Magnetars

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What are magnetars?

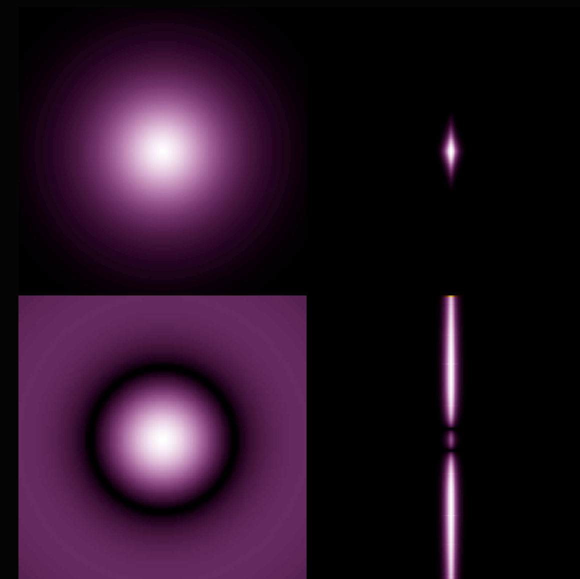
- Magnetically powered neutron stars
- Neutron stars with magnetic fields larger than $B_{\mathrm{QED}} = m^2c^3/(e\hbar) \approx 4.4 \times 10^{13}\mathrm{G}$
- I will use both definitions and also focus on effects that become important as B approaches B_{QED}.

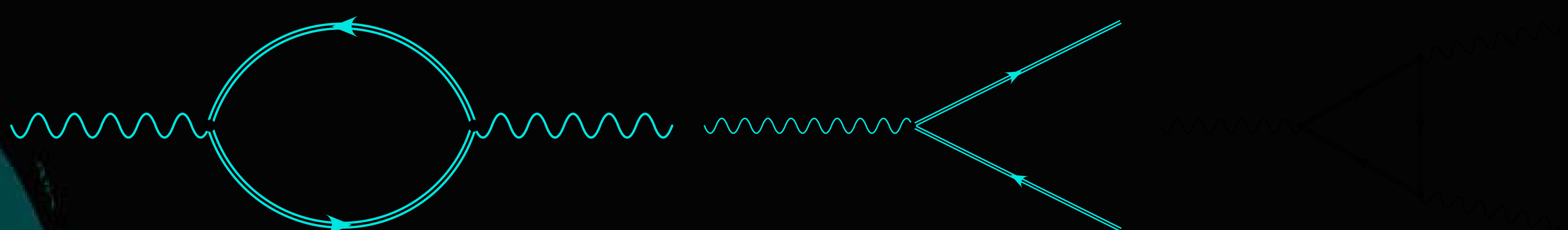
How do they differ?

- No pulsed radio emission - the pulsar mechanism may not work in supercritical fields (Baring & Harding ‘00) or could be geometry (long-periods $\Rightarrow$ small beam).
- X-ray and γ-ray emission in excess of spin-down energy.
- Strong bursts of soft-gamma rays - biggest explosions that repeat

How does the physics differ?

- Magnetic stresses exceed yield stress of the crust (Thompson & Duncan ‘96)
- Atoms strongly distorted; may condense at *P*=0.
- Radiative corrections of QED may be important.





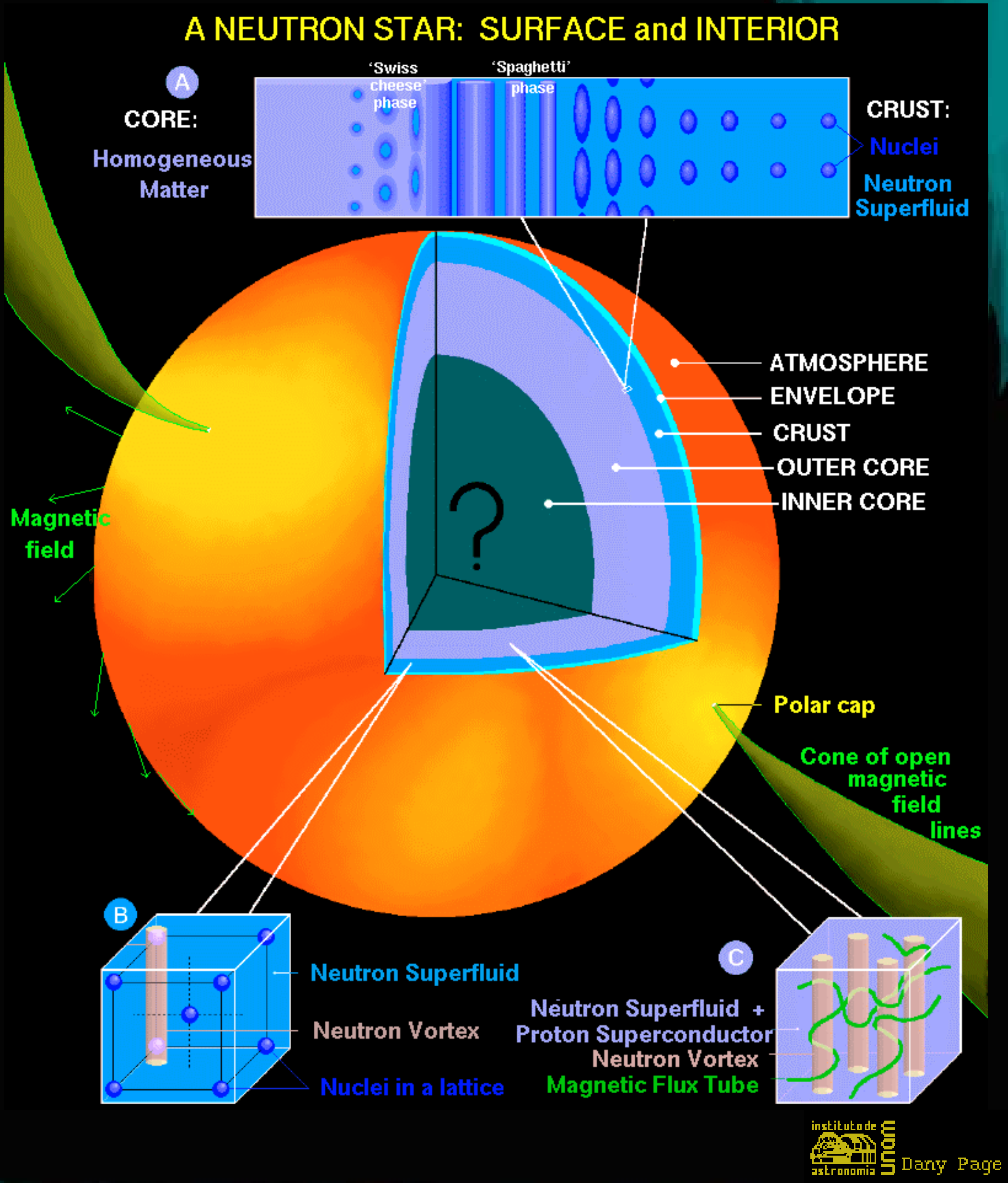
The physics is messy.

Outline

- Thermal emission
  - What comprises the atmosphere?
- Non-thermal emission
  - Optical/IR - Gamma-Rays
- Bursts
  - What are they?

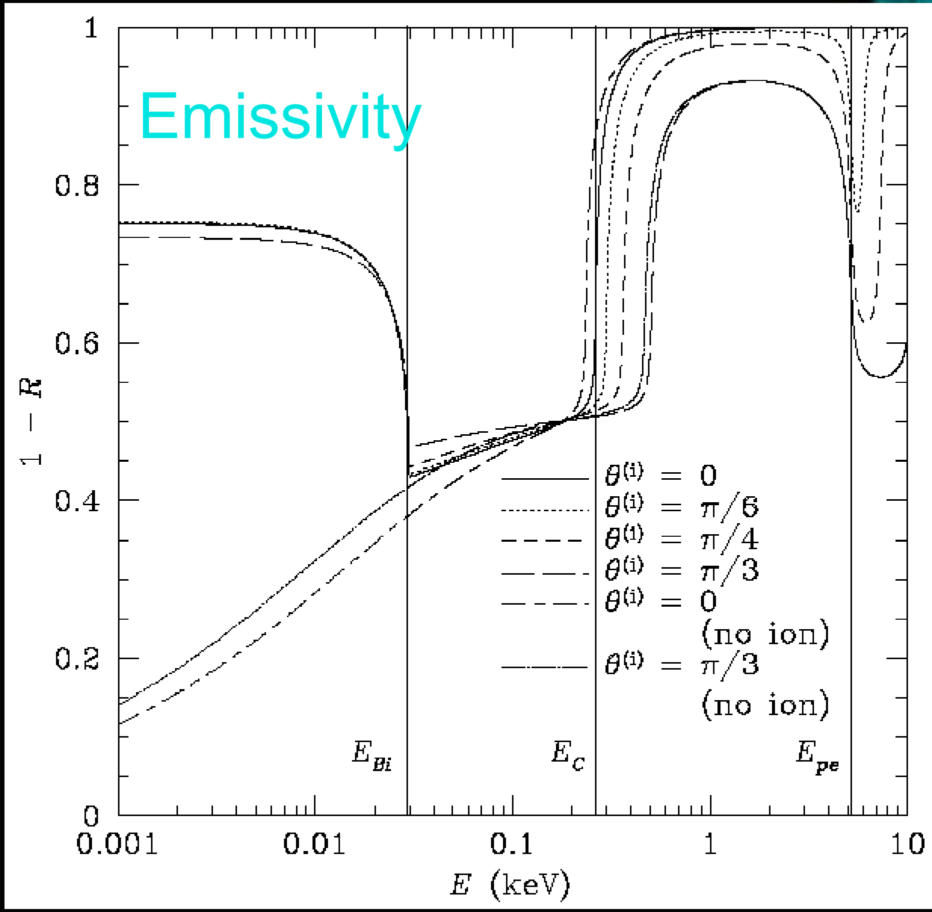
Magnetar Atmospheres

- Atmosphere - thin layer (few centimeters) on the surface of a neutron star in which the spectrum forms.
- Iron, hydrogen or something else?
- What role does the strong field play?



A Condensed Atmosphere

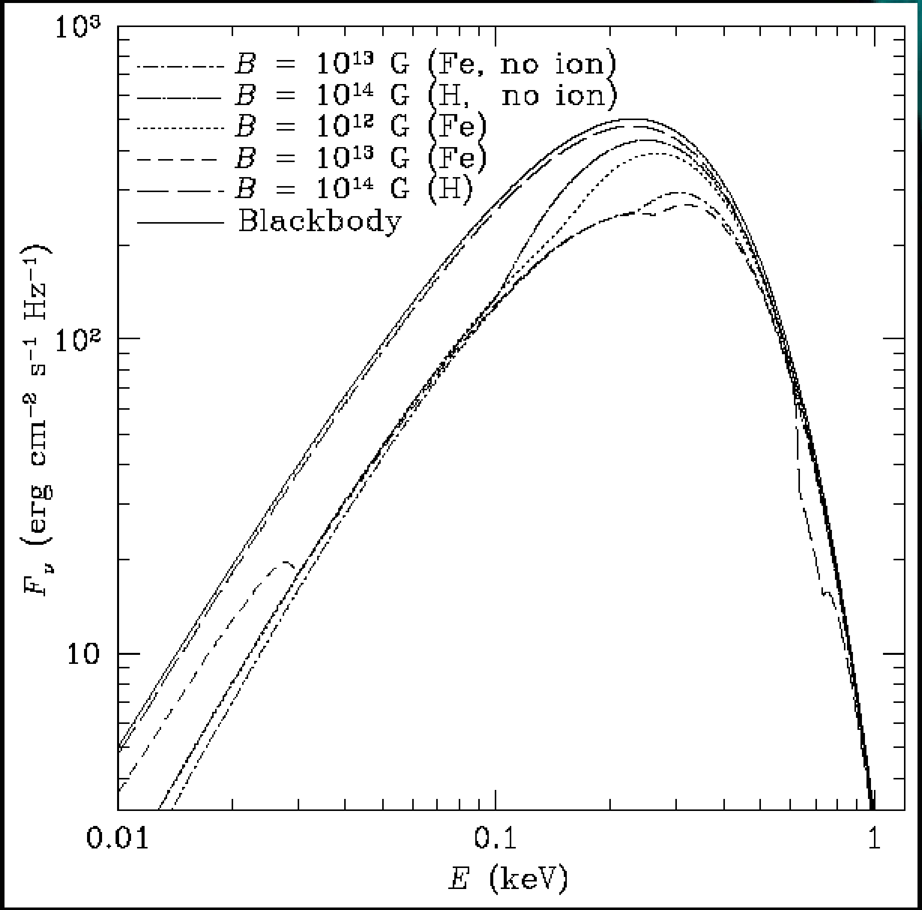
- The "thermal" component of the radiation from magnetars is remarkably close to a blackbody.
- Radiation of all energies reaches high optical depth at the same temperature.
- Calculate dielectric properties of surface



- Adelsberg, Lai, Potekhin '04

The Condensed Spectrum

- After determining the reflectivity, use Kirchoff's Law.
- The spectrum lacks narrow features but isn't a BB either.
- Freezing point:
  - Fe, 10^6 K at ~ 10^{13} G
  - H, 10^6 K > 10^{14} G



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Why hydrogen or iron?

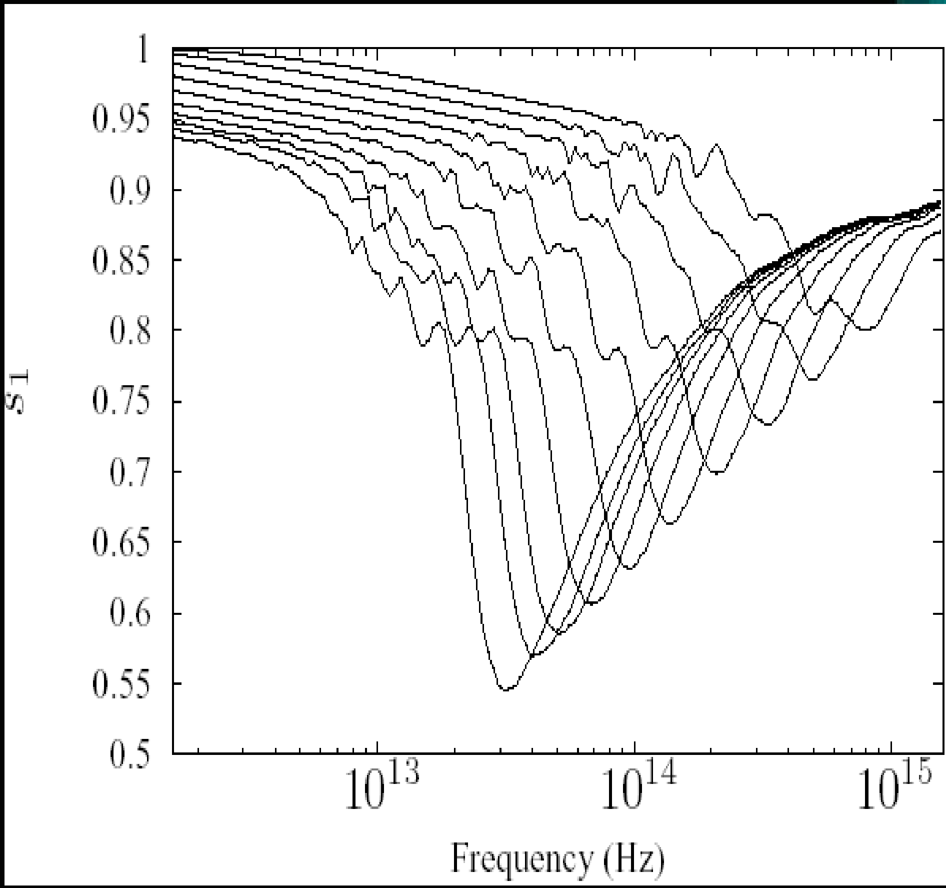
- The conventional wisdom was that the surfaces of neutron stars consist of iron.
  - NSE $\Rightarrow$ Fe $\Rightarrow$ lots of X-ray lines!!!
- When no lines were found, the new conventional wisdom was that the surfaces of neutron stars would consist hydrogen. Fall-back or ISM accretion, plus settling.
  - H-atmospheres help reconcile estimates of neutron star radii: no strange quark stars yet.
  - Don’t expect many lines from hydrogen.

Conventional wisdom: neither conventional nor wise.

- Chang, Arras and Bildsten have calculated the process of diffusive nuclear burning of hydrogen on the surfaces of neutron stars.
- Key ideas:
  - Carbon easily captures protons at the temperatures of hot envelopes: diffusion limited.
  - In cooler neutron stars, nuclear limited
  - Strong magnetic fields reduce the Fermi energy
- Magnetar hydrogen atmosphere is consumed in days. Thick He envelopes don’t last either.

Optical Birefringence

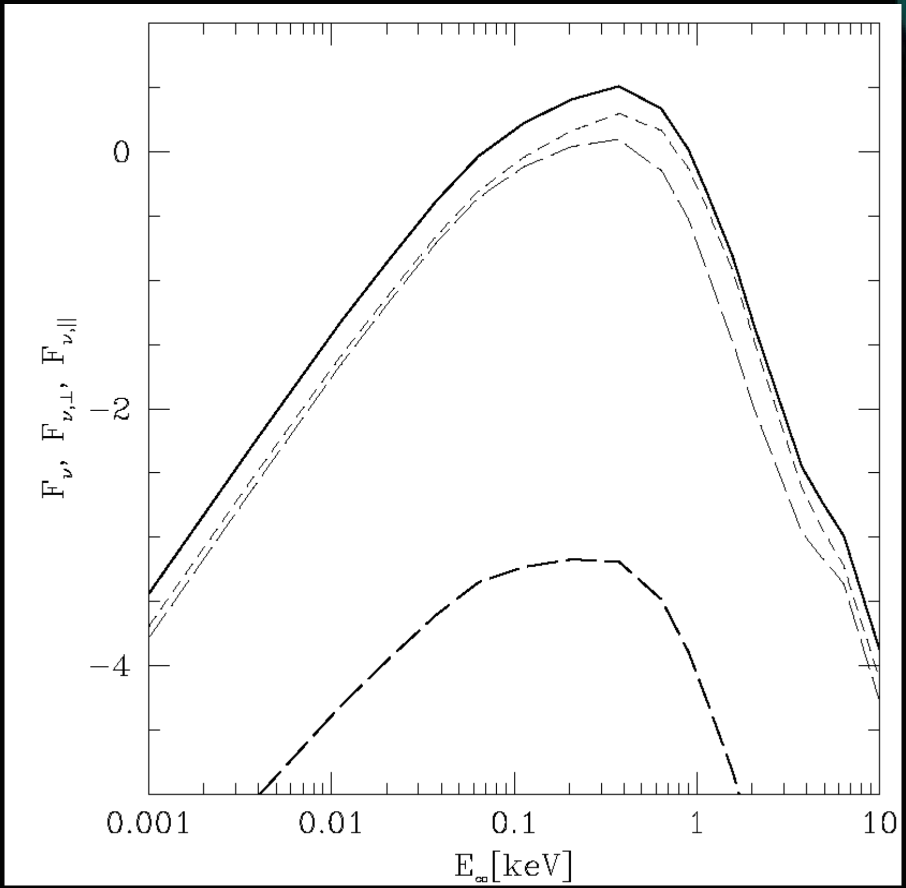
- The observed optical polarization provides a unique diagnostic of the plasma near the neutron star.
- We assume that the radiation is thermal and comes from the entire surface.
- The signature weakens for more strongly magnetized NSs.



- Shannon & Heyl '04

X-ray Birefringence (1)

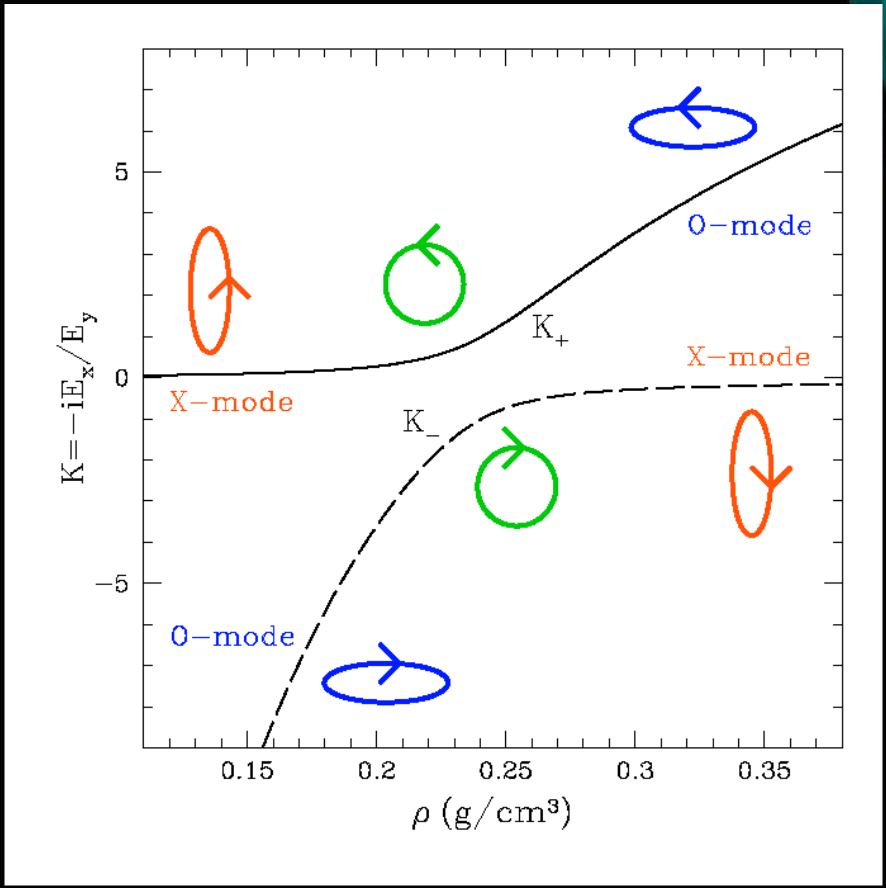
- The thermal radiation from neutron stars is highly polarized.
- Vacuum polarization of the magnetosphere ensures that the observed polarization will be large.



- Heyl, Shaviv & Lloyd ‘04

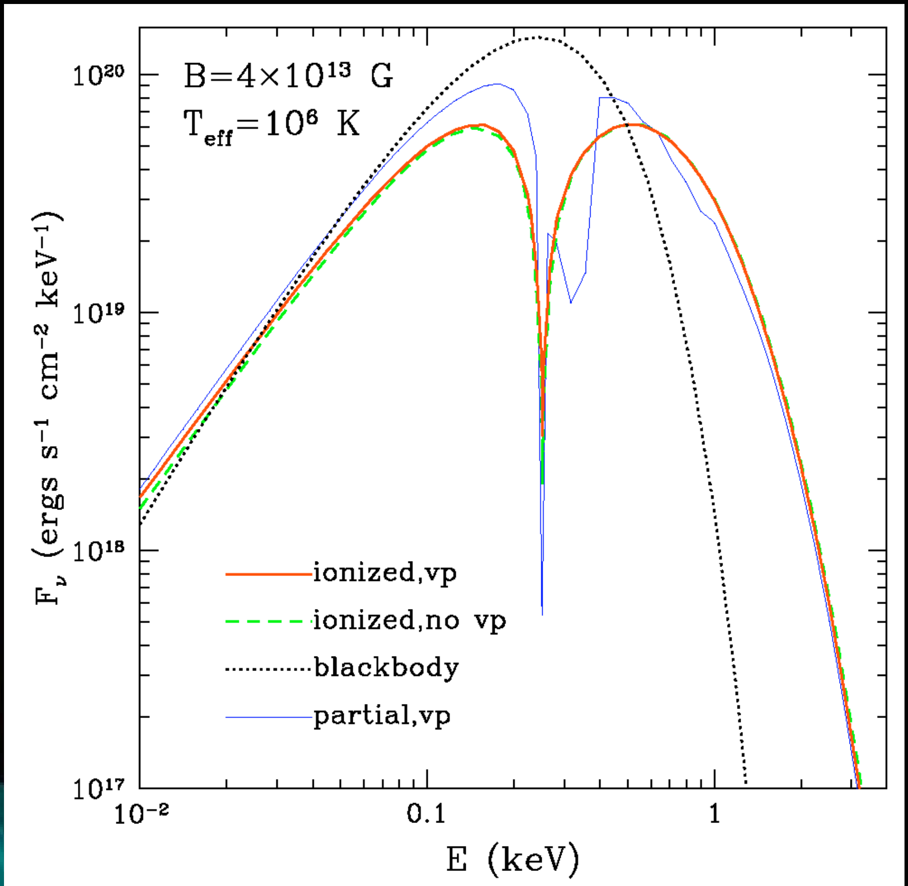
X-ray Birefringence (2)

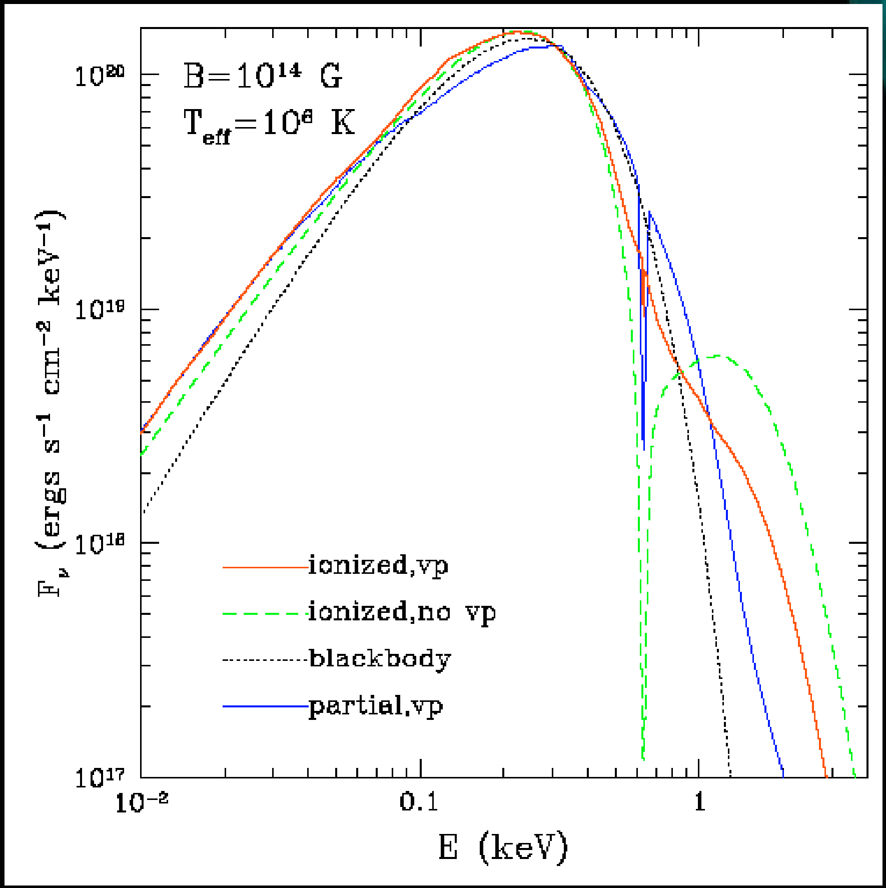
- Deep in the atmosphere the modes are plasma dominated.
- Outside the modes are vacuum dominated.



- Ho & Lai ‘03

X-ray Birefringence (3)

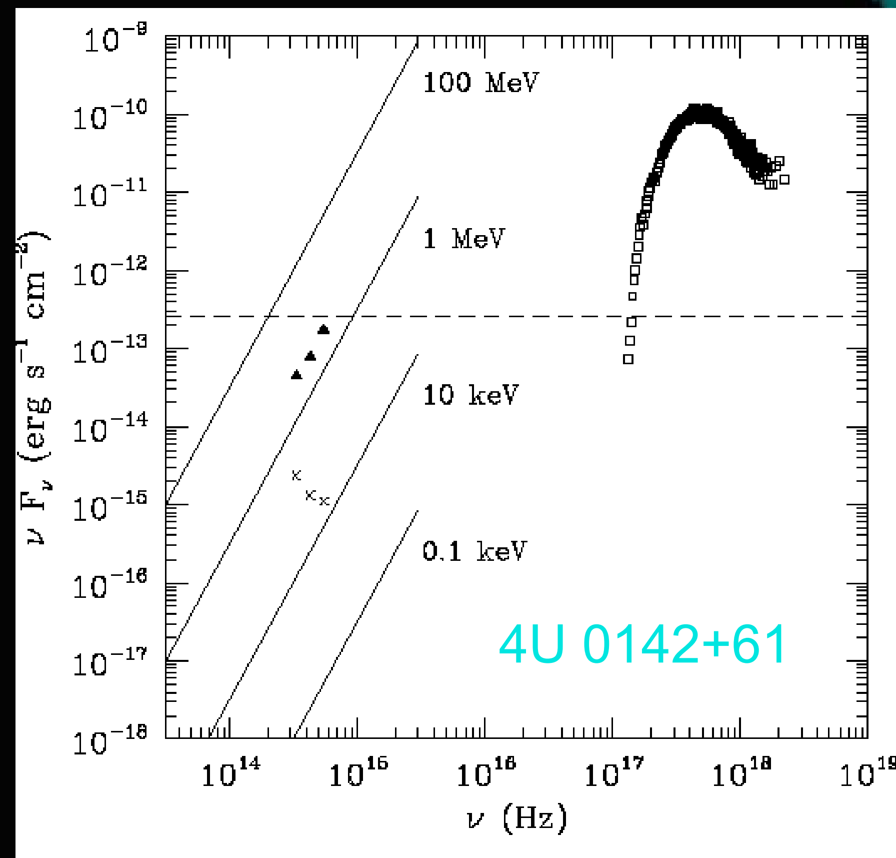




- Ho & Lai '04

Non-thermal Emission (1)

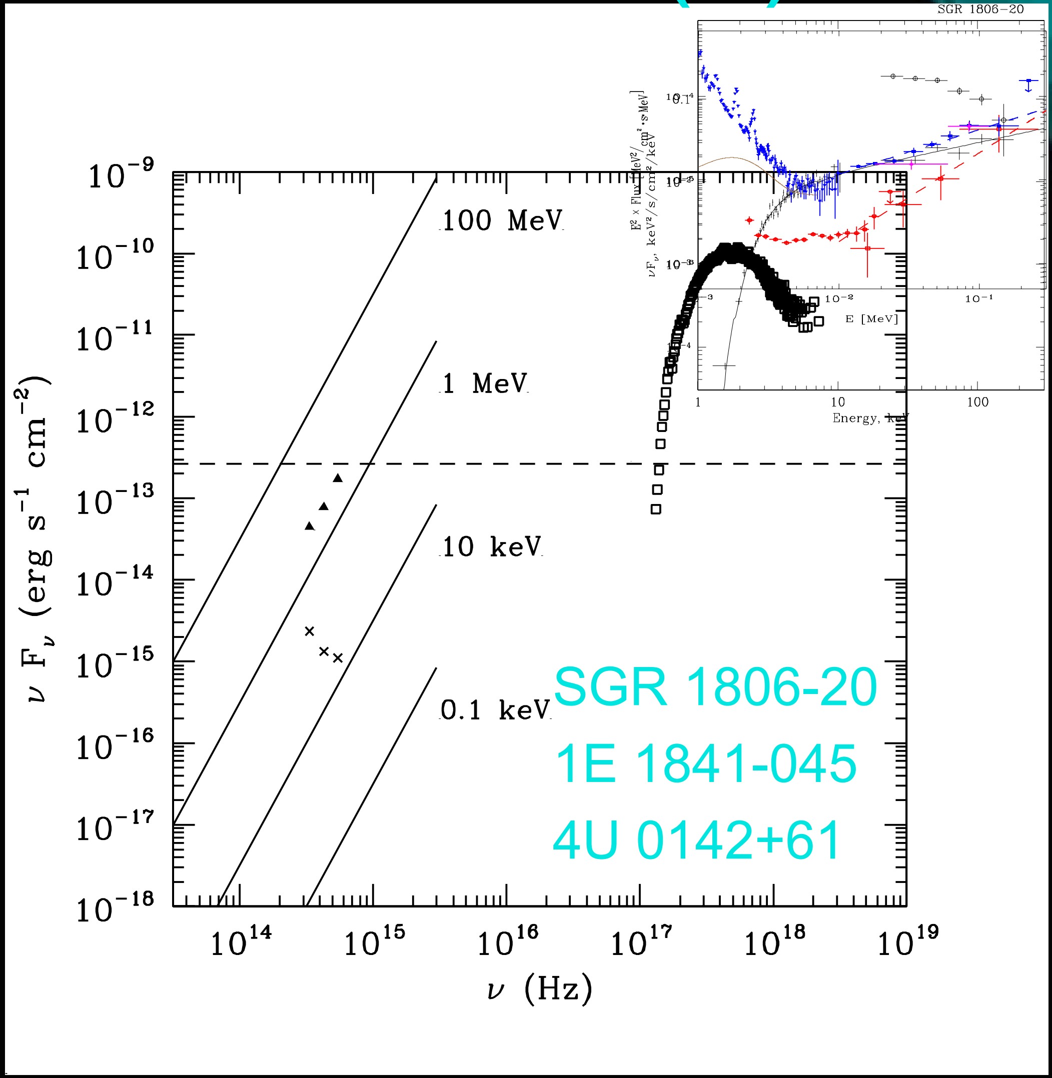
- X-rays, gamma-rays and optical.
- Özel points out that no thermal mechanism powered by energy through the crust can account for the optical emission and be consistent with the X-ray emission.



- Özel ‘04; Hulleman et al. ‘00

Non-thermal Emission (2)

- INTEGRAL and RXTE found persistent non-thermal hard x-rays from two magnetars: Kuiper et al. ‘04, Molkov et al. ‘04, Mereghetti et al.‘04

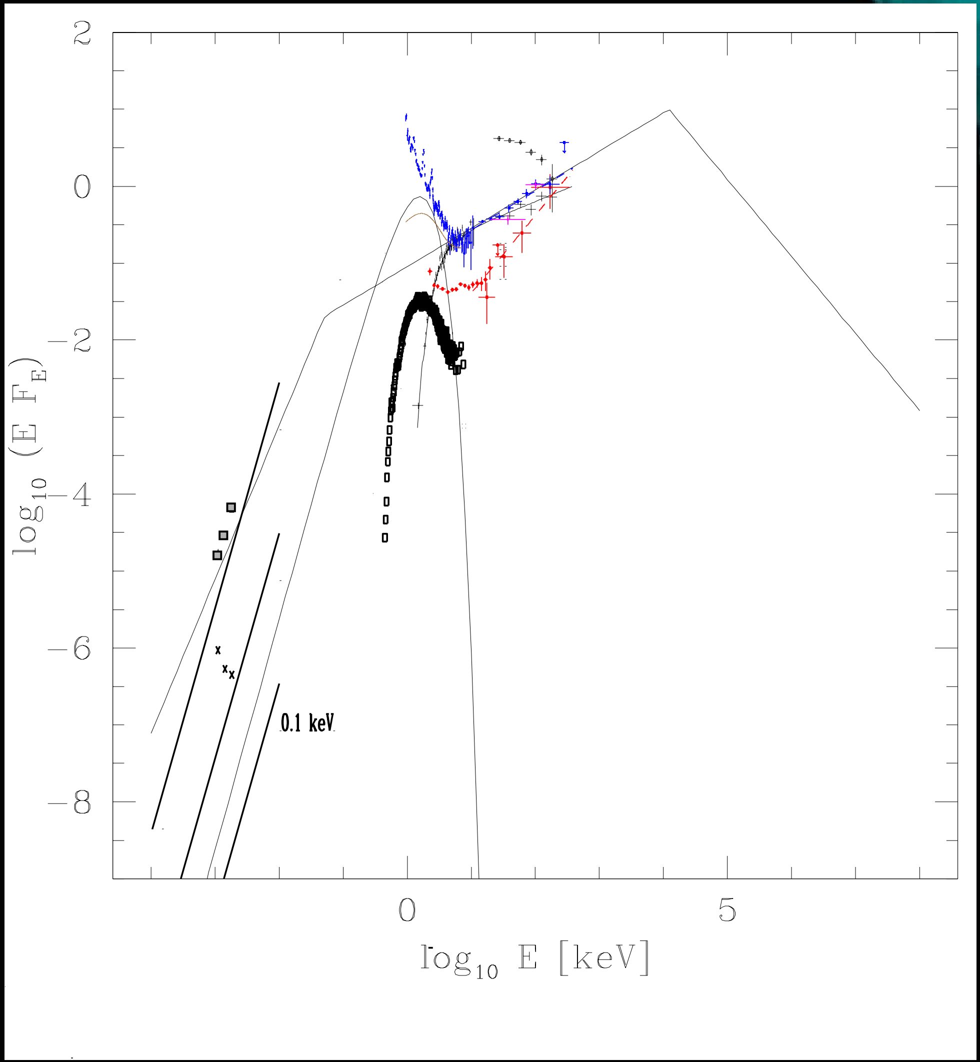


Non-thermal Emission Models

- Özel '04 proposes that that a pair-plasma at the Goldreich-Julian density at *r*~50*R* suffices to explain the optical emission if the typical energy of the electrons $\gamma \propto B^{-1/4}$; yielding $\nu F_\nu \propto \nu^2$. The emission is rotation powered.
- Thompson and Beloborodov '04 propose:
  - Bremsstrahlung in a thin surface layer heated by magnetospheric currents to $kT \sim 100\mathrm{keV}$. $\nu F_\nu \propto \nu^1$
  - If the electron temperature were ~ 1 MeV, this could explain the flux as well. $\nu F_\nu \propto \nu^3$
  - Runaway positrons in the current emit synchrotron radiation; passively cooling spectrum $\nu F_\nu \propto \nu^{1/2}$ up to ~ 1 MeV.

Non-thermal Emission (3)

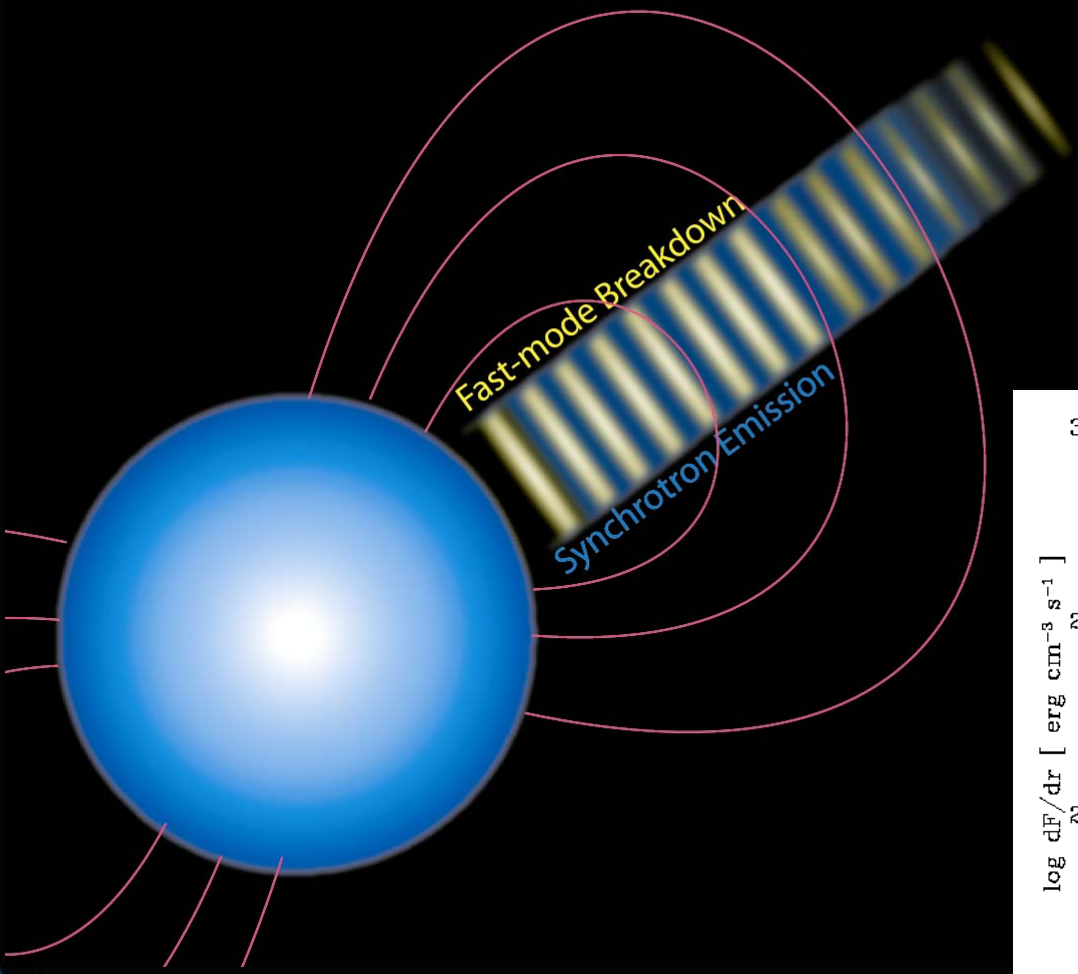
- A simple model can account for the non-thermal emission from optical to GeV.
- The spectrum predicted by T&B is too steep in the optical at high-energy without adding a synchrotron component.



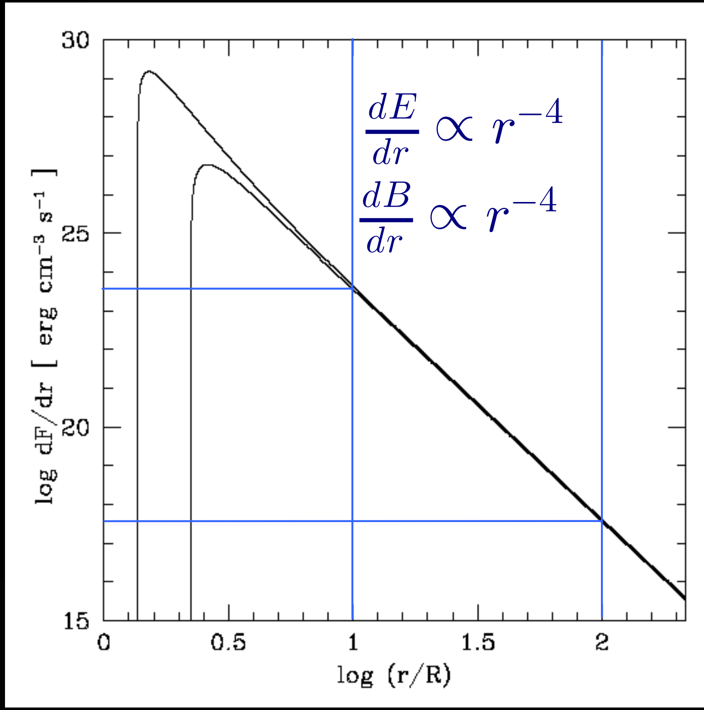
Understanding the bursts

- 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.

Fast-Mode Pair Cascade (1)

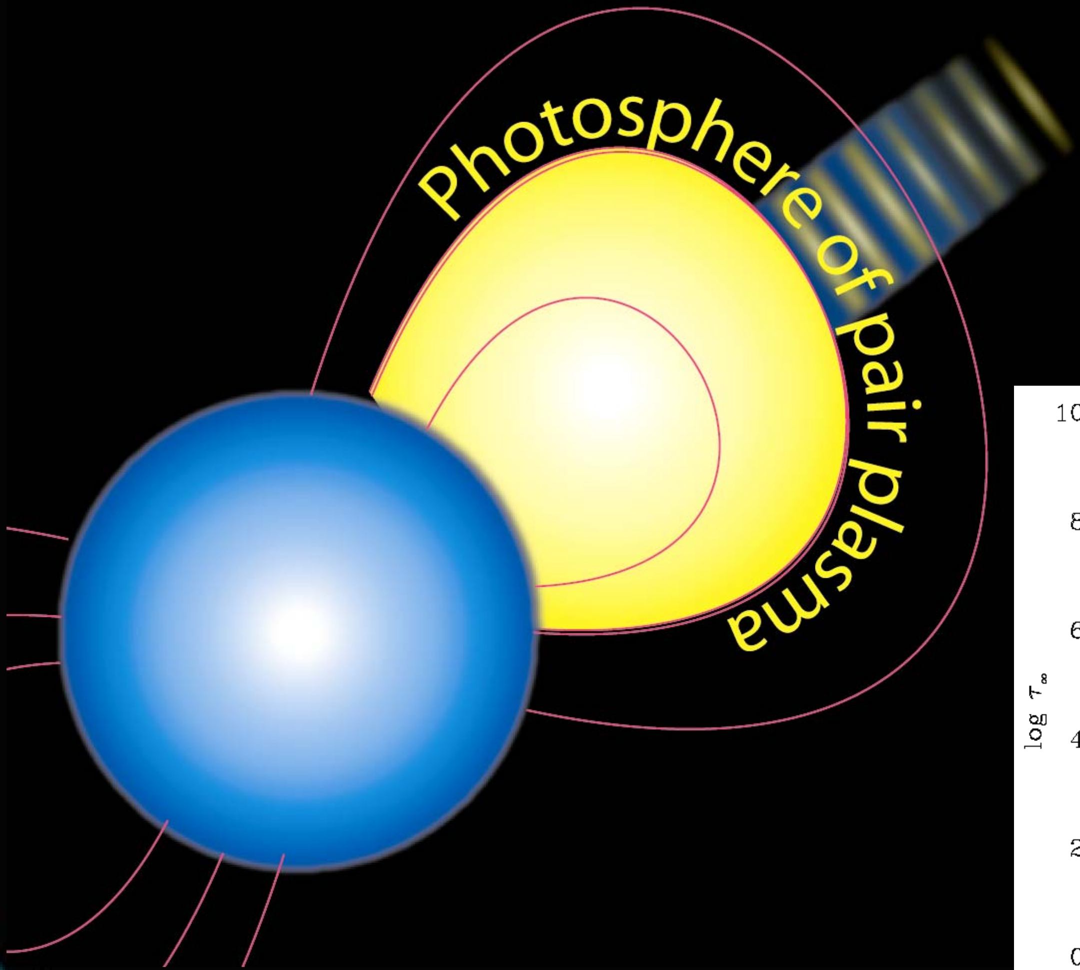


- Equal energy is dumped in equal intervals of *B.*

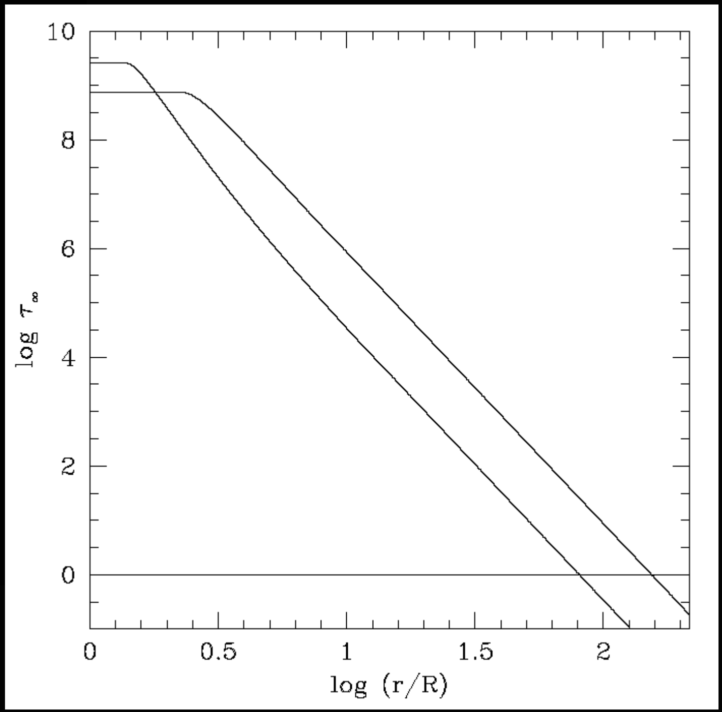


- Heyl & Hernquist '04

Fast-Mode Pair Cascade (2)



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



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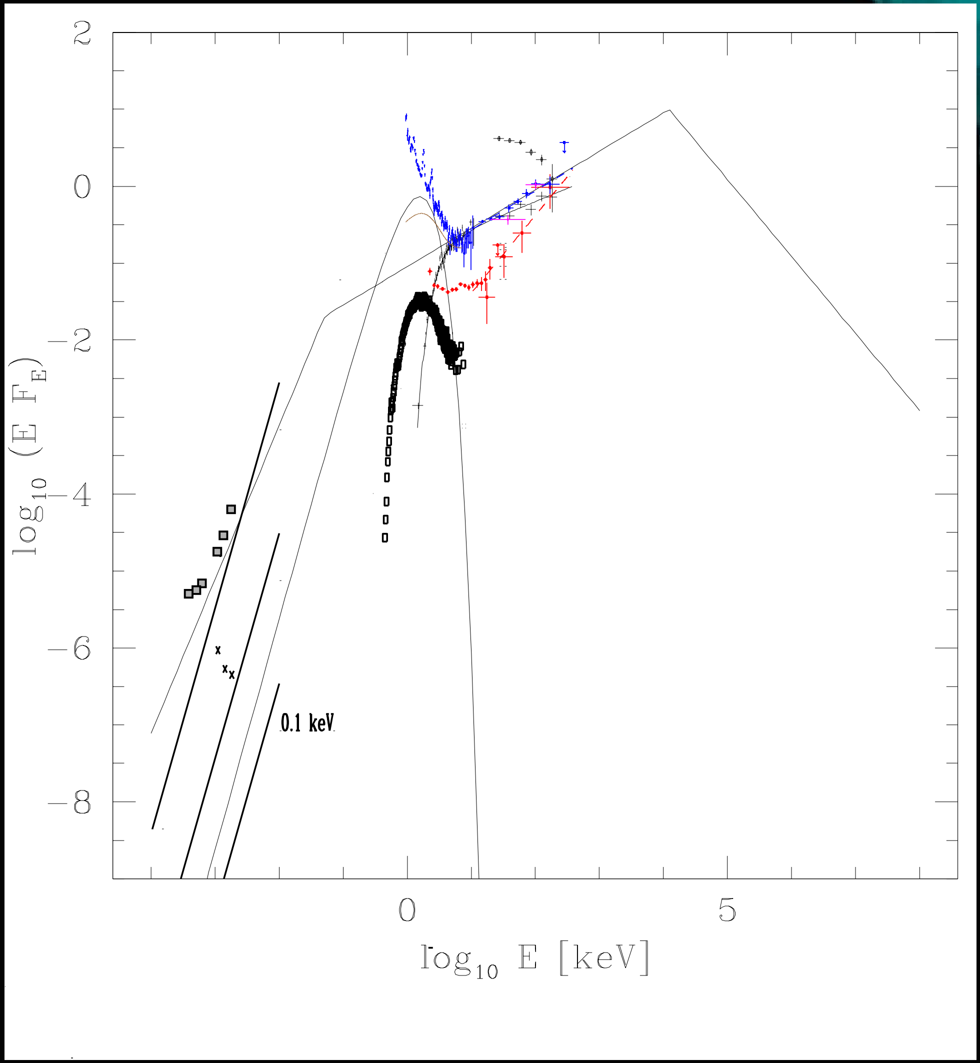
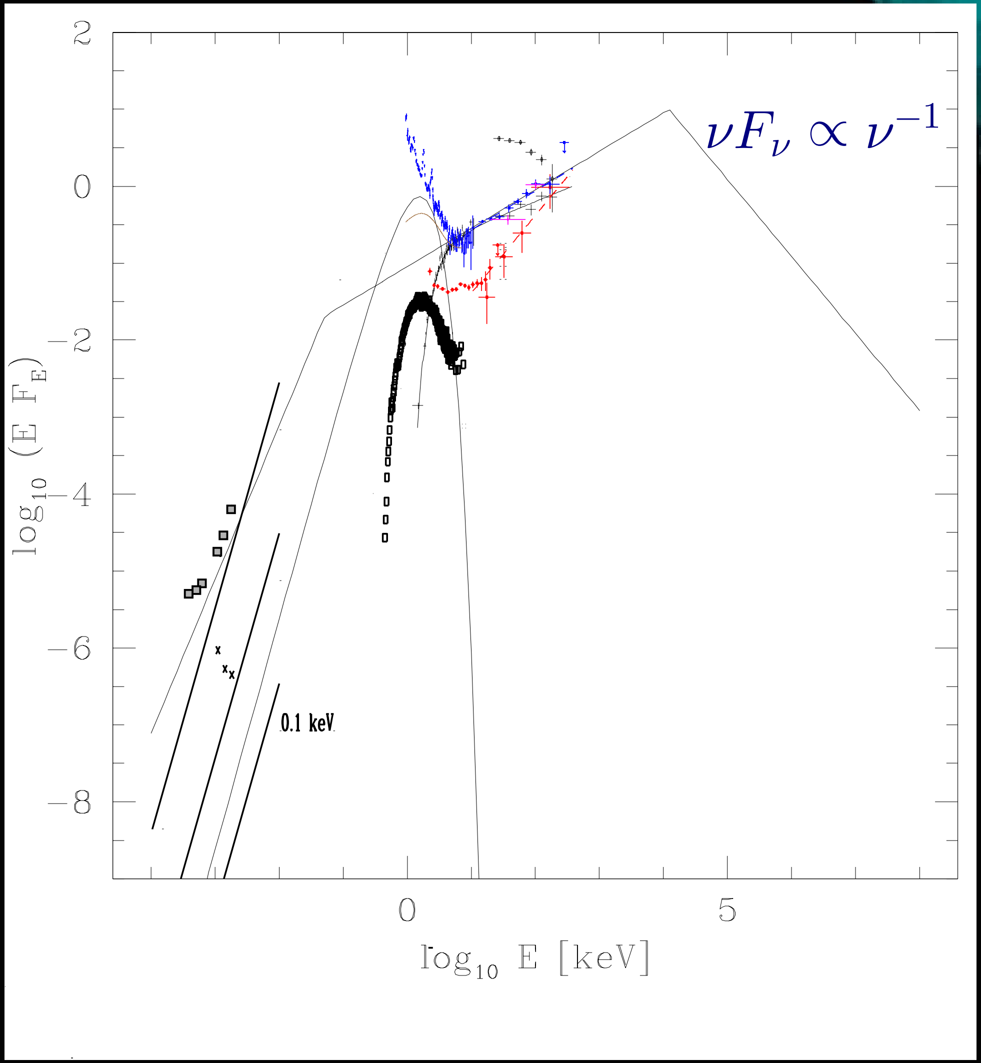
Fast-Mode Pair Cascade (3)

- 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 $E_\gamma \sim 2.5 \times 10^{-3} \frac{B_{\rm QED}}{B} mc^2$ $\frac{dE}{dE_\gamma} \propto E_\gamma^{-2}$



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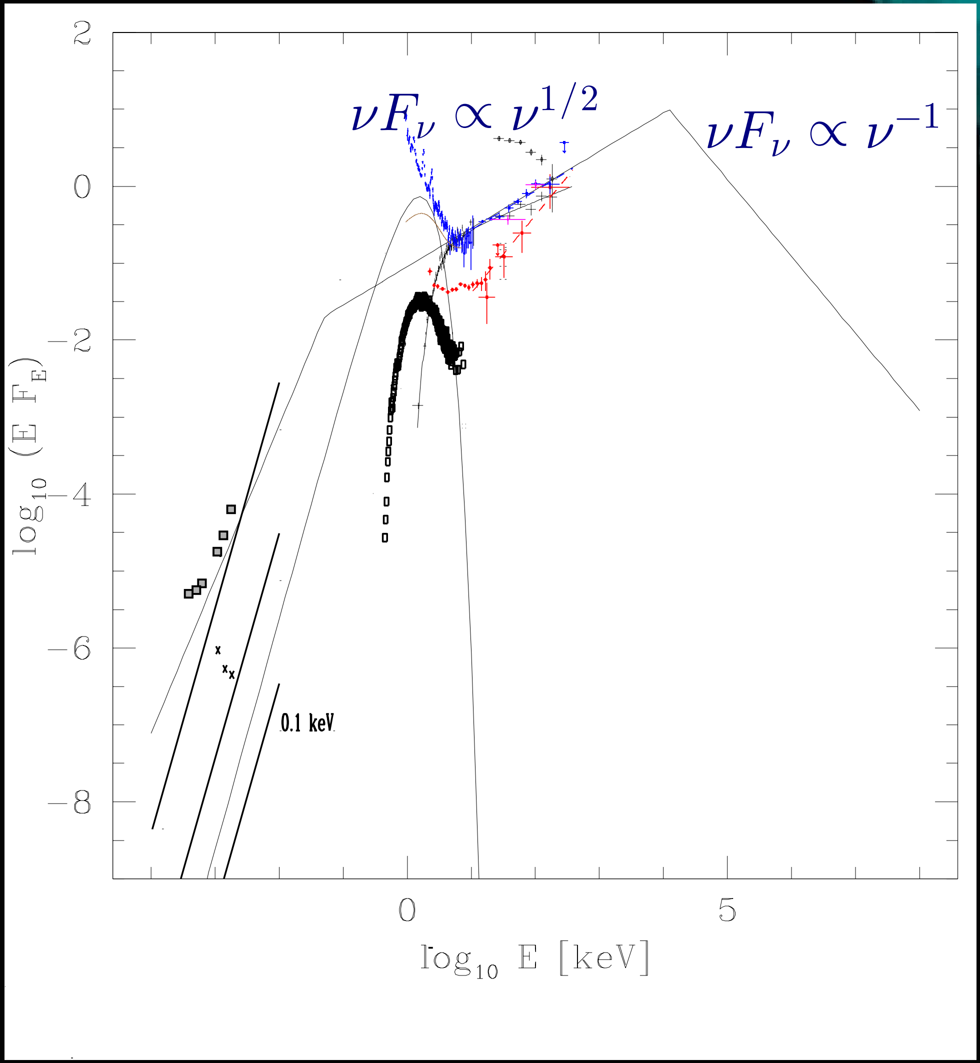

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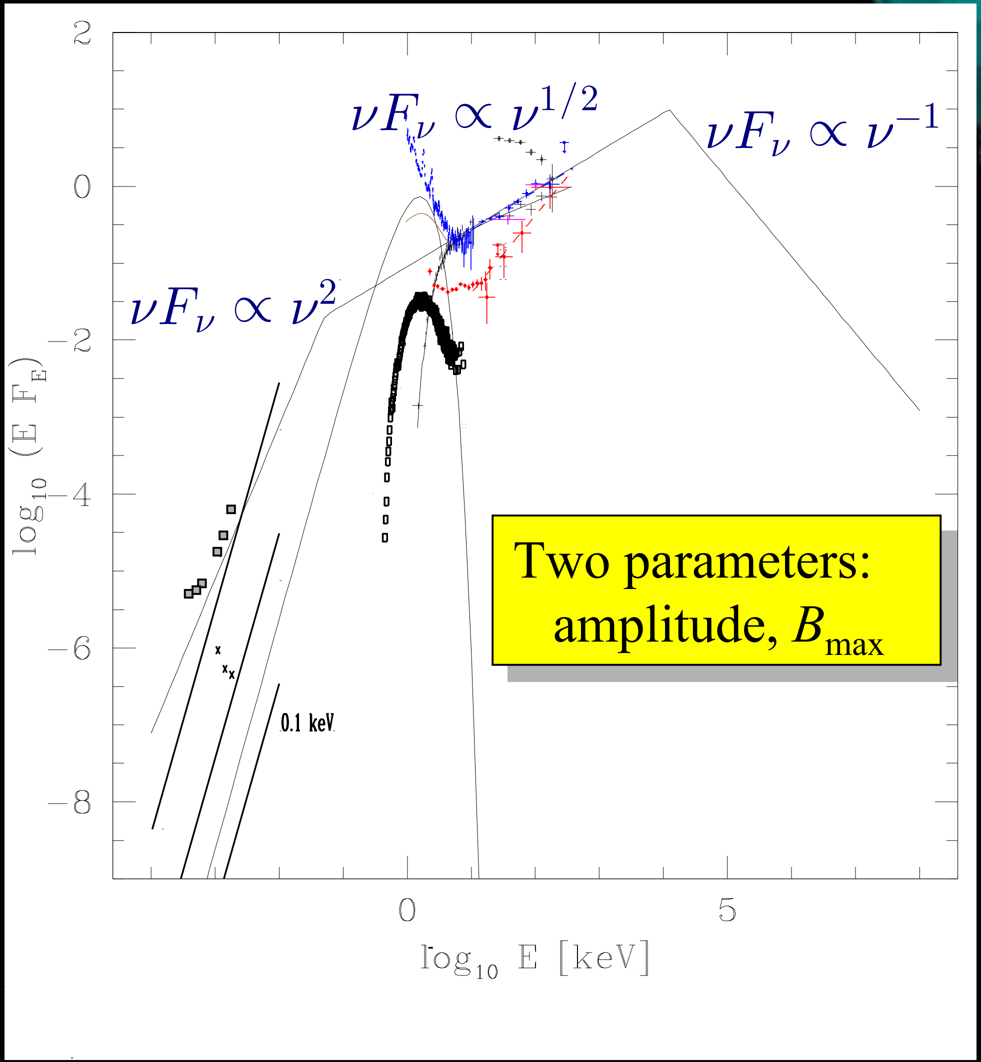
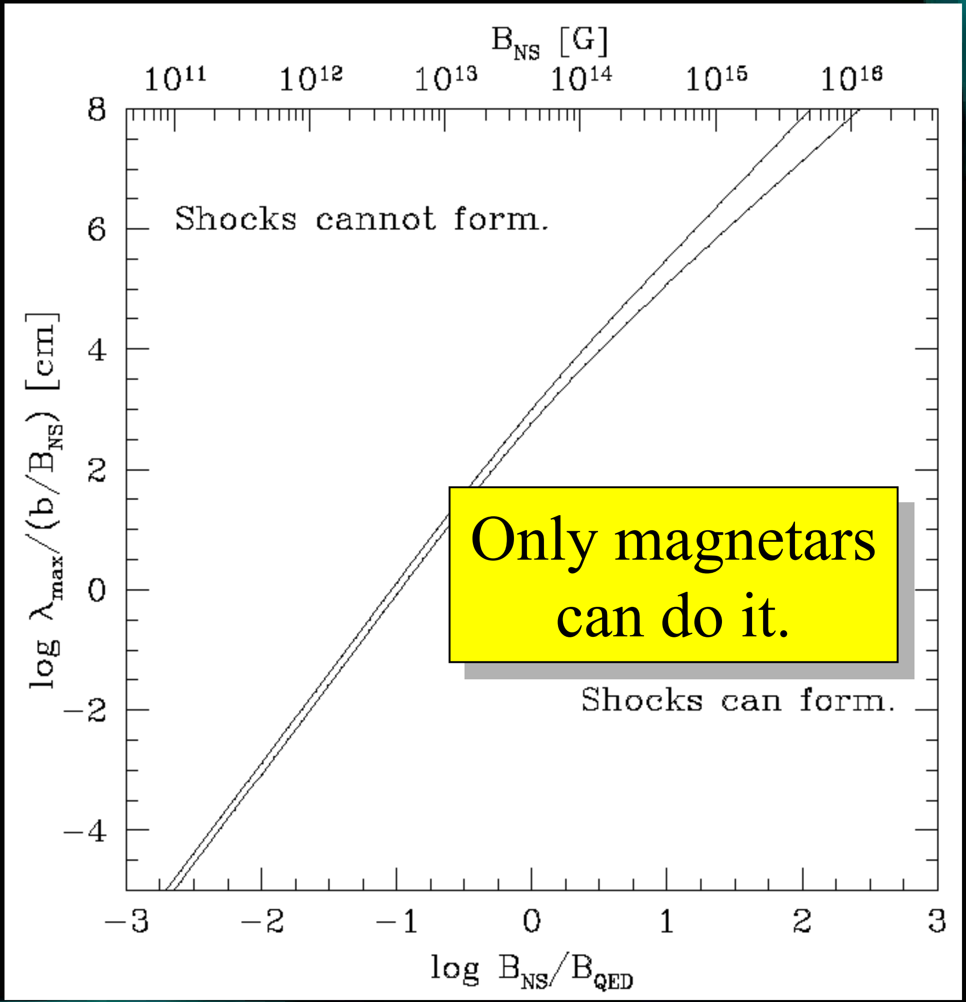
- The innermost pairs cool the most quickly. $\frac{dE}{dE_\gamma} \propto E_\gamma^{-1/2}$
- Cold pairs emit at the cyclotron frequency
  $\frac{dE}{dE_\gamma} \propto E_\gamma^{1}$

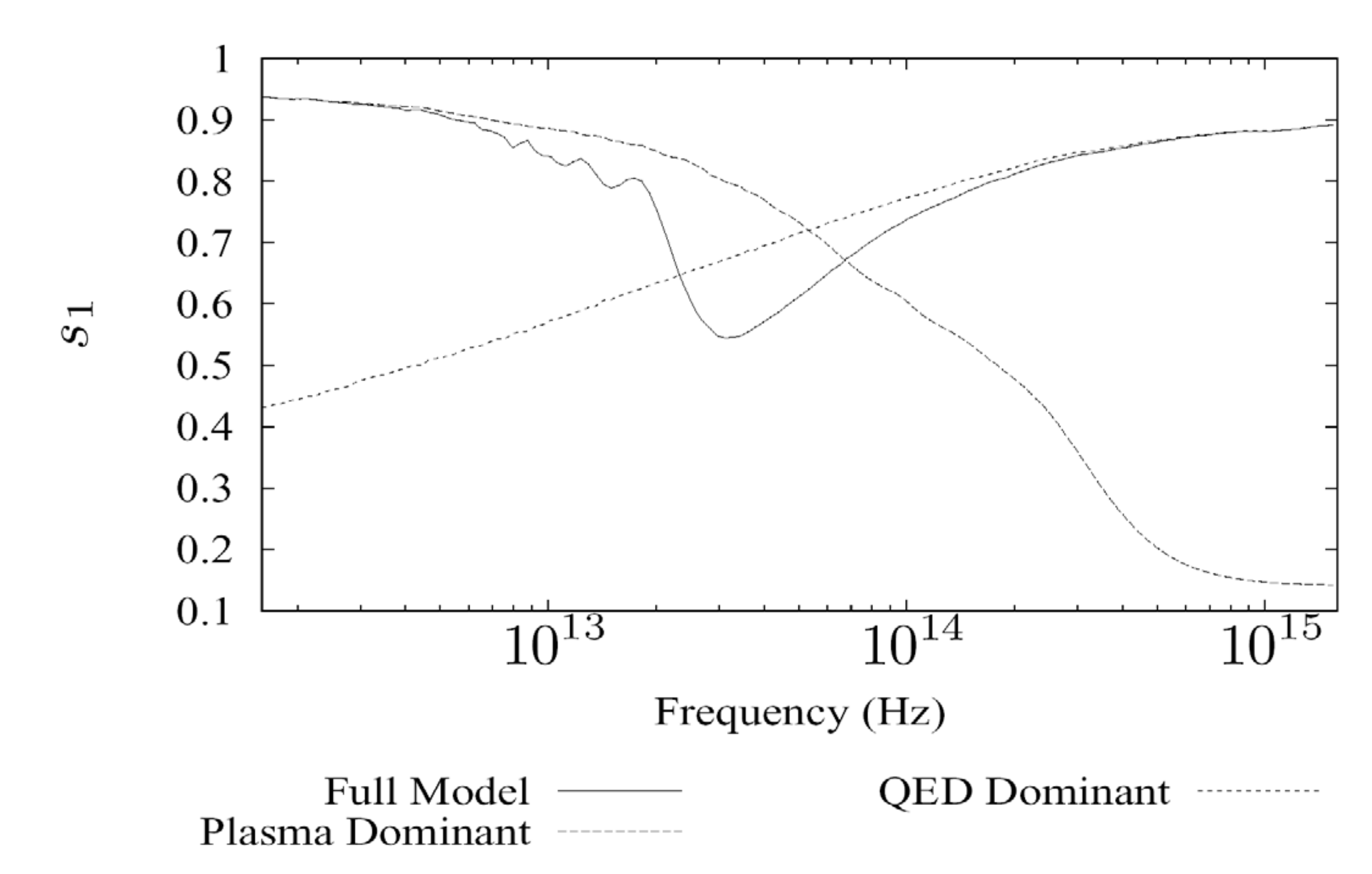


A Model for Magnetars

- The surface of a magnetar emits various MHD waves into the magnetosphere.
  - Alfven waves power the traditional Thompson & Duncan burst.
  - 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.



Shannon & Heyl '04



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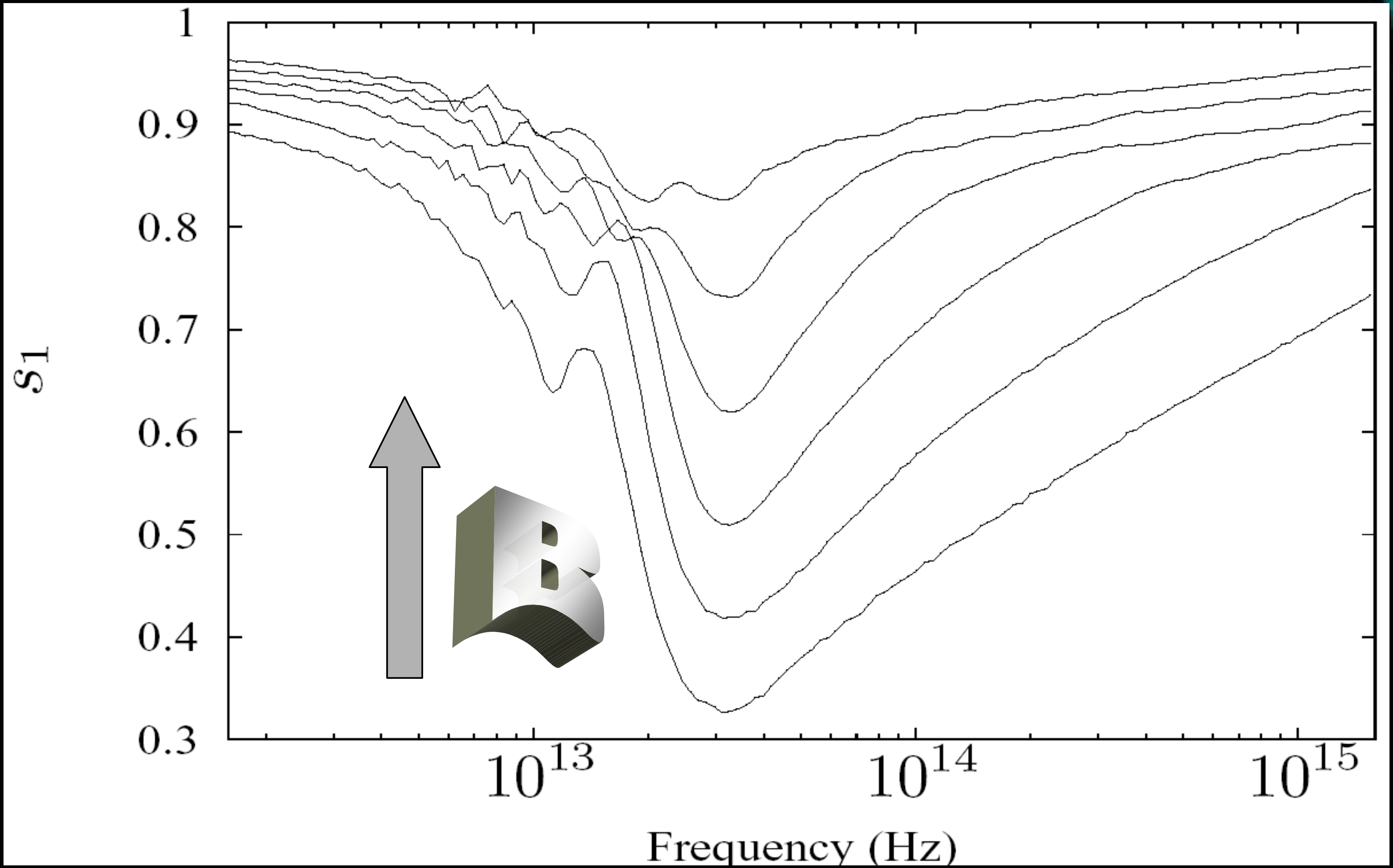

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