Magnetized compact sources: emission mechanisms and future polarization tests

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“Weak” and “strong” magnetic fields

$$\hbar \frac{eB}{m_e c} \sim 1 \left(\frac{B}{10^{11}\ \mathrm{G}} \right) \ \mathrm{keV}$$

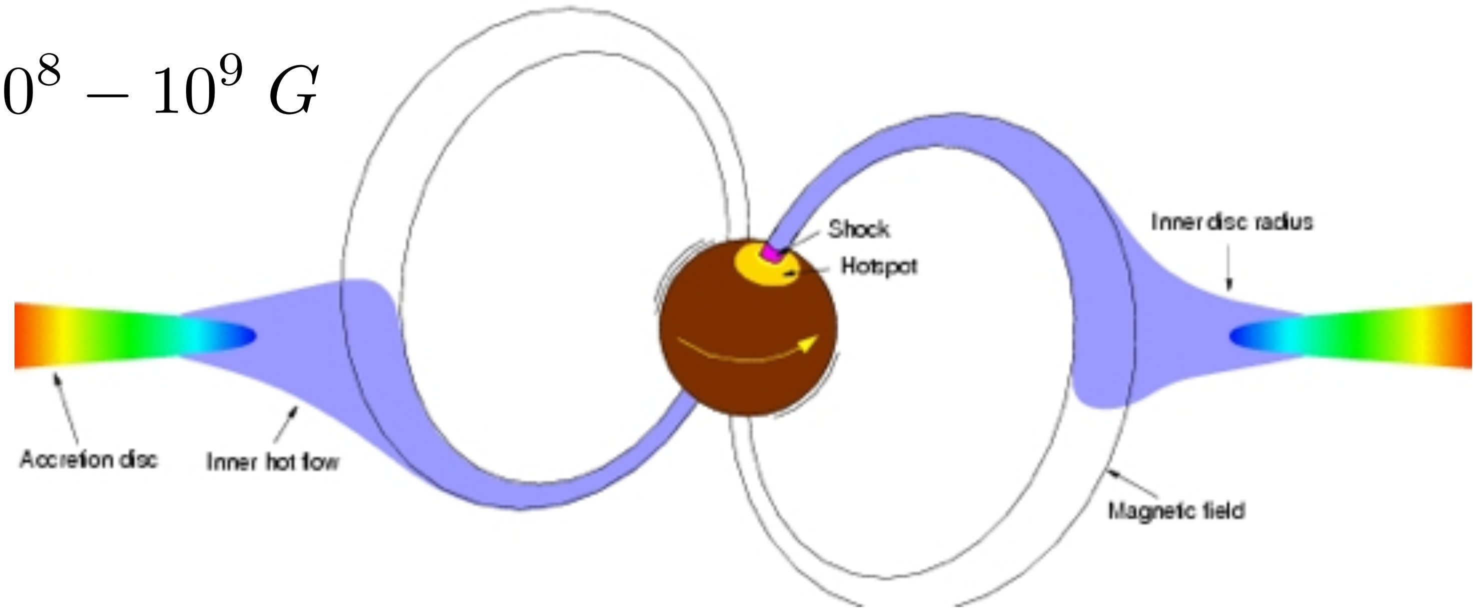
$$B < 10^{11}\mathrm{G} :$$

– weakly affects X-ray emission by non-relativistic particles; then Compton scattering is most important for polarization.

local angular distribution of radiation sets polarization

Accreting millisecond pulsars

$B \sim 10^8 - 10^9 \; G$

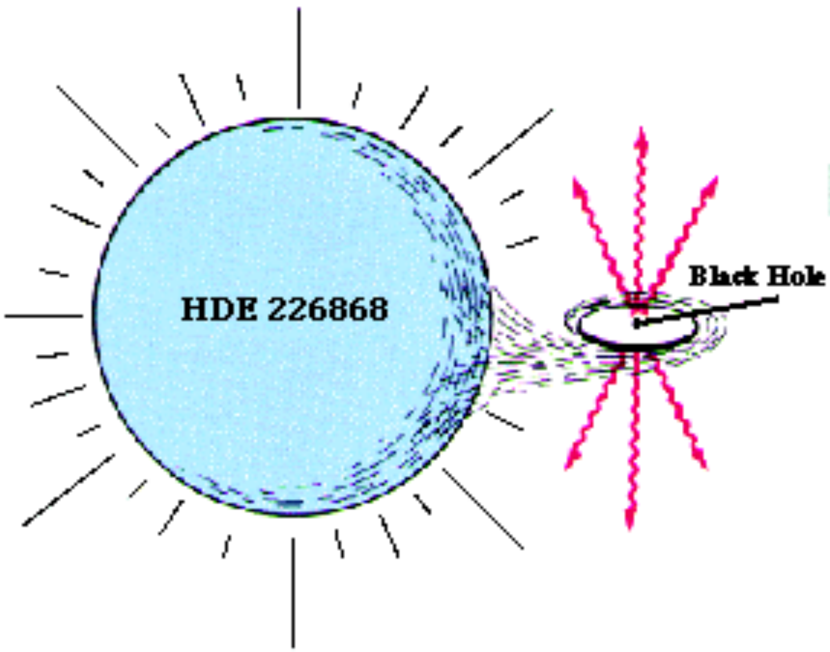


hot spot: "slab" (rather than column)

nuclear bursts: Chandrasekhar $\Pi_{\rm max} \approx 12\%$

accretion shock: Comptonization

Accretion disks in X-ray binaries

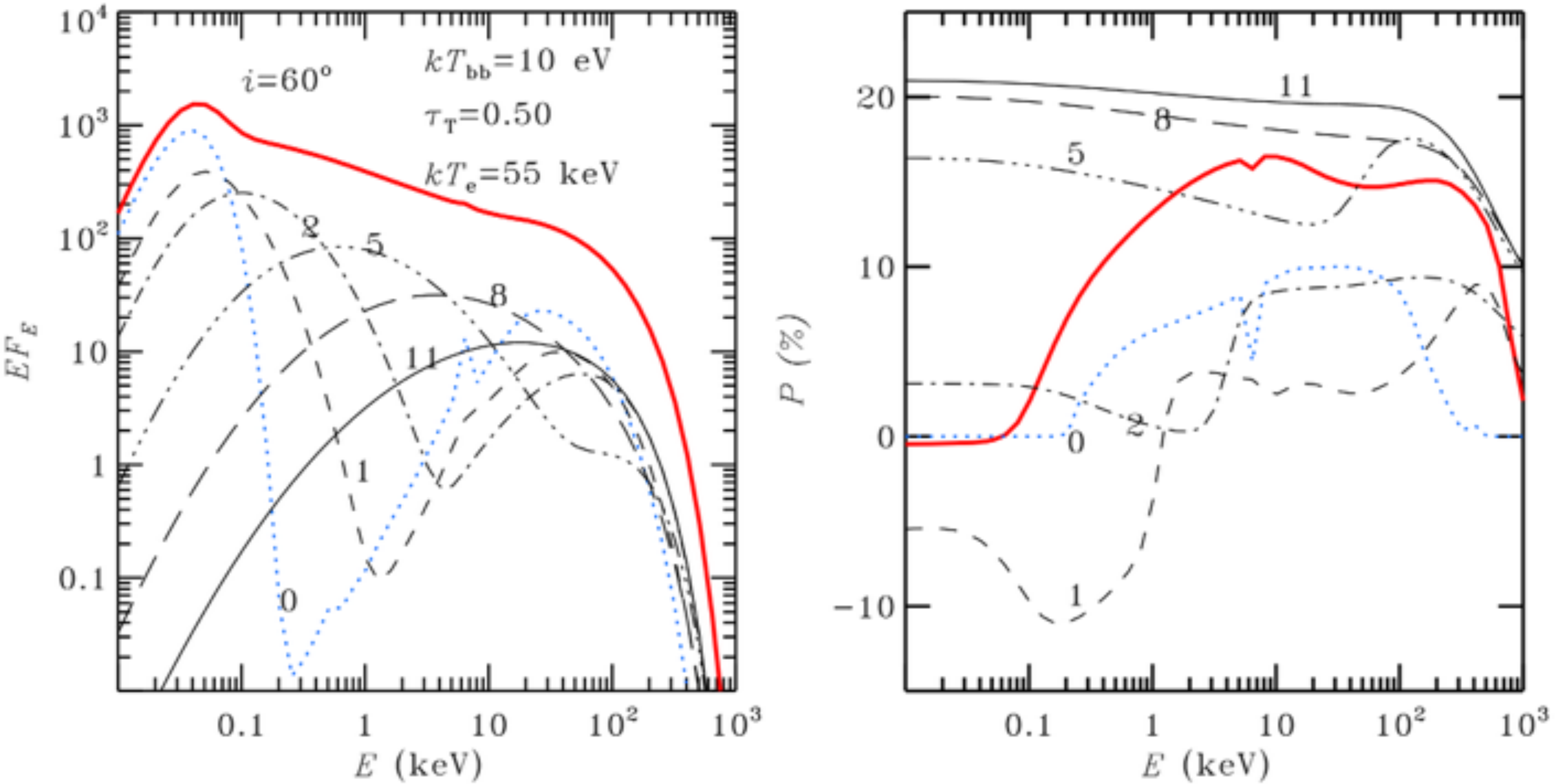


optically thick disk:
Chandrasekhar polarization
12% at 90 degrees

corona: optical depth ~1
temperature ~100 keV

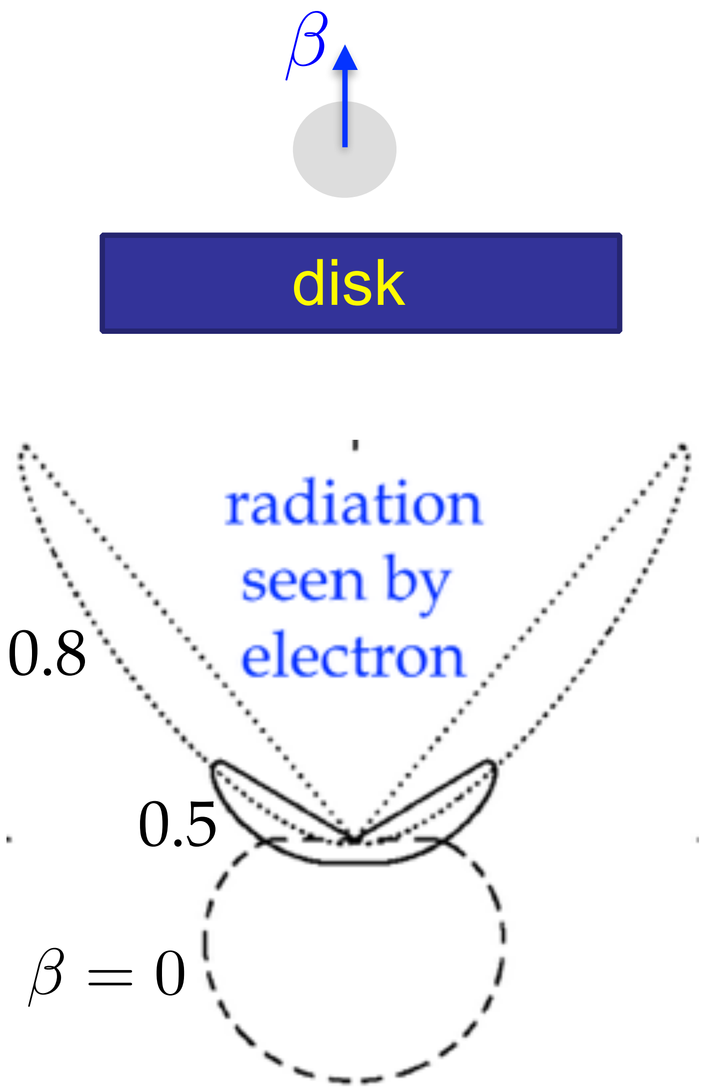
simplest example:
slab geometry

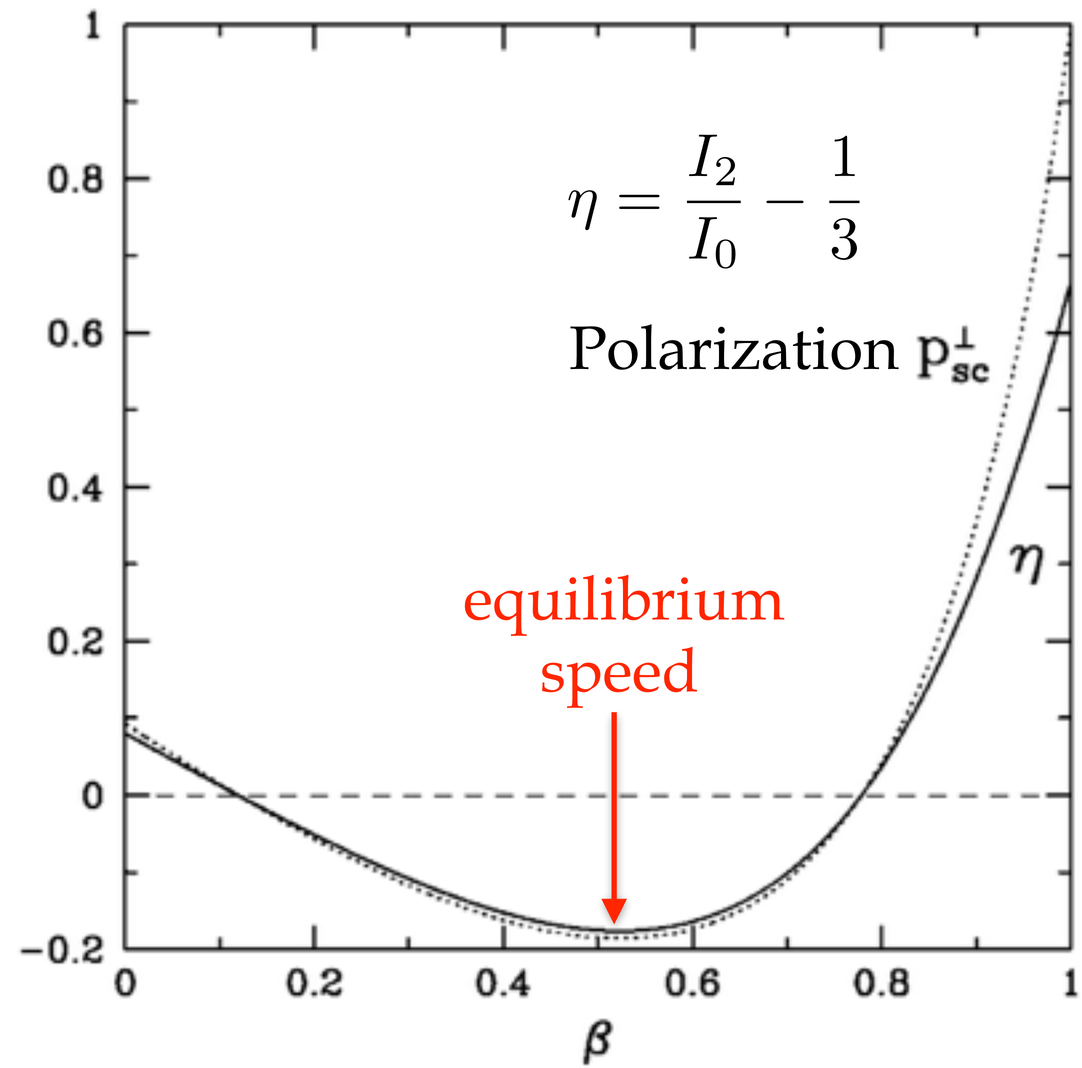
Comptonization in a hot slab



Haardt, Matt 1993; Poutanen, Svensson 1996

Scattering in outflowing corona/jet

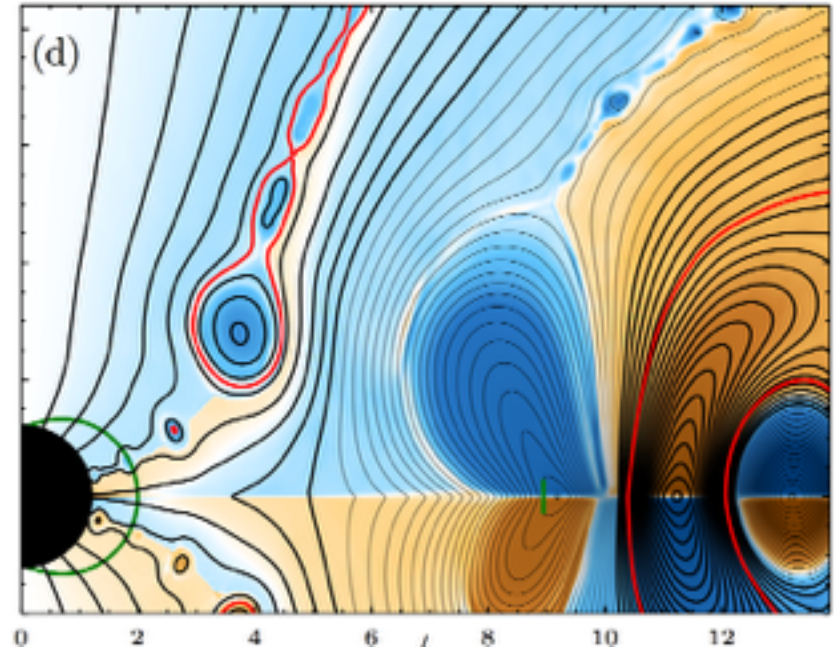




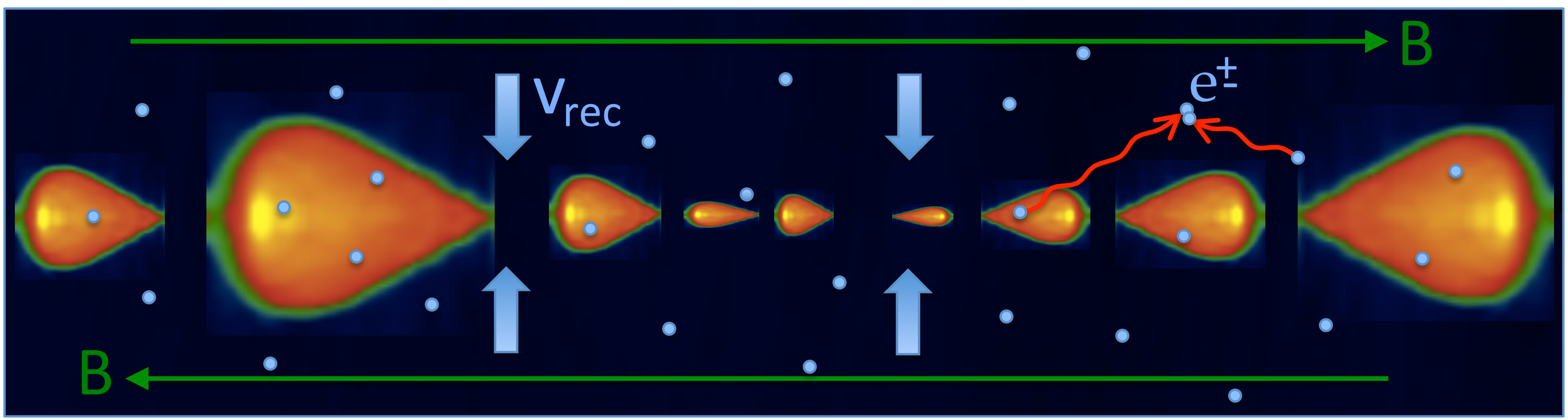
NEW: detection of pair plasma in microquasar V404 Cyg

(Siegert et al. 2016)

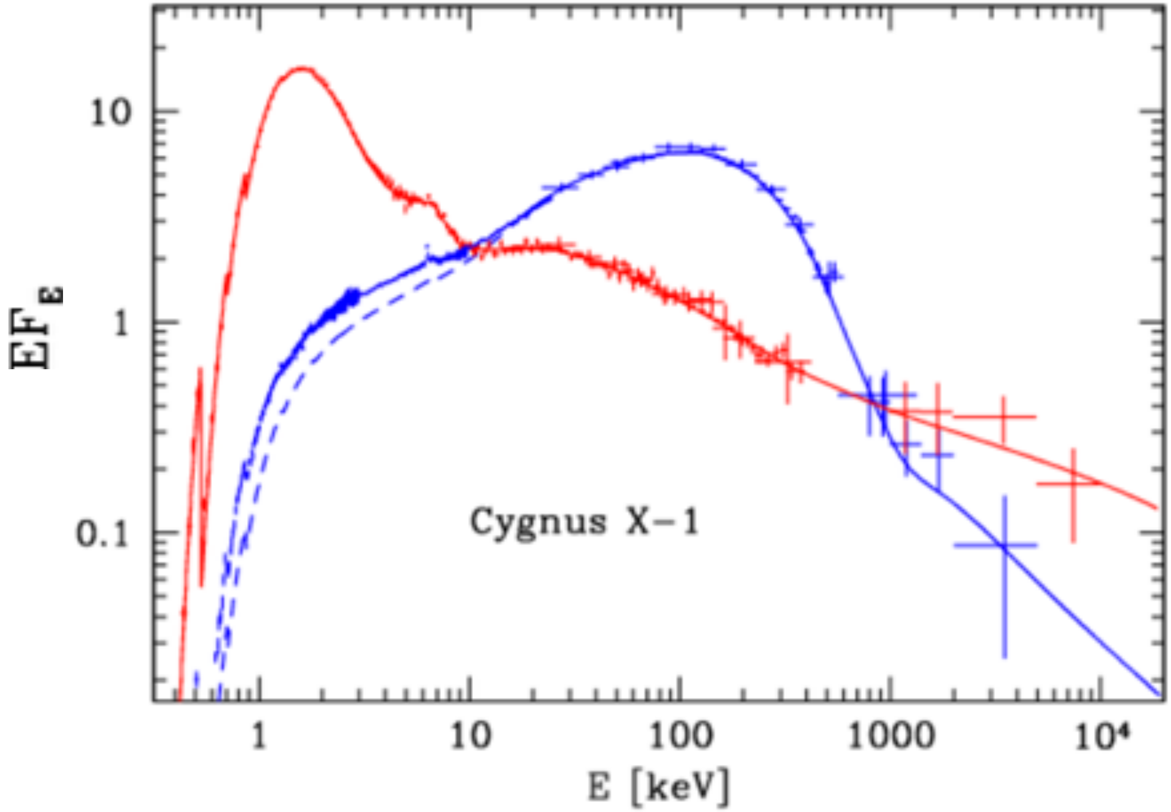
Radiative magnetic reconnection near black holes



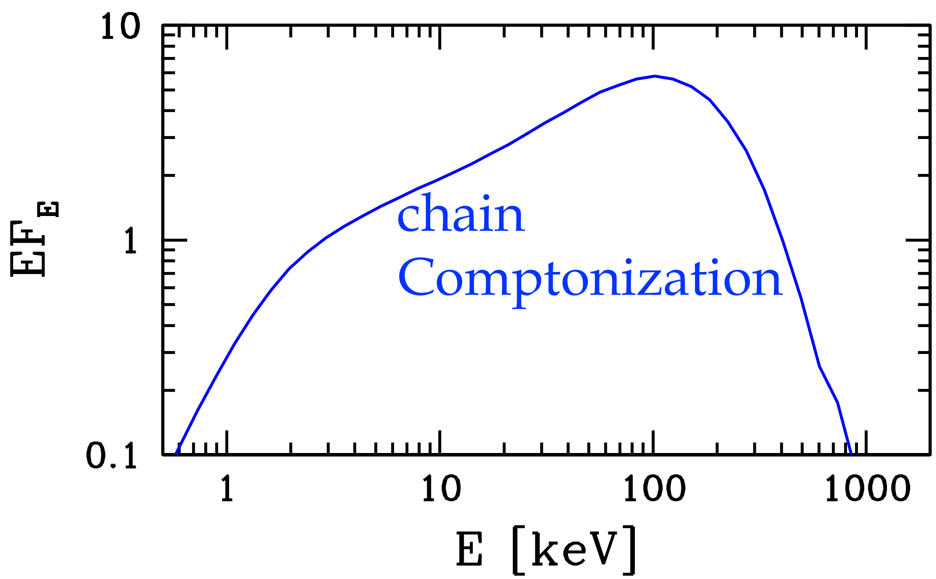
Parfrey, Giannious, AB 2015



AB 2017



McConnell et al. 2002



$$\ell_B = \frac{U_B \sigma_{\rm T} s}{m_e c^2} \sim \frac{m_p}{m_e}$$

AB 2017

Strong magnetic fields

$$\hbar\omega_B > 1\ \mathrm{keV}$$

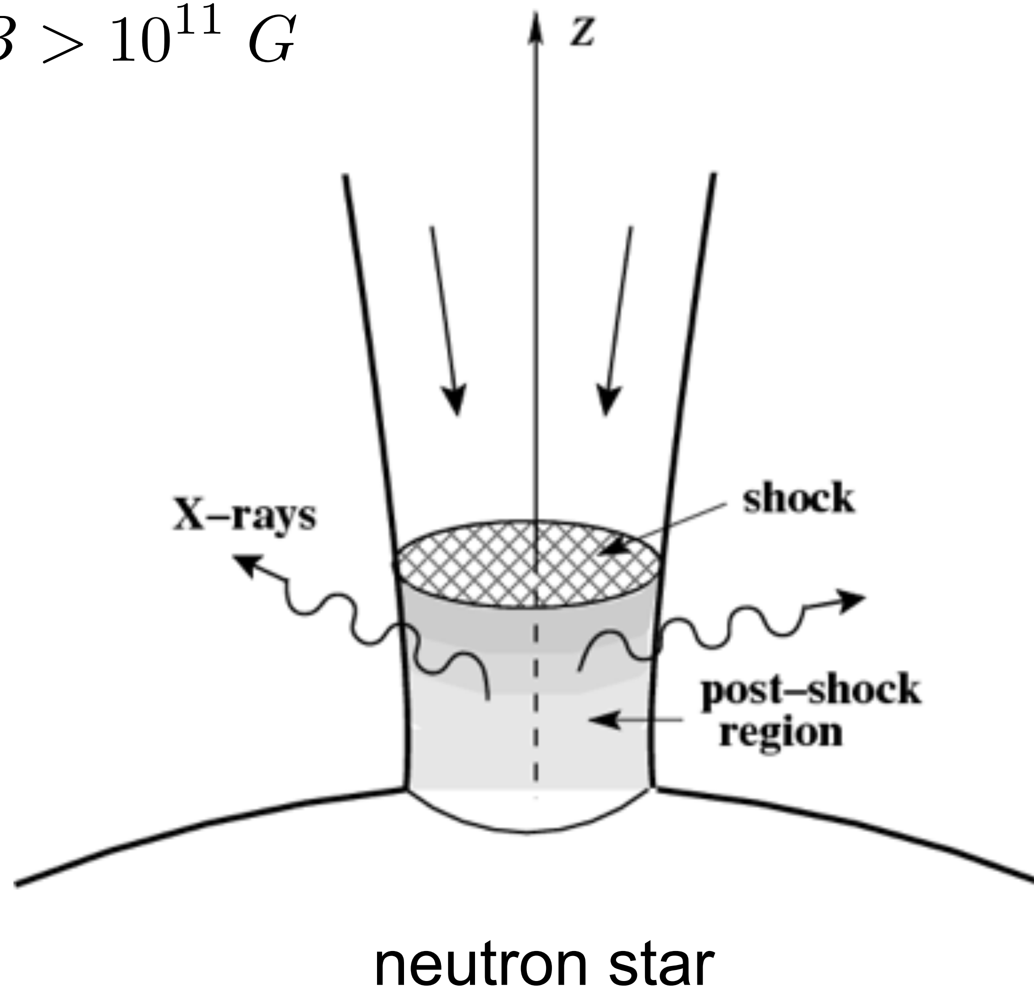
“young” neutron stars

X-ray pulsars

Large scattering optical depth in the column

Strong magnetic fields $B > 10^{11}\ G$

$$\omega < \omega_B = eB/m_e c$$



X-ray pulsars

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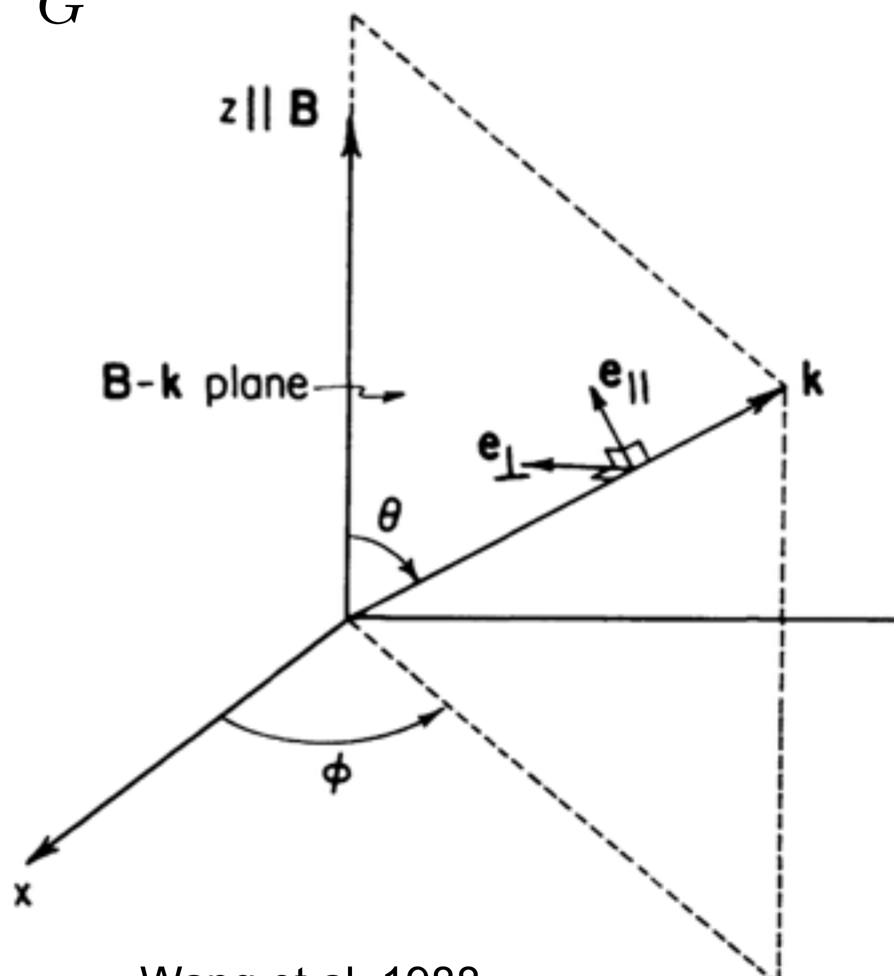
O and E/X polarization states

$$\sigma_O \sim \sigma_{\rm T}, \quad \sigma_X \sim \left(\frac{\omega}{\omega_B}\right)^2 \sigma_{\rm T}$$

Strong polarization

fan vs pencil diagram



Wang et al. 1988

Complications:

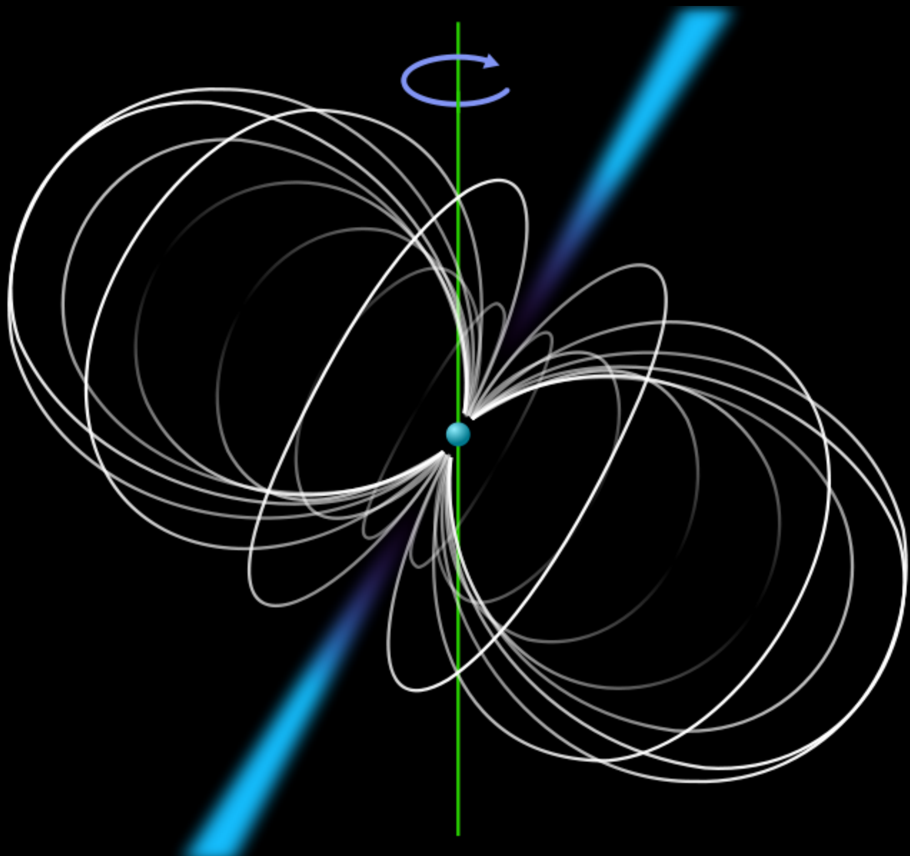
cyclotron resonances, density gradient
uncertain geometry (wall)
sensitivity to parameters (accretion rate, B)
reflection from the star

Basko, Sunyaev 1975
Meszaros et al. 1988
Wang et al. 1988
Becker, Wolf 2007
Mushtukov et al. 2015

Discovery of ULX pulsar in M82: supercritical luminosity

Bachetti et al. 2014

Rotation-powered pulsars



$$\frac{dE}{dt} \approx -\frac{\Omega^4 \mu^2}{c^3}$$

How is rotational energy converted to radiation?

Recent developments: rethinking pulsar mechanism

direct global numerical experiment

$$d\mathbf{p}/dt = e\,\mathbf{E} + e\,\mathbf{v} \times \mathbf{B}/c$$

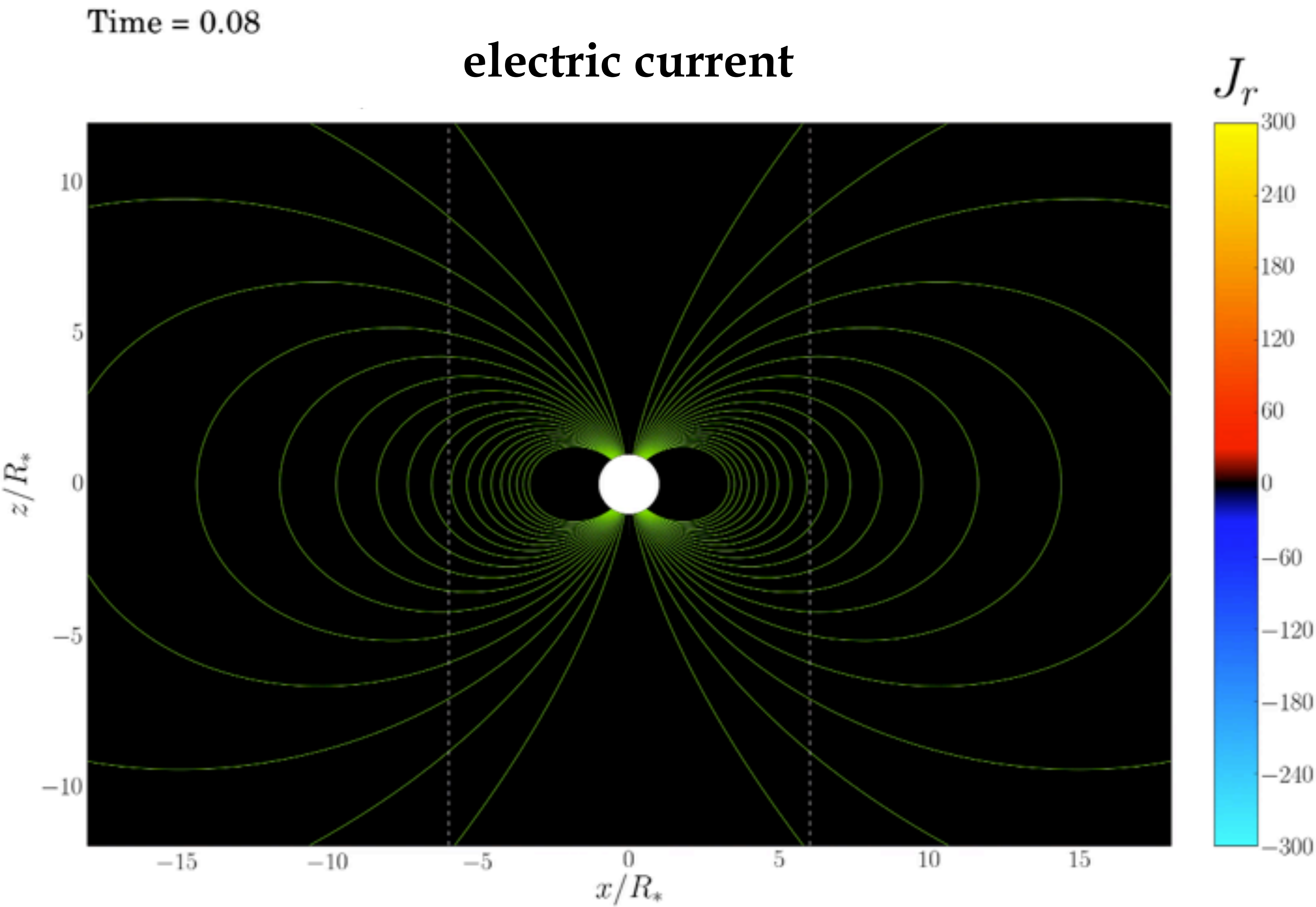
$$\partial\,\mathbf{B}/\partial t = -c\nabla \times \mathbf{E}$$

$$\partial\,\mathbf{E}/\partial t = c\nabla \times \mathbf{B} - 4\pi\,\mathbf{J}$$

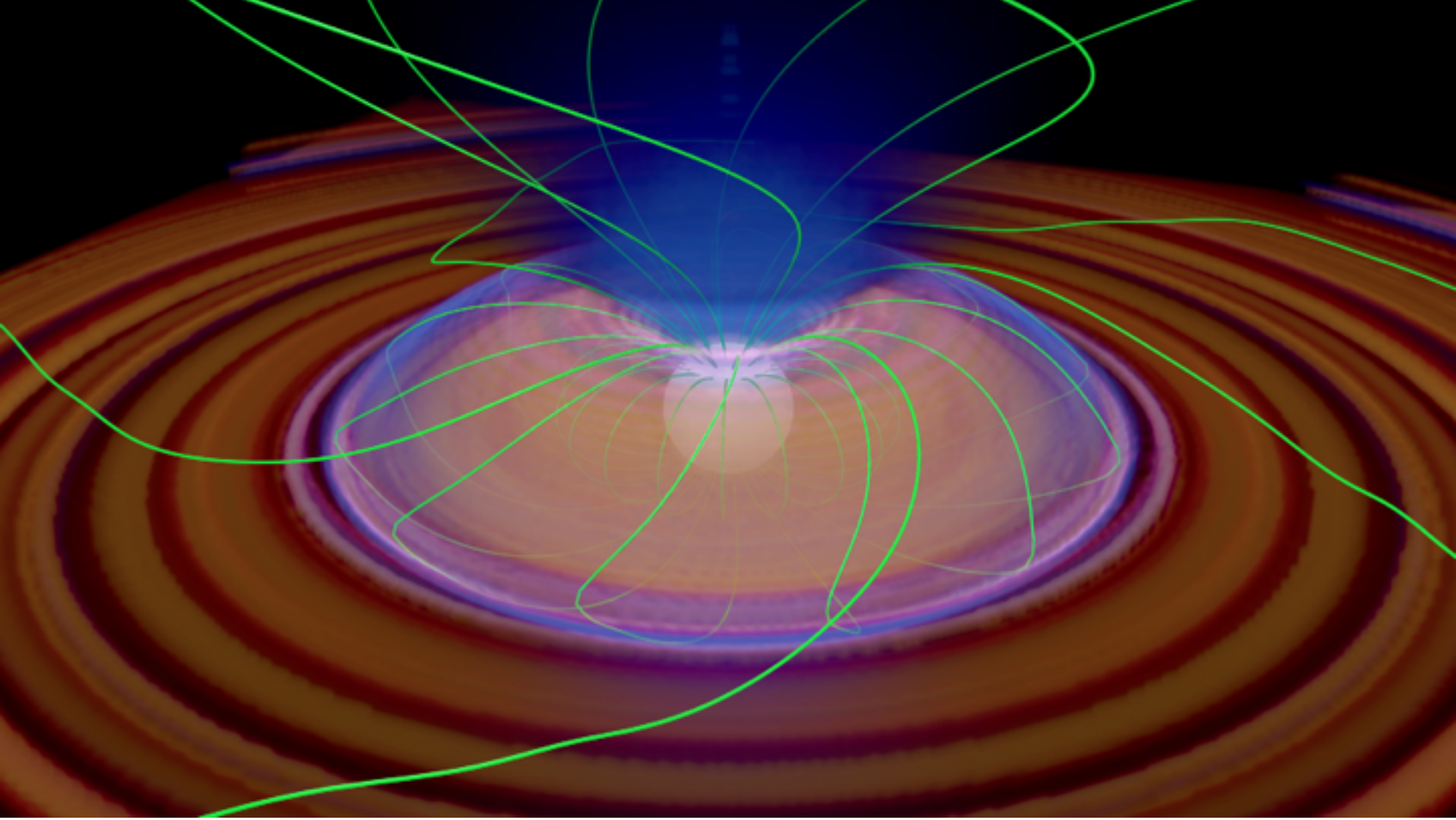
“particle in cell” (PIC):

- fields calculated on a grid
- particles followed individually
- photon emission, tracing, and pair creation: Monte-Carlo

electric current



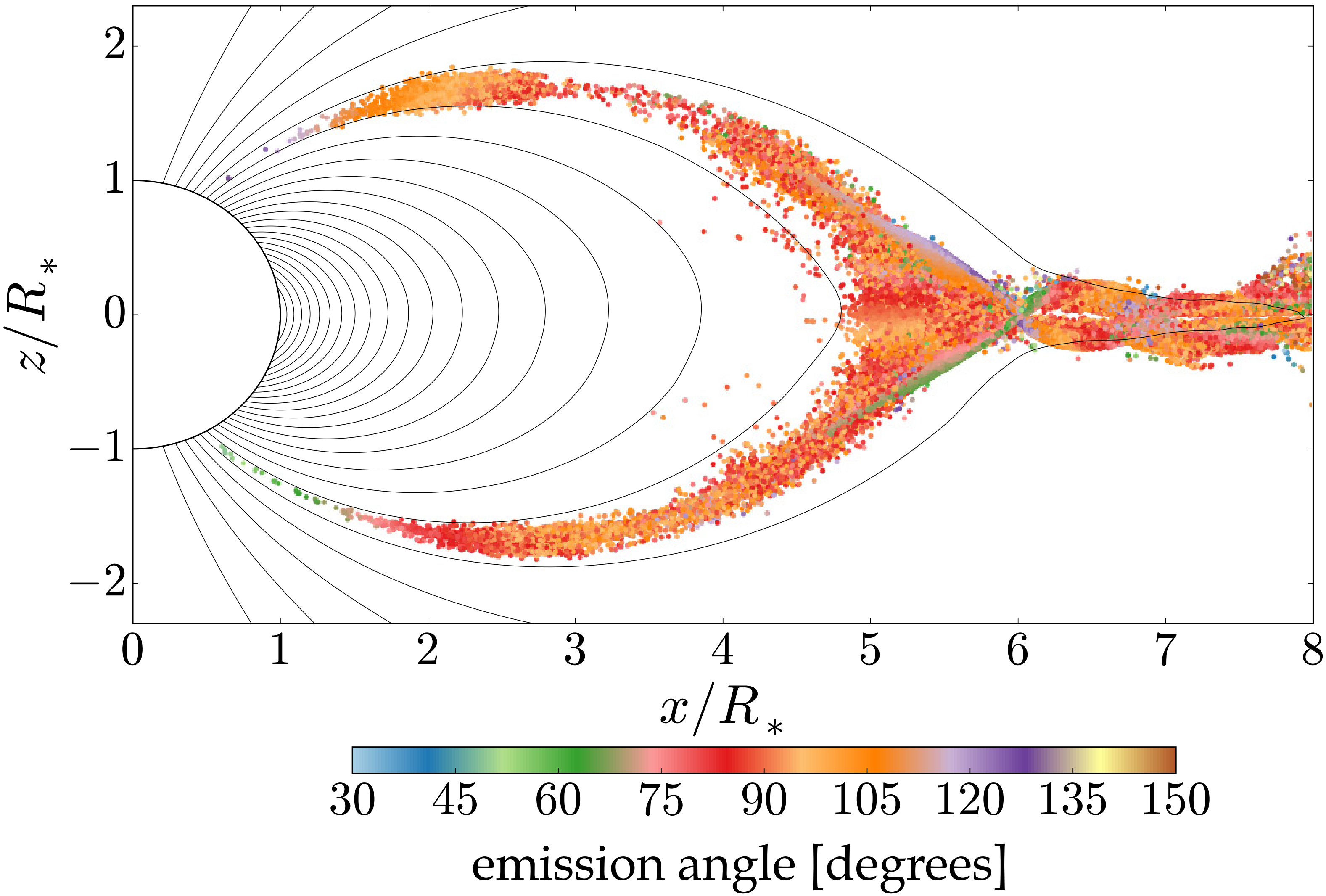
Chen, AB (2014)



aligned rotator

charge density: - blue   + orange

gamma-rays/pair creation



Synchrotron and curvature radiation

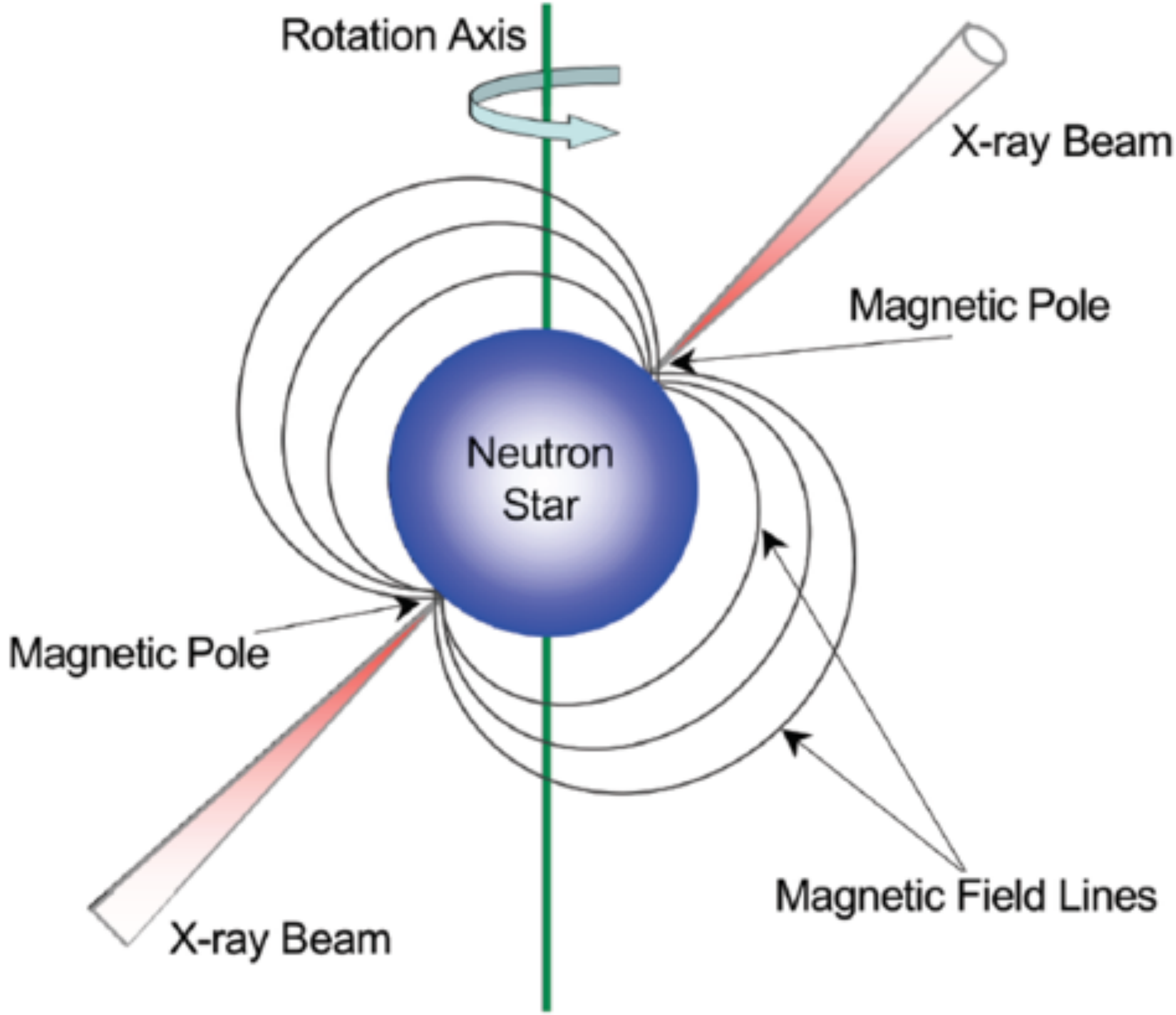
$$P_\nu \approx \frac{4\pi e^2\,\nu_c}{\sqrt{3}c\,\gamma_e^2}\,1.8\left(\frac{\nu}{\nu_c}\right)^{1/3}\exp\left(-\frac{\nu}{\nu_c}\right)$$

synchrotron	curvature
$\nu_c = \dfrac{3}{4\pi}\dfrac{eB_\perp}{m_e c}\gamma_e^2$	$\nu_c = \dfrac{3}{4\pi}\dfrac{c}{R_c}\gamma_e^3$
polarization $\perp$ $\mathbf{B}$	polarization $\parallel$ $\mathbf{B}$

$$\text{power law electrons :}\quad P_\nu \propto \nu^{-(p-1)/2} \qquad \left[\frac{dN_e}{d\gamma_e} \propto \gamma_e^{-p}\right]$$

$$\text{polarization degree}\quad \Pi = \frac{p+1}{p+7/3}$$

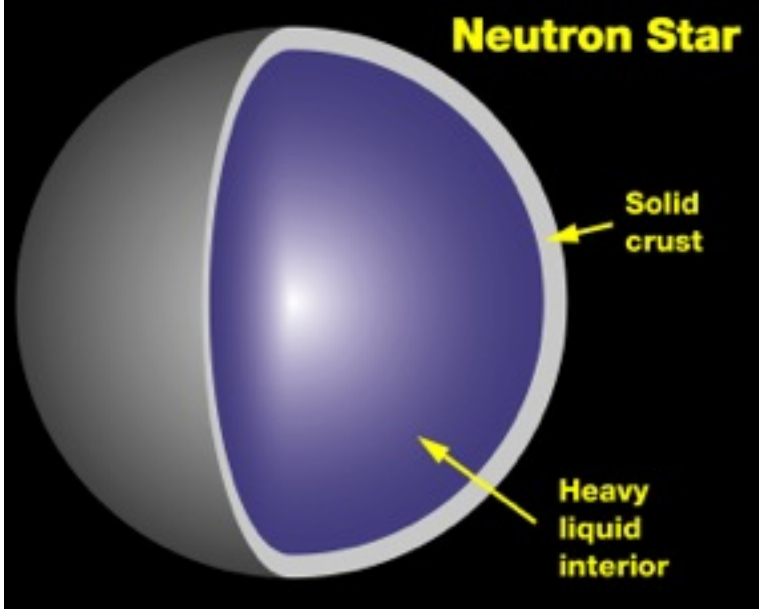
$$\left[\text{fast cooling :}\quad P_\nu \propto \nu^{-1/2} \quad P_\nu \propto \nu^{-p/2}\right]$$



phase-dependent polarization degree and angle
(cf. optical and radio polarization of Crab pulsar)

Surface glow

heat flux from interior can exceed spindown power in slow rotators
– XDINS, magnetars, older pulsars



Radiative transfer in the atmosphere

$$h = 1 - 10 \text{ cm} \qquad \rho = 10^{-1} - 10^{3} \ \frac{\text{g}}{\text{cm}^3}$$

– chemical composition
– equation of state
– ionization
– phase (condensed?)
– magnetic field

Potekhin et al. 2004, 2014
Suleimanov et al. 2010
Taverna et al. 2015
Gonzalez et al. 2016

Polarization states in surface layers

eigen states are determined by the dielectric tensor:

plasma + vacuum polarization

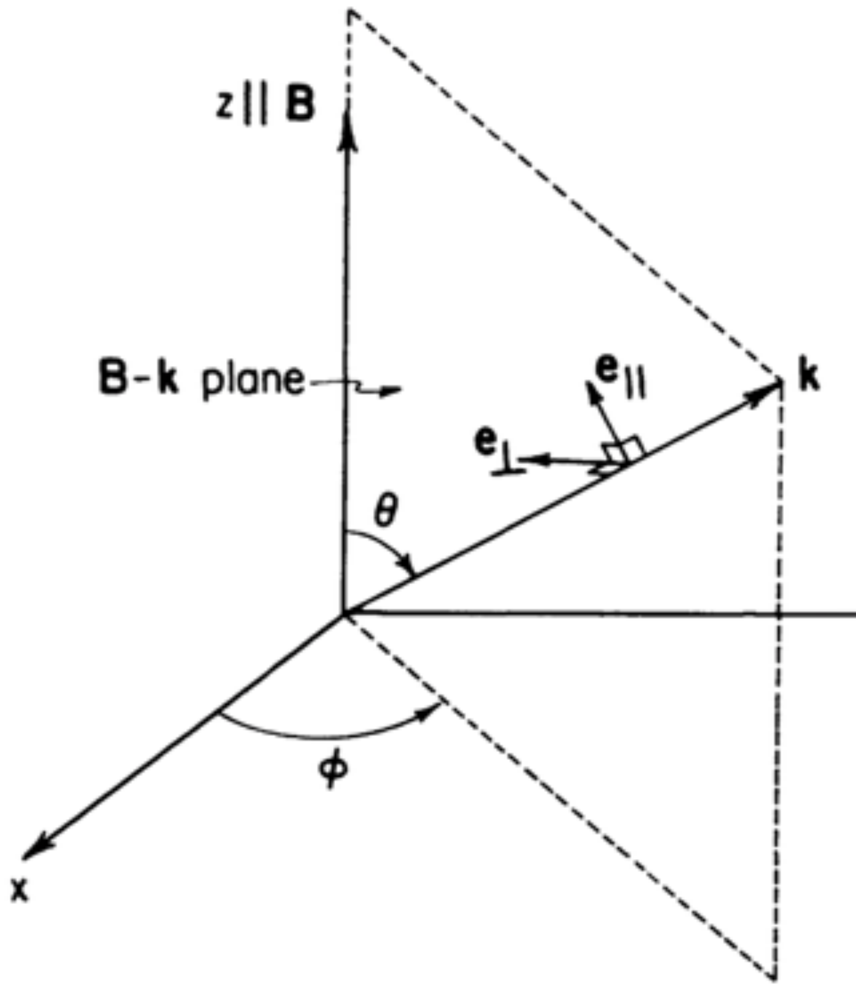
vacuum dominates where

$$\rho < 1 \left(\frac{B}{10^{14}\ \mathrm{G}}\right)^2 \left(\frac{E}{1\ \mathrm{keV}}\right)^2 \frac{\mathrm{g}}{\mathrm{cm}^3}$$

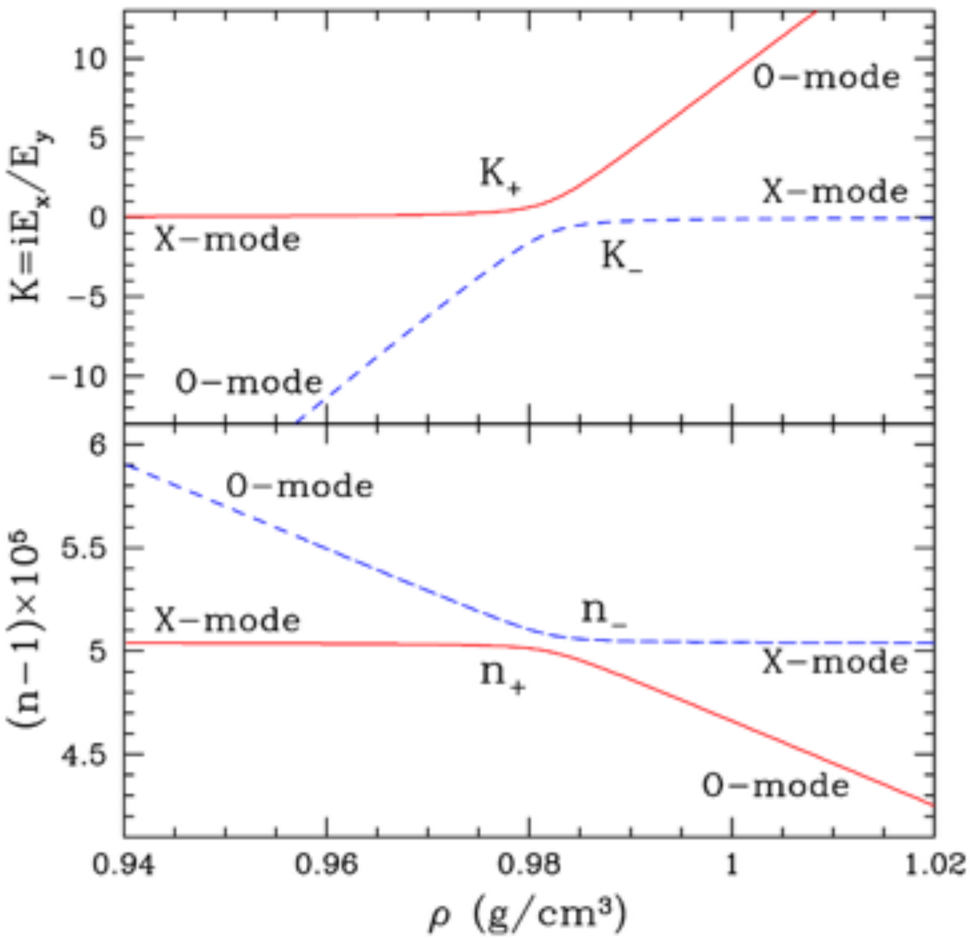
O-mode and X-mode

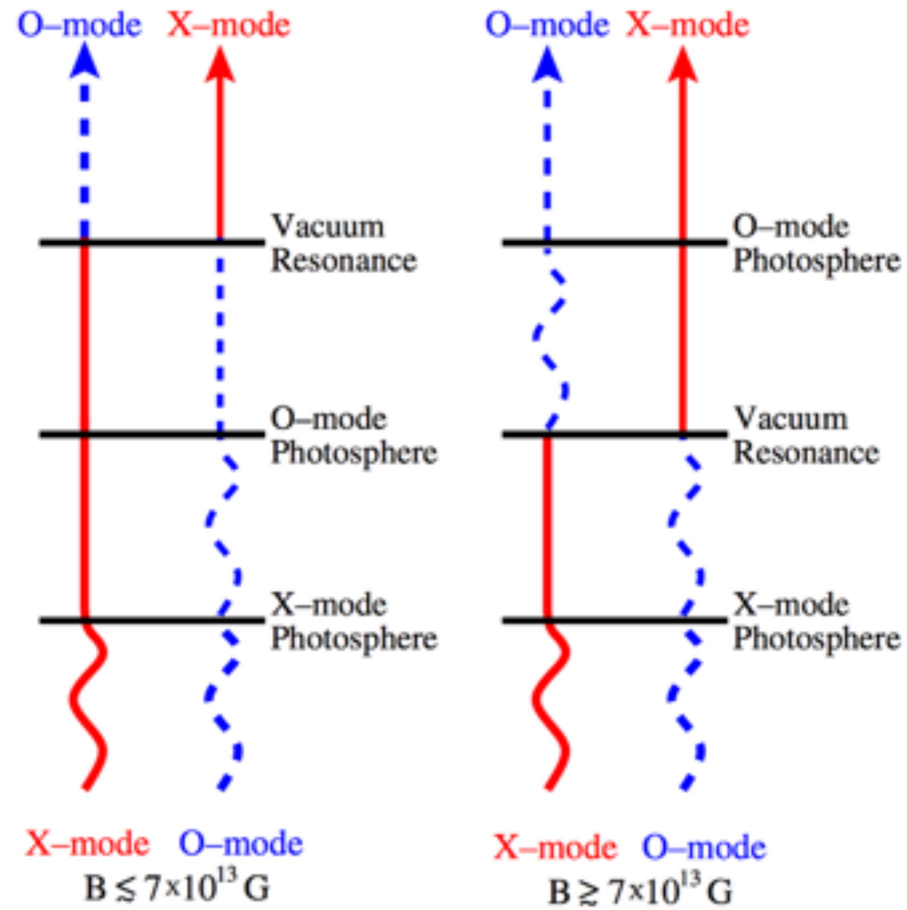
suppressed opacity for X-mode

$$\sigma_X \sim \left(\frac{\omega}{\omega_B}\right)^2 \sigma_{\mathrm{T}}$$



Polarization states in surface layers





Ho et al. 2008

Surface X-rays go through transparent magnetosphere:

modes "adiabatically track" the local B:

$$(n_O - n_X) k l_B \gg 1 \qquad n_O - n_X = \frac{\alpha}{30\pi}\left(\frac{B}{B_Q}\right)^2 \sin^2\theta_{kB}$$

$\Rightarrow$ polarization set at decoupling radius $\gg R_\star$

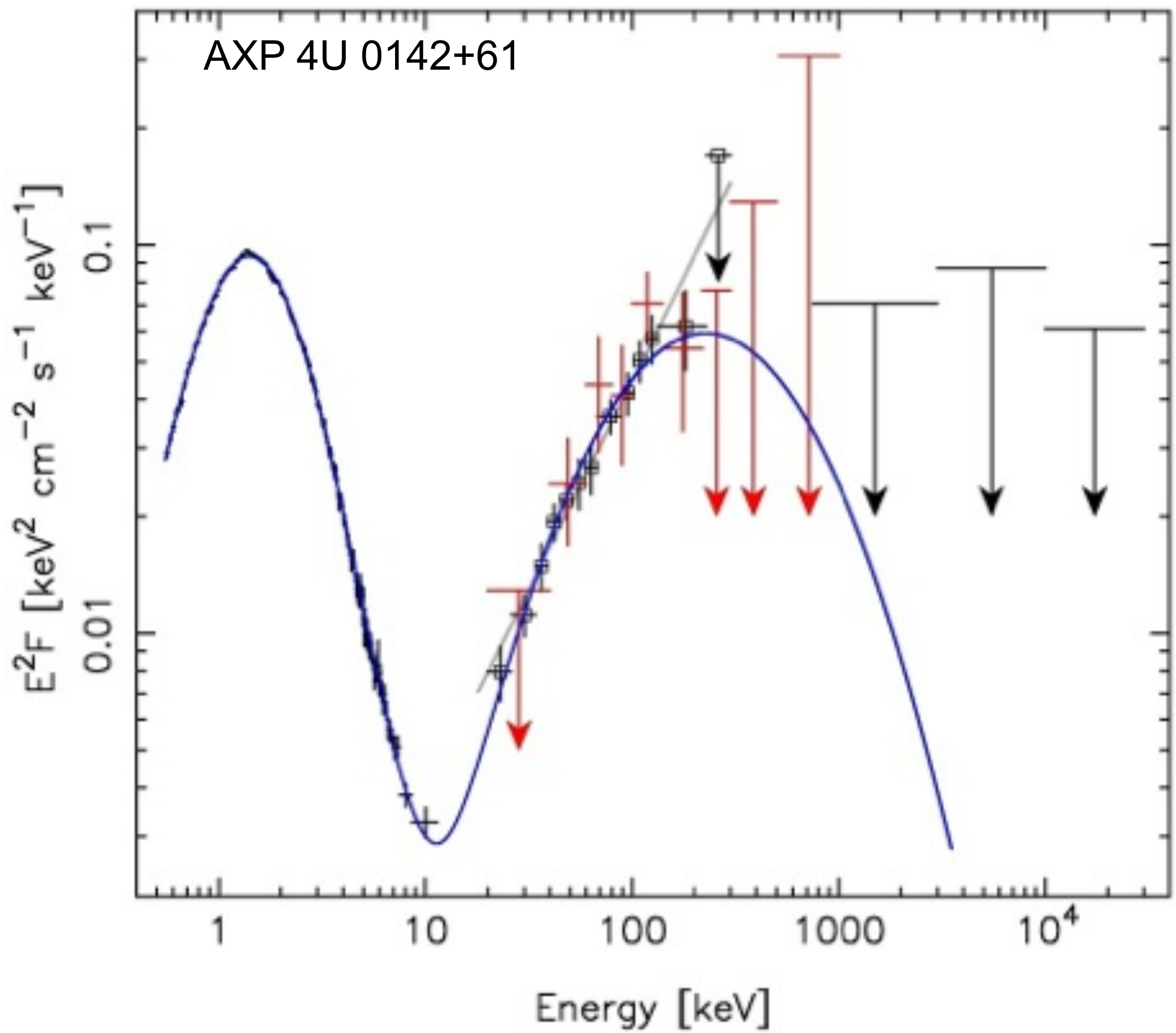
$$\left[B_Q = \frac{m_e^2 c^3}{\hbar e} \approx 4.4 \times 10^{13}\mathrm{G}\right]$$

Heyl, Shaviv, Lloyd 2003

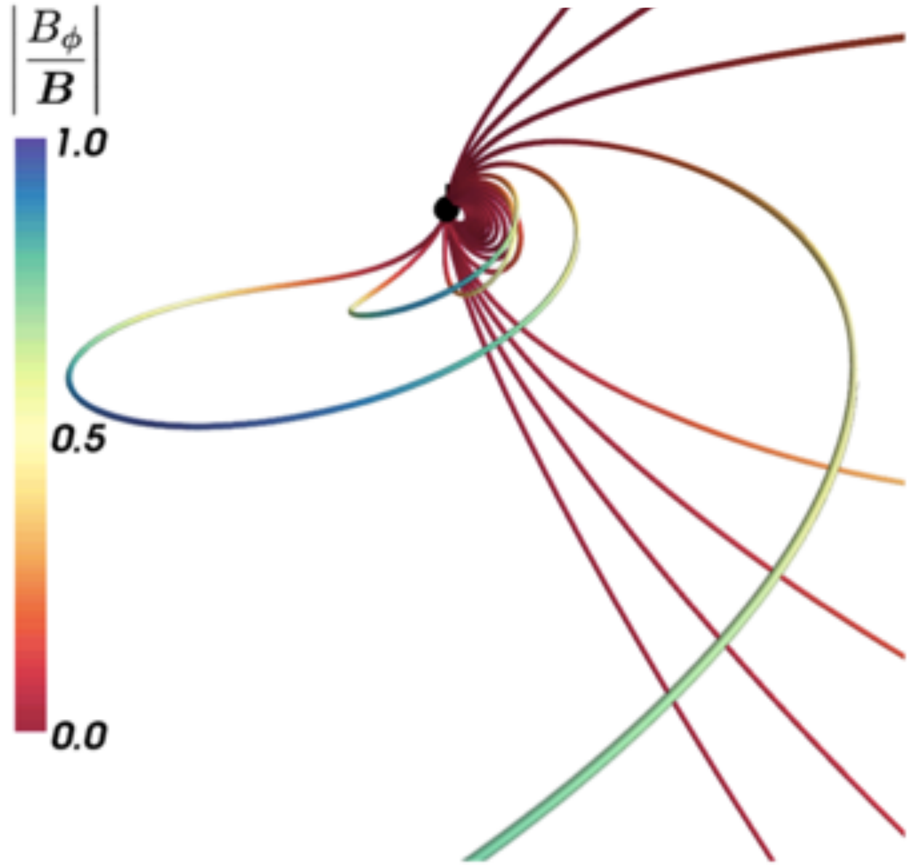
calculations of expected polarization:
see talk by D. Gonzalez

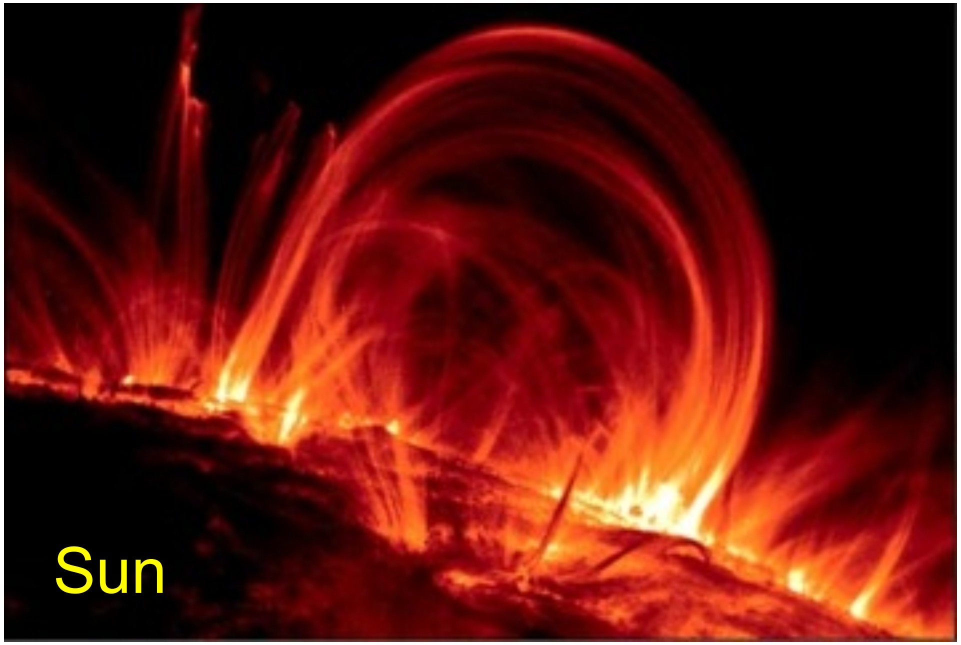
Strong linear polarization

Magnetars: active magnetosphere



Den Hartog et al. (2008)





Thompson et al. 2002; AB 2009; Parfrey et al. 2013

Scattering in the magnetosphere

twisted field => electric discharge: relativistic e+- pairs

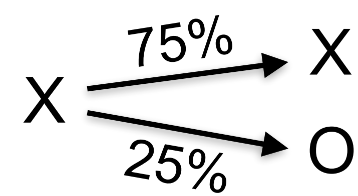
$$\omega \ll \omega_B \ (\text{“1D” electrons}) : \ \sigma_O \sim \sigma_{\mathrm{T}}/\gamma_e^2$$

$$\sigma_X \sim \sigma_{\mathrm{T}} \left(\frac{\omega}{\omega_B} \right)^2$$

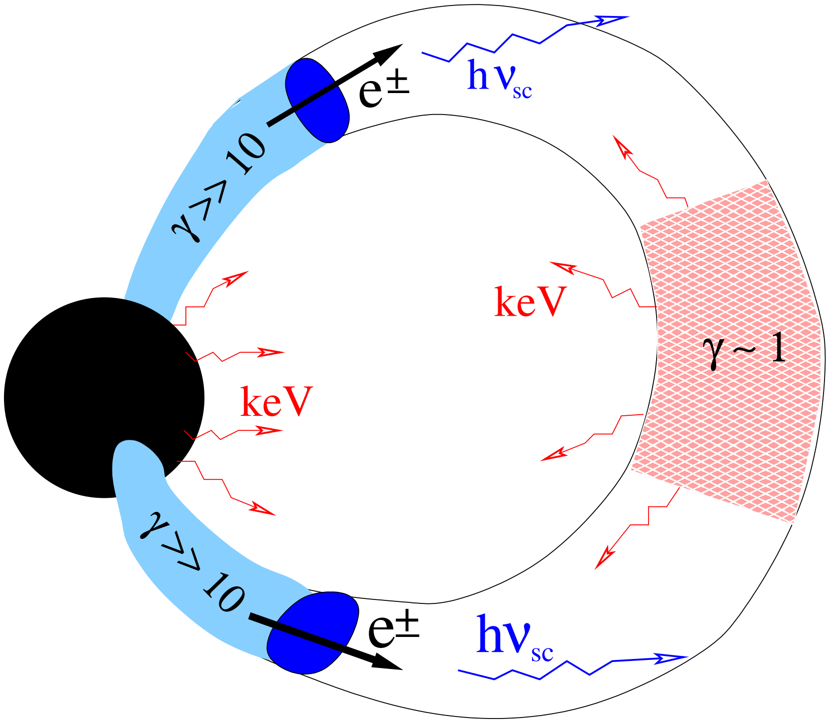
optically thin magnetosphere except at the "resonance surface" where $\omega_B = \gamma_e (1 - \beta_e \cos\theta)\omega$

$$\sigma_{\mathrm{res}} \sim r_e \, \lambda \gg \sigma_{\mathrm{T}}$$

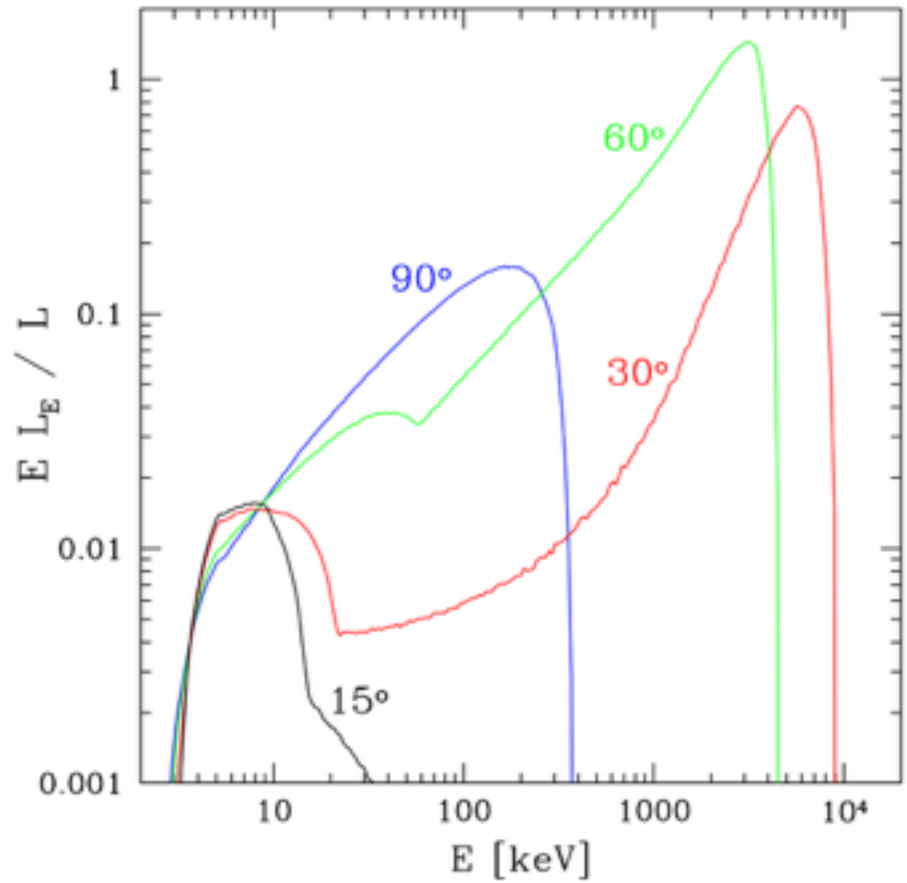
– resonant scattering: mode switching:



"e+- fountain"

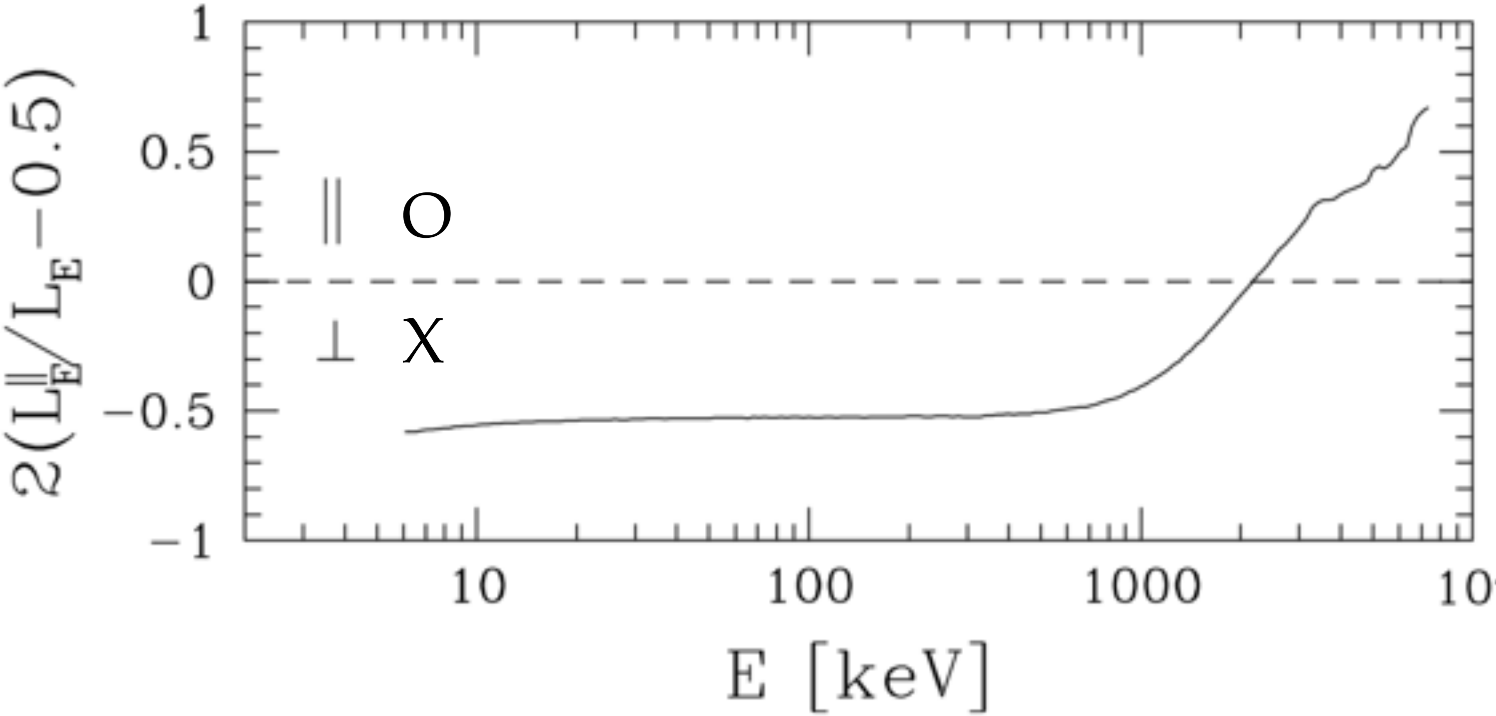


emitted spectrum



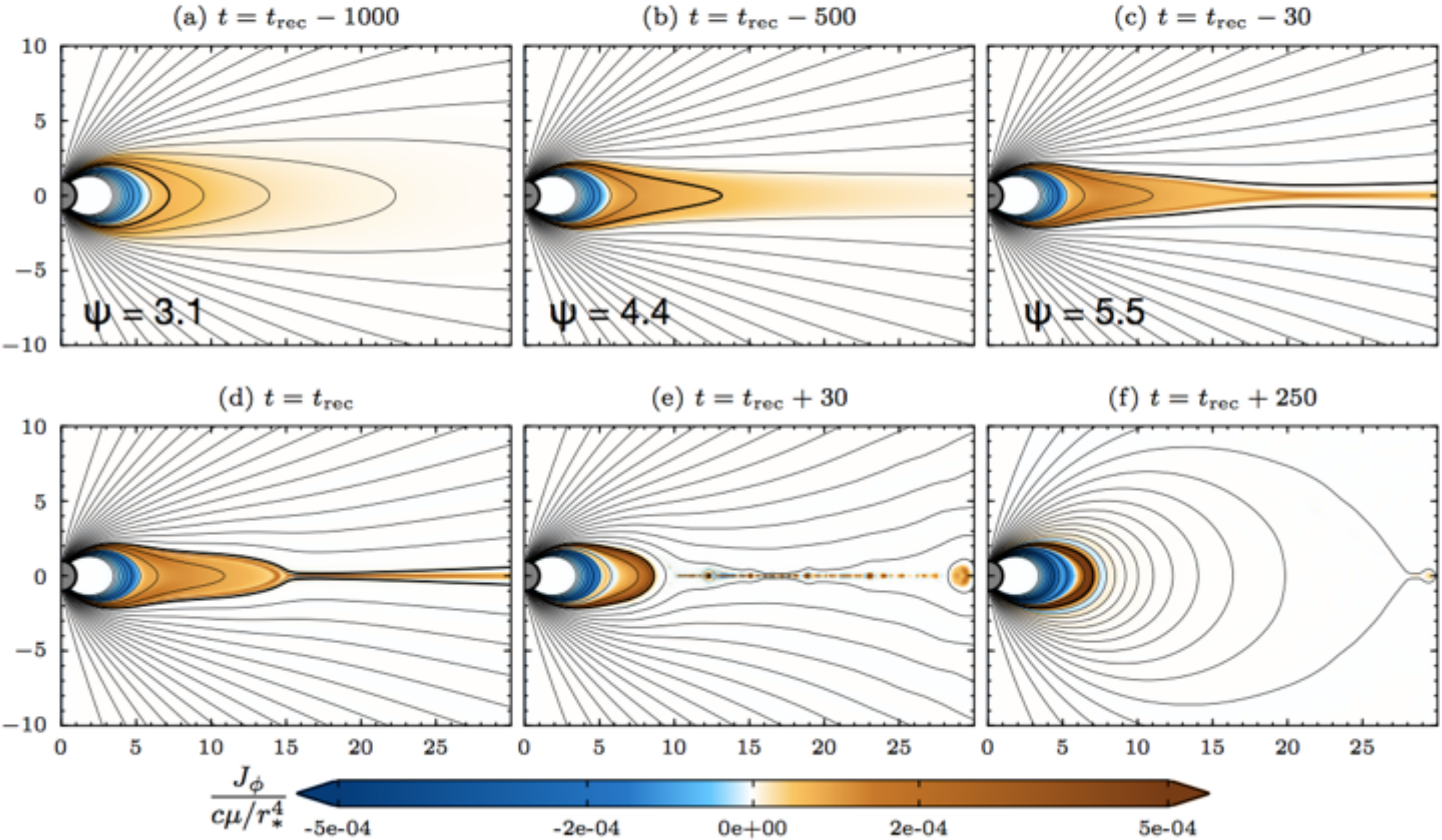
AB 2013; Hascoet et al. 2014; An et al. 2015

Magnetars: polarization of persistent emission



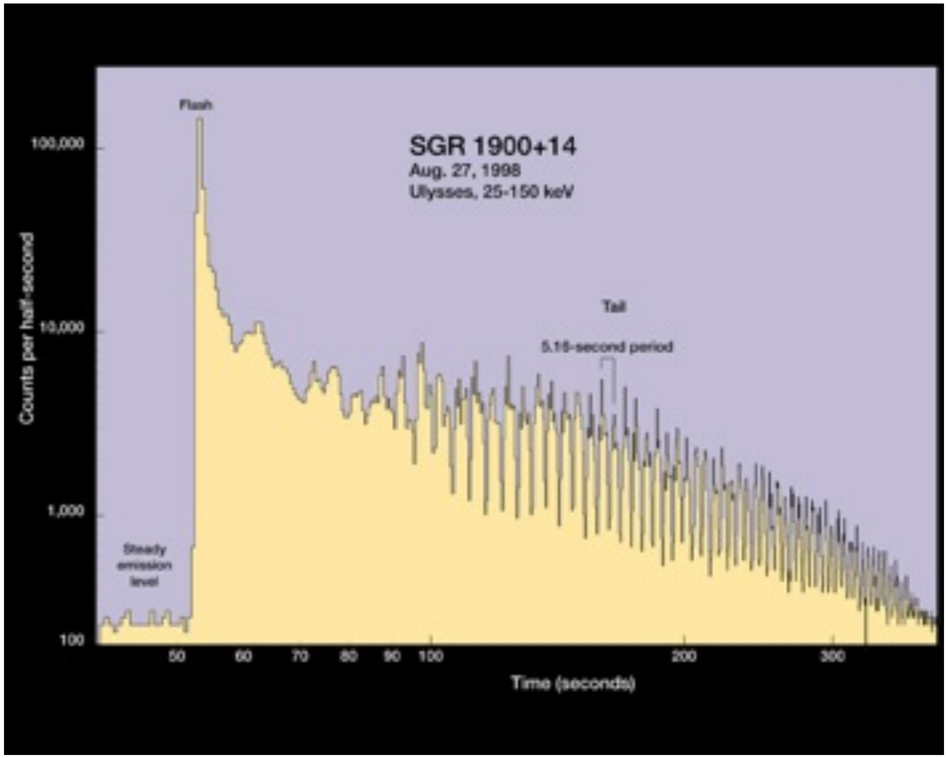
AB 2013

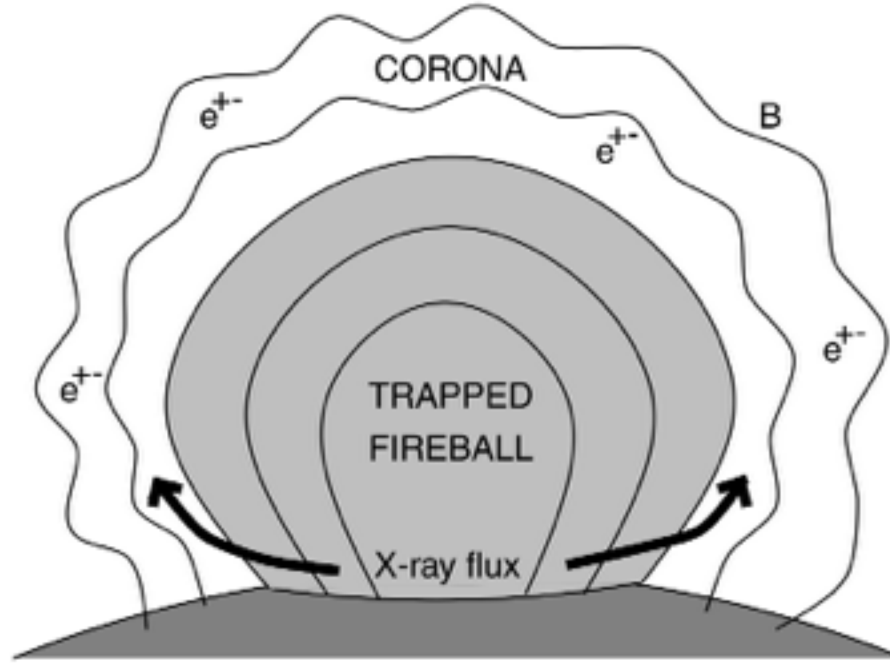
Over-twisted magnetosphere: loss of equilibrium and reconnection



Parfrey et al. 2013

Magnetar flares





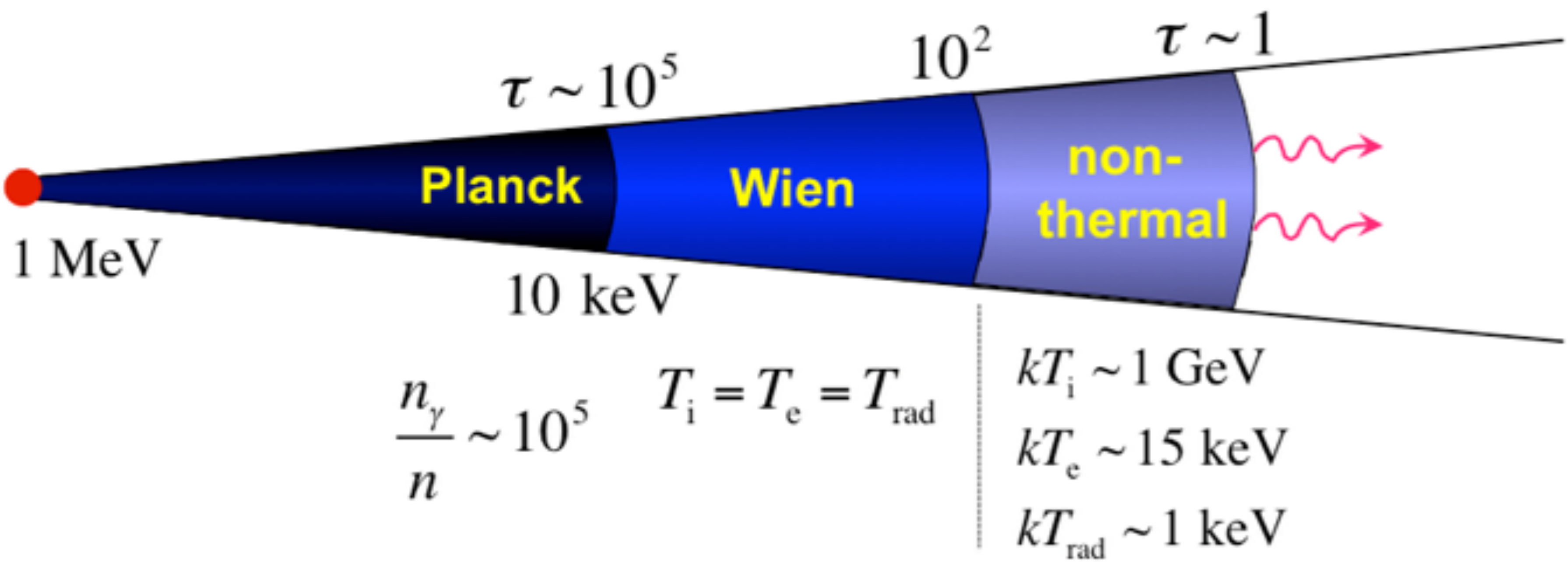
Thompson, Duncan 2001

$$\text{tail of the flare :}\quad 400\ \text{s (many rotations)}$$

$$E_{\text{tail}} \sim 10^{44}\ \text{erg}$$

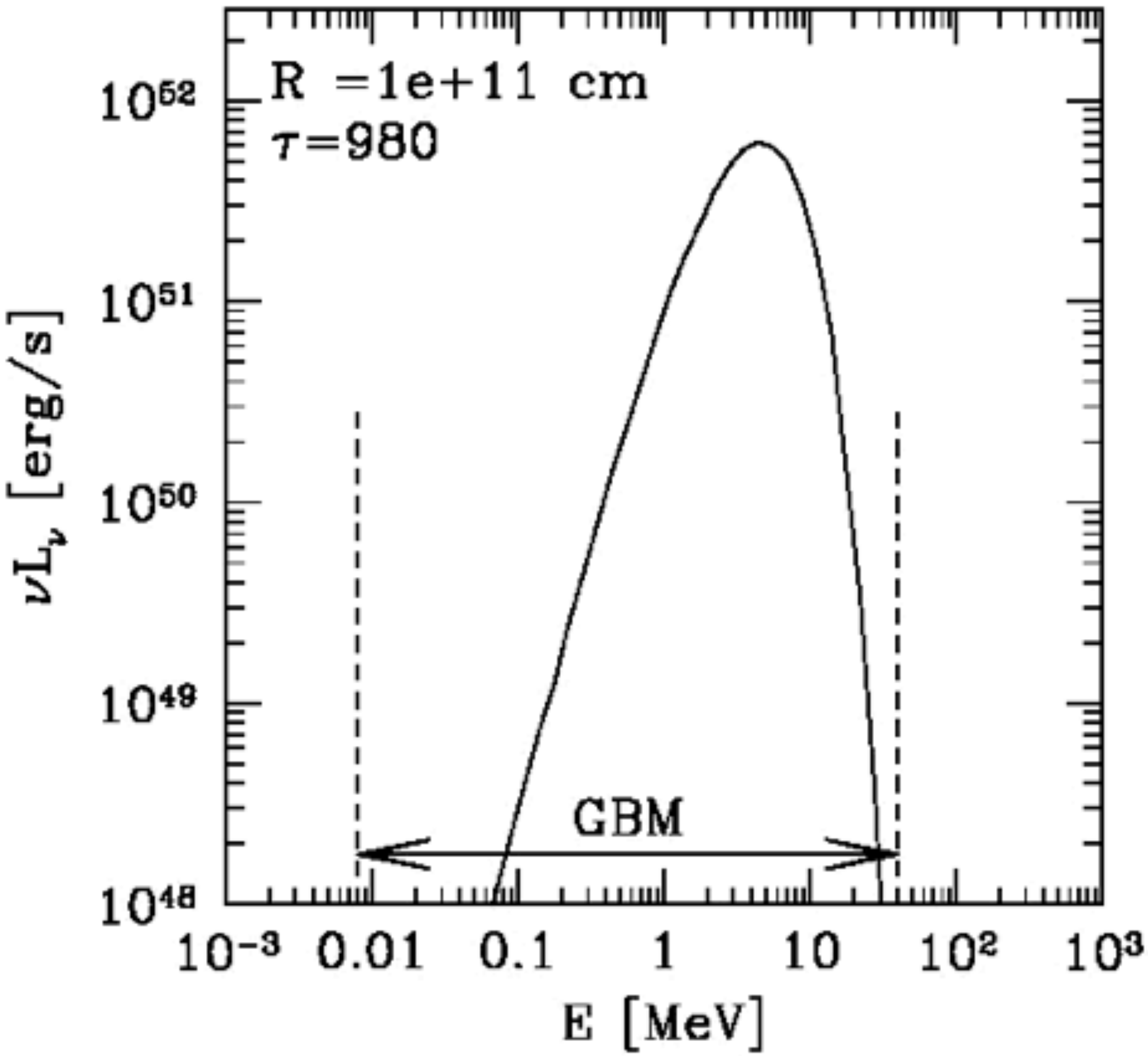
GRB
prompt emission

opaque heated fireball



AB 2013

Radiative transfer calculation (with phenomenological heating)

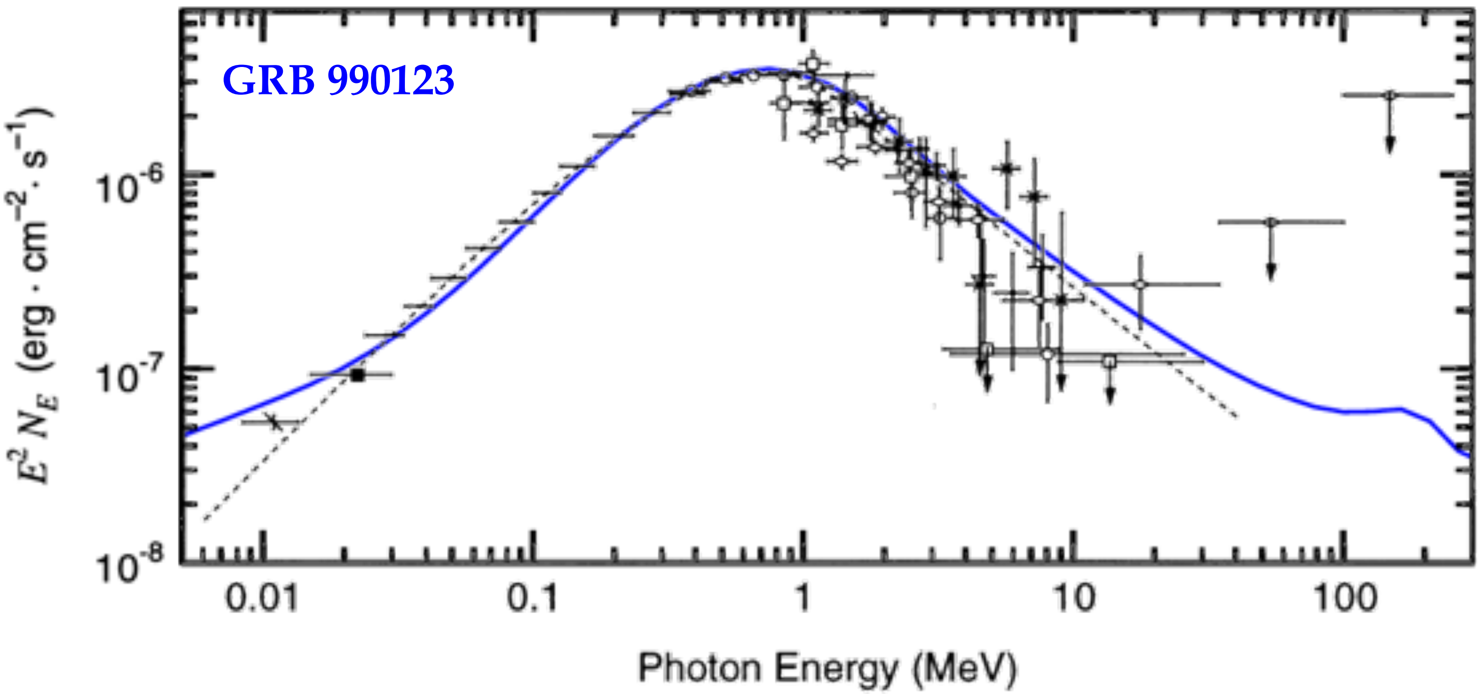


$L_{\mathrm{JET}} = 10^{52}$ erg s^{-1}

$\eta = 300$

$\varepsilon_B = 0.01$

Vurm, AB 2016


GRB 990123
$E^2 N_E$ (erg · cm^{-2} · s^{-1})
10^{-6}
10^{-7}
10^{-8}
0.01
0.1
1
10
100
Photon Energy (MeV)

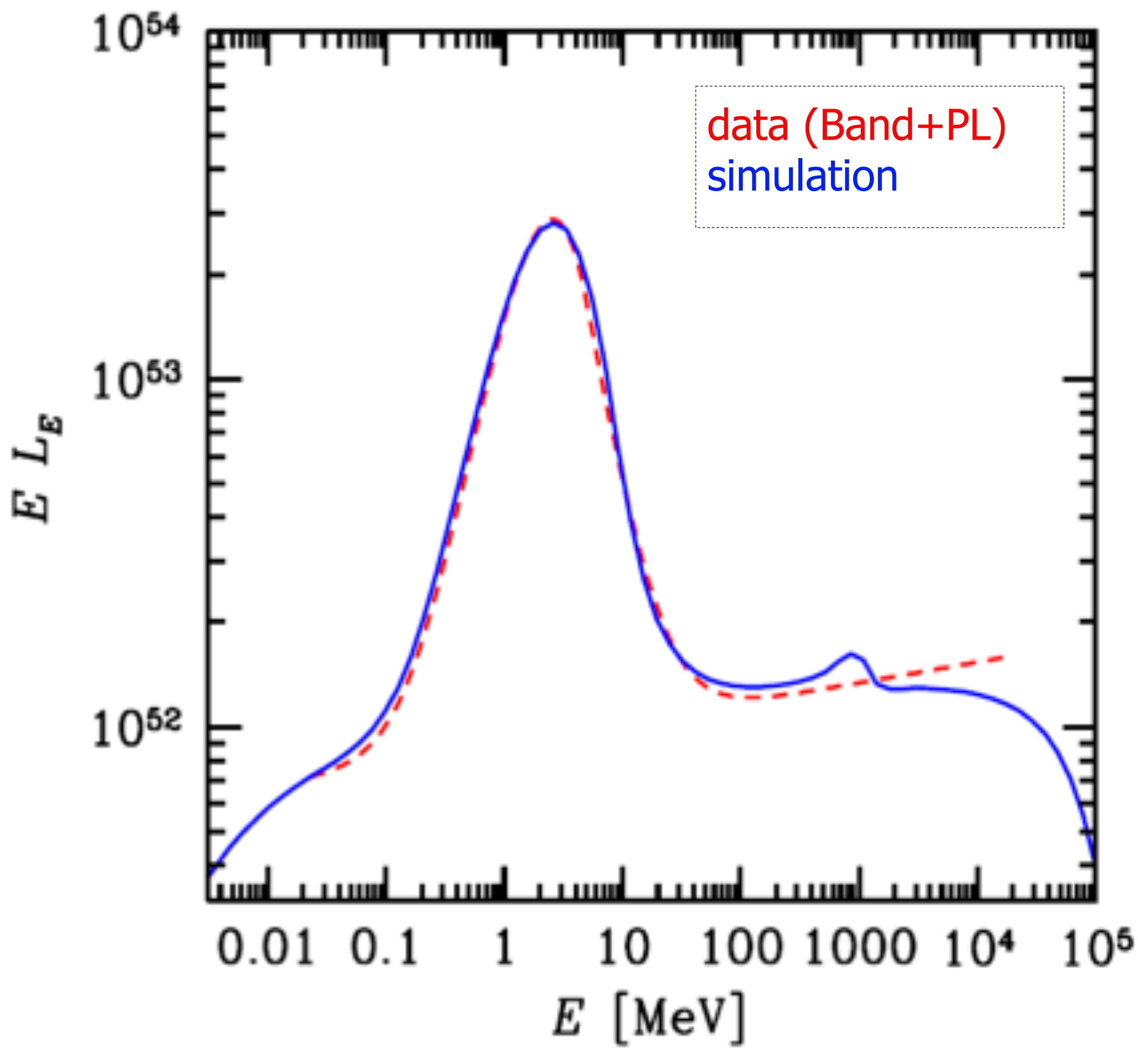
GRB 090902B

Inferred parameters:

Lorentz factor $\Gamma = 1200$

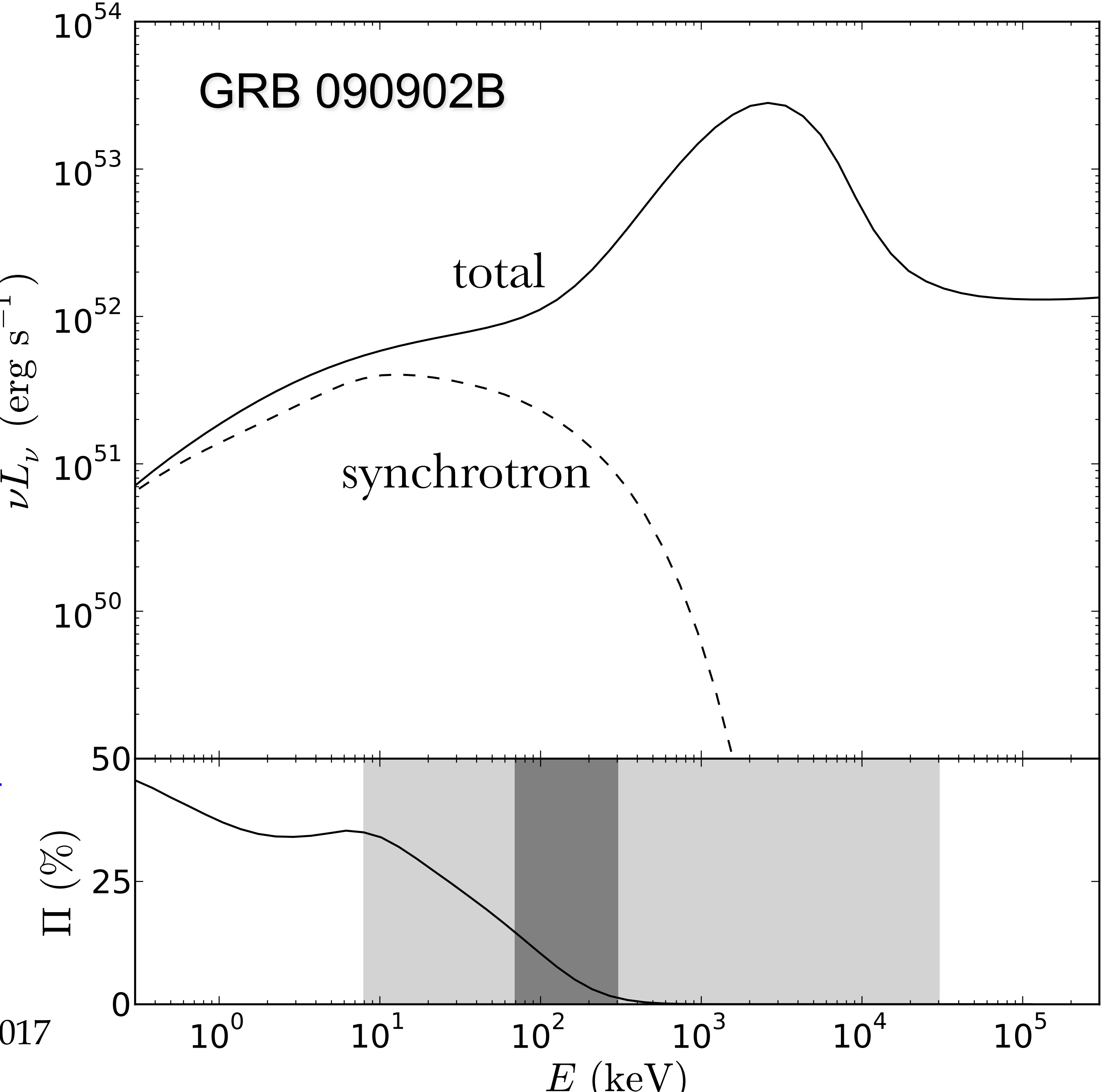
$\varepsilon_B = 0.02$

Strong non-thermal heating



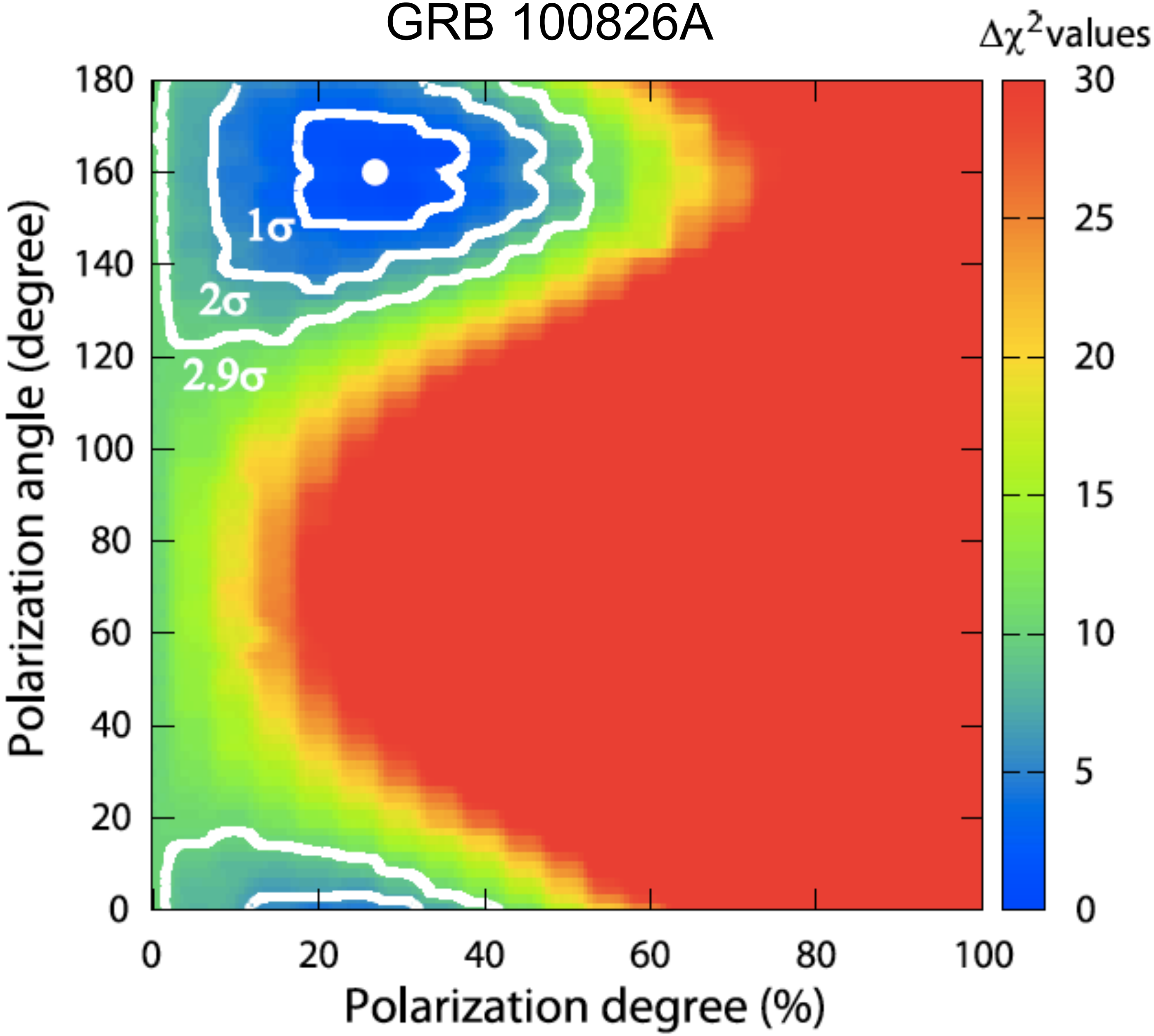
Spectrum

Polarization



Lundman, Vurm, AB 2017

GRB 100826A



Yonetoku et al. (2011)

Promising polarization tests

- Signatures of reconnection/outflows from black holes
- QPO polarization
- Diagnostics of transfer in accretion columns
- Mechanism and location of pulsar emission (phase resolved)
- Vacuum transfer of surface radiation in XDINS
- Resonant scattering in magnetars (phase resolved)
- Synchrotron radiation in GRBs