A resonant cyclotron scattering model for the X-ray spectra of Magnetar Candidates

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AXPs and SGRs as "Magnetars"

- Magnetars: neutron stars with surface field $B > 10\ B_{QED} \sim 4 \times 10^{14}$ G (Duncan & Thomson 1992; Thomson & Duncan 1993)
- Rapid spin-down due to magneto-dipolar losses, bursting/flaring activity, comparison L_X vs E_{rot}, etc

Our "immediate" goal:

✓ 0.5 – 10 keV emission well represented by a blackbody plus a power law: WHY??

✓ Correlation in spectral hardening, luminosity, spin down rate - as in SGR 1806, during the pre (and post)-giant flare (24 Dec 2007) evolution

(see also a poster on the AXP RXJ1708- Zane et al.)

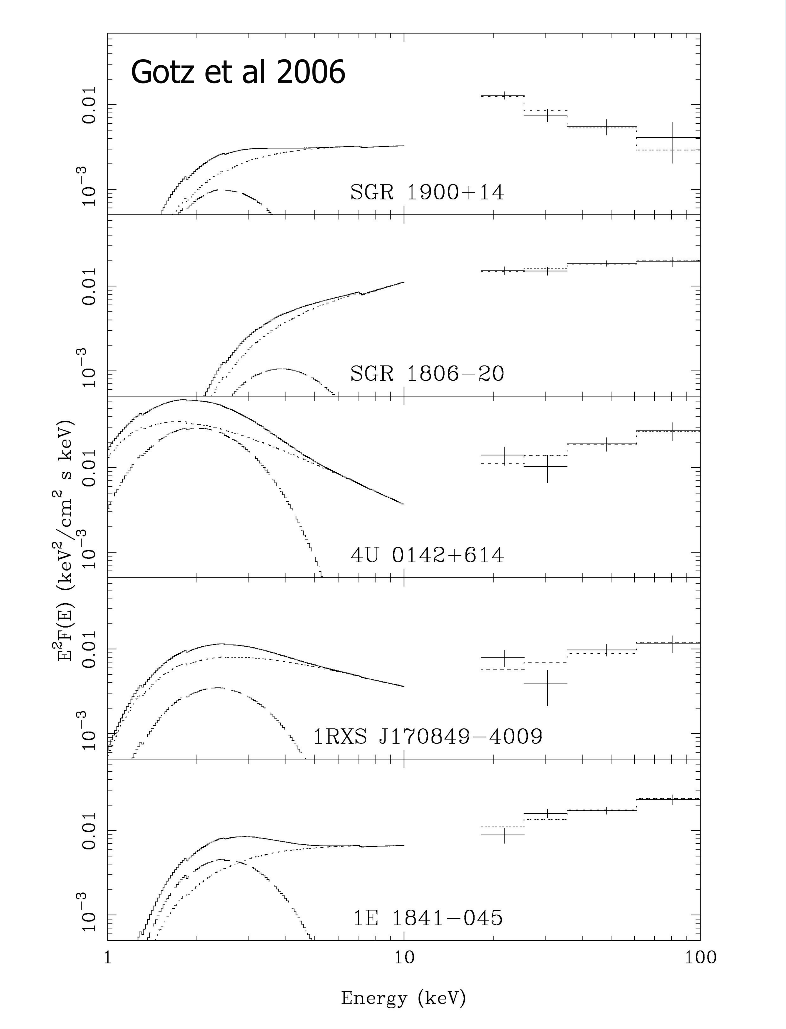
✓ Evolution of "transient" AXPs

Our "medium term" project: Hard X-ray Emission

INTEGRAL revealed substantial emission in the 20 -100 keV band from SGRs and AXPs

Hard power law tails with _ ≈ 1-3, hardening wrt soft X-ray emission required in AXPs

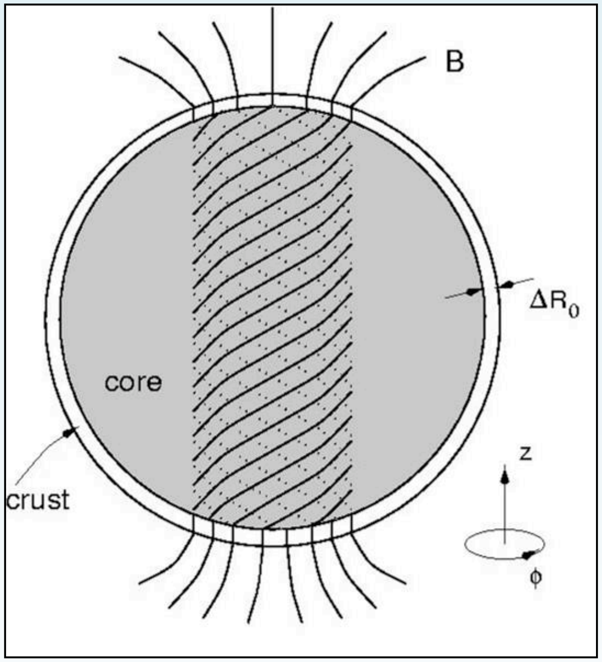
Hard emission pulsed



A twist in the magnetosphere?

- The bb+ PL spectral shape <10keV

- Observed Γ-L-dP/dt correlation
(with increase in bursting activity, in SGR1806 culminated with the giant flare)



Thompson, Lyutikov and Kulkarni (2002):

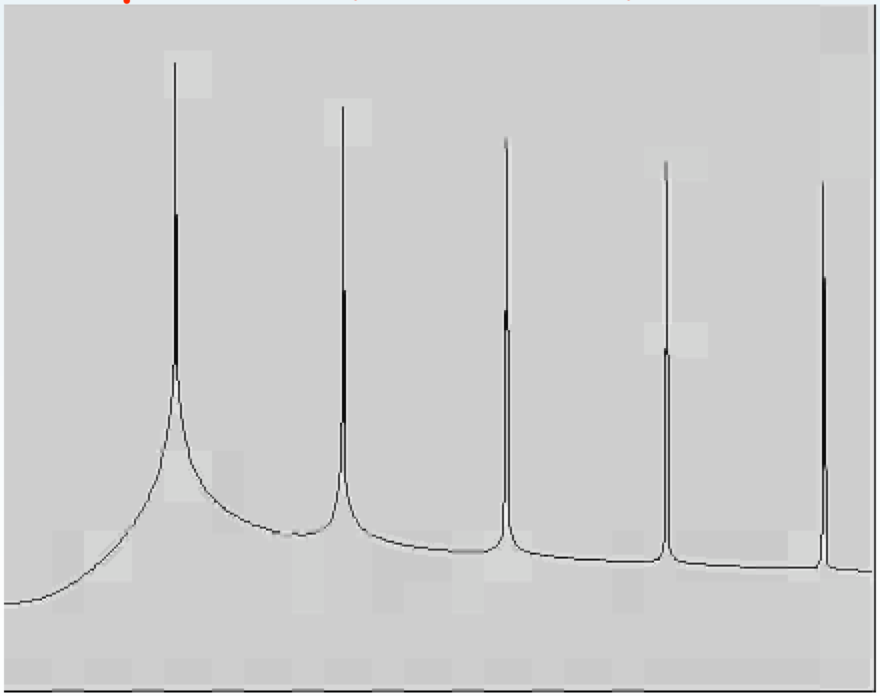
Magnetars (AXPs and SGRs) differ from radiopulsars since their internal magnetic field is twisted up to 10 times the external dipole.

At intervals, it can twist up the external field

Twisted magnetospheres

A key feature of twisted MSs is that they support current flows (in excess of the Goldreich-Julian current).

Thermal seed photons (i.e. emitted from the star surface) travelling through the magnetosphere experience efficient resonant cyclotron scattering onto charged magnetospheric particles (e- and ions)



Movie produced by L. Nobili

⇒ the thermal surface spectrum get distorted !

Twisted magnetospheres

While the twist grows, charged particles (e- and ions) produces:

- an extra heating of the star surface (by returning currents)
  ⇒ X-ray luminosity increases
- a large resonant cyclotron scattering depth
  ⇒ spectral hardening increases
- The B-field flare out slightly ⇒ an open field flux > then in a dipole
  ⇒ spin down torque increases

Qualitatively ok, and quantitatively?

Preliminary investigation (1D)

Lyutikov & Gravriil, 2006: A simplified, 1D semi-analytical treatment of resonant cyclotron up-scattering of soft thermal photons

- Thomson scattering occurs in a thin, plane parallel slab. Photons can only propagate along the slab normal, i.e. either towards or away from the star.

- Static, non-relativistic, warm medium; n_e constant. No electron recoil ($h\nu << m_e c^2$)

- The NS surface emits seed photons (blackbody spectrum)

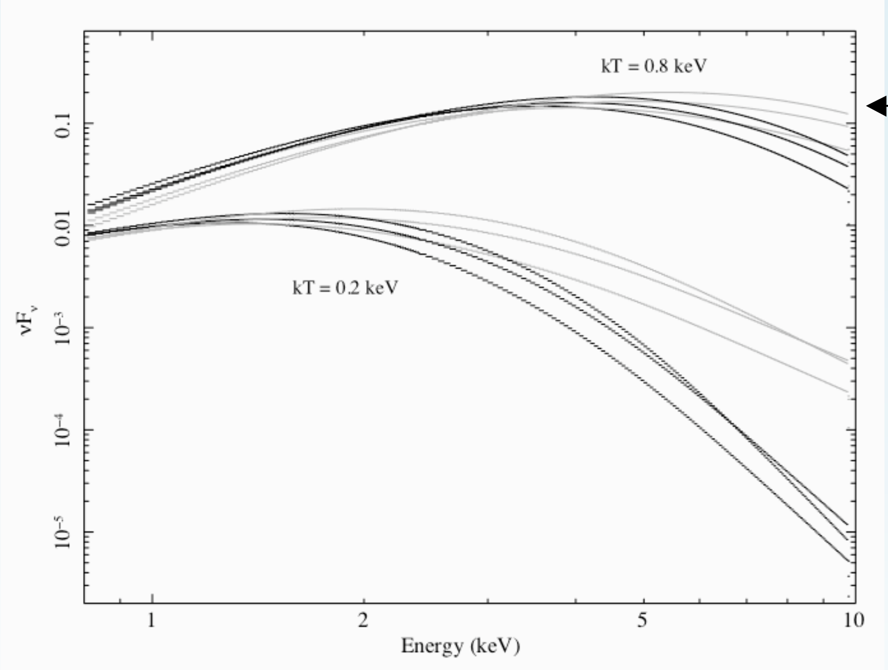
- Magnetospheric charges have a top-hat velocity distribution centered at zero and extending up to $\pm\beta_T$ $\Rightarrow$ mimics a thermal, 1D, motion (β_T $\approx$ mean e- energy $\approx$ temperature of the 1D electron plasma). No bulk motion.
  The e- velocity distribution averages to zero:
  - $\Rightarrow$ a photon has the same probability to undergo up or down scattering
  - $\Rightarrow$ no frequency shift due to the thermal motion of e-

- Photon boosting by particle thermal motion in Thomson limit occurs only due to the spatial variation of the magnetic field.

For a photon propagating from highto low magnetic fields, multiple resonant cyclotron scattering will, on average, up-scatter the transmitted radiation

$\Rightarrow$ hard tail.

Preliminary investigation (1D)



Distorsion of a seed blackbody spectrum through resonant cyclotron scattering onto magnetospheric electrons, for two values of the blackbody temperature, 0.2 keV and 0.8 keV. Black lines: the RCS model for β_T = 0.2 and τ_{res} = 2, 4, 8 (from bottom to top). Grey lines: β_T = 0.4 and τ_{res} = 2, 4, 8 (from bottom to top). The normalizations of the various curves are arbitrary. From Rea et al. 2008

Rea et al, 2006, 2008

- Implemented a grid of such models in XSPEC (3 parameters: τ_{res}, β_T, T + norm.)
- systematic application to ALL magnetars spectra below 10keV

⇒ see next talk by Nanda Rea ⇐

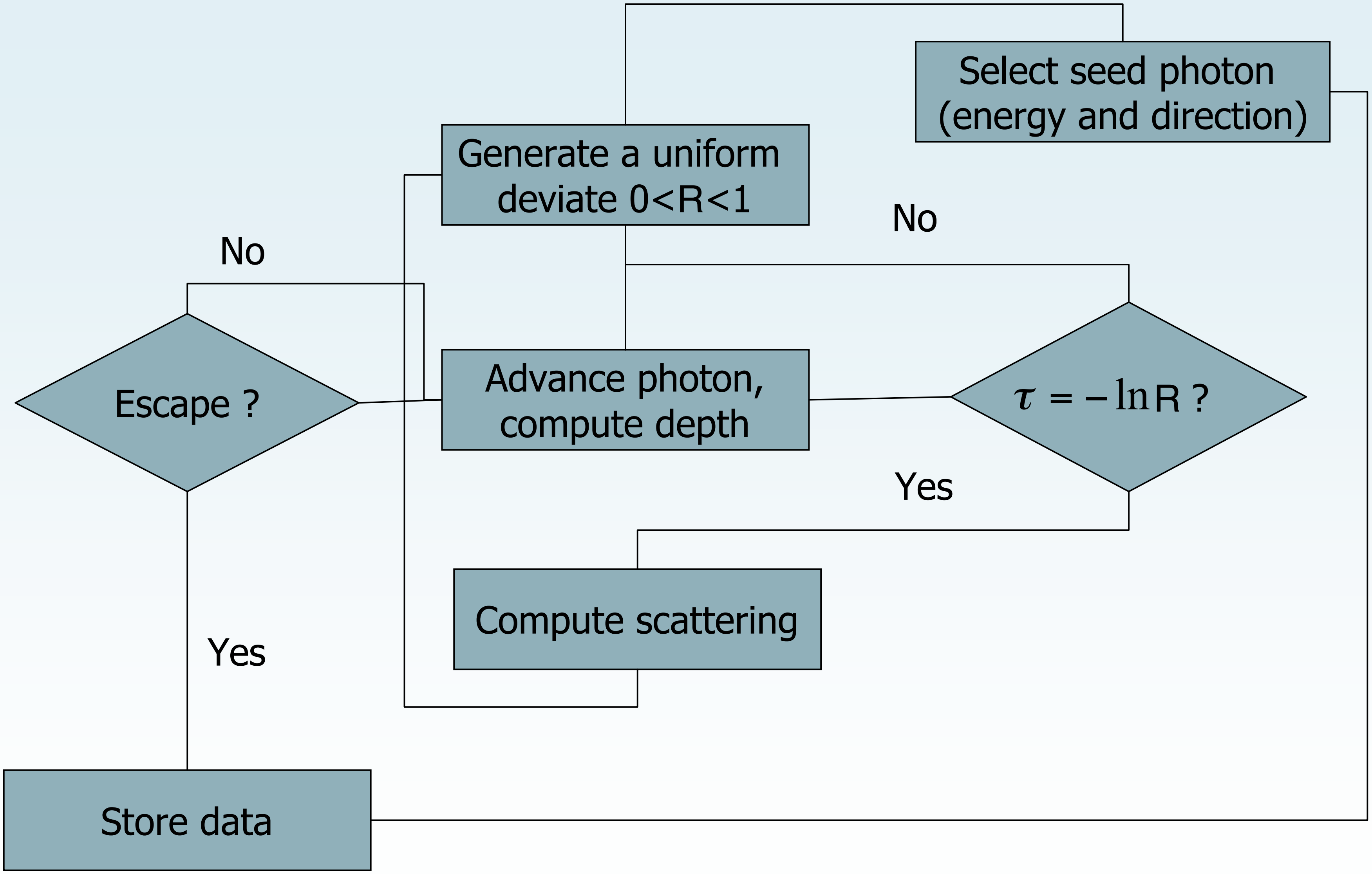
A Monte Carlo Approach

More detailed modeling by Fernandez & Thompson (2006)
New, up-to-dated code (Nobili, Turolla, Zane 2008)

- Follow individually a large sample of photons, treating probabilistically their interactions with charged particles
- Can handle very general (3D) geometries
- Quite easy to code, fast
- Ideal for purely scattering media
- Monte Carlo techniques work well when $N_{scat} \approx 1$

Basic ingredients:

- Space and energy distribution of the scattering particles
- Same for the seed (primary) photons
- Scattering cross sections


Select seed photon
(energy and direction)
Generate a uniform
deviate 0<R<1
No
No
Escape ?
Advance photon,
compute depth
$\tau = -\ln R$?
Yes
Compute scattering
Yes
Store data

Select particle from distribution
Transform photon energy and direction to ERF
Compute photon energy after scattering $\varepsilon' = \varepsilon / [1 + \varepsilon(1 + \cos^2 \Theta)]$
Compute new photon direction

$$R_{\theta'} = \int_0^{2\pi} d\phi' \int_{-1}^{\cos\theta'} d\mu' \, d\sigma(\varepsilon, \vec{k}, \vec{k}') / d\Omega' / \iint_{4\pi} d\Omega' \, d\sigma(\varepsilon, \vec{k}, \vec{k}') / d\Omega'$$

Transform back to LAB

Twisted Magnetospheres

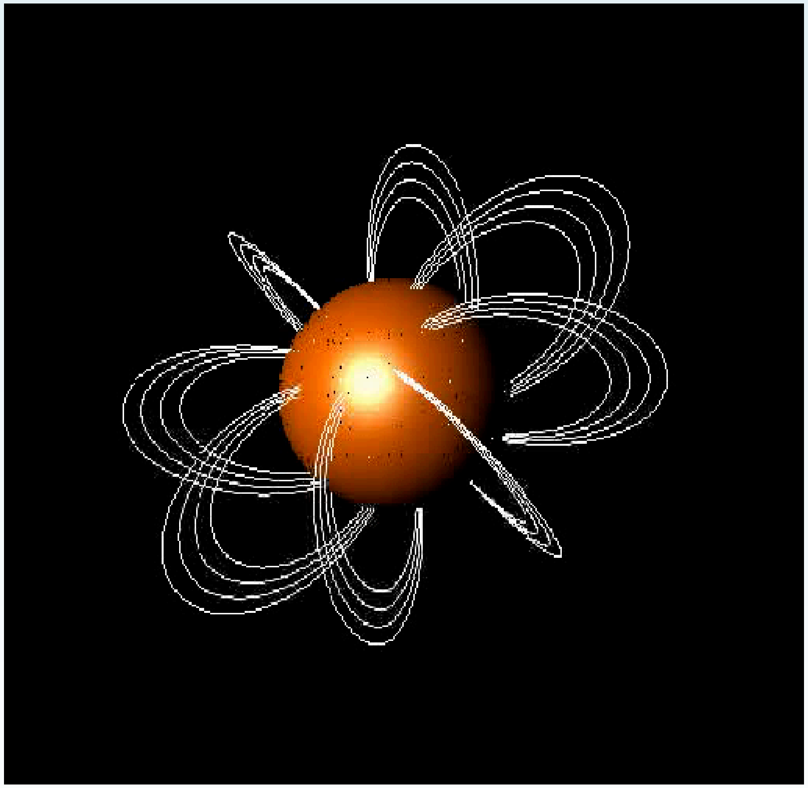
- TLK02 investigated force-free magnetic equilibria

$$(\vec{J} \times \vec{B} = 0)$$

- A sequence of models labeled by the twist angle

$$\vec{\nabla} \times \vec{B} = \alpha(R,\theta)\vec{B}$$

$$\Delta\phi_{N-S} = 2\int_0^{\frac{\pi}{2}} \frac{B_\phi}{B_\theta} \frac{d\theta}{\sin\theta}$$



Movie produced by R. Turolla

Magnetospheric Currents

- Charges move along the field lines $\vec{v} \parallel \vec{B}$
- Spatial distribution

$$n = \frac{p+1}{4\pi e}\left(\frac{B_\phi}{B_\theta}\right)\frac{cB}{r|v_{bulk}|} \approx 10^{16}\left(\frac{B_p}{10^{14}\ \mathrm{G}}\right)\left(\frac{R_{NS}}{10\ \mathrm{km}}\right)^{-1}\ \mathrm{cm}^{-3}$$

- Particle motion characterized by a bulk velocity, v_{bulk}, and by a velocity spread _v (main difference wrt Beloborodov & Thompson 2006)

- Electron contribution only 1D relativistic Mawellian at T_{el} centred at v_{bulk} (+ Landau levels in transverse plane)

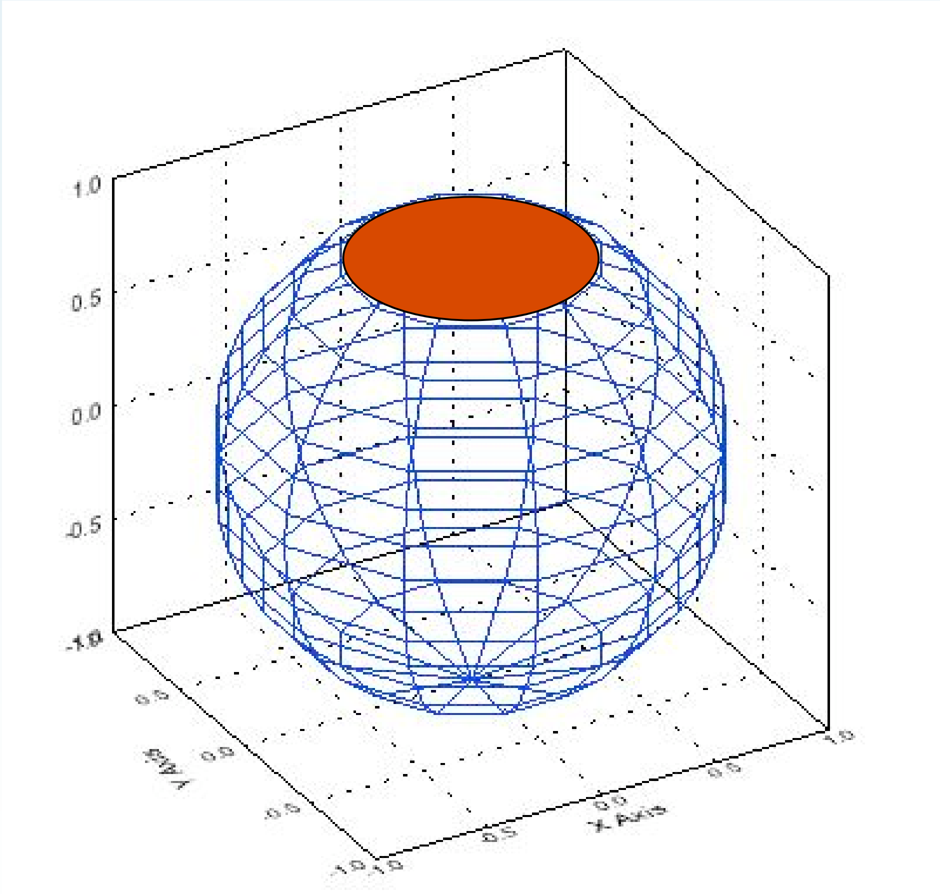
- There may be $e^{\pm}$ in addition to e-p, but no detailed model as yet (neglected!)

Surface Emission

The star surface is divided into patches by a cos θ-φ grid

Each patch has its own temperature and beaming prescription to reproduce different thermal maps

Tests shown today: blackbody, isotropic emission



Photons in a Magnetized Medium

- Magnetized plasma is anisotropic and birefringent, radiative processes sensitive to polarization state
- Two normal modes of photon propagation

The extraordinary (X) and ordinary (O) modes

- At $\rho < \rho_V \approx (B/10^{14}\ \mathrm{G})^2 (\varepsilon / 1\,\mathrm{keV})^2\ \mathrm{g\,cm^{-3}}$ the modes are almost linearly polarized

Scattering Cross Sections

- QED cross section available (Herold 1979, Harding & Daugherty 1991) but unwieldy $\Rightarrow$ NEXT DEVELOPMENT
- Non-relativistic (Thompson) cross section ($h\nu < mc^2/\gamma \approx 50$ keV, $B/B_{QED} < 10$)
- Because of charge motion resonance at $\omega_{res} = \dfrac{\omega_c}{\gamma(1-\beta\cos\theta)}$

Completely differential cross sections at resonance (ERF)

$$\left.\frac{d\sigma}{d\Omega'}\right|_{O-O} = \frac{3\pi r_0 c}{8}\delta(\omega-\omega_c)\cos^2\theta\cos^2\theta' \qquad \left.\frac{d\sigma}{d\Omega'}\right|_{O-X} = \frac{3\pi r_0 c}{8}\delta(\omega-\omega_c)\cos^2\theta$$

$$\left.\frac{d\sigma}{d\Omega'}\right|_{X-X} = \frac{3\pi r_0 c}{8}\delta(\omega-\omega_c) \qquad \left.\frac{d\sigma}{d\Omega'}\right|_{X-O} = \frac{3\pi r_0 c}{8}\delta(\omega-\omega_c)\cos^2\theta'$$

$r_0 = e^2/mc^2, \omega_c = eB/mc, \theta, \theta'$ angles between photon direction and particle velocity before and after scattering

Model Spectra

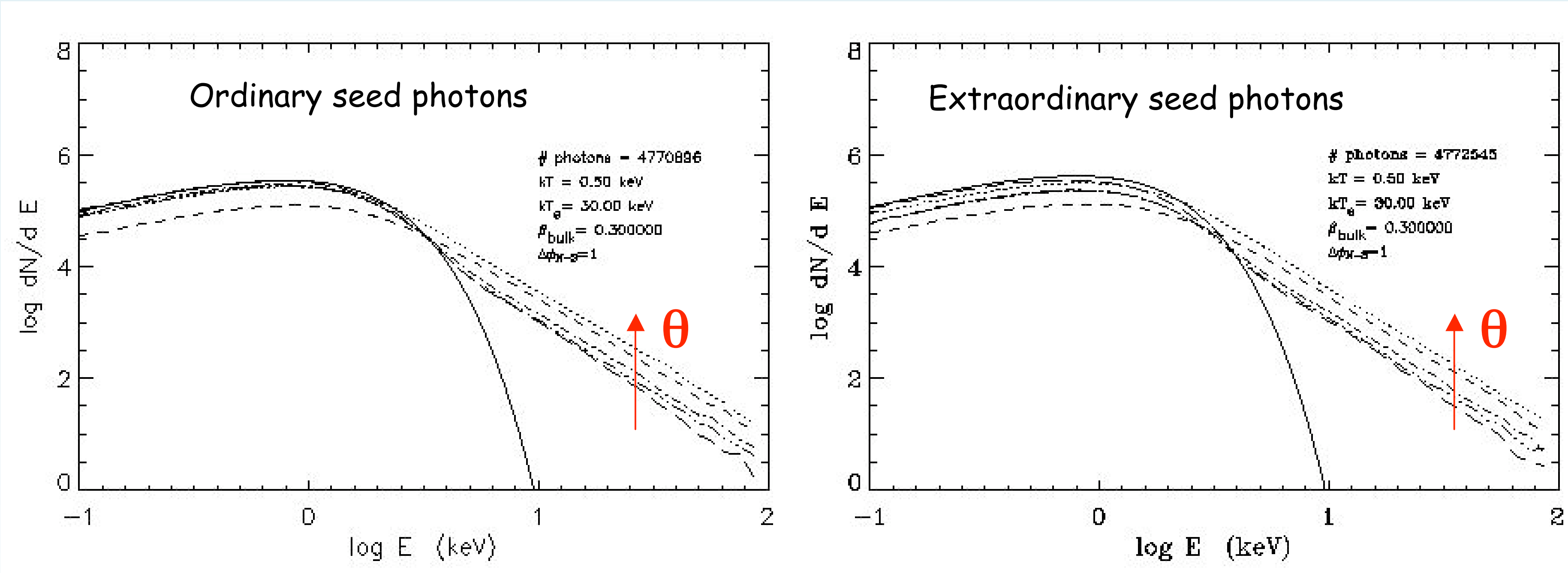
- 5 model parameters: B, T, T_e, β_{bulk}, $\Delta\phi$ (twist angle)
- 3 "prescriptions": i) surface emission map, ii) beaming and iii) polarization state of the seed photons

$\Rightarrow$ next plots: BB surface emission , isotropic radiation

- After each Monte Carlo run, photons are collected in a (θ,φ) grid on the sky at infinity
- In the next plots: no viewing angle effects. Dipolar axis along z

Model Spectra- B = 10^{14} G and we vary the parameters:

1- azimuthal angle θ (at infinity)

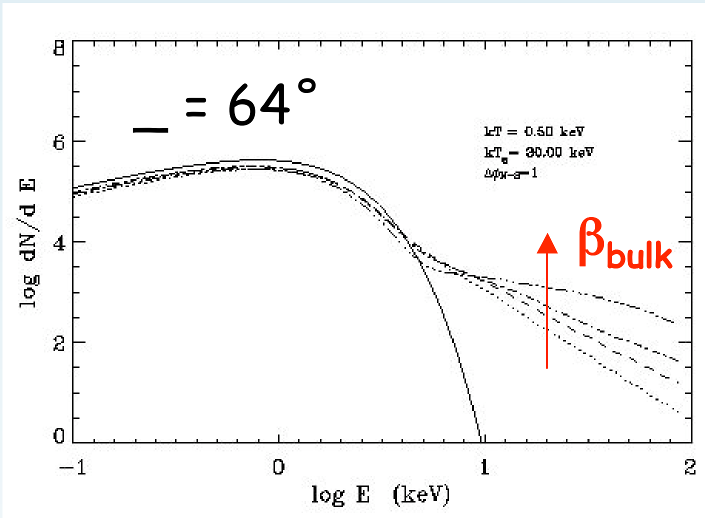


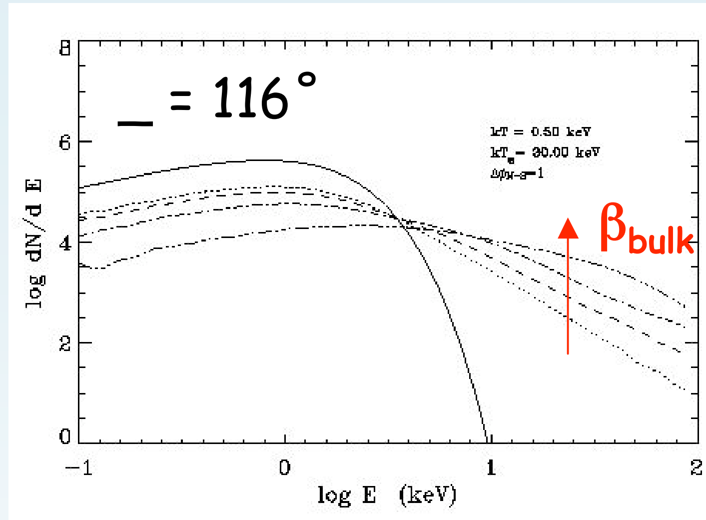
Computed spectra for different values of the colatitude θ: 27° (long dashed), 64° (dashed-dotted-dotted-dotted), 90° (dashed-dotted), 116° (short dashed) and 153° (dotted). The solid line is the seed blackbody, units are arbitrary.

No symmetry between the two hemispheres: as θ increases, spectra become more and more comptonized

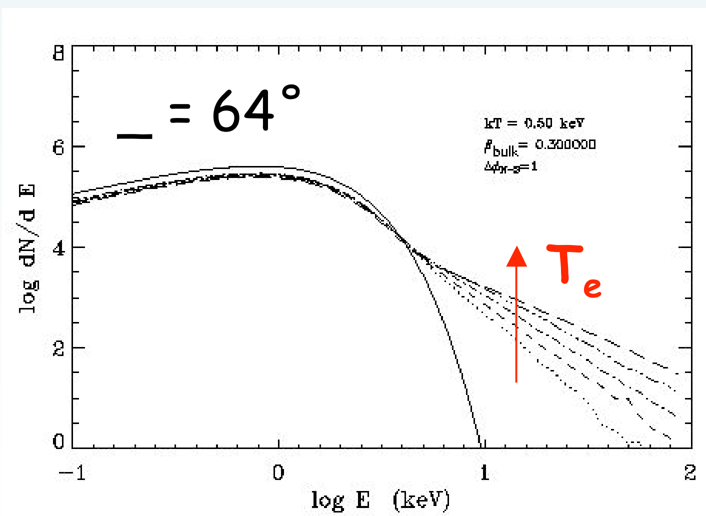
2- currents bulk velocity β_{bulk} and temperature Te

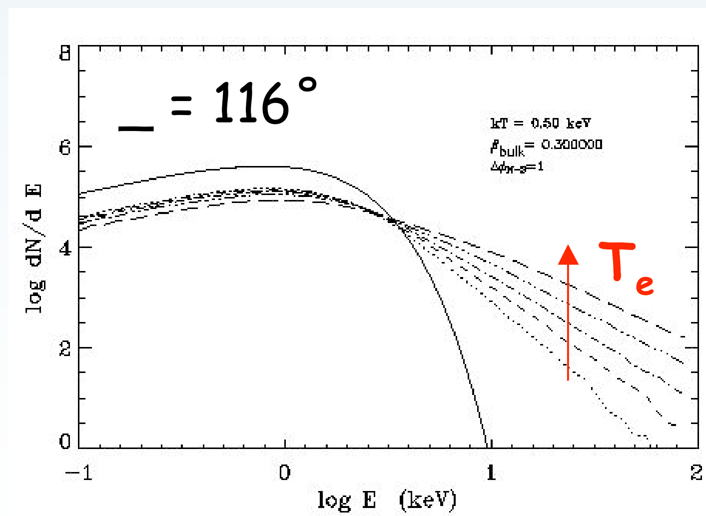
Ordinary seed photons





Computed spectra for β_{bulk}: 0.3, 0.5, 0.7, 0.9

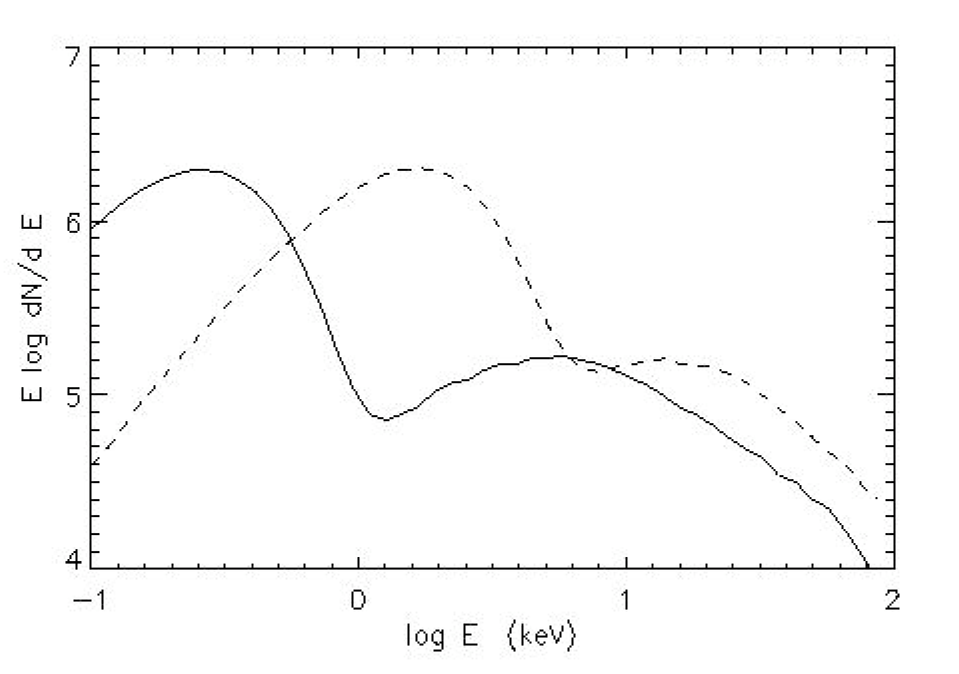




Computed spectra for kT_e: 5, 15, 30, 60 and 120 keV

If comptonization starts to saturate, photons fill the Wien peak of the Bose-Einstein distribution $\Rightarrow$ spectrum is not peaked at ~kT, but at ~kTe

So that… double humped spectra!



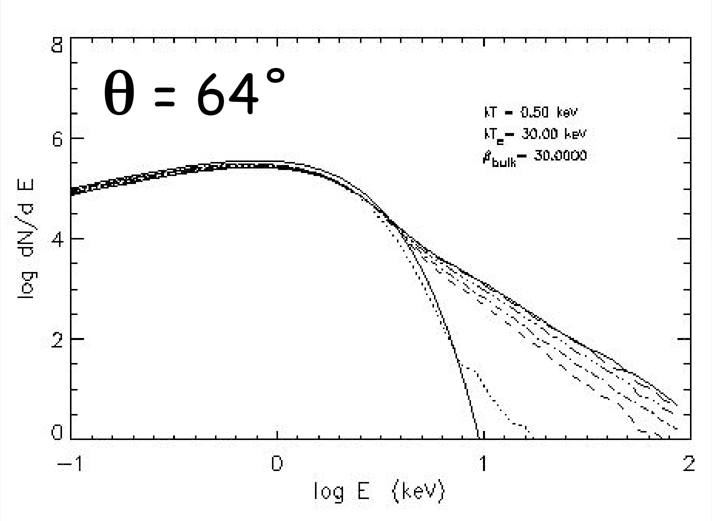
B = 10 14 G, $\Delta\phi$: 0.2
the star is an aligned rotator seen north pole-on.
Unpolarized seed photons, $kT_e \sim\beta_{bulk}$
Solid line: kT = 0.1 keV, β_{bulk}= 0.7
dashed line: kT = 0.6 keV, β_{bulk}= 0.6

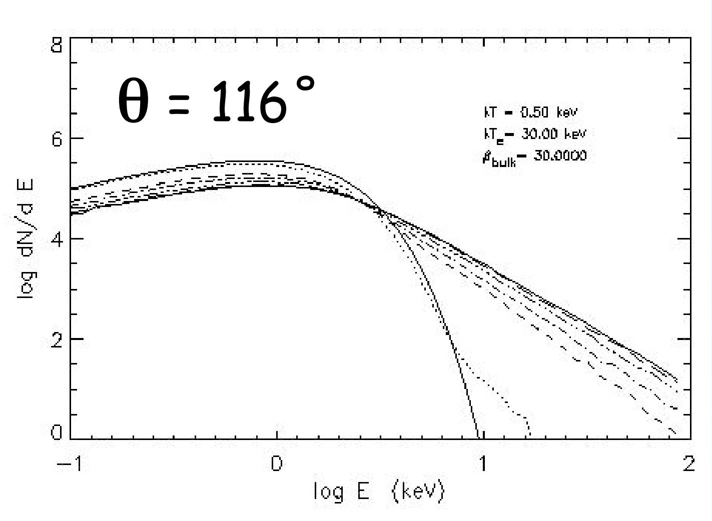
For intermediate values of the parameters spectra can be double humped, with a downturn between the two humps.

Fernandez & Thompson (2007) models with a non-thermal top-hat or a broadband e-velocity distribution also show multiple peaks.
Our model predicts at most two peaks, and the energy of the second one gives a direct information on the energy of the magnetospheric particles.

4- twist angle, $\Delta\phi$

Ordinary seed photons

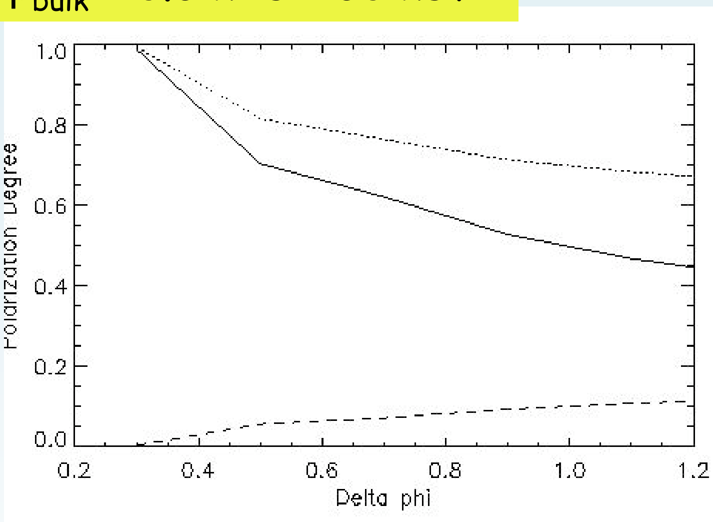




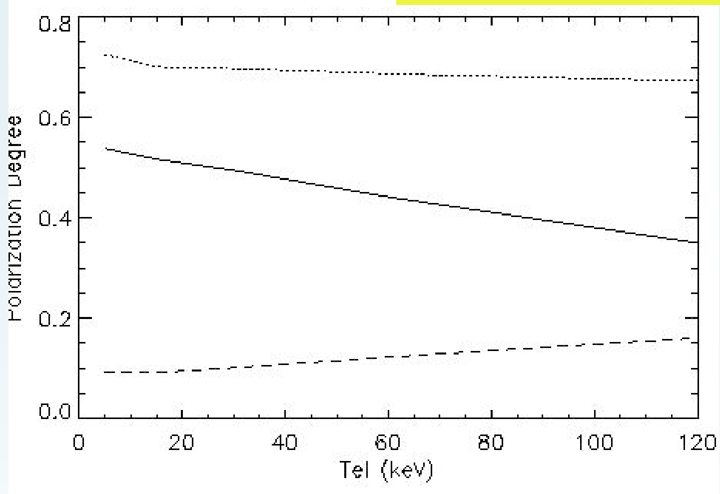
Computed spectra for $\Delta\phi$: 0.3 (dotted), 0.5 (short dashed), 0.7 (dash-dotted), 0.9 (dashed-dotted-dotted-dotted), 1.1 (long dashed, bottom) and 1.2 (long dashed, top). The solid line represents the seed blackbody, units are arbitrary

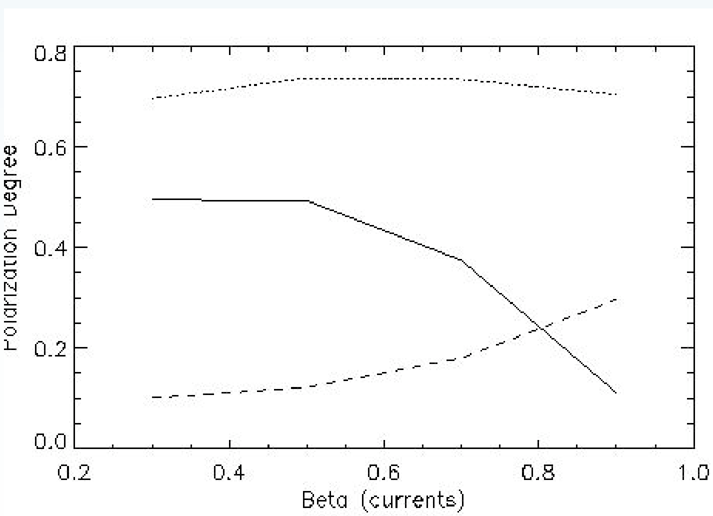
Polarization degree - varying the parameters

β_{bulk} = 0.3 kTe = 30 keV



β_{bulk} = 0.3 $\Delta\phi$ =1





$\Delta\phi$= 1 kTe = 30 keV

B = 10^{14} G kT = 0.5 keV

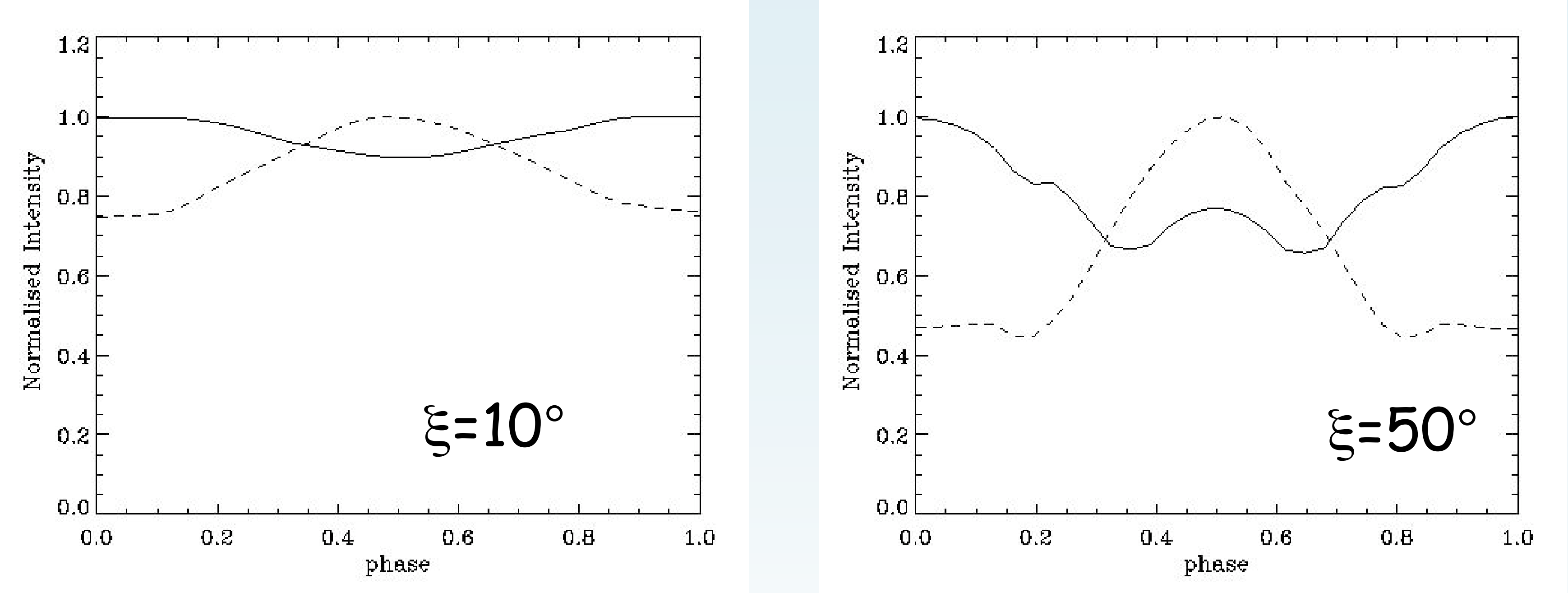
Integrated over all angles at infinity

Solid: O-seed photons

Dotted: E-seed photons

Dashed: unpolarized seed photons

Lightcurves



LC for a star seen equator-on and for two different inclinations of the magnetic axis ξ.
Solid line: 0.5-2 keV; dashed line: 2-6 keV. $\Delta\phi$: 0.7, β_{bulk}=0.3, kT=0.3 keV

In some cases the pulse profiles in the soft (0.5-2 keV) and hard (2-6 keV) band are shifted in phase by ~180°.
By increasing ξ, the pulsed fraction and the pulse shape sensibly change with the energy band: the pulsed fraction increases with the energy

Albano et al., work in progress.

XSPEC implementation: complete archive of models

- 225000 photons per surface patch; 8x4 patches on the star surface 10x10 patches on the sky at infinity
- $B = 10^{14}$ G; BB surface emission, isotropic radiation, ordinary seed photons
- $\gamma_{bulk}-1 = 2^{[1/(1+Te]}/T_e$; then $T_e = T_e/2$
  (bulk kinetic energy = av. E_{th} for a 1D Maxwellian; $T_e=kT_e/m_ec^2$)

A) NTZNOANG (22MB table):

- $0.1 \leq kT \leq 1$ keV 100 values, log spaced
- $0.1 \leq \beta_{bulk} \leq 0.9$ 9 values, step 0.1
- $0 \leq \Delta\phi \leq 2$ 21 values, step 0.1

B) NTZANG (300 MB table)

- The final NTZANG spectrum in XSPEC depends on 6 parameters:
  kT , β_{bulk} , $\Delta\phi$, χ, ξ, K (= a normal. constant)

Preliminary fit to observed spectra (G.L. Israel)

No viewing angle effects (NTZNOANG)

Best fit parameters (errors @ 1 σ):

$N_H = 1.76^{+0.06}_{-0.05} \times 10^{22}$ cm^{-2}

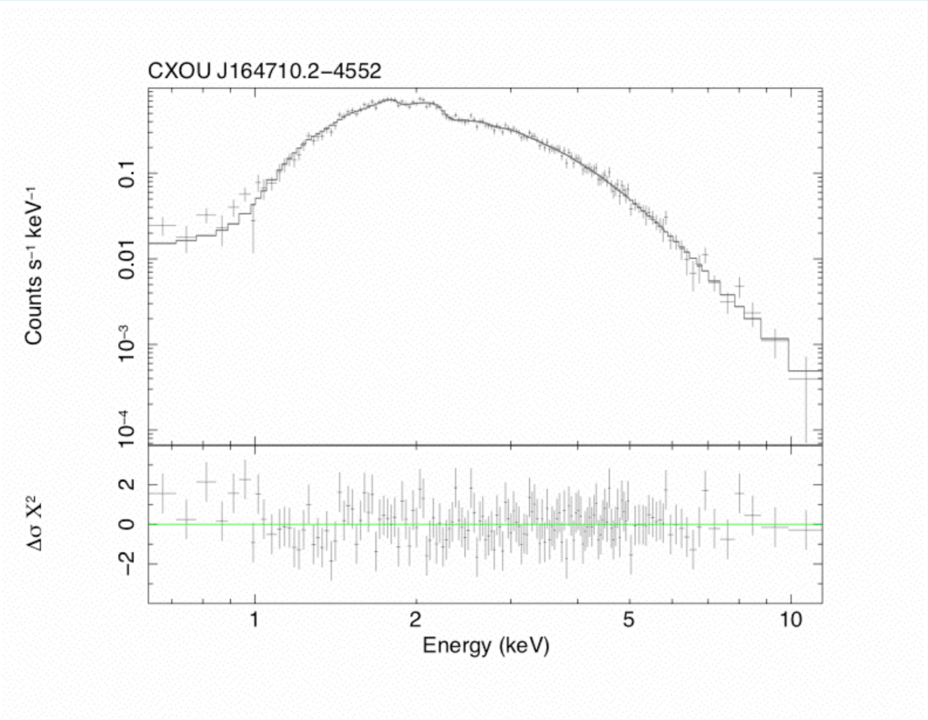
$kT = 0.625^{+0.007}_{-0.008}$ keV

$\beta_{bulk} = 0.60^{+0.03}_{-0.02}$

$\Delta\phi = 0.40^{+0.03}_{-0.32}$

$\chi^2 = 0.81$ for 145 DOF

F^{abs} (1-10keV) = 6×10^{-12} ergs cm^{-2} s^{-1}



Fit of the XMM-Newton EPIC-pn spectrum of the AXP CXOU J1647-4552 with an absorbed ntznoang model. Top: data and best fit model; bottom: residuals. From Nobili et al. 2008, figure provided by G.L. Israel.

Preliminary fit to observed spectra (G.L. Israel)

Viewing angles effects (NTZANG)

Best fit parameters (errors @ 1 σ):

$N_H = 1.76^{+0.04}_{-0.06} \times 10^{22}$ cm^{-2}

$kT = 0.63^{+0.07}_{-0.01}$ keV

$\beta_{bulk} = 0.65^{+0.26}_{-0.07}$

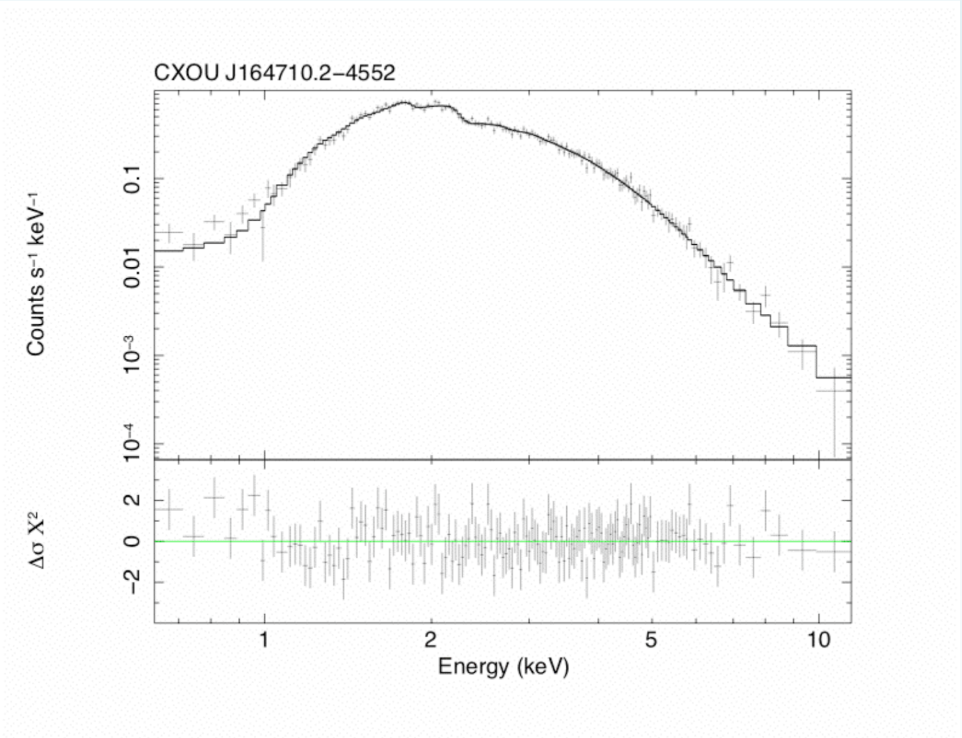
$\Delta\phi = 0.47^{+0.03}_{-0.06}$

$\chi = 2.1 \pm 1.8$

$\xi = 82^{+89}_{-56}$

$\chi^2 = 0.83$ for 143 DOF

F^{abs} (1-10keV) = 6×10^{-12} ergs cm^{-2} s^{-1}



Fit of the same XMM-Newton EPIC-pn spectrum of the AXP CXOU J1647-4552 with an absorbed ntzang model. Top: data and best fit model; bottom: residuals. From Nobili et al. 2008, figure provided by G.L. Israel.

⇒ see next talk by Nanda Rea ⇐

Next step: QED effects in the cross section

Need of the Compton cross-section for e-scattering in the presence of a strong magnetic field:

✓ first study, in the non relativistic limit, by Canuto, Lodenquai & Ruderman, 1971

✓ QED expression derived long ago by many authors (Herold '79, Daugherty & Harding '86, Bussard, Alexander, & Meszaros '86, Harding & Daugherty '91)

However, its form is so complicated to be often of little practical use in numerical calculations.

Relativistic second order cross section for the transition from the ground to an arbitrary state l :

$$\frac{d\sigma_{s\to s'}}{d\Omega'} = \frac{3\sigma_T}{16\pi}\frac{\epsilon'}{\epsilon}\frac{(2+\epsilon-\epsilon')\exp\left[-(\epsilon^2\sin^2\theta+\epsilon'^2\sin^2\theta')/2B\right]}{\left[1+\epsilon-\epsilon'-(\epsilon\cos\theta-\epsilon'\cos\theta')\cos\theta'\right]}\left|\sum_{n=0}^{\infty}\left[F^{(1)}_{n,-}+F^{(1)}_{n,+}+\left(F^{(2)}_{n,-}+F^{(2)}_{n,+}\right)\exp(2i\Phi)\right]\right|^2$$

Major complications:

✓Presence of an infinite sum over all intermediate (virtual) states with principal quantum number n.

✓The $F_{n,\pm}^{(k)}$ are complicated complex functions of B, ε, ε', θ, θ', φ, φ'.

✓They depend also on the initial and final photon polarization mode, and on the spin orientation (up or down) of the electron in the intermediate state.

Next step: QED effects
(Nobili, Turolla & SZ, MNRAS submitted)

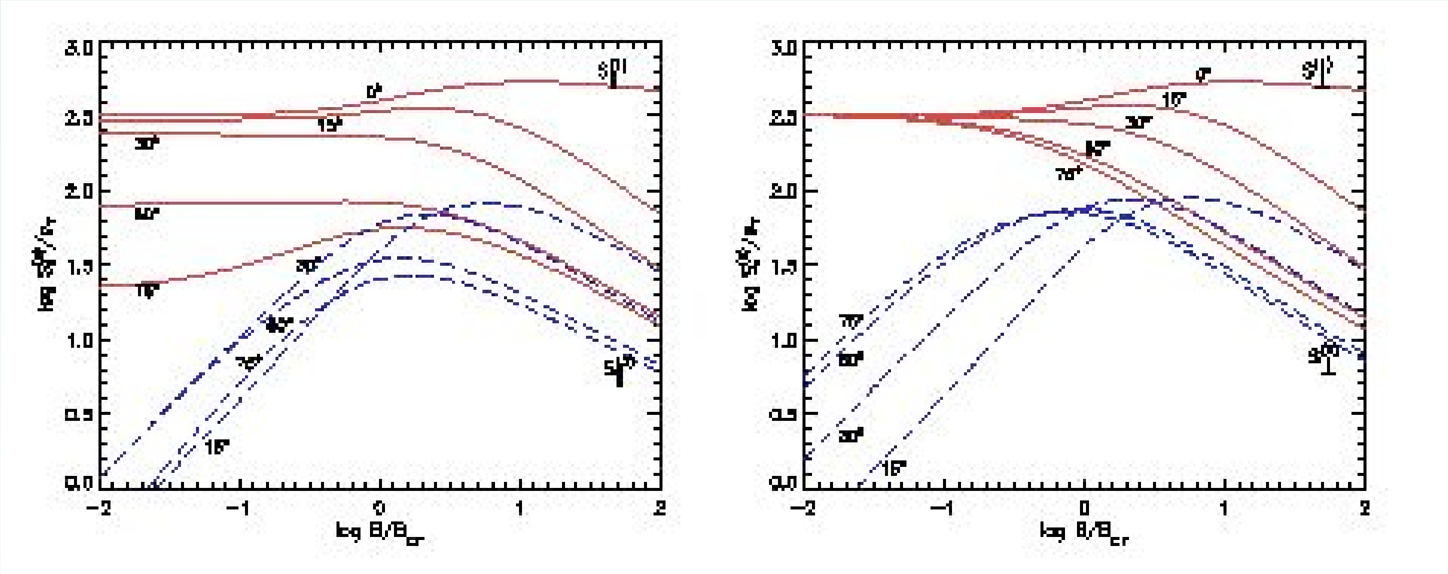
No need for a detailed model of line formation/profile: nearly all electrons scatter *at resonance*. Contribution from non-resonant scattering is negligible.

- ✓ Start from Harding & Daugherty '91 and work out explicit, relatively simple expressions for the magnetic Compton cross-section at resonance which can be included in a Monte Carlo scheme

- ✓ We account for Landau-Raman scattering up to the second Landau level.

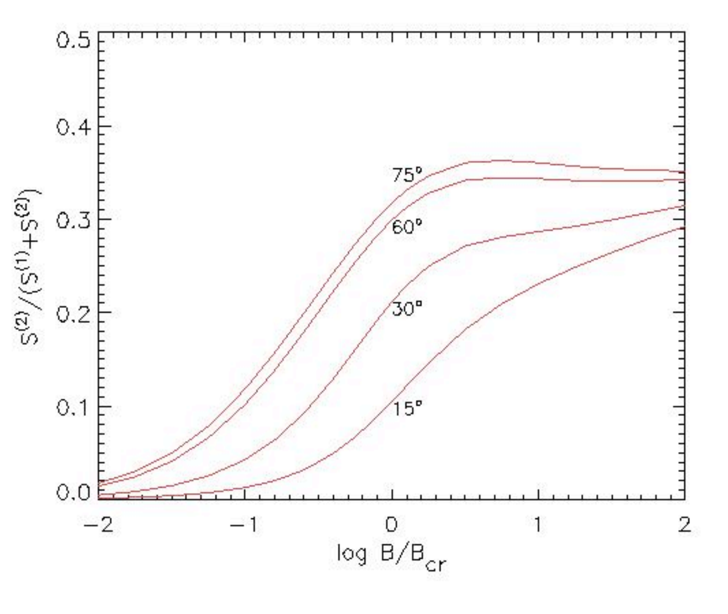
- ✓ Expressions are valid for all magnetic field strengths (no assumption is made)

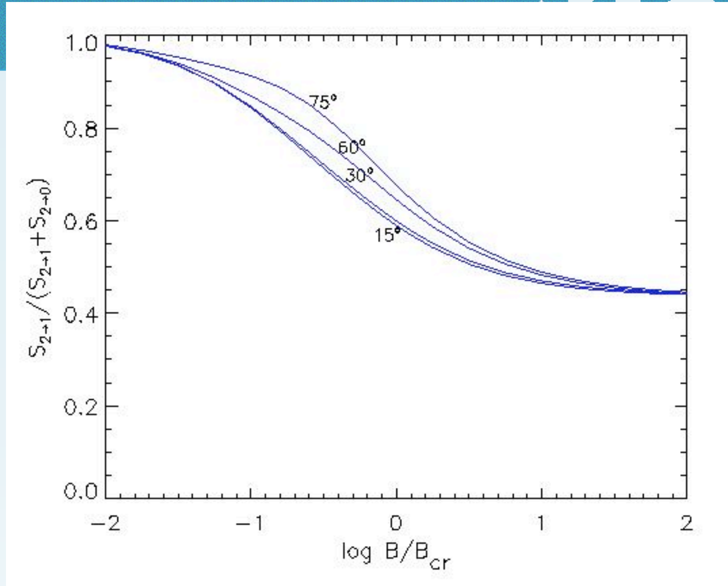
Next step: QED effects
(Nobili, Turolla & SZ, MNRAS submitted)



The resonance factors for the first (upper curves, solid red lines) and second (lower curves, dashed blue lines) intermediate Landau levels as a function of log B; Curves are in unit of the Thomson cross section. Different curves are labelled by the value of the angle between the incident photon direction and the magnetic field. Left: ordinary photons. Right: extraordinary photons (note the weaker angular dependence in the latter case).

relativistic corrections are already ~ 10% at B~ 0.1 B_{QED}
in particular for photons with large values of the incident angle





Ratio between the second resonant term and the total cross section for unpolarized incident photons and different scattering angles. In moderately strong magnetic fields a non-negligible fraction of collisions can excite electrons to the higher Landau level (n=2). From Nobili, Turolla and SZ, 2008.

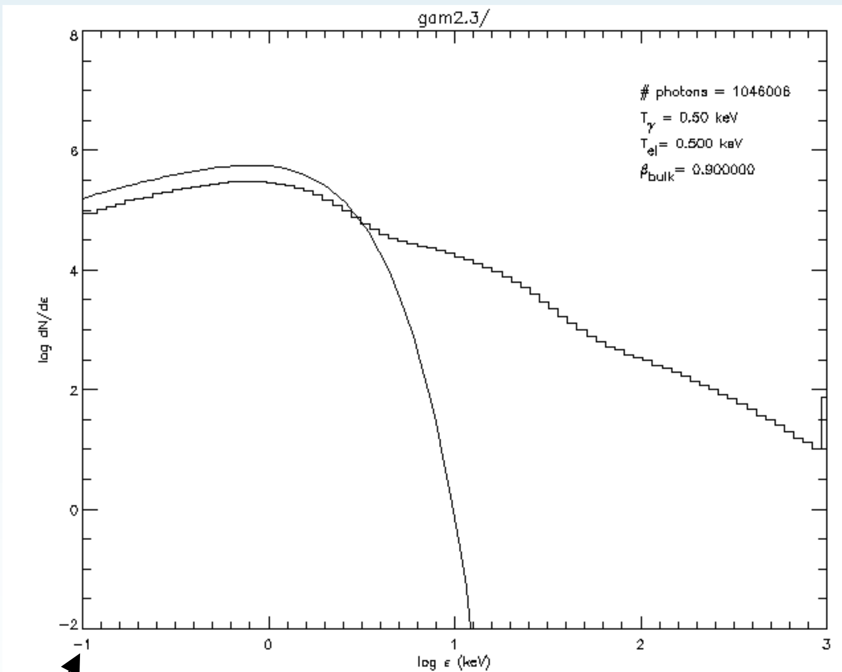
The 2 to 1 transition probability versus magnetic field strength. When n=2, de-excitation of the electron to l=1 state is generally more likely than the direct transition to the ground level. Only for B>>BQED, the two transitions are have comparable probabilities. From Nobili, Turolla & SZ, 2008

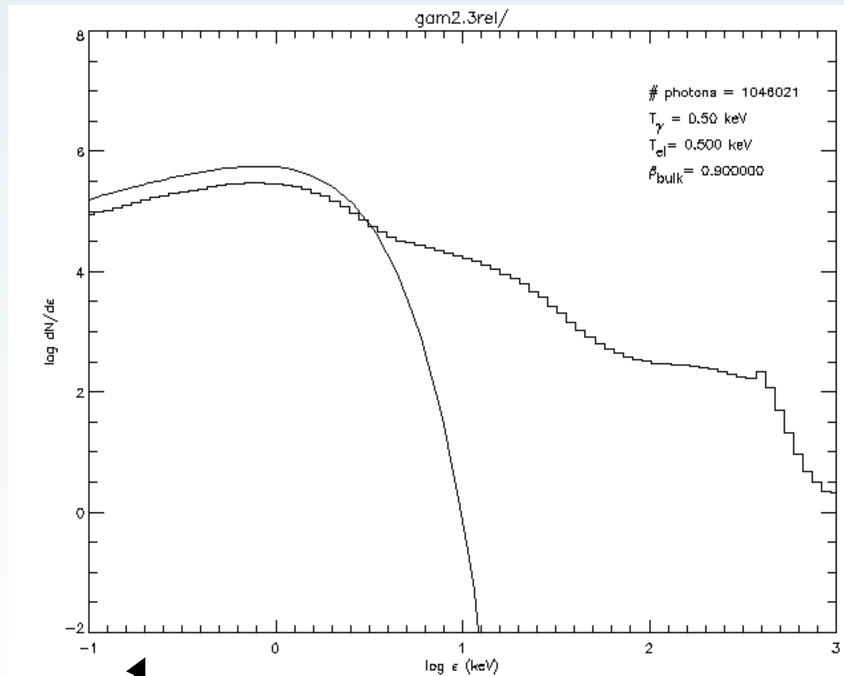
Important consequences on the transfer problem:

⇒ **collisions involving the intermediate state n=2 lead more frequently to the creation of extra photons as the electron returns to the ground level.**

⇒ **the resonant magnetic scattering may NOT conserve the total photon number**

Inclusion of QED cross section in the Monte Carlo code (Nobili, Turolla & SZ, MNRAS in prep)





NO QED, NO e-RECOIL

QED, e-RECOIL

Conclusions & Future Developments

Nobili, Turolla, & SZ

- Twisted magnetosphere model, within magnetar scenario, in general agreement with observations
- Resonant scattering of thermal, surface photons produces spectra with right properties
- More accurate treatment of cross section including QED effects and electron recoil (in progress, Nobili, Turolla & SZ MNRAS submitted)

- Many issues need to be investigated further

  - ✓ Use the model archive to fit model spectra to observations, investigate what causes the long term variability in AXPS and TAXPS (in progress, with N. Rea, G.L. Israel & Alessandra Albano)
  - ✓ Investigate QED effects in spectral formation and polarization pattern
  - ✓ Twist of more general external fields (L. Pavan in progress)
  - ✓ Detailed models for magnetospheric currents (effects of pairs production?)
  - ✓ 10-100 keV tails: up-scattering by (ultra)relativistic ($e\pm$) particles ?

THANKS !