Magnetars: Advances in the Resonant Compton Scattering Model

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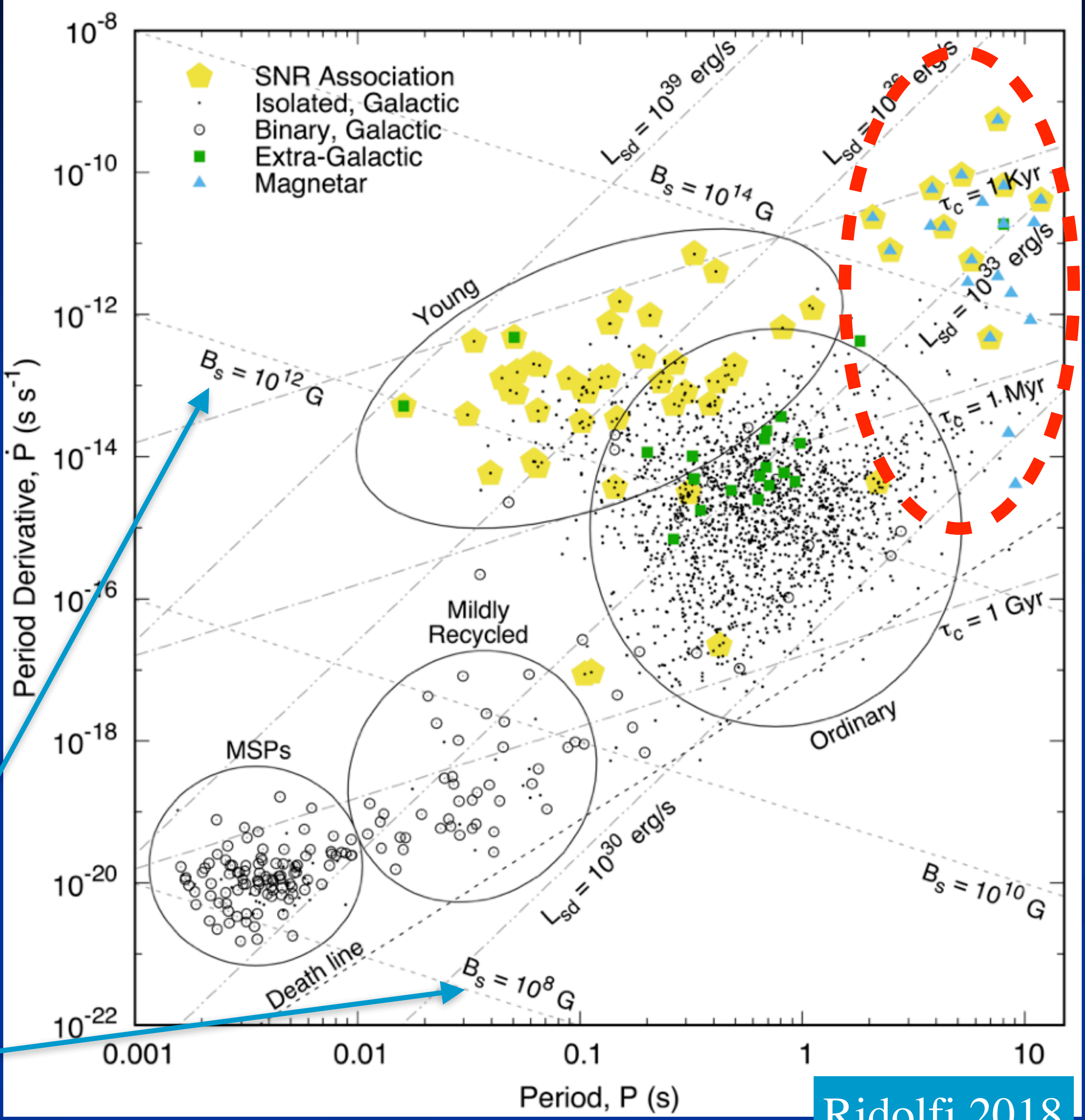
Magnetars in the P—Pdot diagram

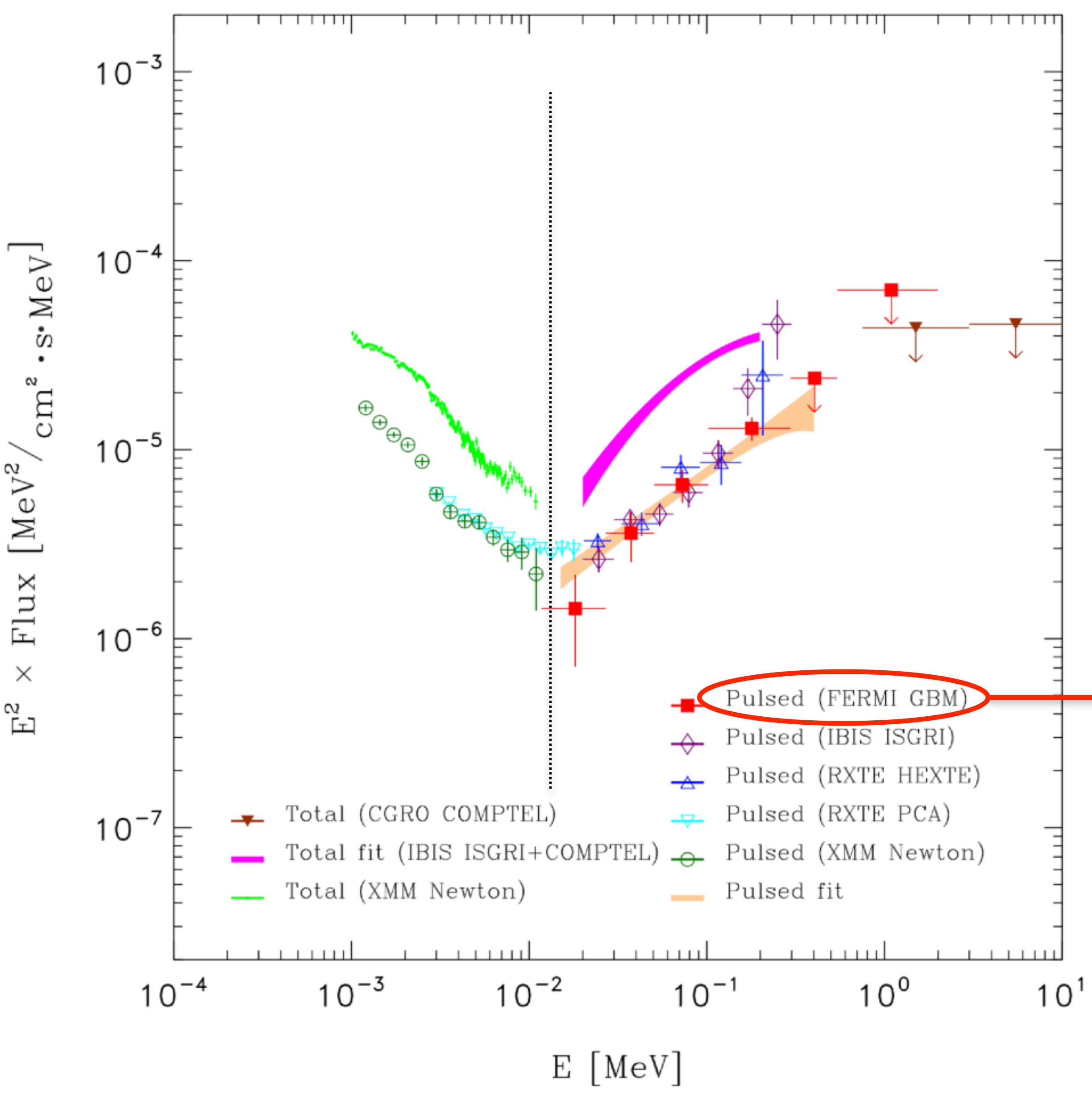
- Standard vacuum rotating dipole model allows for an estimate of the surface magnetic field;
- SGRs and AXPs are not rotation-powered — particle acceleration and emission must ultimately derive from energy stored in the magnetic field configuration

$$B_0 = \left(\frac{3Ic^3 P\dot{P}}{2\pi^2 R^6} \right)^{1/2}$$

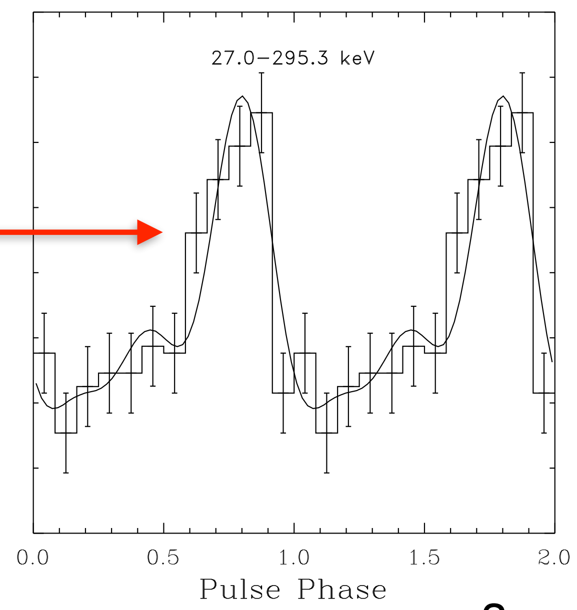


Ridolfi 2018

Persistent Emission: GBM/INTEGRAL/RXTE Spectrum for AXP 1RXJS J1708-4009

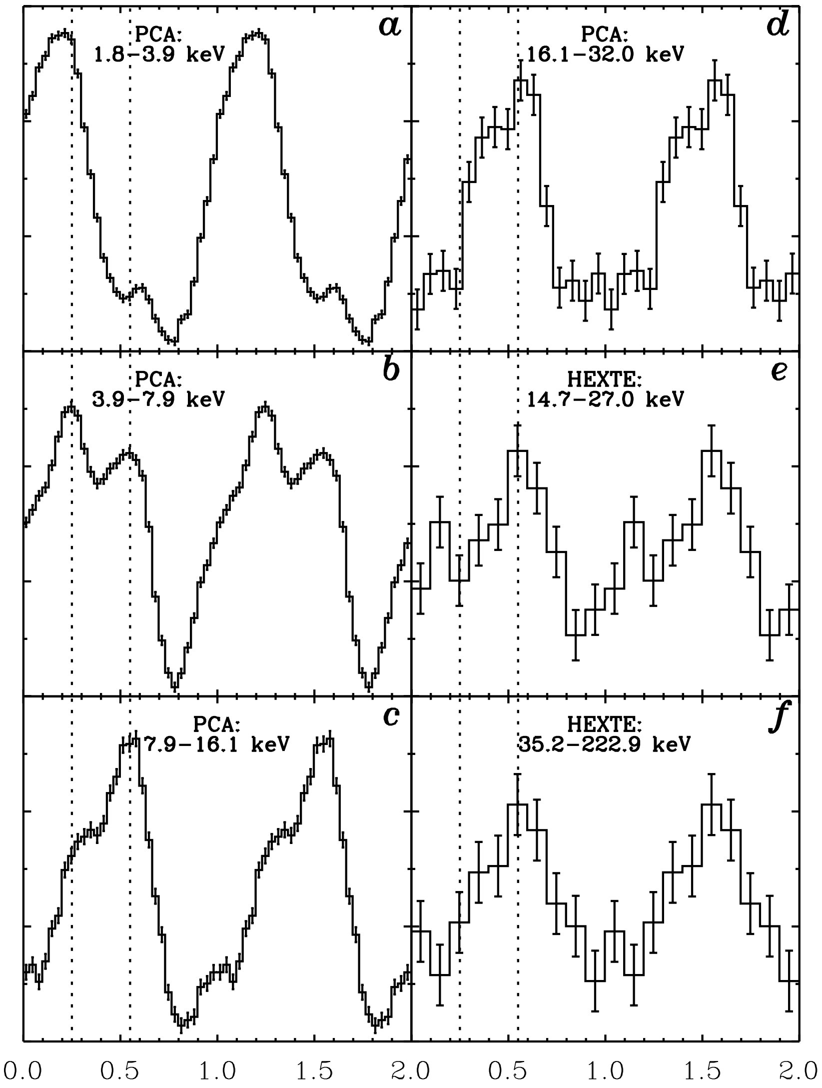


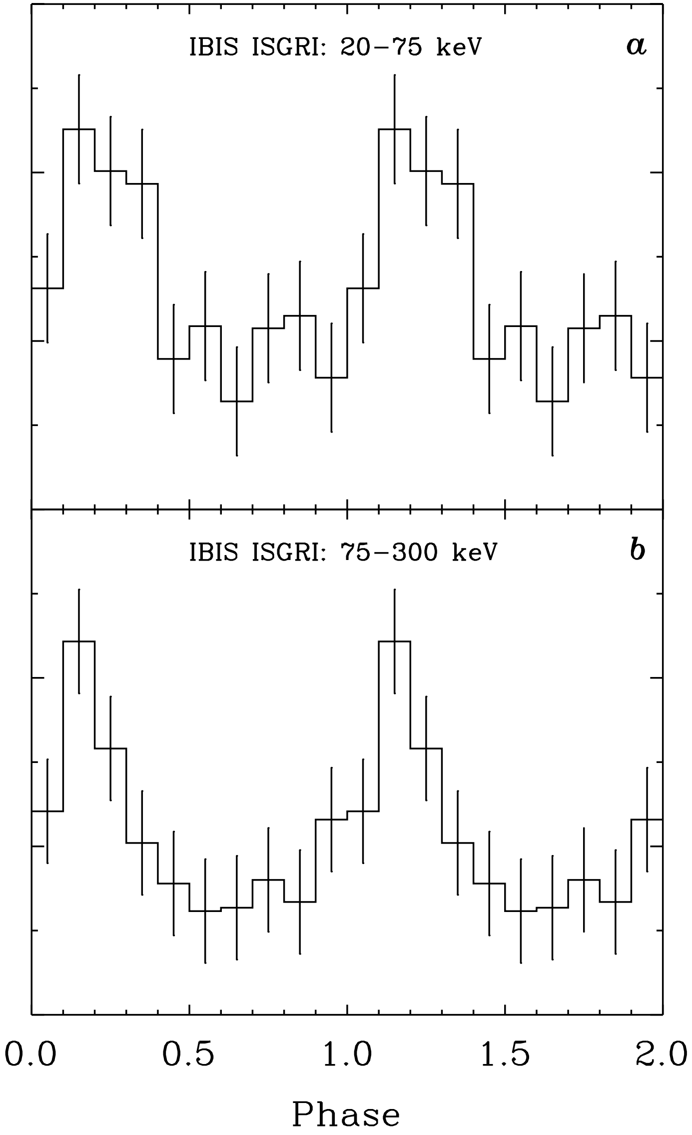
ter Beek (2012)



INTEGRAL/HEXTE Pulse Profiles of Magnetar J1708-4009

Kuiper et al. (2006)

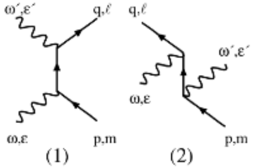




Hard X-ray Tail Modeling

- Preferred hypothesis is the resonant Compton upscattering model (Baring & Harding 2007; Fernandez & Thomson 2007; Nobili, Turolla & Zane, 2008; Baring, Wadiasingh & Gonthier 2011, 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).
- **Currents/charge densities along closed field lines far exceed Goldreich-Julian values.**
- **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.

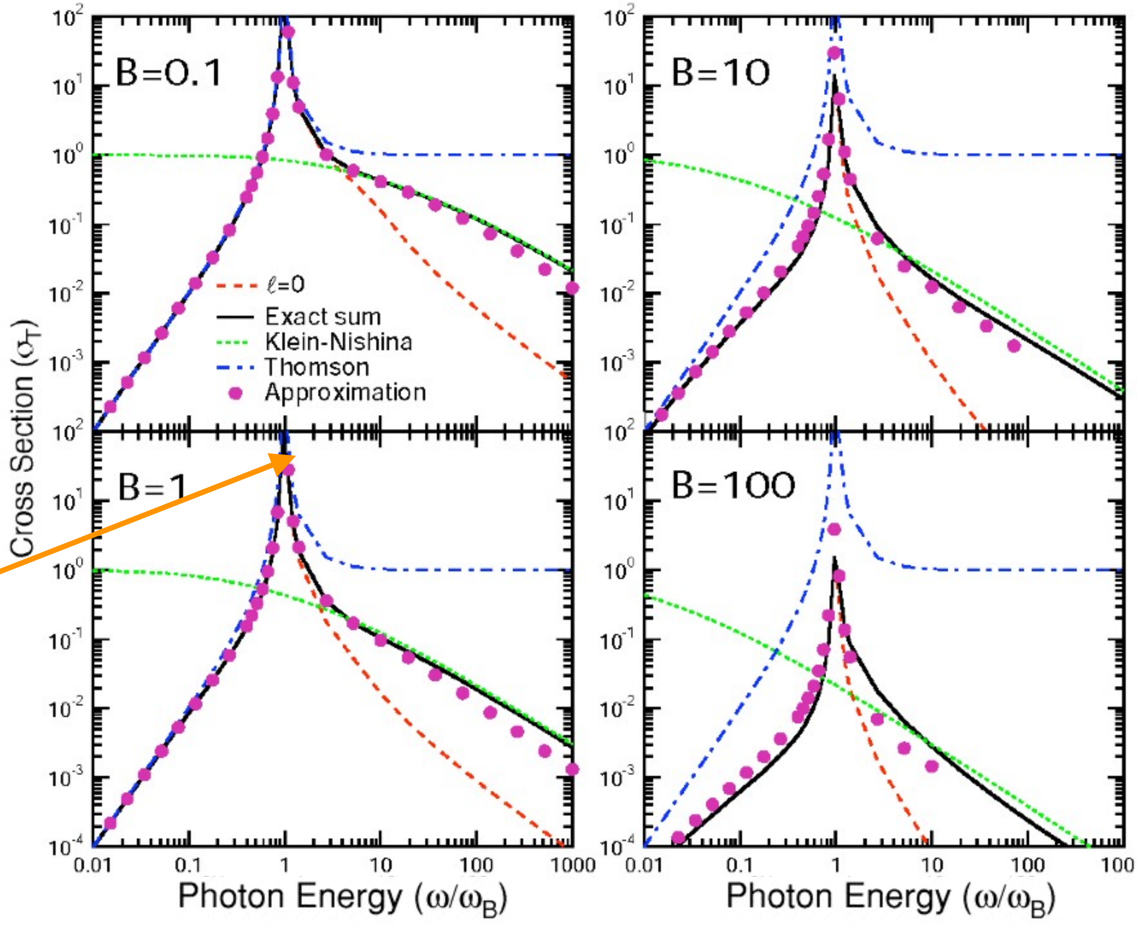
Resonant Compton Cross Sections



- Illustrated for photon propagation along **B**;
- In magnetar fields, cross section declines due to Klein-Nishina reductions;
- Resonance at cyclotron frequency eB/m_ec;
- Below resonance, l=0 provides contribution;
- In resonance, cyclotron decay width truncates divergence.

B=1 => B = 4.41 x 10^{13} G

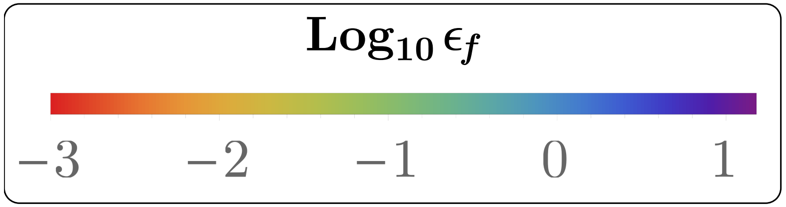
Gonthier et al. 2000



Process becomes effectively first order in the fine structure constant: the virtual electron behaves like a real one in the first excited state and spawns cyclotronic decay.

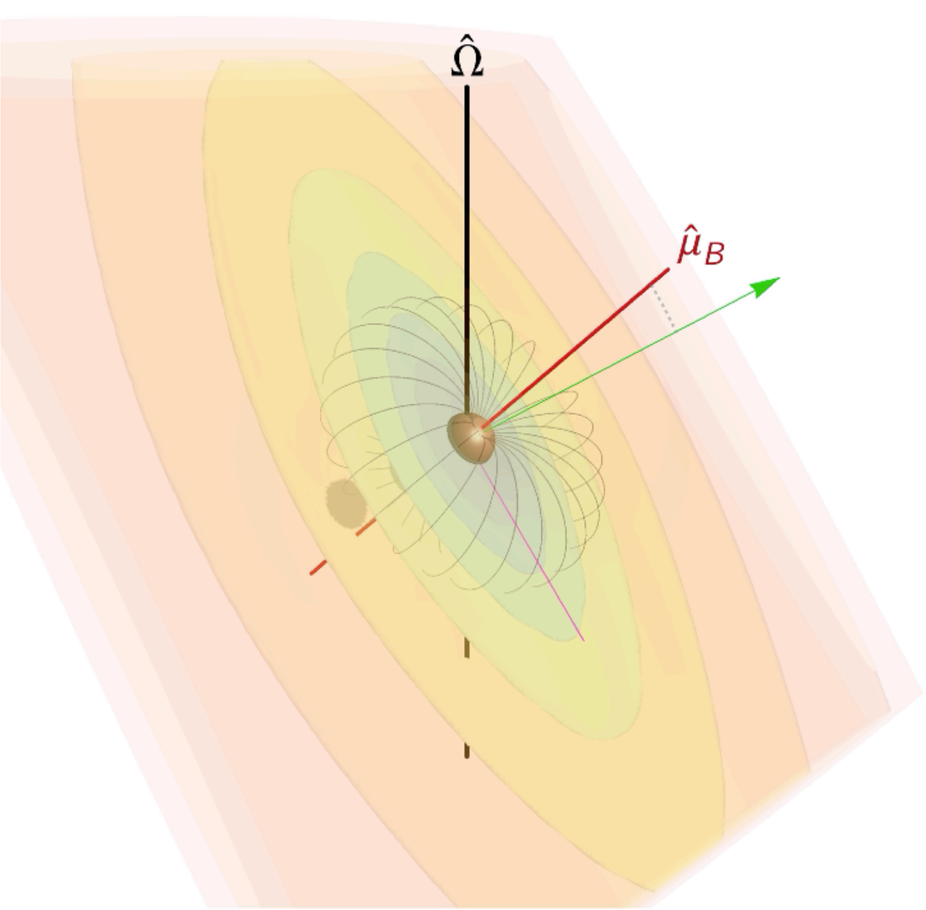
Phase and Energy Dependent Kinematic Resonasphere Surfaces

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

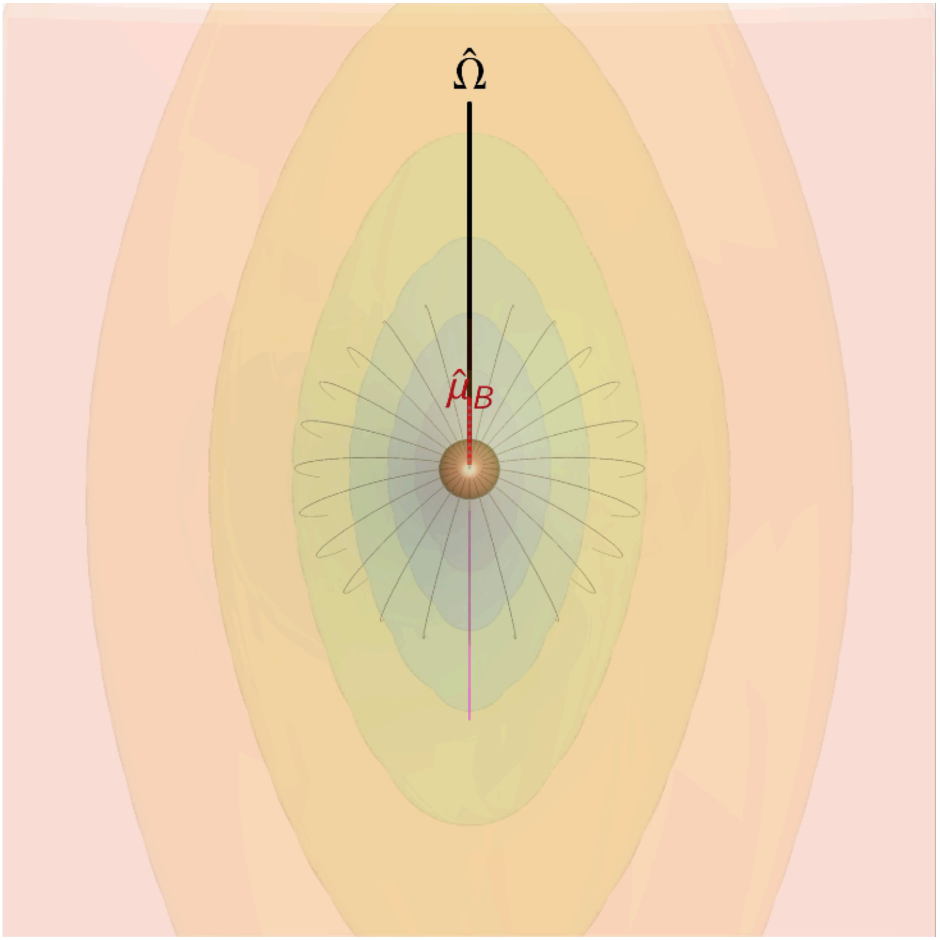


$\alpha = 50°$, $\zeta = 60°$

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



Side View



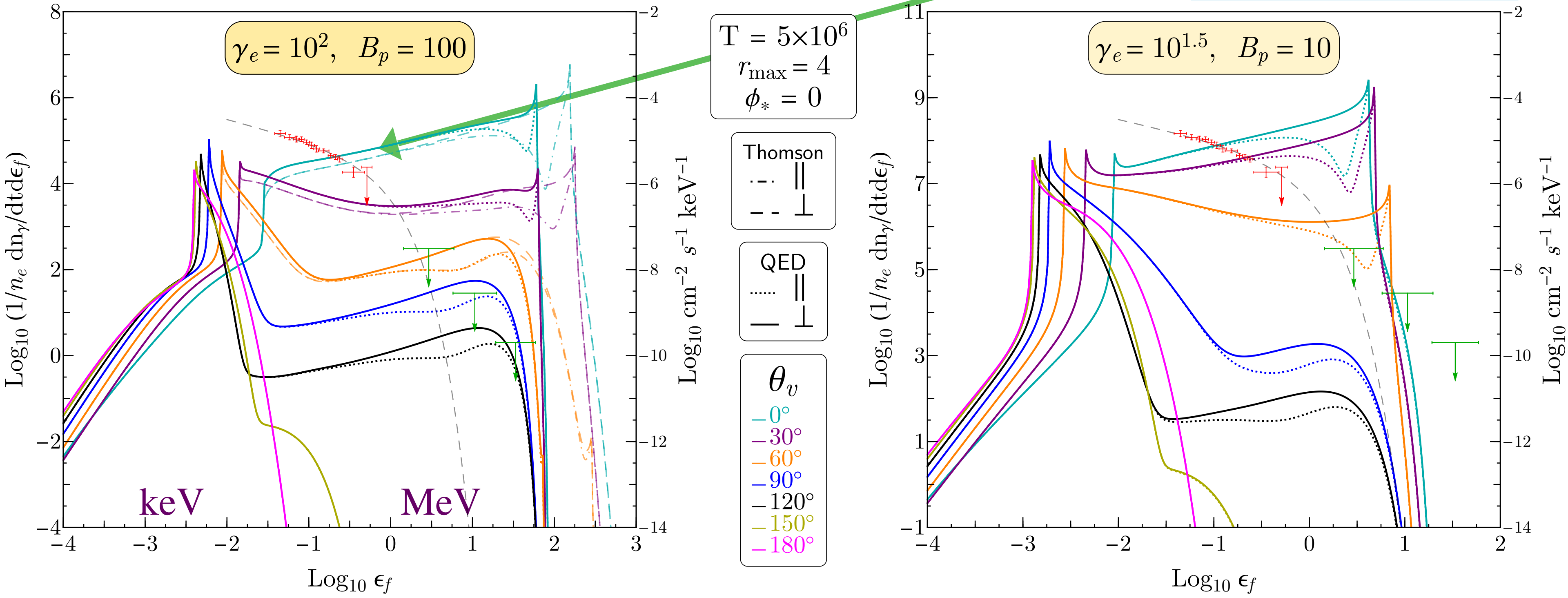
Observer View

Polarization-Dependent Resonant Compton Spectra

Wadiasingh et al. (2018)

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

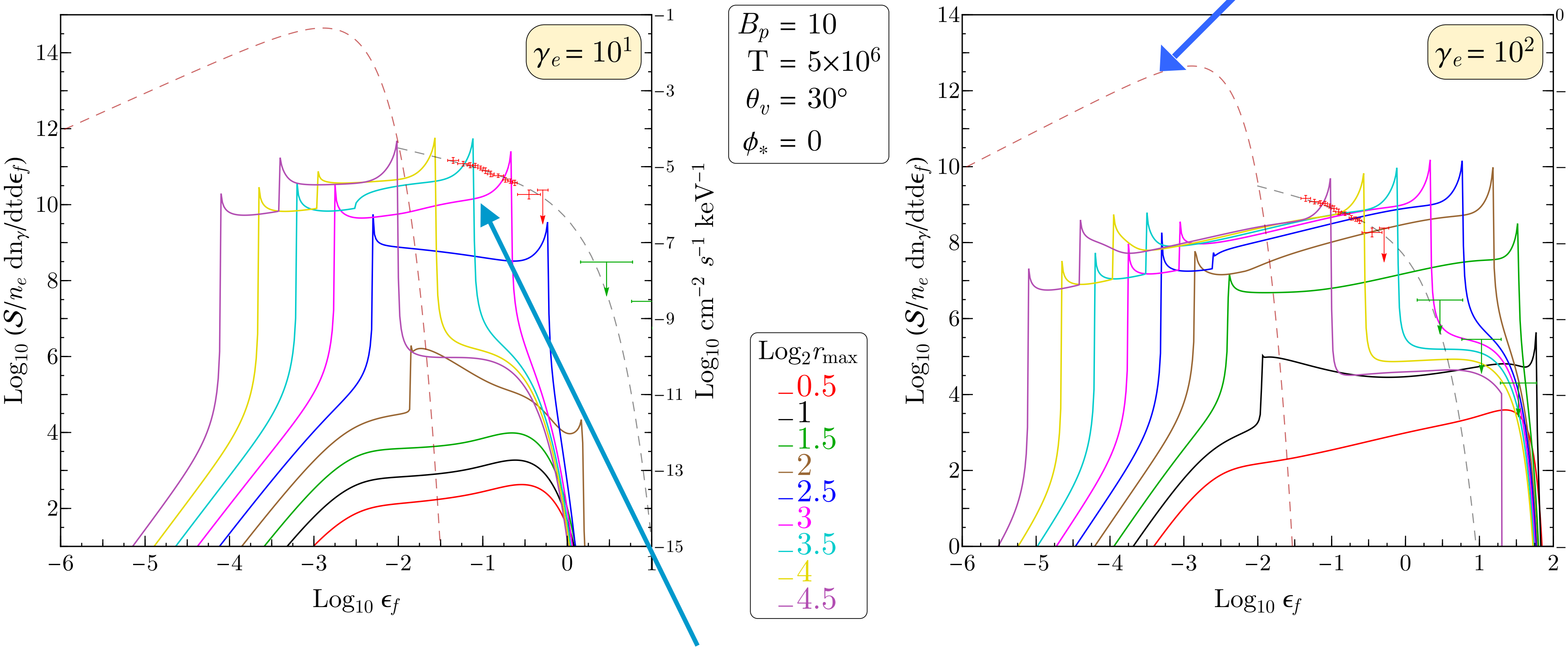
Photon splitting attenuates X-mode above ~50 keV.



- Perpendicular (X-mode) exceeds parallel (O-mode) polarization at the highest energies; photon splitting will mute this above 50 keV.

Upscattering Spectra: Field Foot-Point Influences

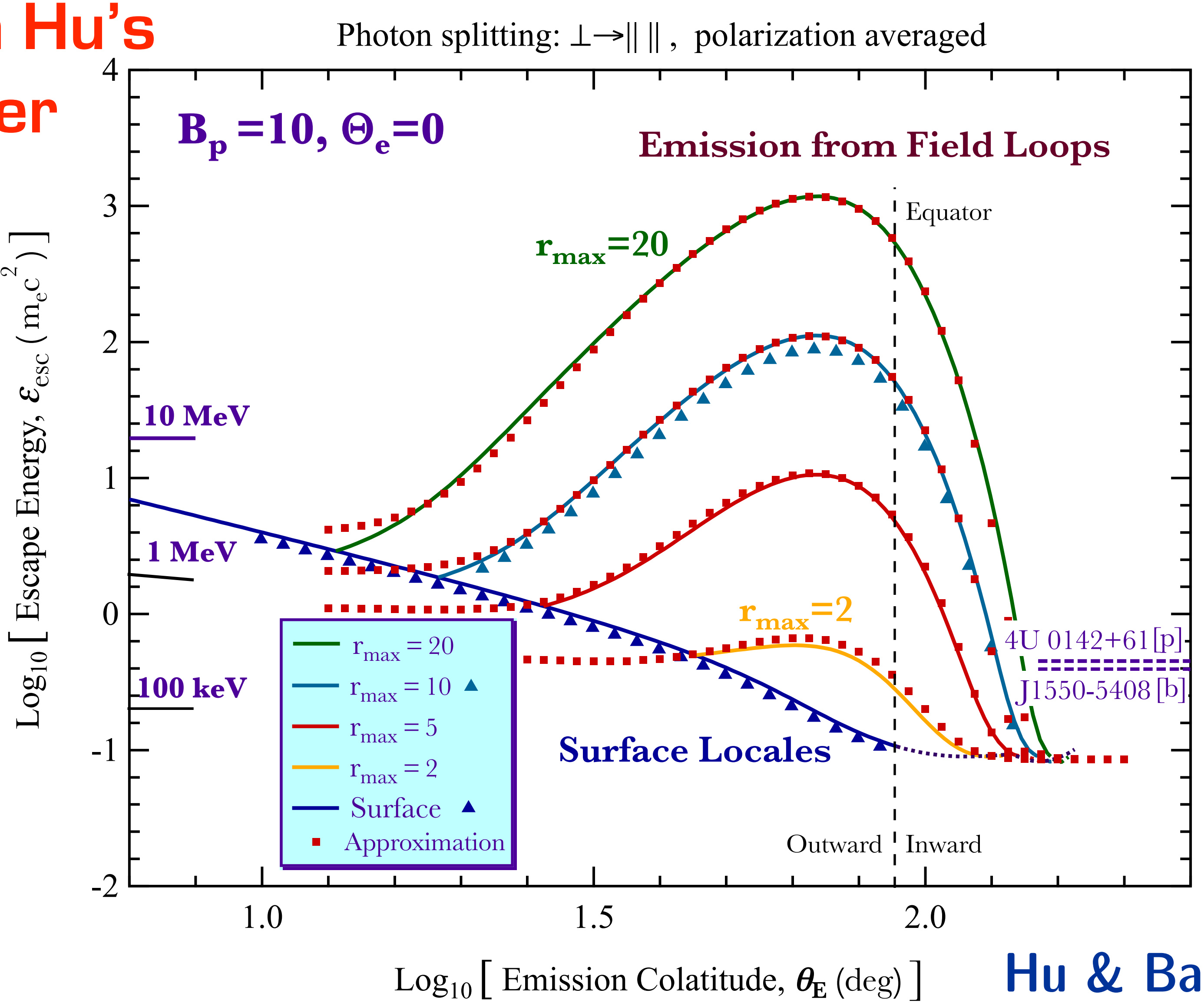
Surface thermal emission swamps Resonant Compton components at low energies



- Spectral summations over various foot-point colatitudes yield an envelope that matches typical hard tail spectra, provided that $\gamma < 10$.
- This suggests that models with more complete cooling and volumetric integrations will match the spectroscopy of hard tails.

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

See Kun Hu's poster

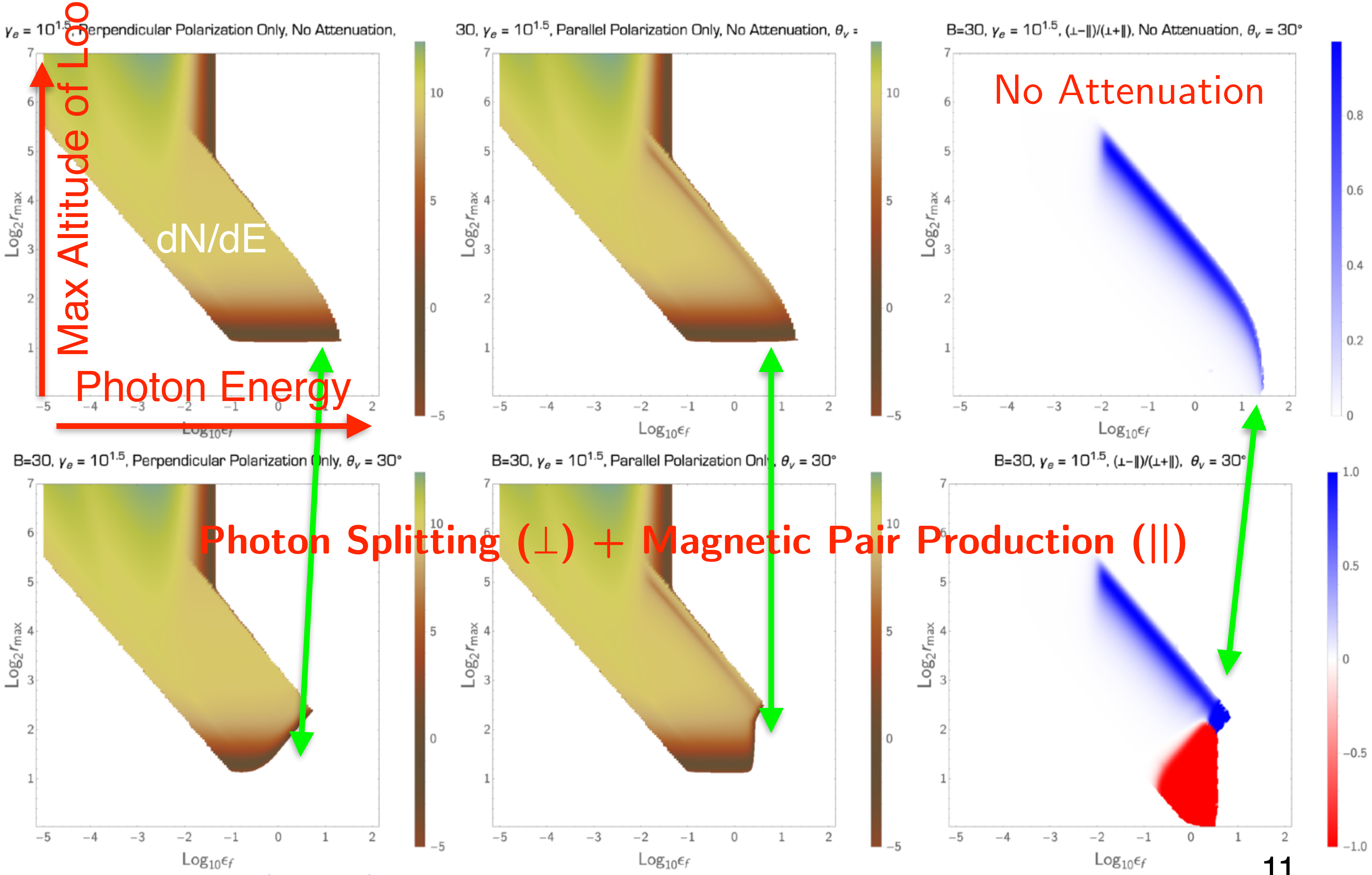


3rd order

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

Hu & Baring, in prep

Towards Altitude Convolutions



$\gamma_e = 10^{1.5}$, Perpendicular Polarization Only, No Attenuation,

30, $\gamma_e = 10^{1.5}$, Parallel Polarization Only, No Attenuation, θ_v =

B=30, $\gamma_e = 10^{1.5}$, (⊥−∥)/(⊥+∥), No Attenuation, θ_v = 30°

B=30, $\gamma_e = 10^{1.5}$, Perpendicular Polarization Only, θ_v = 30°

B=30, $\gamma_e = 10^{1.5}$, Parallel Polarization Only, θ_v = 30°

B=30, $\gamma_e = 10^{1.5}$, (⊥−∥)/(⊥+∥), θ_v = 30°

Max Altitude of Loops

Photon Energy

dN/dE

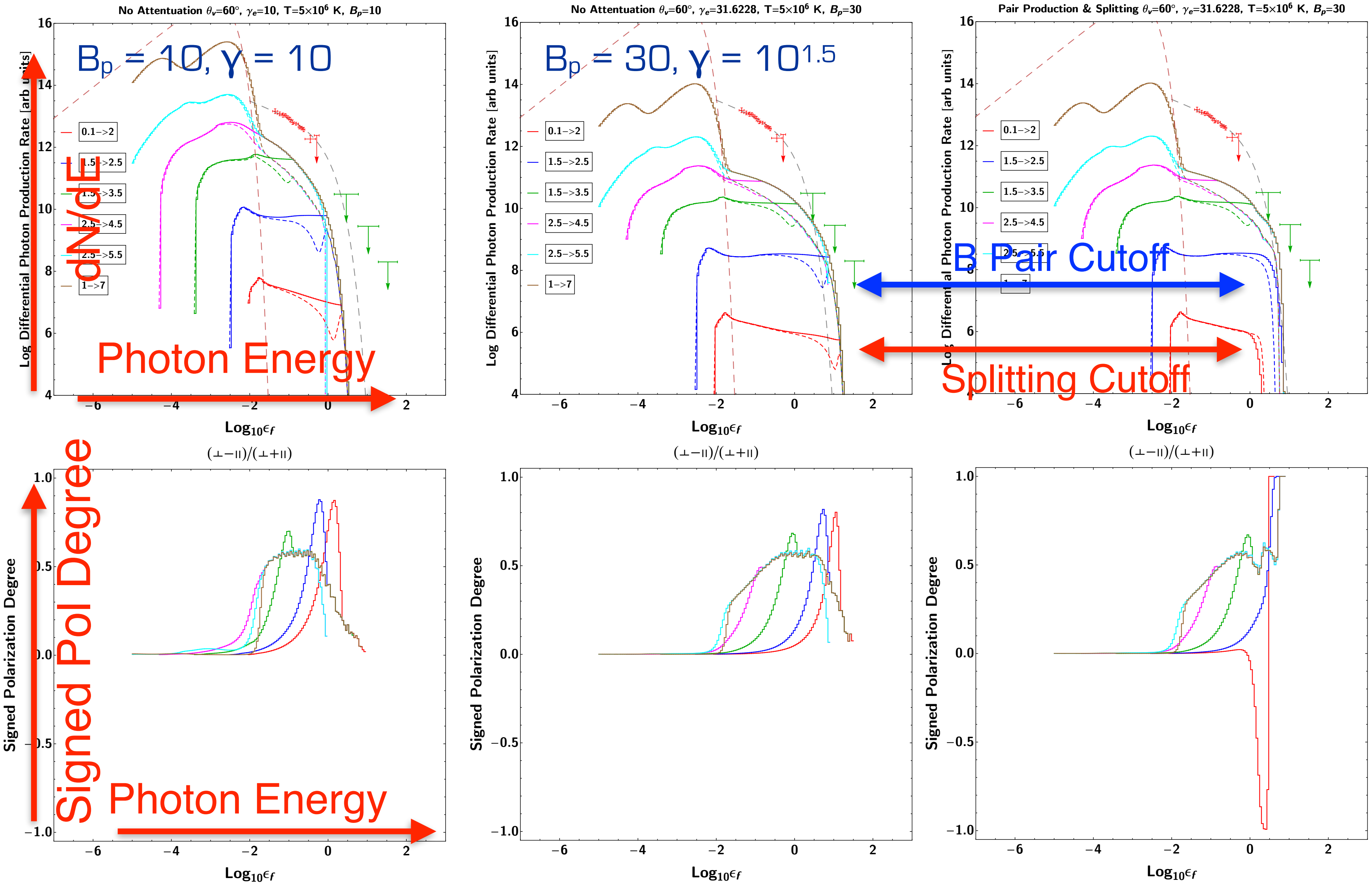
No Attenuation

Photon Splitting (⊥) + Magnetic Pair Production (||)

Wadiasingh et al. (in prep)

Altitude Convolutions

Wadiasingh et al. (in prep)



$B_p = 10, \gamma = 10$

$B_p = 30, \gamma = 10^{1.5}$

dN/dE

Photon Energy

B Pair Cutoff

Splitting Cutoff

Signed Pol Degree

Photon Energy

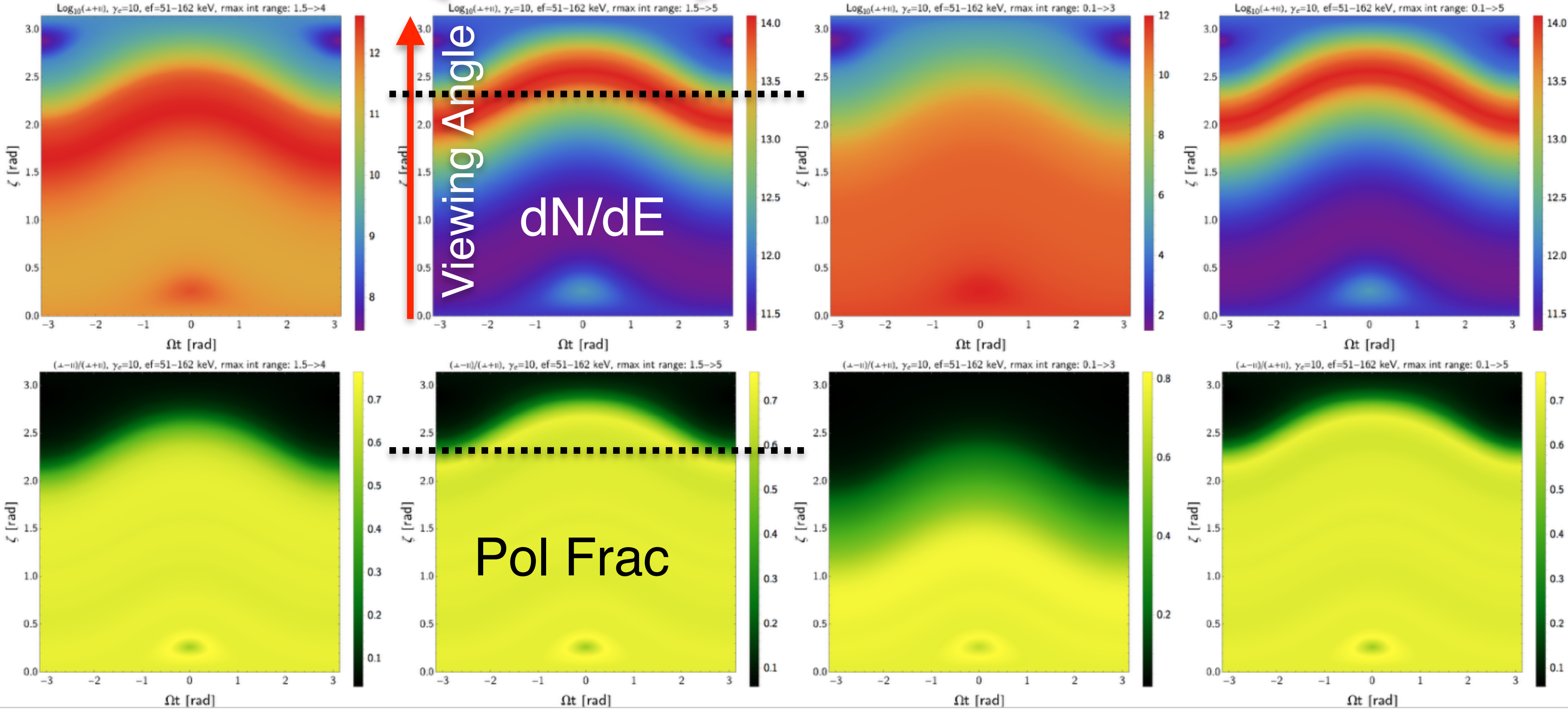
Altitude Convolutions — Pulse Profiles

Wadiasingh et al. (in prep)

α = 15°

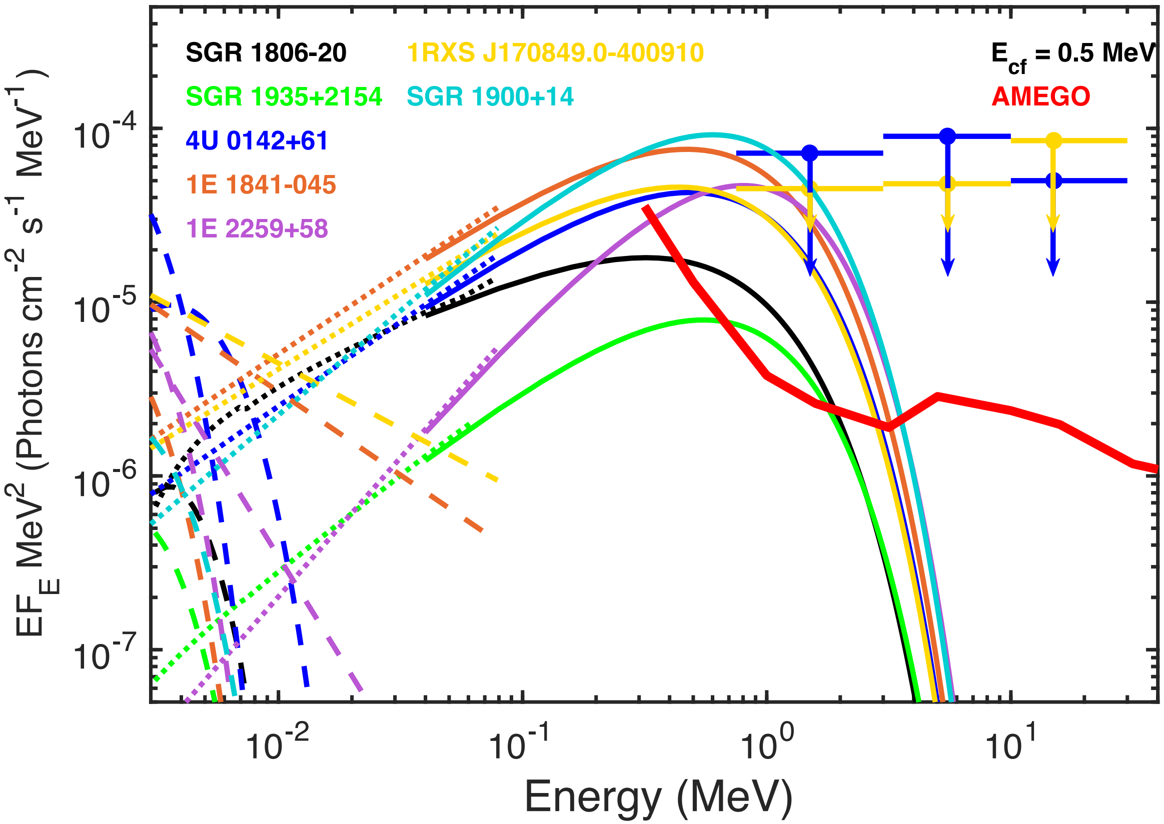
Spin Phase

$B_p = 10, \gamma = 10$



Different Altitude Convolutions

What will AMEGO find?



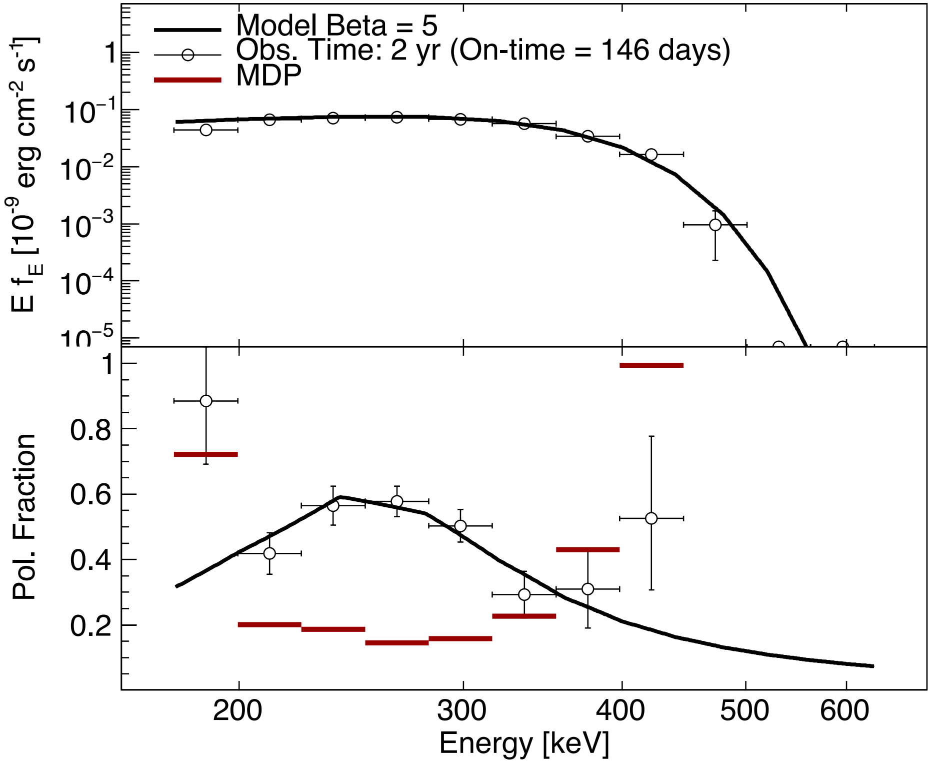
Credit:
George Younes

Probably at least 6 magnetars will be detected.

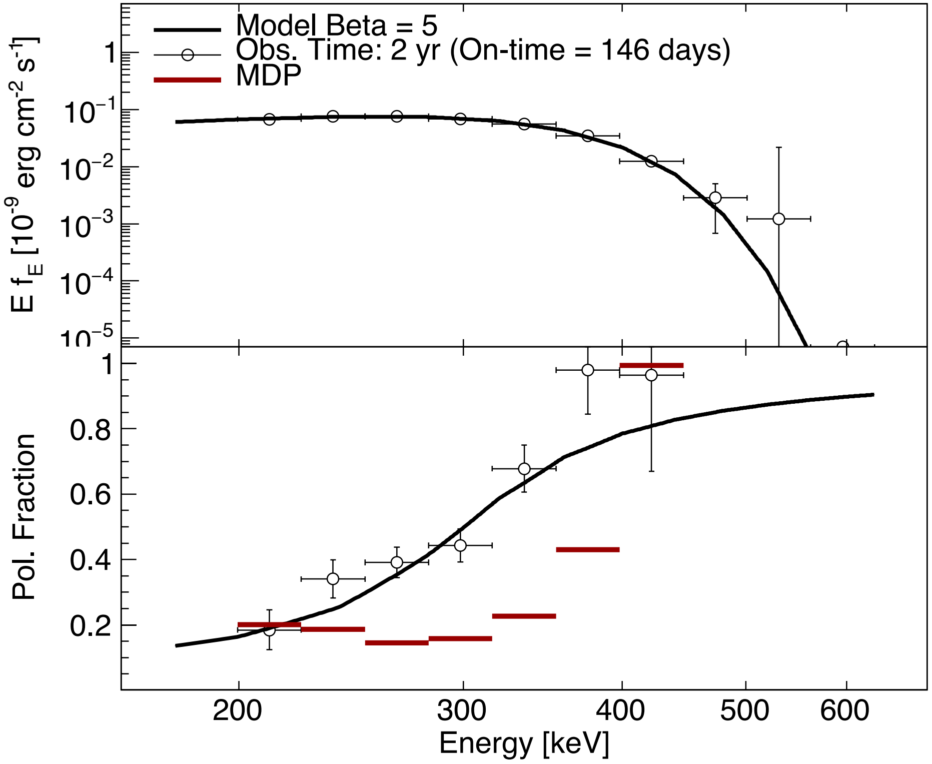
Key science: The hard PL cutoff and phase-resolved spectropolarimetry (full Stokes in spin phase bins and in energy bins, a **6-dimensional dataset**) will be critical to constraining model parameters

What will AMEGO find?

AMEGO spectropolarimetry can uncover QED magnetic photon splitting



Kinematic-like



QED photon splitting-like

Magnetars access a regime of QED beyond any terrestrial experiments

Some Open Questions

- Where does the phase-resolved spectrum of magnetars cut-off and how does it constrain the altitude of emission? What is the influence of photon splitting and magnetic pair production on the spectrum and polarization?
- Does photon splitting actually occur, in accordance with QED?
- What is the α, ζ of magnetars? As a population, does α show any trends with age?
- What is the magnetic field topology? Is it significantly nondipolar? How so? (can be assessed somewhat from pulsations — asymmetry and energy dependence)
- How are particles accelerated and how does it couple to the field topology? What is the spectrum of particle energies? What are the activated zones as a function of magnetic colatitude and azimuth? Are the particles in self-organized criticality (Beloborodov 2013a,b)? Is there a dead zone at low altitudes?
- How does field topology change with outbursts and during outburst evolution?
- What parameters distinguish transient magnetars and high-B pulsars from persistent magnetars?

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