Filamentation Instability in Pair Plasmas

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Collaborators

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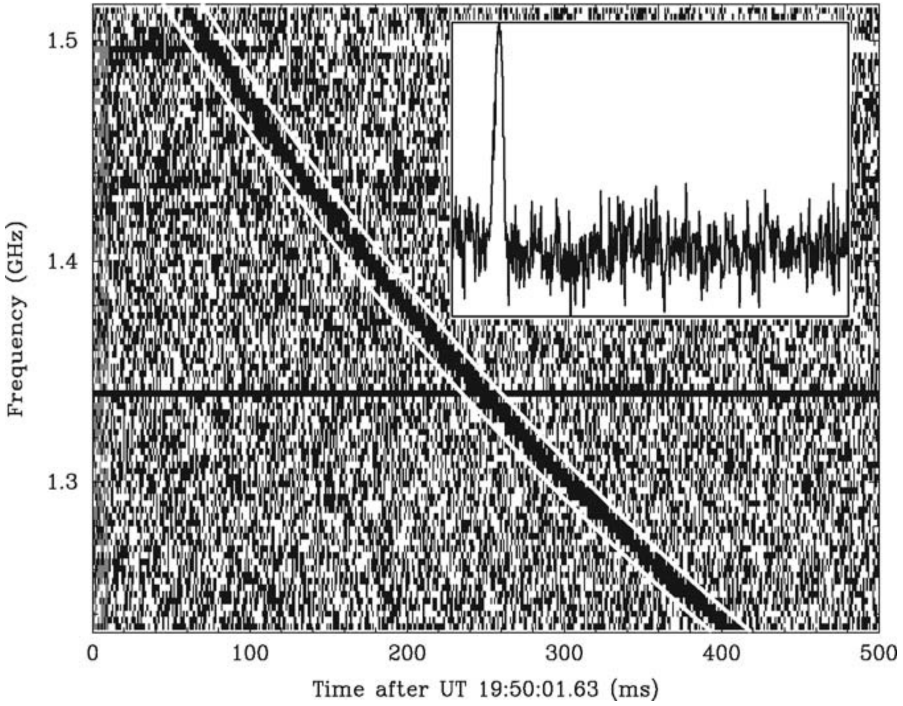
Iwamoto, M., Sobacchi, E., & Sironi, L., 2023, MNRAS, 522, 2

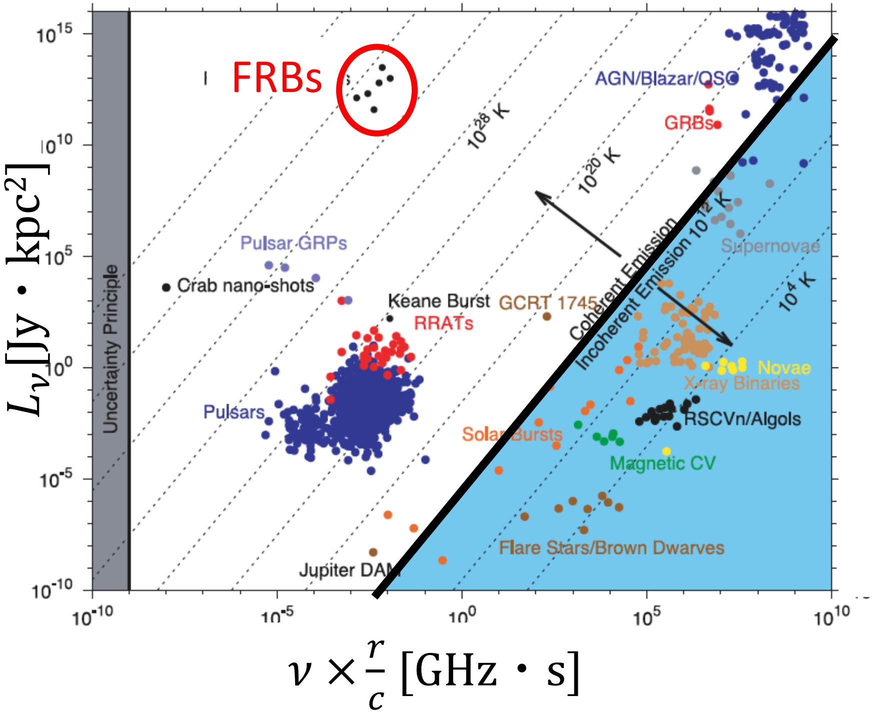
Fast Radio Bursts(FRB)

- ✓ Millisecond-duration intense pulses at radio frequency(Lorimer+ 2007)
- ✓ Extraordinarily high brightness temperature
  →coherent radiation (=emission from electron bunches)

[Lorimer+ 2007]

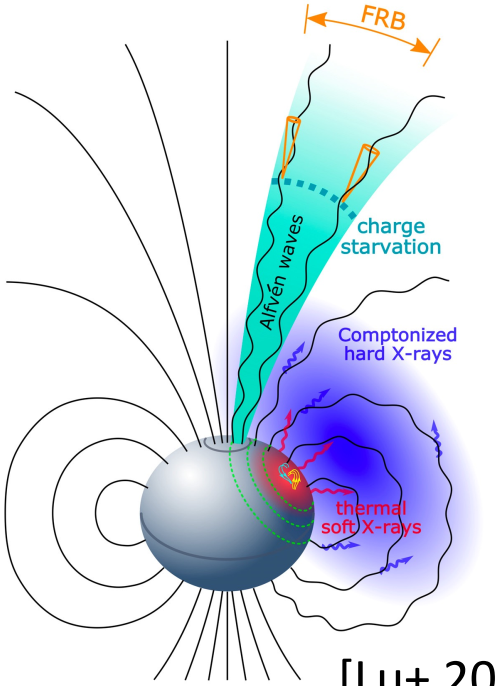


[Pietka+ 2015]



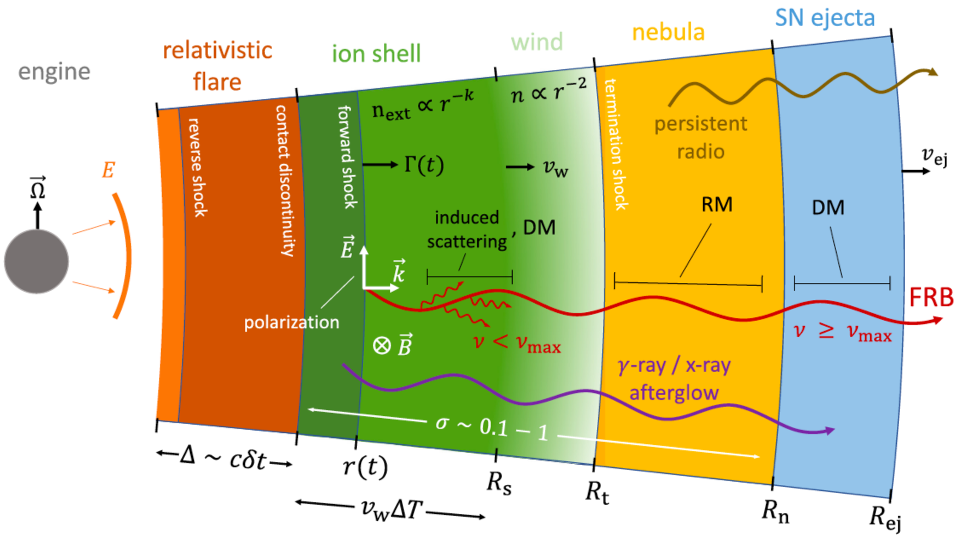
Emission Mechanism of FRBs

Alfven waves near the pole generate electron bunches
→coherent curvature radiation



[Lu+ 2020]

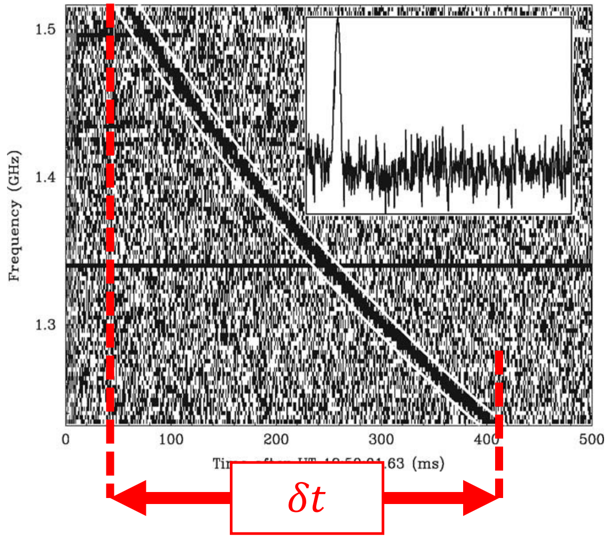
Flares induces relativistic shocks
→synchrotron maser emission

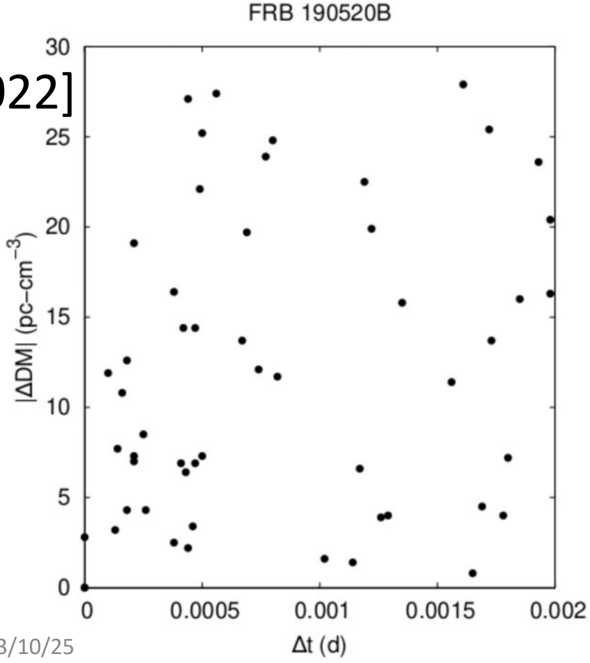


[Metzger+ 2019]

Intense electromagnetic waves propagates through magnetar wind in both scenarios
→Wave-wave interaction in pair plasmas

Dispersion Measure





[Katz 2022]

- ✓ Group velocity of electromagnetic wave in plasma

$$\frac{d\omega}{dk} = c\sqrt{1 - \frac{\omega_{pe}^2}{\omega^2}}$$

- ✓ Group delay of observed pulse is

$$\delta t \sim \frac{2\pi e^2}{m_e c}\left(\omega_1^{-2} - \omega_2^{-2}\right)\boxed{\int_0^L n_e\, ds}$$

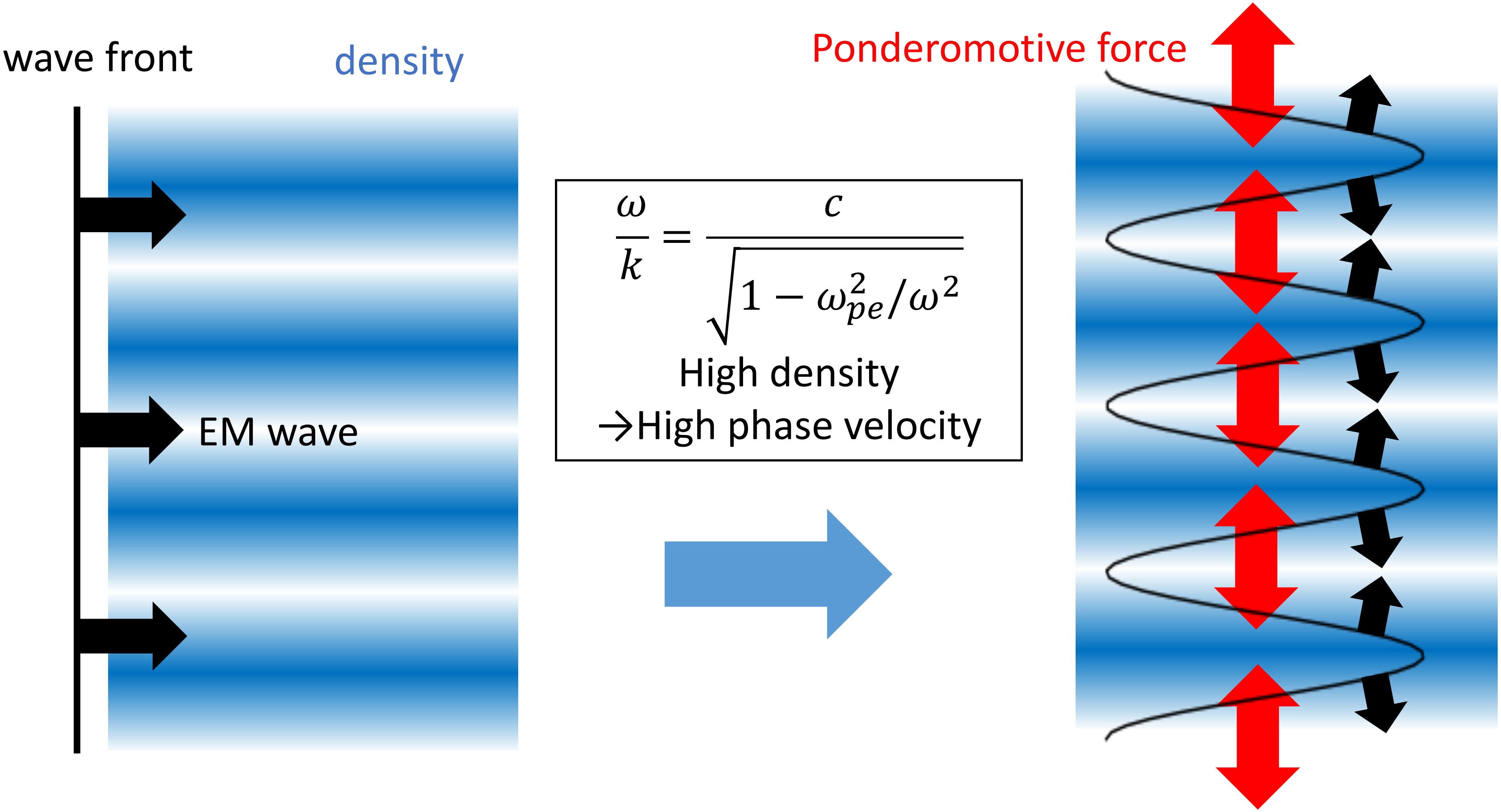
Dispersion Measure (DM)

- ✓ The rapid variations (10-100s) of near-source DM from some FRBs are observed (e.g., Katz 2022;Xu+ 2022)
- ✓ This DM fluctuations may be explained by Filamentation instability (Sobacchi+ 2023)

Filamentation Instability (FI)

Transverse modulation instability (four-wave coupling)

(Kaw+ 1973; Sobacchi+ 2020;2022;2023)

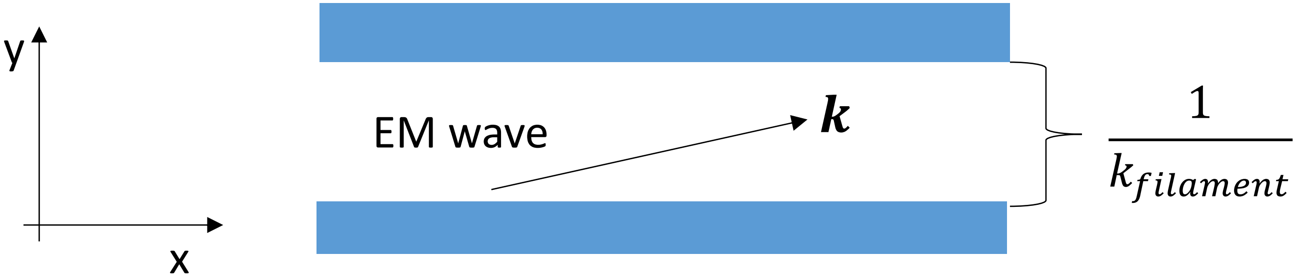


$$\frac{\omega}{k} = \frac{c}{\sqrt{1 - \omega_{pe}^2/\omega^2}}$$

High density

→High phase velocity

Effective DM



- ✓ Electromagnetic waves are accumulated in the near-vacuum region
- ✓ The dispersion relation is described by the TE mode in a wave-guide,

$$\omega^2 = c^2k_x^2 + \boxed{c^2k_{filament}^2}$$

Effective plasma frequency

→Filament wavelength determines DM
→DM fluctuation?

However, previous studies are based on the linear analysis…

Is the filament wavelength determined by the most unstable mode?

Can the FI grow into an substantial amplitude in FRBs?

Simulation Setting

Simulation code

Wuming (Public PIC code)

Assumption

- ✓ plane wave
- ✓ Monochromatic
- ✓ Linear polarization
- ✓ Amplitude

$$a_0 \equiv \frac{eE_0}{mc\omega_0} \ll 1$$

(far away from magnetar $\gtrsim 10^{13}$cm)

- ✓ Frequency

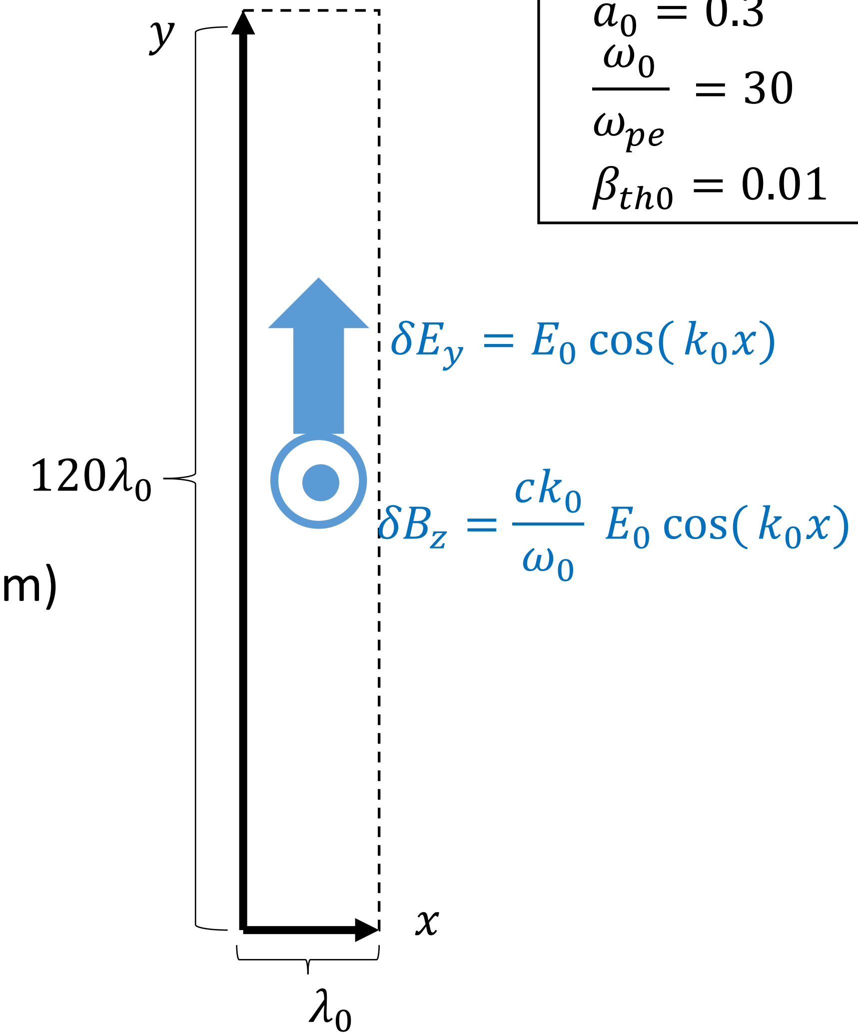
$$\frac{\omega_0}{\omega_{pe}} \gg 1$$

- ✓ Unmagnetized pair plasmas
- ✓ Initial thermal velocity

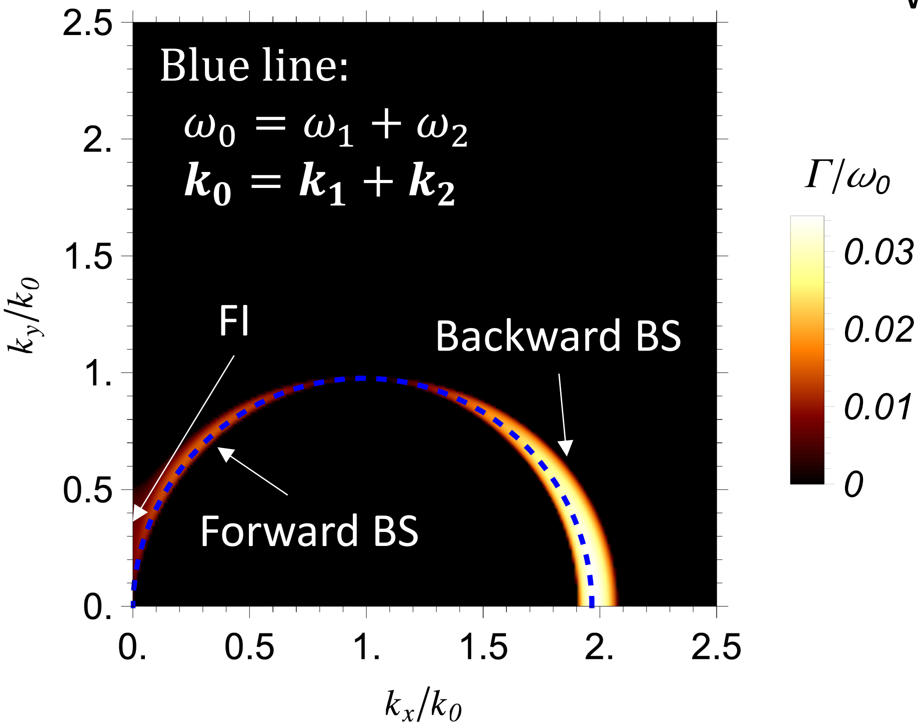
$$\beta_{th0} \ll a_0$$

Initial condition

$$\boxed{\begin{aligned} a_0 &= 0.3 \\ \frac{\omega_0}{\omega_{pe}} &= 30 \\ \beta_{th0} &= 0.01 \end{aligned}}$$



Linear Analysis



Linearly polarized monochromatic pump wave with $a_0 \ll 1$ and $\omega_0 \gg \omega_{pe}$

$$\frac{1}{2}a_0^2\omega_{pe}^2(Q-1)\left(\frac{\cos^2\theta_+}{D_+}+\frac{\cos^2\theta_-}{D_-}\right)=1,$$

$$D_\pm = \omega_\pm^2 - c^2k_\pm^2 - 2\left(1-\frac{1}{4}a_0^2\right)\omega_{pe}^2,$$

$$\cos\theta_\pm = \frac{\boldsymbol{k_0}\cdot\boldsymbol{k_\pm}}{k_0k_\pm},$$

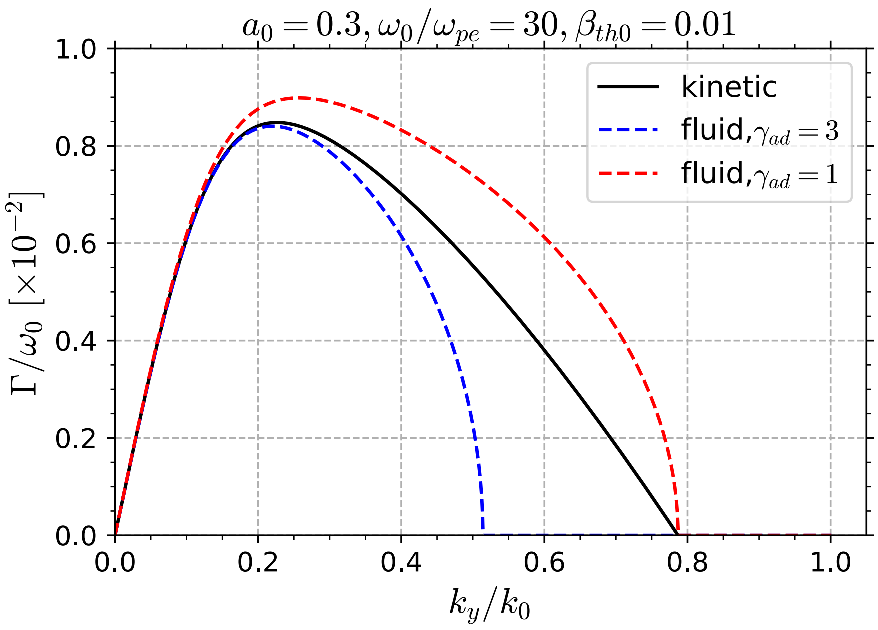
$$\omega_\pm = \omega_0 \pm \omega, \boldsymbol{k_\pm} = \boldsymbol{k_0} \pm \boldsymbol{k},$$

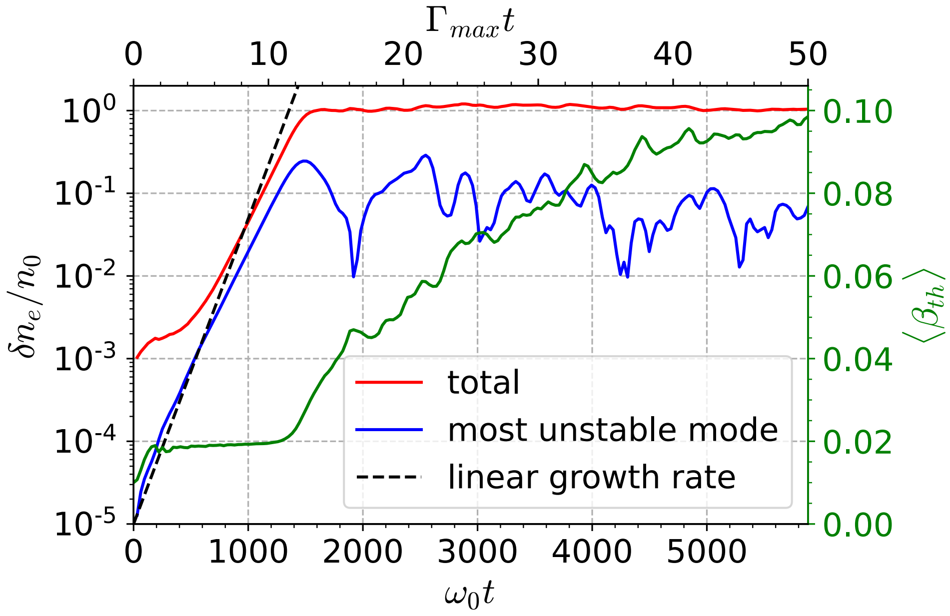
$$Q = \frac{c^2}{2v_{th0}^2}\frac{\mathrm{d}Z}{\mathrm{d}\xi}\ (Z\text{:Plasma dispersion function}),$$

$$\xi = \frac{\omega}{\sqrt{2}v_{th0}k}$$

- ✓ Brillouin Scattering (BS; parametric decay into an acoustic wave) works as well
- ✓ BS is suppressed for realistic pump waves with a broad spectrum (Ghosh+ 2022)
  → FI can be dominant in FRBs
- ✓ Backward BS is most unstable and scattered waves satisfy $k_x \sim -(1-2\beta_{th0})k_0$
  →scattered waves are not resolved in our simulations

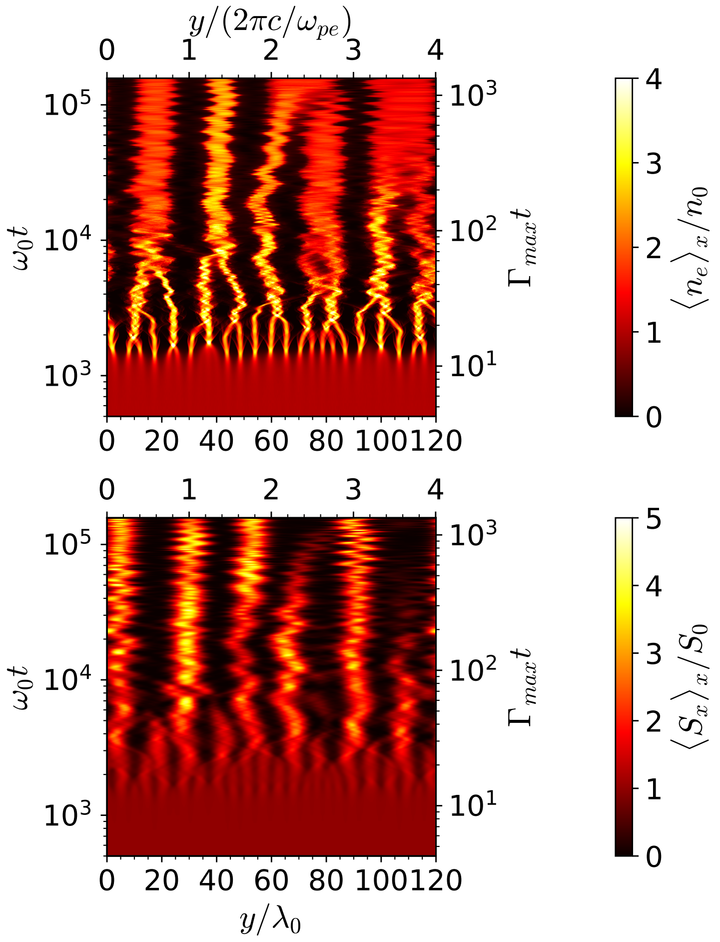
Comparing with Linear Analysis

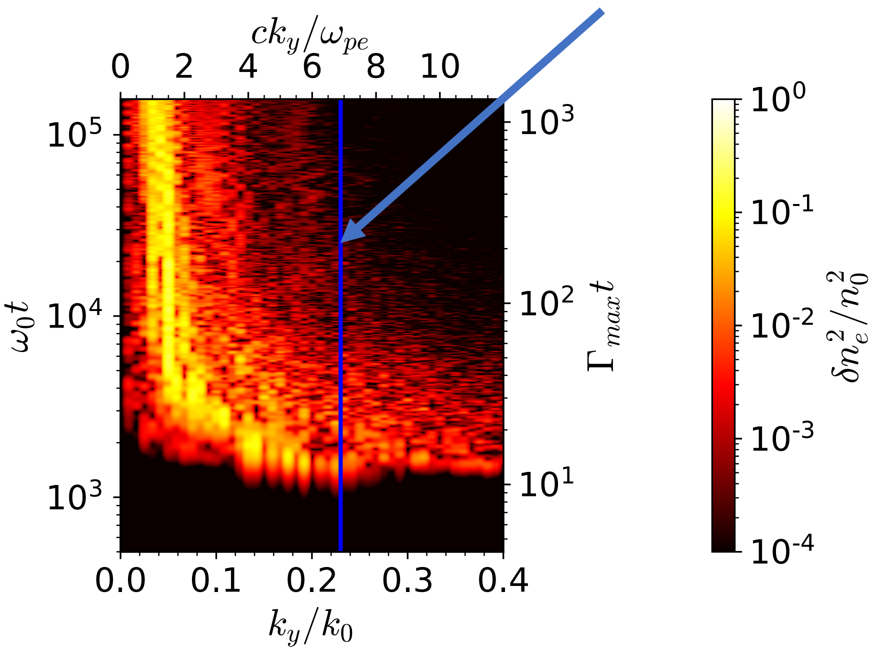




- ✓ Simulation results agree with the linear analysis
- ✓ The saturation level of the most unstable mode declines in time
  →Filament merging

Filament Merging

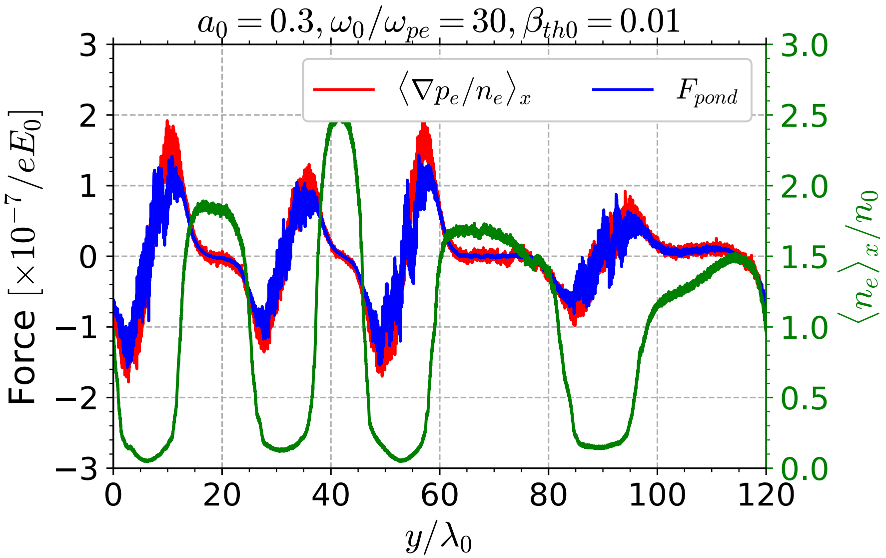


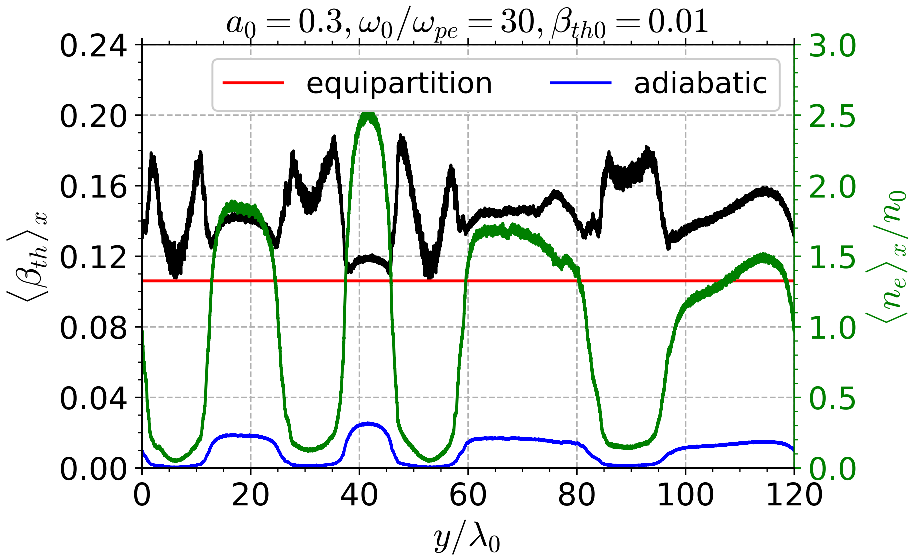


Most unstable mode

- ✓ The density filaments gradually merge for $\Gamma_{max} t \gtrsim 10$
- ✓ The filament merging continues until the wavenumber is comparable to the skin depth

Saturation





- ✓ The FI saturates when force balance between the pressure gradient and ponderomotive force is achieved
- ✓ Plasmas are strongly heated at the saturation stage and non-adiabatic heating is dominant
- ✓ The heating may saturate when the equipartition between the ponderomotive potential and total thermal energy is achieved,

$$\beta_{th} \sim \frac{a_0}{2\sqrt{2}}$$

Implication for FRBs

Based on FRB model by Beloborodov (2020)

- ✓ The time duration of the pulse in the magnetar wind rest frame

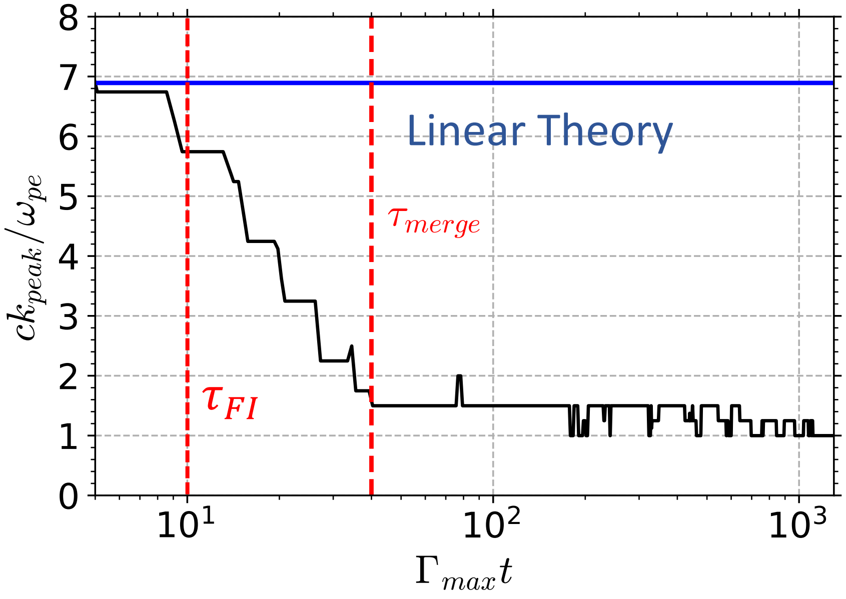
$$\tau_{pulse} = 2\gamma_w \tau_{obs} \sim 200\mathrm{ms}\left(\frac{\gamma_w}{10^2}\right)\left(\frac{\tau_{obs}}{1\mathrm{ms}}\right)$$

- ✓ The time-scale on which the FI exponentially grows

$$\tau_{FI} \sim \frac{10}{\Gamma_{max}} \sim 20\mathrm{ms}\left(\frac{L_{obs}}{10^{42}\ \mathrm{erg\ s^{-1}}}\right)^{-\frac{1}{2}}\left(\frac{\dot{N}}{10^{39} s^{-1}}\right)^{-\frac{1}{2}}\left(\frac{\gamma_w}{10^2}\right)^{\frac{1}{2}}\left(\frac{\nu_{obs}}{1\mathrm{GHz}}\right)$$

- ✓ The filament merging time-scale

$$\tau_{merge} \sim \frac{40}{\Gamma_{max}} \sim 4\tau_{FI}$$



We finally obtain

$$\tau_{FI} \ll \tau_{merge} \lesssim \tau_{pulse}$$

FI can grow into an substantial amplitude in FRB
→DM can fluctuate

Summary and Future Work

Summary

We investigate the filamentation instability (FI) in unmagnetized pair plasmas by using PIC simulation

- ✓ FI generates transverse density filaments and the electromagnetic wave propagates in near vacuum between them, as in the wave-guide
- ✓ The typical time-scale of the FI is shorter than the pulse duration time of FRBs and the FI has significant influence on the propagation process of the radio pulses
- ✓ The fluctuation of the DM may be originated from the FI

Future Work

- ✓ Large-amplitude pump wave $a_0 \gg 1$
- ✓ Background magnetic field