Polarized Surface Emission from Magnetized Neutron Stars

Dong Lai (Cornell University)

Isolated Neutron Stars (T ~ 10^6-5×10^6K)

Accreting X-ray pulsars (T~10^7K)

X-ray Polarimetry Workshop, SLAC, 2/2004

PHYSICAL REVIEW LETTERS

VOLUME 12 | 13 APRIL 1964 | NUMBER 15

SURFACE X-RAY EMISSION FROM NEUTRON STARS

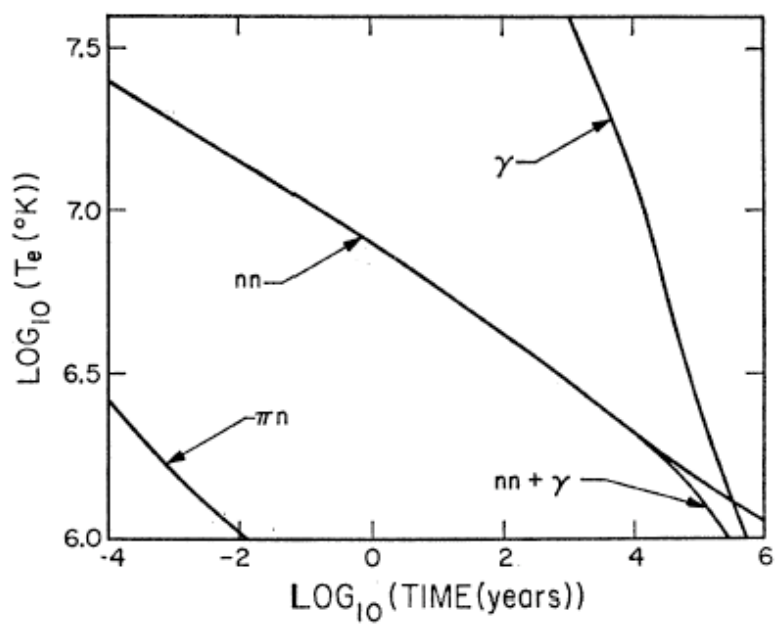
Hong-Yee Chiu* and E. E. Salpeter†
Goddard Institute for Space Studies, New York, New York
(Received 13 February 1964; revised manuscript received 23 March 1964)

PHYSICAL REVIEW | VOLUME 140, NUMBER 5B | 6 DECEMBER 1965

Neutron Stars. II. Neutrino-Cooling and Observability*

JOHN N. BAHCALL AND RICHARD A. WOLF†
California Institute of Technology, Pasadena, California
(Received 19 July 1965)

Calculations of the rates of the cooling reactions $n+n \rightarrow n+p+e^-+\nu_e$ and $n+\pi^-$
sented; the rates of the closely related muon-producing reactions and the four inve
given. Several different arguments are used to obtain estimates of the relevant matrix e
are assumed to form a normal Fermi fluid with a continuous excitation spectrum. T
rates indicate that a neutron star containing quasifree pions would cool within a few
so low that the star would be unobservable. The surface of a star that does not contain
cool to 10^7 °K in a few months and would reach 4×10^6 °K in about 100 years. The ca
strongly indicate that the discrete x-ray sources located in the direction of the galactic
stars.



Thermal (Surface) Radiation from Neutron Stars

Probe the near vicinity and interior of NSs:

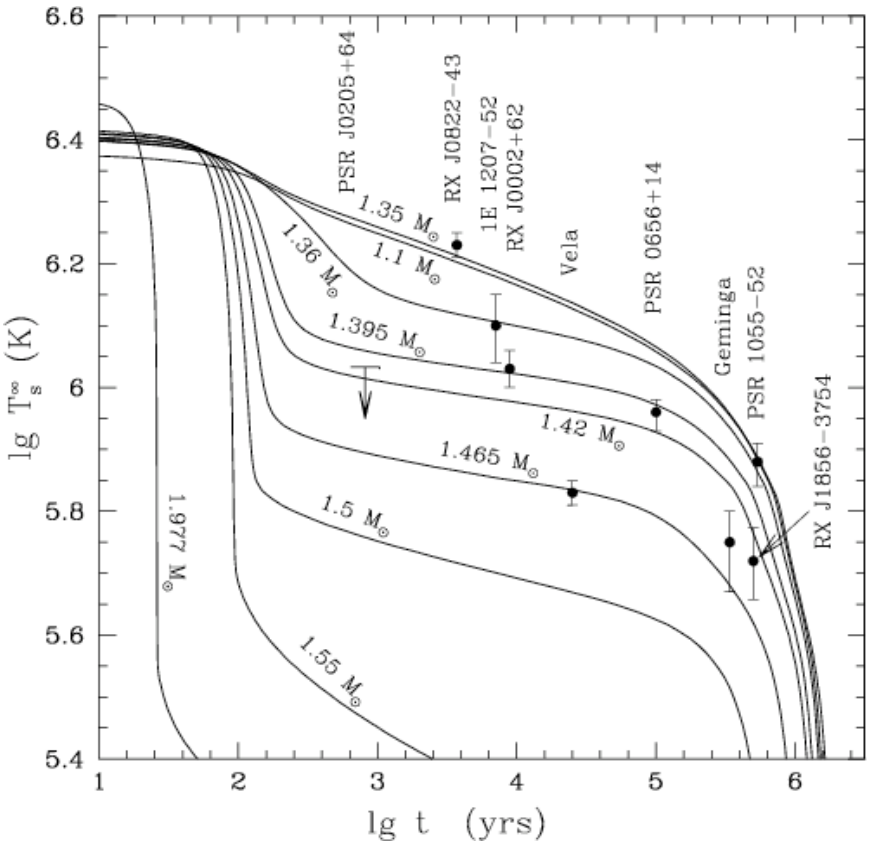
M, R, EOS,
cooling history (exotic processes),
surface B and composition

Has been securely detected from
~ 20 sources:

Radio pulsars

Radio-quiet NSs (young NSs in SNRs
and "dim" Isolated NSs)

Magnetars (AXPs and SGRs)



Yakovlev et al. 2002

Observations (Chandra, XMM-Newton)

The thermal spectra of many observed NSs are

- featureless (imply light element atmospheres ?)

  Vela pulsar
  B0656+14
  B1055-52
  AXPs ……

- sometimes well fit by blackbody

  RXJ1856-3754 (“perfect” X-ray BB)

Spectral lines detected in 3-4 sources:

1E 1207-5209 (0.7, 1.4 keV; maybe 2.1, 2.8 keV?)
RXJ1308+2127 (0.2-0.3 keV)
RXJ1605+3249 (~0.45 keV)
RXJ0720-3125 (~0.3 keV ?)

The full potential of these observations has not been realized:

1. More theoretical work is needed (e.g., Romani, Pavlov-Shibanov, Zane, W. Ho)
2. Source may be complicated (B and geometry): **polarization …**

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

Polarized Surface Emission from Magnetized Neutron Stars

1. Basic polarization signals
2. A surprising signature of QED in polarization signals

   with Wynn Ho (Cornell/KIPAC)
3. What I think Jeremy Heyl would talk about if he were here

X-ray Polarimetry Workshop, SLAC, 2/2004

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

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

Photon Polarization Modes in a Magnetized Plasma

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

Ordinary Mode (O-mode):

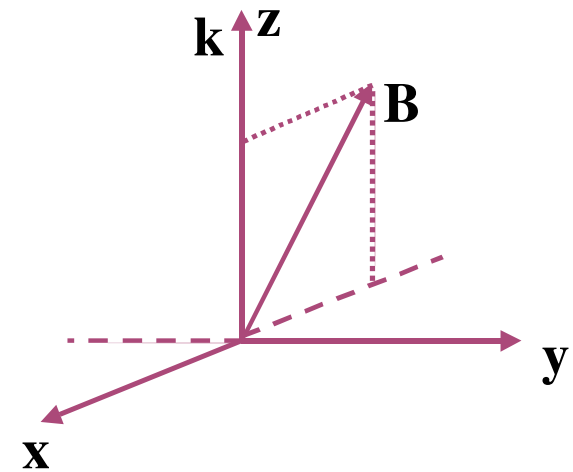
E nearly in the **k-B** plane

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

Extraordinary Mode (X-mode):

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

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

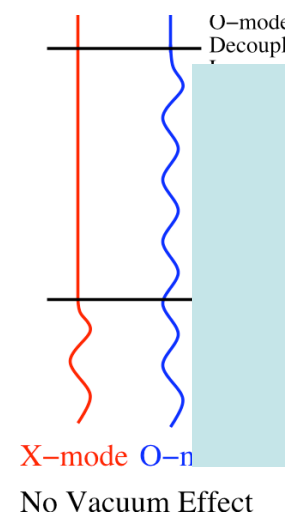


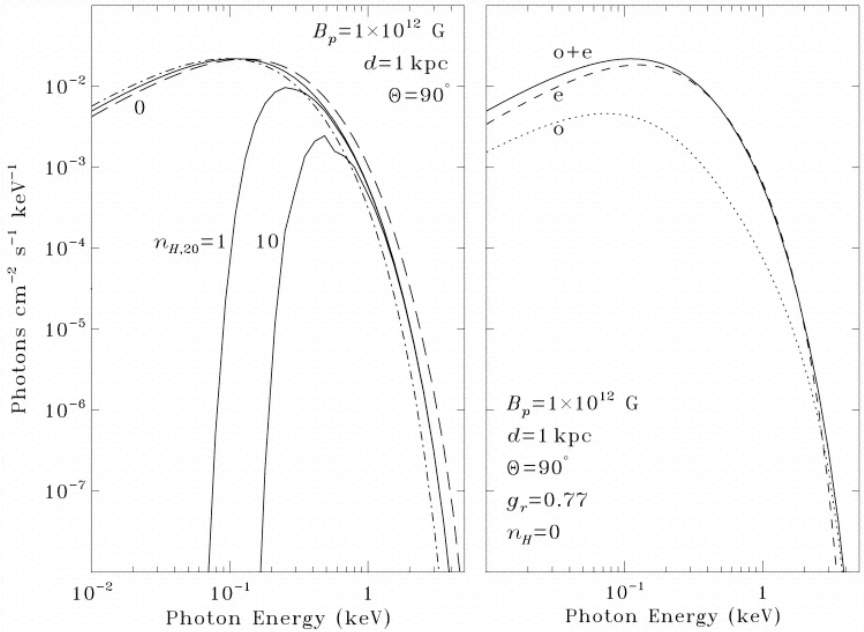
The two modes have different opacities (scattering, absorption):

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

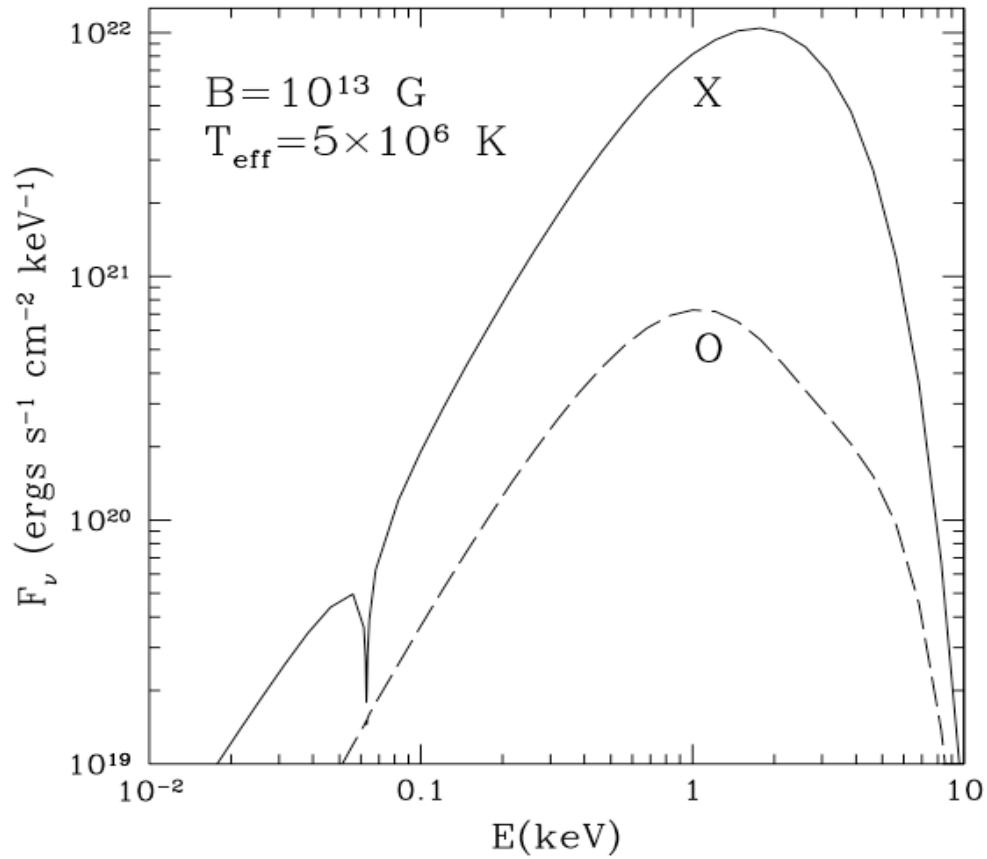
$$\kappa_{\text{(X-mode)}} \sim \kappa_{(B=0)} \, (\omega / \omega_{ce})^2$$

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

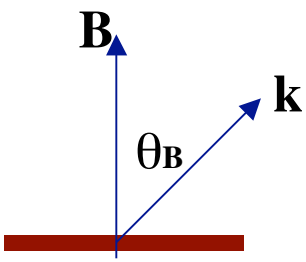




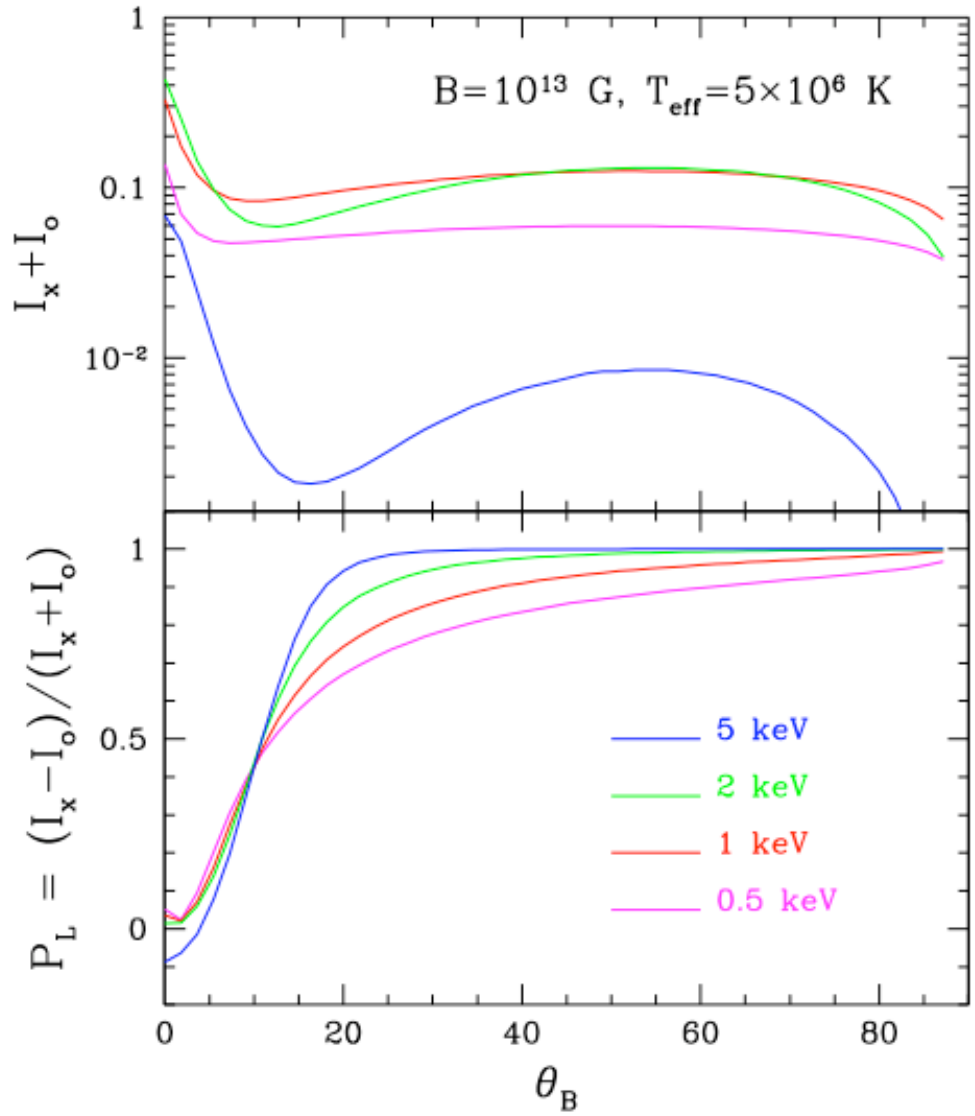
Pavlov & Zavlin 2000



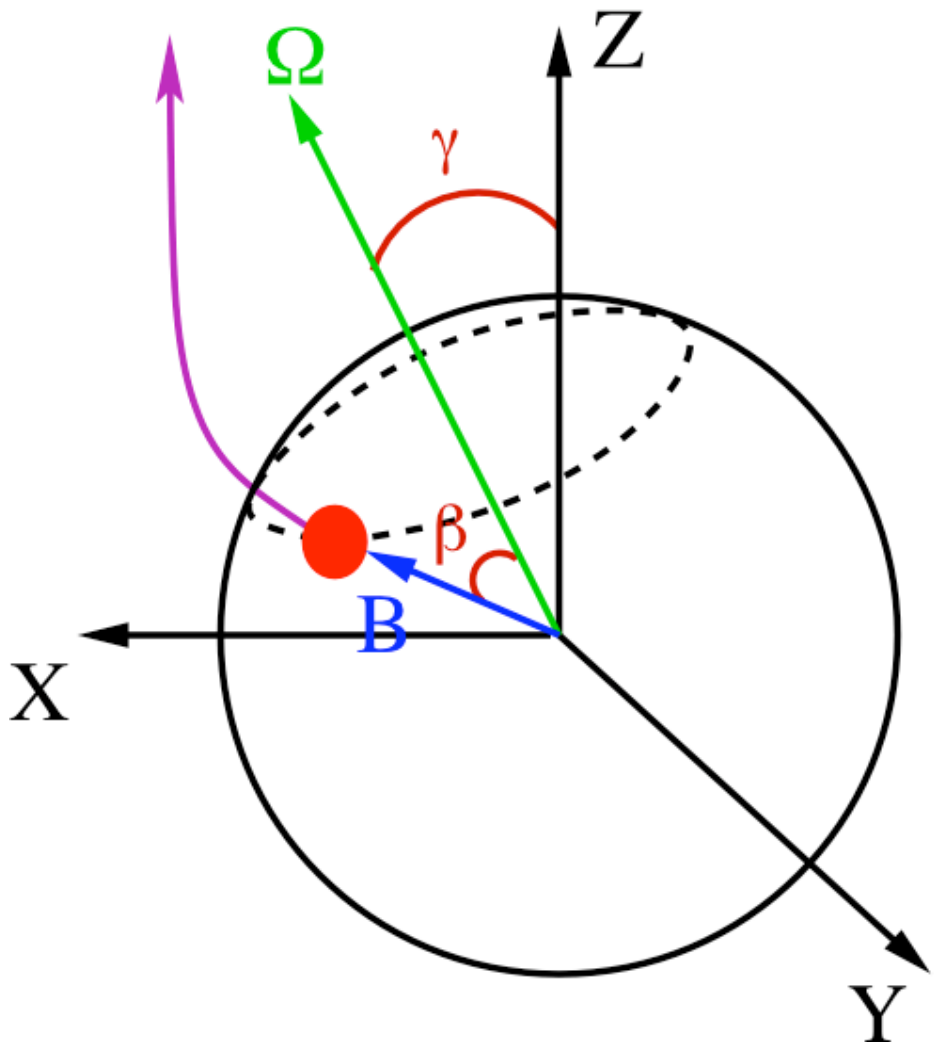
Model by Wynn Ho



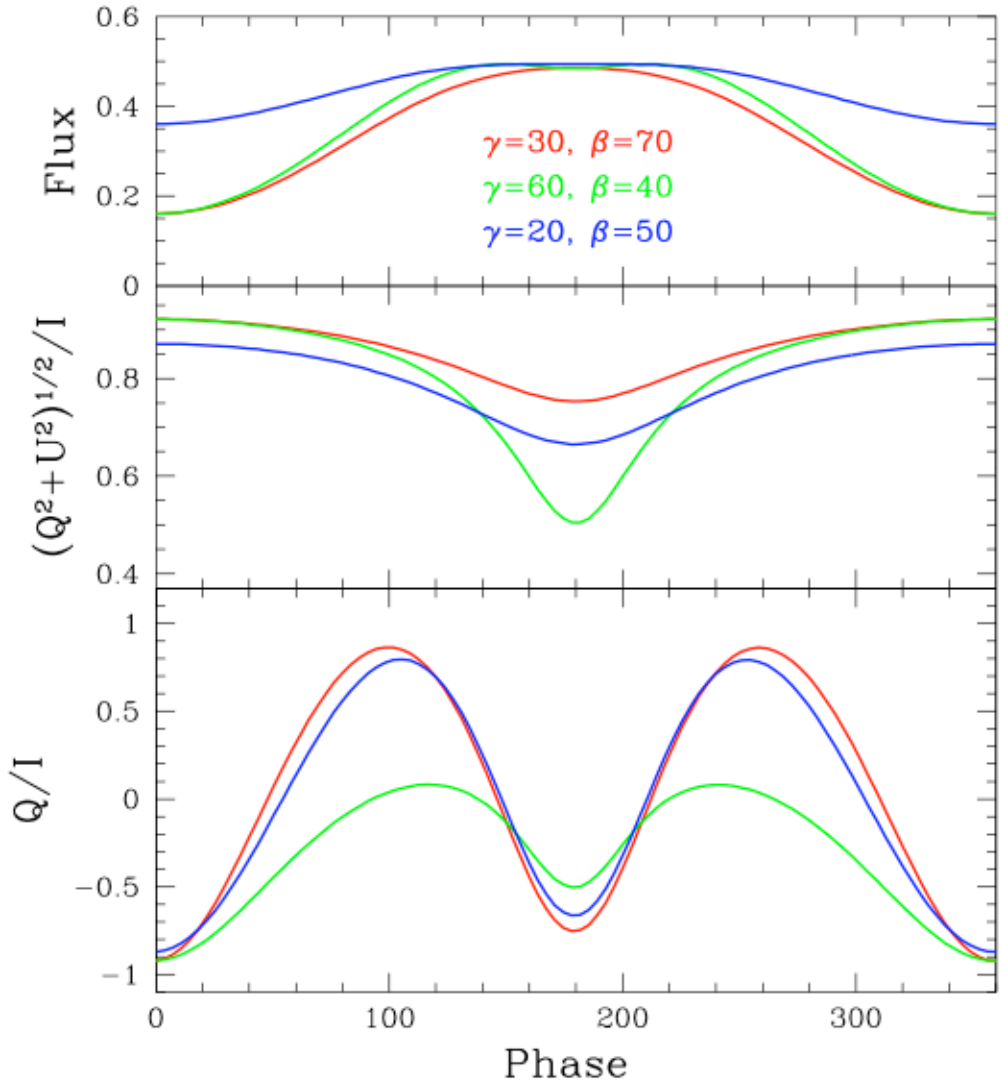
Degree of linear Polarization at emission point

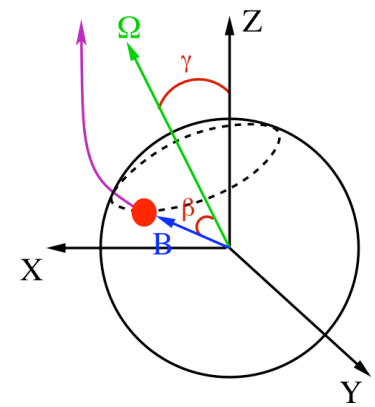


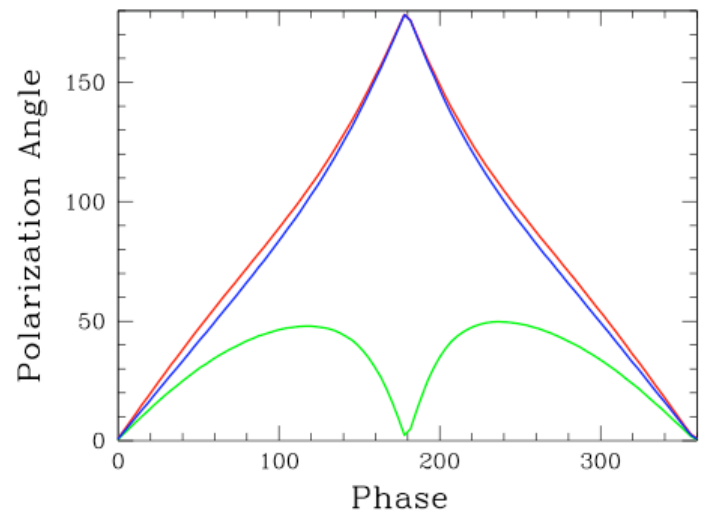
Observer



B=10^{13}G







- Polarization vector ⊥ the **k-B** plane (cf. "rotating vector model" for radio pulsars)

  Linear polarization sweep ===> measure the angles
- Polarization signals can be very different even when total intensities are similar

Information Carried by Polarization Signals:

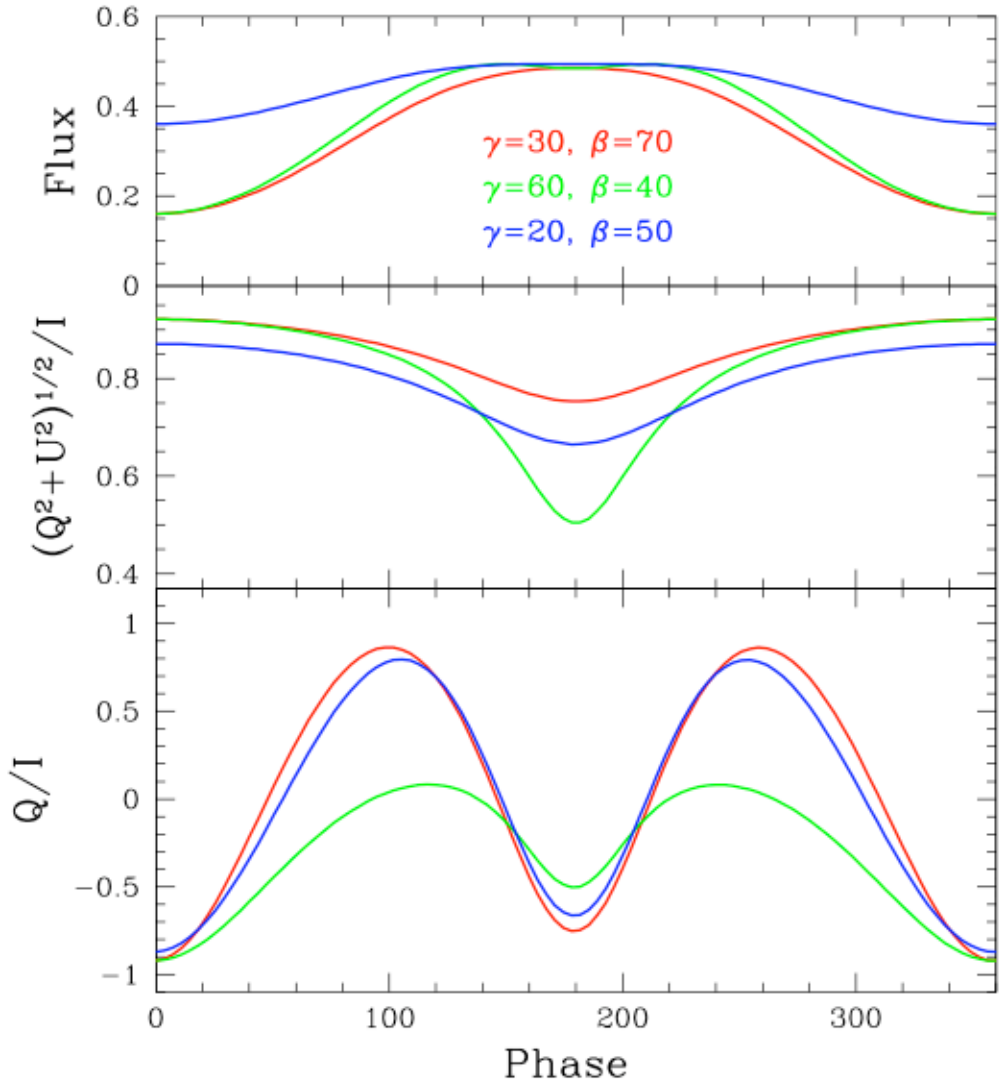
- Geometry (dipole field, rotation axis)
- Dependence on surface field strength

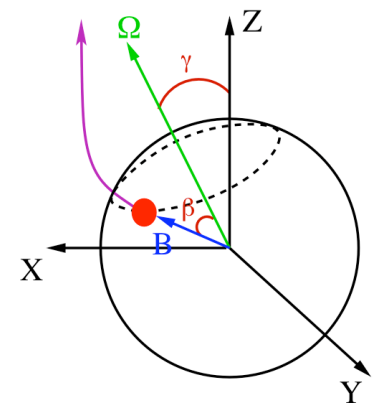
  (e.g., weak polarization in millisecond pulsars)
- Modest dependence on M/R

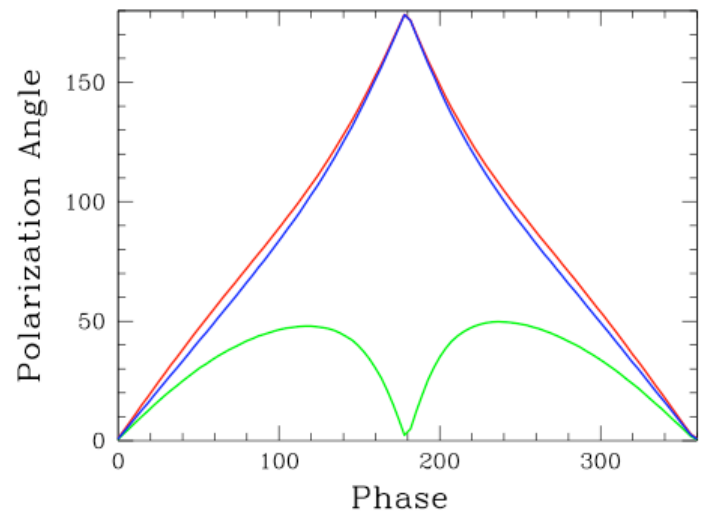
What if emission is from the whole star? Complex surface field?

Answer: Signals largely unchanged (qualitatively) (Jeremy Heyl's talk)

B=10^{13}G

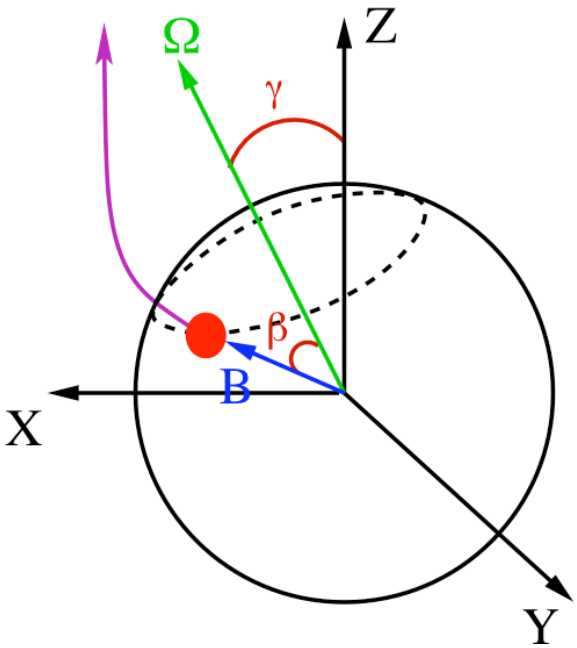




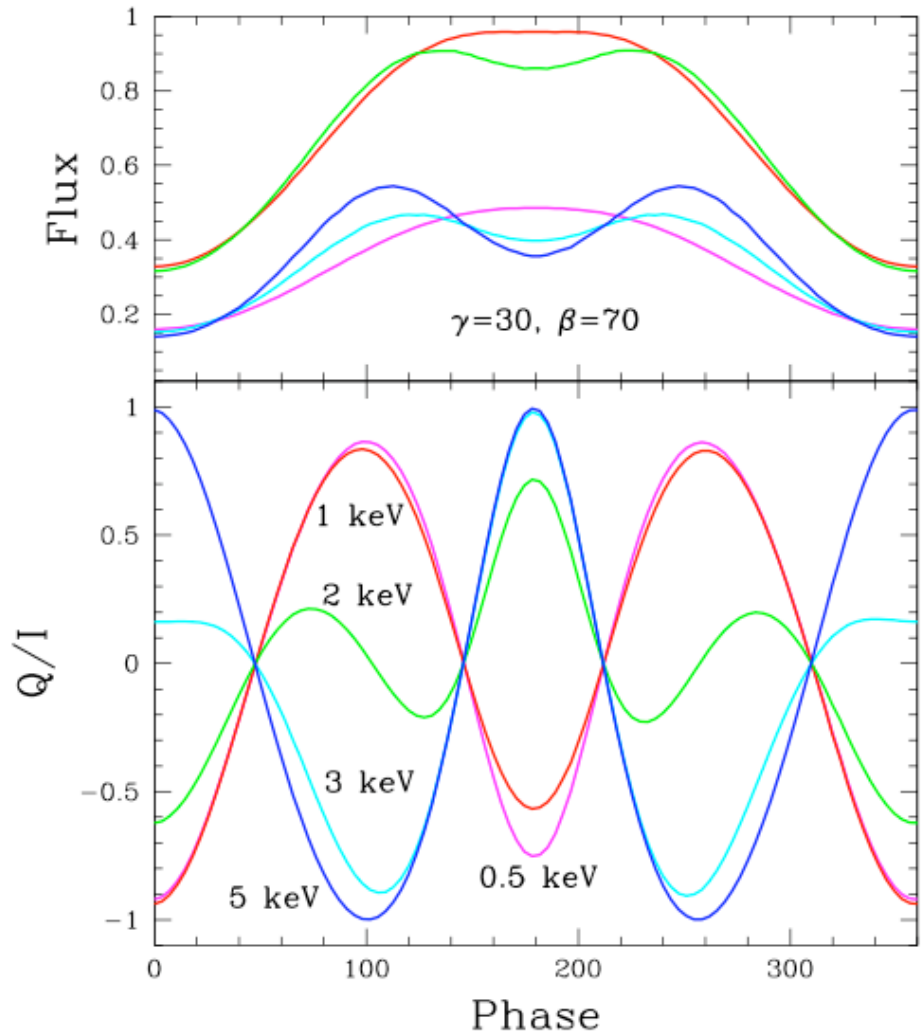


- Polarization vector ⊥ the **k-B** plane (cf. "rotating vector model" for radio pulsars)

  Linear polarization sweep ===> measure the angles
- Polarization signals can be very different even when total intensities are similar



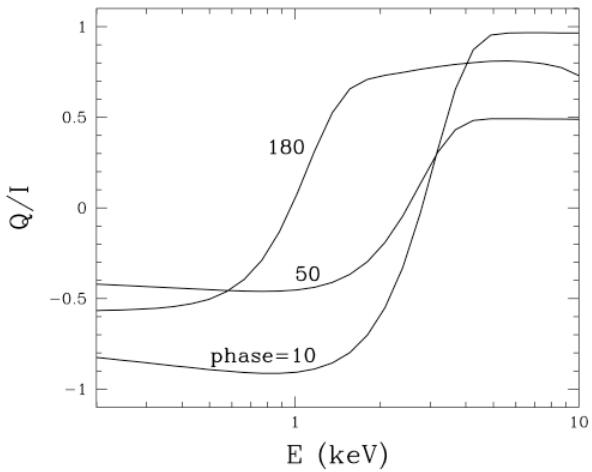
$B=10^{13}$G

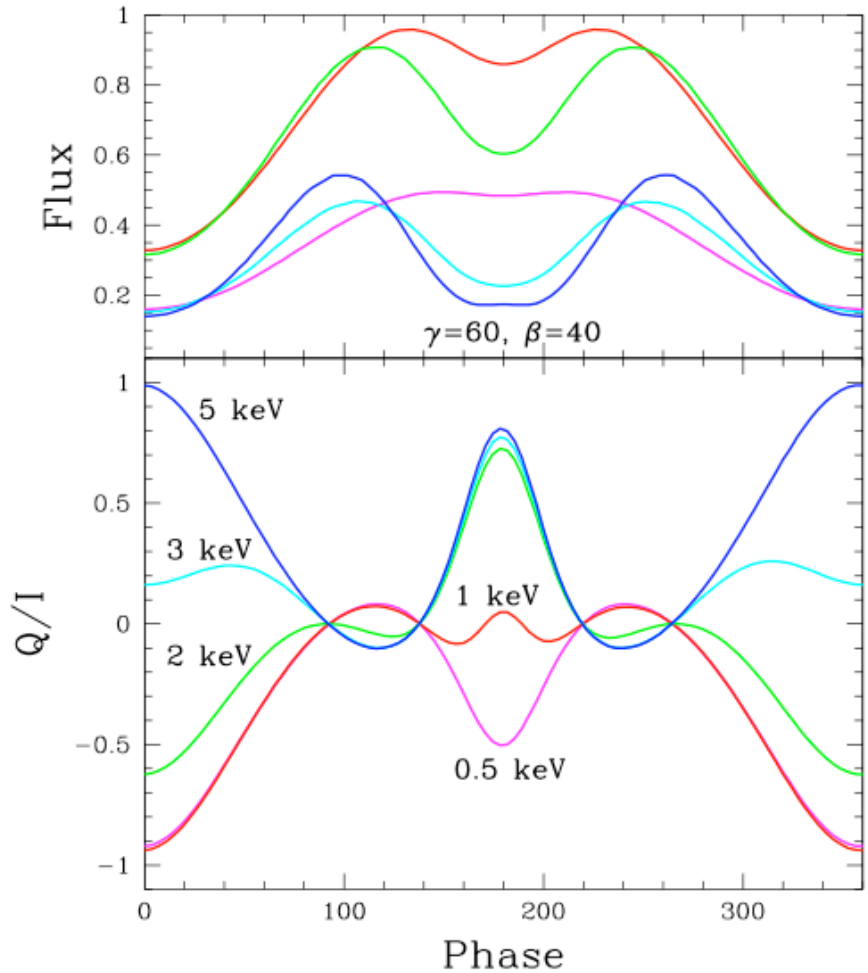


Lai & Ho 2003

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

$B=10^{13}G$

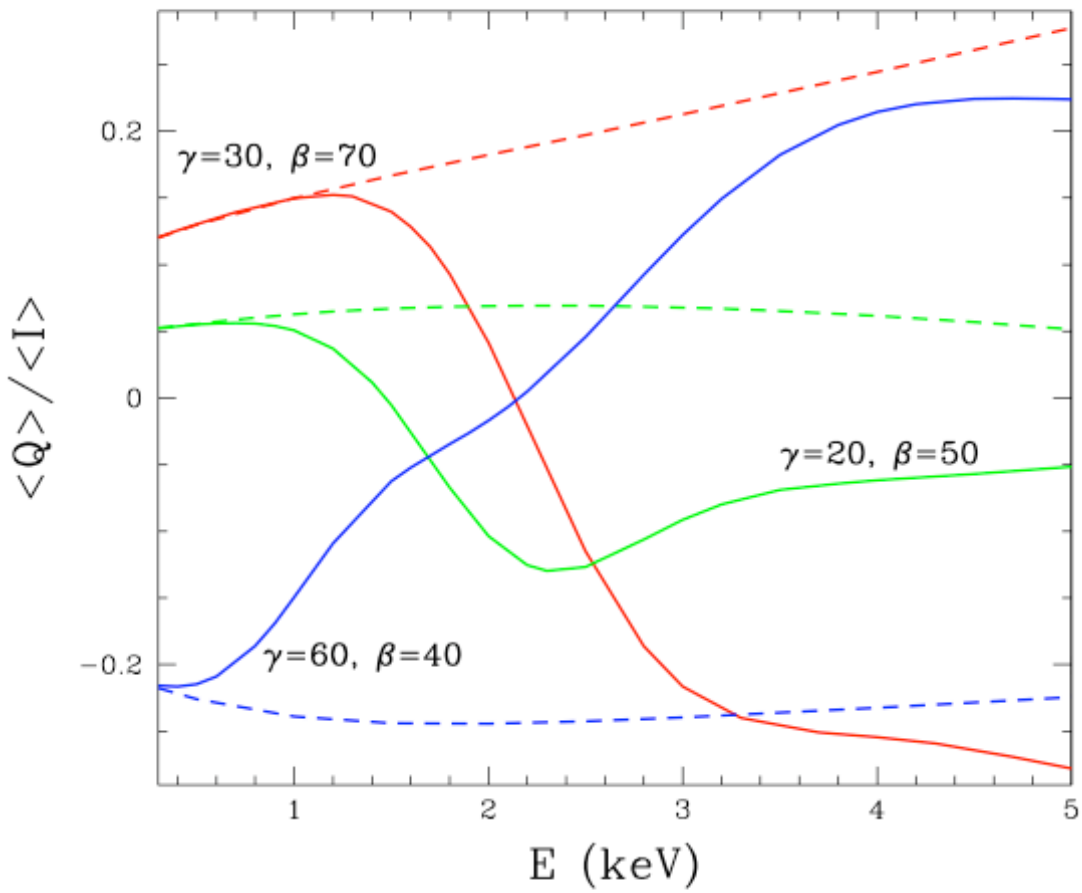


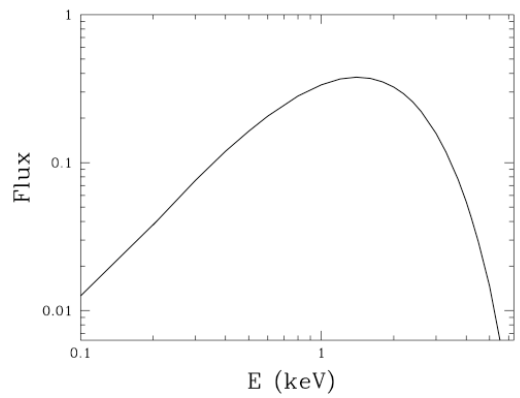


Plane of linear polarization at <1 keV is perpendicular to that at >4 keV.

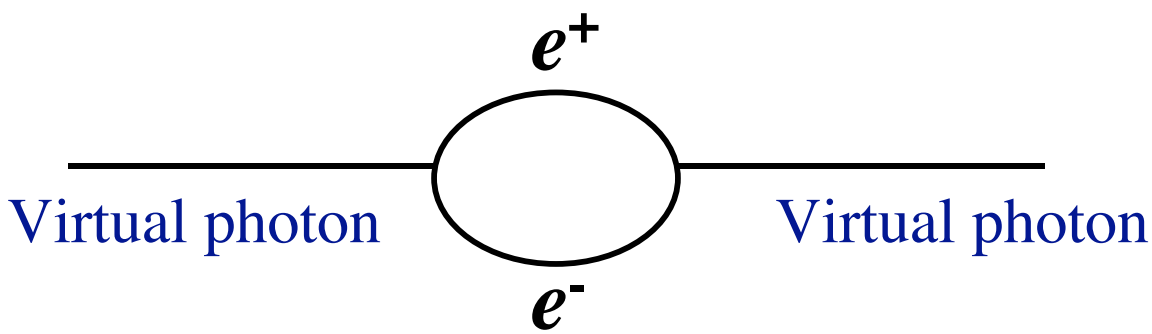
Phase averaged polarization:

B=10^{13}G



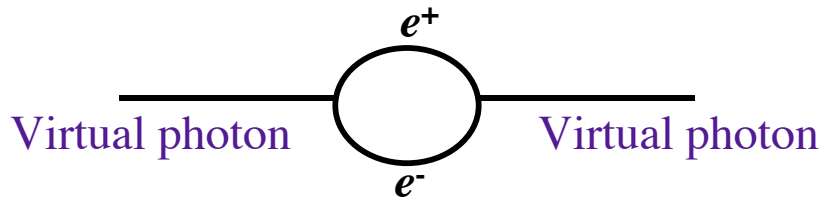


Vacuum Polarization in Strong B



Heisenberg & Euler 1936, Weisskopf 1936; Schwinger 1951; Adler 1971; Tsai & Erber 1975; Heyl & Hernquist 1997 ……

Vacuum Polarization in Strong B



Dielectric tensor of magnetized plasma including vacuum polarization

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

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

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

Vacuum resonance:

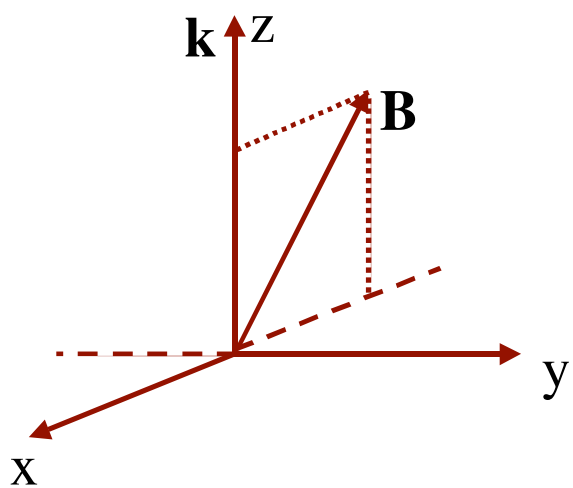
$$\Delta\boldsymbol{\varepsilon}^{(\mathrm{plasma})} + \Delta\boldsymbol{\varepsilon}^{(\mathrm{vac})} \sim 0$$

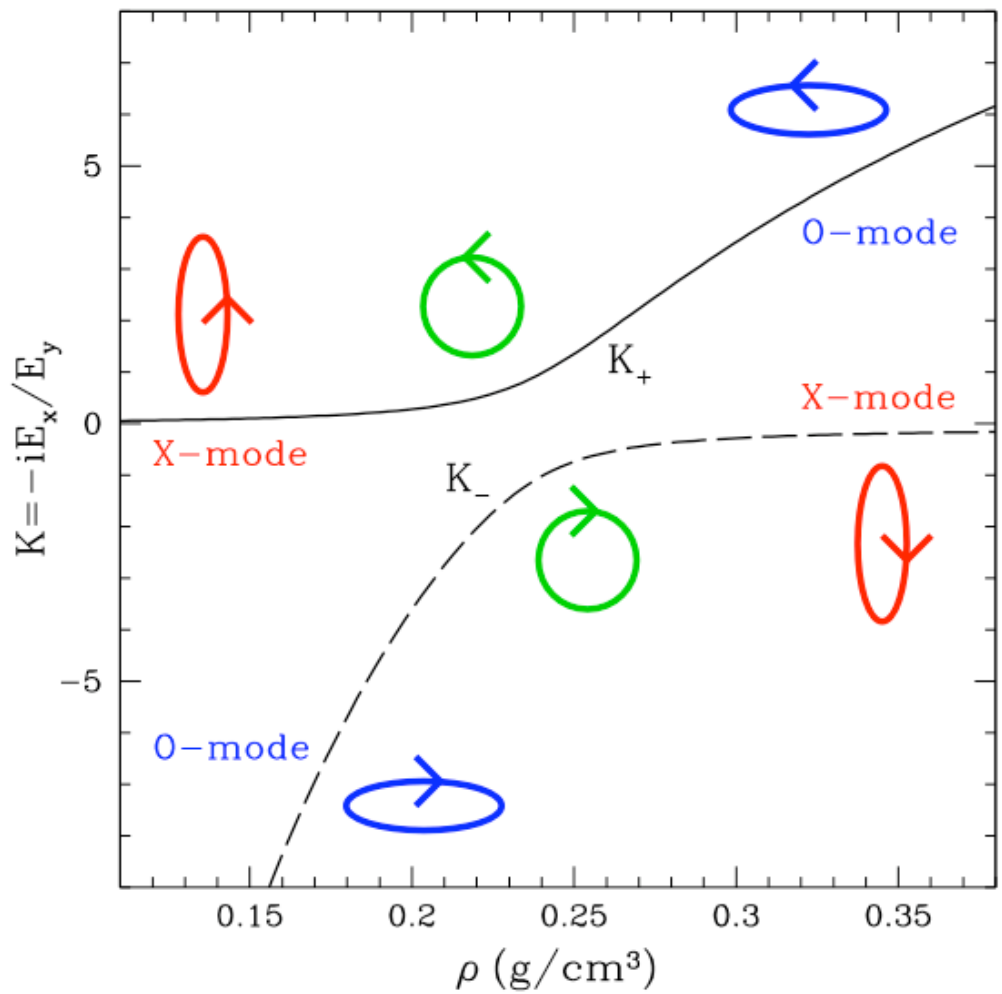
depends on $-(\omega_p/\omega)^2 \propto \rho/E^2$

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

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

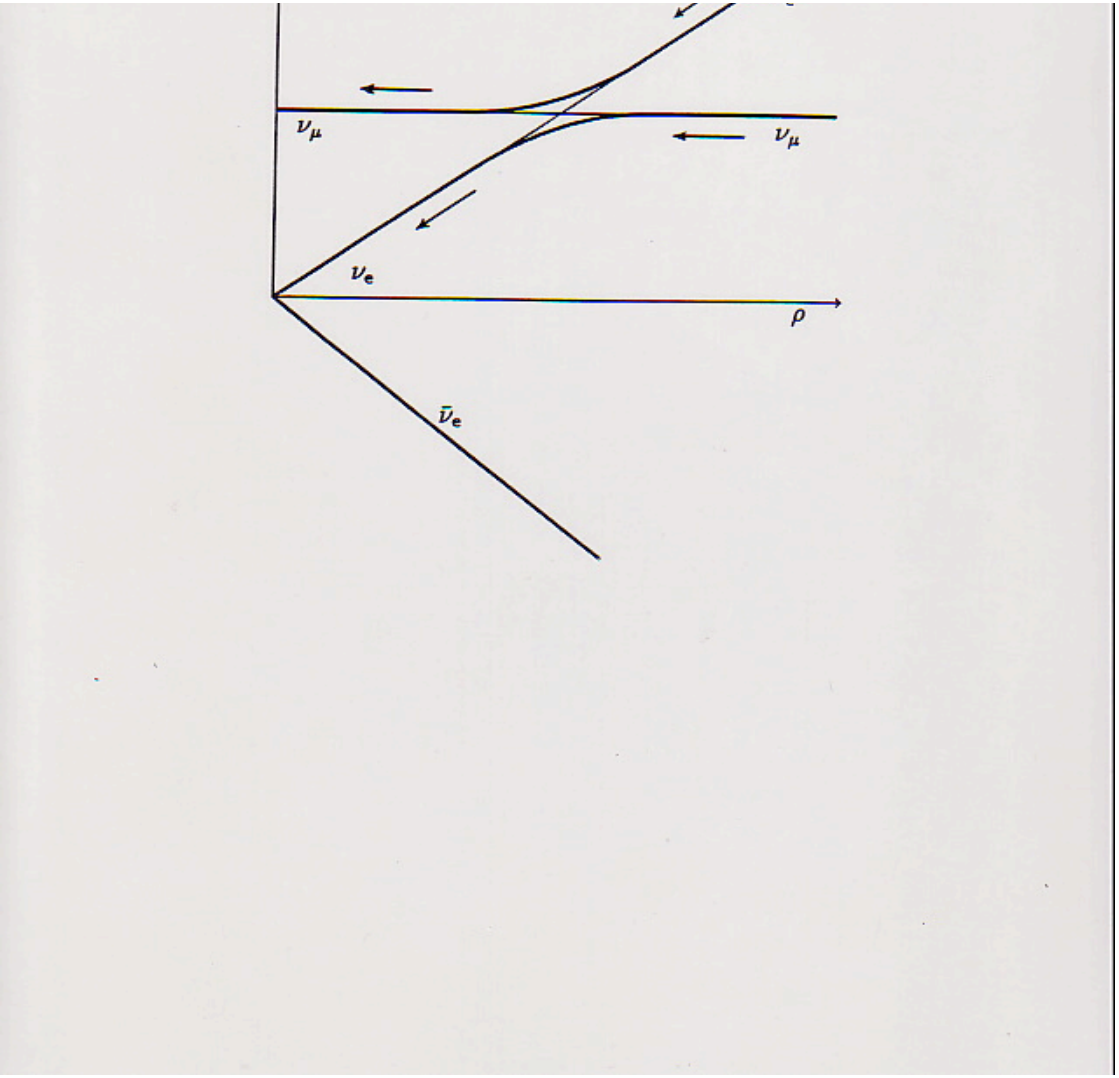
Property of photon modes



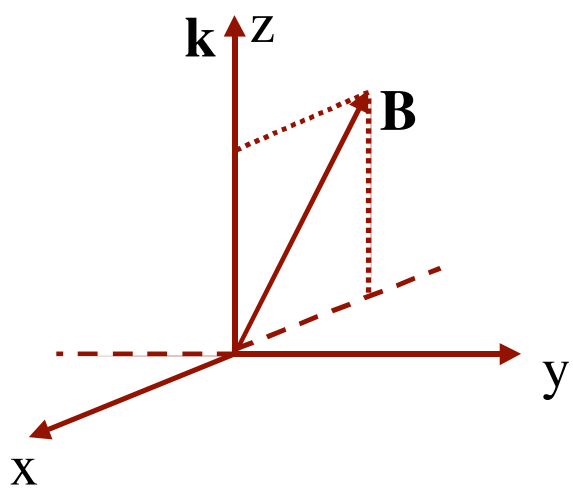


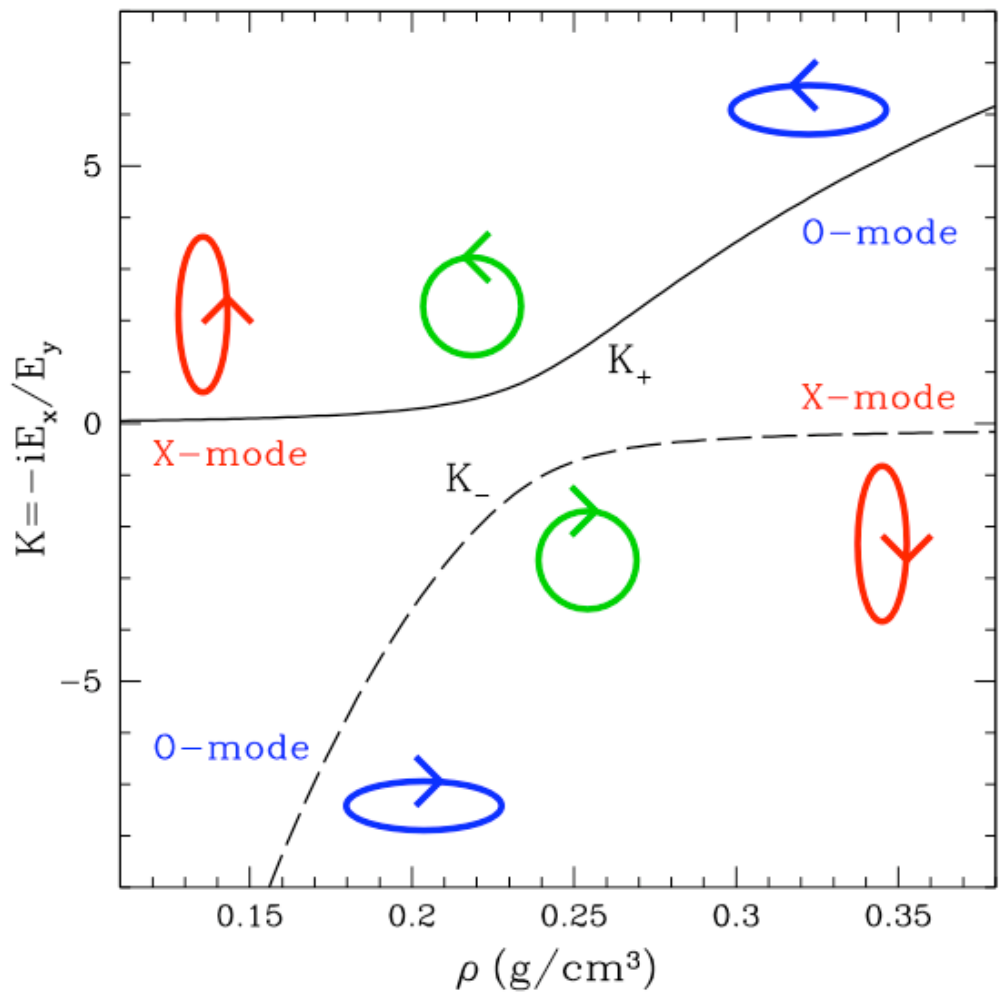
$B=10^{13}$ G, E=5 keV, $\theta_B=45^o$

Mikheyev-Smirnov-Wolfenstein (MSW) Neutrino Oscillation



Property of photon modes





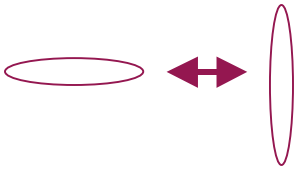
$B=10^{13}$ G, E=5 keV, $\theta_B=45^o$

Adiabatic Condition:

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

$$\Rightarrow \quad E \gtrsim E_{\rm ad} = 2.5\,(\tan\theta_B)^{2/3} \left(\frac{1\,cm}{H}\right)^{1/3} \text{keV}$$

Photons with E > 2 keV, mode conversion



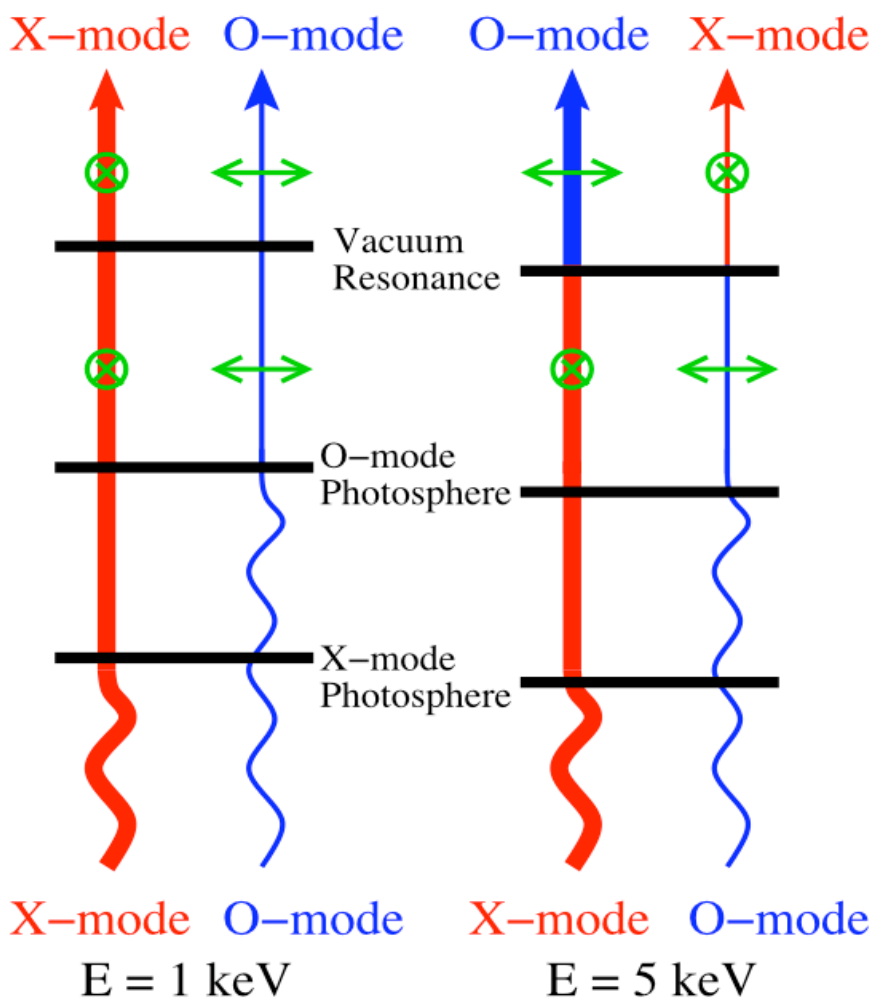
Photons with E < 2 keV, no mode conversion

In general, nonadiabatic "jump" probability

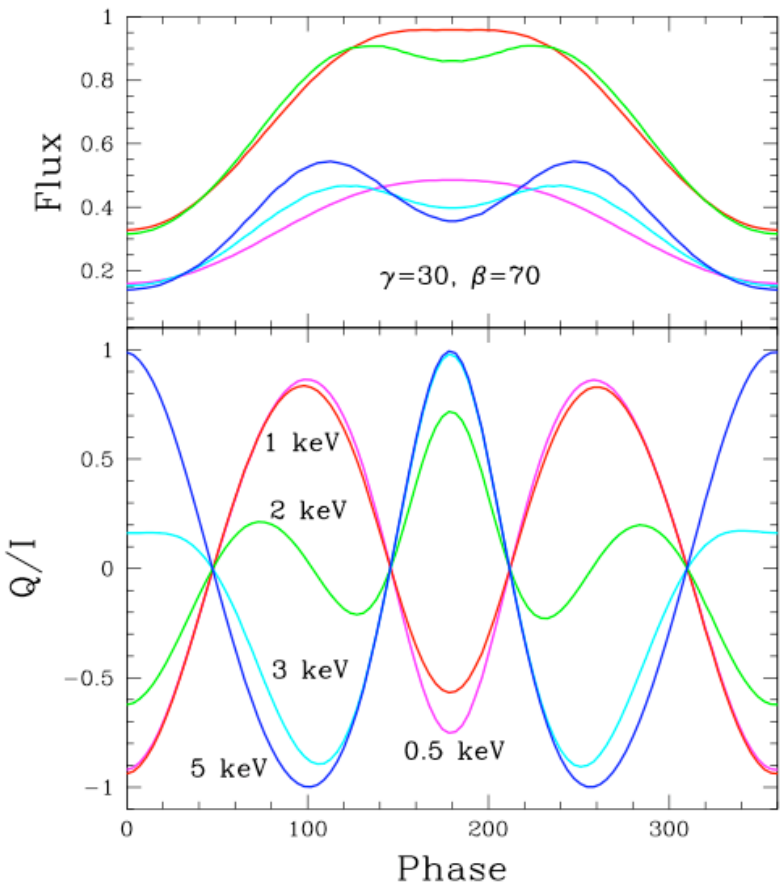
$$P_{\rm jump} = \exp\left[-(\pi/2)\,(E/E_{\rm ad})^3\right]$$

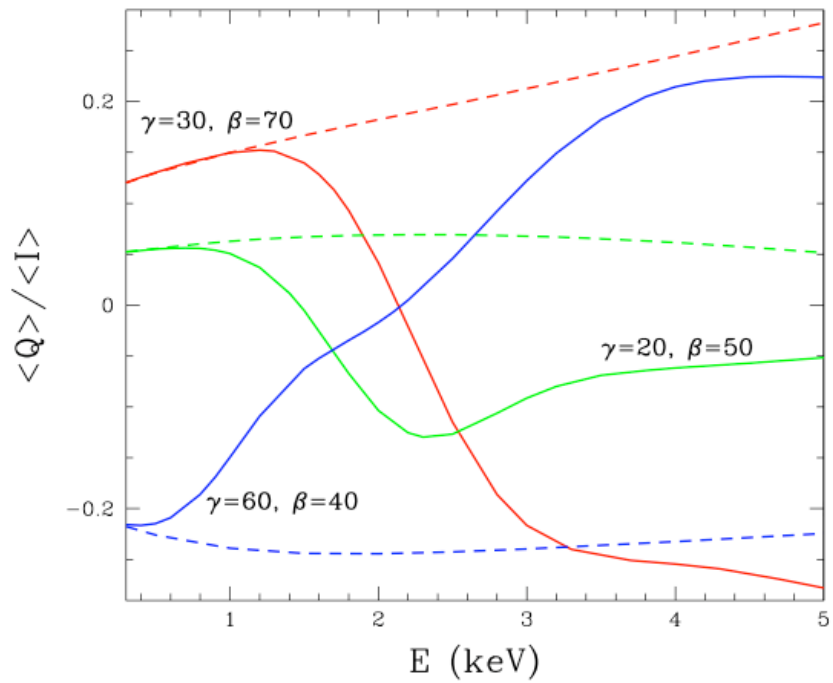
For $B < 7\times10^{13}\ T_6^{-1/8}\ E_1^{-1/4}$ G:

Vacuum resonance lies outside both photospheres



B=10^{13}G Model

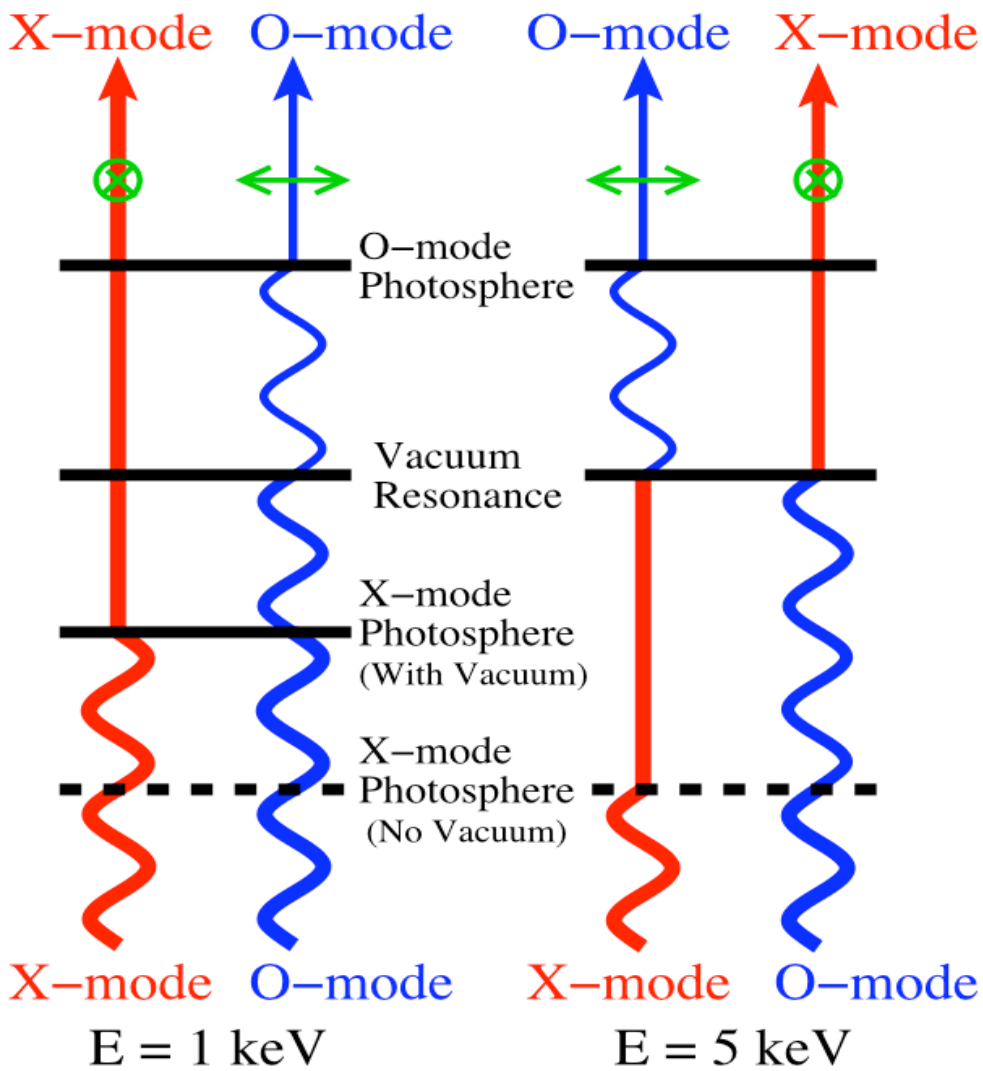




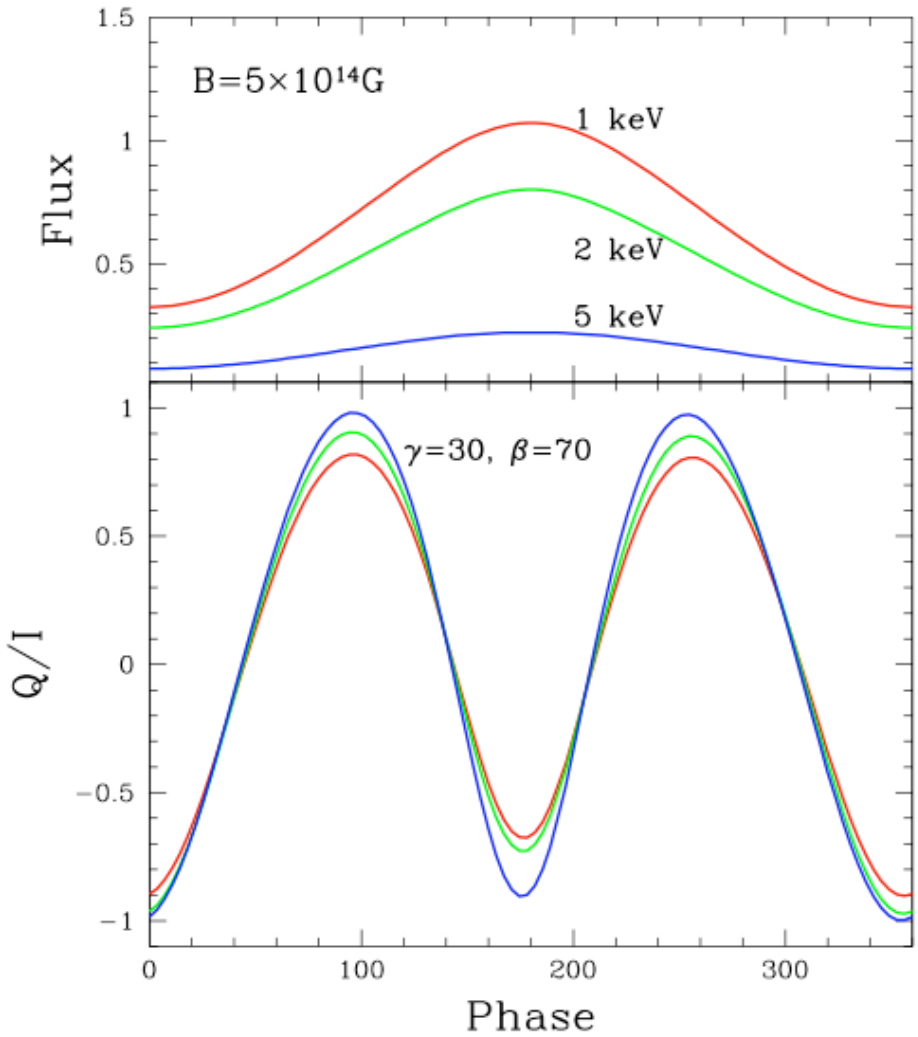
Plane of linear polarization at <1 keV is perpendicular to that at >4 keV.

For $B > 7\times10^{13}\ T_6^{-1/8}\ E_1^{-1/4}$ G:

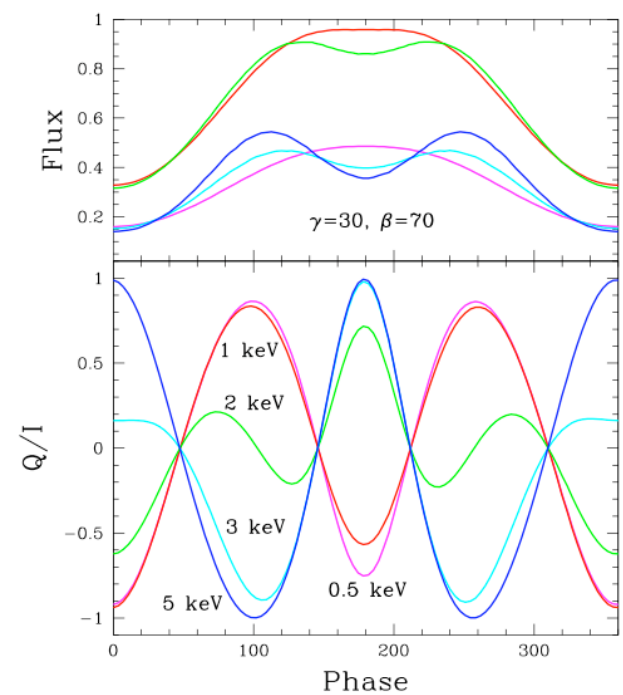
Vacuum resonance lies between the two photospheres



B=5×10^{14}G Model

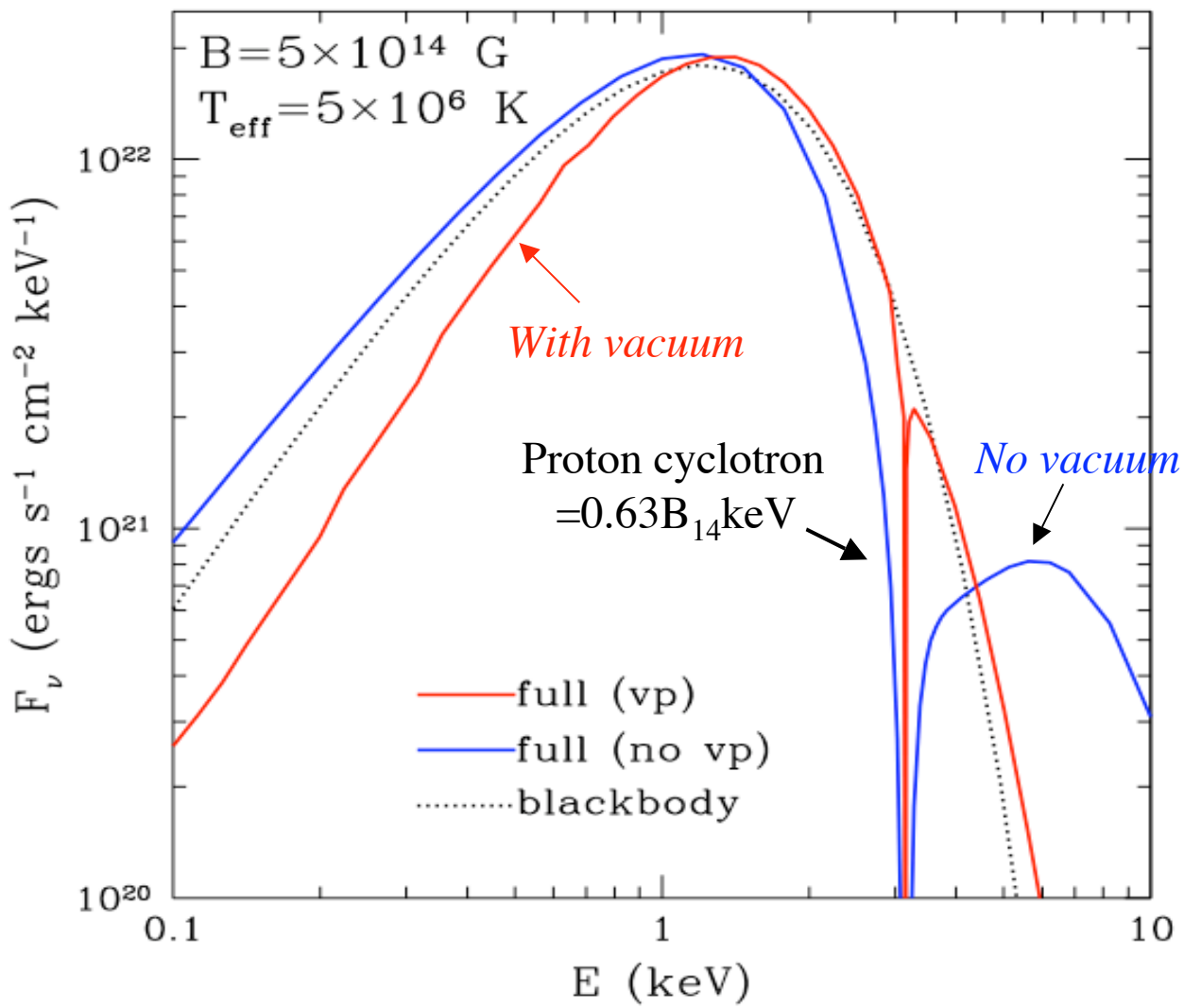


B=10^{13} G model



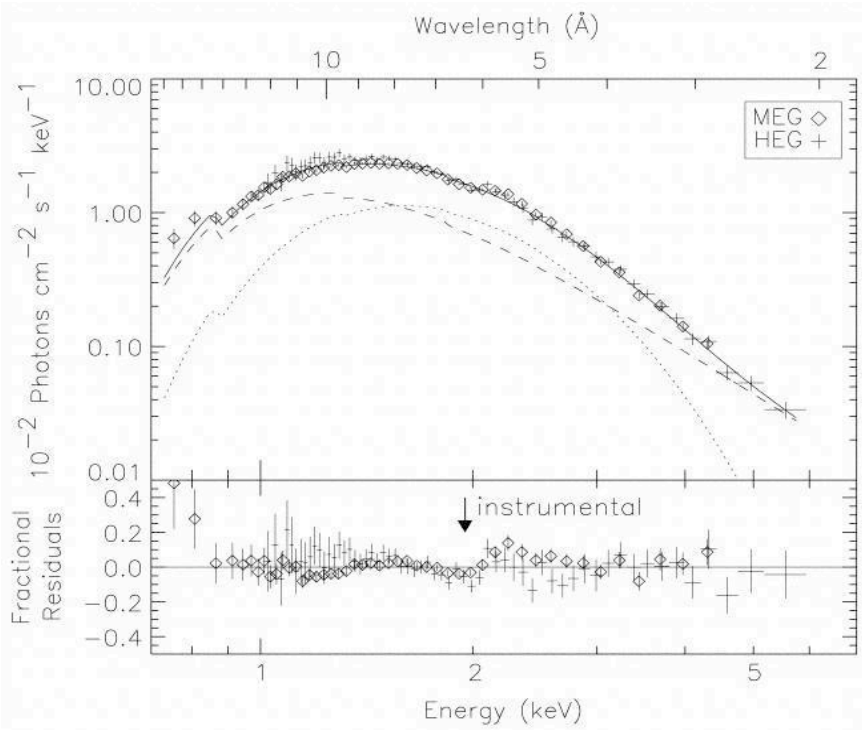
Plane of linear polarization at different E coincide.

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



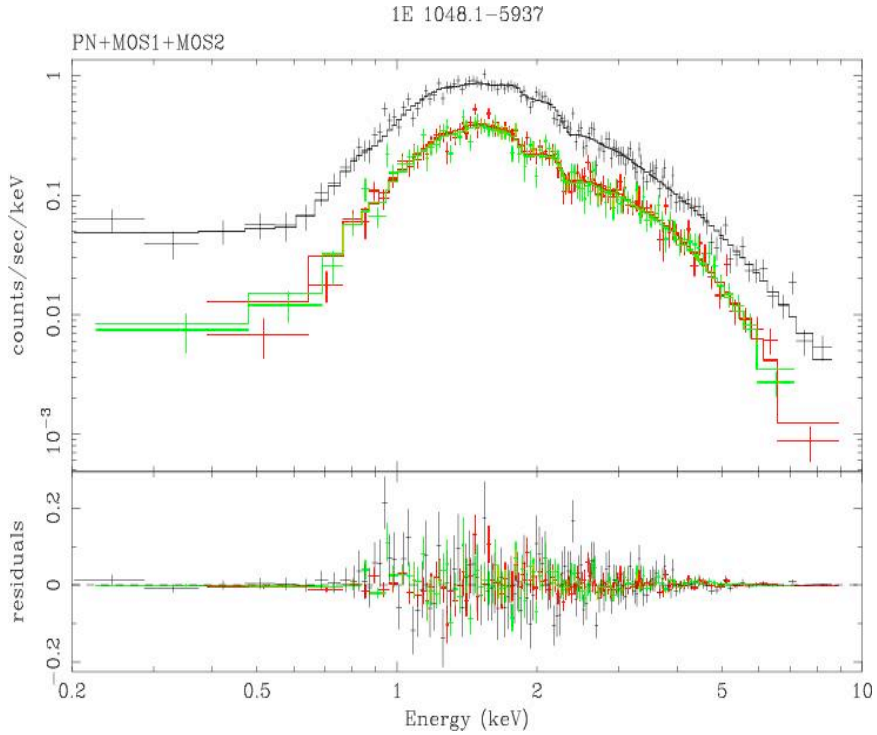
Two Examples of AXP Spectra

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

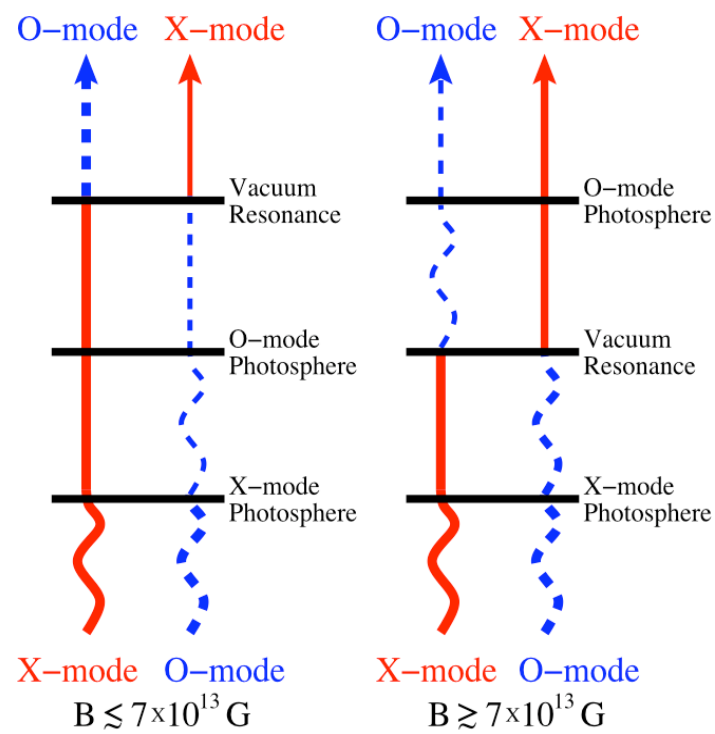
Recapitulation: **Effect of Vacuum Resonance on Thermal Emission**

For B<7×10^{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>7×10^{13} G ($\rho_{o\text{-}mode} < \rho_{vac} < \rho_{x\text{-}mode}$)

- Dramatic effect on spectrum
  (suppress absorption lines, soften hard tails: explain observations of magnetars)
- "Boring" polarization signals
  (plane of linear polarization coincides for different E)

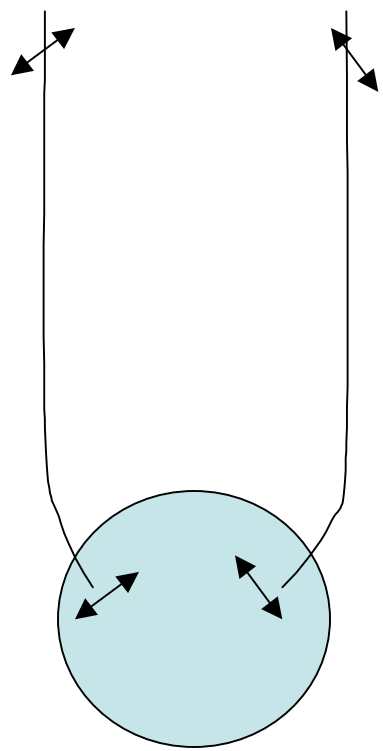


Propagation of Polarization from NS Surface to Observer?

What if emission is from the whole 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**).

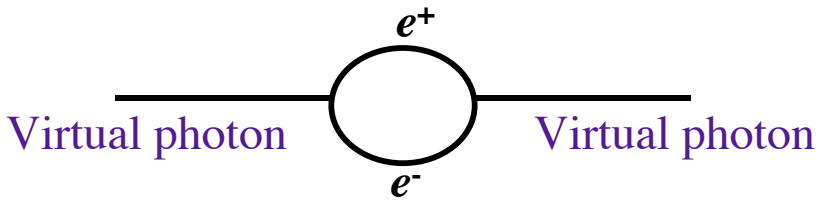
If polarization were parallel-transported to infinity, the net polarization (summed over observable surface of the star) would be reduced.



This is incorrect!

(as first pointed out by Heyl & Shaviv 2002)

Vacuum Polarization in Strong B



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

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

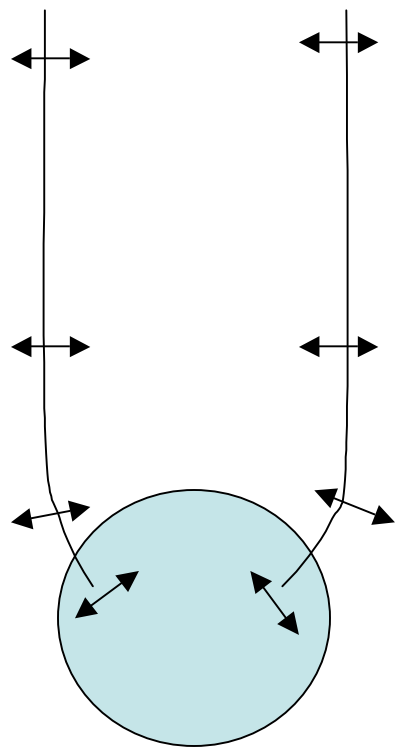
Modes in magnetized vacuum: linearly polarized

X-mode

O-mode

$n_1 \neq n_2$

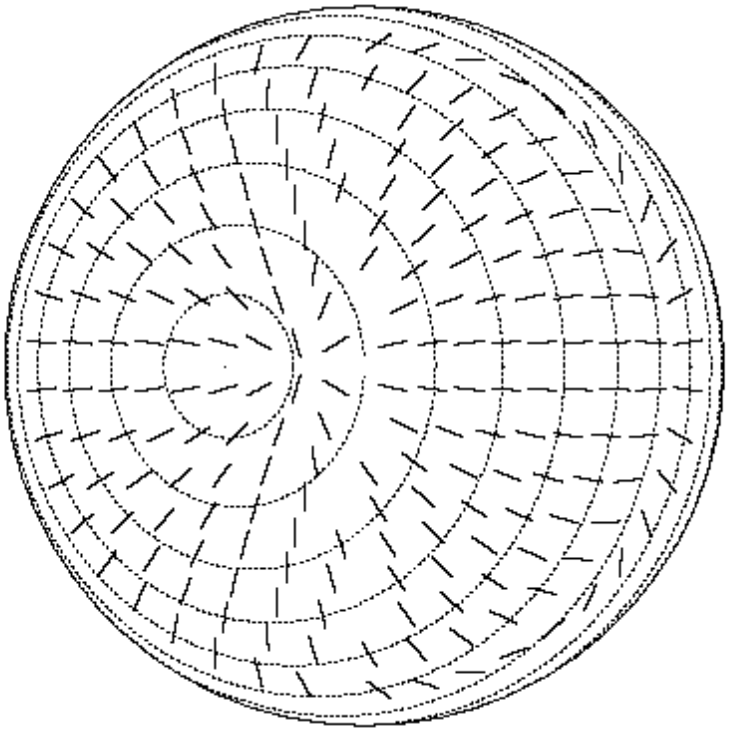
Propagation of Polarization from NS Surface to Observer Through Magnetized Vacuum



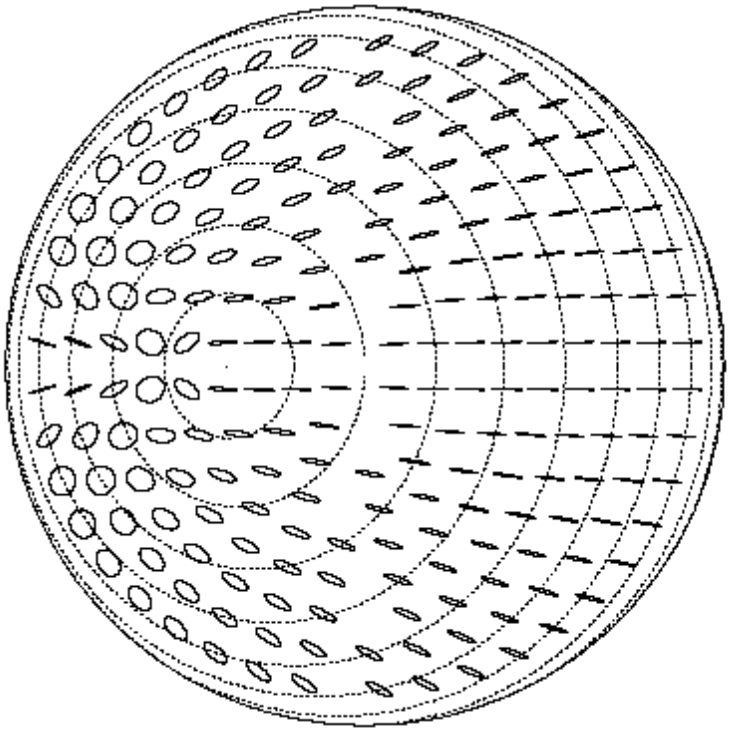
polarization limiting radius >> R

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

Apparent polarization image of a neutron star



No vacuum birefringence



Include vacuum birefringence

Heyl & Shaviv 2002

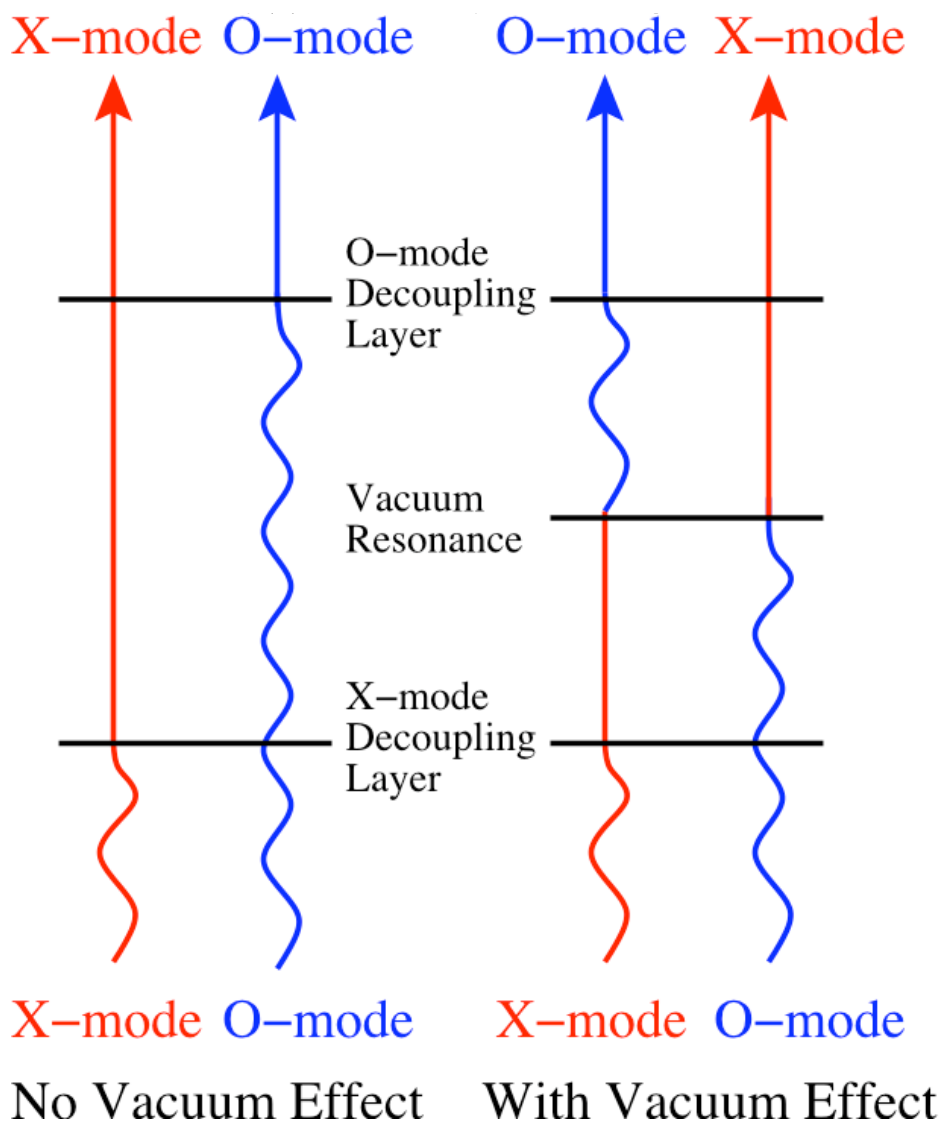
Summary

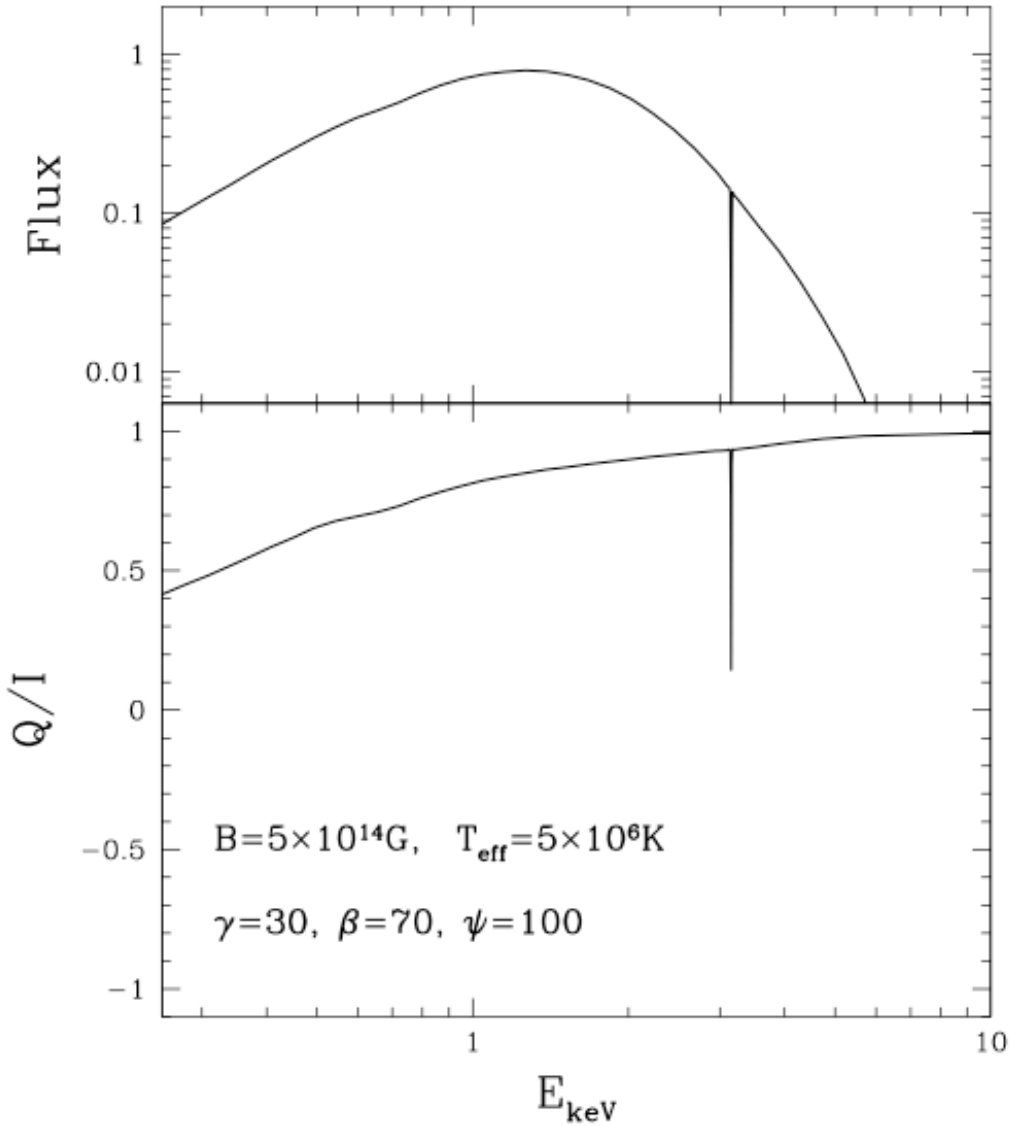
- Surface emission from magnetized neutron stars is highly polarized.
- X-ray polarization probes B-fields, geometry, beam patterns, M-R. Complementary to light curve and spectrum (polarization signal may still be interesting even when spectrum is boring.)
- Strong-field QED (vacuum polarization) plays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

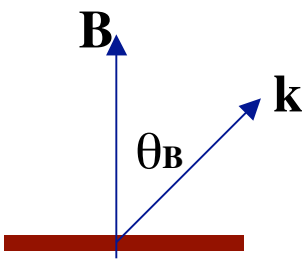
  1. Gives rise to clean energy-dependent polarization signatures
     For $B<7\times10^{13}$G, the plane of polarization at $E<1$ keV is $\perp$ that at $E>5$ keV;
     For $B>7\times10^{13}$G, polarization planes coincide (but spectrum is affected).
  2. Aligns the polarization states of photons from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

  Probe strong-field QED.

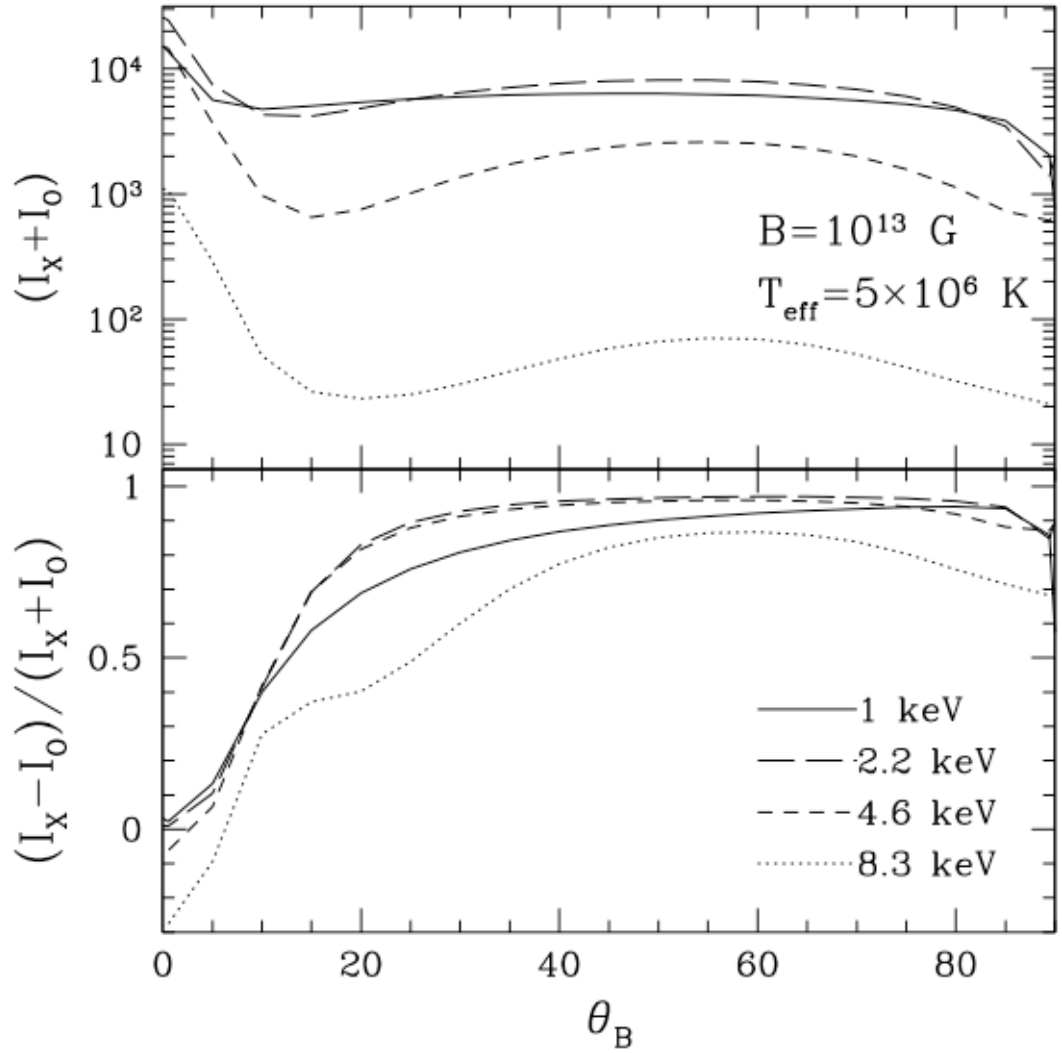
B > 7×10^{13}G regime:

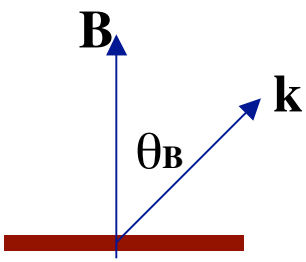



Flux
1
0.1
0.01
Q/I
1
0.5
0
−0.5
−1
B=5×10¹⁴G, T_eff=5×10⁶K
γ=30, β=70, ψ=100
1
10
E_keV

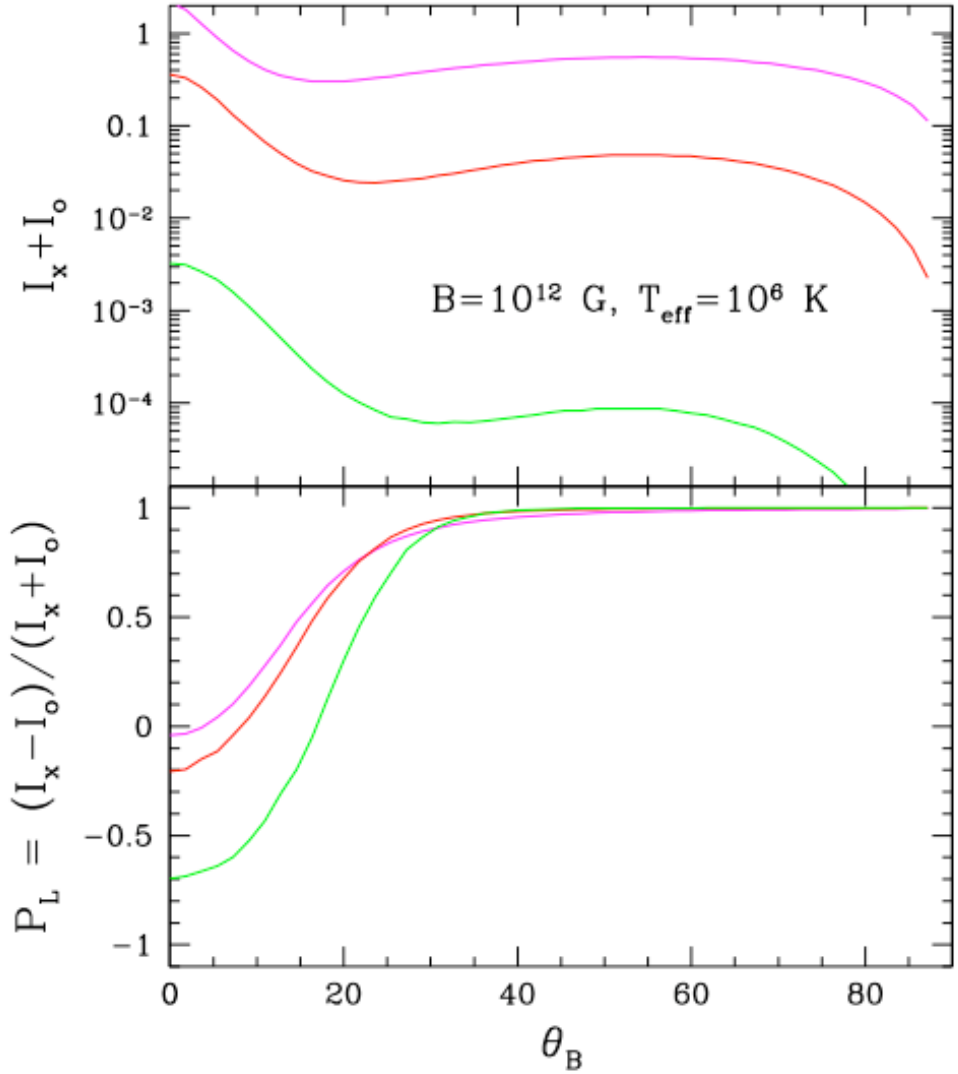


Degree of linear Polarization at emission point

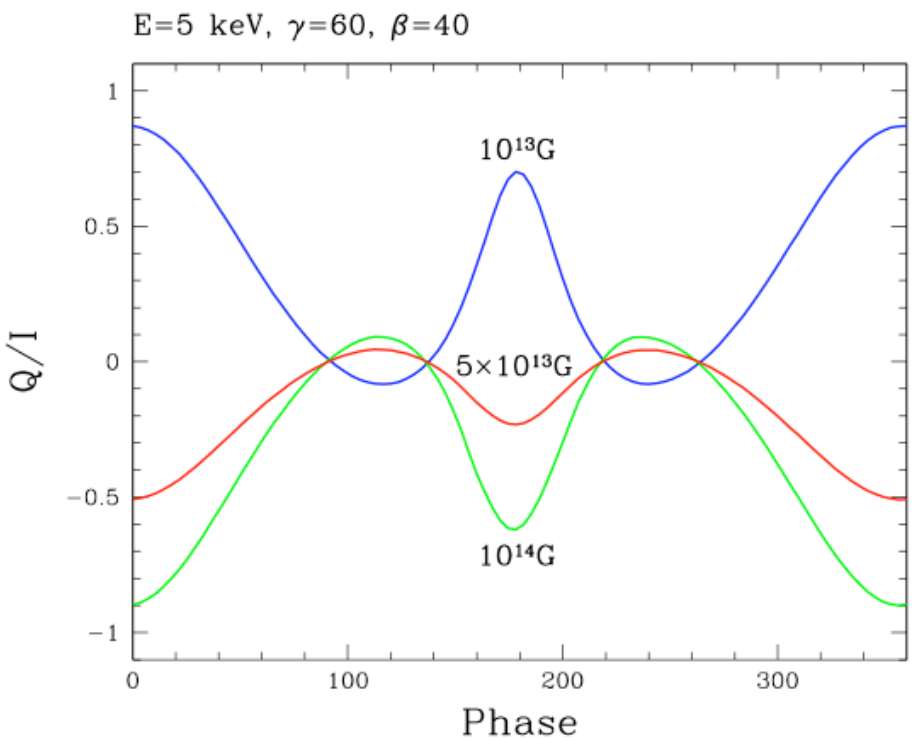


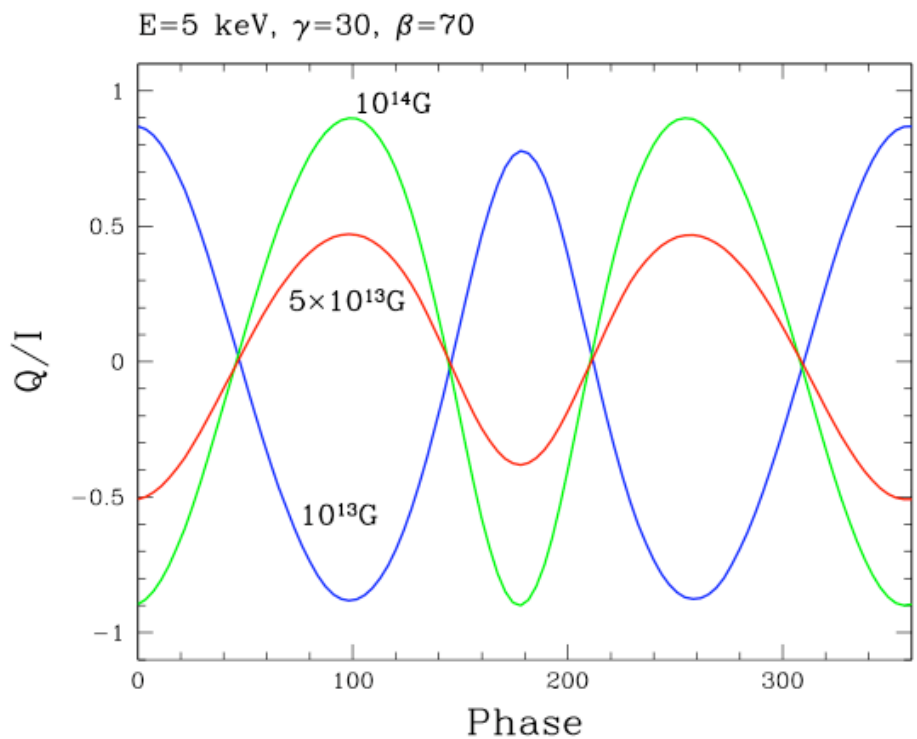


Degree of linear Polarization at emission point

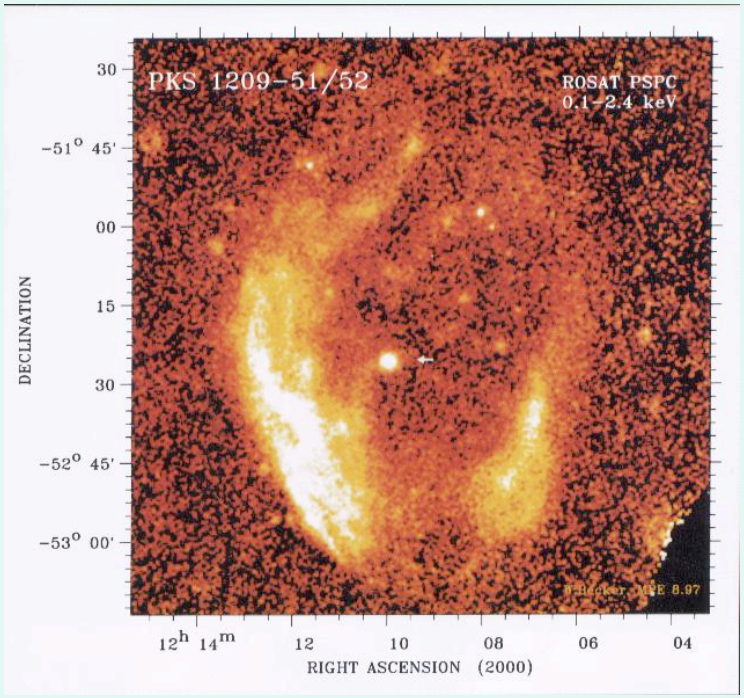


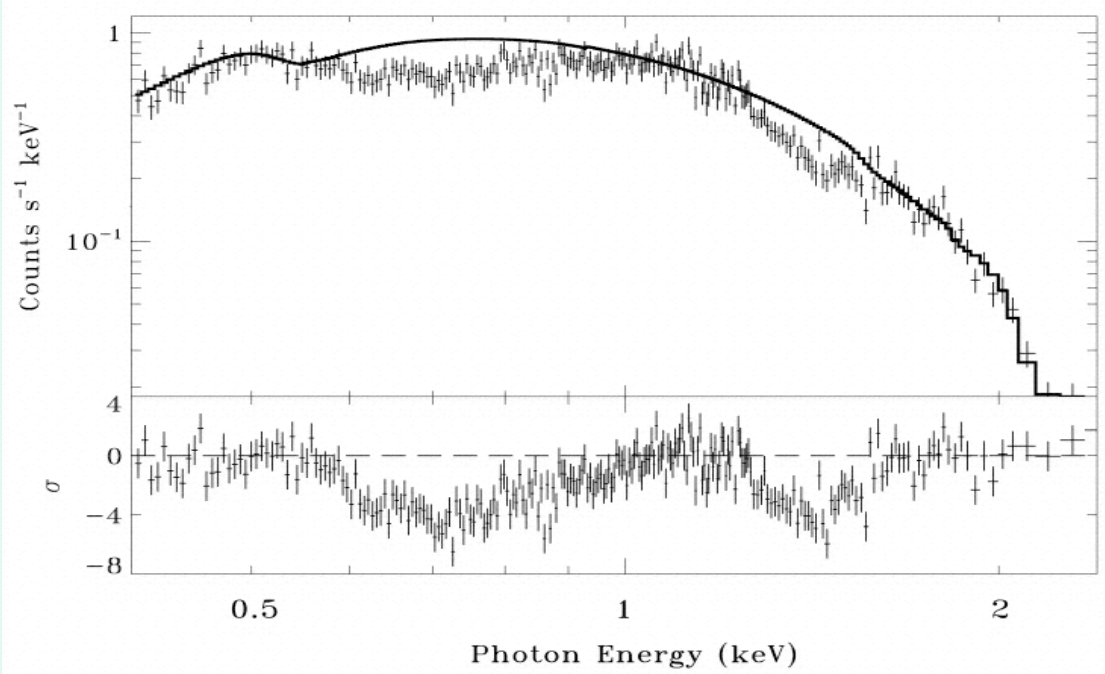
Dependence on B:





1E 1207-5209 in SNR PKS 1209-51/52

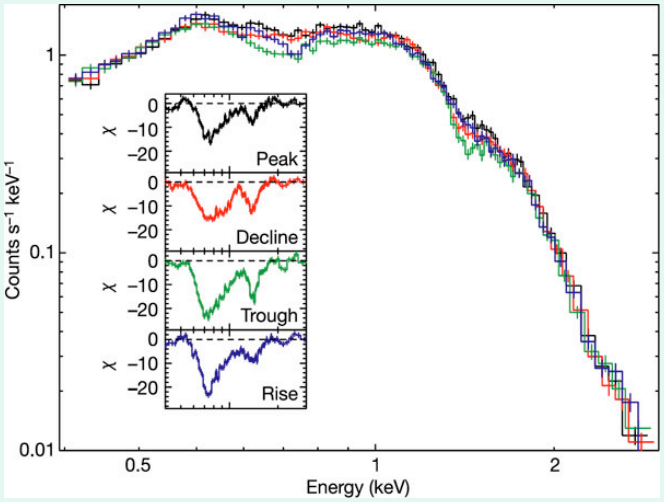




P =0.4 s, age ~ 3-20 kyr, Teff=2 MK

Clear absorption features at 0.7 and 1.4 keV

(Sanwal et al. 2002; Mereghetti et al. 2002)



Bignami et al. (2003) claimed additional absorption at 2.1 keV.

3 similar dim isolated NSs (T= 1MK)

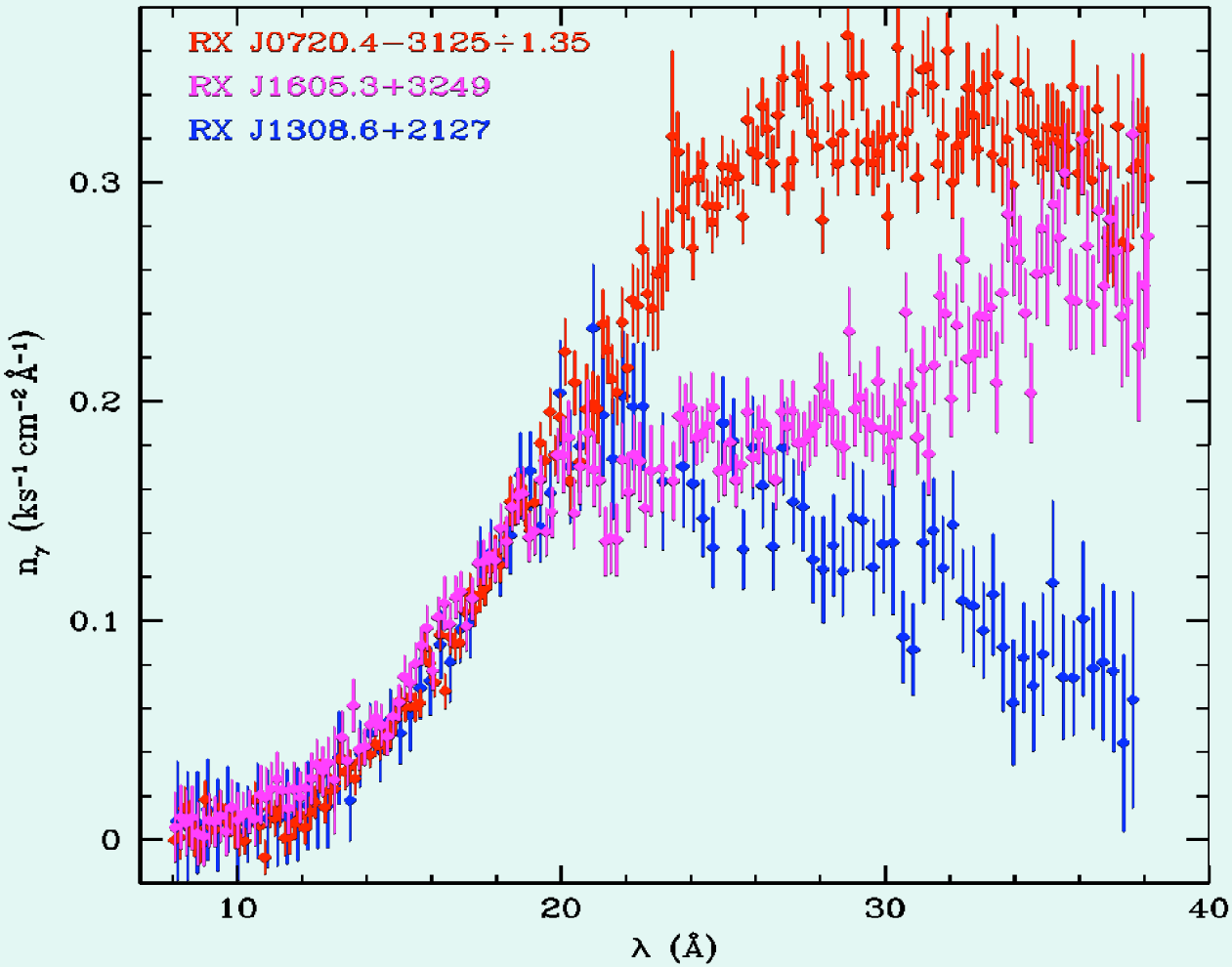


Figure provided by
Marten van Kerkwijk (U.Toronto)