The mechanism of efficient electron acceleration at parallel non-relativistic shocks

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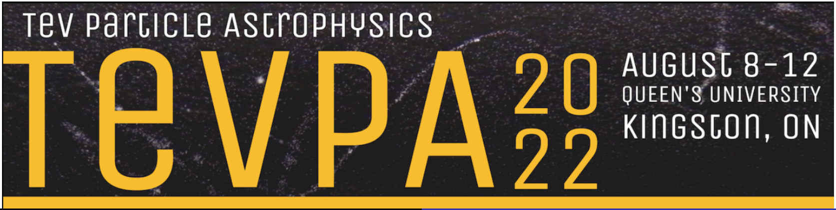
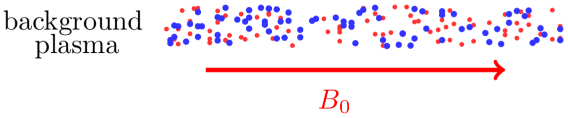
Based on: Shalaby+2021 (ApJ 908 206) & Shalaby+2022 (ApJ 932 86)

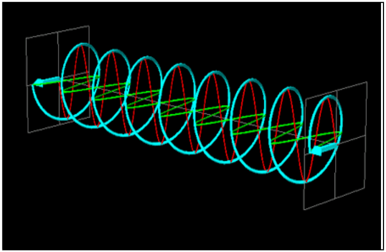


Electron-ion magnetized plasma



Waves along B_0:

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



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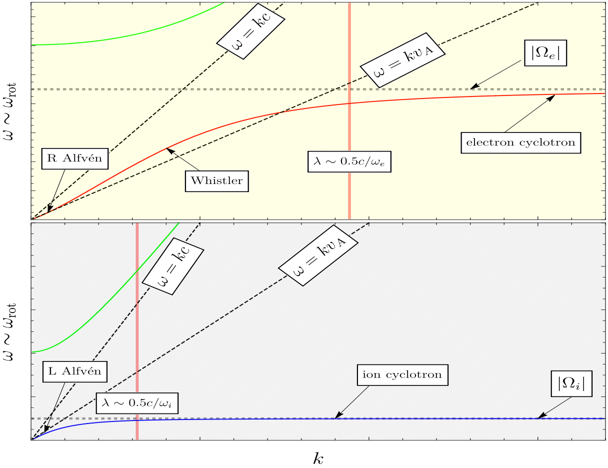
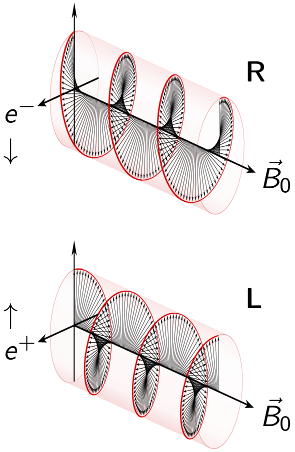
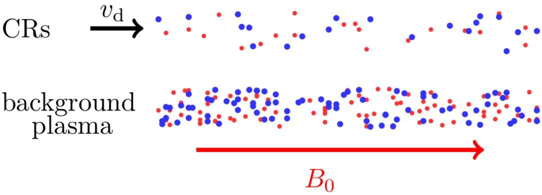




R Alfvén wave: compressional with $v_{\rm ph} \gtrsim v_A$
L Alfvén wave: shear with $v_{\rm ph} \lesssim v_A$

CR driven instability



$\uparrow v_\perp$ Gyrotropic CRs

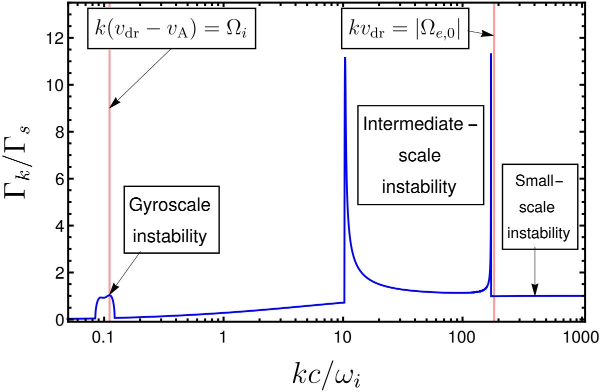
Shalaby+2021; ApJ 908 206

gyroscale: Alfvén Waves

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

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

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



Condition for instability growth

Shalaby+2021; ApJ 908 206

Intermediate-scale: two peaks

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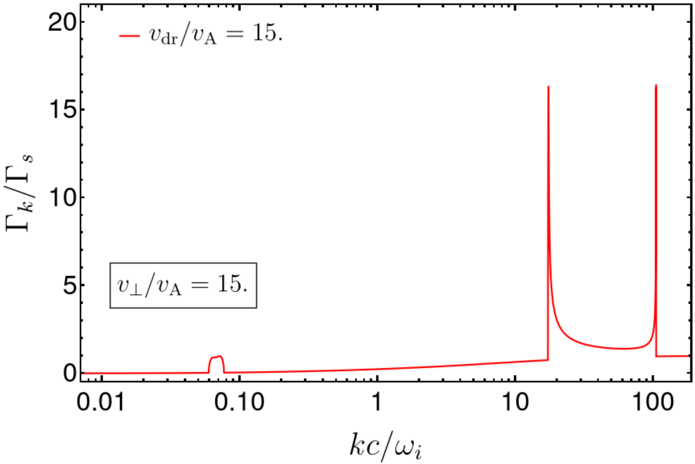

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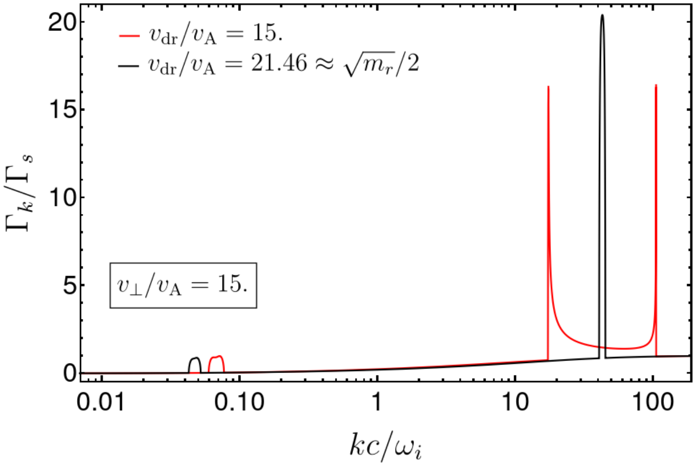

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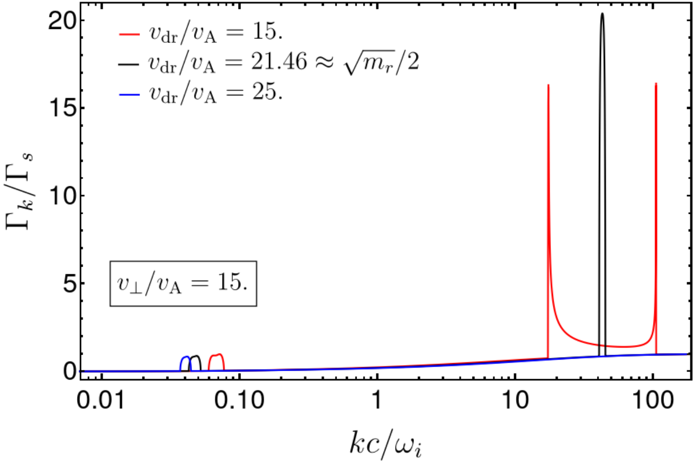

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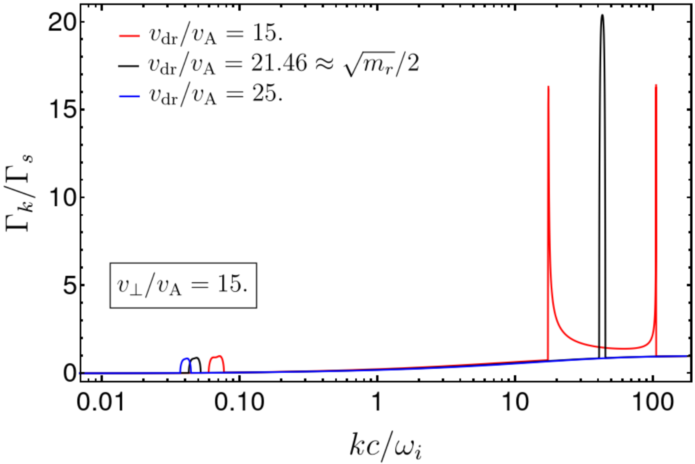


Condition:

$$\frac{v_{\rm dr}}{v_A} < \frac{\sqrt{m_r}}{2}$$

- Impact of the new instability on momentum distribution?

  Electromagnetic wave with $\upsilon_{\rm ph}$ + a particle with velocity $(\upsilon_x, \upsilon_y, \upsilon_z)$

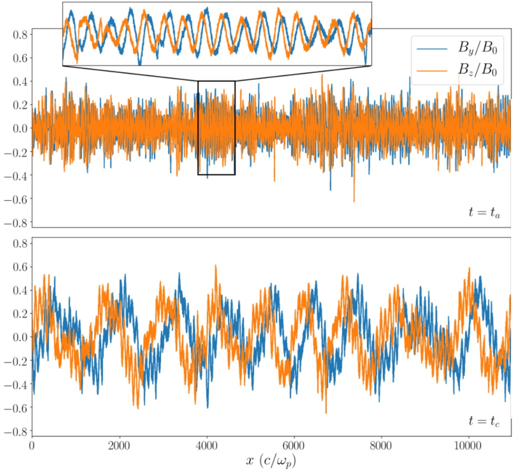
$$\dot{K}_{\|} = \frac{m_s}{2}\frac{d\upsilon_x^2}{dt} = q_s \upsilon_x(\upsilon_y B_z - \upsilon_z B_y),$$

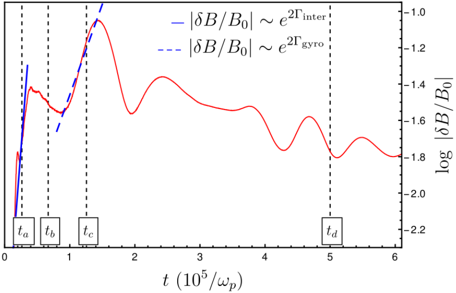
$$\dot{K}_{\perp} = \frac{m_s}{2}\frac{d\upsilon_{\perp}^2}{dt} = -q_s\left[(\upsilon_x - \upsilon_{\rm ph})\upsilon_y B_z - (\upsilon_x - \upsilon_{\rm ph})\upsilon_z B_y\right]$$

  - $\upsilon_x \approx \upsilon_{\rm ph} \quad \Rightarrow \quad \dot{K}_{\perp} \approx 0$, parallel scattering only
  - $\upsilon_{\rm ph} \approx 0 \quad \Rightarrow \quad \dot{K}_{\perp} = -\dot{K}_{\|}$, energy-conserving scattering

- Impact of the new instability on momentum distribution?

1. Fast magnetic field amplification at scales $< d_i$

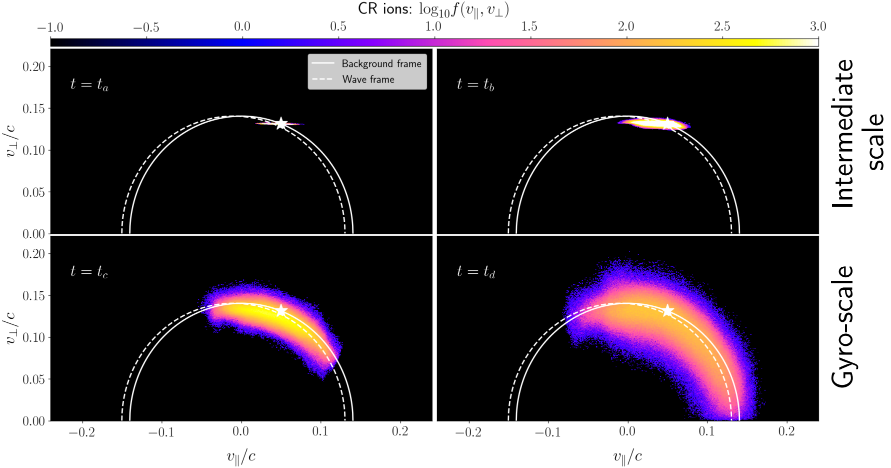




Impact of the intermeidate-scale instability

- Impact of the new instability on momentum distribution?

1. Fast magnetic field amplification at scales $< d_i$
2. decrease average drift speed of ions



Summary

Found a new instability

- Drives comoving ion-cyclotron waves
- Growth only if $\upsilon_{\rm dr}/\upsilon_A < \sqrt{m_i/m_e}/2$
- Typically much faster growth compared to gyro-scale growth

$$\Gamma/\Omega_i = \alpha^{3/4} + \left(\frac{\alpha}{3}\right)^{1/3} \left(\frac{\upsilon_{\rm dr}\upsilon_{\perp}}{\upsilon_{\rm A}^2}\right)^{2/3} \tag{1}$$

- Impacts
  1. Fast magnetic field amplification on scales $< d_i$.
  2. Decrease average drift speed of ions

Implications

Potential implications: ****remains to be shown/quantified****

1. Impacts on ⇒ CR injection and propagation models @ ISM & galaxy sims, i.e., on the distribution of gas, magnetic field amplification, star formation ect.)
   - Increase ($\times$10-20) pressure gradients due to streaming CR.
   - Increase the scattering frequency and thus substantially impacting $\kappa_{||}$
2. For ions, $v_{\rm dr}$ decreases ⇒ impact the confinement near sources, i.e., could enhance the Grammage and thus emission near sources
3. Coupling of CR ions in partially ionized medium (clouds); impact ionization of (emission from) partially ionized clouds

Today's talk **Shown implication**

Role of the new instability in the e-acceleration at non-relativistic shocks

arXiv:2202.05288 & ApJ 932 86

Shalaby+2022; ApJ 932 86

Today's talk/application

Role of the new instability in the acceleration of electrons at non-relativistic shocks

electron injection Problem:

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

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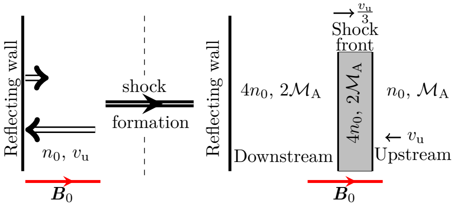

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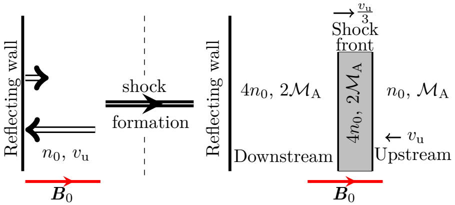
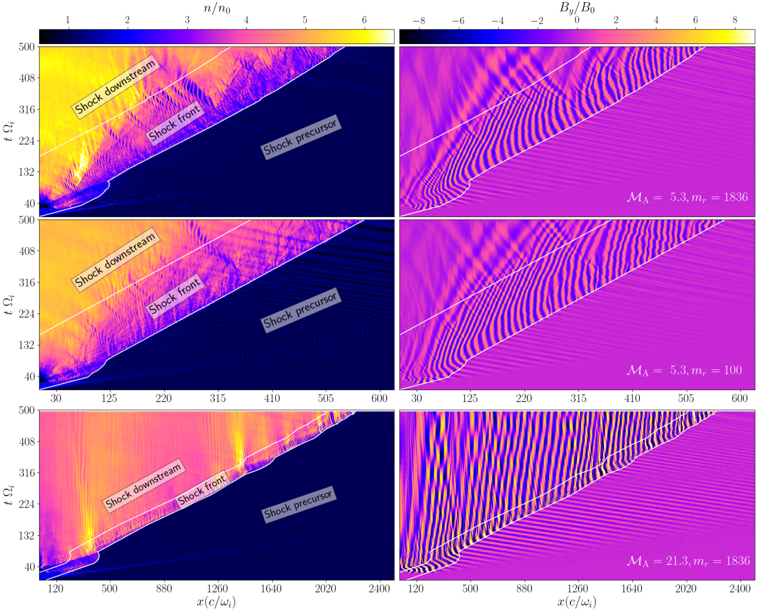


Table 1
Parameters of our electron-ion parallel shock simulations

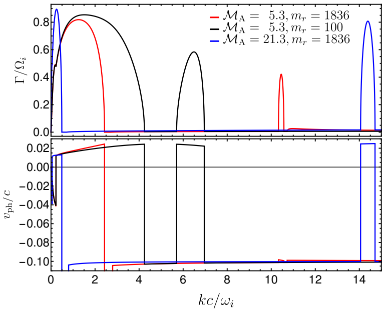
Name	v_u/c [a]	$\mathcal{M}_A$ [b]	$\mathcal{M}_s$ [c]	m_i/m_e	Condition[d]
Ma5Mr1836	-0.1	5.3	365	1836	✓
Ma5Mr100	-0.1	5.3	365	100	×
Ma21Mr1836	-0.1	21.3	365	1836	×

$$\text{Condition}: \quad 2\mathcal{M}_A < \frac{1}{2}\sqrt{\frac{mi}{me}}$$

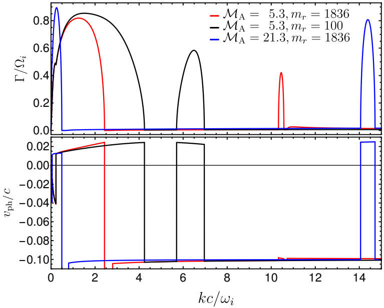
Magnetic field amplification



Impacts of Intermediate-scale instability



Solution of Disp. rel. at shock front (CD rest frame)



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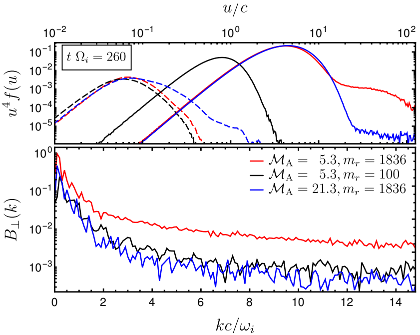
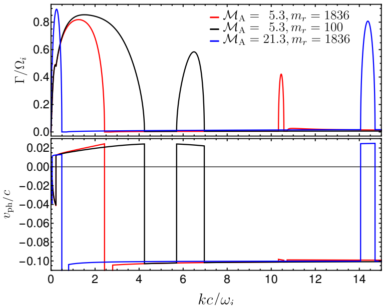
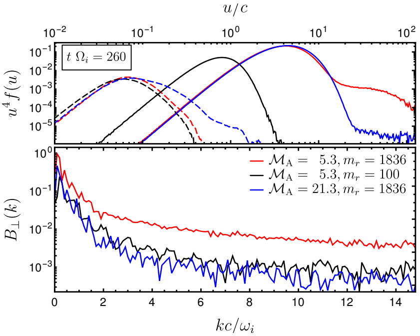
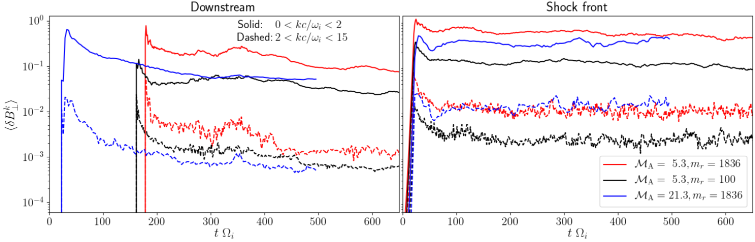


Simulation results

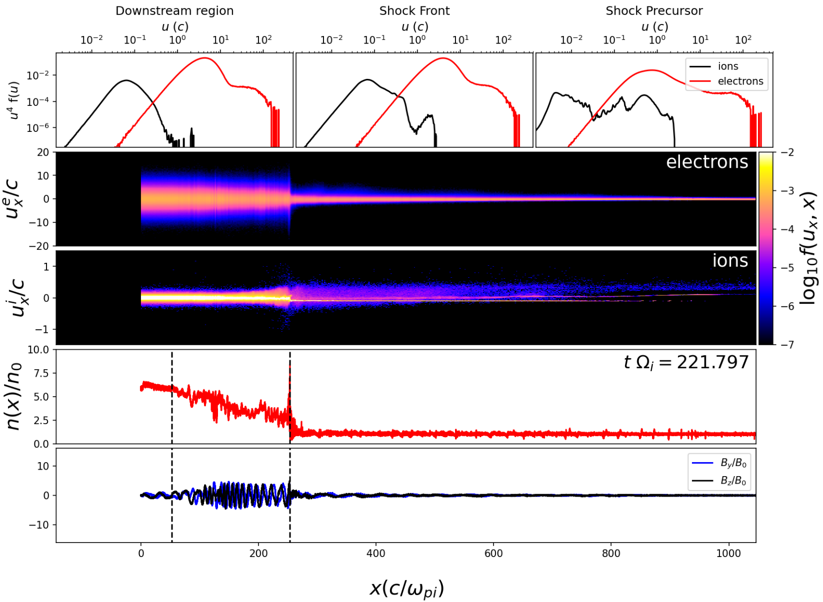
Impacts of Intermediate-scale instability







Where/how e-acceleration



Talk summary

Conclusions:

- new CR-driven dominant instabilities at scales $< c/\omega_i$
- The driven waves facilitates a new mechanism for very efficient electron acceleration
- e acc. occurs at the shock fronts and also throughout shock downstream region.
- more potential impacts so stay tuned for more papers to come!

Thank you for your attention