Neutron Stars: Cosmic Laboratories To Test QED Vacuum Birefringence

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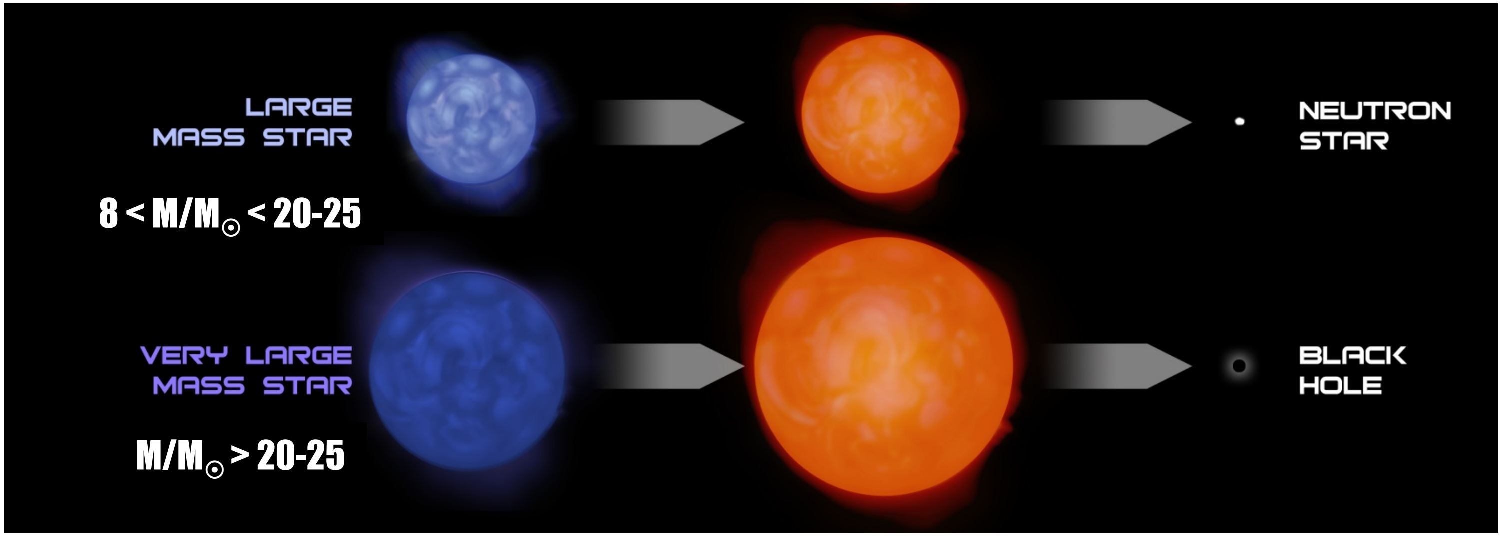
Outline

- ❑ Neutron stars basics
- ❑ The intrinsic and observed polarization signal
- ❑ Predictions for isolated neutron stars
- ❑ Measuring polarization in RX J1856 and vacuum birefringence

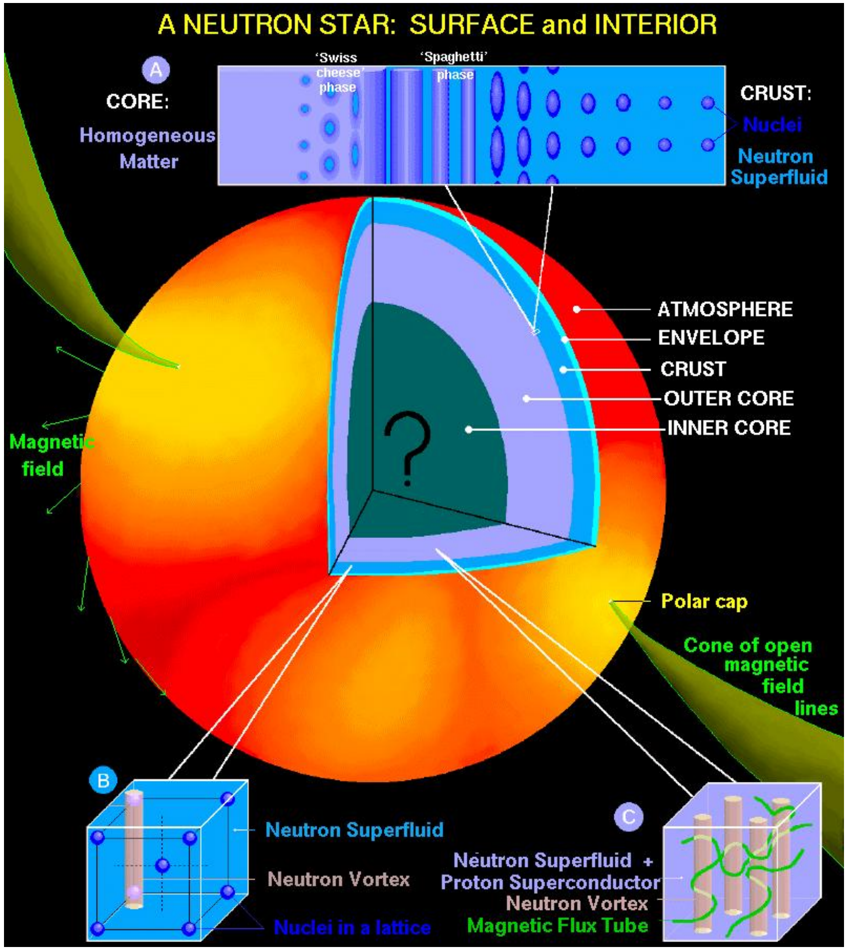
Neutron star basics

- Compact objects are born in the core collapse following a supernova explosion
- Present rate of SN events in the Galaxy: ≈ 0.01/yr (possibly higher in the past)
- Galactic population of compact objects: ≈ $10^8 - 10^9$ (≈ 1% of stars)
- Nature of compact remnant depends on progenitor mass



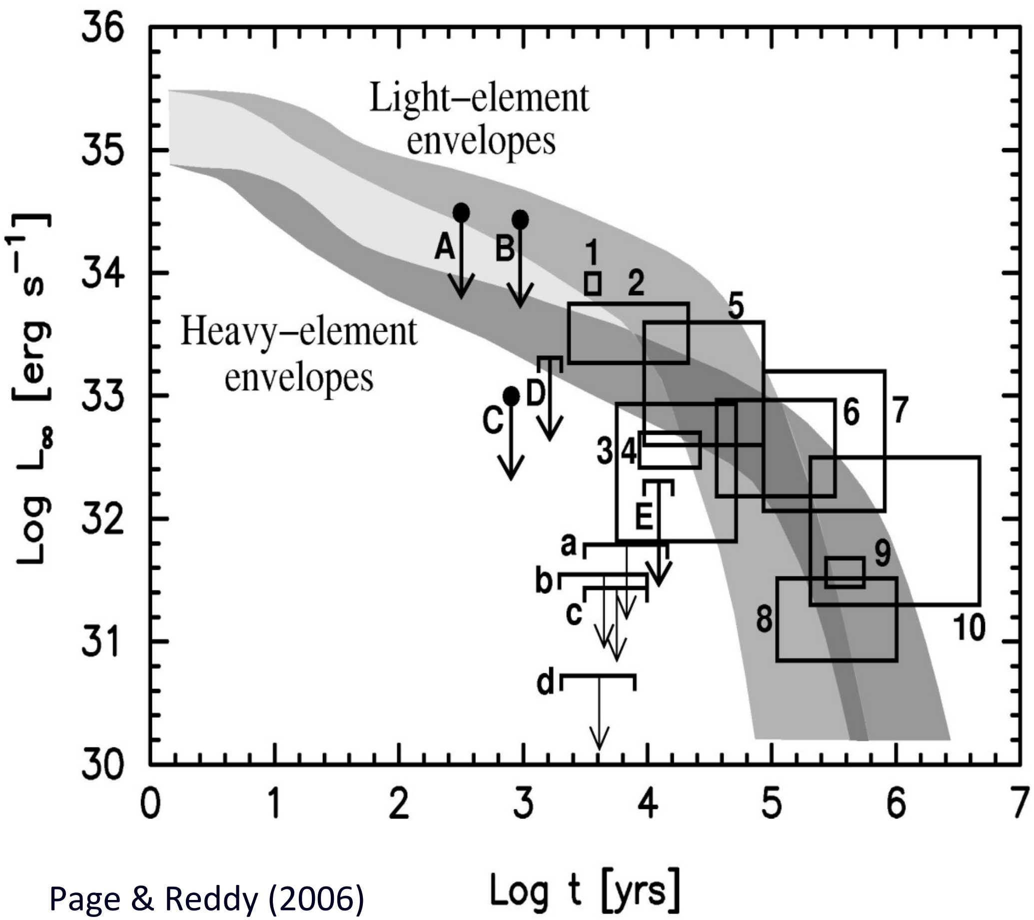
Neutron Stars in a Nutshell

- Vast majority (~ 80-90%) of Galactic compact objects are neutron stars
- Typical radius ≈ 10 km, masses in the range $1.2 < M/M_\odot < 2$ (observed, $0.1 < M/M_\odot < 3$ theoretical)
- Densest objects known, $\rho_c \sim 10^{15}$ g/cm^3
- Strongest magnets in the present universe, surface magnetic field 10^8 G<B<10^{15} G



NS Cooling

- NSs are born very hc T > 10^{10} K
- Cooling history sensitive to NS equation of state
- Neutrino cooling at early stages, photon cooling later on
- Middle-age NSs (≈ 10^5-10^6 yr) shine in the soft X-rays (0.1-1 keV)



Page & Reddy (2006)

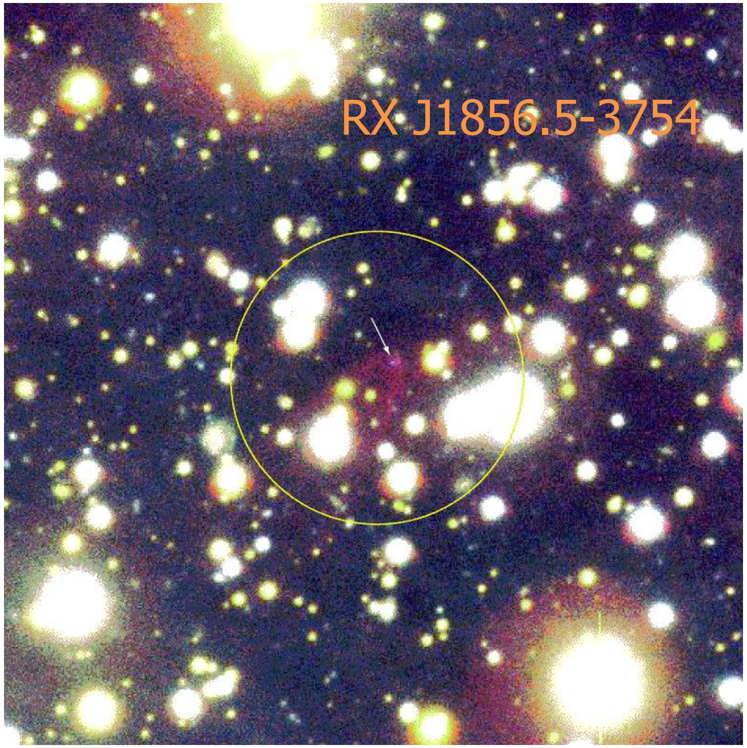
The NS Zoo

- Most neutron stars are known through their pulsed radio-emission (radio-pulsars)
- Observations in the X- and γ-rays revealed the existence of different populations of isolated neutron stars
  - Central Compact Objects (CCOs)
  - X-ray dim isolated neutron stars (XDINSs)
  - Soft γ-repeaters (SGRs) and Anomalous X-ray pulsars (AXPs)
  - Rotating Radio Transients (RRATs)

The Magnetars

XDINSs aka The Magnificent Seven

- Soft thermal spectrum (kT [?] 50-100 eV)
- Radio-quiet, no association with SNRs
- Close-by, D ≈ 100-500 pc
- Very faint optical counterparts
- Brightest source RX J1856.5-3754, V = 25.6



Intrinsic and observed polarization

Photon polarization modes

- Radiation emitted by the star surface layers is expected to be polarized because the strong magnetic field

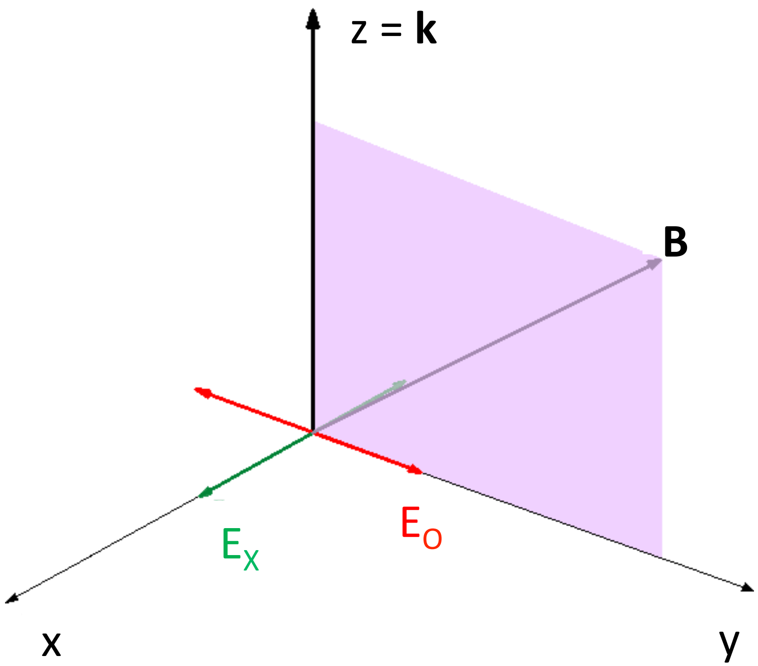
  - Changes the cross-sections and hence the way photons interact with matter

  - 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 $\omega \ll \omega_{ce}$ the two normal modes are almost linearly polarized: the extraordinary (X) and ordinary (O) modes

Photon polarization modes



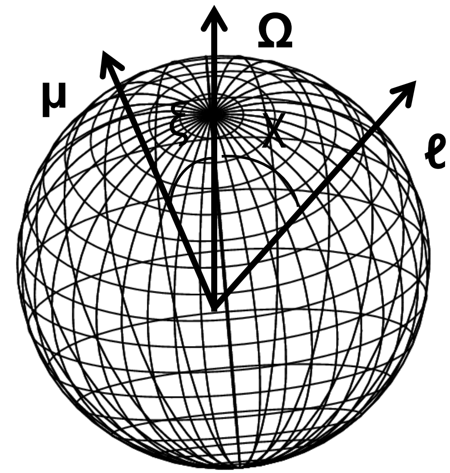
- O-mode opacity almost unaffected by the magnetic field
- X-mode opacity strongly reduced by a factor ≈ ω^2/ω_{ce}^2
- Intrinsic polarization depends on the surface emission model (and on the possible reprocessing in the magnetosphere)
- Either an atmosphere or a condensed surface (bare NS), maybe covered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

Intrinsic polarization of surface emission

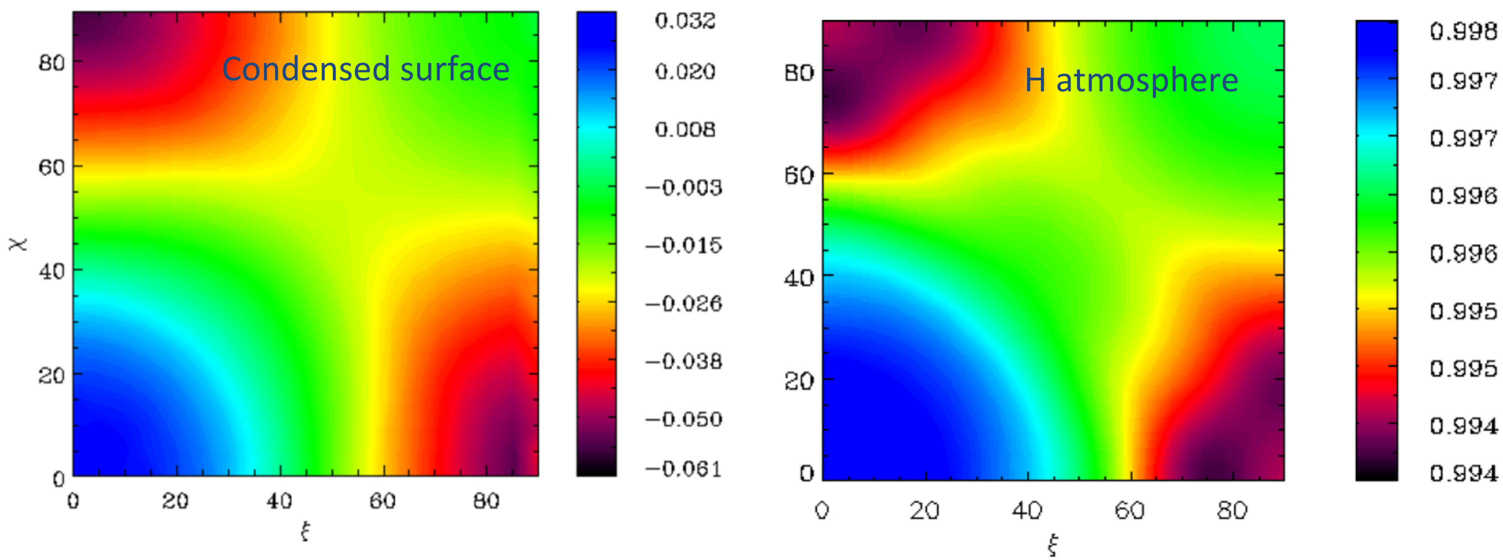
Emission properties depend on local **B** and T

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



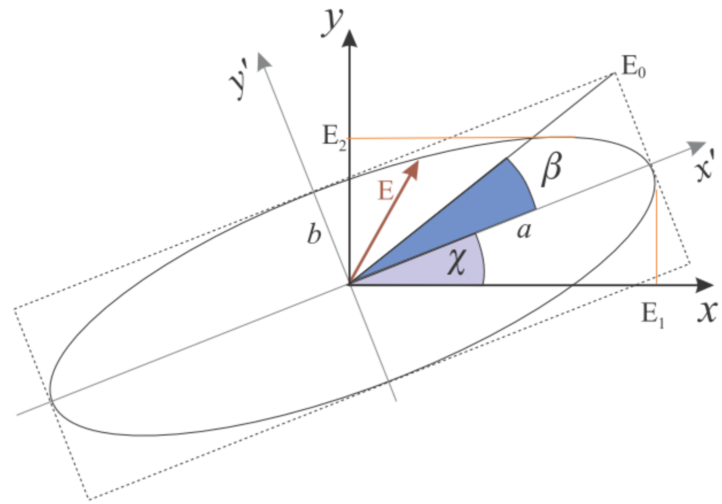
Phase-averaged intrinsic polarization (soft X-rays; Gonzalez Canjulef et al. 2016)



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):

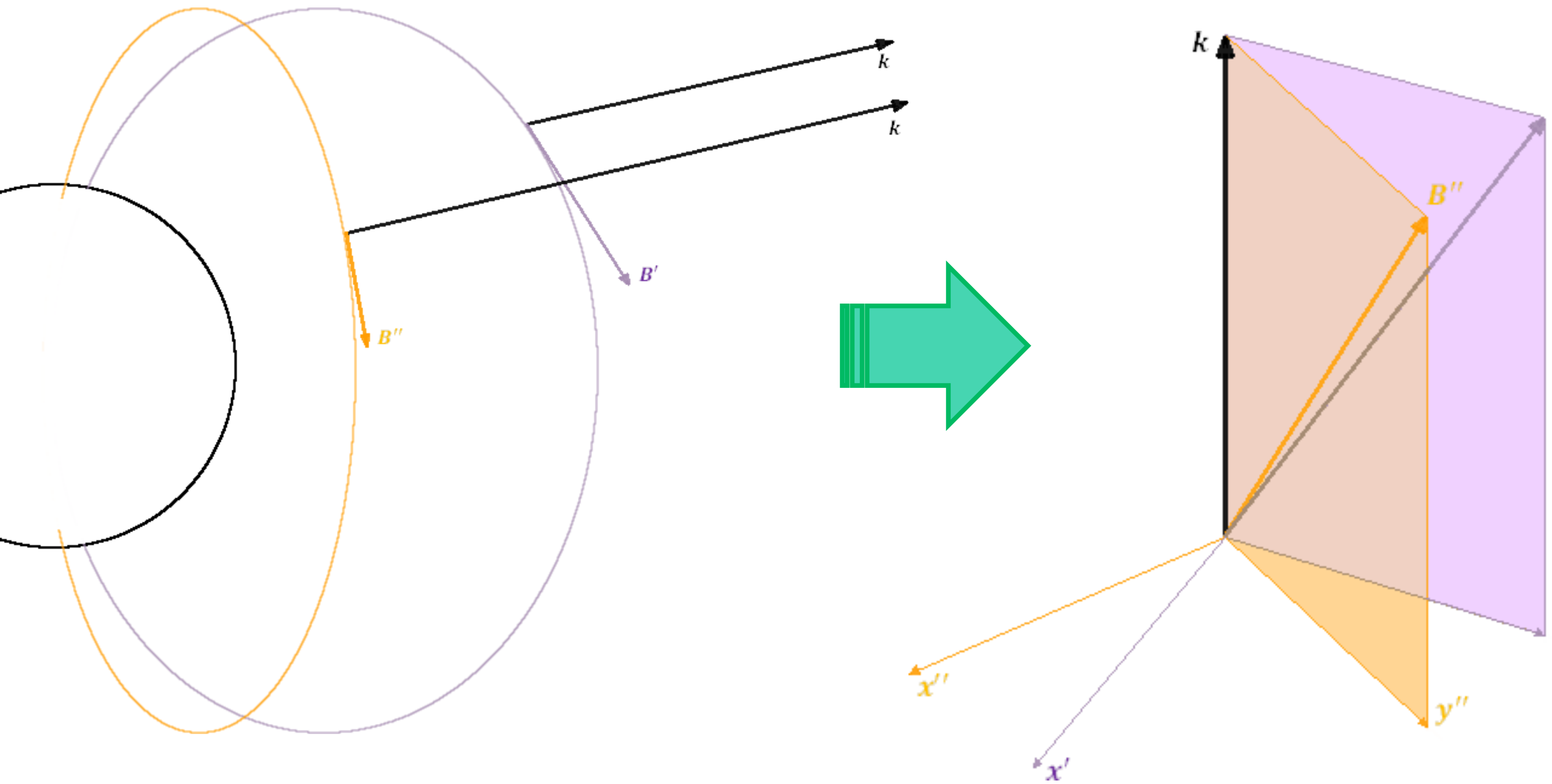
$$I = S_x + S_y = S = a_x^2 + a_y^2$$
$$Q = S_x - S_y = A_x A_x^* - A_y A_y^* = S\cos 2\beta\cos 2\chi = a_x^2 - a_y^2$$
$$U = A_x A_y^* + A_y A_x^* = 2\Re(A_x A_y^*) = S\cos 2\beta\sin 2\chi = 2a_x\,a_y\cos(\varphi_x - \varphi_y)$$
$$V = i\,(A_x A_y^* - A_y A_x^*) = 2\Im(A_x A_y^*) = S\sin 2\beta =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

- 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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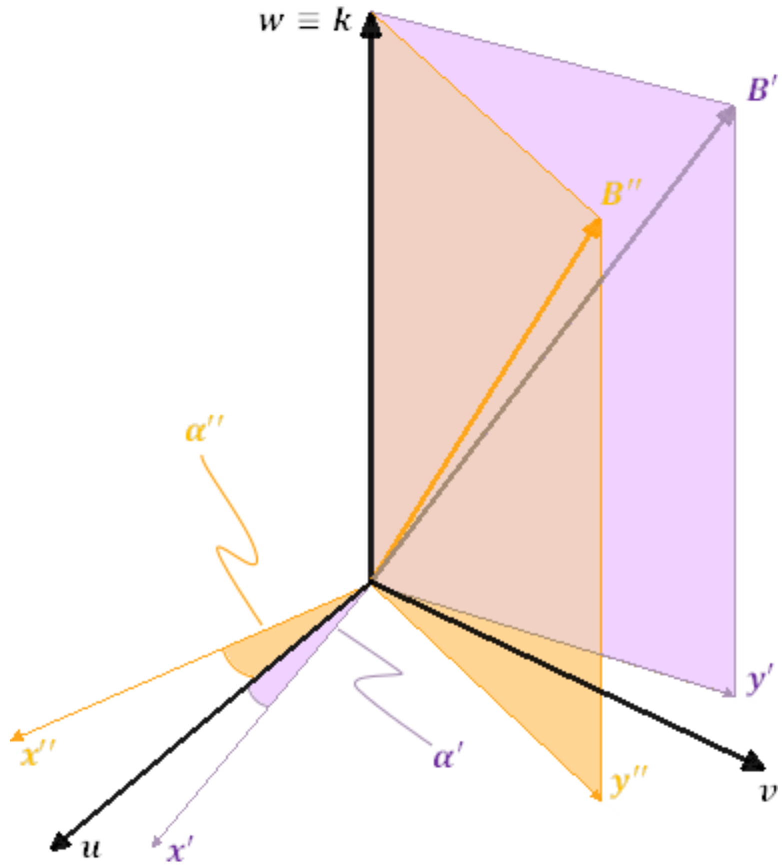


Stokes parameters rotation

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

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

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

Polarization observables

- The polarization properties of NS emission are described by the polarization fraction and polarization angle
- $\Pi_L = \sqrt{Q^2 + U^2} / I$
- $\chi_p = 1/2 \arctan(U/Q)$
- Only in the case $\alpha_i = const$ the observed Π_L and χ_p coincide with the intrinsic ones. If not (as in the case of a varying B-field) **STRONG DEPOLARIZATION**

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)

$$dQ/dz = -k_0 \delta/2\,(2PV)$$

$$dU/dz = -k_0 \delta/2\,(N-M)V$$

$$dV/dz = k_0 \delta/2\,[2PQ + (N-M)V]$$

$k_0 = \omega/c$

Two lengthscales

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

$\delta \propto B^2$

$\ell_B = B/|k \cdot \nabla B| \sim r$

z coordinate along the ray

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

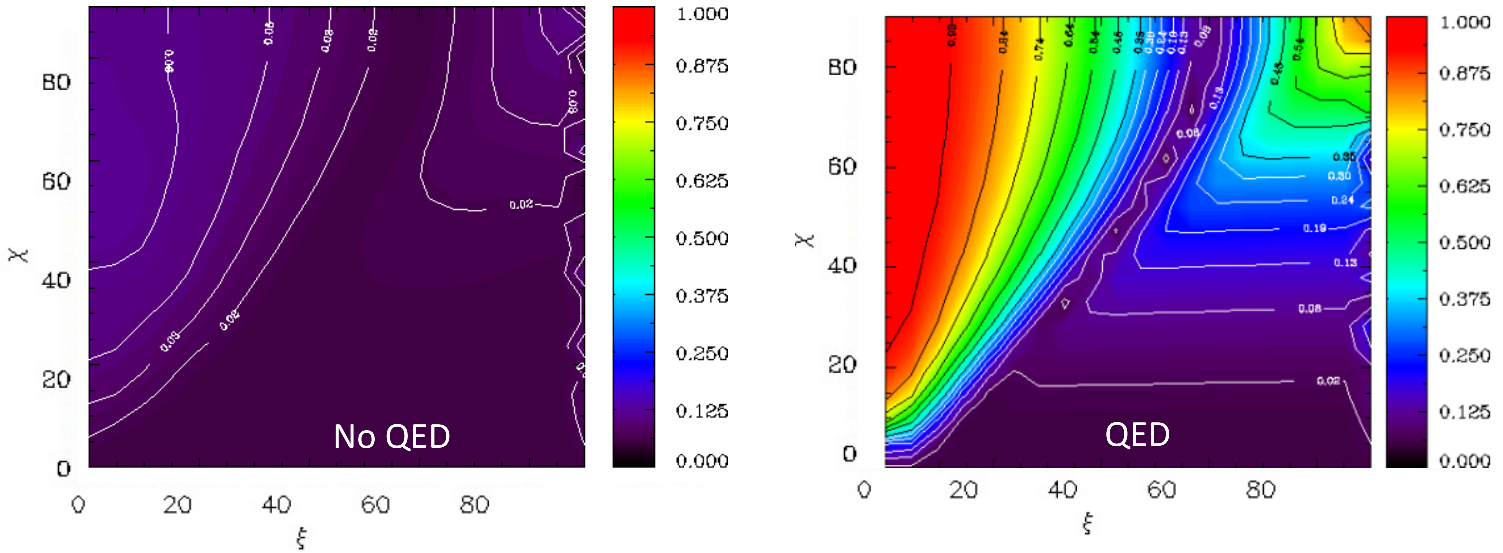
Polarization limiting radius

Predictions for isolated neutron stars

Polarization and QED

- QED effects force the photon to keep its initial polarization up to the polarization-limiting radius r_a
- Rotation of the Stokes parameters must be performed at r_a,

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



Polarization in thermally emitting INSs

- Thermal emission from NSs is peaked at ≈ 0.1-1 keV: ideal targets for X-ray polarimetry
- IXPE, a NASA SMEX mission, the first observatory devoted to X-ray polarimetry, scheduled to fly late in 2020 (Weisskopf et al. 2016)
- IXPE carries a gas pixel detector (GPD) polarimeter working in the 2-8 keV band (Co al. 2014)

Excellent for magnetars

- XDINSs are too soft for the GPD. Need to wait for future soft X-ray polarimeters (e.g. XPP, Krawczynski et al. 2019)
- No radio emission… Look in the optical

XDINSs in the Optical

Phase-averaged polarization fraction (Gonzalez Canjulef et al. 2016)

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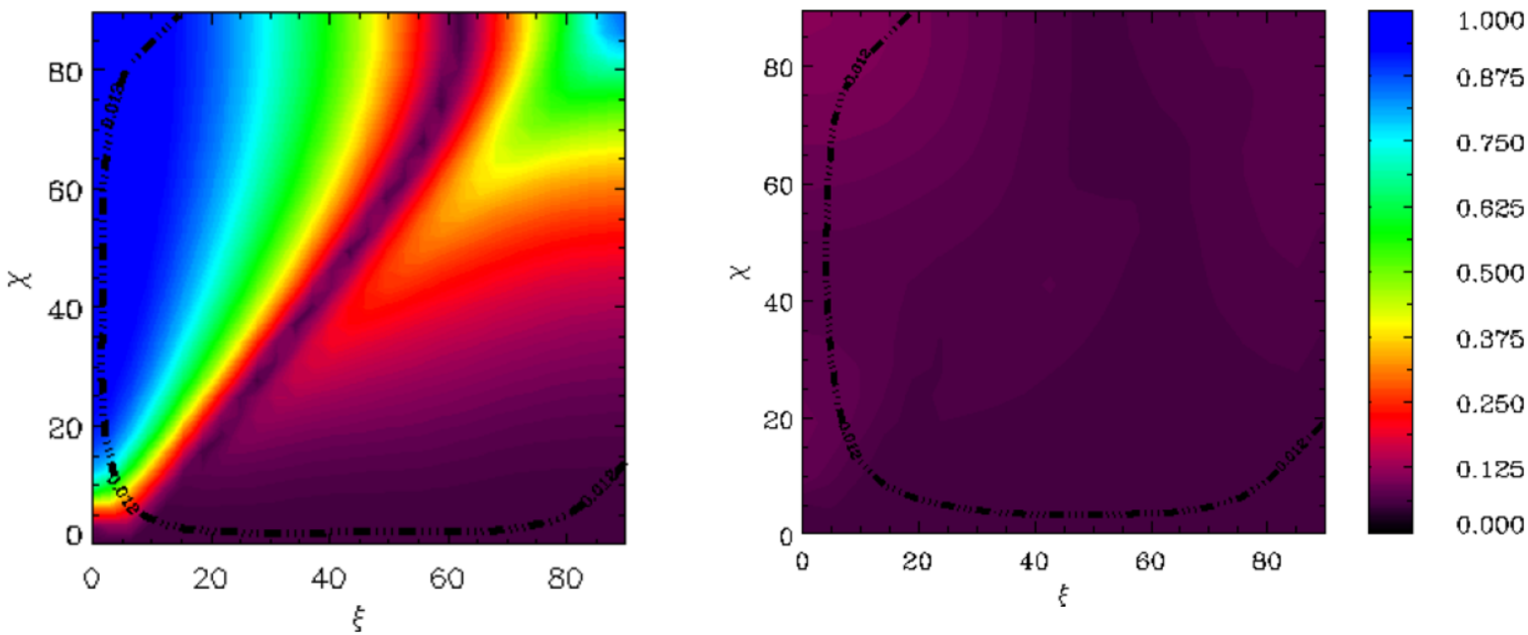


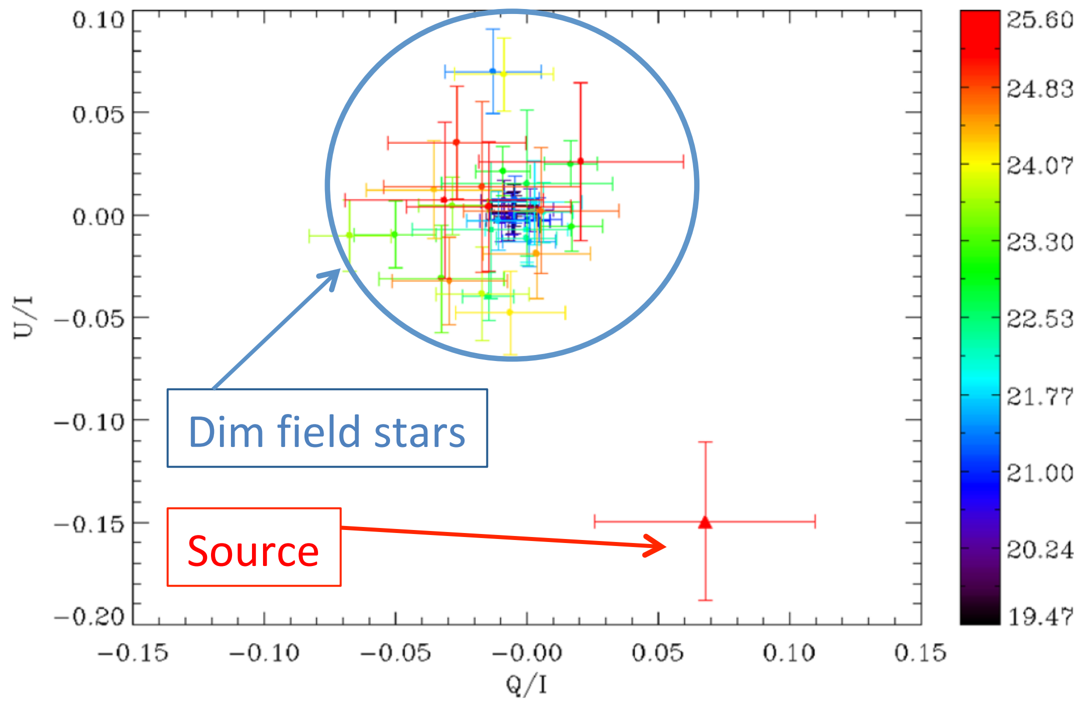
Magnetic H atmosphere

Condensed surface (fixed ions)

Measuring polarization in RX J1856 and vacuum birefringence

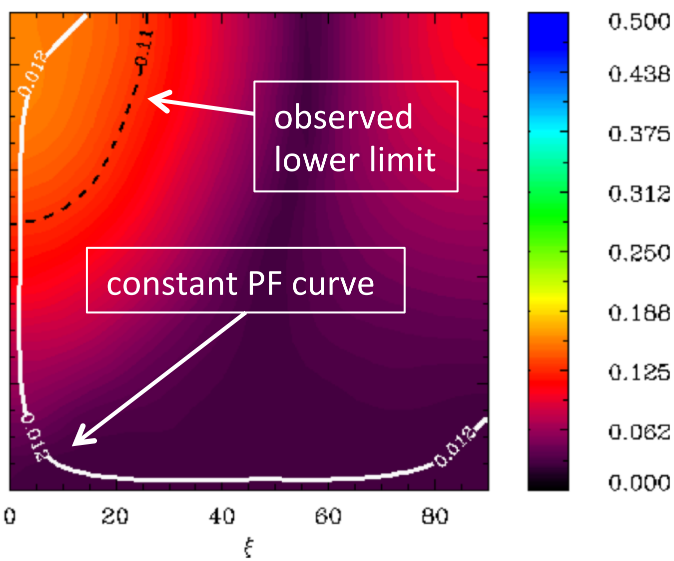
Vacuum polarization detected in the optical ?

- Observations of the XDINS RX J1856 in the B band with the VLT revealed a relatively high polarization degree, 16[?]5% (Mignani et al. 2017)



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



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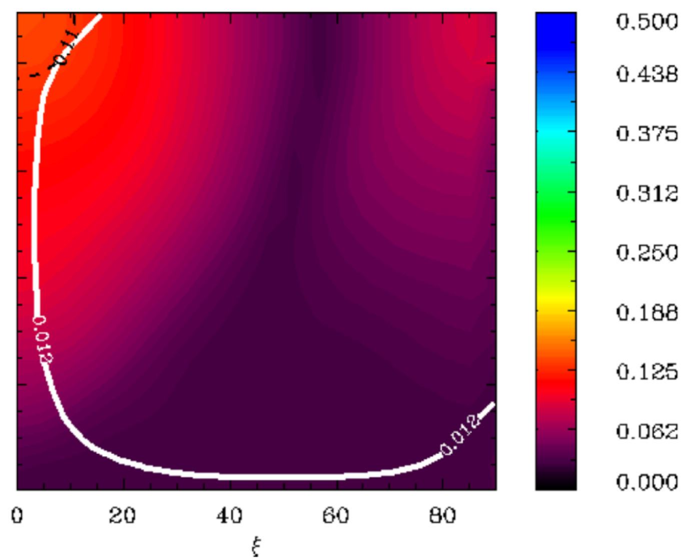
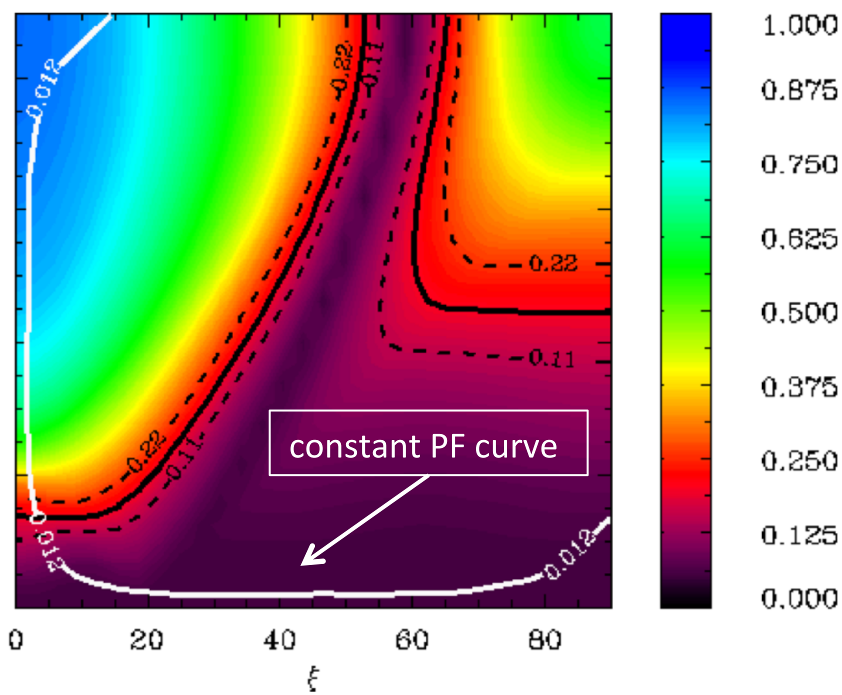


Condensed surface (fixed ions)

Vacuum polarization detected in the optical ?

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



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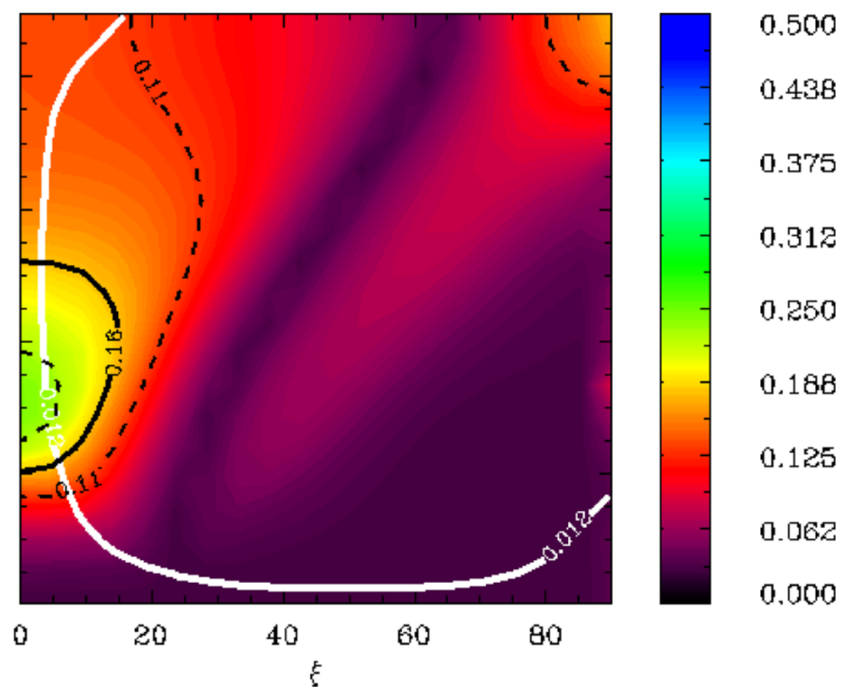

Condensed surface (fixed ions)

Conclusions

Conclusions

- Polarimetry of NS sources can allow a firm detection of vacuum birefringence
- Magnetar sources (AXPs and SGRs) will be a primary science target for IXPE
- 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
- New optical data for RX J1856 already available. More results soon.