IXPE Detection of Polarized X-rays from Magnetar & QED Vacuum Resonance

Dong Lai, 2022, PNAS (almost) submitted

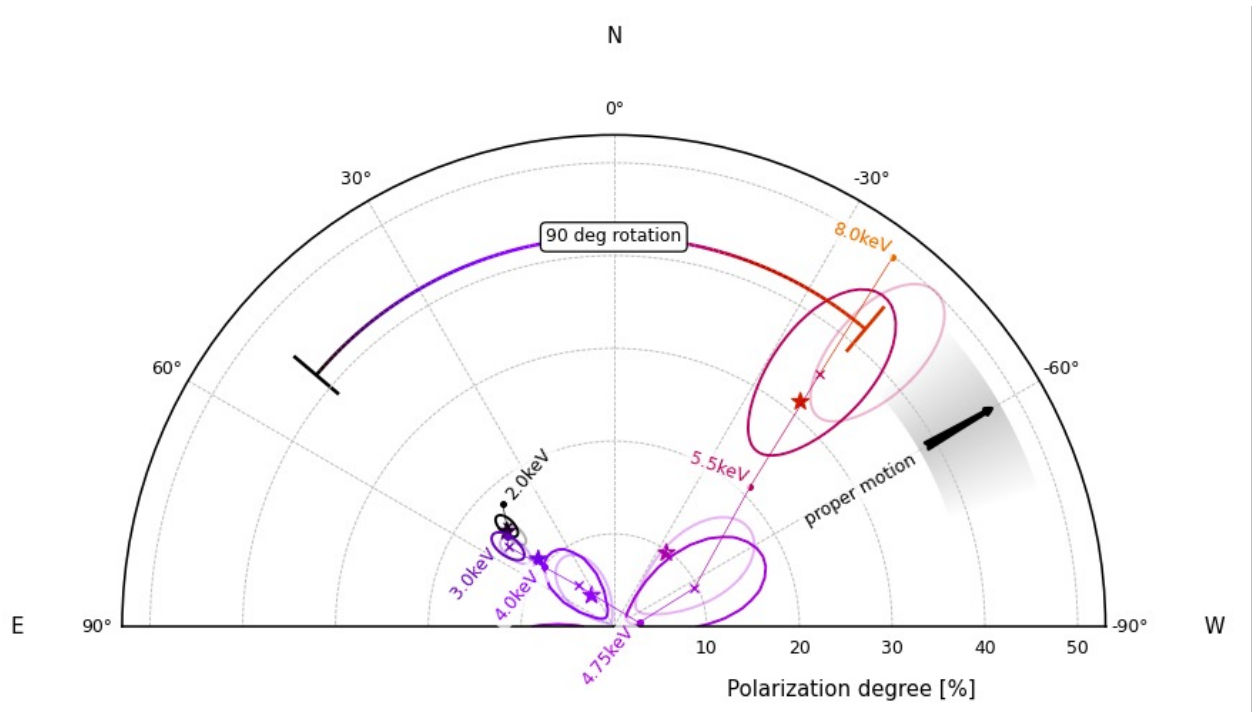
9/7/2022

IXPE (Imaging X-ray Polarimetry Explorer), SMEX-14, Launched 12/2021

Taverna et al. "Polarized X-rays from a magnetar", submitted to Science, arXiv:2205.08898

AXP 4U 0142: P=8.7s; P, Pdot => $B_d \sim 10^{14}$G
T_s = 5 MK (+ PL or another BB)

IXPE found: Linear polarization degree = $(14 \pm 1)\%$ at 2–4 keV and $(41 \pm 7)\%$ at 5.5–8 keV
angle: 90-degree swing at 4-5 keV



VOLUME 91, NUMBER 7 PHYSICAL REVIEW LETTERS week ending 15 AUGUST 2003

Polarized X-Ray Emission from Magnetized Neutron Stars: Signature of Strong-Field Vacuum Polarization

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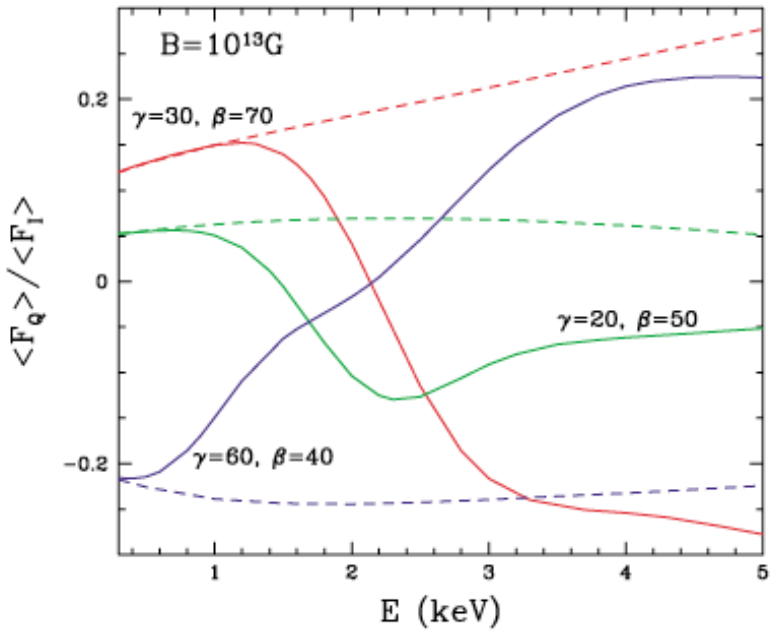
In the atmospheric plasma of a strongly magnetized neutron star, vacuum polarization can induce a Mikheyev-Smirnov-Wolfenstein type resonance across which an x-ray photon may (depending on its energy) convert from one mode into the other, with significant changes in opacities and polarizations. We show that this vacuum resonance effect gives rise to a unique energy-dependent polarization signature in the surface emission from neutron stars. The detection of polarized x rays from neutron stars can provide a direct probe of strong-field quantum electrodynamics and constrain the neutron star magnetic field and geometry.

Predicted 90-degree polarization swing at ~2 keV for B< 7×10^{13}G (for H atmosphere)



Photon Polarization Modes in a Magnetized Plasma

$(\omega << \omega_{ce} = 1160\ B_{14}$ keV$)$

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

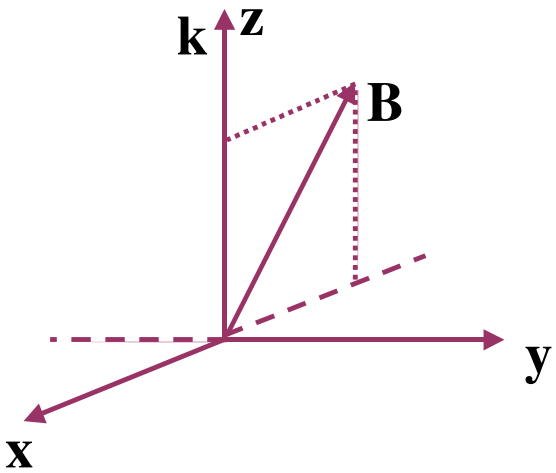
E nearly in the **k-B** plane

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

Extraordinary Mode (X-mode, ⊥-mode):

E nearly ⊥ **k-B** plane

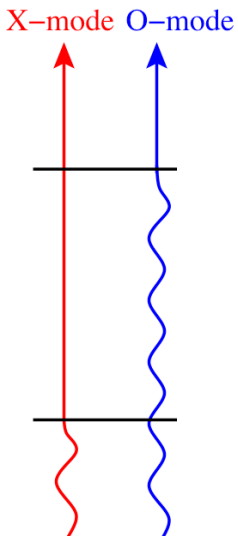
$$|K| = |E_x / E_y| << 1$$



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

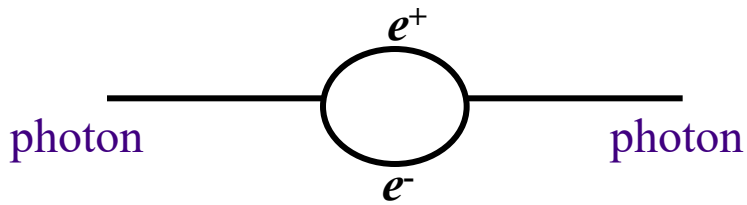
$$\kappa_{\text{(O-mode)}} \sim \kappa_{(B=0)}$$

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



X-mode photons are the main carrier of X-ray flux
(Two photospheres)

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 ($\perp$)

QED Effect in NS Atmosphere

Dielectric tensor of magnetized plasma including vacuum polarization

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

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

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

Vacuum resonance:

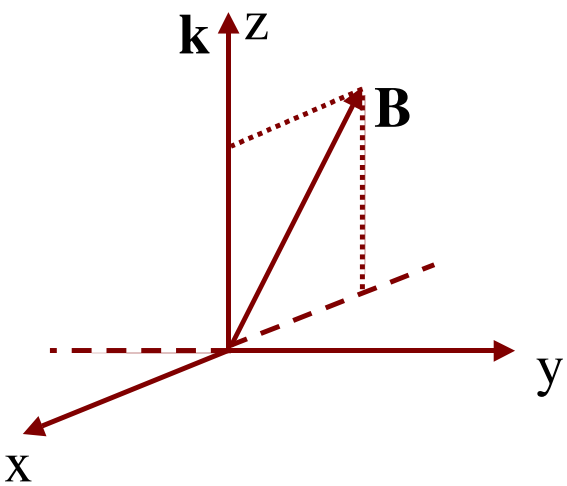
$$\Delta\varepsilon^{(\mathrm{plasma})} + \Delta\varepsilon^{(\mathrm{vac})} \sim 0$$

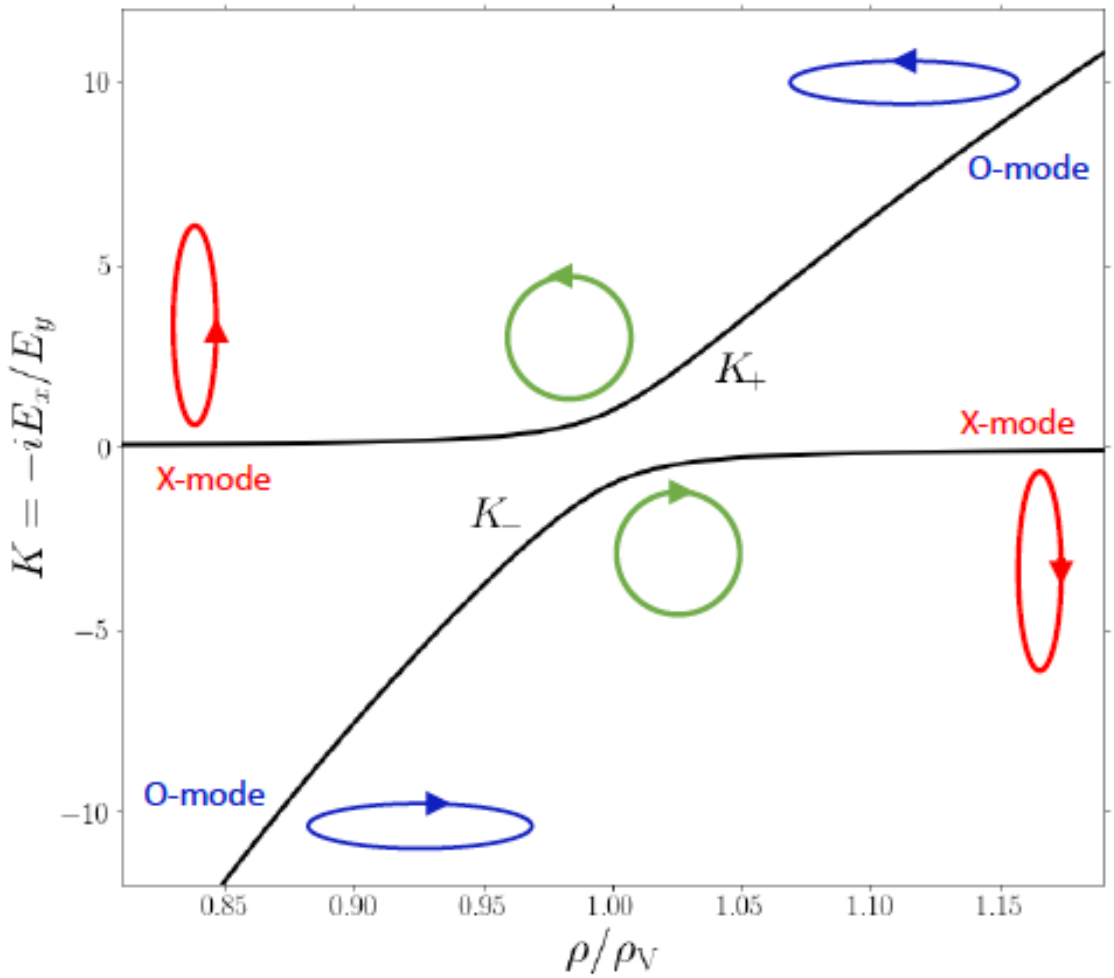
depends on $-(\omega_p/\omega)^2 \propto \rho/E^2$

$$\Rightarrow \quad \rho_{\mathrm{V}} = 0.96\, Y_e^{-1} B_{14}^2\, (E/1\ \mathrm{keV})^2\ \mathrm{g\ cm^{-3}}$$

At resonance, X-mode and O-mode are "similar"

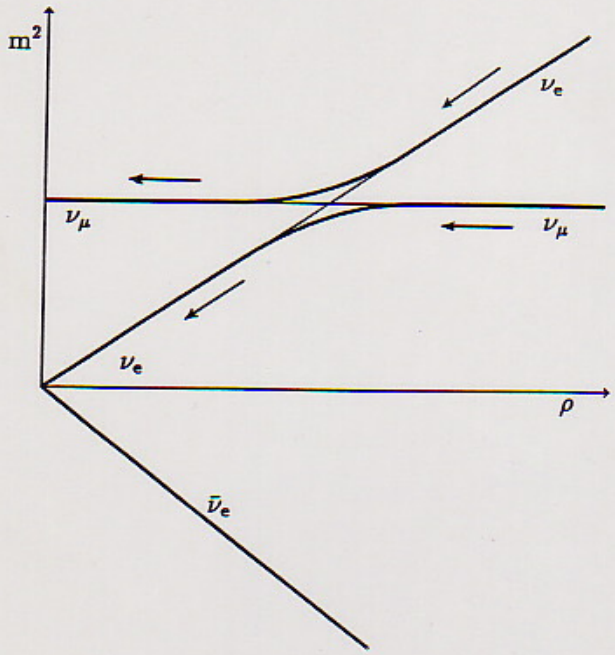
Polarization of photon modes



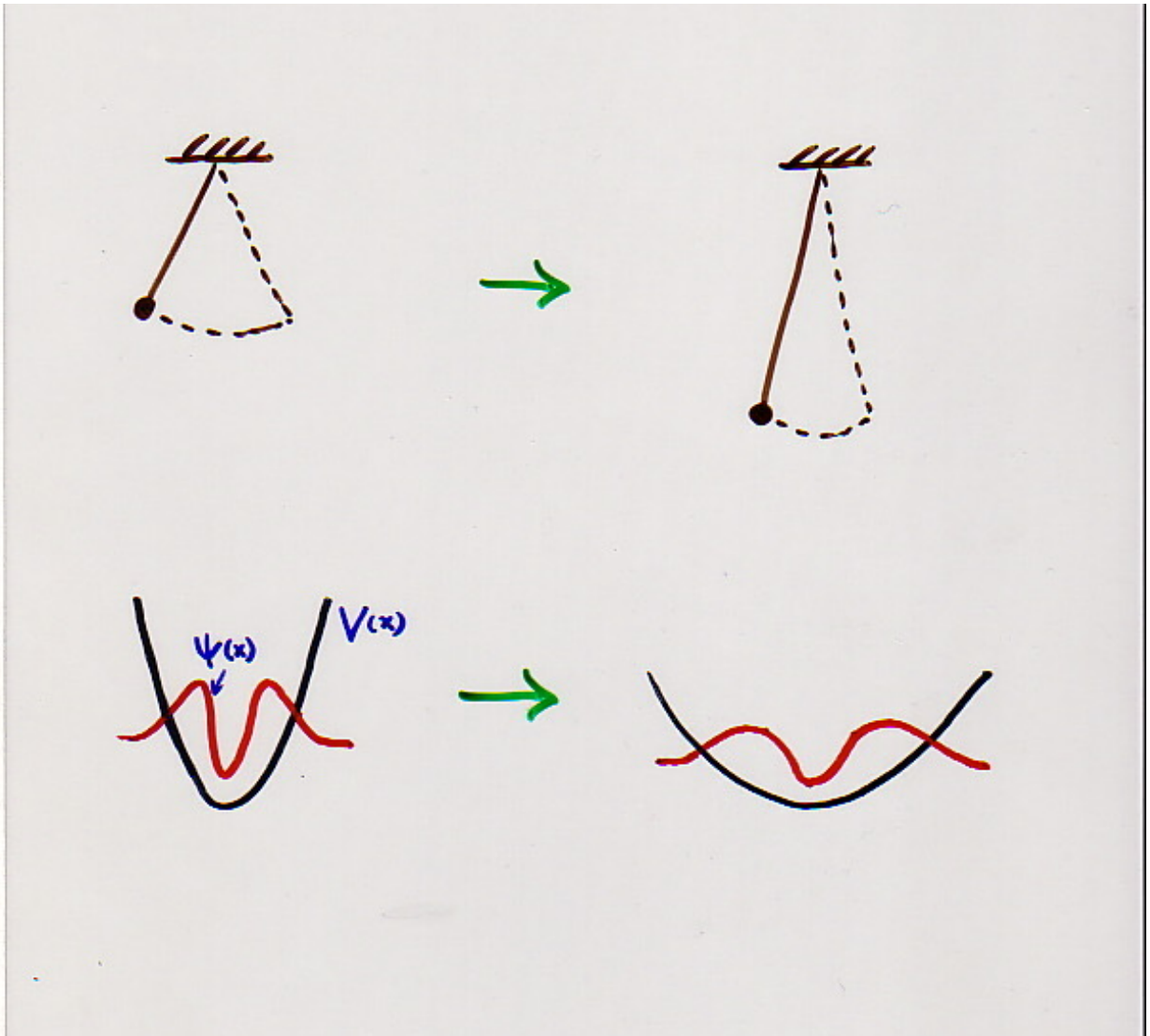


$B=10^{14}$ G, E=5 keV, $\theta_{kB}=30^o$

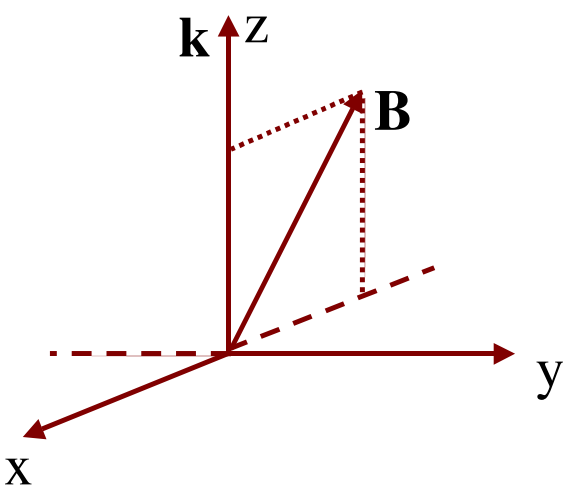
Mikheyev-Smirnov-Wolfenstein (MSW) Neutrino Oscillation

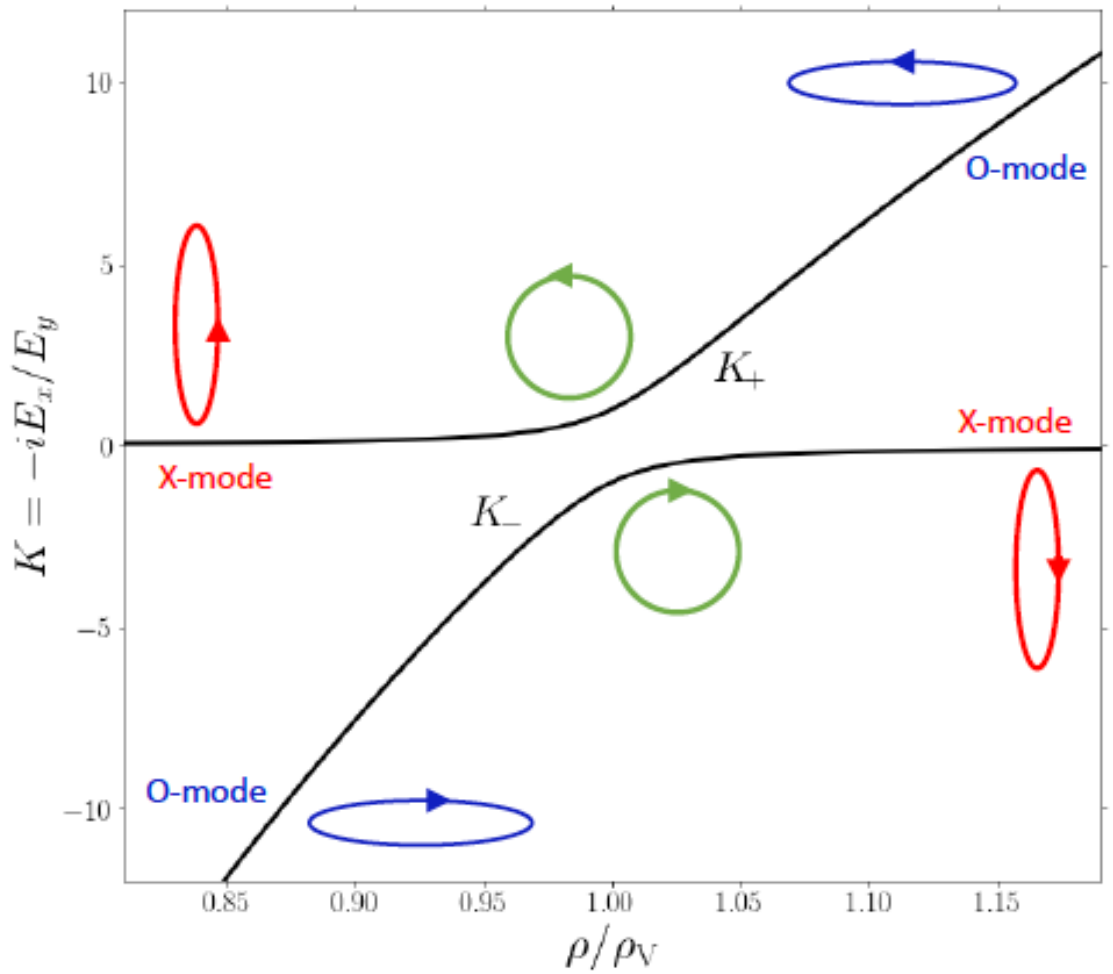


Adiabatic Evolution of a Quantum State



“Plasma+Vacuum” ==> Vacuum resonance





Adiabatic Condition:

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

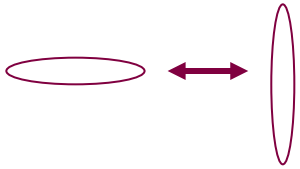
$$\Rightarrow \quad E \gtrsim E_{\rm ad} = 2.52\,(f\,\tan\theta_{kB})^{2/3}\left(\frac{1\,\mathrm{cm}}{H_\rho}\right)^{1/3}\mathrm{keV}$$

$$H_\rho \simeq \frac{kT}{\mu m_p g\cos\alpha} = 0.41\,\frac{T_6}{\mu g_2\cos\alpha}\,\mathrm{cm}$$

$$T_6 = T/(10^6\mathrm{K})$$

$$g = 2\times 10^{14} g_2\,\mathrm{cm/s^2}$$

Photons with E > E_{ad}, mode conversion



Photons with E < E_{ad}, no mode conversion

In general, nonadiabatic "jump" probability

$$P_{\rm J} = \exp\left[-\frac{\pi}{2}\left(\frac{E}{E_{\rm ad}}\right)^3\right]$$

Recall

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

$$\rho_O \simeq 0.59 \left(\frac{\mu g_2 \cos\alpha}{\mathcal{G}\sin^2\theta_{kB}}\right)^{1/2} \left(\frac{E_1}{Z}\right)^{3/2} \left(\frac{A}{T_6^{1/4}}\right) \text{ g cm}^{-3}.$$

$$\rho_X \gg \rho_O$$

-- Vacuum resonance

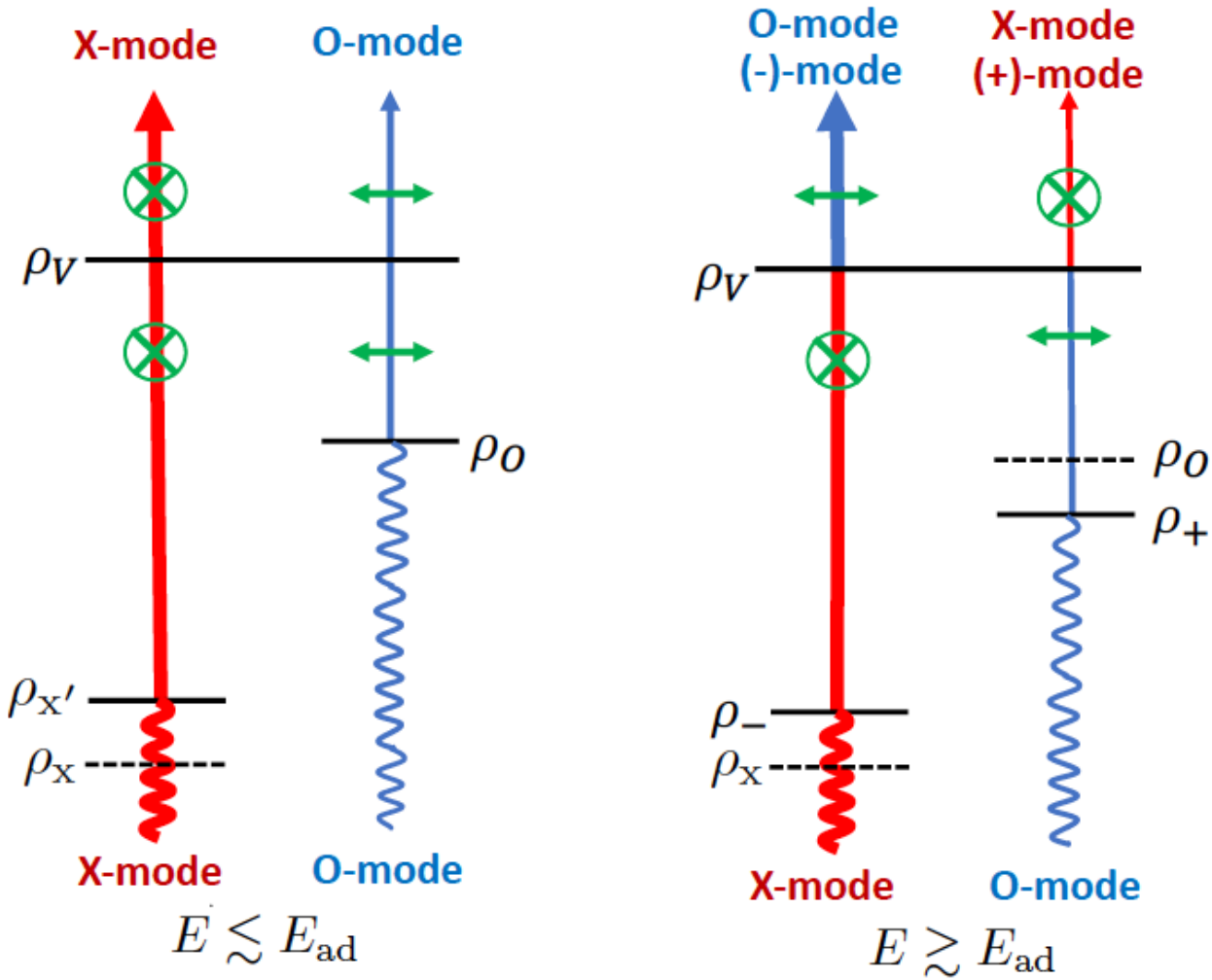
$$\rho_V = 0.96\, Y_e^{-1} B_{14}^2 \ (E/1 \text{ keV})^2 \text{ g cm}^{-3}$$

$\rho_V < \rho_O \Longleftrightarrow$

$$B < B_{OV} = 7.8\times10^{13} \left(\frac{\mu g_2 \cos\alpha}{Z\mathcal{G}E_1 \sin^2\theta_{kB}}\right)^{1/4} \frac{1}{T_6^{1/8}} \text{ G}$$

For $B < B_{OV} = 8\times10^{13}$ (…) $T_6^{-1/8} E_1^{-1/4}$ G:

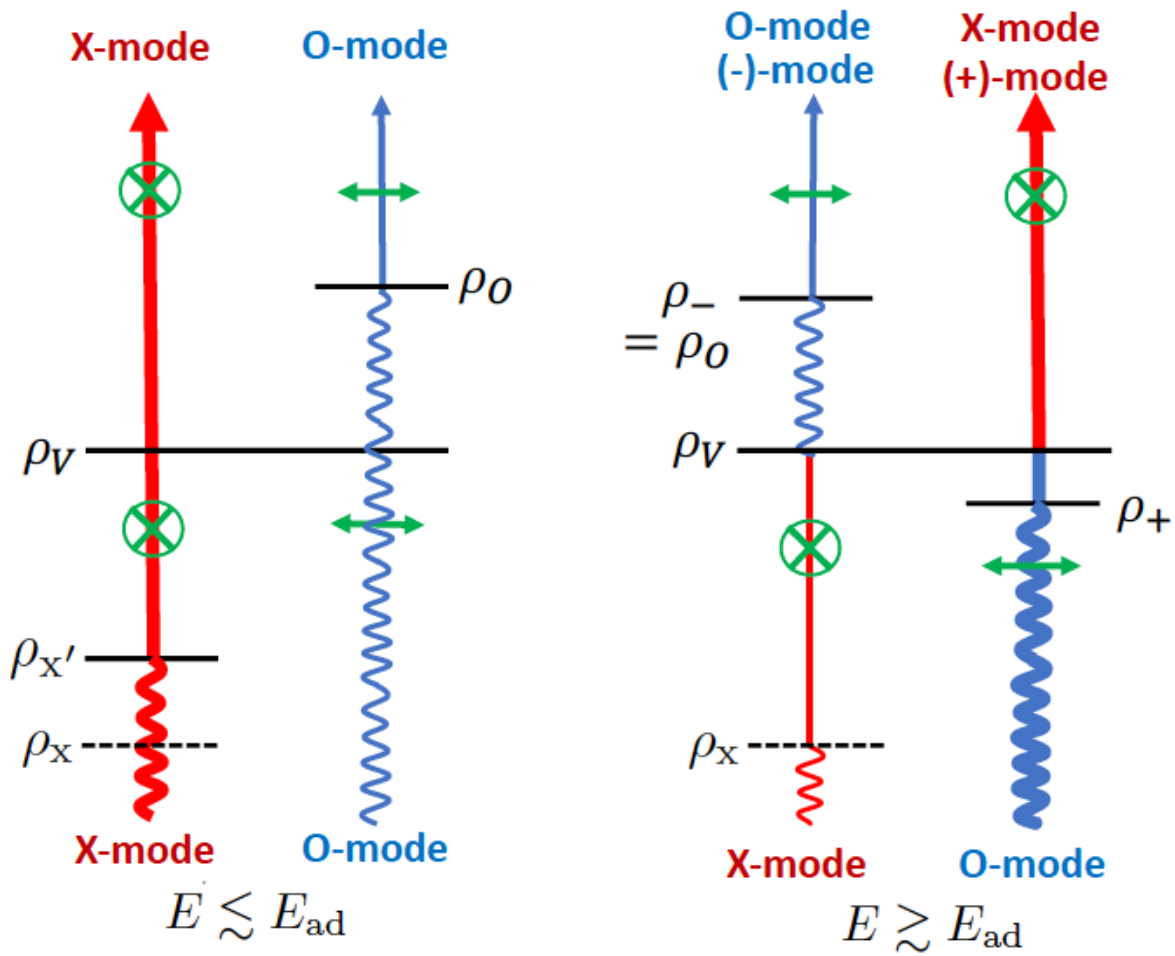
Vacuum resonance lies outside both photospheres



Plane of linear polarization at $< E_{ad}$ is perpendicular to that at $> E_{ad}$.

For $B > B_{OV}=8\times10^{13}$ (…) $T_6^{-1/8}\,E_1^{-1/4}$ G:

Vacuum resonance lies between the two photospheres



Plane of linear polarization at different E coincide

Recap:

To produce 90-degree polarization swing requires

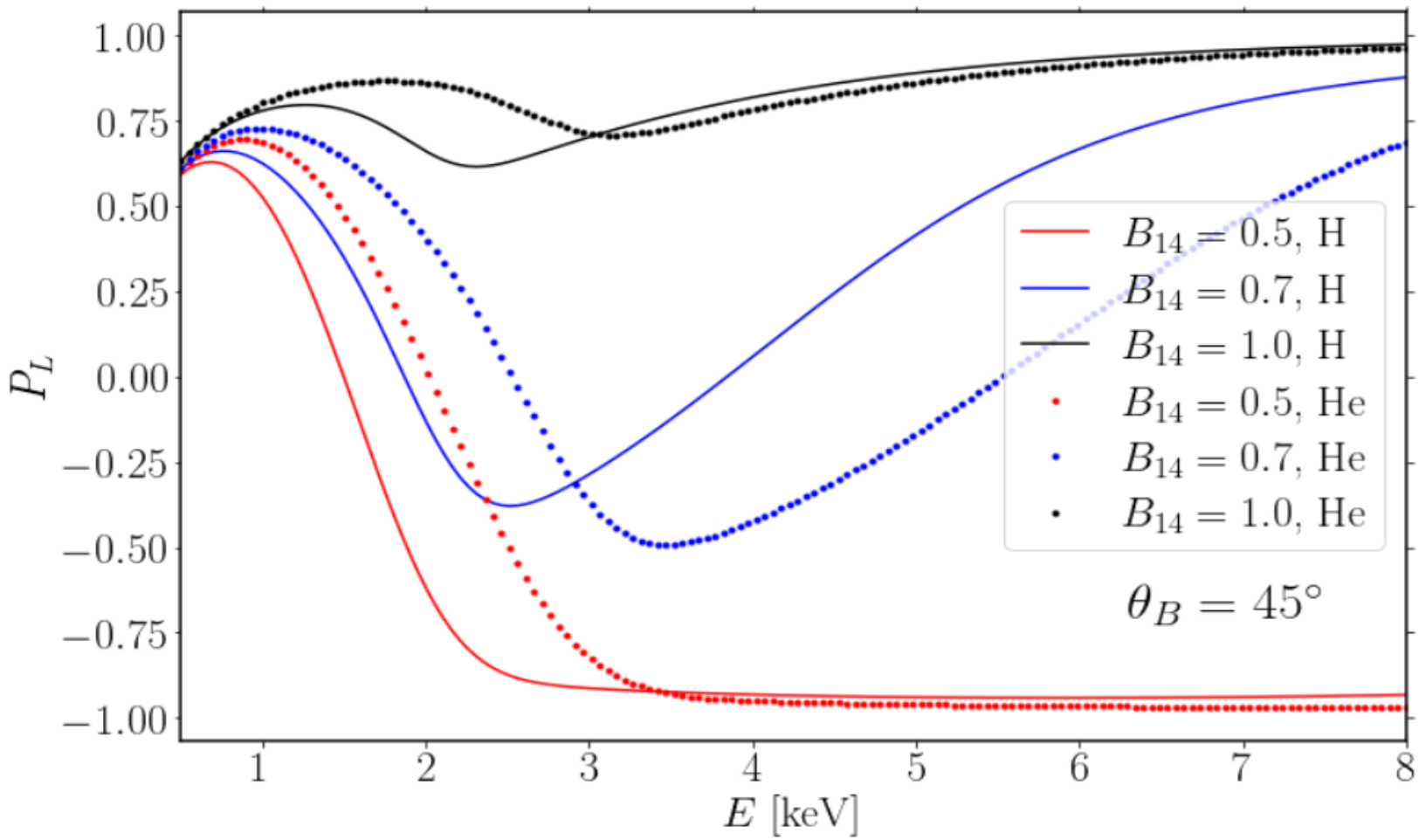
$$\rho_V < \rho_O \Longleftrightarrow B < B_{OV} = 7.8\times10^{13}\left(\frac{\mu g_2 \cos\alpha}{Z\mathcal{G}E_1 \sin^2\theta_{kB}}\right)^{1/4}\frac{1}{T_6^{1/8}}\,\mathrm{G}$$

Transition energy

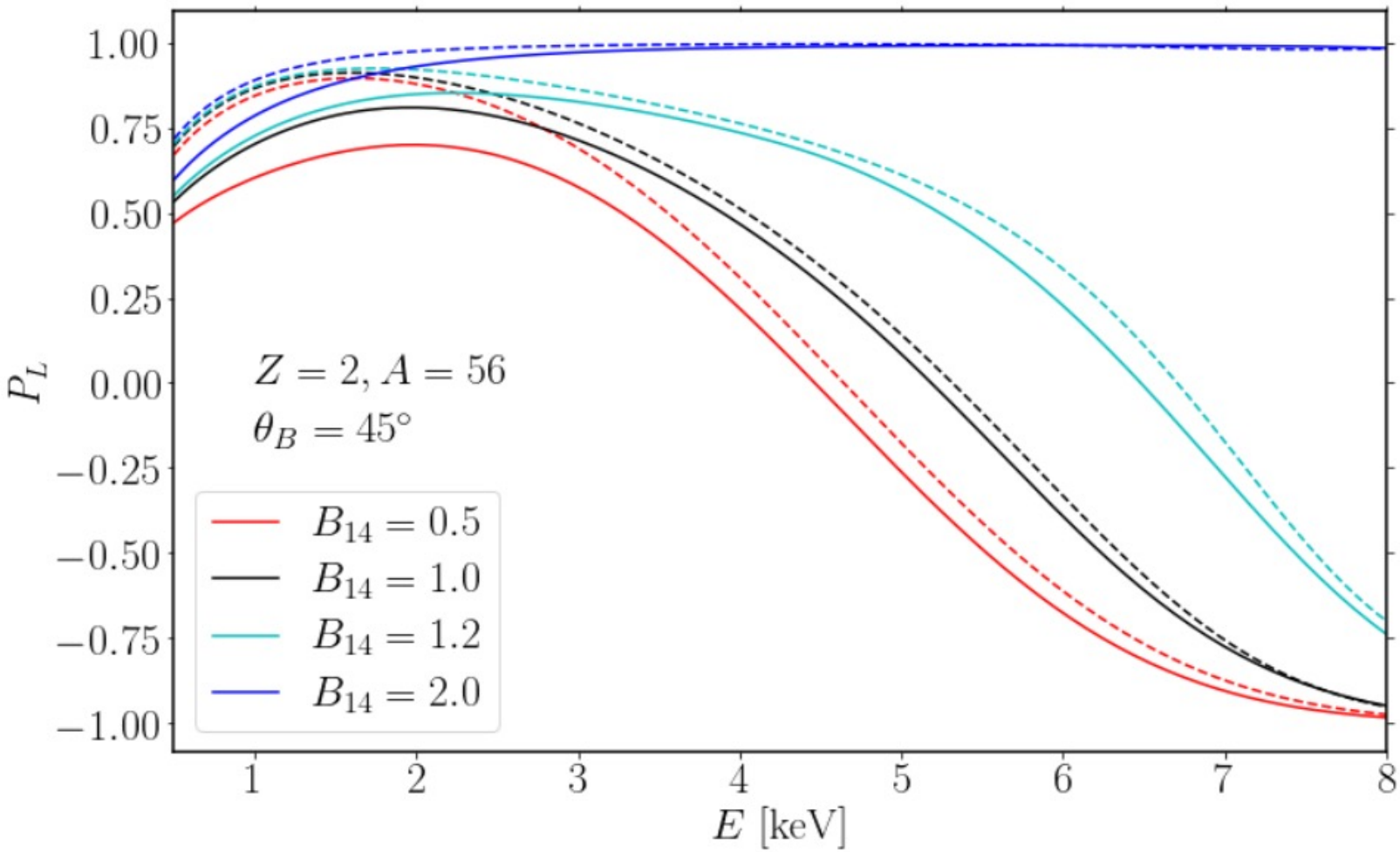
$$E_{\rm ad} = 2.52\left(f\ \tan\theta_{kB}\right)^{2/3}\left(\frac{1\,\mathrm{cm}}{H_\rho}\right)^{1/3}\mathrm{keV}$$

$$H_\rho \simeq \frac{kT}{\mu m_p g\cos\alpha} = 0.41\,\frac{T_6}{\mu g_2\cos\alpha}\,\mathrm{cm}$$

Light-element atmospheres



Heavy-element (partially ionized) atmosphere

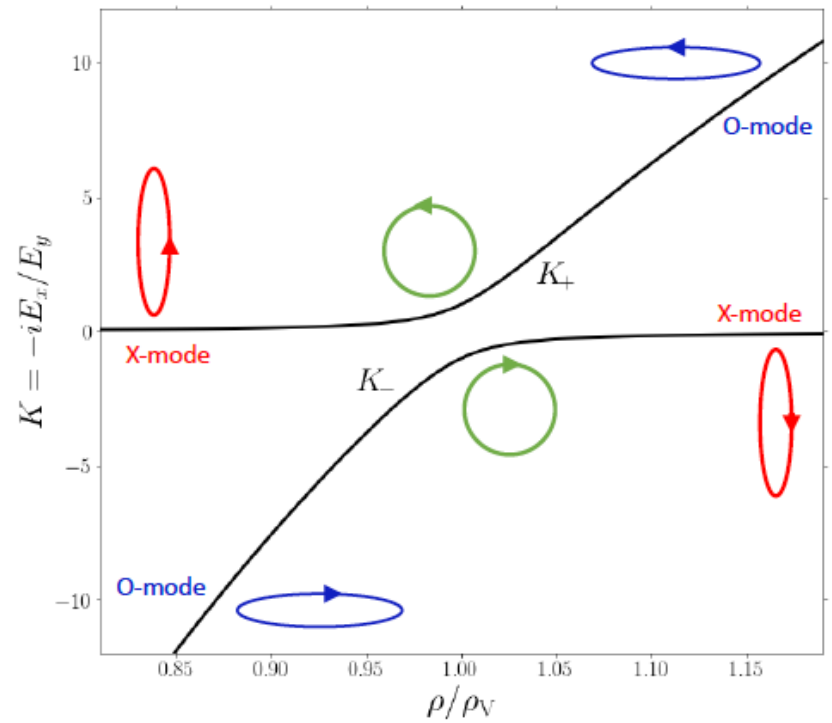


Summary/Implications

-- The observed X-ray polarization swing at 4-5 keV from 4U 0142 can be "naturally" explained by mode conversion associated with vacuum resonance

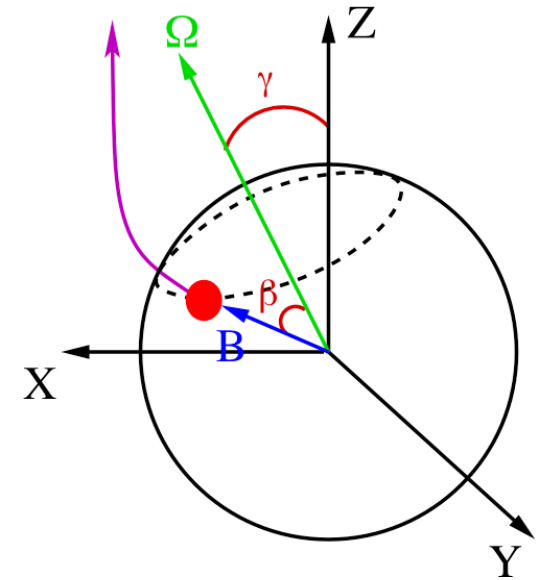
-- Low-E emission dominated by X-mode
High-E emission dominated by O-mode

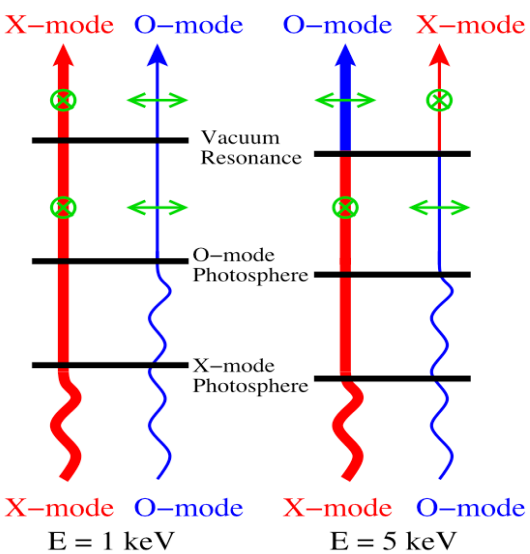
In this interpretation:
the phase-averaged low-E polarization is perp. to spin axis projection in sky
➔ Spin-kick alignment



-- Requires heavy-element atmosphere

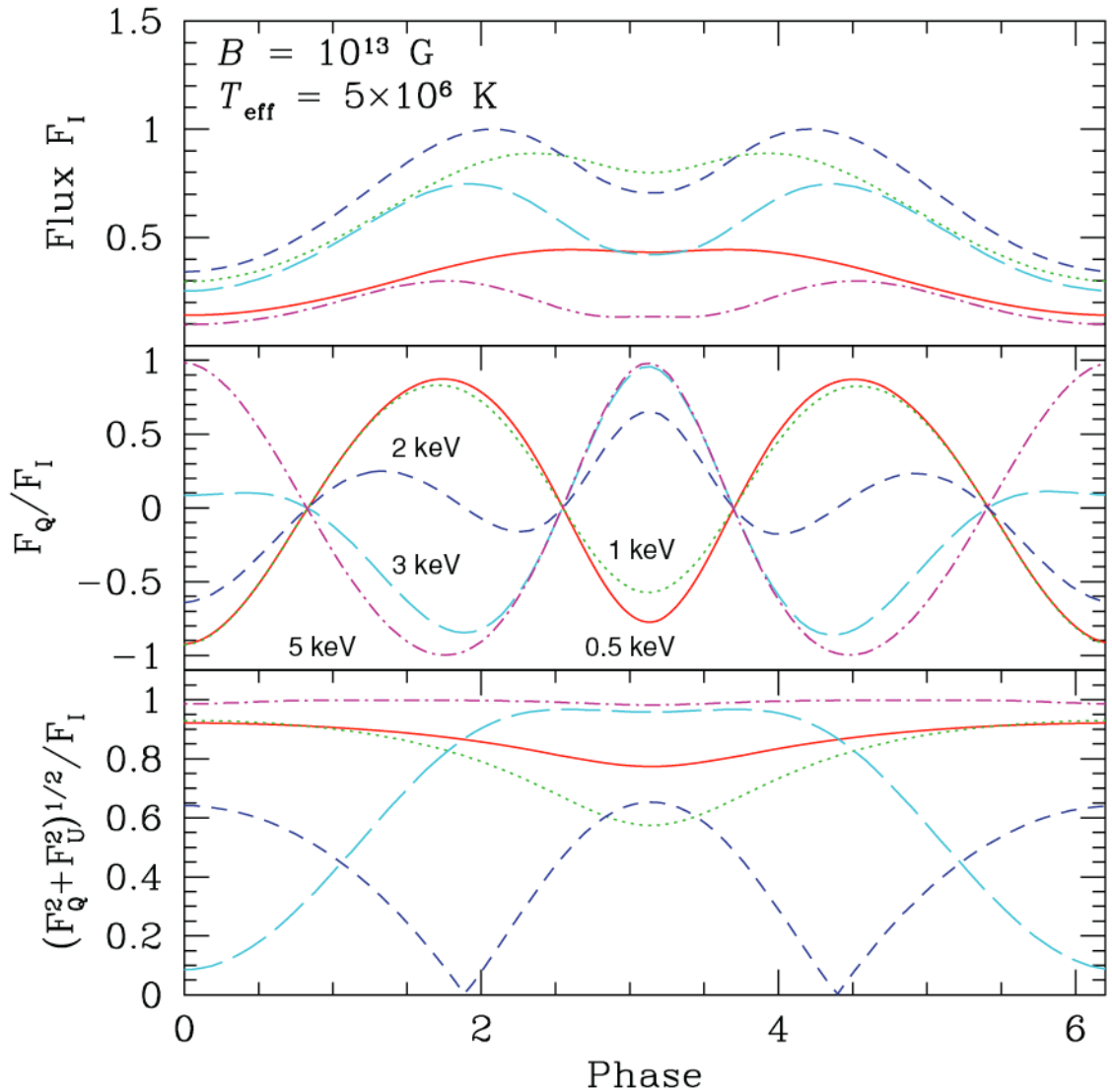
-- "Prefer" the surface B field to be less (a factor of ~2) than dipole field inferred from P, Pdot.
➔ Enhanced spindown torque compared to dipole radiation/force-free magnetosphere; e.g. Relativistic particle wind with $L_{wind} > L_{spindown}$





B=10^{13}G

$\gamma = 30°, \quad \beta = 70°$



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

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

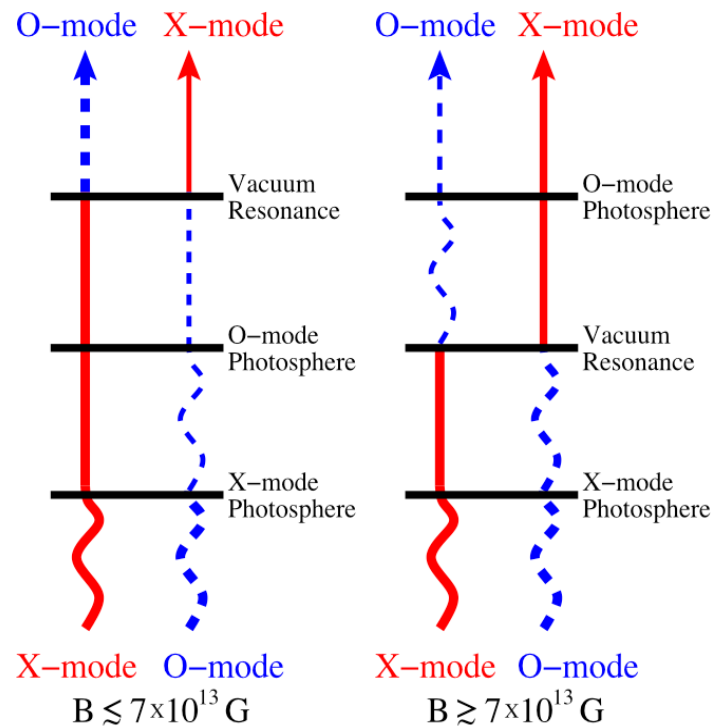
Recapitulation: **Effect of Vacuum Resonance on Surface Emission**

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

- 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 ($\rho_{o\text{-}mode} < \rho_{vac} < \rho_{x\text{-}mode}$)

- 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



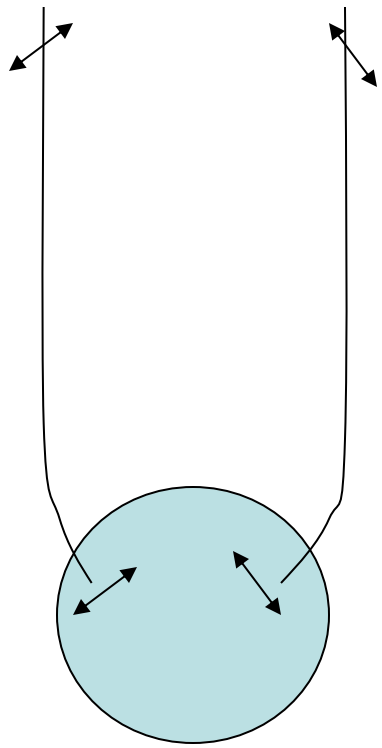
QED Effect in Magnetospheres (=Magnetized Vacuum)
Propagation of Polarized Radiation

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**).

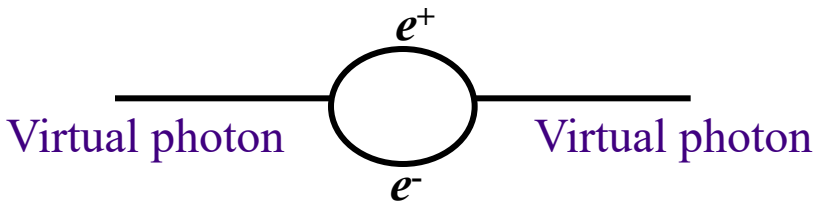
If polarization were parallel-transported to infinity, the net polarization (summed over observable surface of the star) would be reduced.



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

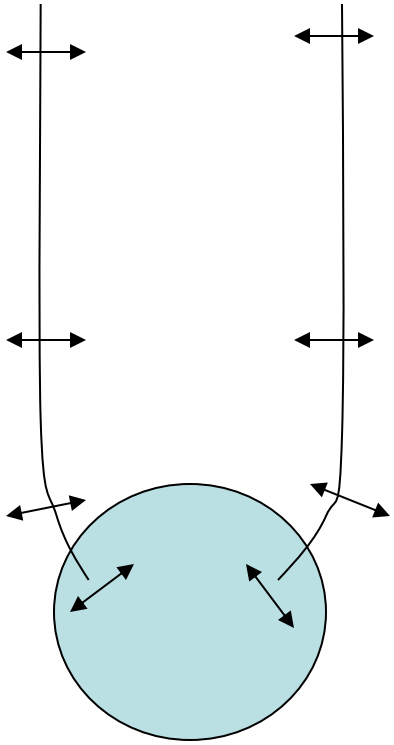
Two photon modes in magnetized vacuum:

Ordinary mode (//)

Extraordinary mode ($\perp$)

$n_1 \neq n_2$

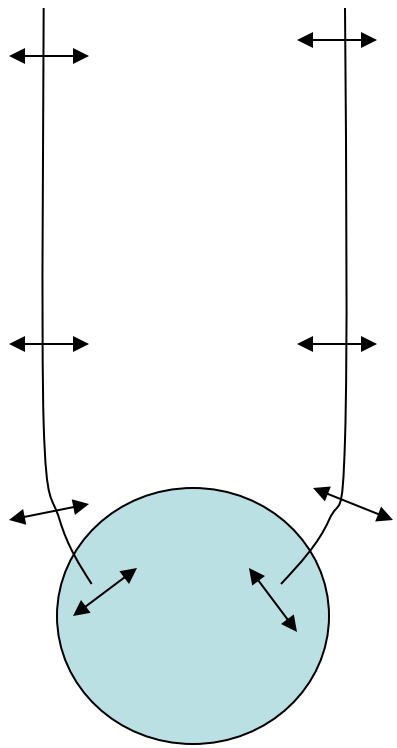
Propagation of Polarization from NS Surface to Observer Through Magnetized Vacuum



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!

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)