Superstrong magnetic fields in neutron stars

Workshop/forum on magnetospheric Physics
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Neutron Stars are 'natural laboratories'

- ✓ are born when a normal star dies, exploding as a supernova, and its core collapses into in a compact remnant
  M □ 1.5 M sun, R □ 10 km
- ✓ are the most extreme stellar configurations directly visible (mass slightly higher □ remnant collapses into a black hole)
- ✓ have a complex and poorly understood interior: condensed matter in bulk quantities
  (exotic particles: pions, superconductivity, super fluidity)
- ✓neutron star have huge magnetic fields and rotate fast
  (young neutron stars typically observed with P □ 1ms and B □ 10^{13} G …. or more ?)

QCD and behavior of matter in strong B-fields

Matter in Ultra-Strong B-Fields

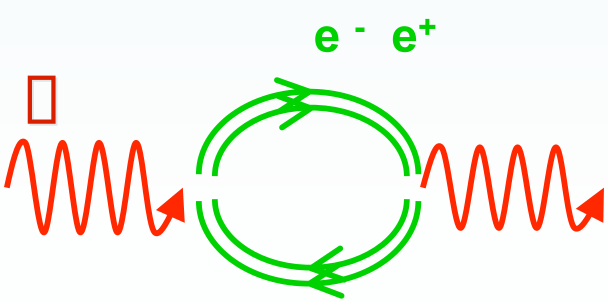
1) $B \geq B_0 \approx 2.35 \times 10^9$ G: we enter the strongly-magnetized regime

increasing **B**

- **Atomic structure distorted**
- **highest static field in terrestrial lab: 45×10^6 G**
- **semiconductors: GaAs $B_0 = 6.6 \times 10^6$ G**
- **medium anisotropic, strong plasma polarization**

2) $B \geq B_Q \approx 4.41 \times 10^{13}$ G : we enter the quantizing regime

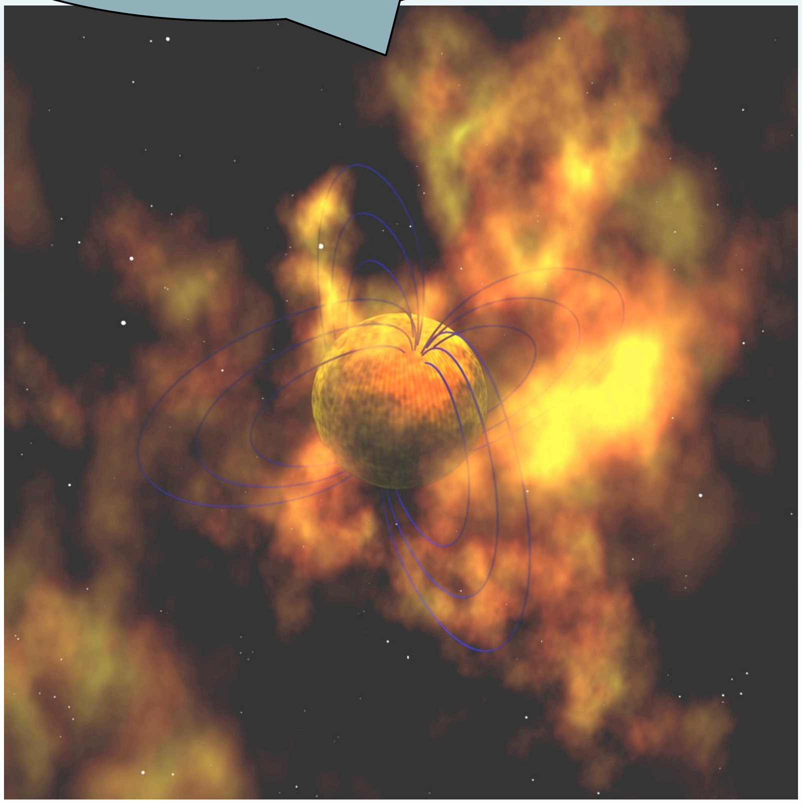
Vacuum polarization: quantum effect for $B > B_Q \approx 4.41 \times 10^{13}$ G



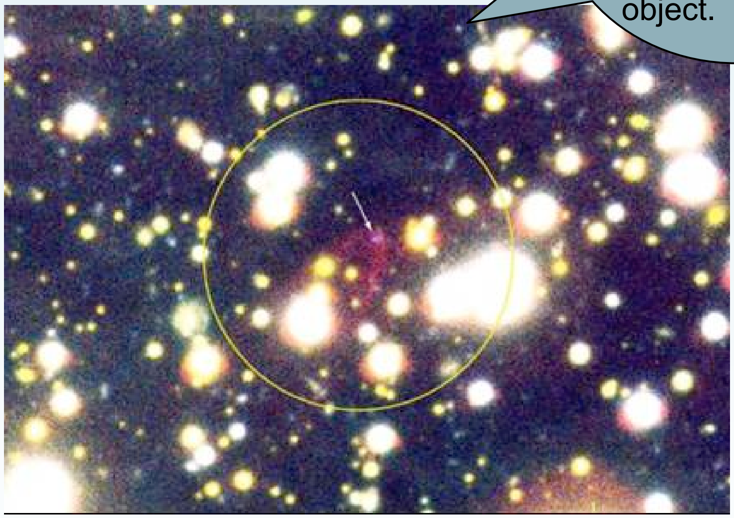
Photons are temporarily converted into e^- - e^+ pairs

"Interesting Neutron Stars": Isolated Dim neutron stars and Magnetars

Soft repeaters an Anomalous X-ray pulsars may contain **magnetars**: probing atomic physics in ultra-magnetized regimes.



HST image of RX J1856.5-3754



7 Dim neutron stars are seen within ~200 pc: probing the central compact object.

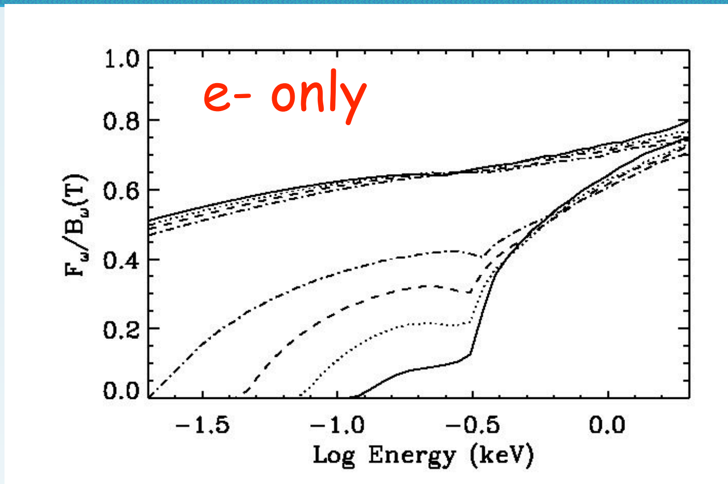
Neutron Star Crustal/atmospheric Emission: a basic, unanswered question

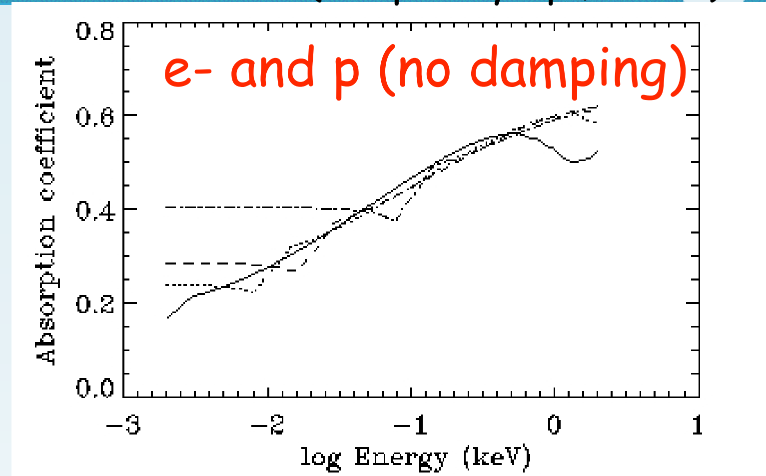
- 1970s: commonly accepted that radiation by NSs came from their solid surface (Brinkmann 1980 and refs)
- Later, the role of the thin gaseous layer which covers the star crust in shaping the emergent radiation spectrum was appreciated and model atmospheres became the standard tool for interpreting the observed emission from isolated NSs.
- However, highly magnetized NSs may be left without atmosphere if they are cool enough. Onset of a phase transition that turns the gaseous atmosphere into a solid when the surface T drops below Tcrit (B) (for a given chemical composition).

If $B \gg m_e e^3 c/h^3$ 2.35 x10^9 G atoms and condensed matter change:

- **Strong magnetic confinement on e-; atoms have cylindrical shape**
- **elongated atoms may form molecular chains by covalent bonding along B**
- **Interactions between linear chains can then led to the formation of 3-D condensates**

Zane et al. (Cospar symp., 2002)





The basic, unanswered question:

How the crust emits at low energies? Can crustal emission be responsible for the enhanced optical excess? e-/phonon damping drastically reduces the emissivity of a system of free e- below ~1 keV.

What is the role of ions?

Ions form a lattice and cannot be considered as free particles (as well as those e- which are bounds to ions).

The simplistic treatment of the dielectric tensor as an e-/ion plasma is unrealistic and not applicable.

If there is an atmosphere, theoretical expertise in radiative transfer is essential

In order to understand the interaction plasma-radiation in the complicated environment of a neutron star, to explain the observed spectra and to make predictions

⇩

we need **sophisticated radiative transfer algorithms**
(ex Zane et al., 1996, 1998, 2000, 2002)

Atmospheric codes must deal with the high magnetic field regime, which implies:

- High anisotropy
- Polarization
- Change in properties of atoms
- Quantum effects above $B \sim 4.4 \times 10^{13}$ G

$$df/dl = p^i \frac{\partial f}{\partial x^i} + \frac{dp^{\hat{a}}}{dl}\frac{\partial f}{\partial p^{\hat{a}}} = G$$

Transfer Equations for f
+ Equations for the photon trajectories

Magnetars: SGRs and AXPs

SGRs census: 4 confirmed + 1 candidate

	P (s)	dP/dt (10^{-11} s/s)	kT (keV)	□	F(2-10 keV) erg/cm^{-2}/s
SGR 1900+14 (G42.8+0.6)	5.2	6.1- 20.0	0.45	2	1.e-11
SGR 1806-20 (G10.0 0.3)	7.5	8.3- 47.0	0.8	1.2	1.5e-11
SGR 0526-66 (N49, in LMC)	8.0	6.6	0.53	3.1	1.e-12
SGR 1627-41 (G337.0-0.1)	6.4?	-		3	3e-13
SGR 1801-23	-	-			

- Class of rare X-ray bursting sources, only 4 of them are confirmed
- Persistent X-ray emitters ($L \approx 10^{35}$ erg/s).
- BB+PL X-ray spectrum (<10 keV) in quiescence
- Radio silent !!
- Initially confused with GRBs. However, unlike GRBs:
  - SGRs do repeat (hence their name !)
  - They show pulsations
  - large spin down rate

AXPs are similar, but much less burst active

(For a review see Woods & Thompson 2004; Mereghetti et al 2006)

Why SGRs and AXPs may be 'magnetars'?

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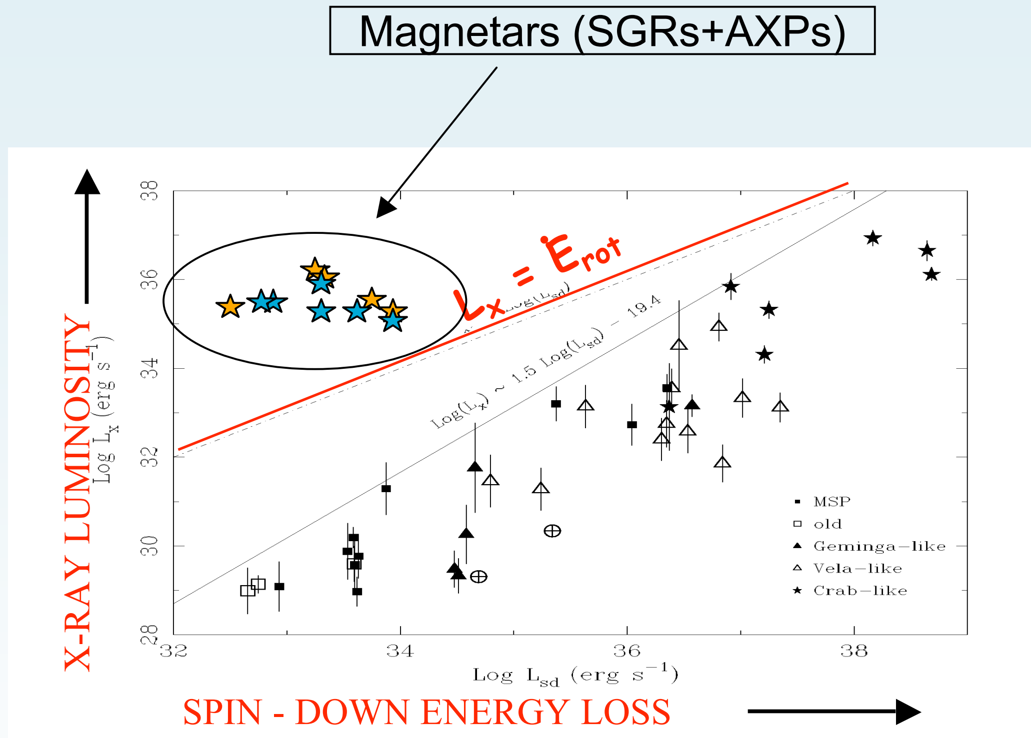
Magnetars: neutron stars with ultra strong magnetic field

$B \gg B_{QED} \sim 4 \times 10^{13}$ G

(Duncan & Thomson 1992; 1995)

1. **Original suggestion driven by the extreme properties of SGRs bursts and flares (Duncan & Thomson '92-'95)**
2. **Their X-ray luminosity is by far (~100) larger than their rotational energy resevoir .**
3. **No evidence for a companion star.**

 Another energy source is needed to explain their emission!



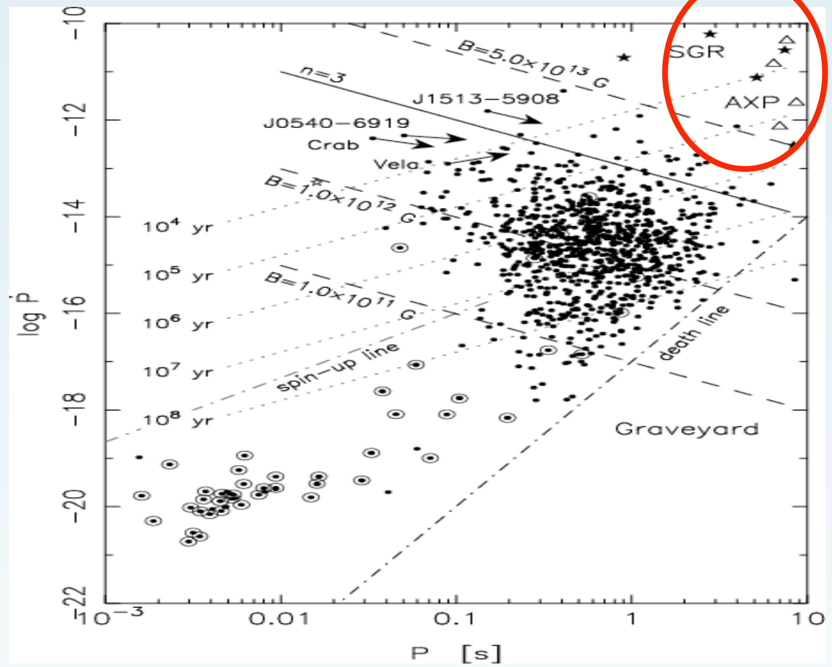
$$L_X > \dot{E}_{rot} = I\Omega\dot{\Omega}$$

Why SGRs may be 'magnetars'?

4. **Interpreting the spin-down as dipolar losses gives a rough estimate of the pulsar magnetic field:**

$$\dot{P} = 10^{-11}(B/10^{14}\ \mathrm{G})^2 P^{-1}\ \mathrm{s\,s^{-1}}$$

10^{14}-10^{15} G> B_{QED} ~ 4×10^{13} G



	P (s)	dP/dt (10^{-11} s/s)	dipolar B (10^{14} Gauss)	Spin-down age (kyr)
SGR 1900+14 (G42.8+0.6)	5.2	6.1- 20.0	5.7	1.3
SGR 1806-20 (G10.0 0.3)	7.5	8.3- 47.0	7.8	1.4
SGR 0526-66 (N49, in LMC)	8.0	6.6	7.4	1.9
SGR 1627-41 (G337.0-0.1)	6.4?	-	-	-
SGR 1801-23	-	-	-	-

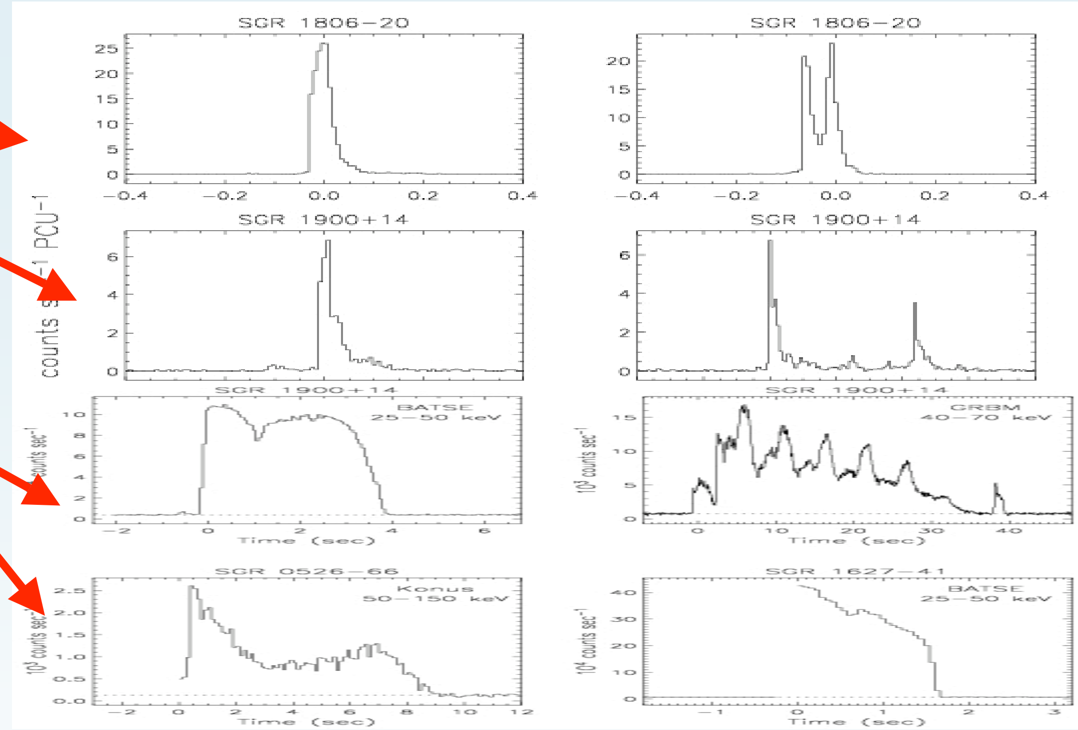
SGRs: different types of X/γ-ray bursts

Short bursts

- most common
- last ~0.1s
- peak ~10^{41} ergs/s
- soft γ-rays thermal spectra

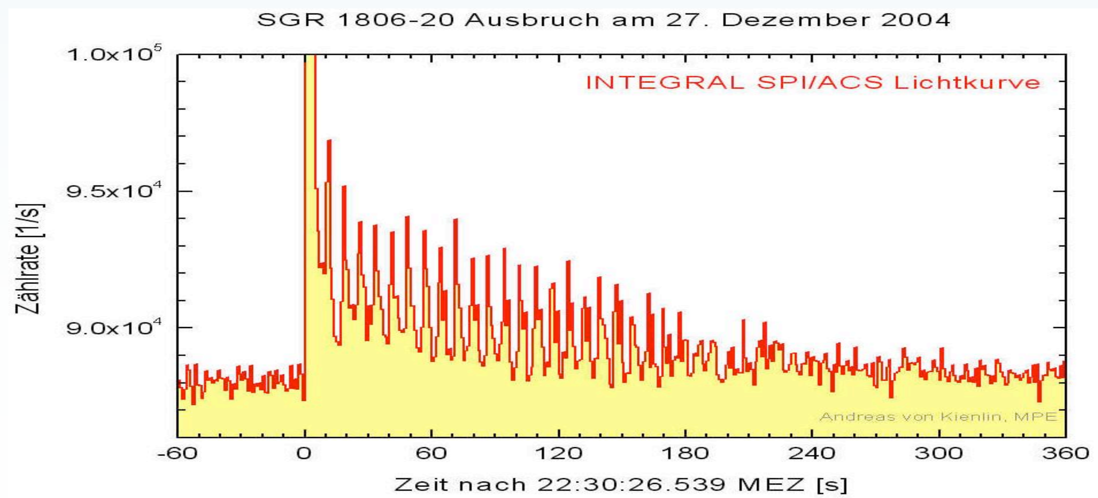
Intermediate bursts

- last 1-40 s
- peak ~10^{41}-10^{43} ergs/s
- abrupt on-set
- usually soft, thermal γ-ray spectra



Giant Flares

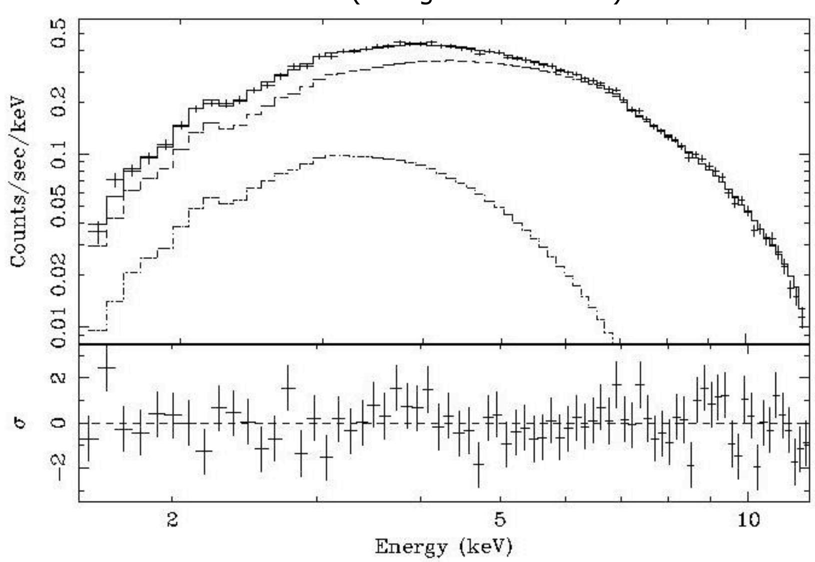
- peak < 1s and ringing tail
- 3 events so far
- isotr. energy release ~10^{44}-10^{46} ergs



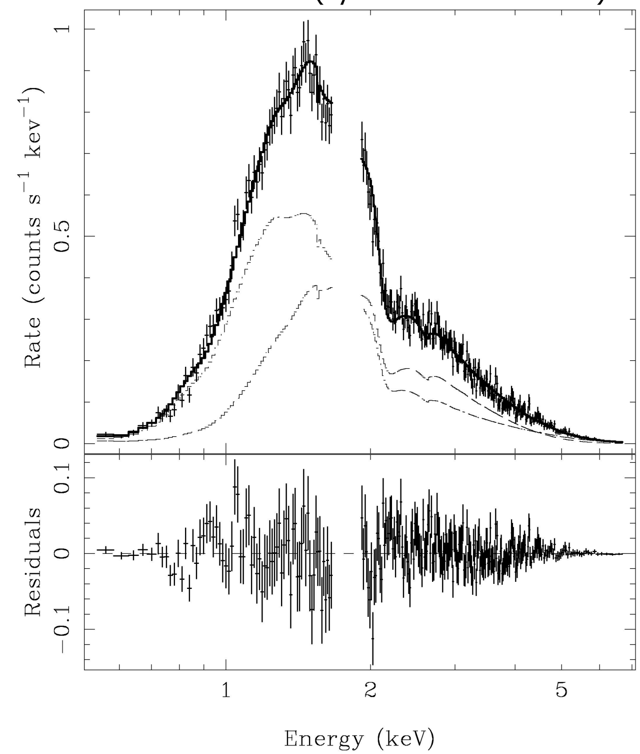
SGRs and AXPs X-ray Spectra - I

- 0.5 – 10 keV emission well represented by a blackbody plus a power law

SGR 1806-20 (Mereghetti et al 2005)



AXP 1048-5937 (Lyutikov & Gavriil 2005)



SGRs and AXPs X-ray Spectra - II

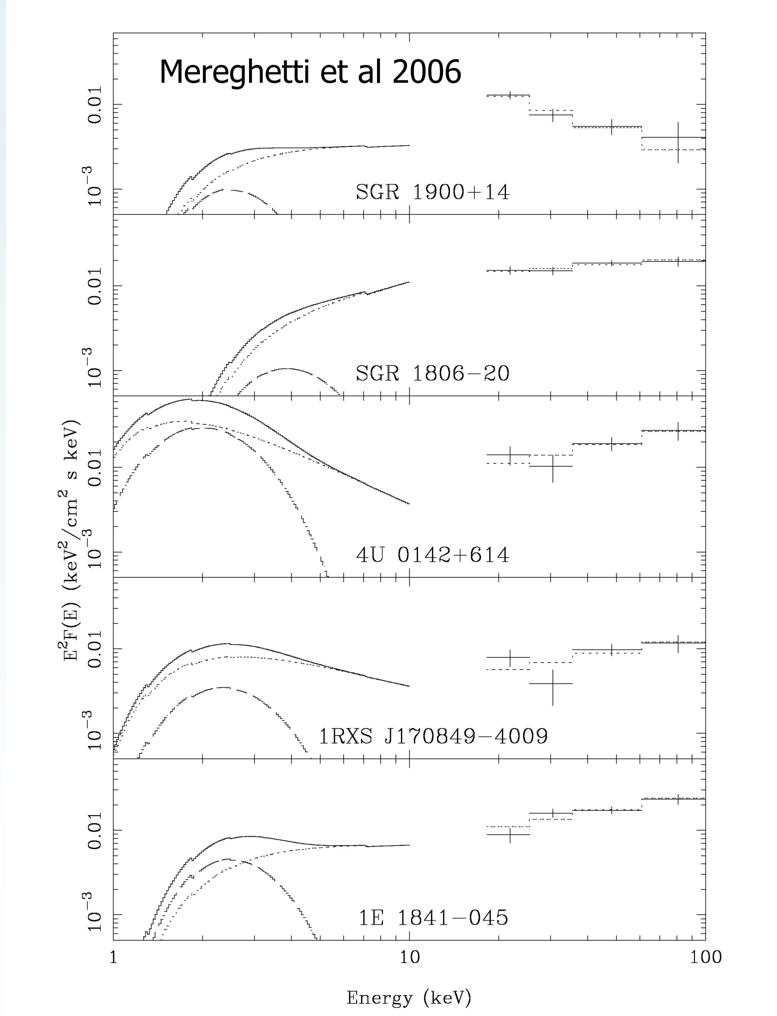
- $kT_{BB} \sim 0.5$ keV, does not change much in different sources
- Photon index □ ≈ 1 – 4, AXPs tend to be softer
- SGRs and AXPs persistent emission is variable (months/years)
- Variability mostly associated with the non-thermal component

Hard X-ray Emission

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

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

Hard emission pulsed



Hard X-ray Emission

Thompson 2005 and Beloborodov et al 2007 discussed the electrodynamics of the magnetar coronae and the production mechanisms for soft gamma-rays:

- Pair cascade high in the magnetosphere

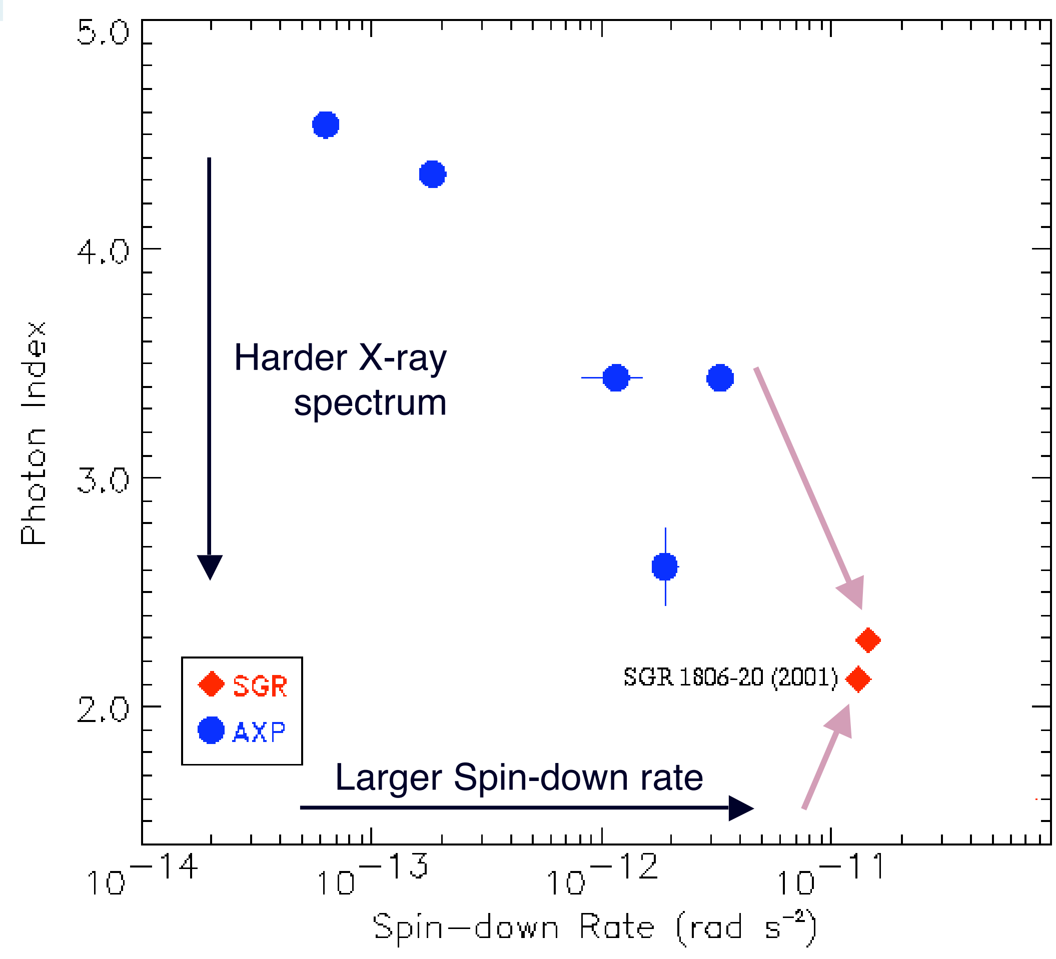
- Bremmstrahlung: existence of a thin transition layer between the corona and the thermal photosphere, where Langmuir turbulence can be excited by a downward beam of current-carrying charges. As a result, the transition layer can be heated up to a typical temperature of 100 keV, and emit, approximatively, an optically thin bremsstrahlung at a single temperature

- Resonant scattering from a population oh highly relativistic currents confined close to the stellar surface (Baring et al 2007)

Hardness vs Spin-down Rate

Correlation between spectral hardness and spin-down rate in SGRs and AXPs (Marsden & White 2001)

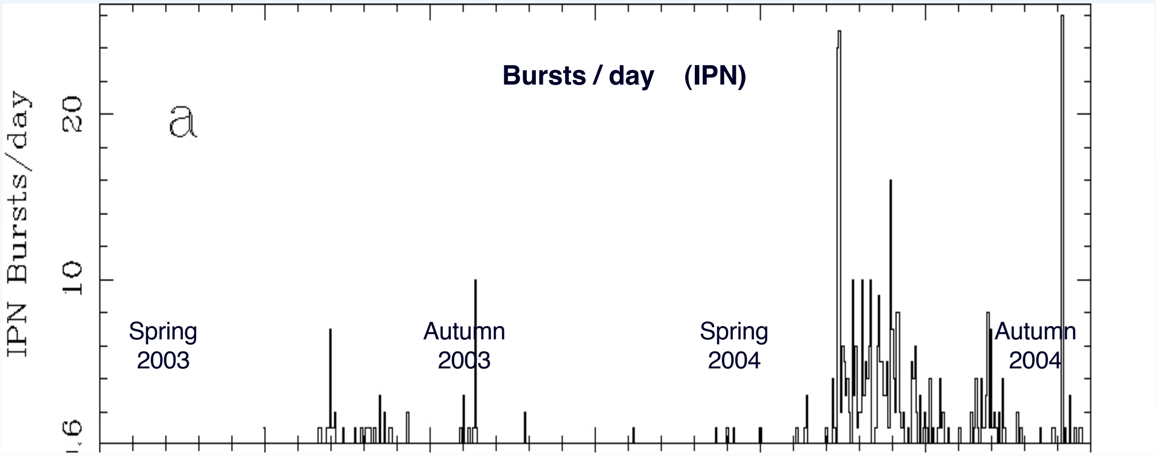
Correlation holds also for different states within a single source (SGR 1806-20, Mereghetti et al 2005; 1 RXS J170849-4009, Rea et al 2005)



SGR 1806: evolution prior the 2004 Dec 27 giant flare- I

SGR 1806-20 displayed a gradual increase in the level of activity during 2003-2004

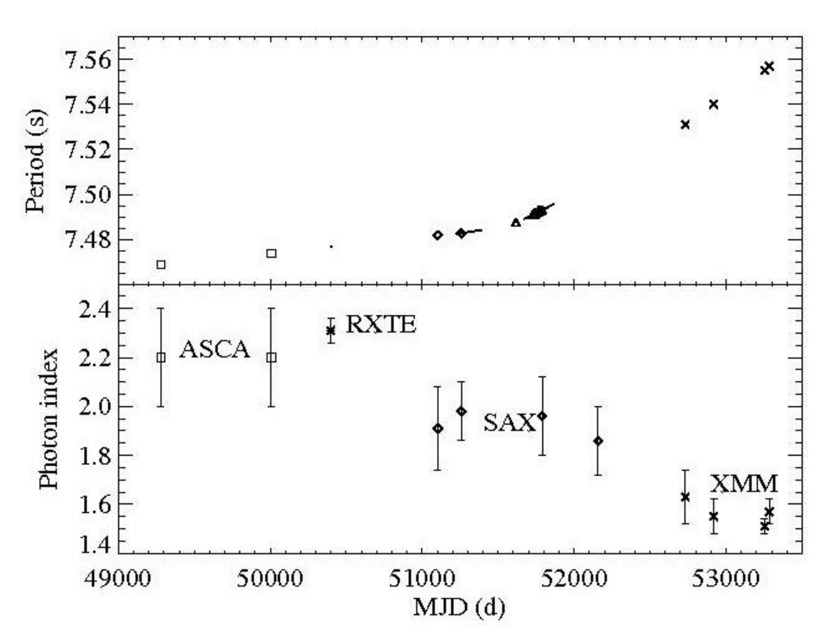
Enlarged burst rate



Woods et al, 2004; Mereghetti et al 2005

SGR 1806: the pre-giant flare evolution - II

- Four XMM-Newton observations (April 2003 to October 5 2004, Mereghetti et al 2005)
- dP/dt ~ 5.5×10^{-10} s/s, higher than the "historical" value
- Harder spectra: Γ ~ 1.5 vs. Γ ~ 2
- The 2-10 keV luminosity almost doubled (L_X ~ 10^{36} erg/s)



From Mereghetti, et al 2005

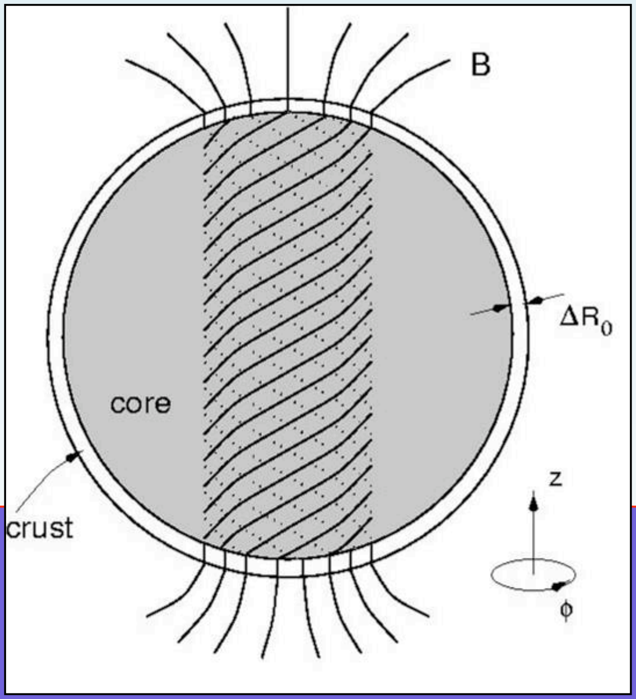
- Aftermath: spectral softening, rapid decay in persistent flux, and spin down rate (Rea et al, 2005; Tiengo et al, 2005)

Increase of spectral hardness and of average spin-down rate are correlated!

Onset of a twist in the magnetosphere?

- Increase in bursting activity activity culminating with the flare

- Observed □-L-dP/dt correlation



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 □ stresses build up in the NS crust, crustal fractures, glitches.

Twisted magnetospheres

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

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

- an extra heating of the star surface (by returning currents)
  → X-ray luminosity increases

- and a large resonant cyclotron scattering depth
  → spectral hardening increases

- The B-field flare out slightly → open field flux > then in a dipole
  → spin down torque increases

- a) Crustal cracks occur when the crust cannot bear the stress anymore or b) a global rearrangement of the field lines. → a forced opening of the field outwards
  → launch of an hot fireball

- And everything is reversed during the aftermath (simplification of the external B-field and by a partial magnetospheric untwisting → rapid drop in the flux, spectral softening, period derivative decrease, etc..)

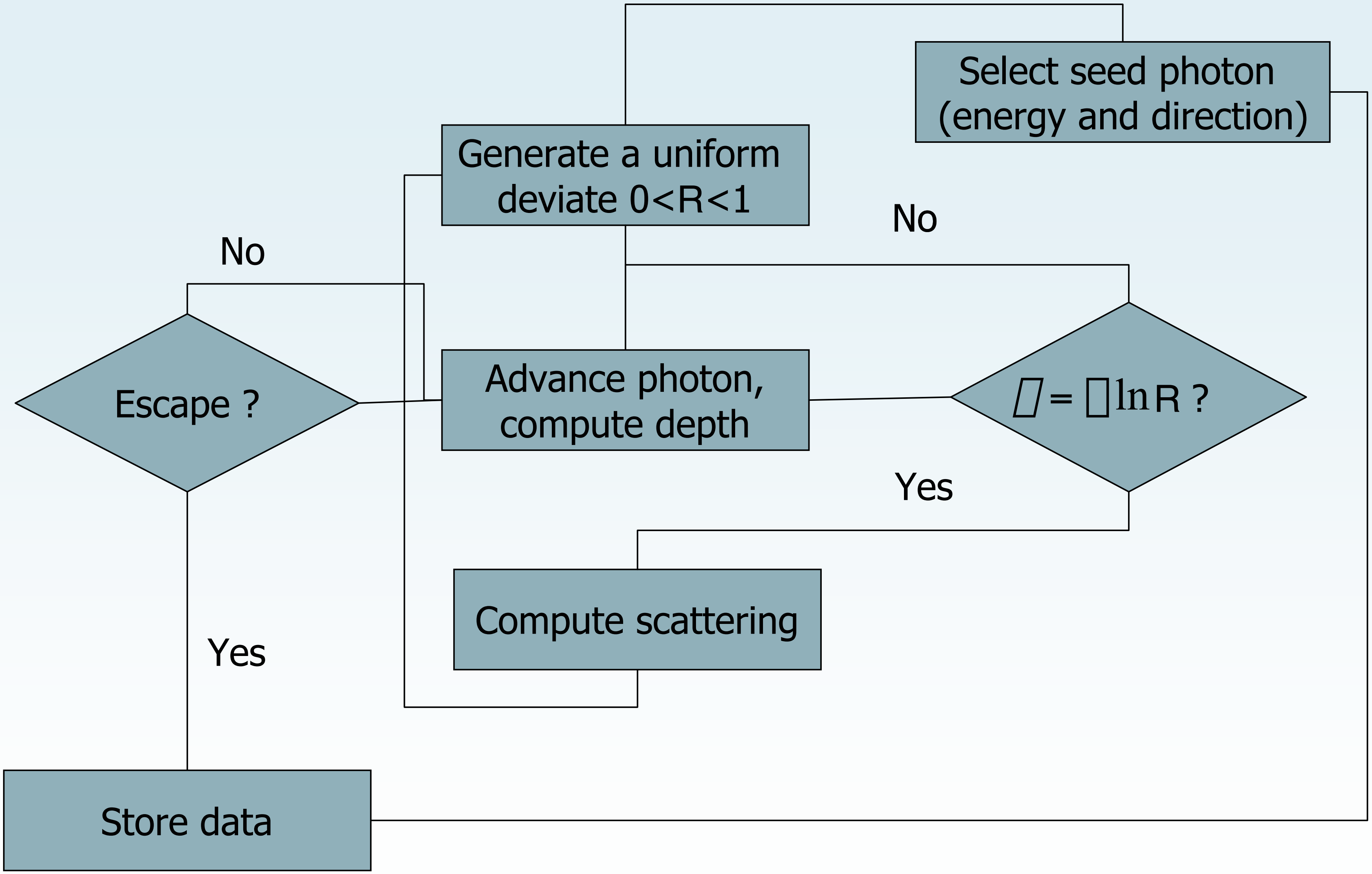
A Monte Carlo Approach

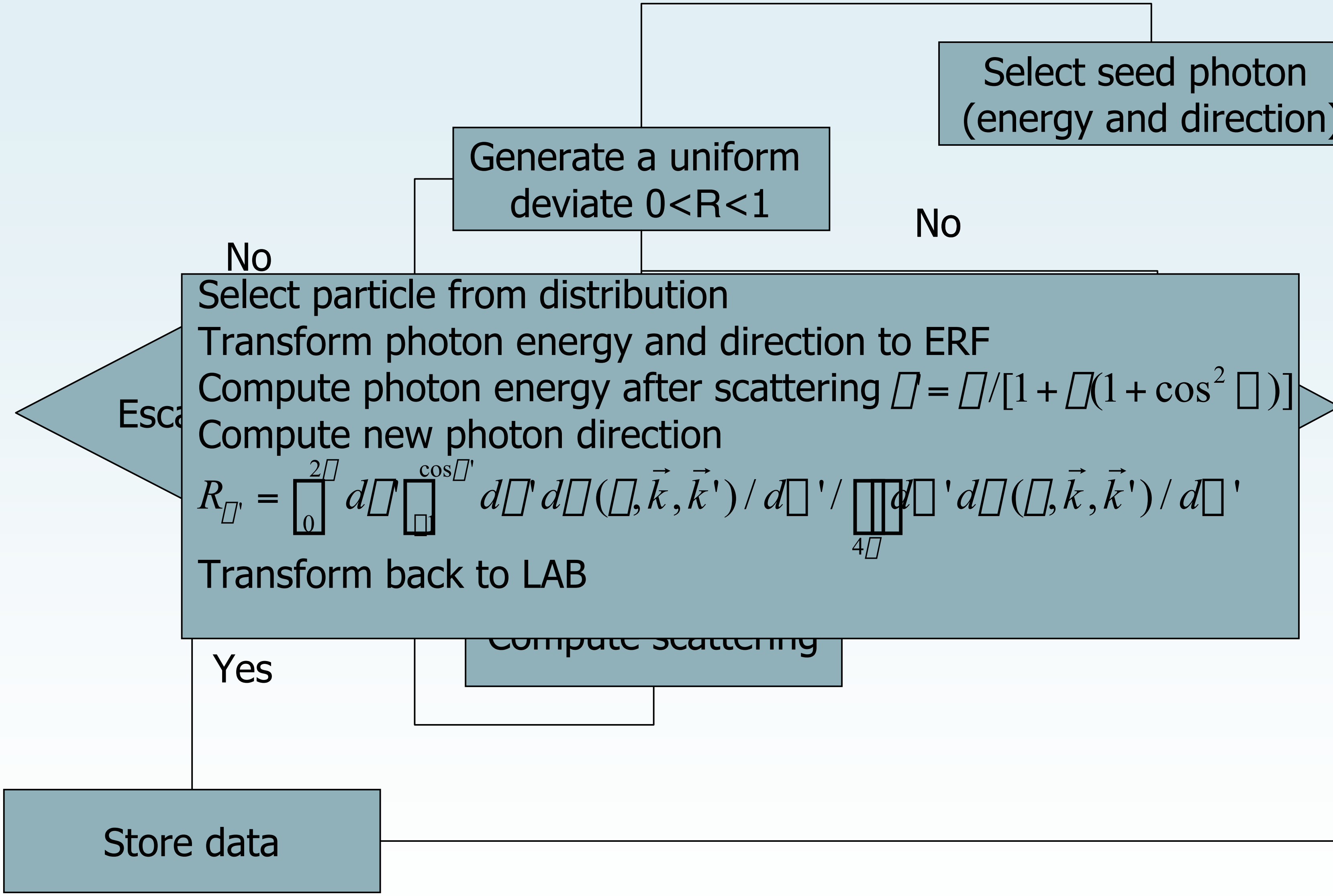
- Follow individually a large sample of photons, treating probabilistically their interactions with charged particles
- Can handle very general (3D) geometries
- Quite easy to code, fast
- Ideal for purely scattering media
- Monte Carlo techniques work well when $N_{scat} \approx 1$

Basic ingredients:

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

Preliminary investigation (1D) by Lyutikov & Gavriil (2005)
More detailed modeling by Fernandez & Thompson (2006)
New, up-to-dated code (Nobili, Turolla, Zane & Sartore 2007)


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


Select seed photon (energy and direction)
Generate a uniform deviate 0<R<1
No
No
Select particle from distribution
Transform photon energy and direction to ERF
Compute photon energy after scattering
Compute new photon direction
Transform back to LAB
Yes
Store data

Twisted Magnetospheres

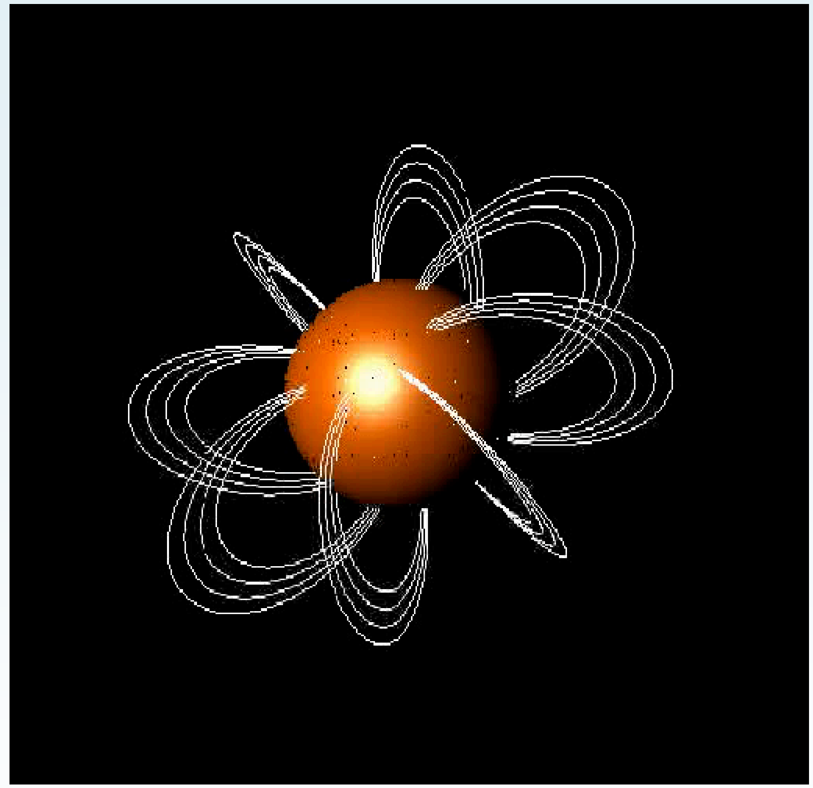
- TLK02 investigated force-free magnetic equilibria

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

- A sequence of models labeled by the twist angle

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

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



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)

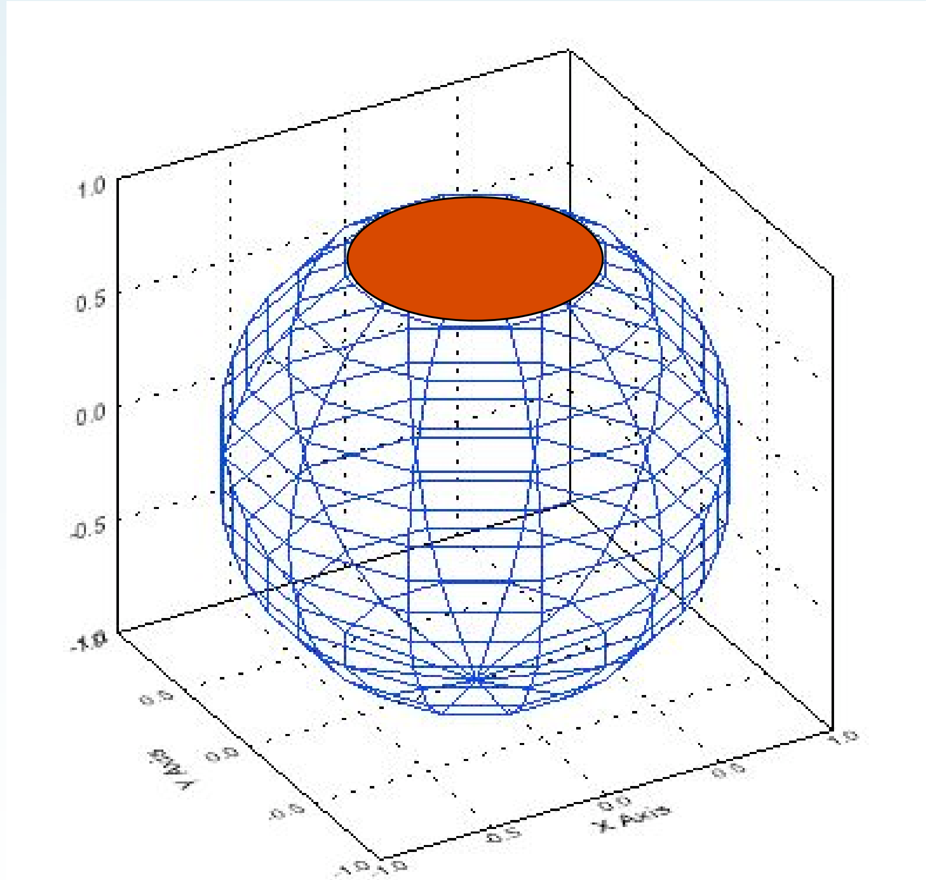
- There may be $e^{\pm}$ in addition to e-p, but no detailed model as yet (neglected!)

Surface Emission

The star surface is divided into patches by a (cos □, □) 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, elliptically polarized modes in the magnetized "vacuum+cold plasma"
- At $\rho < \rho_V \approx (B/10^{14}\ \mathrm{G})^2 (E/1\,\mathrm{keV})^2\ \mathrm{g\,cm^{-3}}$ the modes are almost linearly polarized

The extraordinary (X) and ordinary (O) modes

Scattering Cross Sections

- QED cross section available (Herold 1979, Harding & Daugherty 1991) but unwieldy ⇒ IN PROGRESS
- Non-relativistic (Thompson) cross section ($h\nu \ll mc^2/\gamma \approx 50$ 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)

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

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

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

Model Spectra

- 5 model parameters: B, T, T_e, $□_{bulk}$, □ □

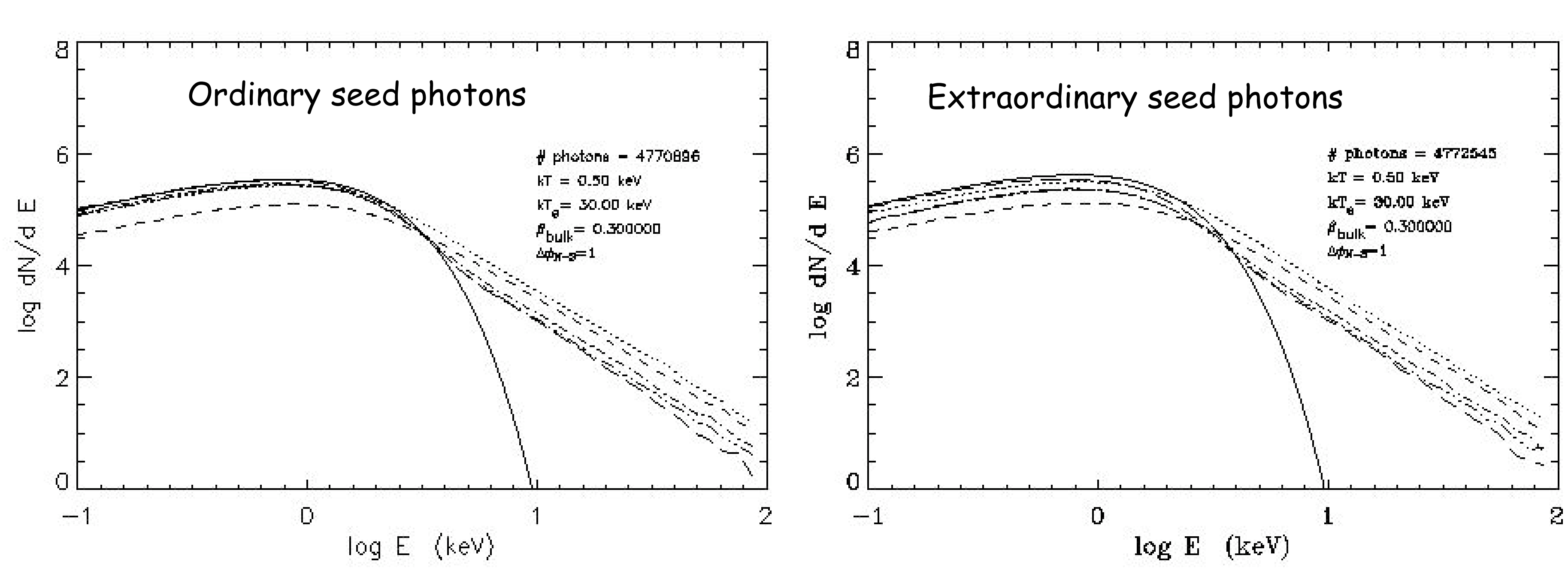
- 3 "prescriptions": i) surface emission map, ii) beaming and iii) polarization state of the seed photons

  □ next plots: BB surface emission , isotropic radiation

- After each Monte Carlo run, photons are collected in a (□,□) grid on the sky at infinity

- In the next plots: no viewing angle effects. Dipolar axis along z

Model Spectra- varying the parameters:
1- azimuthal angle (at infinity)

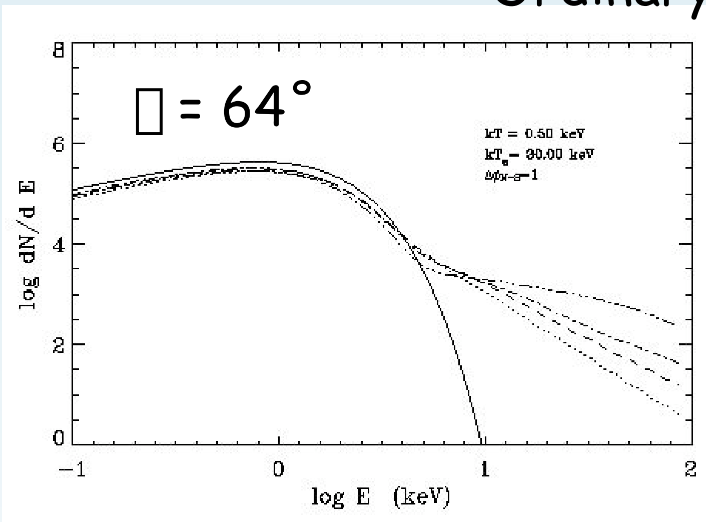


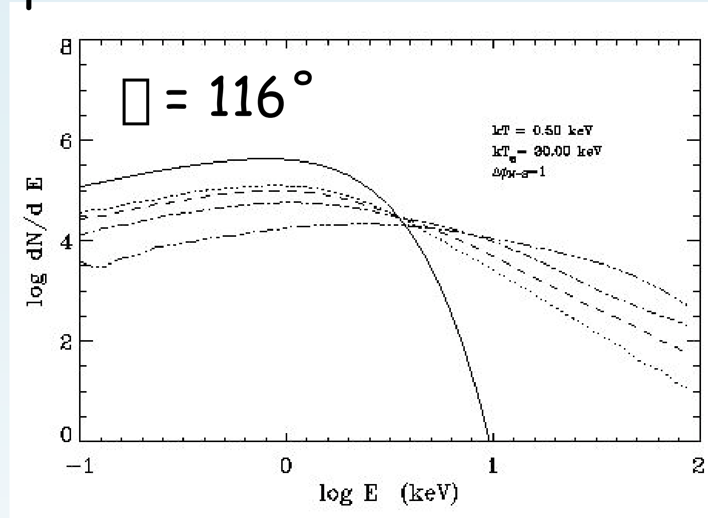
Computed spectra for B = 10^{14} G , kT = 0.5 keV, kT_e =30 keV, β_{bulk} = 0.3, = 1 and different values of the colatitude : 27° (long dashed), 64° (dashed-dotted-dotted-dotted), 90° (dashed-dotted), 116° (short dashed) and 153° (dotted). The solid line is the seed blackbody, units are arbitrary.

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

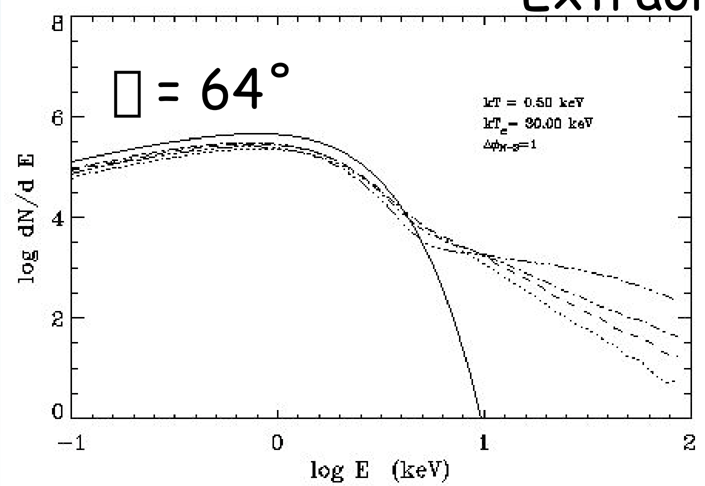
2- currents bulk velocity β_{bulk}

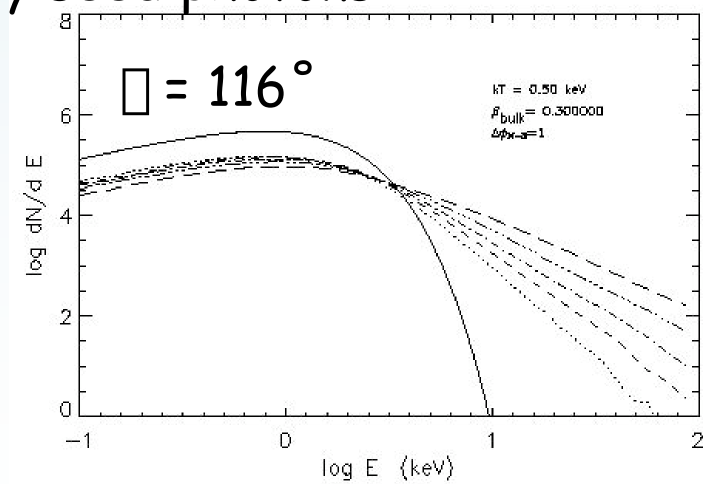
Ordinary seed photons





Extraordinary seed photons





Computed spectra for B = 10^{14} G, kT = 0.5 keV, kT_e = 30 keV, $\Delta\phi$ = 1 and different values of β_{bulk}: 0.3 (dotted), 0.5 (short dashed), 0.7 (dash-dotted) and 0.9 (dashed-dotted-dotted-dotted). The solid line represents the seed blackbody, units are arbitrary

3- temperature of magnetospheric currents, kT_e

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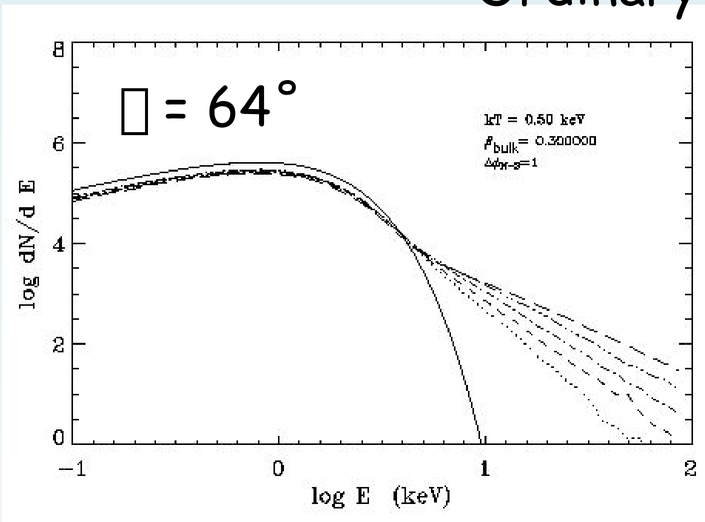
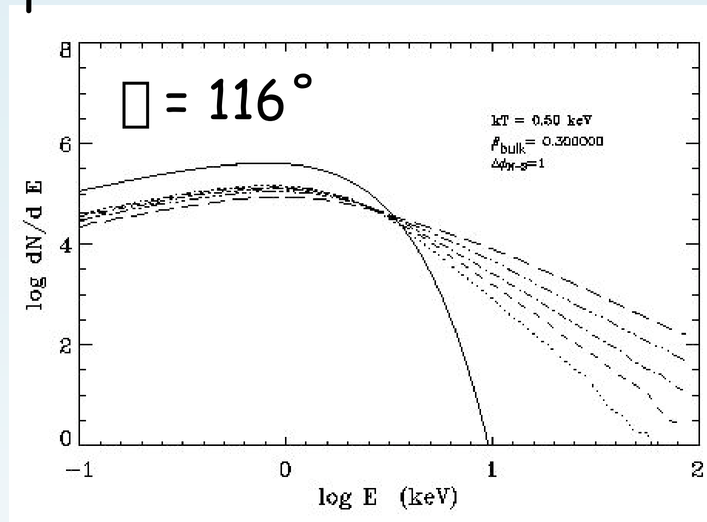
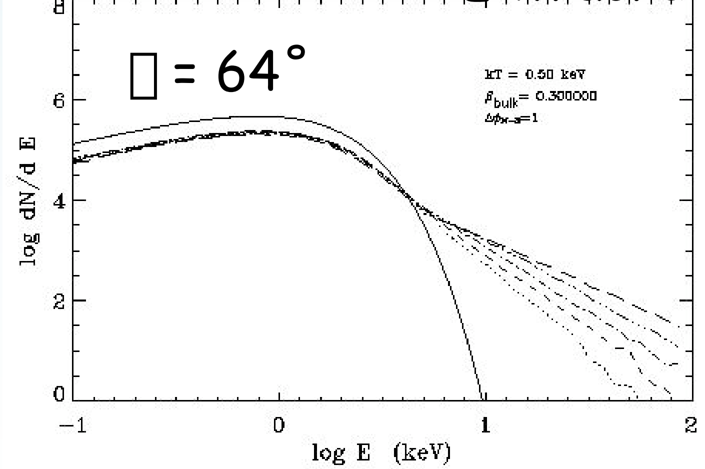
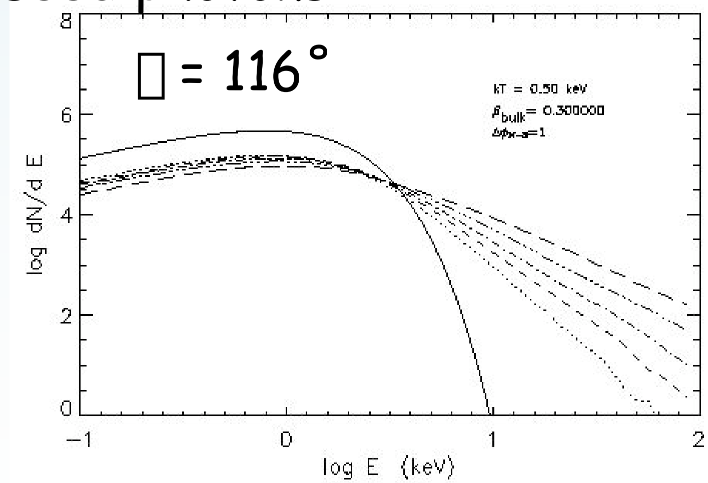
Ordinary seed photons





Extraordinary seed photons



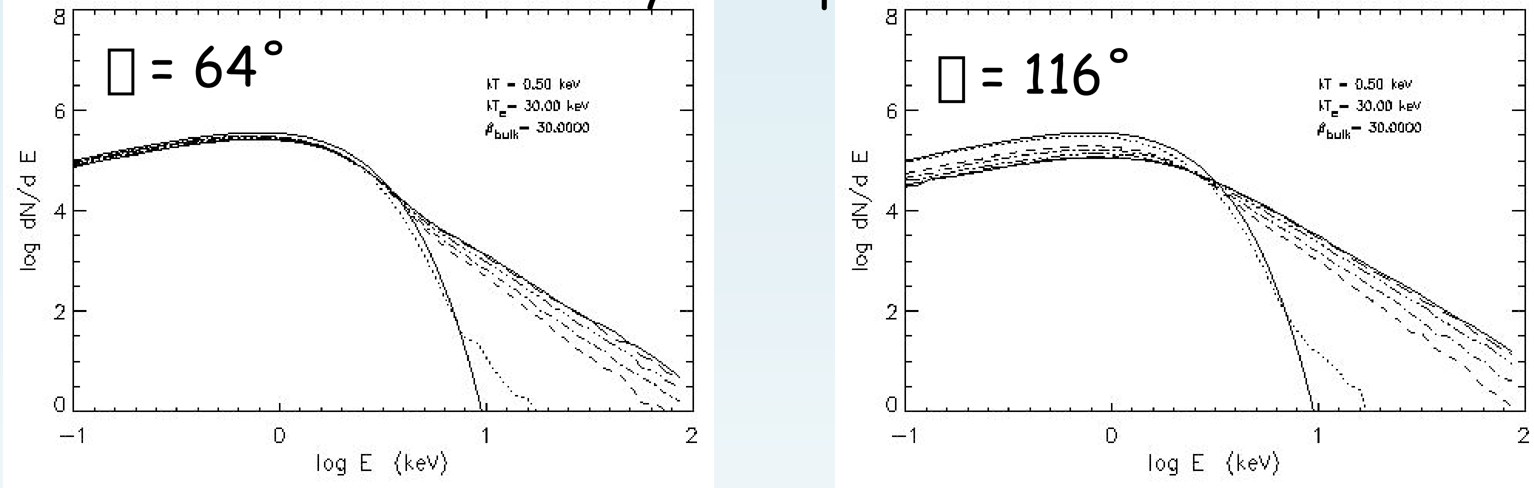


Computed spectra for $B = 10^{14}$ G, kT = 0.5 keV, □□ = 1, $□_{bulk}$= 0.3 and different values of kT_e: 5 keV (dotted), 15 keV (short dashed), 30 keV (dash-dotted), 60 keV (dashed-dotted-dotted-dotted) and 120 keV (long dashed). The solid line represents the seed blackbody, units are arbitrary

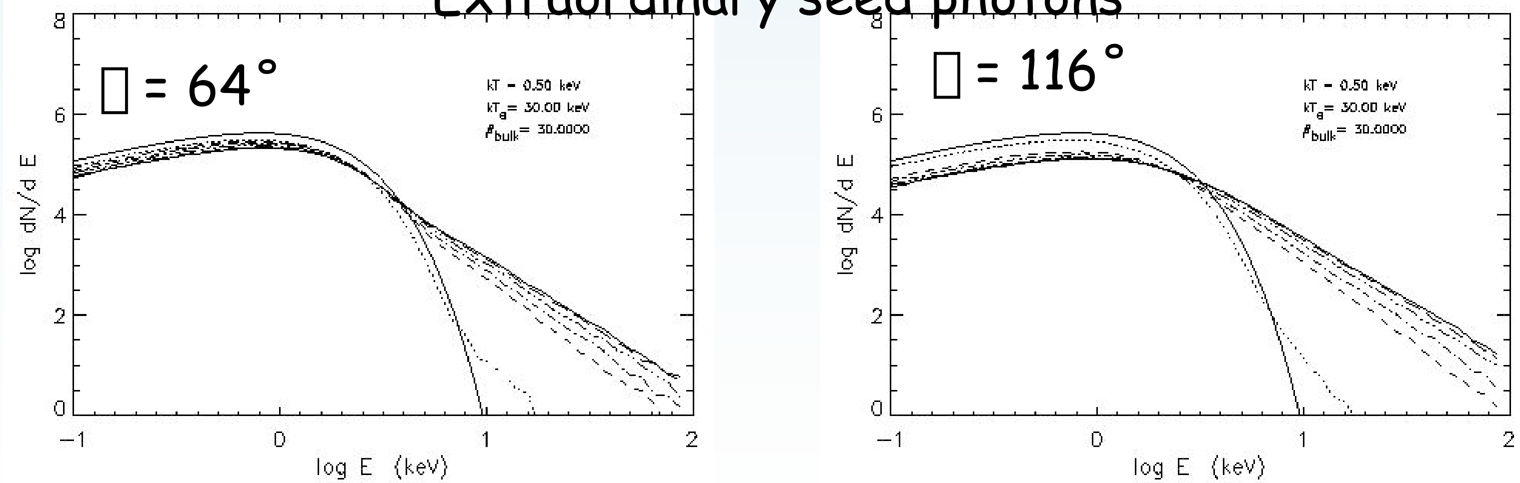
4- twist angle, $\Delta\phi$

UCL

Ordinary seed photons



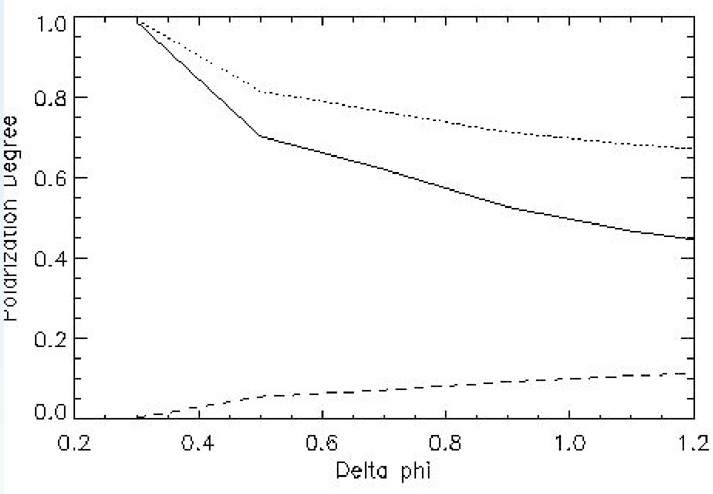
Extraordinary seed photons



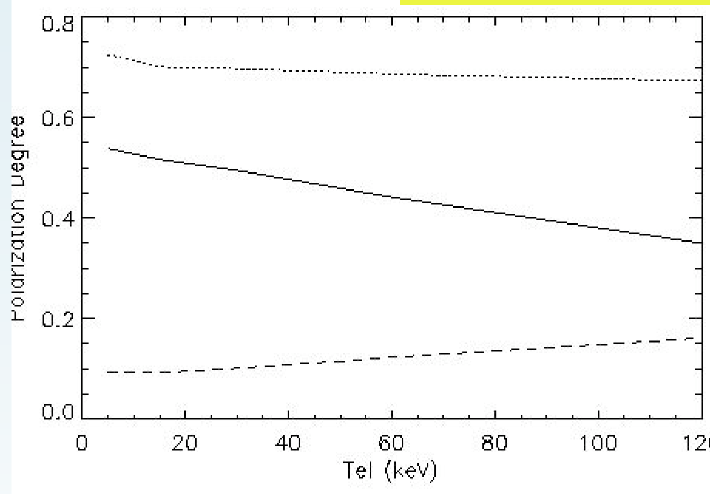
Computed spectra for $B = 10^{14}$ G, kT = 0.5 keV, β_{bulk}= 0.3, kTe =30 keV and different values of $\Delta\phi$: 0.3 (dotted), 0.5 (short dashed), 0.7 (dash-dotted), 0.9 (dashed-dotted-dotted-dotted), 1.1 (long dashed, bottom) and 1.2 (long dashed, top). The solid line represents the seed blackbody, units are arbitrary

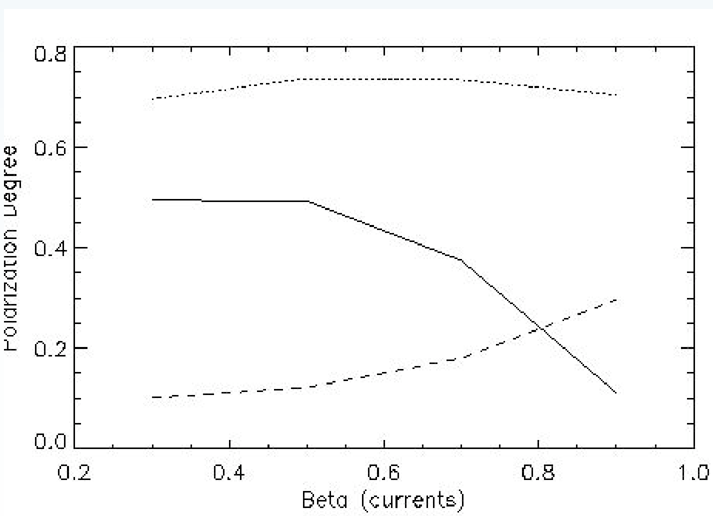
Polarization degree - varying the parameters

$\square_{bulk}$ = 0.3 kTe = 30 keV



$\square_{bulk}$ = 0.3 □□=1





□□ = 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

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
- $□_{bulk}$-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)
- 0.1 □ kT □ 0.9 keV 5 values
- 0.1 < □ □bulk □ < 0.99 10 values
- 0.2 < □ □_ □ < 1.2 11 values
- Viewing angle geometry: 0 □ □ □ < 180 and 0< □ □ □ <90 (7x7 values)
  □ collect patches in view at each phase and compute the phase average spectrum as seen by a distant observer

The final spectrum in XSPEC depends on 6 parameters:
kT , $□_{bulk}$, □□, □, □, K (= a normal. constant)

Preliminary fit to observed spectra (Nanda Rea)
XMM-PN data taken in 2004.
Longest available observation: 60ks.

FROZEN ANGLES:

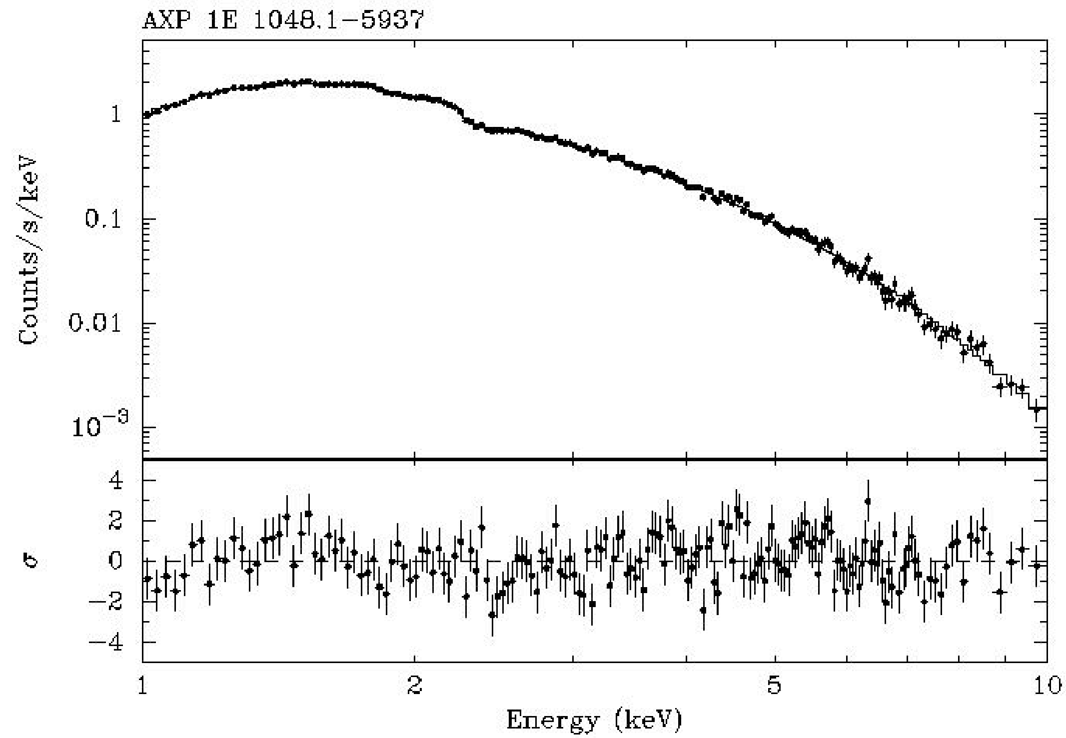
□ = □ = 30° frozen

parametri (errori 1 □):

N_H = (0.78 ± 0.02)x 10^{22} cm^{-2}

kT = 0.590±0.006 keV
$□_{bulk}$ = 0.21±0.02
□□= 1.15 ± 0.39
$□^2$ = 1.239 for 176 DOF

F^{abs} (1-10keV) = 1.1x10 $^{-11}$ ergs cm^{-2} s $^{-1}$



F^{abs} (1-10keV) consistent with the BB+PL fit!

Preliminary fit to observed spectra (Nanda Rea)
XMM-PN data taken in 2004.
Longest available observation: 50ks.

FROZEN ANGLES:

□ = □ = 30° frozen

parametri (errori 1 □):

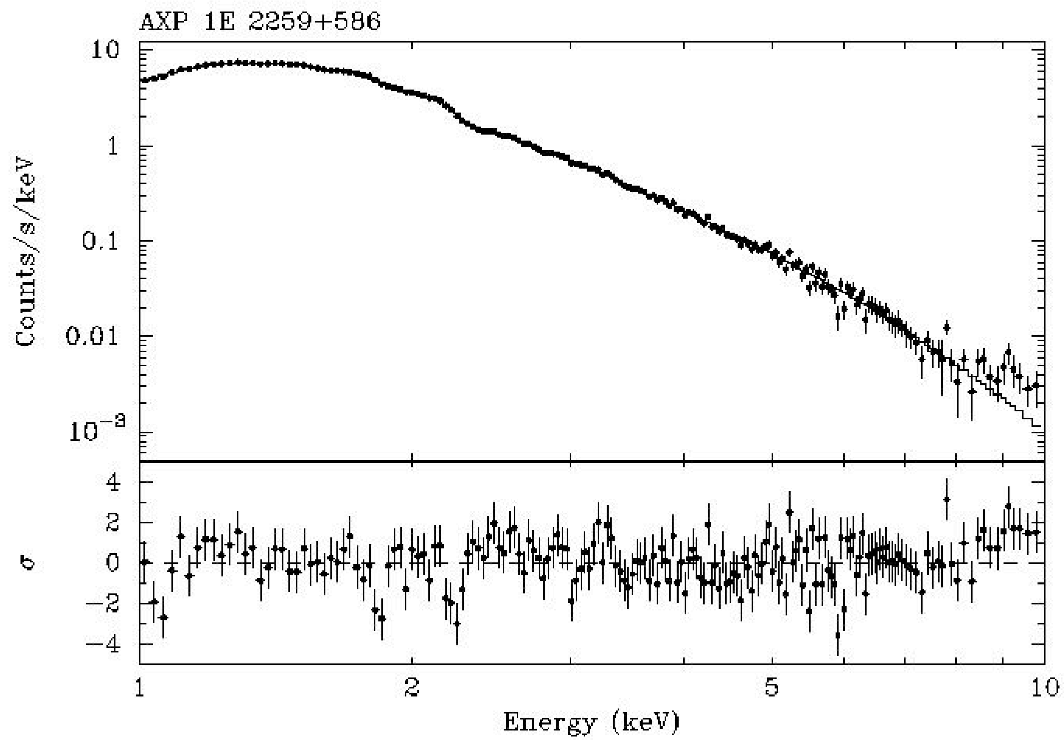
N_H = $(0.64 \pm 0.01) \times 10^{22}$ cm^{-2}

kT = 0.344±0.006 keV

$□_{bulk}$ = 0.17±0.01

□□ = 1.20 ± 0.05

$□^2$ = 1.283 for 179 DOF



F^{abs} (1-10keV) = 2.4x 10^{-11} ergs cm^{-2} s^{-1}

AXP 1E 2259+586 seems to need a PL at high energies. Same slope as in Kuiper et al 2006.

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

- Many issues need to be investigated further
  - ✓ Twist of more general external fields (L. Pavan in progress)
  - ✓ Detailed models for magnetospheric currents
  - ✓ More accurate treatment of cross section including QED effects and electron recoil (in progress)
  - ✓ 10-100 keV tails: up-scattering by (ultra)relativistic ($e^{\pm}$) particles ?
  - ✓ Create a model archive to fit model spectra to observations (in progress, with N. Rea)

THANKS !