Title: Electrodynamics inside and outside magnetars

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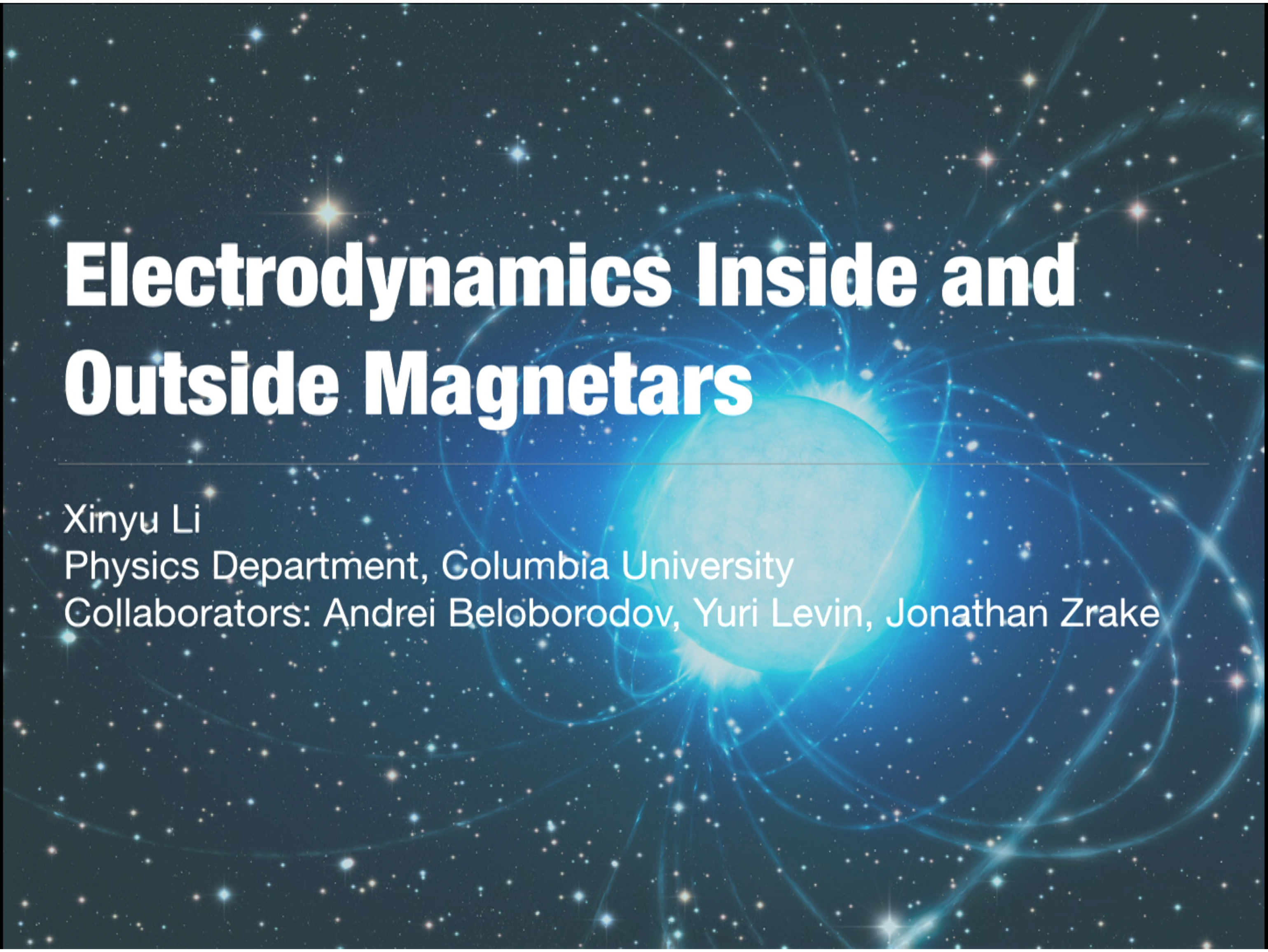
Abstract: <p>The ultra-strong magnetic fields of magnetars have profound implications for their radiative phenomena. We studied the dynamics of strong magnetic fields inside and outside magnetars. Inside the magnetar, the strong magnetic stress can break the crust and trigger plastic failures. The interaction between magnetic fields and plastic failures is studied in two scenarios: 1. Internal Hall waves launched from the core-crust interface can initiate plastic failures and lead to X-ray outbursts. 2. External Alfven waves produced by giant flares can also initiate crustal plastic failures which dissipate the waves and give rise to delayed thermal afterglow. The crustal dissipation of Alfven waves is competed by the magnetospheric dissipation outside the magnetar. Using a high order simulation of Force-Free Electrodynamics (FFE), we found that the magnetospheric dissipation of Alfven waves is generally slow and most wave energy will dissipate inside the magnetar.</p>



Electrodynamics Inside and Outside Magnetars

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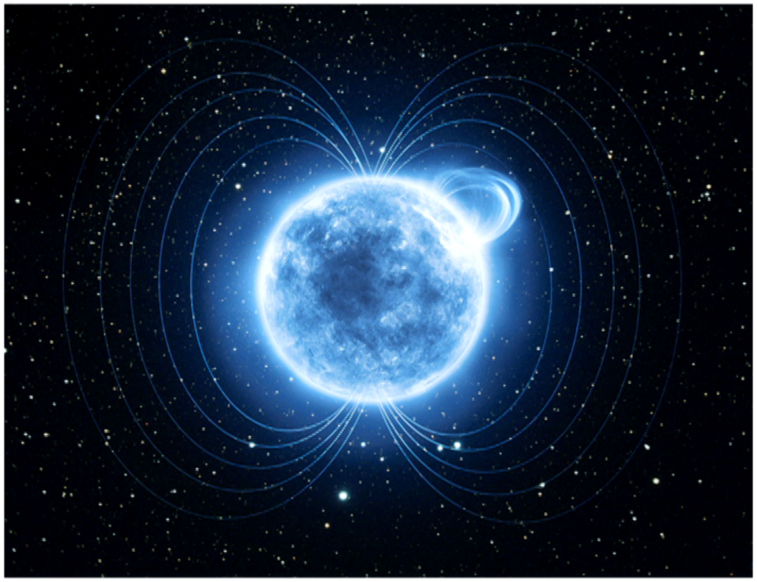
Magnetar

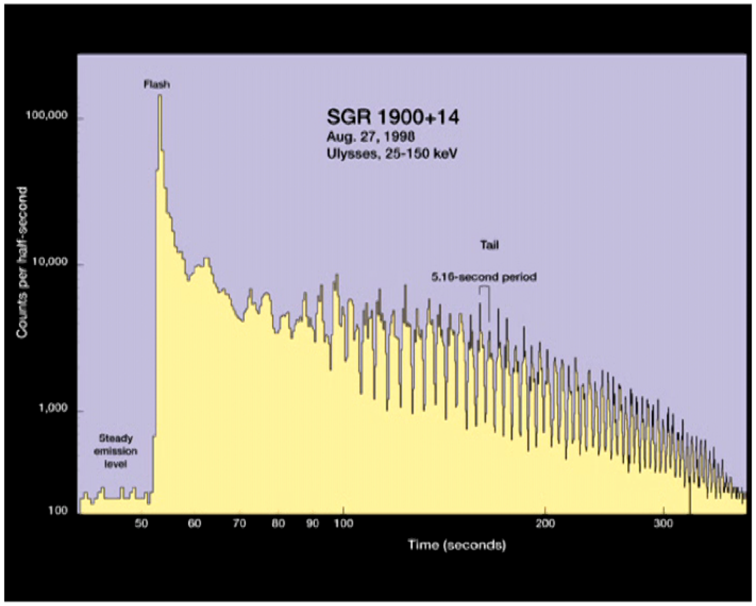
- Neutron star with ultra-strong magnetic field
- Slow rotation period 1-10s
- ~30 sources have been identified by now
- McGill Online catalogue list 29 magnetars
- Online interactive analysis: http://magnetars.ice.csic.es



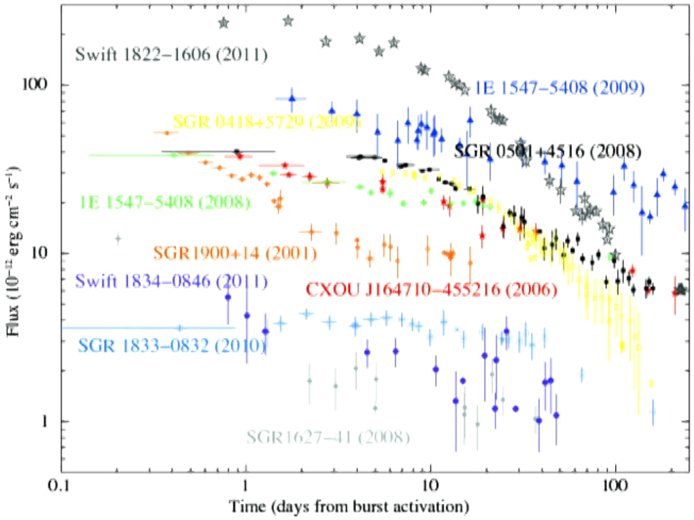
ESA/ATG

Magnetar Activities

- **Giant flares**: peak luminosity 10^{43}-10^{47} erg/s, rises in milliseconds
- **Soft gamma ray bursts**: less energetic ~10^{43} erg/s
- **Outbursts**: 10-1000 times increase of X-ray luminosity (~10^{36} erg/s) and decays exponentially for months to years
- **Persistent X-ray emission**: luminosity usually much larger than the spin-down power
- **High surface temperature**: 10^{35} erg/s (arXiv:1605.09077)
- **Timing anomalies**: glitches and anti-glitches (sudden spin-down)



Giant Flare



Outbursts

Key Questions

- Thompson & Duncan (1995,1996) proposed that bursts and giant flares are powered by the magnetic energy and coined the word “magnetar”.
- **1) (fast) conversion of magnetic energy to radiations**
- Magnetic energy is converted to radiations possibly through a distorted magnetosphere (Parfrey 2013, Beloborodov 2009,2013).
- **2) origin of magnetospheric distortion**

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- **2) origin of magnetospheric distortion**

Outline

- Electrodynamics inside the magnetar:

  1) Plastic deformation of the magnetar crust by magnetic stress

  2) Modeling magnetar outbursts with Hall waves induced plastic failures (1606.04895)

  3) Thermal afterglow of giant flares by crustal damping of Alfven waves (1505.03465)

- Electrodynamics outside the magnetar:

  Magnetospheric dissipation of Alfven waves (1810.10493)

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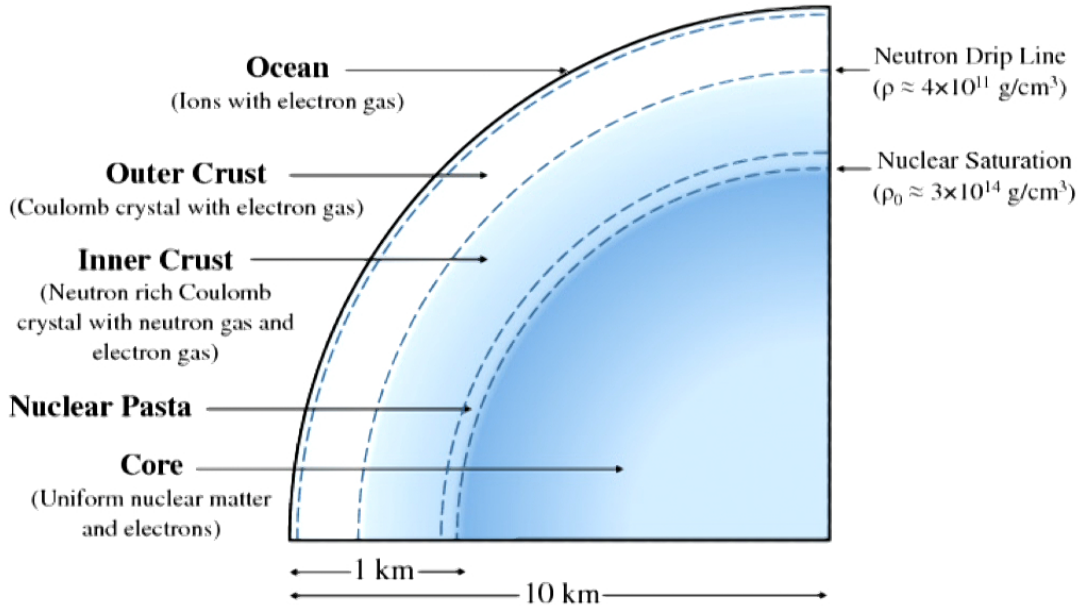
Origin of Magnetospheric Distortion

NS crust



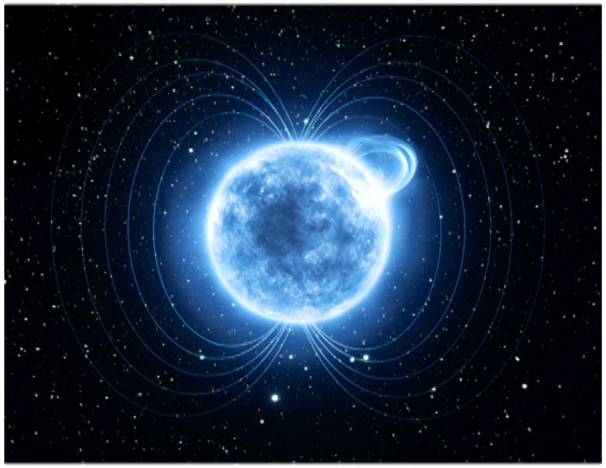
Caplan and Horowitz 2017

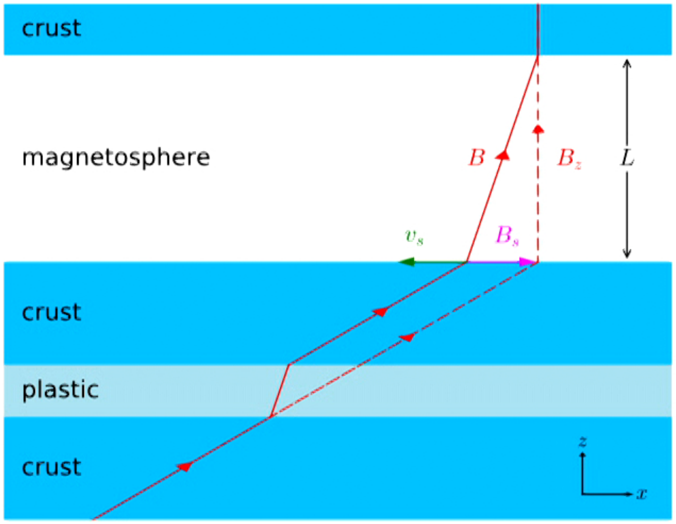
Plastic Deformation of the Crust

- The strong magnetic stress is able trigger the plastic failure when the magnetic stress exceeds $\sigma_{cr} \approx 0.1\mu$

$$B_{cr} = 4\pi\sigma_{cr}/B_z$$

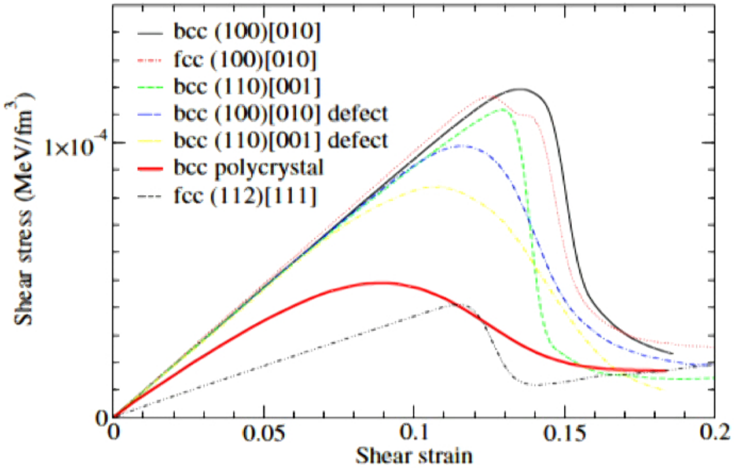
- Magnetic energy is dissipated to heat in the plastic flow
- The magnetic field lines are dragged by the plastic flow and induces footpoint motion which gives rise to the toroidal field





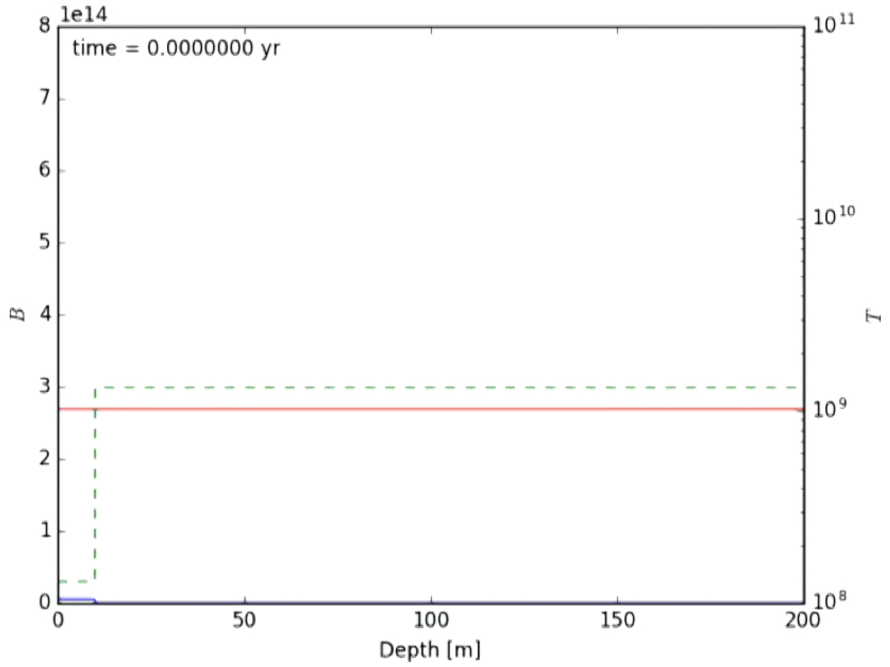
Thermal Responses of the Crust

- The crustal material is softened by the increasing temperature (Chugunov & Horowitz 2010)
- There is also a phase transition in the plastic flow (Horowitz & Kadau 2009)



Thermoplastic Waves (TPW)

- Beloborodov & Levin 2014
- The plastic flow dissipates magnetic energy to heat and diffuses it to the neighboring regions
- The neighboring crustal material is softened by the temperature increase and more plastic failures can be triggered
- The speed of TPW is $v = \sqrt{\frac{\chi \mu_B}{\eta}}$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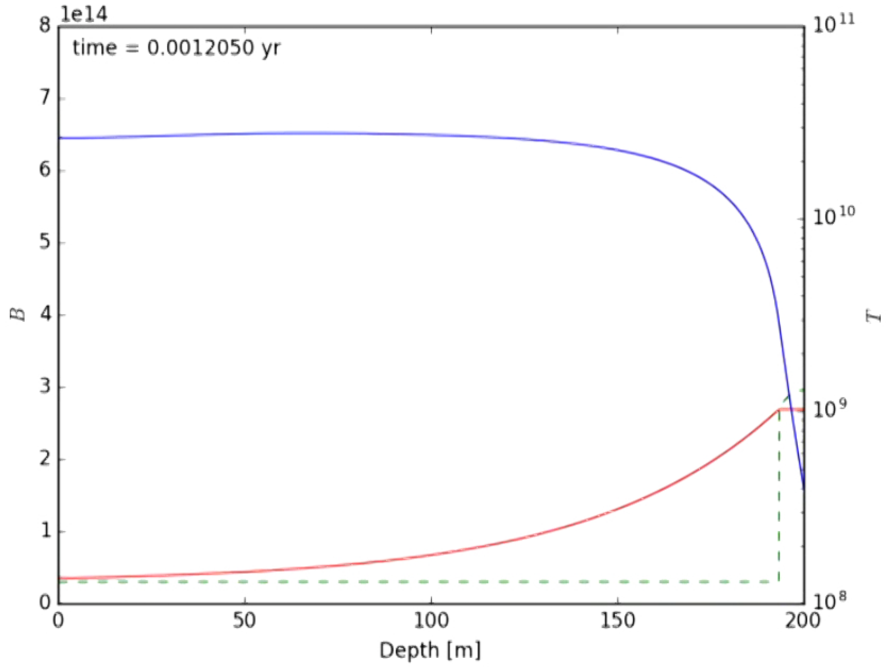
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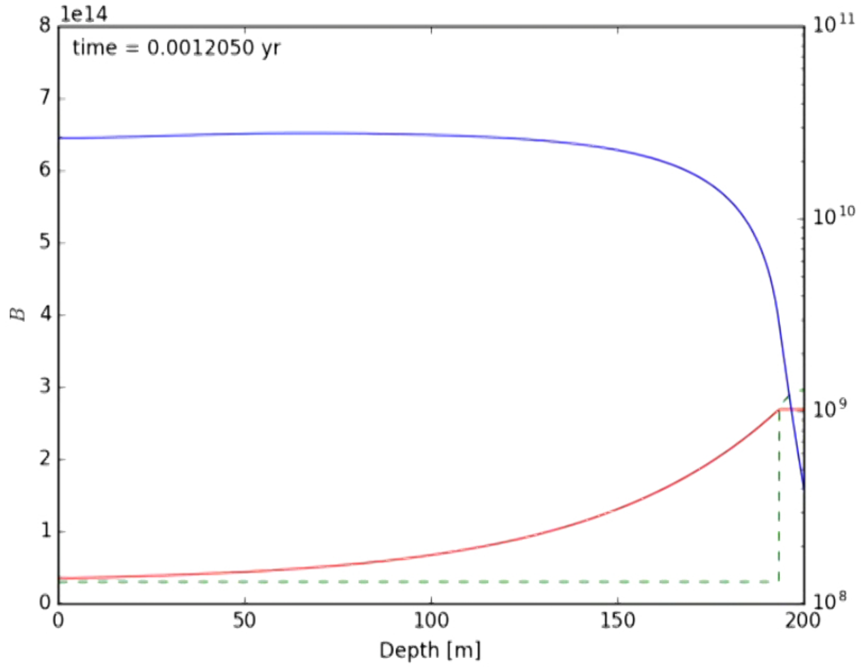
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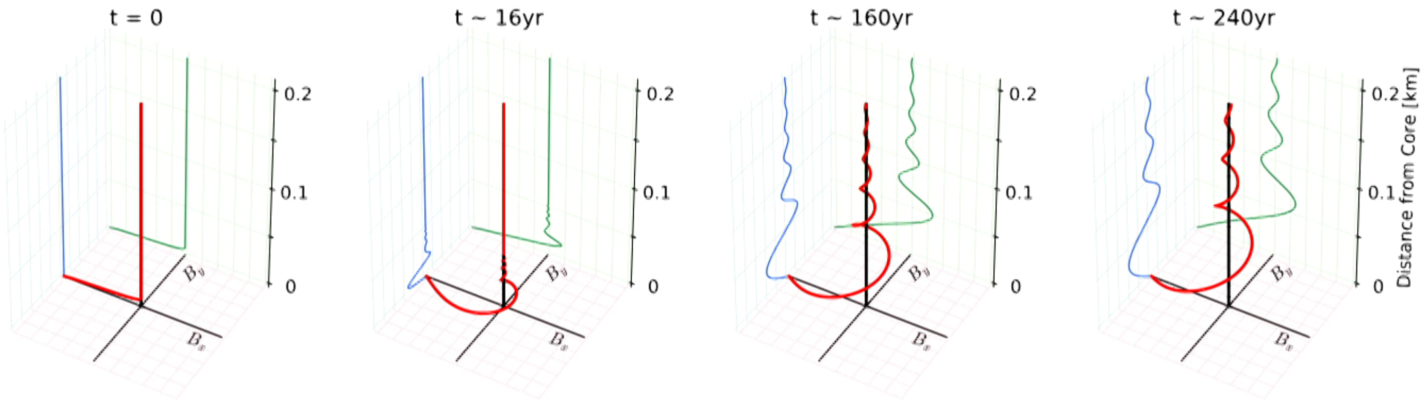
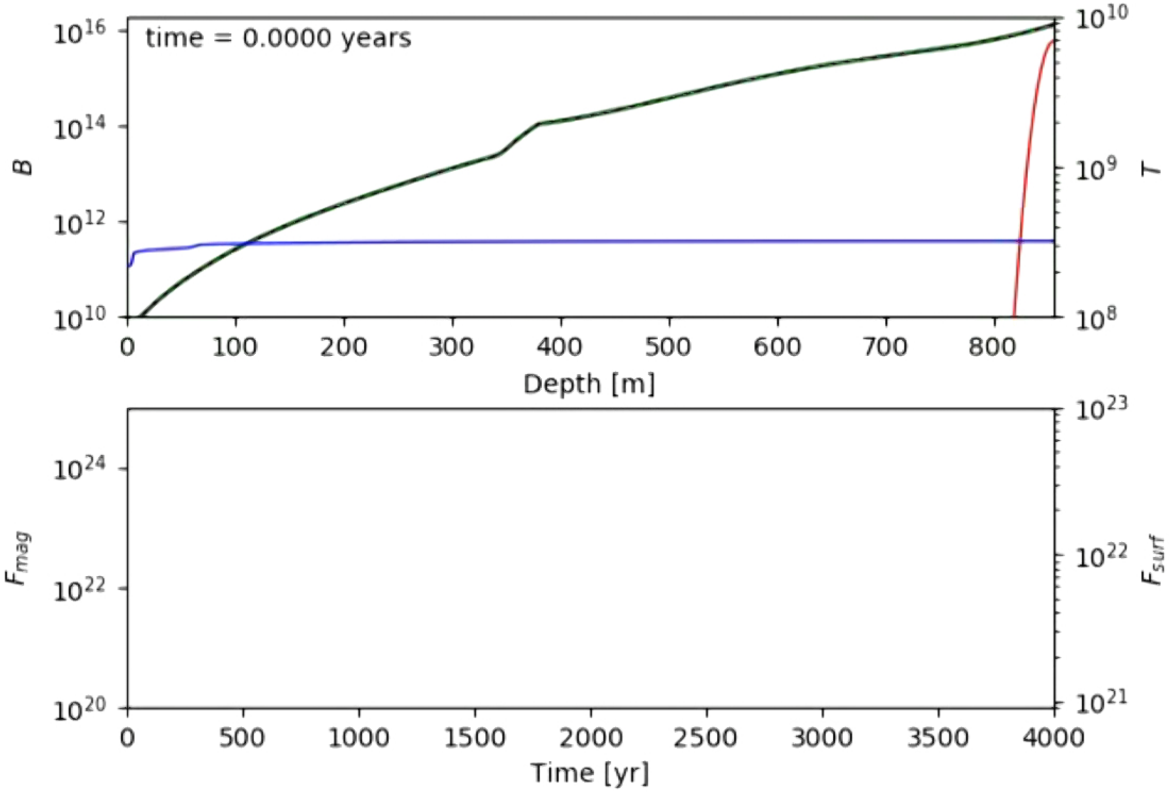
Hall Waves in the Crust

- Hall waves: magnetic field advected by the electron fluid
- Hall waves generated from the core-crust interface accumulate magnetic energy inside the crust.
- Plastic flow is initiated when the magnetic stress is supercritical.



Crustal Response

- **Elastic response**: assume stress balance on the slow time scale of Hall wave propagation
- **Plastic response**: shear magnetic is reduced by the plasma viscosity. Set the timescale for the dissipation of magnetic energy (heating) to be 10^4s. Crust is healed after some time ~1yr
- **Thermal response**: include magnetic heating, Ohmic heating, heat diffusion and neutrino cooling
- We model non-thermal emission from the untwisting of the magnetic field lines in the magnetosphere and measure both thermal and non-thermal fluxes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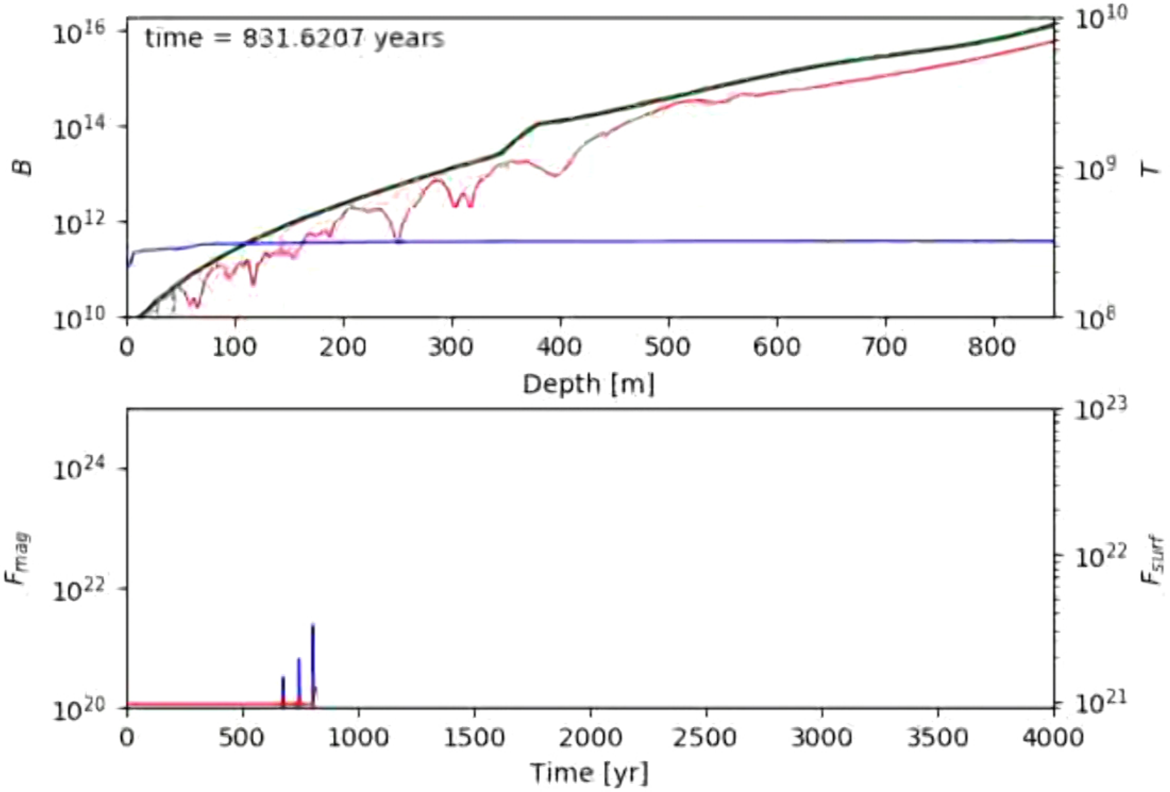
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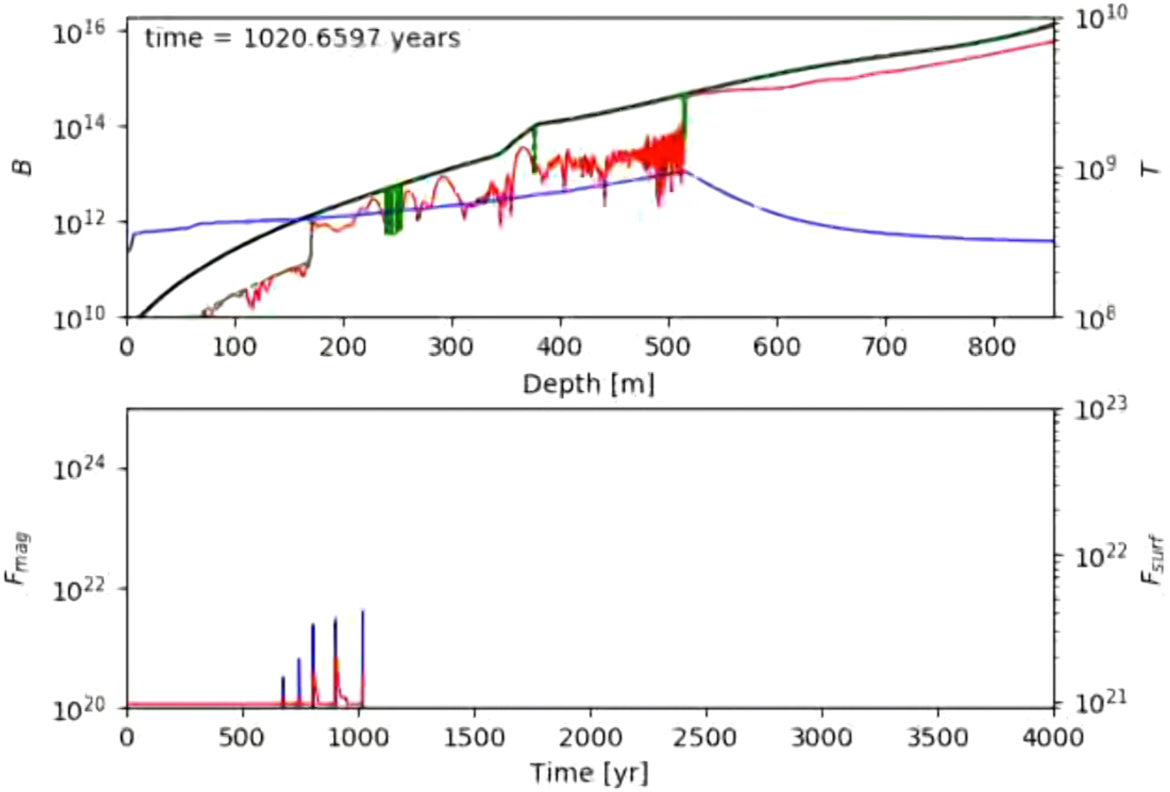
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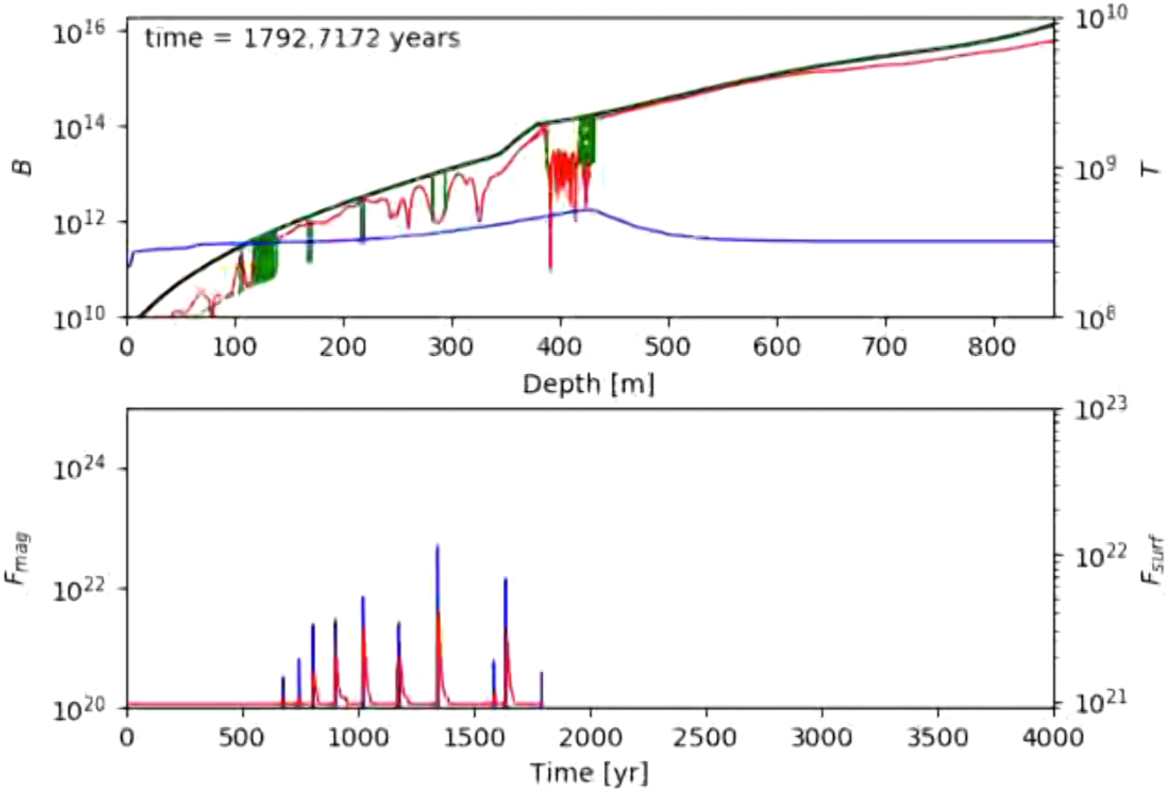

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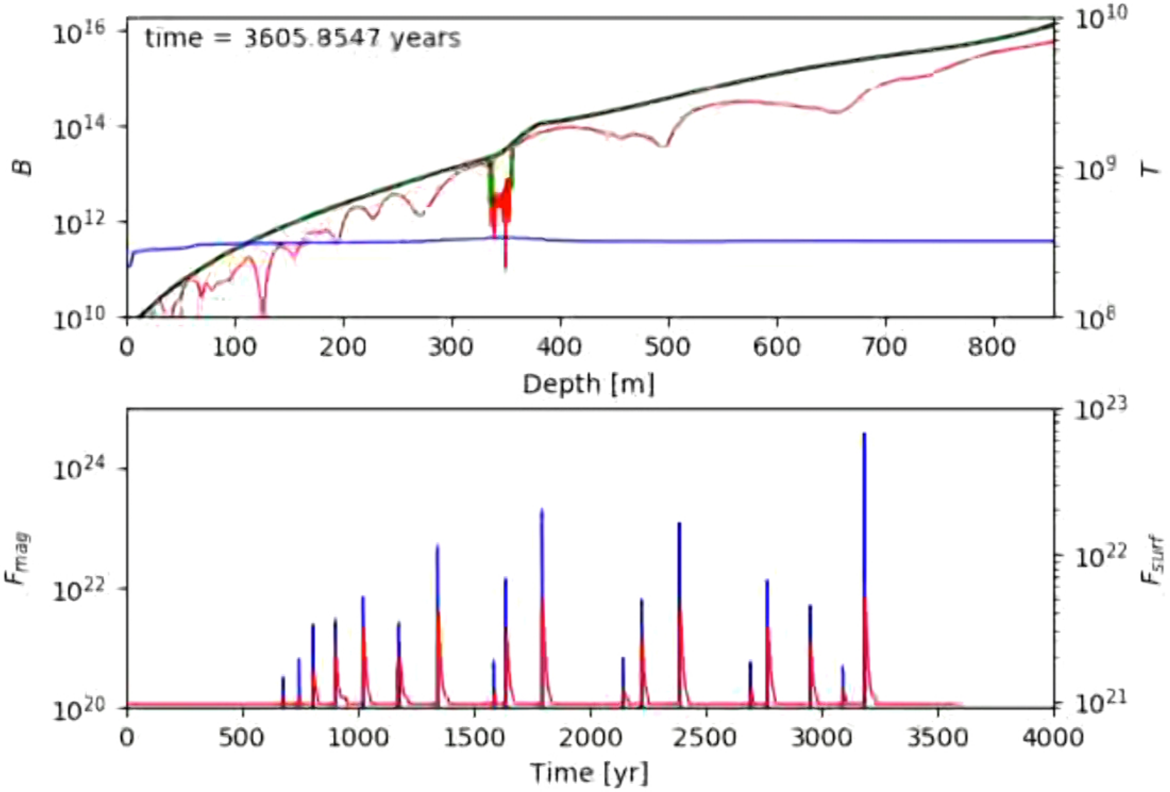
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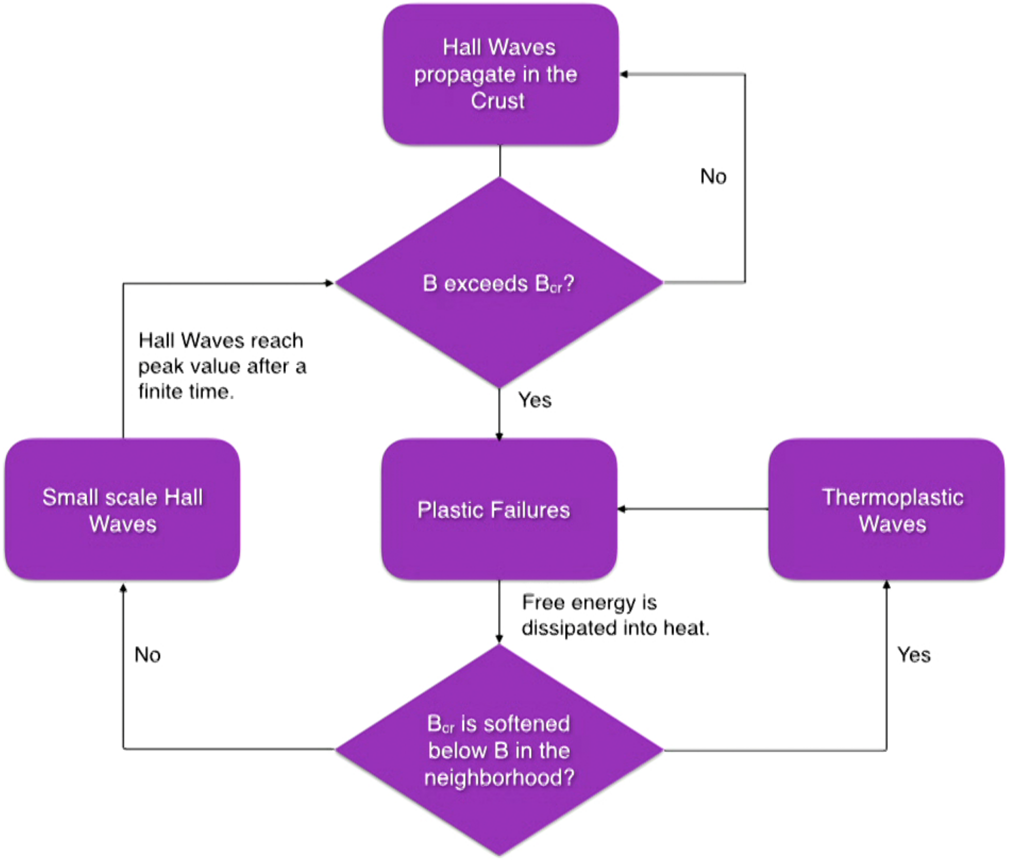


Hall Waves propagate in the Crust

B exceeds B_{cr}?

No

Yes

Hall Waves reach peak value after a finite time.

Small scale Hall Waves

Plastic Failures

Thermoplastic Waves

Free energy is dissipated into heat.

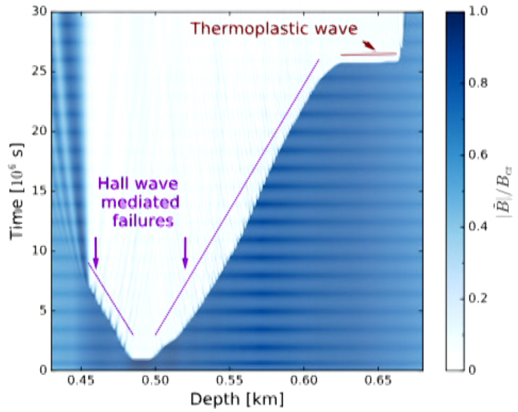
B_{cr} is softened below B in the neighborhood?

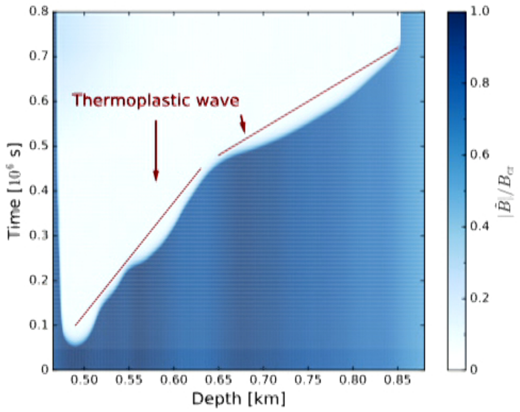
No

Yes

Hall-mediated Avalanches vs Thermoplastic Waves

- Hall-mediated mode has speed $v \sim \sqrt{\alpha \frac{B_z c}{4\pi n_e e}}$
- Much smaller than the speed of TPW $v \sim \sqrt{\alpha \chi}$





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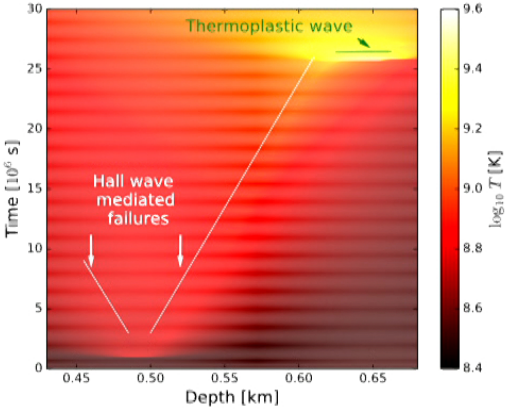
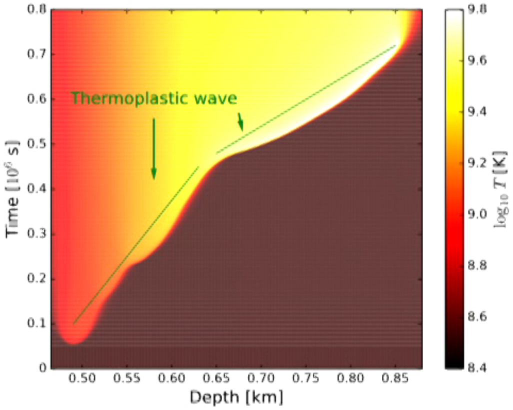
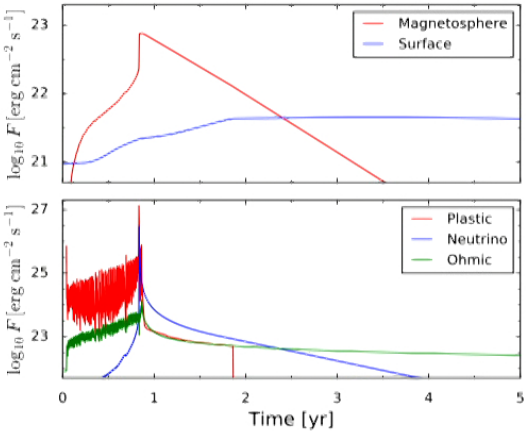
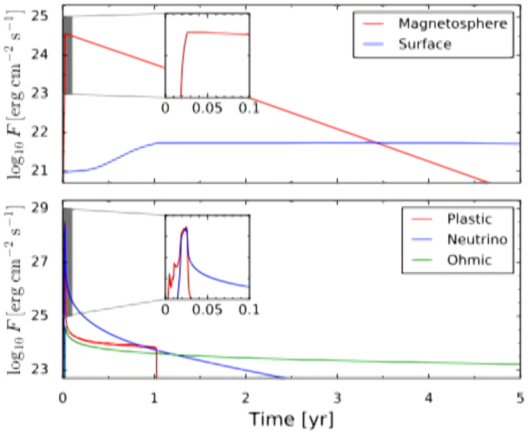




Light Curves



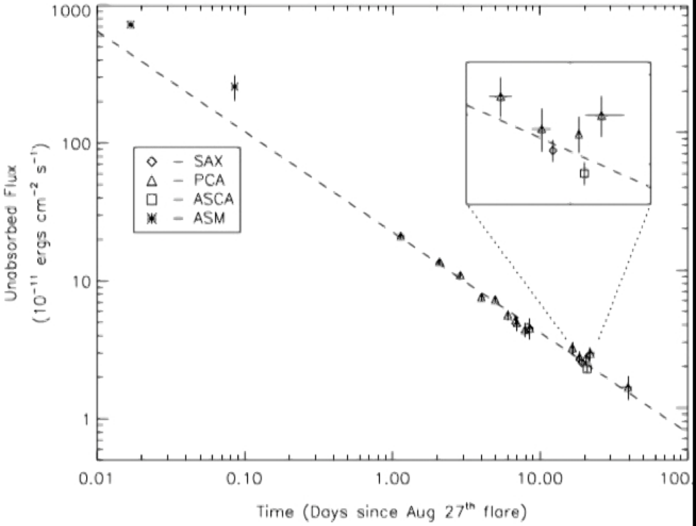


Plastic Damping of Alfven Waves in the Magnetar

- Plastic failures can also be driven by external waves. e.g. Alfven waves are generated in the giant flares (Parfrey 2013).

- The wave energy is dissipated and heat up the crust.

- Such crustal heating can give rise to thermal afterglow after giant flares. e.g. SGR 1900



Woods et al. (2001)

Plastic Damping of Alfven Waves in the Magnetar

- Waves trapped along closed field lines bounce between magnetic footpoints.
- Part of the wave will be transmitted into the magnetar when they hit the stellar surface.
- We run 1D simulation following the dynamics of Alfven waves from the magnetosphere into the crust.

NASA/CXC/M.Weiss

Alfven Wave Dynamics Inside the Magnetar

- Alfven speed inside the magnetar

$$v^2(z) = \frac{B_z^2/4\pi + \mu(z)}{B_z^2/4\pi c^2 + \rho(z)}.$$

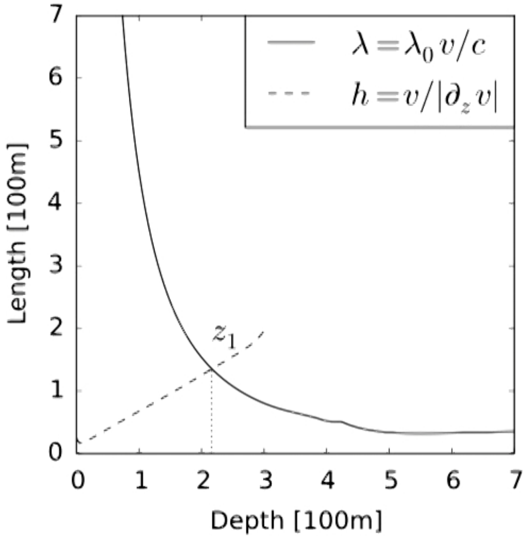
- The transmission coefficient is found to be 10%-20%

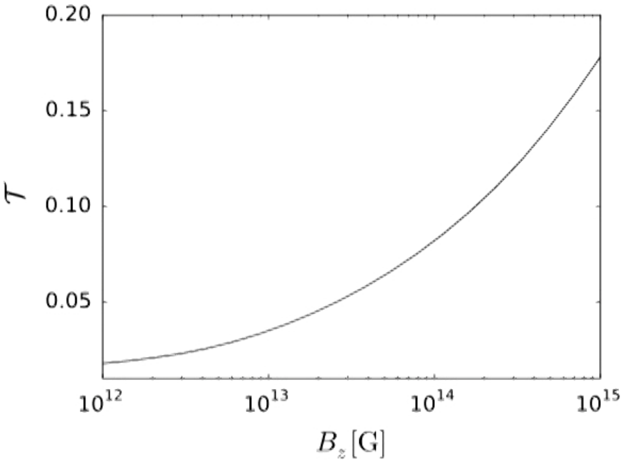
$$\mathcal{T} \sim \frac{4Z(z_1)Z(0)}{[Z(z_1)+Z(0)]^2} \approx \frac{4v(z_1)}{c}.$$

- WKB applies in the inner crust

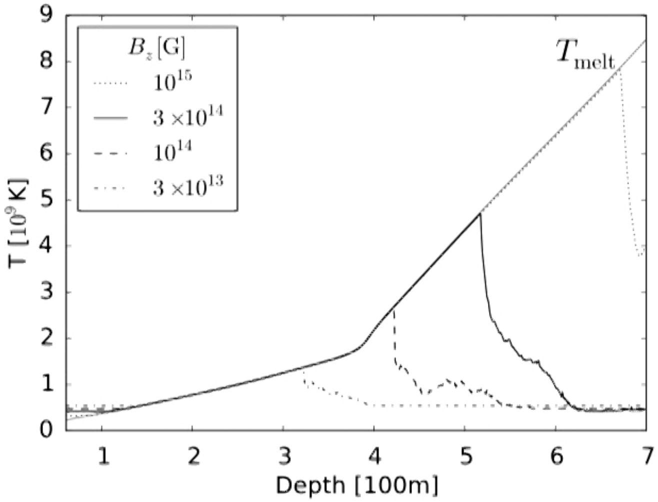
$$s \propto \rho^{1/4}$$

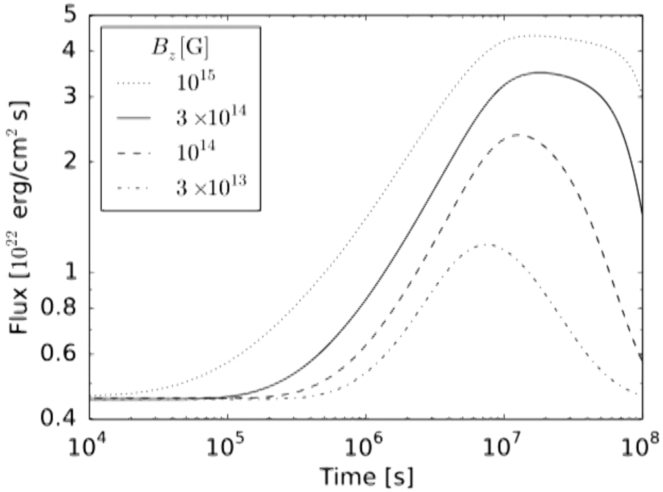
- The strain increases with density!





Temperature Profile and Light Curve

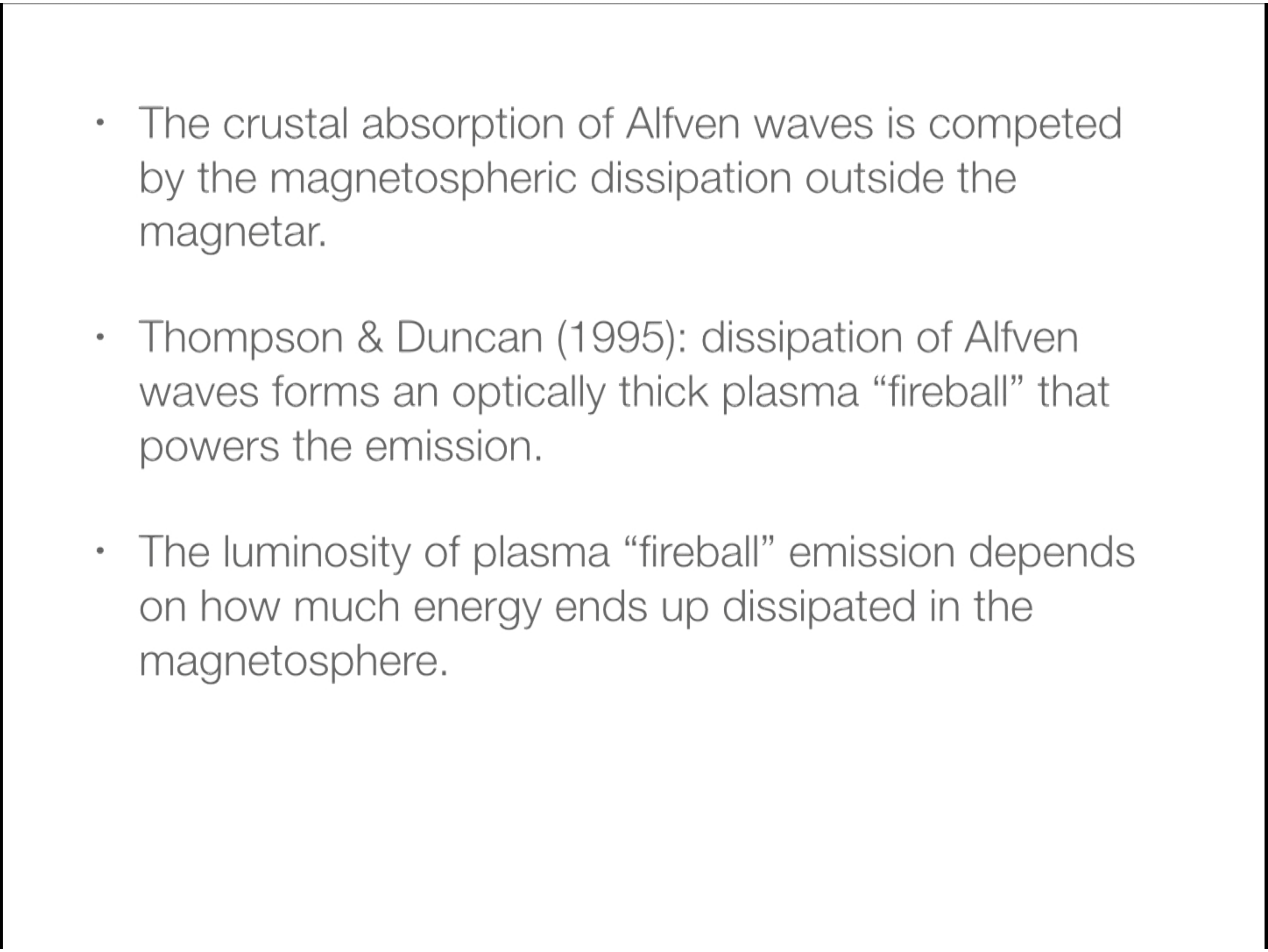




- No plastic flow if the crust is melted

$$T_{\mathrm{melt}} \approx 2.4 \times 10^9 \rho_{12}^{1/3}\ \mathrm{K}.$$

- Most heat is lost to neutrino emissions.
- The peak luminosity will saturate. Increasing heating will not increase the thermal luminosity!

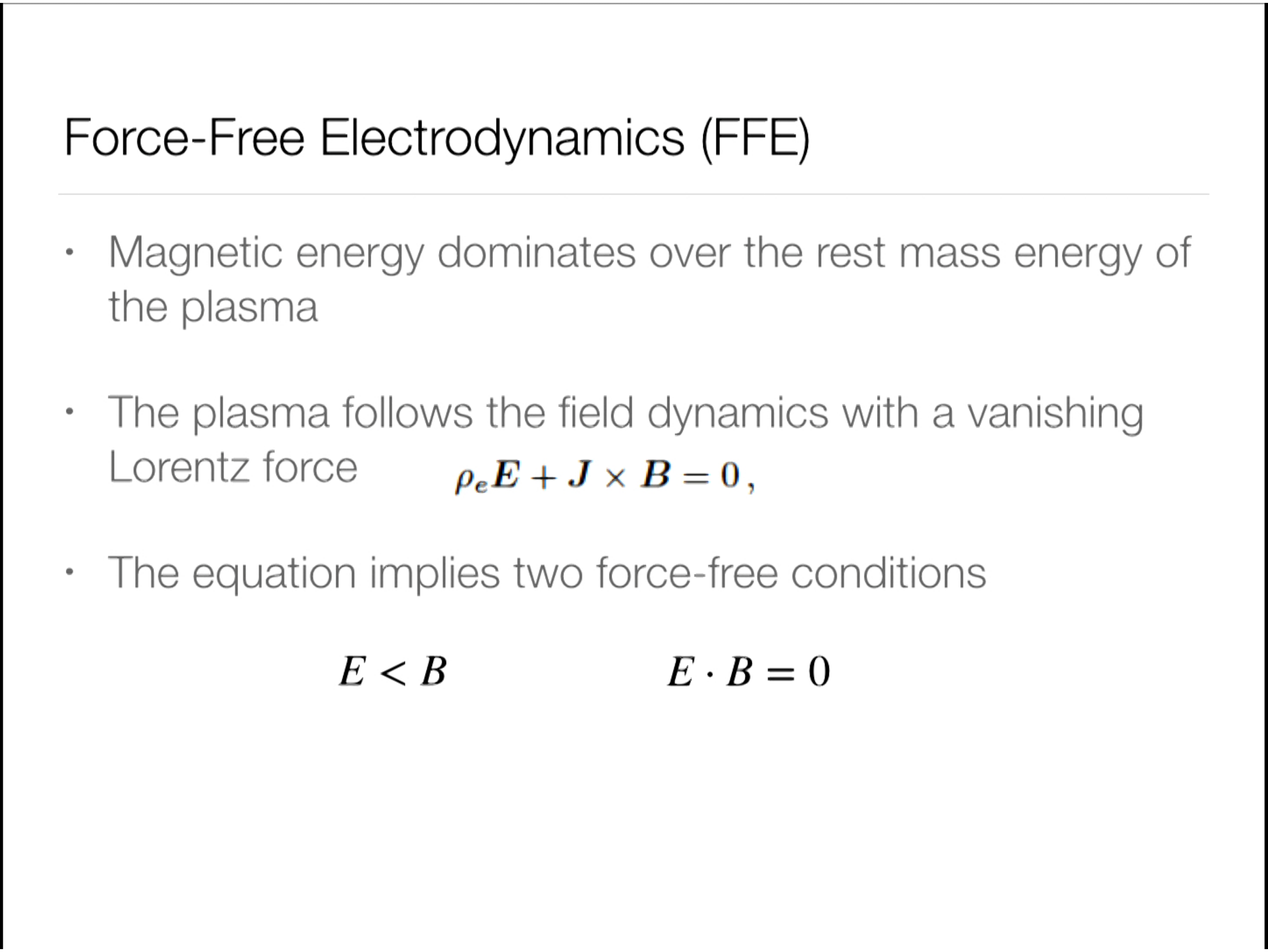


- The crustal absorption of Alfven waves is competed by the magnetospheric dissipation outside the magnetar.
- Thompson & Duncan (1995): dissipation of Alfven waves forms an optically thick plasma “fireball” that powers the emission.
- The luminosity of plasma “fireball” emission depends on how much energy ends up dissipated in the magnetosphere.

Magnetospheric Dissipation

- **How does magnetospheric dissipation take place?**
- Alfven waves can lose energy through

1. Turbulent dissipation from nonlinear interactions
2. Conversion to fast waves that can escape the magnetosphere
3. Magnetic reconnection?
4. QED shocks (Heyl and Hernquist 1998)?



Force-Free Electrodynamics (FFE)

- Magnetic energy dominates over the rest mass energy of the plasma
- The plasma follows the field dynamics with a vanishing Lorentz force $\rho_e \boldsymbol{E} + \boldsymbol{J} \times \boldsymbol{B} = 0\,,$
- The equation implies two force-free conditions

$$E < B \qquad\qquad E \cdot B = 0$$

Waves and Interactions in FFE

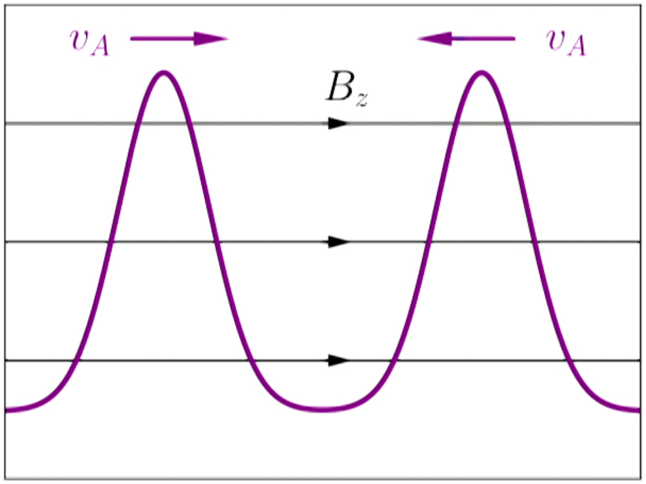
- Alfven waves $\omega = |k_z|$
- Fast waves $\omega = |k|$
- Three-wave interactions are not possible for

$$A + A \rightarrow A \qquad\qquad F + F \rightarrow F$$

- $A + A \rightarrow F$ is a valid channel (Thompson & Blaes 1998)

Simulation Set-up

- We simulate collision of a pair of counter-propagating Alfven wave pulses in a periodic Cartesian box.



Numerical Methods

- Very high order scheme: 5th order WENO + Roe solver
- Hyperbolic divergence cleaning
- $\boldsymbol{E} \cdot \boldsymbol{B}$ is dynamically damped (Parfrey 2017)
- $\boldsymbol{E} \to \sqrt{\frac{B^2}{E^2}}\boldsymbol{E}$. to restore magnetic dominance

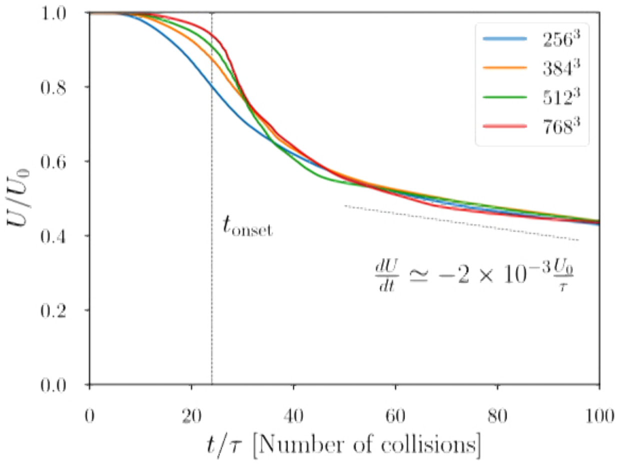
Numerical Dissipation in the Code

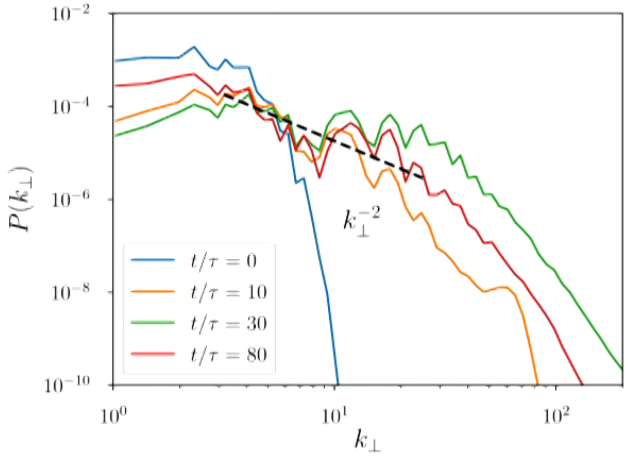
- 1) Hyperbolic divergence cleaning
- 2) Cleaning of $\boldsymbol{E} \cdot \boldsymbol{B}$
- 3) Reduction of electrical field $\boldsymbol{E} \rightarrow \sqrt{\frac{B^2}{E^2}}\boldsymbol{E}$
- 4) Grid-heating
- Channel 1 and 2 should converge away with increasing resolution
- Channel 4 is expected to capture the true dissipation rate for a turbulent cascade with constant flux
- Channel 3 will be discussed later

Development of turbulent spectrum in 3D

- Forward cascade with anisotropic power-law spectrum $k_\perp^{-2}$ is observed

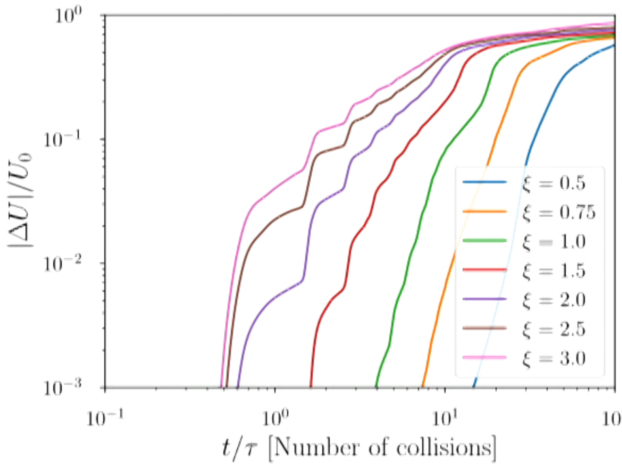
- The dissipation comes from grid heating with a certain onset time independent of grid resolution

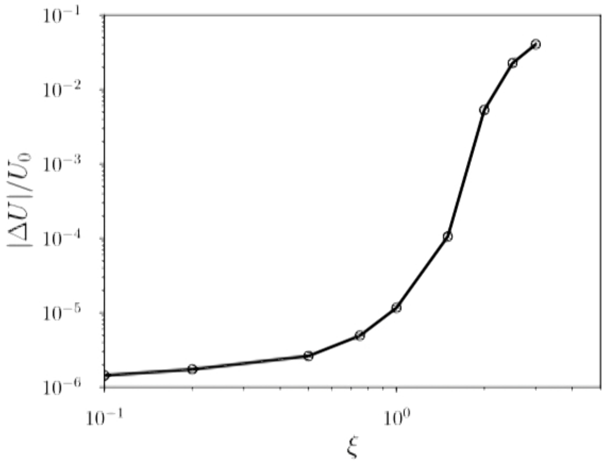




Turbulent dissipation rate

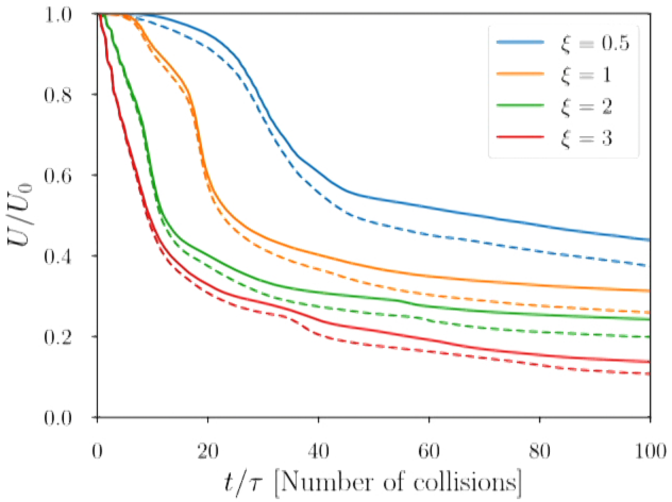
ξ: wave amplitude





Energy Carried Away by Fast Waves

- Add ohmic dissipation layer on the boundary of transverse plane to damp wave energy which mimics the energy lost due to the escape of fast waves
- Alfven waves are confined on the field lines and can not reach the dissipative boundary
- Only fast waves are damped



- Compared with ~10% transmission rate of Alfven waves into the magnetar, the magnetospheric dissipation is weak unless the amplitude is much larger than unity or wavelength much smaller than the closed field lines.

- Most wave energy is lost inside magnetar and power thermal emission.

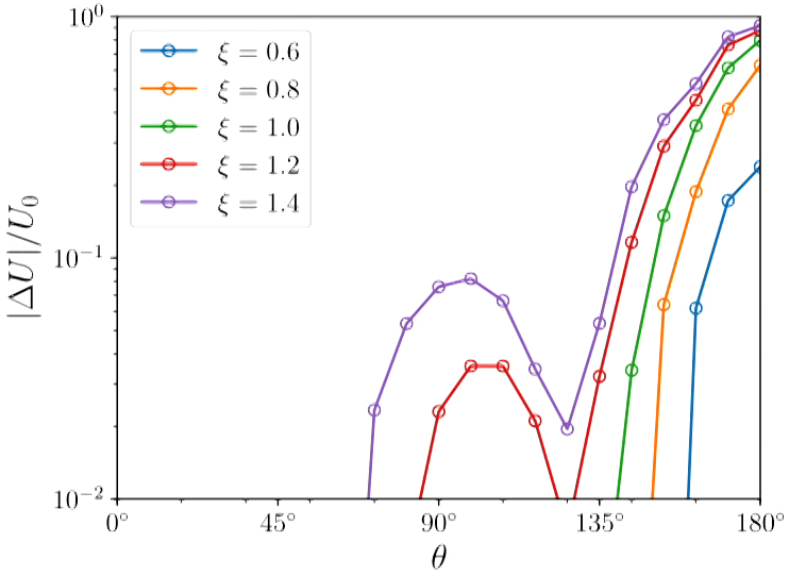
- The residue wave energy dissipated in the magnetosphere powers the fireball emission.

- The wave energy can be much larger than the observed radiation since most heat is lost to neutrinos (Beloborodov & Li 2015).

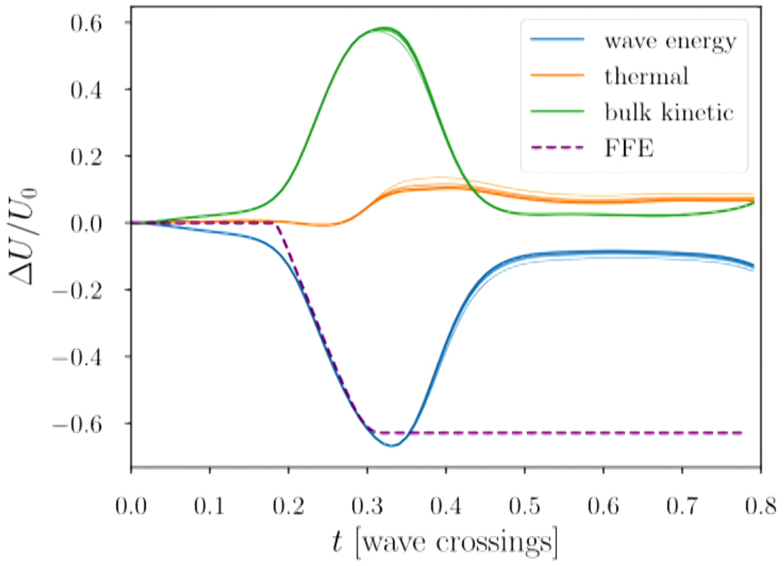
Immediate Dissipation in FFE

- All previous simulations are done for Alfven waves have same polarizations (same direction of B field along a given field line).
- When they are not aligned, nonlinear interaction can induce E>B and break the force-free condition.
- Usually, one reduces E field by hand and assumes this process simulates the realistic fast dissipation there (McKinney 2006, Spitkovsky 2006).

Energy Loss in a Single Collision for 1D Waves



Comparison with Relativistic MHD



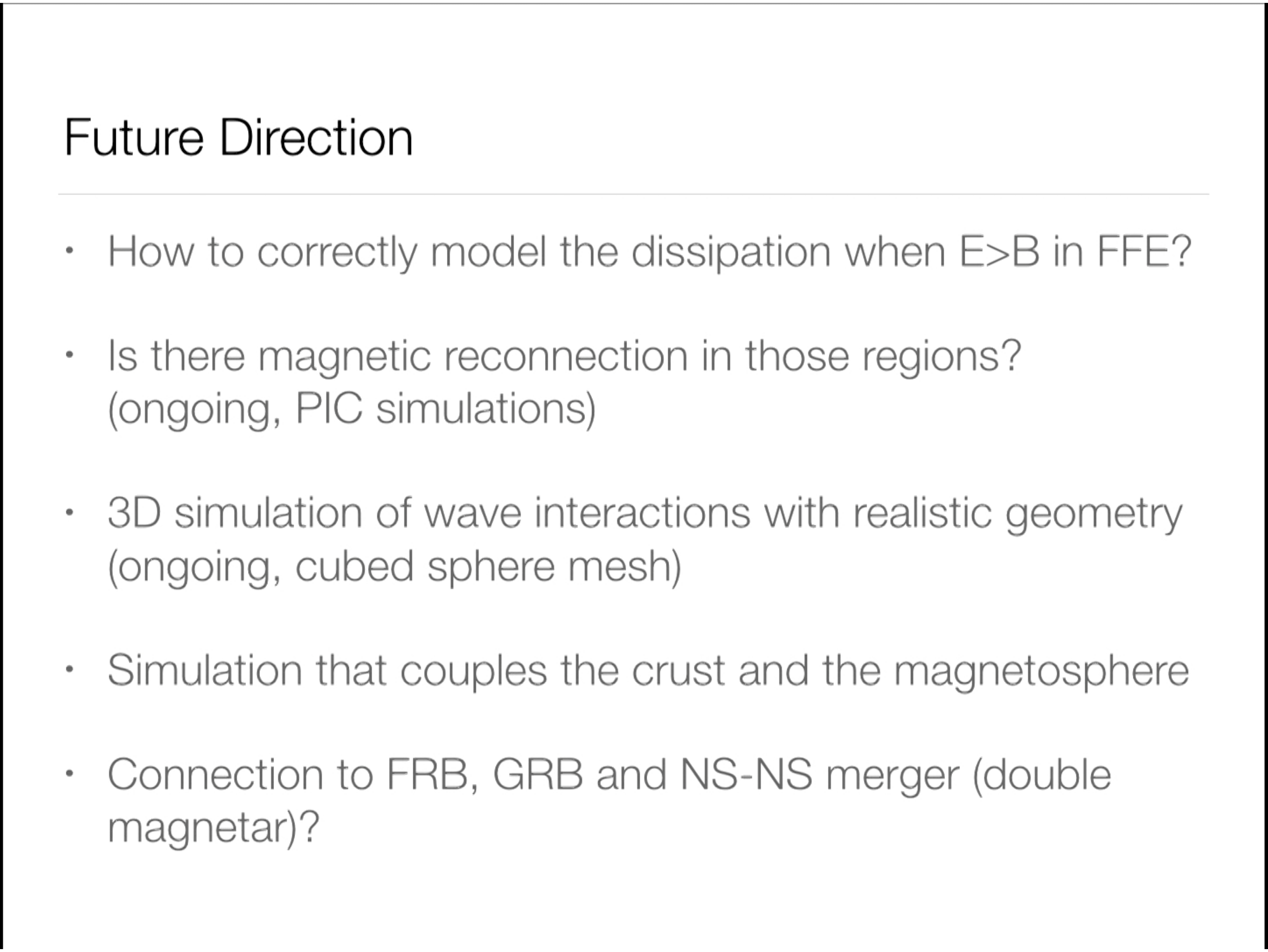
Conclusion

Inside the magnetar:

- Hall-mediated avalanches and TPW are able to reproduce light curves for outbursts of transient magnetars.
- External Alfven waves can also trigger plastic flow and lead to thermal afterglow.

Outside the magnetar:

- Loss of wave energy to turbulent dissipation or fast waves is slow
- Most Alfven wave energy is dissipated inside the magnetar



Future Direction

- How to correctly model the dissipation when E>B in FFE?
- Is there magnetic reconnection in those regions? (ongoing, PIC simulations)
- 3D simulation of wave interactions with realistic geometry (ongoing, cubed sphere mesh)
- Simulation that couples the crust and the magnetosphere
- Connection to FRB, GRB and NS-NS merger (double magnetar)?