Title: Unveiling a Novel Plasma Instability: Impacts on Galaxy Formation and Electron Acceleration at Astrophysical Shocks

Speakers: Mohamad Shalaby

Series: Strong Gravity

Date: October 26, 2023 - 1:00 PM

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Abstract: Cosmic-ray-driven instabilities play a crucial role in particle acceleration at shocks and during the propagation of GeV cosmic rays in galaxies and galaxy clusters within the self-confinement picture of CR transport. These instabilities amplify magnetic fields, which, in turn, scatter cosmic rays and thus self-regulate their transport. This leads to a strong coupling between the collisionless cosmic ray population and the thermal background plasma, implying potentially significant dynamic feedback. In this presentation, I discuss a recent discovery of a new cosmic ray-driven instability, referred to as the intermediate-scale instability, which triggers comoving ion-cyclotron electromagnetic waves at sub-ion skin-depth scales. Its growth rate is notably faster compared to the ion gyro scale (streaming) instability, which is commonly assumed to be the dominant instability in the self-confinement picture. Therefore, this new instability could play a vital role in the transport of cosmic rays in galactic and stellar environments. I then explore the implications of this instability for electron acceleration at non-relativistic shocks. Through Particle-in-cell (PIC) simulations, it is demonstrated that the new instability triggers the dominant mechanism for efficient electron acceleration at parallel electron-ion shocks, addressing a persistent issue with electron injection at these shocks. The PIC simulations also reveal that the common practice of using reduced ion-to-electron mass ratios in shock simulations, which artificially suppresses the intermediate instability, not only hinders electron acceleration but also leads to incorrect electron and ion heating in downstream and shock transition areas.

Zoom link https://pitp.zoom.us/j/91367222746?pwd=REpEdXE3ZGdLeVQ1bnh0NldIQktWQT09

Unveiling a Novel Plasma Instability: Impacts on Galaxy Formation and Electron Acceleration at Astrophysical Shocks

Mohamad Shalaby – mshalaby@live.ca

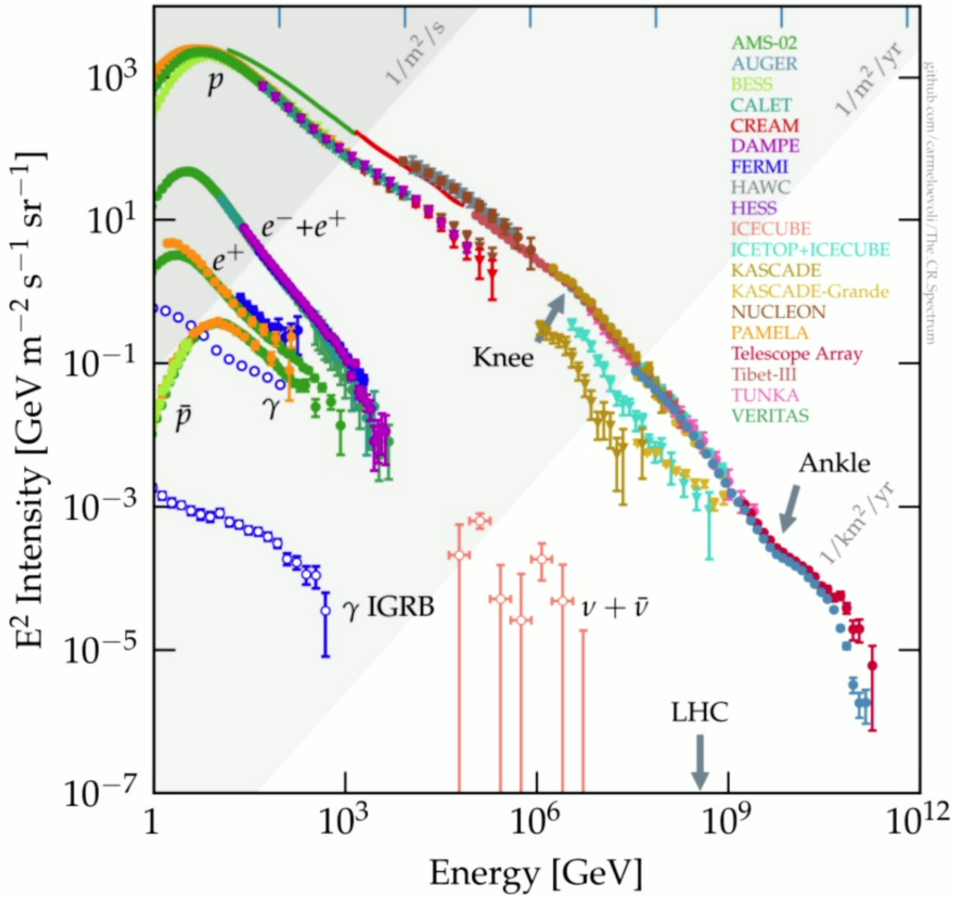
Collaborators: Rouven Lemmerz, Timon Thomas, Virginia Bresci and Christoph Pfrommer
Leibniz Institute for Astrophysics Potsdam

MS+(2021; ApJ 908 206 & 2022; ApJ 932 86)
MS+2023; arXiv:2305.18050 (JPP letter in press)

Cosmology and Strong Gravity Seminar
Perimeter Institute for Theoretical Physics
Waterloo, Canada

Thursday, 26.10.2023

What are Cosmic Rays



Credit: Boncioli 2023

Importance of CR research

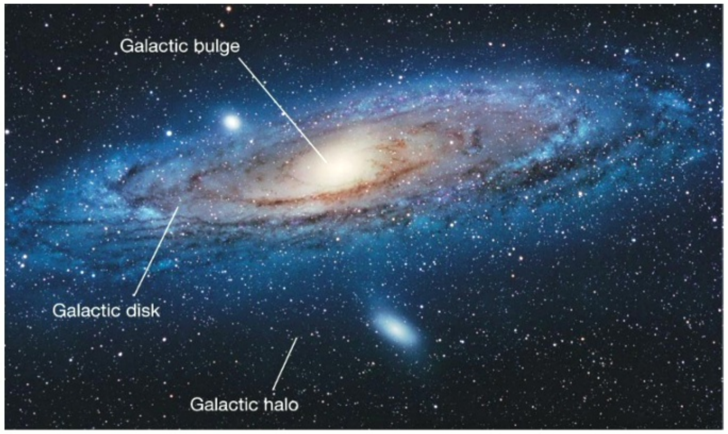
The Decadal Survey on Astronomy and Astrophysics 2020 panel

“The impact of CRs is one of the largest uncertainties in understanding feedback in galaxy formation. The primary uncertainty is how CRs are scattered by small-scale fluctuations in the magnetic field, which sets whether CRs can escape a region or whether their pressure builds up to the point where it can drive an outflow. [. . .] It is remarkable that tiny solar-system scale fluctuations in the galactic magnetic field are a key ingredient in understanding how galaxies drive winds on scales of tens of kiloparsecs, or that the large scale magnetic field properties or distant supernovae can affect the formation of pre-stellar cores”

Coupling of CRs to background plasma

Estimating time spent by CRs in a galactic disk

- few GeV CRs (protons) are collisionless species
- light crossing time of young thin Milky Way-type disk ($h < 3$ kpc, $c \sim 0.3$ pc/year) $\Rightarrow$ $t_{\text{light}} \lesssim 10^3$ years.



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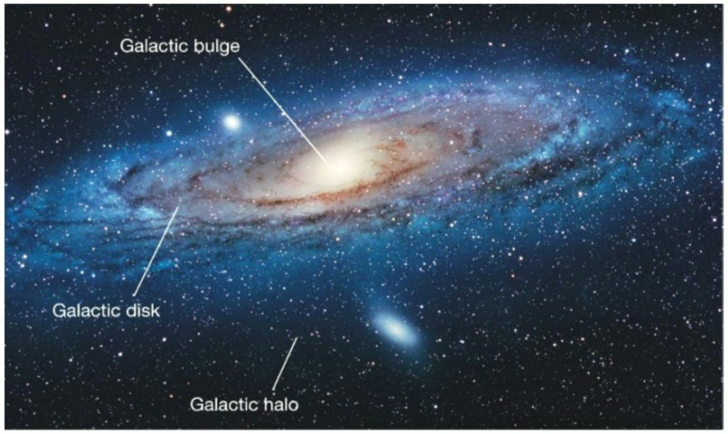
- using the ratios of spallation products of CR primaries $\Rightarrow$ $t_{\rm conf} \sim 2 - 3 \times 10^7$ years.



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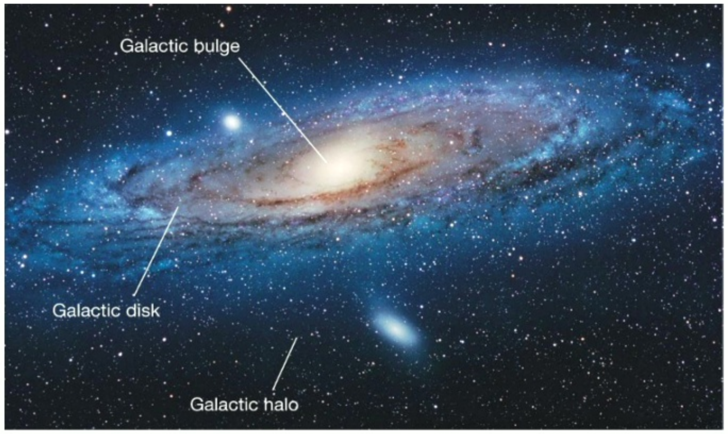
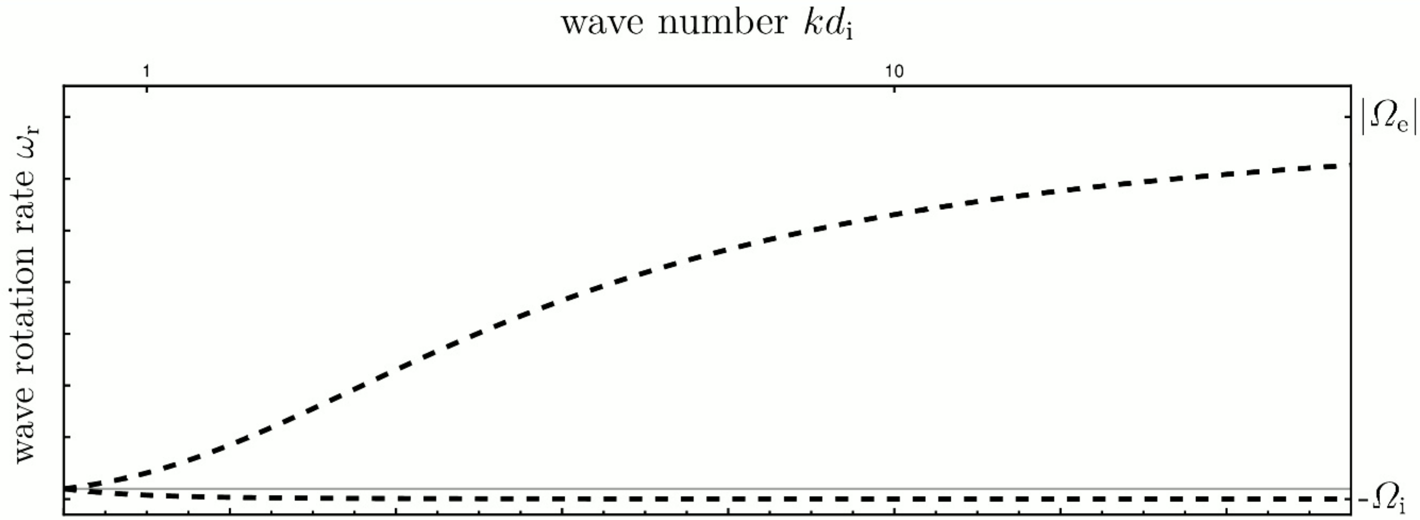
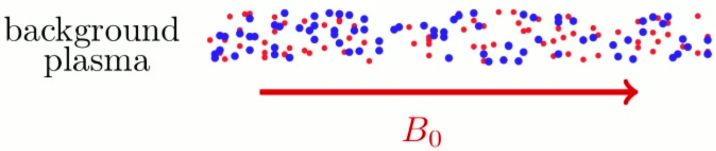
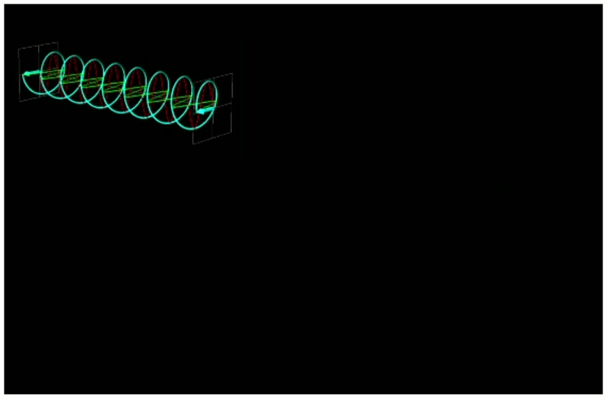


$\Rightarrow$ **CRs are strongly coupled by scattering on magnetic field irregularity**
$\Rightarrow$ what are plasma instabilities
$\Rightarrow$ how/what cosmic rays driven plasma instabilities.

CR driven instabilities







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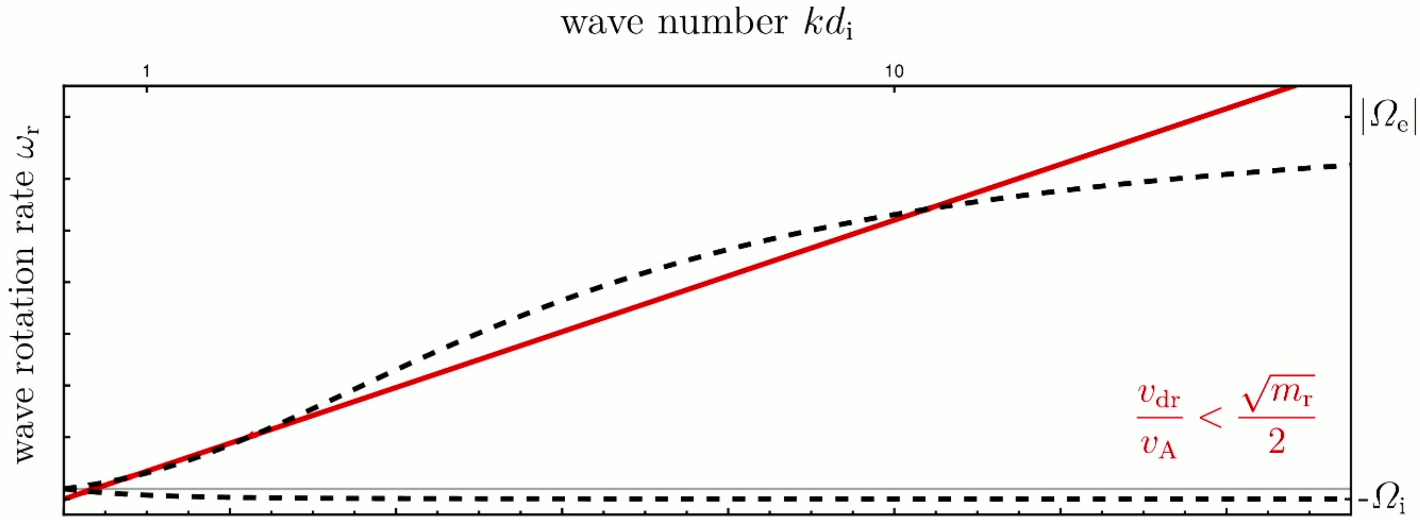
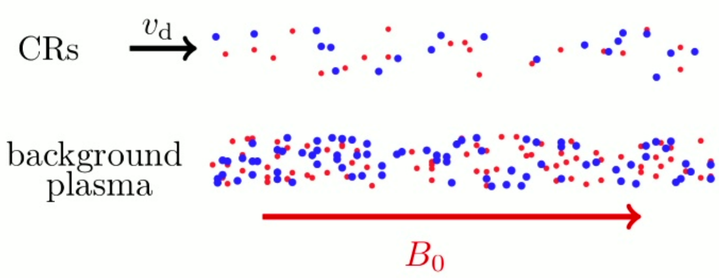
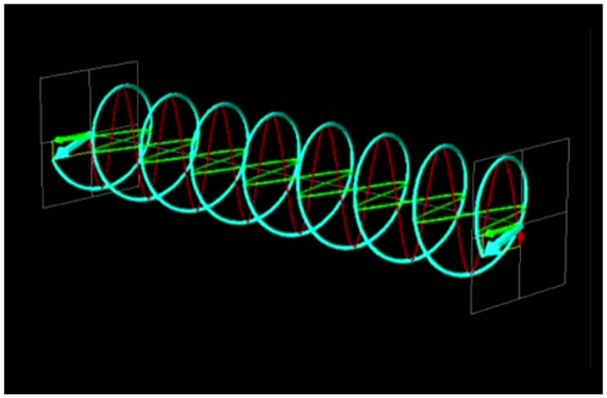
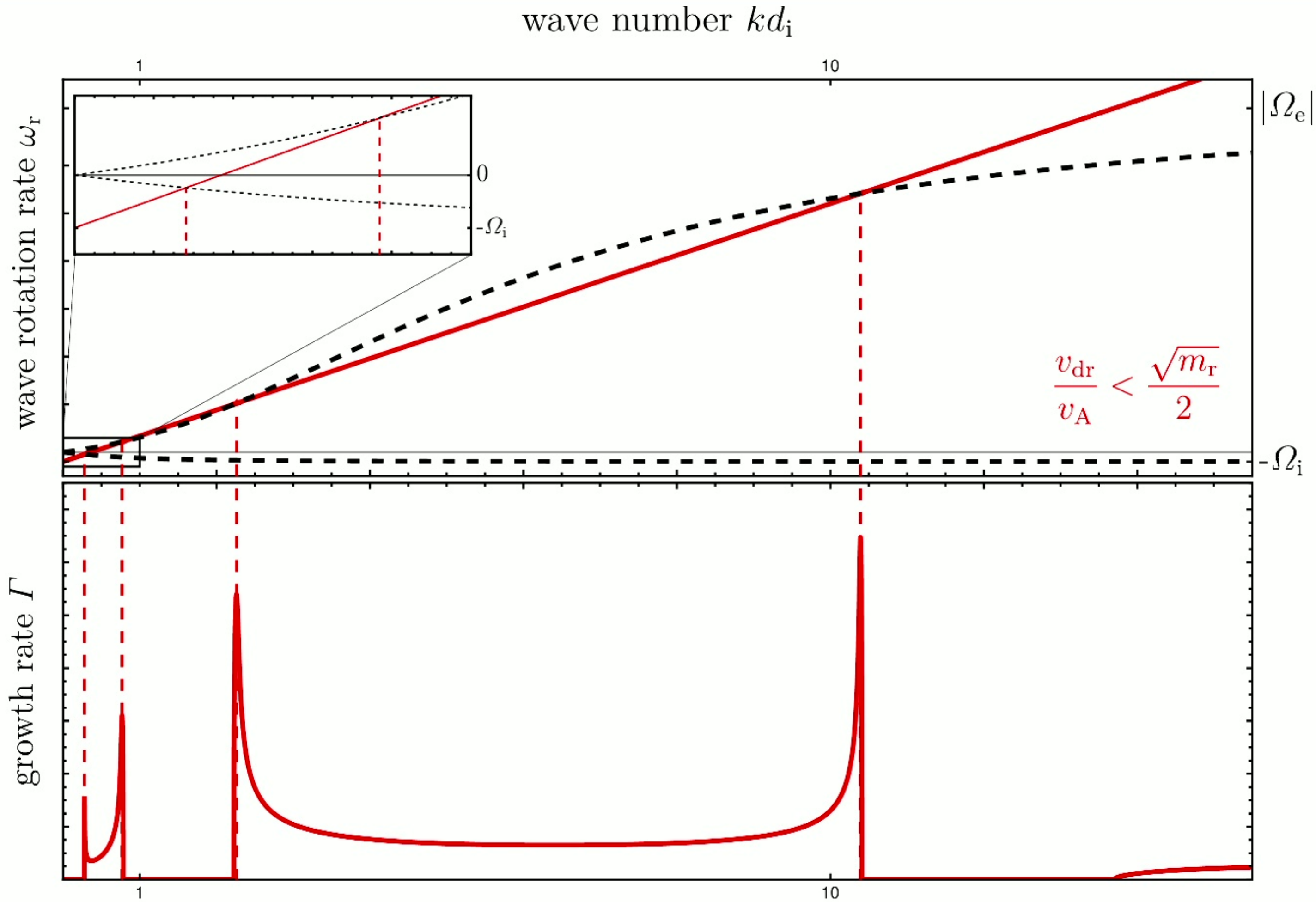






CR driven instabilities



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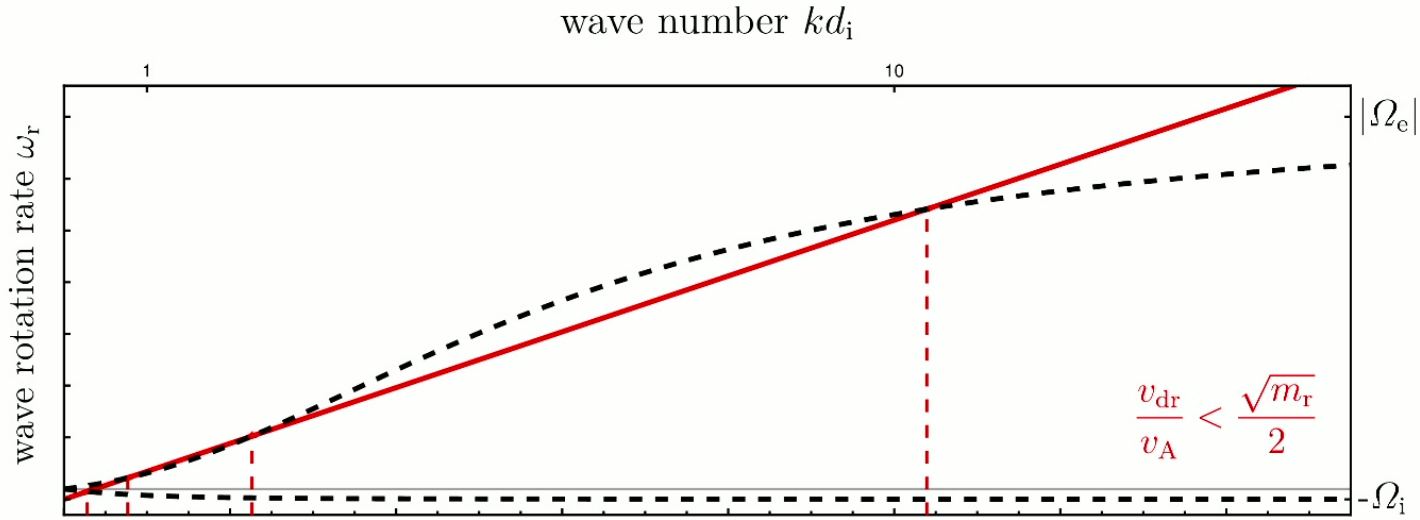
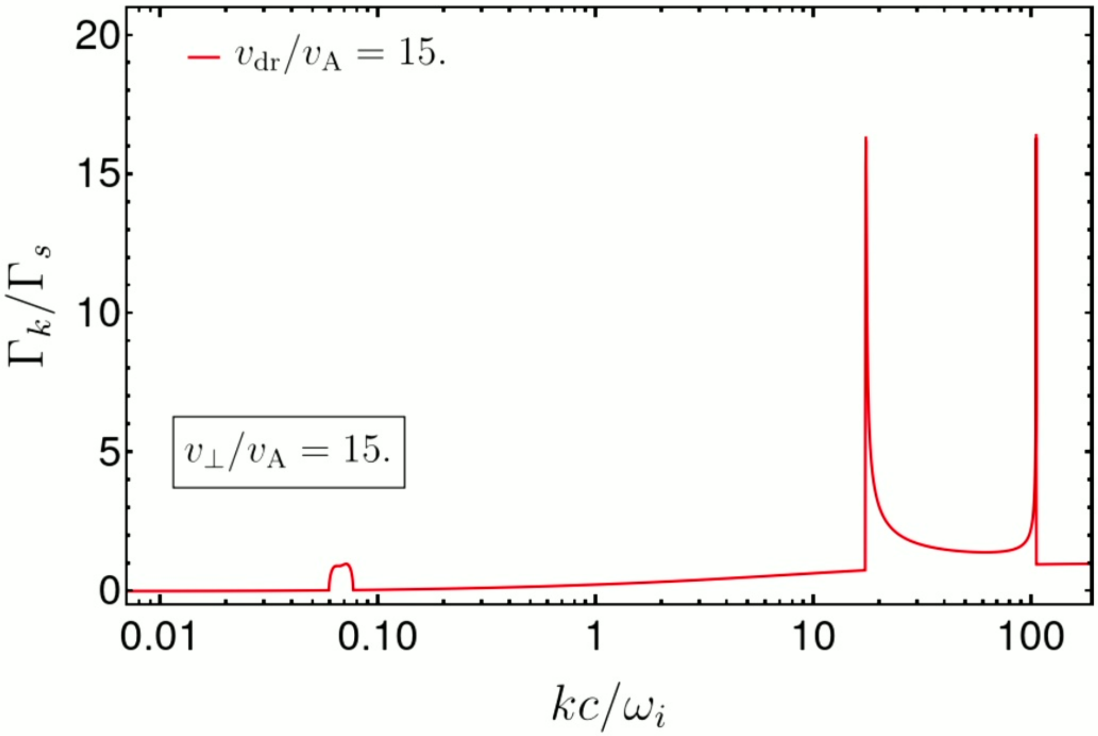


Condition for instability growth



Shalaby+2021; ApJ 908 206

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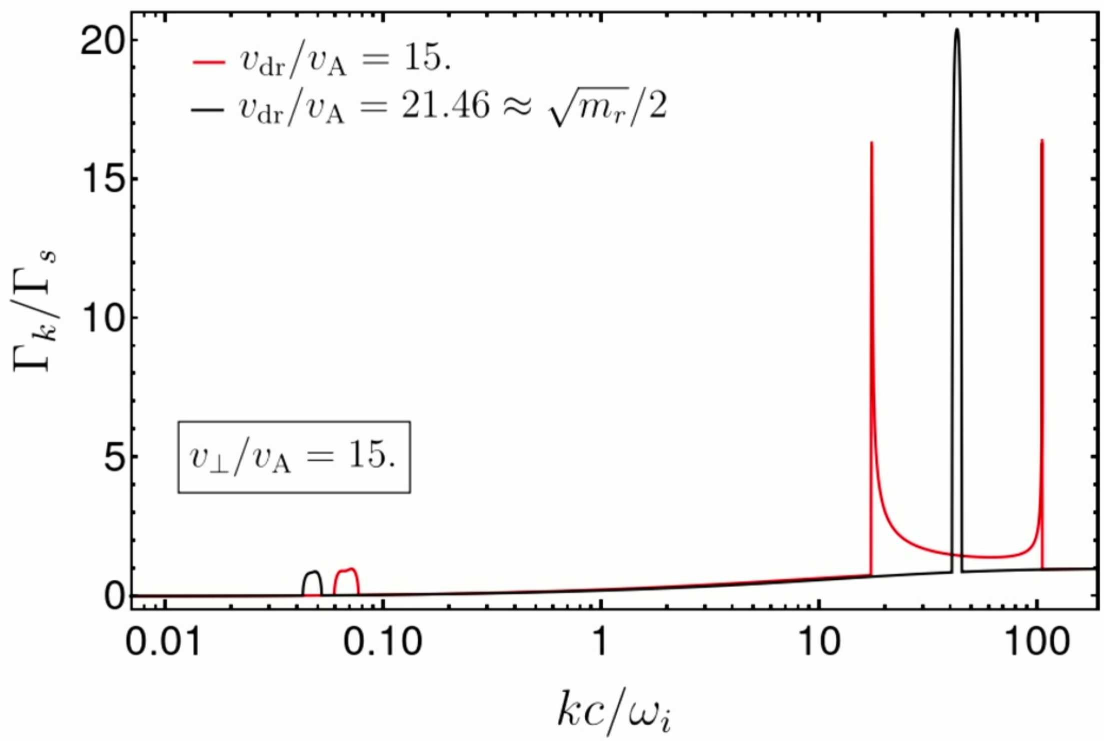

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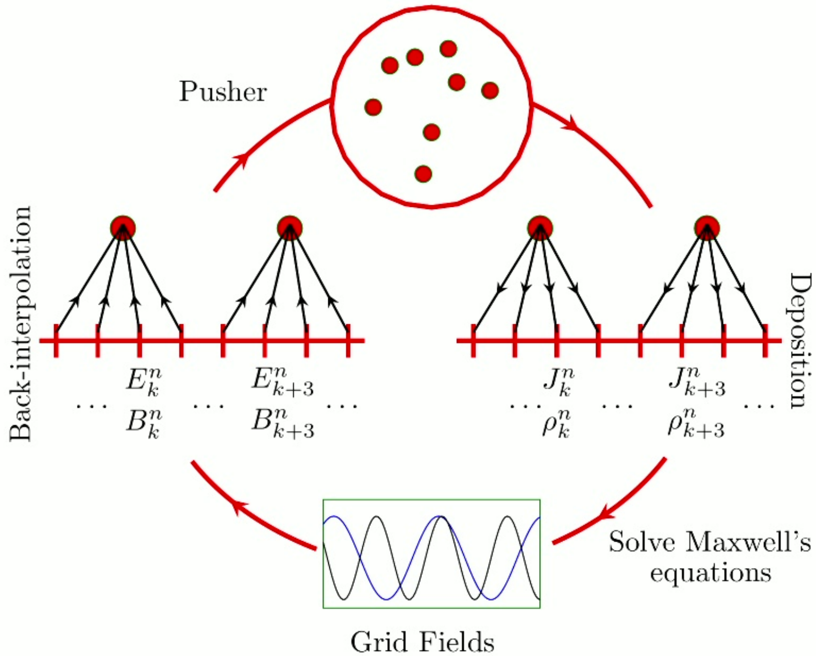
Particle-in-cell algorithm

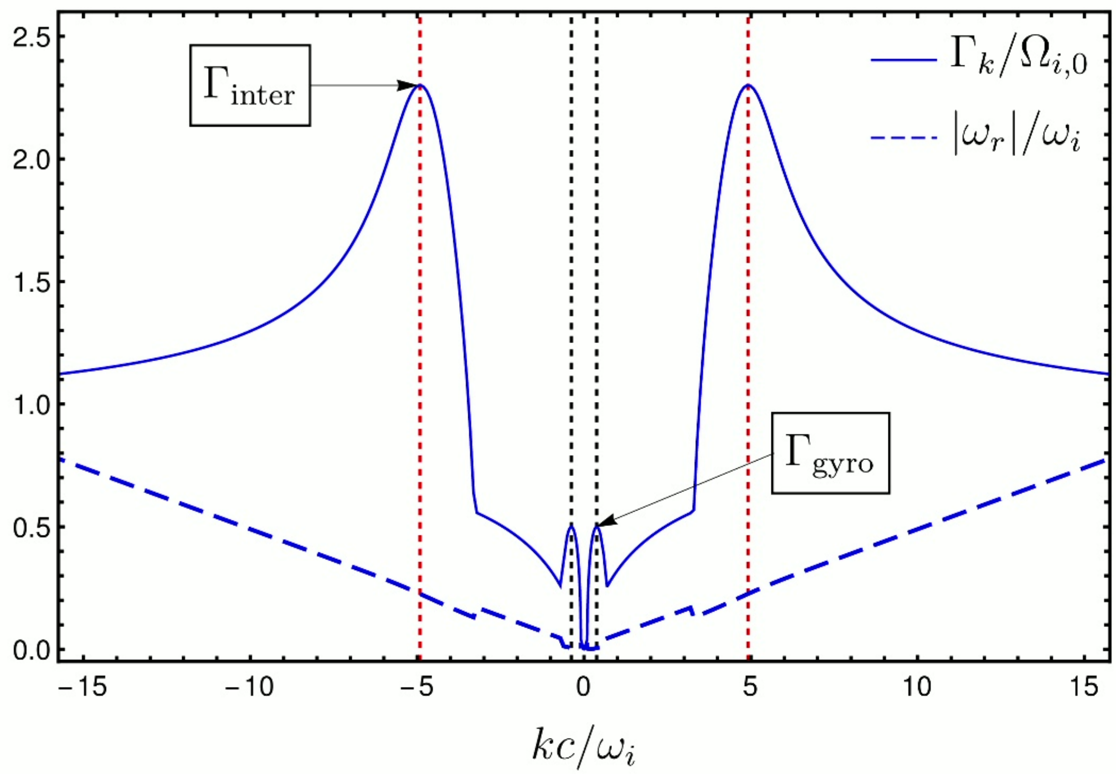
- Solve kinetic equations
- Couple Eulerian (grid) and Lagrangian (particles) methods.



SHARP code (MS+ 2017, ApJ 841 52): fifth order spline interpolation exact charge and momentum conservation.

Kinetic simulation for instabilities

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



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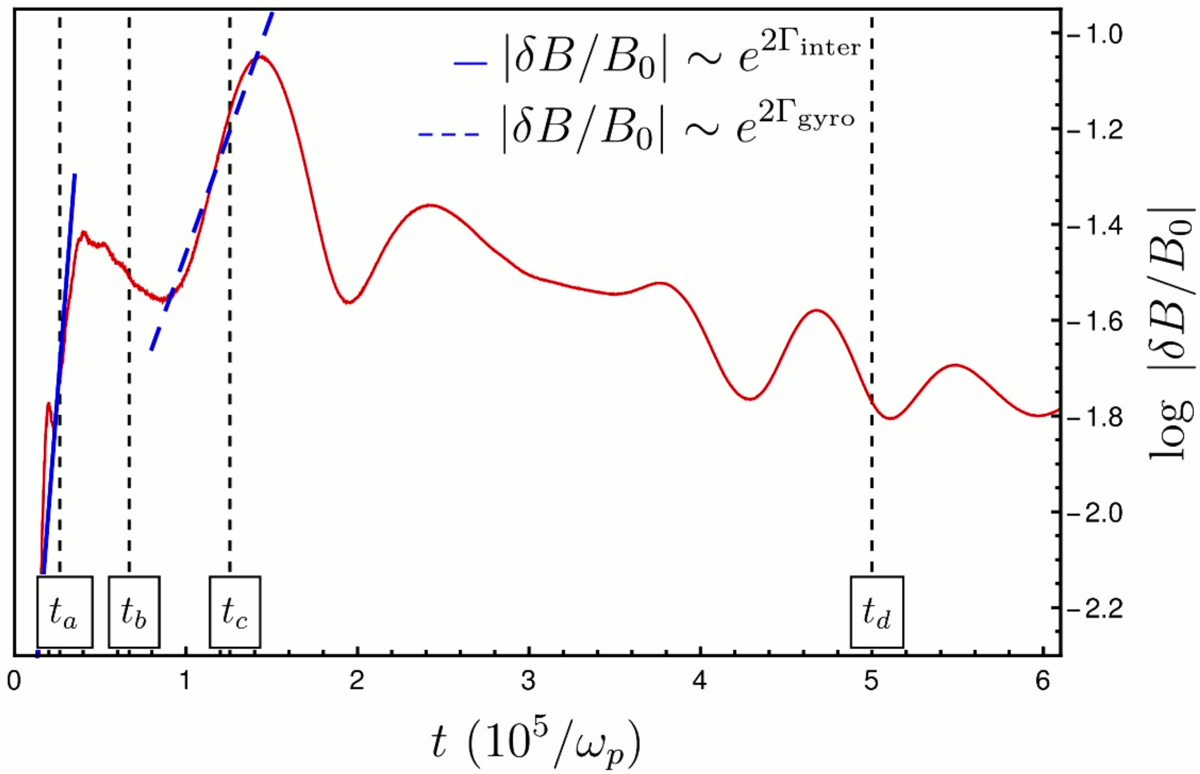

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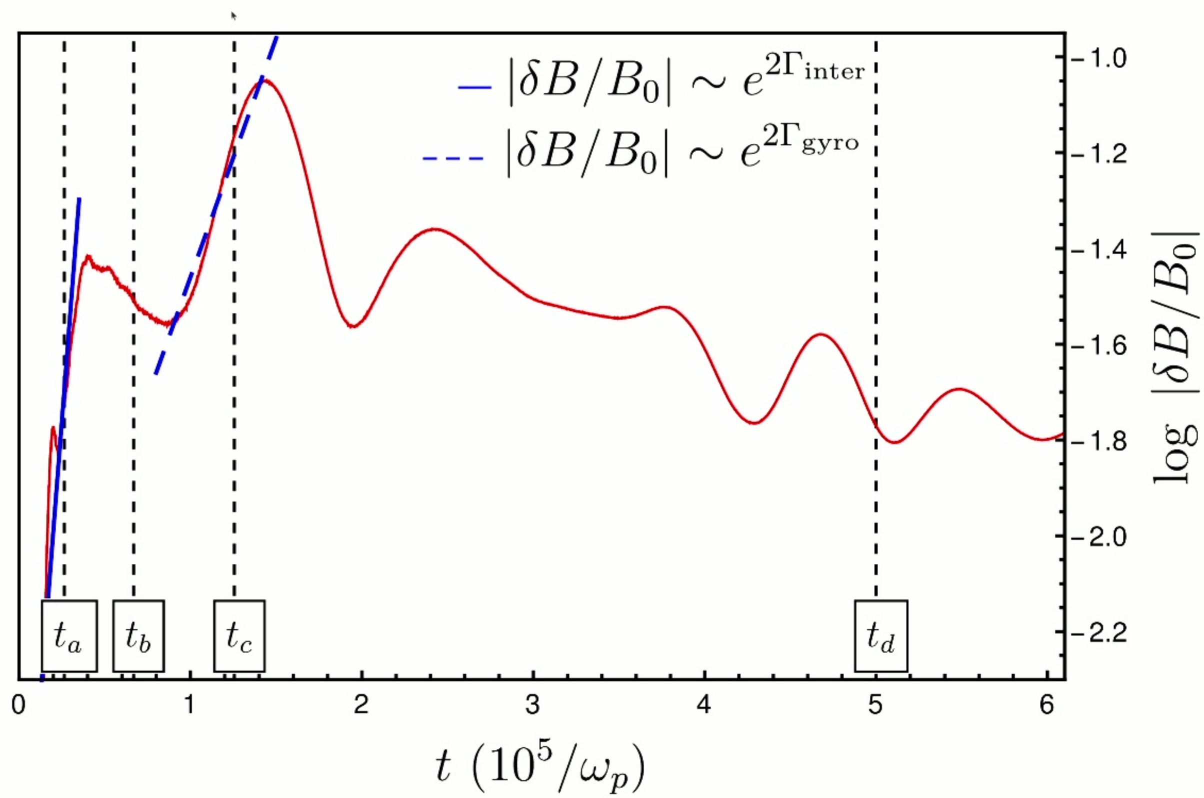

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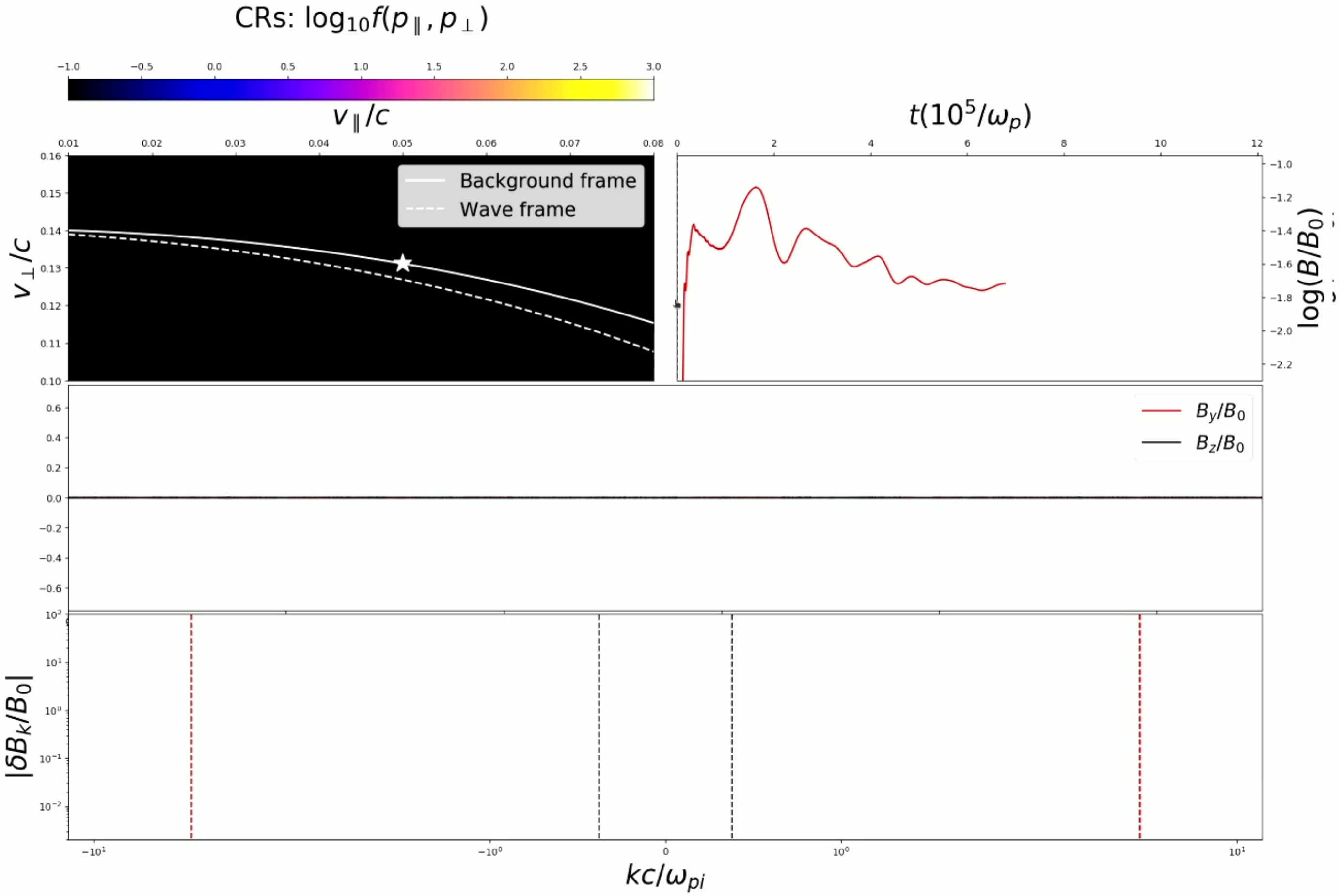

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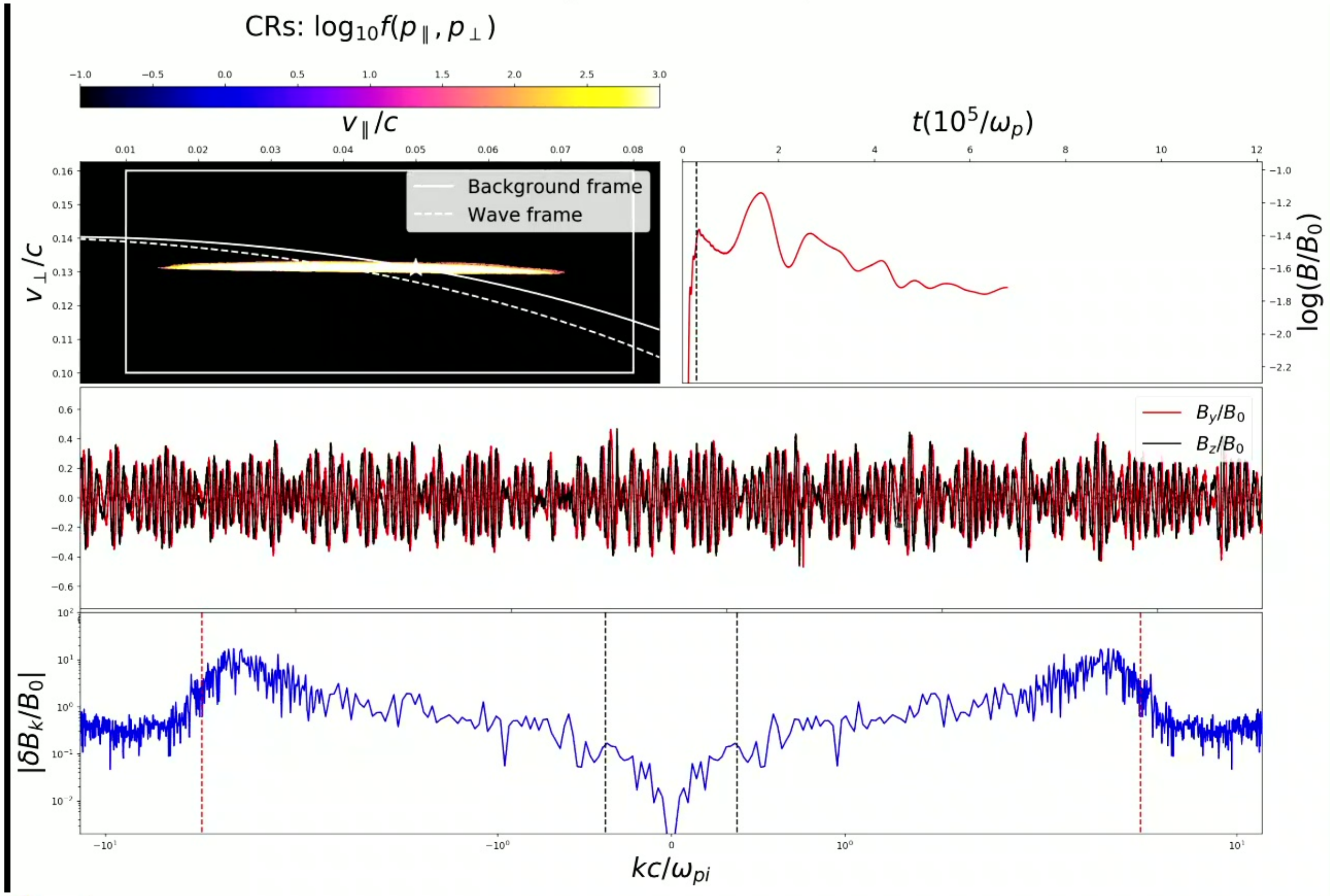

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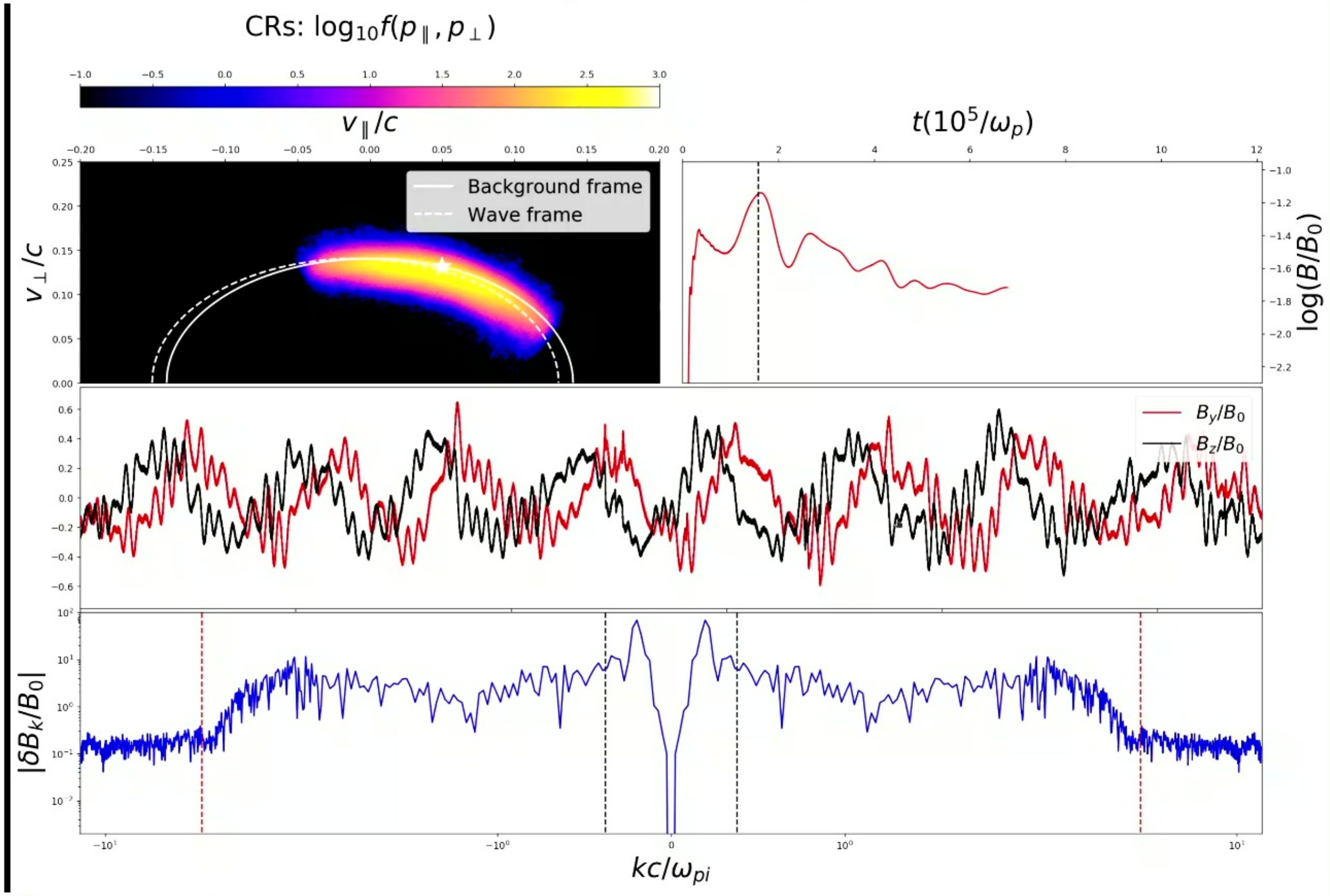


Summary

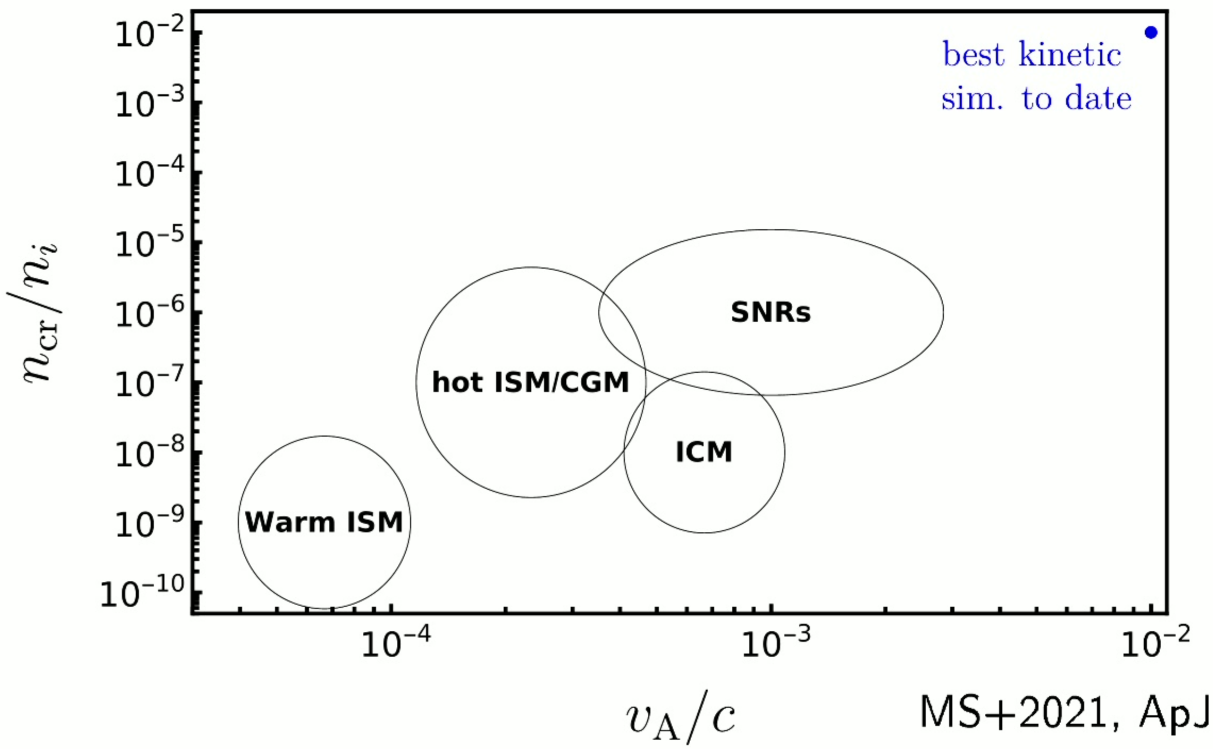
Found a new instability

- drives co moving ion-cyclotron waves
- growth only if $v_{\rm dr}/v_{\rm A} < \sqrt{m_{\rm i}/m_{\rm e}}/2$
- much faster growth compared to gyro-scale growth

Potential implications:

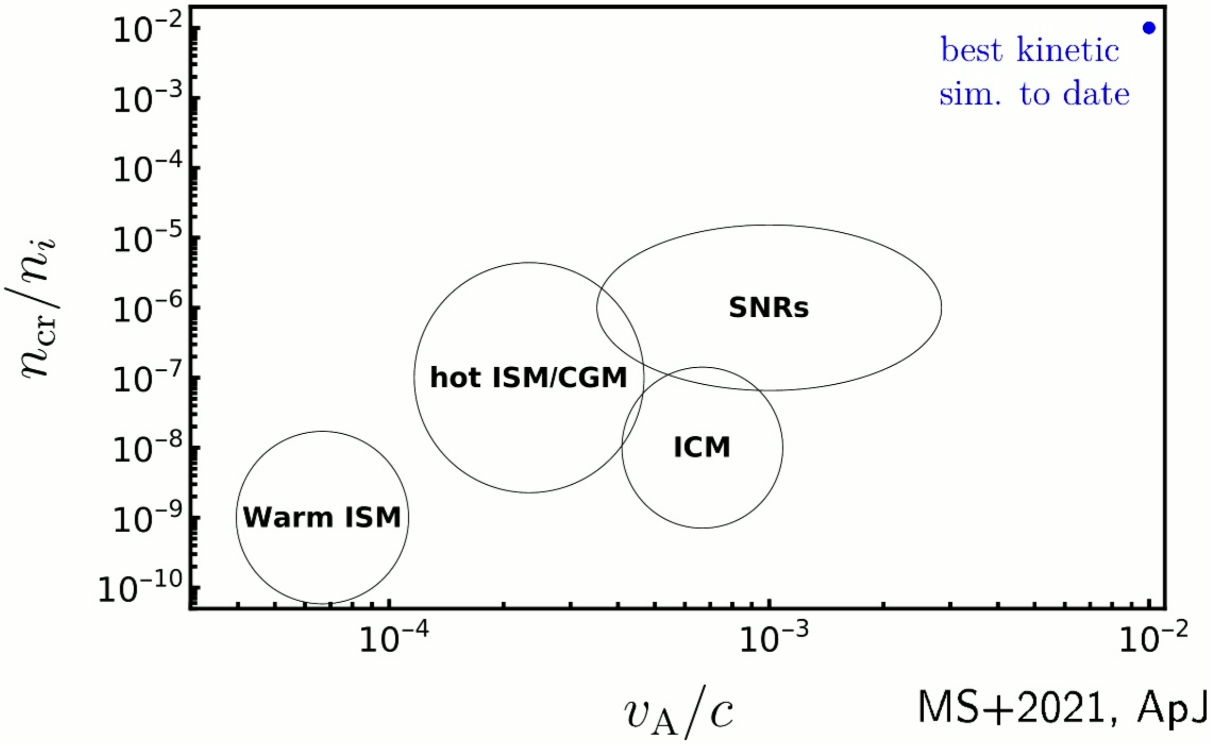
- impact on CR confinement and propagation in galaxies
  $\Rightarrow\Rightarrow$ On going projects [only highlights]
- **impact on electron injection and acceleration in astrophysical collisionless shocks**

Saturation with realistic parameters



MS+2021, ApJ 908 206

Saturation with realistic parameters

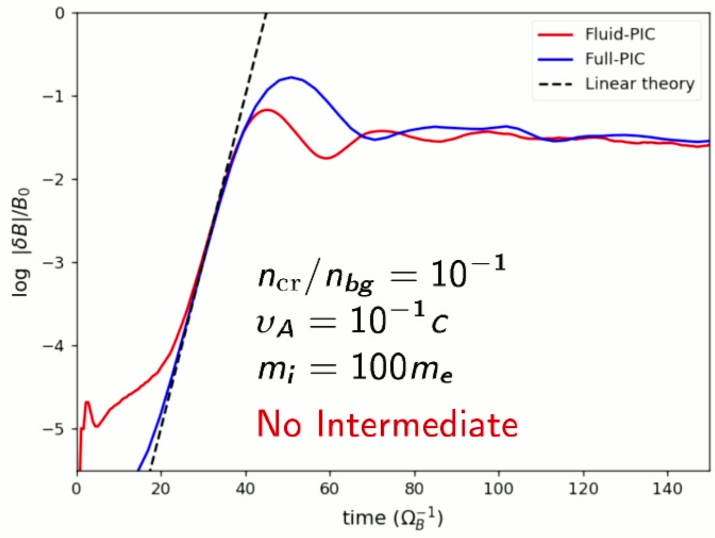


MS+2021, ApJ 908 206

- Going towards realistic parameters changes the saturation level and the saturation mechanism
- How to proceed (in 1D3V); replace background plasma with ideal fluid

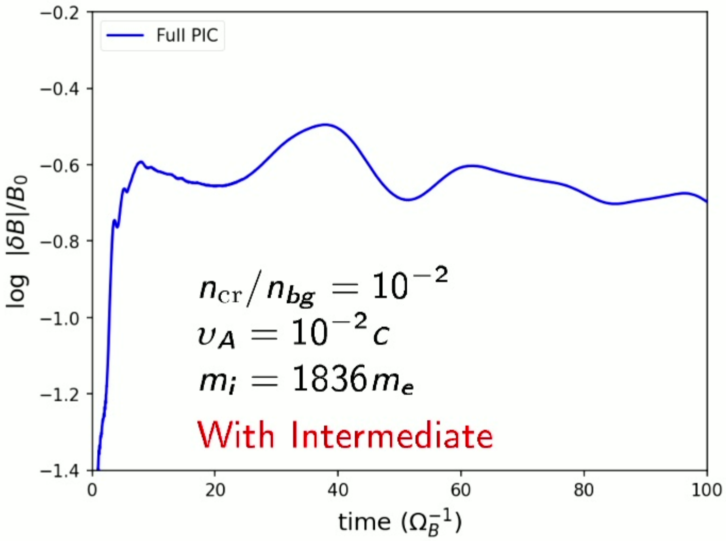
Saturation with realistic parameters

- PIC vs Fluid-PIC simulations



Shalaby+2021

- Closer to realistic parameters



Lemmerz+2023
Shalaby+2021

Saturation with realistic parameters

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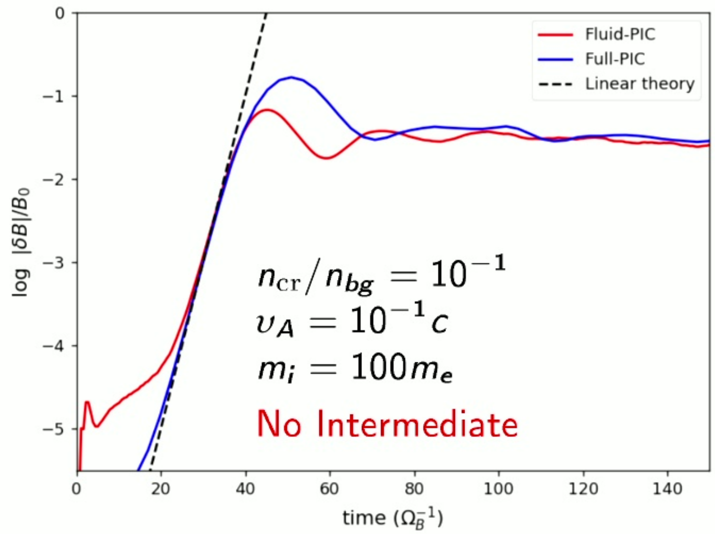

Shalaby+2021

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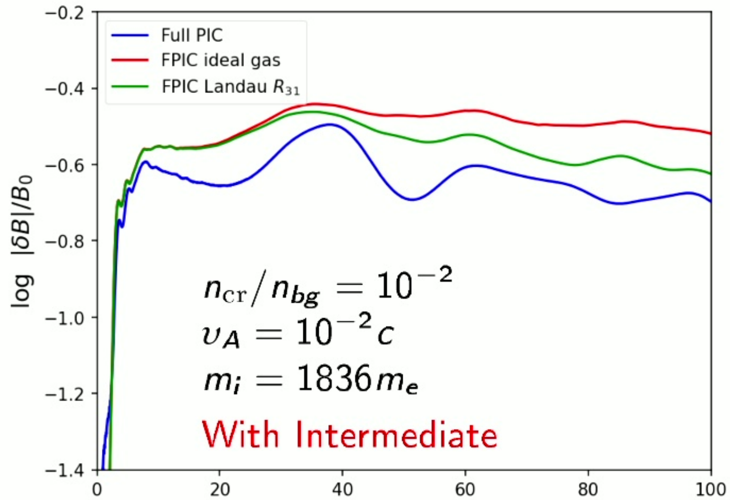


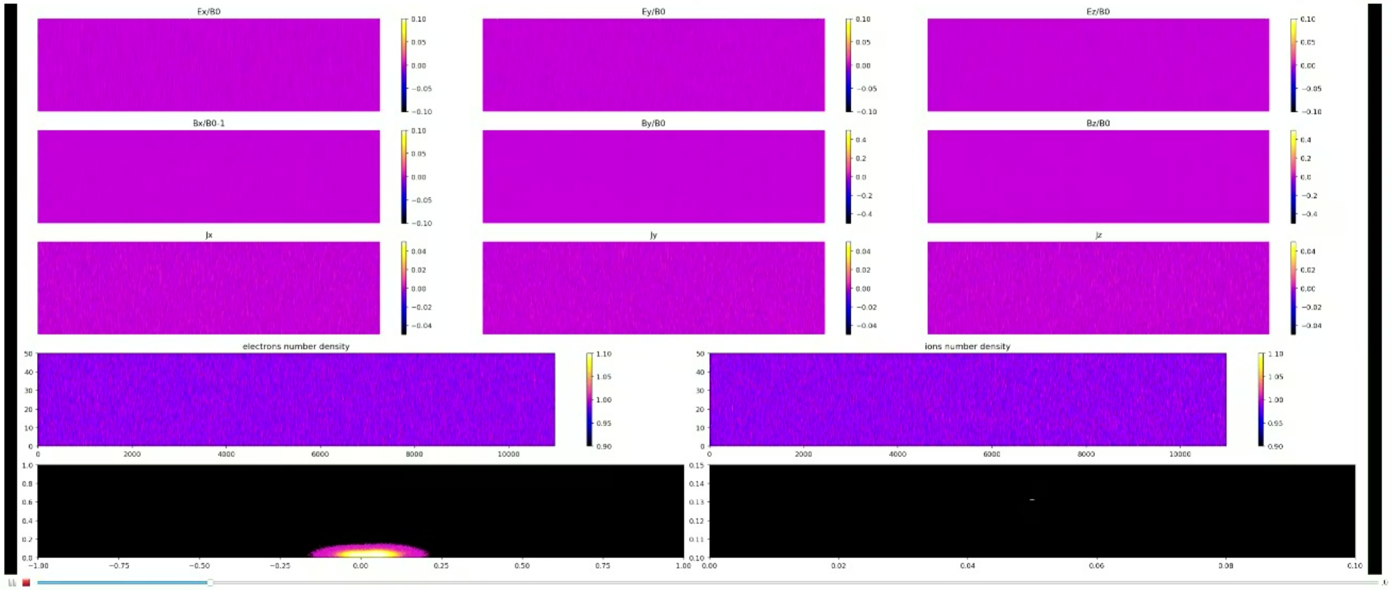
Lemmerz+2023
Shalaby+2021

Rouven Lemmerz

Saturation in 2D3V simulations

1D3V ⇐ saturation seems to be via inverse cascade

What happens in 2D3V simulations? (Full PIC sims; preliminary work)



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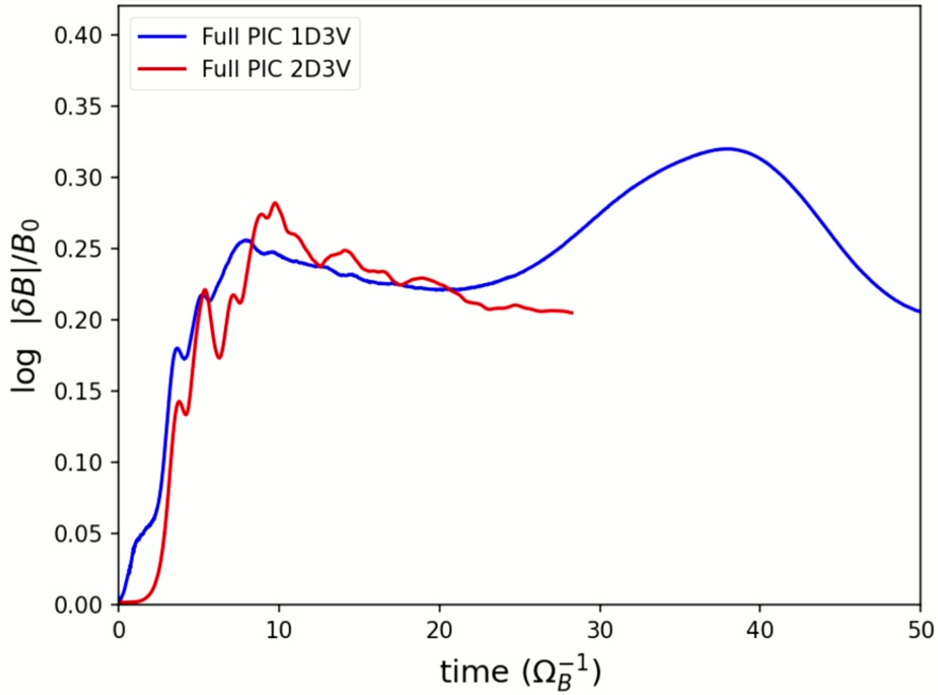

$n_{\rm cr}/n_{bg} = 10^{-2}$

$v_A = 10^{-2} c$

$m_i = 1836 m_e$

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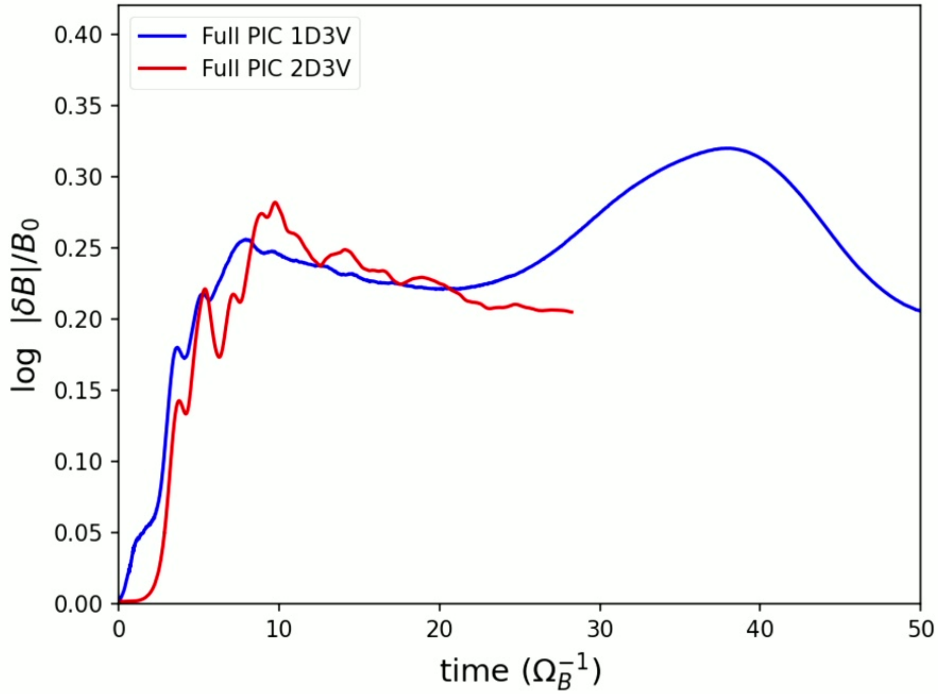
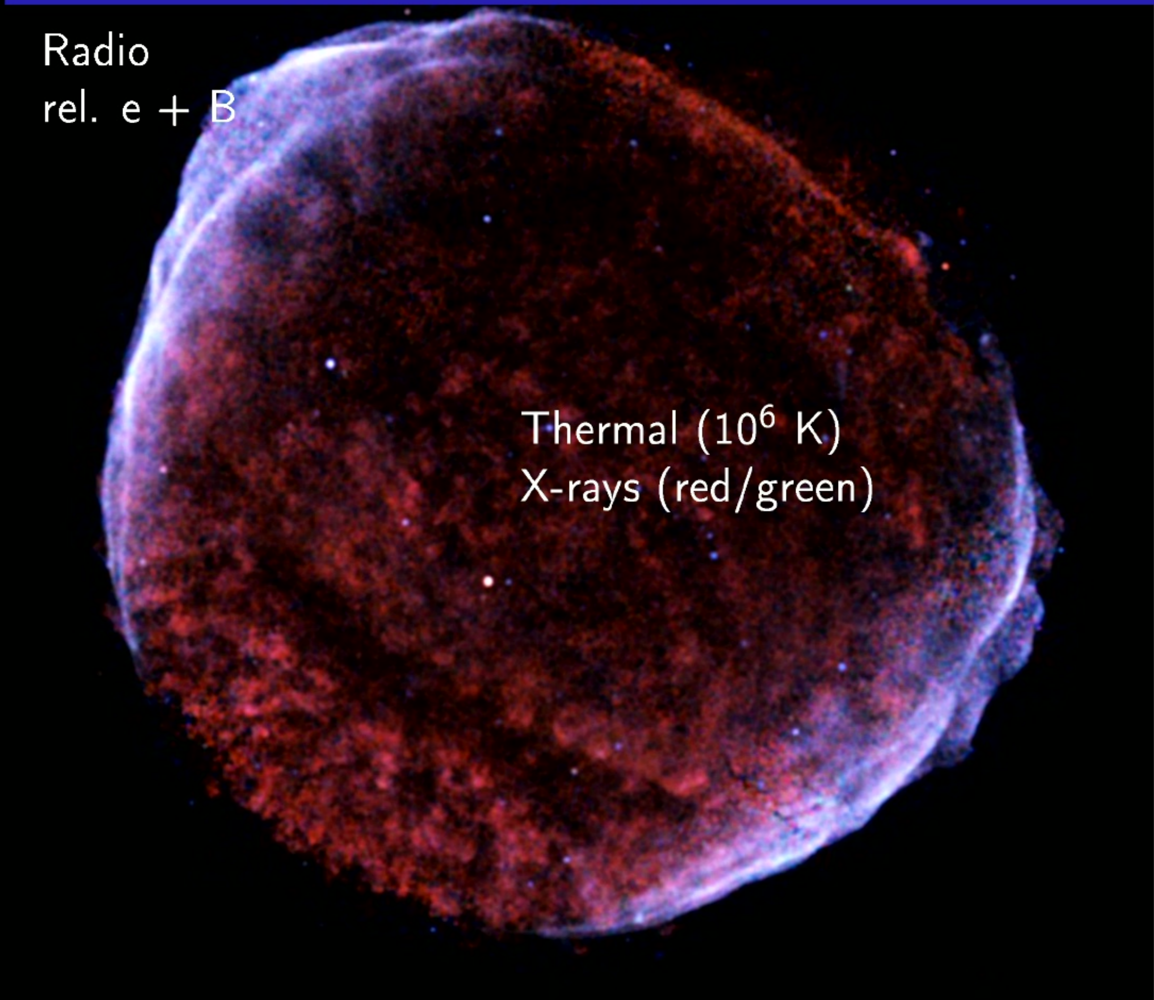


$n_{\rm cr}/n_{bg} = 10^{-2}$
$v_A = 10^{-2}c$
$m_i = 1836 m_e$

$\Rightarrow$ replace background with ideal (HD) fluids [✓]
$\Rightarrow$ replace background with landau (HD) fluids

electron acceleration at non-relativistic shocks



SN 1006
Chandra's image

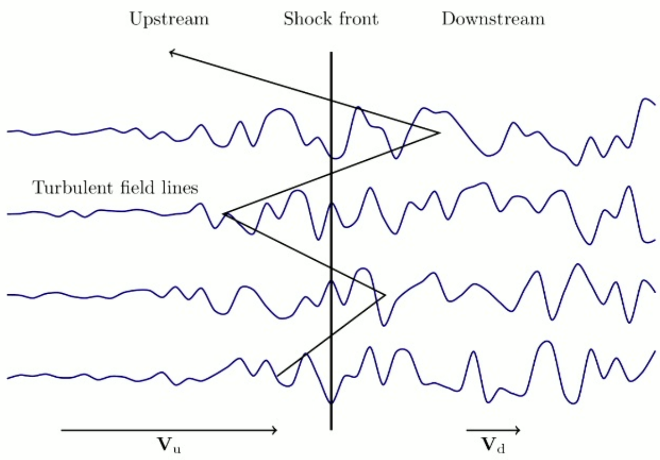
electron acceleration at non-relativistic shocks

(How) can non-relativistic shocks accelerate electrons?

Electron injection problem

- shock-width $\sim$ few x ion's skin depth
- magnetic perturbations on ion's gyro-radius, r_i
- gyro-radii: $r_\mathrm{e} = (m_\mathrm{e}/m_\mathrm{i}) r_\mathrm{i}$.
- thermal electrons can not be scattered across the shock front

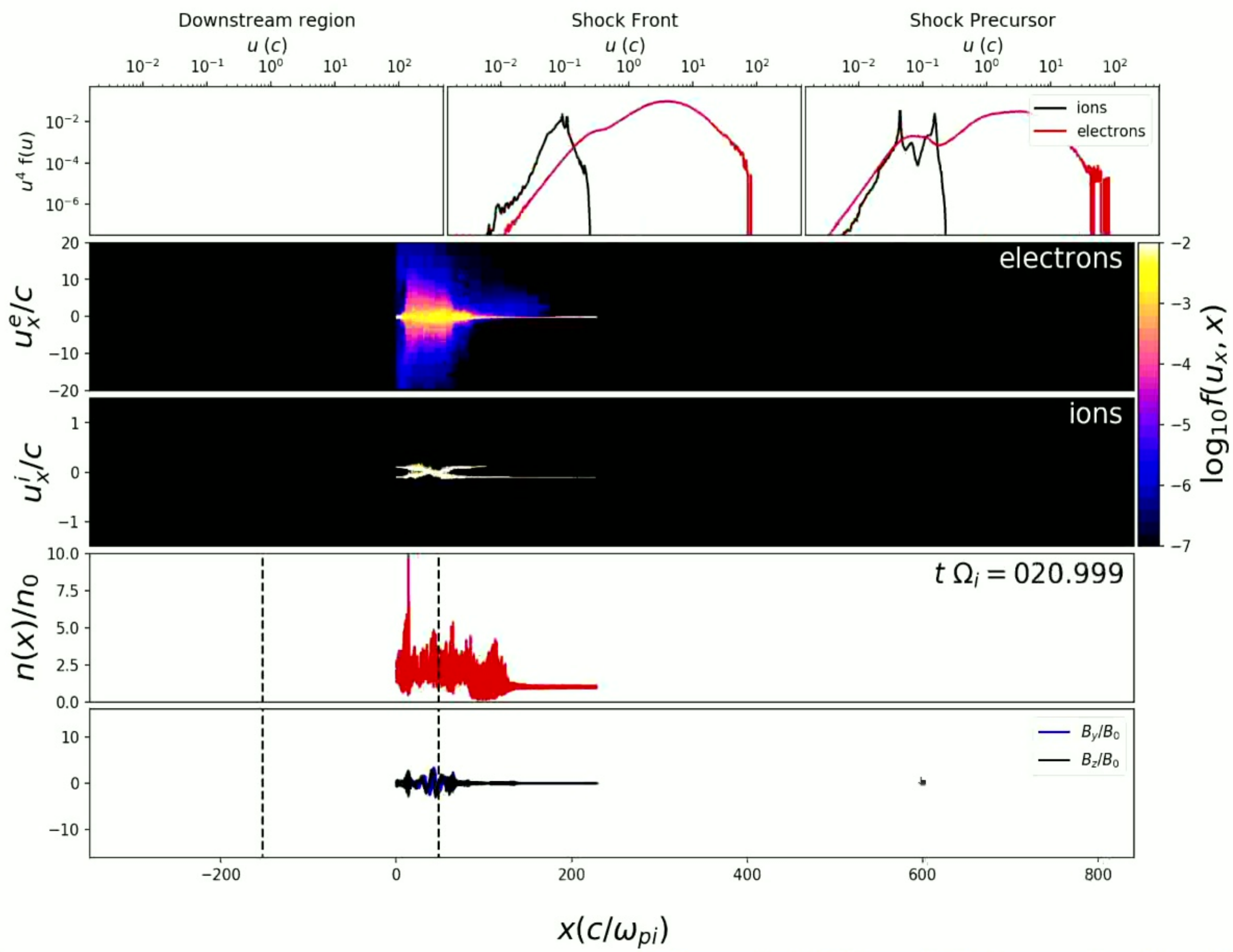
acceleration of ions



Mark Pulupa's space physics illustration

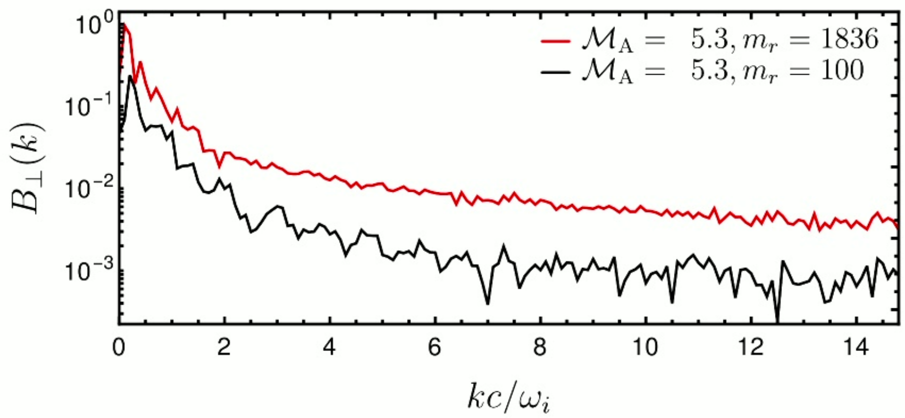
$\Rightarrow$ Need a mechanism to *destabilize* smaller scale waves *efficiently*.

How/where e-acc occurs @ red simulation



Impacts of Intermediate-scale instability

Shalaby+2022; ApJ 932 86

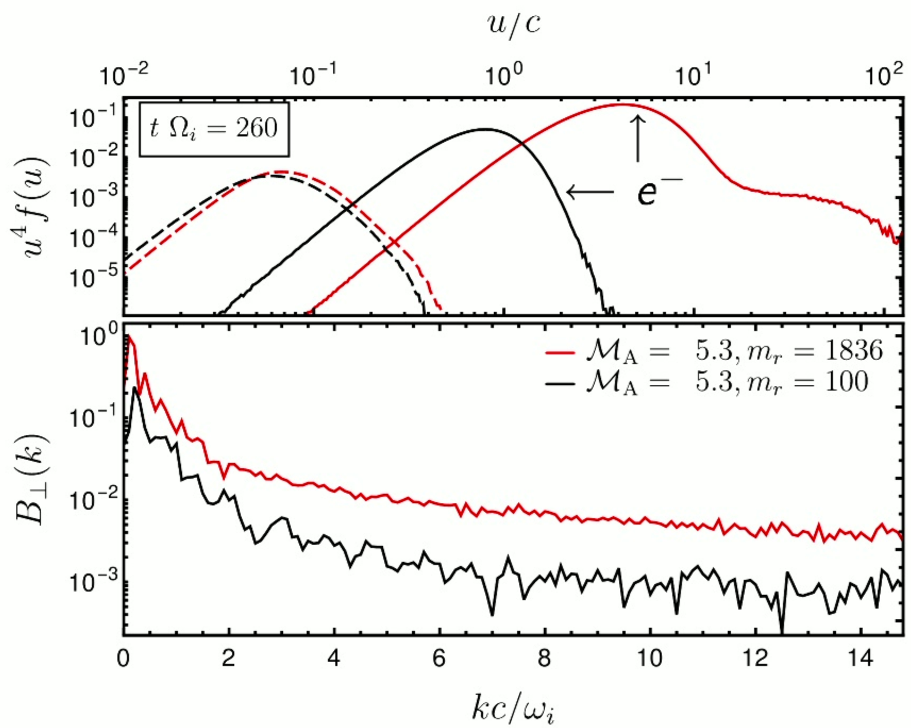


B amplification

- the red simulation satisfies the condition for the new instability
- the black simulation does not

Impacts of Intermediate-scale instability

Shalaby+2022; ApJ 932 86



particles' momenta

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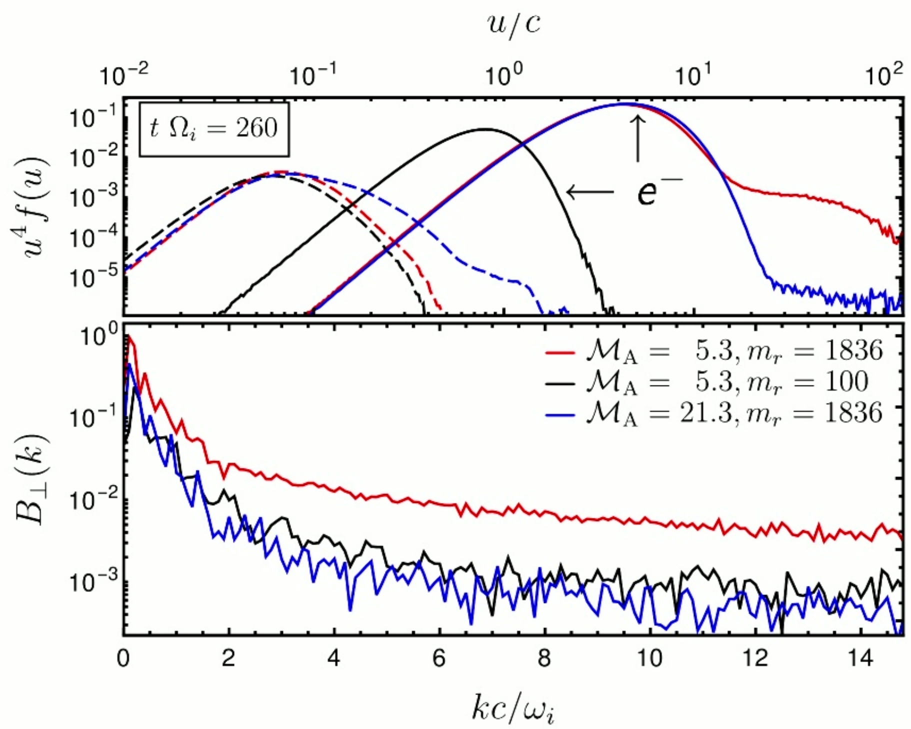
Impacts of Intermediate-scale instability

Shalaby+2022; ApJ 932 86



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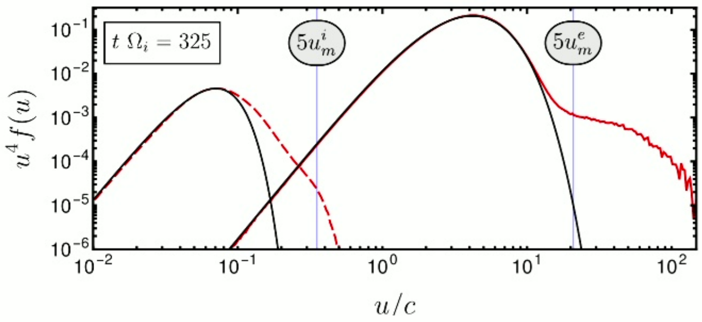
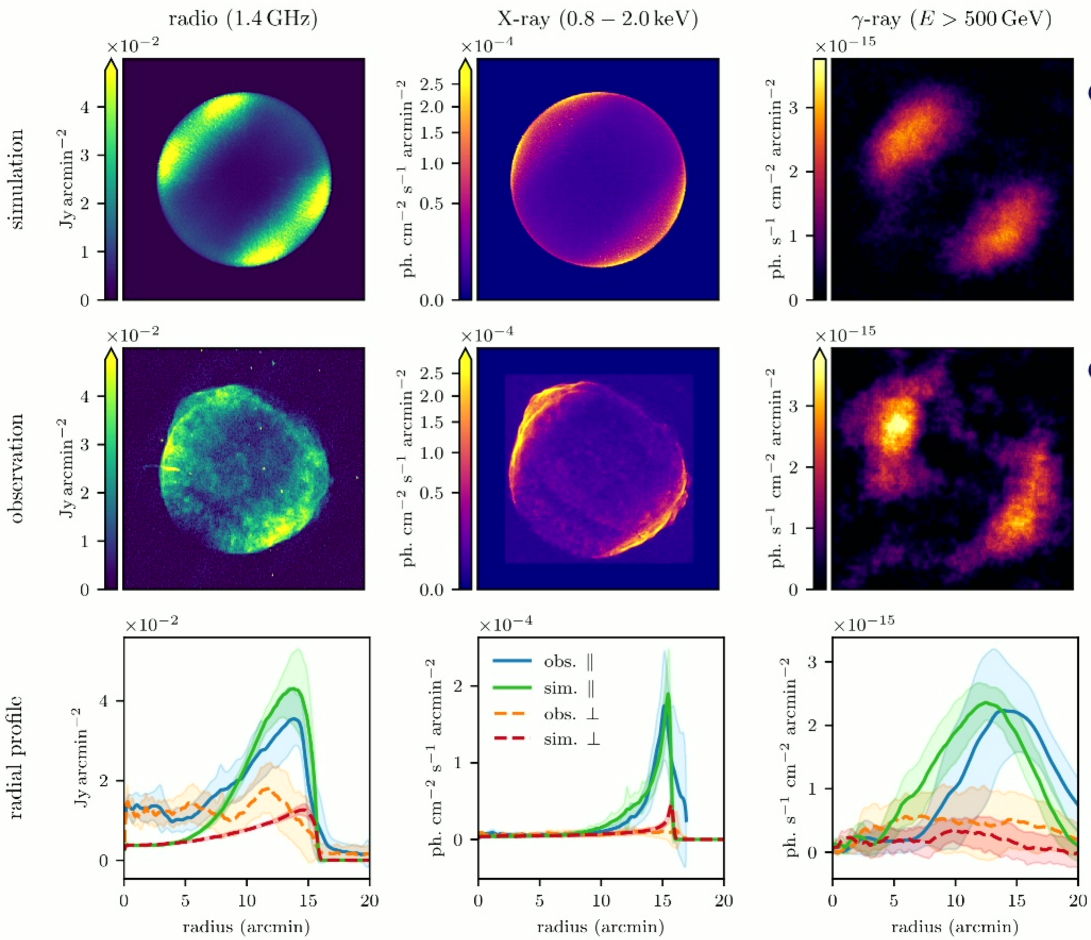
Acceleration efficiency



- electron (solid) and ion (dashed) momentum distribution (rest-frame) in the red simulation
- $K_{ei} = \dfrac{E_e(u > 5u^e_m)}{E_i(u > 5u^i_m)}$

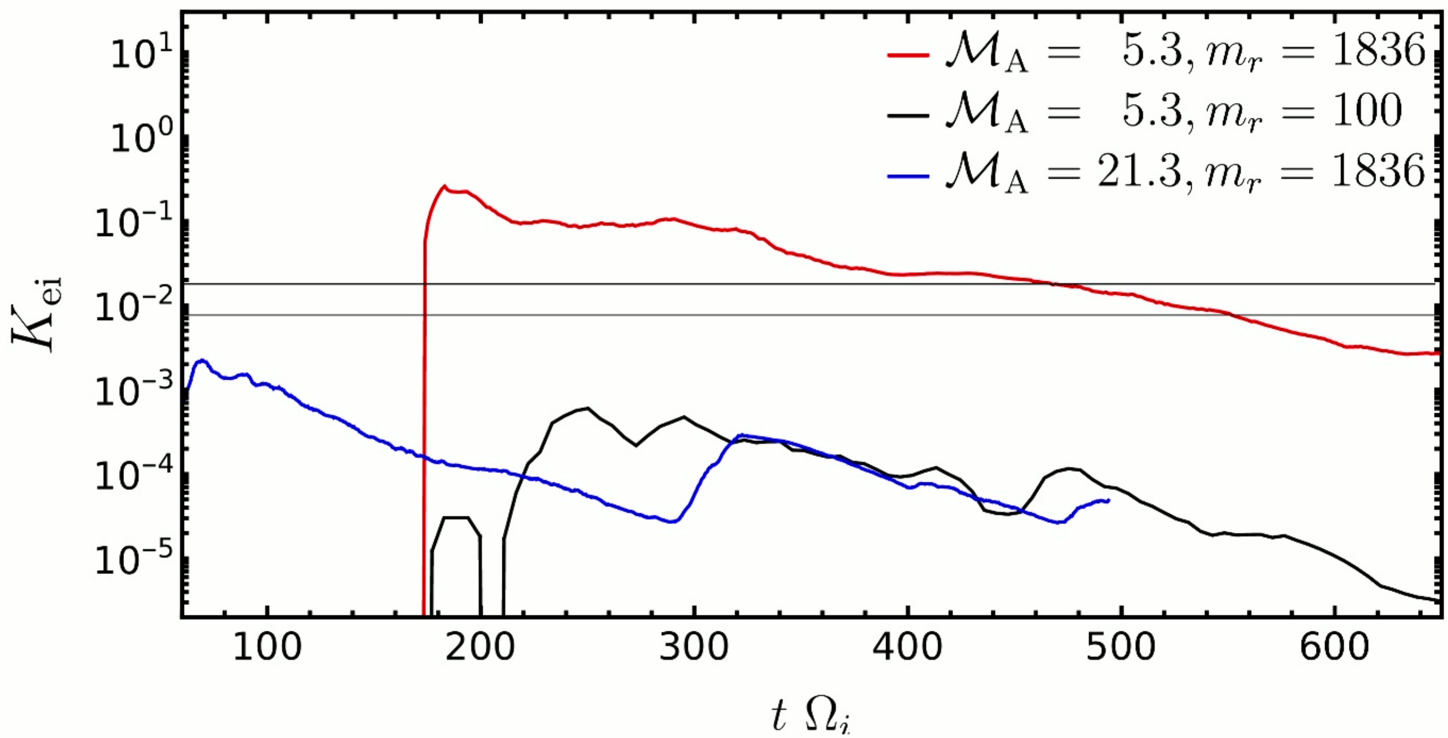
SN 1006 modeling



- 3D MHD blast waves in magnetized ISM-like fluid
- What is the required K_{ei} required to fit the radio emission?

Winner+ 2020 (MNRAS)

SN 1006 modeling



Conclusions

- New CR-driven dominant instabilities at scales $< c/\omega_{\rm i}$.
  Last one relevant for CR transport was found over 60 years ago
- Significant progress to address most uncertain ingredient in our understanding of galaxy formation
- The driven waves facilitates a new mechanism for very efficient electron acceleration (e injection at both shock downstream and transition regions)
- True $m_{\rm i}/m_{\rm e} \Leftarrow$ correct heating and acceleration physics
- More potential impacts so stay tuned for more papers to come!

This project has received funding from the European Research Counsil (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No PICOGAL-101019746).

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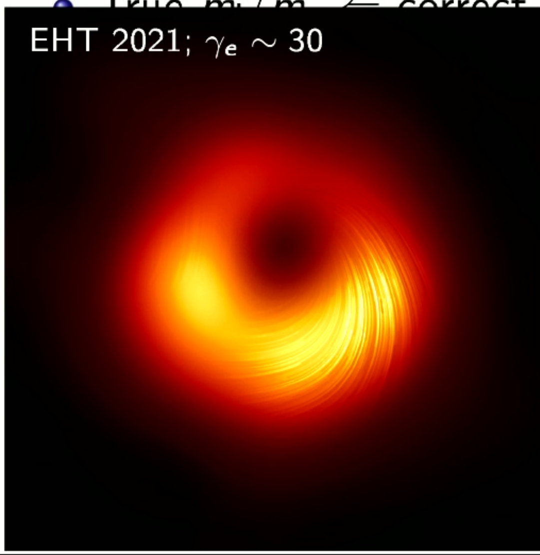

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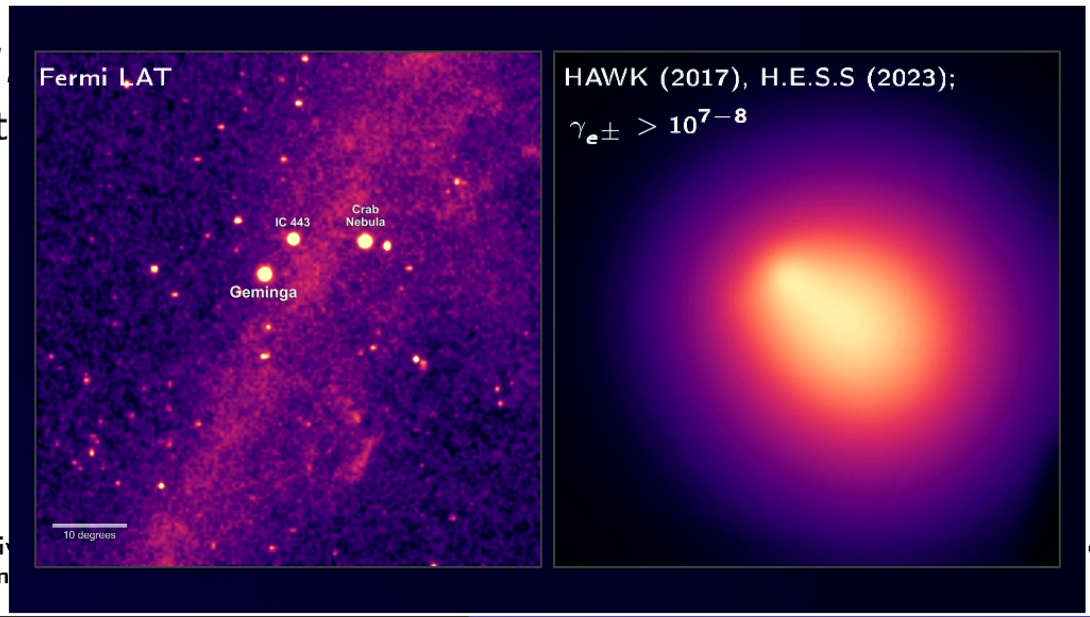

This project has recei orizon
2020 research and inn

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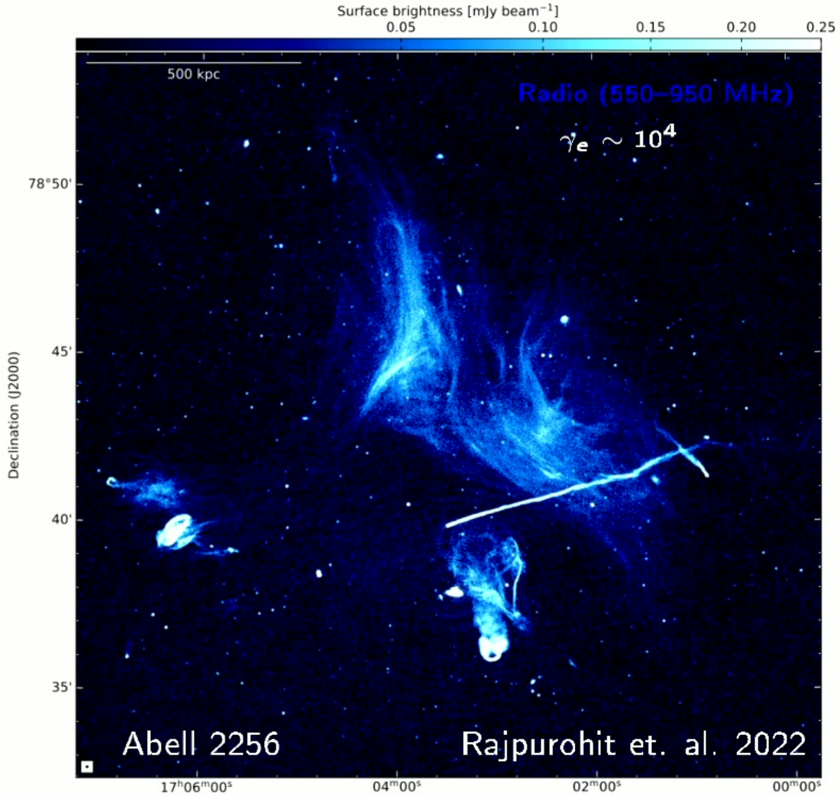

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