Polarized (Surface) X-Rays from Highly Magnetized Neutron Stars

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The Coming Age of X-Ray Polarimetry, April 29, 2009, Rome, Italy

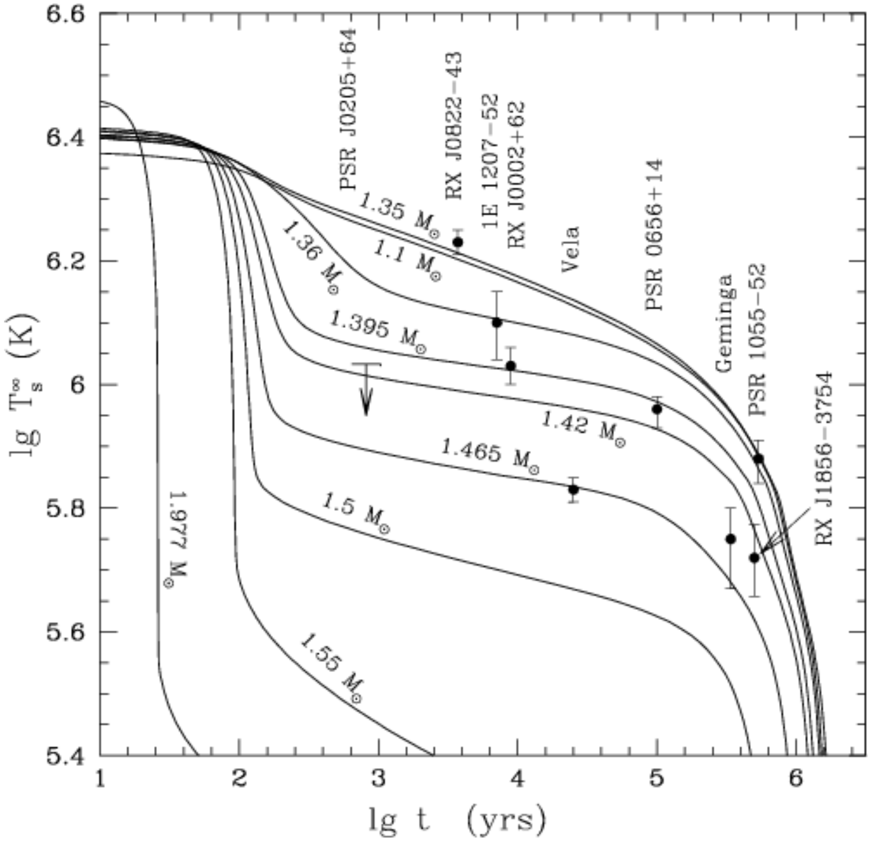
Thermal (Surface) Radiation from Neutron Stars

Probe the near vicinity and interior of NSs:

- M/R, EOS,
- cooling history (exotic processes),
- surface B and composition

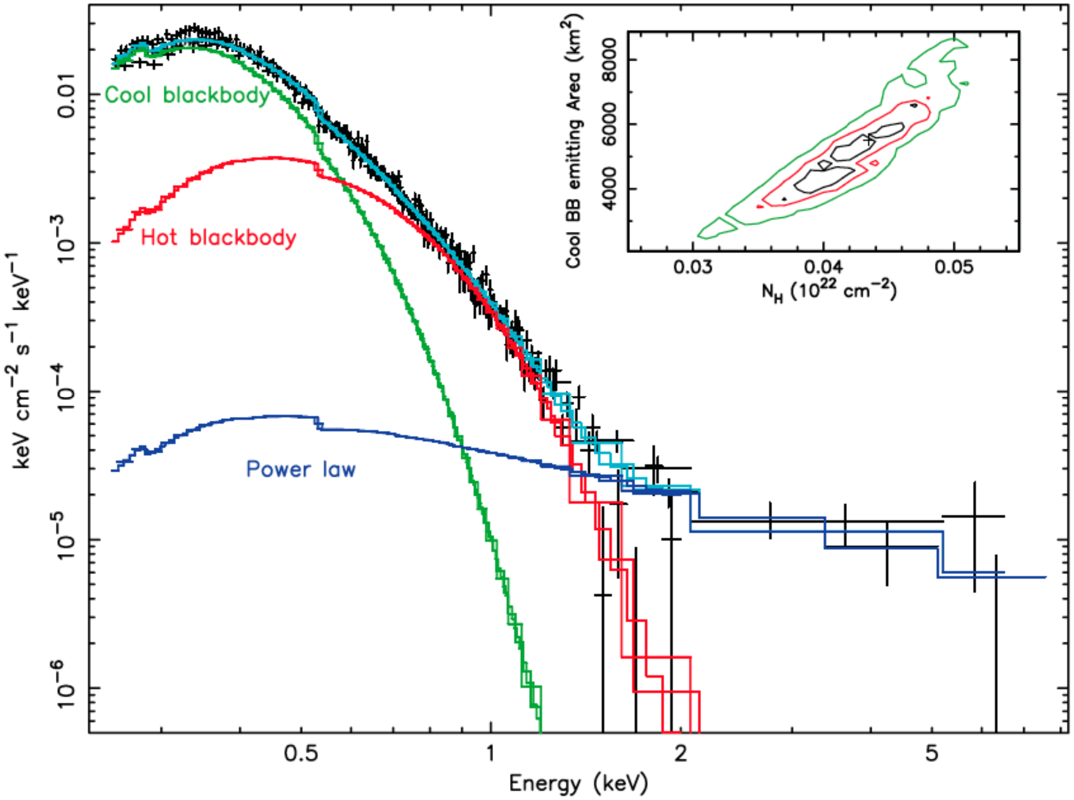
Has been securely detected from many types of NSs (e.g. Chandra, XMM-Newton)

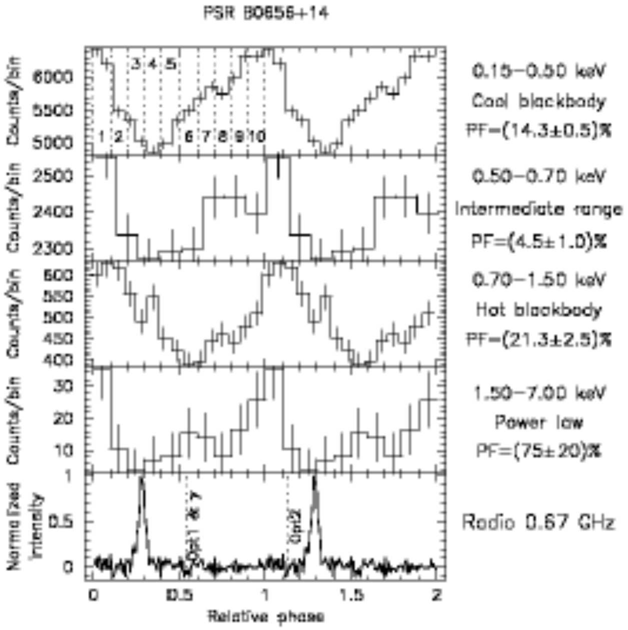
- Radio pulsars
- Magnetars (AXPs and SGRs)
- Radio-quiet NSs (young NSs in SNRs and "dim" Isolated NSs)



Yakovlev & Pethick 2005

Radio Pulsars

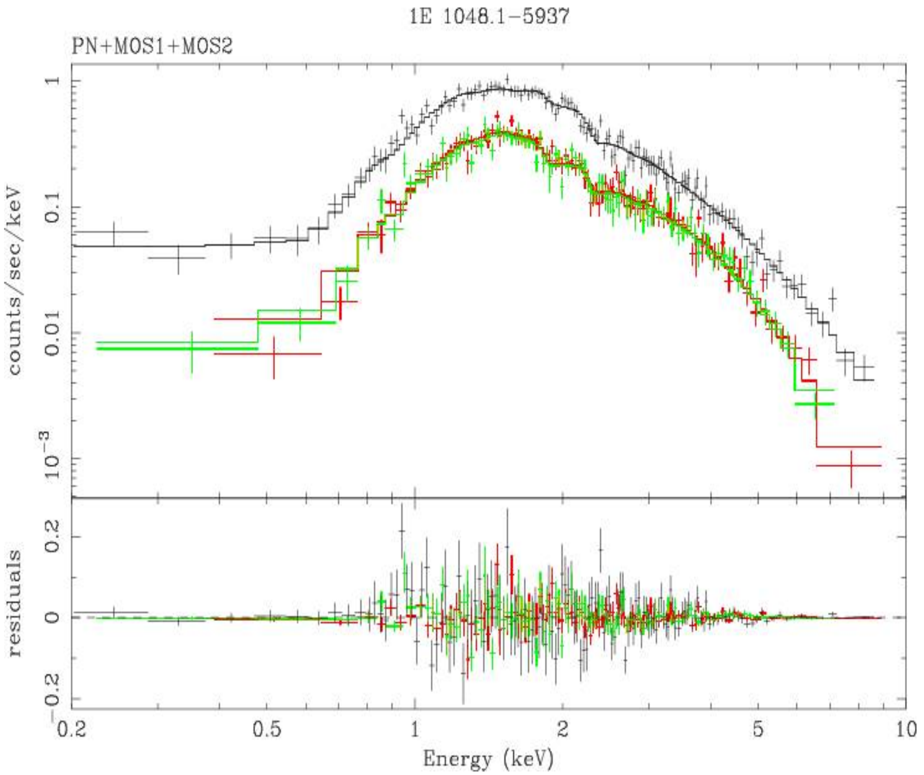




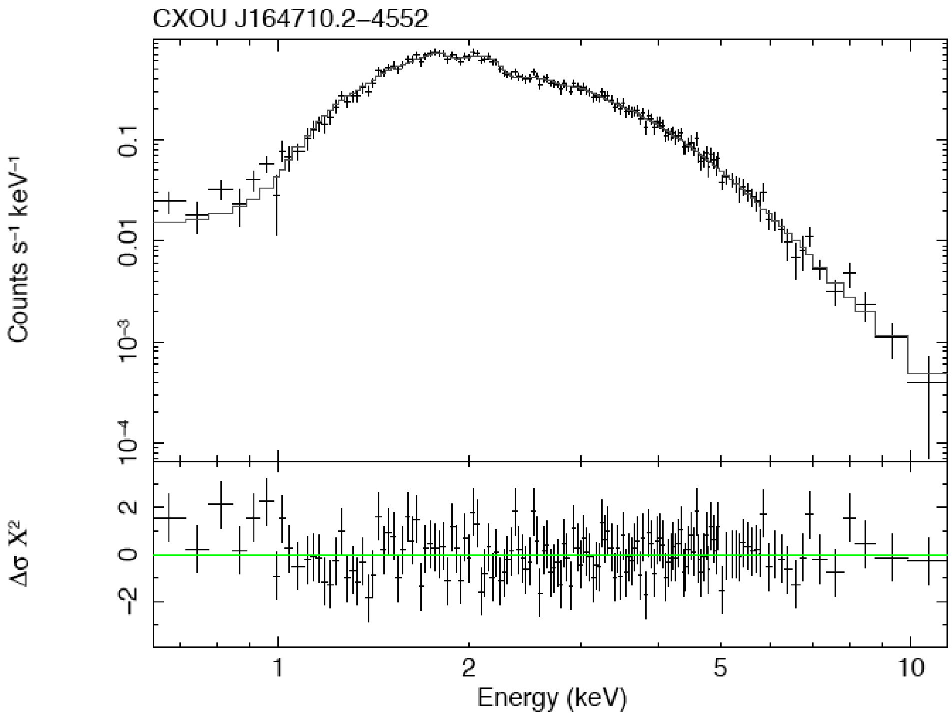
PSR B0656+14 (one of three musketeers)

De Luca et al. 2005

Magnetars



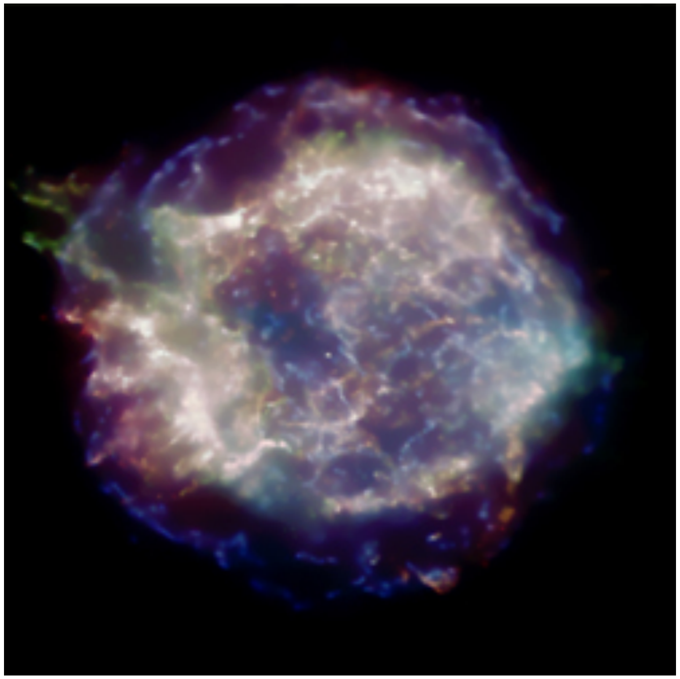
Tiengo et al. 2005



Nobini et al. 2008

Quiscent emission: Blackbody T=0.5 keV, Power-law n=2.7-3.5

Central Compact Objects (CCOs) in SNRs



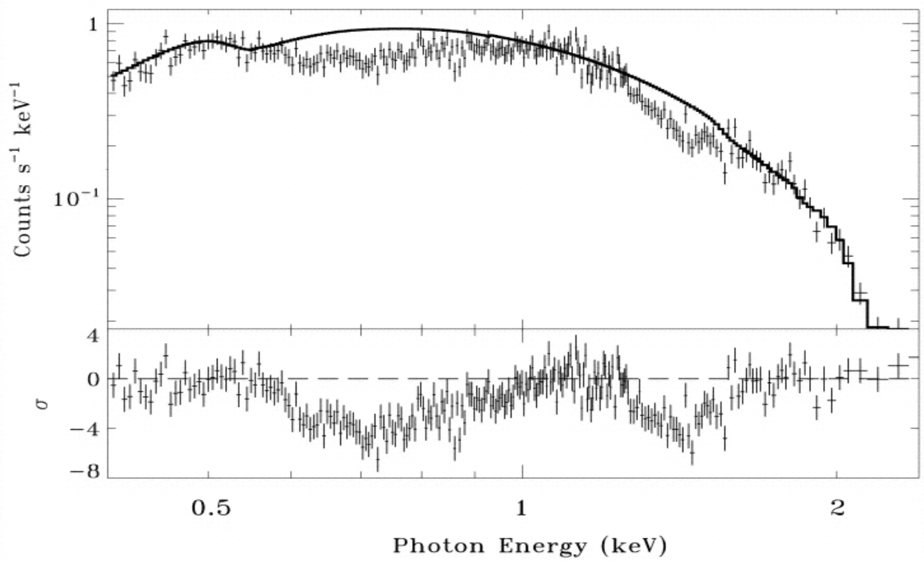
-- 6-8 sources

-- Several have P, Pdot

-- Two have absorption lines

1E 1207-5209: T=2 MK, lines at 0.7, 1.4 KeV

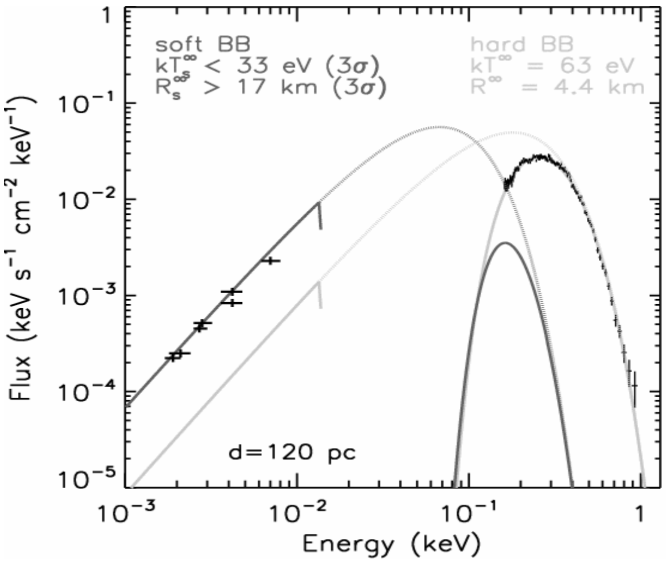
(Sanwal et al. 2002; Mereghetti et al. 2002;
Bignami et al 2003;Mori et al. 2005)



“Dim” Isolated NSs

“Perfect” X-ray blackbody:

RX J1856.5-3754



Burwitz et al. (2003)

Spectral lines detected:

(e.g., van Kerkwijk & Kaplan 06; Haberl 06)

RXJ1308+2127 (0.2-0.3 keV)
RXJ1605+3249 (~0.45 keV)
RXJ0720-3125 (~0.3 keV)
RXJ0420-5022 (~0.3 keV)?
RXJ0806-4123 (~0.5 keV)?
RBS 1774 (~0.7 keV)?

$\Longrightarrow B \sim 10^{13-14}$G? magnetar descendant & off-beam radio pulsar?

Isolated Neutron Stars (as revealed by X-rays)

- --Radio pulsars
- --Magnetars
- --Other radio-quiet NSs:
  - --Central Compact Objects in SNRs
  - --"Dim" isolated NSs

Future goals:

--Understand the evolution and links between different types of NSs

--Understand observed manifestations of theses NSs

(e.g., Radiative processes in NS atmospheres and magnetospheres)

--Use these NSs to probe physics under extreme conditions

(e.g., Strong gravity, high density, and strong B fields)

X-ray polarization provides a new window (in addition to spectra/timing)

Even when spectrum or light curve is boring, polarization can still be interesting

Polarized (Surface) X-Rays from Highly Magnetized Neutron Stars

1. Basic polarization signals
2. QED effects in polarization signals
3. Probe axions

Collaborators: Wynn Ho (Cornell-->KIPAC-->CfA-->U. Southampton)
Matt van Adelsberg (Cornell-->Colorado-->Rome/Milan-->KITP)
Chen Wang (Cornell/Beijing)
Jeremy Heyl (UBC)

Also thanks to experimentalists (e.g. Costa et al 2001) for motivation;
to Jean Swank and Tim Kallman for push/encouragement

Surface emission from magnetic NSs is highly polarized (up to 100%)

Gnedin & Sunyaev 1974
Pavlov & Shibanov 1978
Meszaros et al. 1988
Pavlov & Zavlin 2000
Ho & DL 2001
Heyl et al. 2003
……

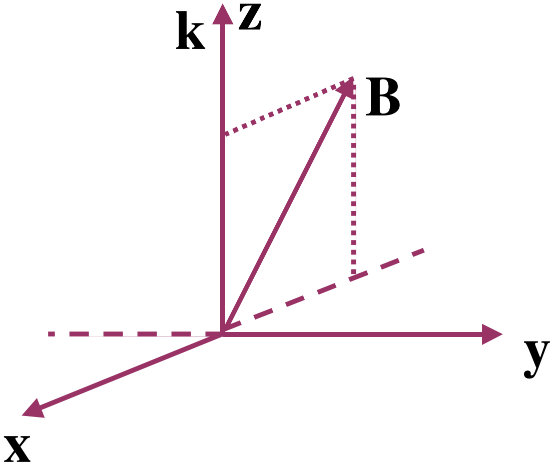
Photon Polarization Modes in a Magnetized Plasma

$(\omega << \omega_{ce} = 11.6\, B_{12}\ \mathrm{keV})$

Ordinary Mode (O-mode, //-mode):

E nearly in the **k-B** plane

$$|K| = |E_x / E_y| >> 1$$

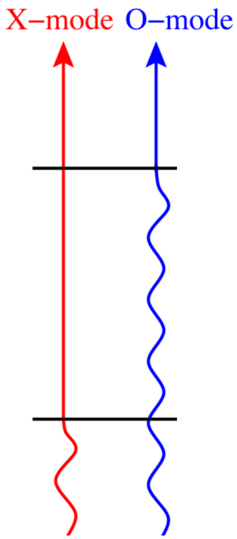


Extraordinary Mode (X-mode, ⊥-mode):

E nearly ⊥ **k-B** plane

$$|K| = |E_x / E_y| << 1$$

The two modes have different opacities (scattering, absorption):



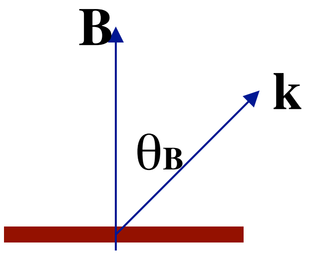
$$\kappa_{\text{(O-mode)}} \sim \kappa_{(B=0)}$$

$$\kappa_{\text{(X-mode)}} \sim \kappa_{(B=0)} \, (\omega/\omega_{ce})^2$$

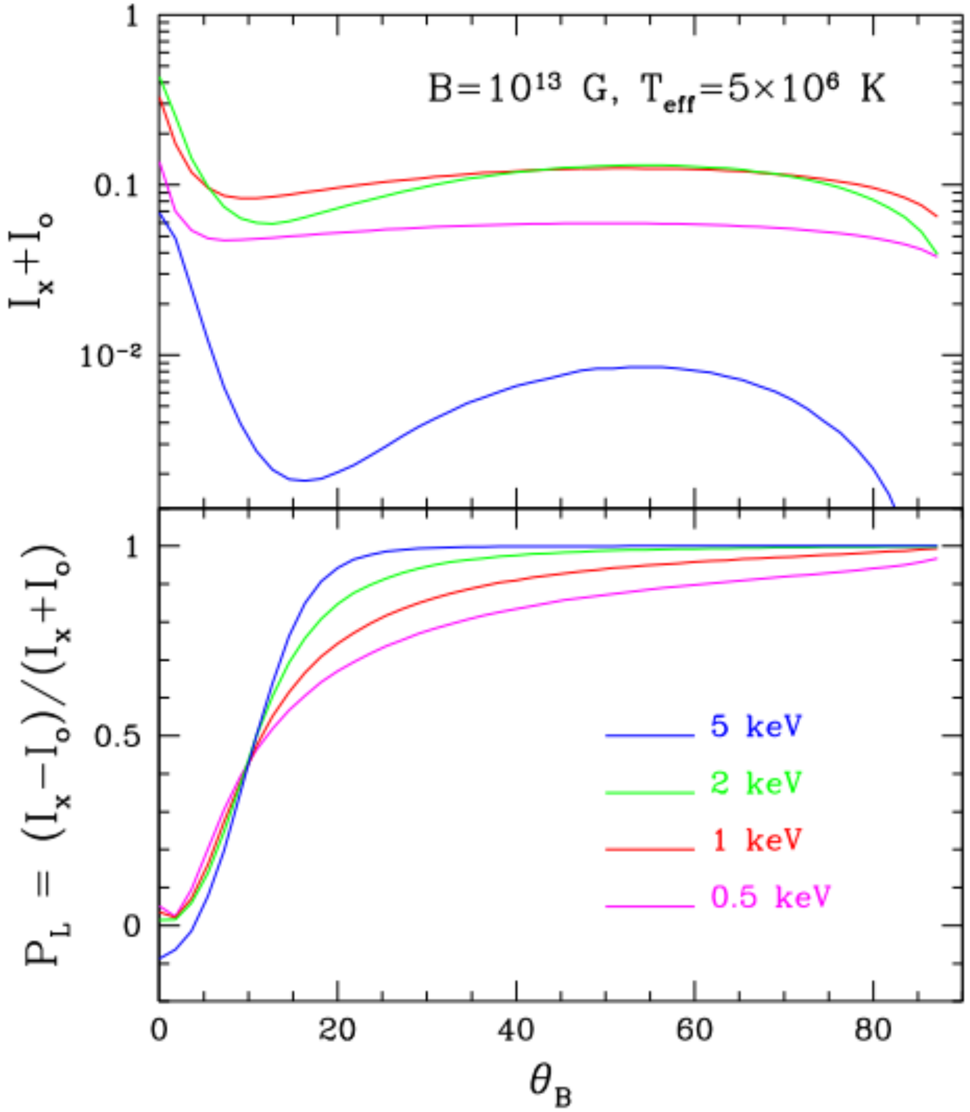
X-mode photons are the main carrier of X-ray flux

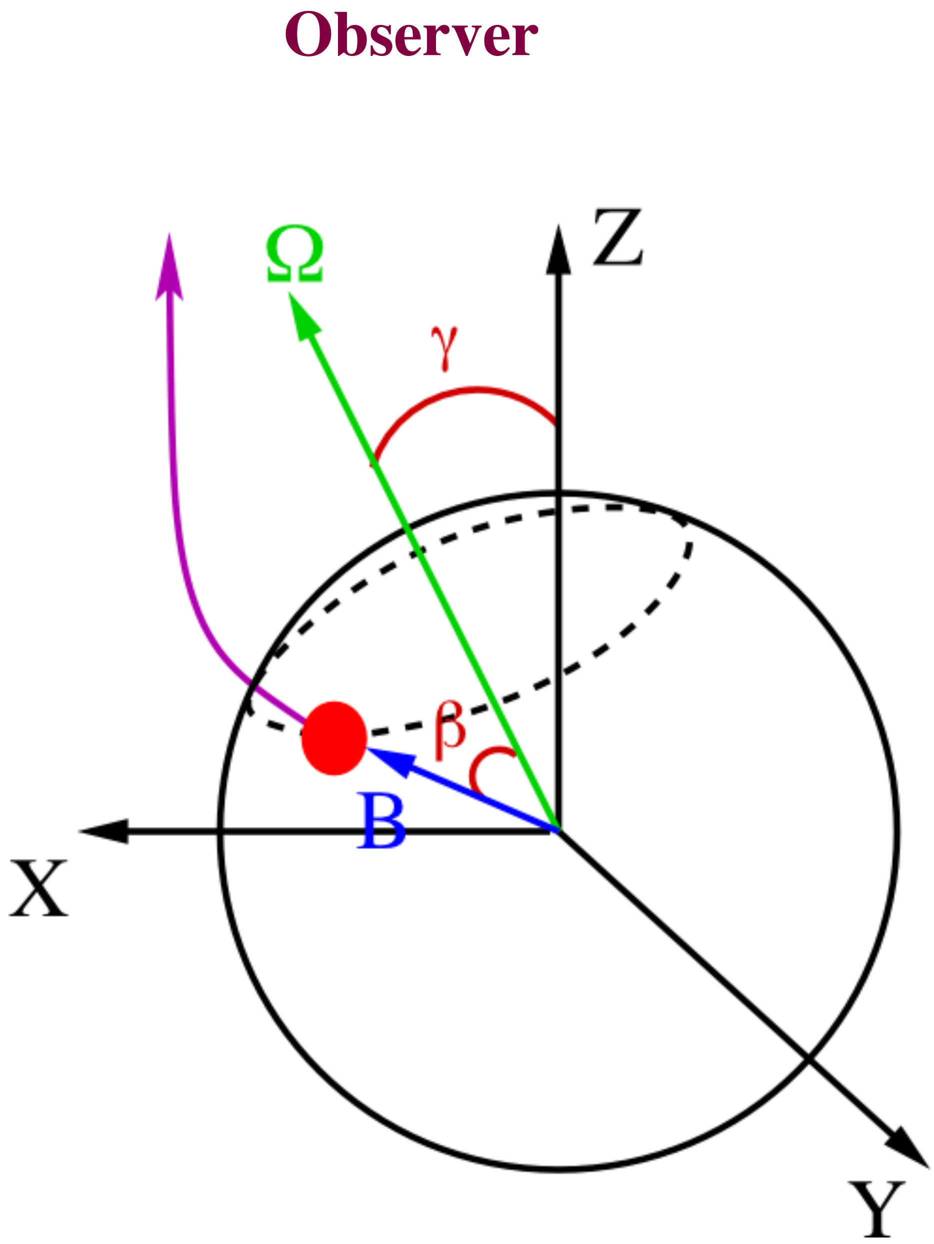
(Two photospheres)

Putting a polarimeter on the NS surface…



Degree of linear Polarization at emission point



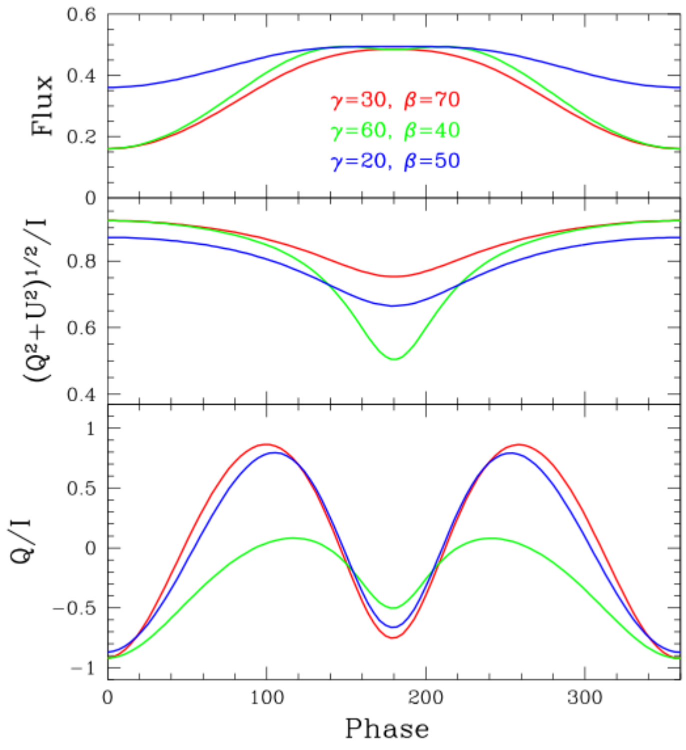

Observer
Ω
Z
γ
β
B
X
Y

General Expected X-ray Polarization Characteristics

- Polarization vector ⊥ or // to **k-μ** plane (depending on E and surface |**B**|) even when surface field is non-dipole!

- Linear polarization sweep ==> geometry ("rotating vector model" for radio pulsars)

- Polarization signals can be very different even when total intensities are similar



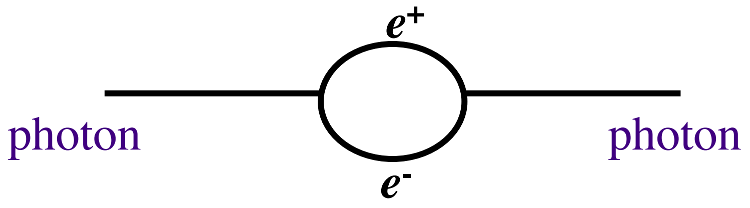
$$\frac{(Q^2+U^2)^{1/2}}{I} = \text{Linear Polarization Fraction}$$

$$\frac{Q}{(Q^2+U^2)^{1/2}} = \cos 2\Phi_{\rm Pl}$$

Information Carried by Polarization Signals:

- Geometry (dipole field, rotation axis)
- Dependence on surface field strength
- Modest dependence on M/R
- **QED effects**

QED Effect: Vacuum Polarization in Strong B



Heisenberg & Euler,
Weisskopf, Schwinger,
Adler…

Dielectric tensor: $\boldsymbol{\varepsilon} = \mathbf{I} + \Delta\boldsymbol{\varepsilon}_{\mathrm{vac}}$

$$|\Delta\varepsilon_{\mathrm{vac}}| \sim 10^{-4}(B/B_Q)^2, \text{ with } B_Q = 4.4 \times 10^{13} \text{ G}$$

Two photon modes in magnetized vacuum:
Ordinary mode (//)
Extraordinary mode (⊥)

Influence polarization signals in two ways:

1. In NS atmosphere: mode conversion
2. Polarization evolution in magnetosphere: mode decoupling

QED Effect in NS Atmosphere

Dielectric tensor of magnetized plasma including vacuum polarization

$$\boldsymbol{\mathcal{E}} = \mathbf{I} + \Delta\boldsymbol{\mathcal{E}}^{(\mathrm{plasma})} + \Delta\boldsymbol{\mathcal{E}}^{(\mathrm{vac})}$$

where $\Delta\boldsymbol{\mathcal{E}}^{(\mathrm{vac})} \sim 10^{-4}\,(B/B_Q)^2 f(B)$, with $B_Q = 4.4\times10^{13}\mathrm{G}$, $f(B) \sim 1$

cf. Gnedin, Pavlov & Shibanov 1978;
Meszaros & Ventura 1978, etc

Vacuum resonance:

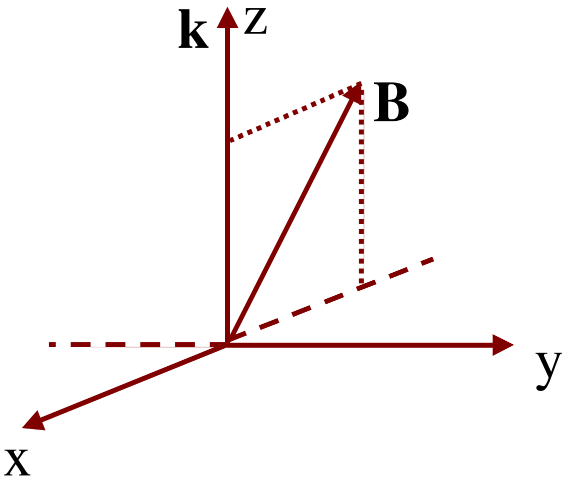
$$\Delta\mathcal{E}^{(\mathrm{plasma})} \;+\; \Delta\mathcal{E}^{(\mathrm{vac})} \;\sim\; 0$$

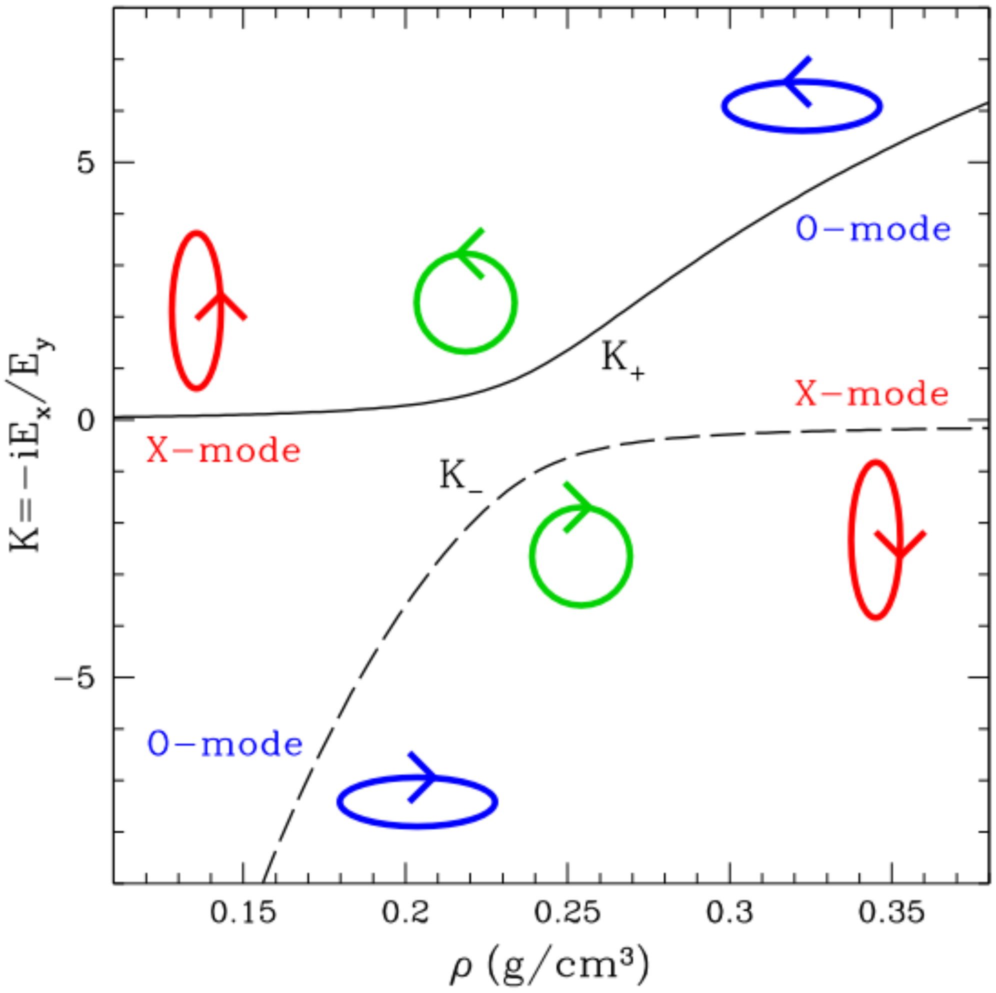
depends on $-(\omega_p/\omega)^2 \propto \rho/E^2$

⇨ $\rho_{\mathrm{vac}} = 1.0\, B_{14}{}^2 f(B)^{-1} (E/1\ \mathrm{keV})^2\ \mathrm{g\ cm^{-3}}$

At resonance, X-mode and O-mode are “similar”

Polarization of photon modes





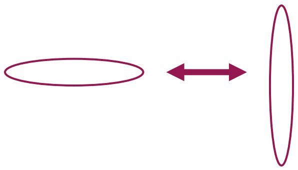
$B=10^{13}$ G, $E=5$ keV, $\theta_B=45^o$

Adiabatic Condition:

$$\left| n_1 - n_2 \right| \gtrsim (\,\cdots\,)\, \left| \mathrm{d}\rho/\mathrm{d}r \right|$$

⇒ $$E \gtrsim E_{\mathrm{ad}} = 2.5\,(\,\tan\theta_B\,)^{2/3}\,(1\ \mathrm{cm}/H)^{1/3}\ \mathrm{keV}$$

Photons with E > 2 keV, mode conversion



Photons with E < 2 keV, no mode conversion

In general, nonadiabatic "jump" probability

$$P_{\mathrm{jump}} = \exp\,[-\,(\pi/2)\,(E/E_{\mathrm{ad}})^3]$$

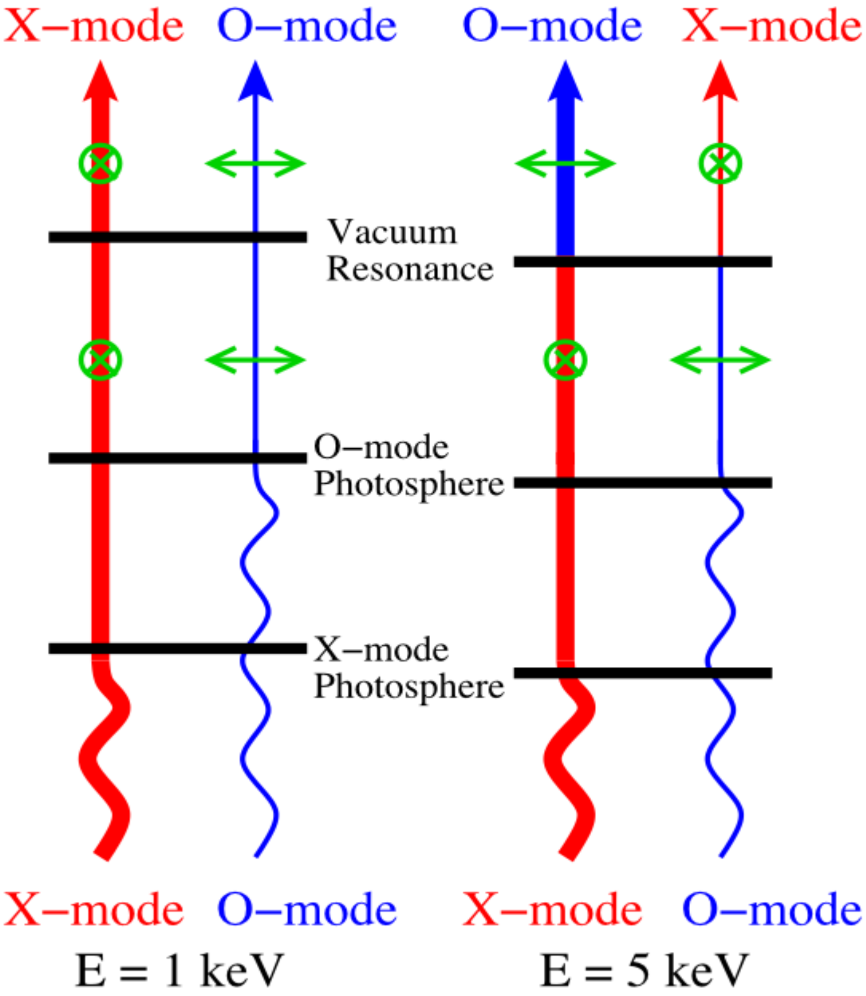
Recall

-- X-mode and O-mode have different photospheres

-- $\rho_{\mathrm{vac}} = 1.0\, B_{14}^{2}\, f(B)^{-1}\, (E/1\ \mathrm{keV})^{2}\ \mathrm{g\ cm^{-3}}$

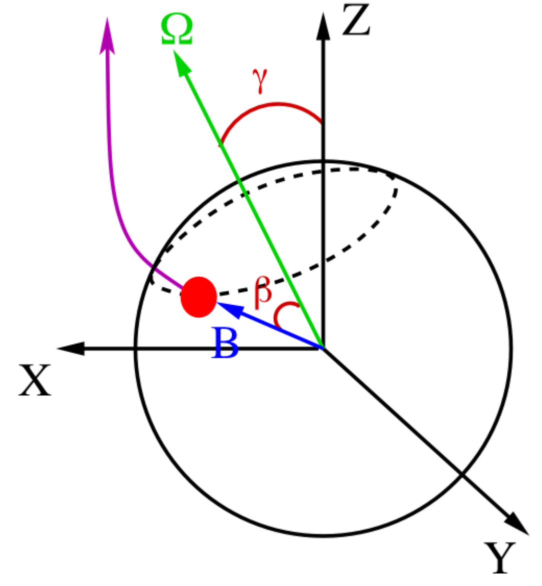
For B < $7 \times 10^{13}\, T_6^{-1/8}\, E_1^{-1/4}$ G:

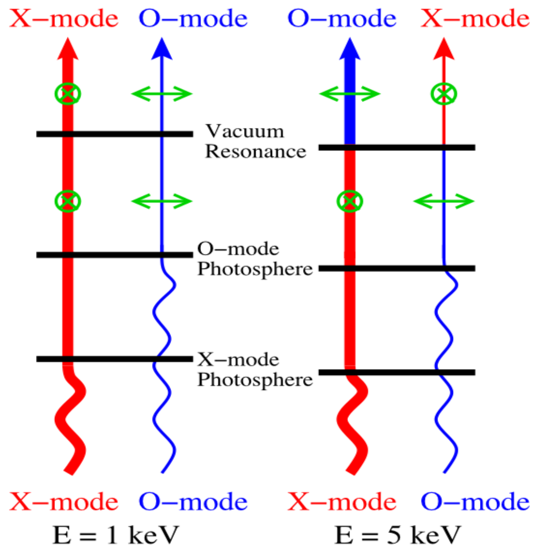
Vacuum resonance lies outside both photospheres

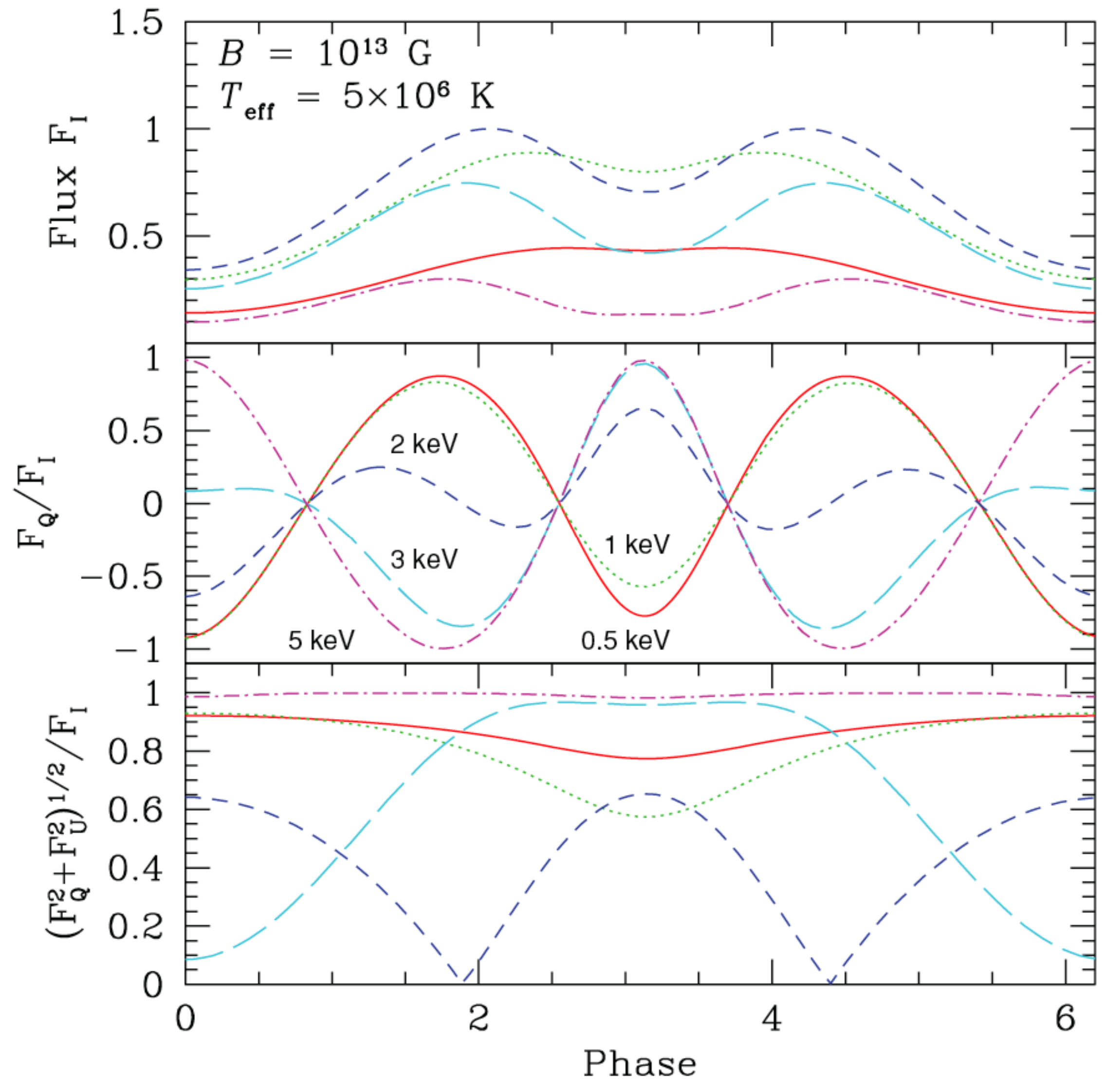


$B=10^{13}$G

$\gamma = 30^\circ, \quad \beta = 70^\circ$





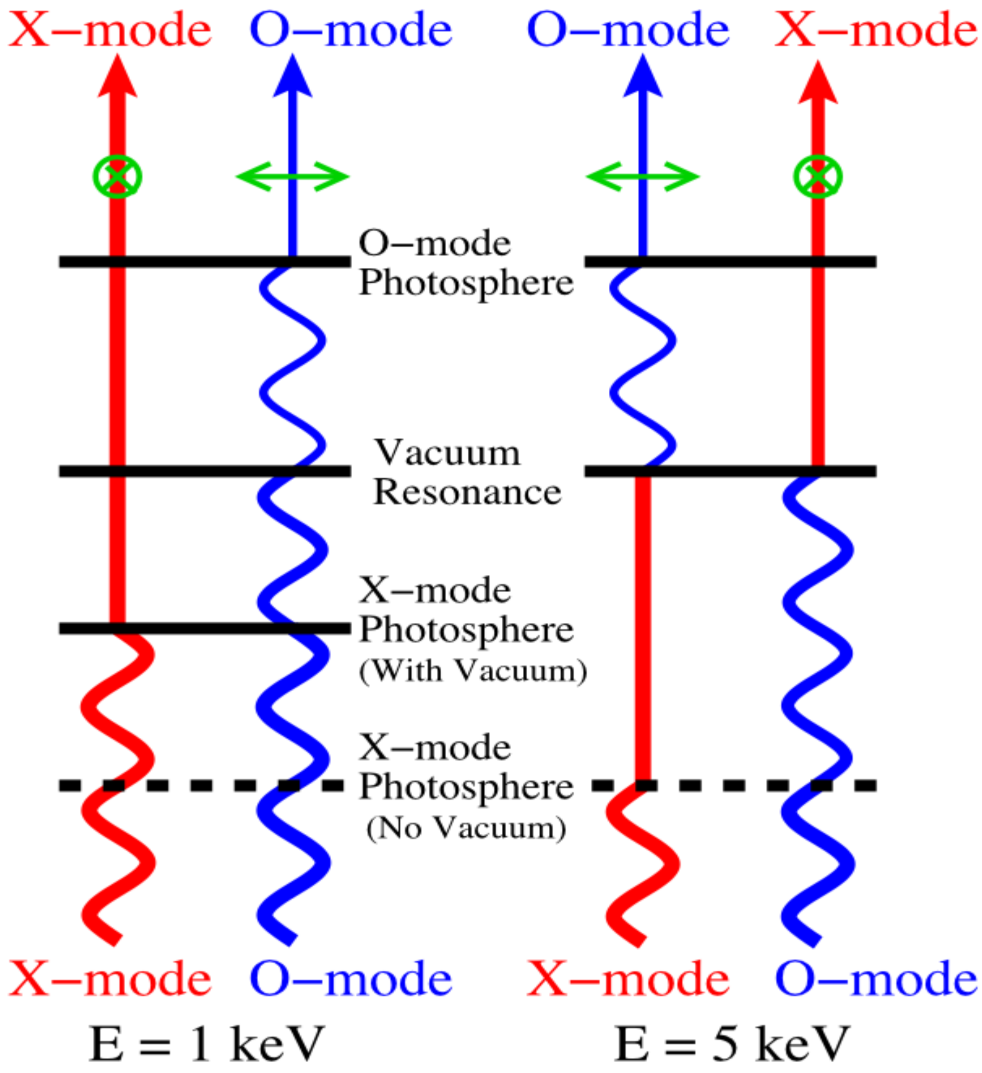


Van Adelsberg & DL 2006 (also DL & Ho 2003)

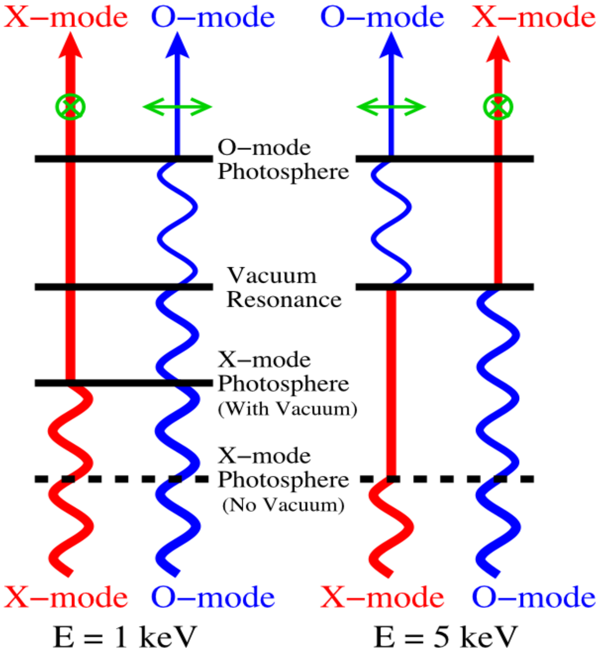
➡ **Plane of linear polarization at <1 keV is perpendicular to that at >4 keV.**

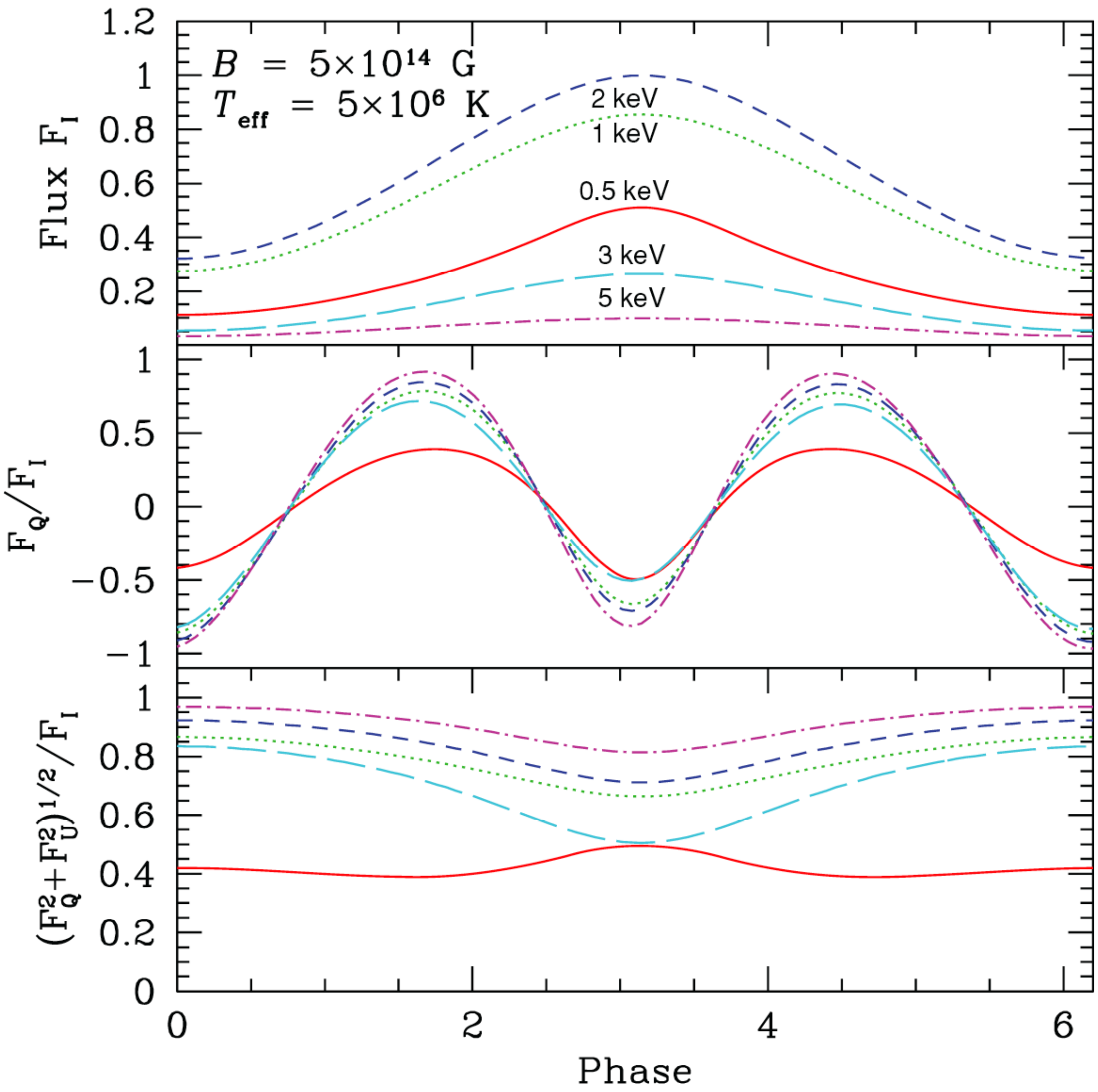
For B > 7×10^{13} T$_6^{-1/8}$ E$_1^{-1/4}$ G:

Vacuum resonance lies between the two photospheres



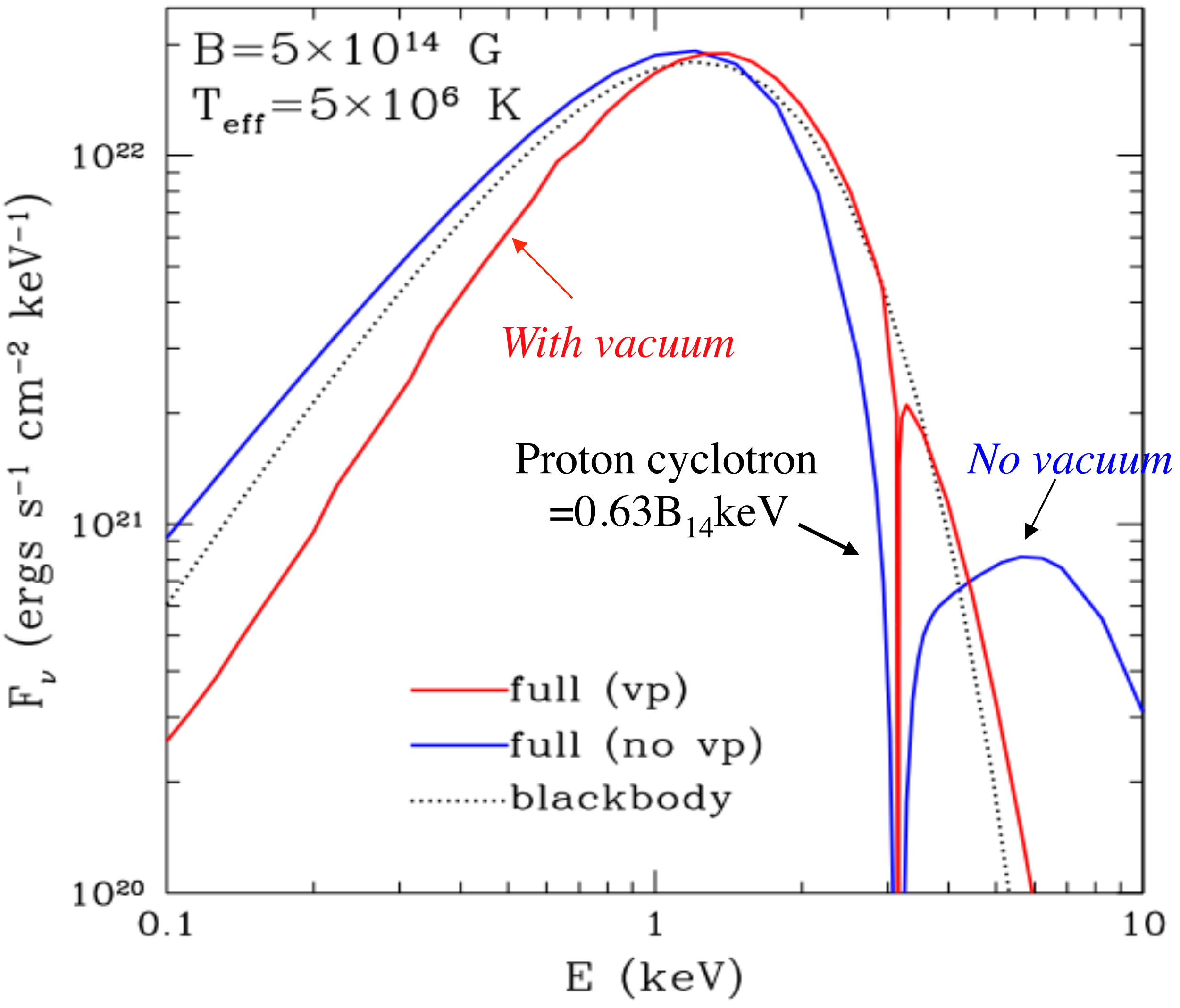
B=5×10^{14}G Model





Plane of linear polarization at different E coincide.

For B > $7\times10^{13}\,T_6^{-1/8}\,E_1^{-1/4}$ G:
Spectrum is significantly affected by vacuum polarization effect



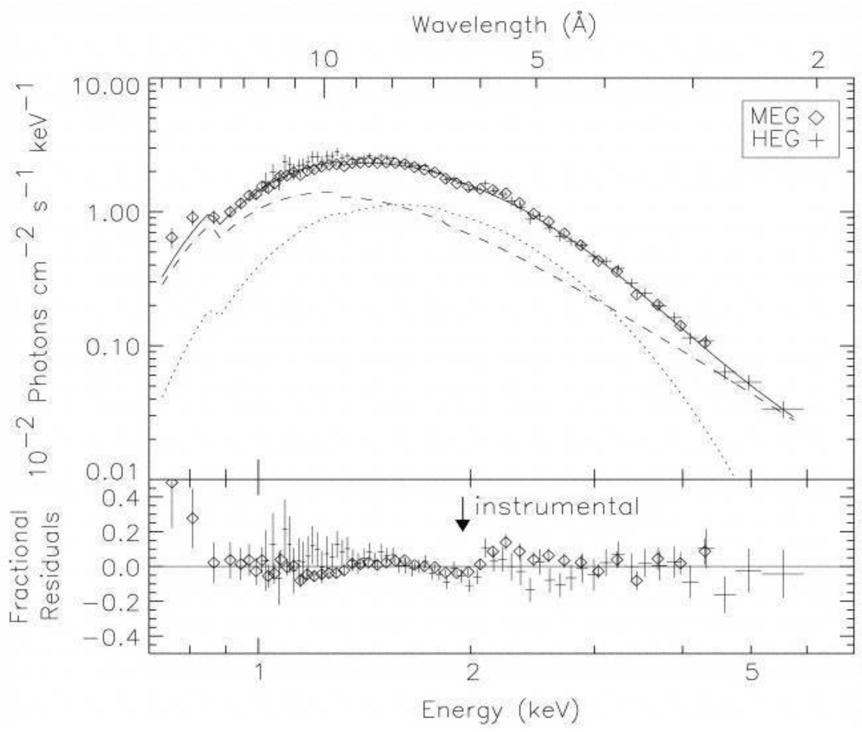
With vacuum

Proton cyclotron
$=0.63B_{14}$keV

No vacuum

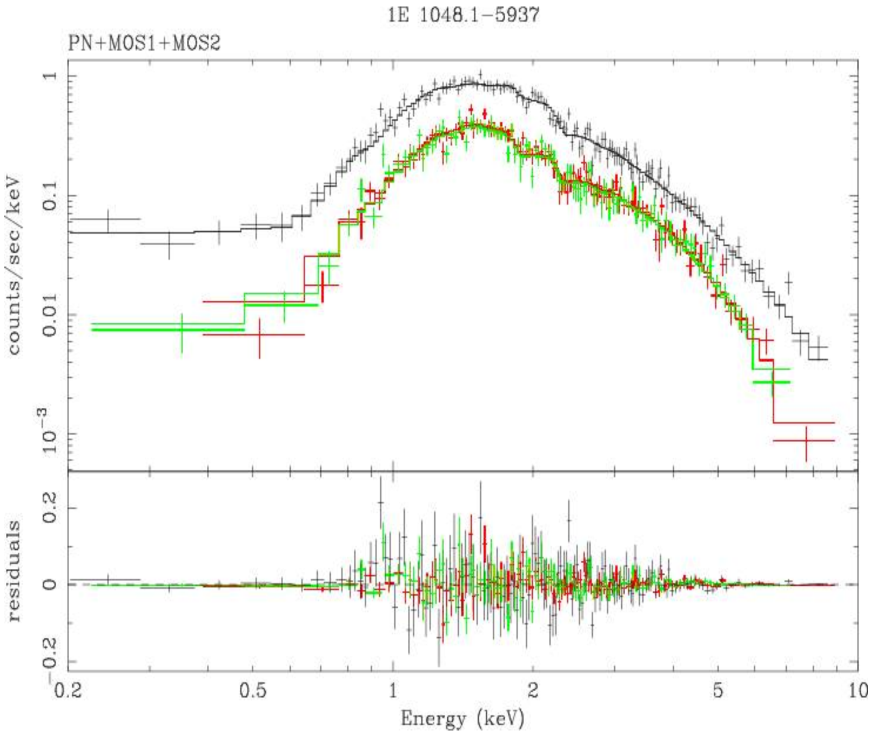
Two Examples of AXP Spectra

AXP 4U0142+61 **(Chandra-HETGS)**
BB T=0.4 keV, power-law n=3



Juett et al. 2002; Patel et al 2003

AXP 1E1048-5937 **(XMM-Newton)**
BB T=0.6 keV, Power-law n=2.9

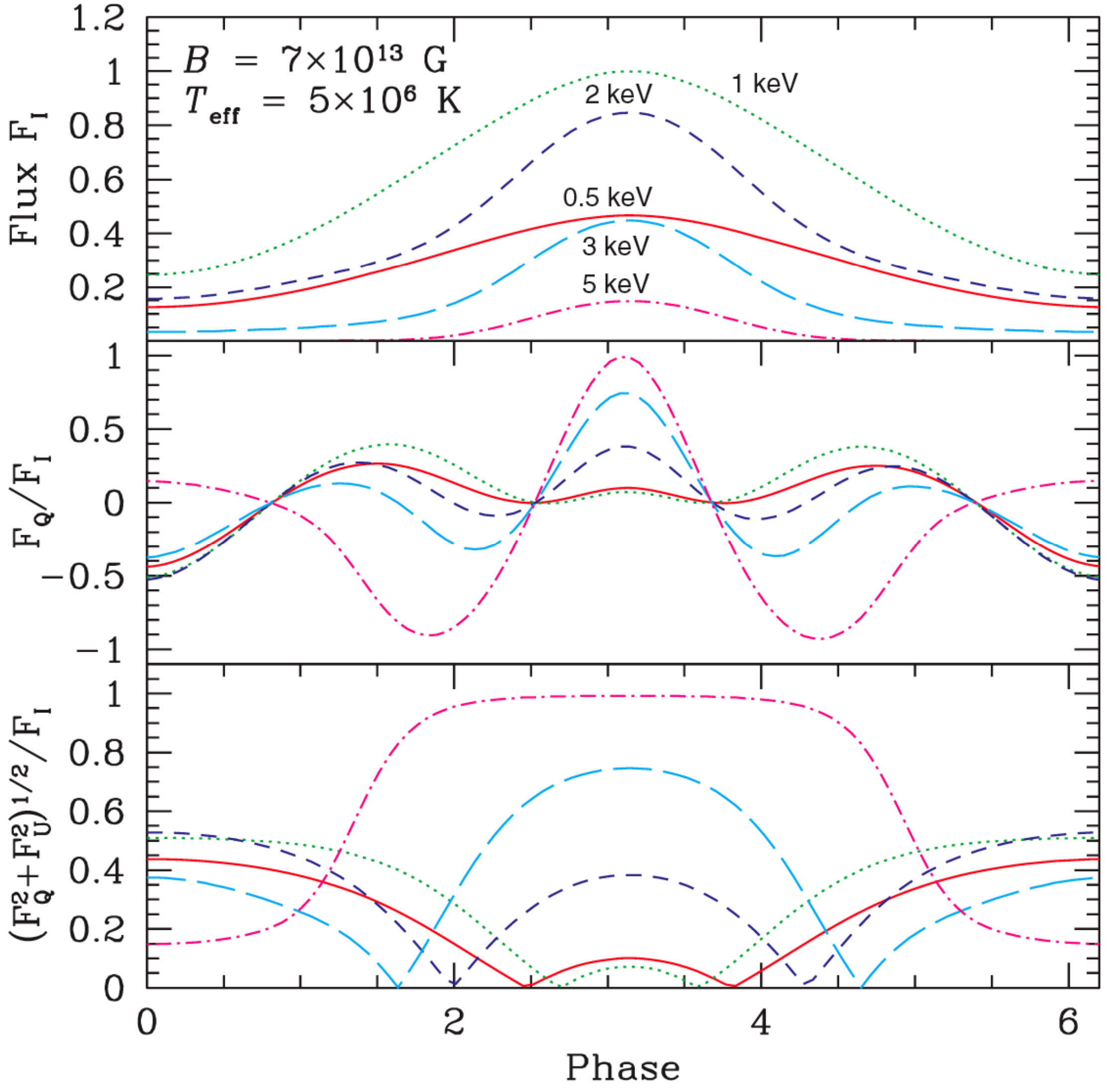


Tiengo et al.2002

Ion cyclotron absorption $E_{Bi}=0.63\ B_{14}$ keV
Why not see?

QED at work

B=7×10^{13}G Model



Van Adelsberg & DL 2006

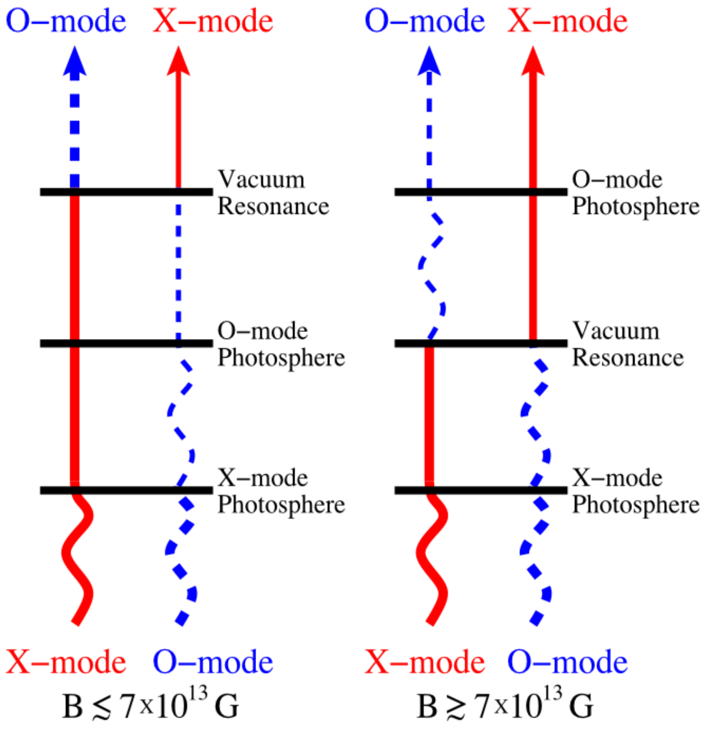
Recapitulation: **Effect of Vacuum Resonance on Surface Emission**

For $B<7\times10^{13}$G ($\rho_{\mathrm{vac}} < \rho_{\text{o-mode}} < \rho_{\text{x-mode}}$)

- Negligible effect on spectrum
  (spectral line possible: already observed?)
- Dramatic effect on X-ray polarization signals
  (plane of linear polarization depends E)
  --- A "clean" QED signature

For $B>7\times10^{13}$ G ($\rho_{\text{o-mode}} < \rho_{\mathrm{vac}} < \rho_{\text{x-mode}}$)

- Dramatic effect on spectrum
  (suppress absorption lines, soften hard tails: observations of magnetars)
- Polarization signals affected by QED:
  plane of linear polarization coincides for different E



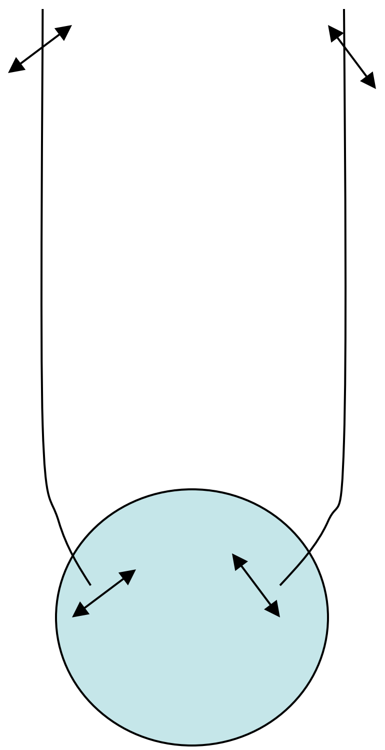
QED Effect in Magnetospheres (=Magnetized Vacuum)
Propagation of Polarized Radiation

Propagation of Polarization from NS Surface to Observer

What if emission is from large patch of star? Complex surface field?

Recall: At the surface, the emergent radiation is dominated by one of the two modes (let's say X-mode, polarized ⊥ the local **B**).

If polarization were parallel-transported to infinity, the net polarization (summed over observable surface of the star) would be reduced.



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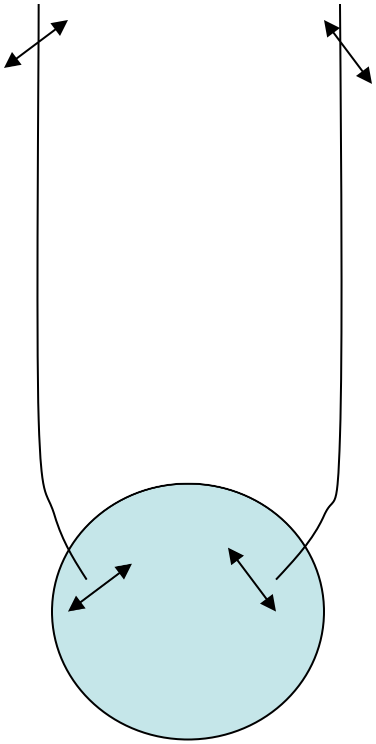
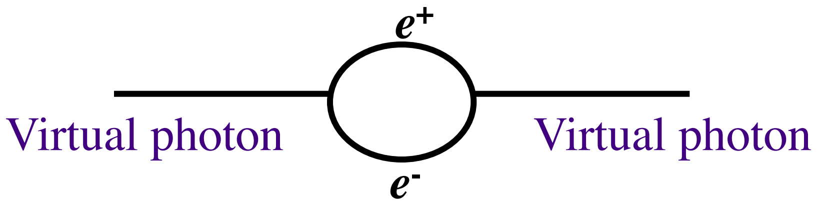


This is incorrect!

(Heyl & Shaviv 2002;
Lai & Ho 2003…)

Vacuum Polarization in Strong B



Dielectric tensor outside the neutron star: $\boldsymbol{\varepsilon} = \mathbf{I} + \Delta\boldsymbol{\varepsilon}^{(\mathrm{vac})}$

where $\Delta\boldsymbol{\varepsilon}^{(\mathrm{vac})} \sim 10^{-4}\,(B/B_Q)^2 f(B)$, with $B_Q = 4.4\times10^{13}\mathrm{G}$, $f(B) \sim 1$

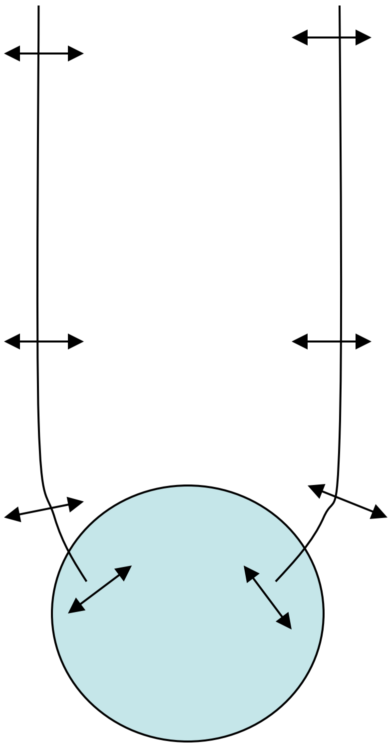
Two photon modes in magnetized vacuum:

Ordinary mode (//)

Extraordinary mode (⊥)

$n_1 \neq n_2$

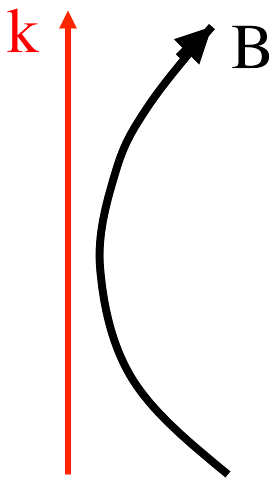
Propagation of Polarization from NS Surface to Observer Through Magnetized Vacuum

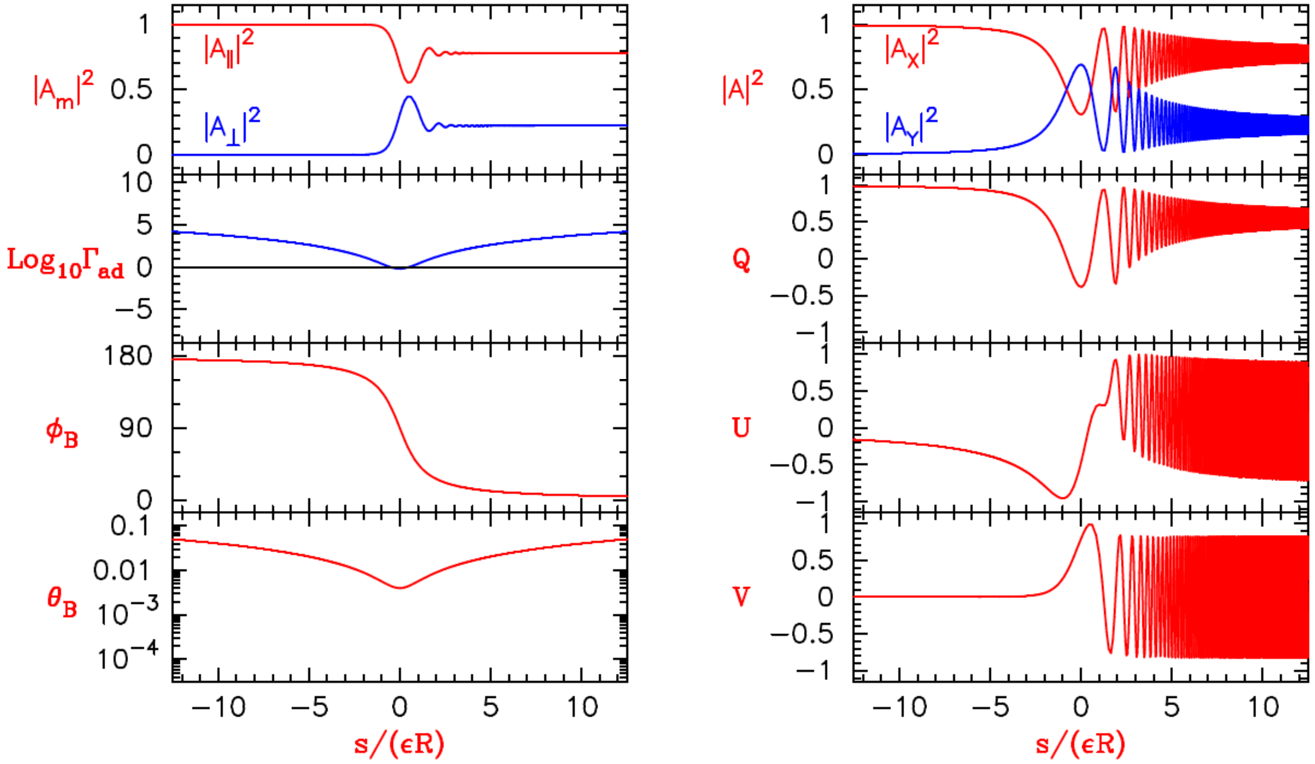


polarization limiting radius >> R

Polarization states of photons from different patches of the star are aligned at large r, and (largely) do not cancel --- Thanks to QED!

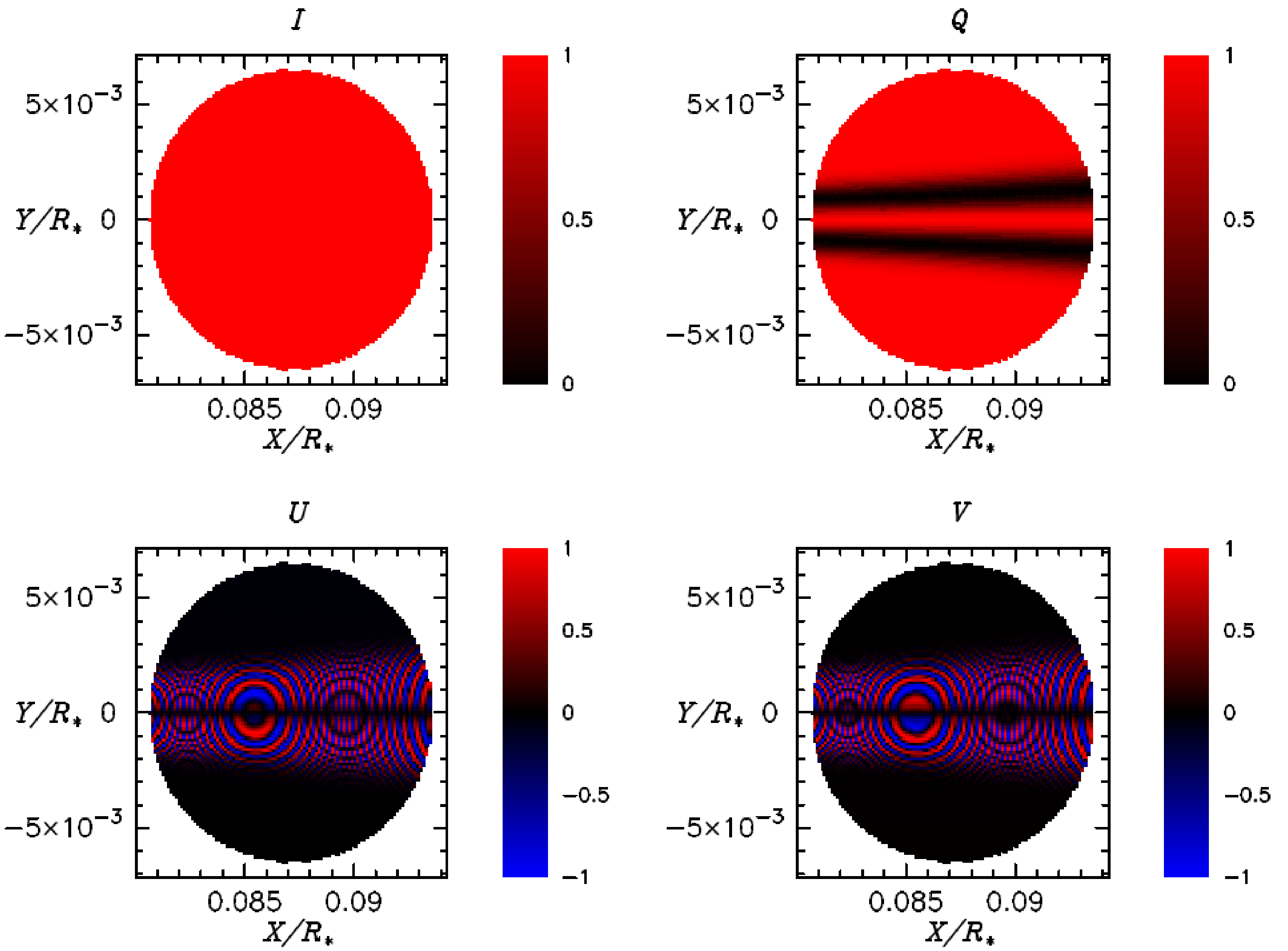
But… Propagation through quasi-tangential region





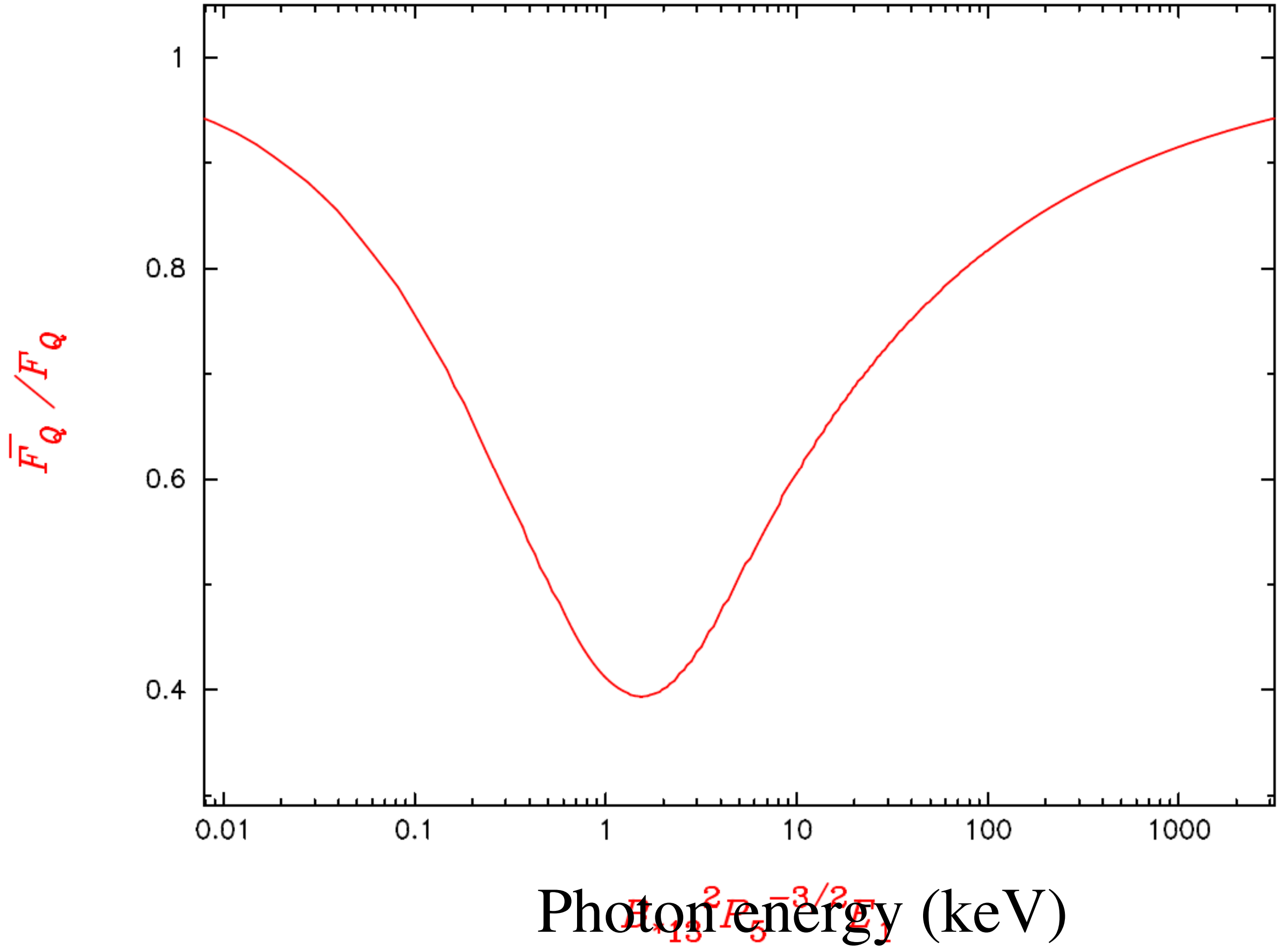
Wang & DL 2009

Polarization map of polar cap (hot spot)



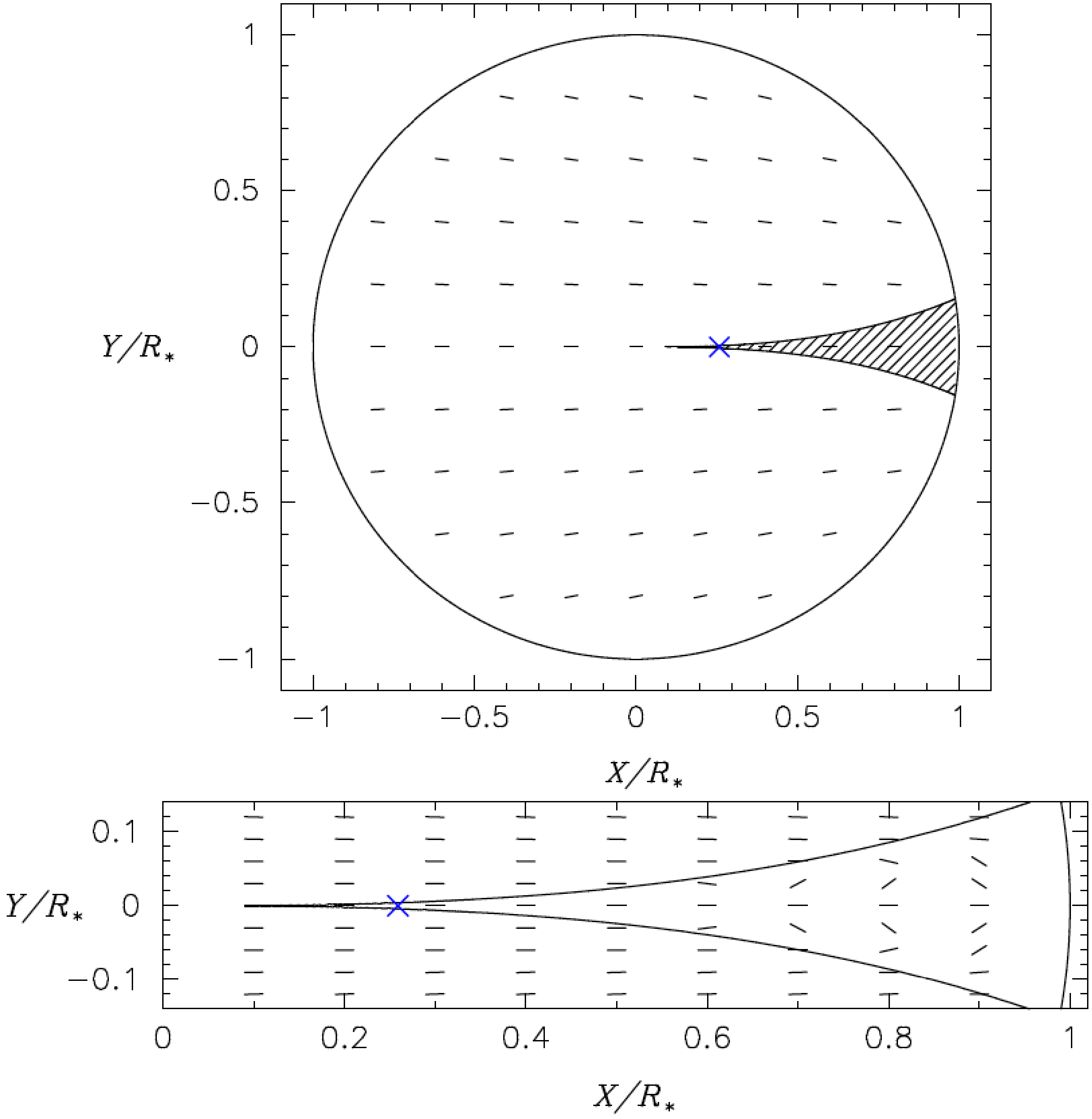
Wang & DL 2009

Reduction of linear polarization due to quasi-tangential propagation



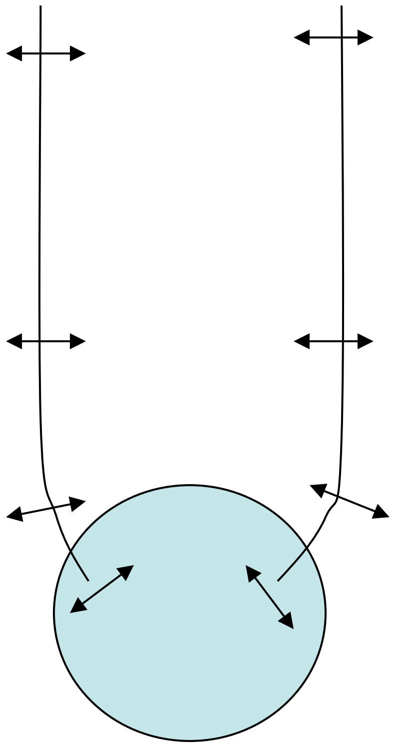
Wang & DL 2009

Polarization map of the whole NS



Wang & DL 2009

Propagation of Polarization from NS Surface to Observer Through Magnetized Vacuum



Polarization states of photons from **most** region of the NS surface are aligned at large r, and do not cancel --- Thanks to QED!

===>
Observed polarization direction depends only on the dipole component of the field, regardless of surface field structure.

(Recall: Intensity light curves depend on surface field structure)

Summary

- Surface emission from magnetized neutron stars is highly polarized.
- X-ray polarization probes B-fields, geometry, beam patterns. Complementary to light curve and spectrum (polarization signal may still be interesting even when spectrum or lightcurve is boring.)
- Strong-field QED (vacuum polarization) plays an important role in determining the X-ray polarization signals:

  1. Gives rise to clean energy-dependent polarization signatures
     For $B<7\times10^{13}$G, the plane of polarization at $E<1$ keV is $\perp$ that at $E>5$ keV;
     For $B>7\times10^{13}$G, polarization planes coincide (but spectrum is affected).
  2. Aligns the polarization states of photons from different patches of the star so that net polarization remains large.

  Probe strong-field QED.

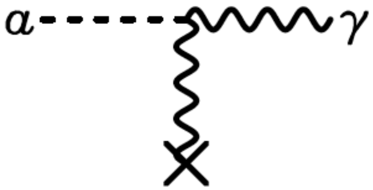
Probing Axions with Magnetic Neutron Stars

Probing Axions with Magnetic NSs

Axions: pseudoscalar particles, arise in the Peccei-Quinn solution of the strong CP problem; could be dark matter candidates (1980+)
Recent motivation from string theory

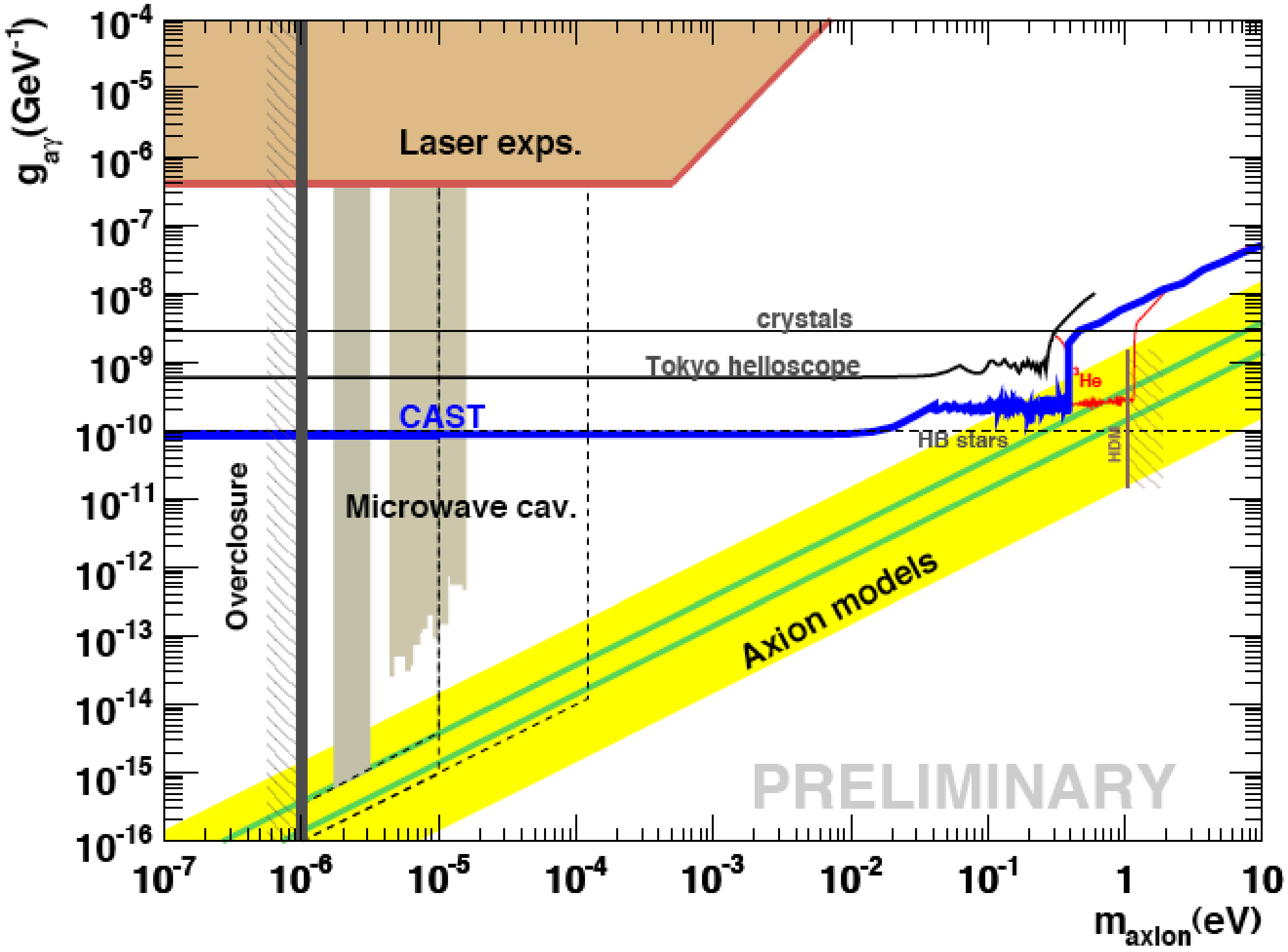
Can be produced or detected through the **Primakoff process:**

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} \ \mathbf{E} \cdot \mathbf{B} \, a$$



==> //-component of photon can be coupled to axion

Current constraints on axion mass and coupling parameter



arXiv:0810.1874 (CAST collaboration)

Photon-Axion Conversion in Magnetic Neutron Stars

In the atmosphere and magnetized vacuum of NSs, photons (//-polarization comp) can convert into axions

==> modify radiation spectra and polarization signals

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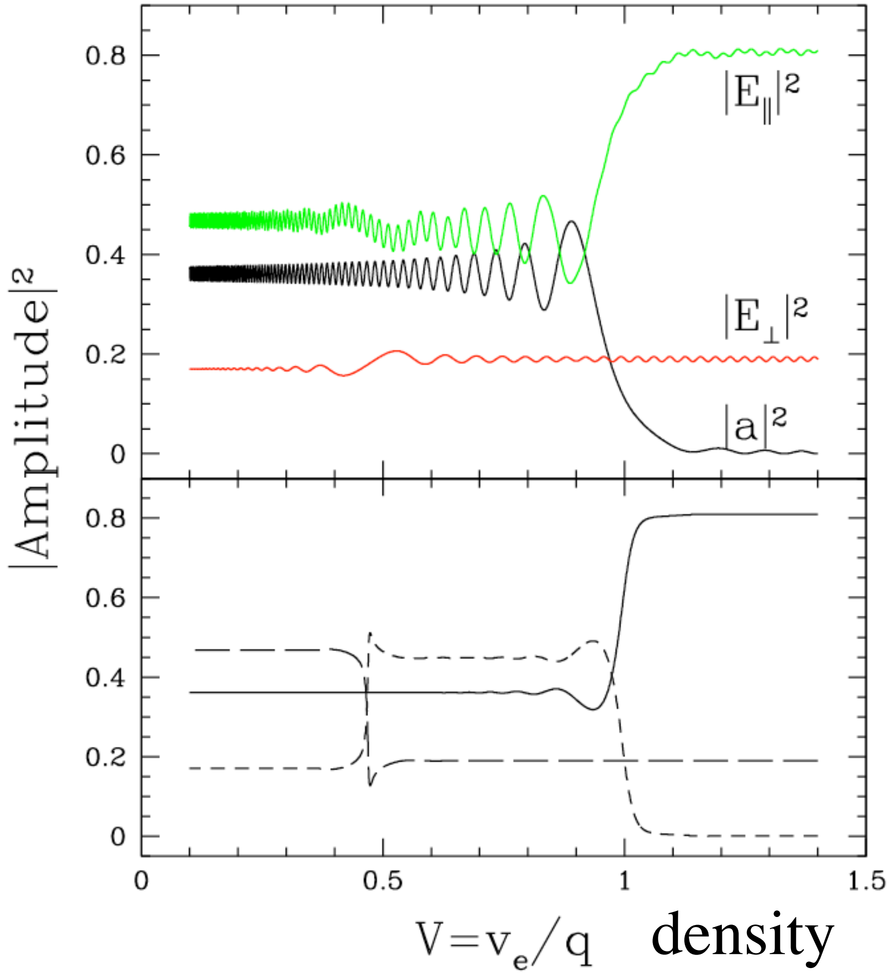

density

DL & Heyl 2007

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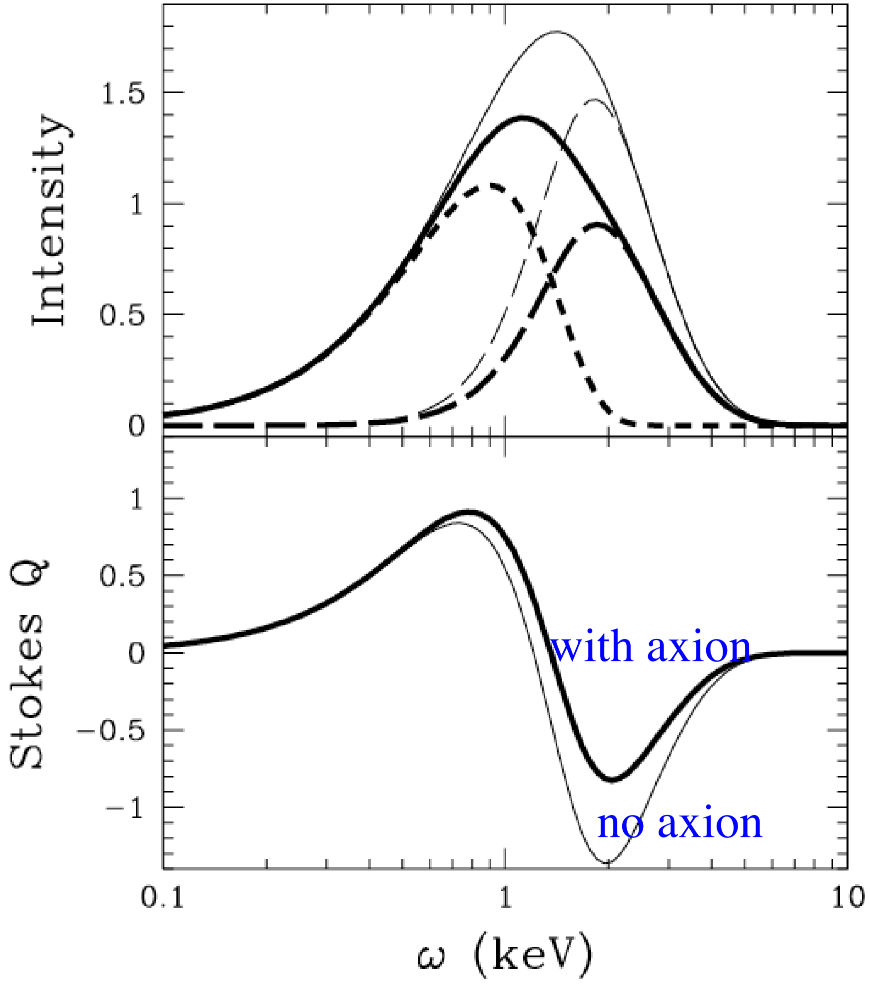

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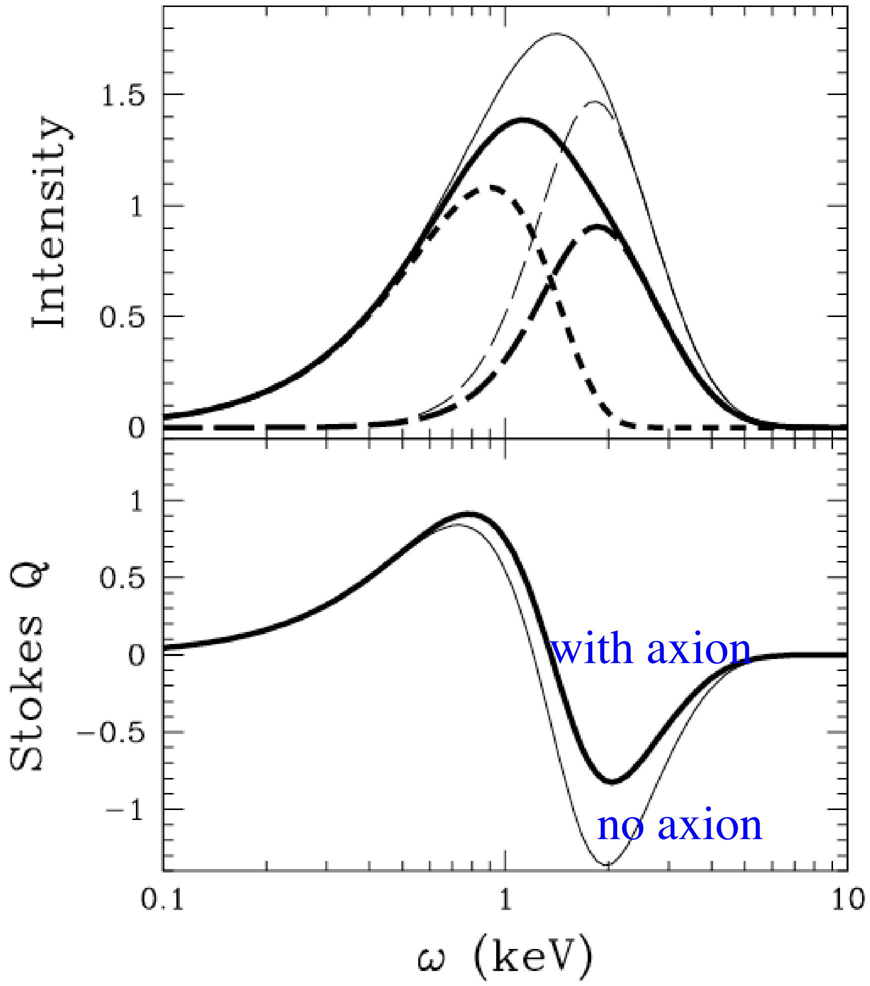


Can in principle probe axions with parameters inaccessible by other experiments/constraints.

Unclear if we can separate out astrophysical uncertainty of the sources.
(cf. Other indirect search of WIMPs)

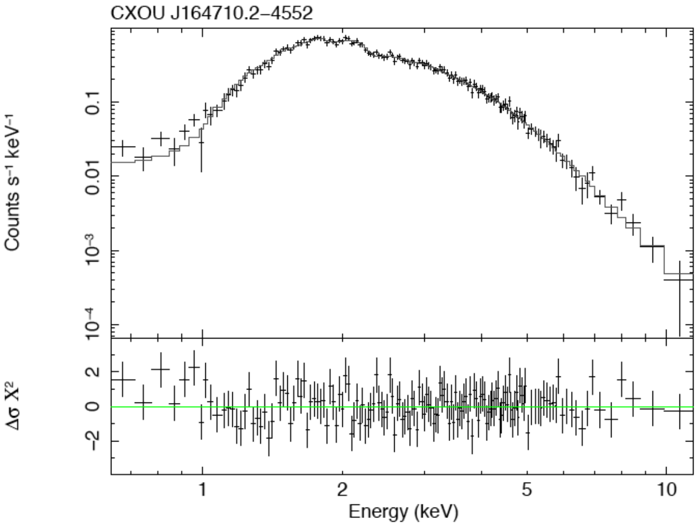
Thank you!

Power-law emission of magnetars

- Likely due to resonant up-scatterings of surface photons by magnetosphere electrons/positrons (Thompson et al 2002; Fernandez & Thompson 2007)
- Magnetosphere charges (super-GJ) arise from twisting of field lines by crust (Thompson et al 2002; Beloborodov & Thompson 2007; Thompson 2009)

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J}, \quad n_e = J/(ec)$$

- Spectral modeling
  by Fernandez & Thompson 2007
  and Nobili et al 2008



- My guess is that the input polarization will be mostly perserved…

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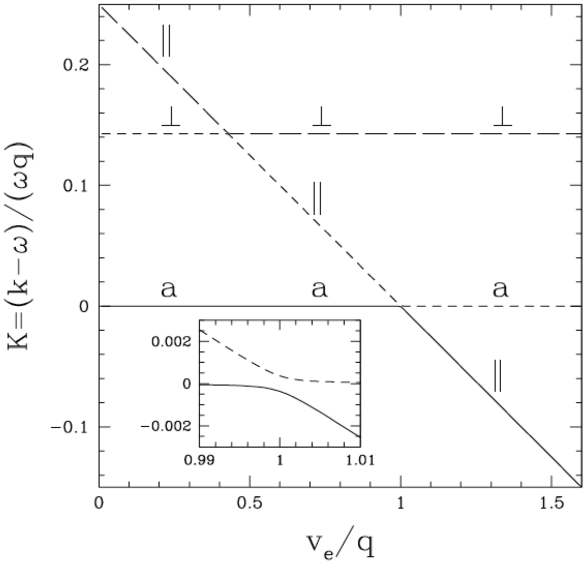

===> modify radiation spectra and polarization signals

DL & Heyl 2007