Alfven Wave Dynamics in the Magnetar Magnetosphere

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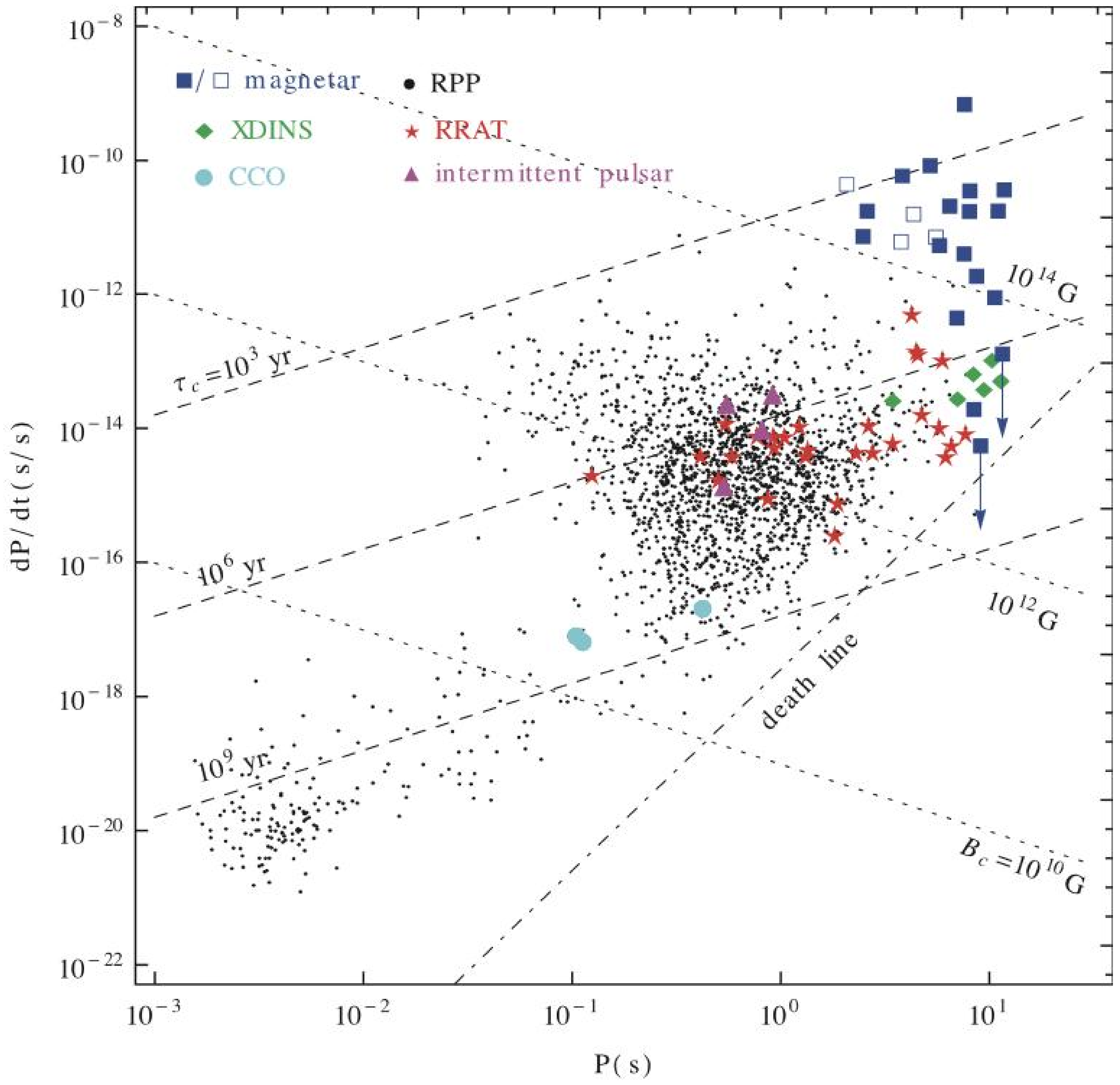
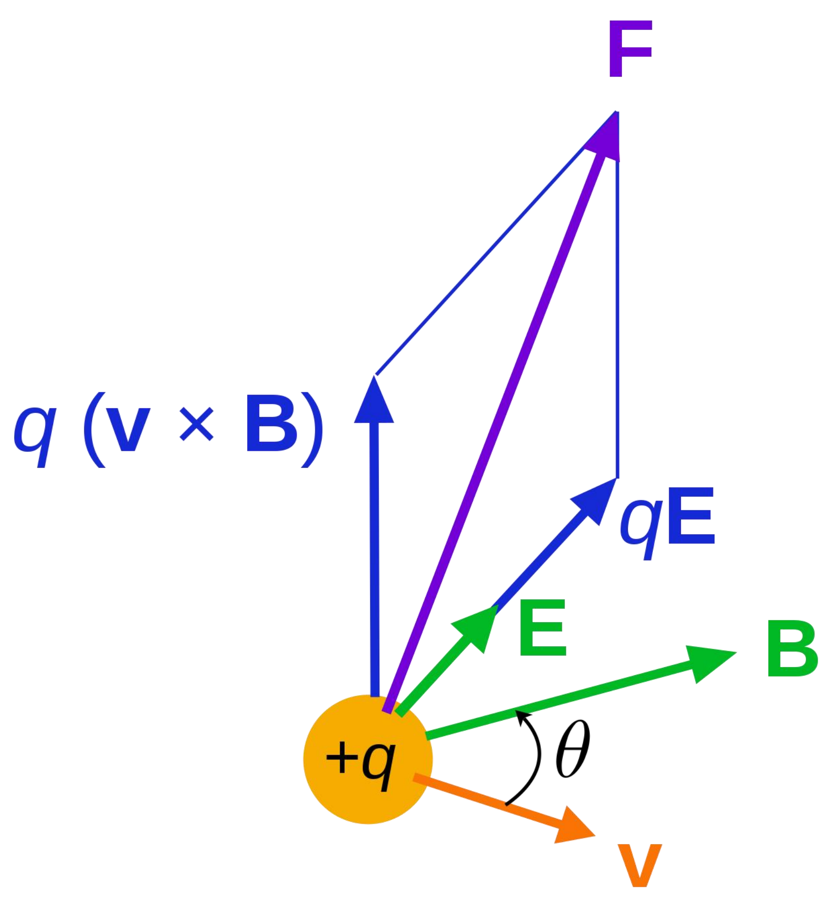
Magnetars

- Ultra-strong magnetic field up to 10^{15} G
- Slow rotation period 1-10s
- SGR1935: FRB with X-ray bursts

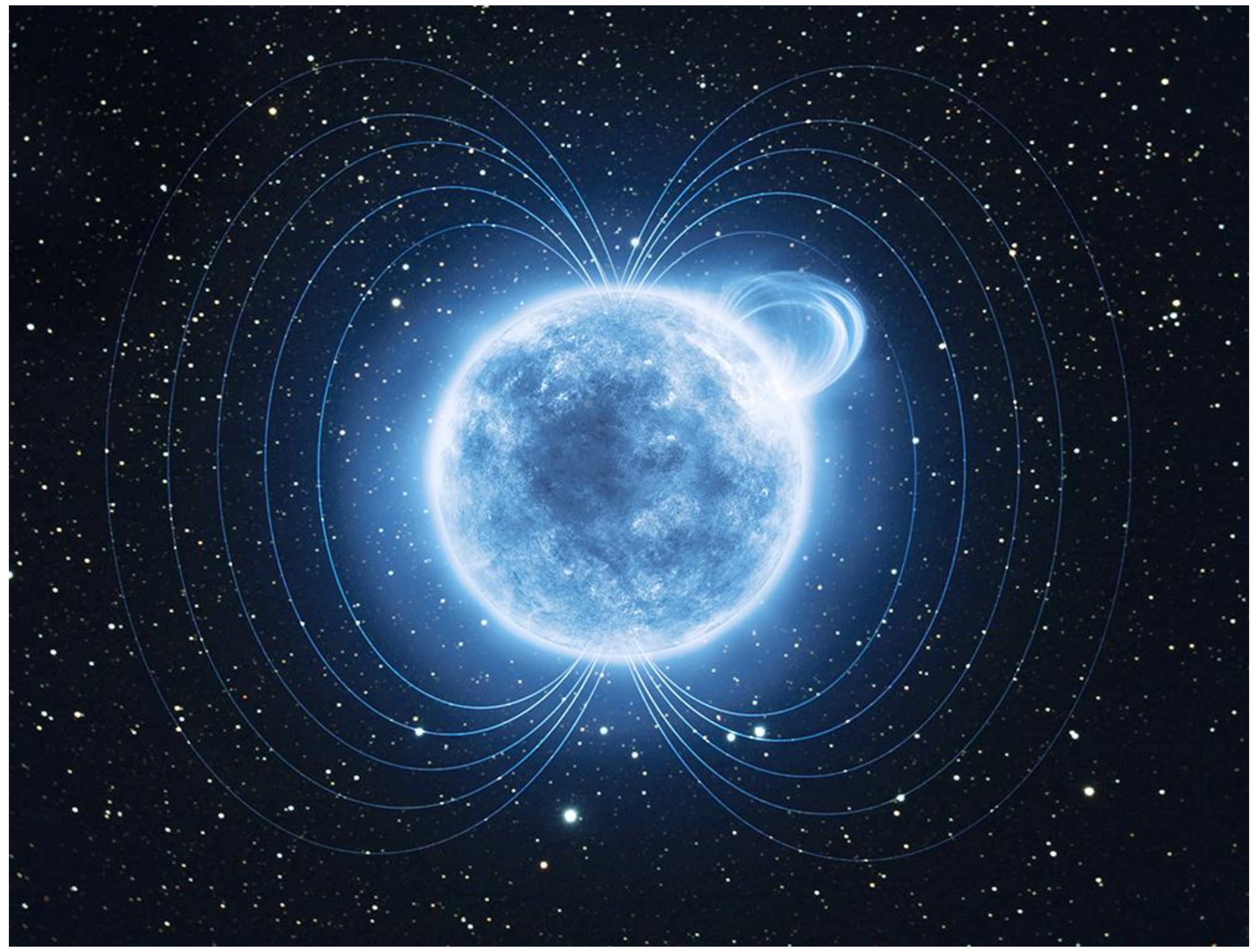


Magnetosphere: Force-Free Electrodynamics (FFE)

- Magnetic energy dominates over the rest mass energy of the plasma
- The plasma follows the field dynamics with a vanishing Lorentz force

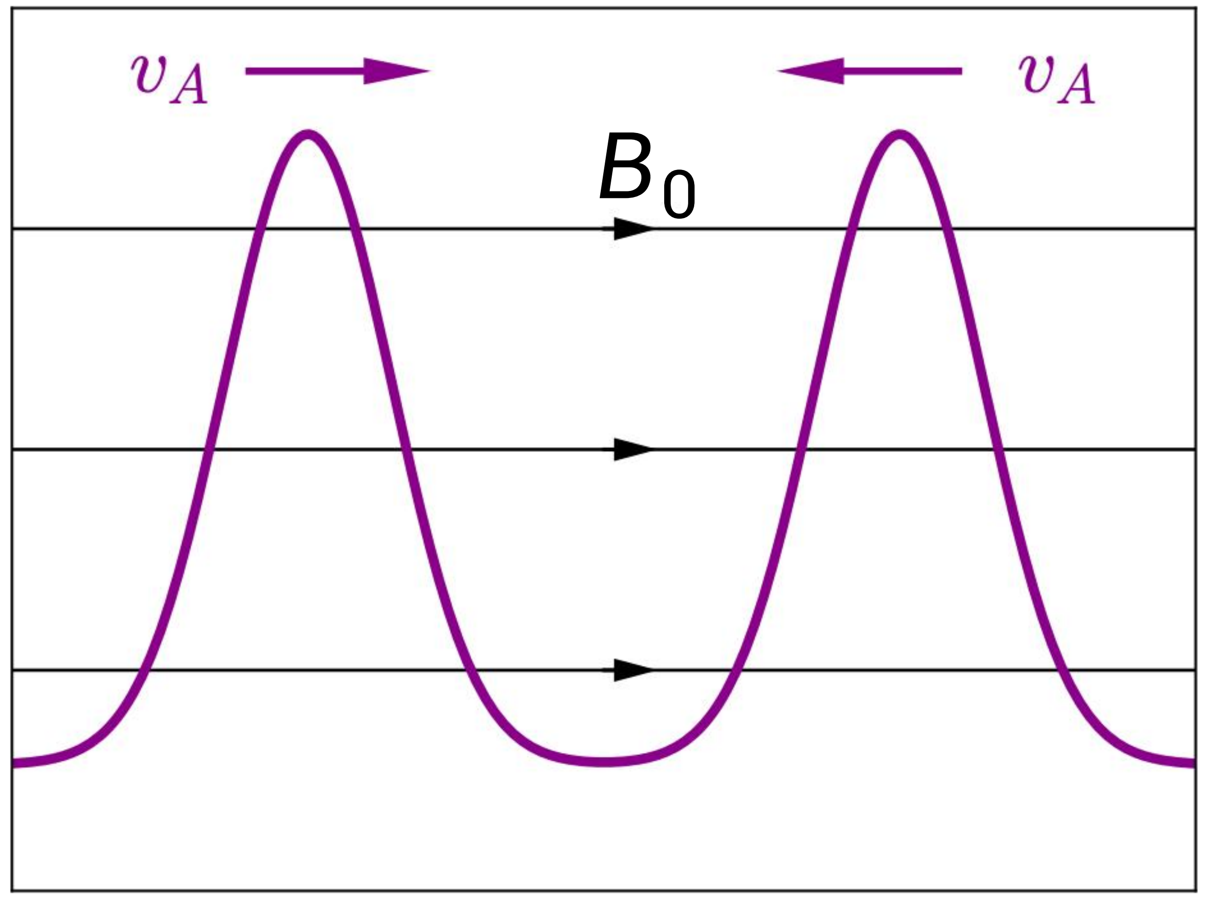


- Need force-free conditions $E < B \quad E \cdot B = 0$
- **Alfven waves**: guided to move along field lines
- **Fast waves**: propagate like in vacuum
- Three-wave interactions through $A + A \to F$

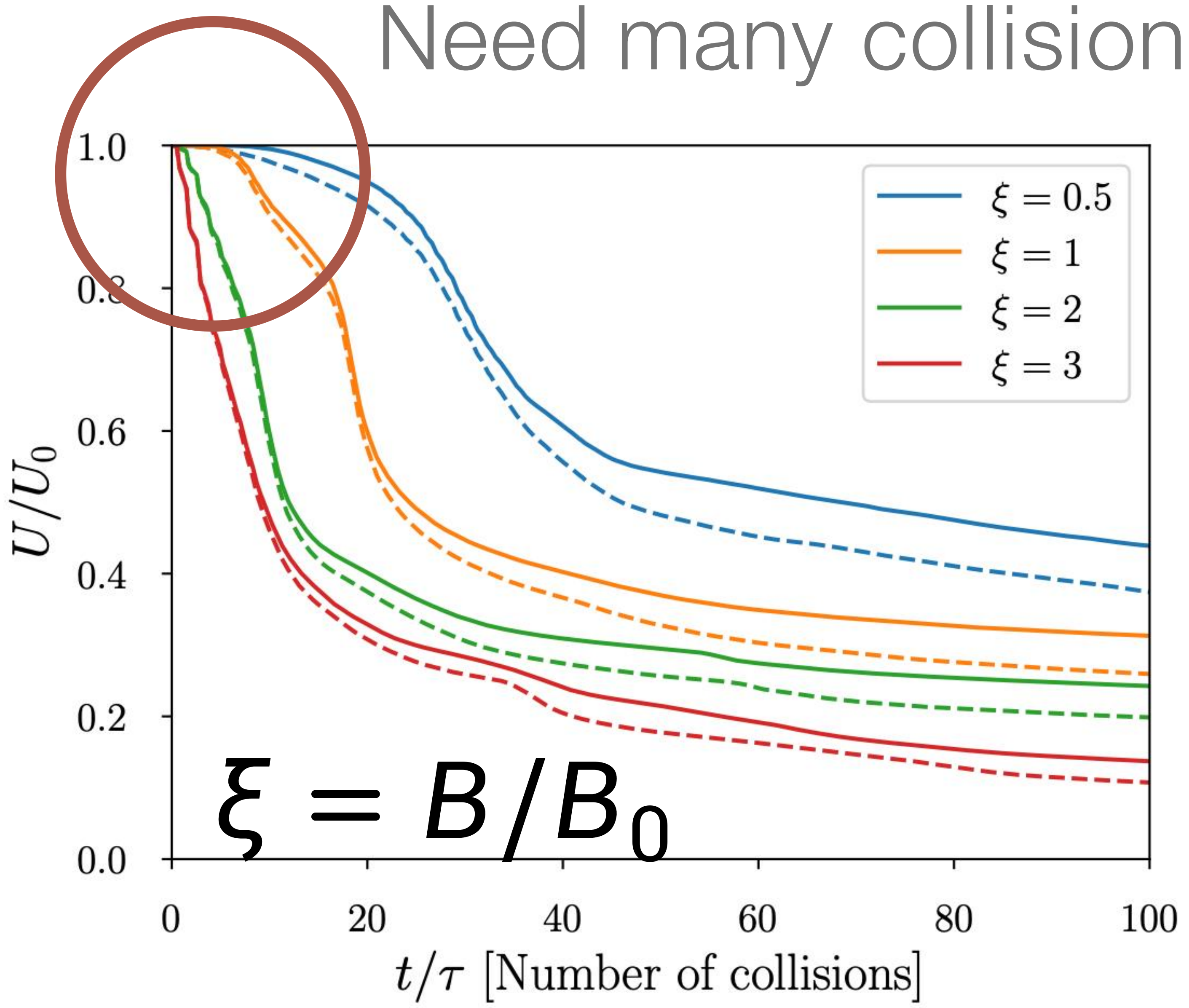


Nonlinear Wave Interaction in FFE

- FFE simulation (WENO) of a pair of counter-propagating Alfven waves in a periodic box
- Turbulent anisotropic forward cascade, dissipation is weak
- Fast waves carries away a few percent of wave energy



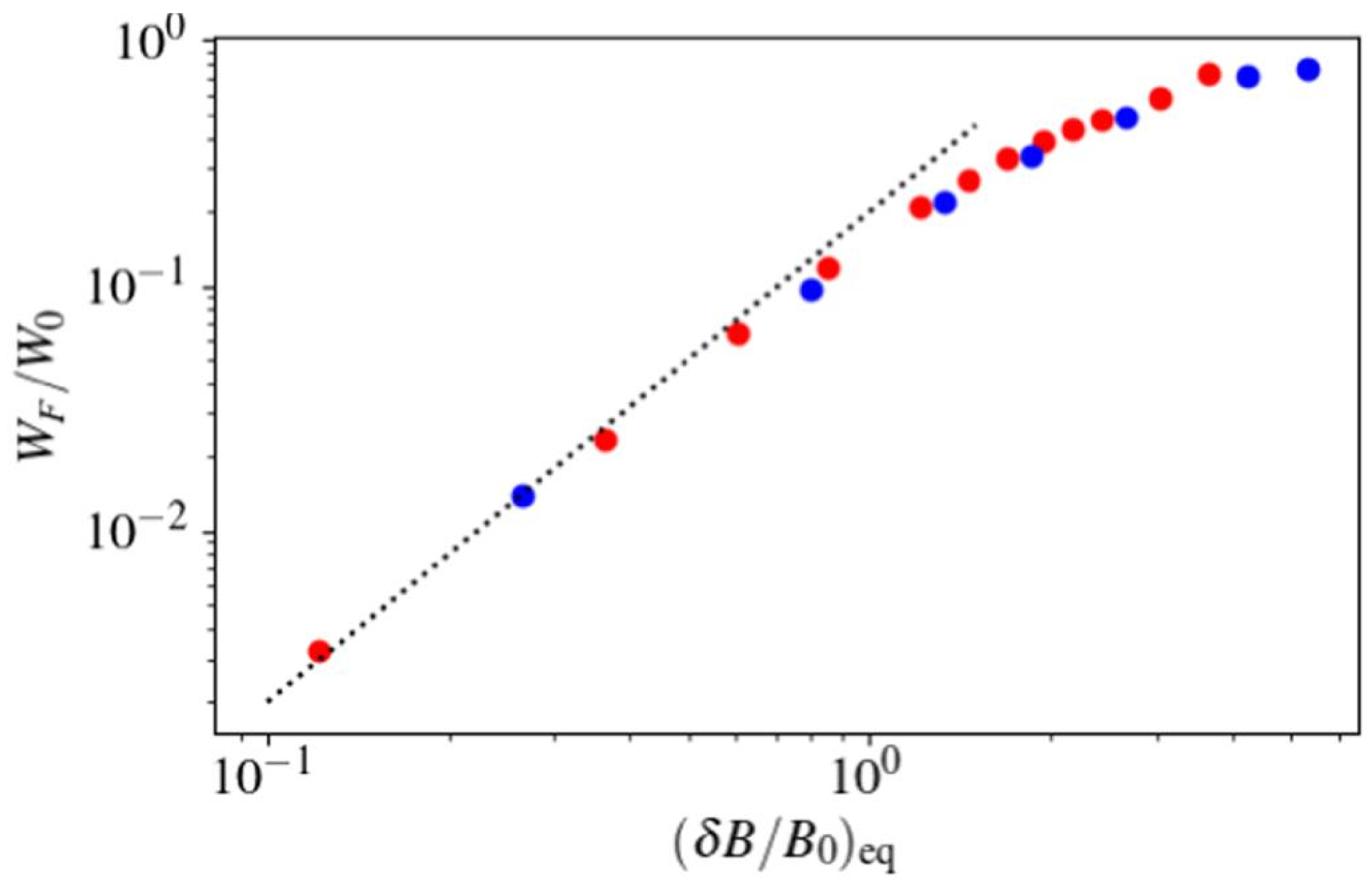
Need many collisions



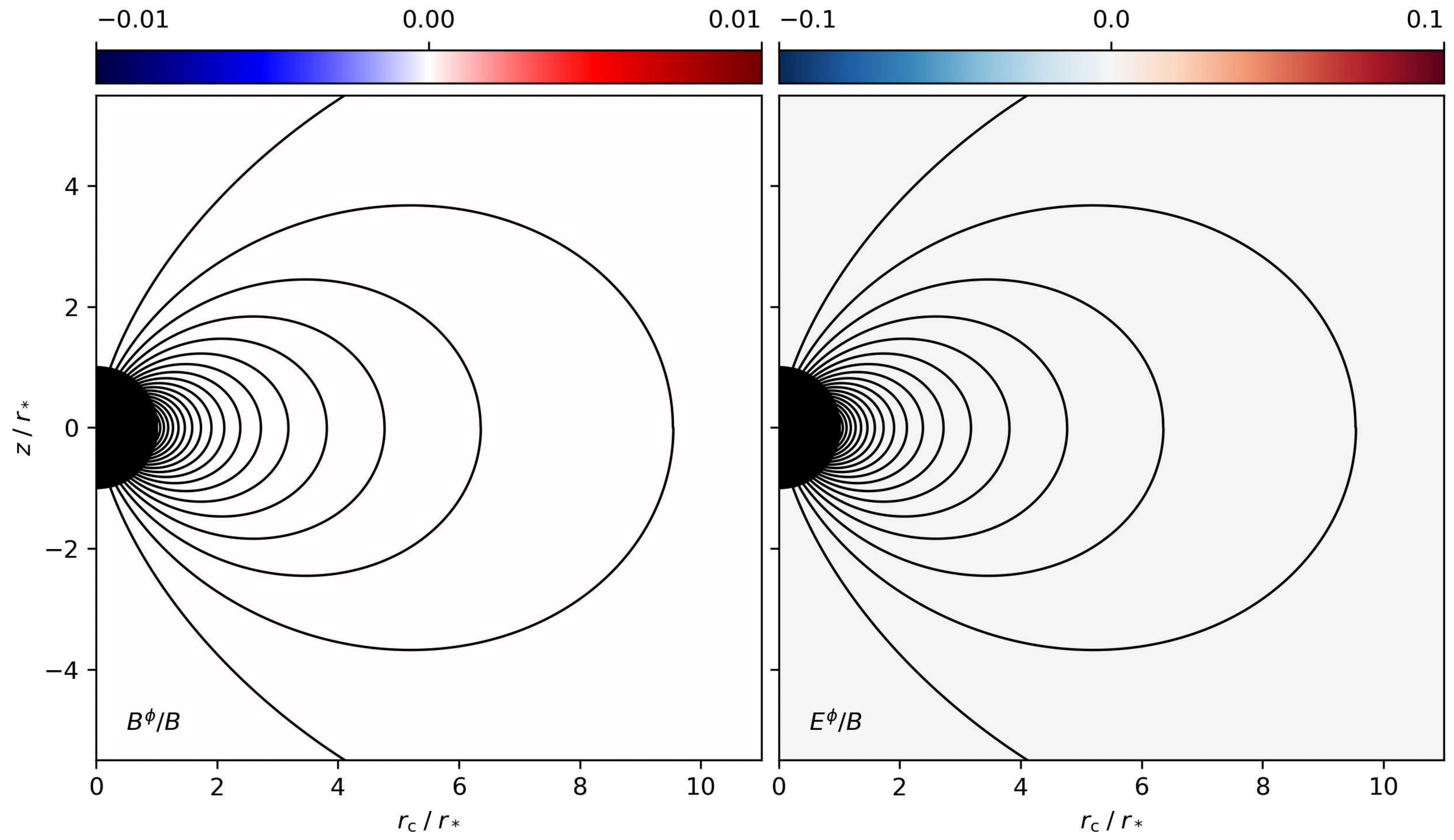
Li et al. 2019

Alfven Wave in the Dipole Magnetosphere

- Outgoing fast waves are spontaneously launched
- Alfven waves become strongly sheared



Yuan et al. 2021

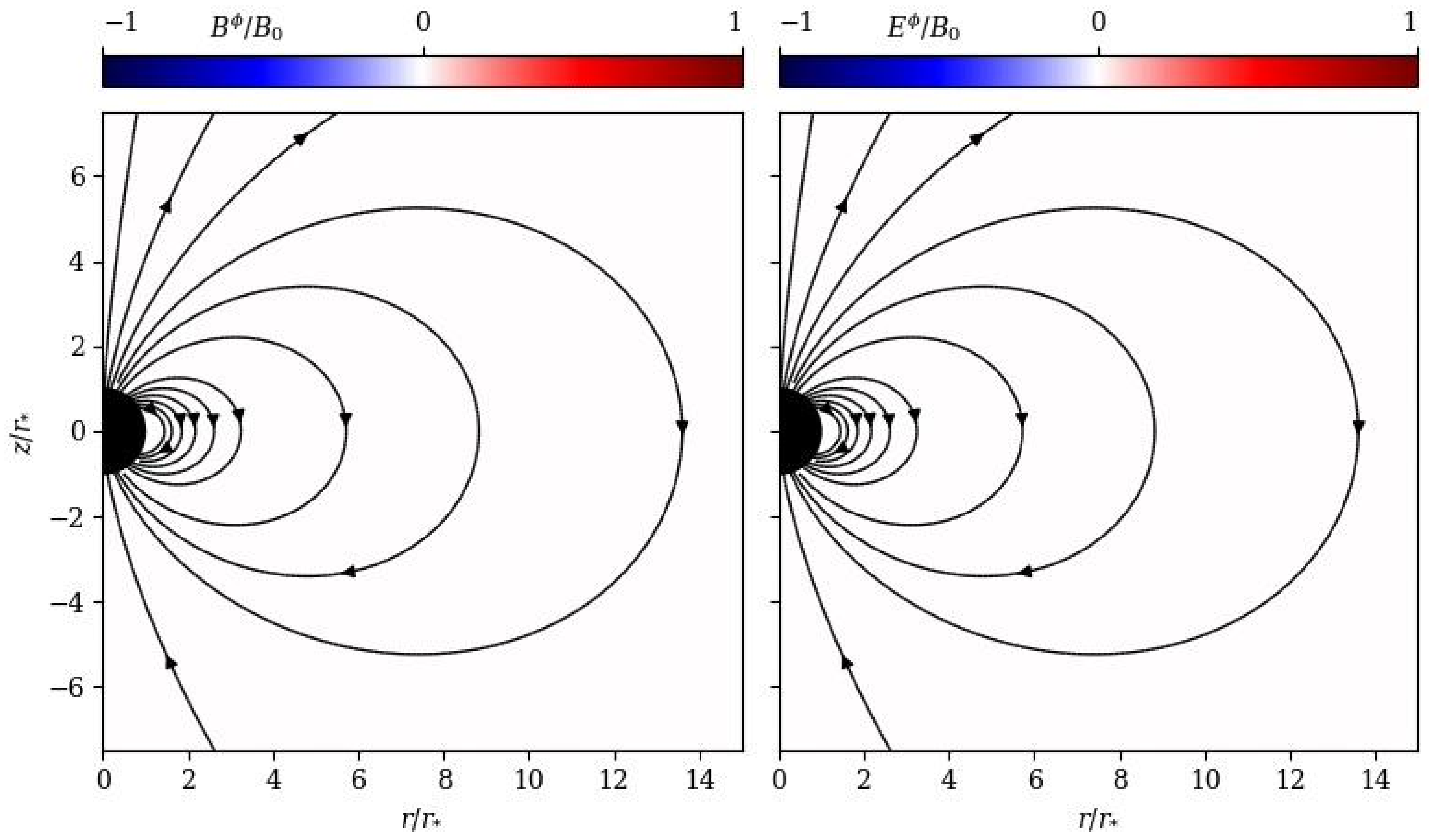


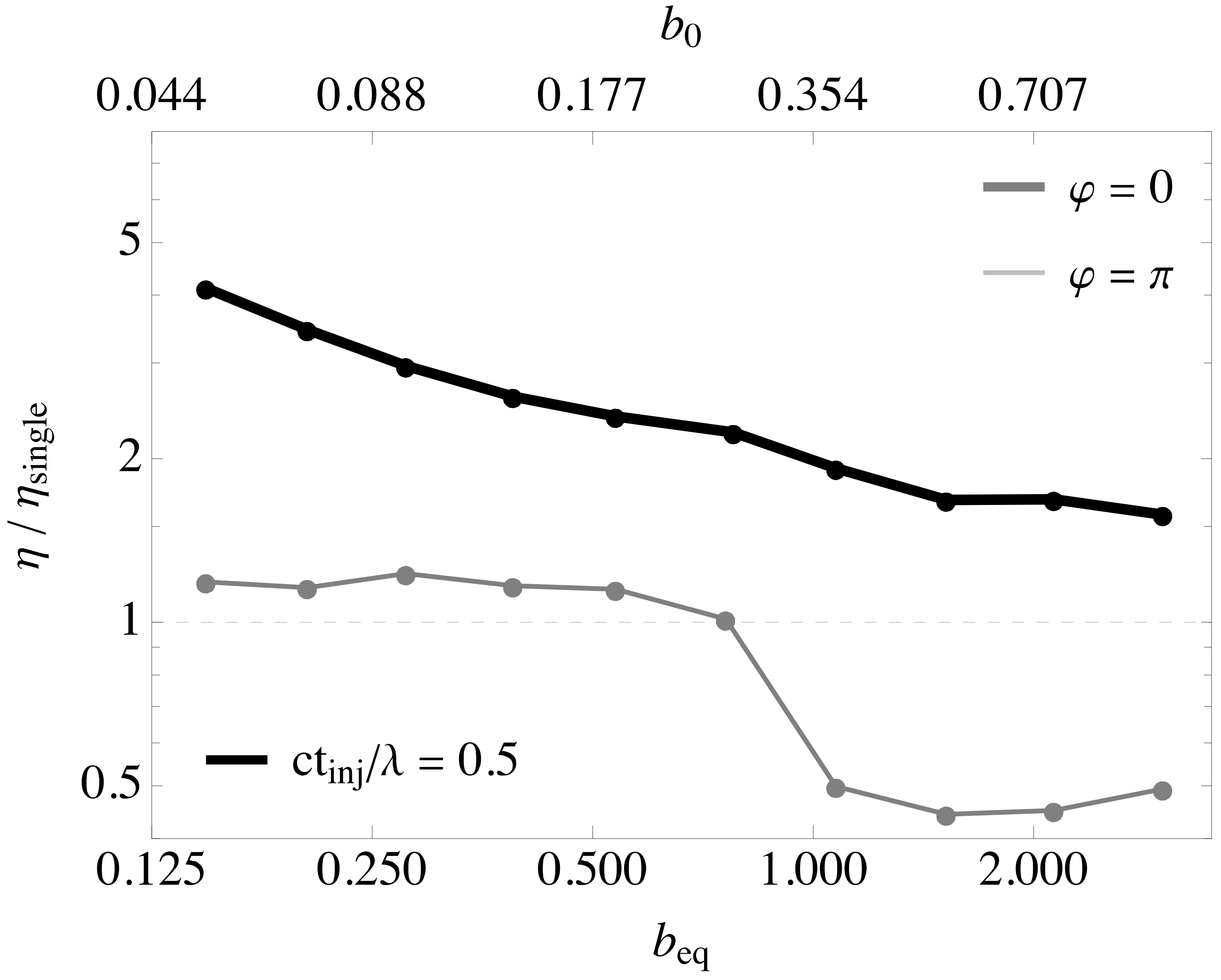
Mahlmann & Li, in prep

Wave Interactions in the Dipole Magnetosphere

- Enhanced rate of fast wave generation ——only for the case the two waves have the same polarization

- Fast waves propagating outward can break the FFE condition





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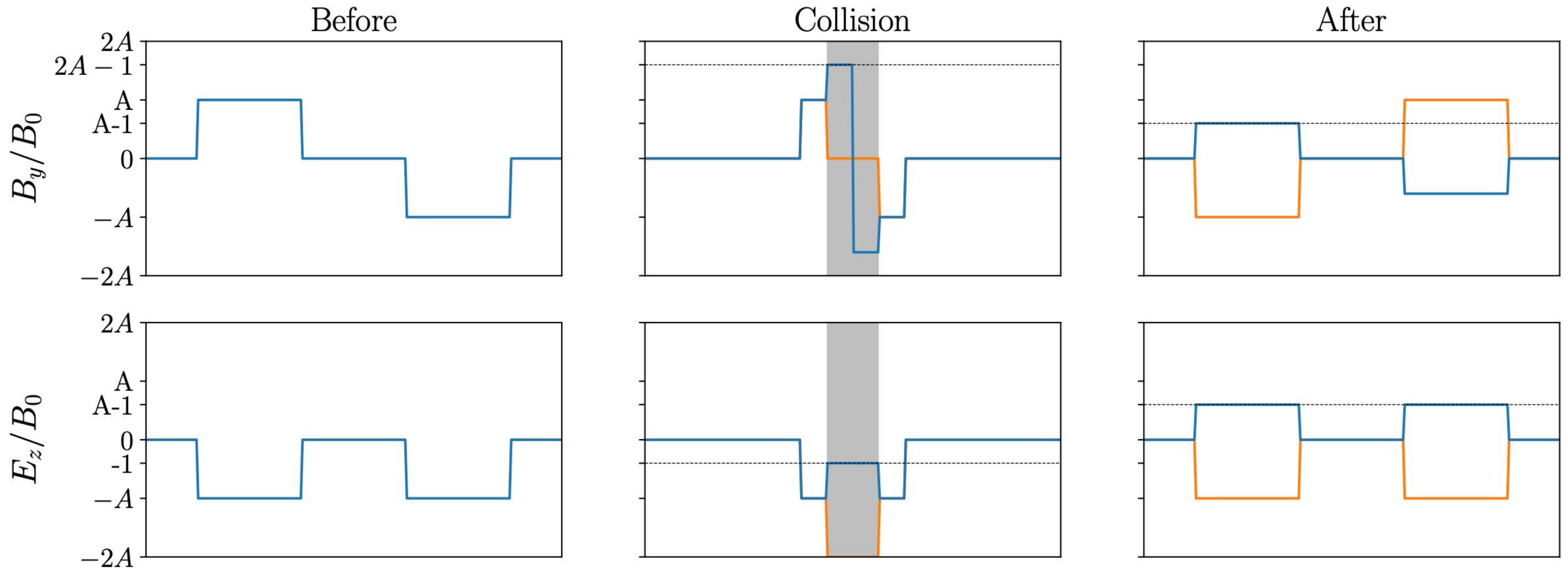
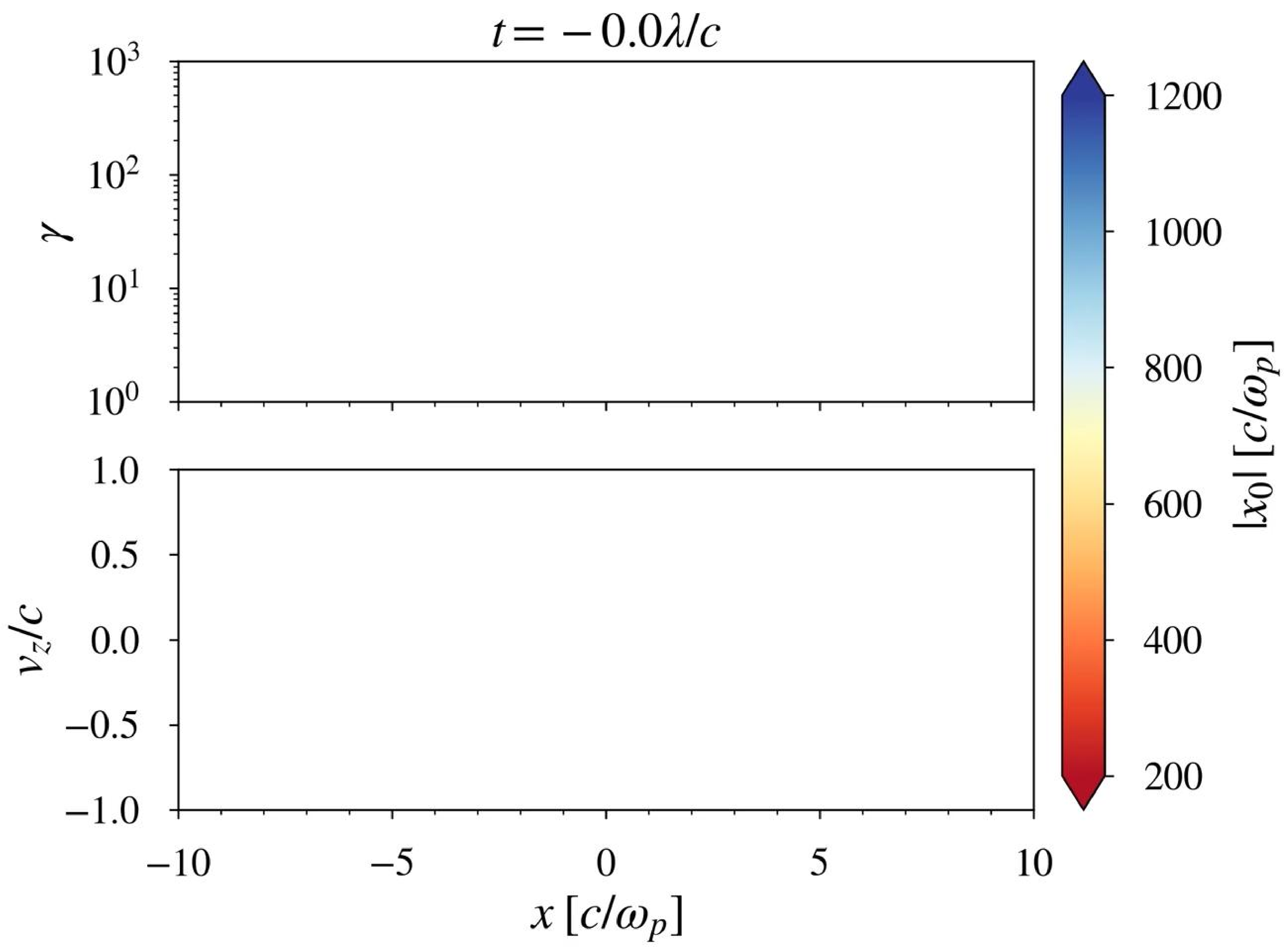
Wave Collision: Break the FFE Condition

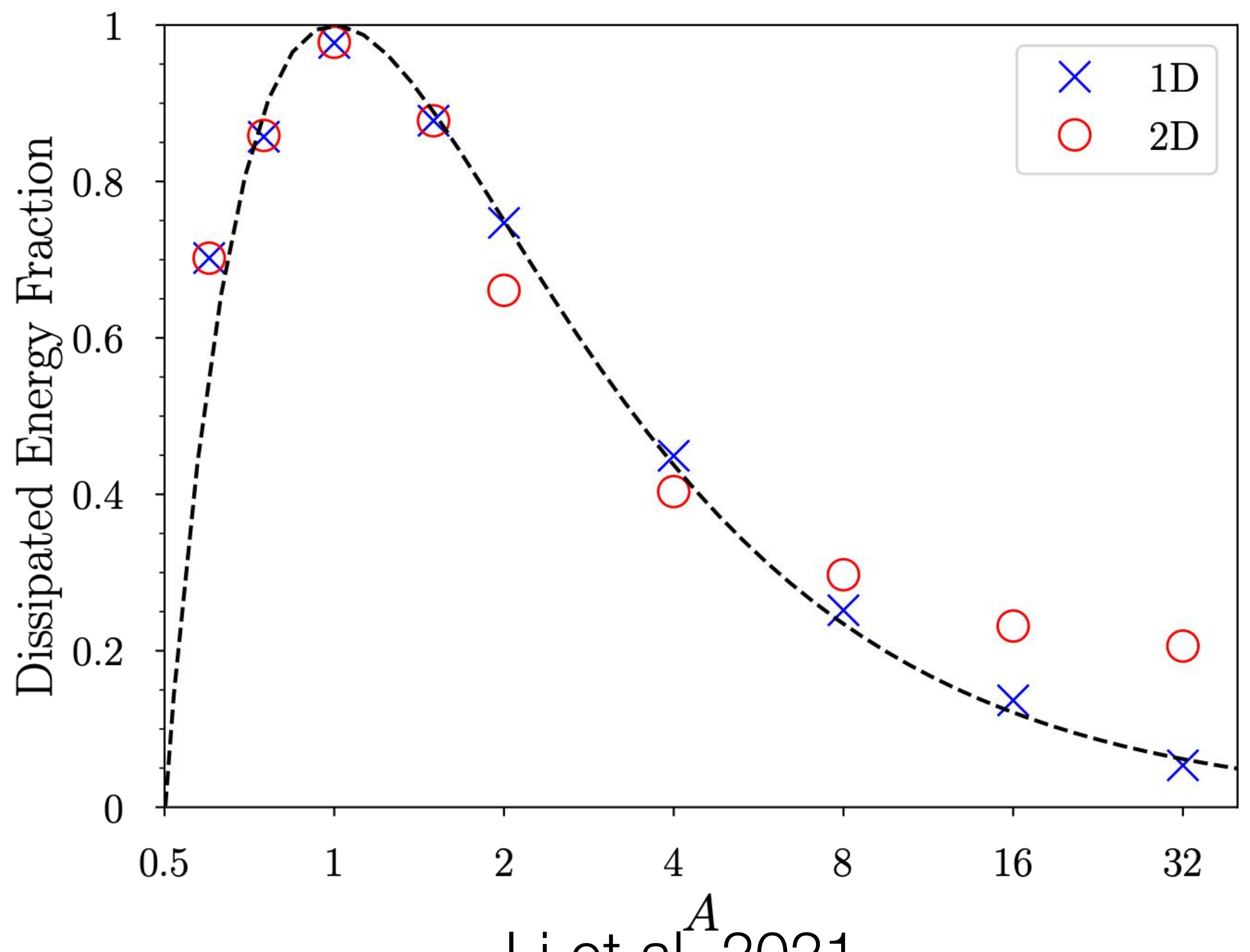
- Particles are accelerated to form a current sheet and reduce the electrical field close to B_0.
- Incoming waves are reflected with amplitude |A-1|.
- A large part $f = (2A - 1)/A^2$ of the incoming wave energy is dissipated to particles.



Wave Collision: Break the FFE Condition

- 1D dissipation agrees with analytical calculations $f = (2A-1)/A^2$, ~100% efficiency for A=1.
- For 2D cases, dissipation of large amplitude waves is dominated by normal reconnection with dissipated fraction ~20%.





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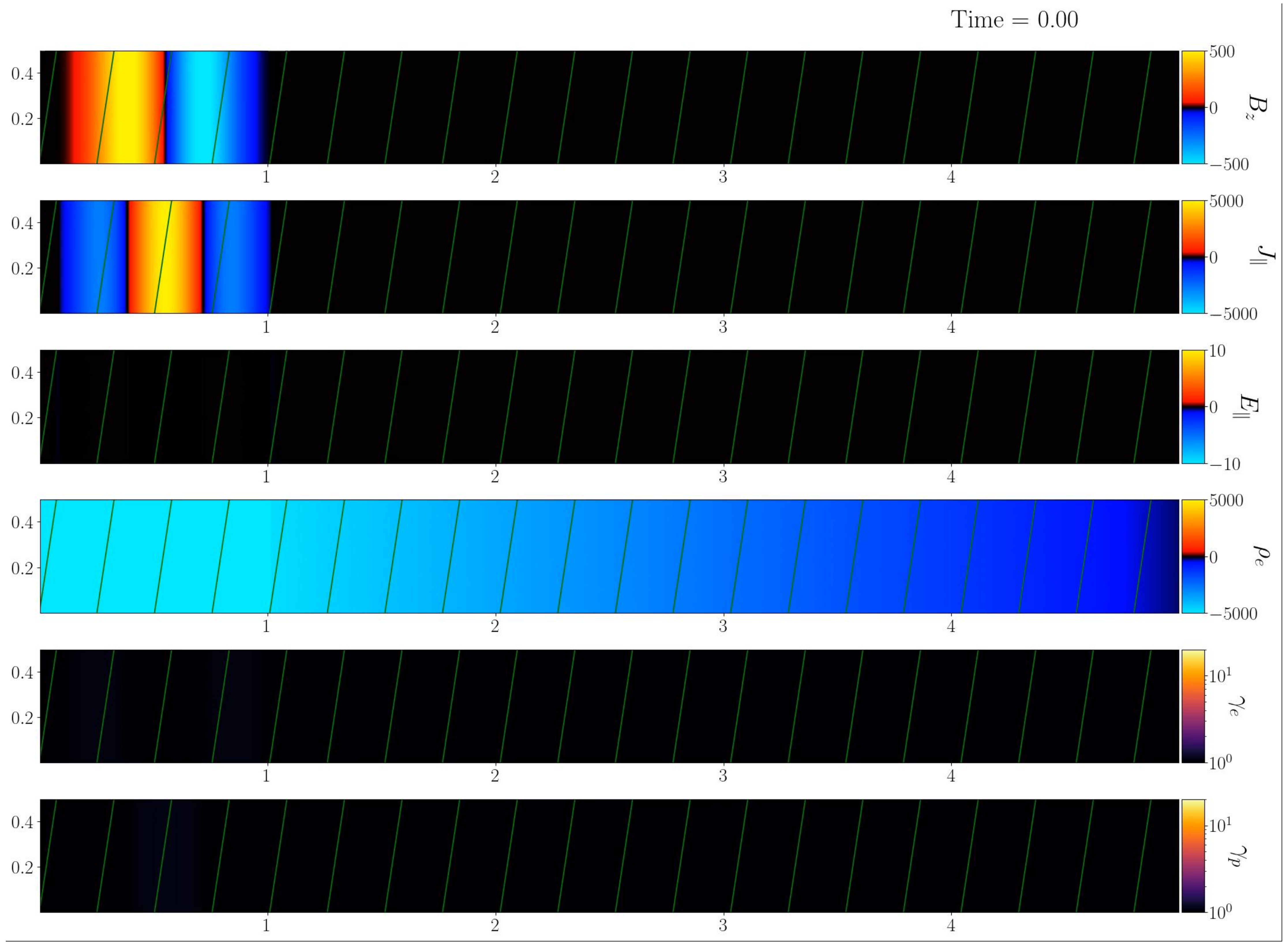
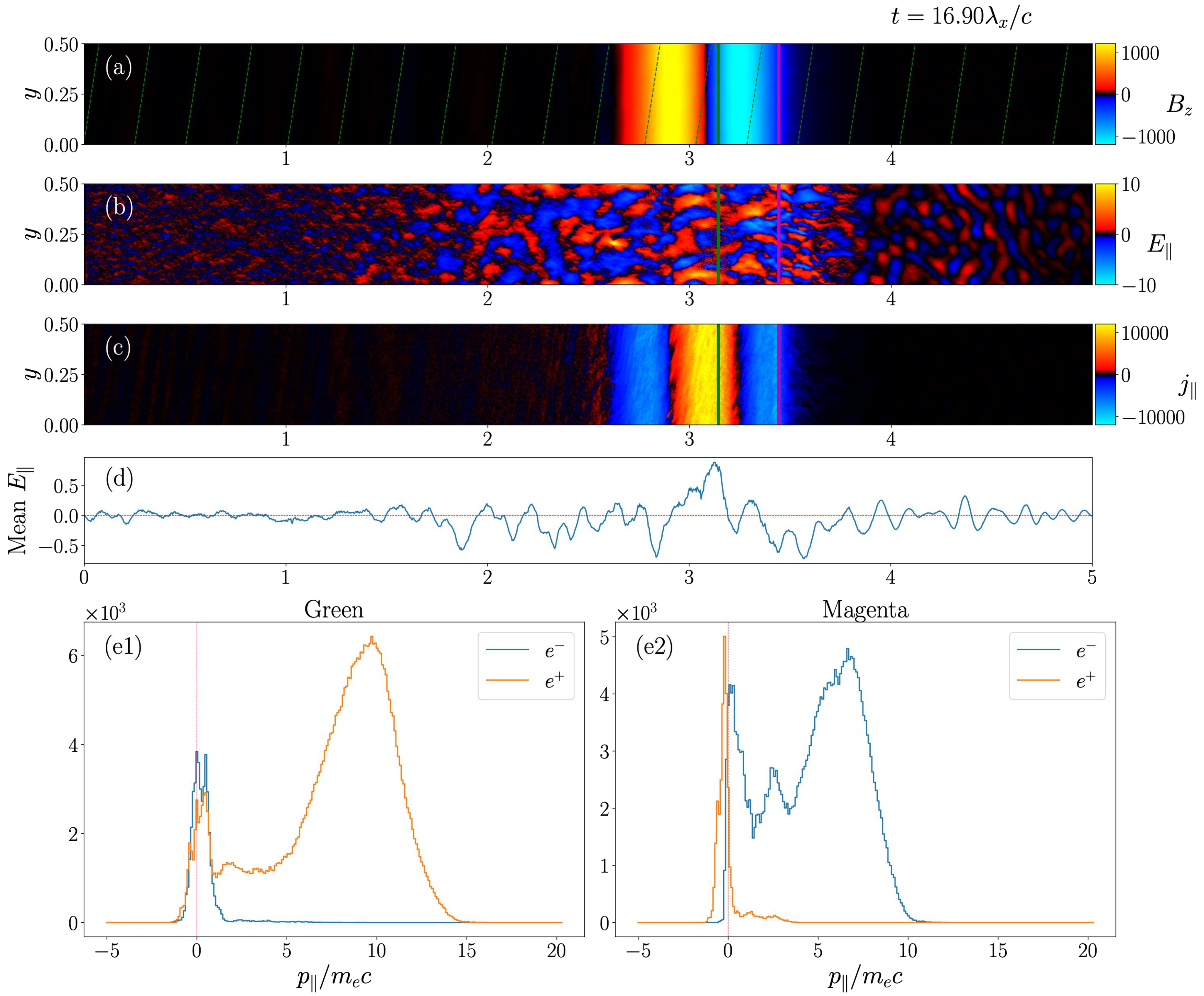
Strongly Sheared Alfven Waves

- **No charge starvation!** Particles advected with the waves get accelerated to support the current for wave propagation.





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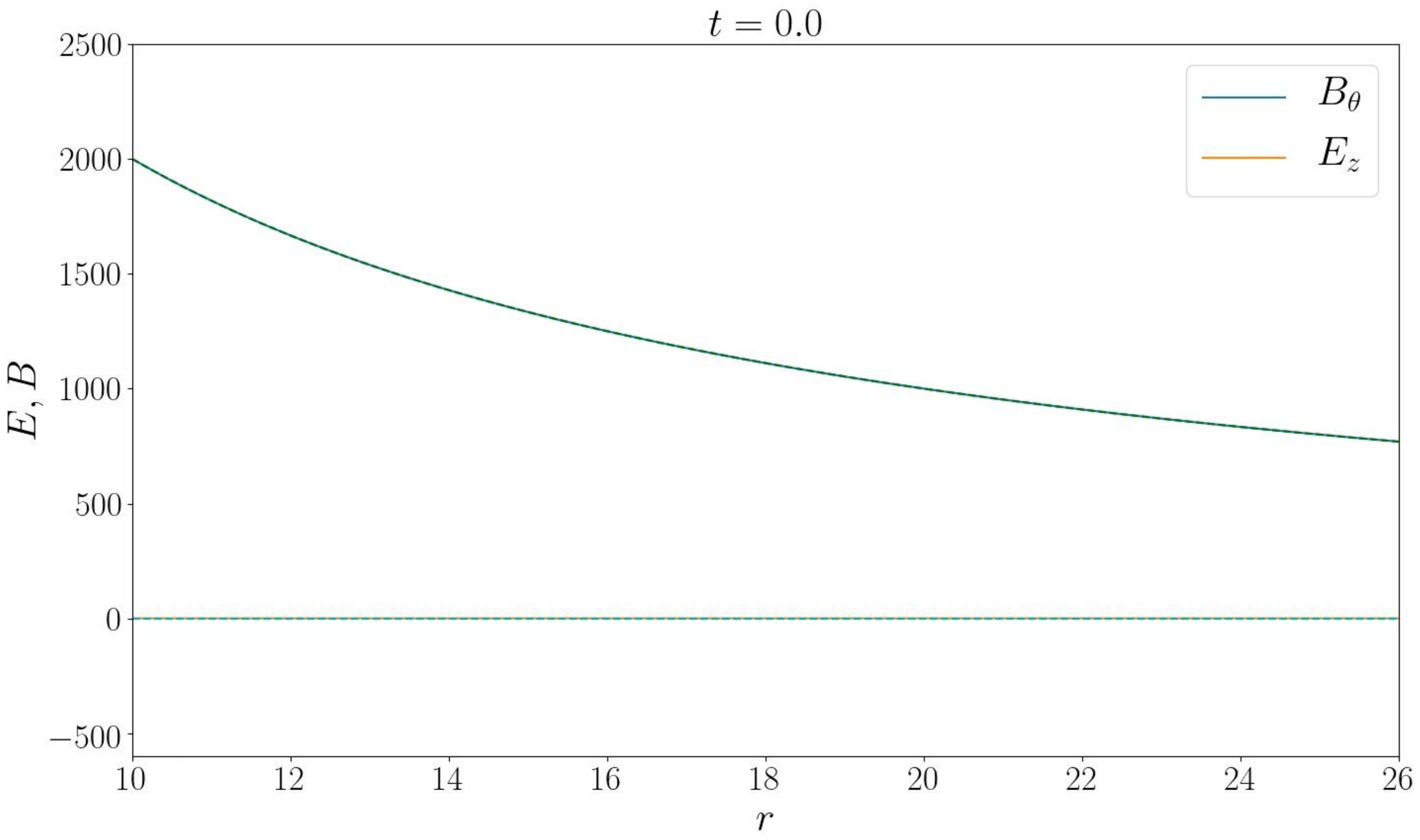
Strong Wave Propagation

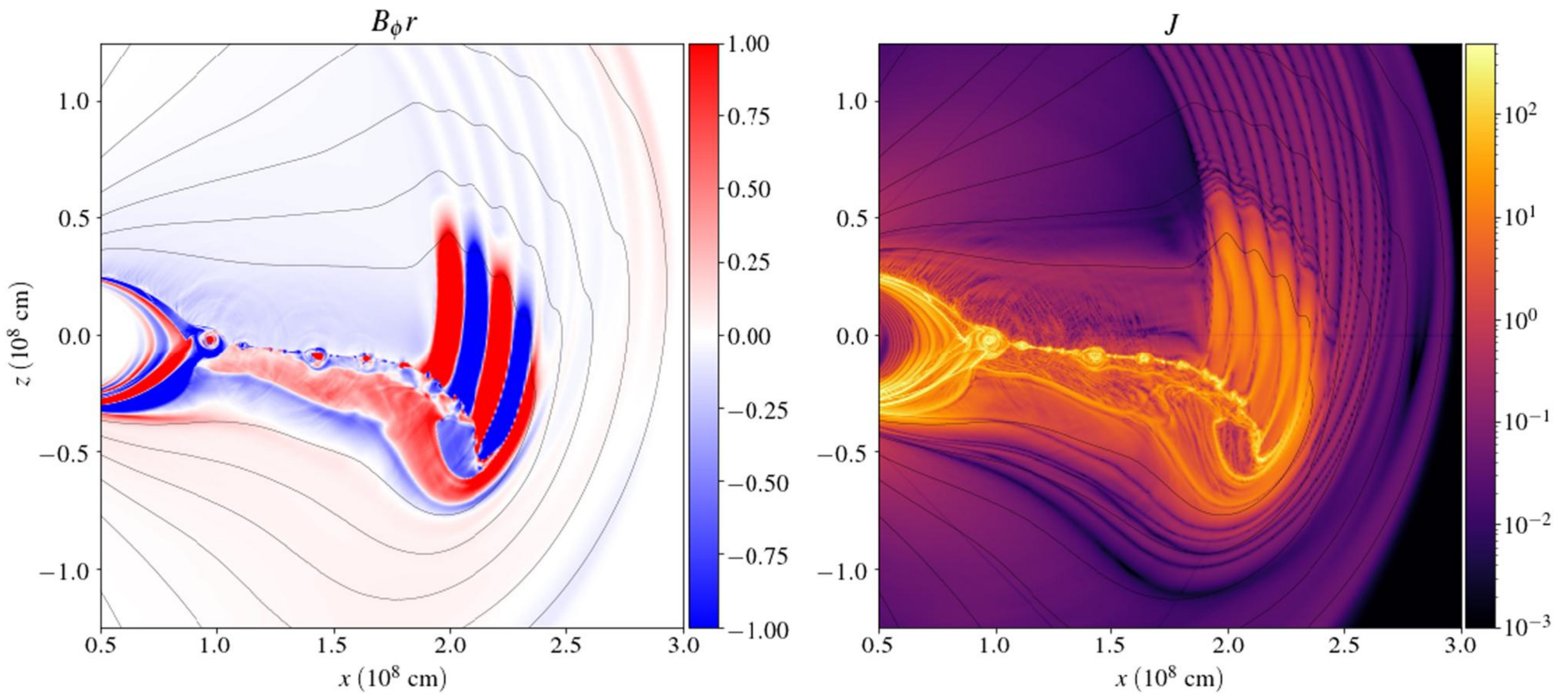
- Wave steepens into a shock. Plasma particles drift into the shock and undergo coherent gyration, and subsequently become thermalized.
- Quickly dissipates the energy of strong waves emitted deep within the magnetosphere, preventing GHz waves (FRB) from escaping (Beloborodov 2021,2022,2023)
- May provide an alternative way to launch shocks in the magnetosphere without requiring a relativistic ejecta



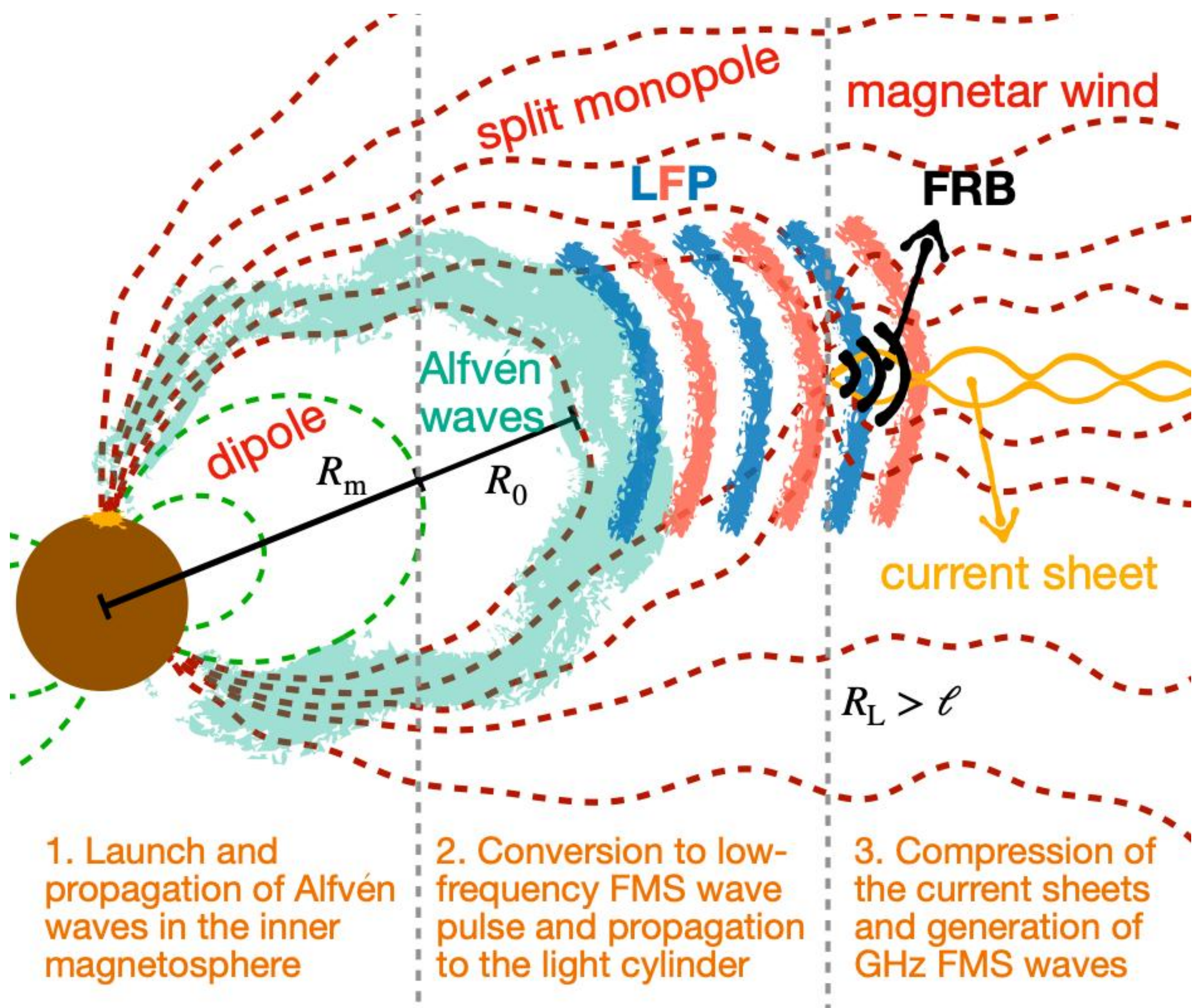
Chen et al. 2022

Application to FRB models

- **Near Field Model**: No charge starvation. Strong GHz waves (FRB) generated near the magnetar can't escape (Beloborodov 2021,2022,2023)
- **Far Field Model**: Relativistic plasmoid ejection drives blast waves to form shocks (Yuan 2020)
- **Intermediate Field Model**: Fast wave driven reconnection (Wang et al. 2022)



Yuan et al. 2021



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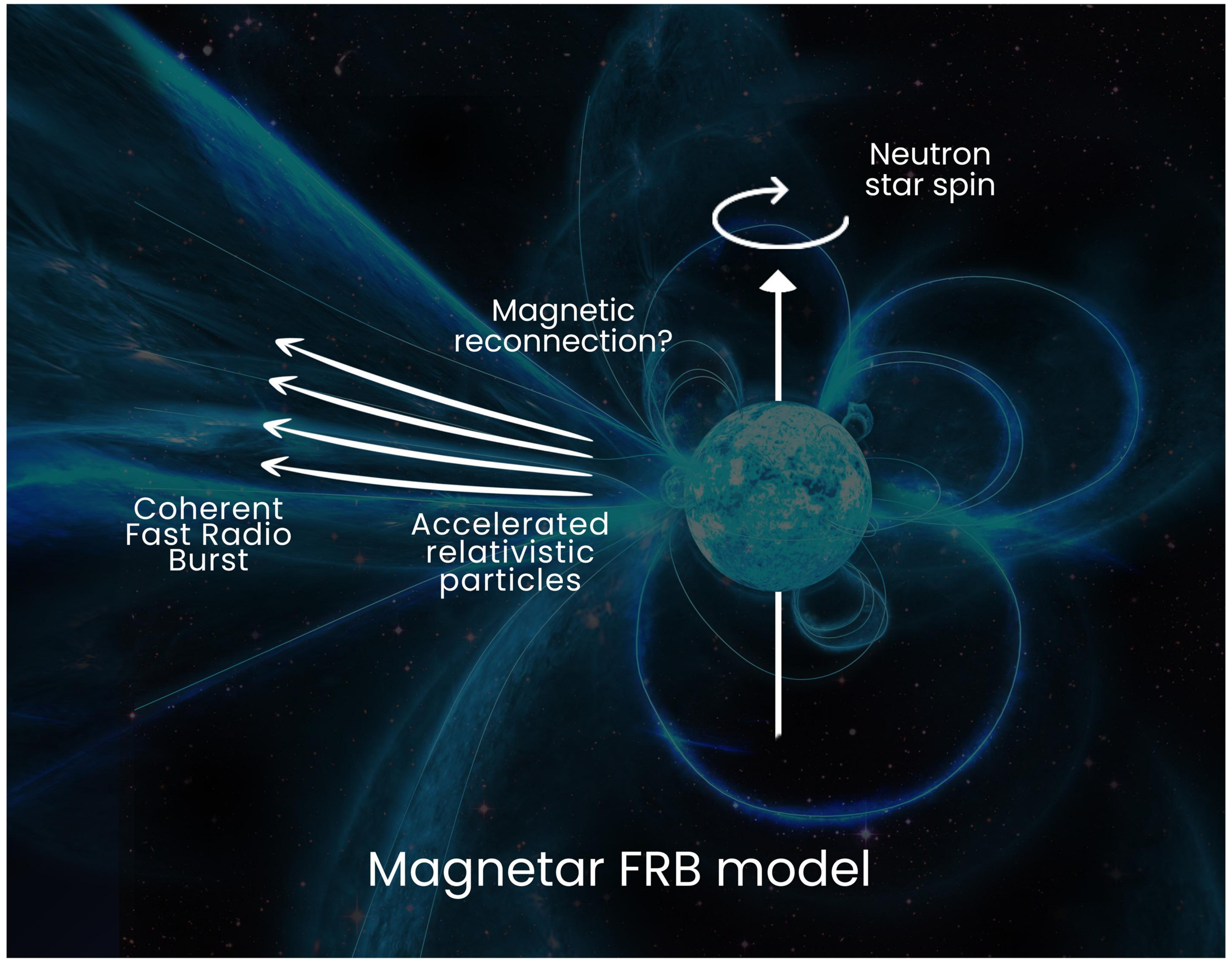
Conclusion

- Rich physics of Alfven waves and plasmas in the magnetosphere!
- More work needed to understand it before we can fully figure the origin of fast radio bursts



Thank you for your attention!