Highly Magnetized Neutron Stars and Polarized X-Rays

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Institute of High-Energy Physics, CAS, Jan. 12, 2016

Neutron Stars:

Different Observational Manifestations

-- Isolated NSs
-- Accreting NSs
-- Merging NSs

Isolated Neutron Stars

Radio pulsars: $P, \dot{P} \Rightarrow$

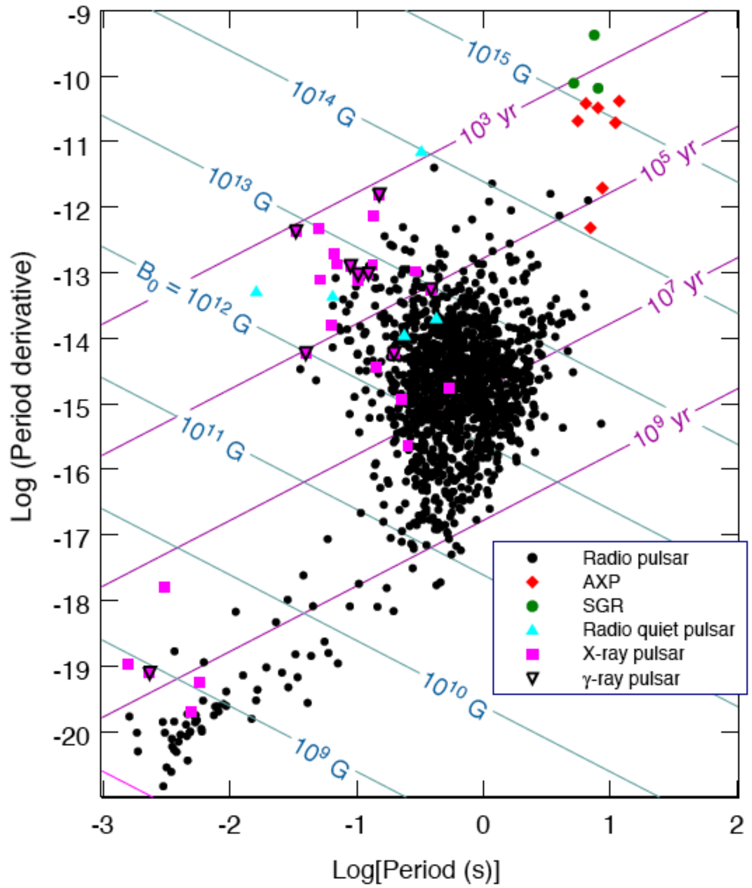
$\text{Most pulsars}: \; B \sim 10^{12-13} \text{ G}$

$\text{Millisecond pulsars}: \; B \sim 10^{8-9} \text{ G}$

$\text{High} - \text{B radio pulsars}: \; B \sim 10^{14} \text{ G}$

Radiation at all wavelengths:

radio, IR, optical, X-rays, Gamma-rays



New Odd Behaviors:

- RRATs (rotating radio transients)
  radio busrts (2-30 ms), quiescence (min-hrs);
  period ~ sec
- Intermittent Pulsars ("Sometimes a pulsar")
  e.g. PSR B1931+24: "on" for ~ a week,
  "off" for ~ a month

FRBs??

Magnetars

Neutron stars powered by superstrong magnetic fields ($B>10^{14}$G)

Soft Gamma-Ray Repeaters (SGRs) (7+4 systems)
Anomalous X-ray Pulsars (AXPs) (9+3 systems)

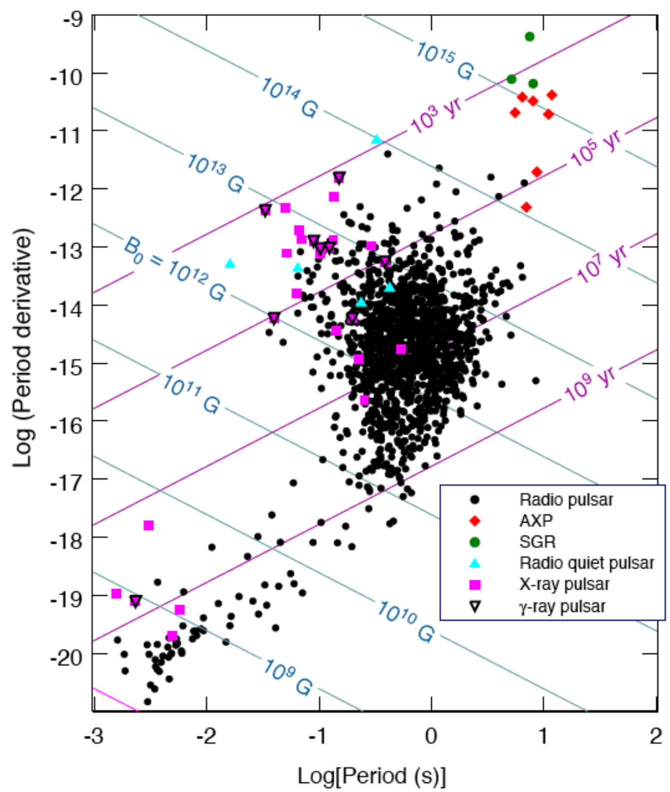
Even in quiescence, $L \sim 10^{34-36} \text{erg s}^{-1} \gg I\Omega\dot{\Omega}$

AXP/SGR bursts/flares (e.g. Kaspi, Gavriil, Kouveliotou, Woods, etc)

Giant flares in 3 SGRs

12/04 flare of SGR1806-20 has $E>10^{46}$erg

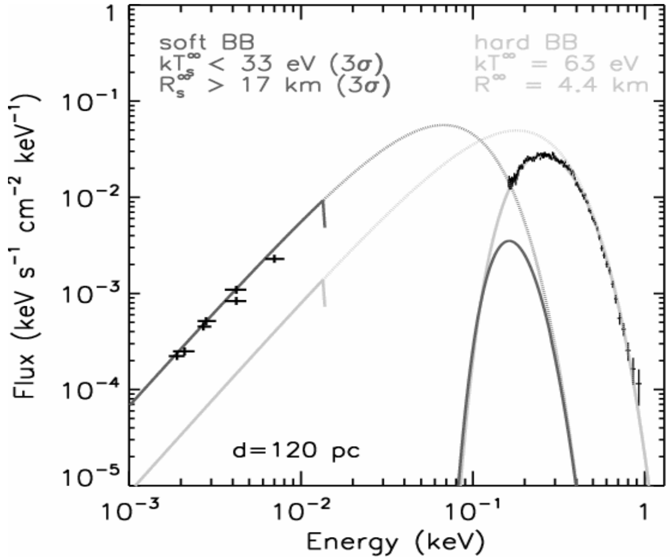
QPOs during giant flares (e.g Israel, Strohmayer, Watts, etc)



Thermally Emitting Isolated NSs

"Perfect" X-ray blackbody:

RX J1856.5-3754



Burwitz et al. (2003)

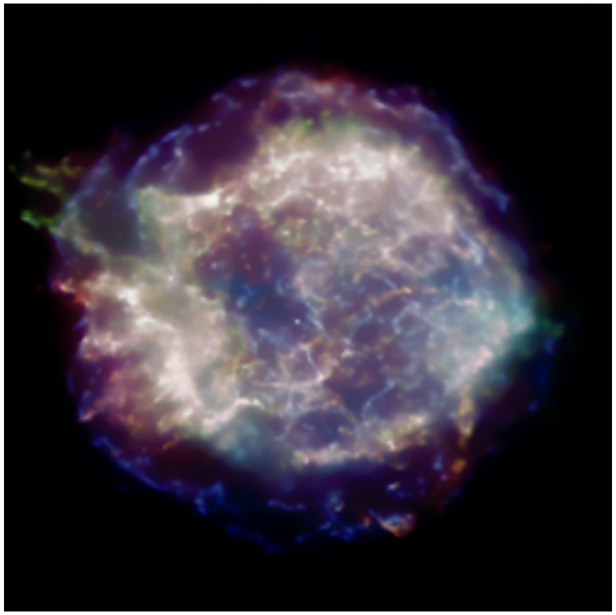
Spectral lines detected:

(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?

Central Compact Objects (CCOs) in SNRs



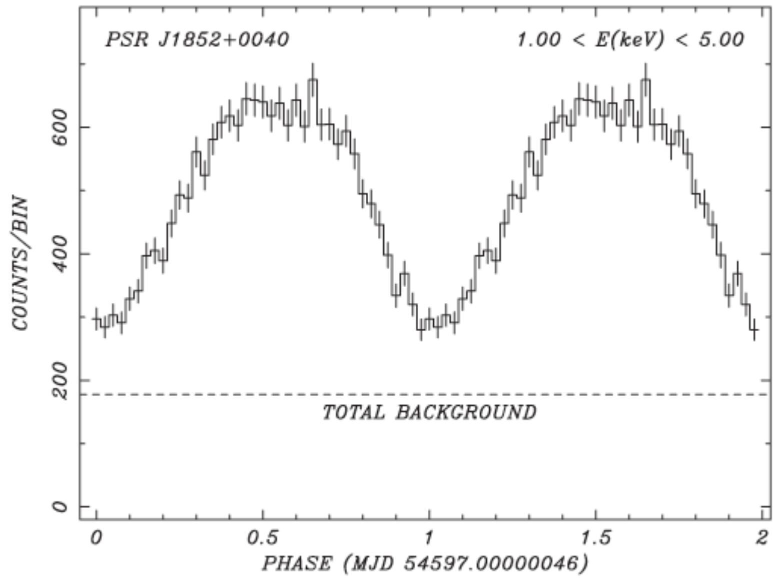
CCO	SNR	Age (kyr)	d (kpc)	P (s)	f_p[a] (%)	B_s (10^{11} G)
RX J0822.0 − 4300	Puppis A	3.7	2.2	0.112	11	<9.8
CXOU J085201.4 − 461753	G266.1 − 1.2	1	1	...	<7	...
1E 1207.4 − 5209	PKS 1209 − 51/52	7	2.2	0.424	9	<3.3
CXOU J160103.1 − 513353	G330.2 + 1.0	$\gtrsim$3	5	...	<40	...
1WGA J1713.4 − 3949	G347.3 − 0.5	1.6	1.3	...	<7	...
CXOU J185238.6 + 004020	Kes 79	7	7	0.105	64	0.31
CXOU J232327.9 + 584842	Cas A	0.33	3.4	...	<12	...

Halpern & Gotthelf 2010

Small surface dipole field …   (are they "anti-magnetars"?)

Hidden Magnetic Fields of Neutron Stars

- NS in Kes 79 SNR has $B_{\rm dipole} \simeq 3 \times 10^{10}$ G, but large pulse fraction 60%



(Halpern & Gotthelf 2010)

=> $B_{\rm crust} \sim$ a few $\times 10^{14}$ G

(Shabaltas & DL 2011)

- SGR 0418+5729, with $B_{\rm dipole} \simeq 4 \times 10^{12}$ G (Rea et al. 2010)

➔ Internal field is much larger (Turolla et al 2011)

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)

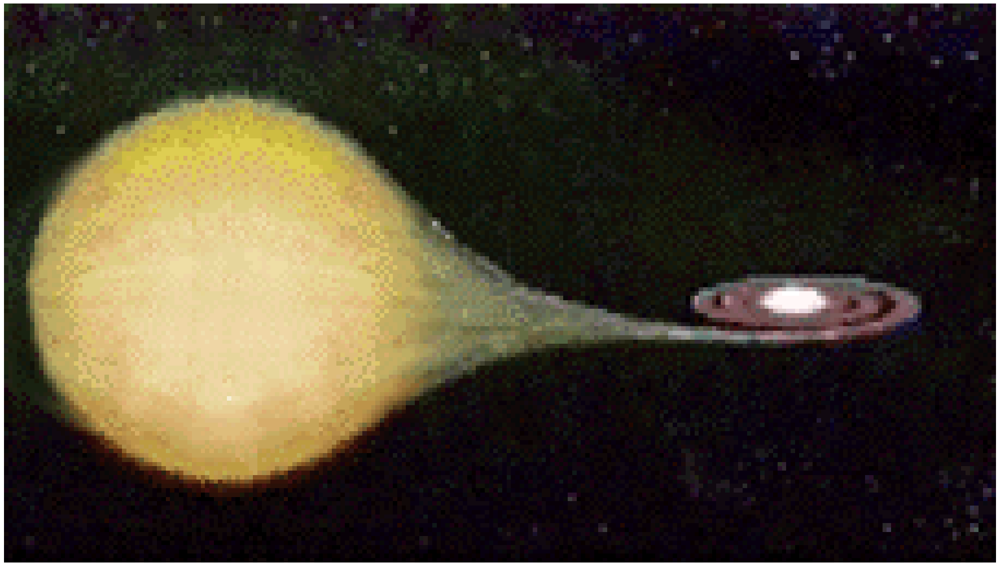
--Use these NSs to probe physics under extreme conditions

(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

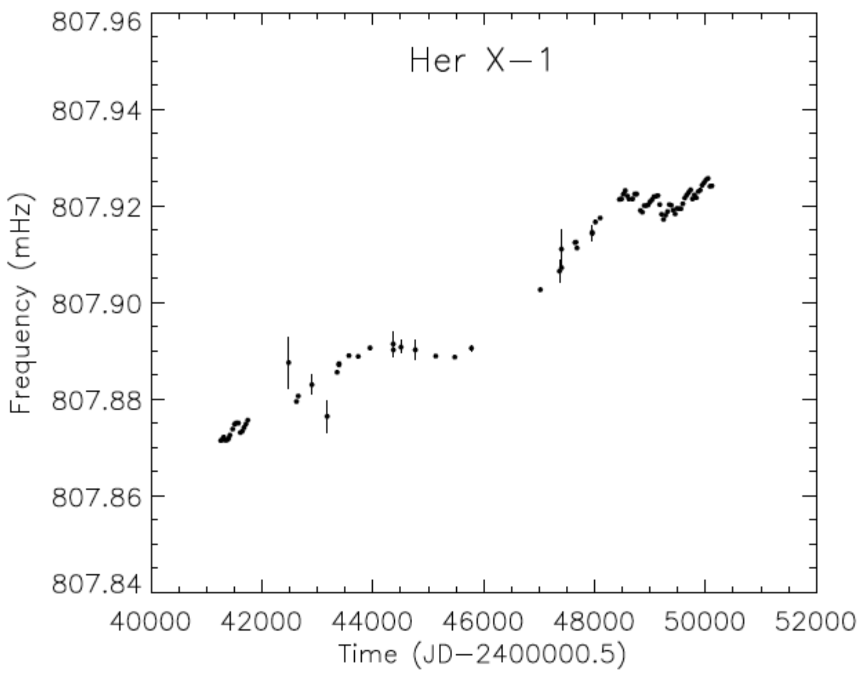
Accreting Neutron Stars

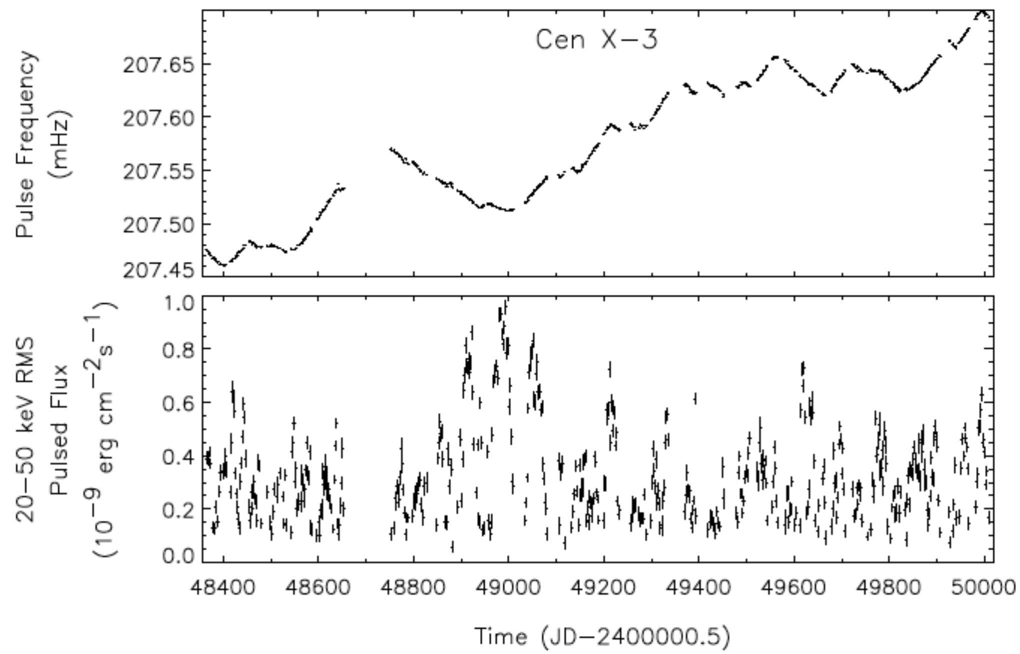


-- Non- or weakly magnetized NSs (LMXBs)

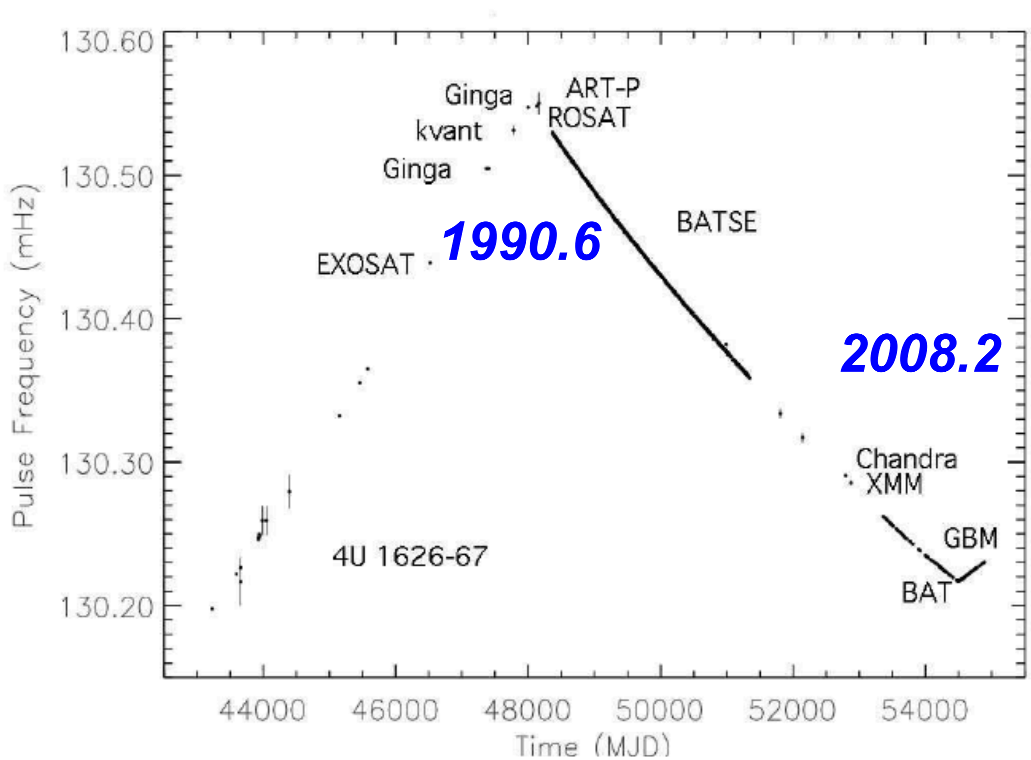
-- Highly magnetized NSs (HMXBs)

Puzzle:
Spinup/Spindown of Accreting X-ray pulsars





Bildsten et al. 1997

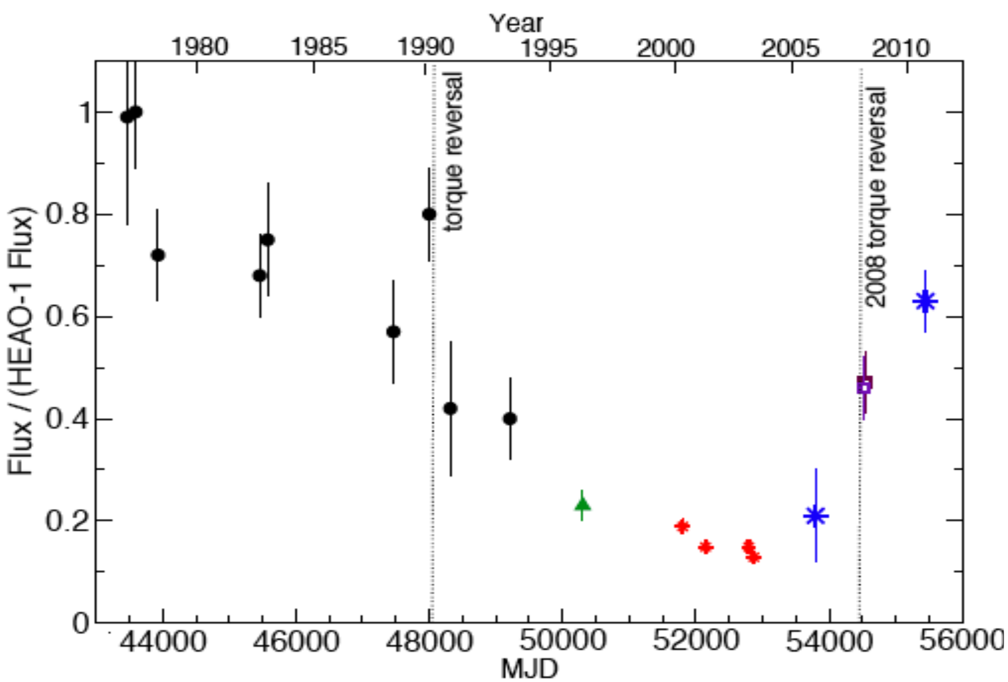


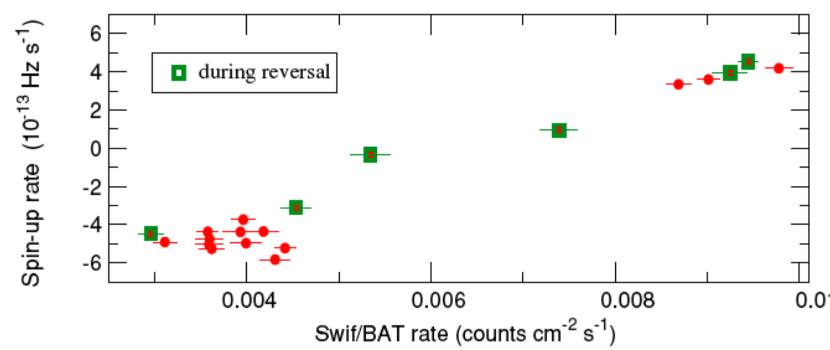
4U1626-67

7.66s

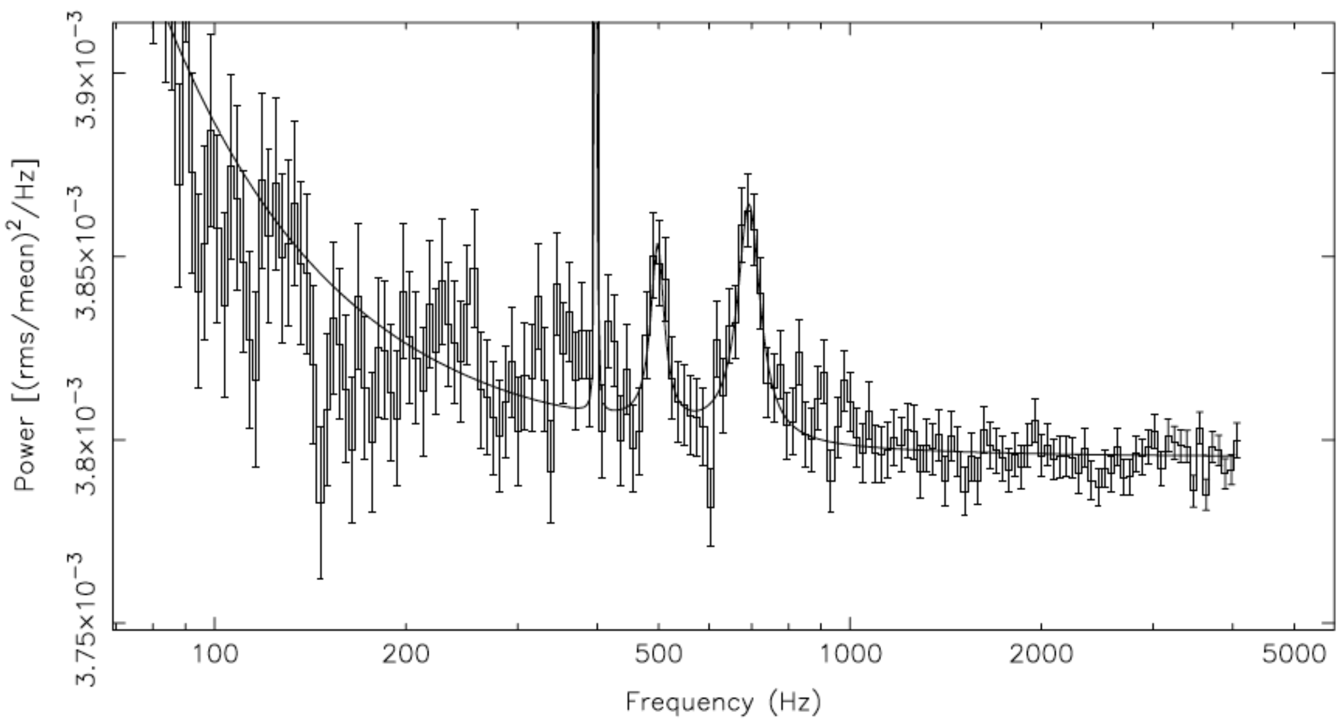
Transition lasted 150 days

Camero-Arranz et al. 2010,2012





kHz QPOs in Accreting Millisecond Pulsars

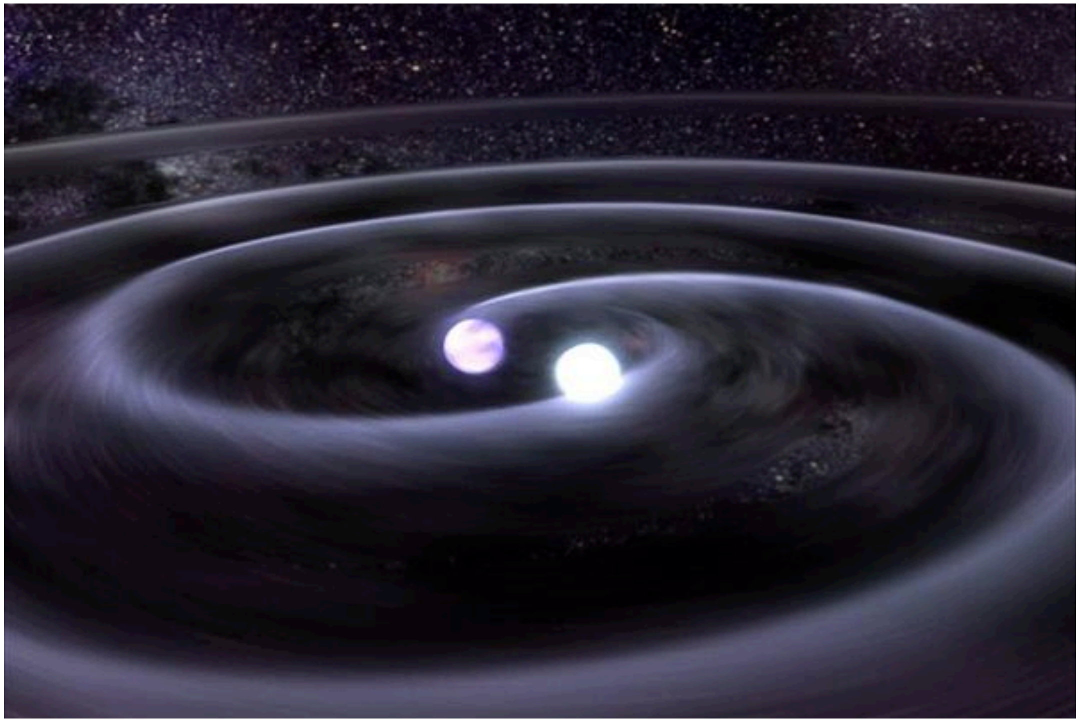


Van der Klis 2005

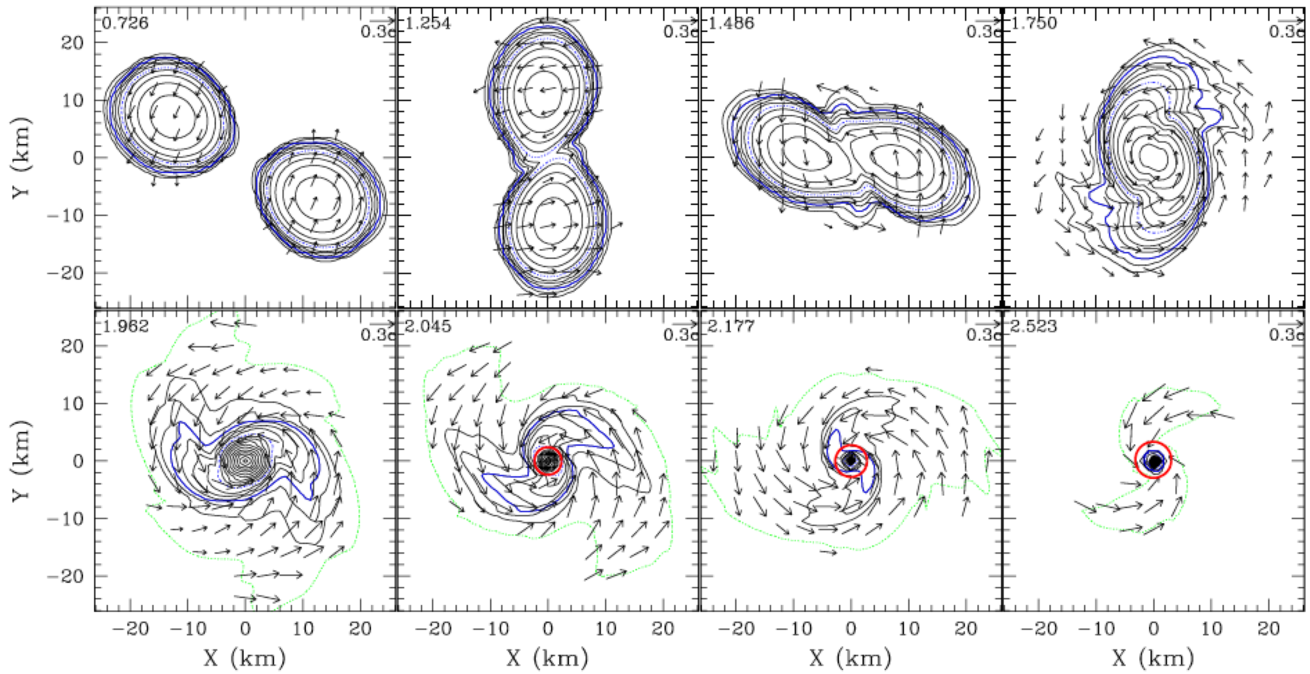
SAX J1808.4-3658: $\nu_s = 401$ Hz, $\nu_h - \nu_l \simeq \nu_s/2$ ($\pm$a few Hz)

XTE J1807.4-294: $\nu_s = 191$ Hz, $\nu_h - \nu_l \simeq \nu_s$

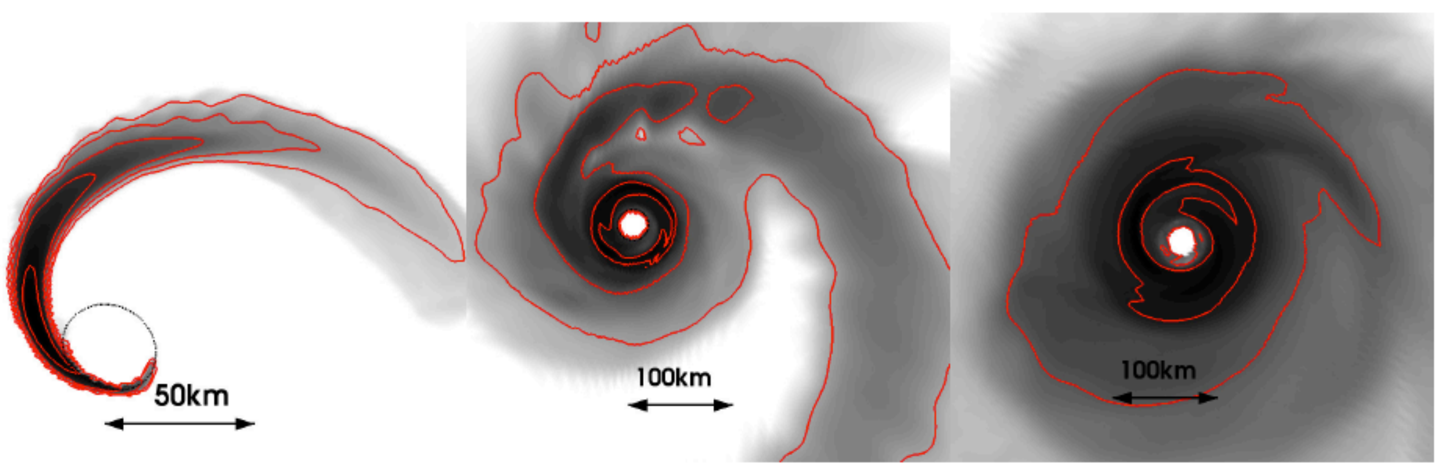
Merging Neutron Stars



NS/NS and NS/BH binaries: *GWs for LIGO/VIRGO*
EM counterparts (short GRBs, kiloNova)

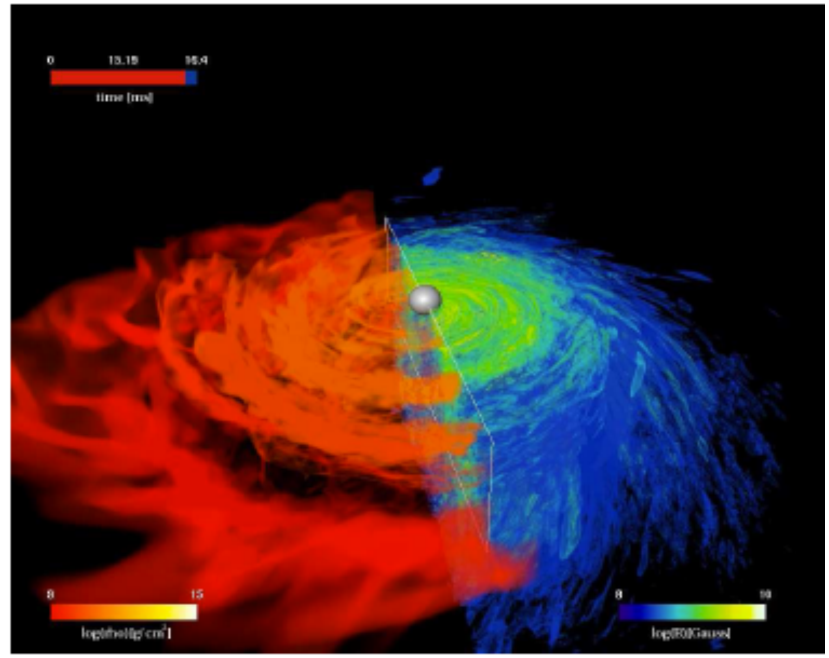


Shibata et al. 2006



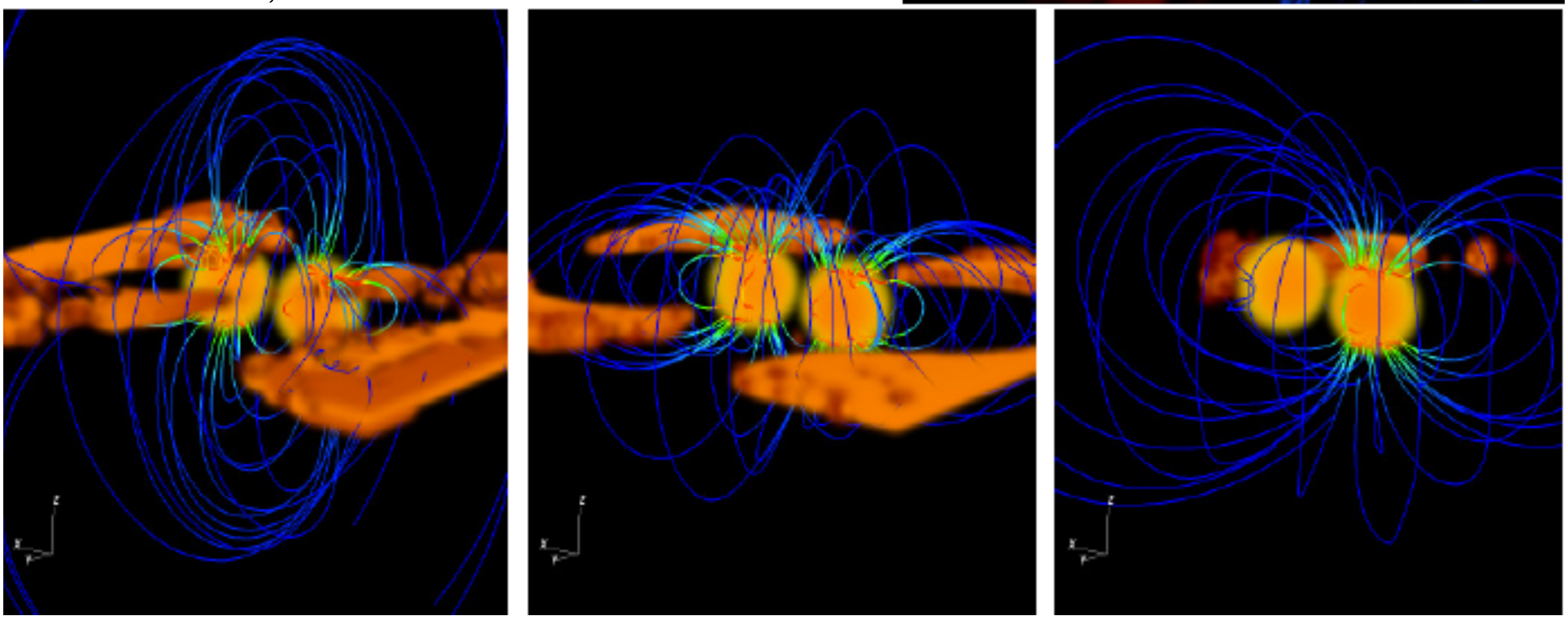
Foucart et al. (Cornell) 2011,13

Merger Simulation with B Fields

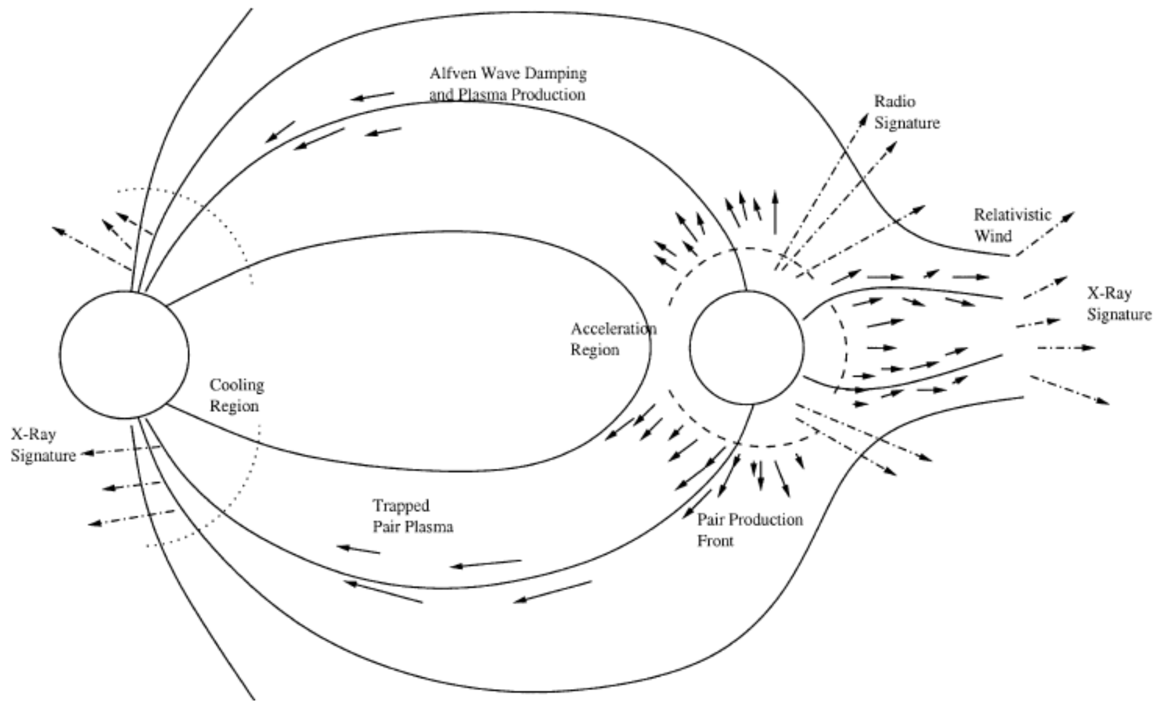


Giacomazzo, Rezzolla et al 2011

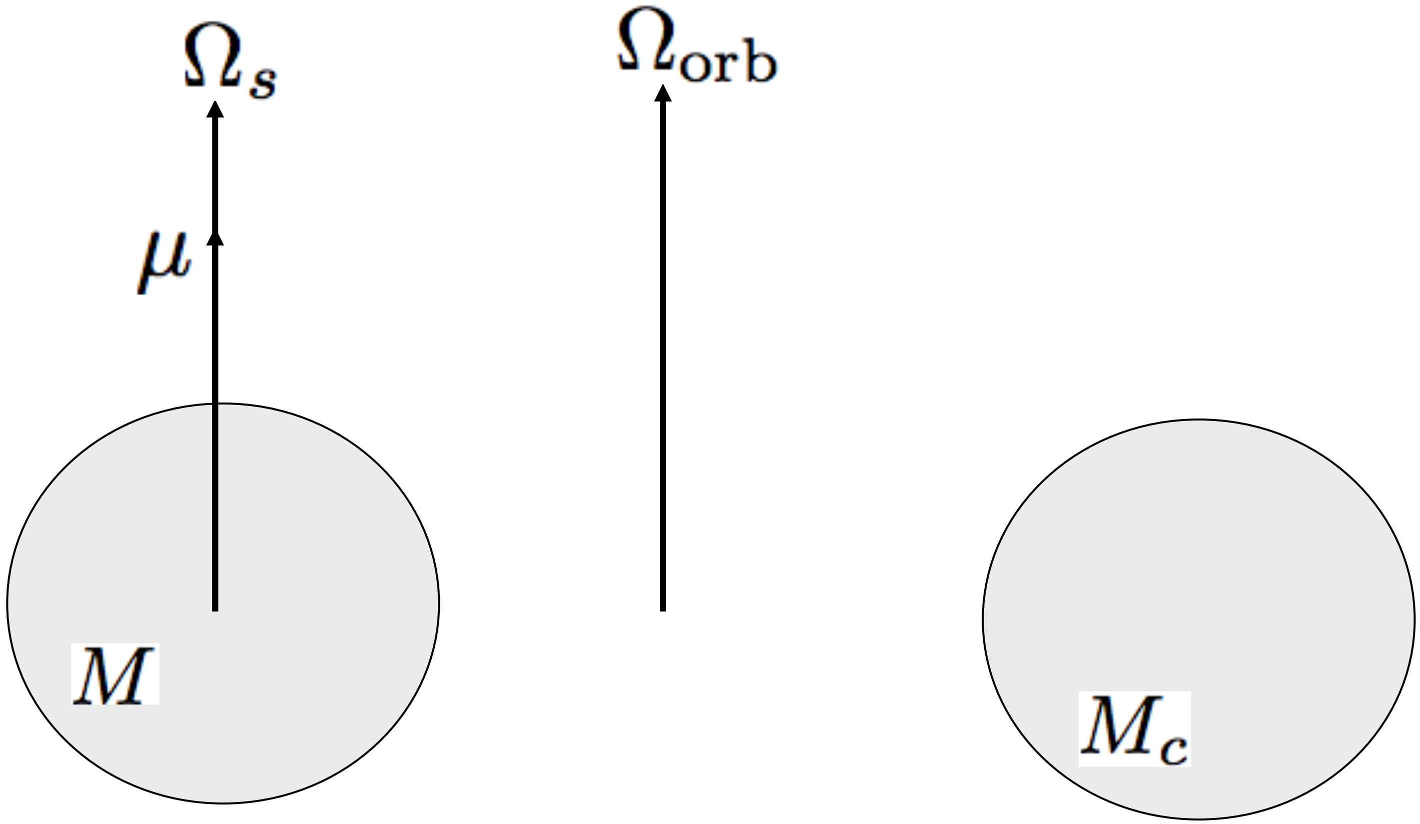
Palenzuela, Lehner et al. 2013



Merger of Magnetospheres



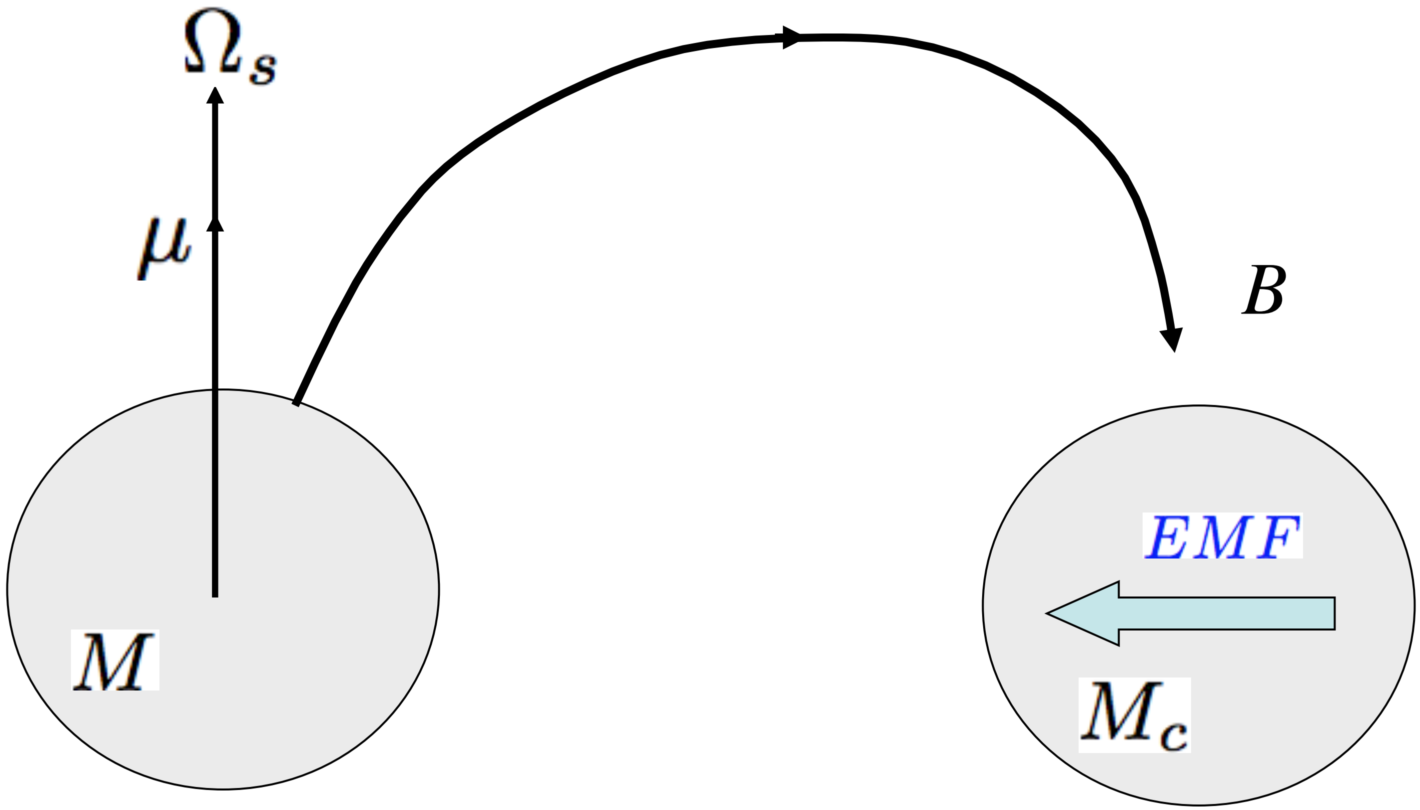
Hansen & Lyutikov 2001



Consider a binary with

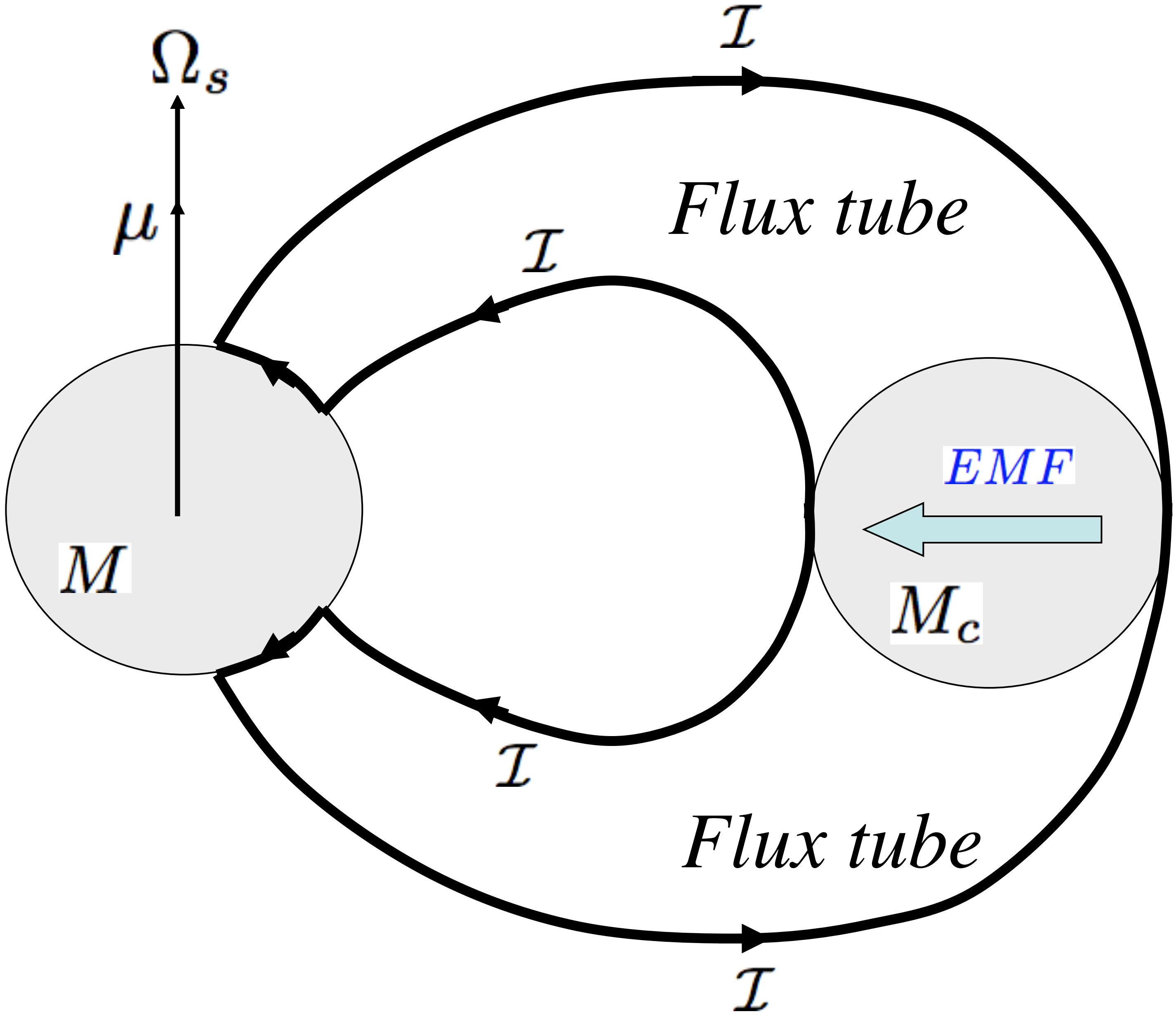
-- magnetic NS (>10^{12}G) + non-magnetic NS

-- embedded in a tenuous plasma (magnetosphere)



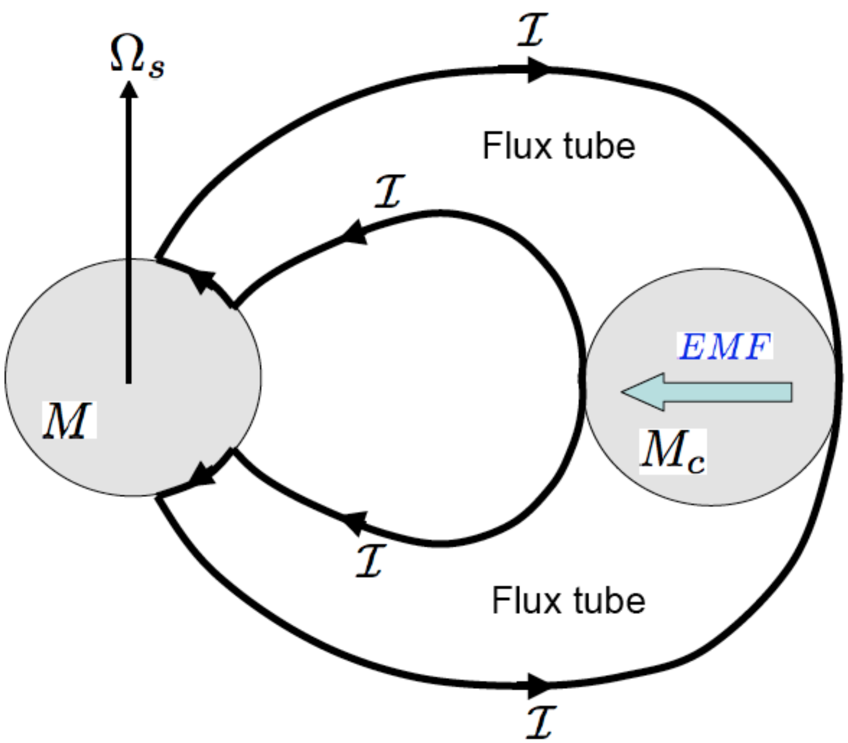
$$\text{EMF}: \quad \Phi = 2R_c \left| \frac{\mathbf{v}}{c} \times \mathbf{B} \right|$$

e.g. $\Phi \sim 10^{13}$ Volt at $f_{\rm orb} = 20$ Hz



Ω_s
μ
$\mathcal{I}$
$\mathcal{I}$
Flux tube
$\mathcal{I}$
M
EMF
M_c
$\mathcal{I}$
Flux tube
$\mathcal{I}$

DC Circuit Powered by Orbital Motion



$$\text{EMF}: \quad \Phi = \frac{2\mu R_c}{ca^2}(\Omega_{\rm orb} - \Omega_s)$$

$$\text{Current}: \quad \mathcal{I} = \frac{\Phi}{\mathcal{R}}$$

$$\text{Dissipation}: \quad \dot{E}_{\rm diss} = \frac{\Phi^2}{\mathcal{R}}$$

Energy Dissipation in the Magnetosphere of Pre-merging NS Binary

DL 2012

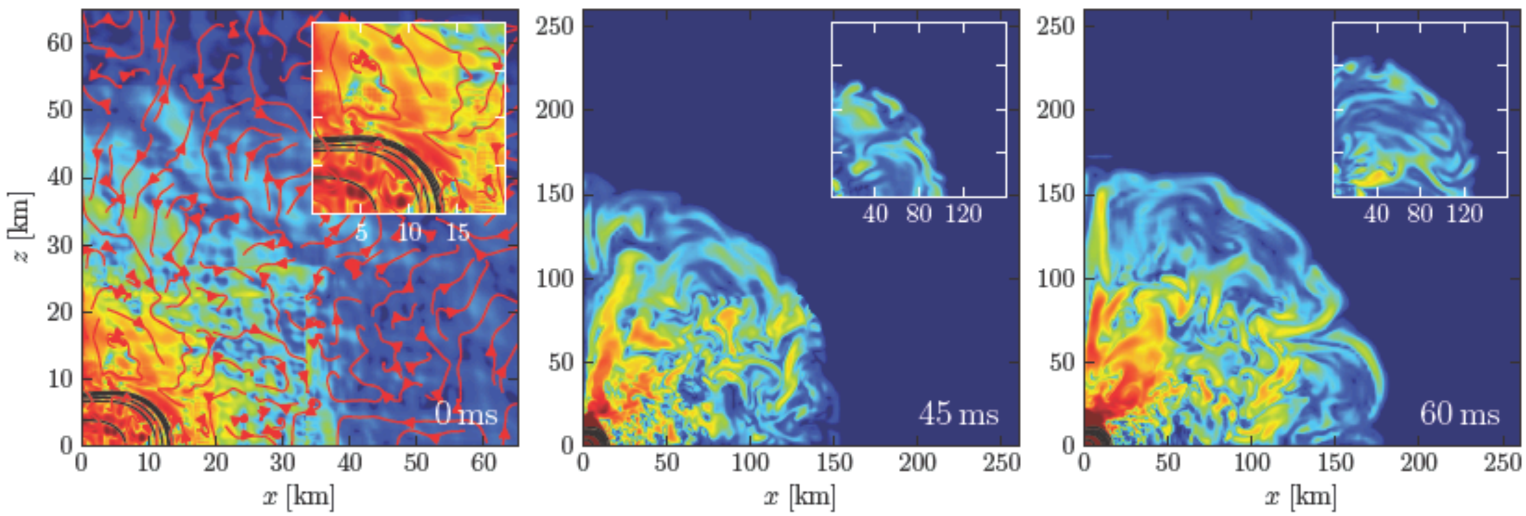
$$\dot{E}_{\rm max} \simeq 7 \times 10^{44} \left(\frac{B_{\rm NS}}{10^{13}\,{\rm G}} \right)^2 \left(\frac{a}{30\,{\rm km}} \right)^{-13/2} {\rm erg~s^{-1}}$$

- This Edot will not affect orbital decay rate (GW signal)
- Radio emission prior to binary merger (?) cf. Vietri 96; Hansen & Lyutikov 01

cf. isolated pulsars:

$$\dot{E} \simeq 10^{33} \left(\frac{B_{\rm NS}}{10^{13}\,{\rm G}} \right)^2 \left(\frac{P}{1\,{\rm s}} \right)^{-4} {\rm erg~s^{-1}}$$

Magnetic Fields in the Merger Remnant



Siegel, Ciolfi & Rezzolla 2014

-- Field amplification by differential rotation (MRI resolved?)

-- Wind/outflow

-- Formation of ms magnetar?

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

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

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
……

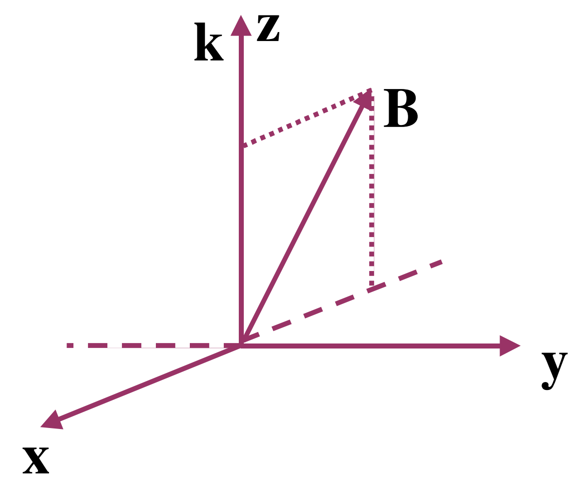
Photon Polarization Modes in a Magnetized Plasma

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

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

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

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



Extraordinary Mode (X-mode, ⊥-mode):

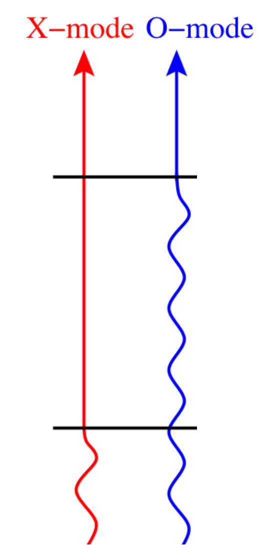
E nearly ⊥ **k-B** plane

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

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

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

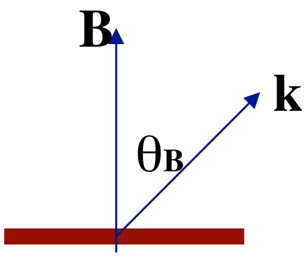
$\kappa_{\text{(X-mode)}} \sim \kappa_{(B=0)} \, (\omega/\omega_{ce})^2$

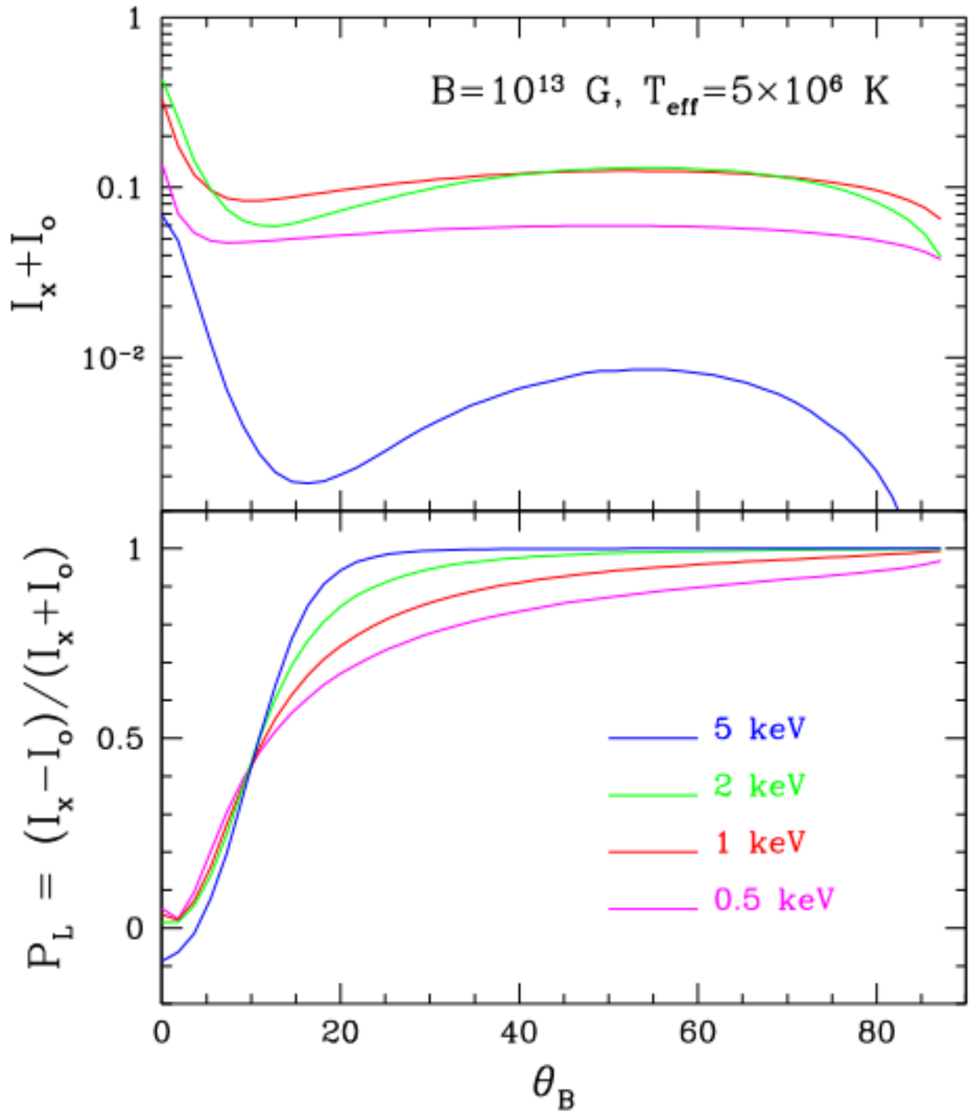


X-mode photons are the main carrier of X-ray flux

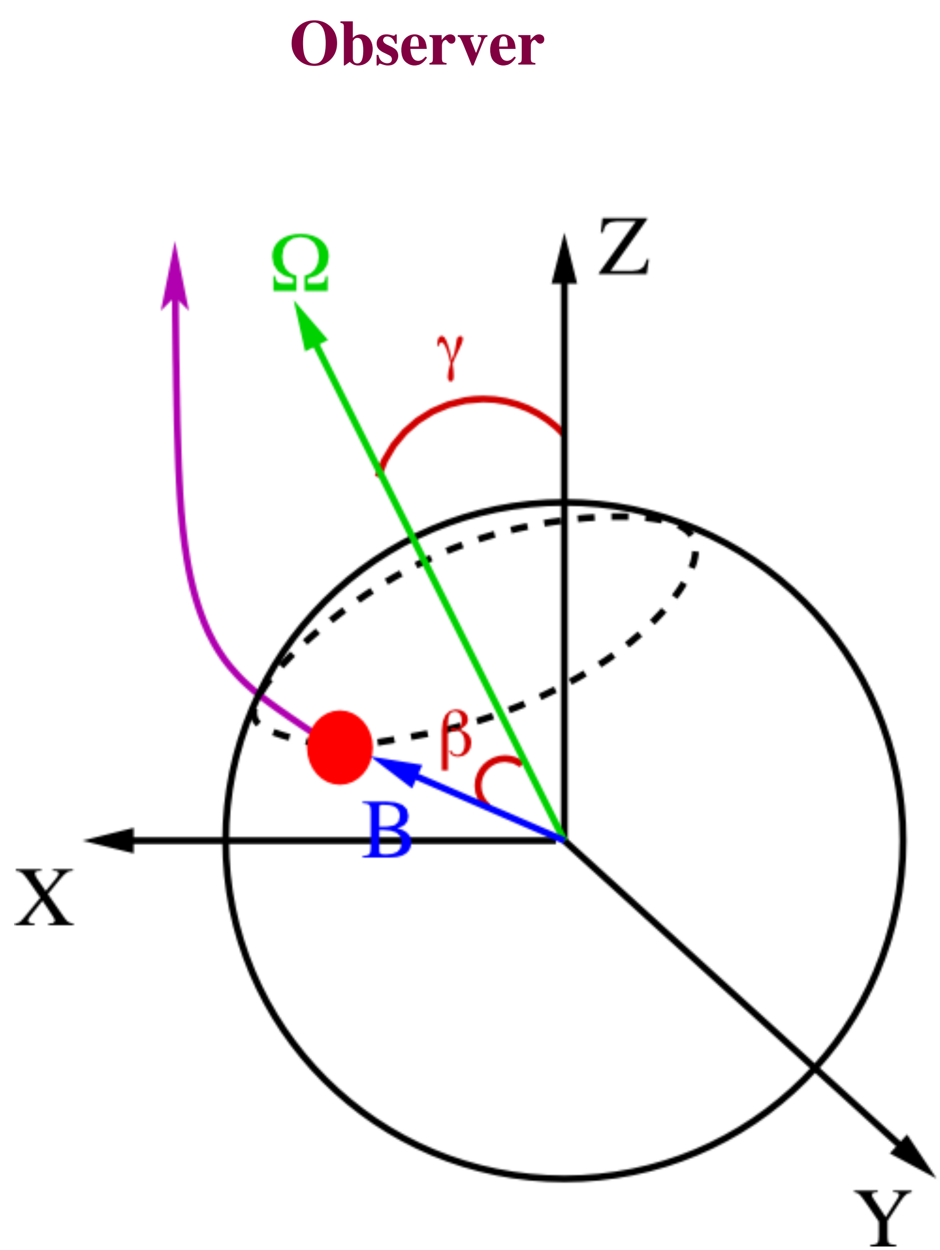
(Two photospheres)

Putting a polarimeter on the NS surface…





Degree of linear Polarization at emission point

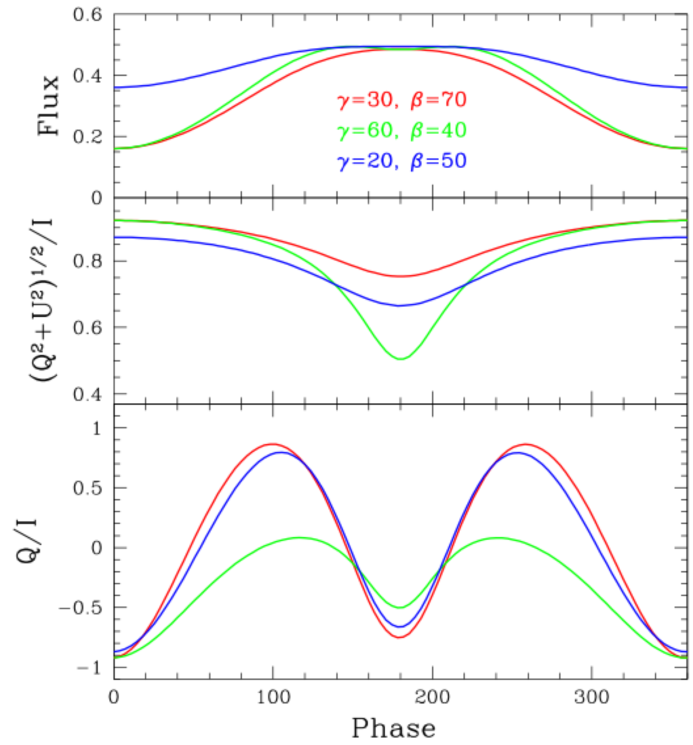

Observer
Ω
Z
γ
β
B
X
Y

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



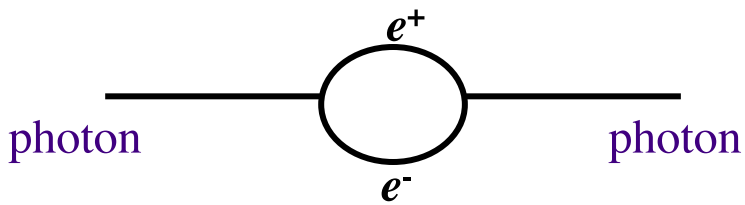
$$\frac{(Q^2+U^2)^{1/2}}{I} = \text{Linear Polarization Fraction}$$

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

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: $$\boldsymbol{\varepsilon} = \mathbf{I} + \Delta\boldsymbol{\varepsilon}_{\rm vac}$$

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

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

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

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

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

Vacuum resonance:

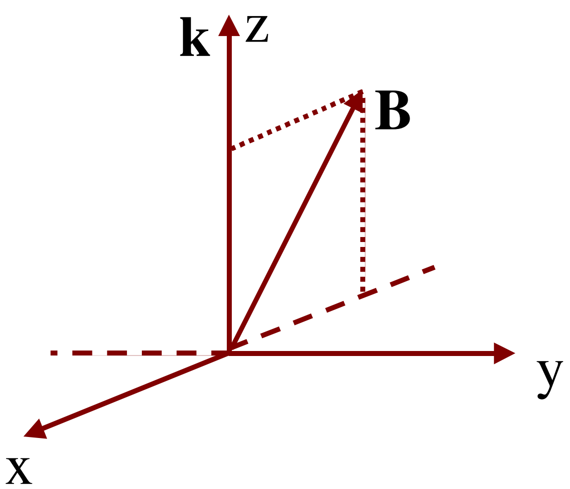
$$\Delta\boldsymbol{\varepsilon}^{(\mathrm{plasma})} + \Delta\boldsymbol{\varepsilon}^{(\mathrm{vac})} \sim 0$$

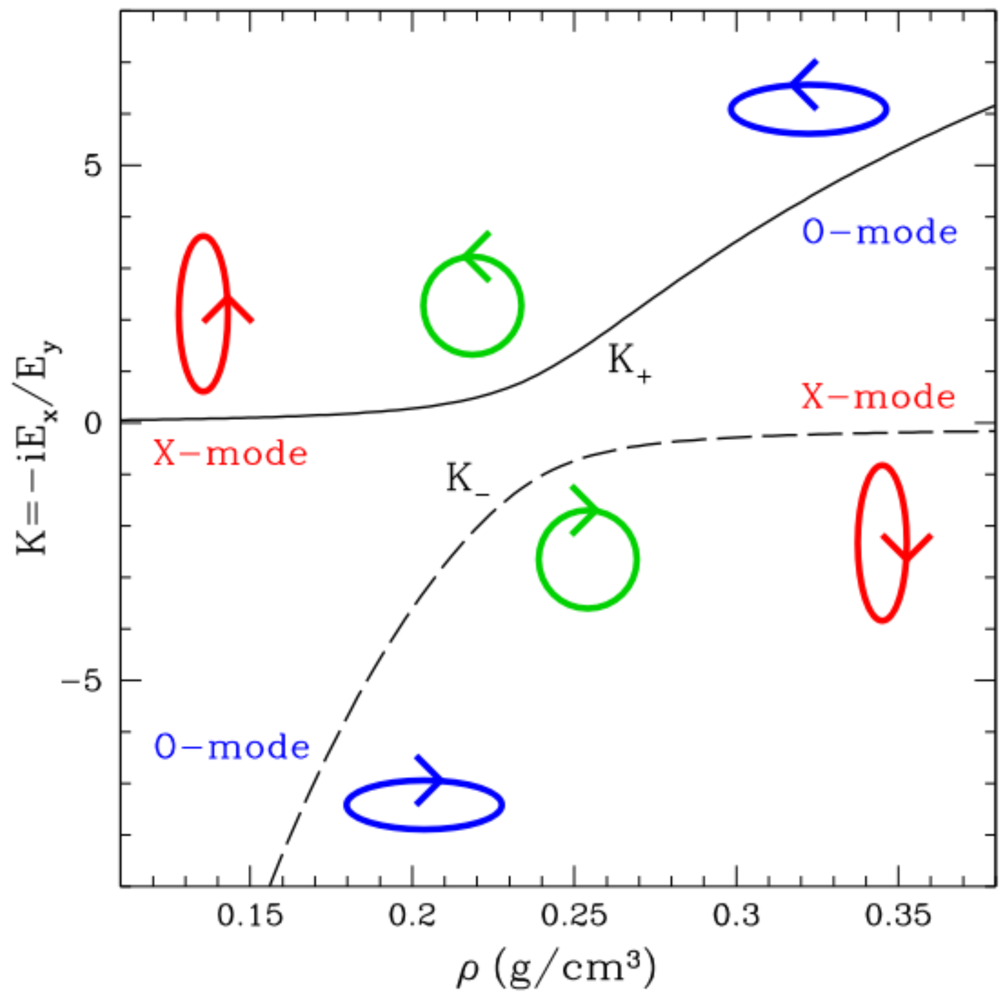
depends on $-(\omega_p/\omega)^2 \propto \rho/E^2$

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

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

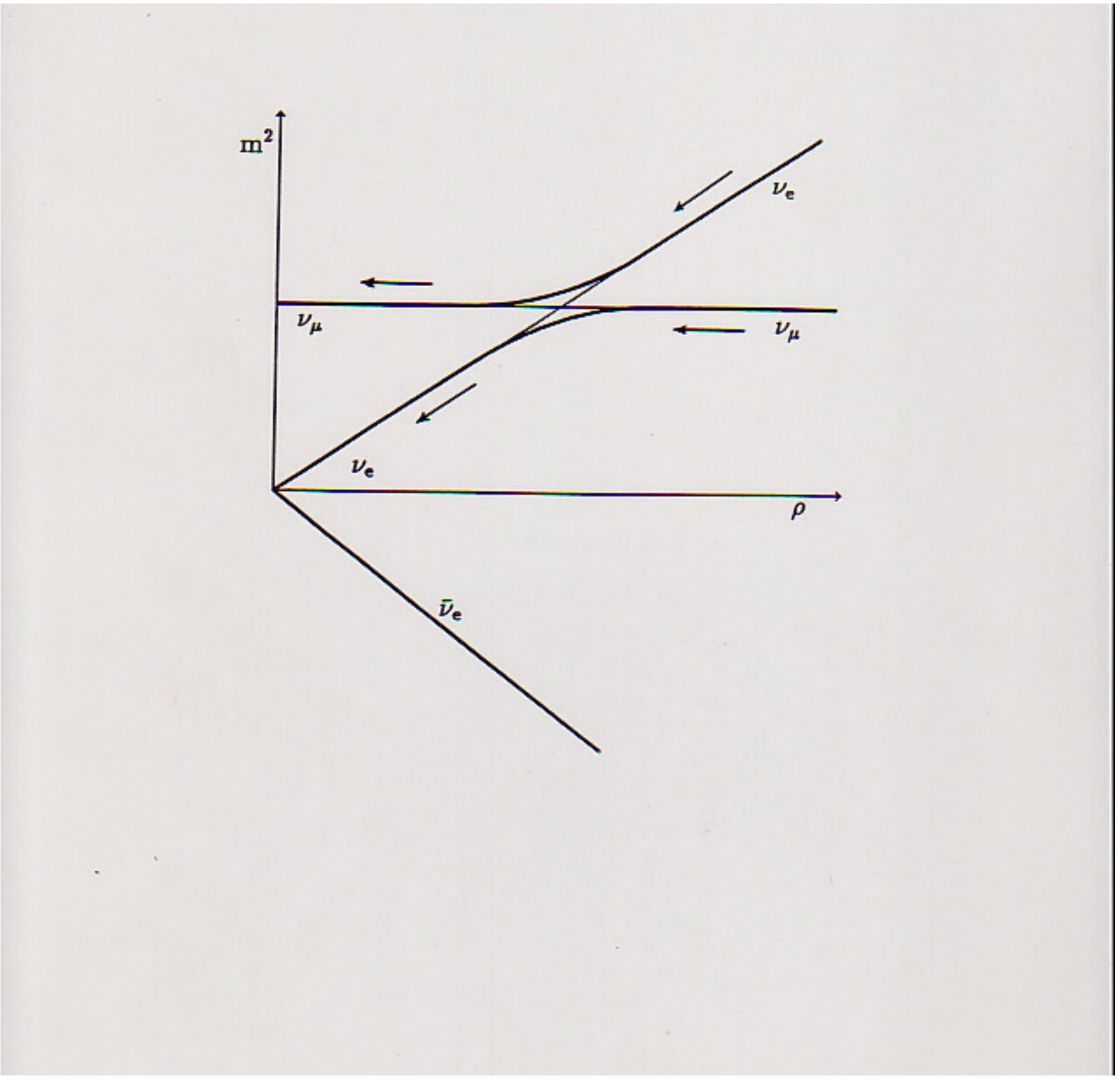
Polarization of photon modes



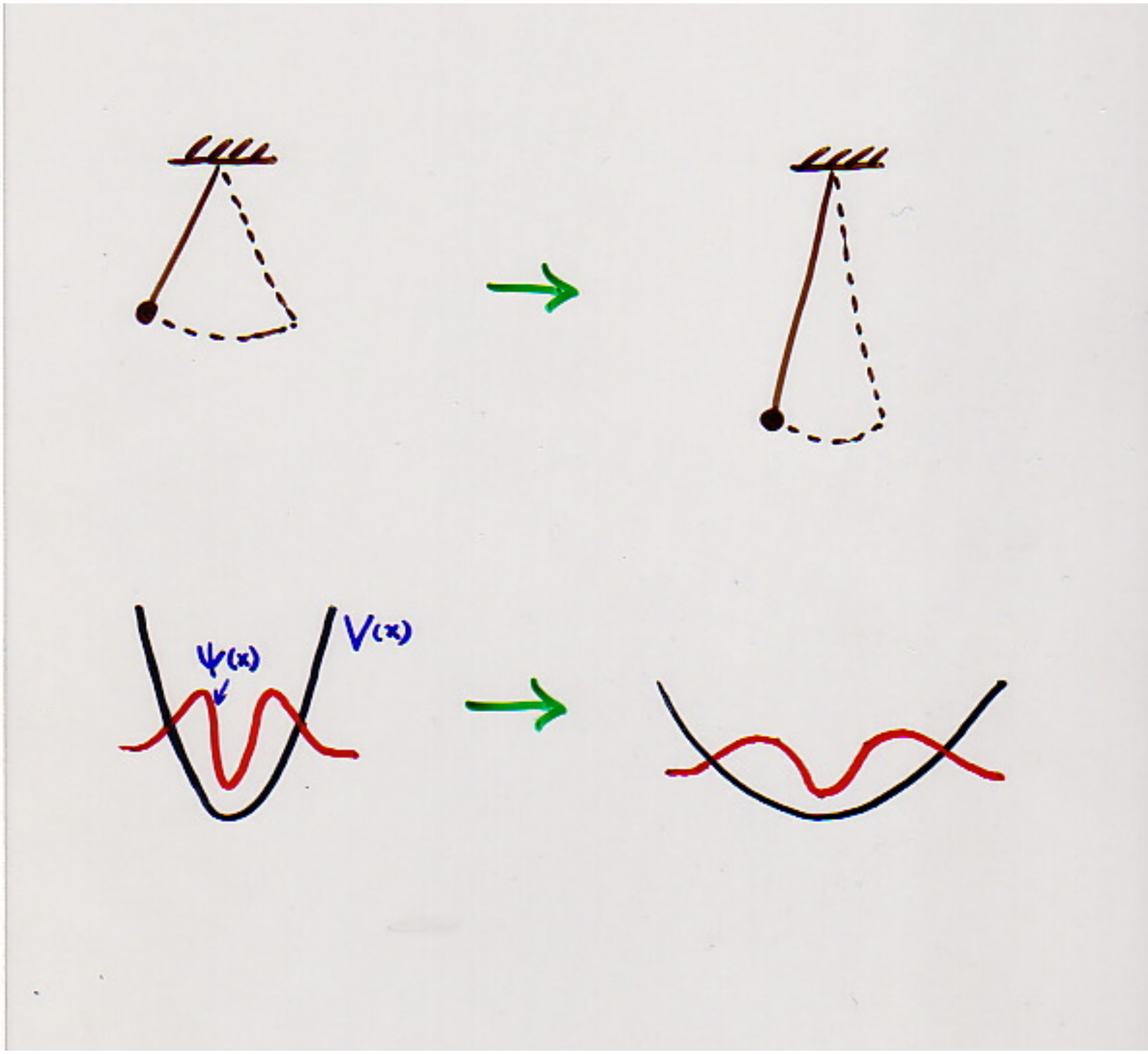


B=10^{13} G, E=5 keV, θ_B=45°

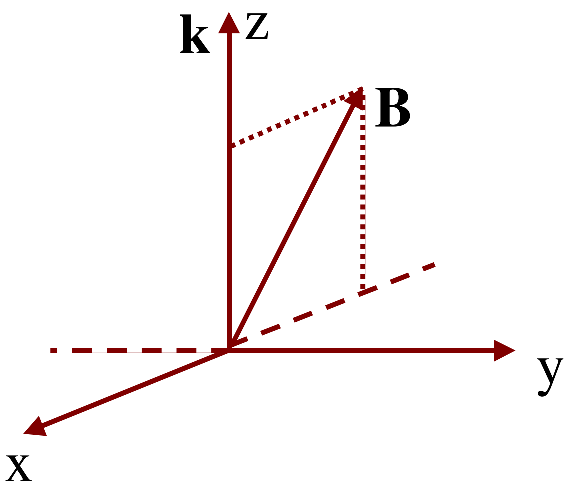
Mikheyev-Smirnov-Wolfenstein (MSW) Neutrino Oscillation

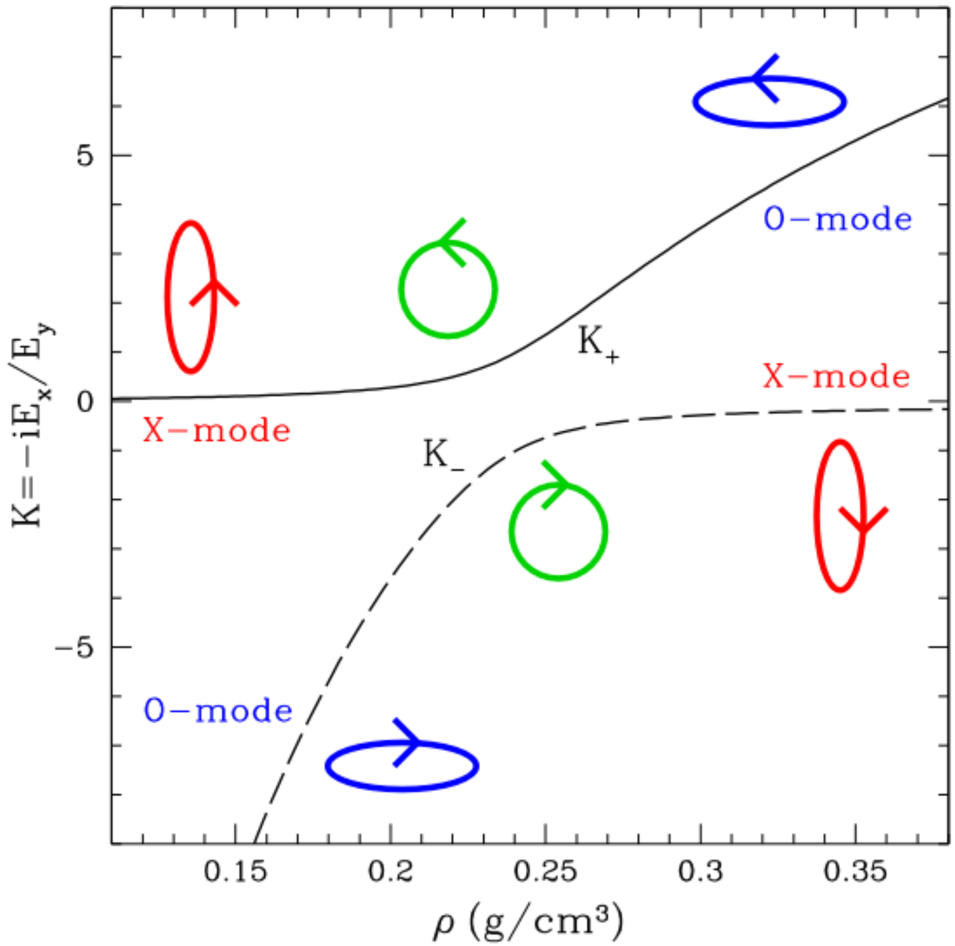


Adiabatic Evolution of a Quantum State



“Plasma+Vacuum” ==> Vacuum resonance



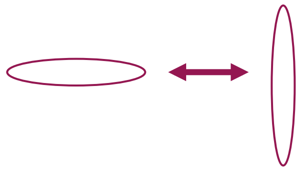


Adiabatic Condition:

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

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

Photons with E > 2 keV, mode conversion



Photons with E < 2 keV, no mode conversion

In general, nonadiabatic “jump” probability

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

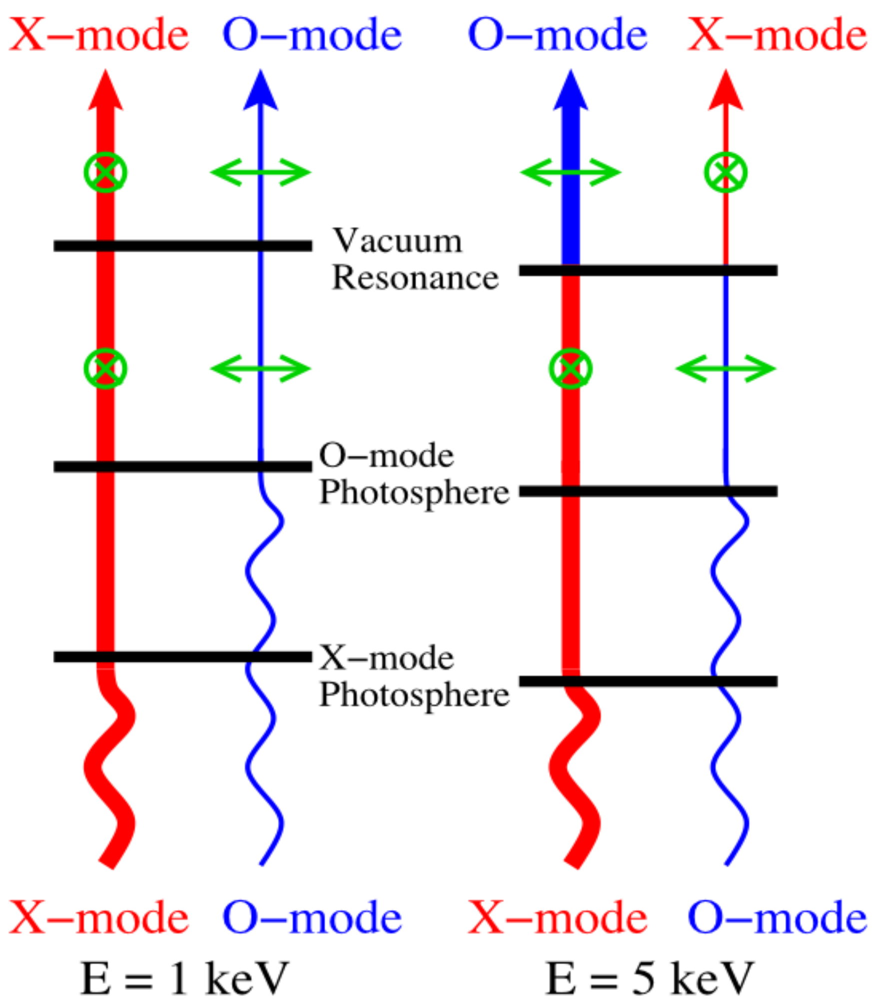
Recall

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

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

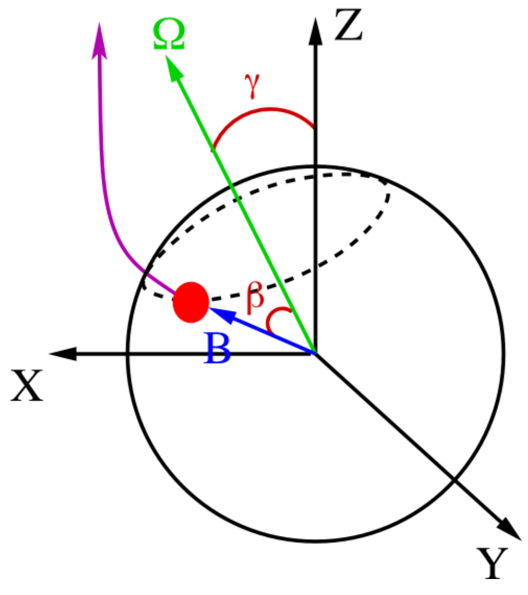
For B < $7\times10^{13}\,T_6^{-1/8}\,E_1^{-1/4}$ G:

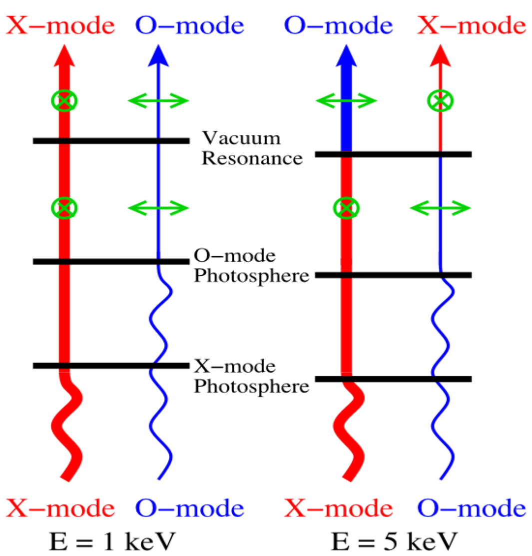
Vacuum resonance lies outside both photospheres

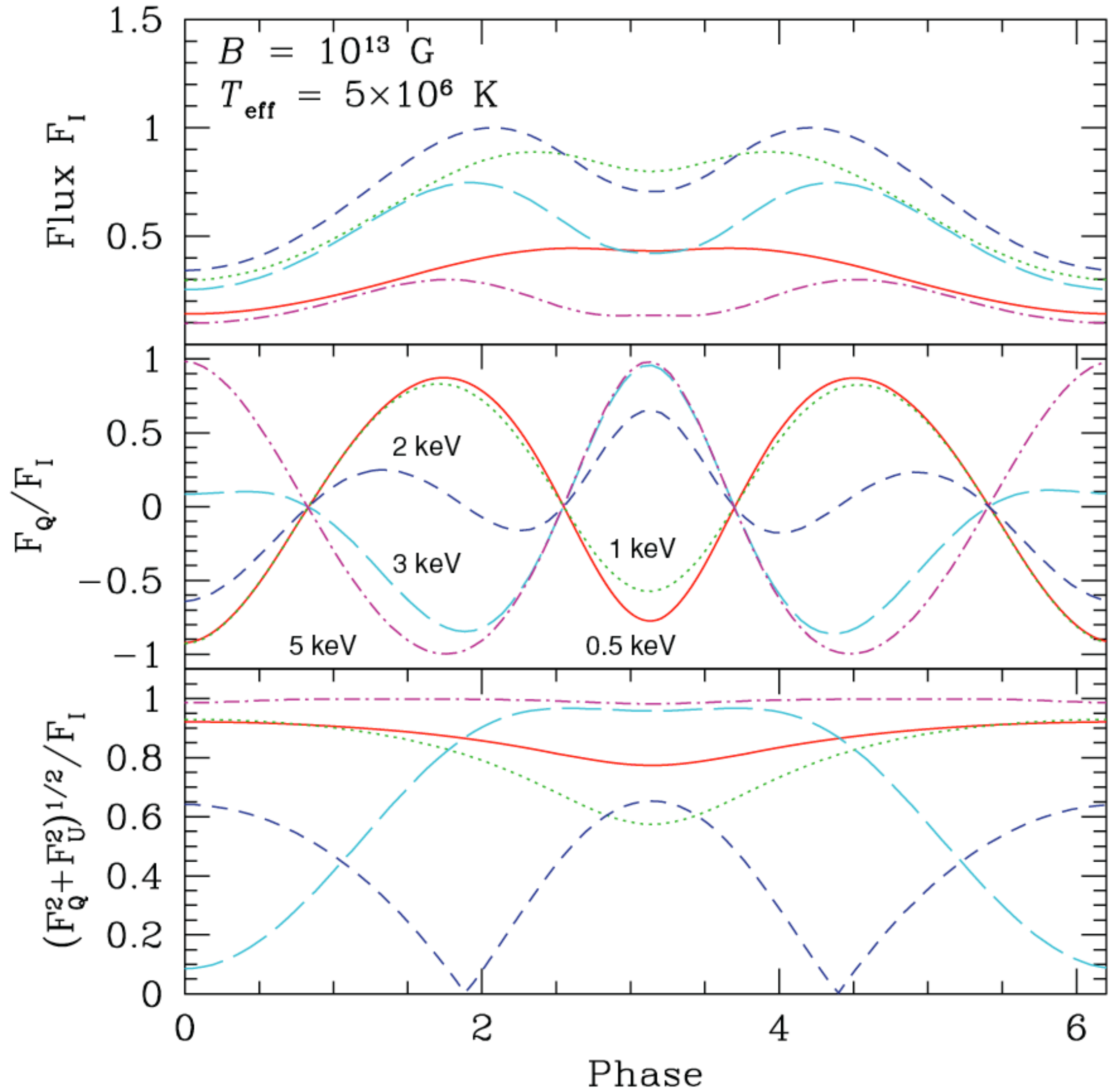


B=10^{13}G

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





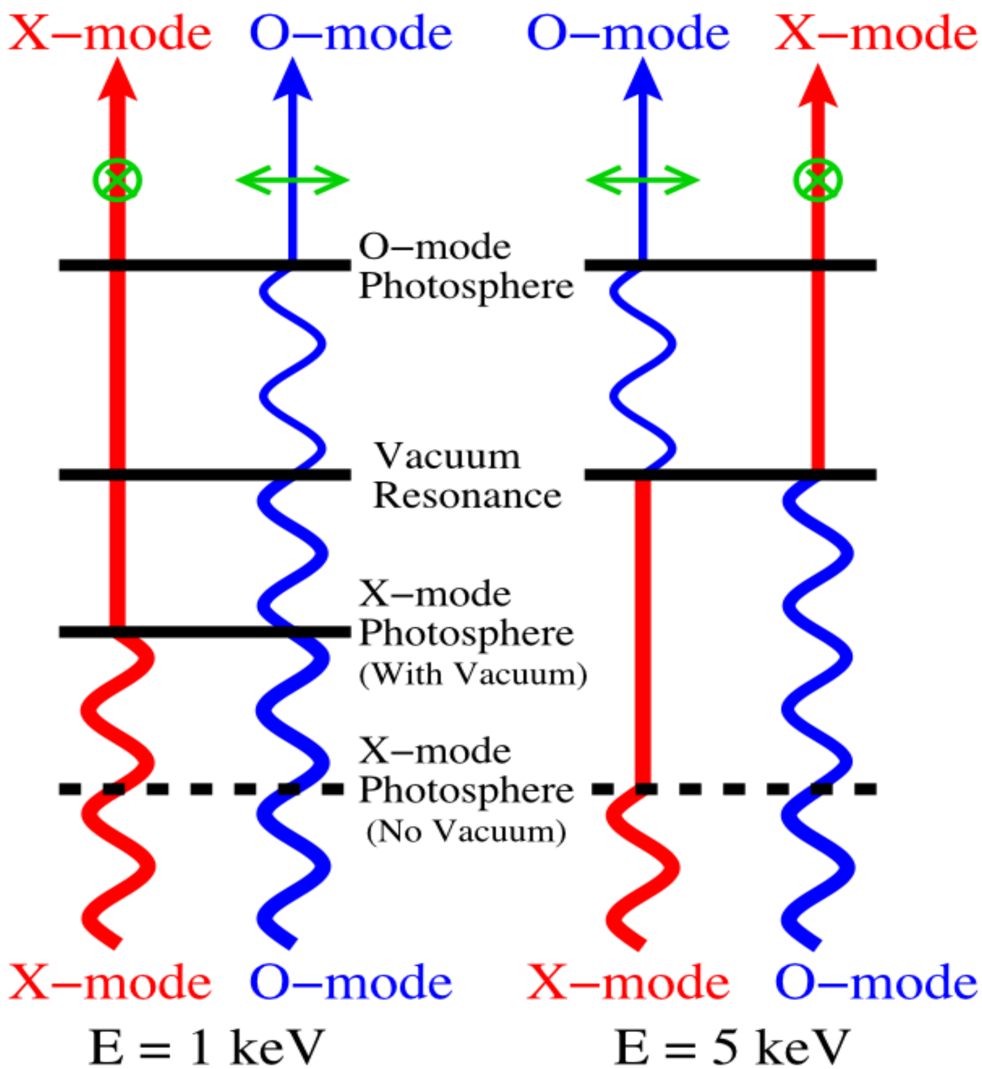


Van Adelsberg & DL 2006 (also DL & Ho 2003)

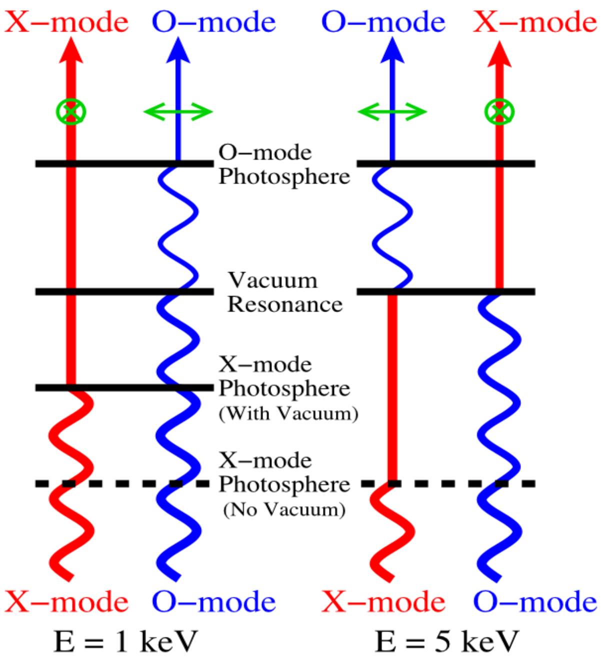
Plane of linear polarization at <1 keV is perpendicular to that at >4 keV.

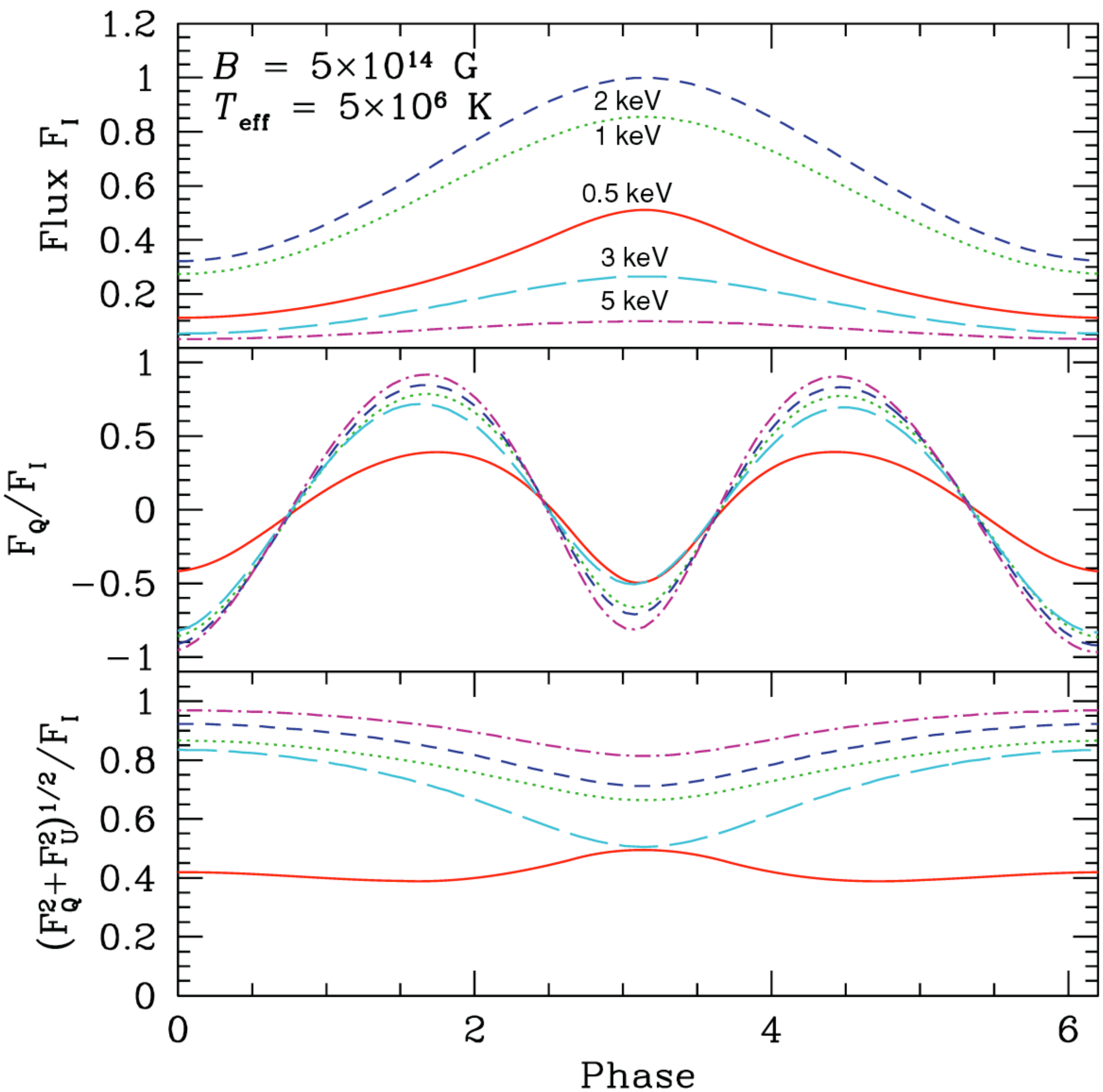
For B > $7\times10^{13}\, T_6^{-1/8} E_1^{-1/4}$ G:

Vacuum resonance lies between the two photospheres



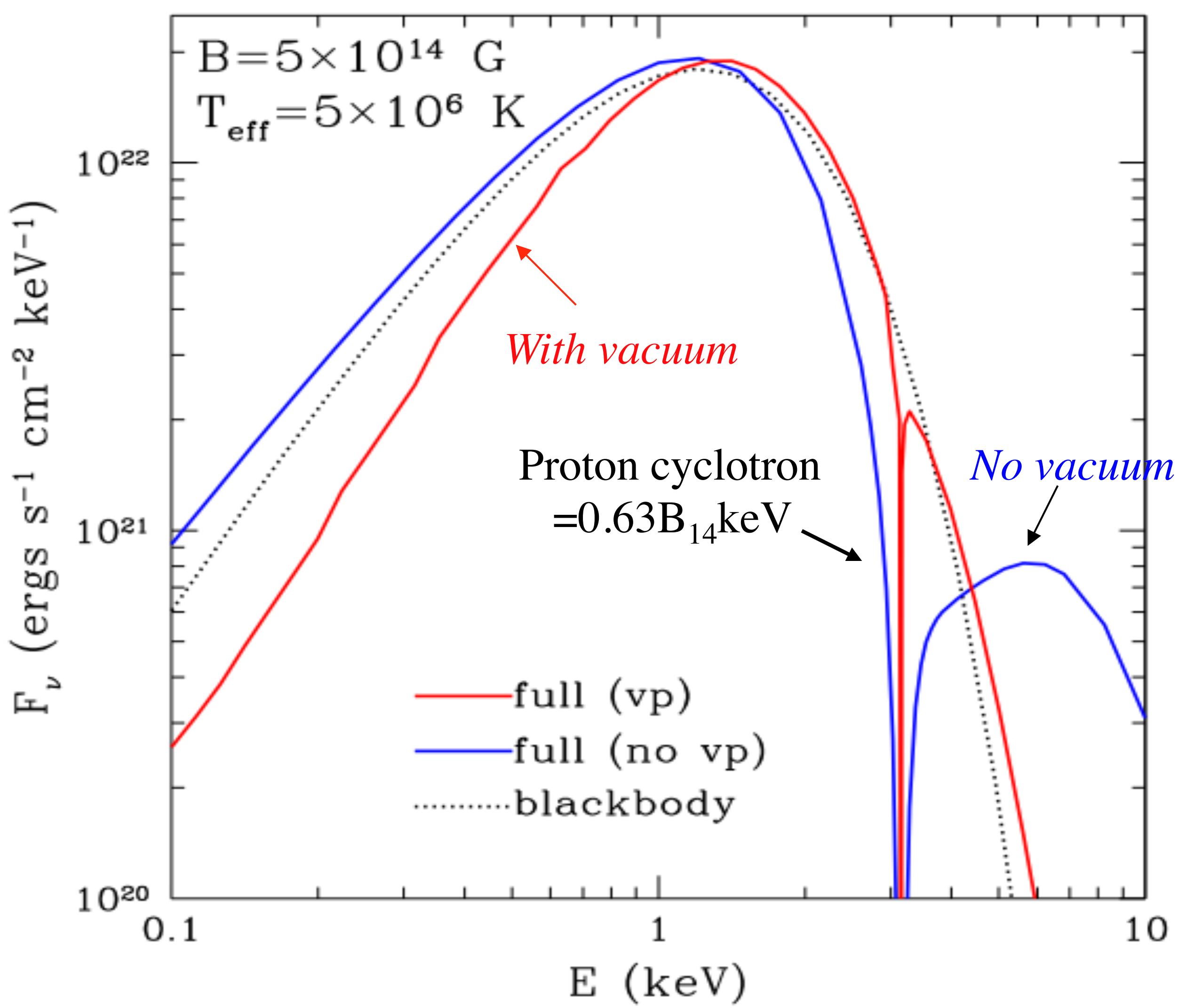
B=5×10^{14}G Model





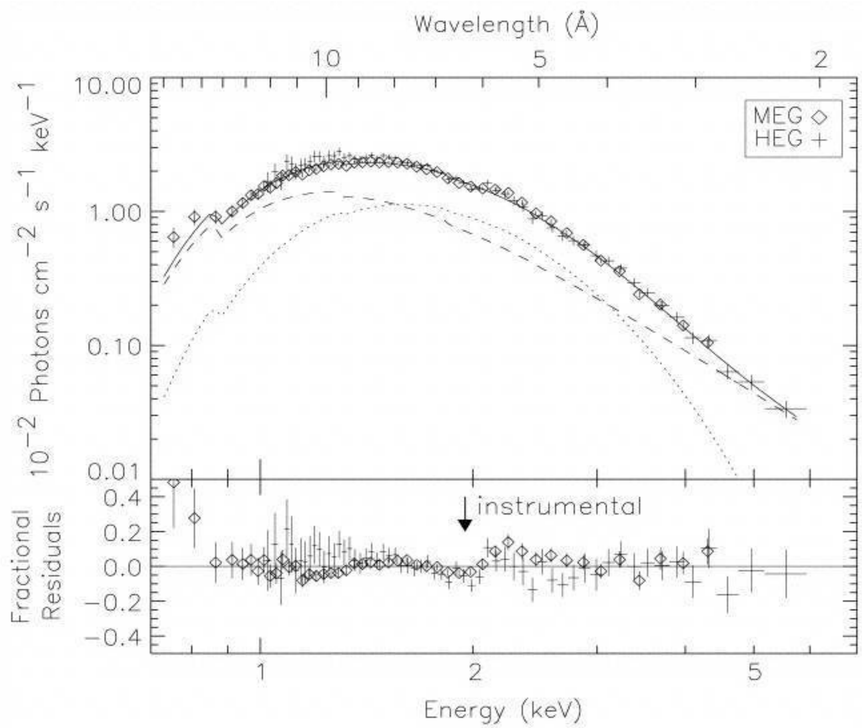
Plane of linear polarization at different E coincide.

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



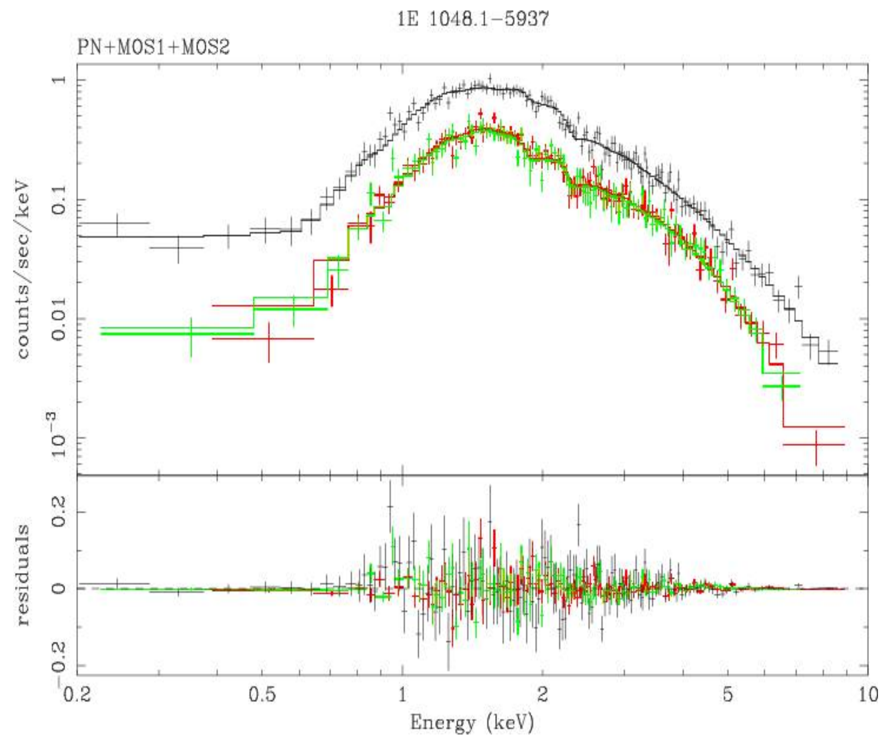
Two Examples of AXP Spectra

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

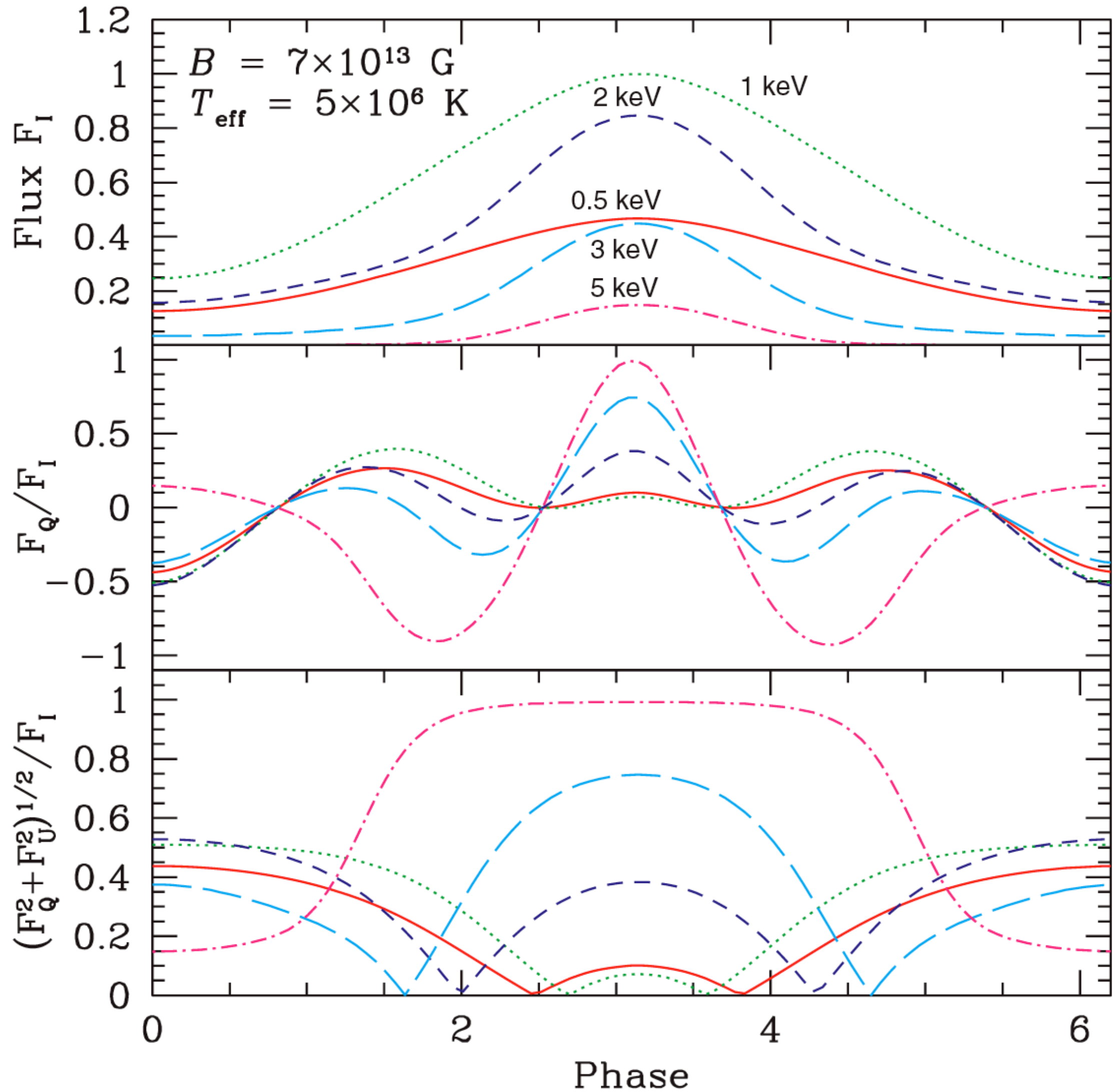


Tiengo et al.2002

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

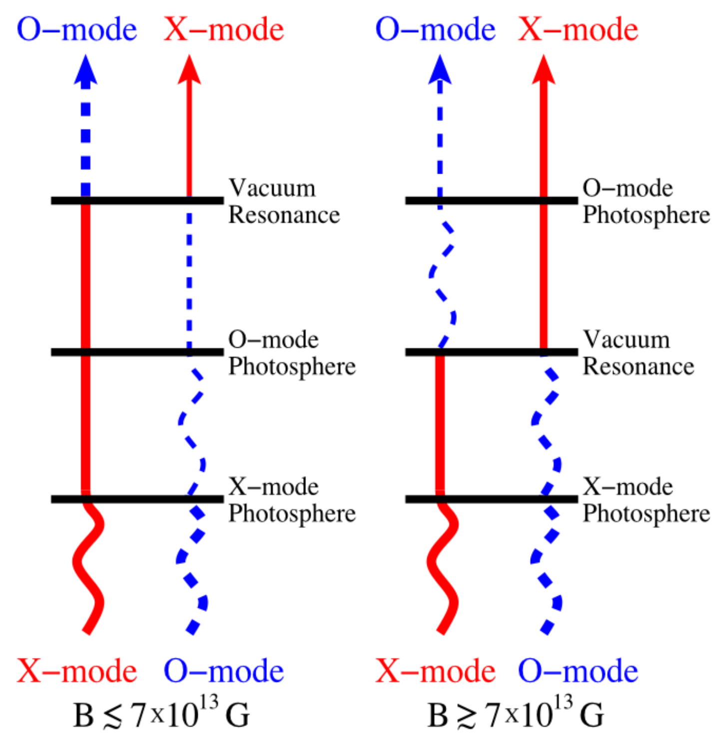
Recapitulation: **Effect of Vacuum Resonance on Surface Emission**

For B<7×10^{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: observations of magnetars)
- Polarization signals affected by QED:
  plane of linear polarization coincides for different E



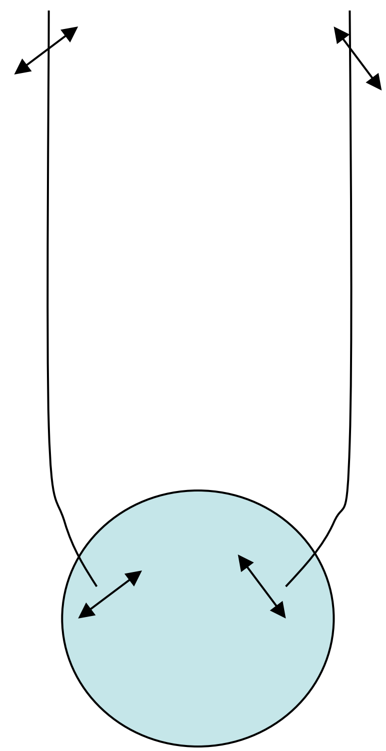
QED Effect in Magnetospheres (=Magnetized Vacuum)
Propagation of Polarized Radiation

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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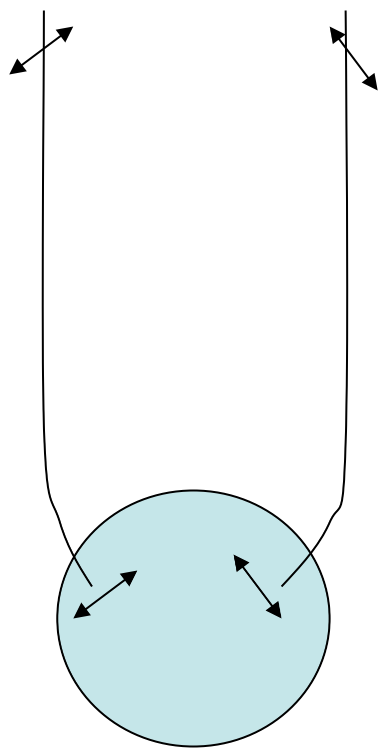
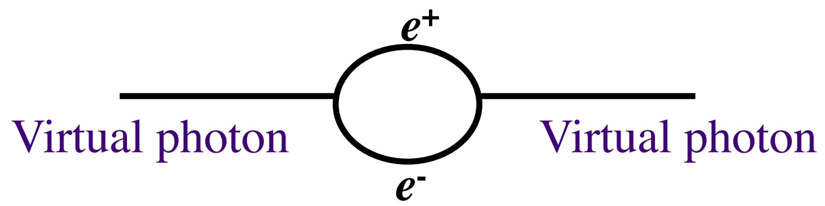


This is incorrect!
(Heyl & Shaviv 2002; Lai & Ho 2003…)

Vacuum Polarization in Strong B



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

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

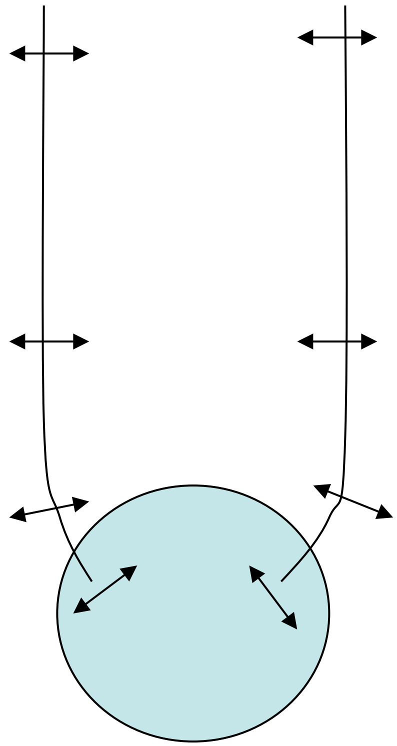
Two photon modes in magnetized vacuum:

Ordinary mode (//)

Extraordinary mode (⊥)

$n_1 \neq n_2$

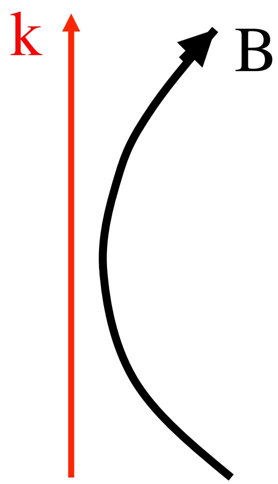
Propagation of Polarization from NS Surface to Observer Through Magnetized Vacuum

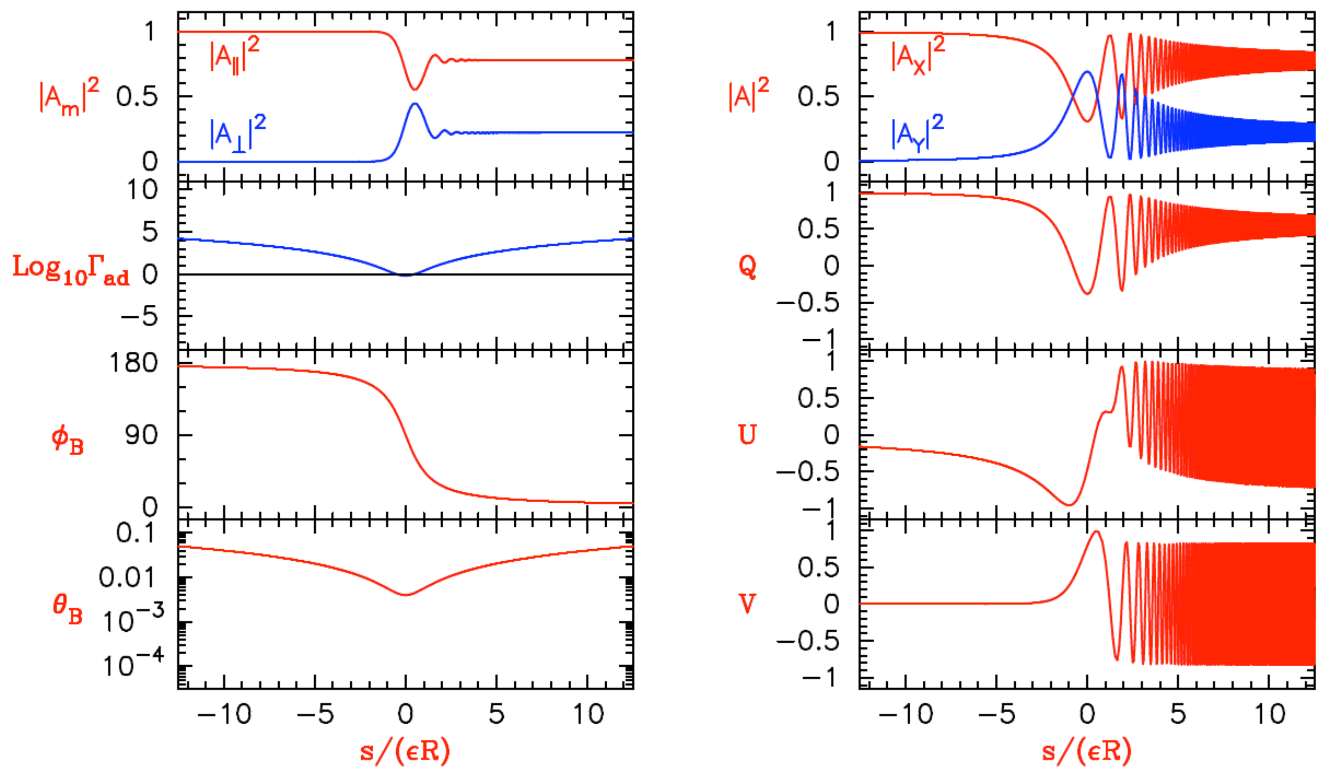


polarization limiting radius >> R

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

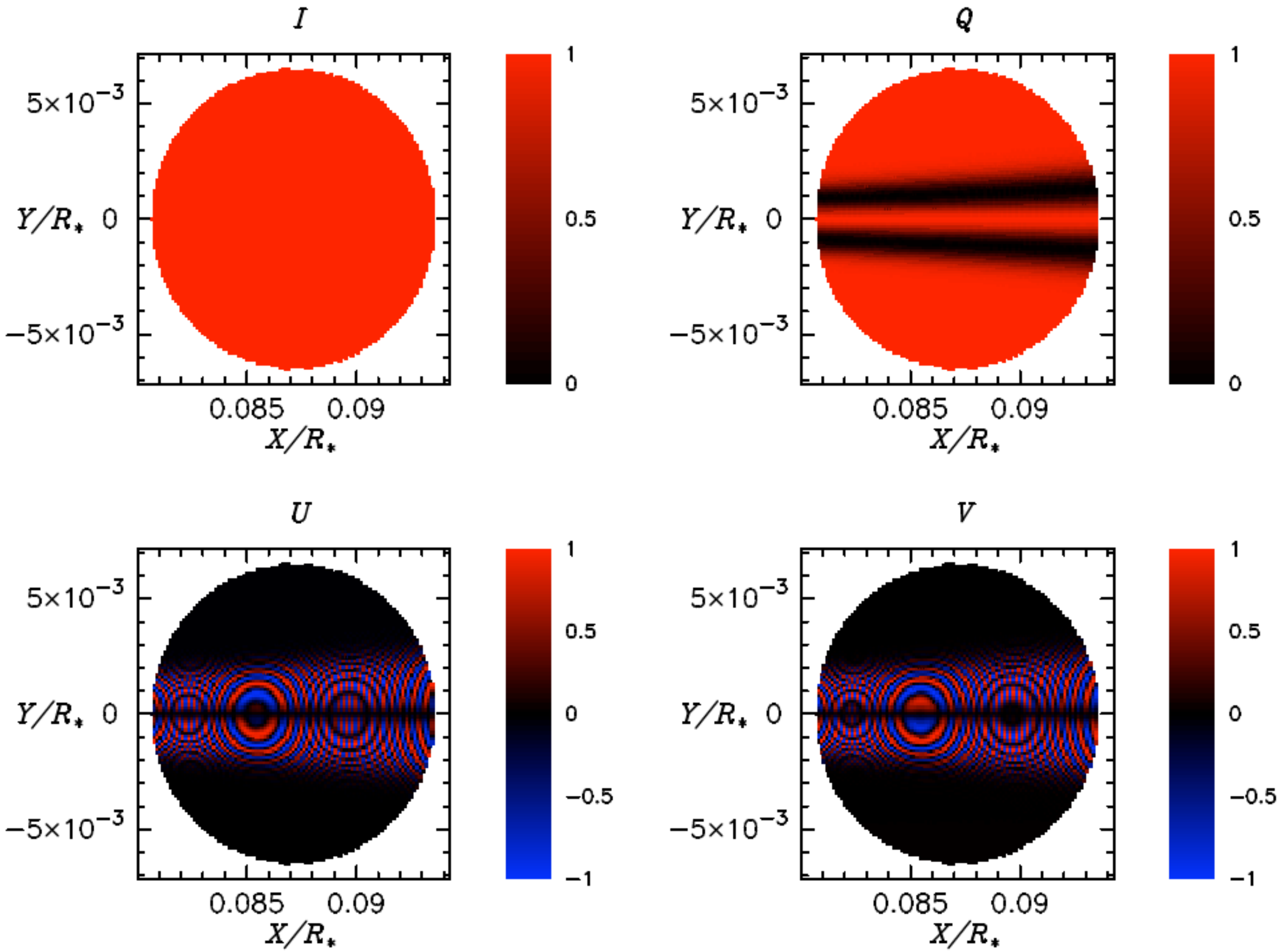
But… Propagation through quasi-tangential region





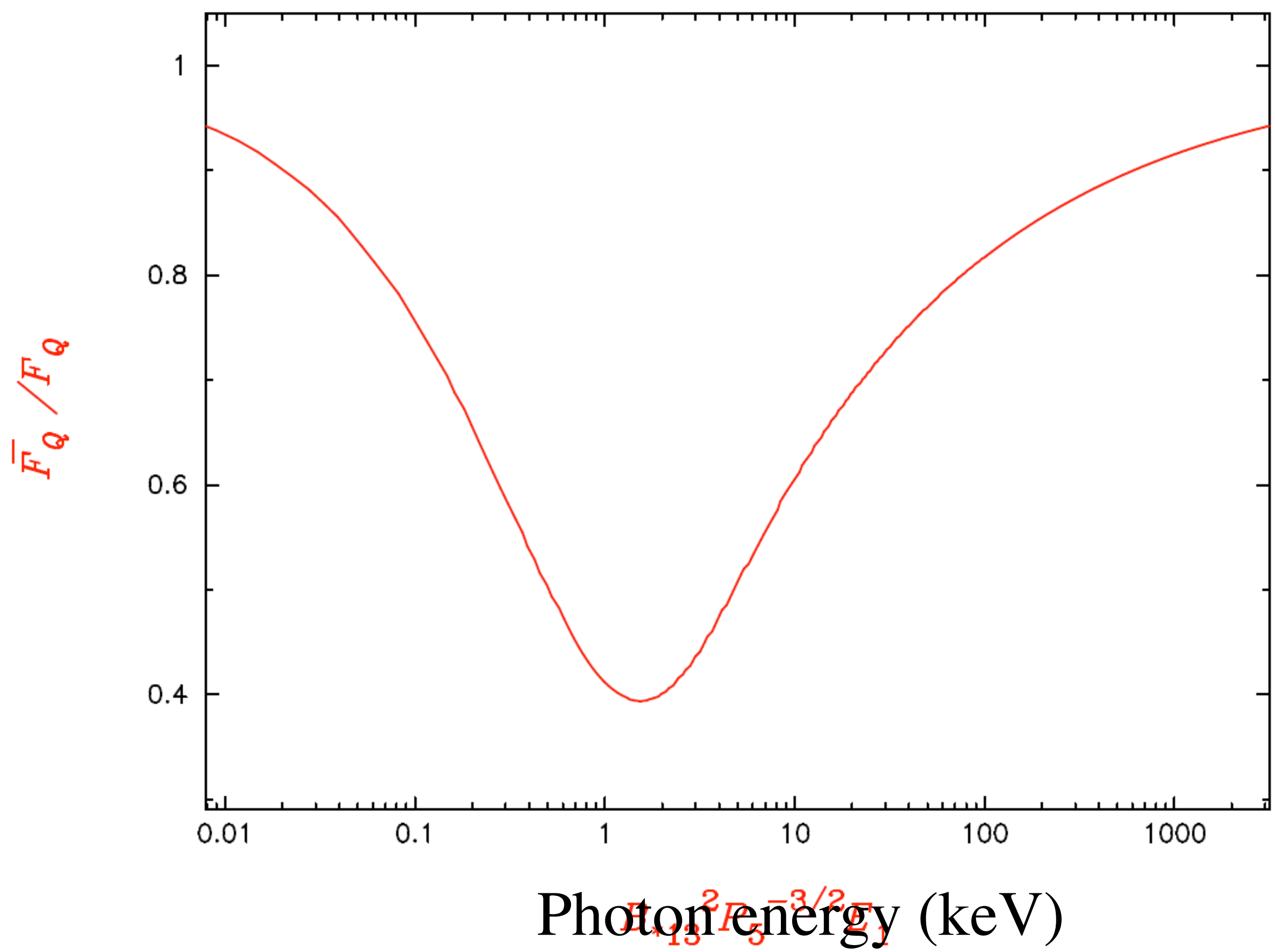
Wang & DL 2009

Polarization map of polar cap (hot spot)



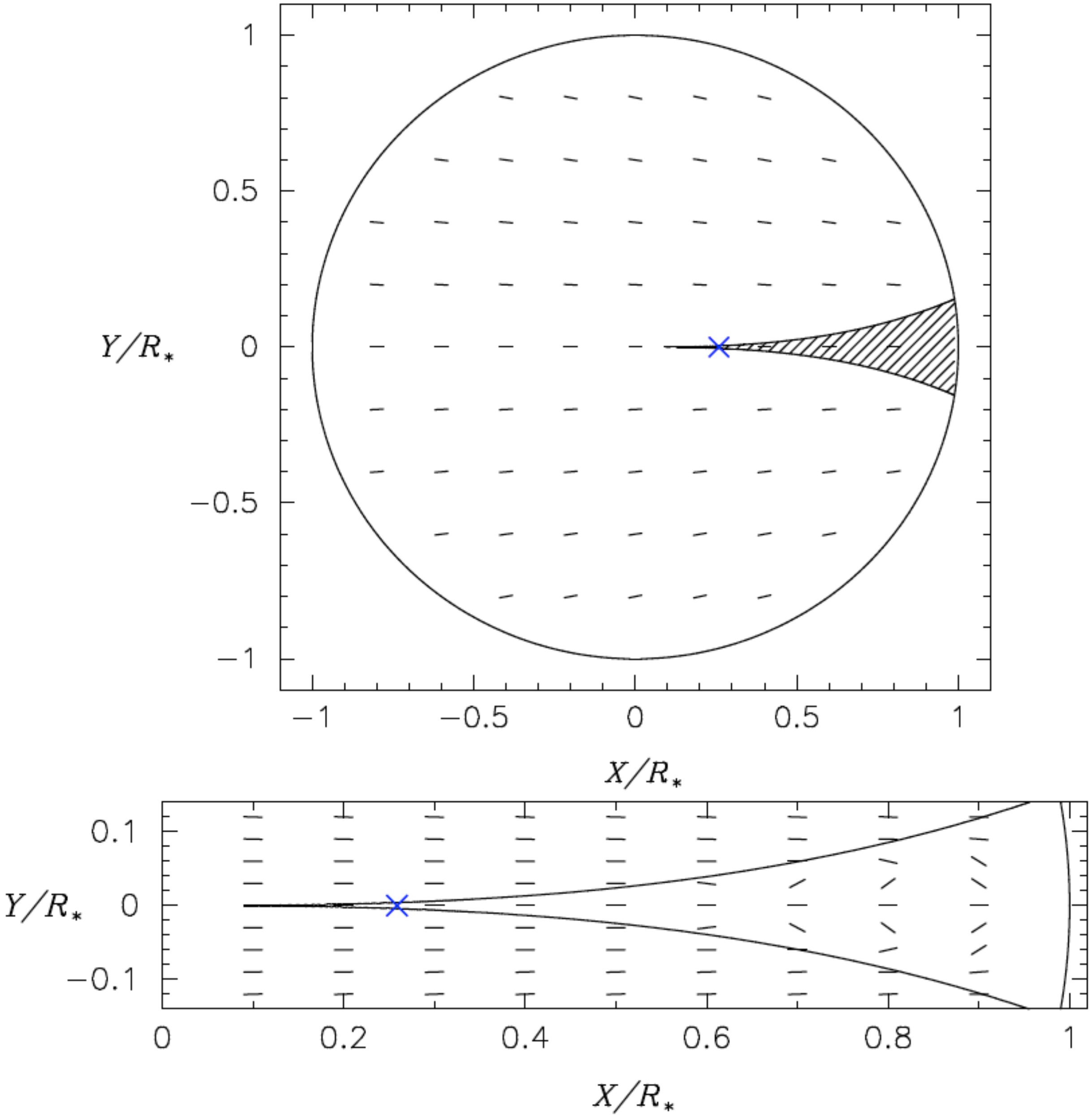
Wang & DL 2009

Reduction of linear polarization due to quasi-tangential propagation



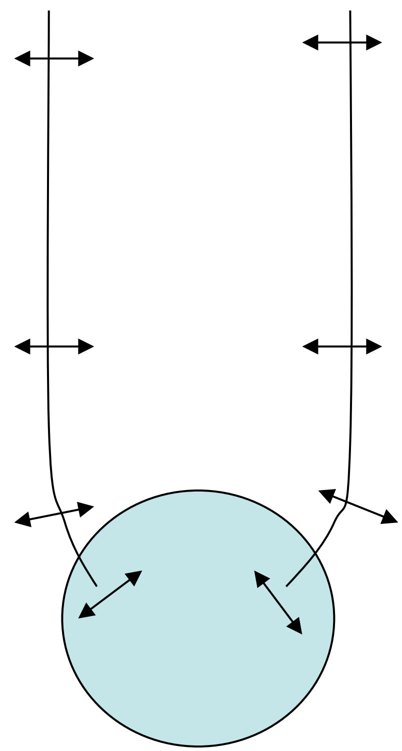
Wang & DL 2009

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.

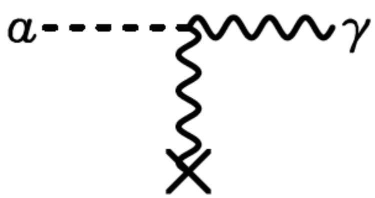
Probing Axions with Magnetic Neutron Stars

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

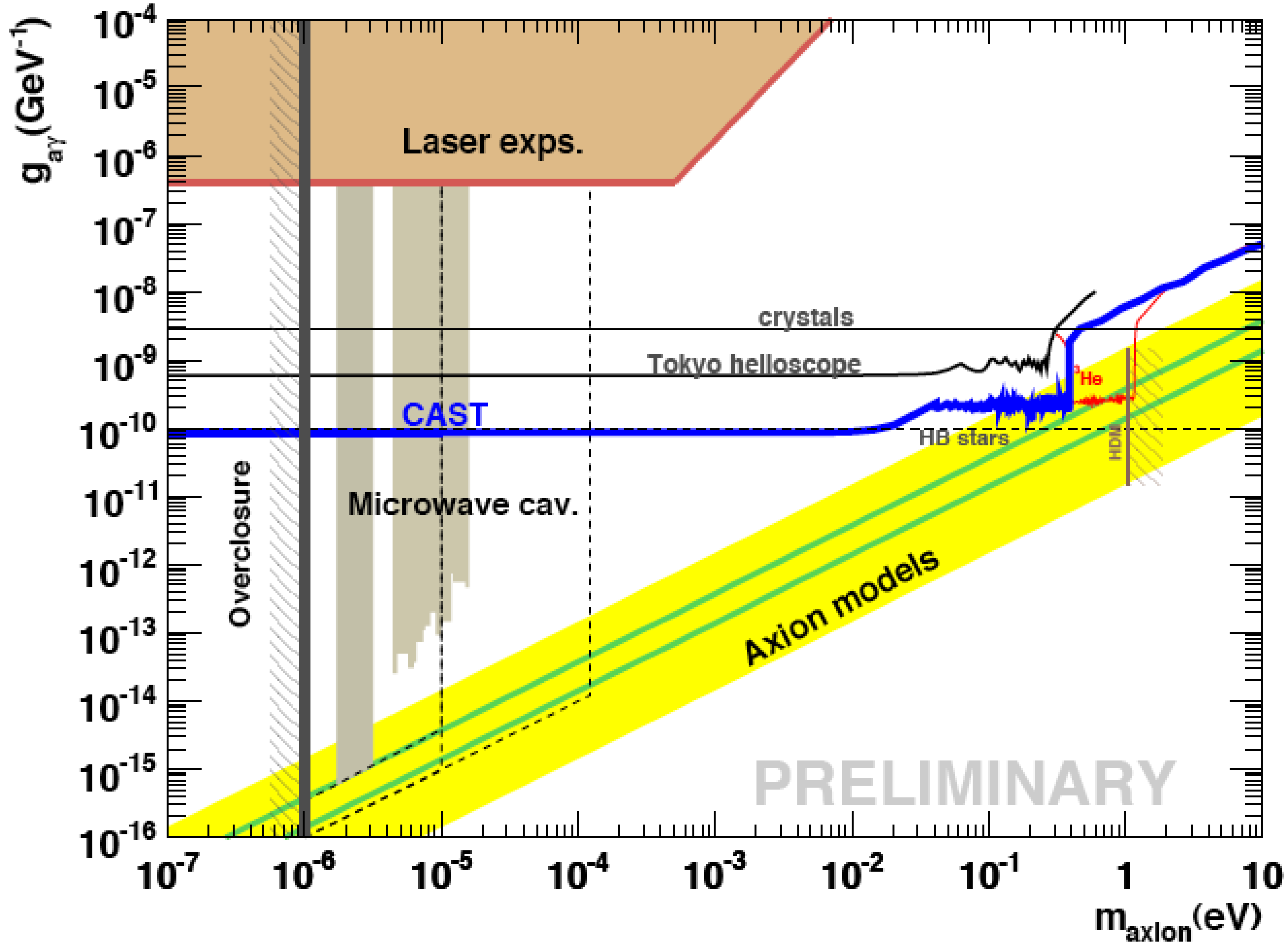
Can be produced or detected through the **Primakoff process:**

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



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

Current constraints on axion mass and coupling parameter



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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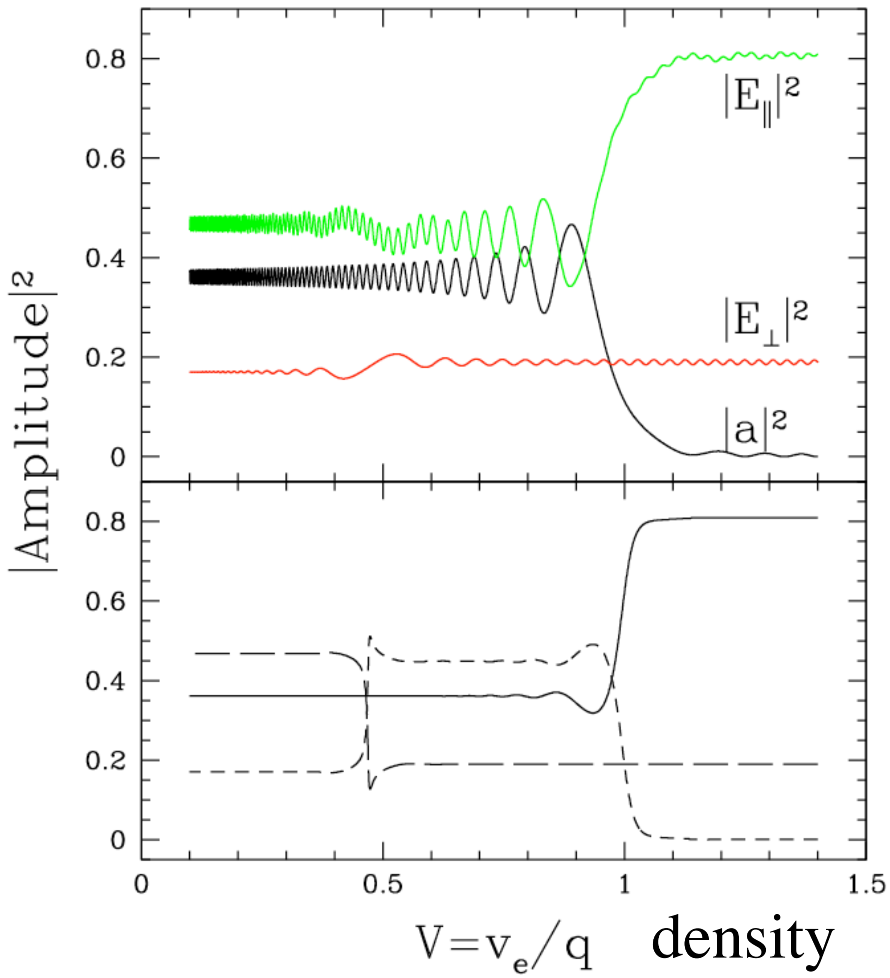

DL & Heyl 2007

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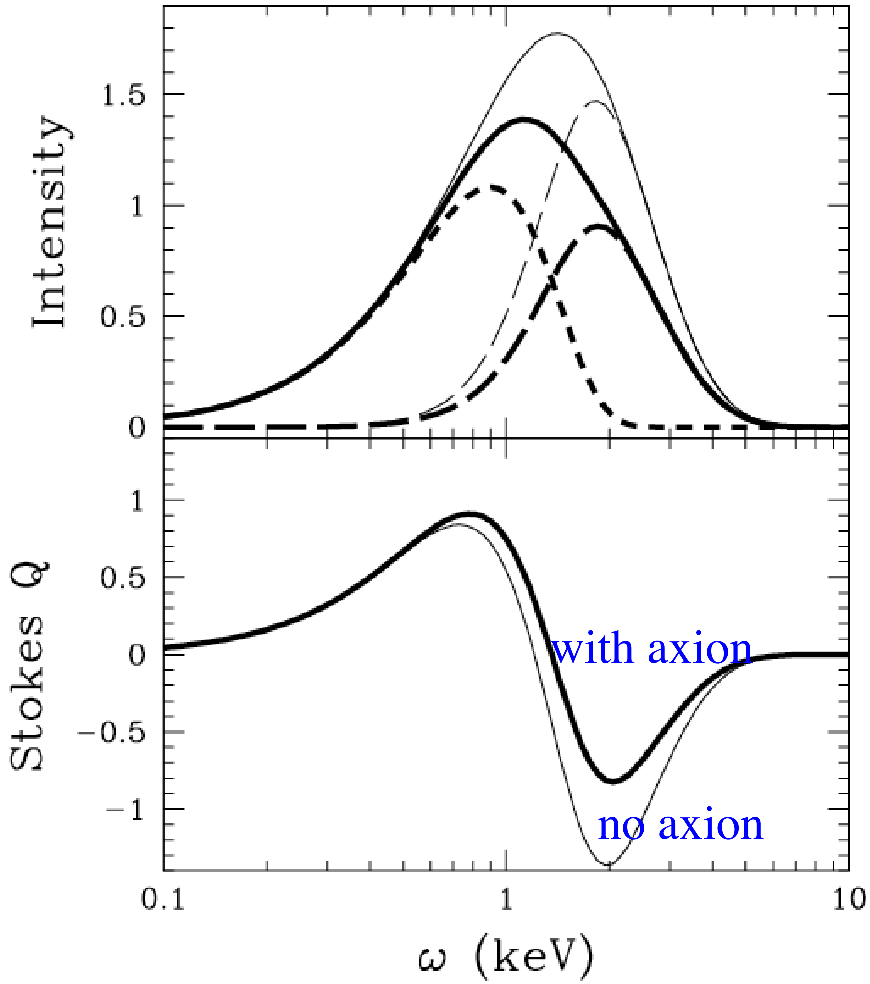

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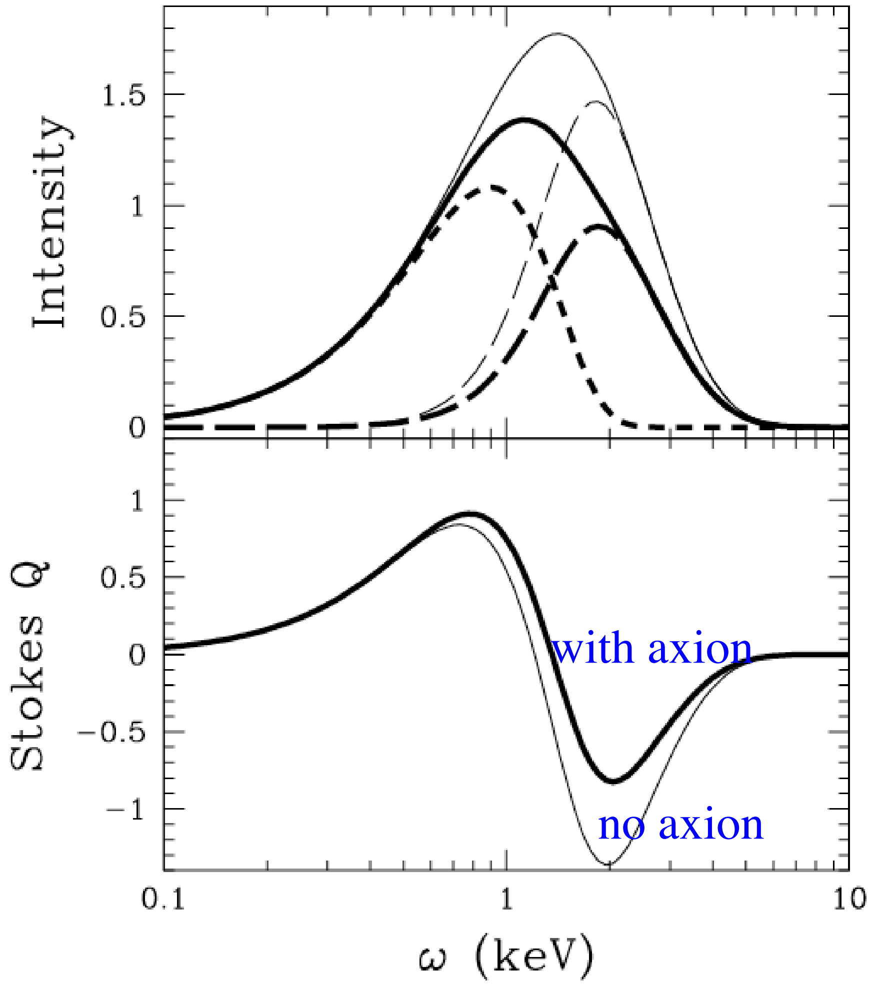


Can in principle probe axions with parameters inaccessible by other experiments/constraints.

Unclear if we can separate out astrophysical uncertainty of the sources.

(cf. Other indirect search of WIMPs)

Thank you!

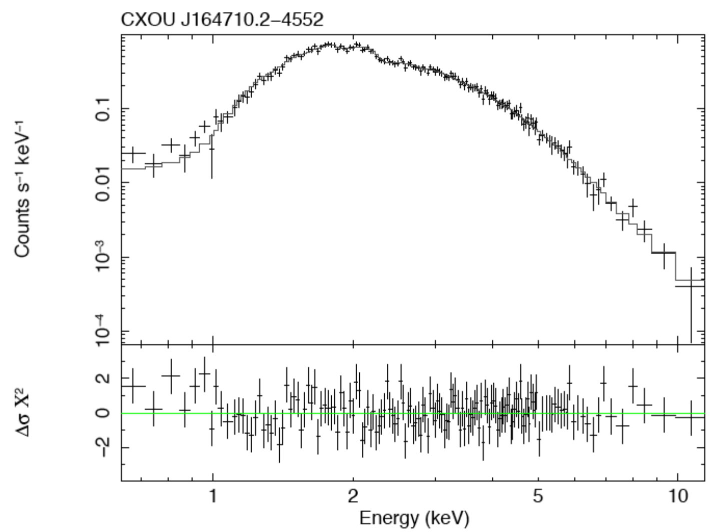
Power-law emission of magnetars

• 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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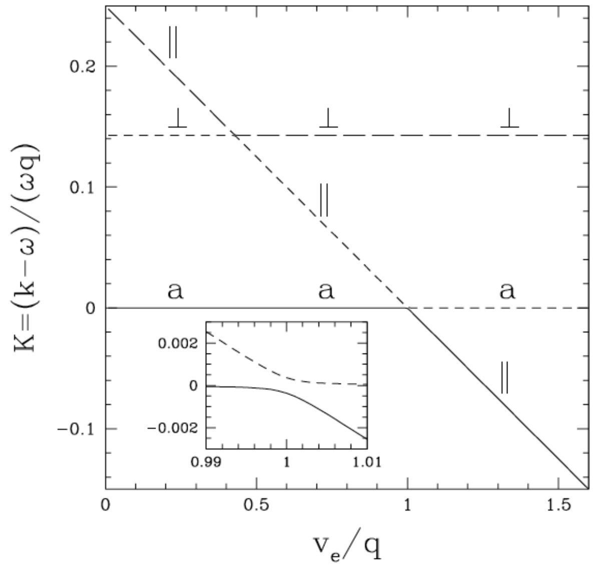

===> modify radiation spectra and polarization signals

DL & Heyl 2007