QED and the Hard X-Ray Emission from AXPs/SGRs

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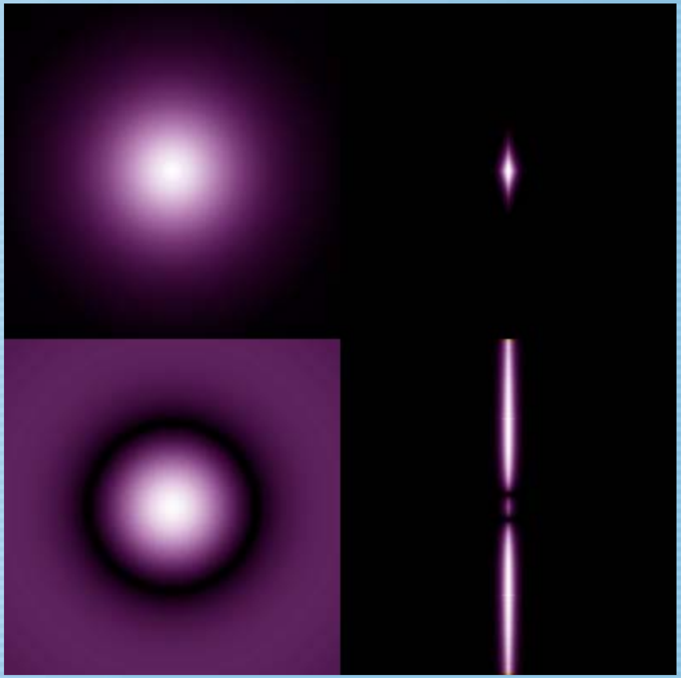
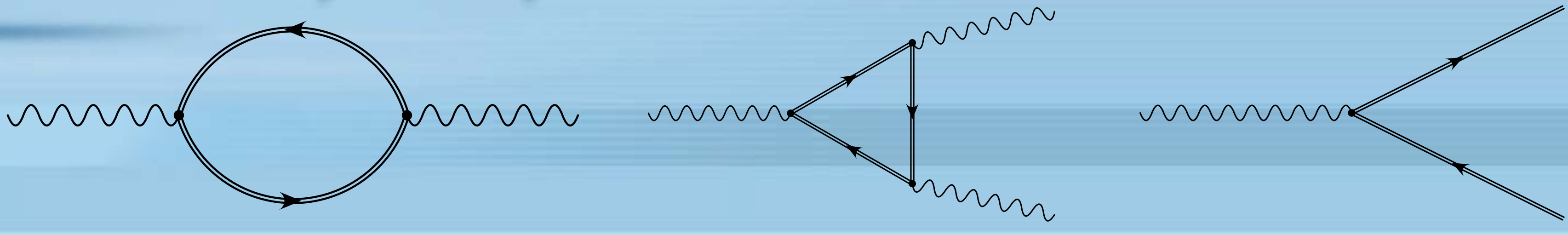
What are magnetars?

- Magnetically powered neutron stars
- Neutron stars with magnetic fields larger than $B_{QED} = m^2c^3/(e\hbar) \approx 4.4 \times 10^{13}\,\mathrm{G}$
- I will use both definitions and also focus on effects that become important as B approaches B_{QED}.

How does the physics differ?

- Radiative (photons and neutrinos) transfer is strongly anisotropic (Hungerford).
- Atoms strongly distorted; may condense at P=0 (Lai, Turbiner)
- Radiative corrections of QED may be important.

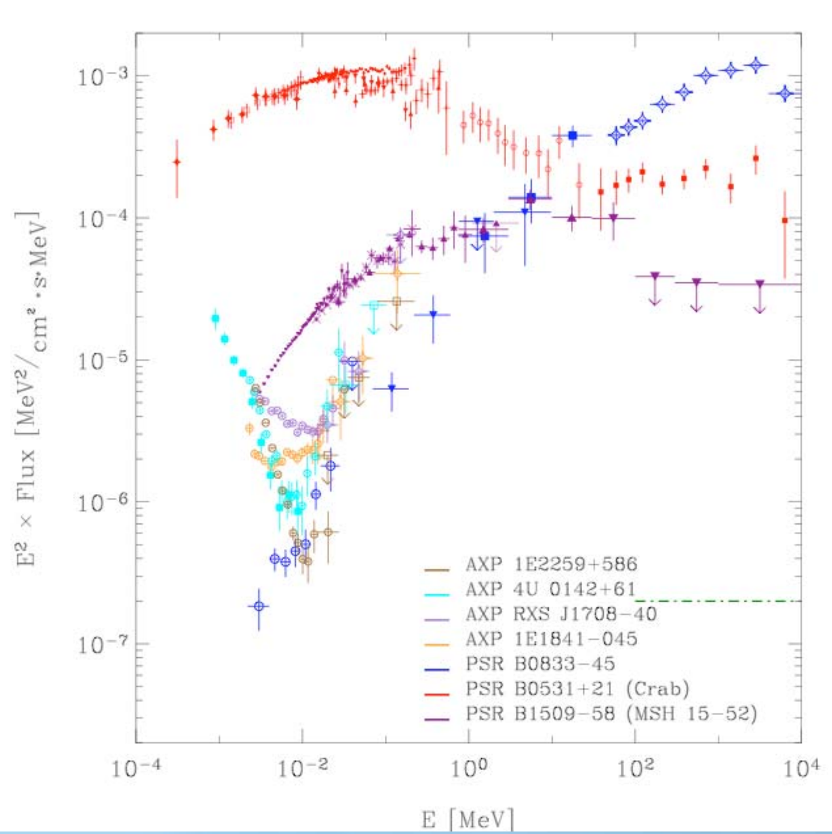




The physics is messy.

The SGR/AXP Connection

All are hard except SGR 1900+14!



Kuiper et al. 2006

- INTEGRAL/RXTE observations have found hard X-ray emission from
  - SGR 1900+14
  - SGR 1806-20
  - 4U 0142+614
  - 1RXS J170849-4009
  - 1E 1841-045
  - 1E 2259+586

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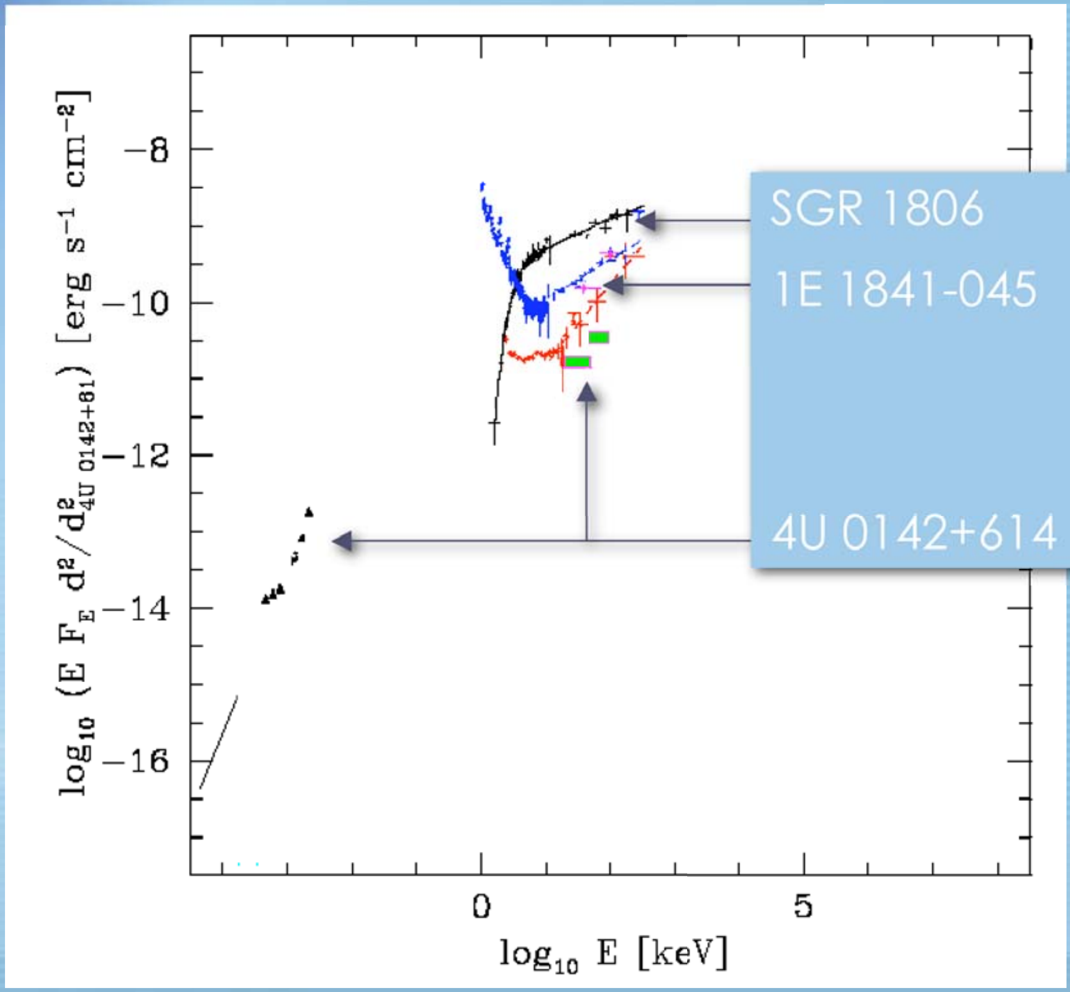
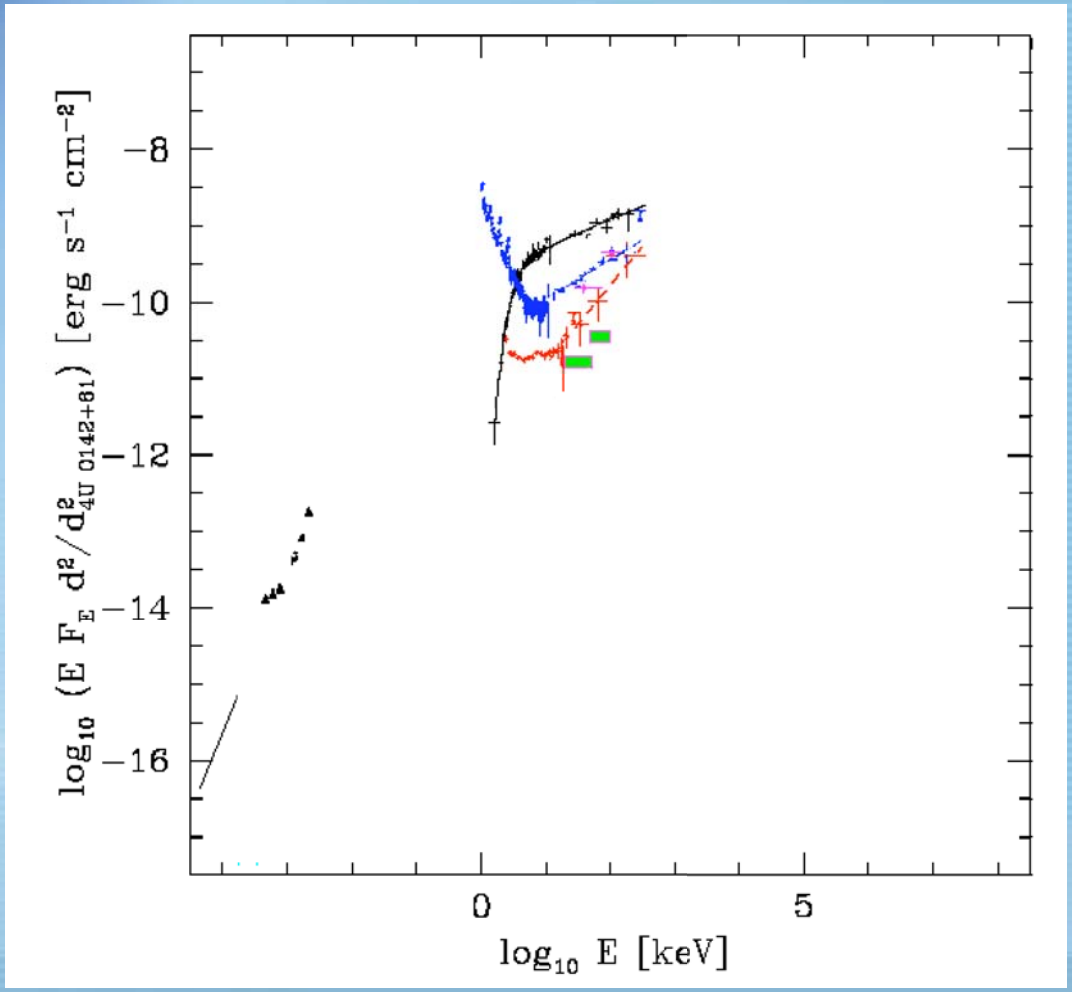


Non-thermal Emission

- X-rays, gamma-rays and optical.
- Özel points out that no thermal mechanism powered by energy through the crust can account for the optical emission and be consistent with the X-ray emission

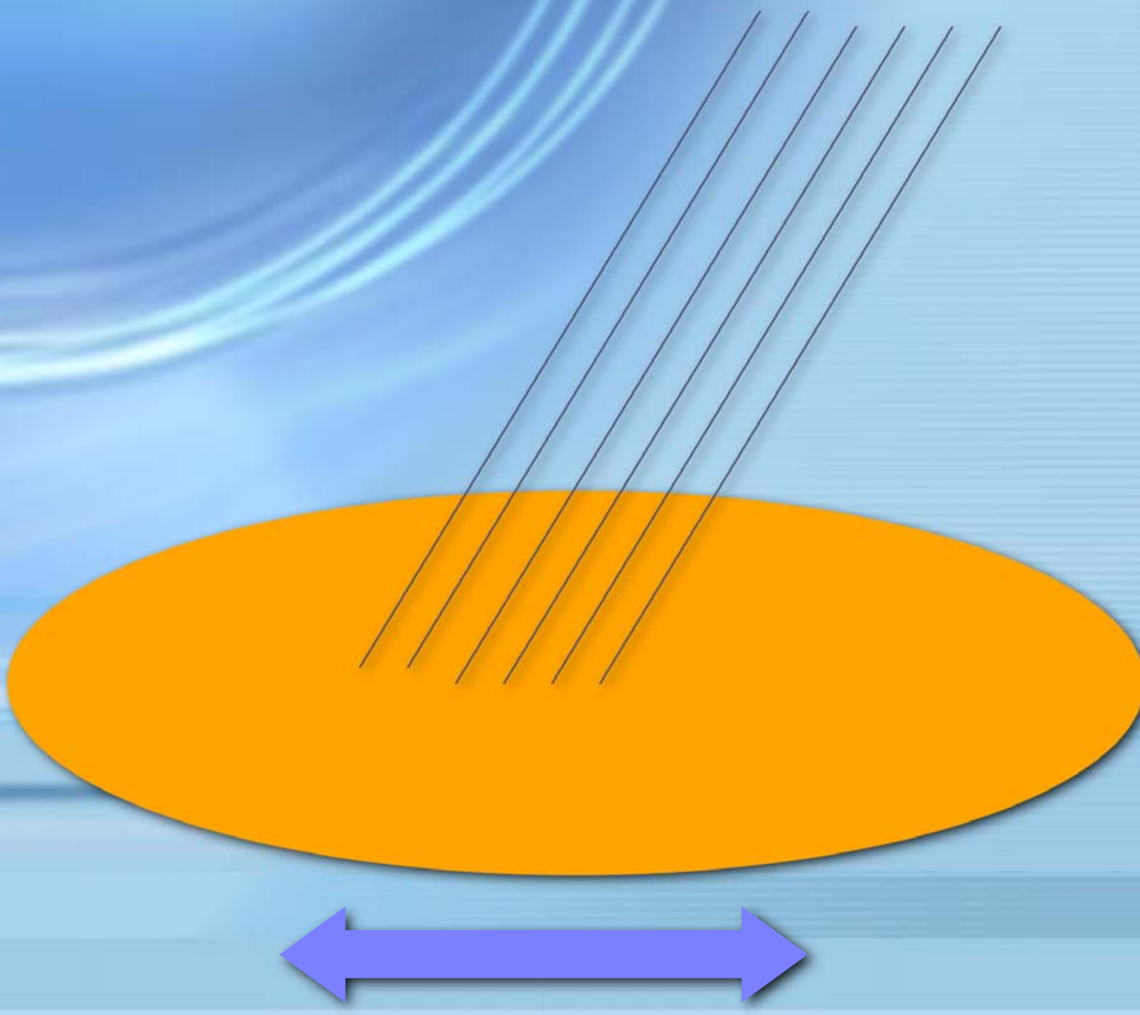


Özel '04; Hulleman et al. '00

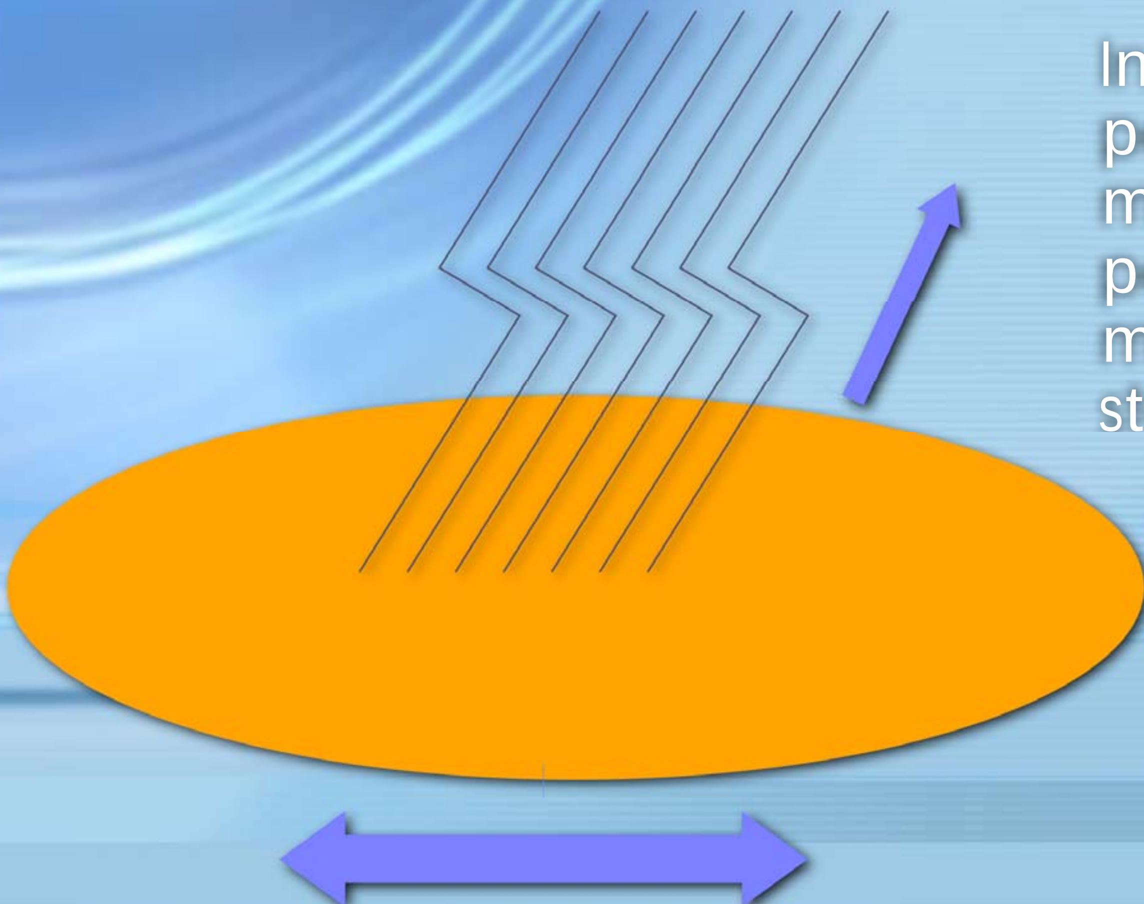
Understanding the bursts

- Standard model (Thompson & Duncan ‘96); magnetic reconnection of an evolving supercritical field; imagine the sun with a solid crust.
  - Magnetic helicity flows through the crust sporadically driving strong currents through the magnetosphere (Alfvenic cascade)
- Alternative picture - reconnection also generates fast waves that shock.

Understanding the bursts

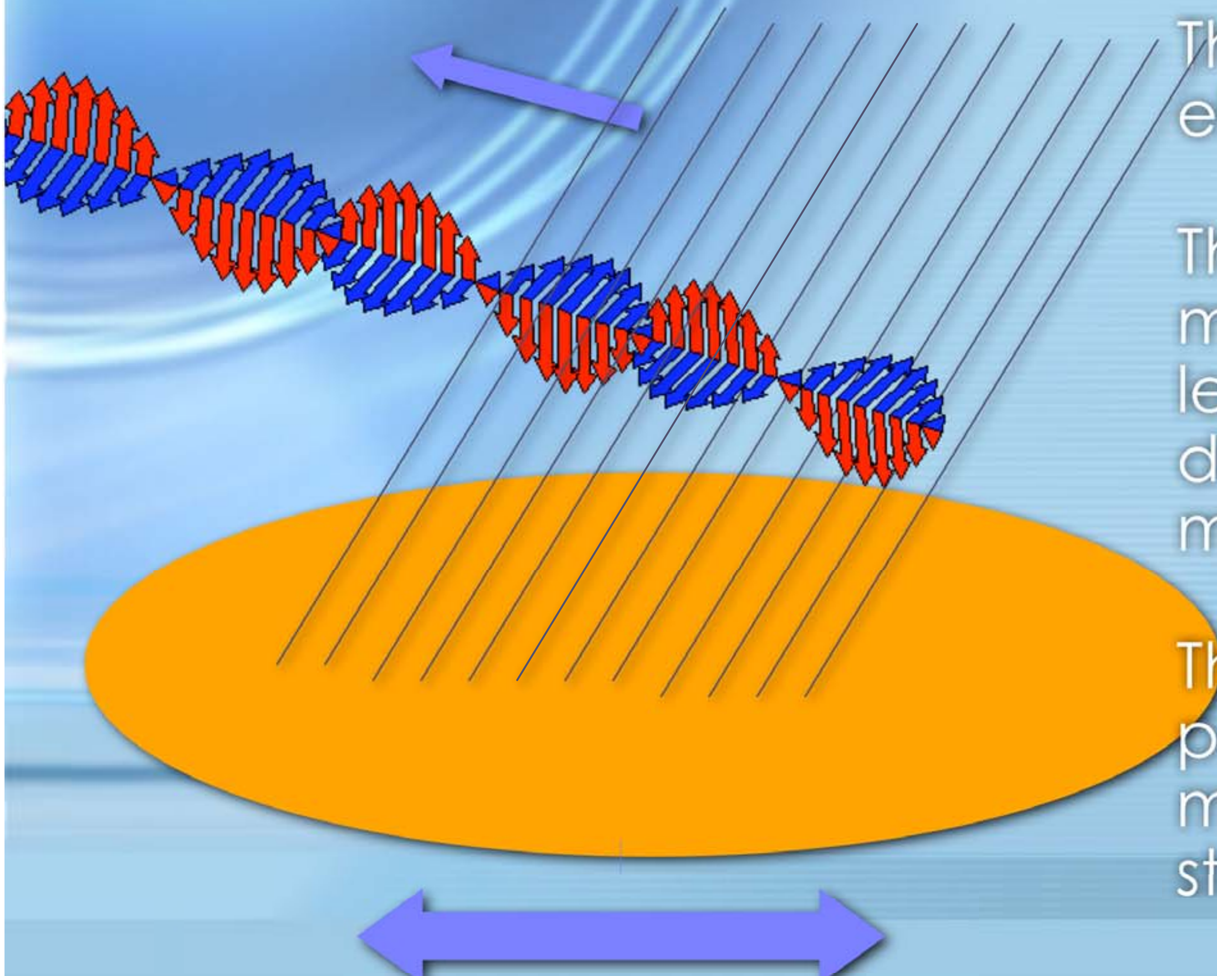


Understanding the bursts



In an Alfven wave, the perturbation to the magnetic field is perpendicular to the magnetic field of the star.

Understanding the bursts

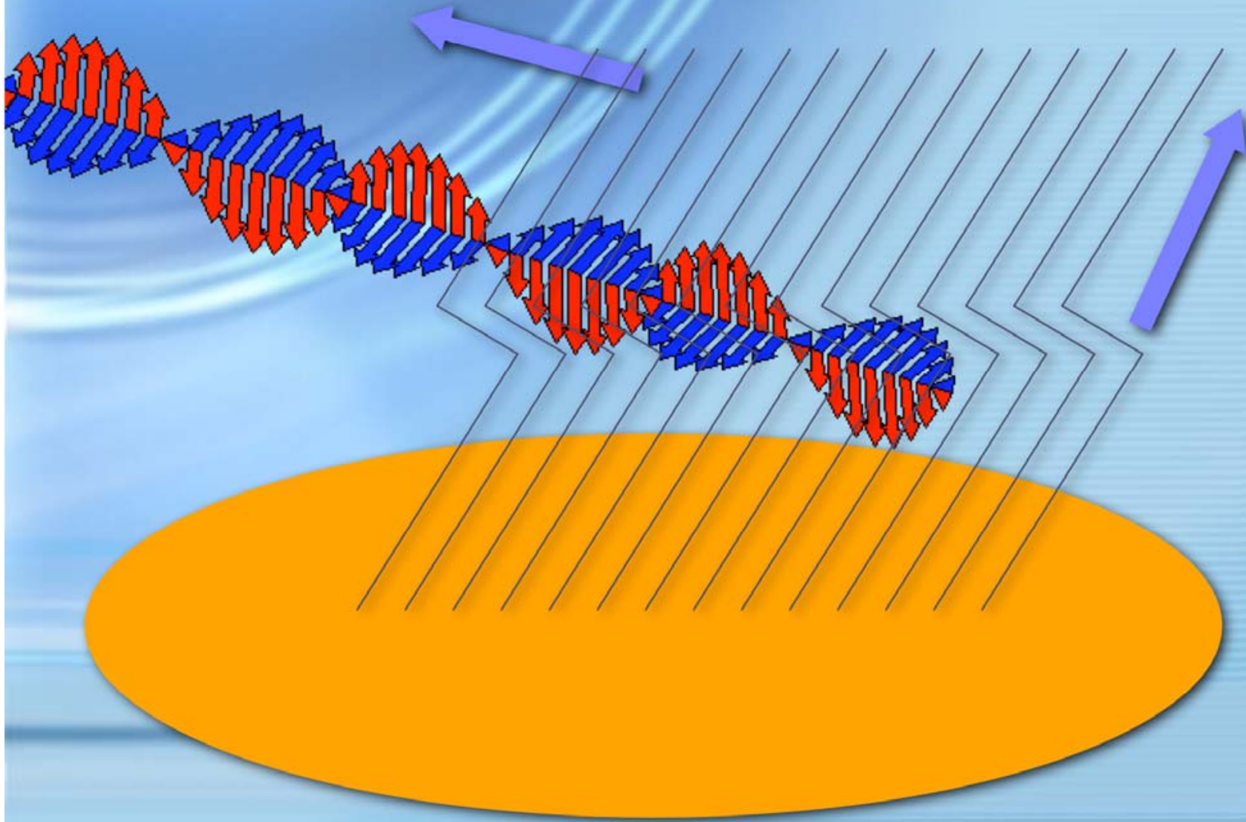


The fast mode is an electromagnetic wave.

The perturbation to the magnetic field lies at least in part in the direction of the magnetic field.

The electric field is perpendicular to the magnetic field of the star.

Understanding the bursts



Both types of wave can be produced in the magnetosphere without any action in the crust. The sun does it all of the time.

Non-Linear Electrodynamics

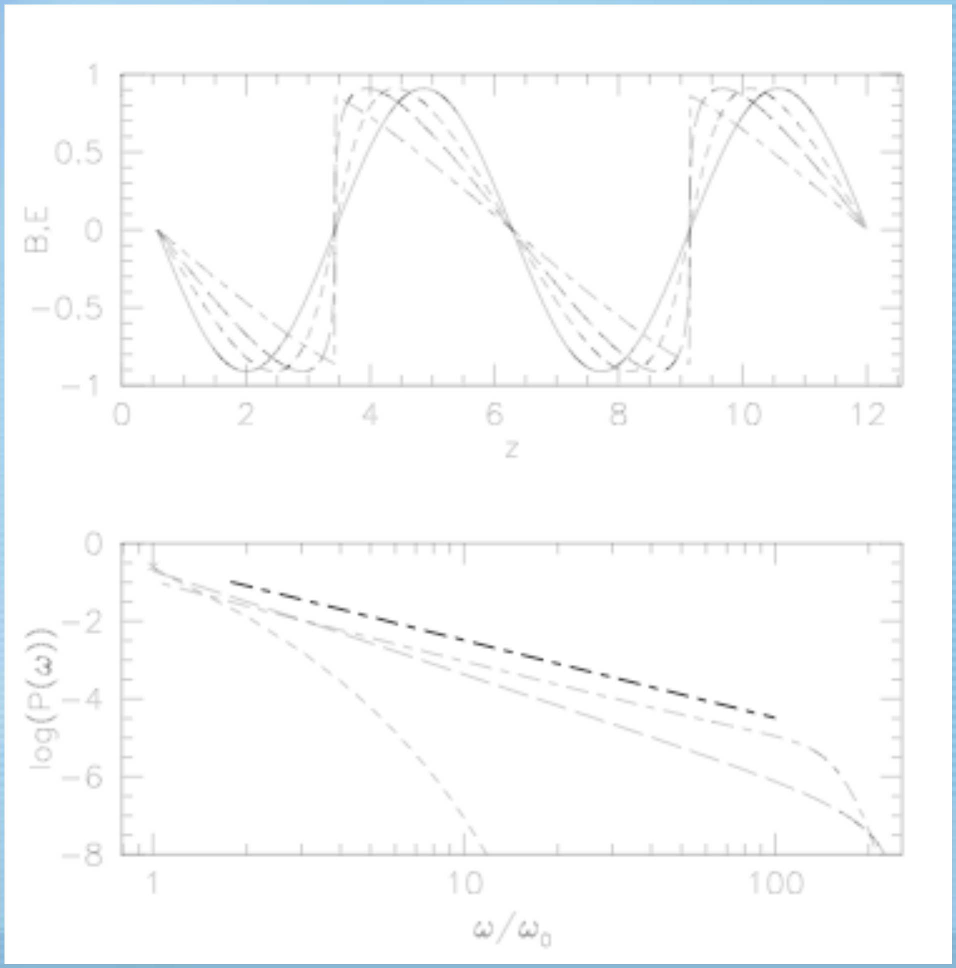
- The Lagrangian of the electromagnetic field is a complicated function of the field invariants.

$$\mathcal{L} = -\frac{1}{4} I + \frac{\alpha}{8\pi^2} B_k^2 \int_0^\infty \frac{d\zeta}{\zeta} e^{-i\zeta} \left[\frac{ab}{B_k^2} \coth\left(\zeta \frac{a}{B_k}\right) \cot\left(\zeta \frac{b}{B_k}\right) - \frac{1}{\zeta^2} \right]$$

  where $-2(a+bi)^2 = I + iJ$, $I = F_{\mu\nu}F^{\mu\nu}$, $J = F_{\mu\nu}F^{\mu\nu}$ and $B_k = 4.4\ 10^{13}$ G.
- Non-linearity leads to shocks that can be understood using characteristics.

Fast-Mode Shocks

- When an electromagnetic (or MHD) wave travels through a strong magnetic field, shocks can form.
- After the shock forms, the energy is dissipated



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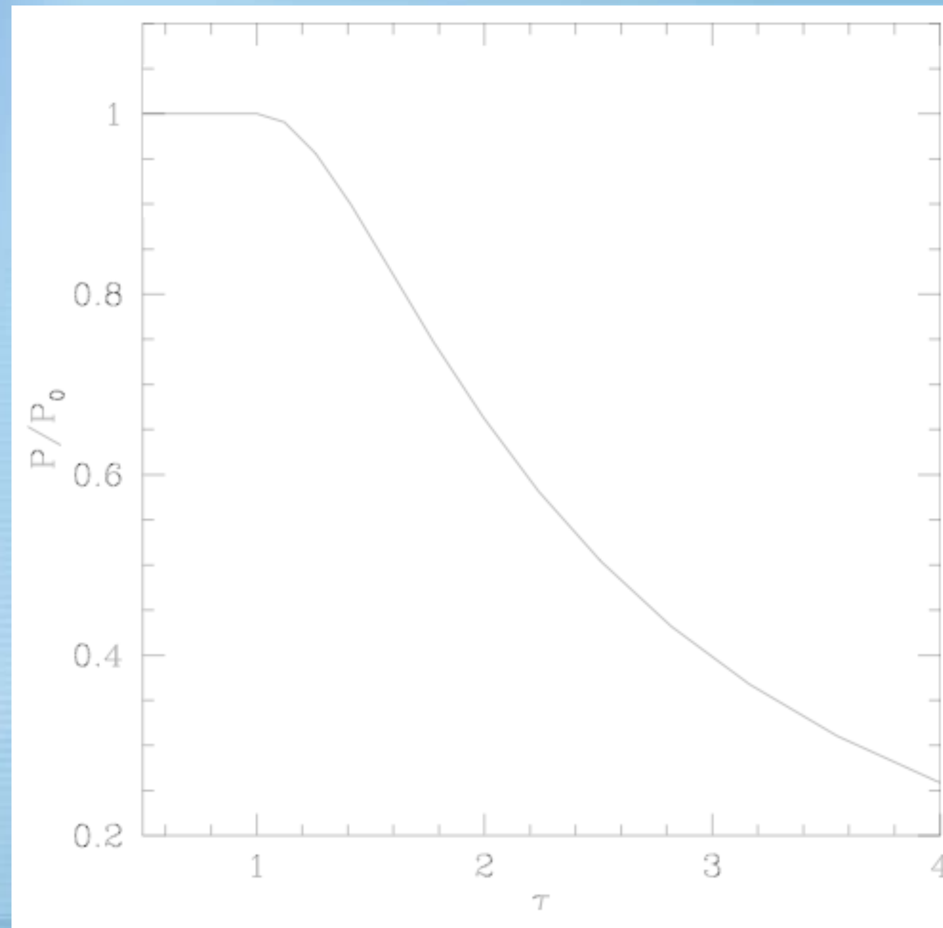
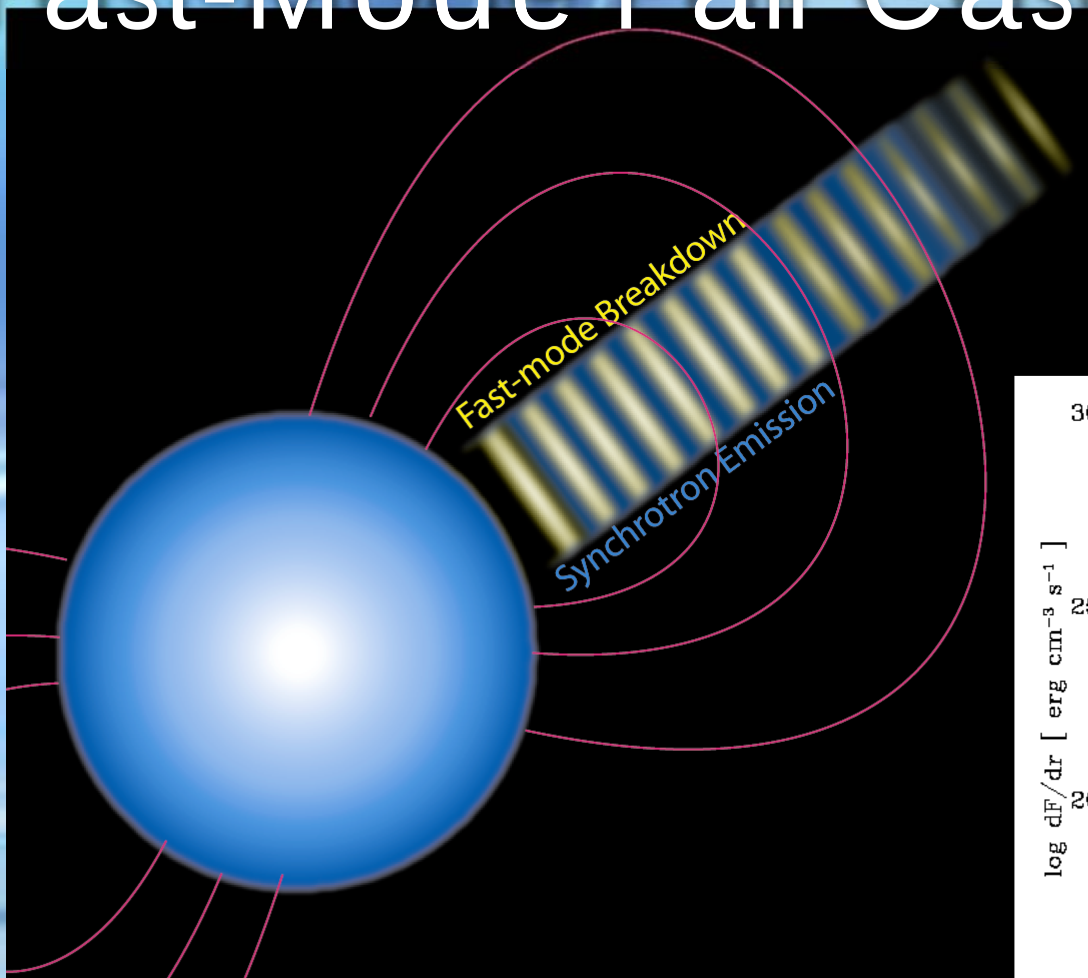


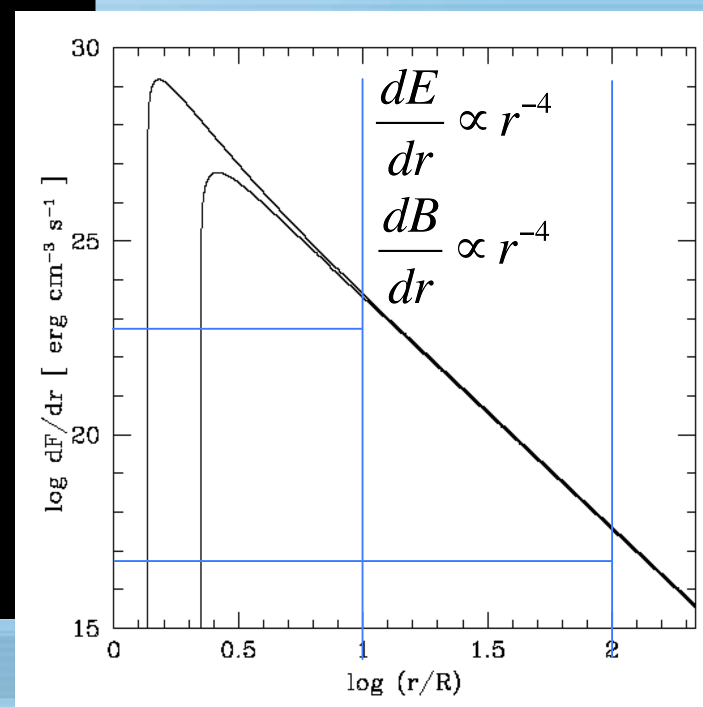
Fast-Mode Pair Cascade

- What happens if there are so many pairs that the magnetosphere becomes optically thick?
- What is the optically thin emission?
  - Simple treatment using asymptotic scalings
  - More accurate treatment using wave equation

Fast-Mode Pair Cascade(1)

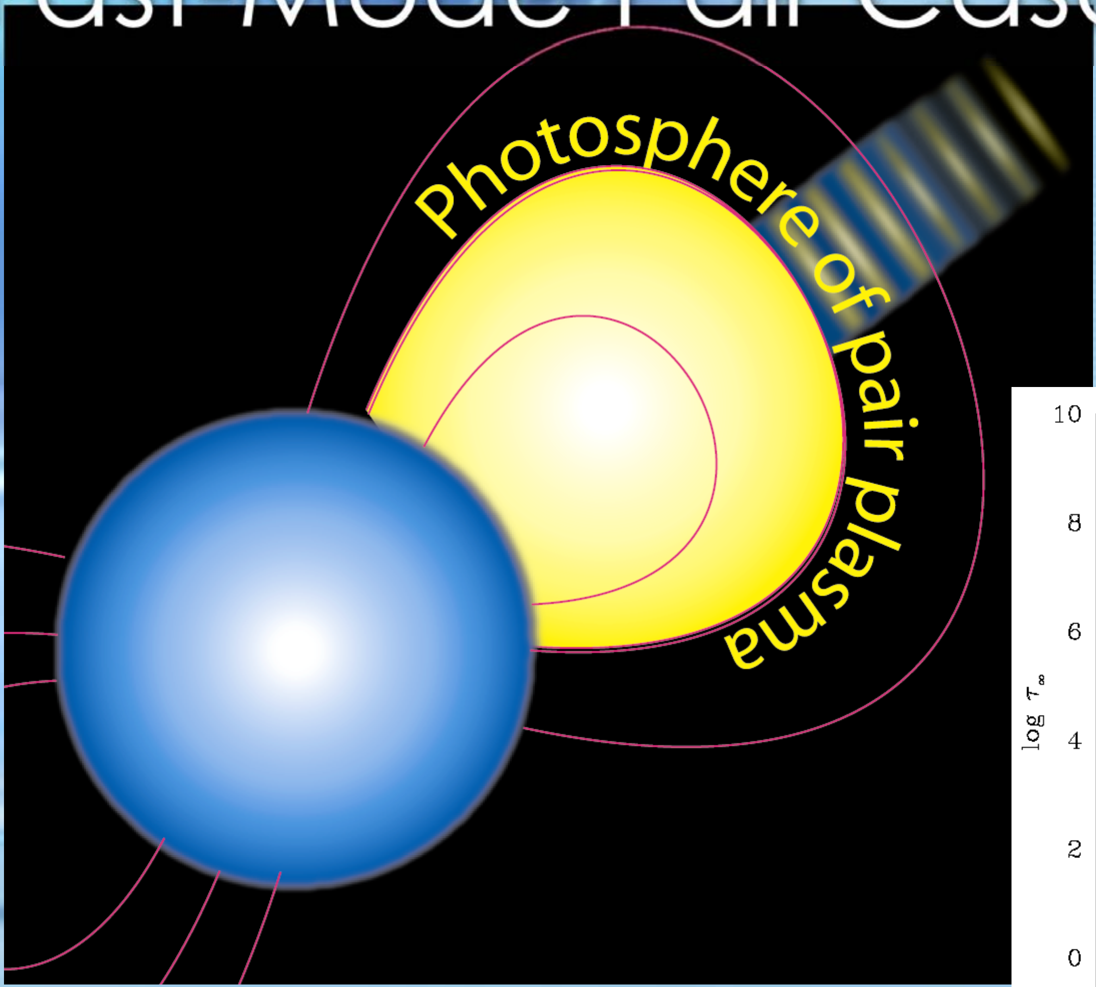


Equal energy is dumped in equal intervals of *B.*

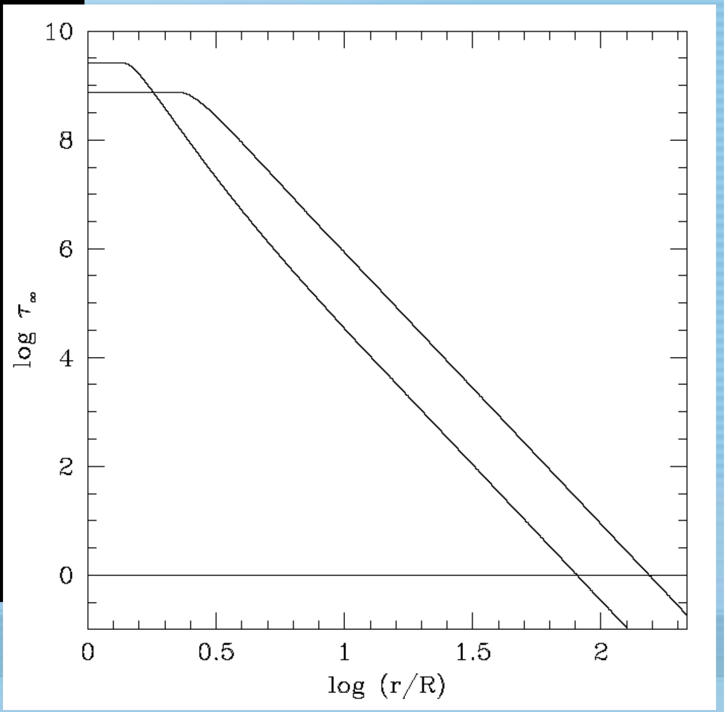


Heyl & Hernquist '04

Fast-Mode Pair Cascade(2)



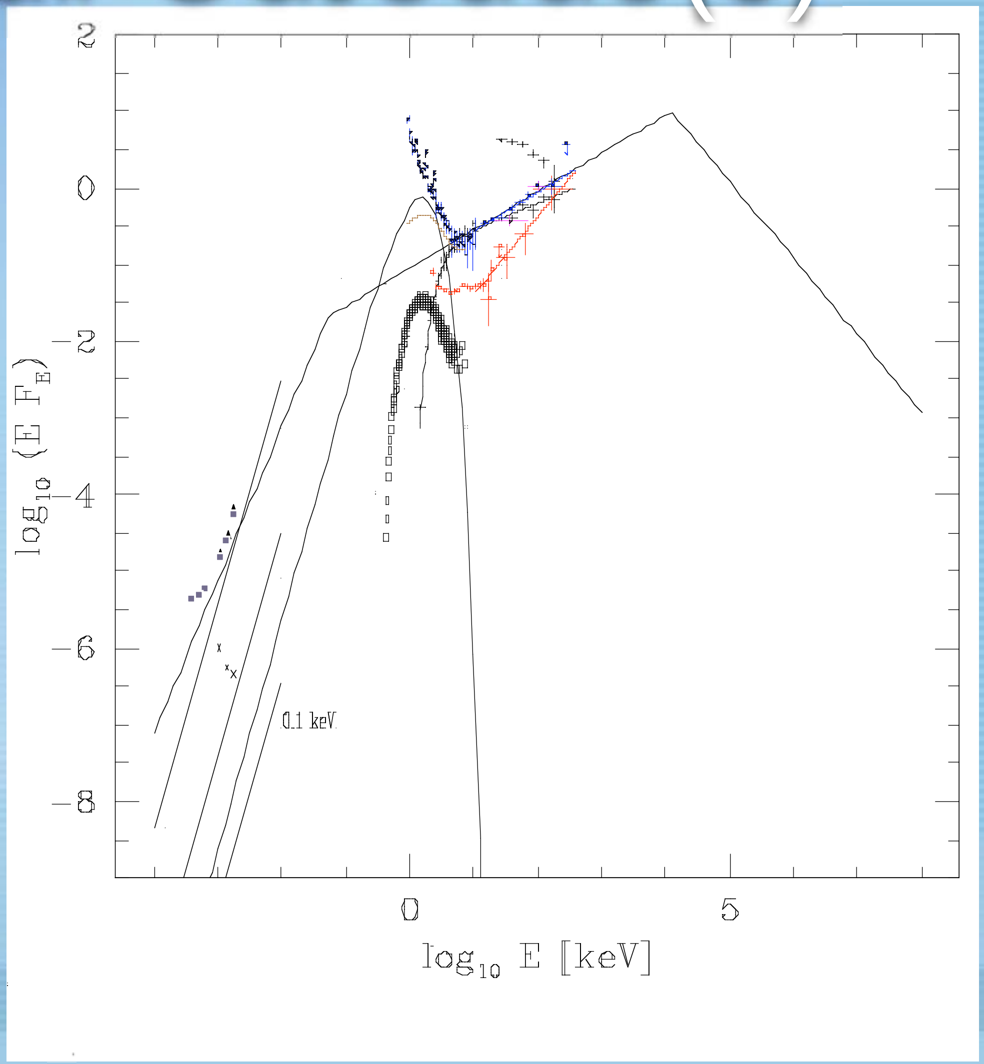
Enough pairs may be produced near the star to make a fireball.



Heyl & Hernquist ‘04

Fast-Mode Pair Cascade(3)

Non-thermal emission:



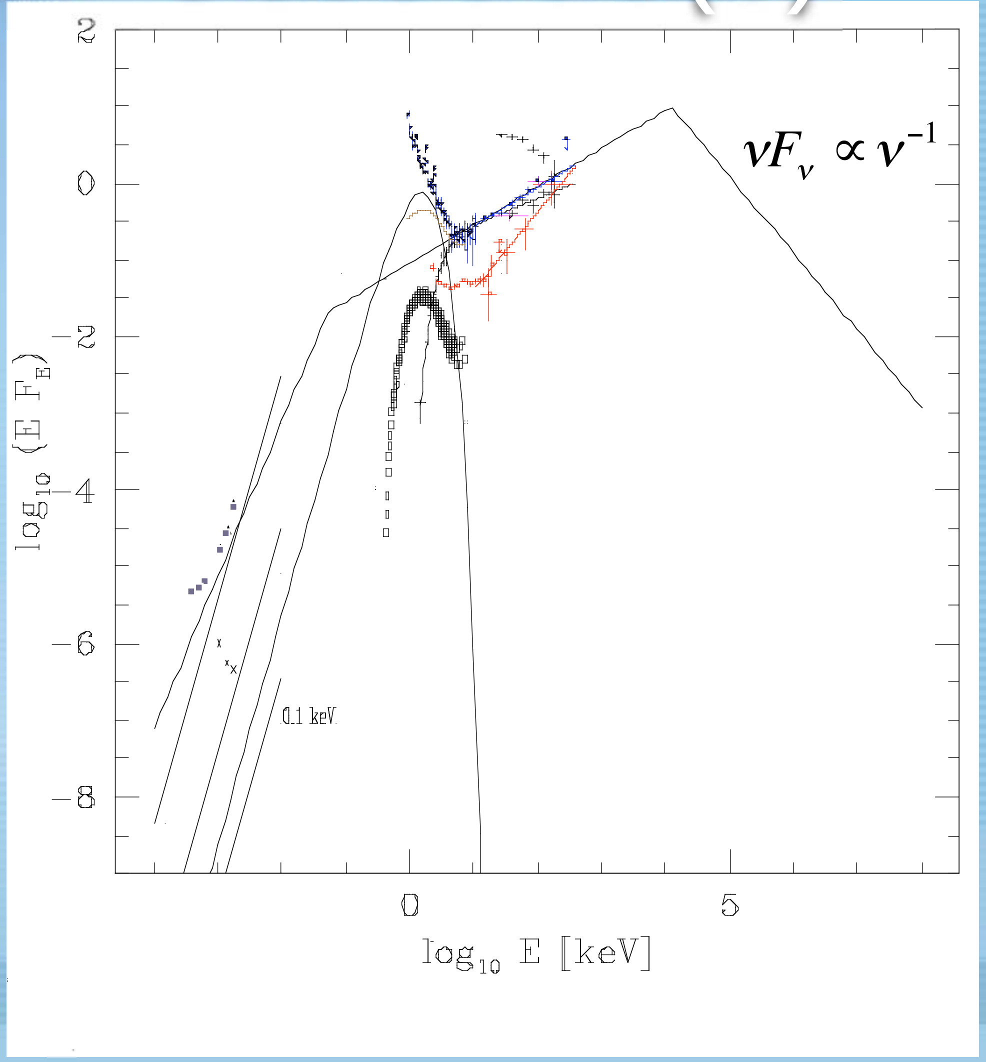
Fast-Mode Pair Cascade(3)

Non-thermal emission:

Initial pairs are at rest in the frame of the wave. Early generations of synchrotron photons pair produce until

$$E_\gamma \sim 2.5\times10^{-3}\frac{B_{\rm QED}}{\rm B}mc^2$$

$$\frac{dE}{dE_\gamma}\propto E_\gamma^{-2}$$



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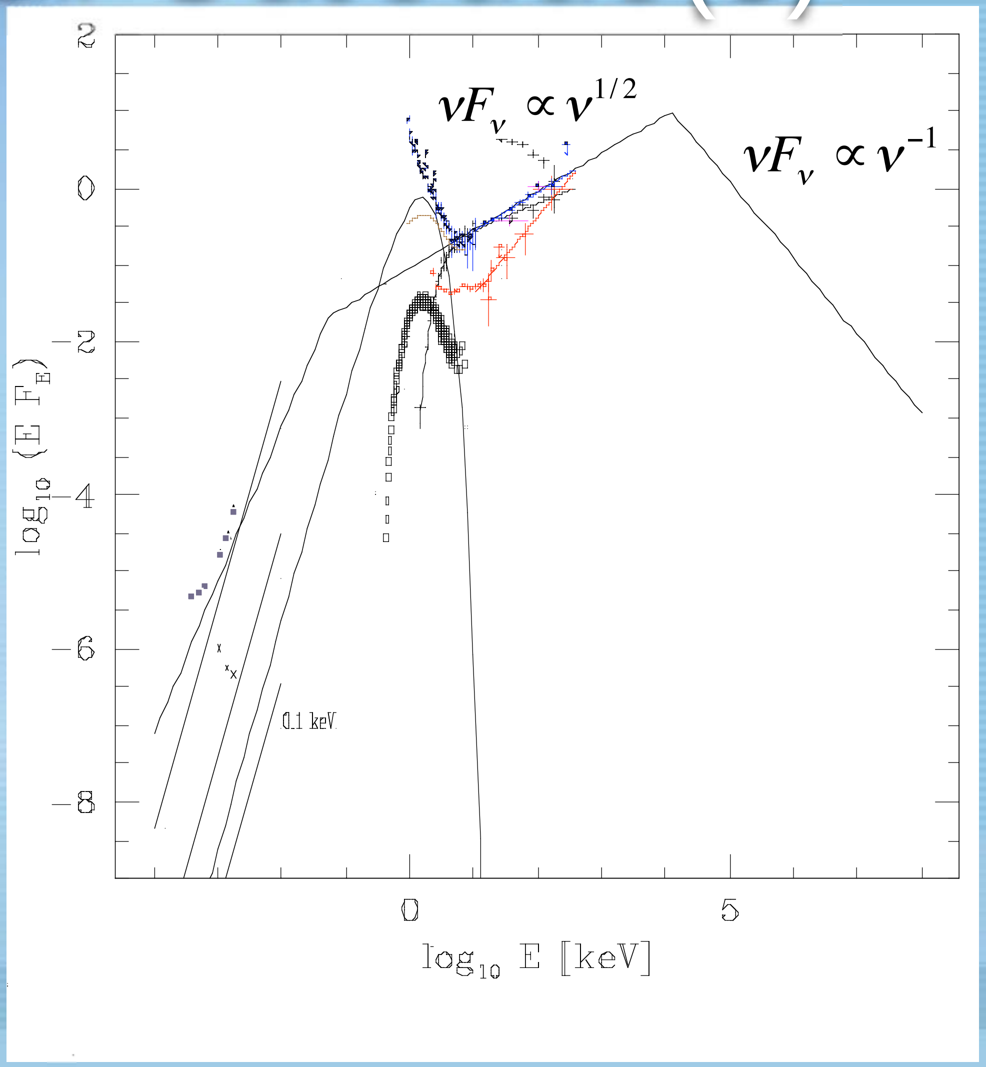
The innermost pairs cool the most quickly.

$$\frac{dE}{dE_\gamma}\propto E_\gamma^{-1/2}$$



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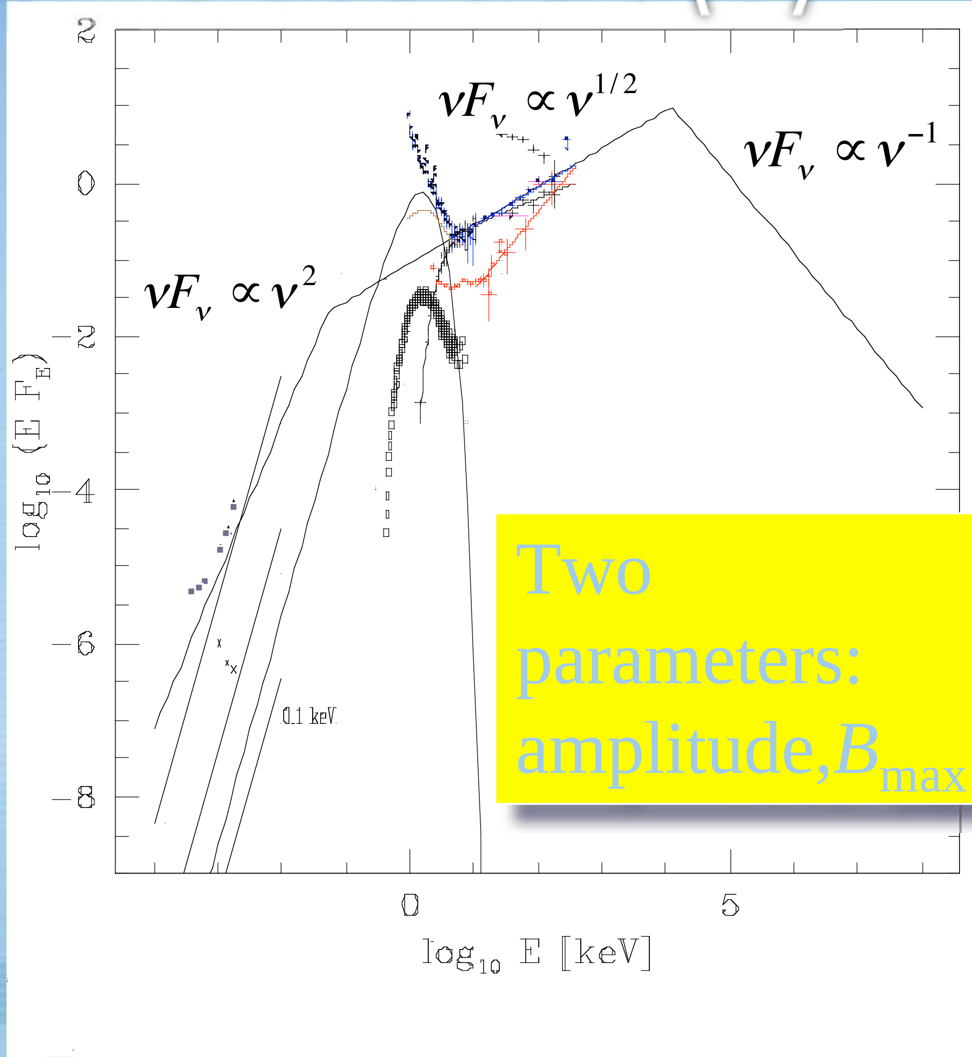
Cold pairs emit at the cyclotron frequency:

$$\frac{dE}{dE_\gamma}\propto E_\gamma^{1}$$



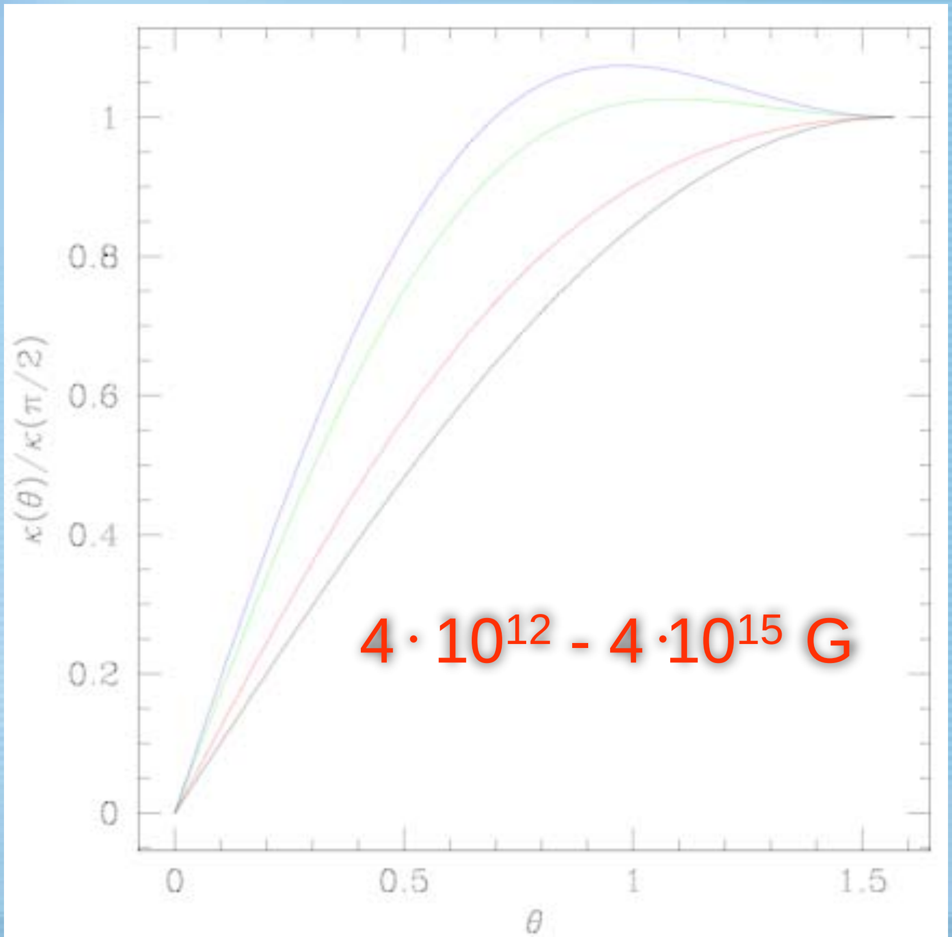
Two parameters: amplitude, $B_{\max}$

Fast Mode Pair Cascade (4)

- The strength of the wave determines at which magnetic field strength it will break.
- Important parameters:
  - Wave direction and product of amplitude and frequency.
  - Magnetic dipole moment of the neutron star.

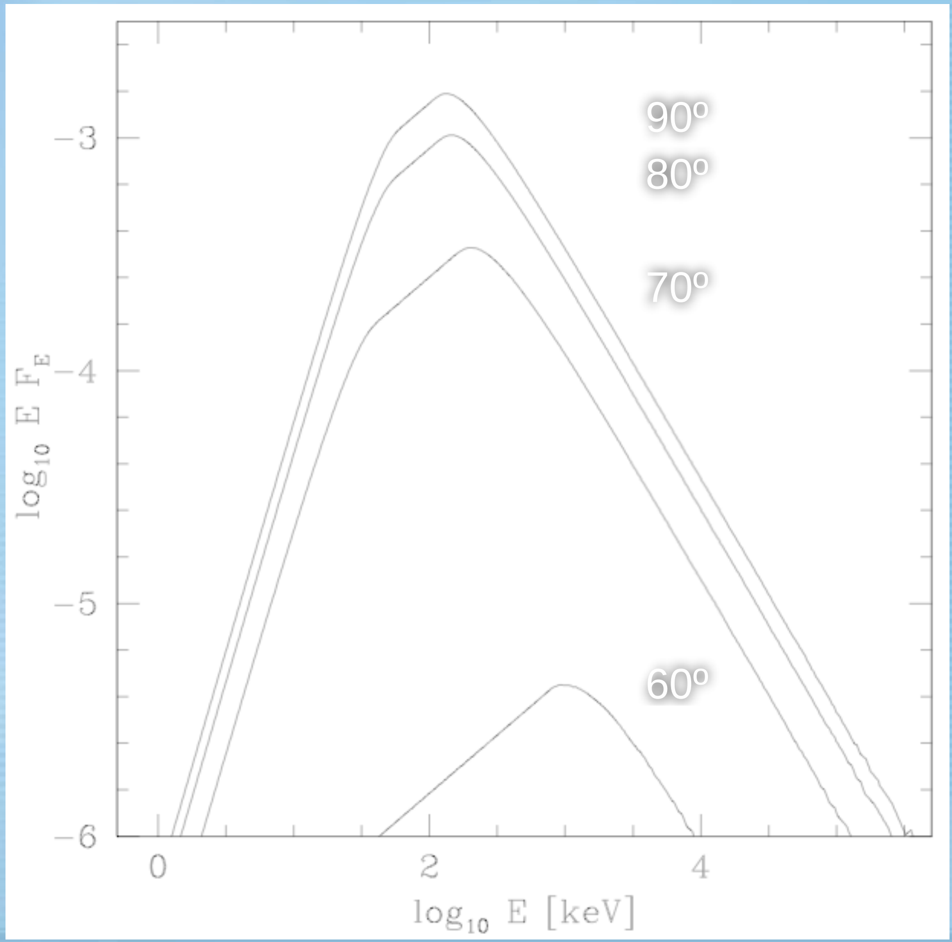
Angular Dependence

- The rate at which shocks form depends on the magnetic field strength and the angle of propagation.

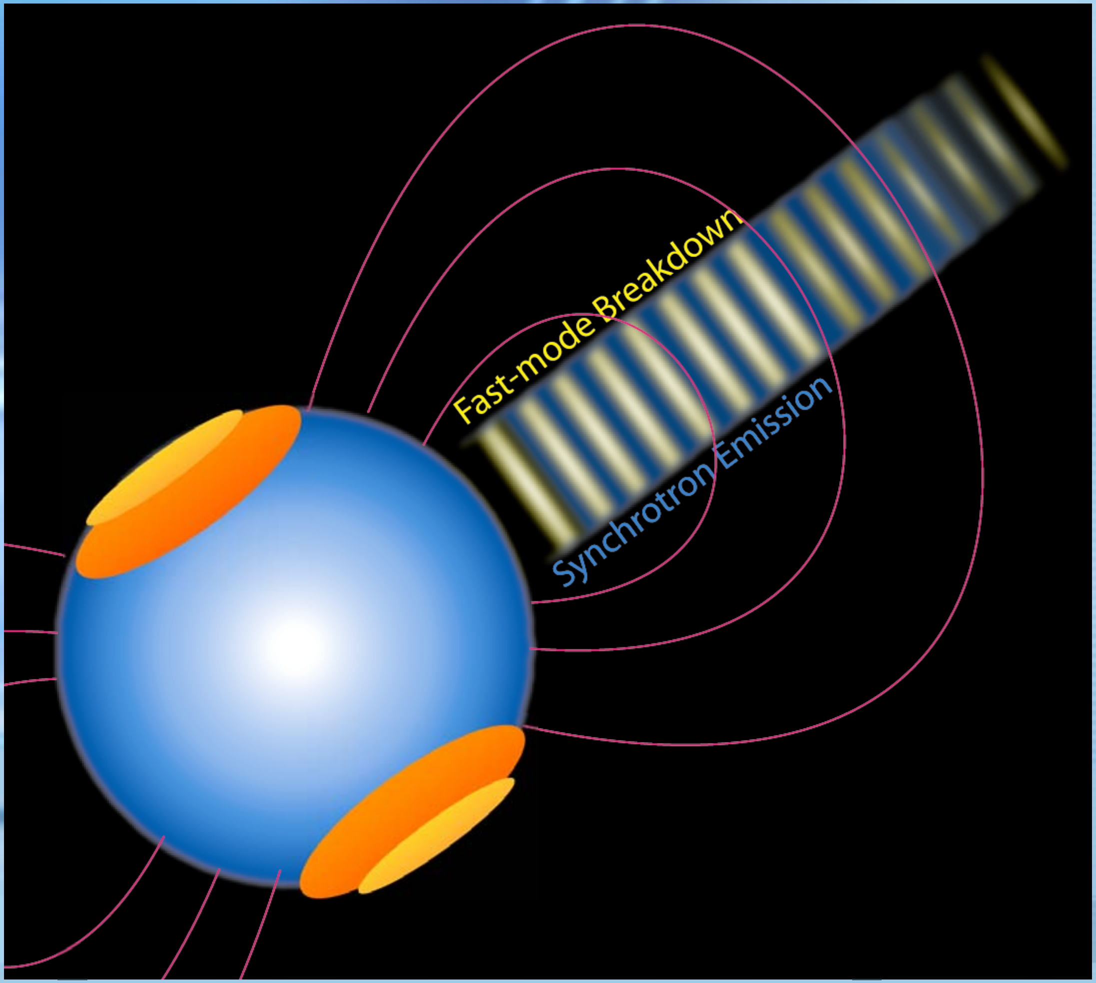


Angular Dependence

- $B_{NS}=30B_{QED}$, $b=2B_{QED}$, $\lambda=100$m
- The emission from the cascade depends strongly on angle (cuts off at 59°)



Angular Dependence



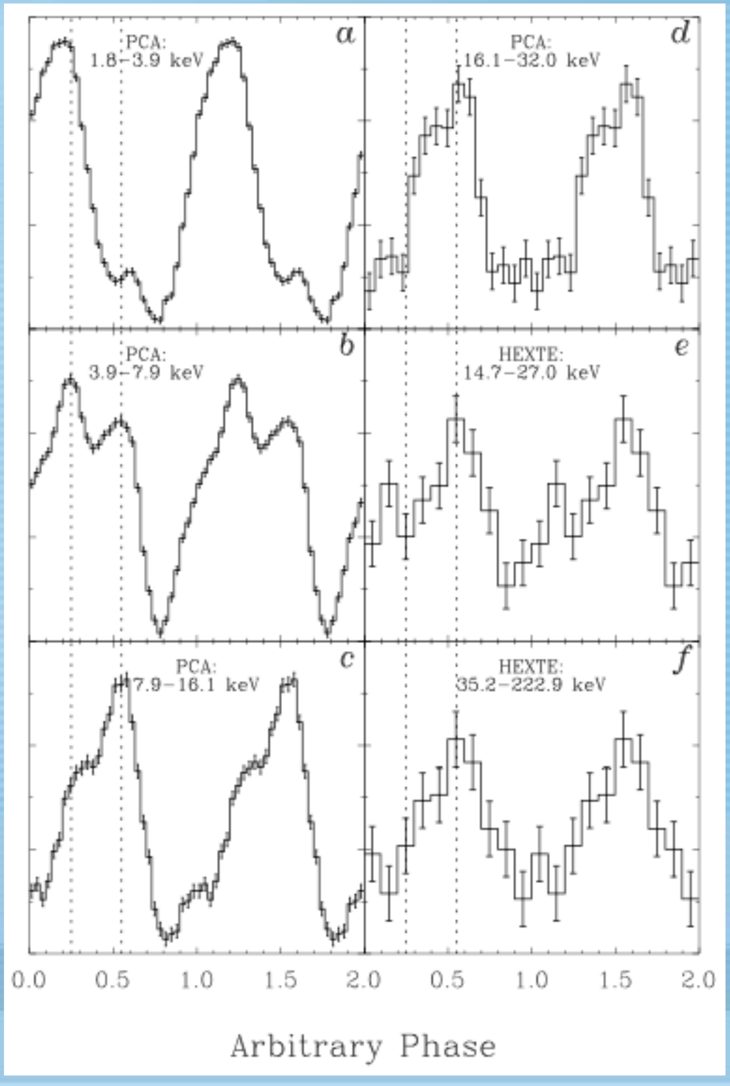
- Thermal emission peaks along the field lines.
- Non-thermal emission peaks across the field lines.

Angular Dependence

- Thermal emission will peak out of phase with non-thermal emission.
- If you see both hot spots, the non-thermal emission is 90-180º out of phase from the main peak.
- If you only see one hot spot, the non-thermal emission is 180º out of phase.

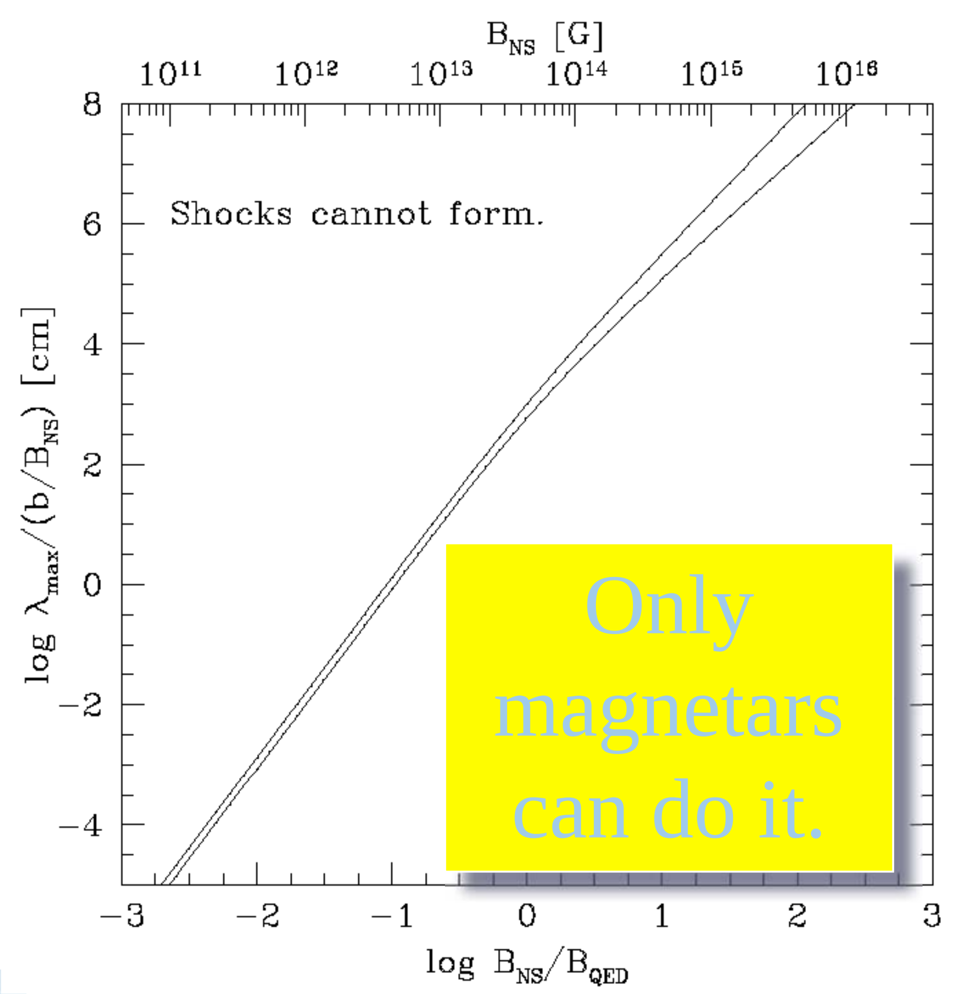
Angular Dependence

- 1RXS J1708 - 4009 - Kuiper et al 2006
- Low energy peaks 110° before high energy.
- Similar but less dramatic trends in 4U 0142+61 and 1E 2259+586



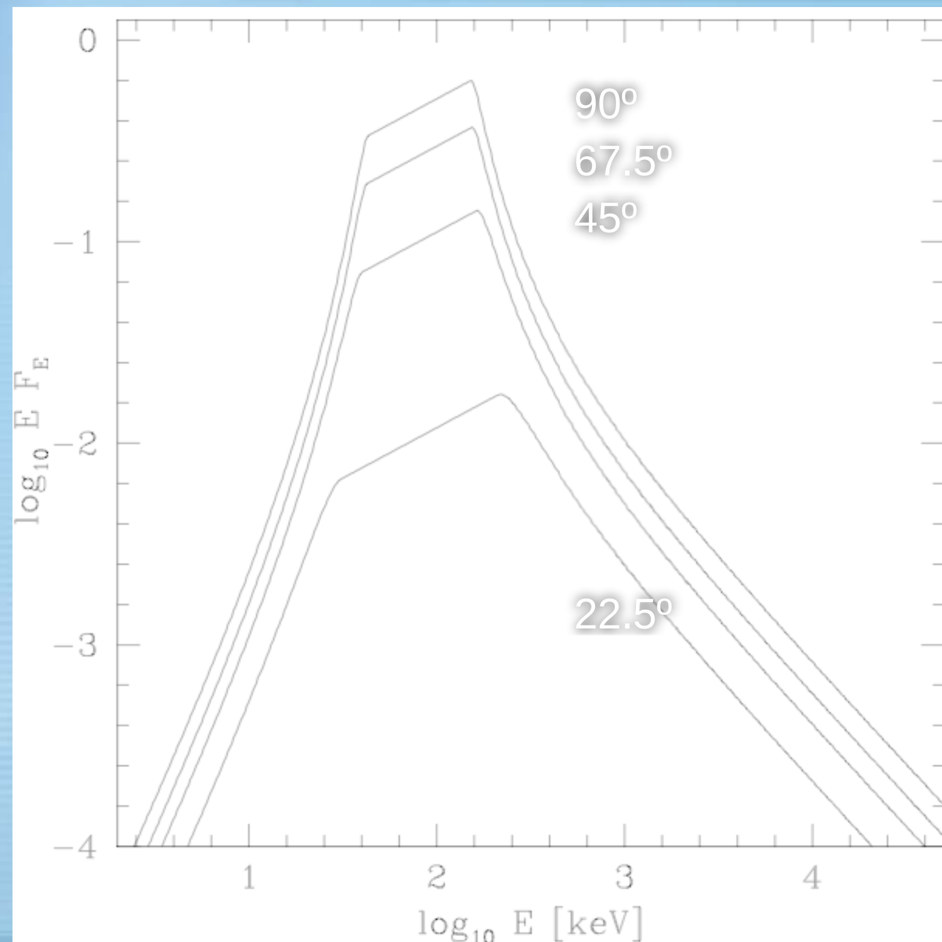
Field Dependence

- The rate at which shocks form depends on the magnetic field strength and the angle of propagation.
- In weak fields, it is difficult to get shocks.



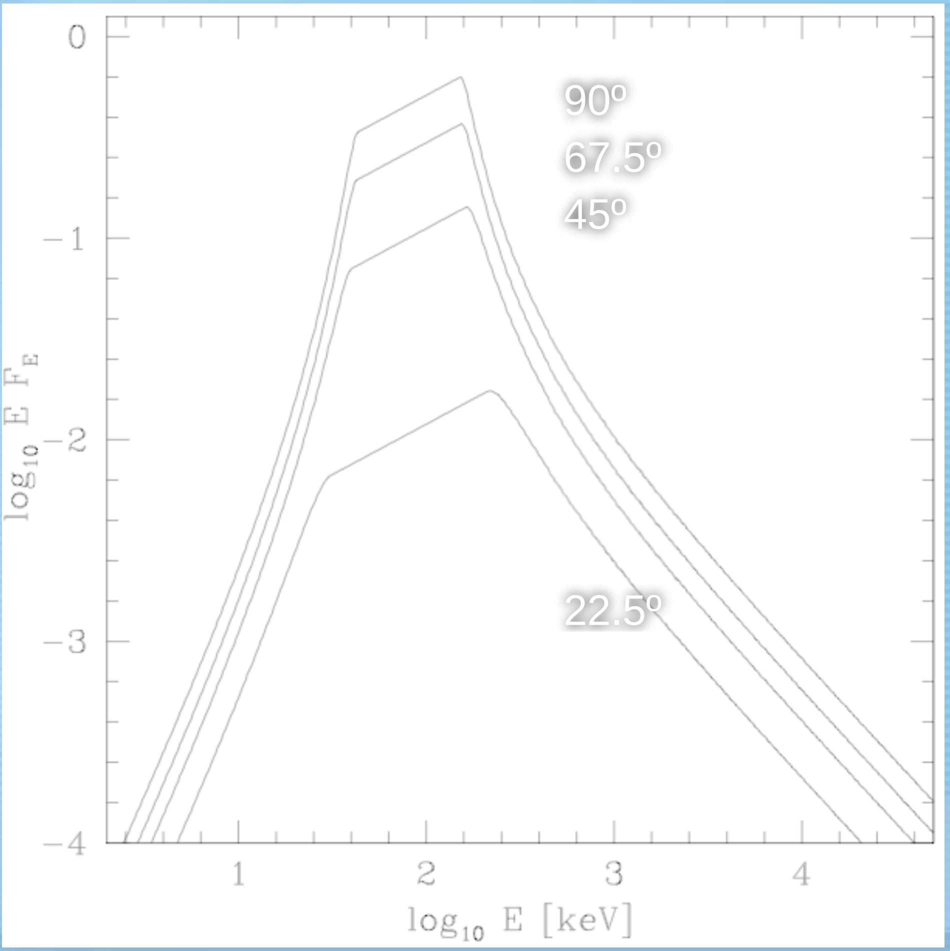
Field Dependence

- $B_{NS}=0.1B_{QED}$, $b=0.01B_{QED}$, $\lambda=20\mu$
- To get shocks in such a weak field, the initial wavelength must be unrealistically small.



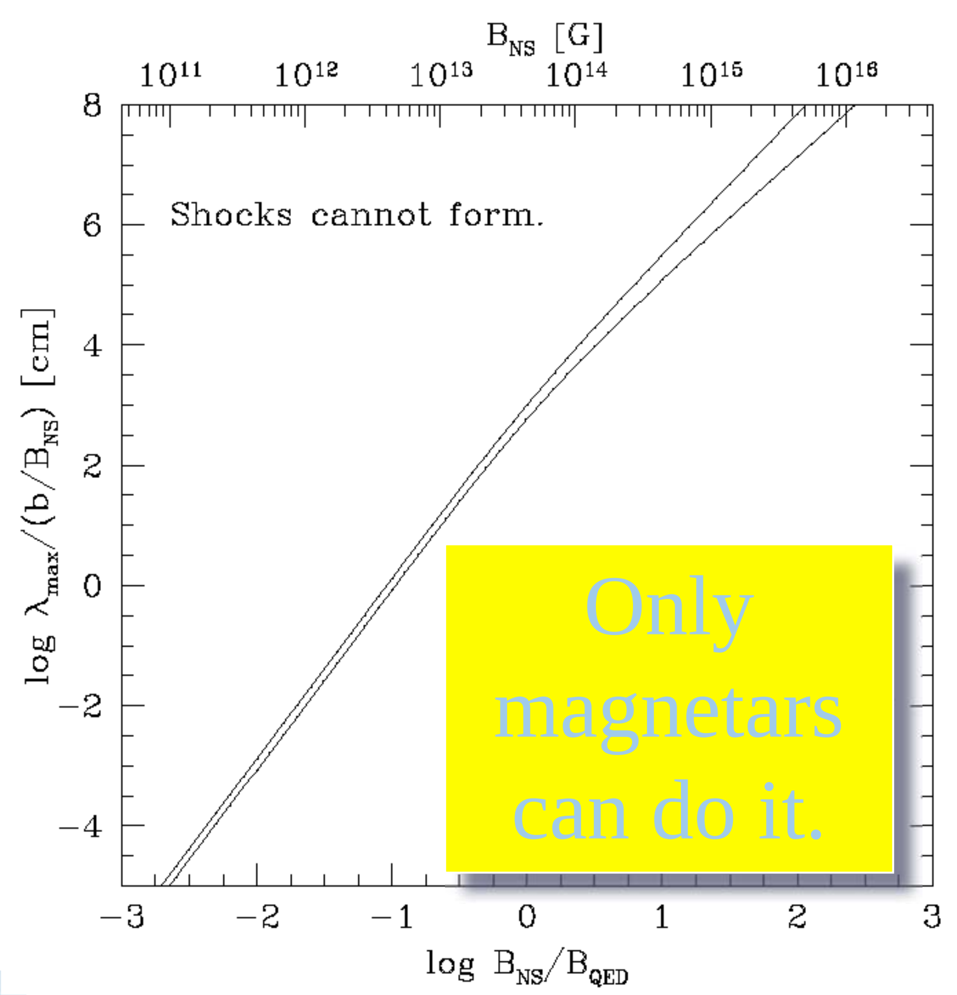
Field Dependence

- Here the shock forms close to the star.
- Energy dissipated over a narrow range of fields.
- Most of the wave is dissipated.



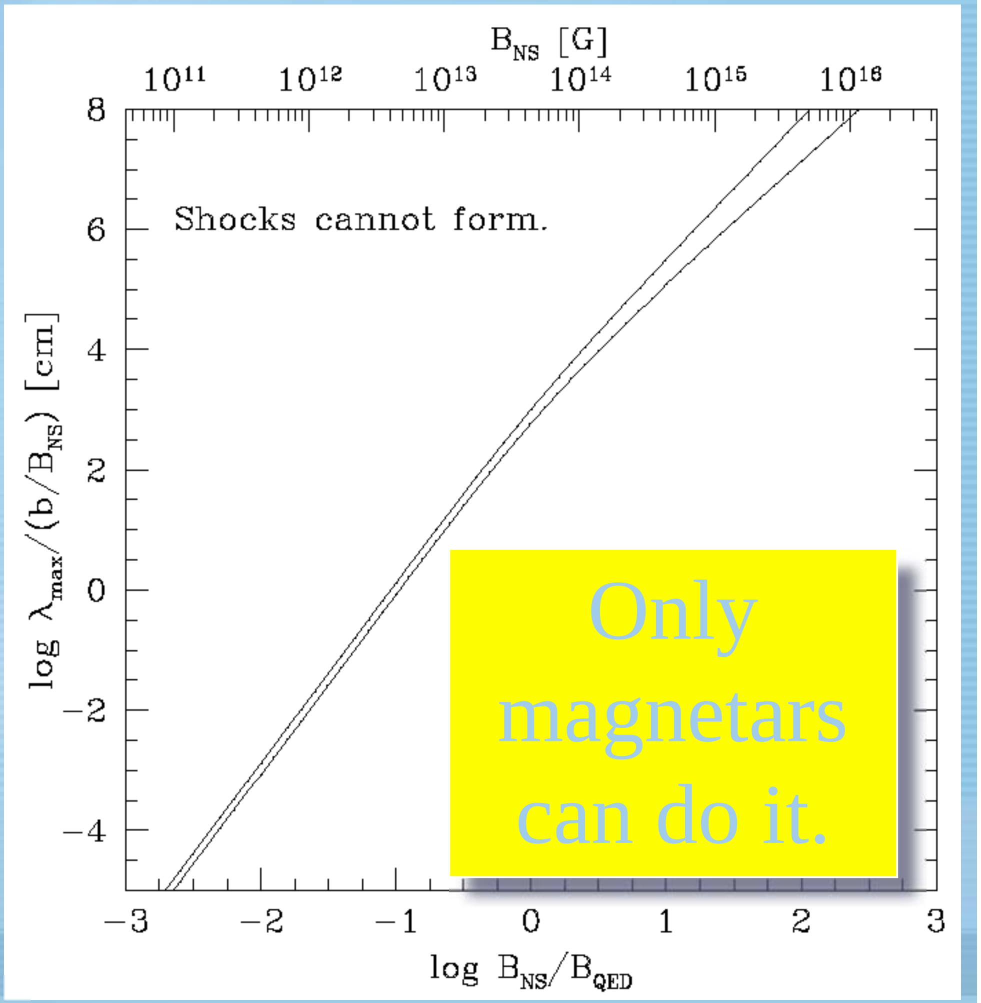
A Model for Magnetars

- The surface of a magnetar emits various MHD waves into the magnetosphere.
  - Alfven waves power the traditional Thompson & Duncan burst.
  - The currents ICS photons from the surface.
  - Can generate any spectrum and time dependence.
  - No magnetic field cutoff.



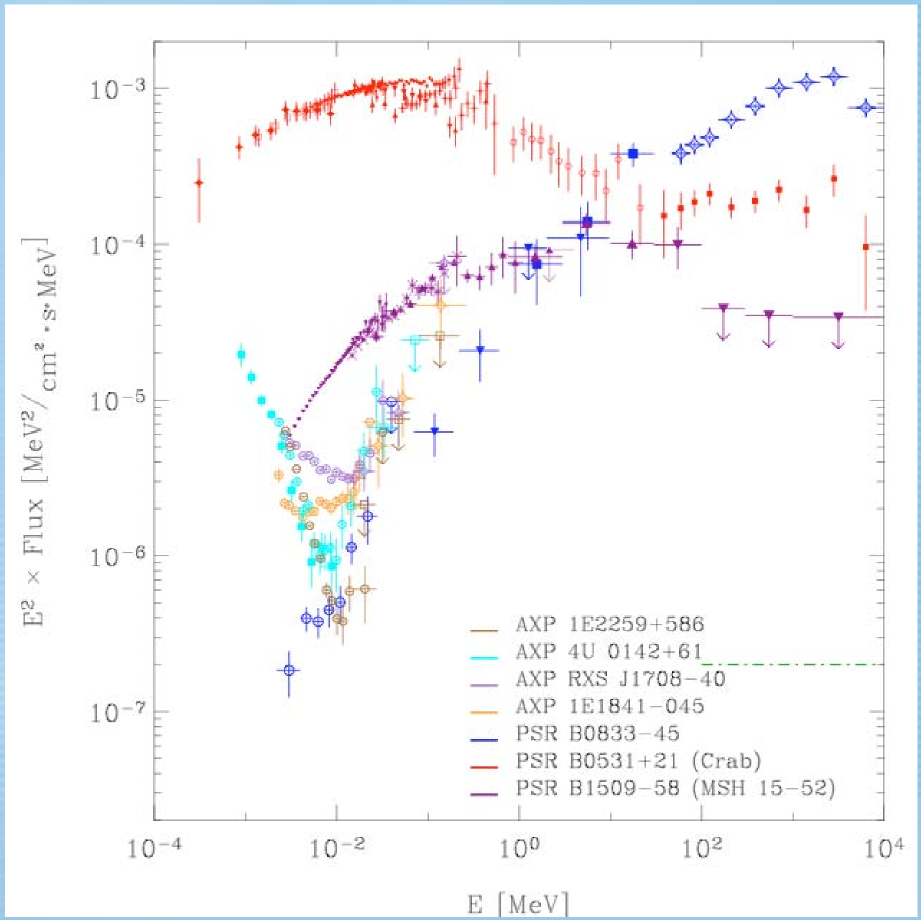
A Model for Magnetars

- The surface of a magnetar emits various MHD waves into the magnetosphere.
  - Fast waves form shocks due to QED. Sometimes the wave is large enough to produce a fireball; otherwise it generates non-thermal emission from the optical to γ-ray.
  - Magnetic field cutoff
  - Specific spectrum and time dependence.



The Future

- The upper limits from CGRO seem to indicate that the hard emission doesn't extend past 1MeV.
- Do the sources vary on long timescales?
- A pair cascade naturally ends 1MeV, so one could expect a break at this energy.



Kuiper et al. 2006

The Future

- What happens to all of the pairs?
  - Do they annihilate?
  - Does this produce a line or an excess?
- What about polarization?
- What happens to the spectrum if the cascade occurs in the strong field region?
- What type of spectrum does a distribution of initial wave intensities and angles yield?

What would I like to know?

- From the nuclear people:
  - Is there a gap? I don't really care whether it's 0.5 or 2 MeV (neutron stars are cold).
  - Is the proton superconductor Type I or Type II? If it is Type II, do currents along the vortices make it act like Type I?
  - Where is the quark-hadron phase transition? Sure, the quark phase has lots of structure but it may be completely irrelevant.

What would I like to know?

- From the observers:
  - Should I really believe these lines, periods, period derivatives, errorbars etc.? More Monte Carlo including instrumental uncertainties.
  - Rare systems can tell us lots (e.g. 0737). Get me more! How about some eclipsing binaries in globular clusters or really young cooling neutron stars?
  - Coordinated timing campaigns as BATSE did for accreting neutron stars.