

Alfven Wave Dynamics in the Magnetar Magnetosphere

with applications to Fast Radio Bursts

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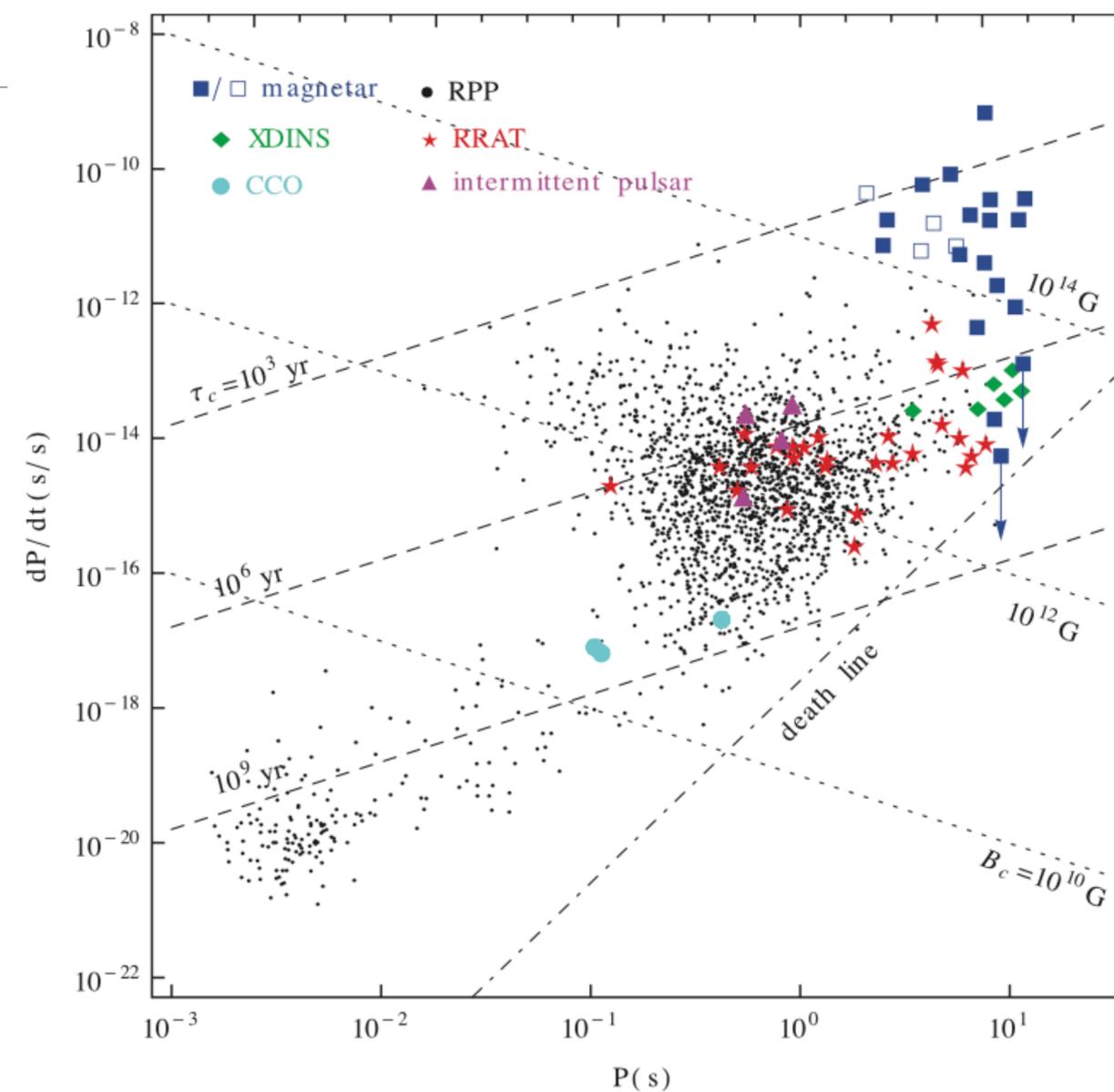
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Magnetars

- 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?

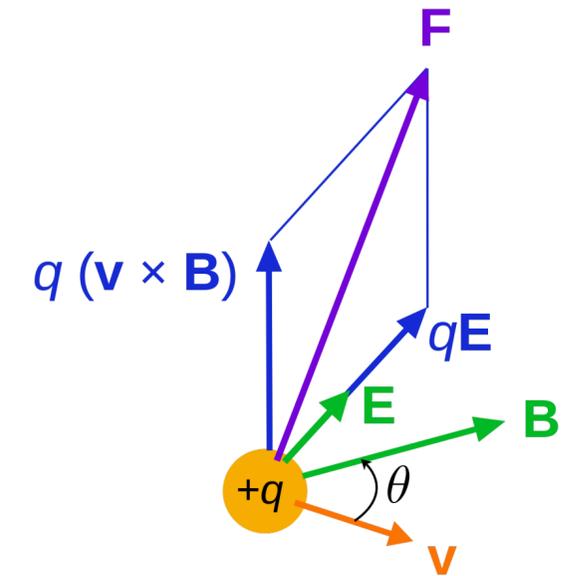


Outline

- **Magnetar magnetosphere**
 1. Wave interactions
 2. Wave collisions
- **Fast Radio Bursts**
 3. Charge starvation?
 4. Strong wave propagation
 5. A new model

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



Waves and Interactions in FFE

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

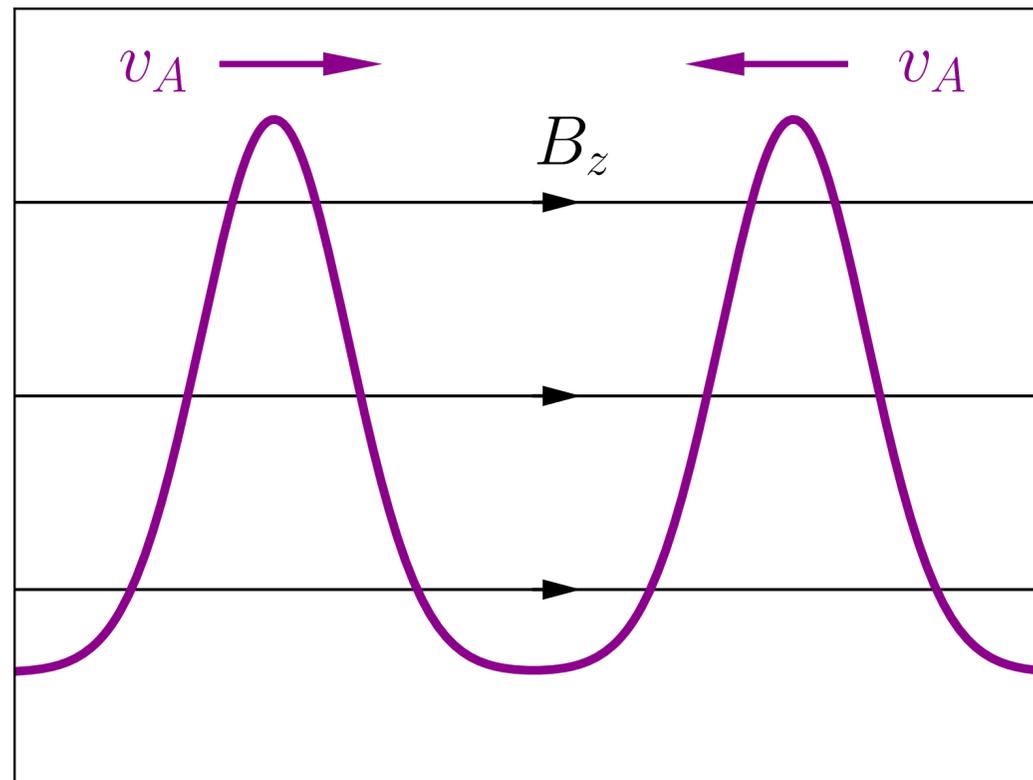
$$A + A \rightarrow A$$

$$F + F \rightarrow F/A$$

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

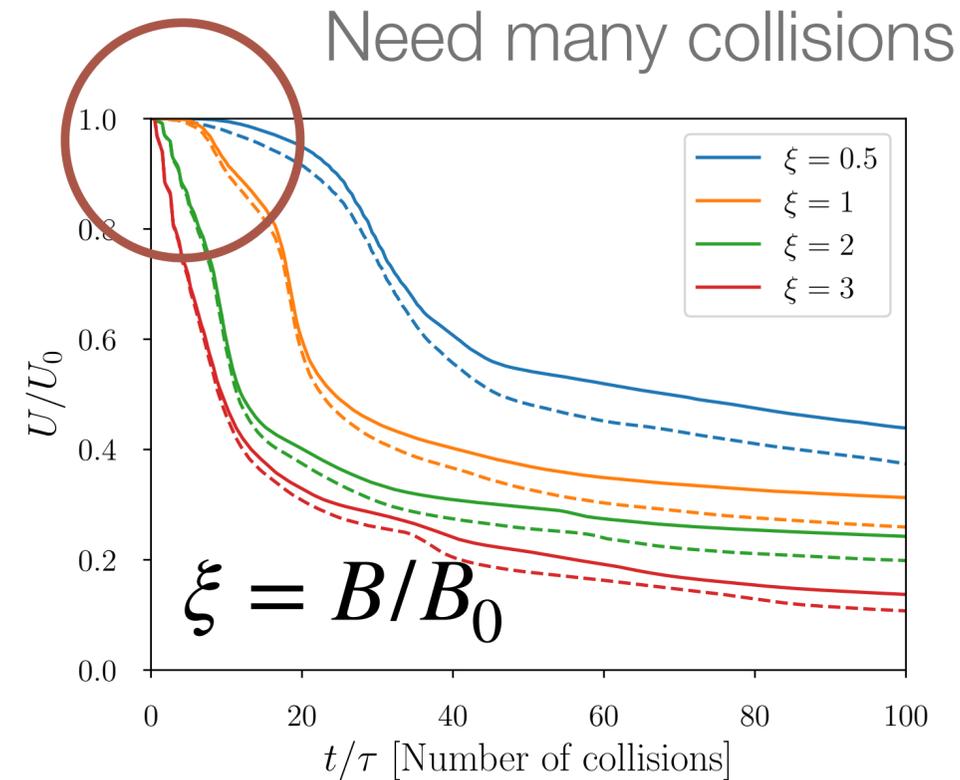
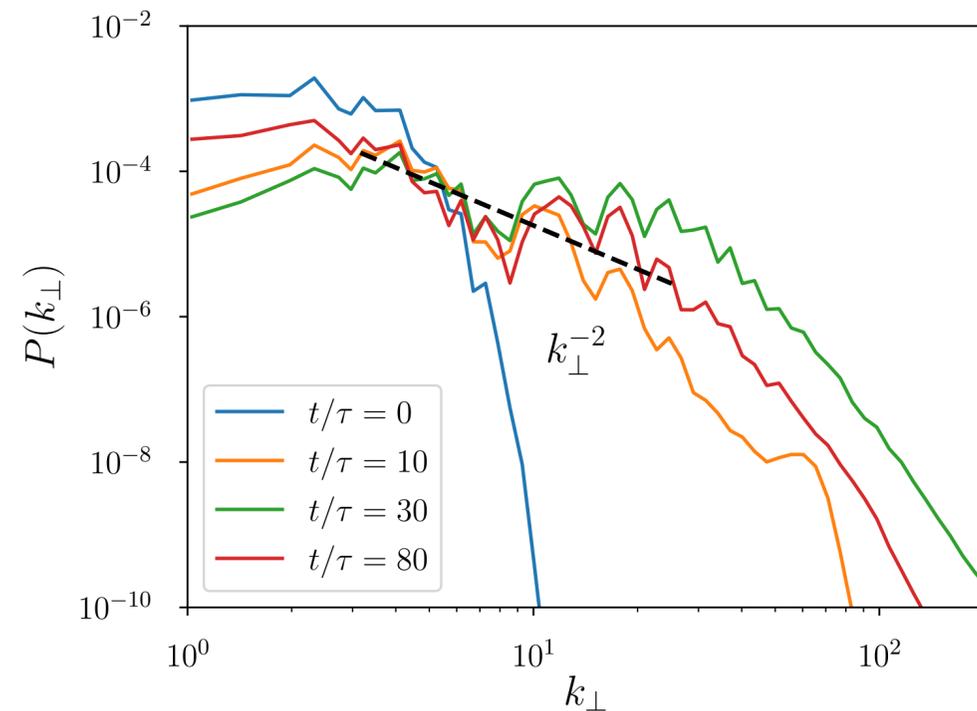
Simulation Set-up

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



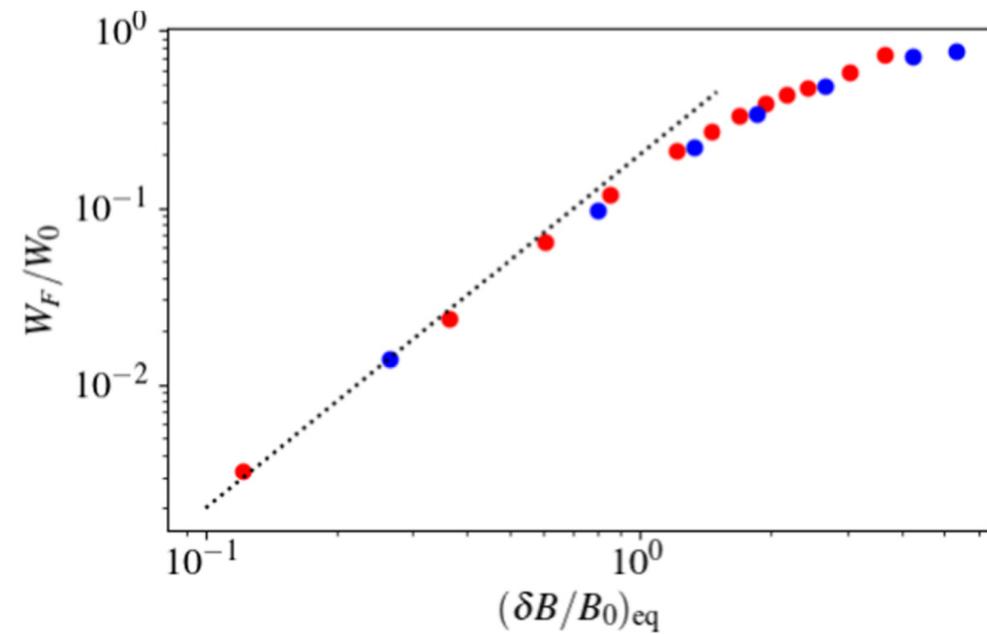
Nonlinear Wave Interaction in FFE

- Turbulent anisotropic forward cascade, with anisotropic power-law spectrum k_{\perp}^{-2}
- The dissipation is weak
- Fast waves carries away a few percent of wave energy

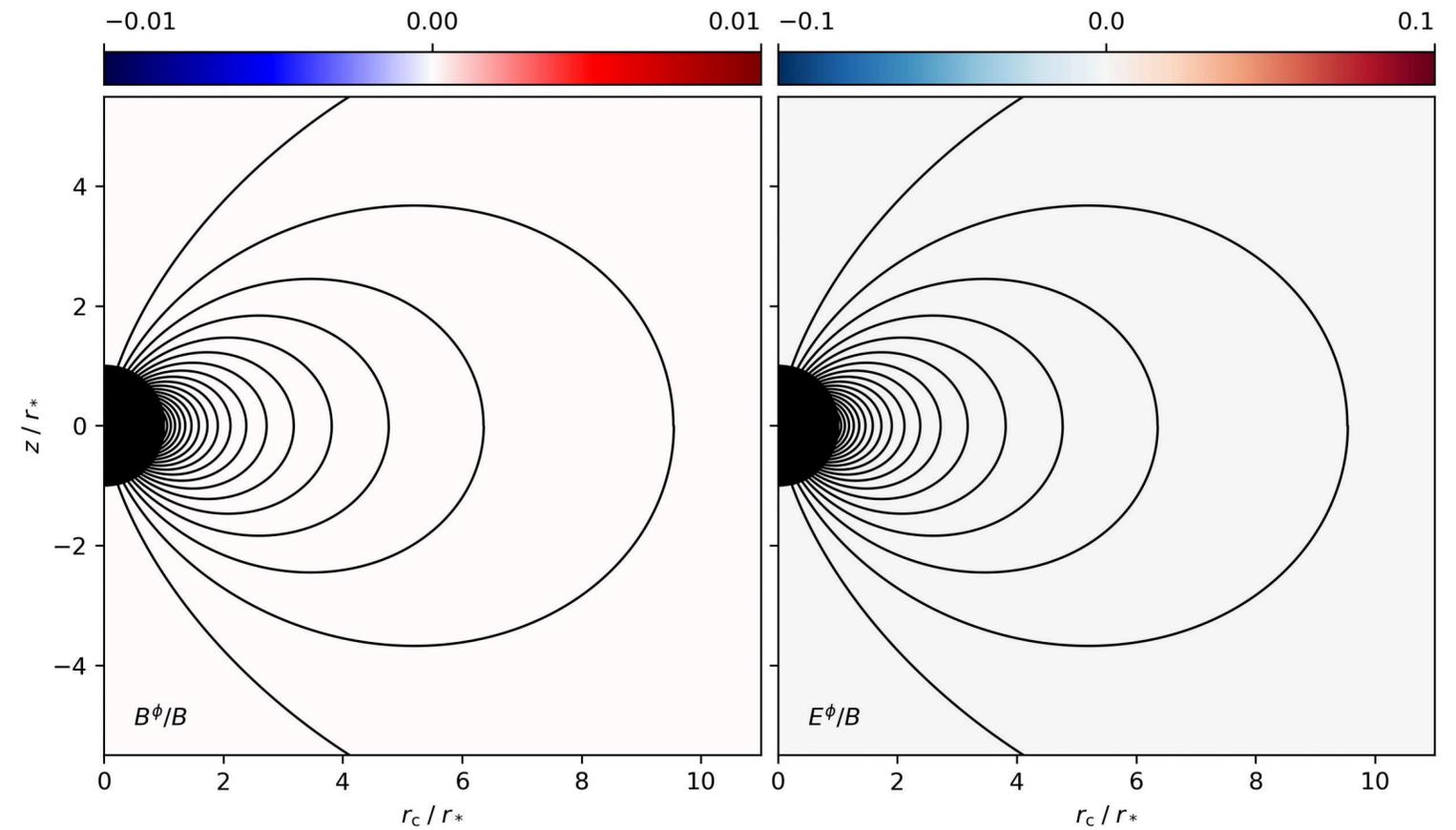


Alfven Wave in the Dipole Magnetosphere

- Outgoing fast waves are spontaneously launched (Yuan et al. 2021, Chen et al. 2024)
- Alfven waves become strongly sheared



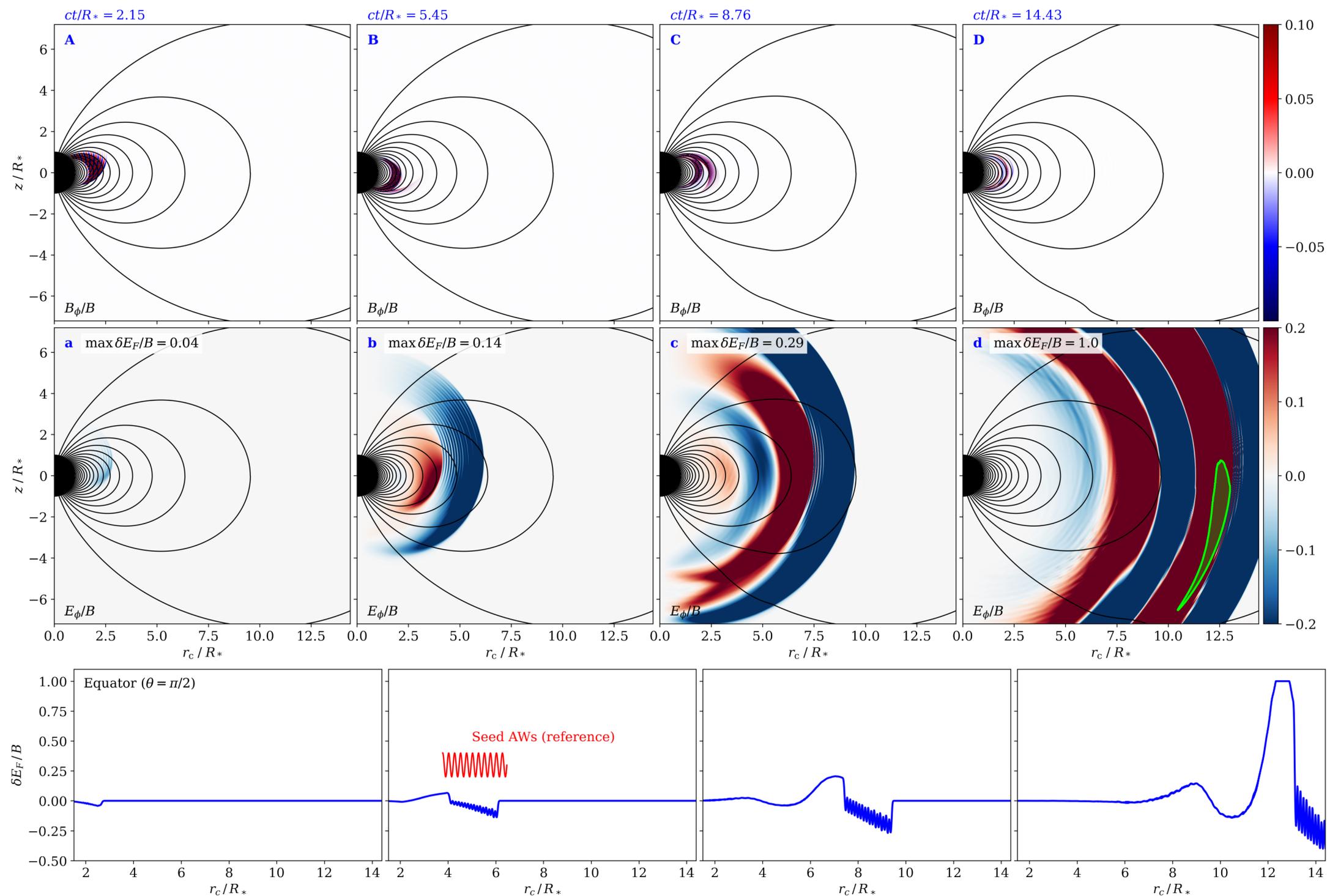
Yuan et al. 2021



Mahlmann, Aloy & Li 2024

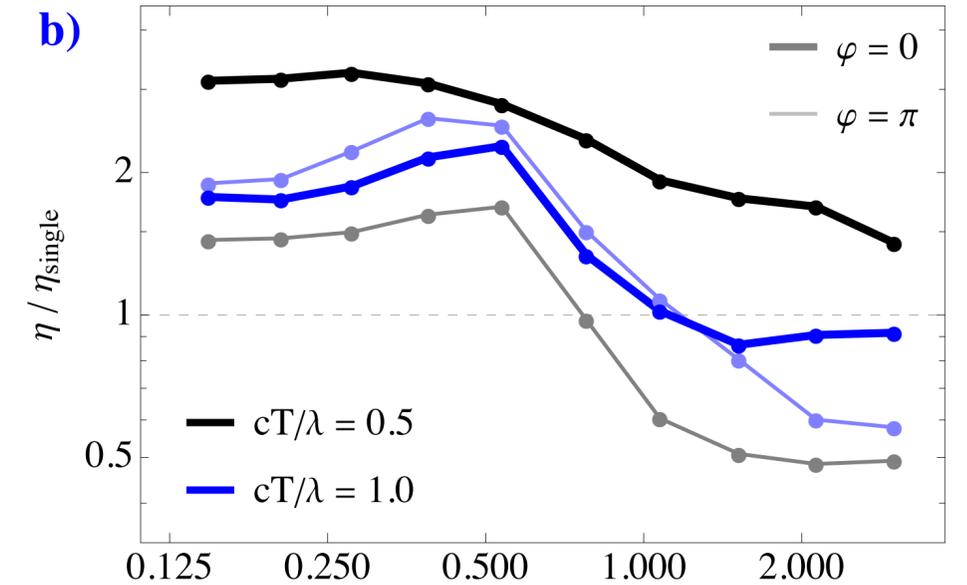
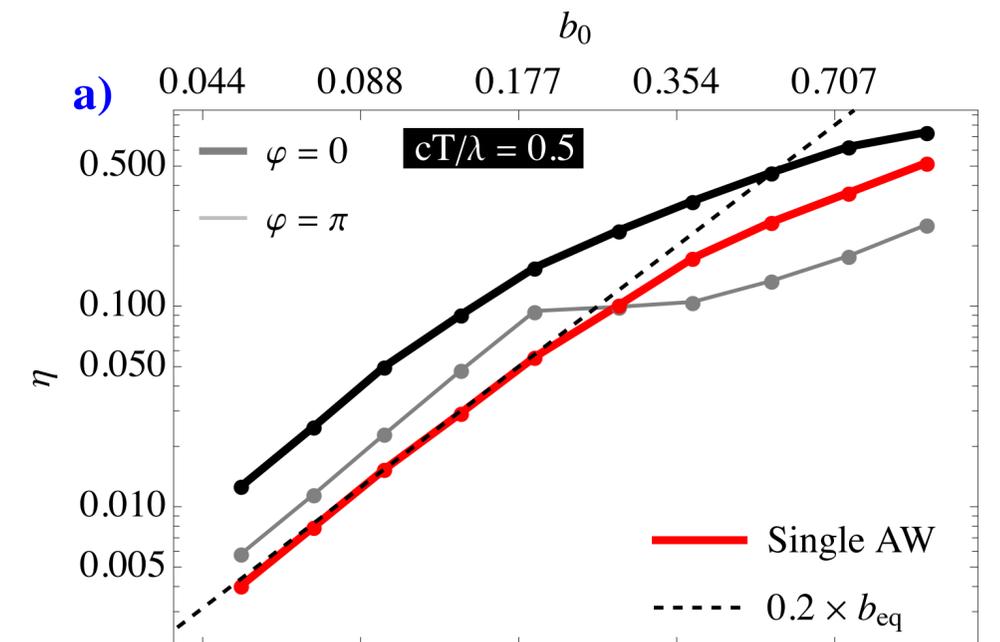
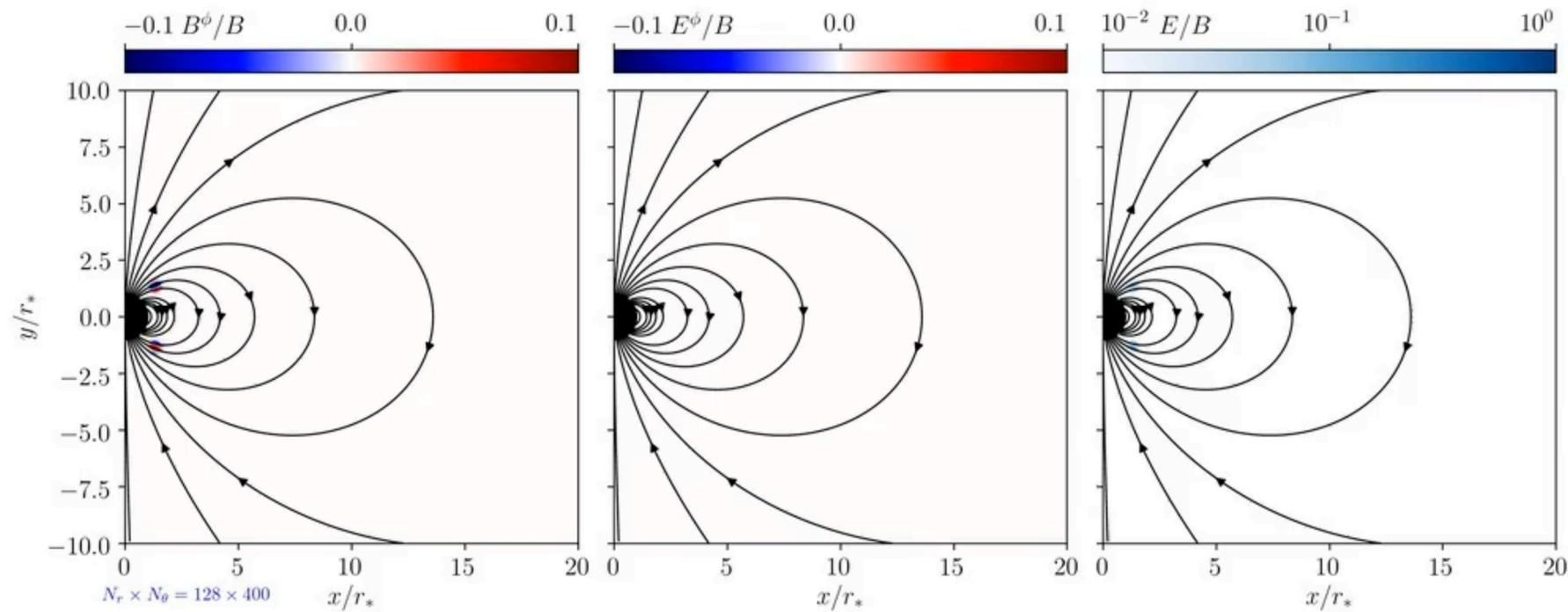
A closer look at fast waves

- High frequency waves of $2 \times$ Alfvén frequency is launched mostly in the first passing, due to the curved magnetic lines.
- Low frequency pulses are launched each time the wave bounces back from the surface. (Mahlmann et al. 2024, Bernardi et al. 2024)



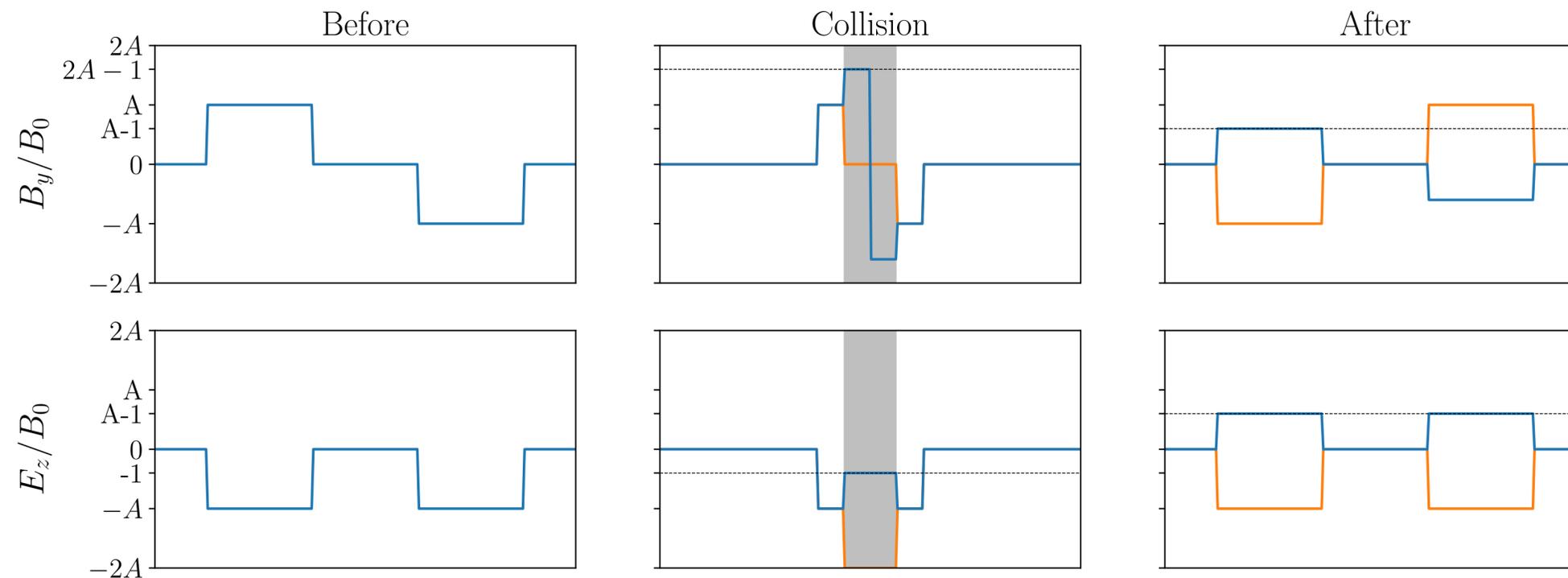
Wave Interactions in the Dipole Magnetosphere

- 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



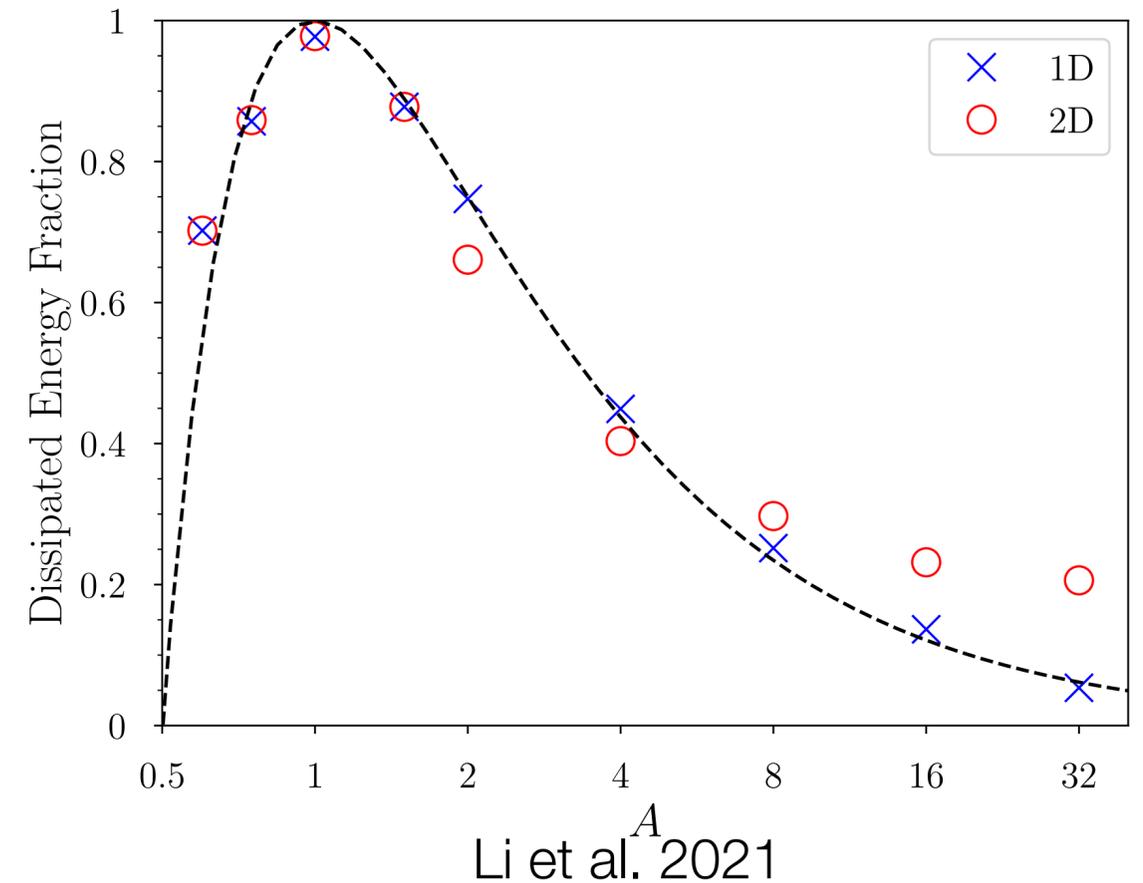
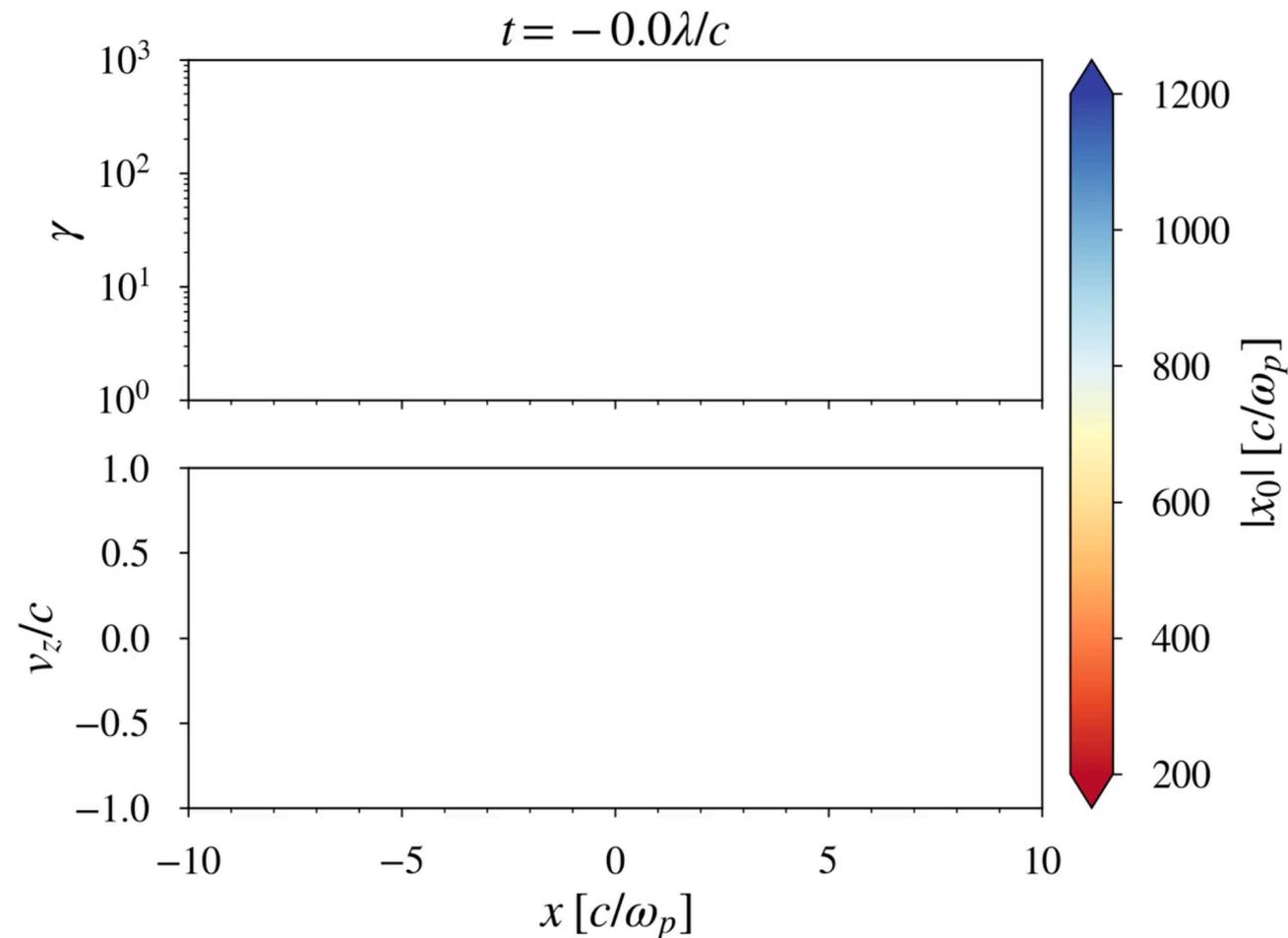
Wave Collision: Break the FFE Condition

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



Wave Collision: Break the FFE Condition

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



A short summary so far

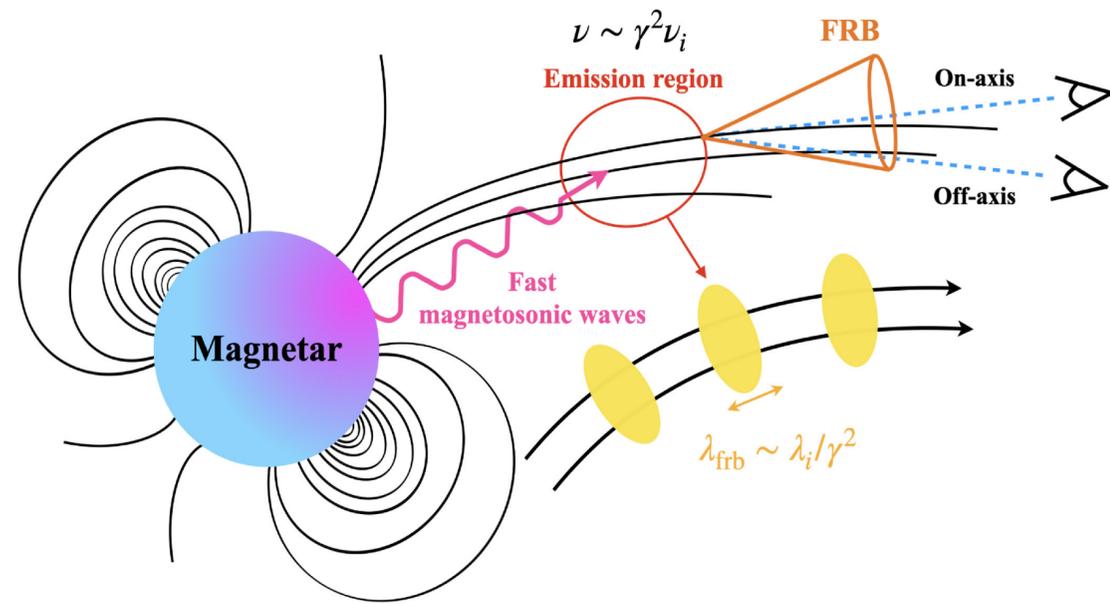
1. Wave interactions in FFE may proceed through three-wave interactions
2. In the dipole magnetosphere, fast waves are spontaneously created from Alfvén waves, high frequency component + low frequency pulses
3. FFE condition may be broken in many situations

Fast Radio Bursts

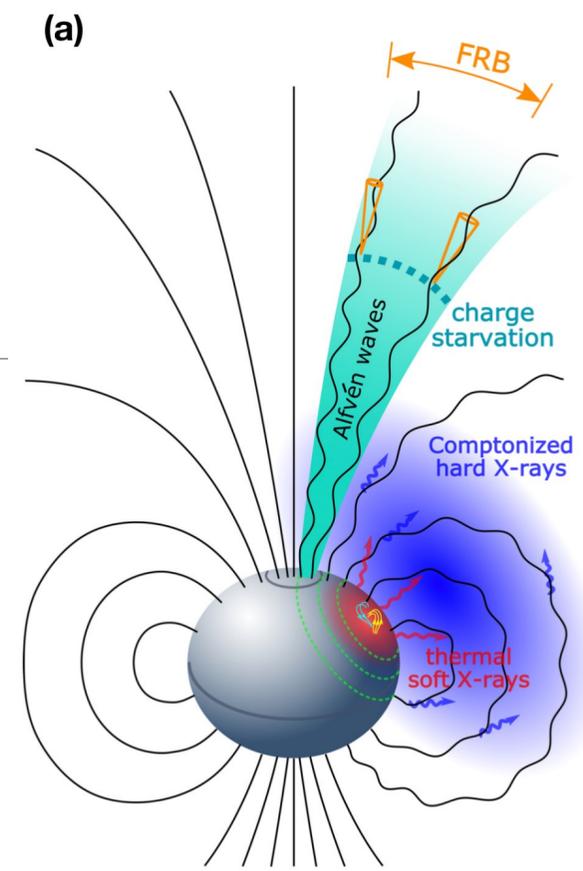
- ms-long radio pulses with high dispersion measure
- many interesting features: polarization swing, periodicity, etc
- many hints suggest it originates from neutron stars/magnetars: energetics and SGR1935



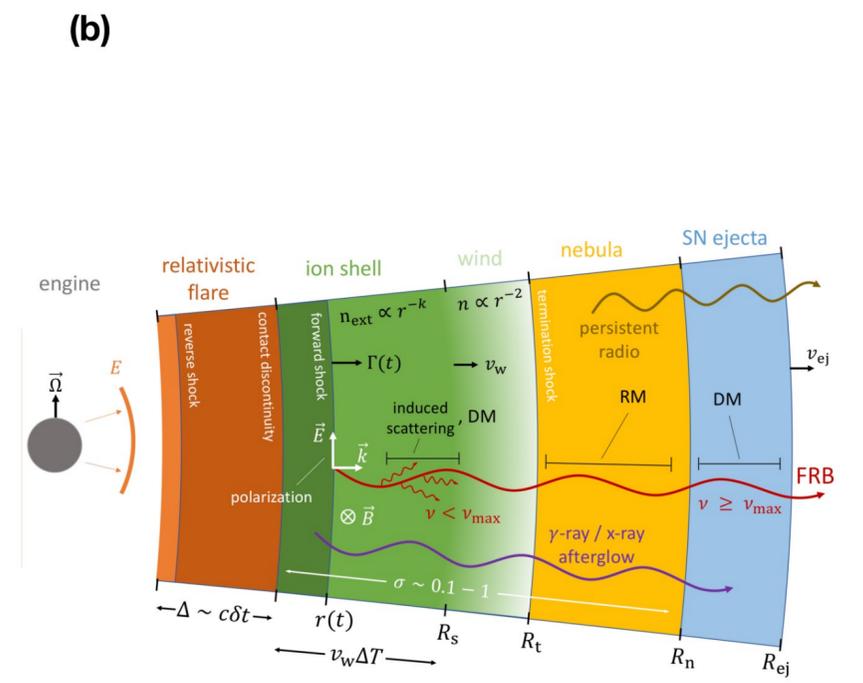
Magnetosphere vs Shock model



Magnetosphere (Kumar, Lu, Zhang)



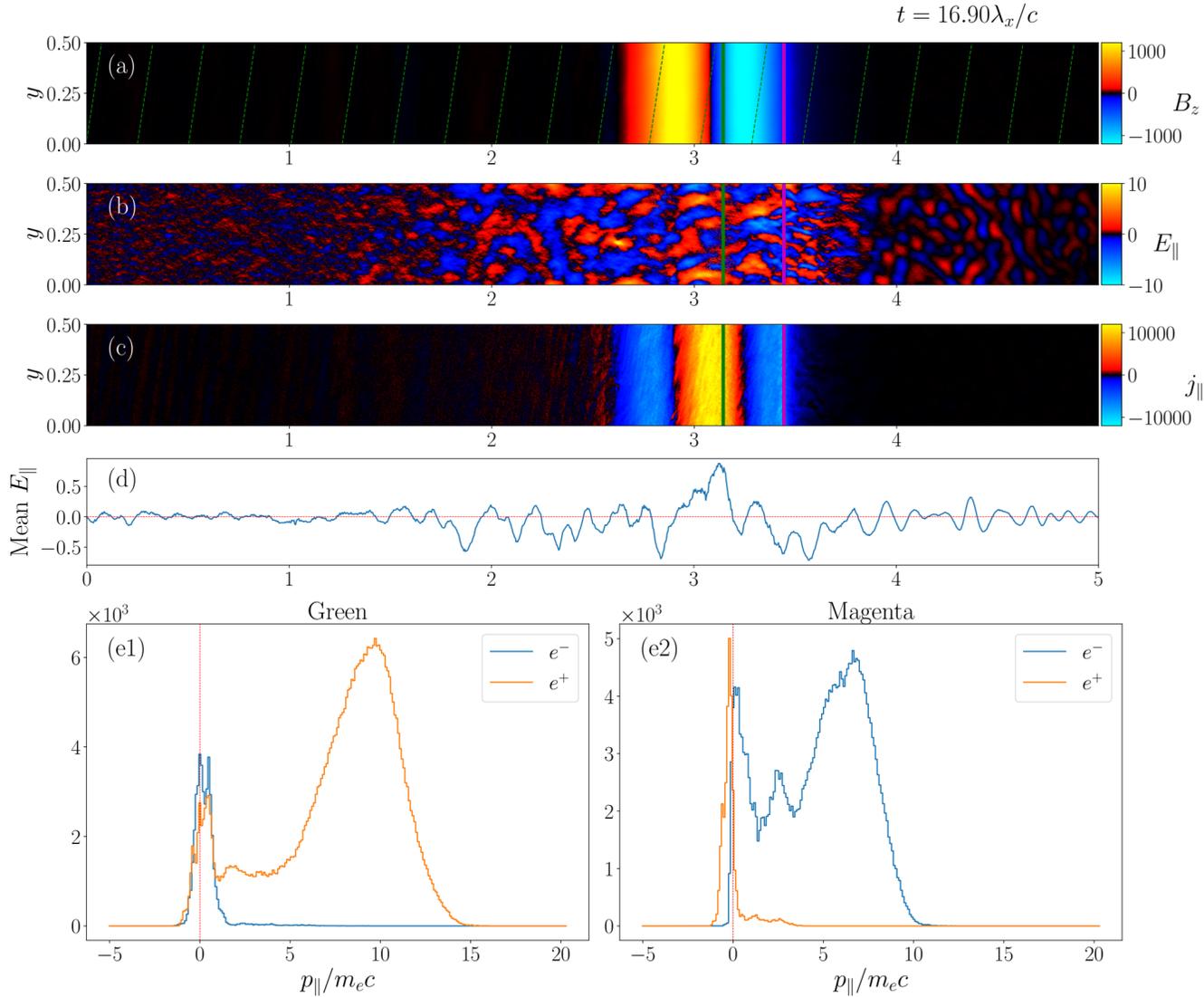
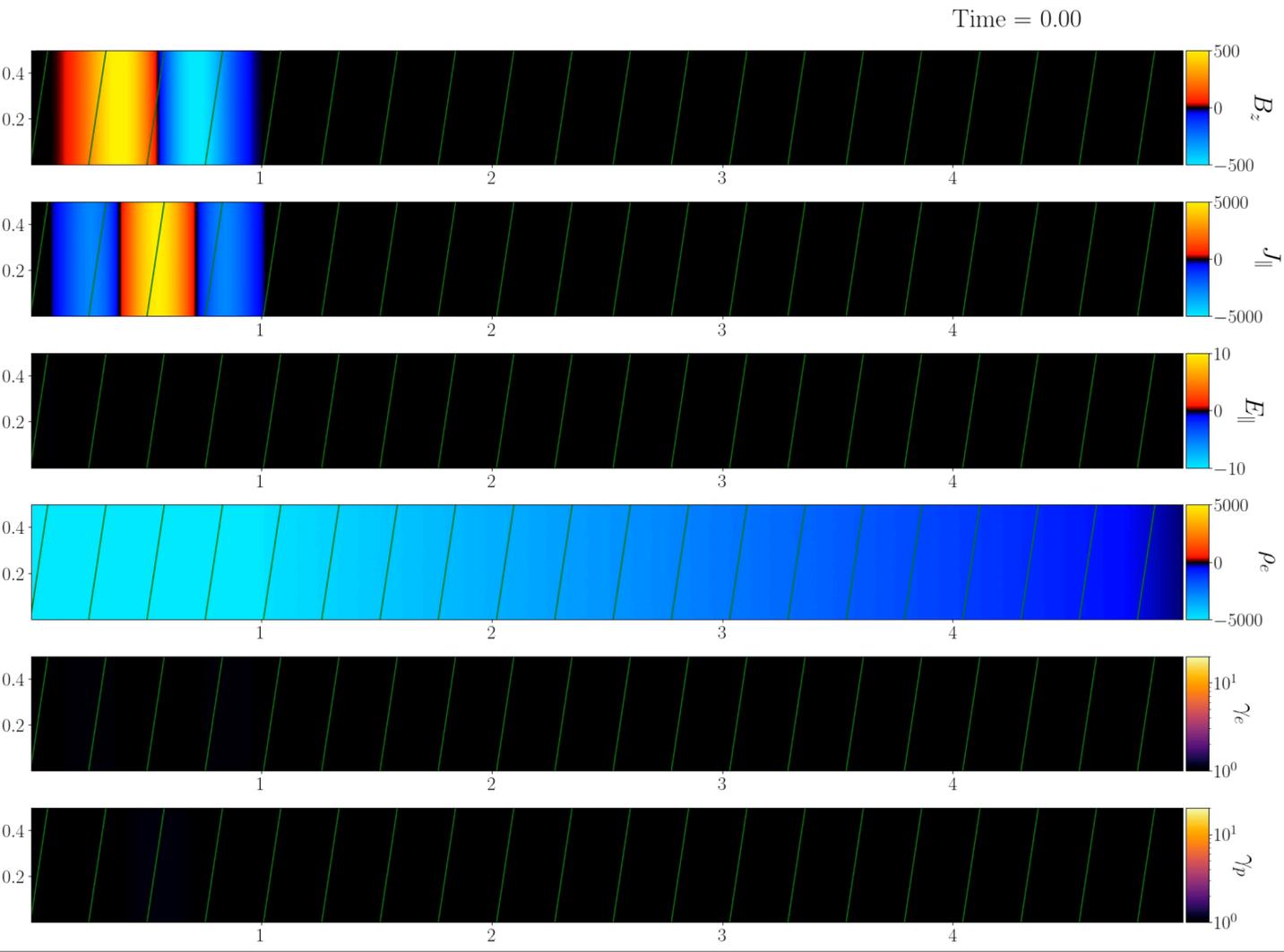
Shock (Columbia)



Region	Magnetosphere close to the NS	shock front far away from the star (10^{13} - 10^{14} cm)
Emission	Radiation by coherent bunches	Synchrotron Maser
Cons	No working mechanism for coherent bunch formation; strong	How to explain the sub second QPO; variation of polarization angle

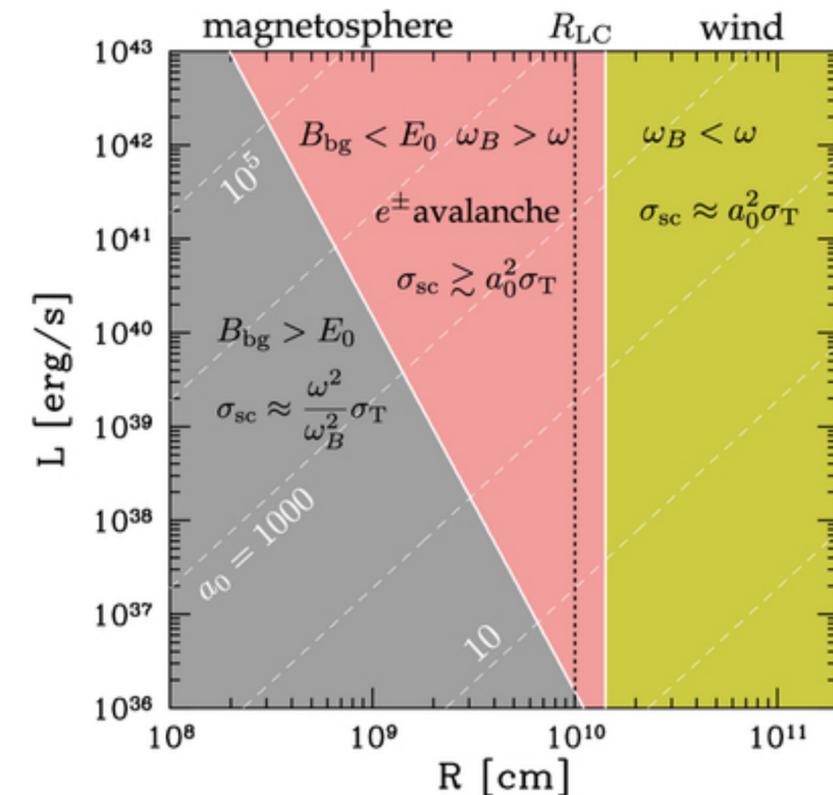
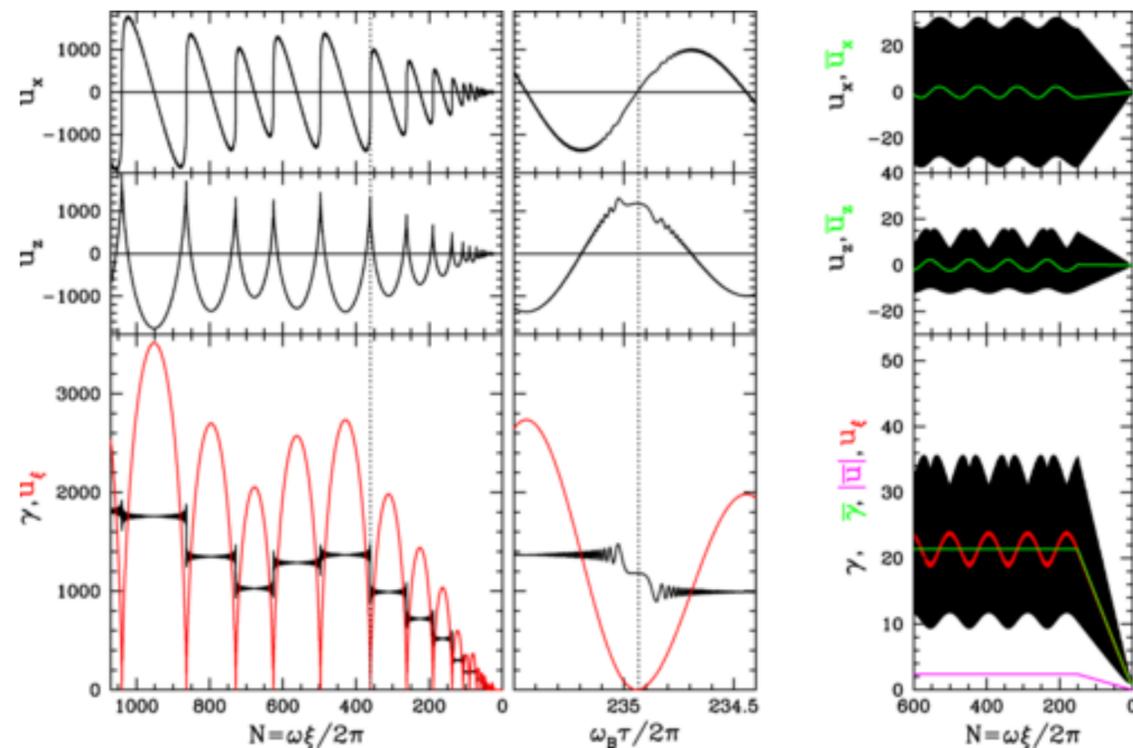
Strongly sheared Alfvén waves

- No charge starvation!** Particles advected with the waves get accelerated to support the current for wave propagation. (Chen et al. 2022)



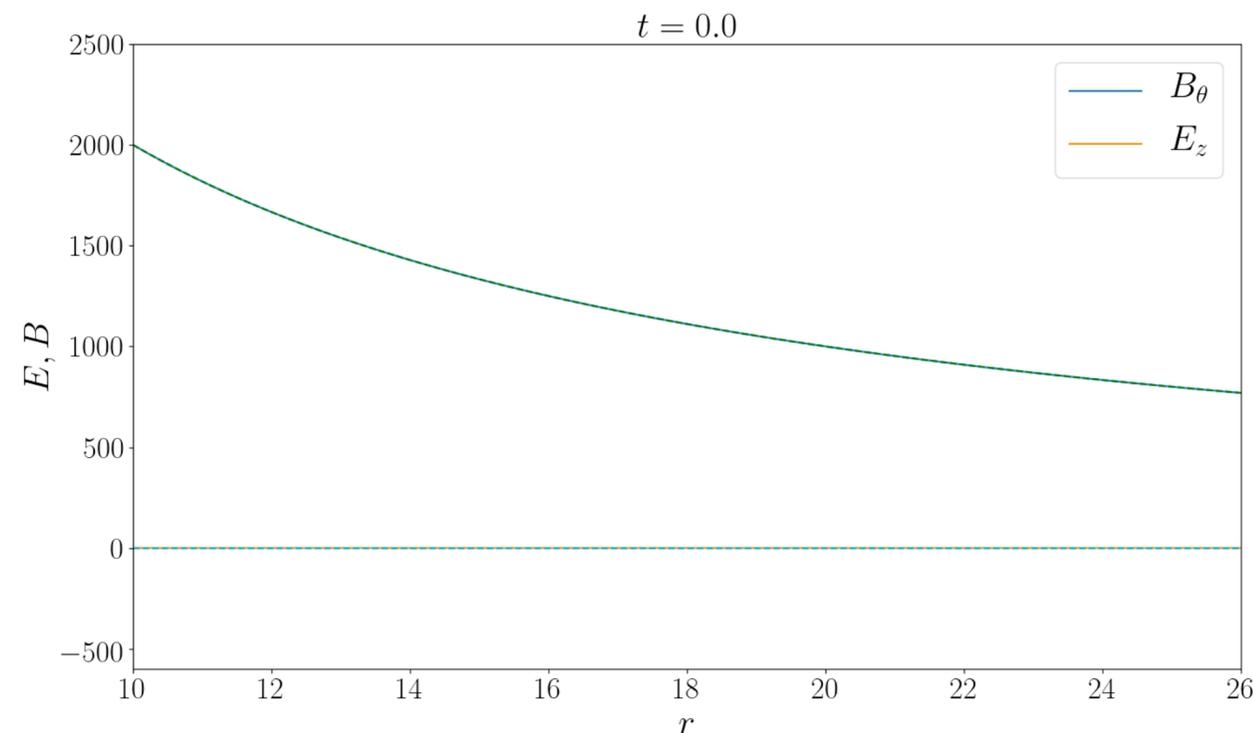
Can strong wave escape the magnetosphere?

- As we have seen in the previous simulation, strong fast waves can break FFE condition as it propagates away.
- Quickly dissipates the energy of strong waves emitted deep within the magnetosphere, preventing GHz waves (FRB) from escaping (Beloborodov 2021, 2022, 2023)



Strong wave propagation

- Kinetic simulation of strong wave propagation
- Wave steepens into a shock. Plasma particles drift into the shock and undergo coherent gyration, and subsequently become thermalized.
- May provide an alternative way to launch shocks in the magnetosphere without requiring a relativistic ejecta



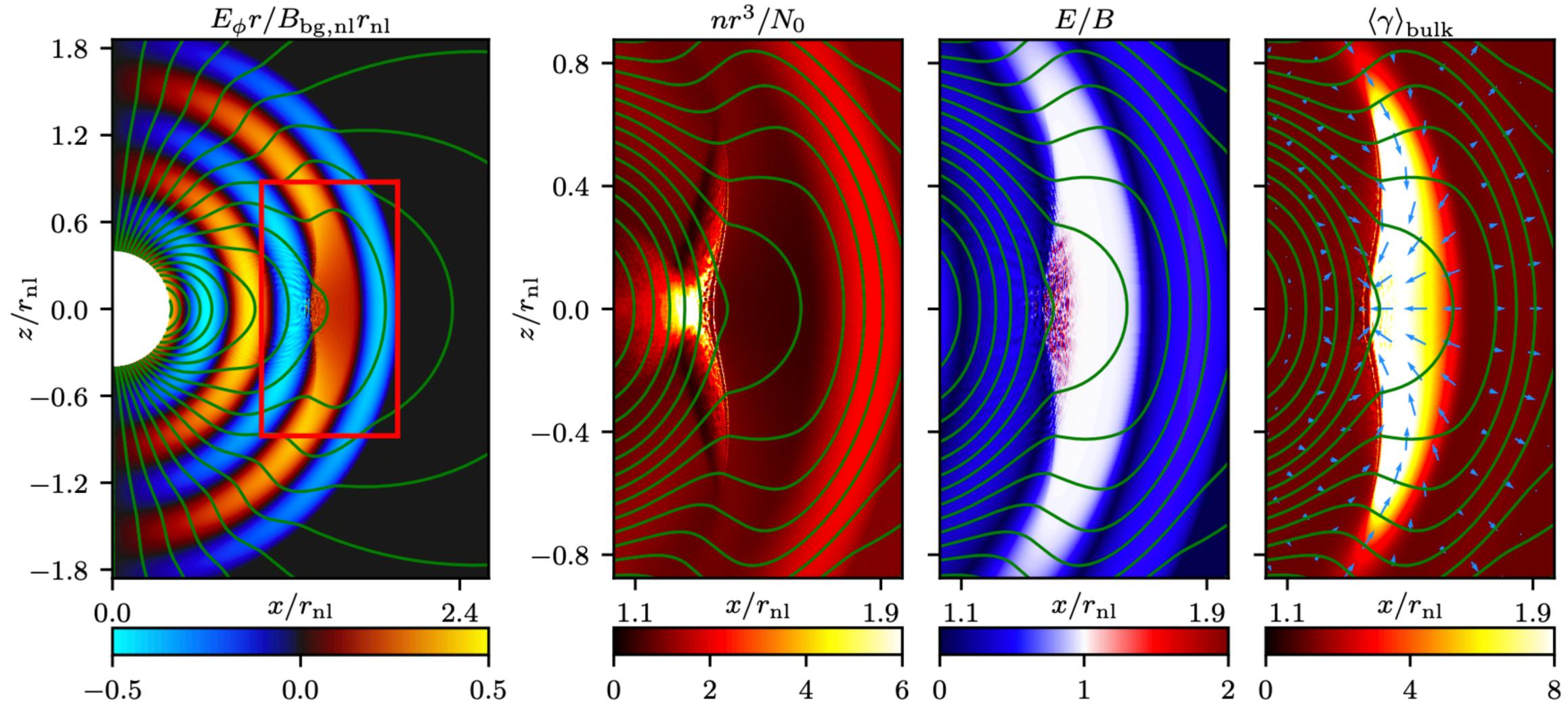
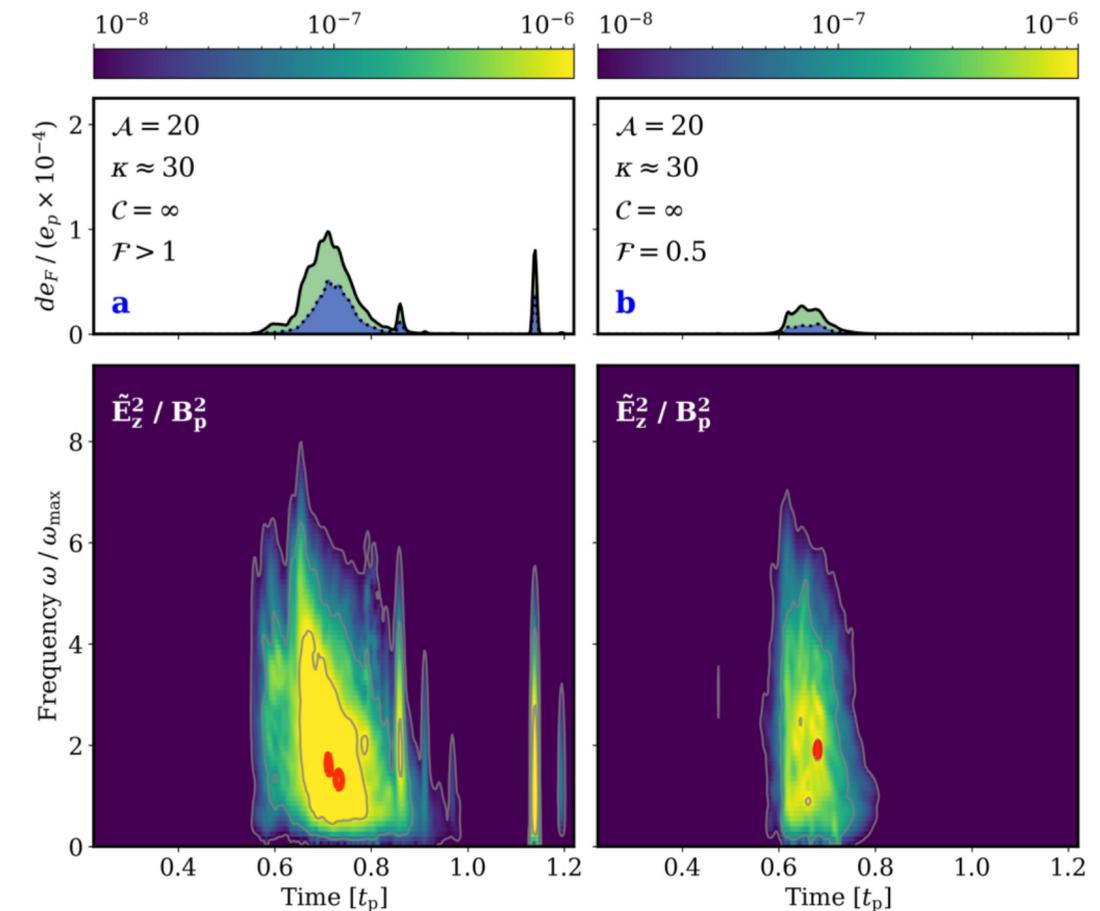
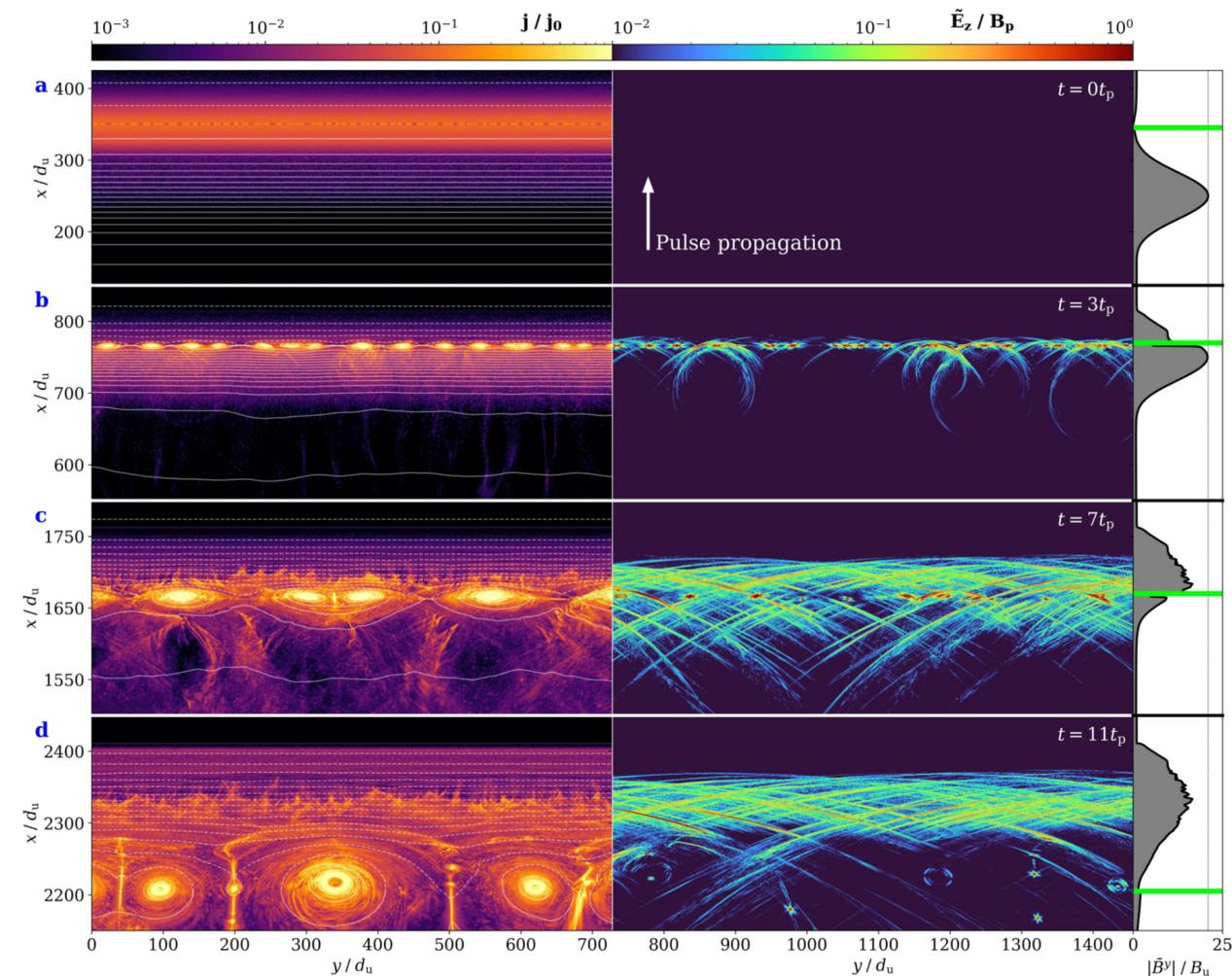


FIG. 1. Global structure of the monster shock from our fiducial simulation with fast wave wavelength $\lambda = 0.6r_{\text{nl}}$ and $\sigma_{\text{bg,nl}} = 250$. The snapshot is taken at time $t = 1.6r_{\text{nl}}/c$. The left panel shows $E_{\phi}r/B_{\text{bg,nl}}r_{\text{nl}}$, where $B_{\text{bg,nl}}$ is the equatorial magnetic field at the nonlinear radius. The subsequent three panels show a zoomed-in view of the region within the red box in the left panel, with colors representing the scaled plasma density nr^3/N_0 (where $N_0 = n_{\text{bg}}r^3$ is a constant), the ratio of the electric field to the magnetic field, and the Lorentz factor of the bulk flow, respectively. In all panels the green lines are the magnetic field lines. In the rightmost panel, the blue arrows indicate the direction of the bulk flow, and the arrow lengths are proportional to the bulk velocity.

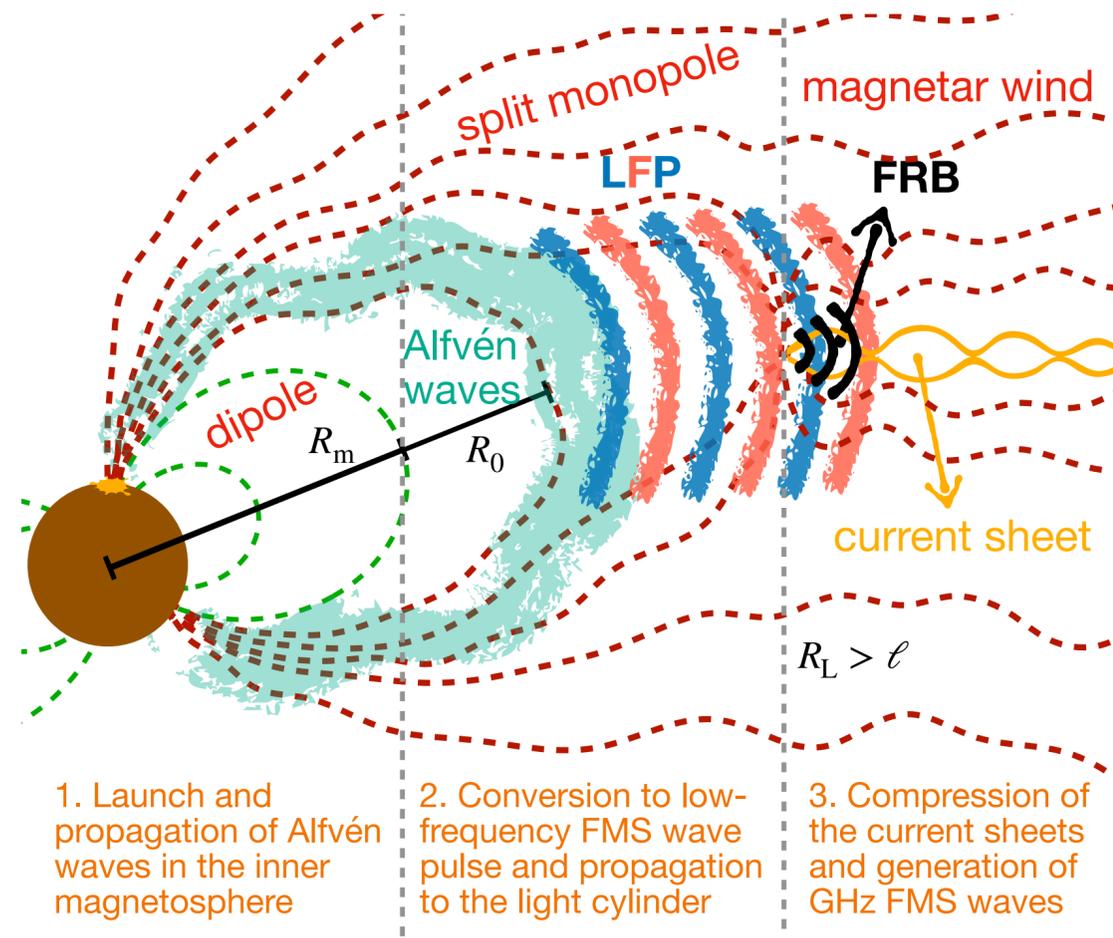
Another coherent emission mechanism

- Coherent emission from reconnection when a current sheet is compressed by a low frequency pulses (Lyubarsky 2020, Mailman et al. 2023)
- Plasmoid merge to larger ones, so the emission will shift to lower frequencies



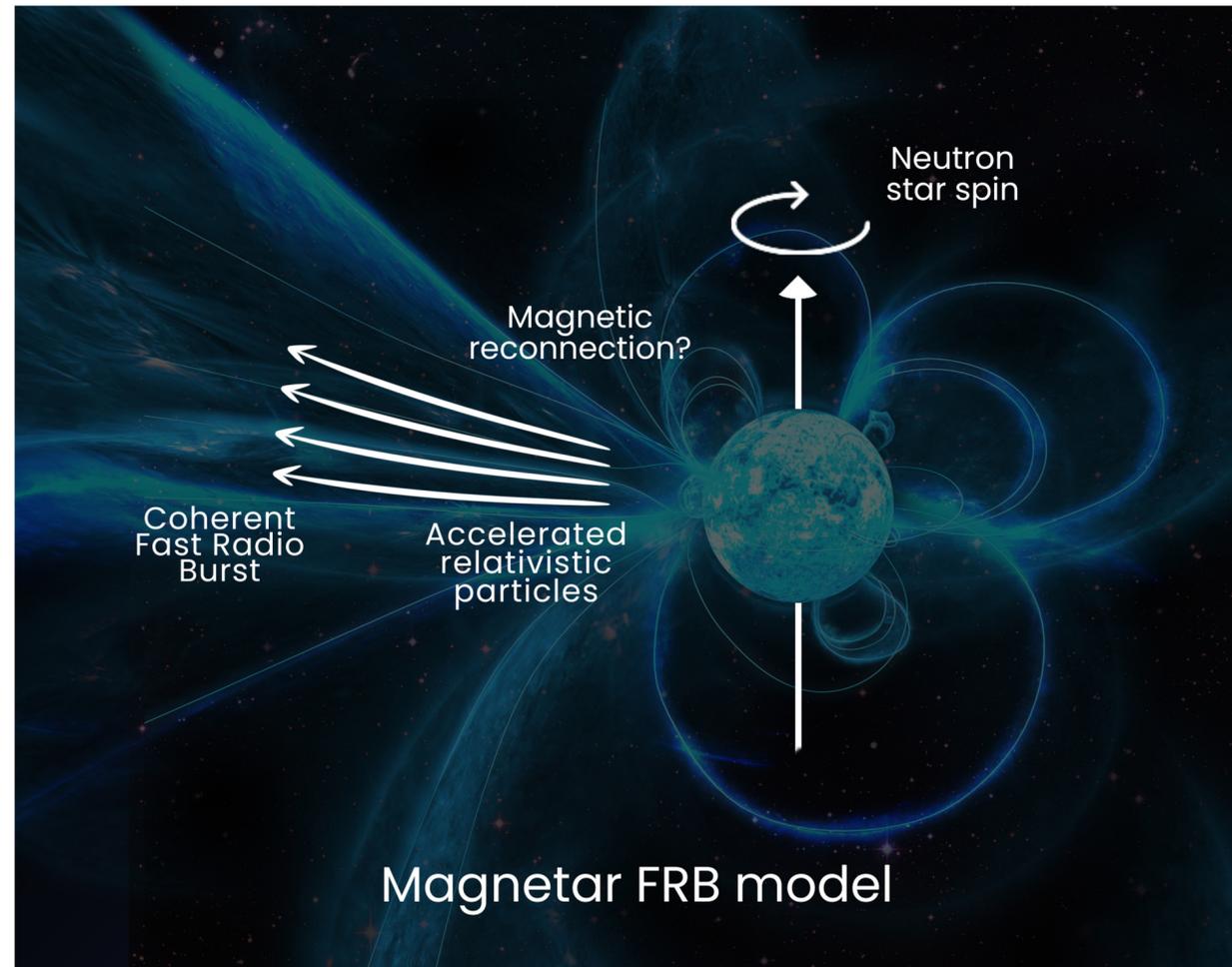
A new FRB model

- Low frequency pulses converted from Alfvén waves compress the current sheet beyond Y-point and produce coherent emissions



Conclusion

- Rich physics of Alfvén 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!

