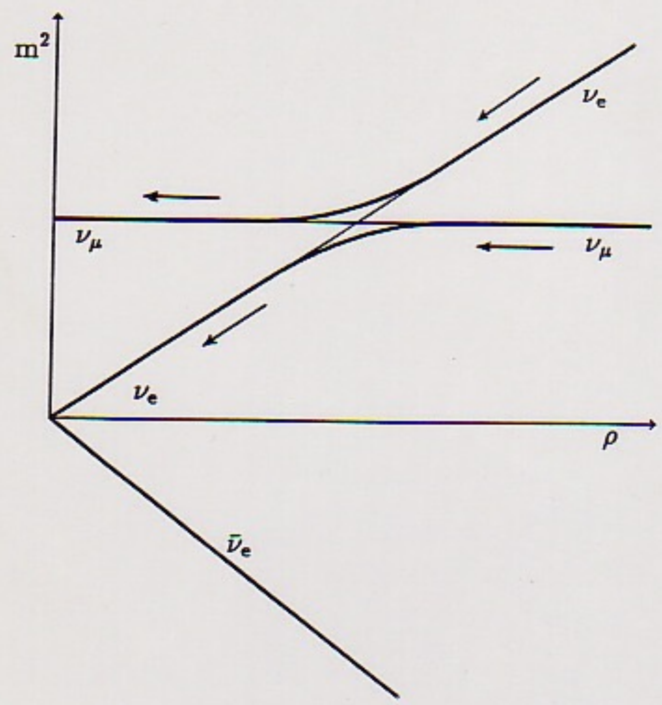
Polarized X-rays from Magnetars (& Solar Neutrinos)

Dong Lai

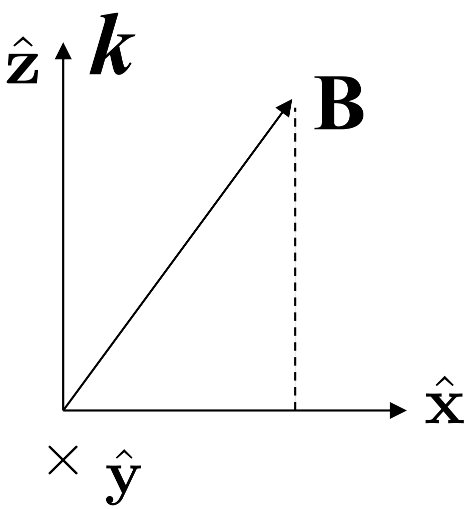
IAS Bahcall Lunch, 9/17/2024

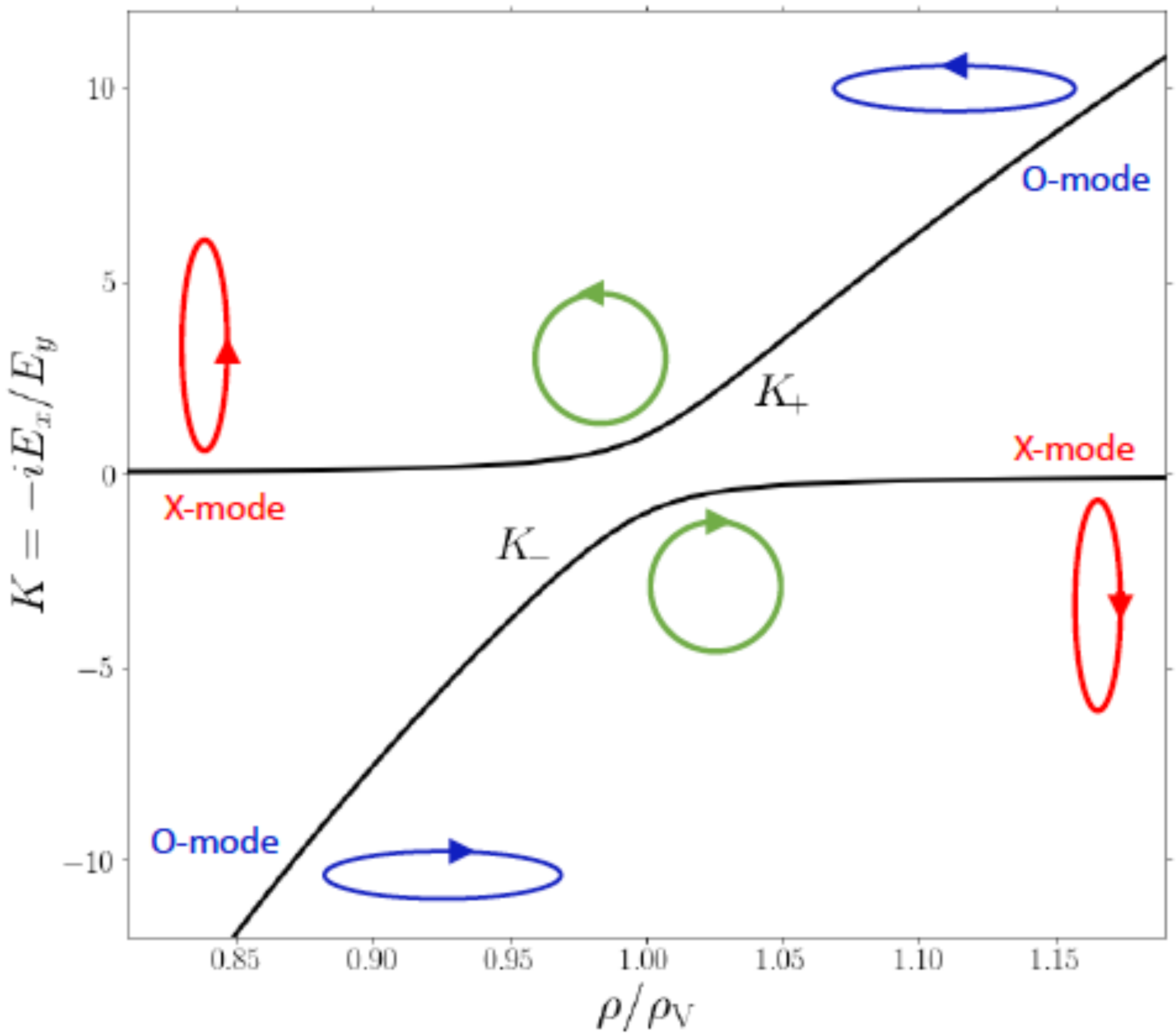
MSW Neutrino Oscillation/Conversion in the Sun



See Bahcall "Neutrino Astrophysics"

Polarization of photon modes: Plasma + QED vacuum





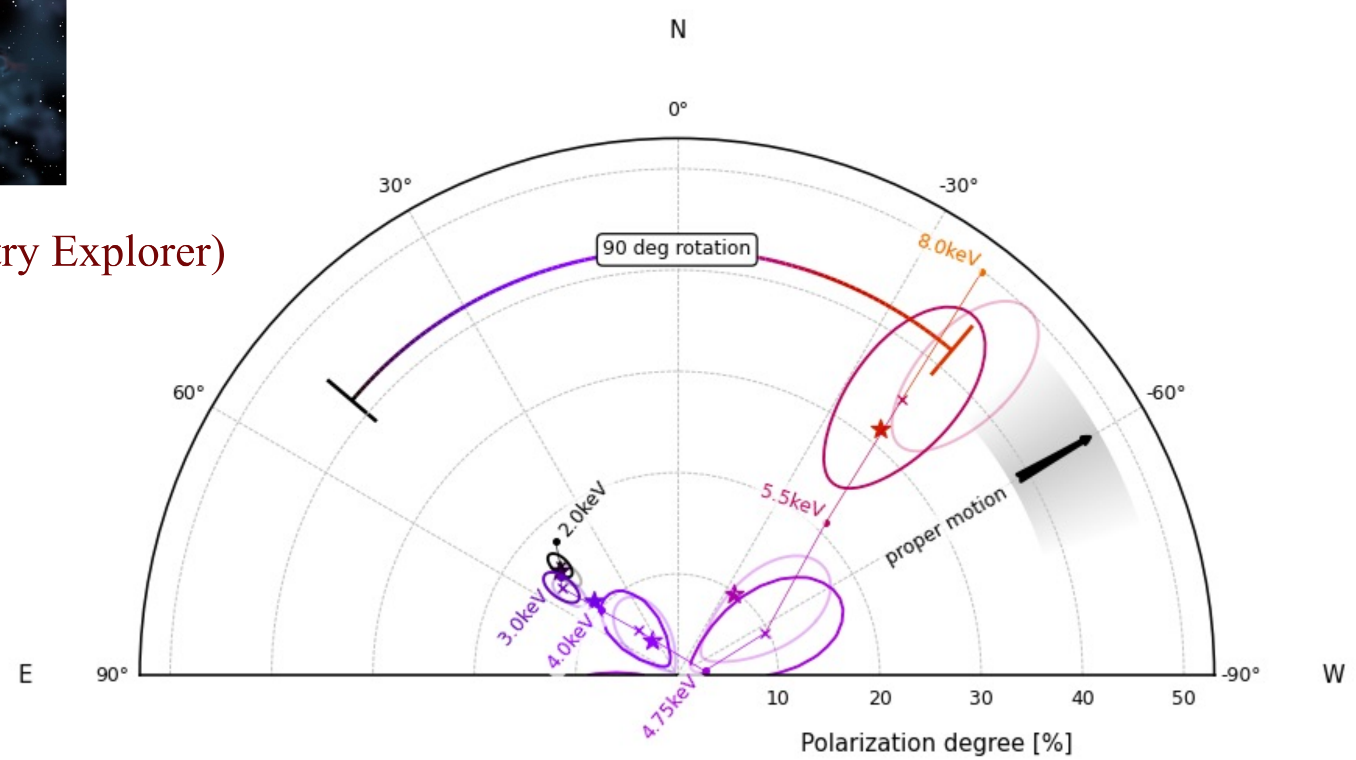
B=10^{14} G, E=5 keV, θ_{kB}=30^o

Taverna et al. 2022, Science, “Polarized X-rays from a magnetar”

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

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

IXPE (Imaging X-ray Polarimetry Explorer)
Launched 2021



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This can be explained by QED vacuum resonance
Lai (2023), PNAS + …
(see also Lai & Ho 2003, PRL)

Neutron star atmosphere:

magnetized (partially ionized) plasma

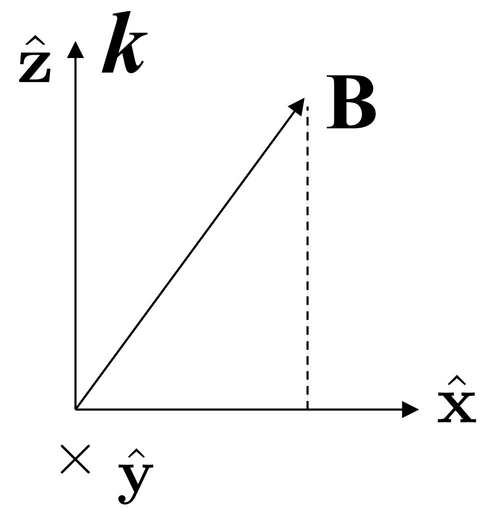
Scale height: $H \simeq \frac{kT}{m_p g} \sim 1 \text{ cm}$

Density: 0.1 – 100 g/cm^3

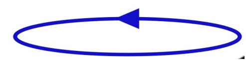
Photon Polarization Modes in a Magnetized Plasma

Dielectric tensor: $\boldsymbol{\varepsilon} = \mathbf{I} + \Delta\boldsymbol{\varepsilon}^{\text{(plasma)}}$

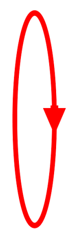
For photon energy $\omega << \omega_{ce} = 1160\, B_{14}$ keV



Ordinary Mode (O-mode):

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

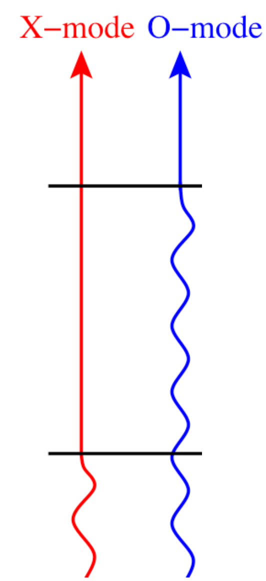
Extraordinary Mode (X-mode):

E nearly $\perp$ **k-B** plane: 

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

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

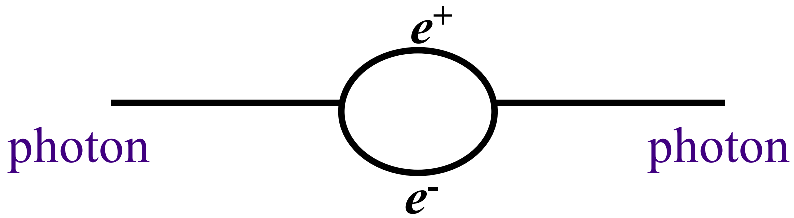
$\kappa_{\text{(X-mode)}} \sim \kappa_{(B=0)} \, (\omega/\omega_{ce})^2$



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

(Two photospheres)

QED Effect: Vacuum Polarization in Strong B

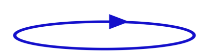


Heisenberg & Euler, Weisskopf, Schwinger, Adler…

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

$$\Delta\mathcal{E}^{(\mathrm{vac})} \sim 10^{-4}\,(B/B_{\mathrm{Q}})^2\,, \quad \text{with } B_{\mathrm{Q}} = 4.4\times10^{13}\mathrm{G}$$

Two photon modes in magnetized vacuum:

Ordinary mode (//) 

Extraordinary mode (⊥) 

This is a small effect: Why bother?

QED Effect in NS Atmosphere

Dielectric tensor of magnetized plasma including vacuum polarization

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

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

Vacuum resonance:

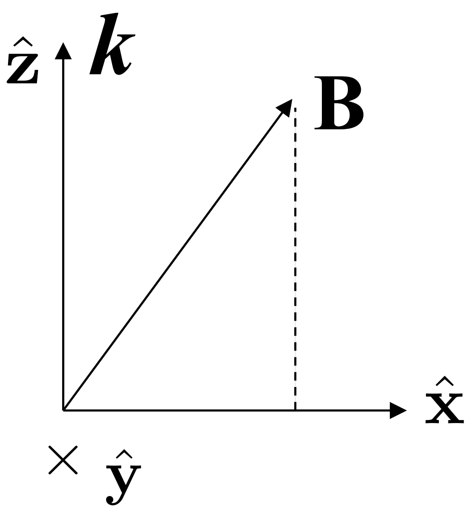
$$\Delta\boldsymbol{\mathcal{E}}^{(\text{plasma})} + \Delta\boldsymbol{\mathcal{E}}^{(\text{vac})} \sim 0$$

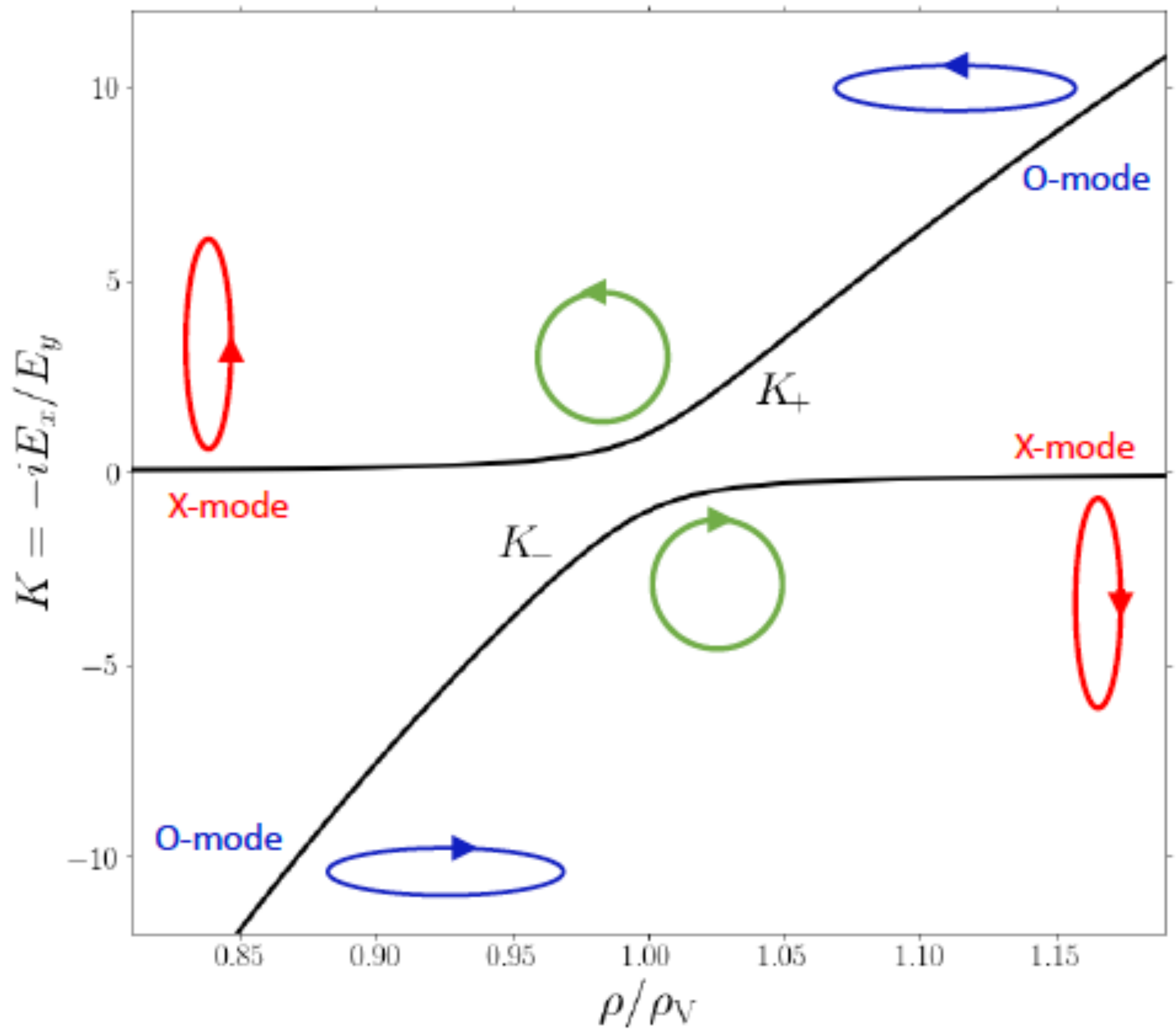
depends on $-(\omega_p/\omega)^2 \propto \rho/E^2$

$\Longrightarrow$ $$\rho_V = 1.0\,Y_e^{-1} B_{14}^2\,(E/1\ \text{keV})^2\ \text{g cm}^{-3}$$

$Y_e = Z/A, \quad n_e = Y_e \rho/m_p$

Polarization of photon modes: Plasma + QED vacuum





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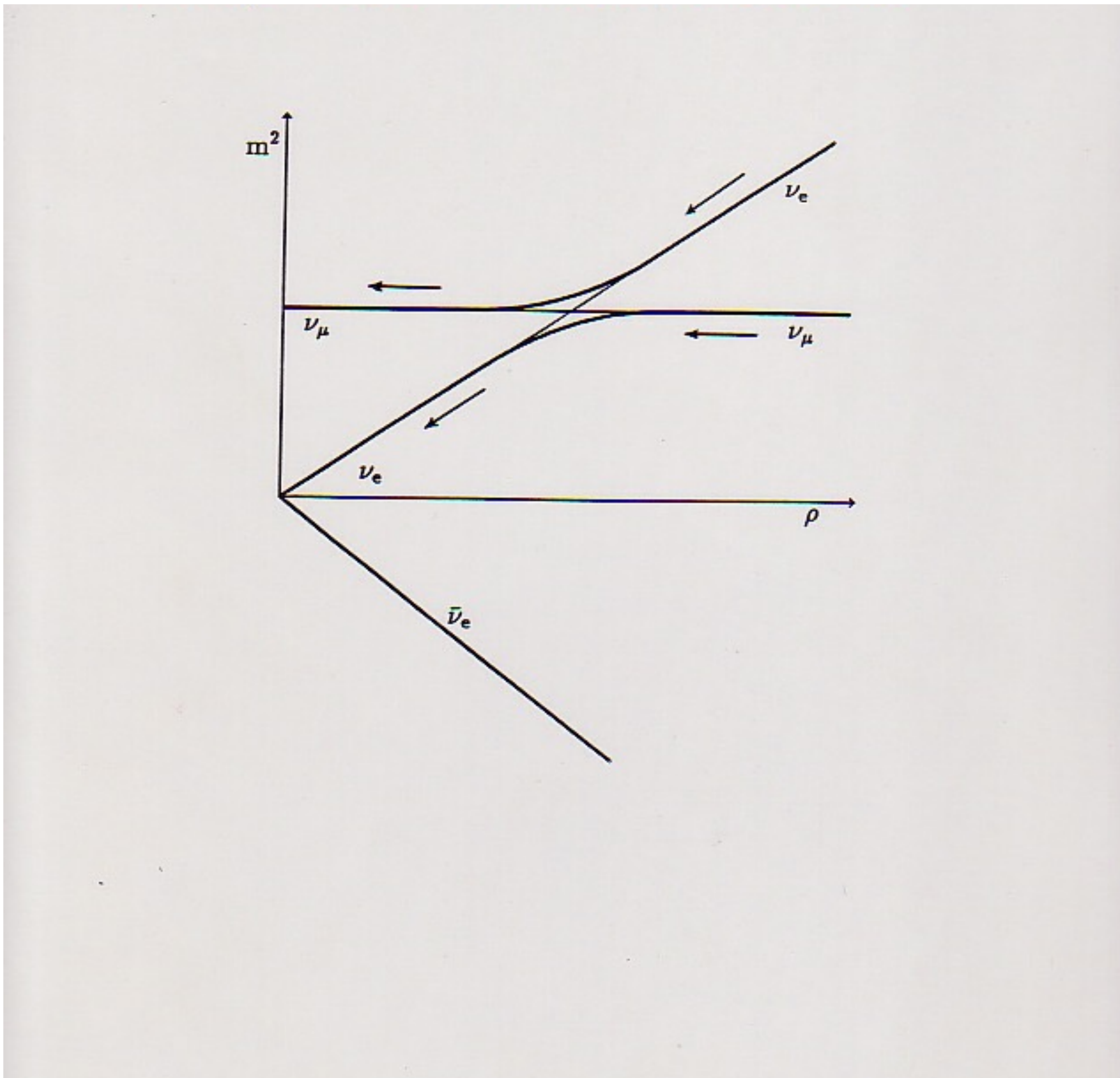
Mikheyev-Smirnov-Wolfenstein (MSW) Neutrino Oscillation/Conversion in the Sun



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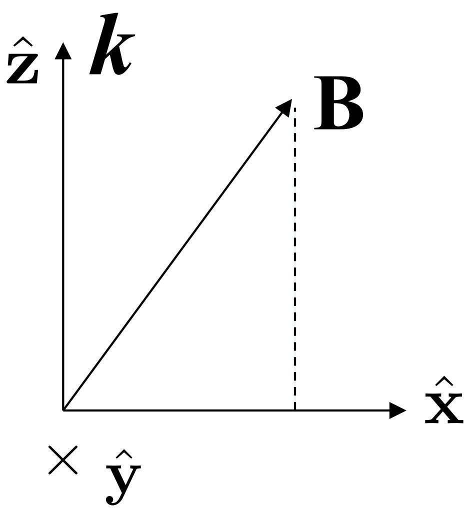
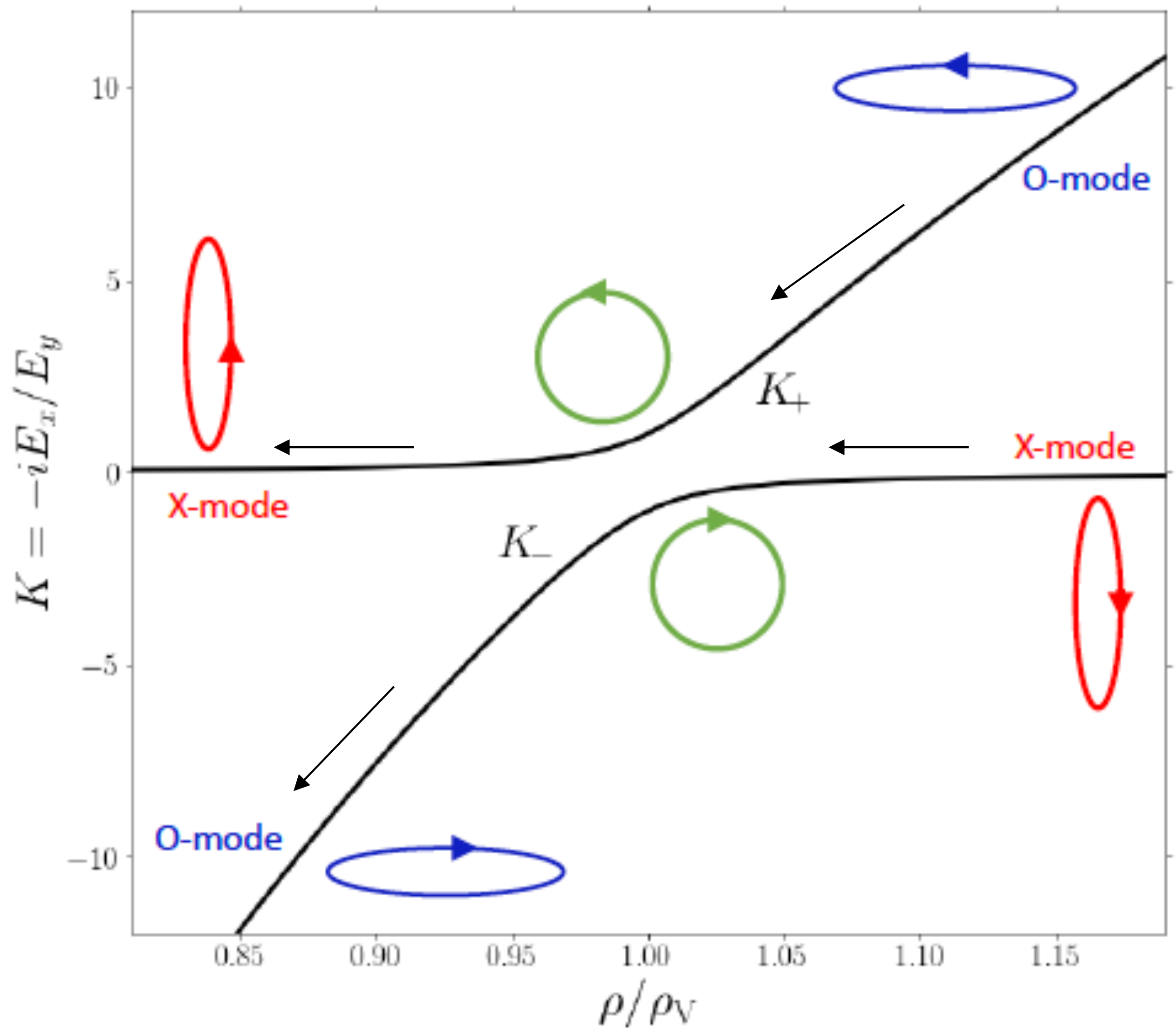




B=10^{14} G, E=5 keV, θ_{kB}=30°

Adiabatic Condition:

$$\left|n_1 - n_2\right| \gtrsim (\cdots) \left|d\rho/ds\right|$$

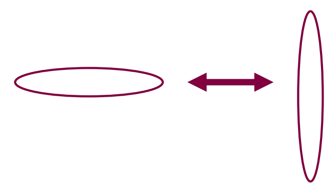
$$\Rightarrow \quad E \gtrsim E_{\rm ad} = 2.52 \left(f \ \tan\theta_{kB}\right)^{2/3} \left(\frac{1\,{\rm cm}}{H_\rho}\right)^{1/3} \ {\rm keV}$$

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

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

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

Photons with $E > E_{ad}$, mode conversion



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

In general, nonadiabatic "jump" probability

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

The observed X-ray polarization signatures depend on

ρ_V (Vacuum resonance)

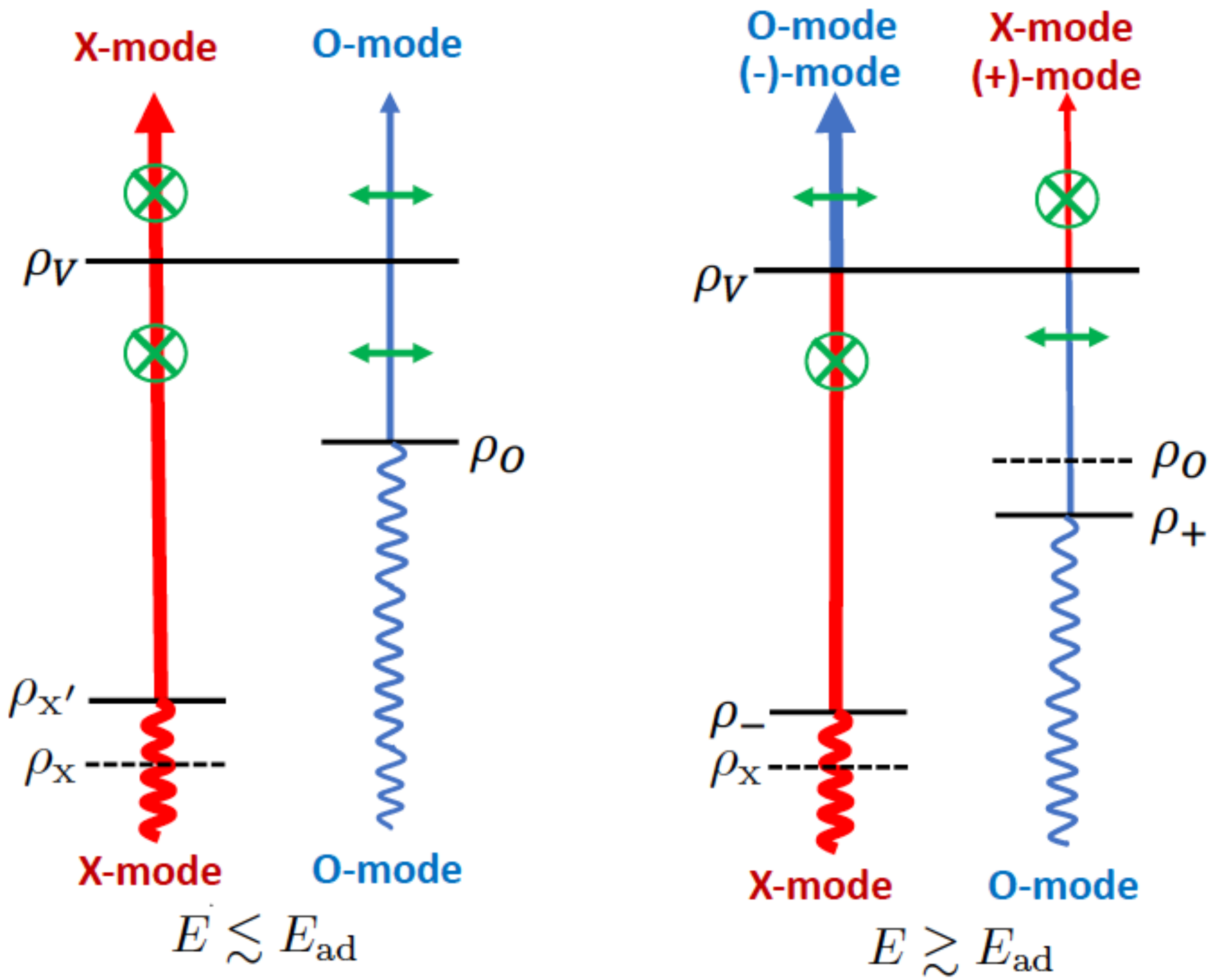
vs

ρ_O (O-mode photosphere)

Note: X-mode photosphere is always deeper

For B < $B_{OV} \sim 10^{14}$ (…) $T_6^{-1/8} E_1^{-1/4}$ G:

Vacuum resonance lies outside both photospheres



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

This is what is observed in

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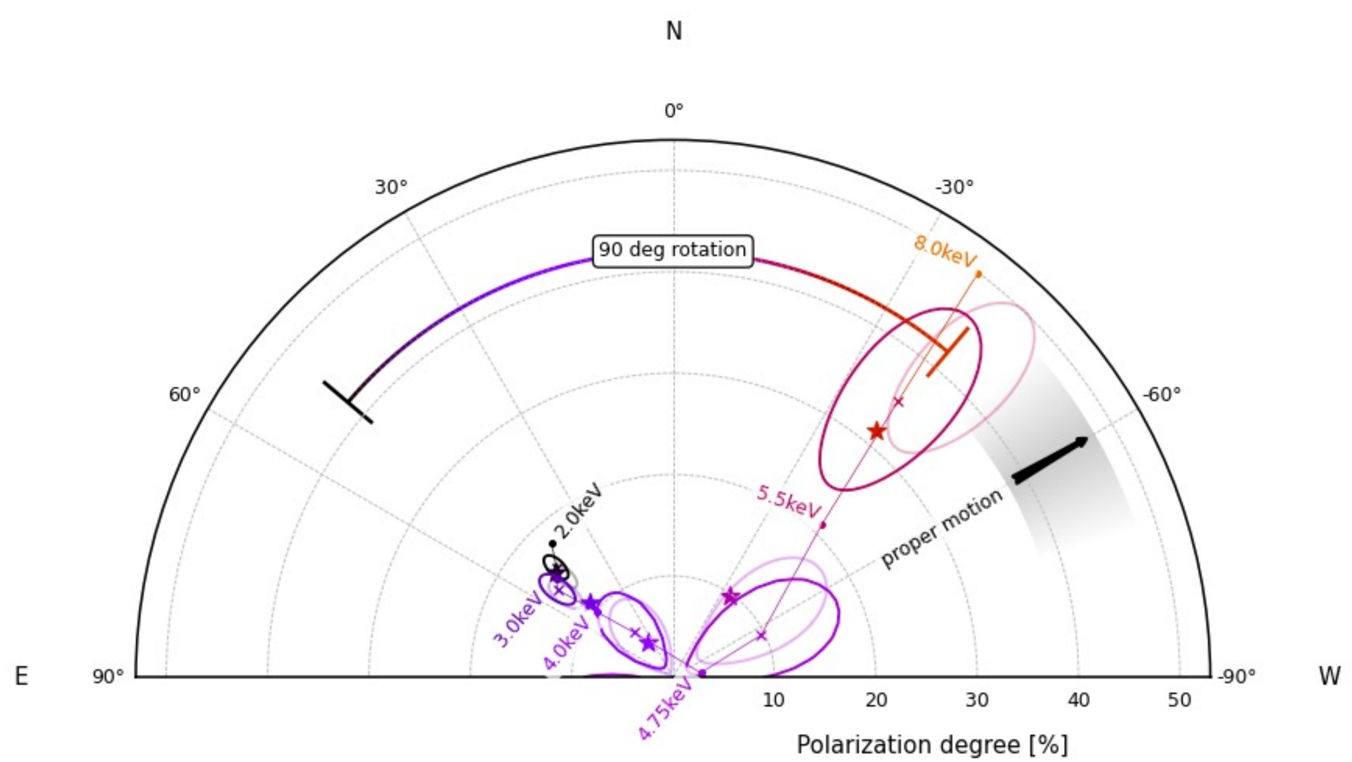
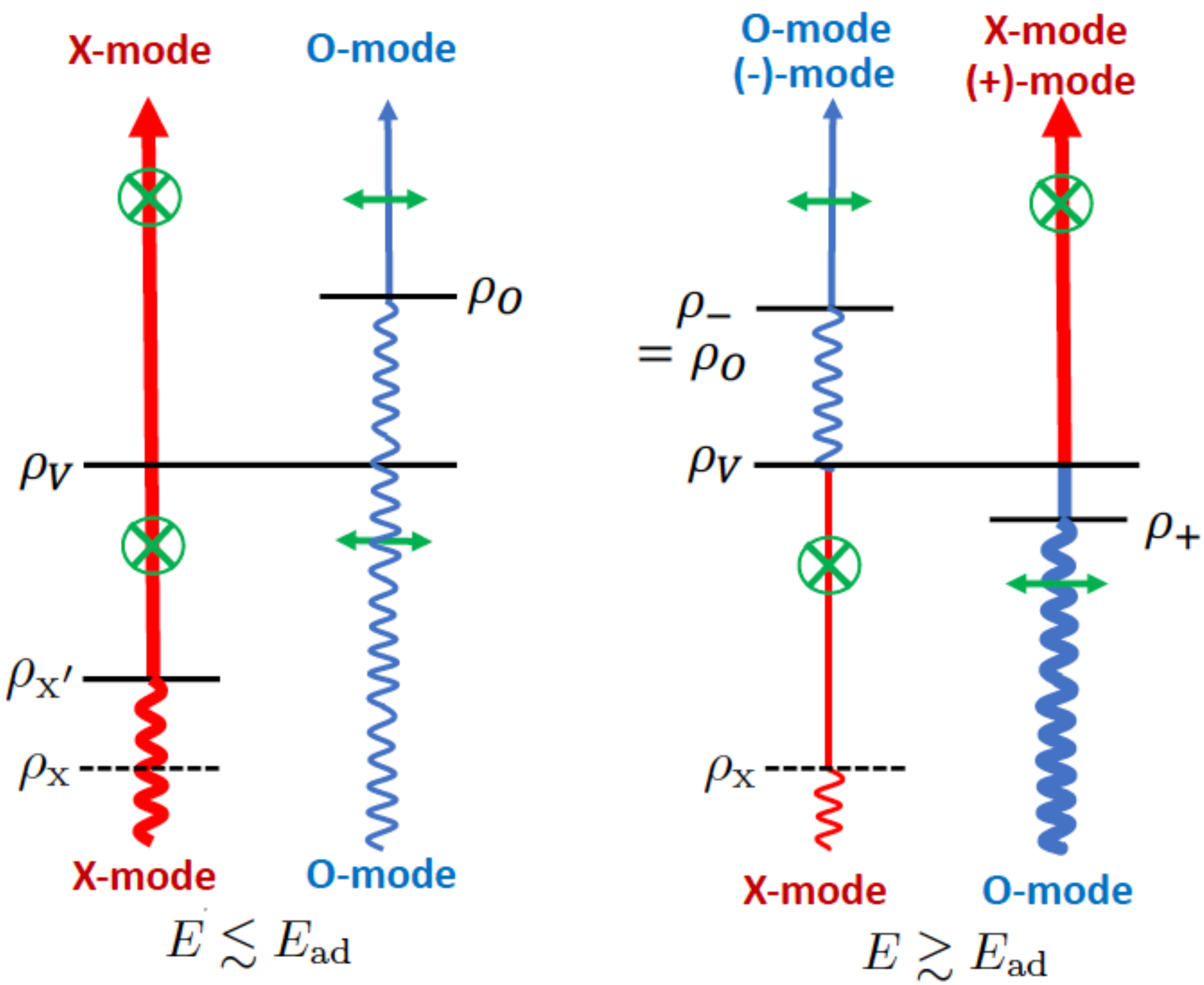


For B > B_{OV}~10^{14} (…) $T_6^{-1/8}$ $E_1^{-1/4}$ G:

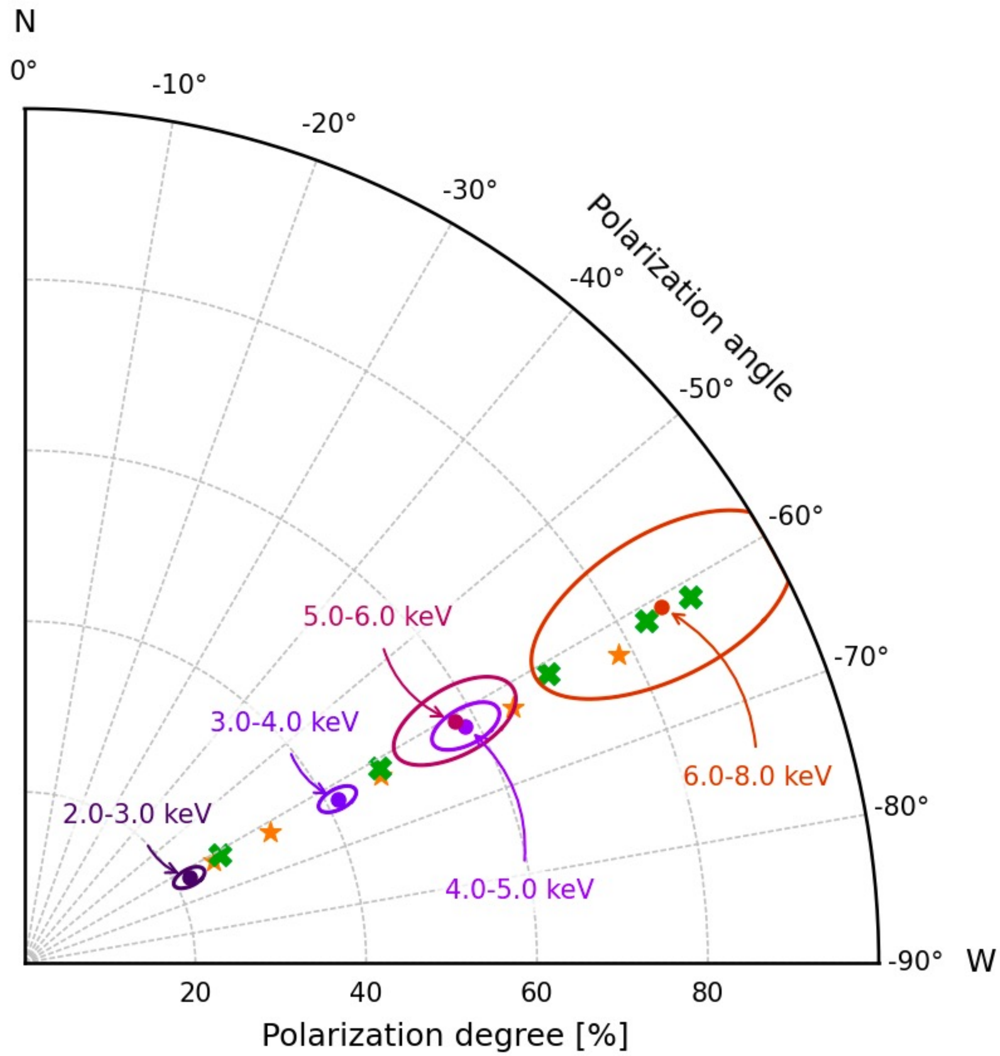
Vacuum resonance lies between the two photospheres



➔ **Plane of linear polarization at different E coincide**

IXPE detection of magnetar 1RXS J1708

Zane et al. 2024



Linear polarization degree:
ranges from 20% at 2-3 keV
to 80% at 6-8 keV

Polarization angle:
independent of photon energy

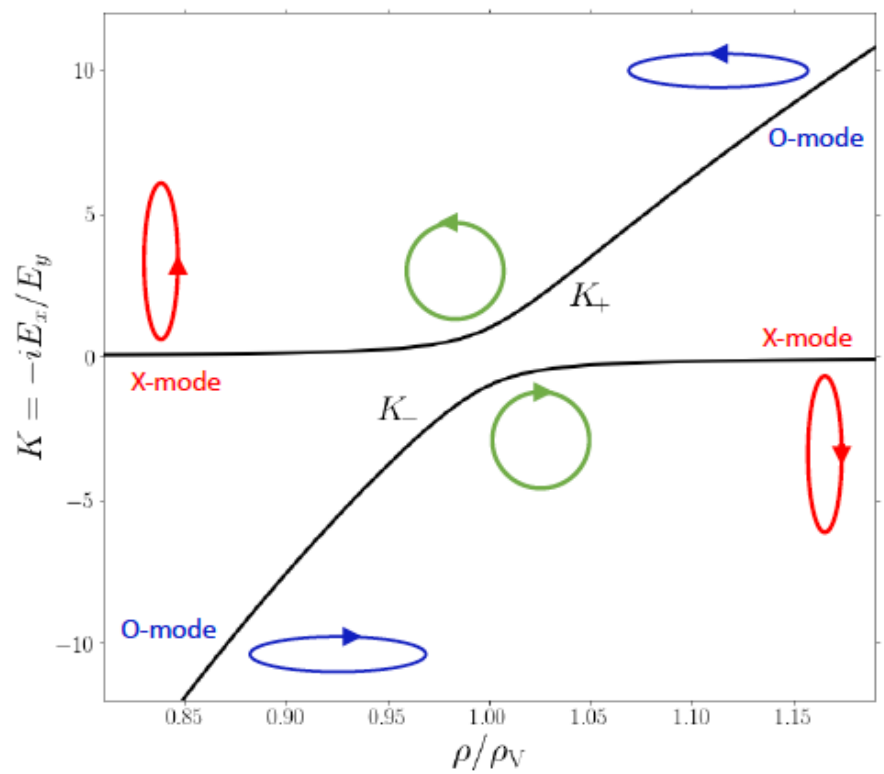
For this magnetar:
P, Pdot ➔ $B_d = 5 \times 10^{14}$G

Take-home message

Photon (EM wave) propagation in magnetized plasma…

Small QED effect + small plasma effect
➔ Vacuum resonance
➔ Large effect on photon propagation
(polarized radiation)
Observed !

Caveats: Non-thermal radiation from magnetar corona may affect the interpretation



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