Magnetodynamics Inside and Outside Magnetars

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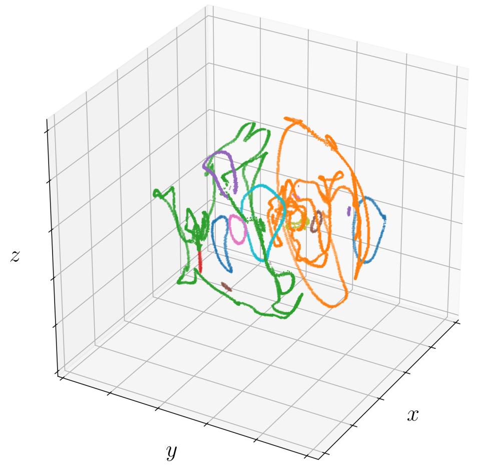
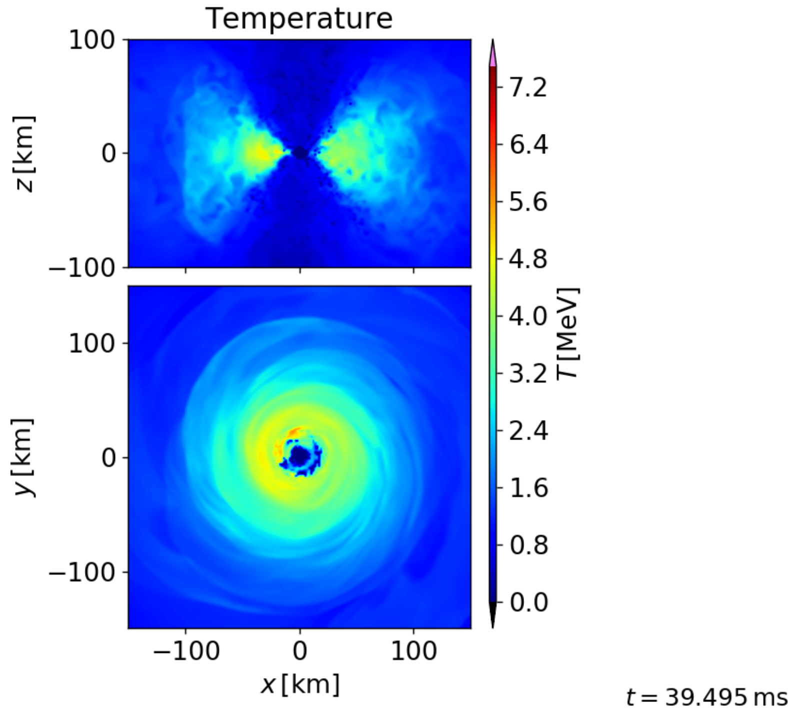
My Research Interests

FDM Vortices, tidal heating of streams



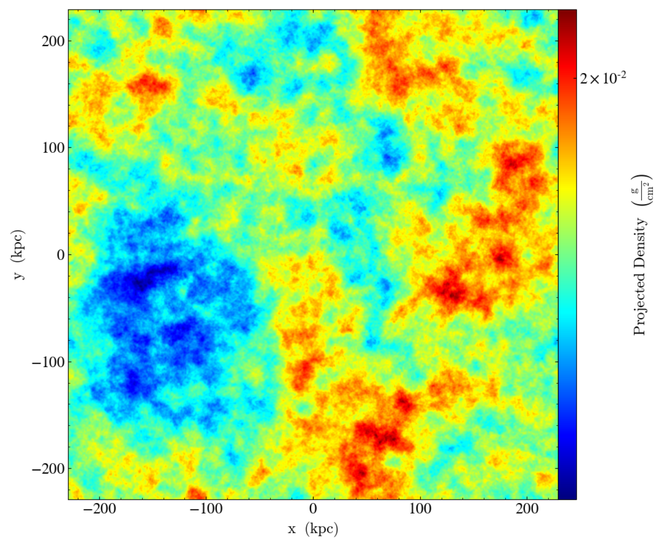
Post-Merger Disk: neutrino transport, fast conversion instability
GRMHD with M1 neutrino transport



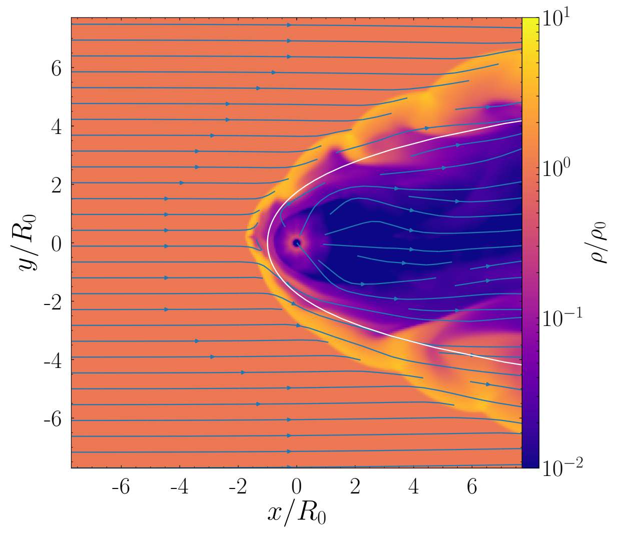
Mpc

kpc

10km



Fuzzy Dark Matter: large scale structure
SPoS: Schridinger-Poisson Solver

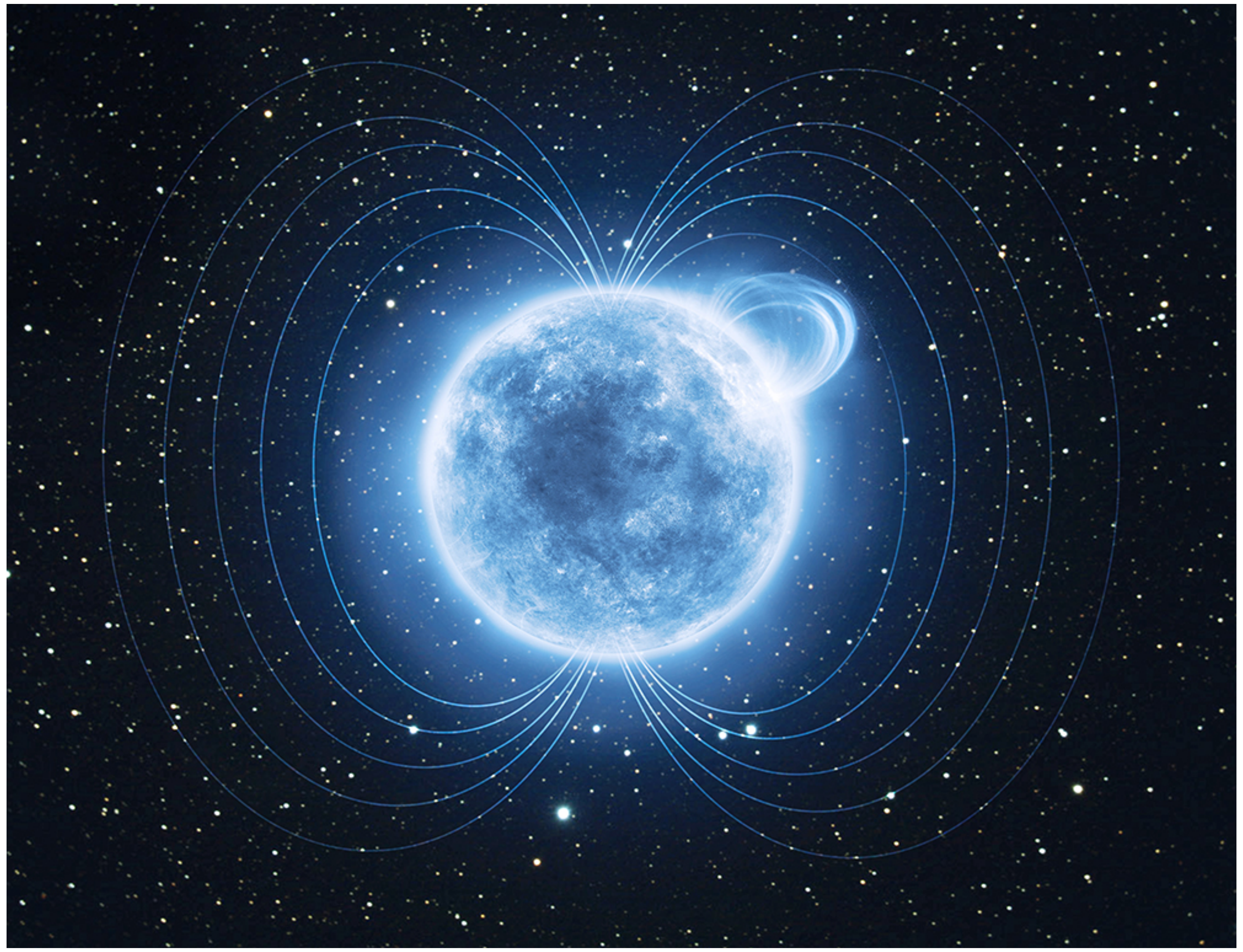


“Negative Dynamical Friction”
Hydro

Magnetar: magnetosphere, interior, waves, X-ray polarization and FRB
FFE & PIC

Magnetar

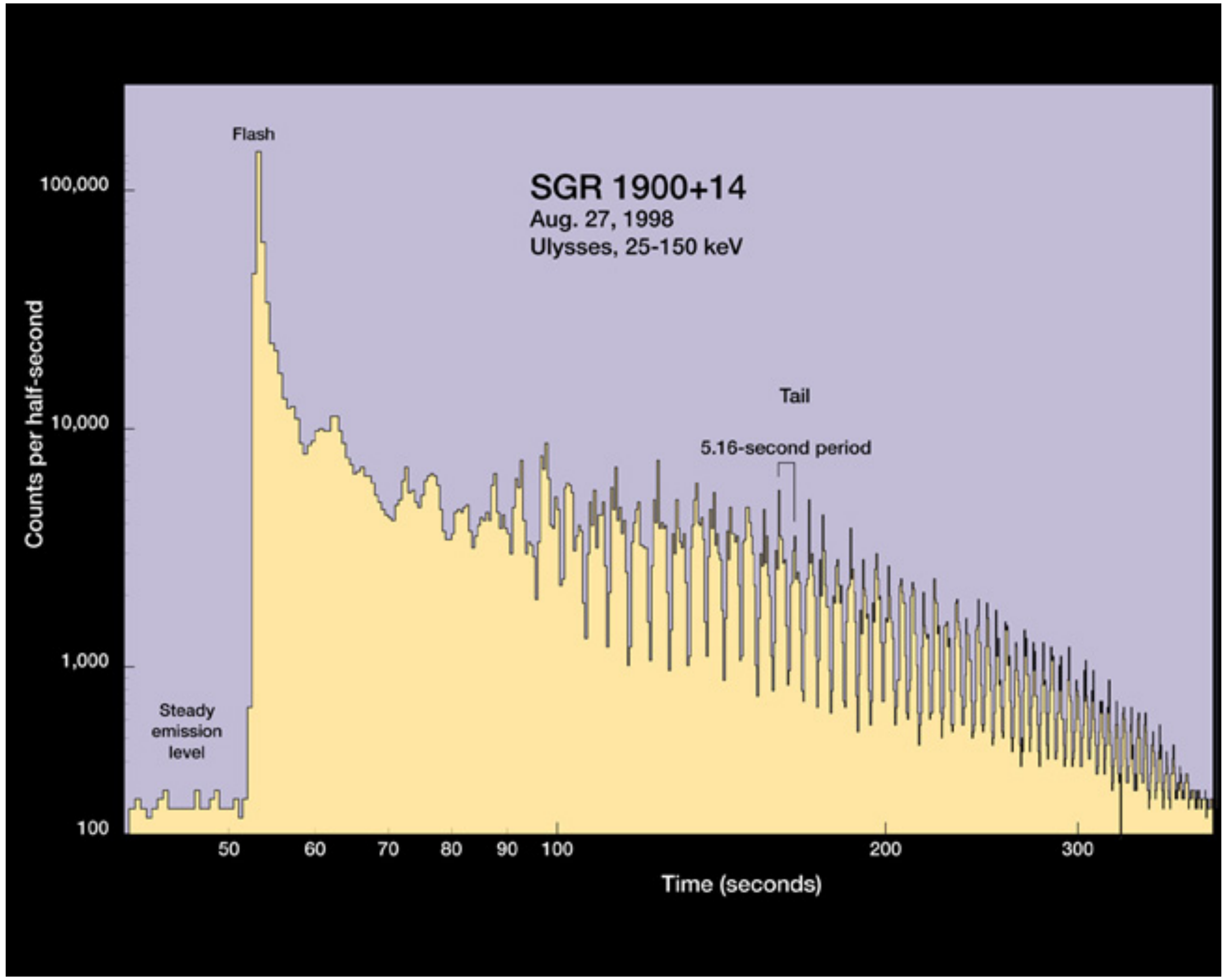
- Neutron star with ultra-strong magnetic fields up to 10^{15}G
- ~30 sources have been identified by now
- Slow rotation period 1-10s
- SGR 1935+2154 and FRB200428, FRB from magnetar?



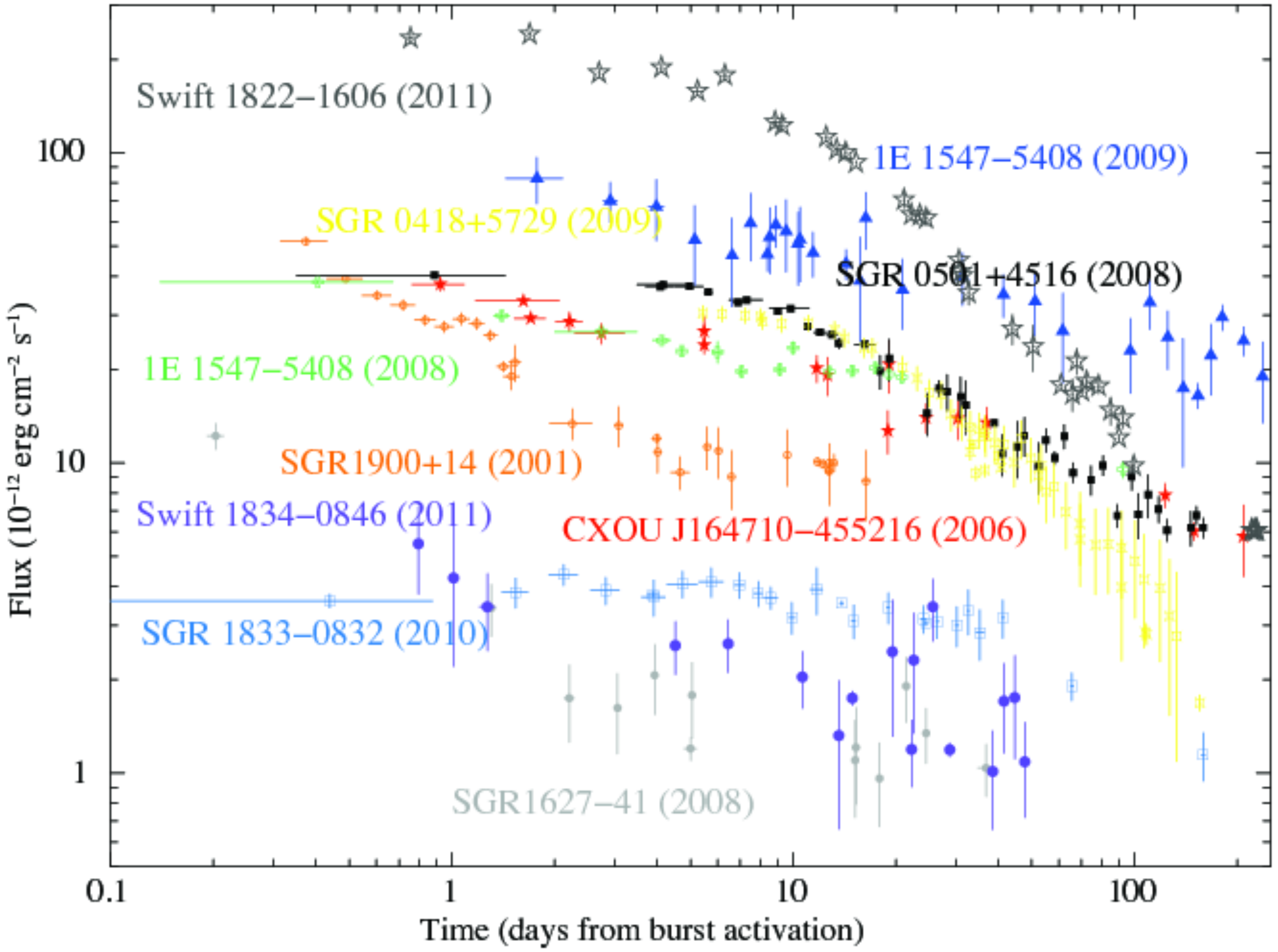
ESA/ATG

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**

Untwisting of Magnetosphere

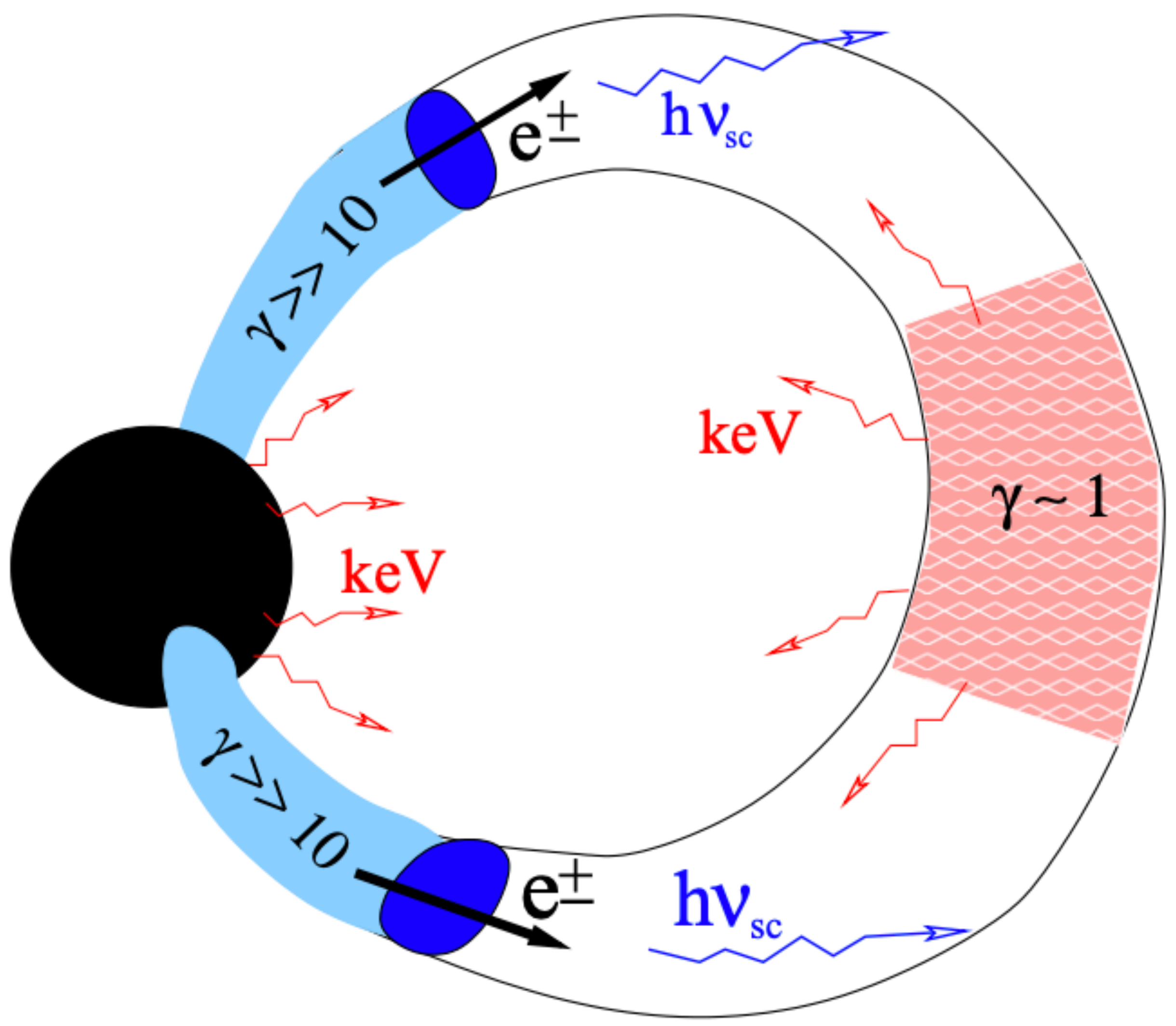
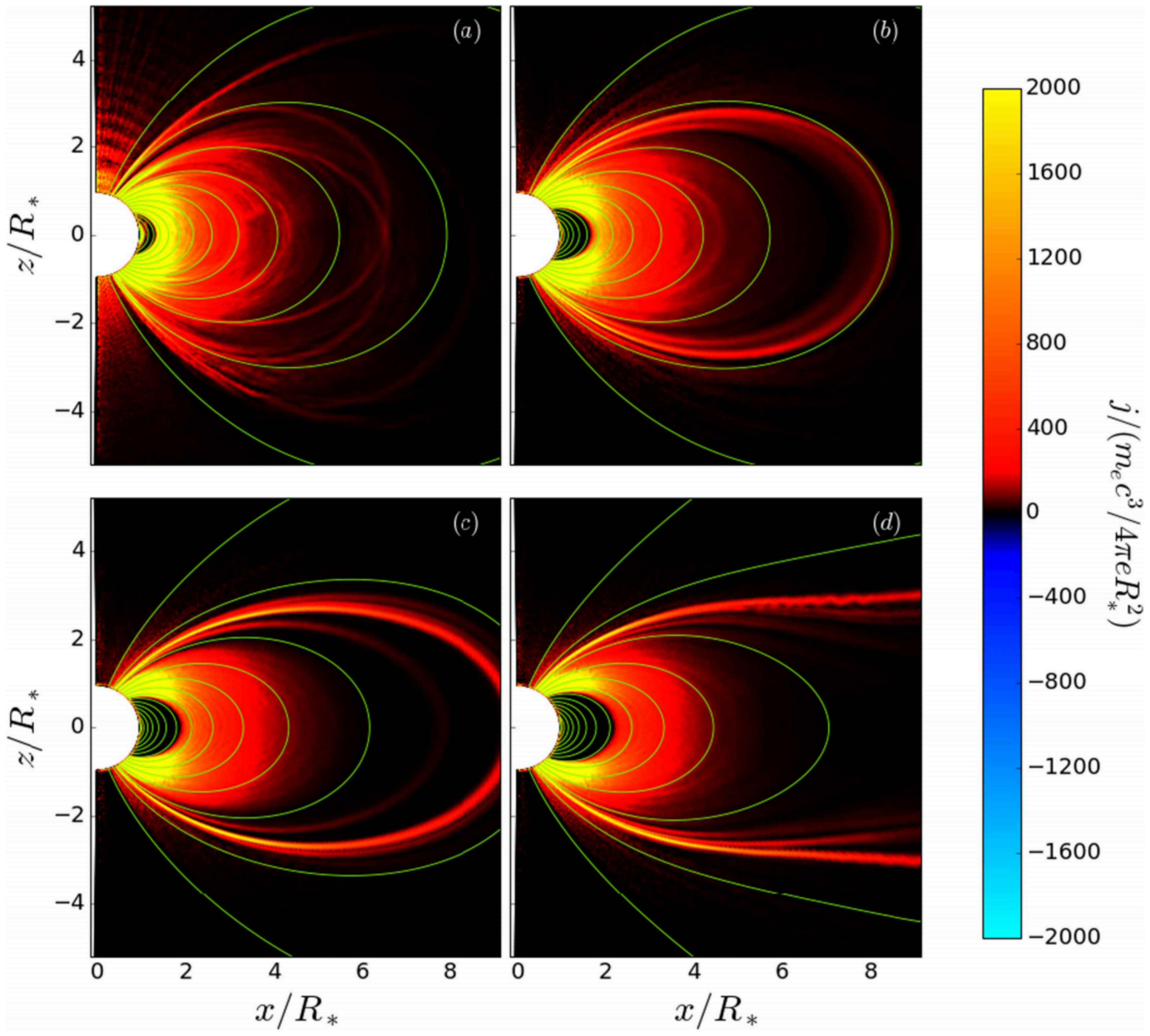


Figure 1. Sketch of an activated magnetic loop. Relativistic particles are injected near the star where $B > B_Q = 4.4 \times 10^{13}$ G. Large $e^{\pm}$ multiplicity $\mathcal{M} \sim 100$ (Equation (11)) develops in the adiabatic zone $B > 10^{13}$ G (shaded in blue). The outer part of the loop is in the radiative zone; here the scattered photons of energy $E = h\nu_{sc}$ escape and form the hard X-ray spectrum that is calculated in Section 3. The outflow decelerates (and annihilates) at the top of the loop, shaded in pink; here it becomes very opaque to the thermal keV photons flowing from the star. Photons reflected from the pink region have the best chance of being upscattered by the relativistic outflow in the lower parts of the loop, and control its deceleration (Section 2.2).



(Chen & Beloborodov 2017)

Outline

- Magnetodynamics inside the magnetar:

  1) Plastic deformation of the magnetar crust by magnetic stress

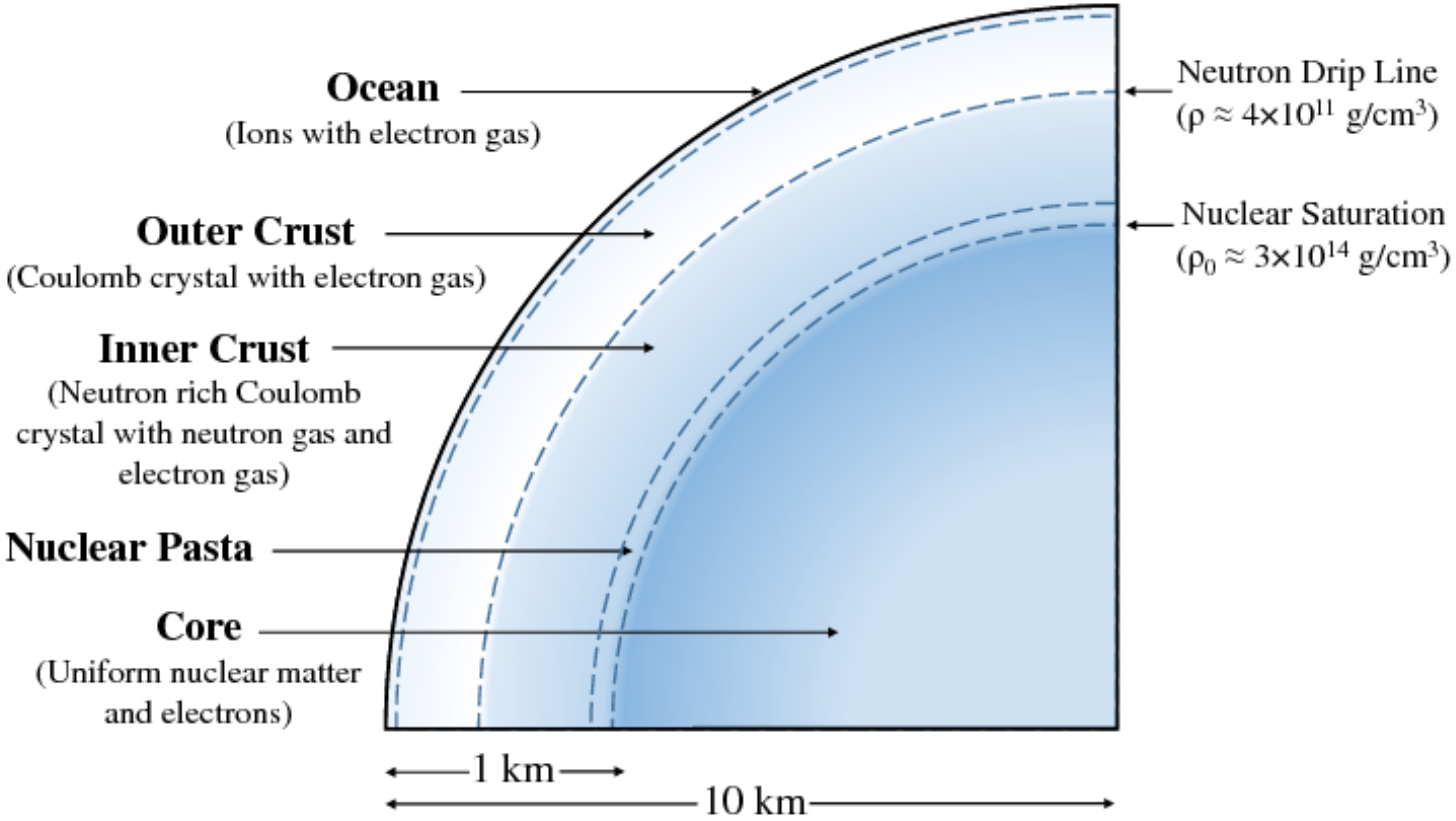
  2) Modeling magnetar outbursts with Hall waves induced plastic failures (1606.04895)

- Magnetodynamics outside the magnetar:

  1) Turbulent dissipation of Alfven waves (1810.10493)

  2) Collision of Alfven waves (in prep.)

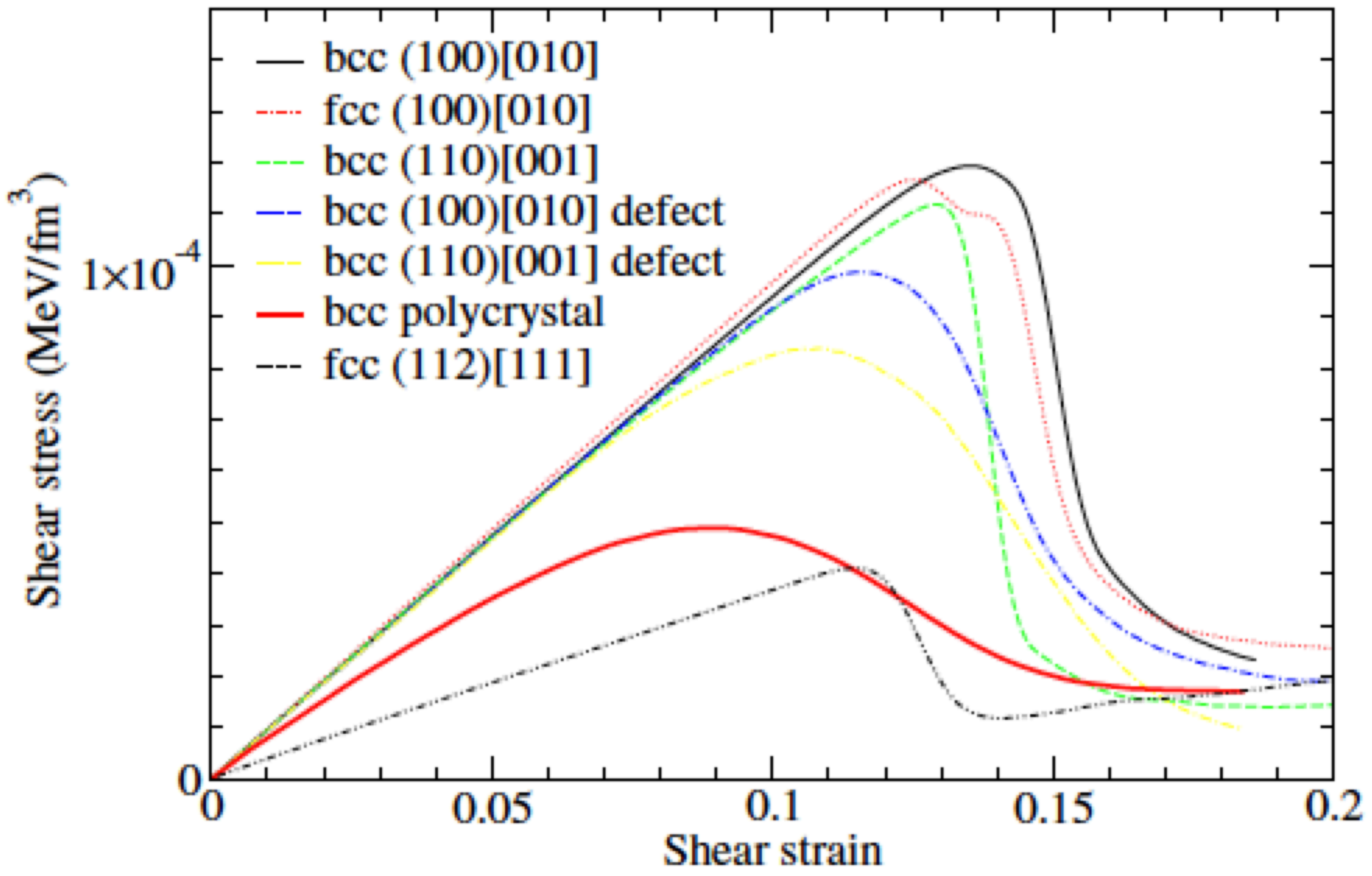
Neutron Star Crust



Caplan and Horowitz 2017

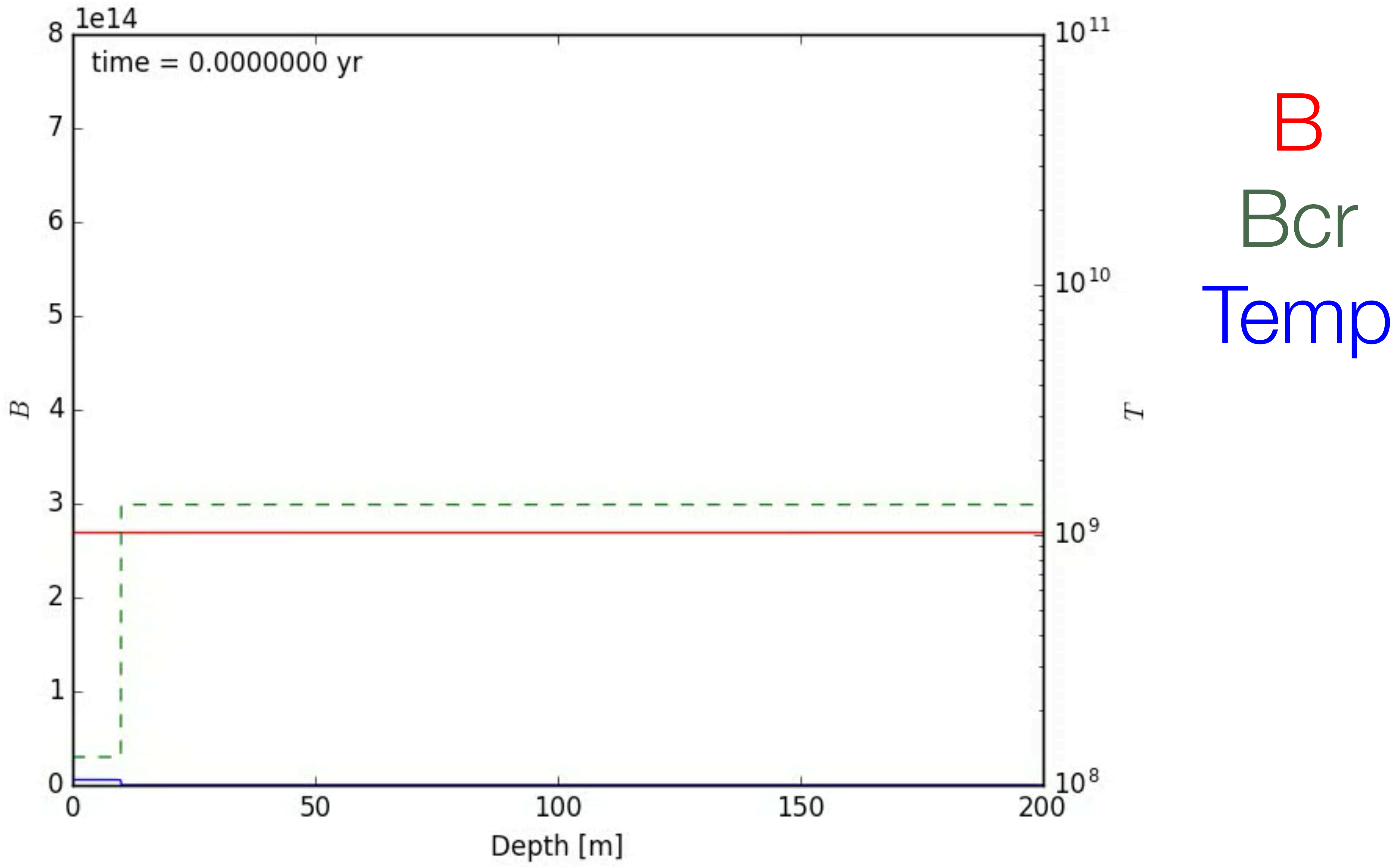
Plastic Deformation of the Crust

- The strong magnetic stress triggers plastic deformation when the magnetic stress exceeds the critical value and magnetic energy is dissipated to heat in the plastic flow
- 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)

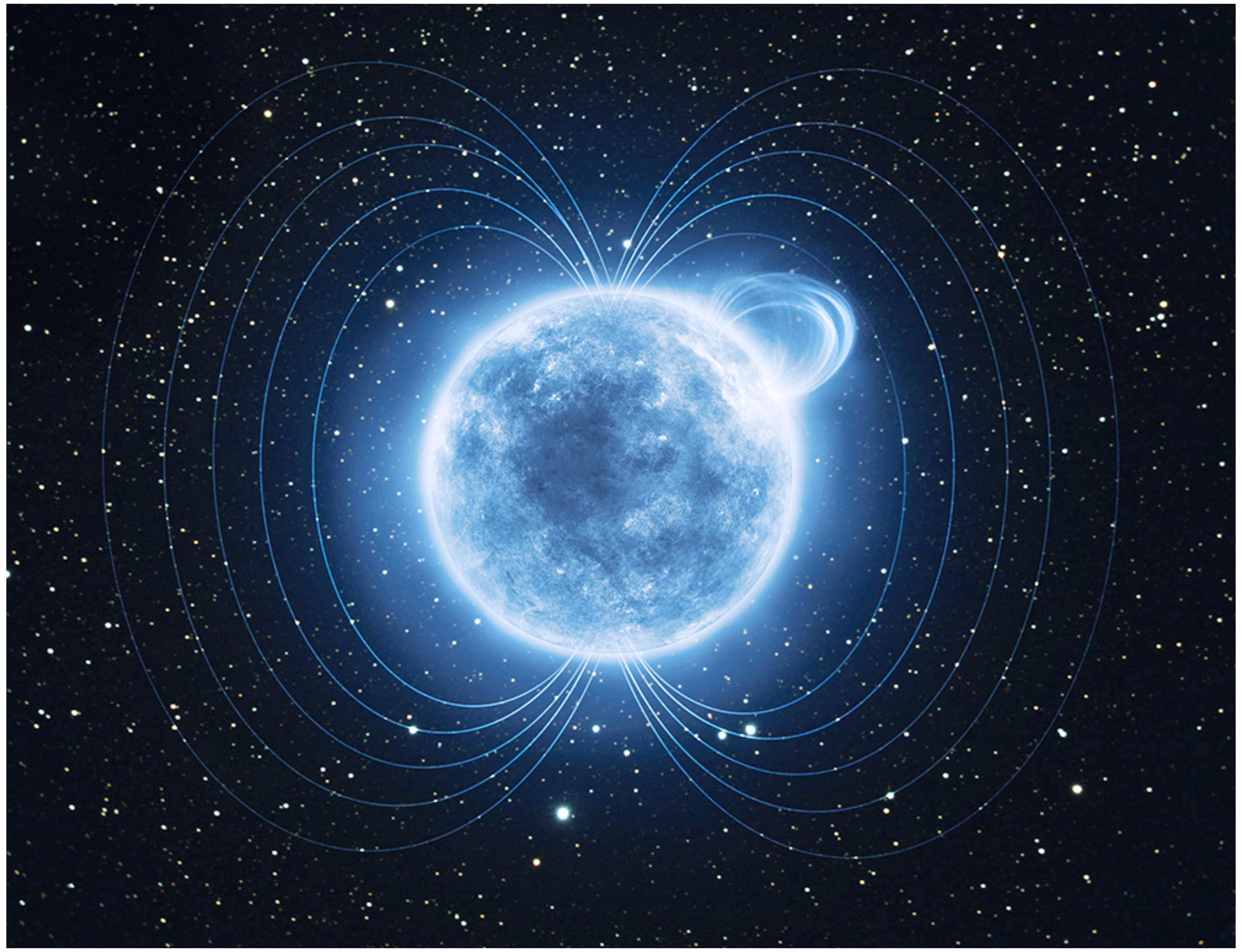


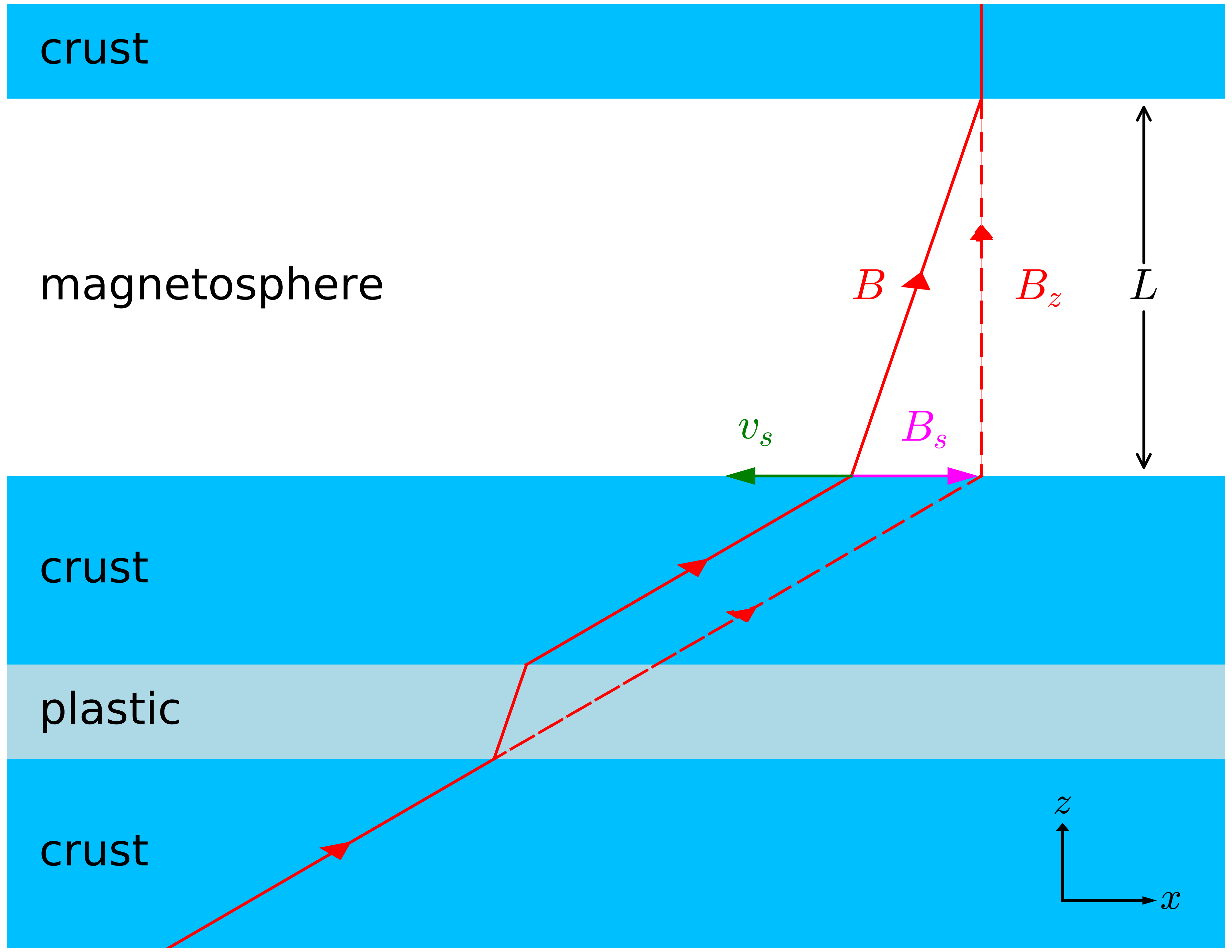
Thermoplastic Waves (TPW)

- 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



Twisting the Magnetosphere

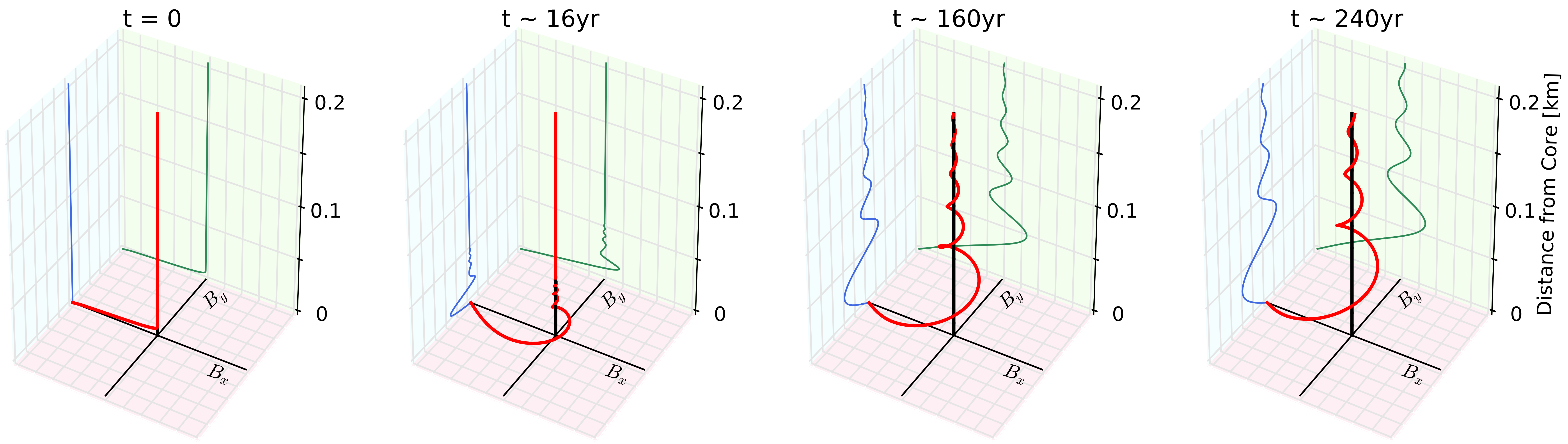


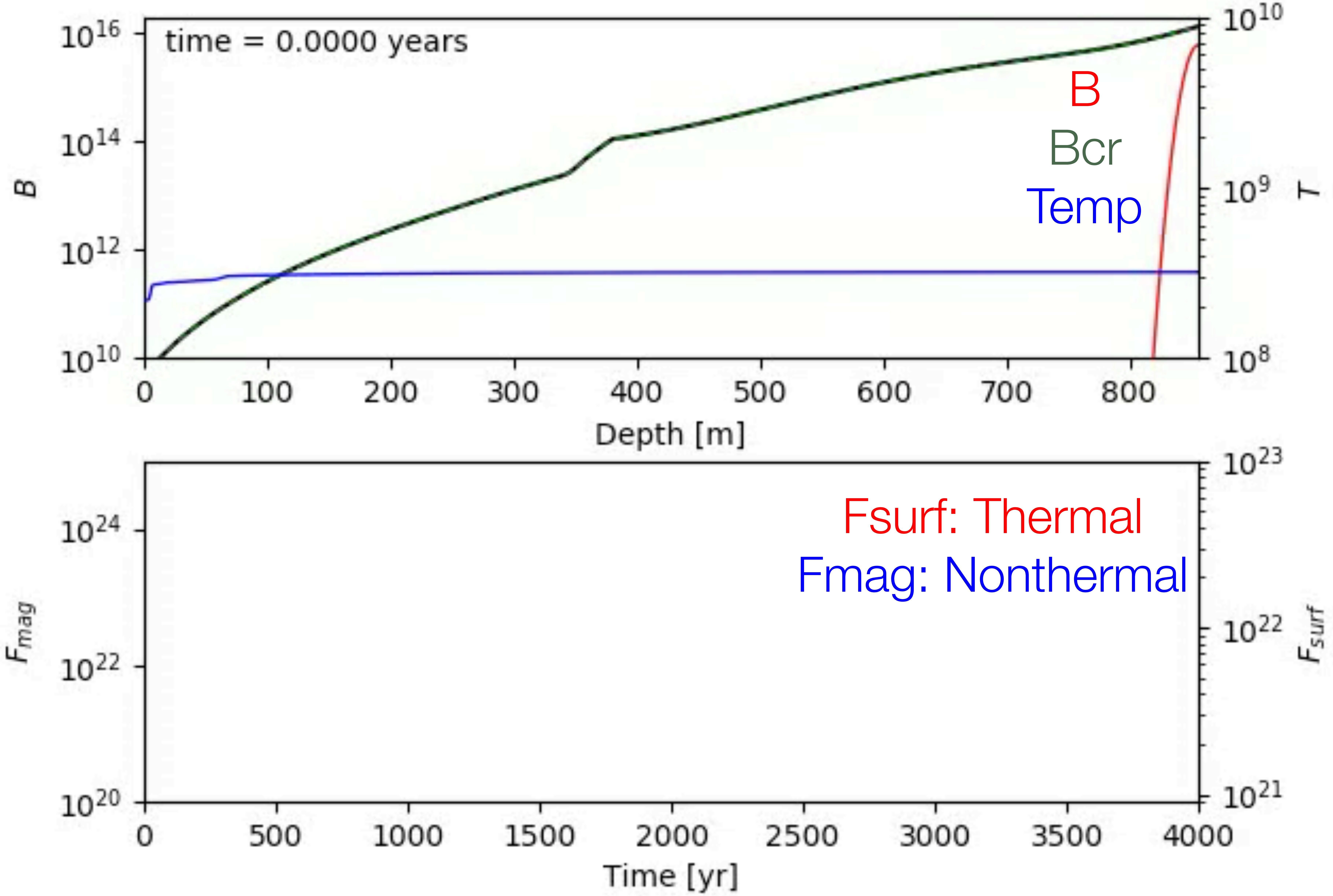


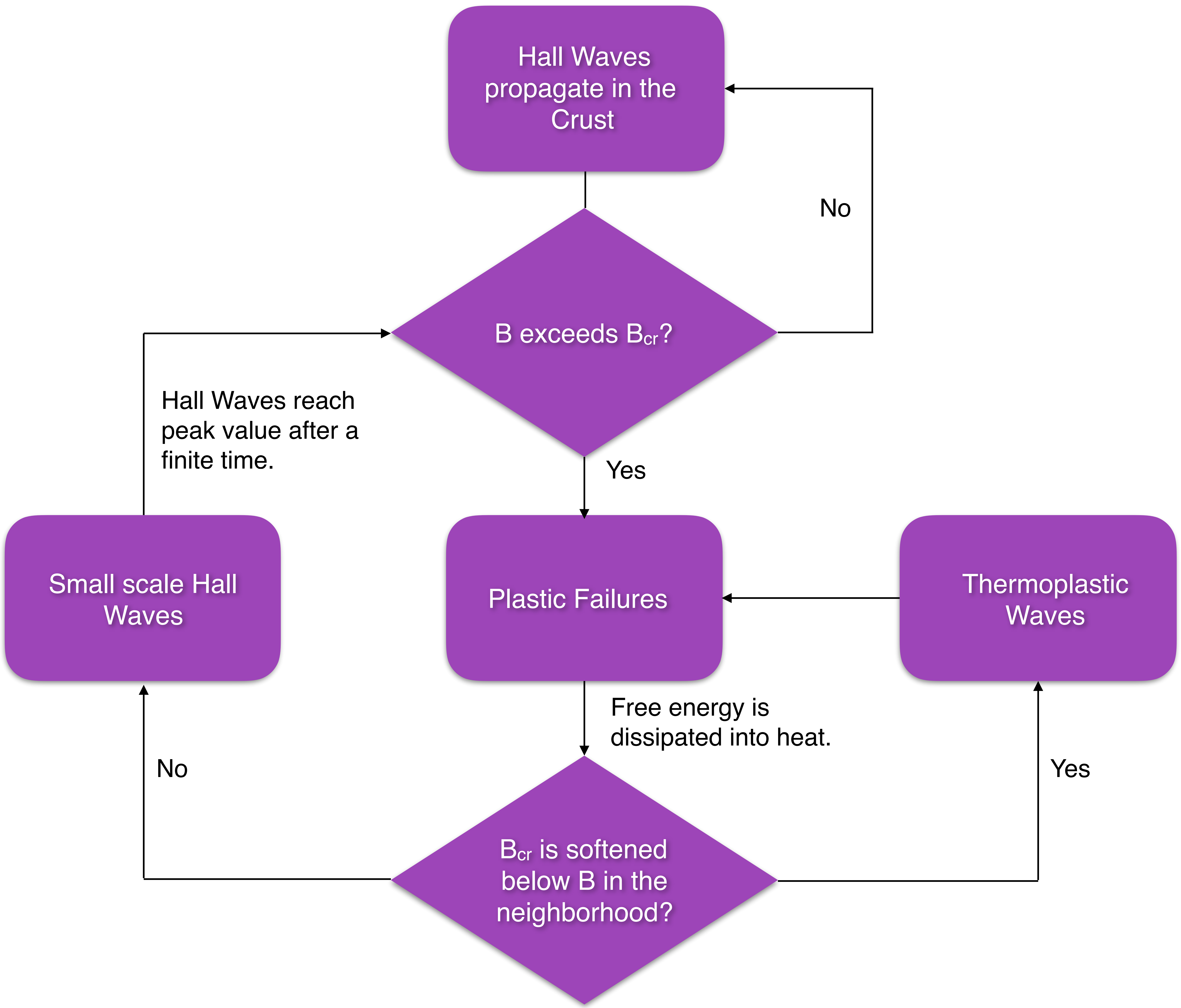
The magnetic field lines are dragged by the plastic flow and induces footpoint motion which gives rise to the toroidal field

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.

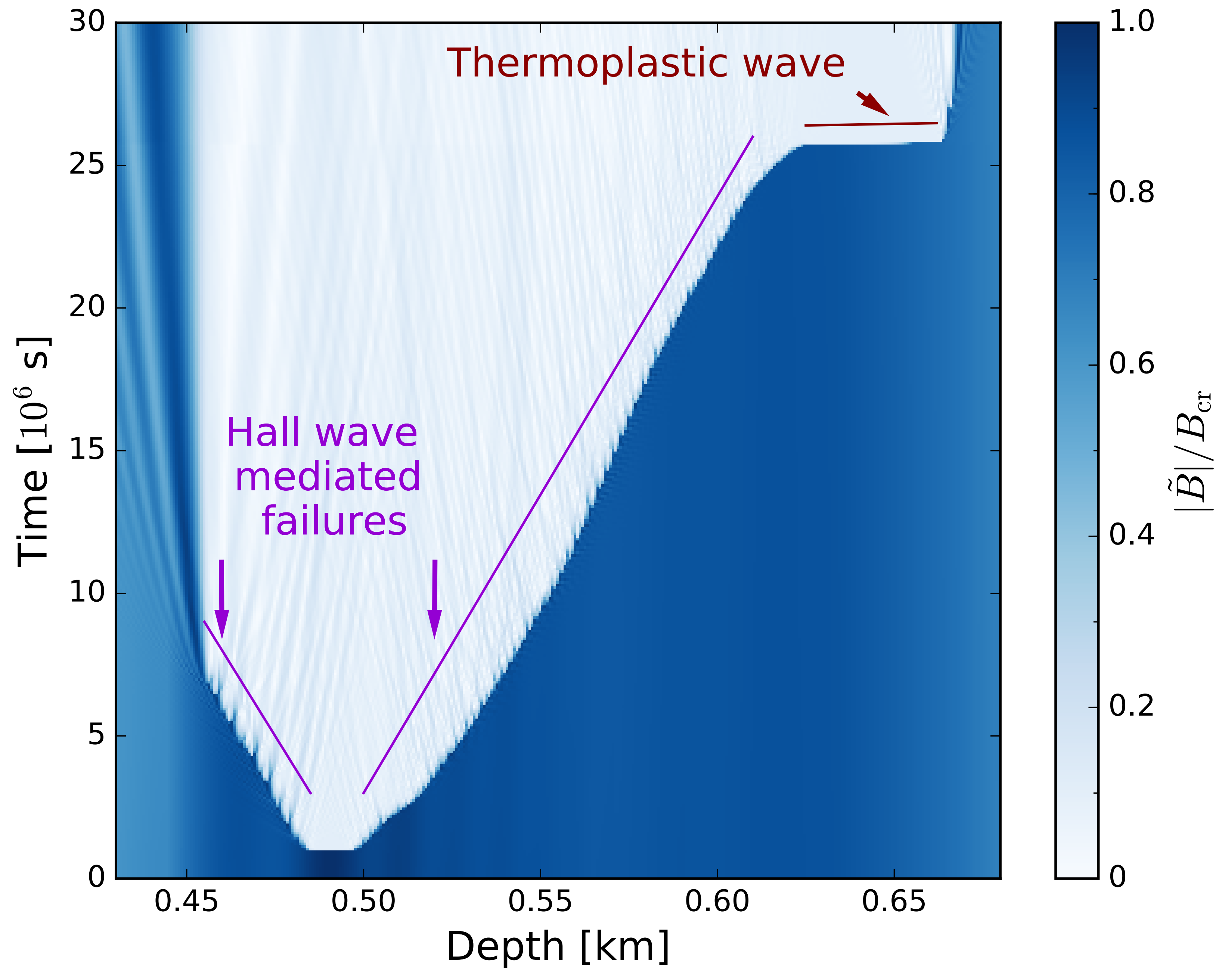


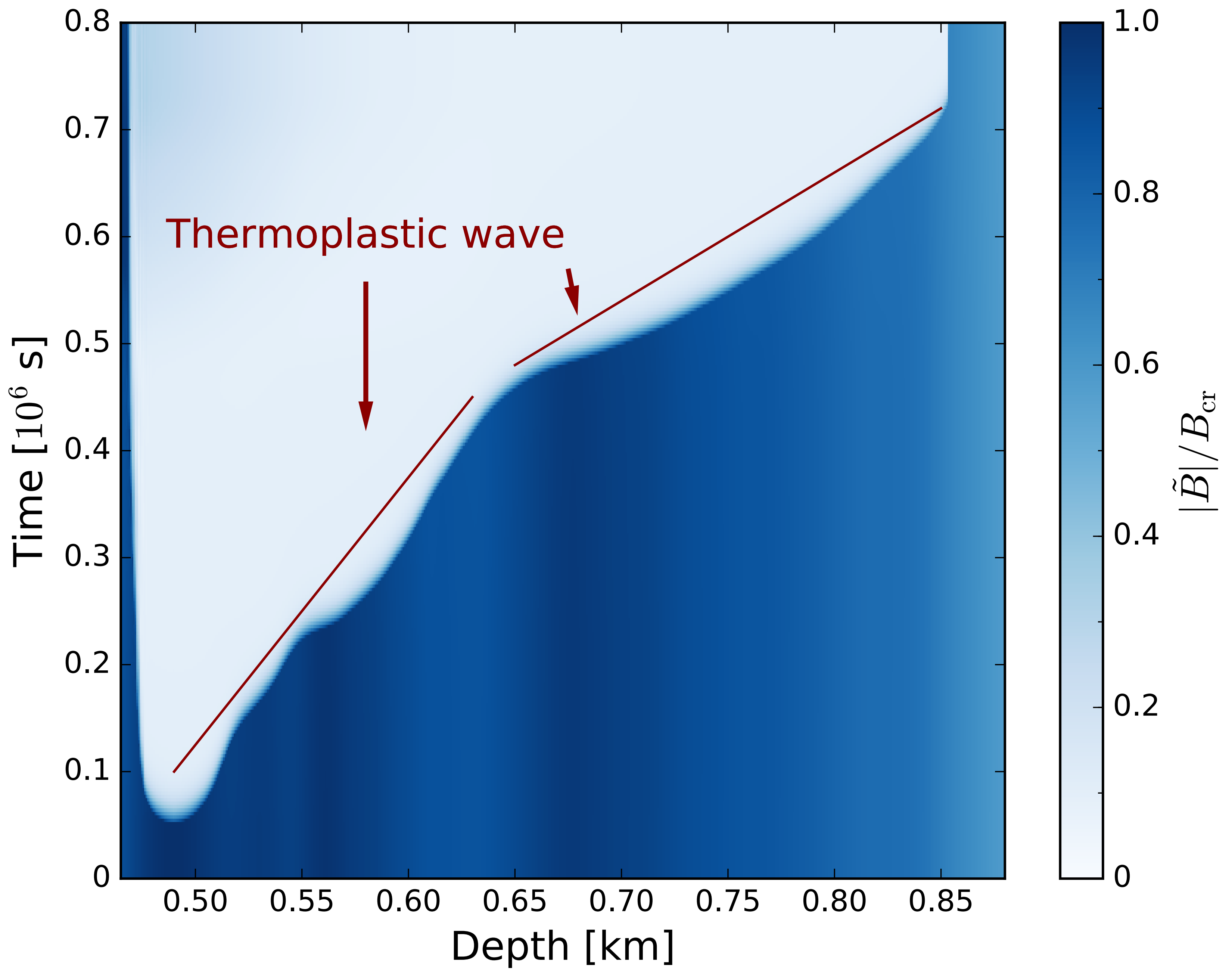

time = 0.0000 years
B
Bcr
Temp
B
T
Depth [m]
Fsurf: Thermal
Fmag: Nonthermal
F_{mag}
F_{surf}
Time [yr]


Hall Waves propagate in the Crust
No
B exceeds B_{cr}?
Hall Waves reach peak value after a finite time.
Yes
Small scale Hall Waves
Plastic Failures
Thermoplastic Waves
Free energy is dissipated into heat.
No
Yes
B_{cr} is softened below B in the neighborhood?

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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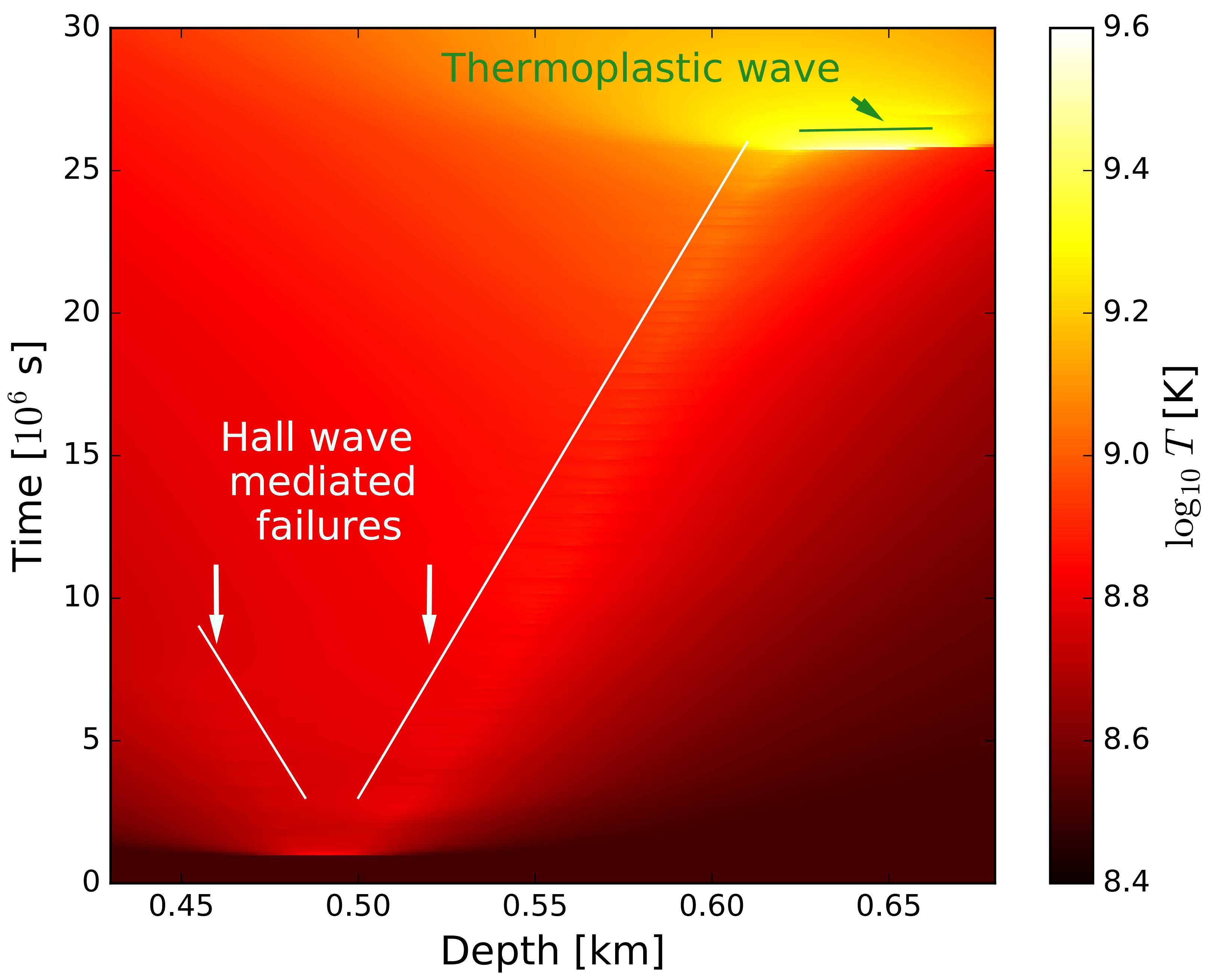
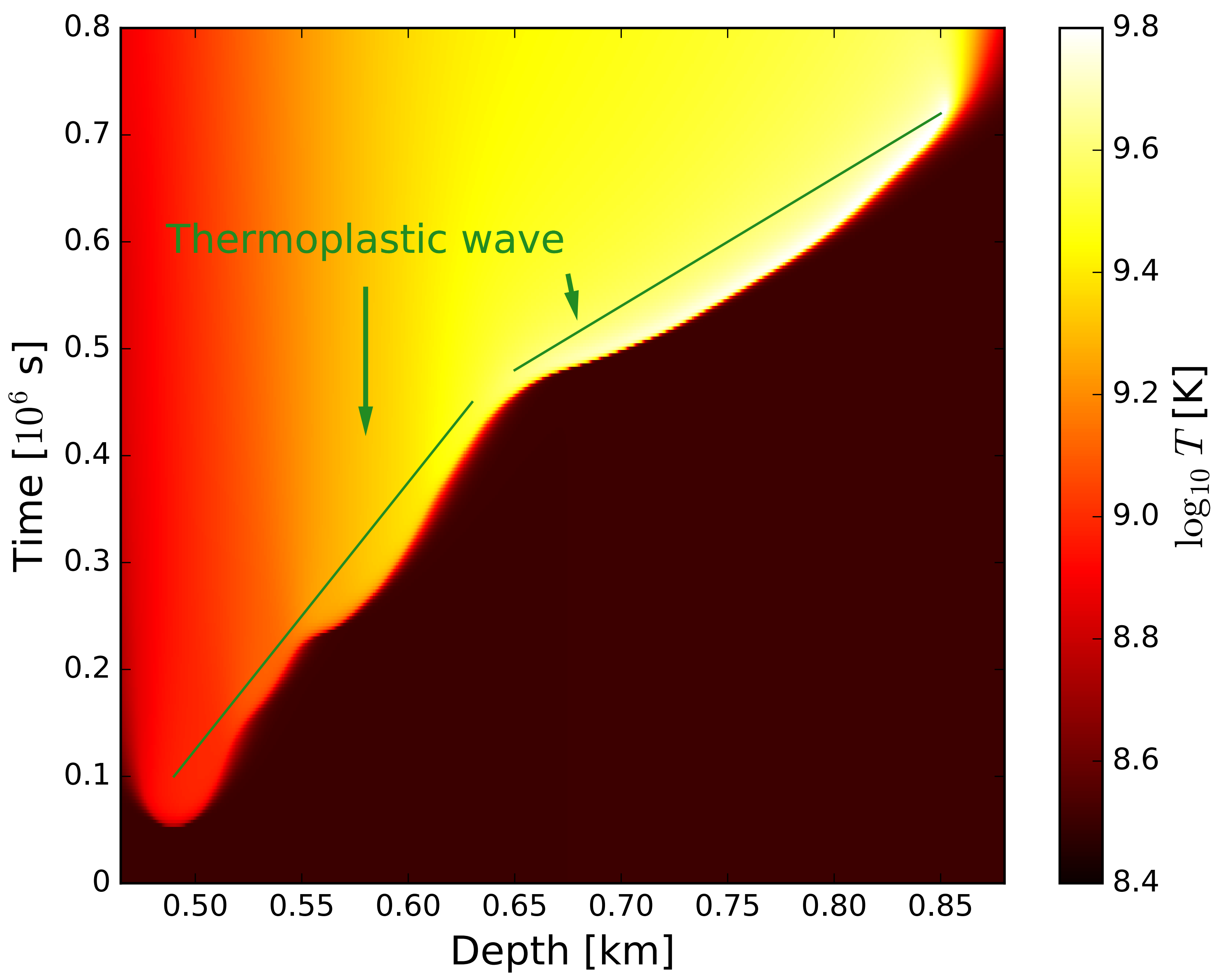
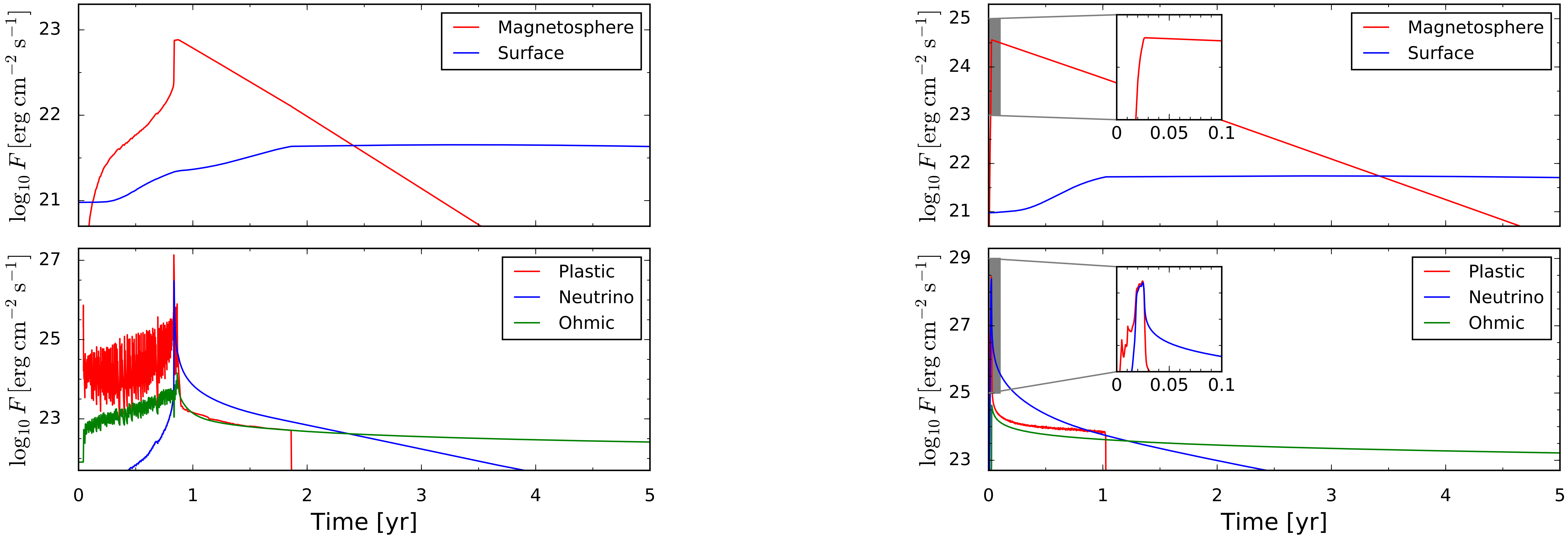




Light Curves

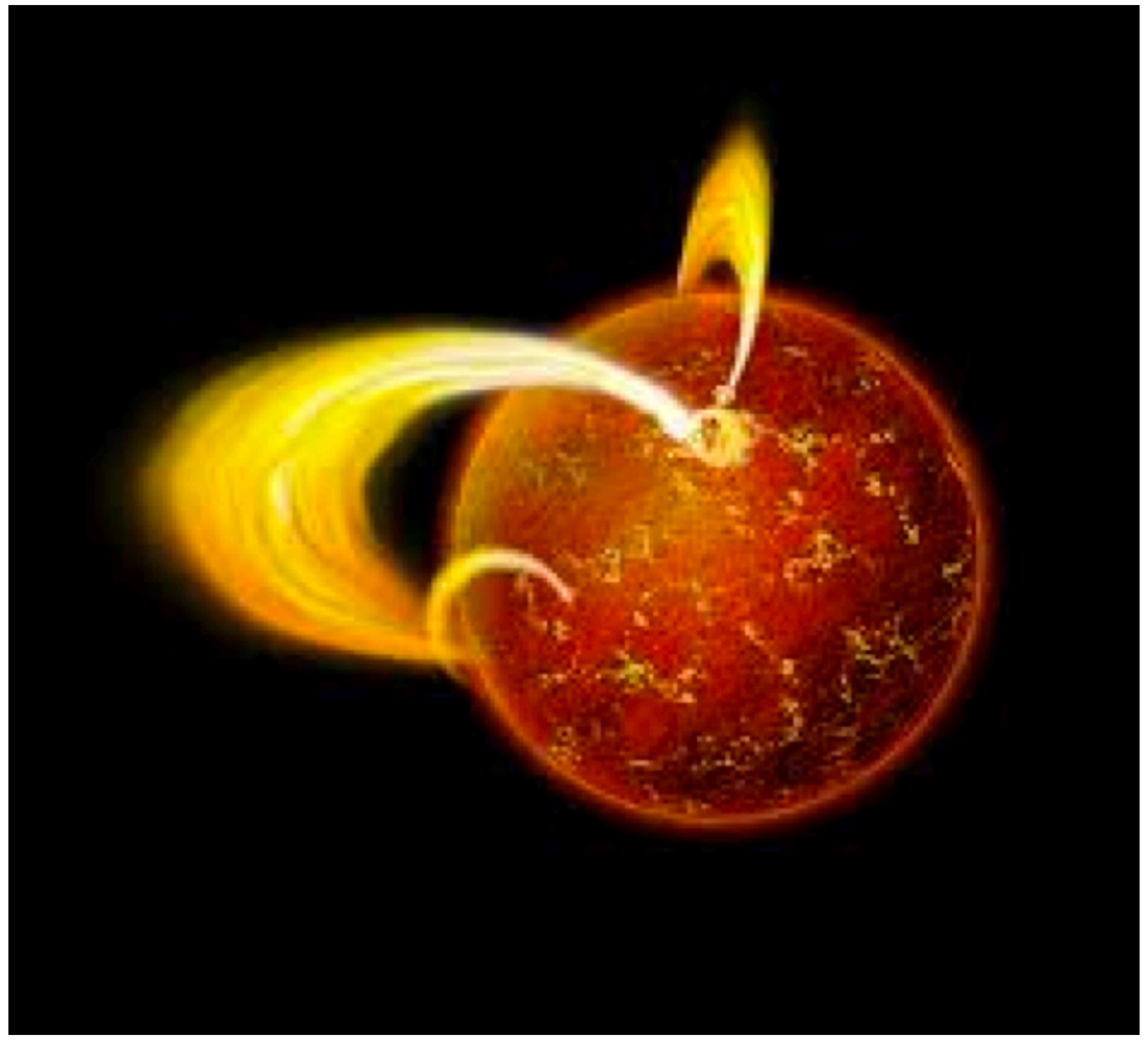


- The distorted magnetosphere produce Alfven waves.

- Thompson & Duncan (1995, 2001): dissipation of Alfven waves forms an optically thick plasma “fireball” that powers the emission.

- Lyubarsky (2020): fast magnetosonic waves as the FRB radio emission from magnetic reconnection or nonlinear interaction of Alfven waves.

- Kumar (2020): charge-starved Alfven waves to produce FRB.



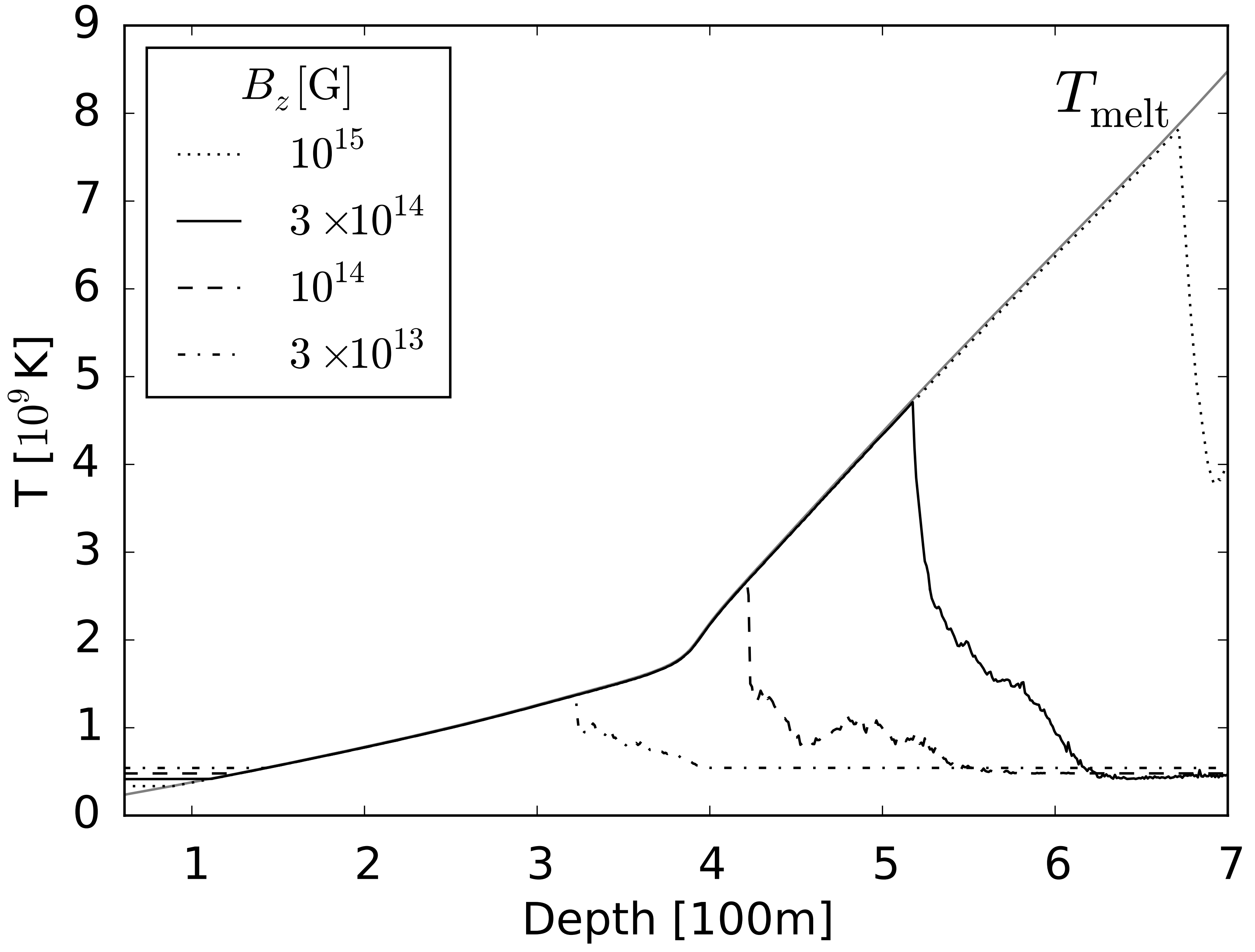
Wave Dissipation

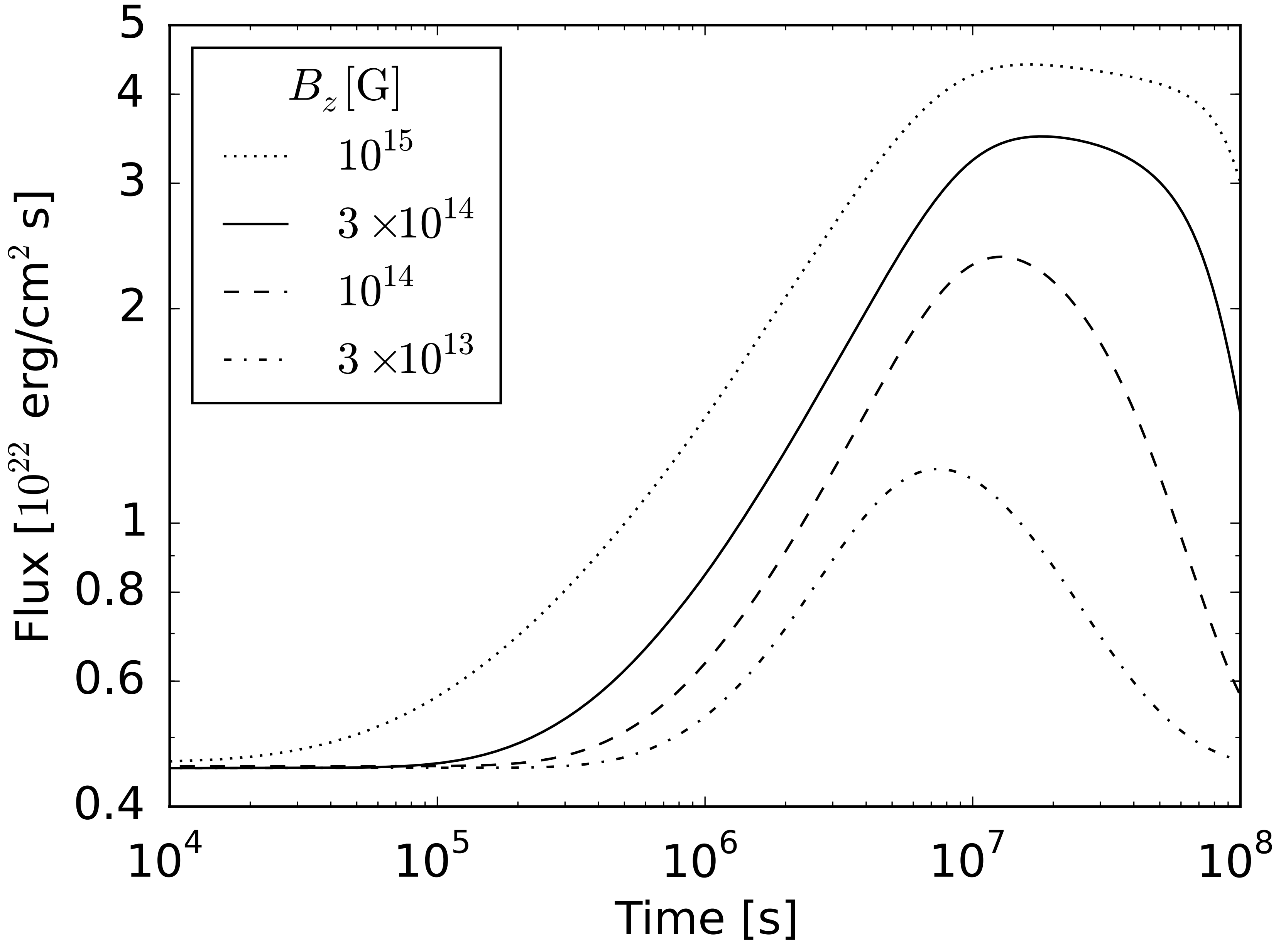
- **How does wave dissipation take place?**
- Alfven waves can lose energy through

1. Turbulent dissipation from nonlinear interactions
2. Conversion to fast waves that can escape the magnetosphere
3. Absorption by the magnetar (1505.03465)
4. Magnetic reconnection?
5. QED shocks (Heyl and Hernquist 1998)?

Crustal Absorption

- 10-20% transmission of Alfven waves into the crust.
- Trigger plastic deformation and dissipate energy to heat.
- Produce a thermal afterglow after ~1year.





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

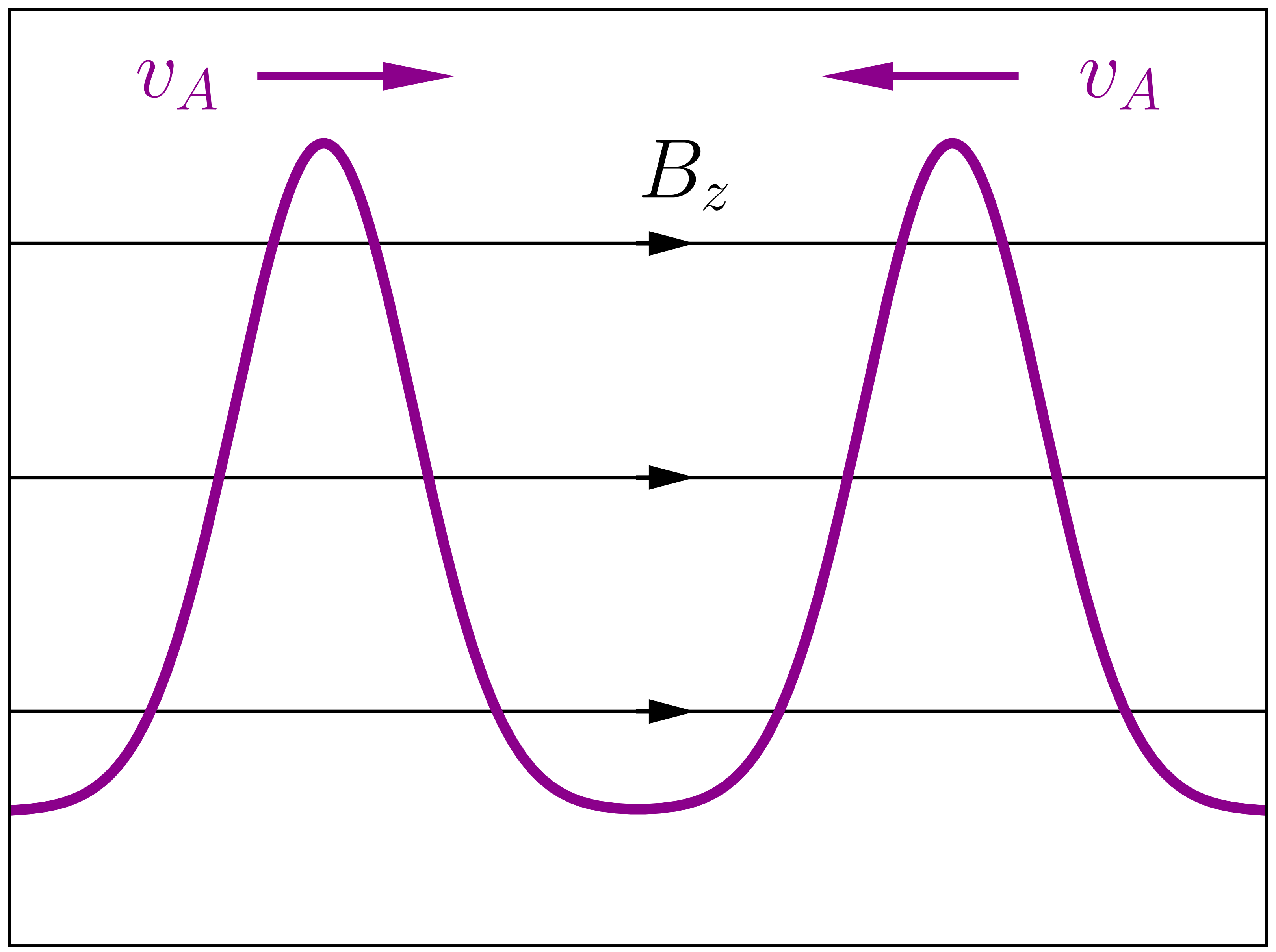
- Alfven waves $\omega = |k_z|$
- Fast waves $\omega = |k|$
- Three-wave interactions are not possible for

$$A + A \to A \qquad\qquad F + F \to F/A$$

- $A + A \to F$ 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.

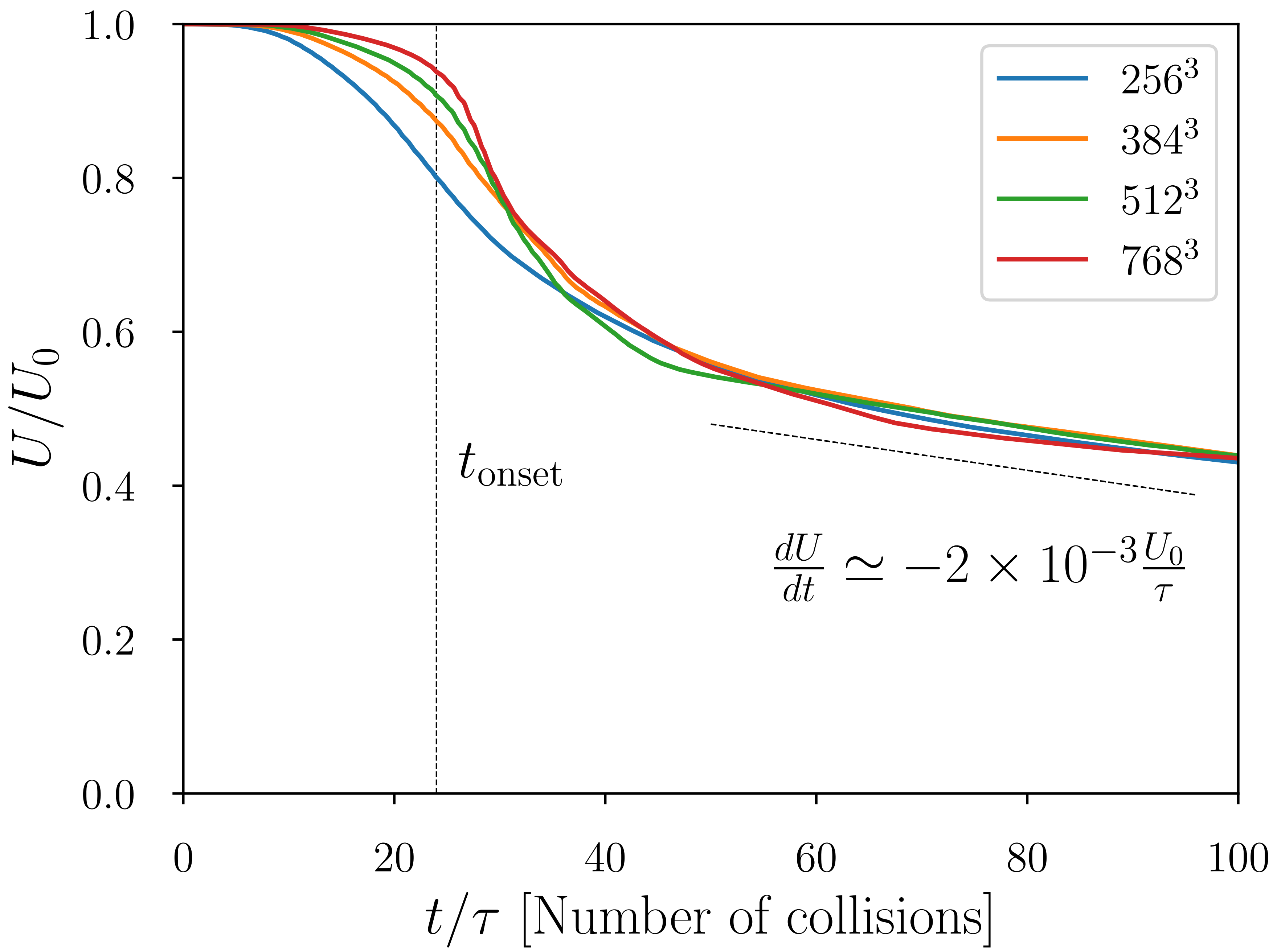


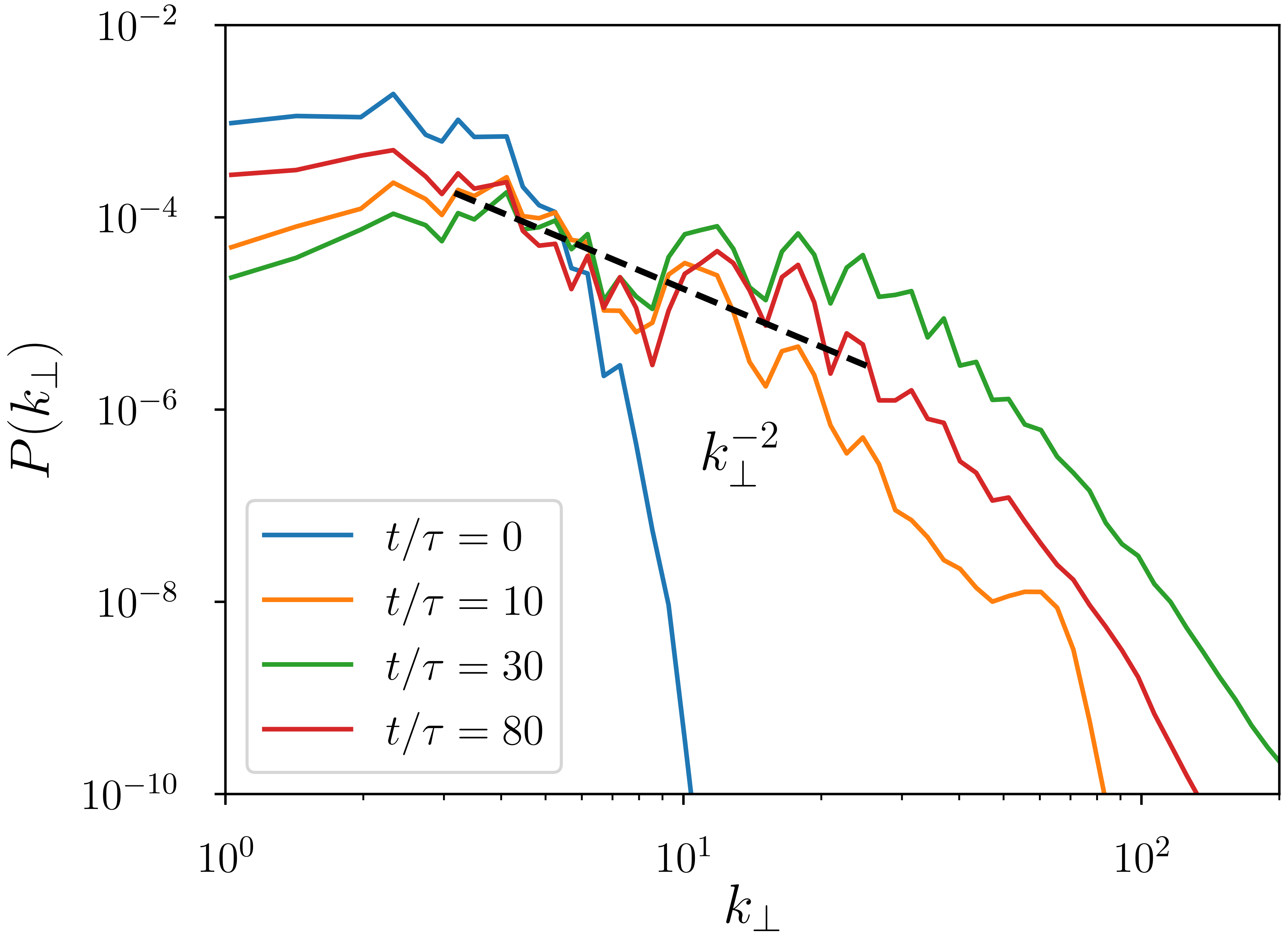
Numerical Methods

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

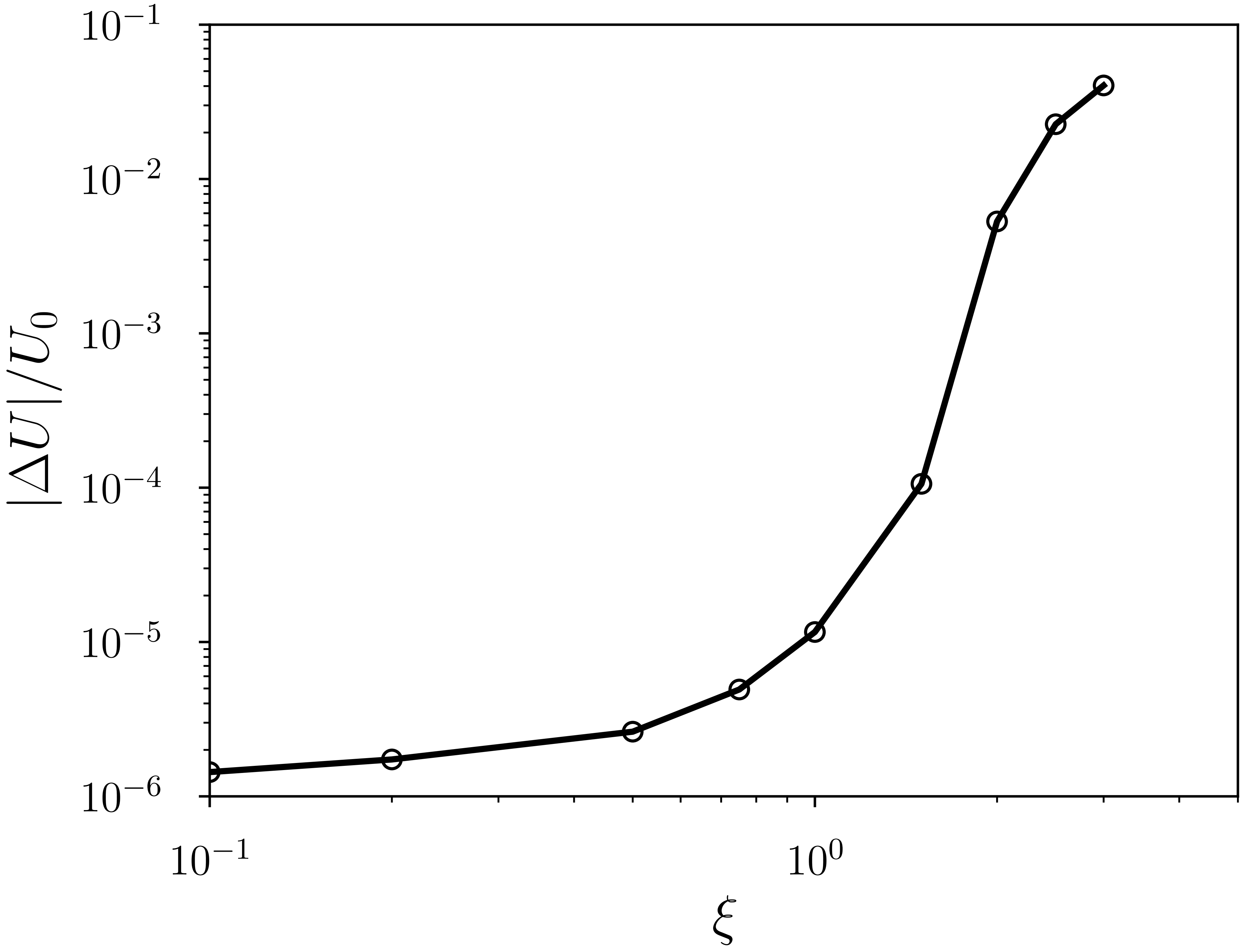
Development of turbulent spectrum in 3D

- 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

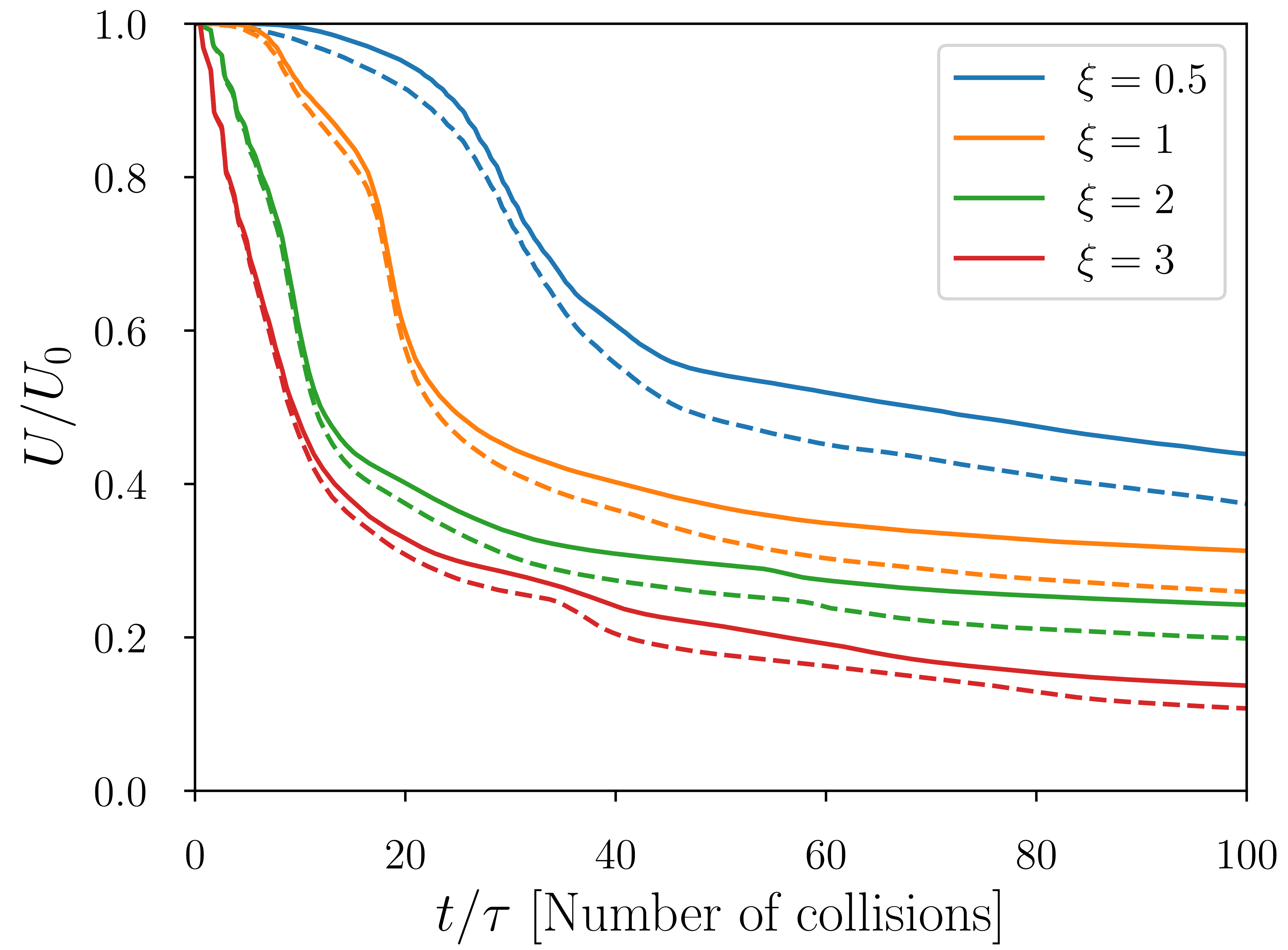


$$\xi = B/B_0$$

Compared with ~10% transmission rate of Alfven waves into the magnetar, the turbulent dissipation is weak unless the amplitude is much larger than unity.

Energy Carried Away by Fast Waves

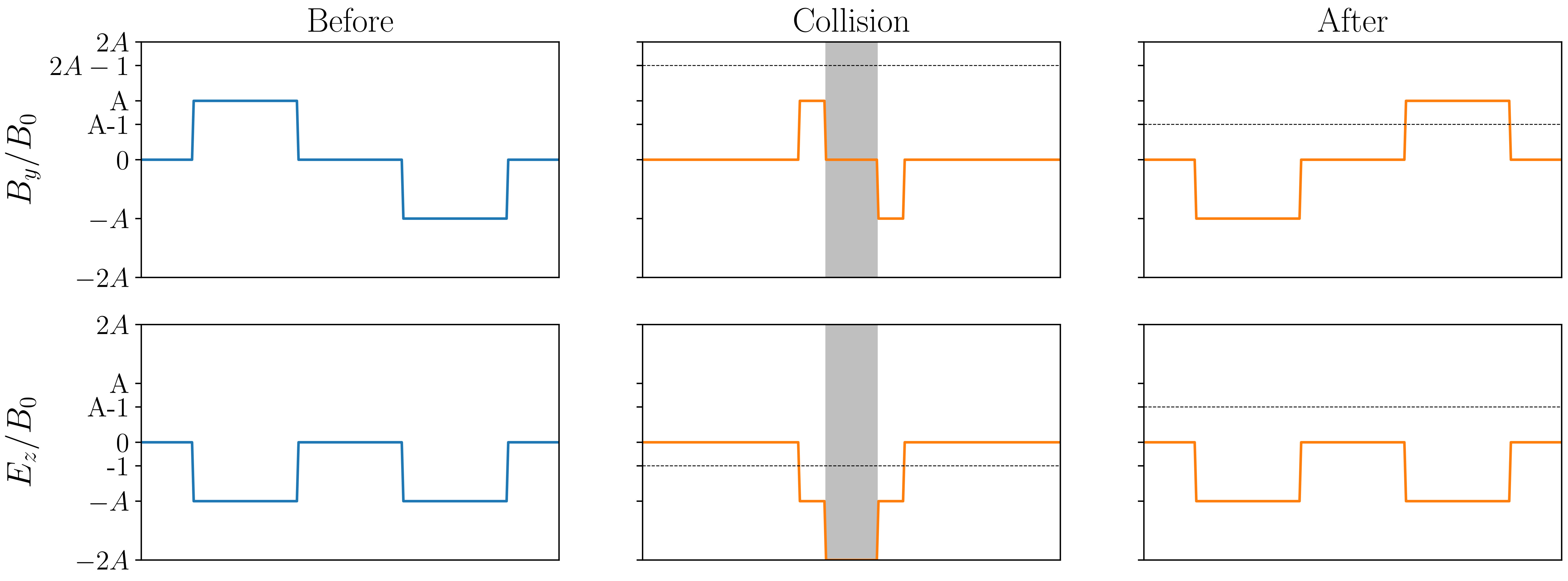
- Add ohmic dissipation layer on the boundary of transverse plane (perpendicular to the background field) to damp wave energy.
- This mimics the energy lost due to the escape of fast waves.
- Alfven waves are confined and can not reach the dissipative boundary
- Only fast waves are damped



Failure of FFE

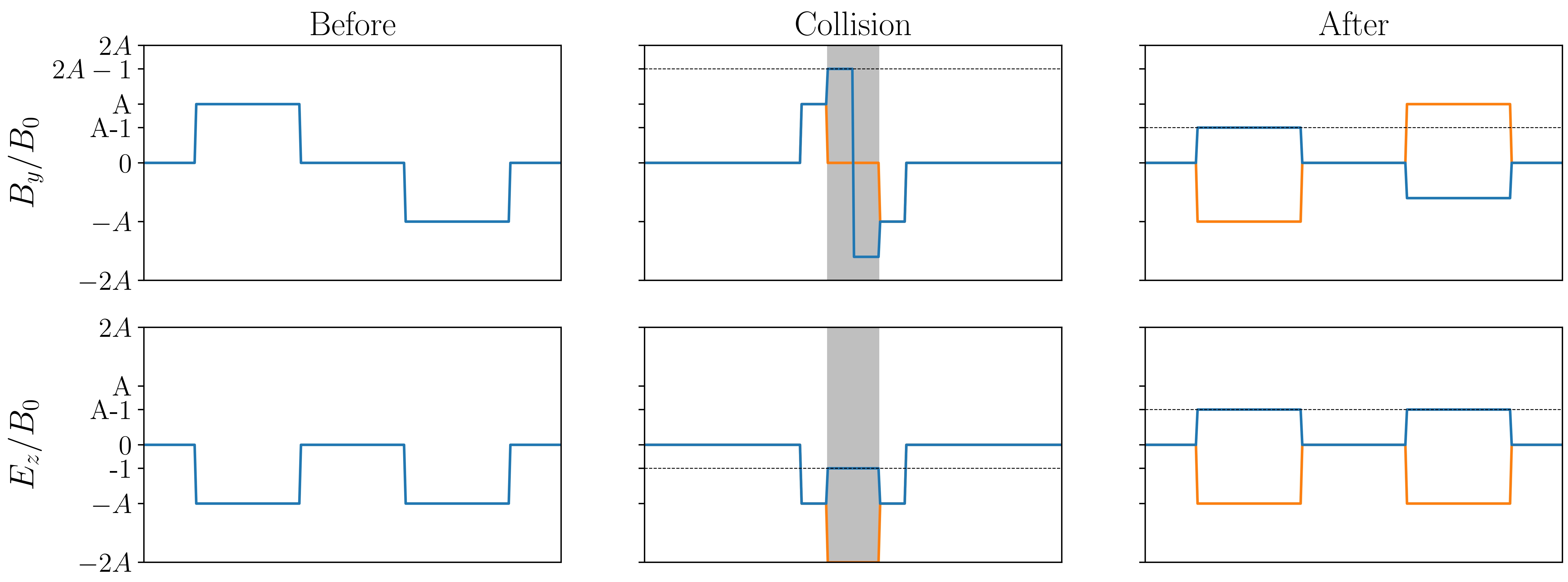
- When Alfven waves have opposite B field, even linear superposition can induce E>B and break the force-free condition. Usually, one reduces E field by hand and assumes this process reflects the realistic fast dissipation (McKinney 2006, Spitkovsky 2006).

- NOT physical.



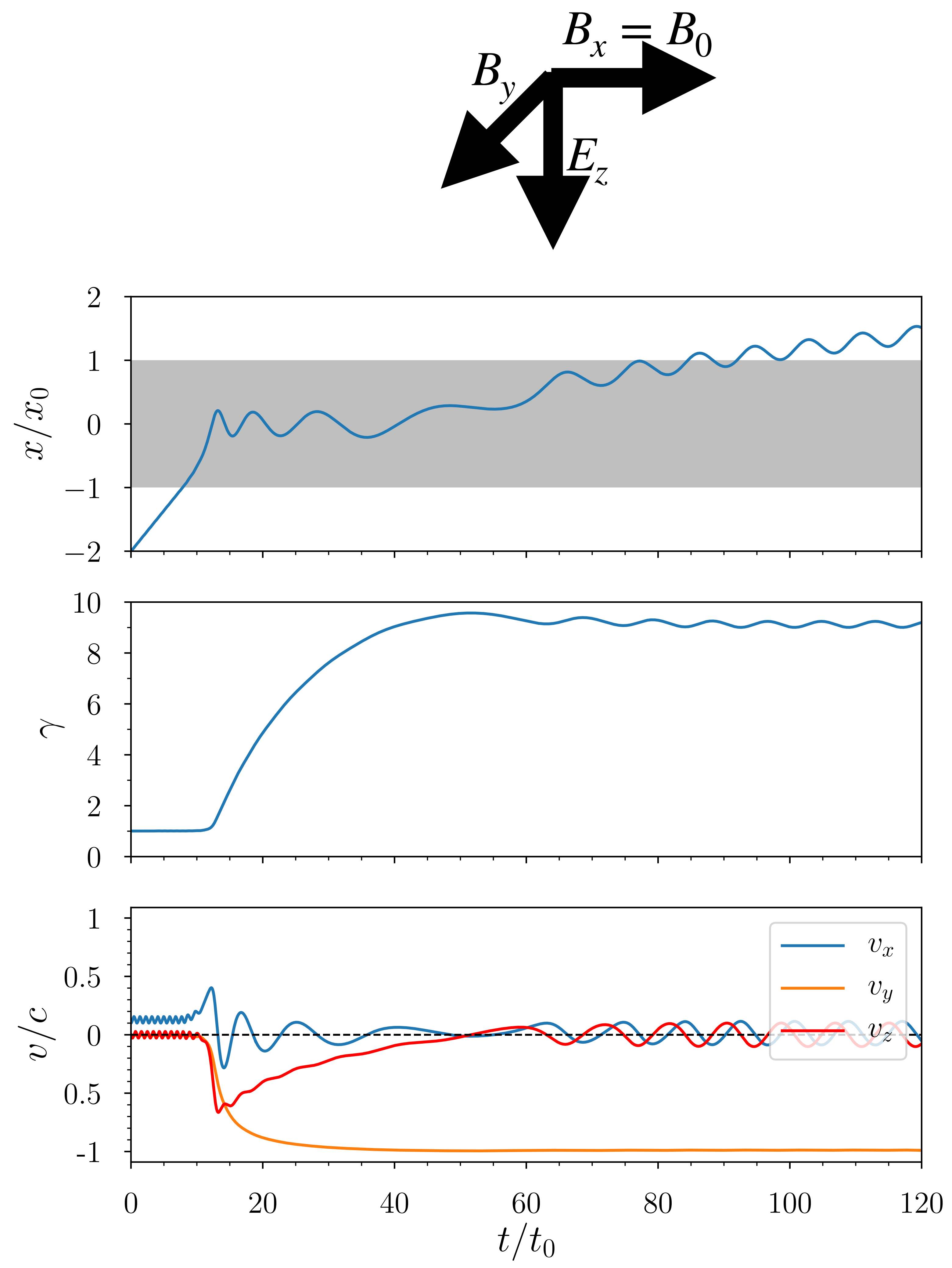
Wave Dynamics: Theory

- A transient current sheet is formed at the centre to reduce the electrical field.
- Incoming waves are reflected.
- The jump of magnetic fields is increased.

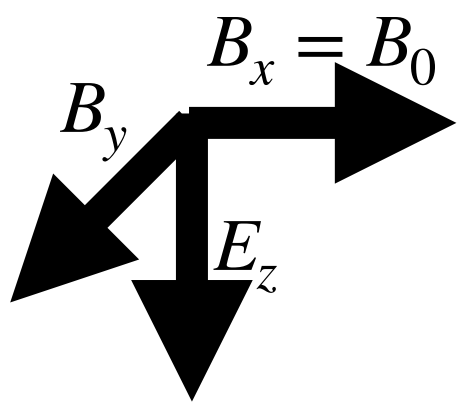


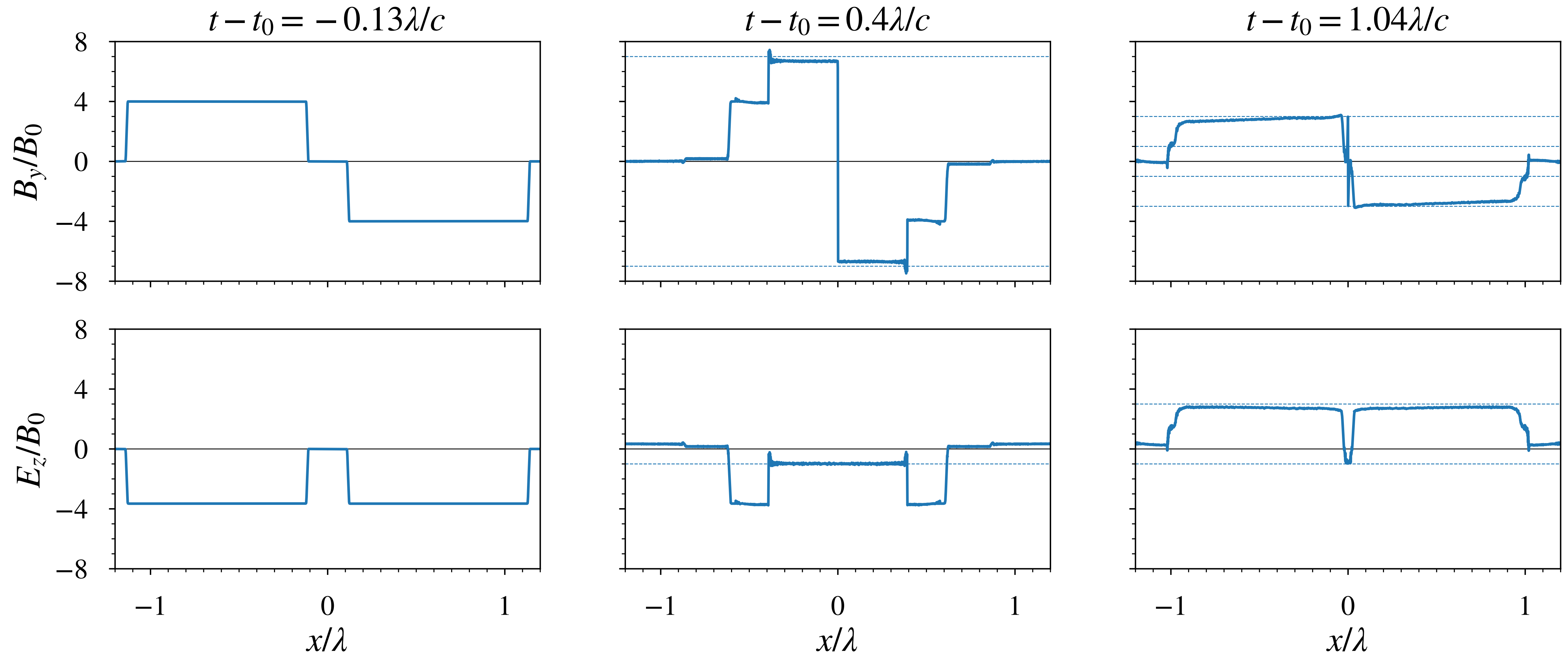
Particle Motion and Acceleration: Theory

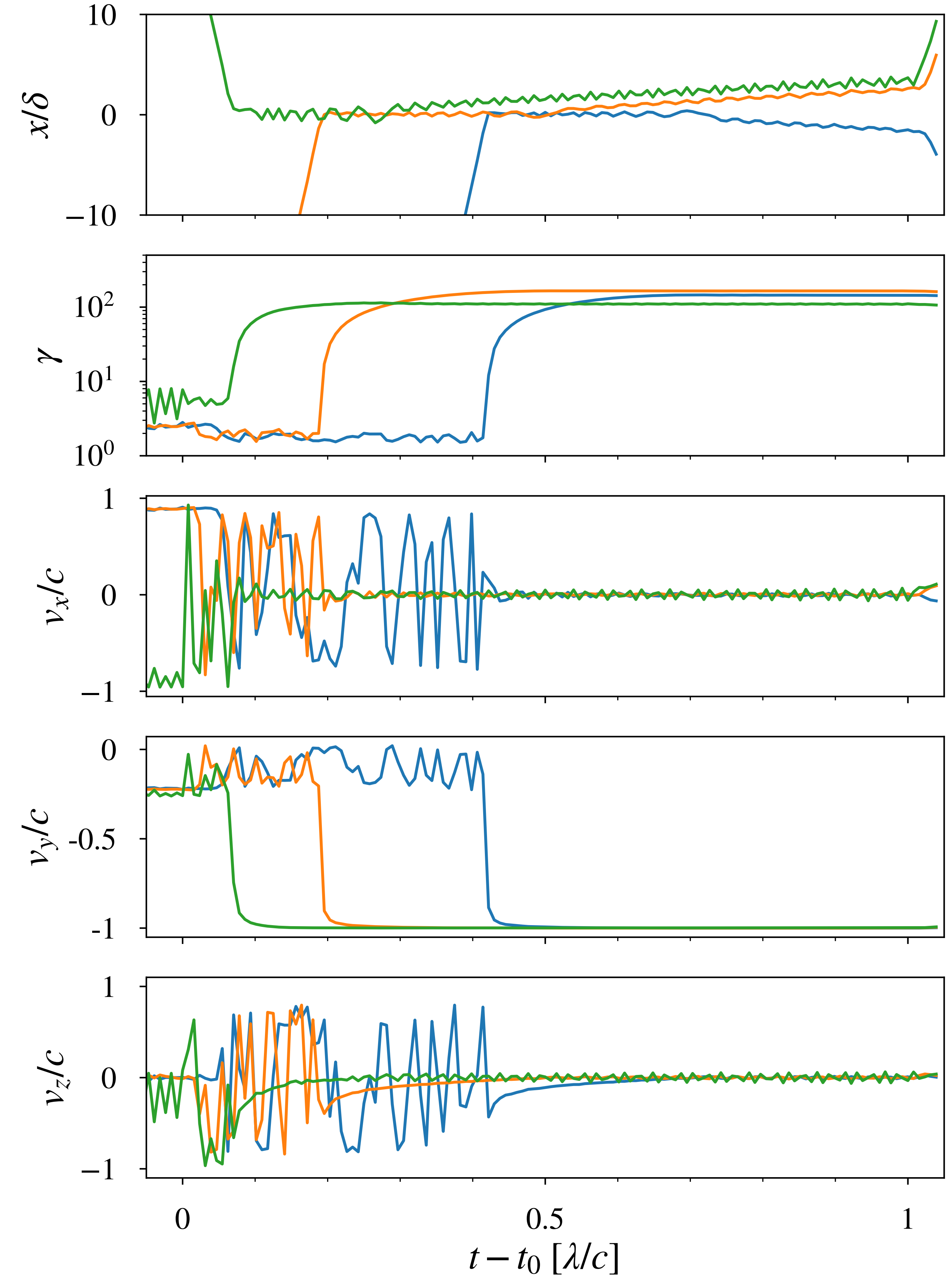
- The particle is first accelerated to develop v_z.
- $F_x = v_z B_y$ points towards the centre, confining the particle.
- $E_z * v_z$ keeps doing positive work, accelerates the particle.
- As the particle finishes half of the gyration, v_z and F_x reverses sign, pushing the particle outward.
- The particle escapes with energy gain.



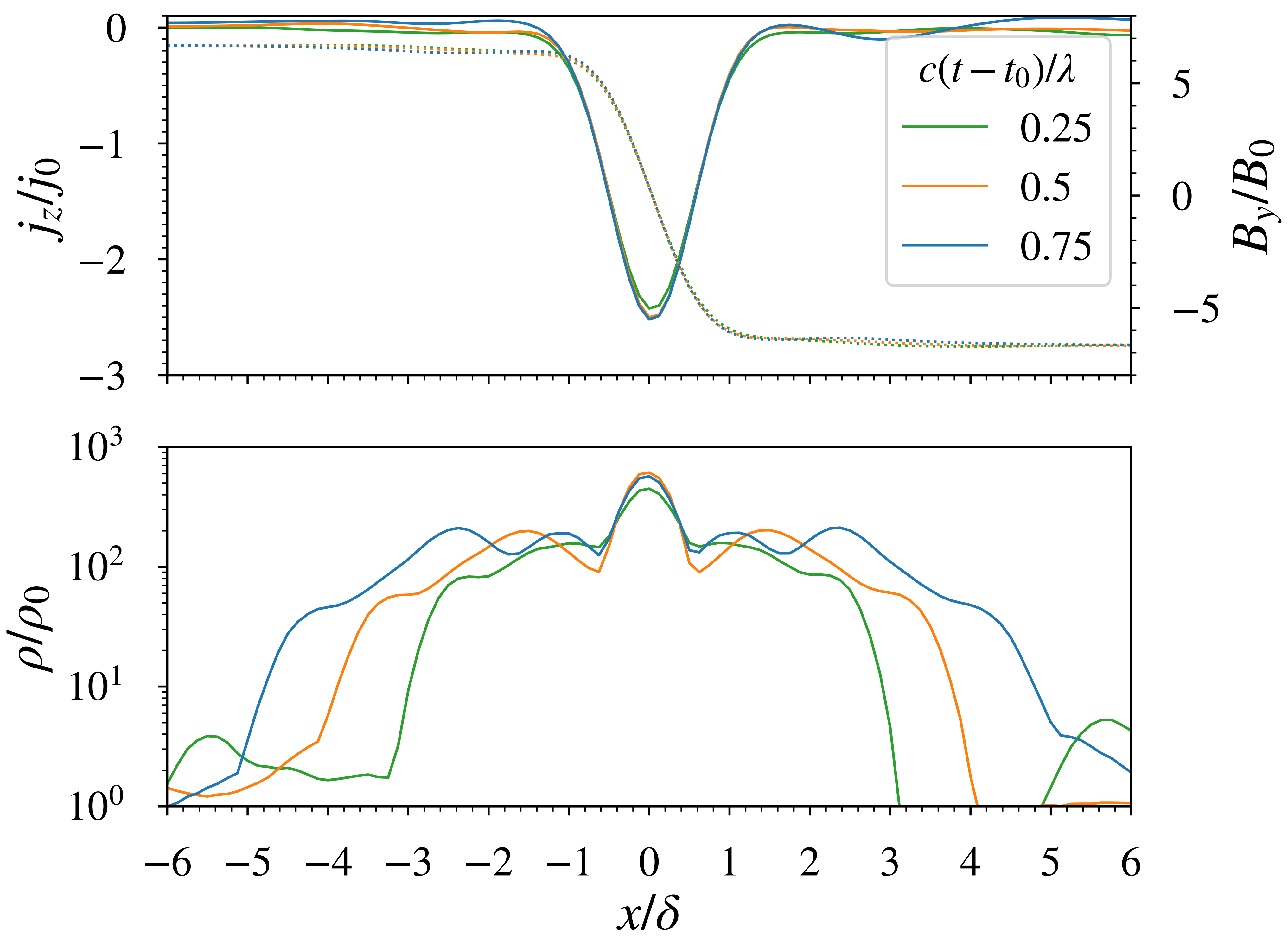
Kinetic Simulations — 1D





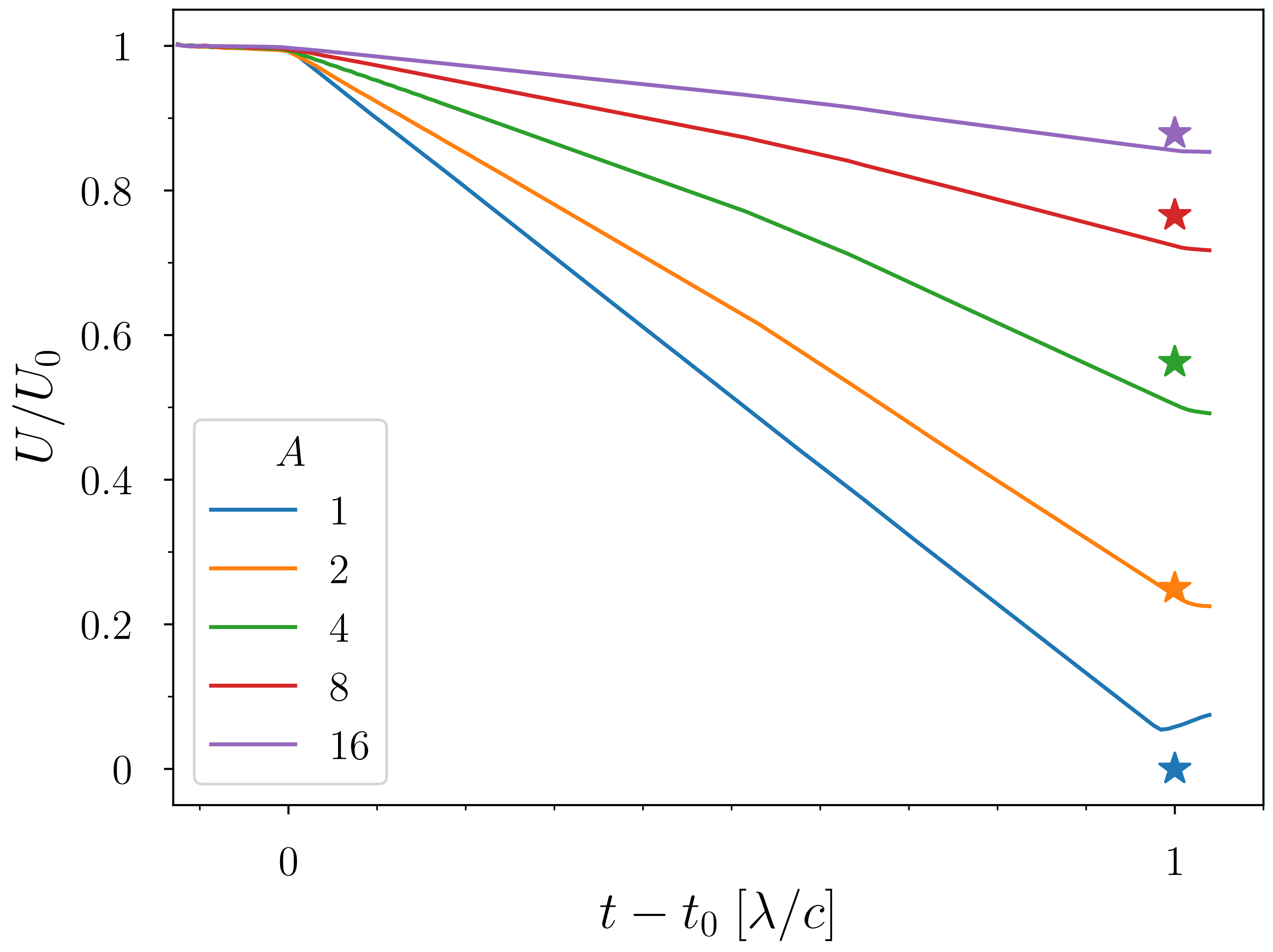


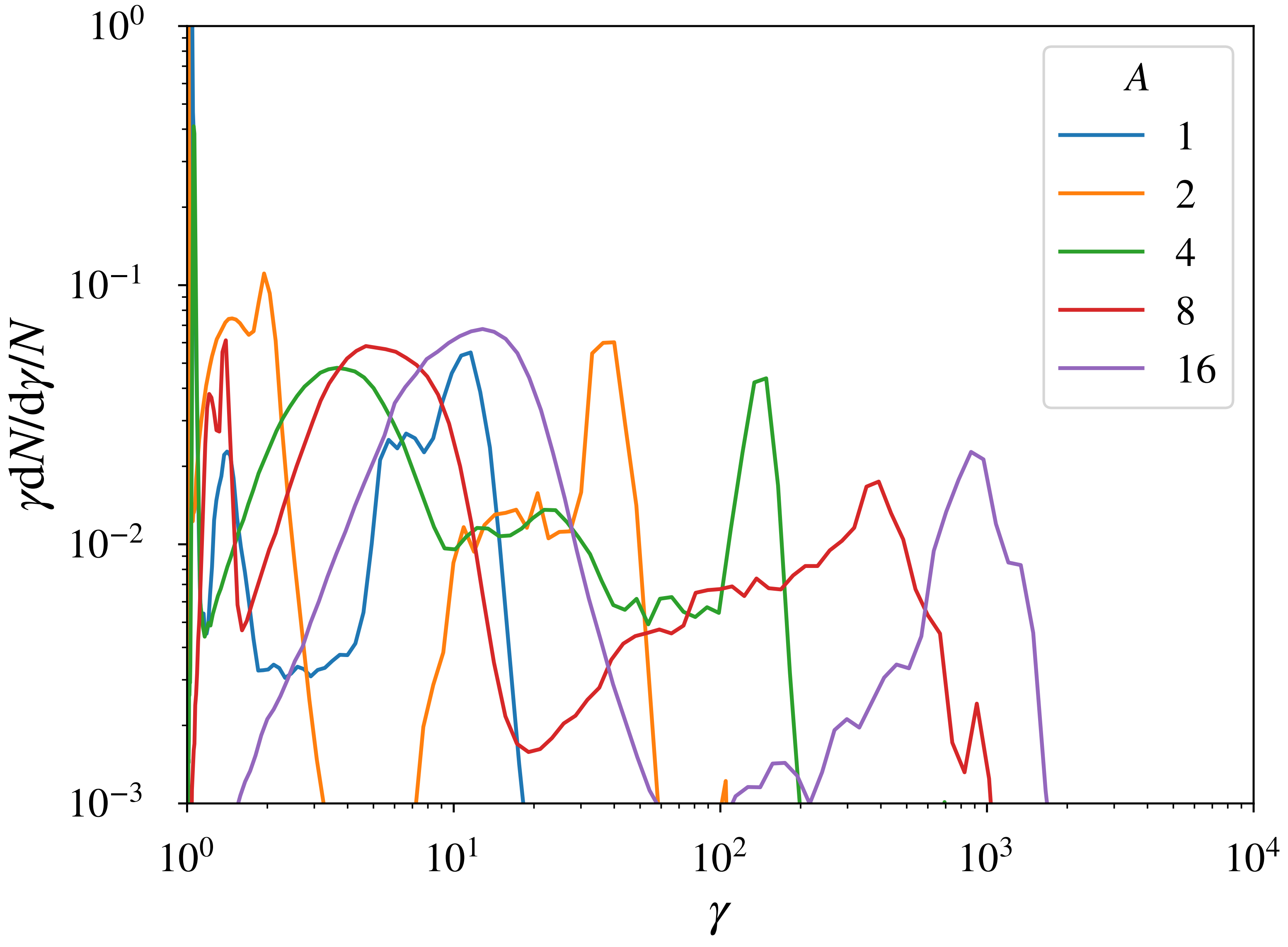
- At the central current sheet, particles support a steady current to balance curl B.
- Poynting flux is converted to particle energy, at a constant rate.



1D Dissipation Rate

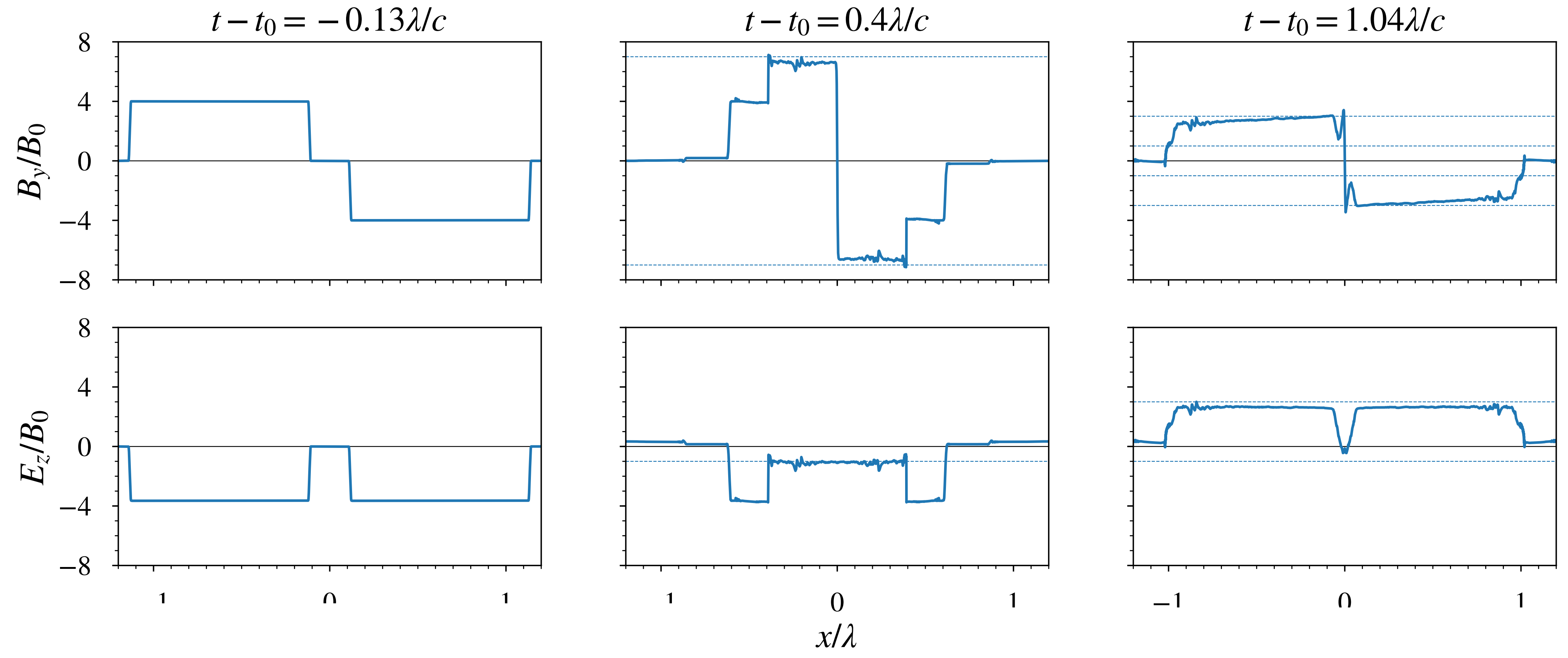
- The energy difference between incoming and reflected waves is dissipated.
- Particle energy spectrum shows a narrow high energy peak.
- Coherent emission from the high energy particles?

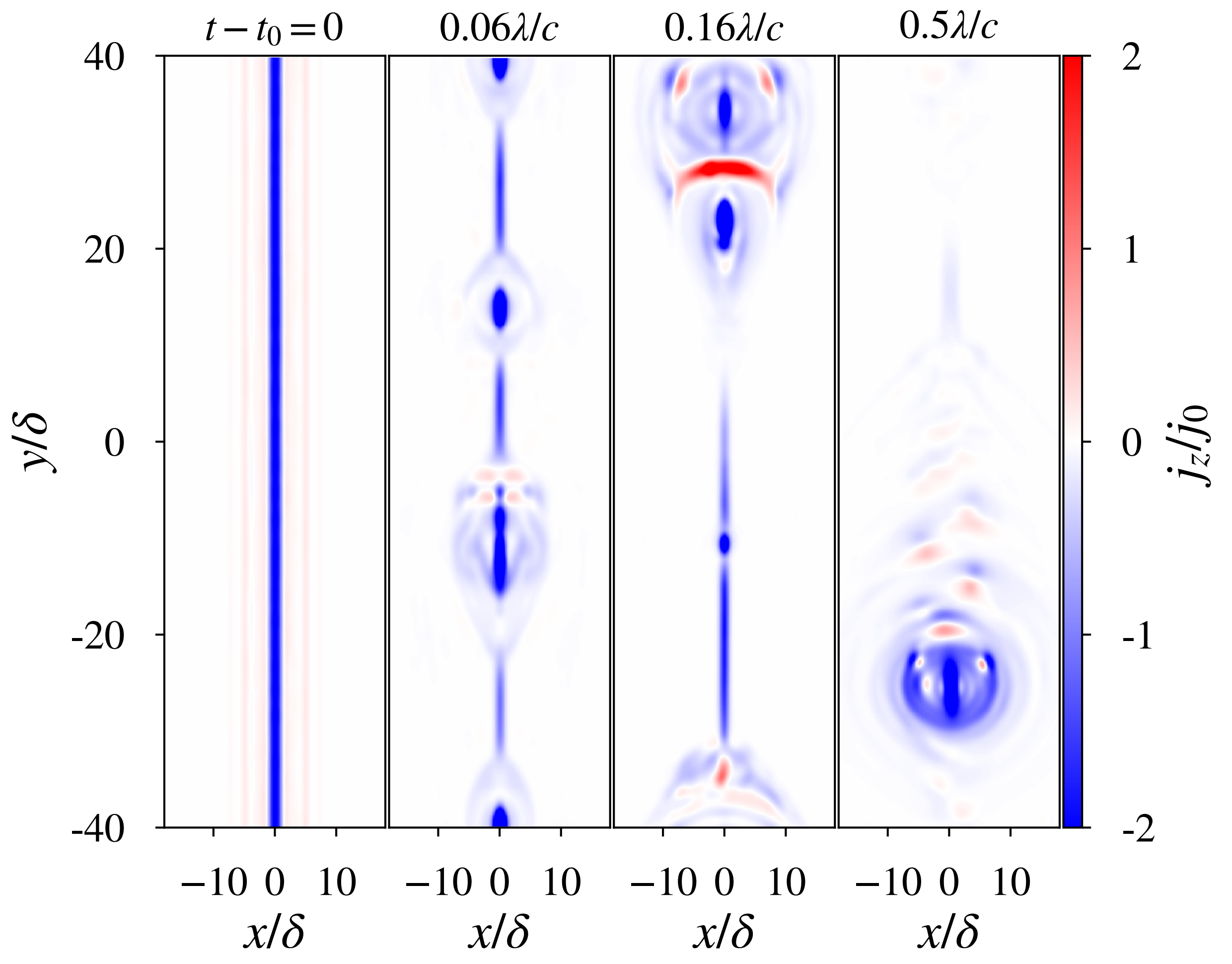


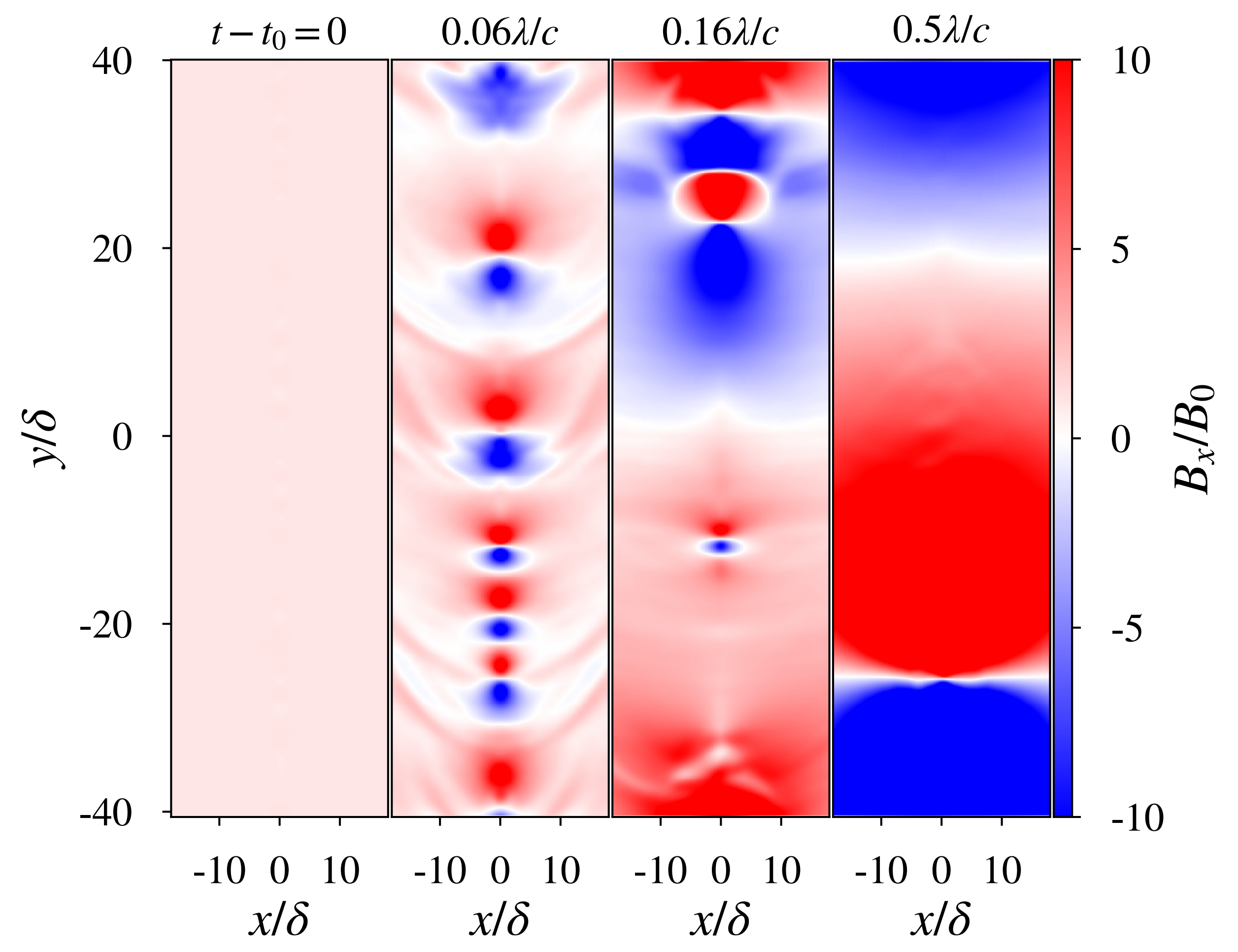


Kinetic Simulations —2D

- Tearing instability is triggered to initiate magnetic reconnection.

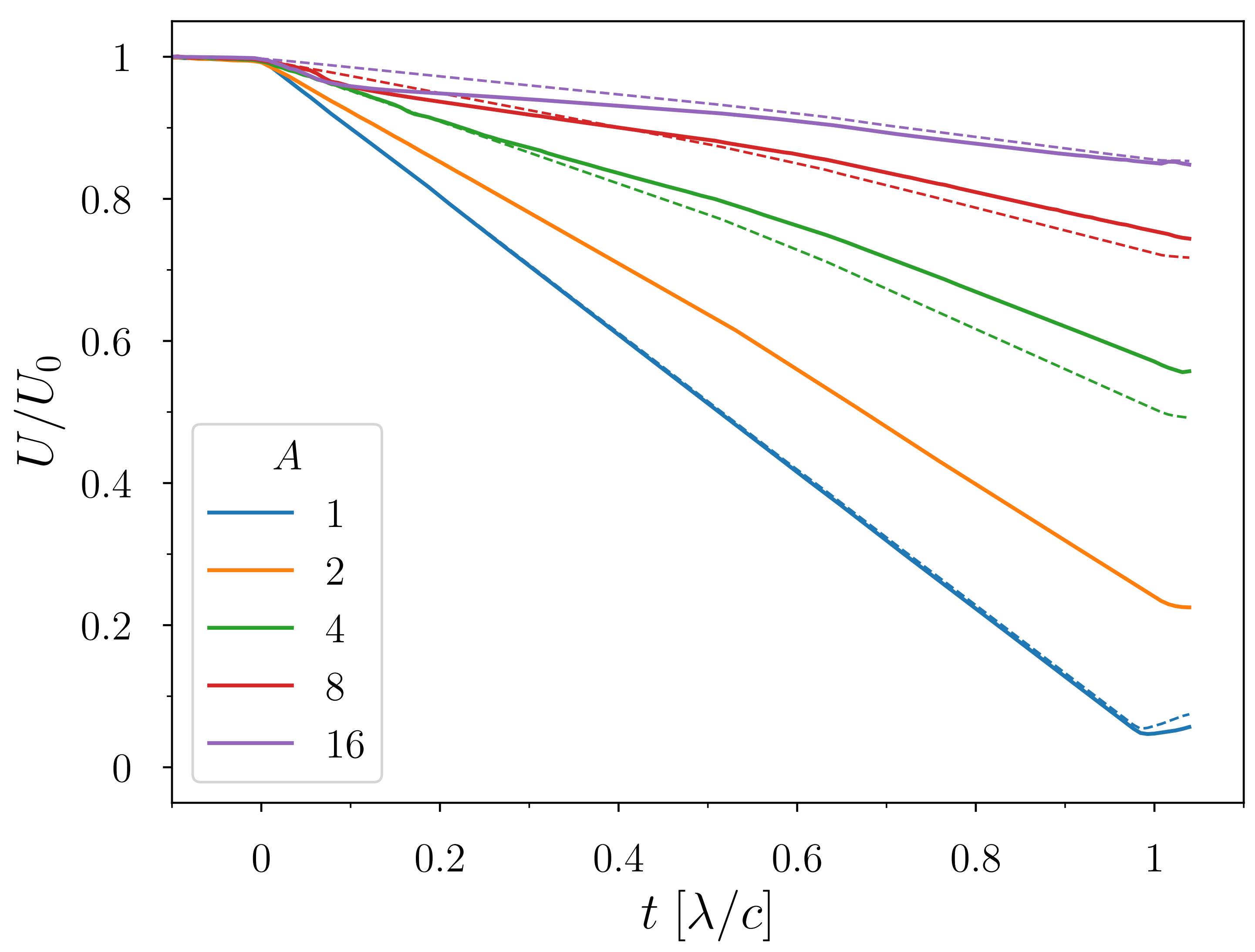


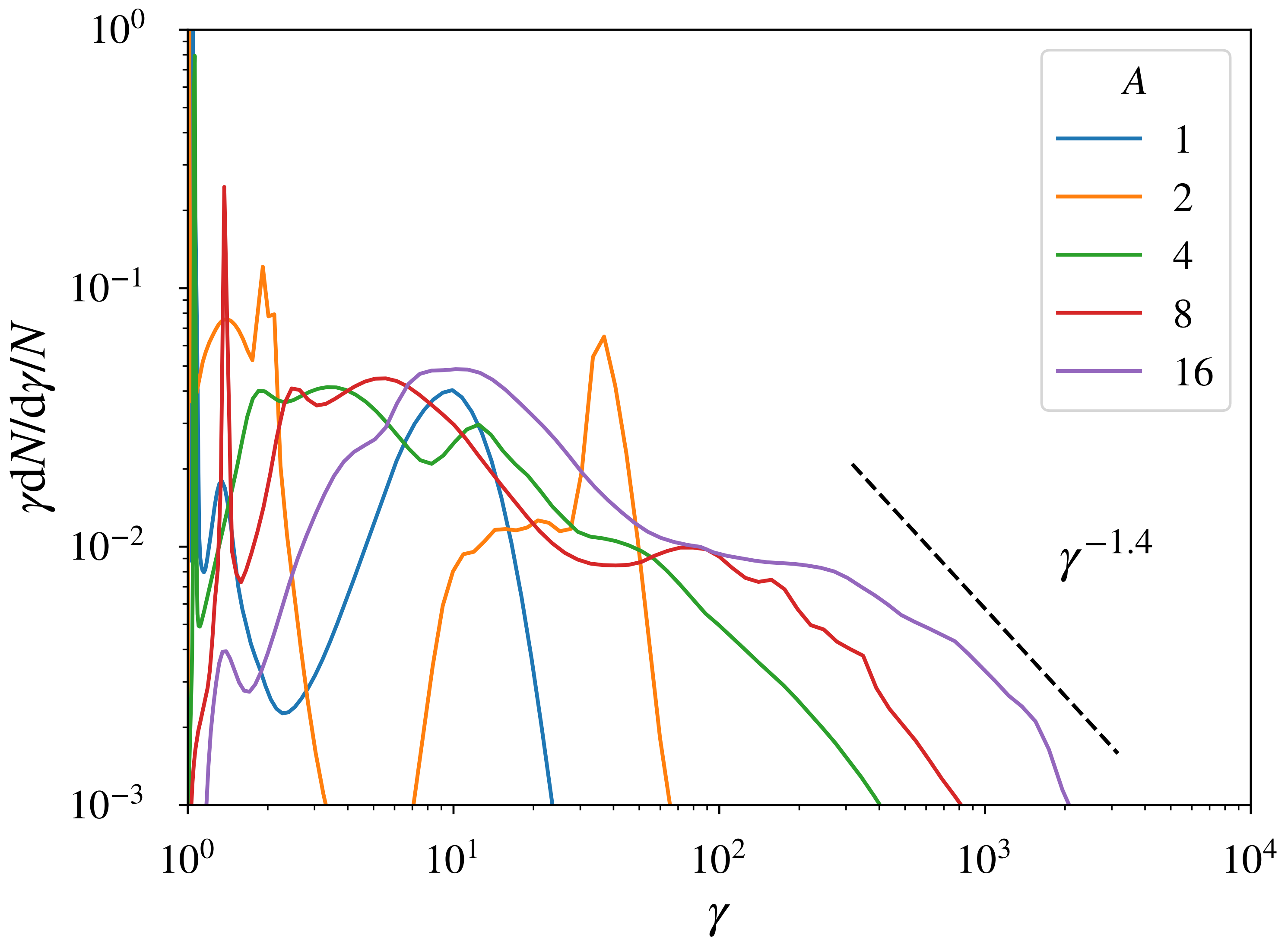




2D Dissipation Rate

- The overall dissipation is the same as 1D.
- Reconnection smooths the peak to power law.





Conclusion

Inside the magnetar:

- Hall-mediated avalanches and TPW are able to reproduce light curves for outbursts of transient magnetars.

Outside the magnetar:

- Loss of wave energy to turbulent dissipation or fast waves is slow.

- Breakdown of magnetic dominance during wave collision provides a novel efficient channel for energy dissipation and particle acceleration.

Some Open Questions

- Alfven wave collision over a realistic dipole magnetic field. The geometry can lead to spontaneous conversion to fast modes. Will the fast waves explain FRB?

- Radiative response of the accelerated particles. Can they produce coherent nonthermal emission?

- When two NS with reversed magnetic fields inspire, can this process makes EM signal proceeding the binary merger?

- X-ray polarization transport and signal: e.g. resonant scattering produce 1/4 O-mode and 3/4 E-mode. Annihilation bremsstrahlung produces pure O-mode.

Thank you for your atten