Magnetars: Advances in the Resonant Compton Scattering Model

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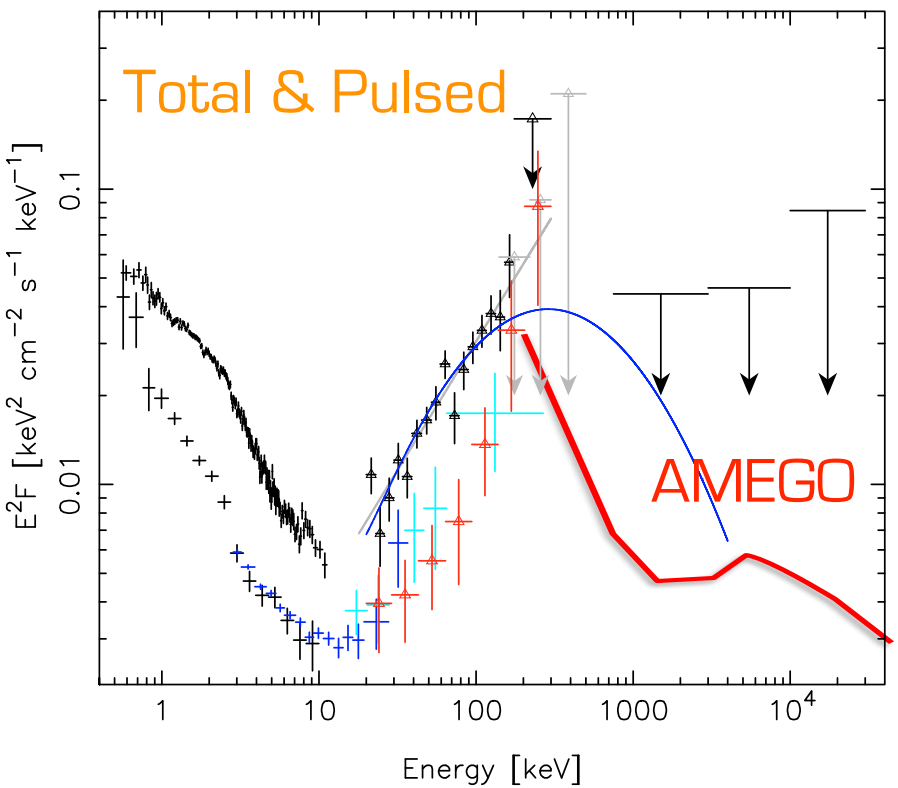
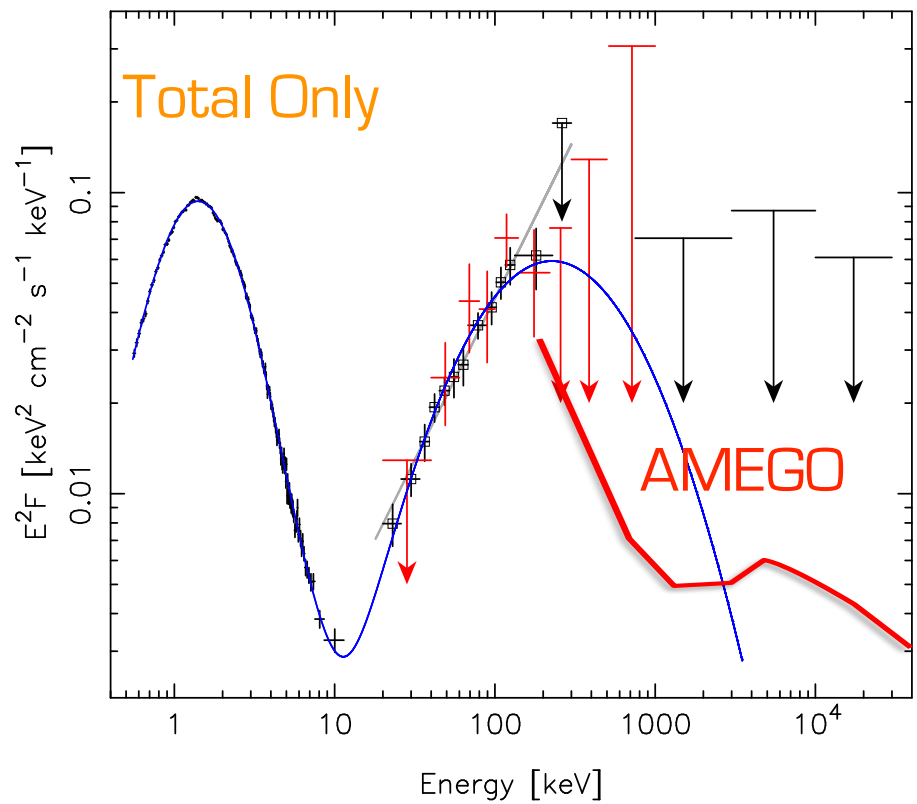
Persistent Emission: XMM/INTEGRAL/RXTE Spectra

1RXS J1708-40



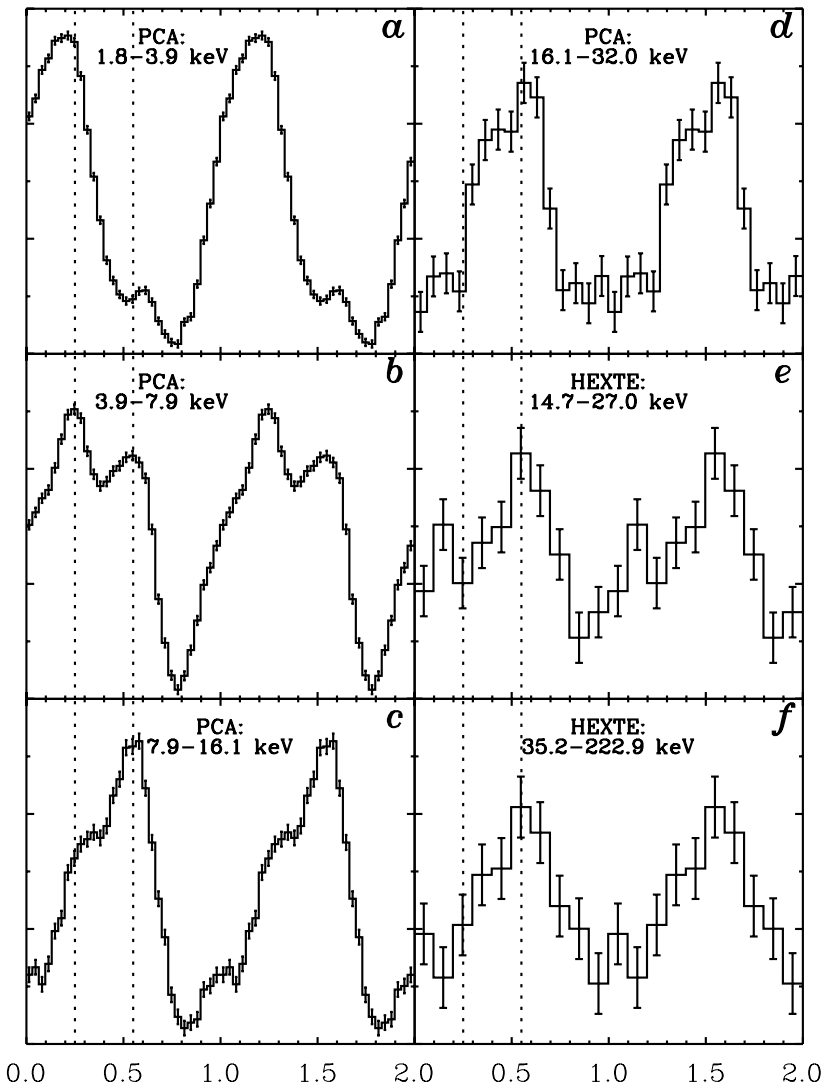
4U 0142+61

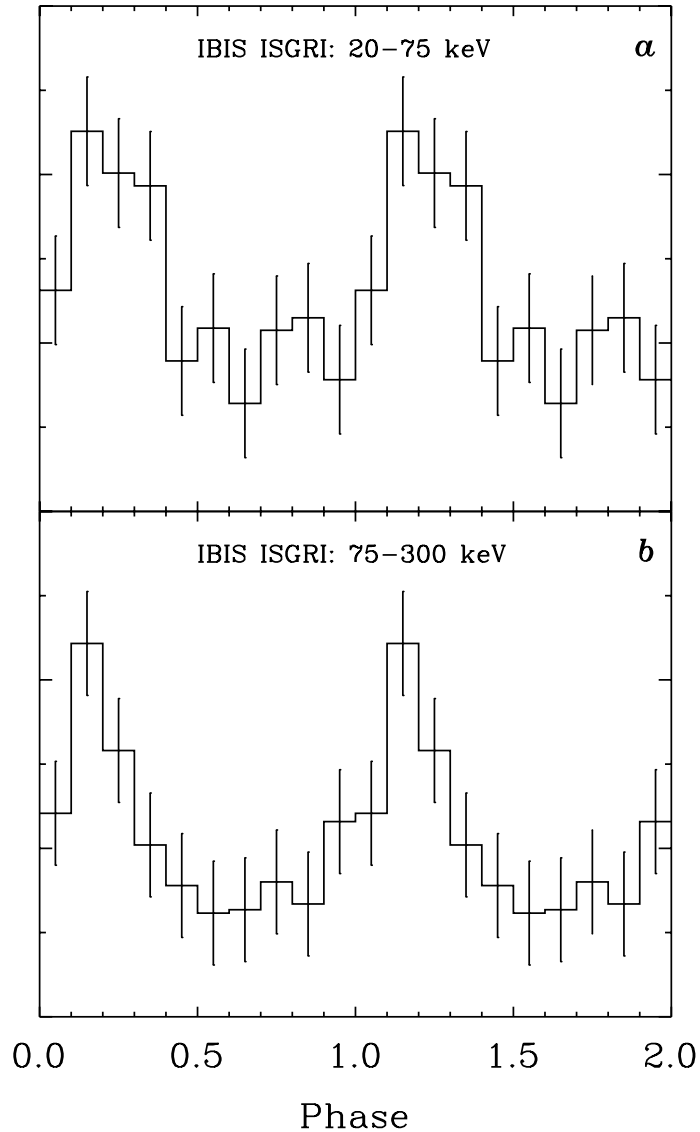


den Hartog et al. 2008ab

INTEGRAL/HEXTE Pulse Profiles of Magnetar J1708-4009

Kuiper et al. (2006)



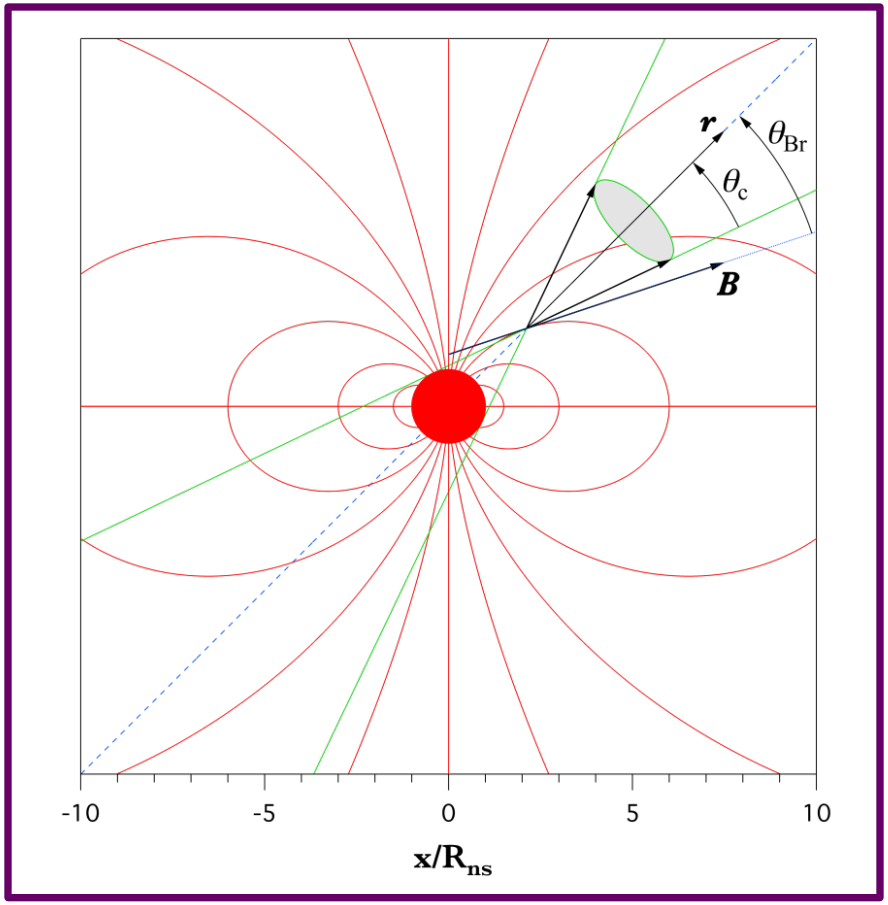


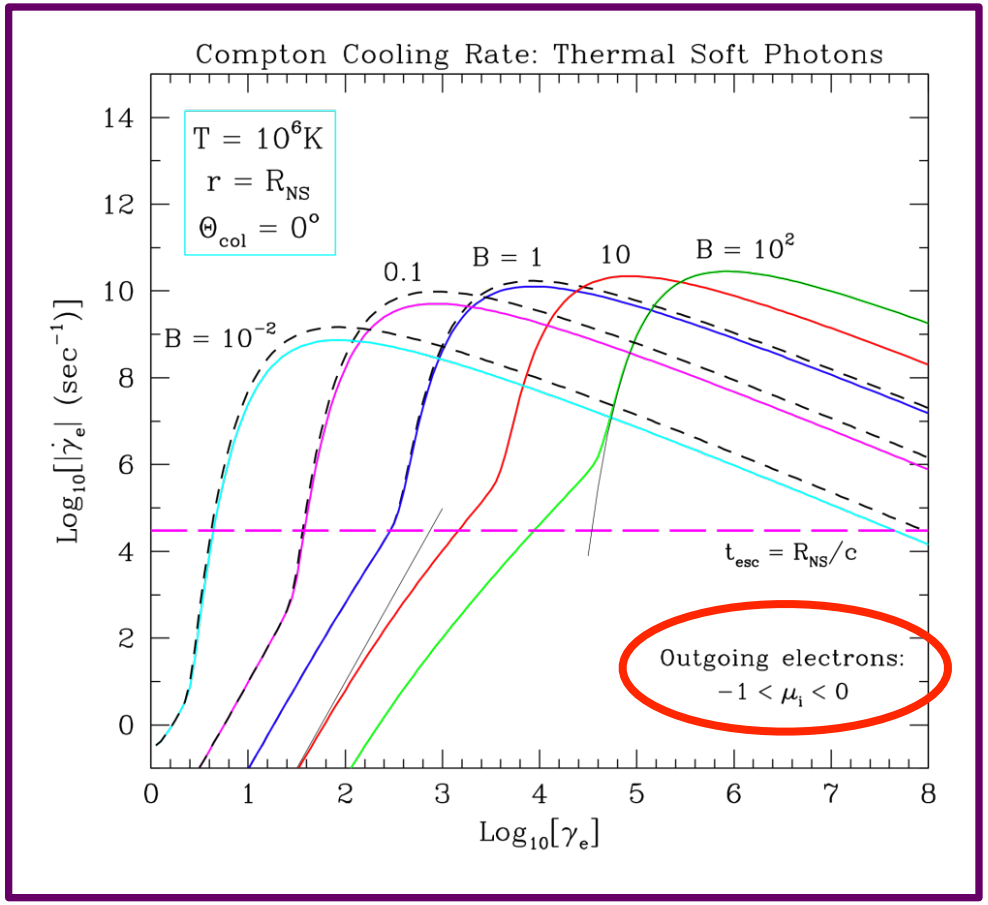
Hard X-ray Tail Modeling

- Preferred hypothesis is the resonant Compton upscattering model (Baring & Harding 2007; Fernandez & Thompson 2007; Nobili, Turolla & Zane, 2008; Beloborodov 2013ab, Wadiasingh et al. (2018) and later papers):
  - non-thermal hard X-rays are spawned by inverse Compton heating of soft, atmospheric photons by relativistic electrons.
- The electrons are presumed to be accelerated probably along closed field lines, by static electric potentials, or dynamic ones associated with large scale currents and twists in the magnetic field (e.g. Thompson & Beloborodov 2005; Parfrey et al. 2013).
- **The activated portion of the closed region is largely unknown (6D particle distribution phase space — but somewhat simplified since charges move along B).**
- The putative locale of scattering is the inner magnetosphere, within 1-10 stellar radii of the surface.
- **We are the first to use full QED cross sections for the hard component modeling, important for B fields attained in magnetars**

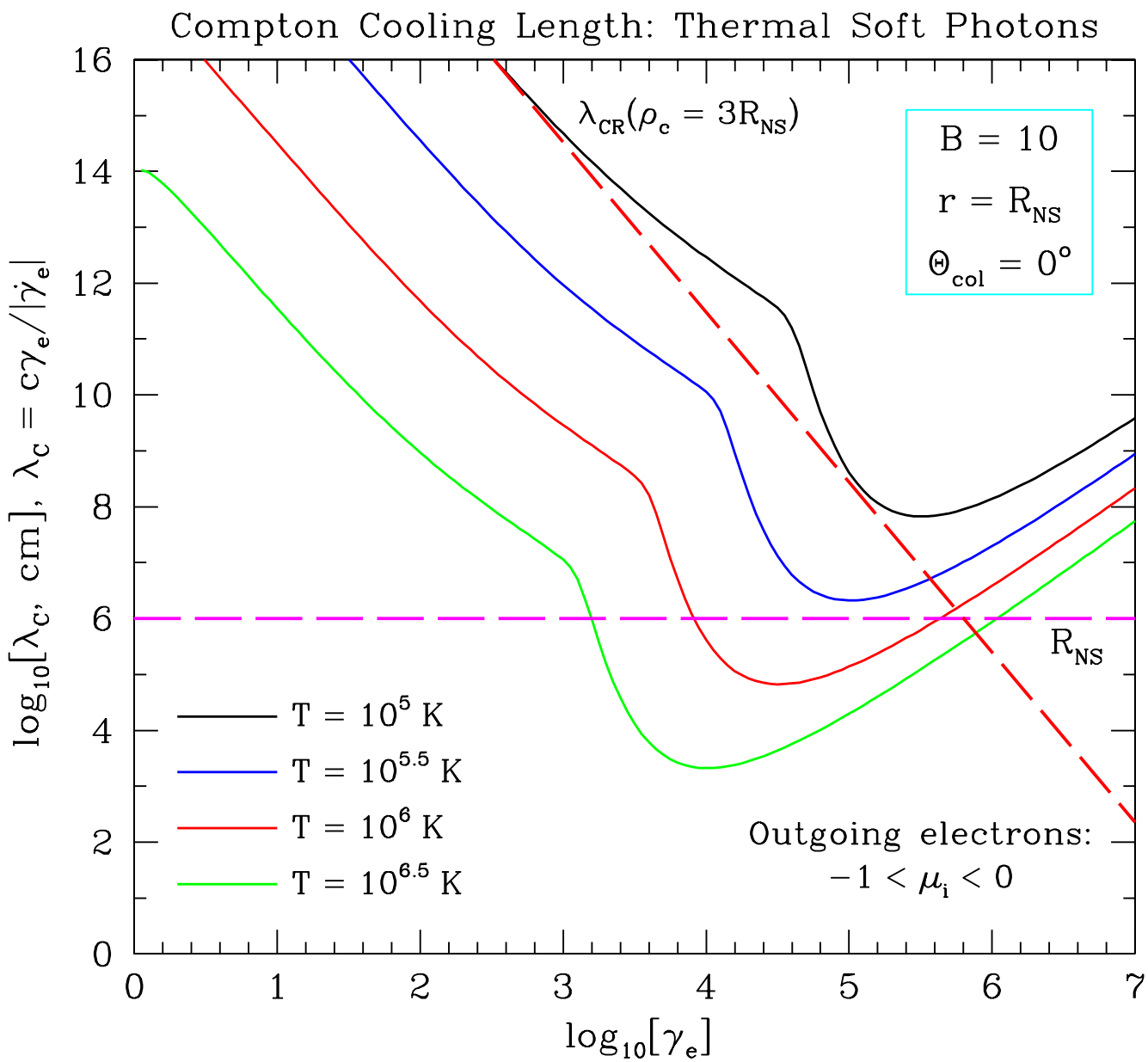
QED treatment necessary when $\hbar\omega_{\rm B} \sim m_e c^2$

High *B* Resonant Compton Cooling

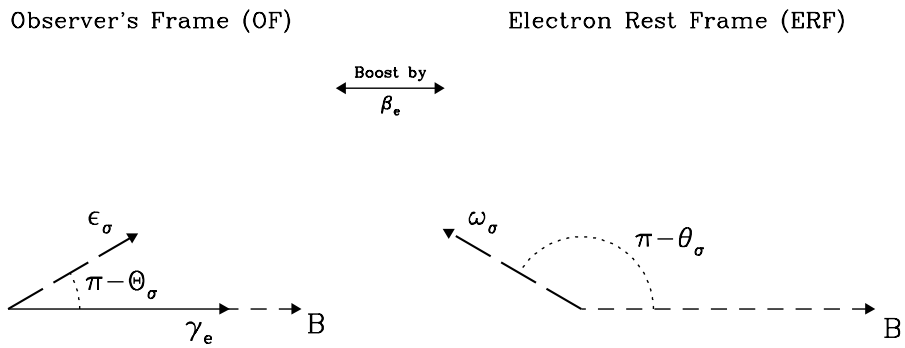


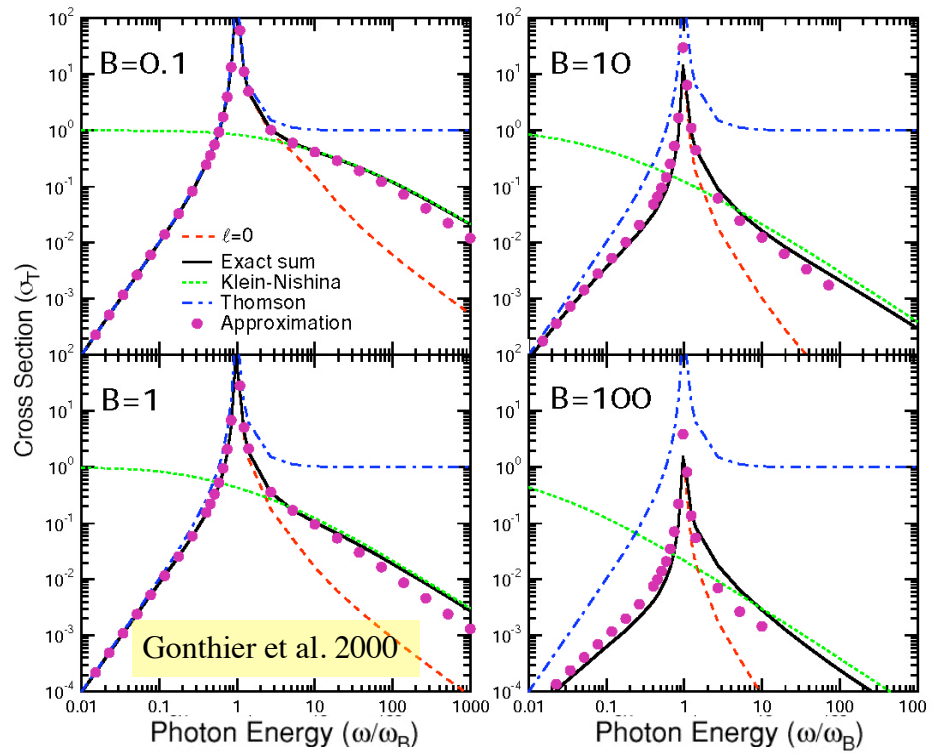


- Baring, Wadiasingh & Gonthier (2011) computed resonant Compton cooling rates for hemispherical soft photons in magnetospheric geometry as shown on left.
- Resonant cooling is strong for all Lorentz factors γ above the kinematic threshold for its accessibility; magnetic field dependence as a function of **B** is displayed at the right.

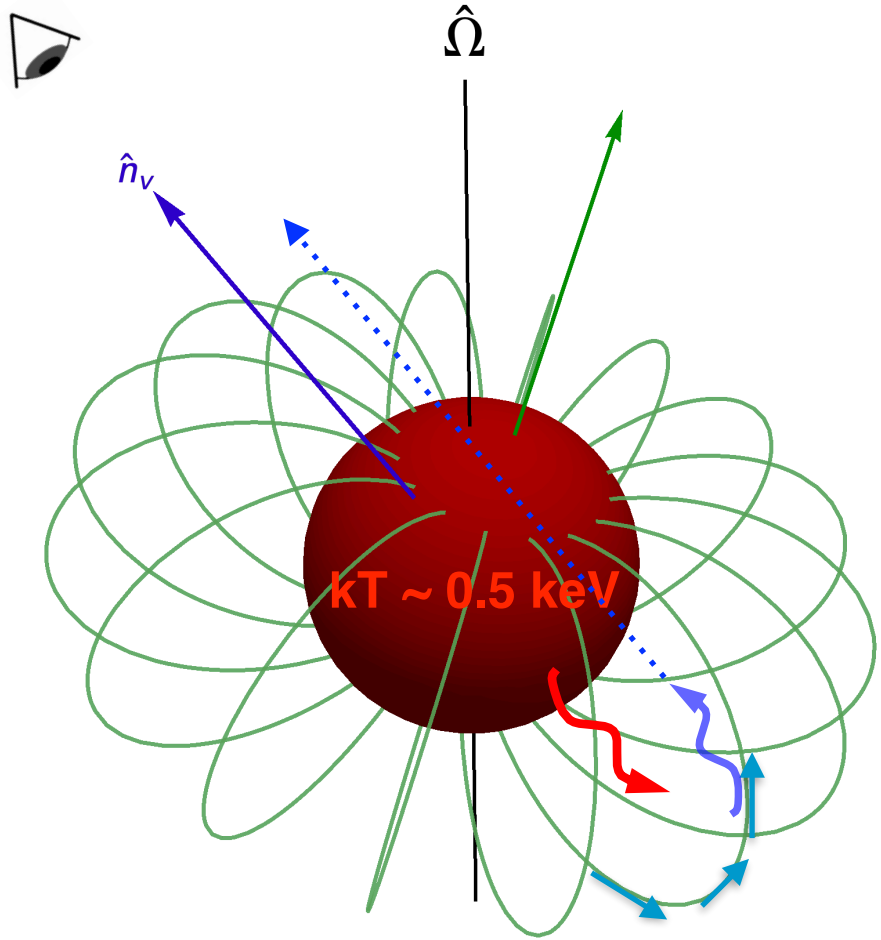

Compton Cooling Length: Thermal Soft Photons
$\lambda_{CR}(\rho_c = 3R_{NS})$
B = 10
r = R_{NS}
$\Theta_{col} = 0°$
R_{NS}
T = 10^5 K
T = $10^{5.5}$ K
T = 10^6 K
T = $10^{6.5}$ K
Outgoing electrons:
$-1 < \mu_i < 0$
$\log_{10}[\lambda_c,\ \mathrm{cm}],\ \lambda_c = c\gamma_e/|\dot{\gamma}_e|$
$\log_{10}[\gamma_e]$
0
2
4
6
8
10
12
14
16
0
1
2
3
4
5
6
7

$$\gamma\varepsilon_i(1-\beta\cos\theta_{kB,i}) \approx B \sim \gamma\varepsilon_f(1-\beta\cos\theta_{kB,f})$$

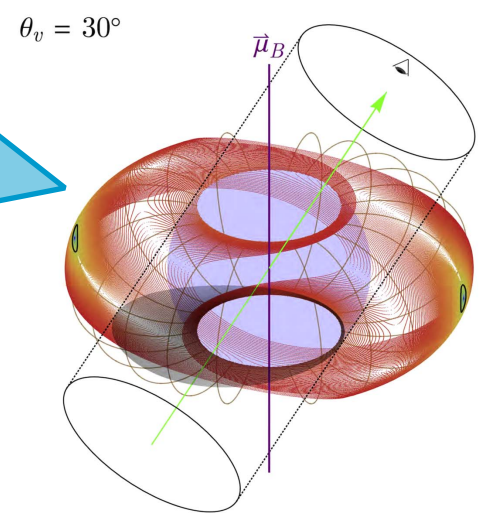




B=1 $\Longrightarrow$ B = 4.41 x 10^{13} G

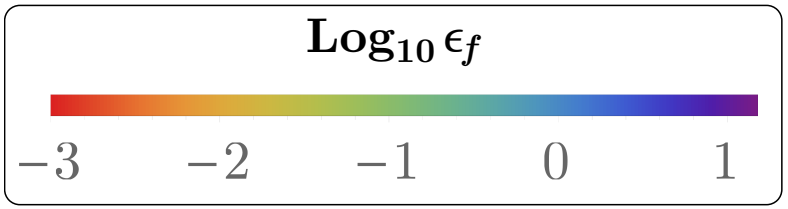


e^-/e^+ with Lorentz factor γ_e



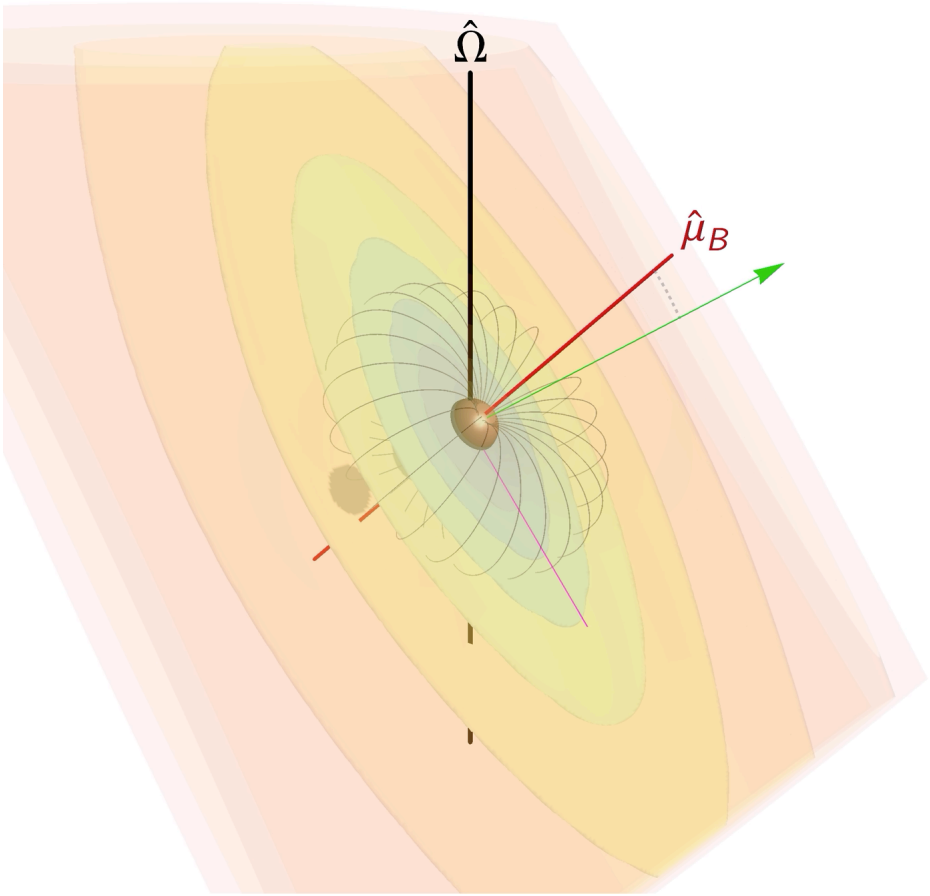
Outgoing Photons: Kinematic Resonasphere Surfaces

Red: low-energy resonant large angle scatterings
Blue: nearly head-on

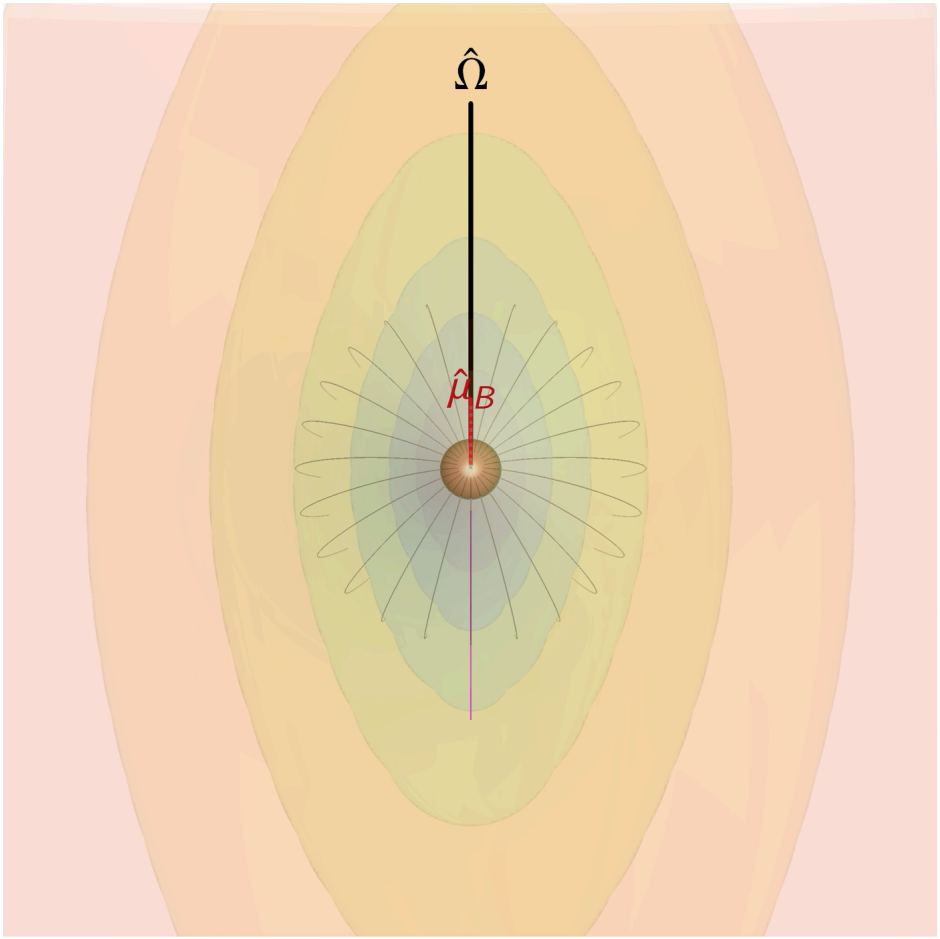


$\alpha = 50°$, $\zeta = 60°$

$B_p = 10$, $\gamma = 15$



Side View

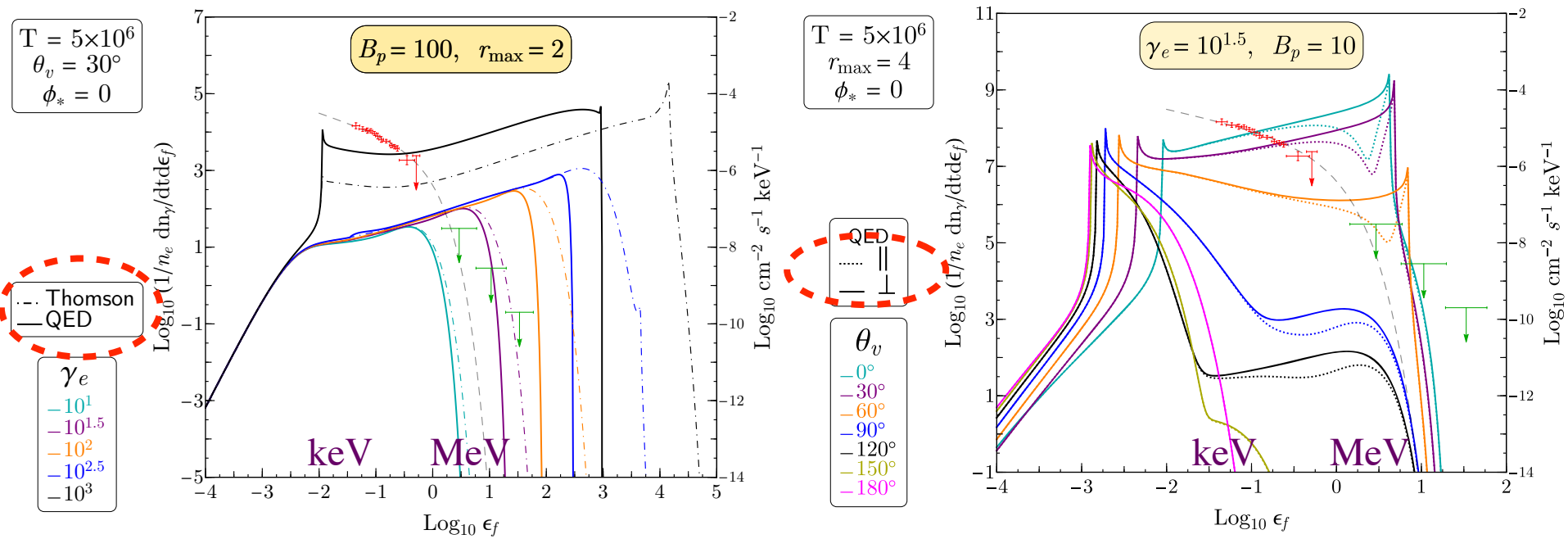


Observer View

Polarization-Dependent Resonant Compton Spectra

Wadiasingh et al. (2018)

Meridional loops only



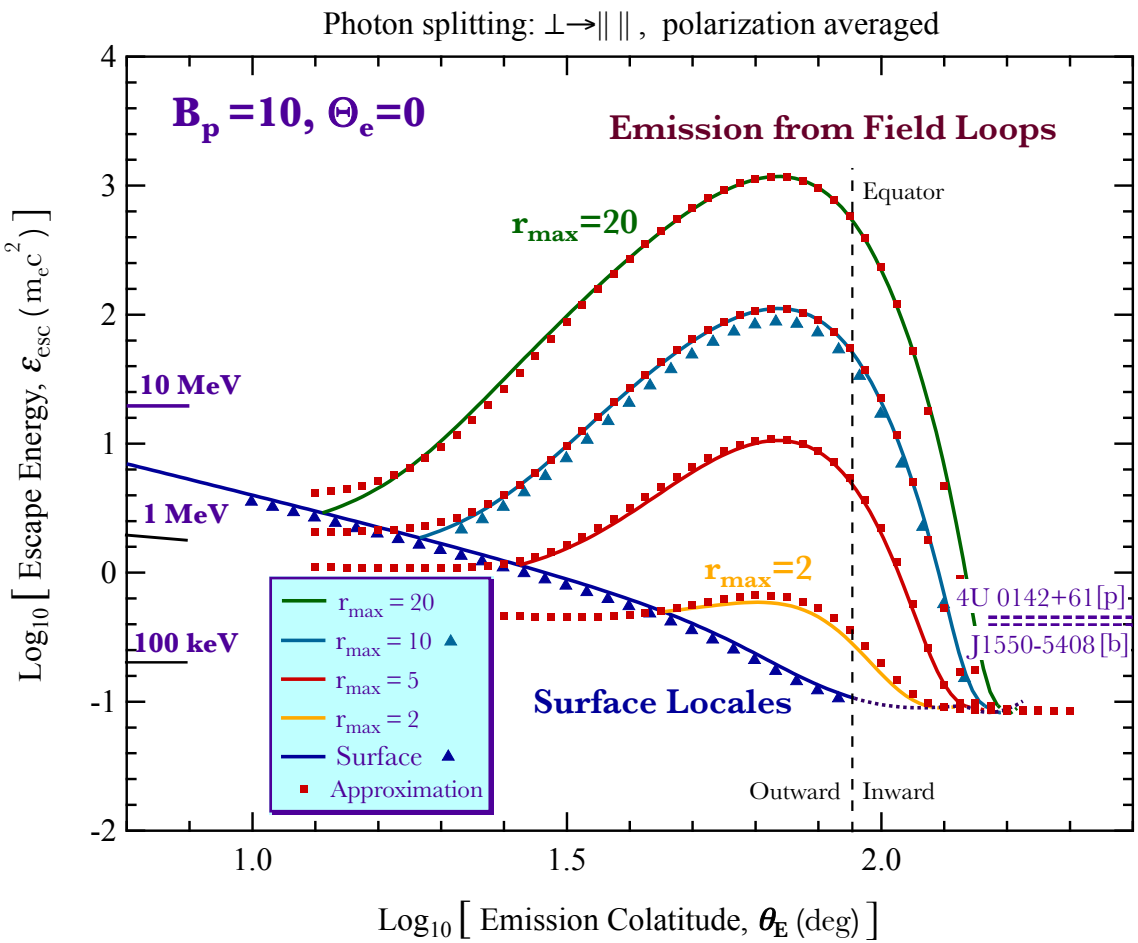
- Meridional field loops, varying γ_e: emission is harder for higher local ***B*** fields (Wadiasingh et al. 2018). Guide spectrum: e.g. AXP 4U 0142+61.
- Perpendicular (X-mode) exceeds parallel (O-mode) polarization at the highest energies.

Calculations of escape energies, $\gamma B \rightarrow \gamma\gamma$

- Magnetosphere is opaque to γ rays
- Resonant ICS — ⊥ dominates ∥ at higher energies
- Magnetic pair creation: only above the 2 $m_e c^2$ threshold — rate $R_{\parallel} > R_{\perp}$
- Photon Splitting: ⊥ → ∥ ∥ is the only allowed mode*

*CP symmetry of QED allows: ⊥ → ∥ ∥, ⊥ → ⊥ ⊥, and ∥ → ⊥ ∥ but kinematic selection rules (Adler 1971) when vacuum dispersion is small only allow ⊥ → ∥ ∥

It is an open question which modes are allowed due to the nonlinear/nonperturbative regime of QED at high B.

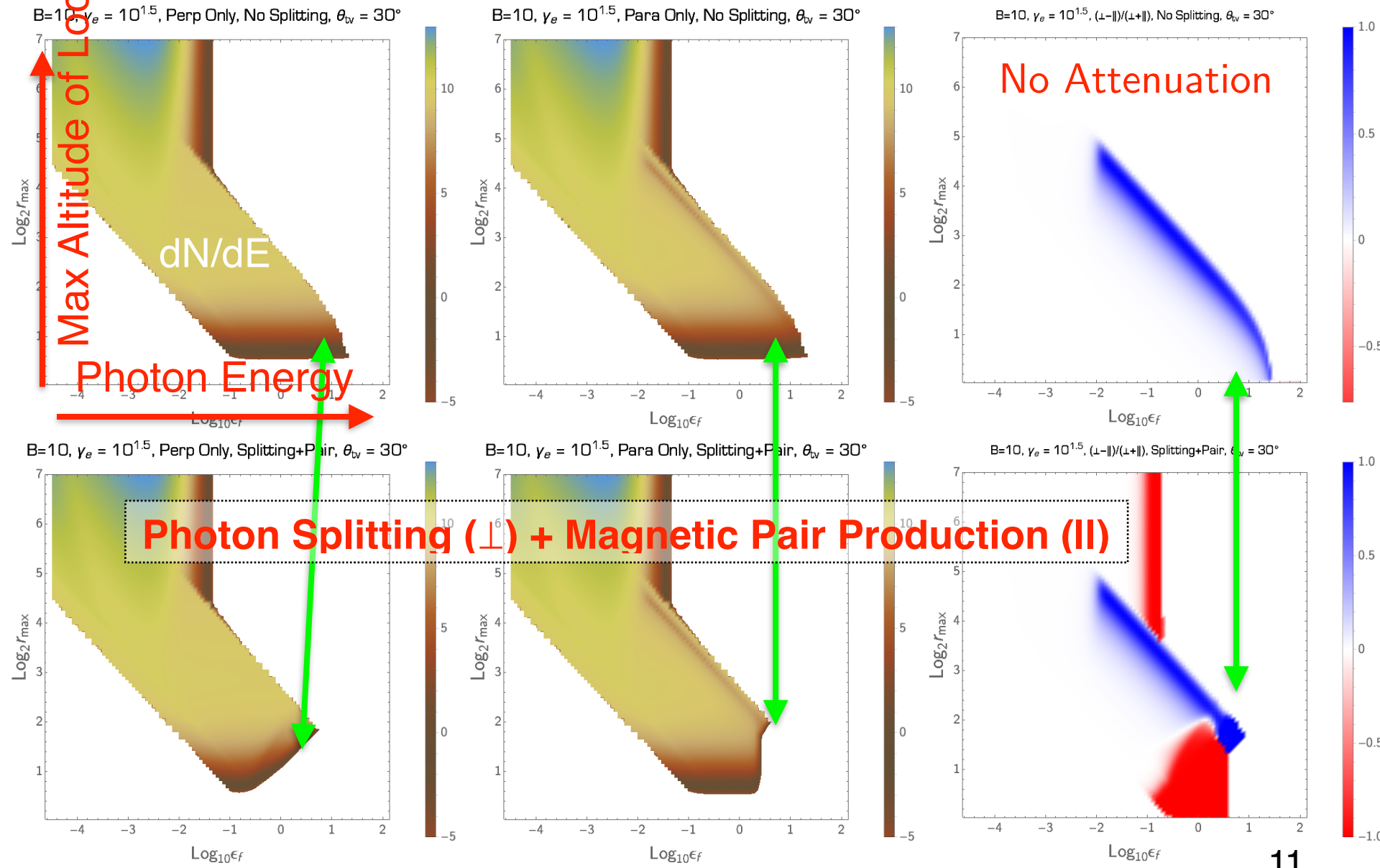


3rd order

$$T_{sp}(\omega) \approx \frac{\alpha^3}{10\pi^2}\frac{1}{\lambda\!\!\!^{-}}\left(\frac{19}{315}\right)^2 B'^6 \mathscr{C}(B')\omega^5 \sin^6\theta_{kB}$$

Hu et al. MNRAS

Towards Altitude Convolutions



Wadiasingh et al. (in prep)

Model Spectra and polarization

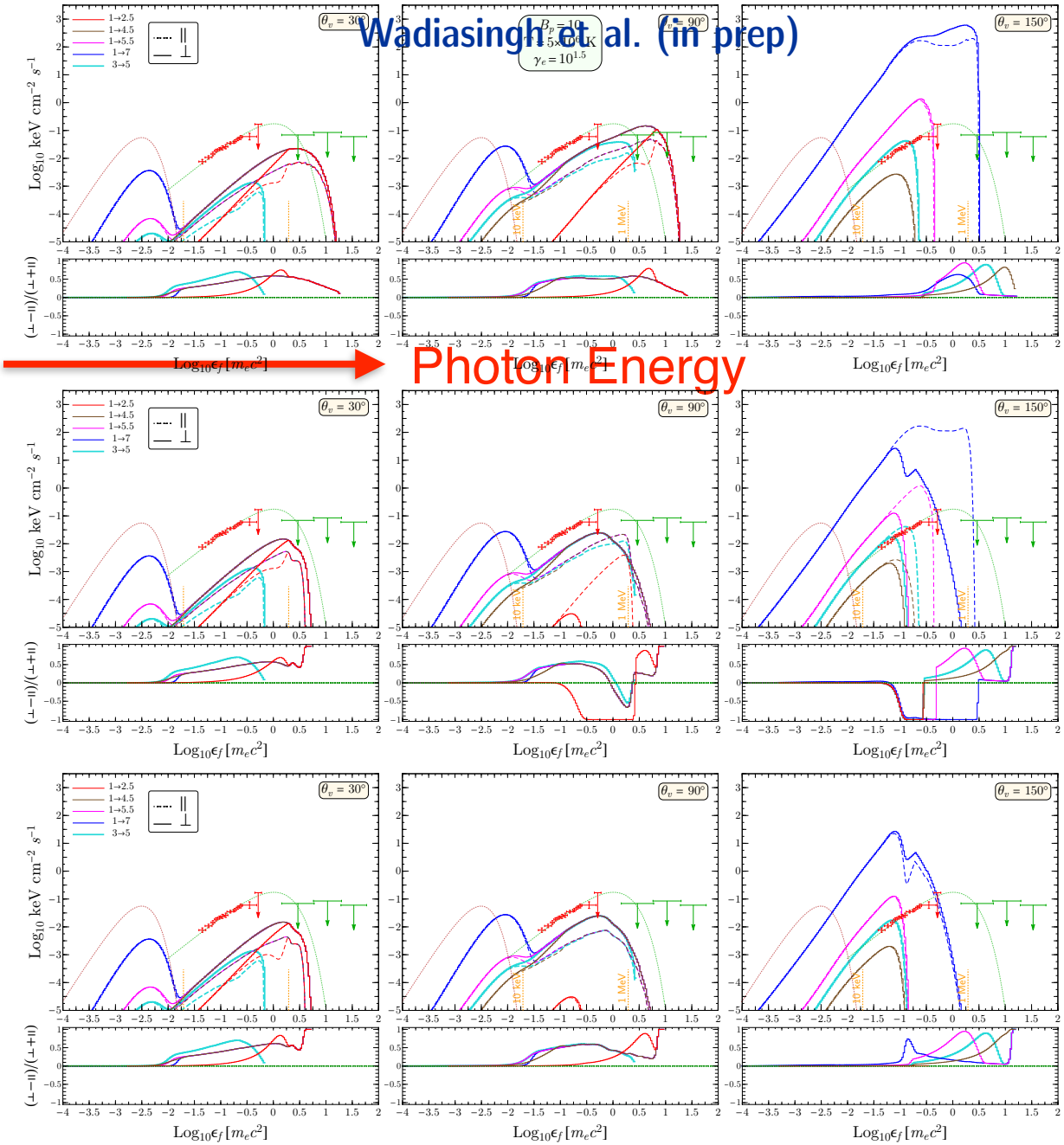
Wadiasingh et al. (in prep)

E²dN/dE

polarization degree

Photon Energy

Splitting Cutoffs



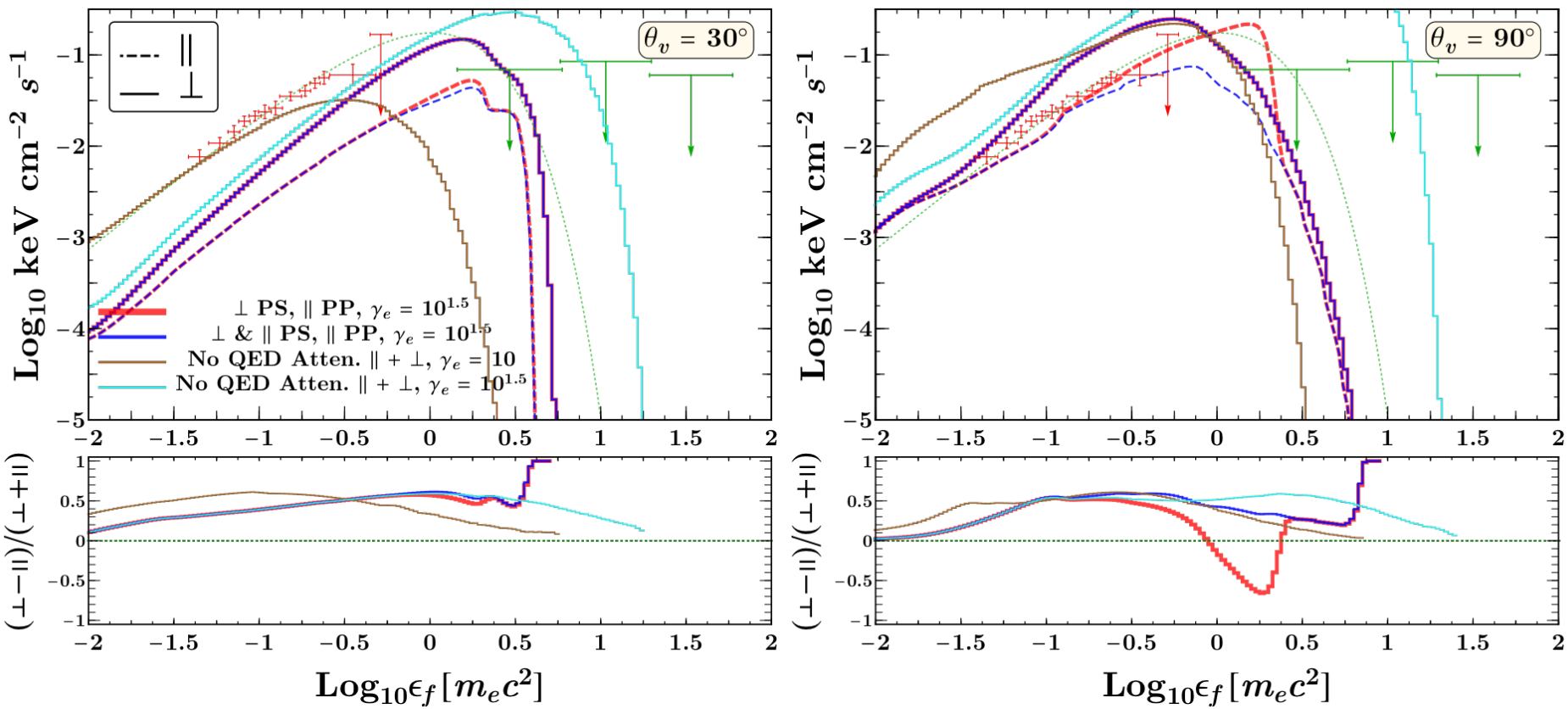
QED attenuation OFF

⊥ mode splitting only (weak vacuum dispersion limit)

⊥ and ∥ mode splitting (allowed by CP symmetry)

Spectro-Polarimetry Diagnostics

Wadiasingh et al.



- Phase-resolved model RICS spectra of a generic magnetar with arbitrary normalization overlaid on phase-averaged data for 4U 0412+61. The inverse Compton emission is highly polarized and spin-phase dependent.

Altitude Convolutions — Pulse Profiles, 50-160 keV

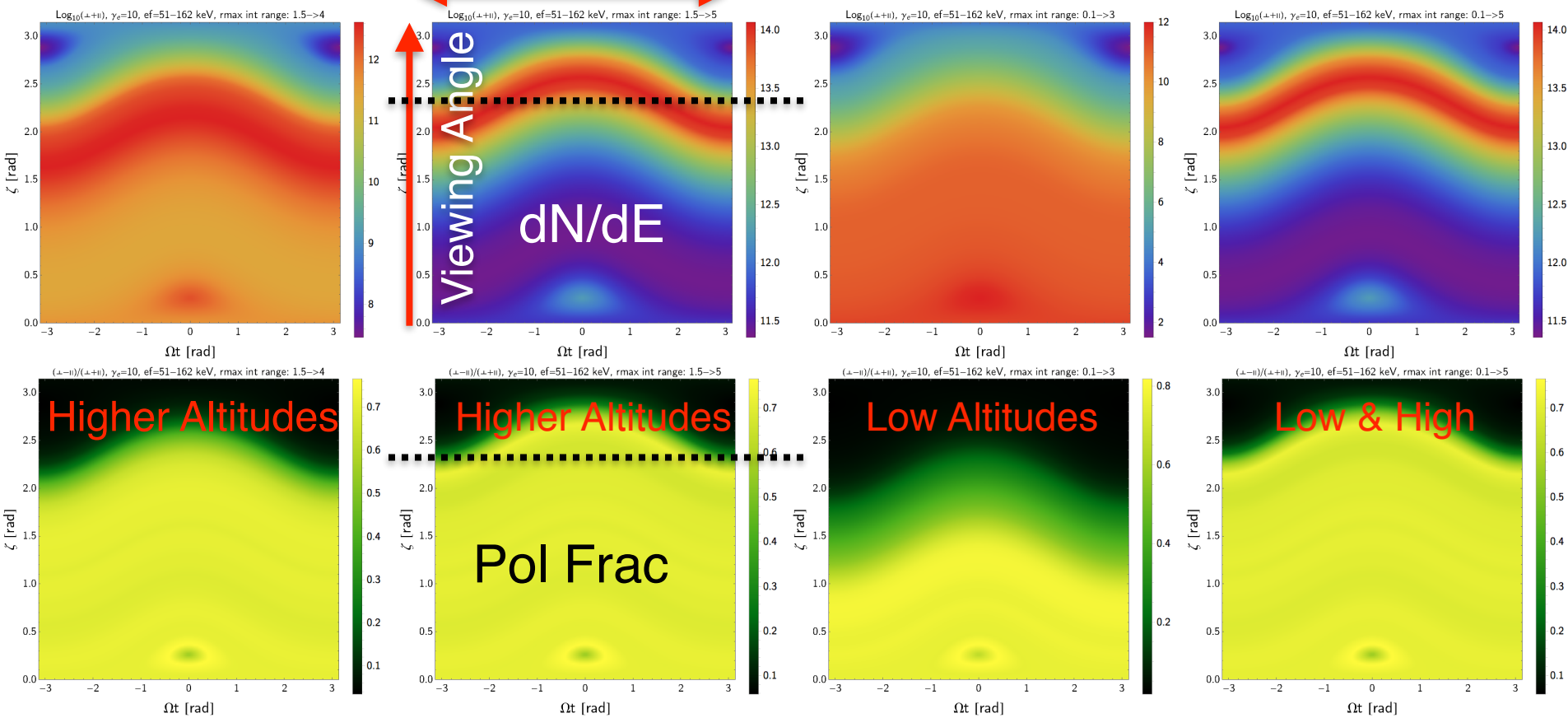
Wadiasingh et al. (in prep)

No QED opacities

$\alpha = 15°$

Spin Phase

$B_p = 10, \gamma = 10$

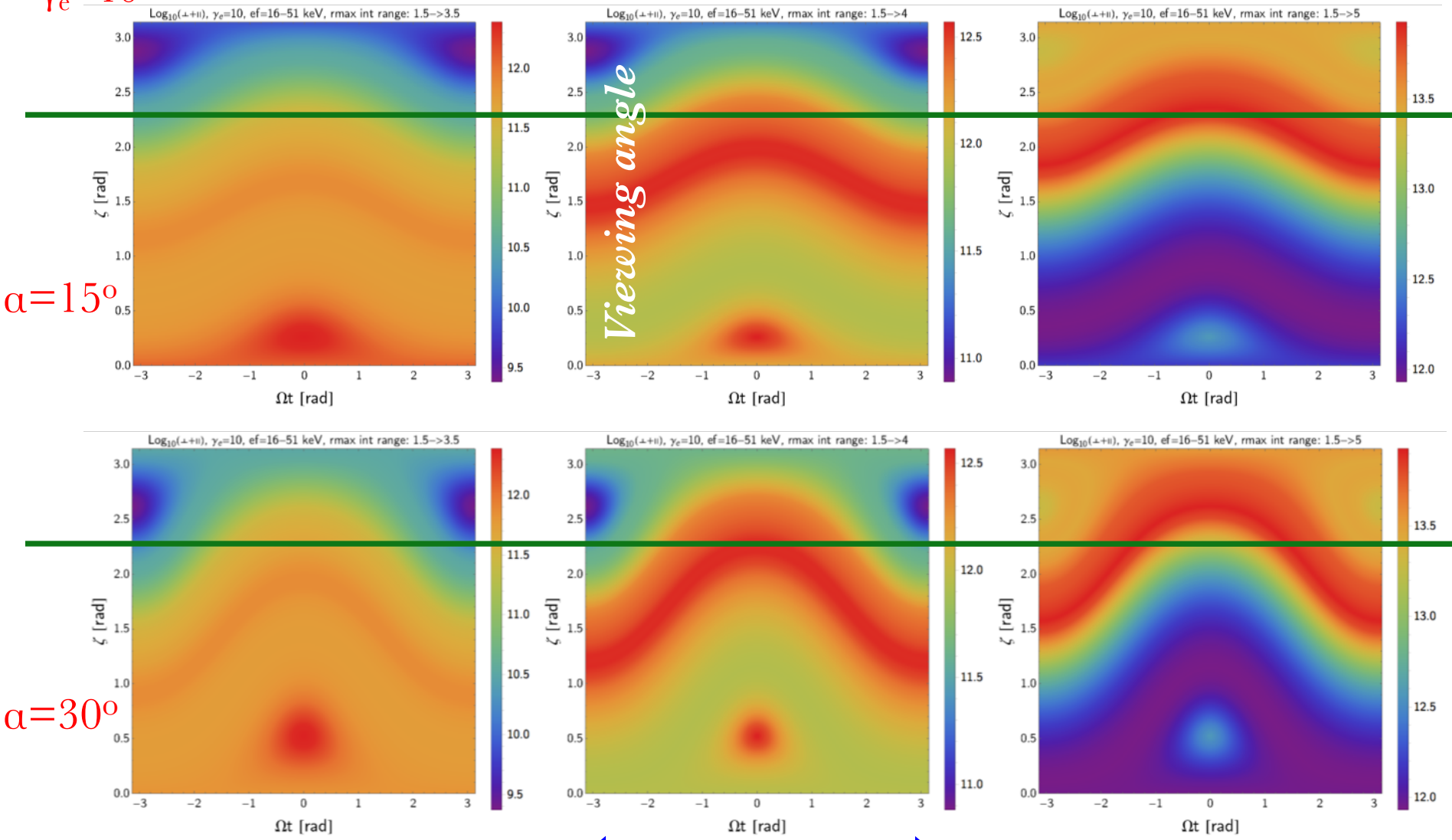


Different Altitude Convolutions

Intensity "Sky maps" 16-50 keV

Wadiasingh et al., in prep.

γ_e=10



Small toroidal volume

Pulse phase

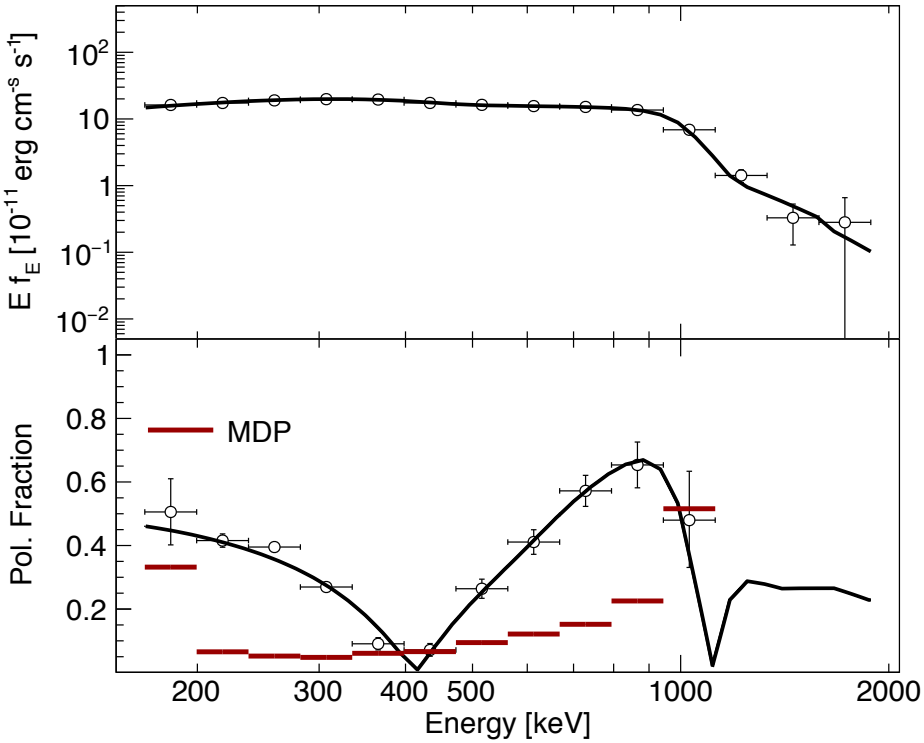
Large toroidal volume

AMEGO

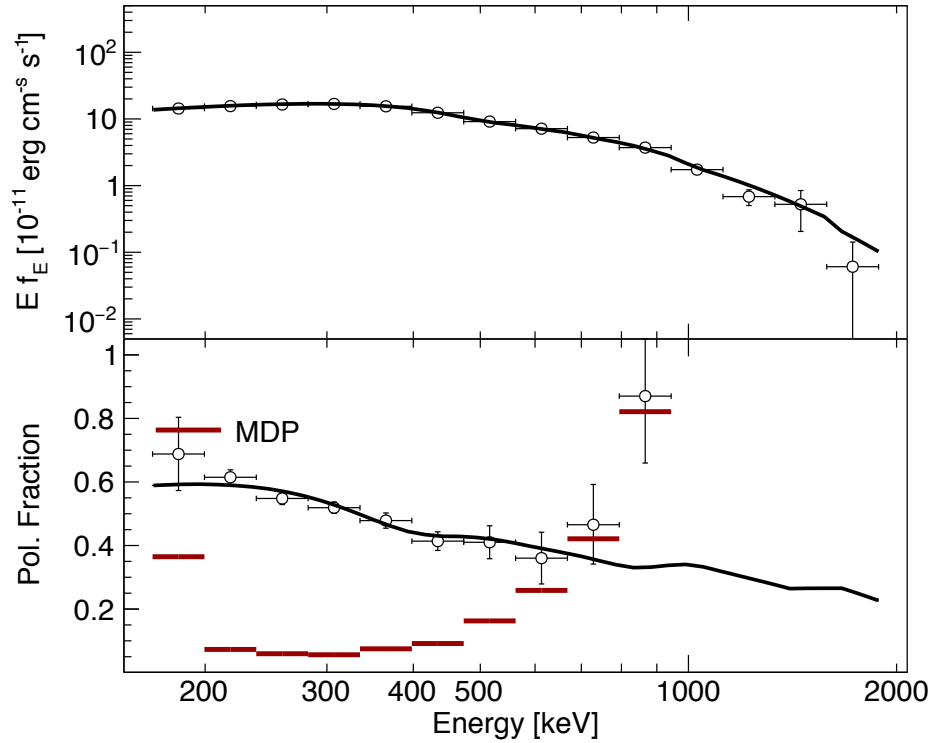
AMEGO can not only discover the spectral cut-off but assess its character

Below: GPST simulations of model spectra

See associated Astro2020 White Paper: 1903.05648



Perp mode splitting



Both splitting modes allowed

AMEGO spectropolarimetry can uncover QED magnetic photon splitting

What we can learn with a Compton telescope

- **Key:** assess the phase-resolved spectrum of magnetars, the hard tail cut-off energy, and the shape of the cut-off.
- **Key:** Using **spectropolarimetry**, assess how the cut-off regime is influenced by photon splitting and magnetic pair production $\Longrightarrow$ probe unknown regime of QED.
- Assess how the cut-off energy constrains the altitude of emission, and evaluate if the spectral shape and polarimetry can pinpoint the mechanism.
- Constrain the α, ζ of magnetars. Try to answer if α show any trends with age or other parameters.
- Appraise the magnetic field topology. Is it significantly nondipolar?
- Probe how are particles accelerated, and assess if it couples to the field topology.