Polarized thermal emission from strongly magnetized neutron stars

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Outline

1) X-ray Isolated Neutron Stars (XDINSs and magnetars).

- Surface emission models
- Vacuum birefringence outside the star.
- Observable polarization signal: *Optical* & *X-ray expectations (for XDINSs)*.

2) Optical polarimetry of RX J1856.5-3754 with the VLT.

- First evidence for vacuum birefringence.

3) Transient magnetars & eXTP

- Untwisting magnetosphere.
- Expectations for X-ray polarimetry.

4) Conclusions.

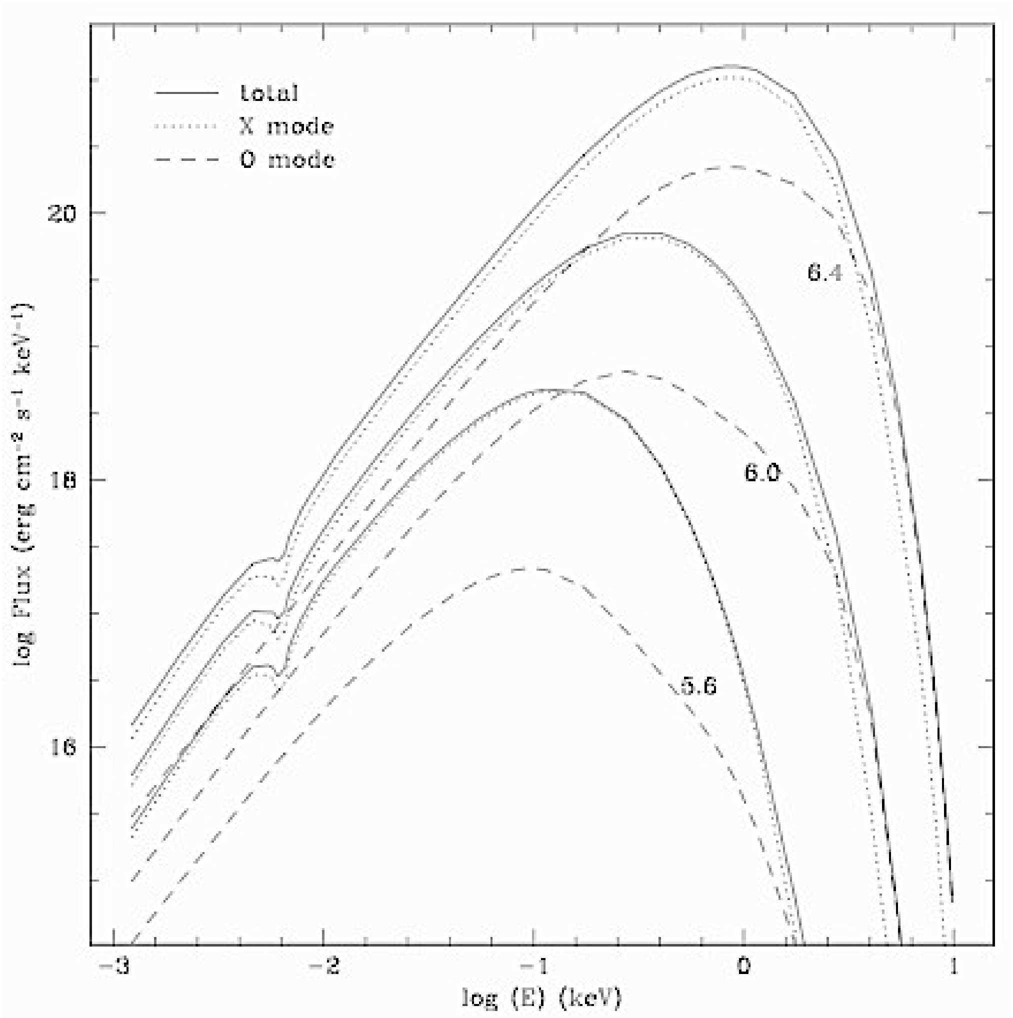
Introduction

- **X-ray isolated NSs (XDINSs & Magnetars).**
  - Strongly magnetized NSs: $B \sim 10^{13} - 10^{14} G.$
  - XDINSs thermal emission observed in X-ray & Optical bands: $T \sim 10^{6}\ K$.
  - Magnetars thermal component $T \sim 10^{7}\ K.$
- **Puzzling**
  - Atmosphere or Condensed surface? (depending on the temperature, magnetic field may drive a phase transition at the NS surface).
- **Magnetic field strong enough to induce QED vacuum birefringence.**
  - Polarization properties strongly modified as radiation travel through the magnetosphere.

Magnetized atmosphere

- **Strongly magnetized and fully ionized plasma.**
  - Free-free & scattering opacities.
- **Radiative transfer equation:**
  - A system of two-coupled differential equations for O-mode and X-mode.
  - Plane parallel atmosphere in local thermodynamic equilibrium.

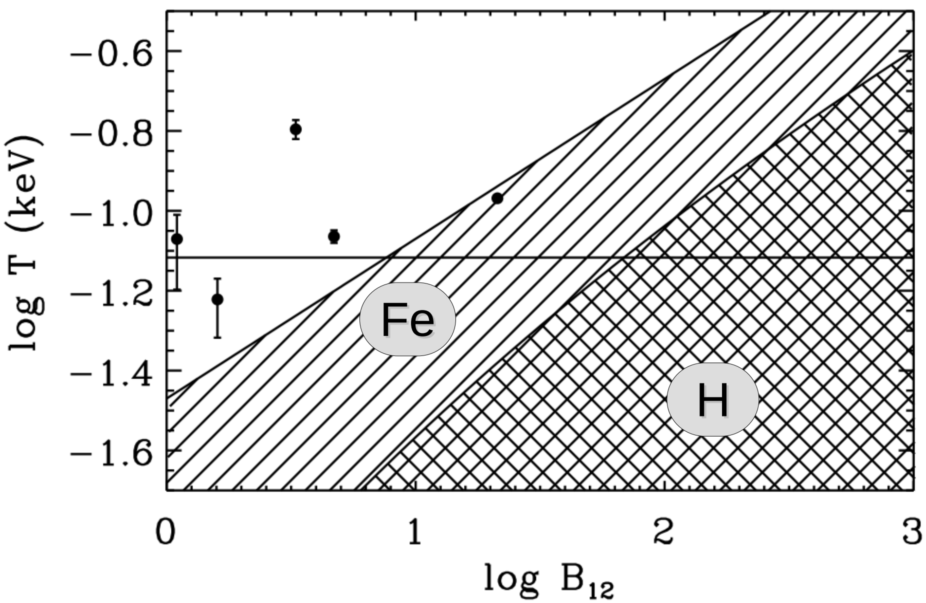
Magnetized atmosphere



Hydrogen
Fully ionized
B = 10^{13} G
Lloyd (2003)

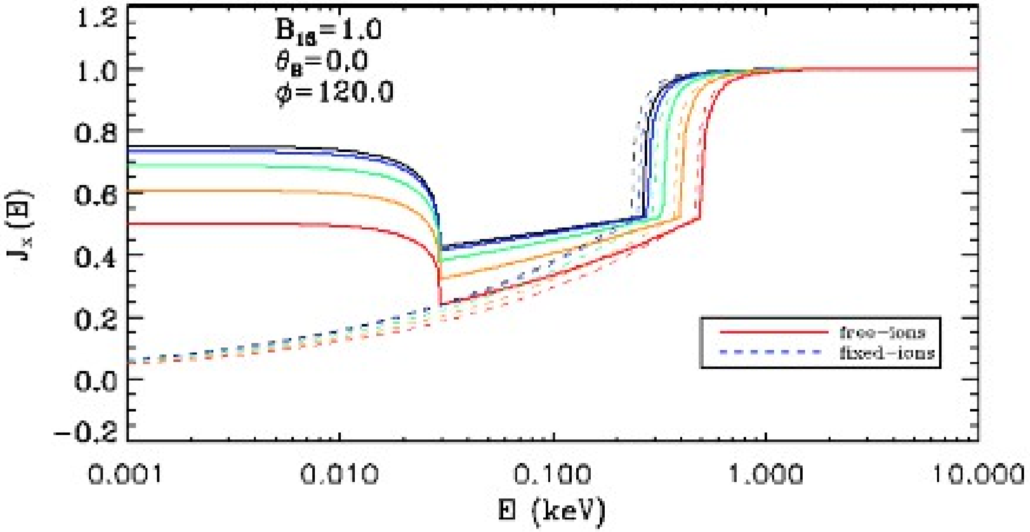
Condensed surface

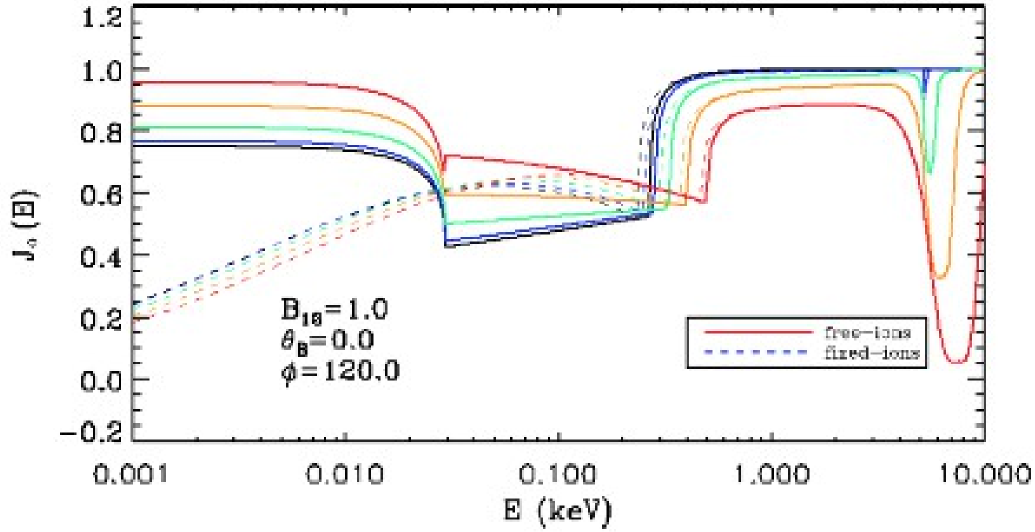
- **Condensed Fe surface for the coldest Nss (XDINSs).**
- **Poorly known dielectric tensor of the condensed surface.**
  - **Free ions**: full response to an EW.
  - **Fixed ions**: no response to an EW.
- **Intensity of the radiation depends on the emissivity of the surface.**
  - Reflectivity for an incident EW between two media with different dielectric tensor: ***vacuum*** & ***metallic surface***.



Turolla et al. 2004

Condensed surface

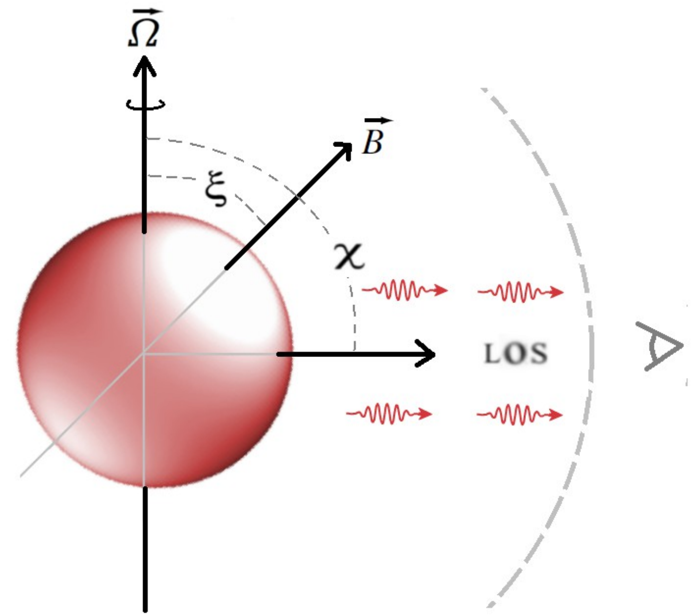




Condensed Iron Surface
$B = 10^{13}$ G
Potekhin et al. 2012

QED Vacuum birefringence

- Strong ***B*-**field induces temporary creation of virtual electron-positron pairs in the vacuum surrounding the NS.
- ***E*-**field of radiation coupled to the local direction of the NS magnetic field (until "adiabatic radius").
- Vacuum polarization included in our ray tracing method.
  - Polarization properties computed for different viewing angles.



Heyl & Shaviv 2000,
Harding & Lai 2006,
Taverna et al. 2016

QED Vacuum birefringence

- Polarization properties computed at the adiabatic radius.

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

- Stokes parameters, polarization fraction & angle.

$$Q = \int_0^{2\pi} \mathrm{d}\Phi_s \int_0^1 \mathrm{d}u^2 (n_X - n_O)\cos(2\alpha)$$

$$U = \int_0^{2\pi} \mathrm{d}\Phi_s \int_0^1 \mathrm{d}u^2 (n_O - n_X)\sin(2\alpha)$$

$$\Pi_L = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\chi_P = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)$$

Taverna et al. 2015

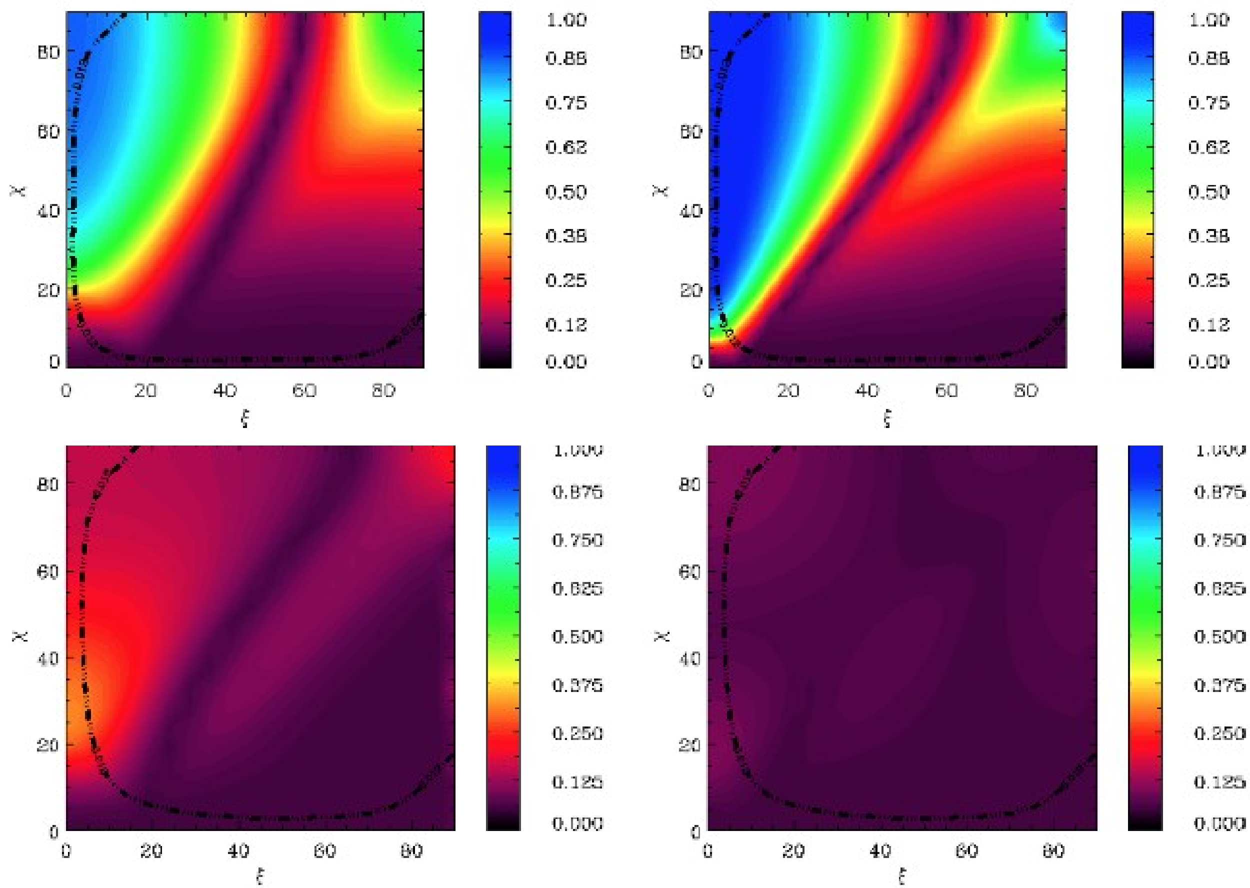
Results: Phase-averaged polarization fraction for XDINSs (RX J1856.5 - 3754)

Optical (B filter)

X-ray (0.1 – 0.4 keV)

Atmosphere

Condensed



González Caniulef et al. 2016

Results: Phase-averaged **polarization angle** for XDINSs (RX J1856.5 - 3754)

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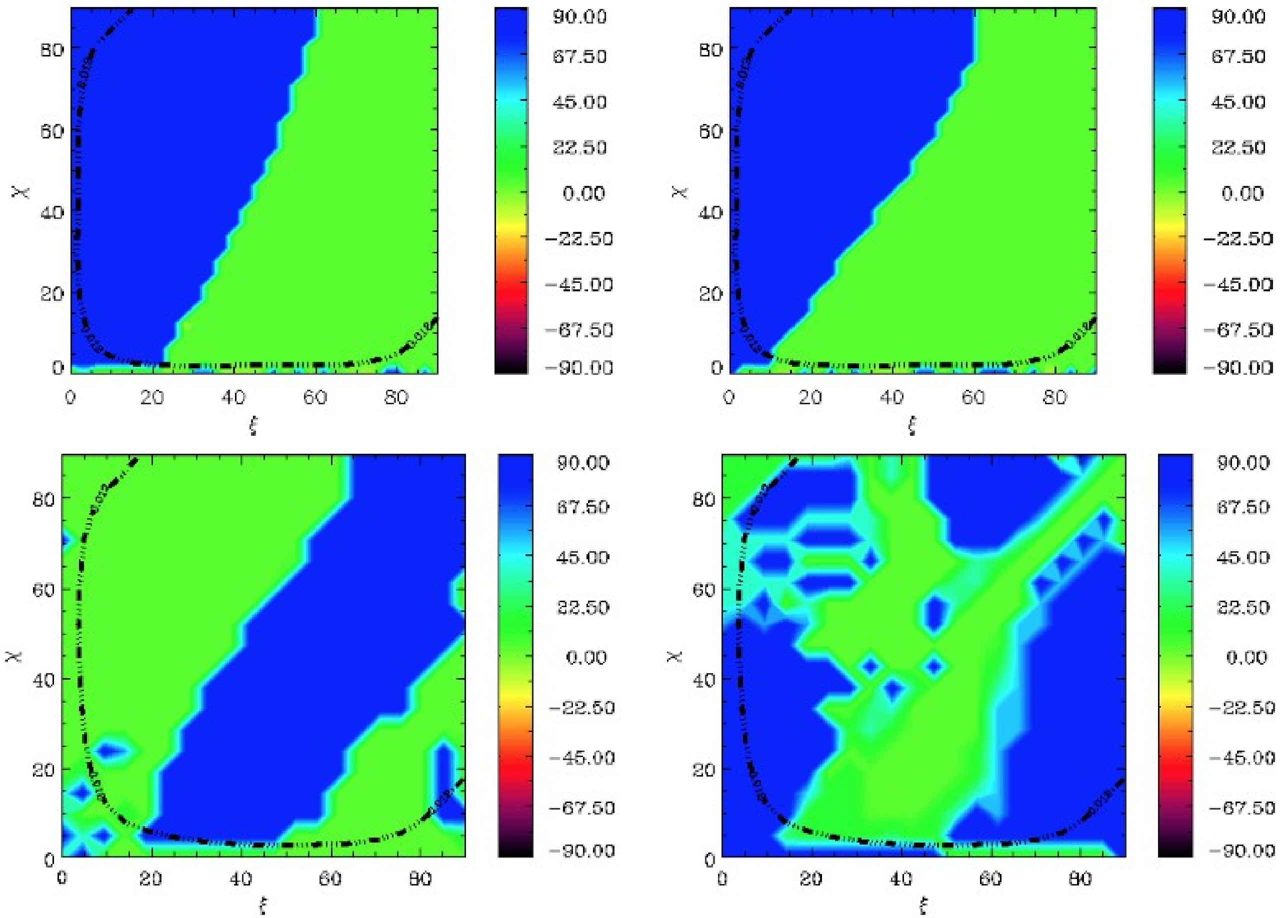
Atmosphere

Condensed



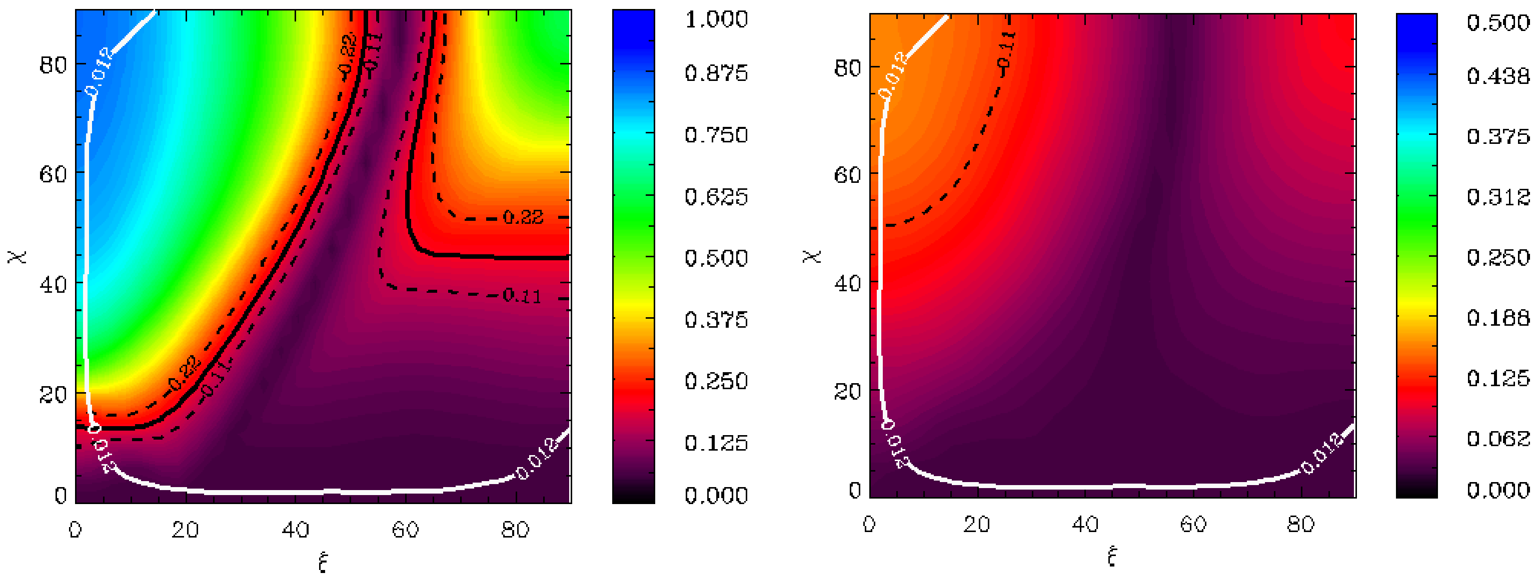
González Caniulef et al. 2016

Optical polarimetry of RX J1856.5-3754

- VLT polarimetry observation of RX J1856.5-3754 (*Mignani et al 2017*).
- First detection of polarized thermal radiation from an M7 object.
  - **Polarization degree, P.D. = 16.43 ± 5.26 %**
  - **Polarization angle, P.A. = 145º39 ± 9º11**
- We ruled out potential sources of contamination:
  - Contribution from near cloud complex < 1% degree of polarization.
  - Bow shock: Electron scattering and Faraday conversion have insignificant effect.

RX J1856.5-3754 and vacuum birefringence

QED on

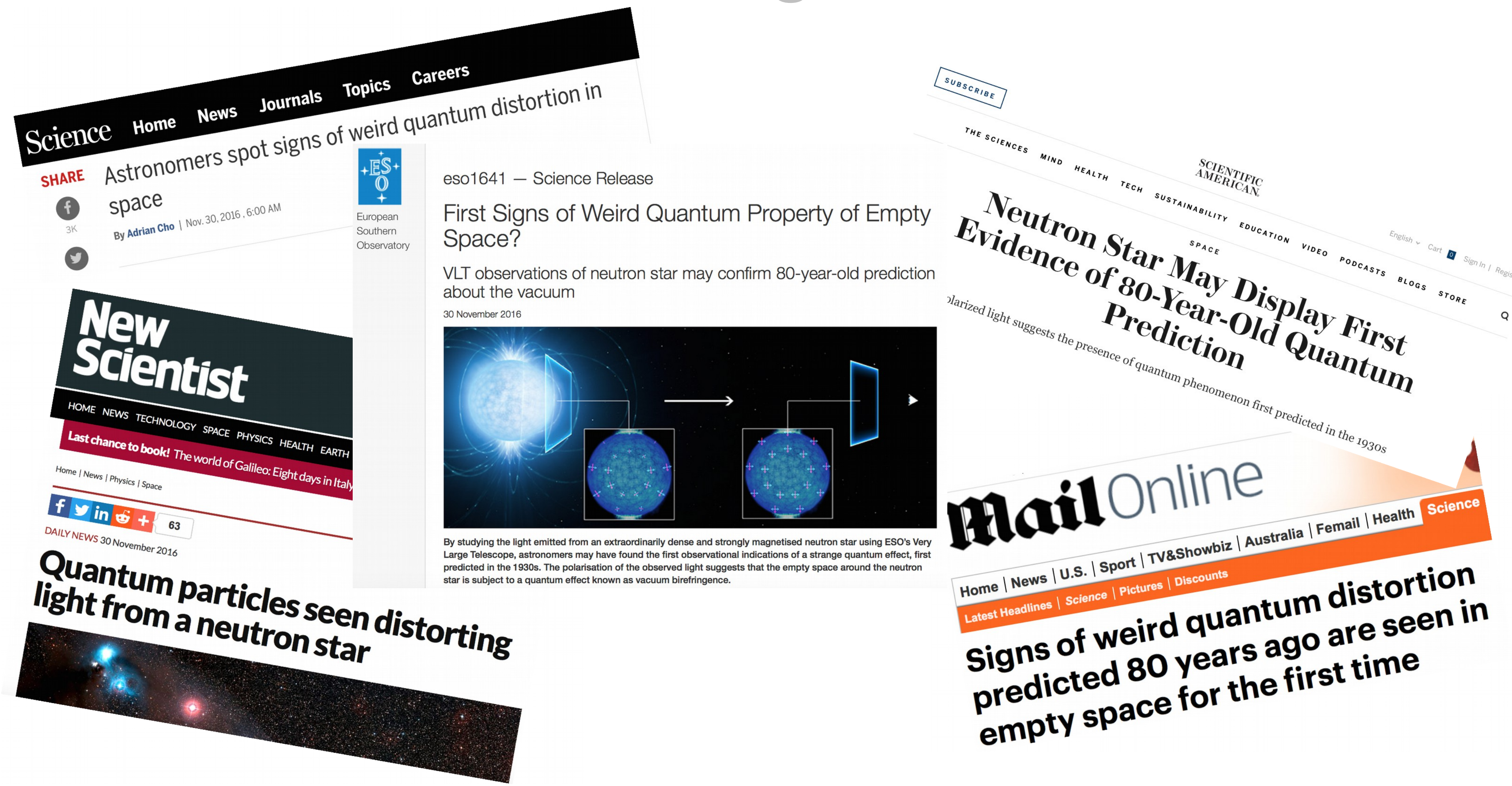


QED off

Mignani et al. 2017

- Atmosphere model, condensed surface & black body require **vacuum birefringence** to be operating outside the star to reproduce the VLT optical polarimetry observation.

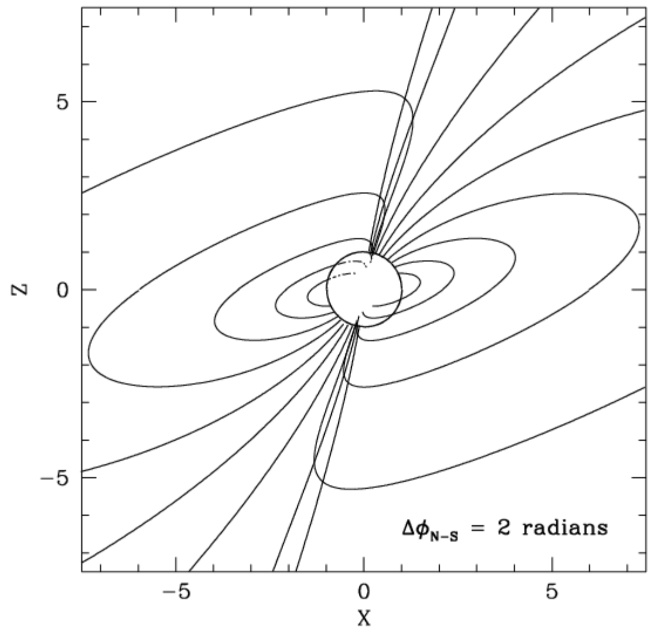
RX J1856.5-3754 and vacuum birefringence



Transient and Persistent Magnetars

- **Observation**
  - Magnetic field: B ~ 10^{14} G.
  - Number of transients: ~1 per year
  - Persistent Magnetars: > 20 Sources (growing number)
  - Soft Xray spectrum (<10keV): BB+PL but often 2 or 3 BBs

    (ex CXOU J10043.1, SGR 0418, XTE J1810, CXOU J1647, SGR 1833, SW J 1834, SGR J1745, 3XMM J1852, PSR J1622, …)
  - Hot sources: Transients show variation in the X-ray flux up to 3 orders-of-magnitude.
- **Theory**
  - Magnetar model
  - Untwisting magnetosphere.



Thompson et al. 2002

Transient Magnetars: polarimetry

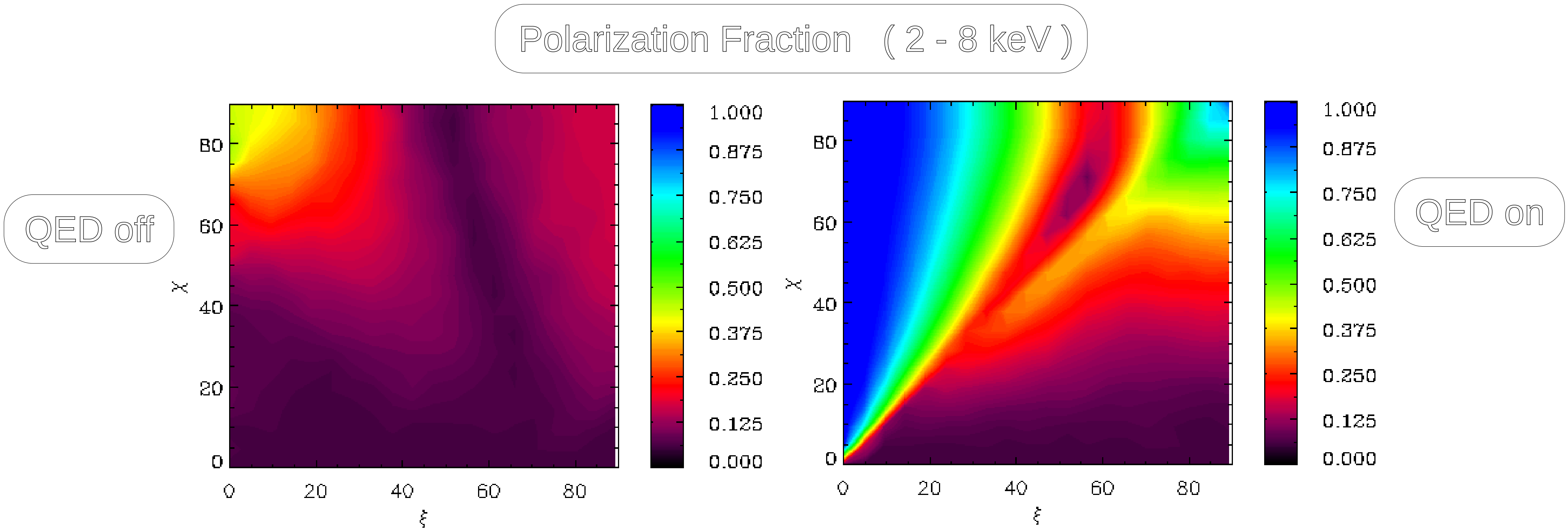
Model:

- Gaseous atmosphere.
- Hot spots: 15% of the area of the star.
- Untwisting magnetosphere
  - Temperature decreases from T~ 1.0 keV to T ~ 0.5 keV.
  - Initial: $\Delta\Phi$ = 1.0 rad
  - Final: $\Delta\Phi$ = 0.5 rad

$$\Delta\phi(\theta) = 2\int_{\theta}^{\pi/2} \frac{B_{\phi}(\theta)}{B_{\theta}(\theta)} \frac{d\theta}{\sin\theta}$$

- Parameters from ***XTE J1810-197*** and ***CXOU J164710.2-455216***

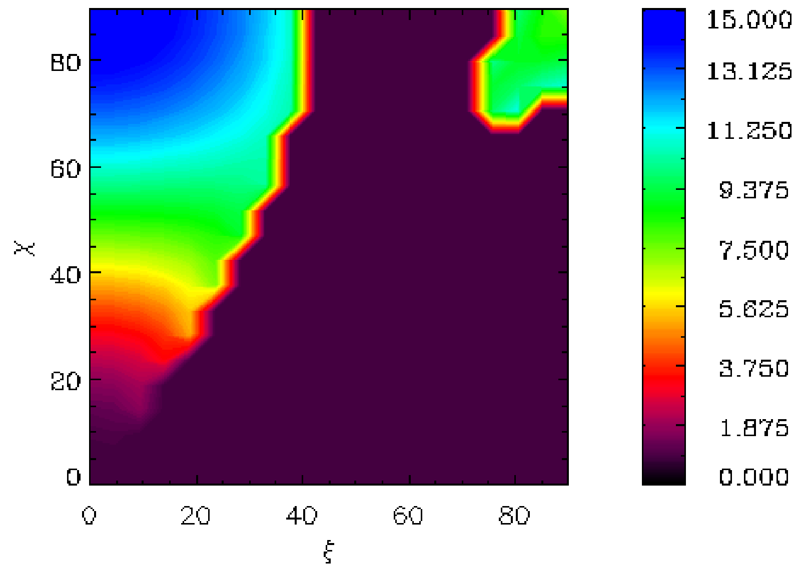
Transient Magnetars: Two caps



- **QED off:** polarization fraction below 40%.
- **QED on:** polarization fraction up to 99%.
- In both cases, polarization fraction does not change during the magnetosphere untwisting.

Transient Magnetars: Two caps

Variation of the polarization angle during untwisting
($\Delta\Phi$ decreases from 1.0 to 0.5 rad)



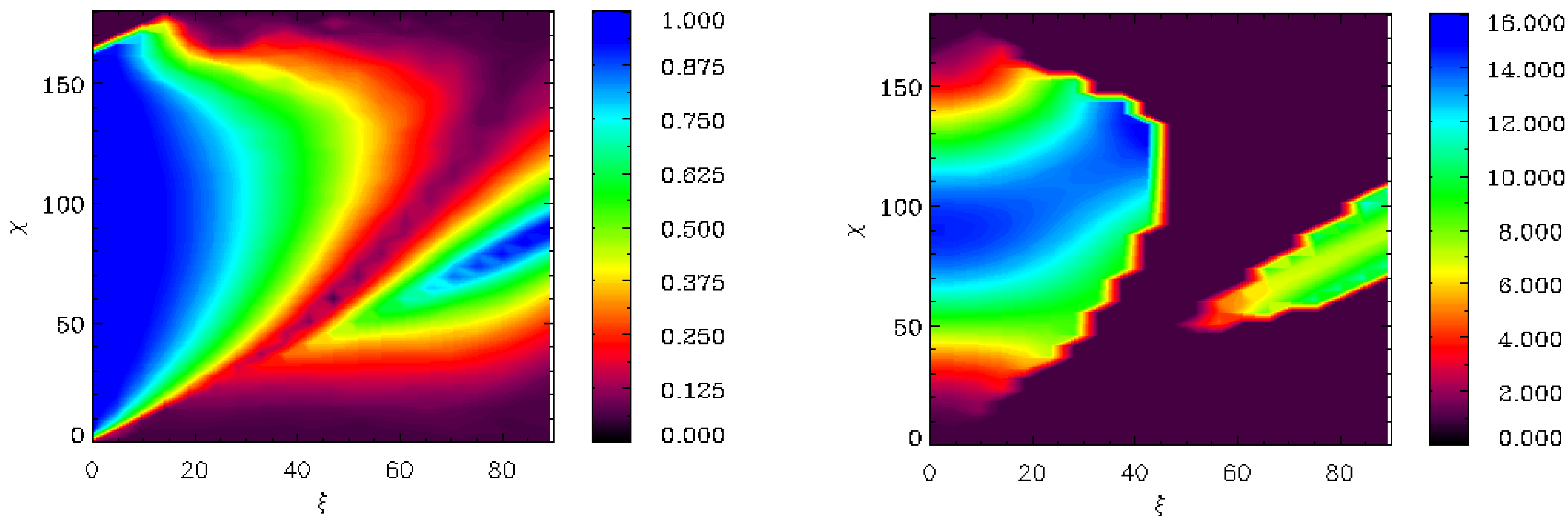
QED on

- **QED off:** Polarization angle does not change during the magnetosphere untwisting.
- **QED on:** Polarization angle can change up to 15 degree during magnetosphere untwisting.

Transient Magnetars: One cap

Polarization Fraction (2 - 8 keV)

Polarization Angle ($\Delta\Phi$ from 1.0 to 0.5 rad)



- **QED off:** polarization fraction below 44% and <u>no change</u> in the polarization angle during untwisting.
- **QED on:** polarization fraction up to 99% and <u>polarization angle can change up to 16 degree</u> during magnetosphere untwisting.

Conclusions

- Our optical VLT polarimetry observation of J1856.5-3754 shows a first evidence for **QED vacuum birefringence** induced by strong magnetic fields.
- Future mission of **X-ray polarimetry such eXTP** may confirm this results in Transient Magnetars:
  - **QED off:** polarization fraction under 40 % and constant polarization angle during magnetosphere untwisting
  - **QED on:** polarization fraction up to 99% and change of the polarization angle up to 15 degree during magnetosphere untwisting.
  - **Observation time required at the peak of the outburst (max flux, 2 – 6 keV):** ~ 3 ks (PF ~ 70%) and ~ 10 ks (variation PA ~ 10 deg)
  - **Observation time required at after the outburst decay (min flux, 2 - 6 keV)**: ~ 180 ks (PF ~ 70%) and ~ 700 ks (variation PA ~ 10 deg)
  - Simulations carried for XIPE, similar results for eXTP- even better if # of PFA's will increase

- eXTP will probe QED systematically in a number of magnetars
- Future X-ray polarimetry missions in the **soft X-ray band** can help us to constrain the state of the matter in X-ray dim isolated neutron stars
  - Atmosphere or condensed surface?