A New Cosmic-Ray-driven Instability

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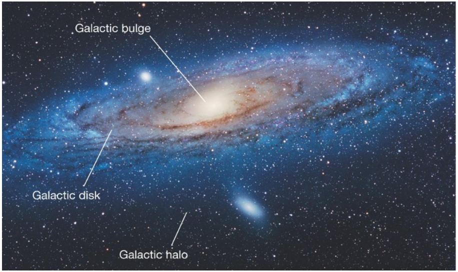
July 15, 2021

How do CR couple to background plasma

Estimating time spent by CRs in galactic disk

- In presence of uniform mag. field: GeV CR aligned with the field travel with $c/3$



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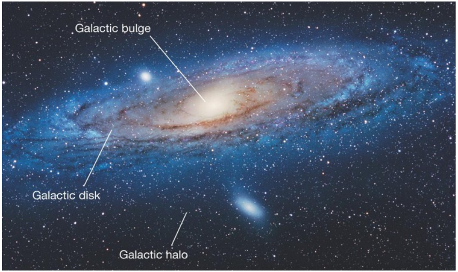

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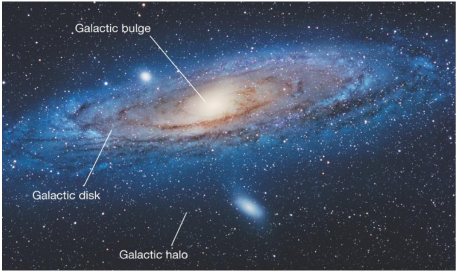

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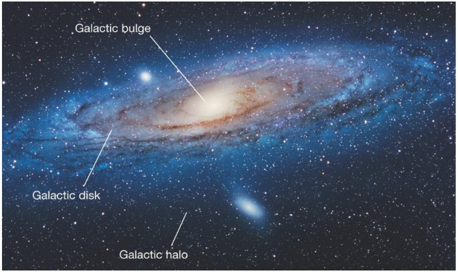

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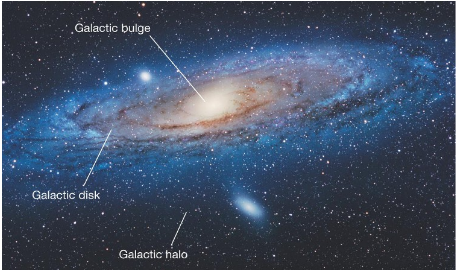


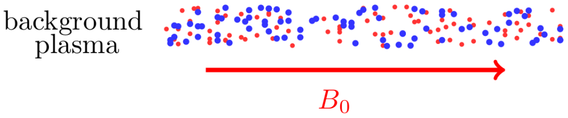
$\Rightarrow$ **CR strongly couple by scattering on magnetic field irregularity**

How do CR couple to background plasma

Plan for the talk:

- How GeV cosmic rays couple strongly; plasma instabilities.
- Applications of the new instability
  1. Electron injection at non-relativistic magnetized shocks.
  2. CR dynamical impacts on galactic scales (see also Timon Thomas talk).

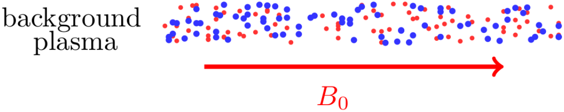
Electron-ion magnetized plasma



Waves along B_0:

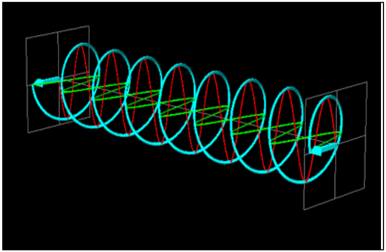
- Electrostatic

Electron-ion magnetized plasma

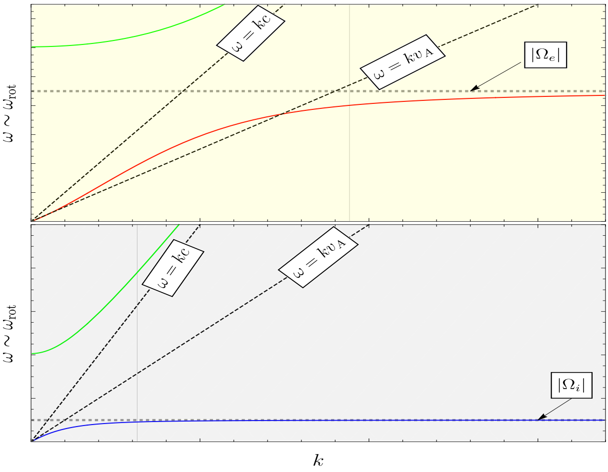


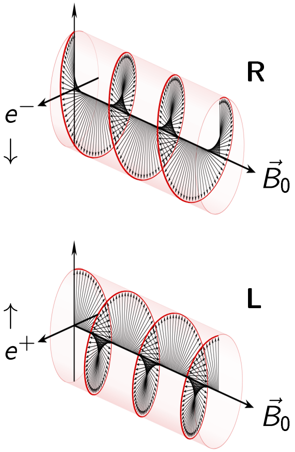
Waves along B_0:

- Electrostatic
- Electromagnetic
  Circularly (R & L)
  polarized waves



electron-ion magnetized plasma





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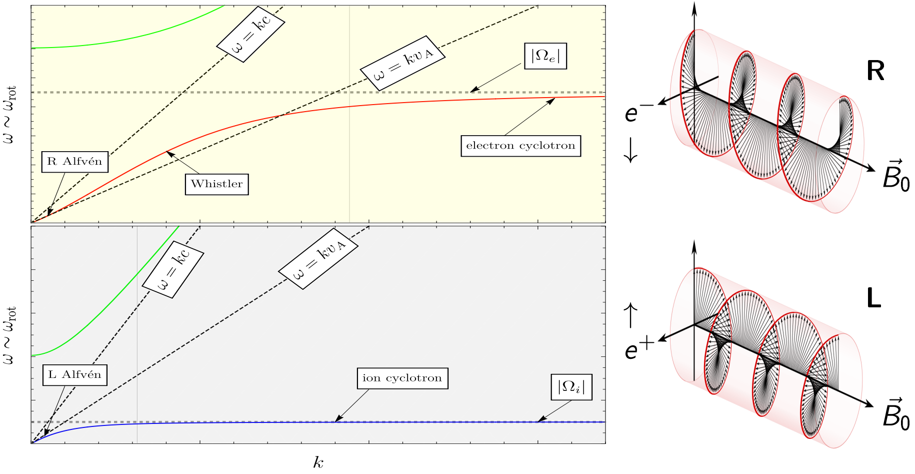

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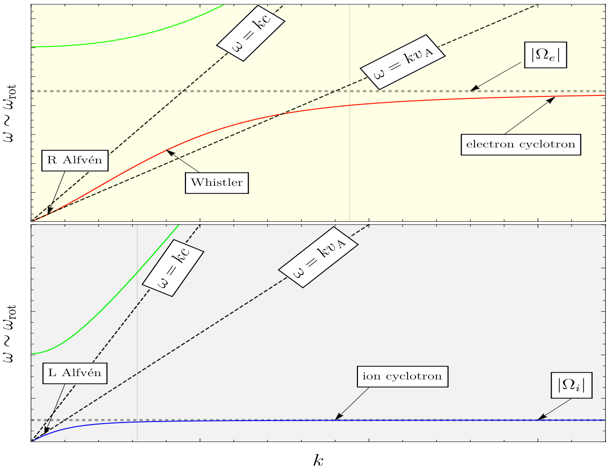
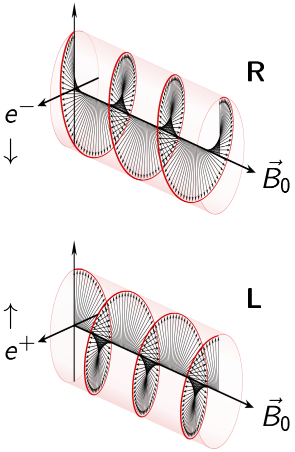
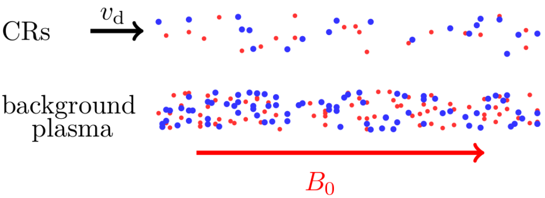




R Alfvén wave: compressional with $v_{\rm ph} \gtrsim v_A$

L Alfvén wave: shear with $v_{\rm ph} \lesssim v_A$

CR driven instability: Gyrotropic CRs



Shalaby+2020; ApJ 908 206

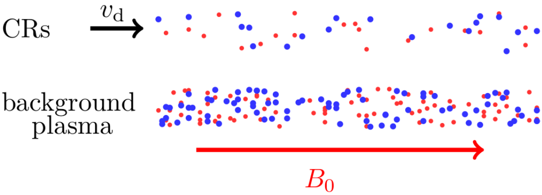
Dispersion relation ($\Omega_{e,0} = -m_i/m_e\Omega_{i,0}$):

$$\frac{k^2c^2}{\omega^2} - 1 = \frac{\omega_i^2}{\omega\left(-\omega \pm \Omega_{i,0}\right)} + \frac{\omega_e^2}{\omega\left(-\omega \pm \Omega_{e,0}\right)} \quad \Leftarrow \text{Background}$$

$$\text{CRe} \Rightarrow \quad + \frac{\alpha\omega_e^2}{\gamma_e\omega^2}\left\{\frac{\omega - kv_\mathrm{dr}}{kv_\mathrm{dr} - \omega \mp \Omega_{e,0}/\gamma_e}\right\}$$

$$\text{CRi} \Rightarrow \quad + \frac{\alpha\omega_i^2}{\gamma_i\omega^2}\left\{\frac{\omega - kv_\mathrm{dr}}{kv_\mathrm{dr} - \omega \pm \Omega_i} - \frac{v_\perp^2\left(k^2c^2 - \omega^2\right)/c^2}{2\left(kv_\mathrm{dr} - \omega \pm \Omega_i\right)^2}\right\}$$

CR driven instability: Gyrotropic CRs



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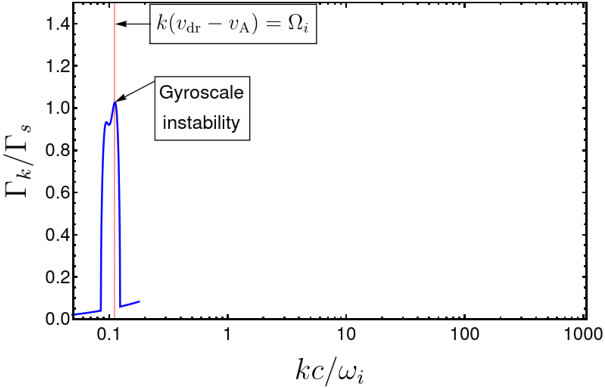

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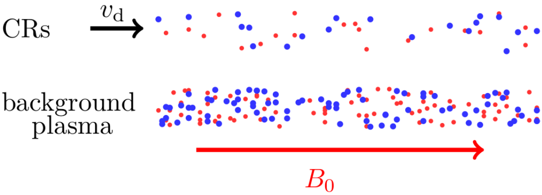

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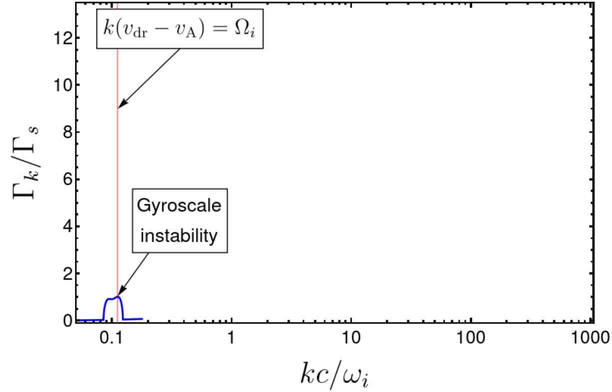

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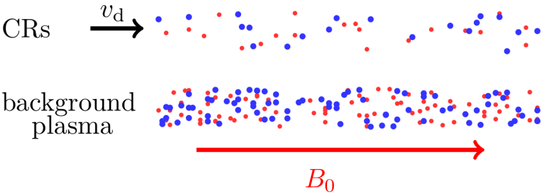

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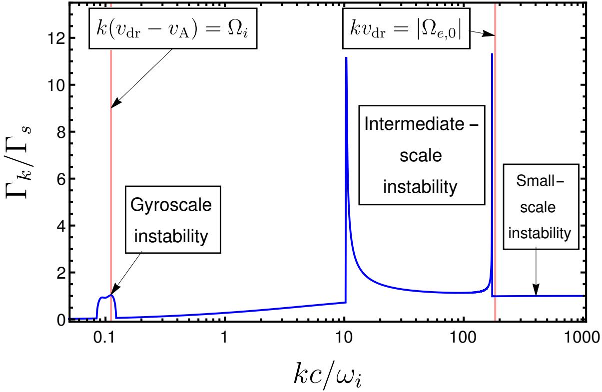

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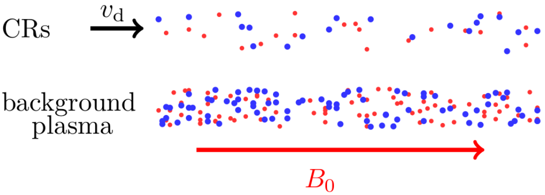

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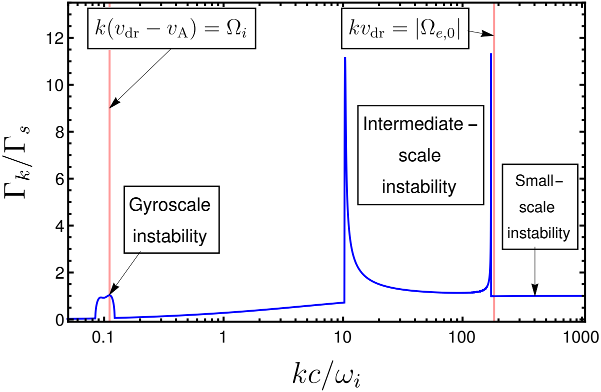
gyroscale: Alfvén Waves

$$\frac{kc}{\omega_i} = \frac{1}{(v_{\rm dr}/v_A) - 1}$$

intermediate-scale: ion-cyclotron waves (2-peaks)

$$\frac{kc}{\omega_i} \sim \left\{ \frac{v_{\rm dr}}{v_A}, \; \frac{m_r v_A}{v_{\rm dr}} - \frac{v_{\rm dr}}{v_A} \right\}$$



New CR-driven instability

Shalaby+2020; ApJ 908 206

Intermediate-scale: two peaks

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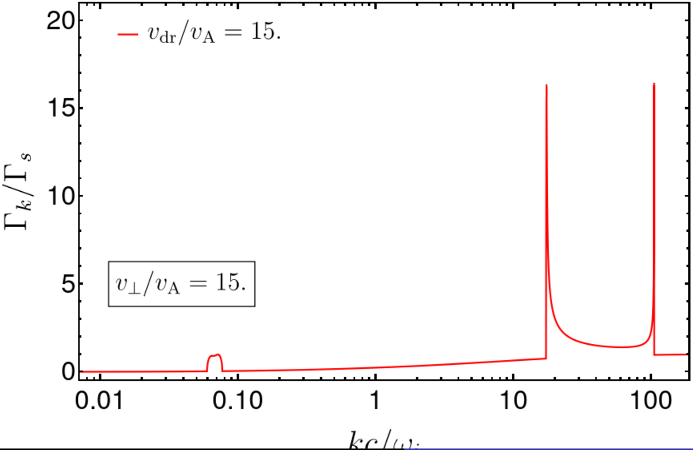

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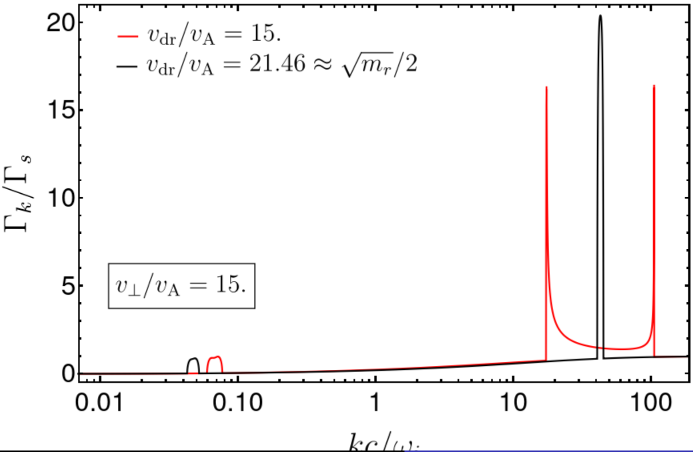

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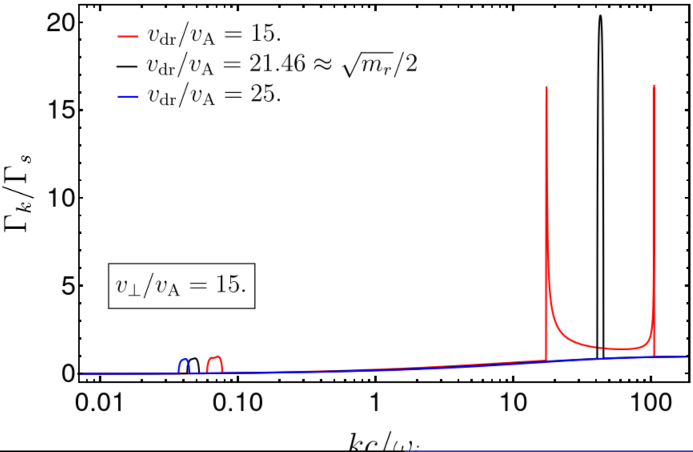
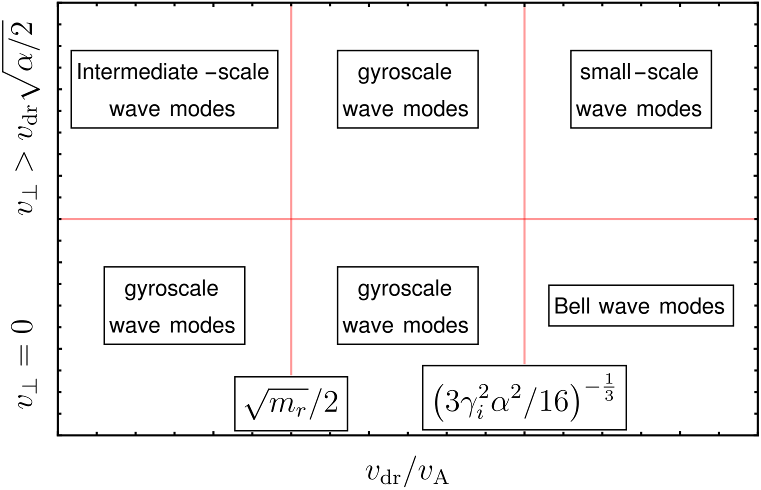
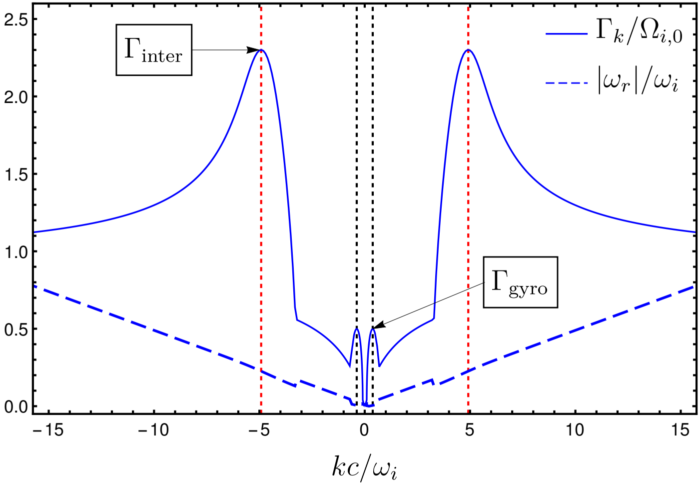


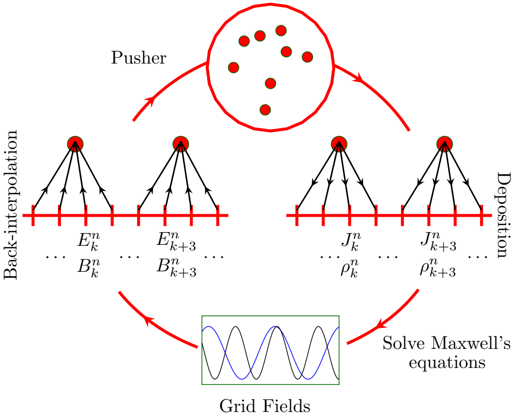
Classification



Kinetic simulation using Particle-in-Cell:

$v_A = 0.01c,\ m_i/m_e = 1836,\ v_{\mathrm{dr},0} = 5v_A,\ v_{\perp,0} = 13v_A \Rightarrow \theta_0 \sim 70^o$





MS+ 2017, ApJ 841 52

Kinetic simulation for instabilities

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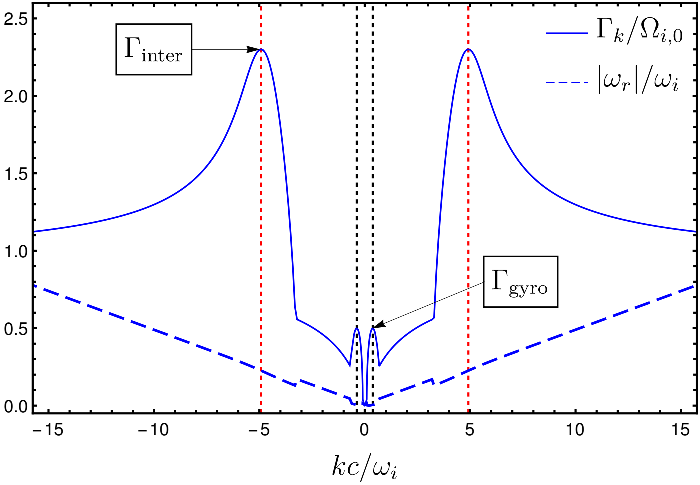

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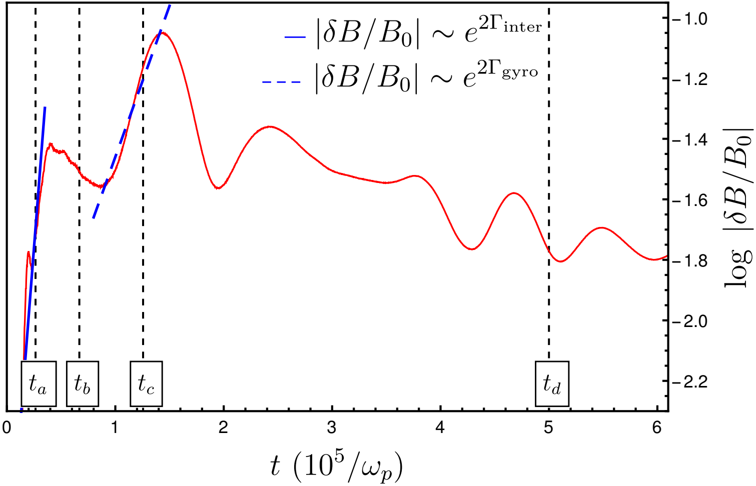
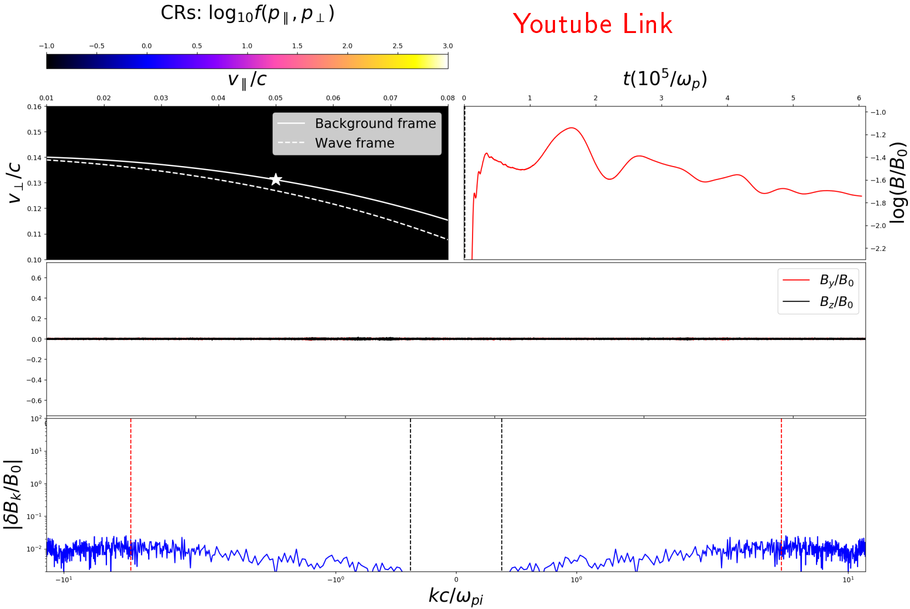


Kinetic simulation for instabilities

Youtube Link



Intermediate-scale instability

To summerize:

- New instabilities with much faster growth rate if $v_{\rm dr}/v_A < \sqrt{m_r}/2$
- **Only** 2 successful full-kinetic simulations of gyroscale instability
  1. Holcomb+2019 @ $v_A = 10^{-1}c,\ m_r = 100$ (energy error $\sim 300\epsilon_{\rm cr}$)
  2. MS+2020 @ $v_A = 10^{-2}c,\ m_r = 1836$ (energy error $\sim 0.002\epsilon_{\rm cr}$)

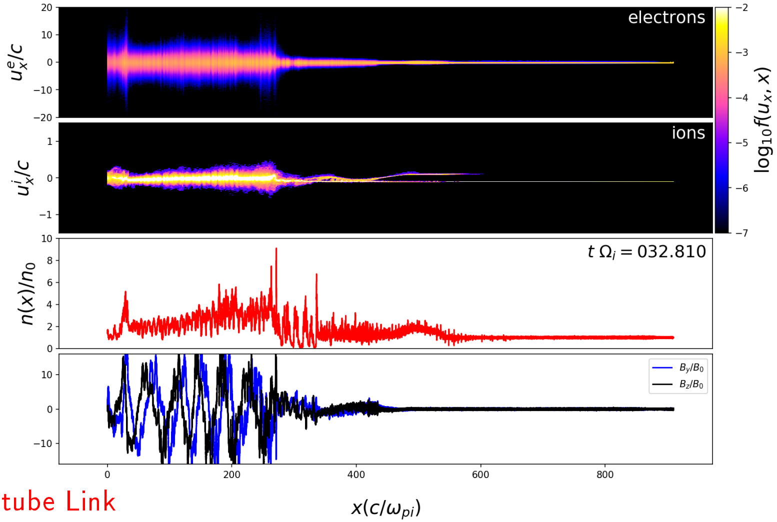
  Both report no-full isotropization in general

Next: applications

electron injection Problem:

- electrons: $r_e = (m_e/m_i)r_i$.
- electrons can not scatter at shock front
- Intermediate-scale instability provide large-amplitude magnetic perturbation at sub ion-gyroscale
  $\Rightarrow$ a solution?

CD rest frame; mi/me=1836; $v_u = -0.1c$; $v_A = 0.00625c$.



Youtube Link

Dynamical impact on galactic scales

In the self-confinement picture

$$\frac{d\varepsilon_c}{dt} + \nabla \cdot \left[\vec{W}(\varepsilon_c + P_c) - \boldsymbol{\kappa} \cdot \nabla \varepsilon_c \right] = \vec{W} \cdot \nabla P_c, \tag{1}$$

$$\vec{W} \cdot \nabla P_c = -2 \int d\omega dk \Gamma(\omega, k) I(\omega, k), \tag{2}$$

$$|\boldsymbol{\kappa}| \sim \kappa_{\parallel} \sim \frac{c^2}{2} \left\langle \frac{1 - \mu^2}{\nu_+ + \nu_-} \right\rangle \tag{3}$$

$\vec{W}$ is the effective streaming speed of CRs

New instability: higher linear growth rate

- larger pressure gradient: ∇P_c
- larger scattering rate $\Rightarrow$ lower diffusion coefficient
- Very low Ion-neutral damping rate (10^6 smaller) $\Rightarrow$ mechanism for efficient coupling of MeV CRs to partially ionized plasma, e.g., MC

Conclusions and thoughts

- CR strongly couple via kinetic instabilities
- New instability:
  - much higher rate $\Rightarrow$ new CR transport
  - Can't be suppressed by ion-neutral friction (damping) $\Rightarrow$ potential role in the ionization of molecular clouds by MeV CRs.
- CR impact/regulate galactic outflows and ISM chemistry
- CR transport mode strongly impact CGM gas and magnetic field distribution

Thank you for your attention

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