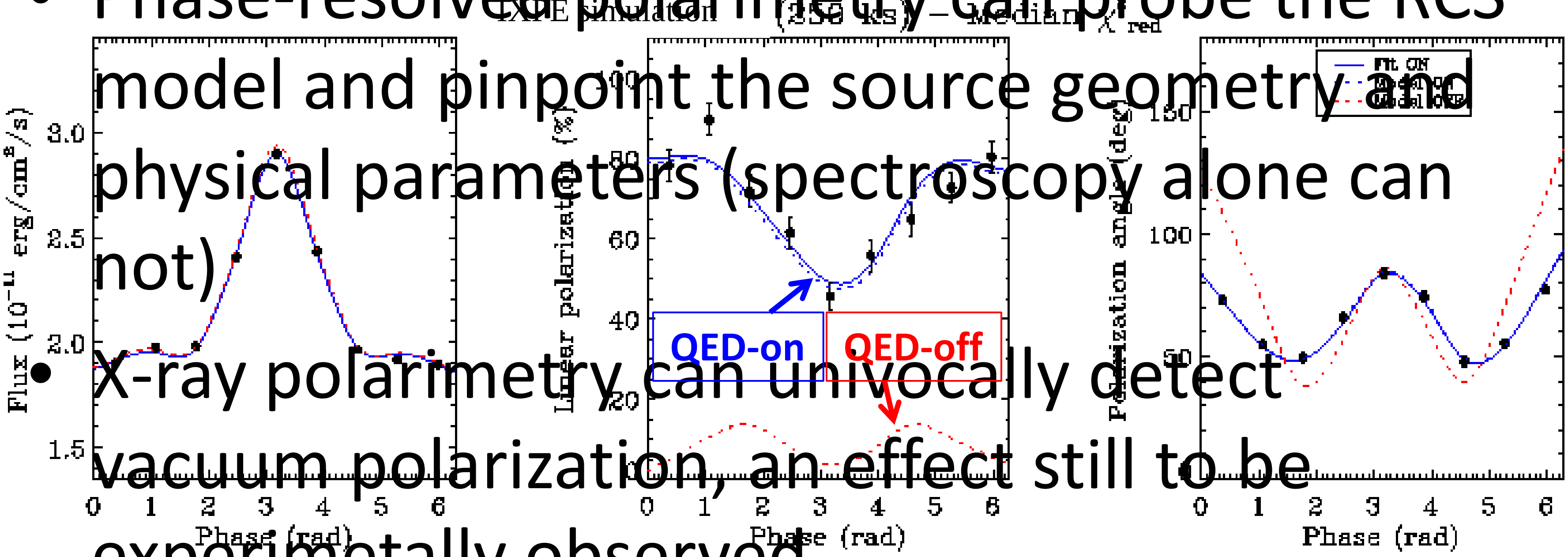


What we will measure (and what we have already measured)

Magnetars: persistent

XIPE and IXPE simulations for a bright magnetar source (AXP 1RXS J1708)

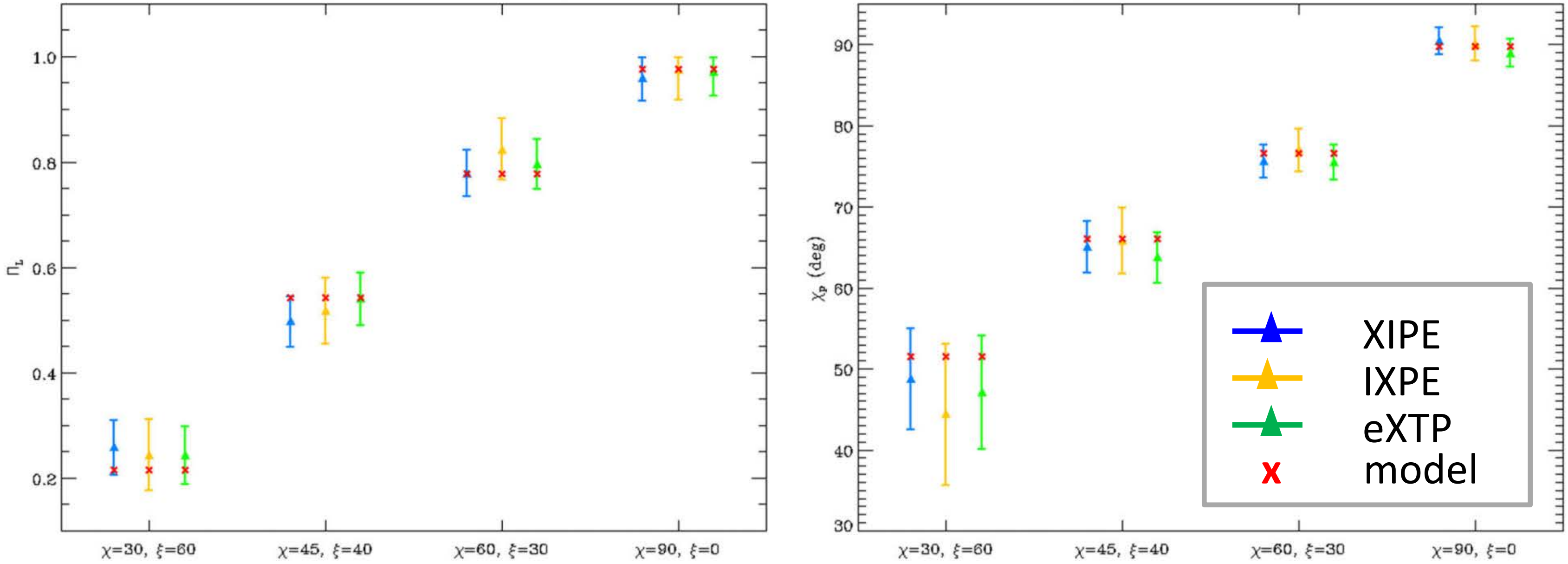
- Phase-resolved polarimetry can probe the RCS model and pinpoint the source geometry and physical parameters (spectroscopy alone can not)
- X-ray polarimetry can univocally detect vacuum polarization, an effect still to be experimetally observed



	β	$\Delta\phi_{\rm N-S}$ (rad)	χ (deg)	ξ (deg)	$\chi^2_{\rm red}$
Input value	0.34	0.5	90	60	—
Fit value	0.35 ± 0.005	0.47 ± 0.013	91.68 ± 1.52	58.54 ± 0.78	1.13

Magnetars: bursts & flares

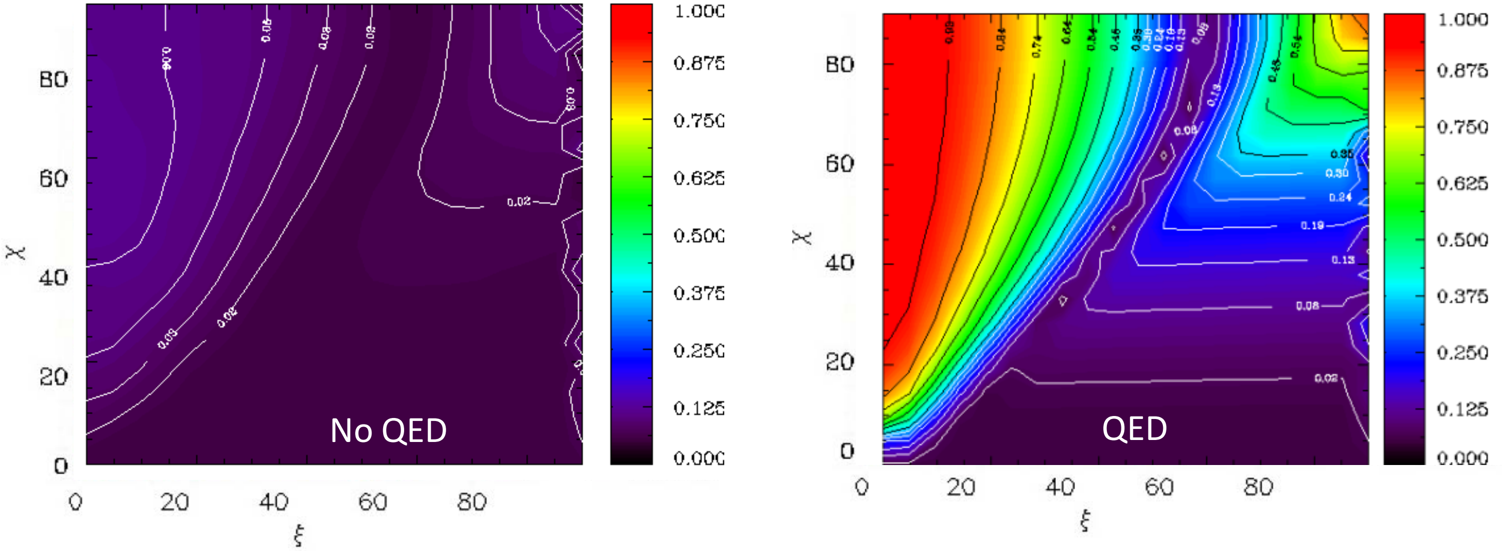
- Polarimetry will get insight on the physical processes at work in bursts
- Simulations for the intermediate flare IF1 from SRG 1900+14 (Israel et al. 2007; Taverna & Turolla 2017)



Thermally emitting INSs

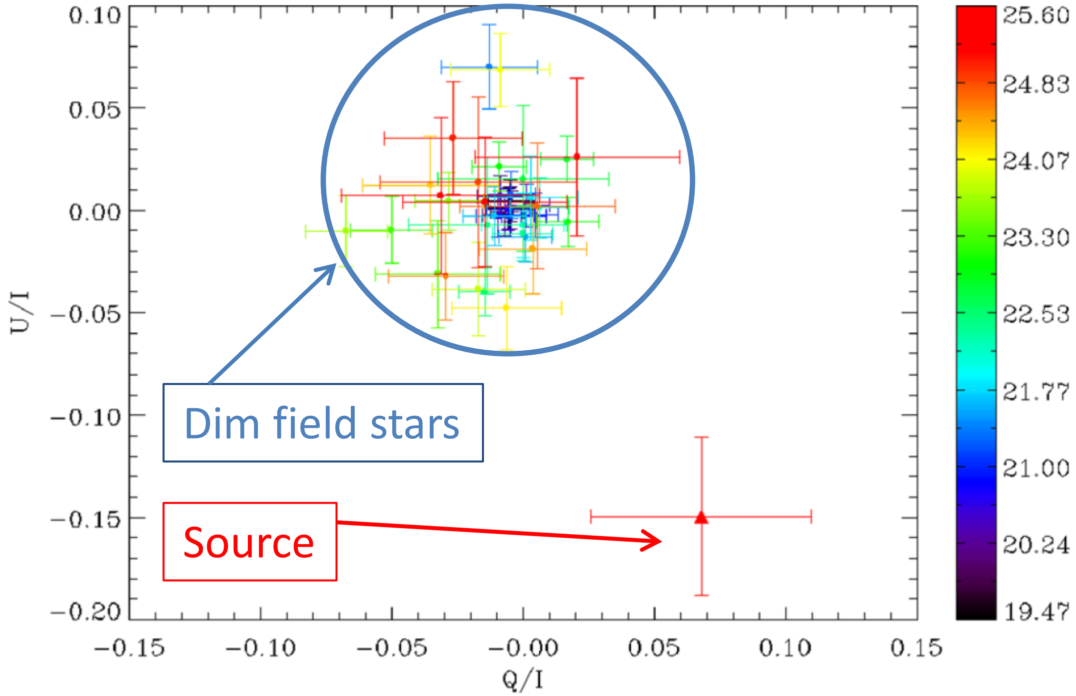
- Thermal emission from the XDINSs too soft for the GPD. Need to wait for future soft X-ray polarimeters (e.g. Marshall et al. 2015)

Phase-averaged polarization fraction (Taverna et al. 2015)



Vacuum polarization detected in the optical ?

- Observations of the XDINS RX J1856 in the B band with the VLT revealed a relatively high polarization degree, 16.43±5.26% (Mignani et al. 2017)

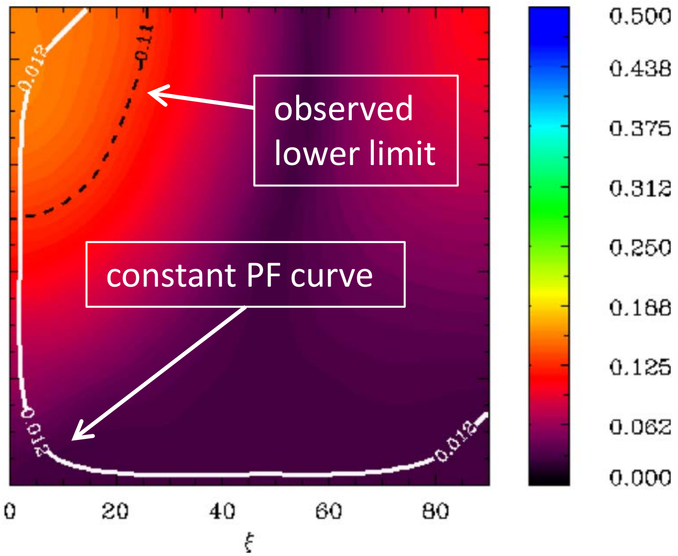


Dim field stars

Source

Vacuum polarization detected in the optical ?

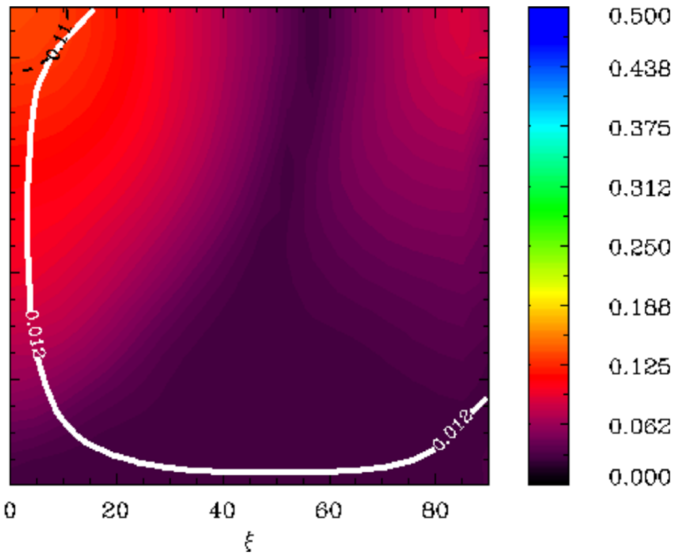
- Current surface emission models hardly compatible with such a high polarization degree **if no QED effects are accounted for** when contraints from the X-ray pulsed fraction are included



observed lower limit

constant PF curve

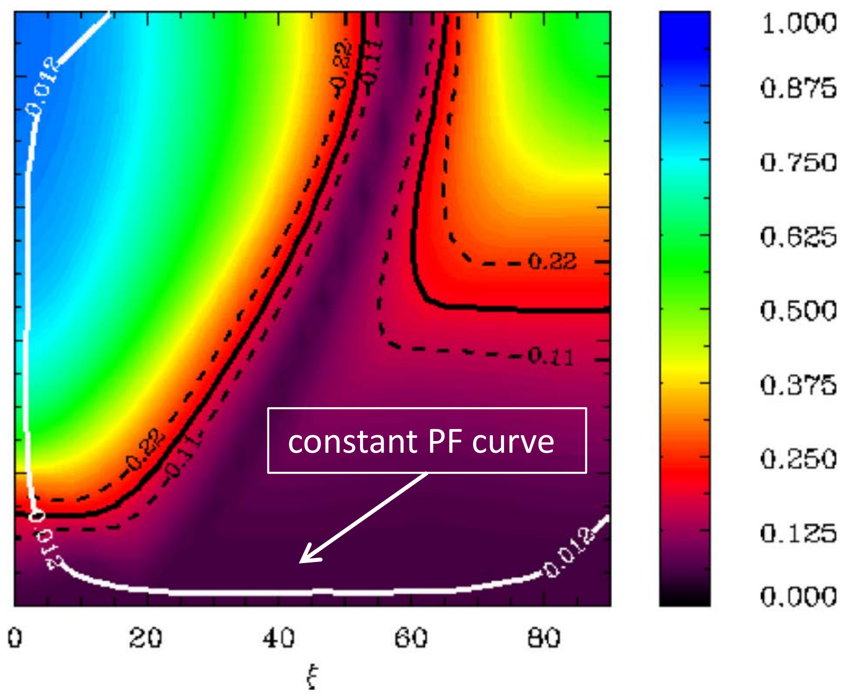
Magnetic H atmosphere



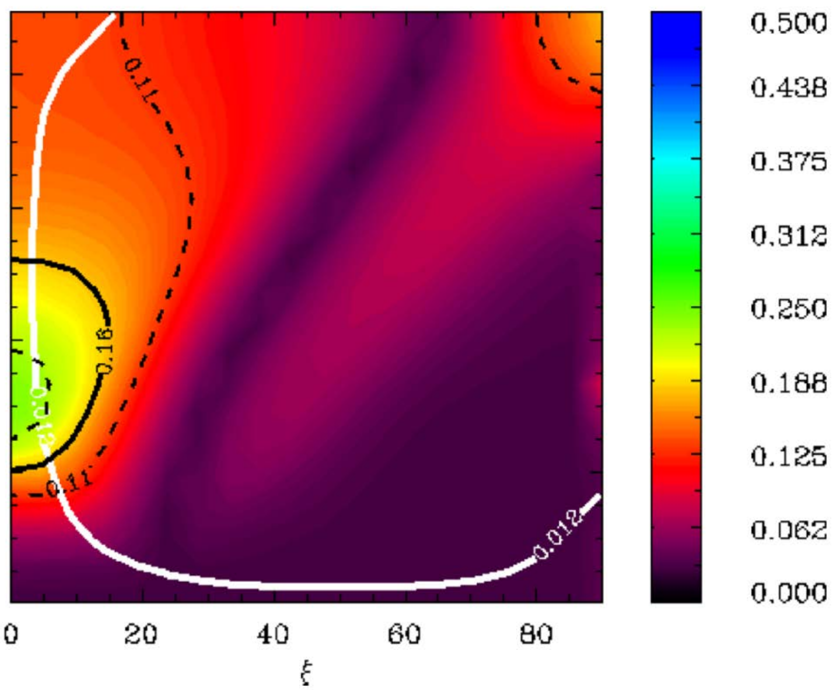
Condensed surface (fixed ions)

Vacuum polarization detected in the optical ?

- On the other hand they work quite well when vacuum polarization is there !



Magnetic H atmosphere



Condensed surface (fixed ions)

Conclusions

Conclusions

Conclusions

- X-ray polarimeters will target several magnetar sources, allowing a firm detection of vacuum birefringence
- Polarization measurements will provide crucial tests for current models for magnetar persistent and bursting emission
- Future missions will extend polarimetry to the soft X-ray band and target thermally emitting INSs, probing their emission mechanism and providing further checks of vacuum birefringence