Colloquium, KIAA-PKU, Beijing, 07/09/2015

# Cosmic-Ray Streaming Instabilities

## using **MHD-Particle-in-Cell** Method

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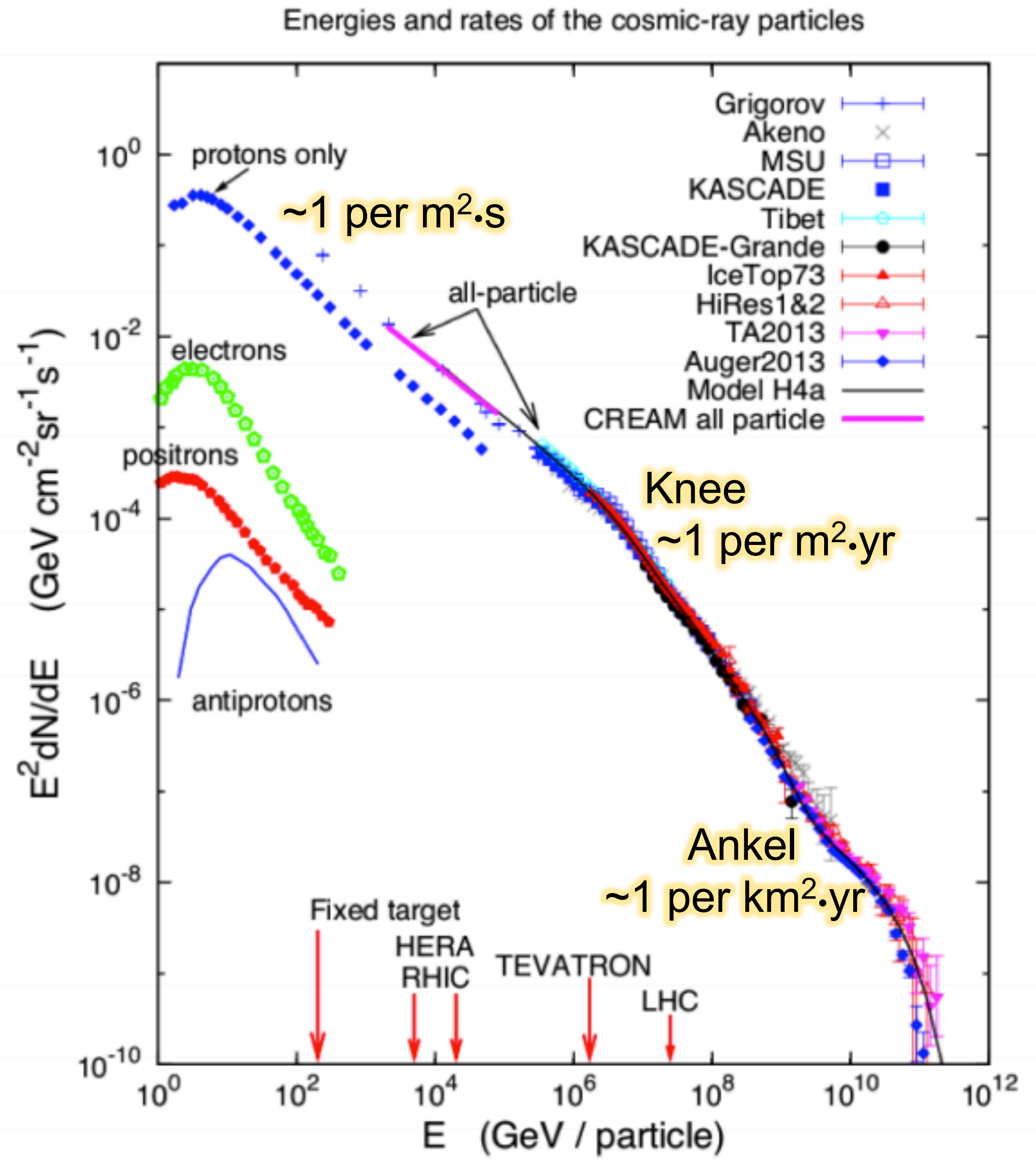
# What are cosmic-rays?

Victor Hess on his way to measure ionizing radiation around 1911-1912 from Vienna



(Blasi 2013)

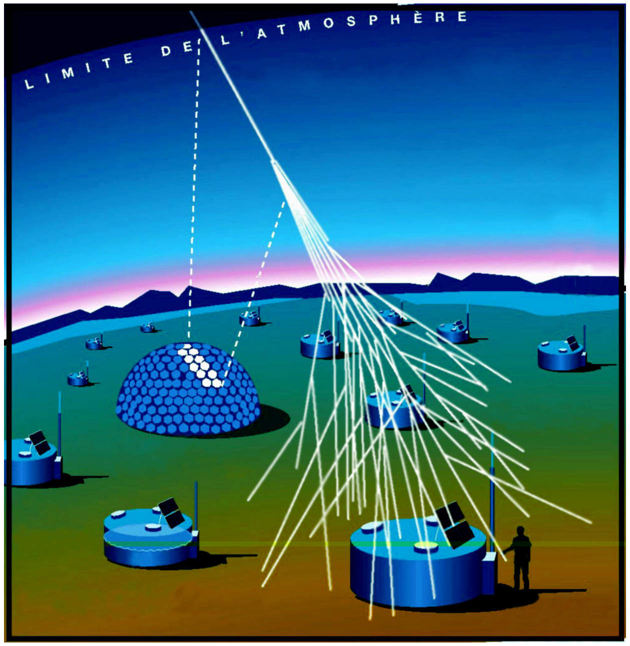
# Why are cosmic rays interesting?

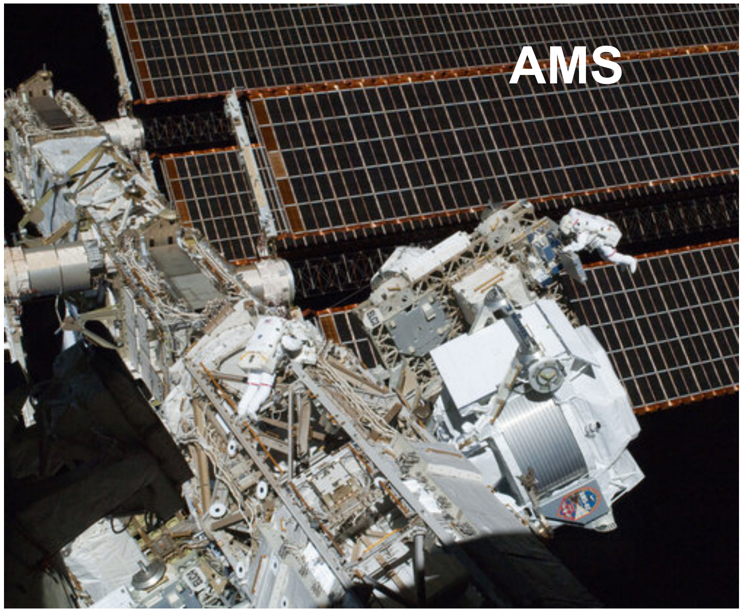
- Important window to constrain astrophysical scenarios.

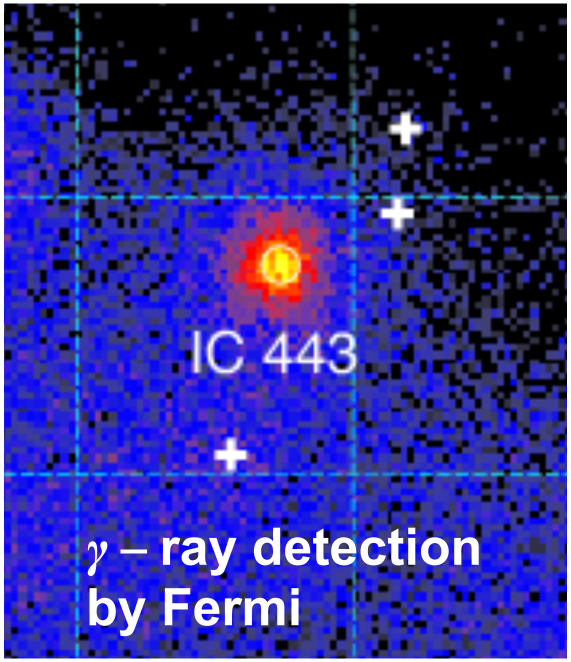
  What is the origin of CRs, how are they accelerated?

  How do they escape from acceleration sites and propagate?

  How to explain the observed CR spectrum and composition?







Ackermann+2013

# Why are cosmic rays interesting?

- (Low energy) CRs provide pressure support and dynamical feedback at large scales

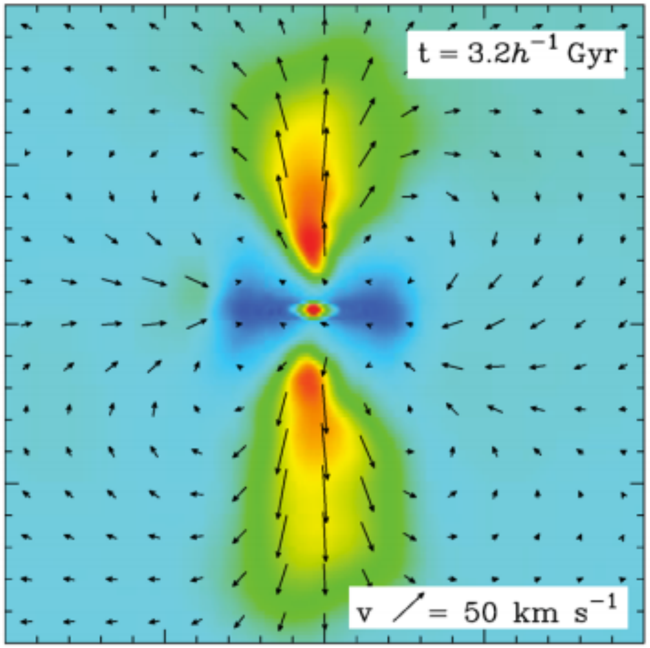
CRs are dynamically important in the Galaxy and possibly others.

Driving of galactic wind/fountain and magnetic dynamo?

Feedback on galaxy formation or even in galaxy clusters?

M82 super-wind

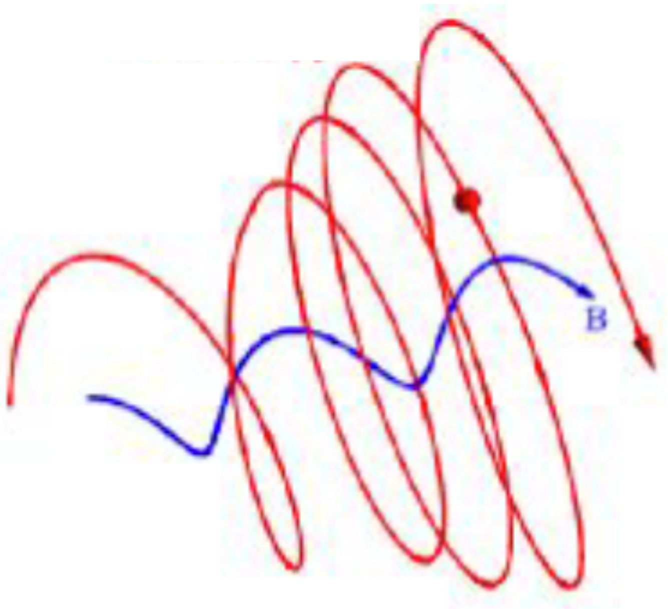
NASA/JPL-Caltech/STScI/CXC/UofA



Uhlig+2012

# How do CRs interact with a thermal plasma?

- CRs are essentially collisionless:



Coulomb cross section (GeV): ~$10^{-30}$ cm$^{-2}$

Mean free path: ~$10^{30}$ cm =>

1% chance of collision in a Hubble time

- CRs diffuse by scattering off magnetic irregularities (waves/turbulence):

Galactic CRs' residence time: (e.g., Ginzburg & Syrovatskii, 1964)

3 Myrs in the disk, ~20 Myr total.

Diffusion coefficient: $\kappa \sim R^2/T \sim 10^{28}$cm$^2$s$^{-1}$.

# How do CRs interact with a thermal plasma?

- CRs affect the dynamics of background plasma by exerting external current:

$$F = -\nabla_\perp P_{\rm CR} = -\frac{\boldsymbol{J}_{\rm CR} \times \boldsymbol{B}}{c}$$

Effectively, it provides pressure support perpendicular to B.

- CRs streaming through background plasma faster than Alfven speed will excite instabilities.

CRs transfer energy and momentum to gas via Alfven waves.

(Kulsrud & Pearce, 1969, Bell, 2004)

# Outline

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  Initial results from the MHD-PIC approach
- CR propagation and self-confinement

  The Kulsrud-Pearce instability

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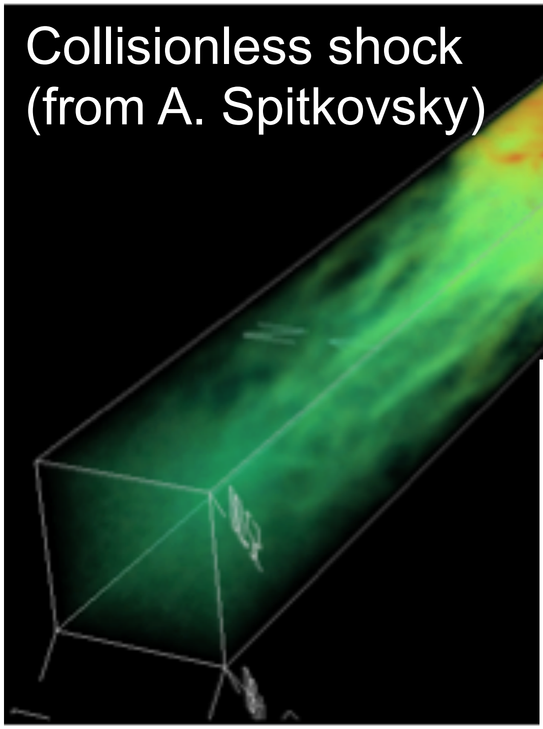
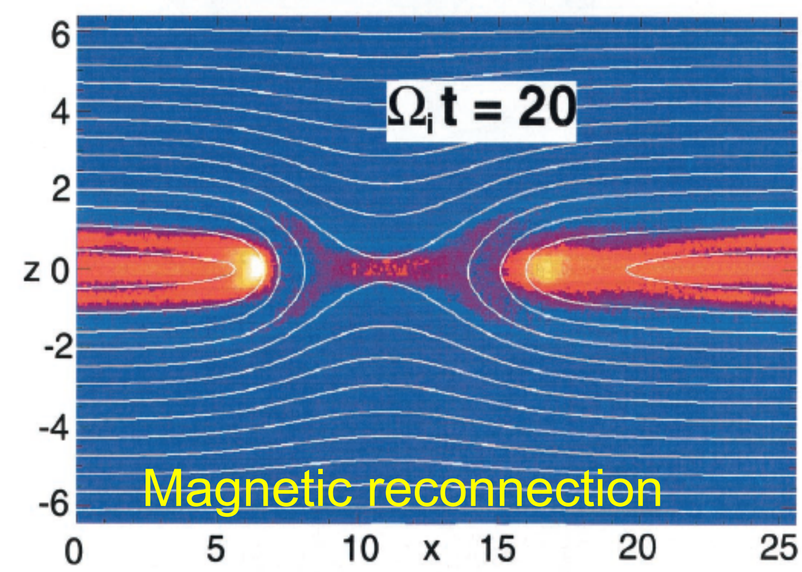
- Summary

# Motivation

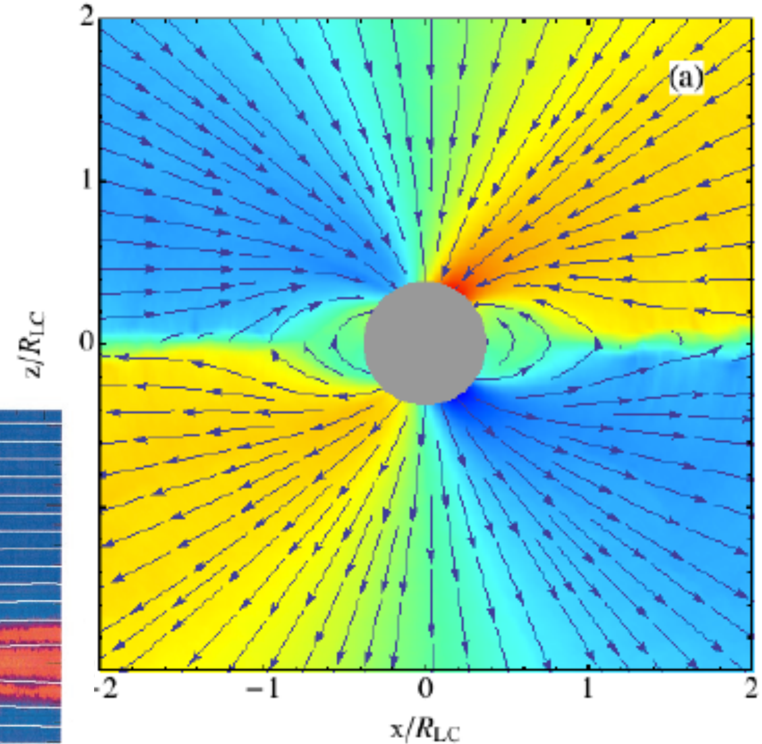
- Plasma kinetics is typically studied self-consistently using particle-in-cell (PIC) simulations.


Collisionless shock (from A. Spitkovsky)



Magnetic reconnection

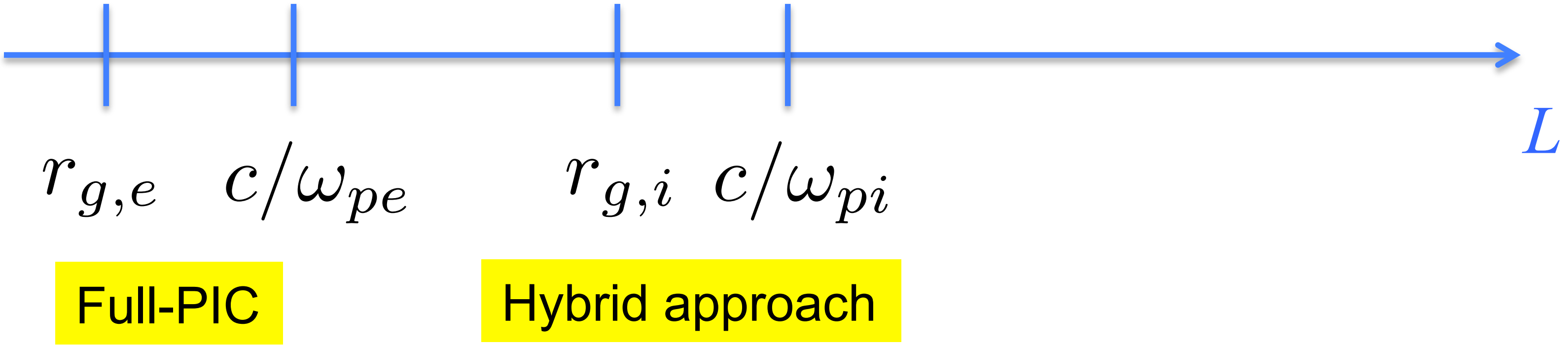
(Hesse+ 2001)



(Philippov+ 2015)

# Motivation

- Plasma kinetics is typically studied self-consistently using particle-in-cell (PIC) simulations.
- For PIC simulations, it is essential to resolve microscopic scales.



$r_{g,e}$ $c/\omega_{pe}$ $r_{g,i}$ $c/\omega_{pi}$ $L$

Full-PIC

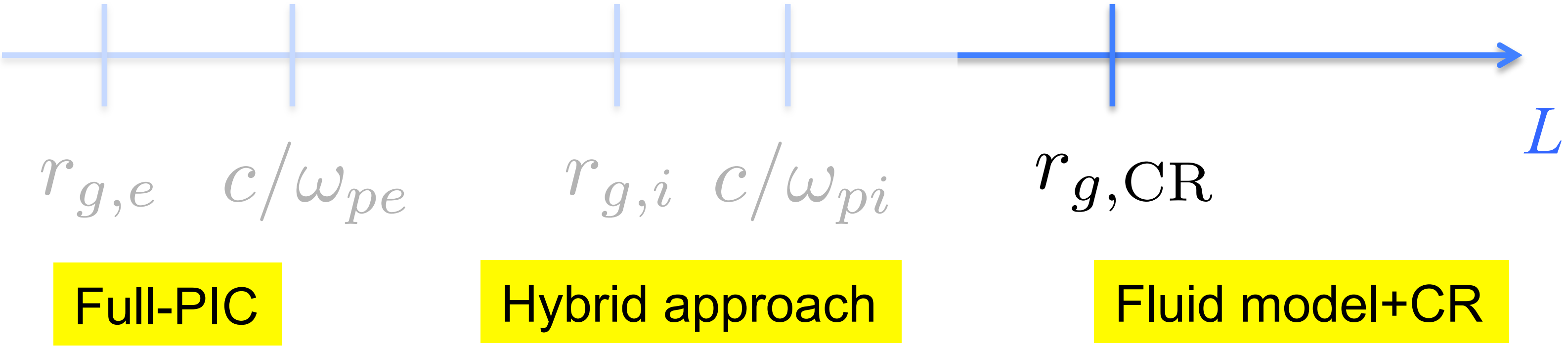
Hybrid approach

Very computationally expensive: Small box, short duration.

# Motivation

- Most physics results from the interaction between the CRs and the thermal gas.

- Alternative approach: treat thermal plasma with MHD, treat CRs kinetically (PIC), with feedback.



$L$

$r_{g,e}$ $c/\omega_{pe}$ $r_{g,i}$ $c/\omega_{pi}$ $r_{g,\mathrm{CR}}$

Full-PIC

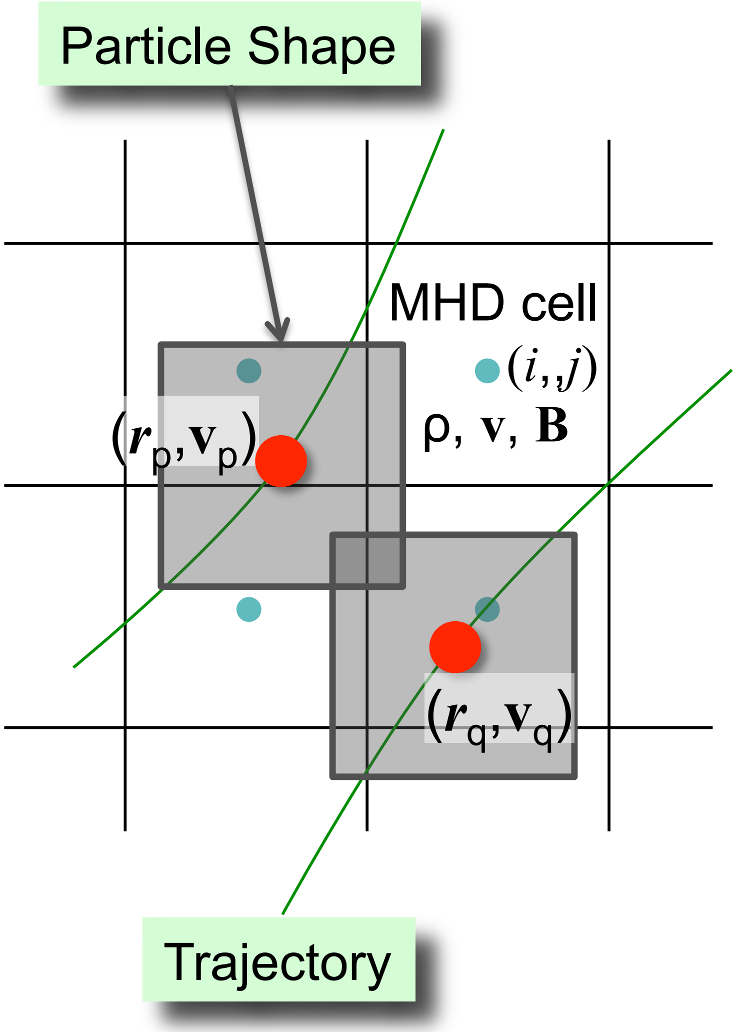
Hybrid approach

Fluid model+CR

- Bypassing the small plasma scales: computationally cheap!

# MHD-PIC approach

- Each computational particle (i.e., super-particle) represents a large collection of real CR particles.
- Each super-particle carries an effective shape, designed to facilitate interpolation from the grid.
- Individual CR particles move under the electro-magnetic field from MHD.
- Total momentum and energy must conserve: particles feedback to MHD cells by depositing changes in momentum and energy locally.



# Formulation and implementation

Equations for the (relativistic) CR particles:

$$\frac{d(\gamma_j \boldsymbol{u}_j)}{dt} = \frac{q_j}{m_j}\left(\boldsymbol{E} + \frac{\boldsymbol{u}_j}{c} \times \boldsymbol{B}\right)$$

Specify the numerical speed of light $c$ >> any velocities in MHD.

Full equations for the gas:

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \mathbf{P}^*) =$$ - Lorentz force on the CRs

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P^*)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})] =$$ - energy change rate on the CRs

Implementation to the Athena MHD code (Stone+2008), described in Bai+2015.

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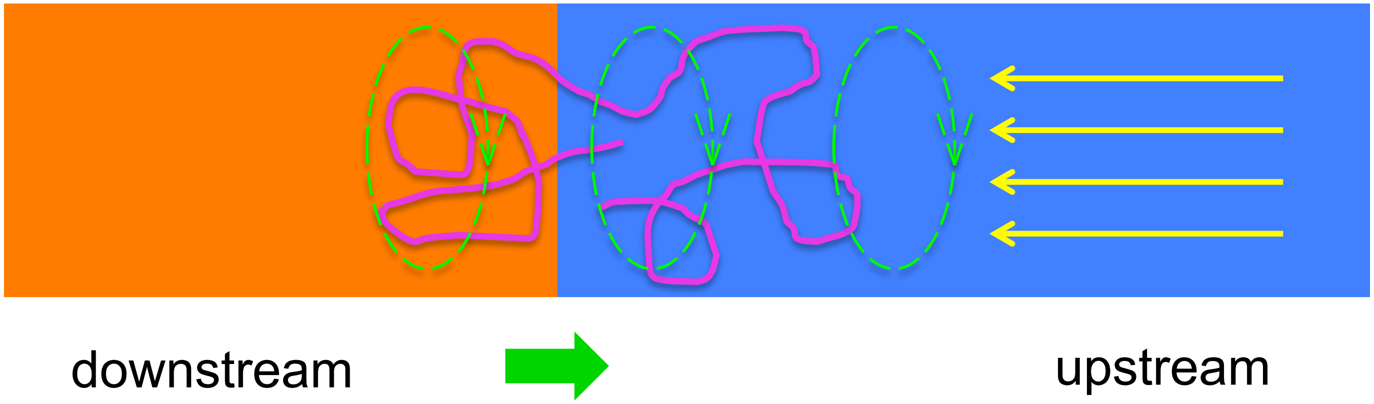
# Origin of cosmic rays: shocks

- First-order Fermi mechanism: test particles gain energy at each reflection in a converging flow.

(Blandford & Ostriker; Bell; 1978)



downstream
(post-shock)

shock velocity

upstream
(pre-shock)

- Particle scattering by electromagnetic turbulence
- Turbulence generated by streaming CRs

# Most powerful accelerator: SNR shocks

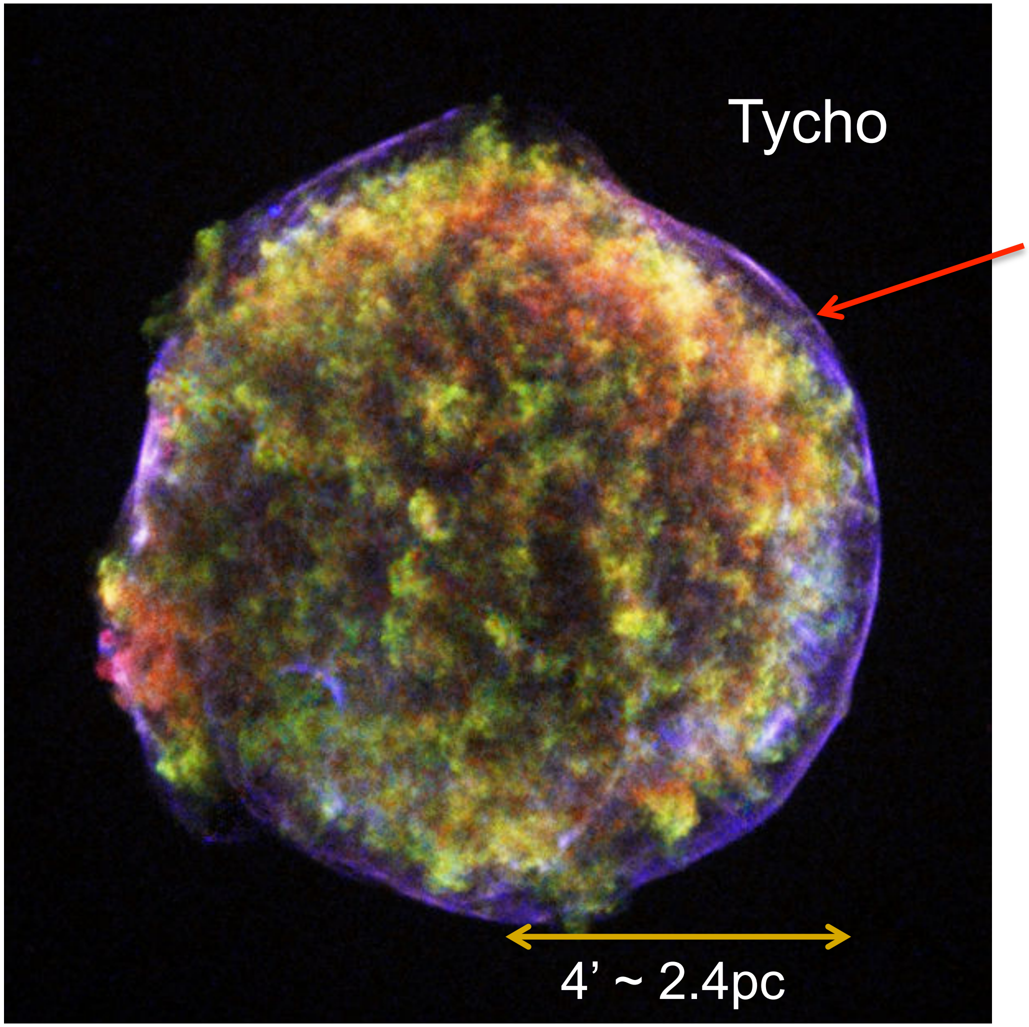


Image from Chandra

forward shock (primary site for particle acceleration)

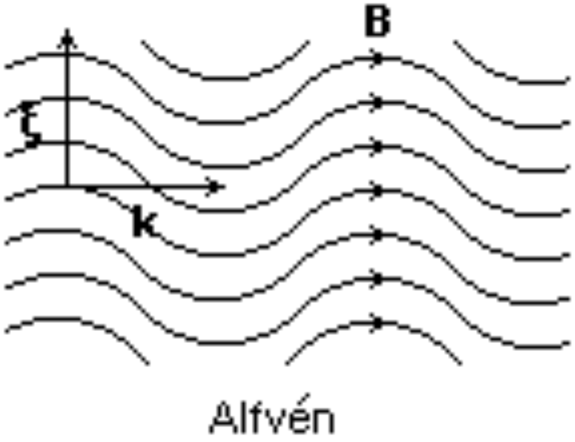
shock velocity: ~$10^{3\text{-}4}$ km/s

First speculated:
Baade & Zwicky, 1934, PNAS

How efficient can shock accelerate CRs?

What is the maximum CR energy that can be achieved?

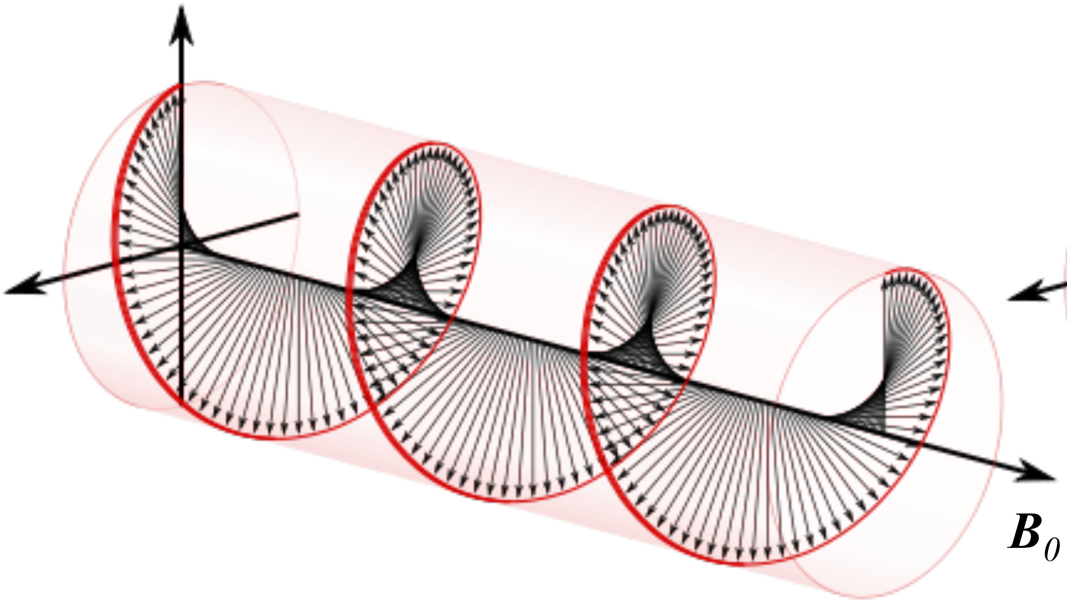
# Alfvén waves



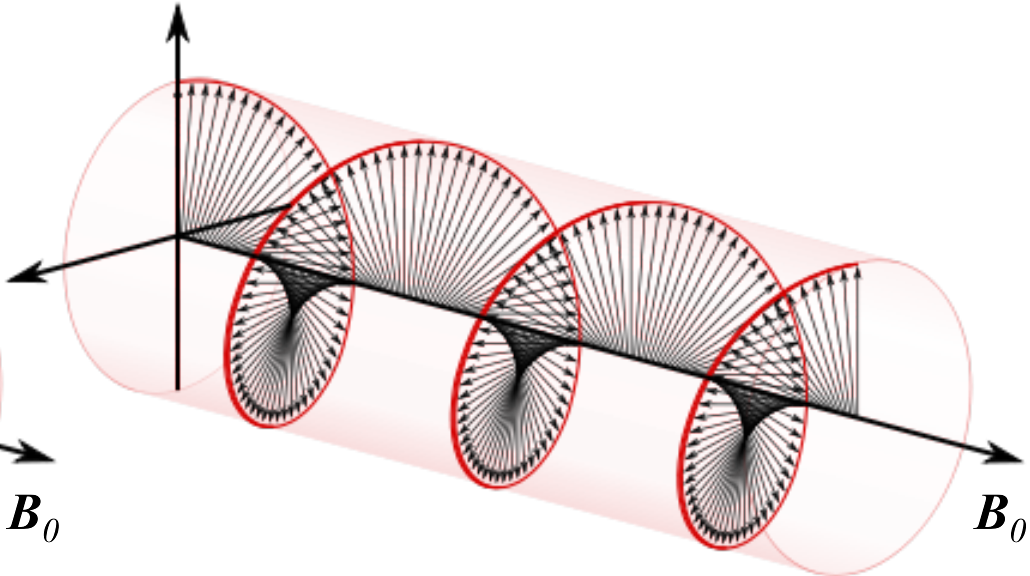
Incompressible, transverse wave; restoring force is magnetic tension.

$$v_A = \frac{B}{\sqrt{4\pi\rho}}$$

Left polarization:

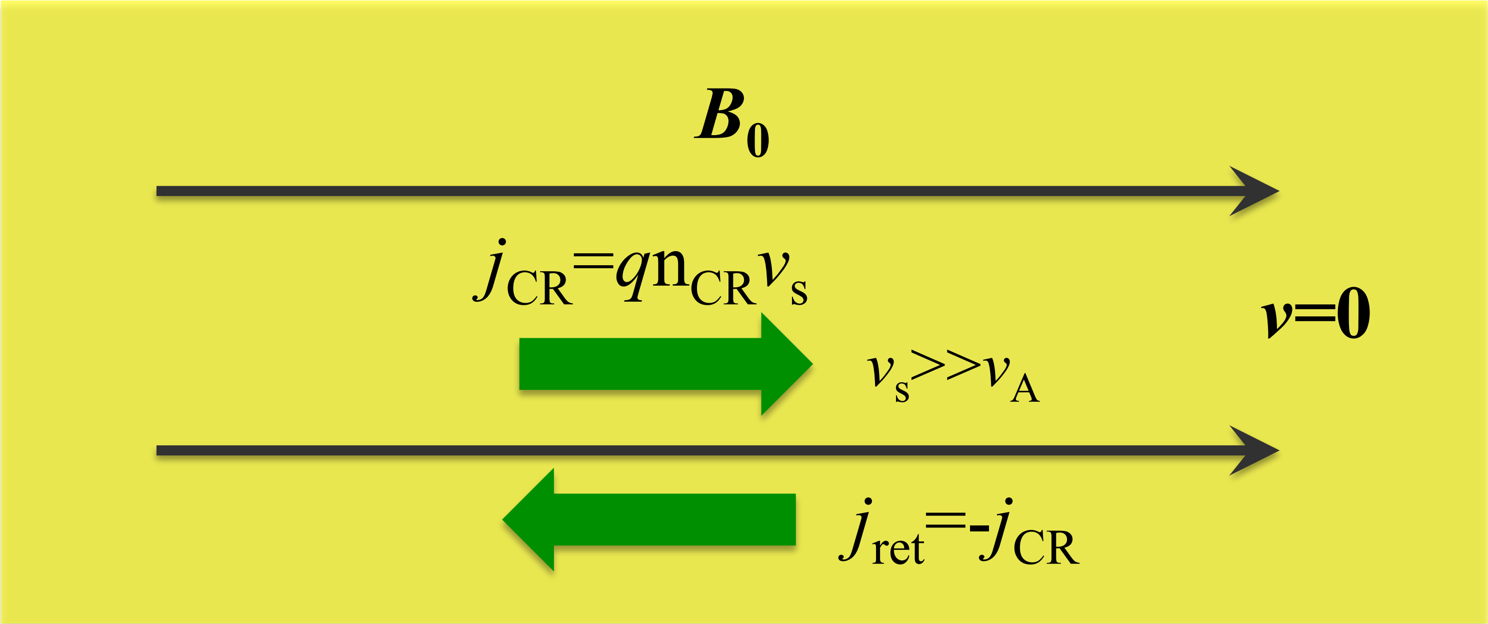


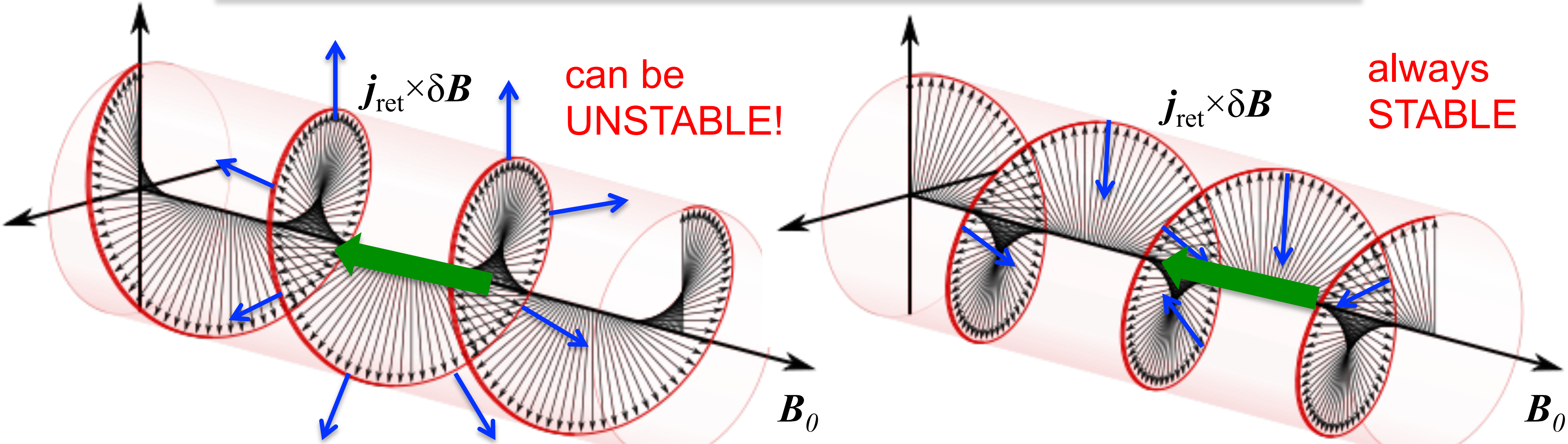
Right polarization:



# The Bell instability

(Bell, 2004)





can be UNSTABLE!

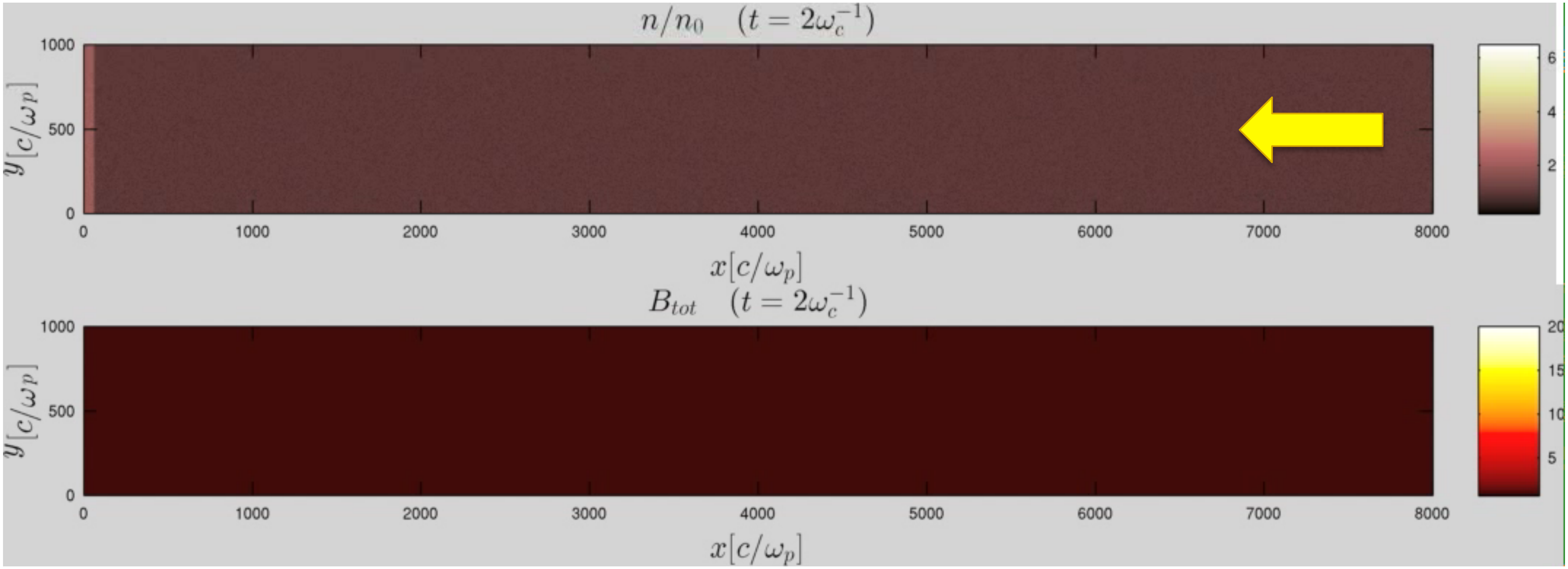
always STABLE

Left pol:

Right pol:

# Non-relativistic collisionless shock

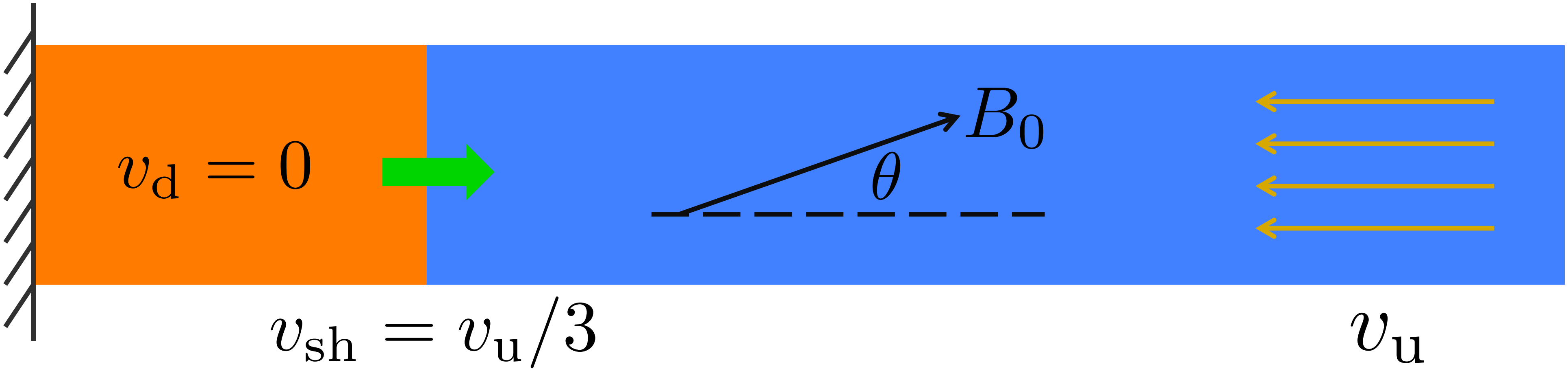
- First-principle hybrid-PIC simulations (kinetic ions, fluid electrons, need to resolve the ion scale).



Caprioli & Spitkovsky (2013)

Computationally very expensive.

# Setting up the shock problem



Fiducial parameters: $M_A$~30, parallel shock $\theta$=0.

Resolution: 12 ion skin depths per cell (*v.s. 0.5 in hybrid-PIC*)

Particle injection: artificial (as proof-of-concept)

# Setting up the shock problem

- Manually inject higher-energy CR particles at the shock front.
  - Shock detection based on transversely averaged profiles of $\rho$, $v_x$.

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  - With fixed energy $E=10E_{sh}$ (e.g., Caprioli & Spitkovsky, 2014a).

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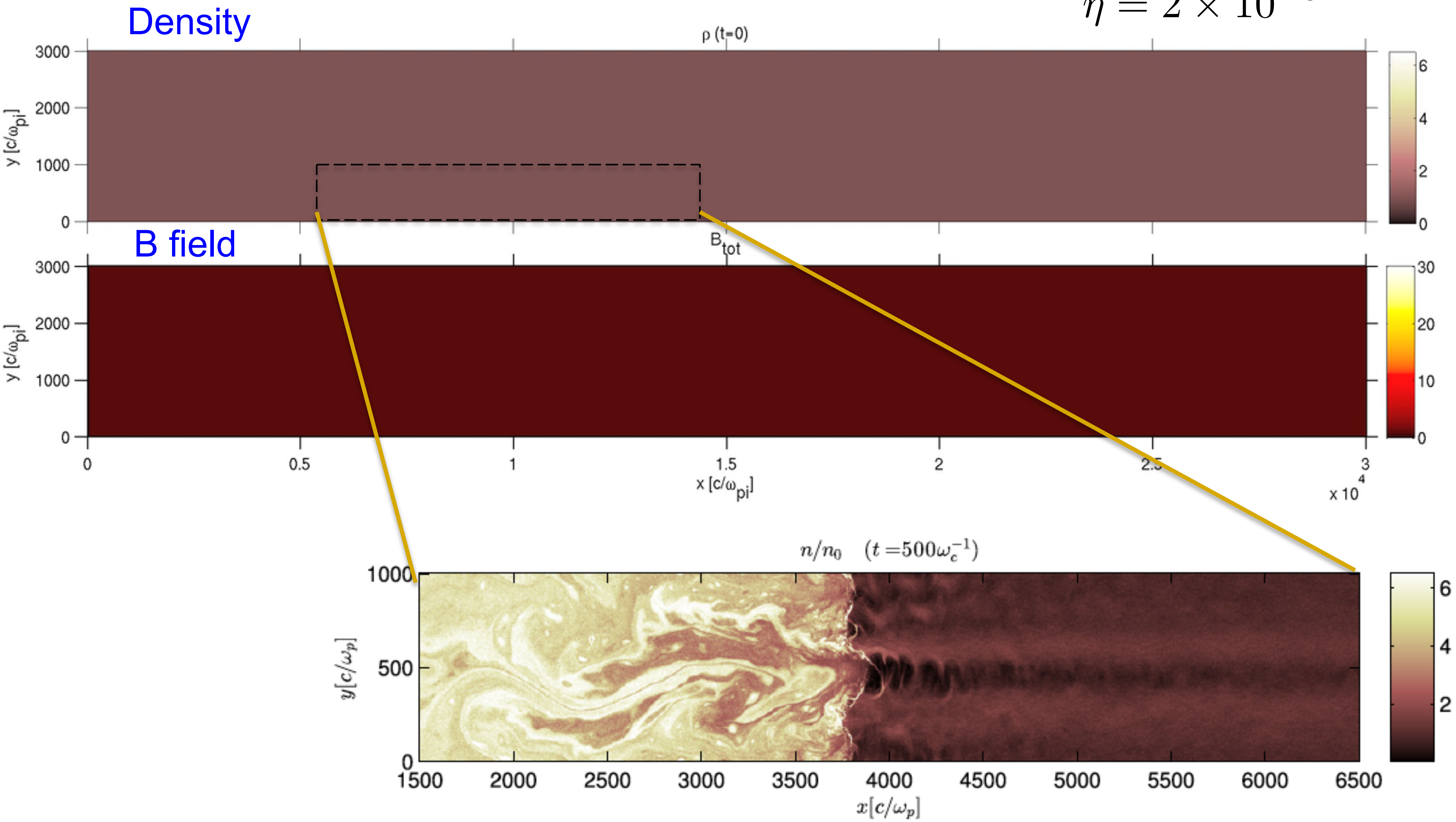
- Manually inject higher-energy CR particles at the shock front.
  - Shock detection based on transversely averaged profiles of $\rho$, $v_x$.
- Particles are injected isotropically in the shock frame.
  - With fixed energy $E=10E_{sh}$ (e.g., Caprioli & Spitkovsky, 2014a).
- Amount of CR injected: $\eta$ x gas mass processed by the shock.
  - Choose $\eta=2\times10^{-3}$ as fiducial injection efficiency.

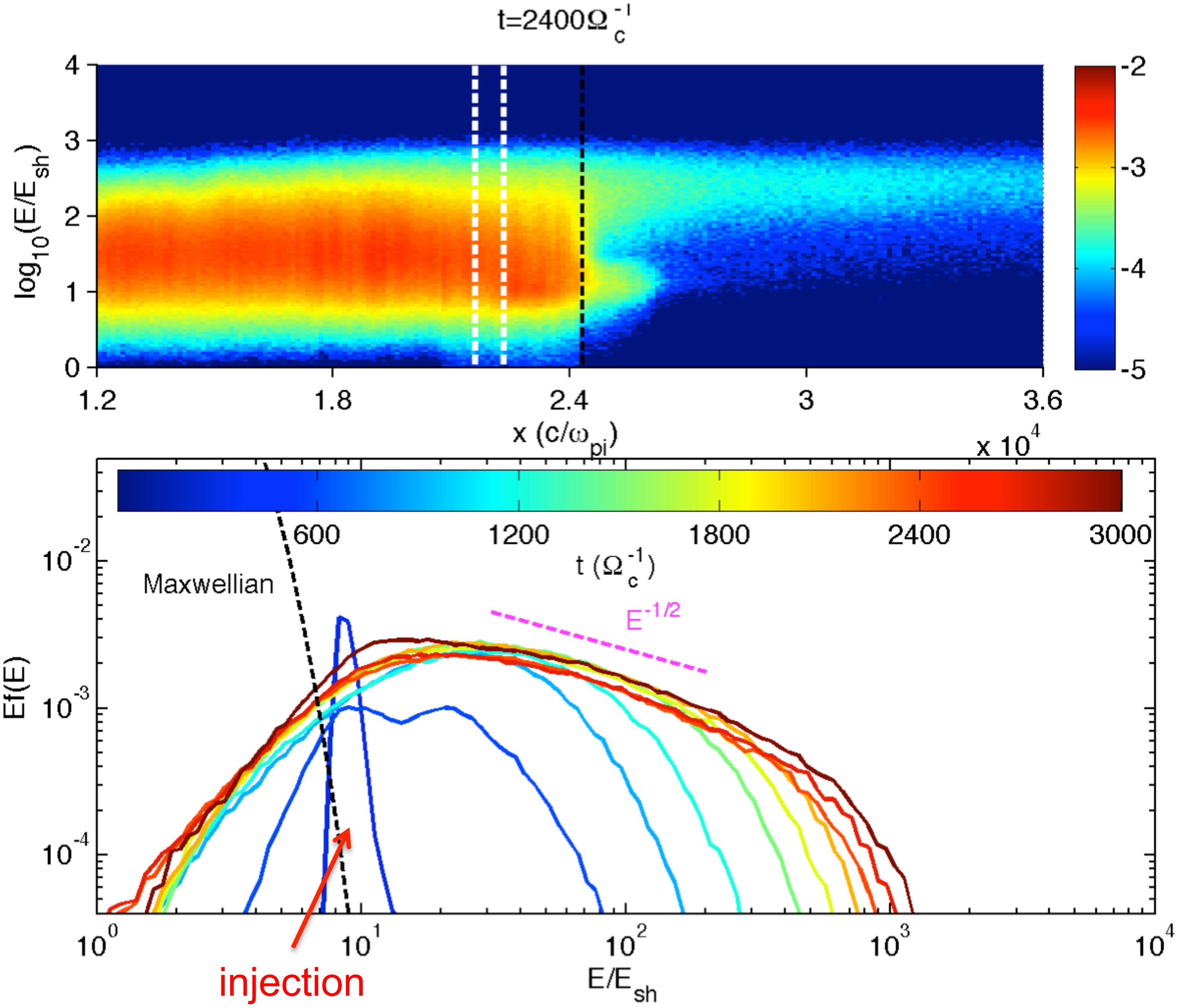
# Non-relativistic shock: fiducial run

$$\eta = 2 \times 10^{-3}$$



(Caprioli & Spitkovsky, 2013)

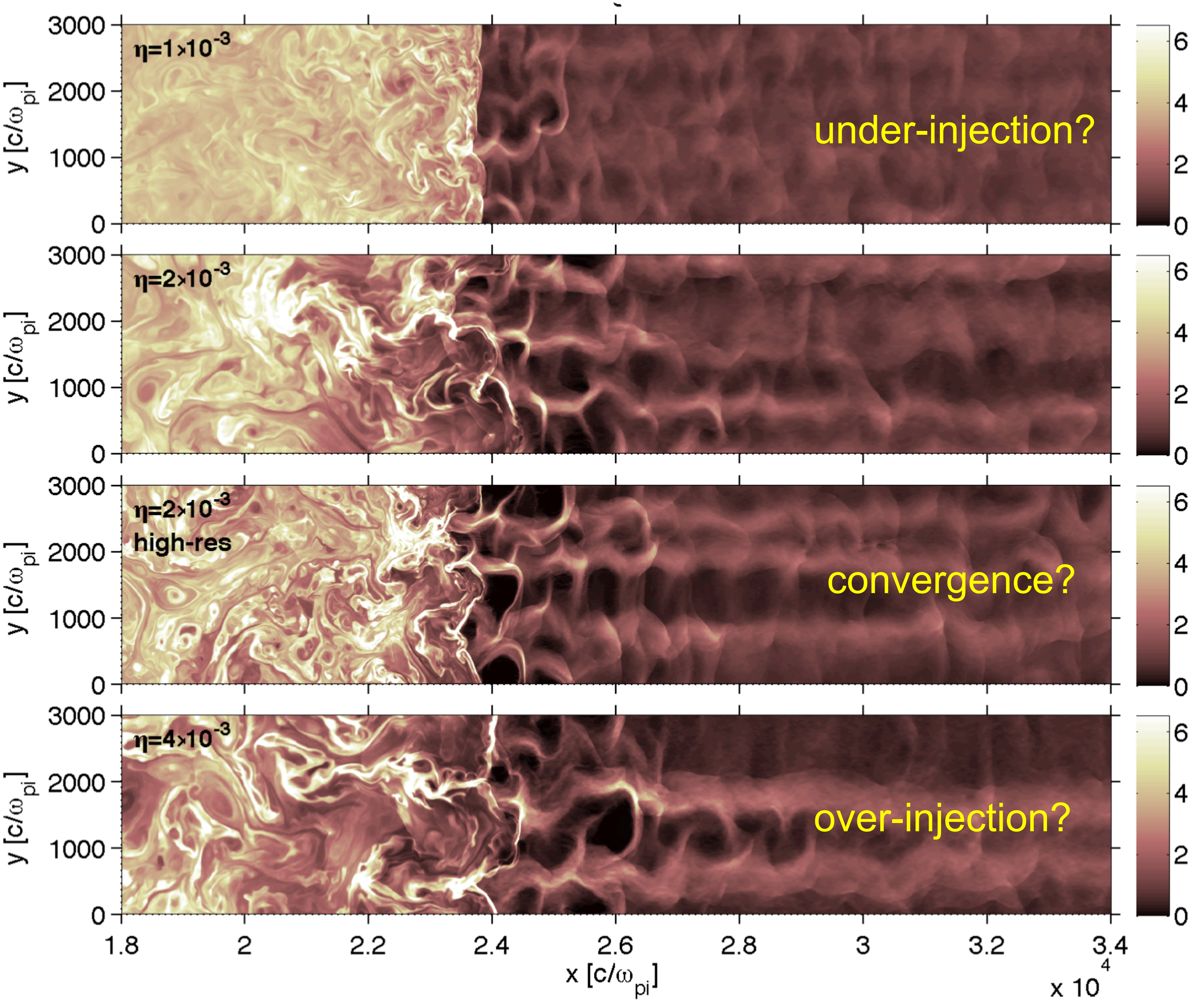
# Particle acceleration



$f(E) \sim E^{-3/2}$ (non-relativistic)

Acceleration efficiency: $\xi \sim 13\%$

# Dependence on injection efficiency



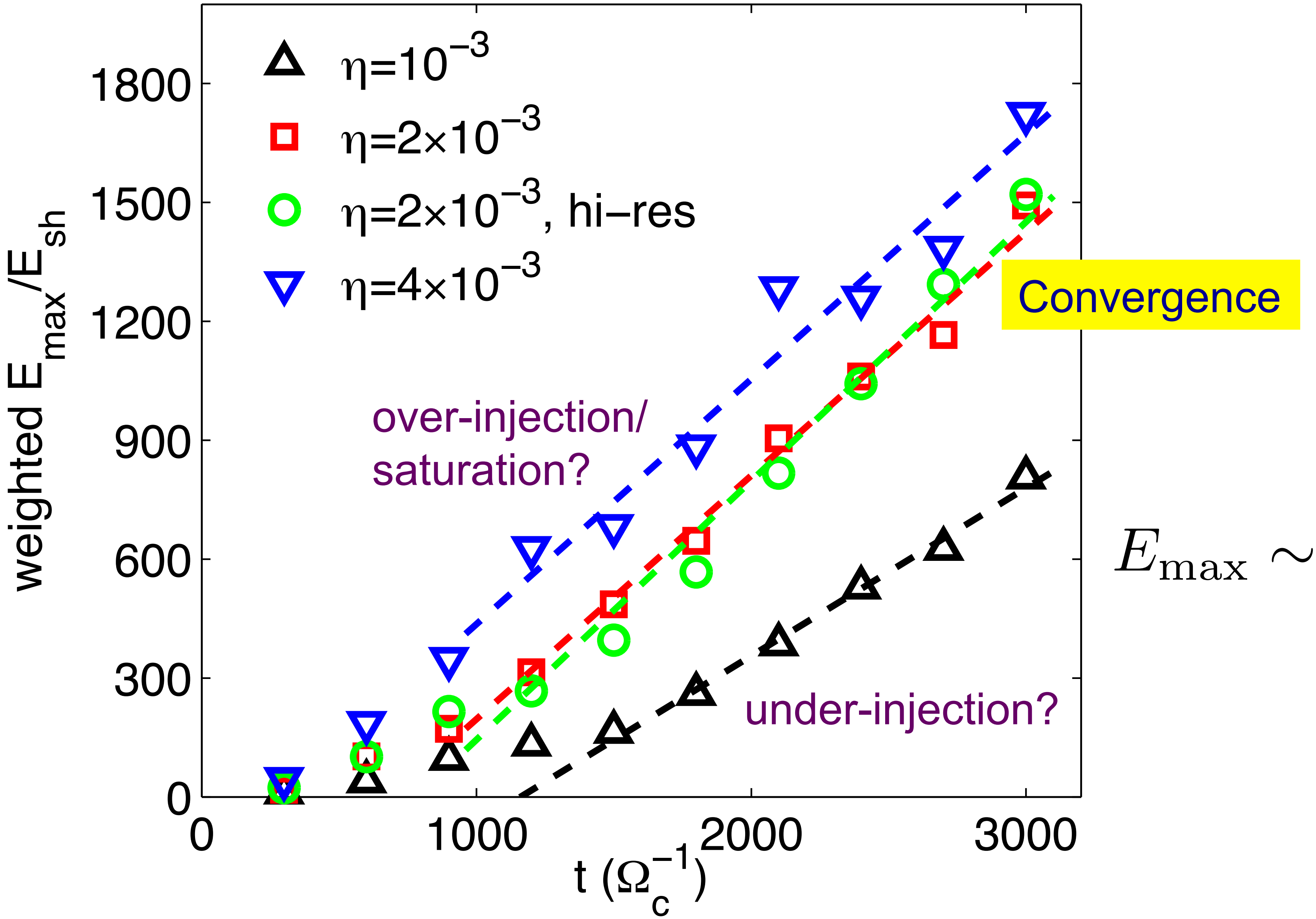
ξ~6%

ξ~13%

ξ~13%

ξ~20%

# Maximum particle energy



Convergence

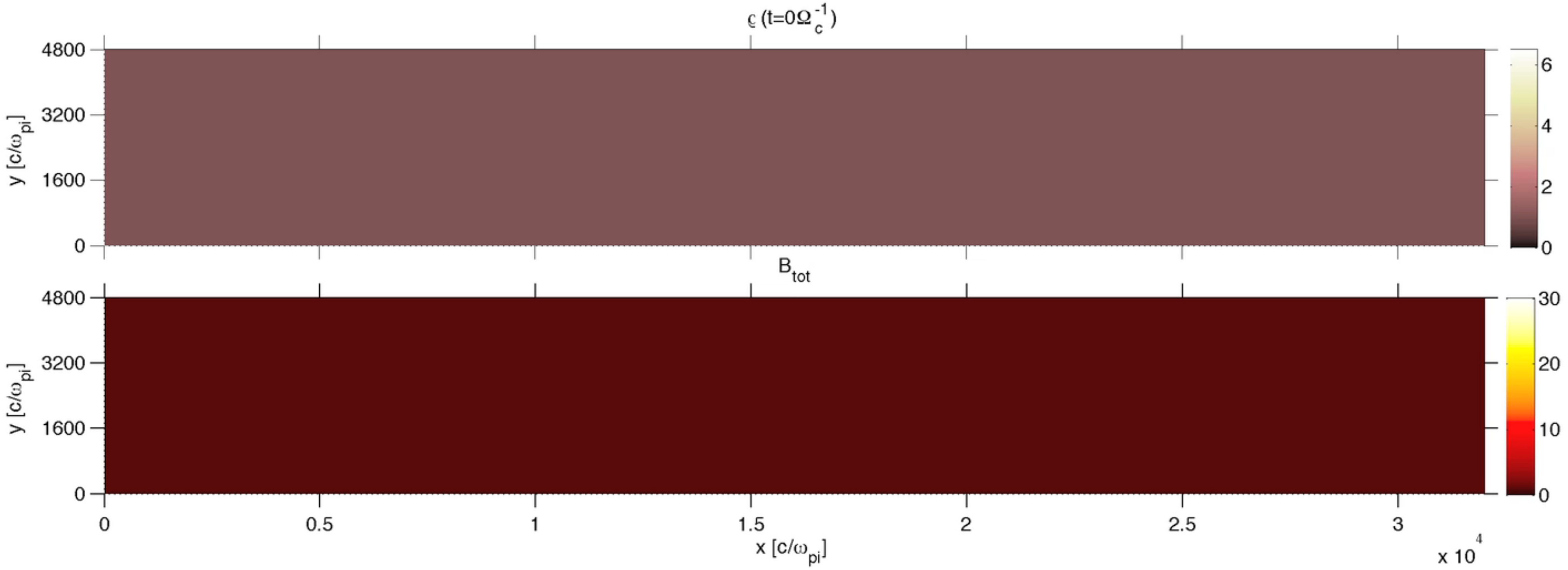
over-injection/
saturation?

under-injection?

$$E_{\max} \sim \frac{eB}{c} V_{sh}^2 t$$

# Simulation with relativistic particles

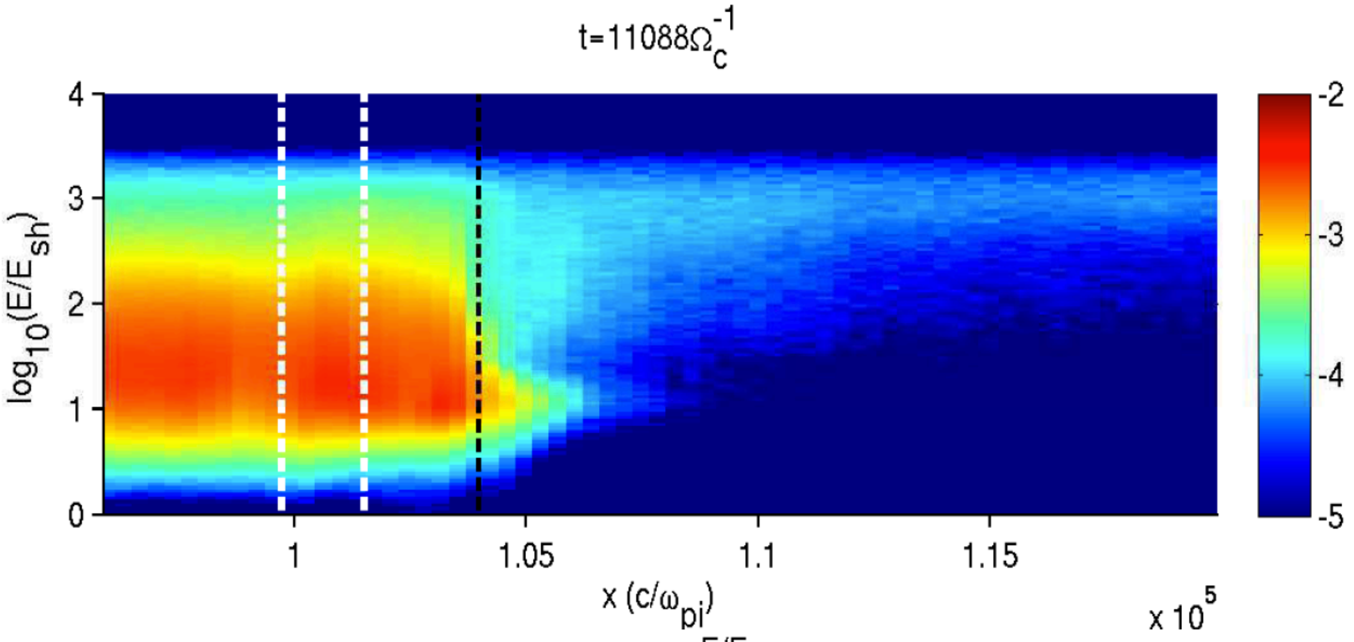
Set numerical speed of light $c$ a factor ~10-20 larger than $v_{sh}$ to follow particle acceleration to relativistic regime.

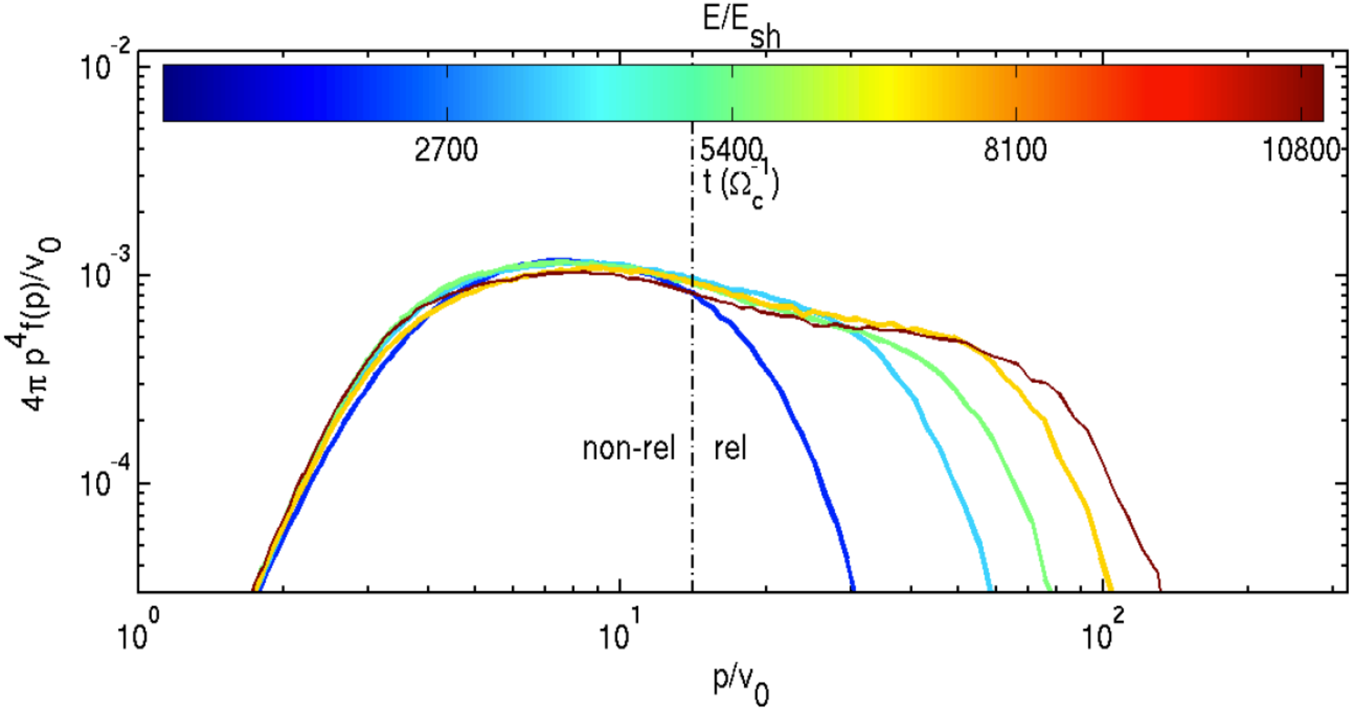


Very large box size (4800 $c/\omega_{pi}$ wide), and very long evolution (~$10^5\Omega_c^{-1}$)

Reduction of shock speed toward later evolution.

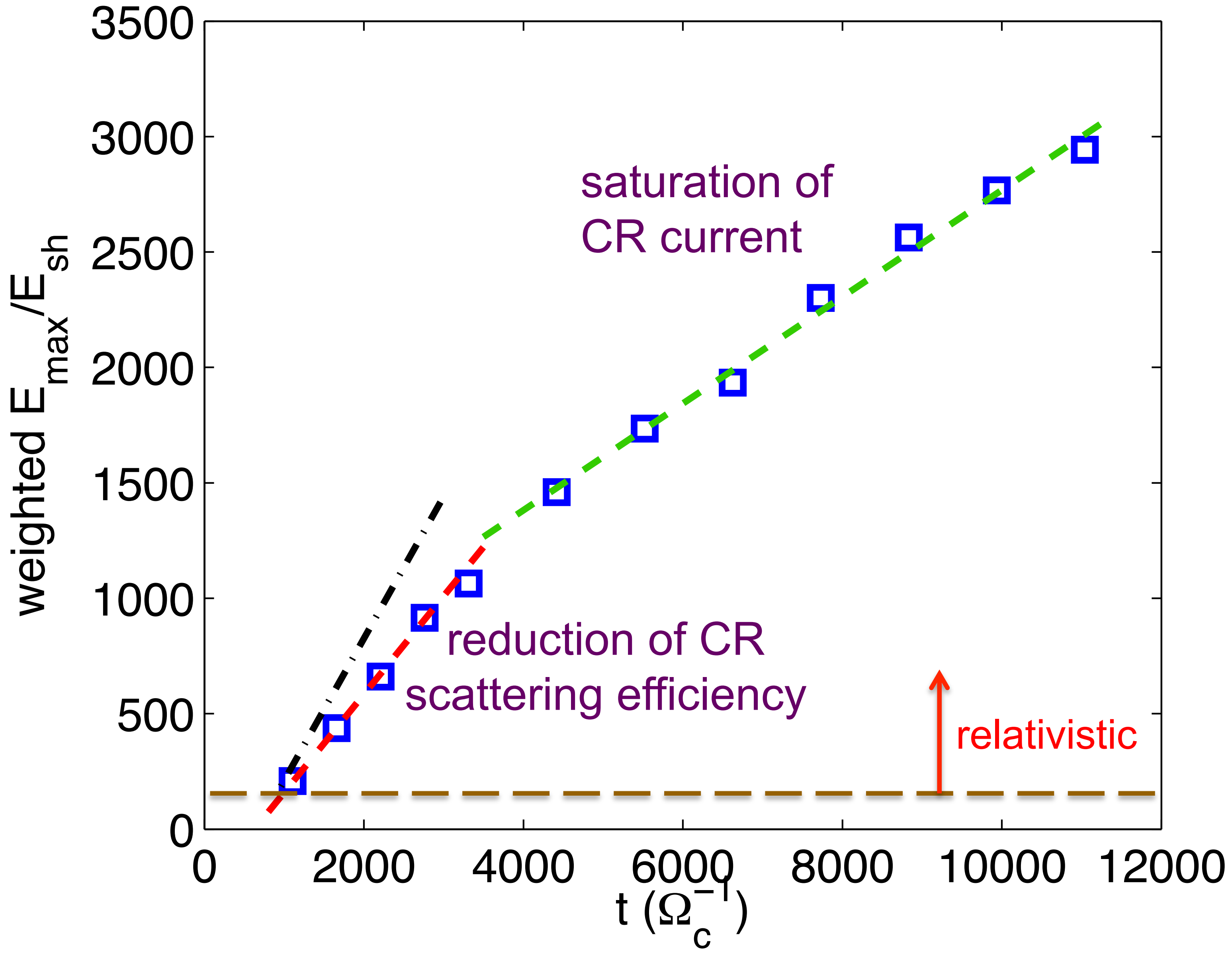
# Particle acceleration into relativistic regime





$f(p) \sim p^{-4}$ through the transition + a drop in normalization.

# Evolution of maximum particle energy



# Future works: non-relativistic shocks

- Injection mechanism:

  Currently results depend on the specific prescriptions.

  Need to better understand the injection physics.

  (e.g., Guo & Giacalone 2013, Caprioli, Pop & Spitkovsky, 2015)

  Detailed comparison with PIC (hybrid) simulations for calibration.

- Parameter study: shock geometry and Mach number (e.g., Caprioli & Spitkovsky 2014a,b). Toward realistic parameters with long term evolution + large box.
- Toward macroscopic scales, and CR escape (e.g., Bell et al. 2013).

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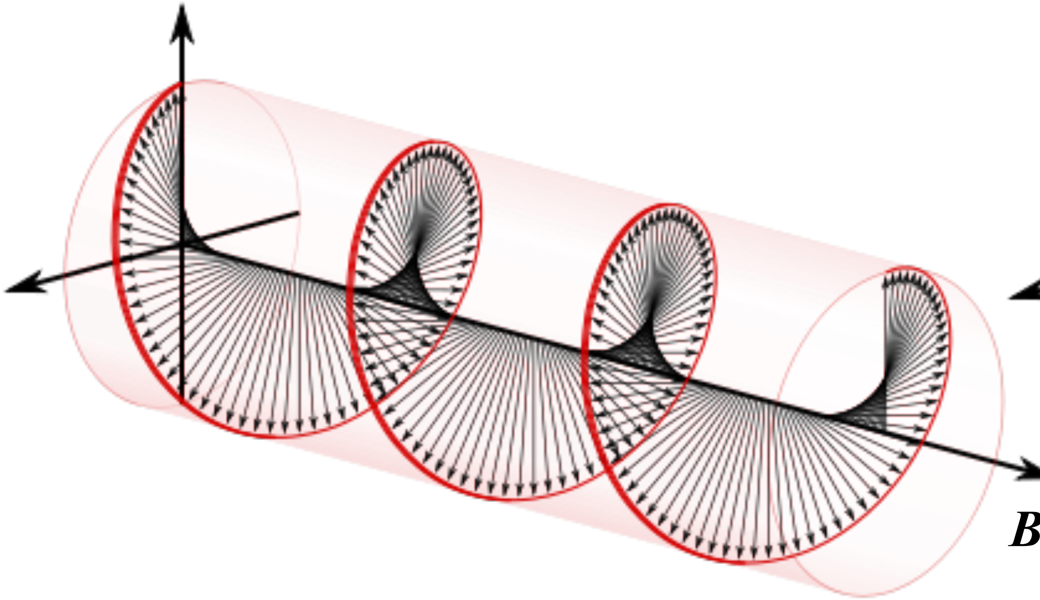
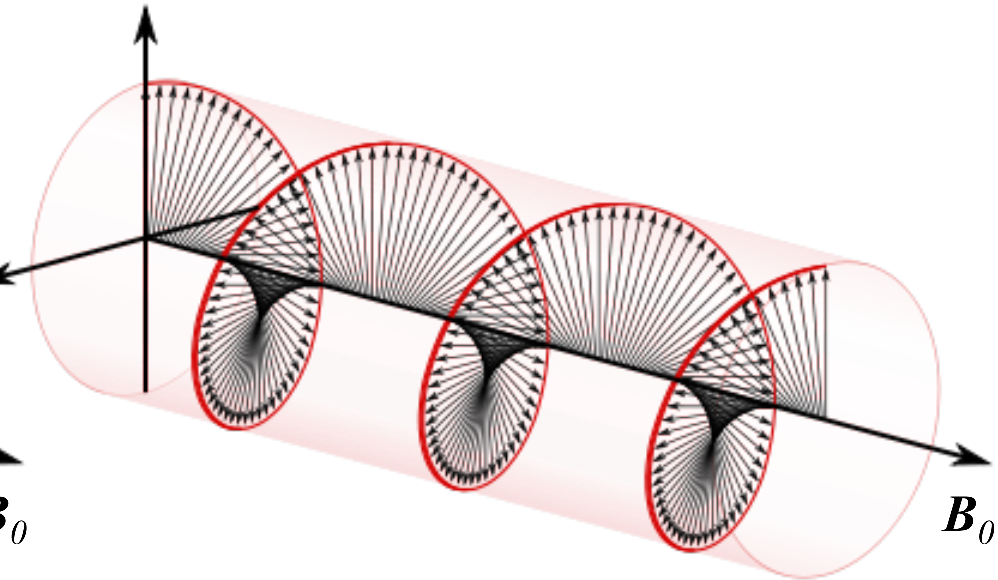
# Resonant interactions with Alfvén waves

Left polarization:



Resonant with backward-traveling ions.

Right polarization:



Resonant with forward-traveling ions.

Gyro resonance: $\omega\text{-}kv_z=\pm\Omega$

In general, $\omega<<\Omega$: $v_z=\pm\Omega/k$

# CR diffusion by external ISM turbulence

## ISM is turbulent:

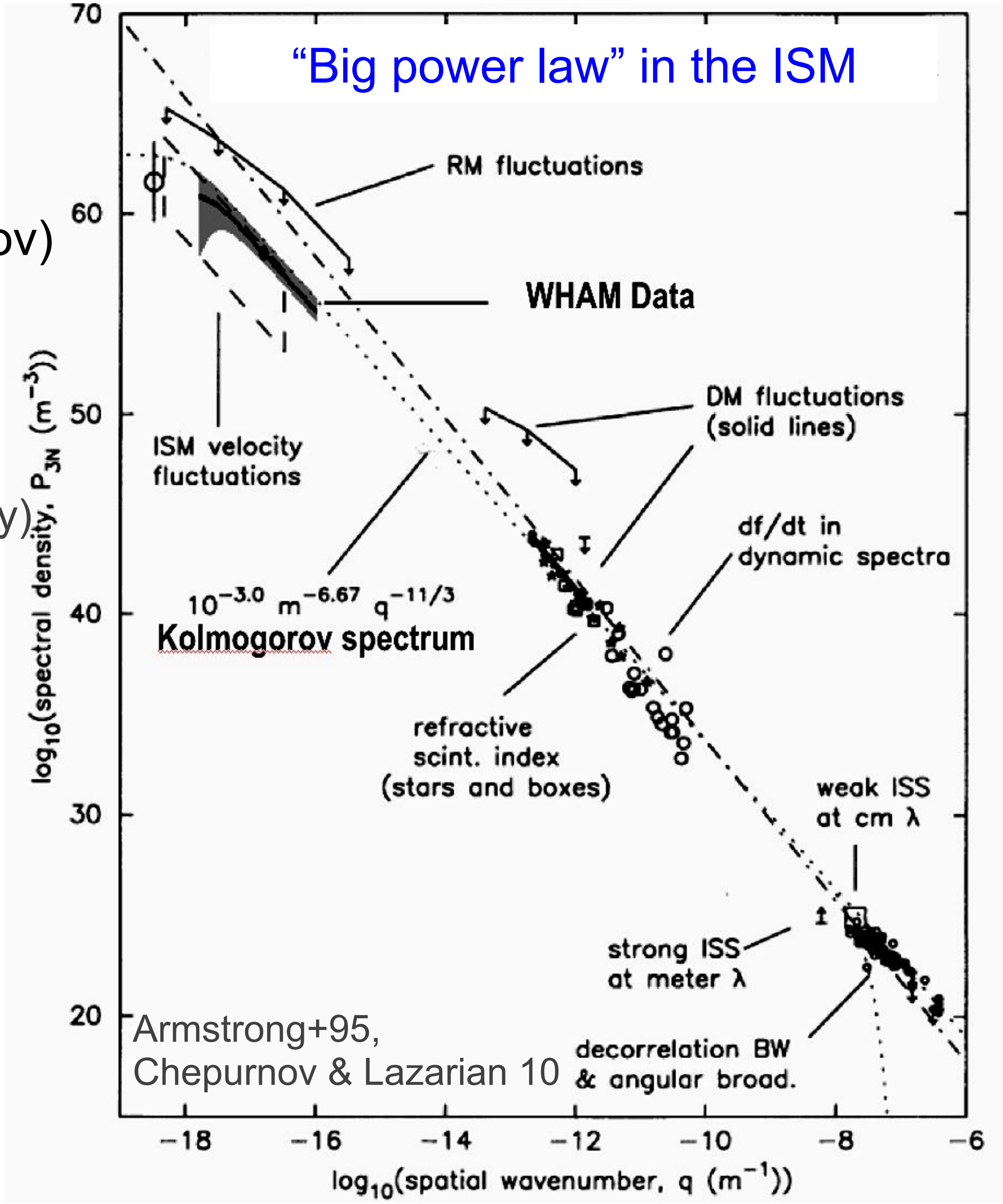
turbulent energy ~ thermal energy

3D power spectrum ~$k^{-11/3}$ (~Kolmogorov)

## CRs transport by MHD turbulence (pitch angle, momentum, spatial)

Jokipii 66, …, Yan & Lazarian 02,04,08 (theory),

Beresnyak+11, Xu & Yan 13 (simulations)



“Big power law” in the ISM

Armstrong+95, Chepurnov & Lazarian 10

## Resonant scales:

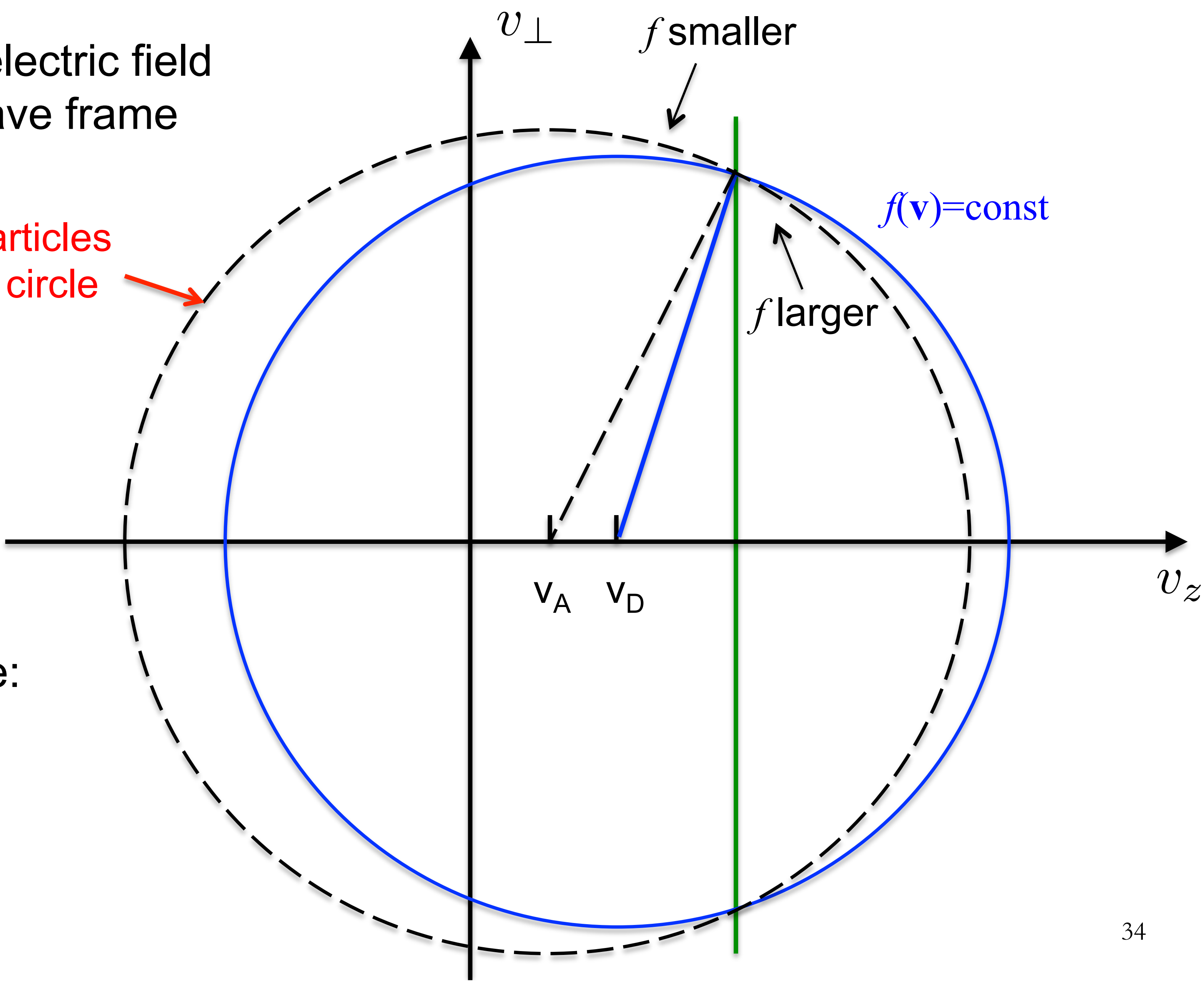
$$R_g \sim \left(\frac{E}{10^{15}\mathrm{eV}}\right)\left(\frac{B}{\mu G}\right)^{-1}\ \mathrm{pc}$$

Turbulent transport less effective towards low-energy CRs (lower power, stronger anisotropy).

# CR streaming instability: basic physics

Alfven wave: electric field vanishes in wave frame

Individual CR particles move along this circle



Gyro resonance:

$$v_z = \Omega / k$$

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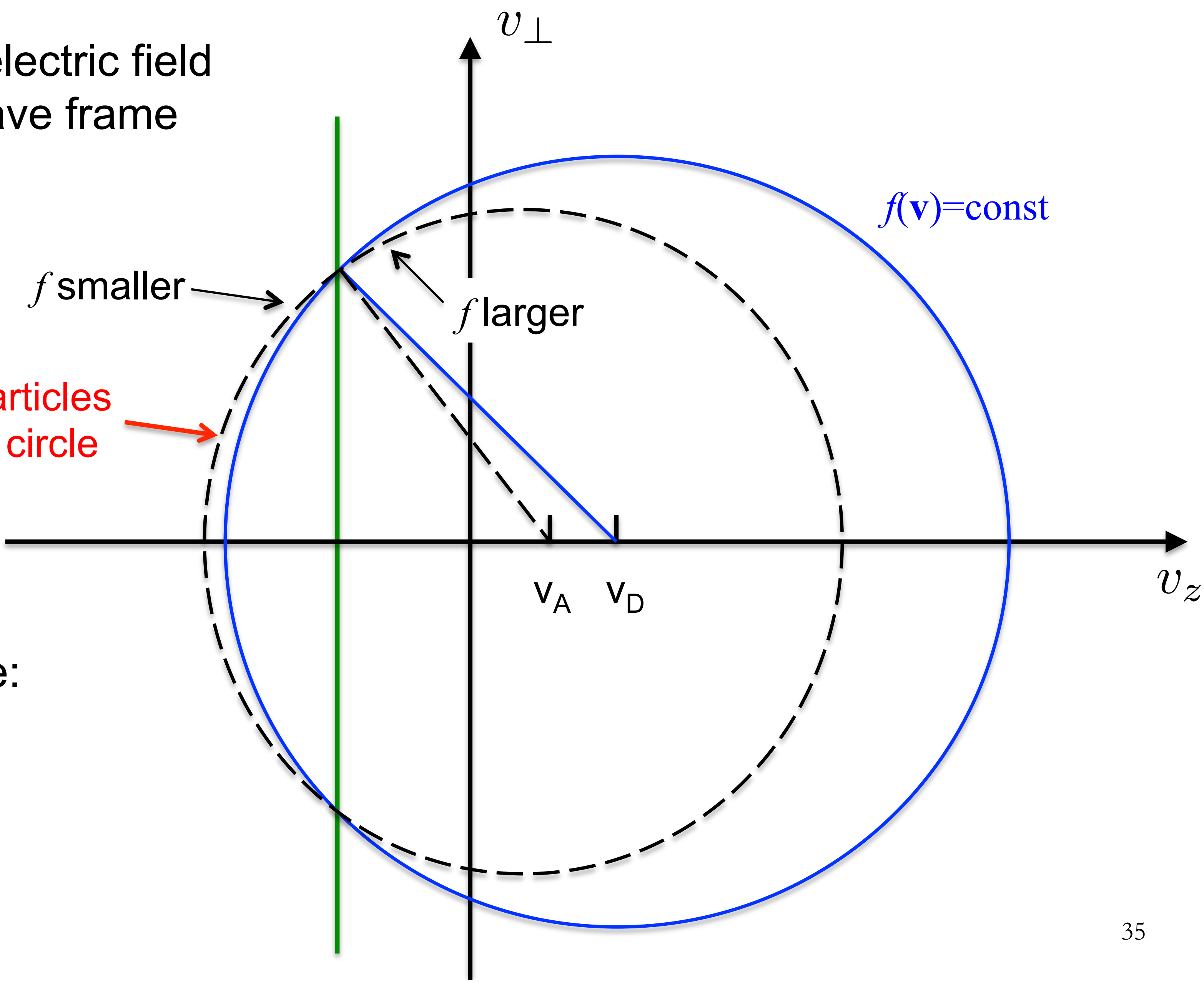
Alfven wave: electric field vanishes in wave frame



Individual CR particles move along this circle

Gyro resonance:

$$v_z = \Omega / k$$

# Basic properties

When CR drift velocity $v_D$ exceeds $v_A$:

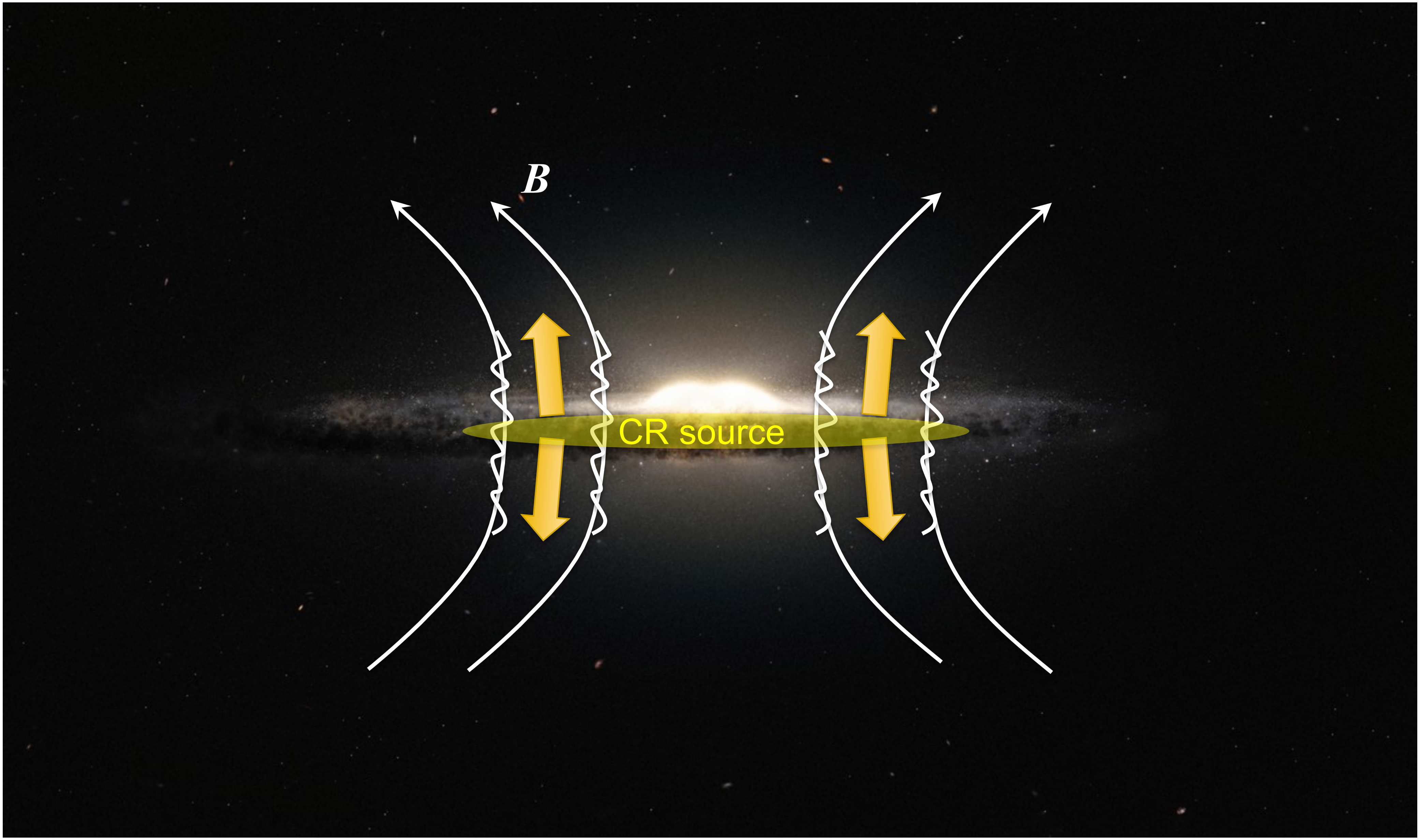
- Forward-traveling CRs resonantly excite (right) polarized, forward-propagating Alfven waves.
- Backward-traveling CRs resonantly excite (left) polarized, forward propagating Alfven waves.
- Backward-propagating Alfven waves are suppressed.

Characteristic growth rate:

$$\Gamma(k) \approx \Omega_c \frac{N_{\mathrm{CR}}(p > p_{\mathrm{res}}(k))}{n_i} \frac{v_D - v_A}{v_A}$$

More generally, when CR anisotropy exceeds ~$v_A/c$, certain Alfven modes become resonantly unstable.

# CR self-confinement and CR-driven wind



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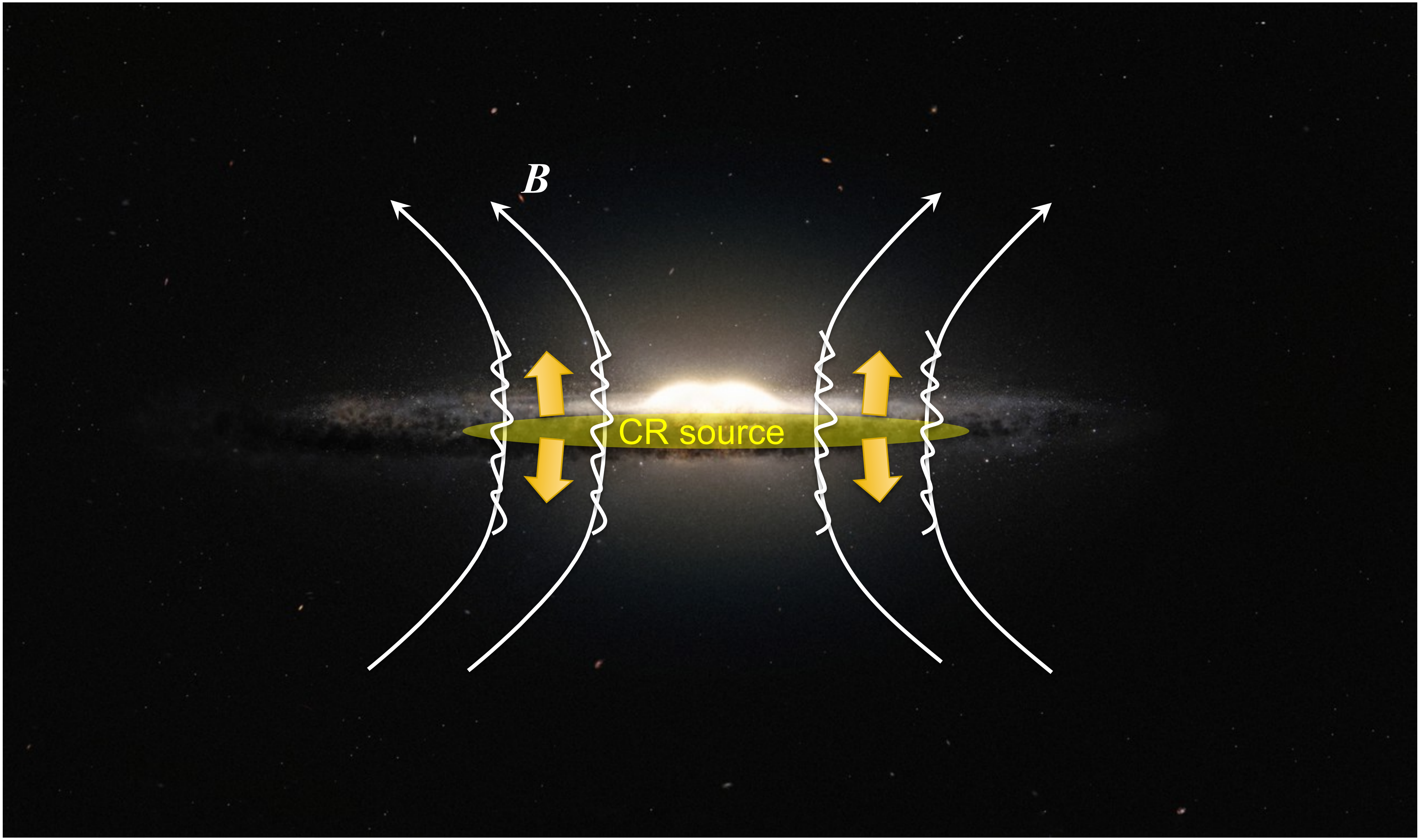
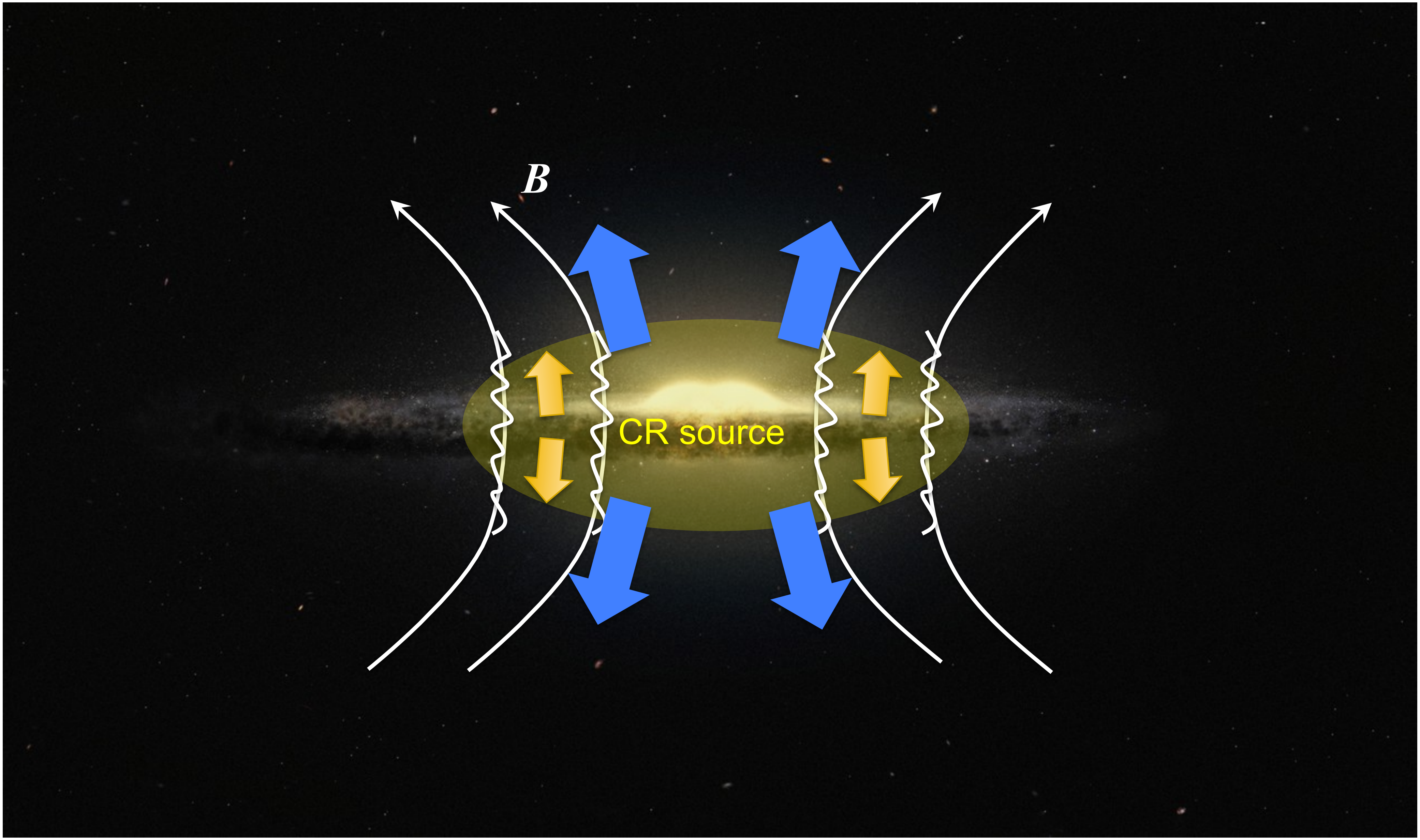


# CR self-confinement and CR-driven wind



# Current understandings

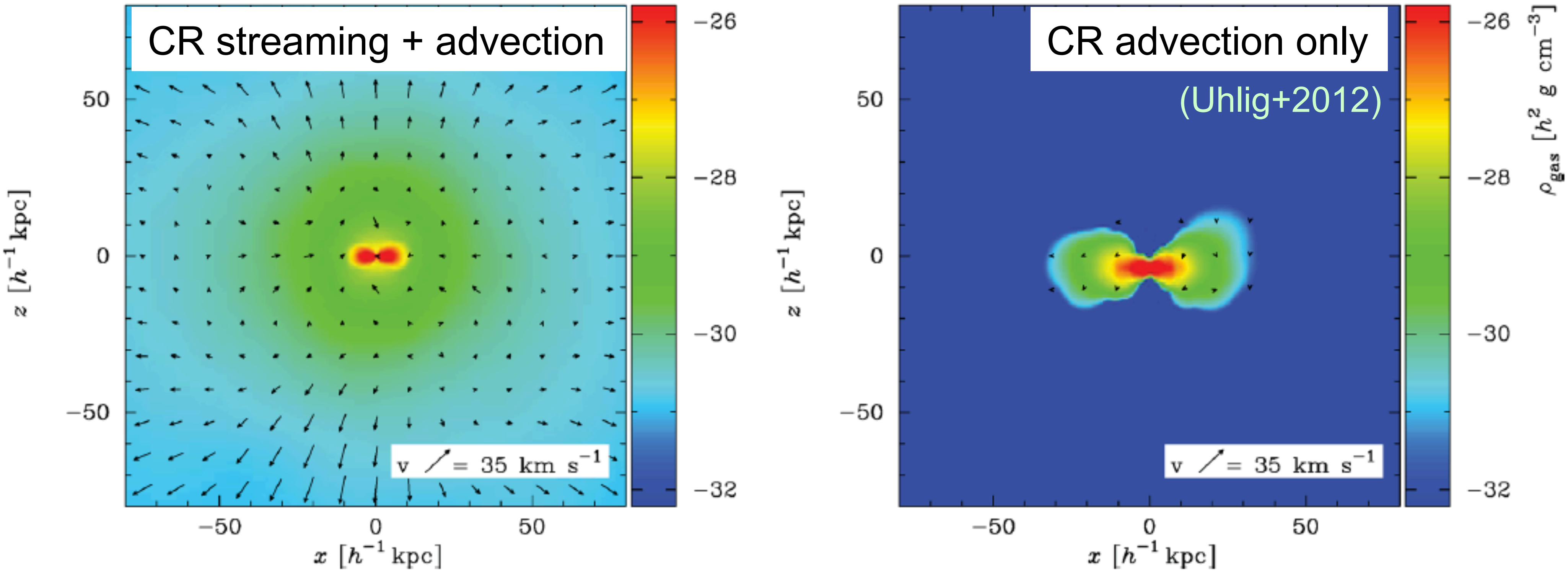
- Linear and quasi-linear theories worked out in 1D (Wentzel 68, Kulsrud & Pearce 69, Skilling 71, 75abc, Felice & Kulsrud 01, etc.).
- Various wave damping mechanisms identified (ion-neutral, non-linear Landau, turbulent), which are environment dependent (e.g., Farmer & Goldreich 04, Guo & Oh 08, etc.).
- Concept of CR-driven wind well developed (Ipavich 75, Breitschwerdt+91, Zirakashivili+96, Ptuskin+97, Socrates+08, Everett+08, Samui+10, Dorfi & Breitschwerdt 12), though largely based on quasi-linear theory, and CR diffusion coefficient not well known.

What are the non-linear properties of the instability?

Multi-dimensional effects?

# How to model CR in cosmological simulations?

- CRs are at the beginning of being incorporated into (hydro) cosmological simulations in a highly simplified form of streaming (Uhlig+12), or diffusion (Booth+13, Hanasz+13, Salem & Bryan14).



What is the right prescription of the CRs?

# Challenges for conventional PIC method

- Huge scale separation:

Microscopic plasma scale that must be resolved: ion skin depth

$$\delta_i = \frac{c}{\omega_{pi}} = \frac{v_A}{\Omega_c}$$

CR resonant wavelengths are much longer:

$$\lambda \approx \frac{p_{\rm CR}}{m\Omega_c}$$

$$\boxed{\frac{\lambda}{\delta_i} \sim \frac{c}{v_A}}$$

One may consider using reduced CR speed, but instability really requires c>>vA.

MHD-PIC approach shows tremendous advantage.

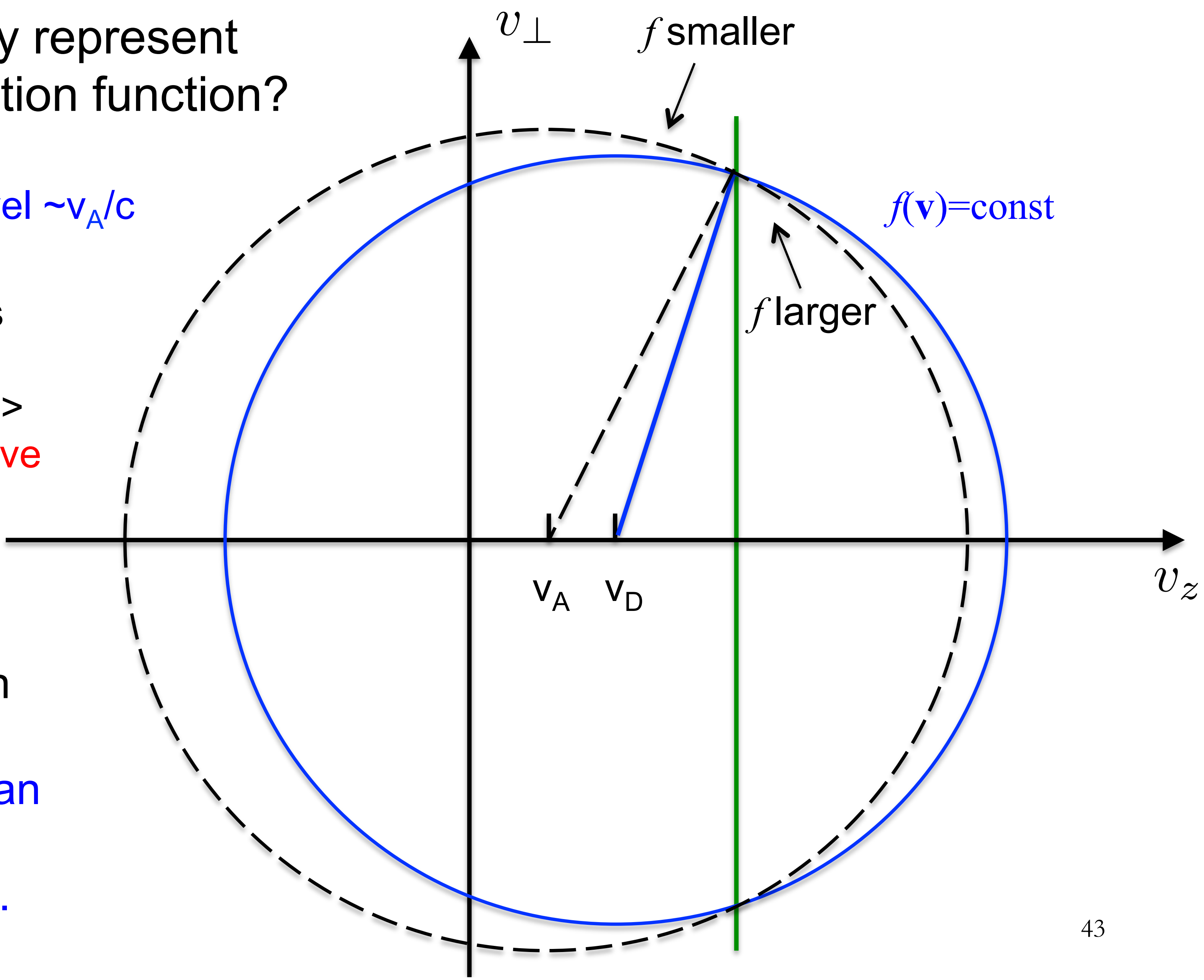
# Further challenge

How to properly represent the CR distribution function?

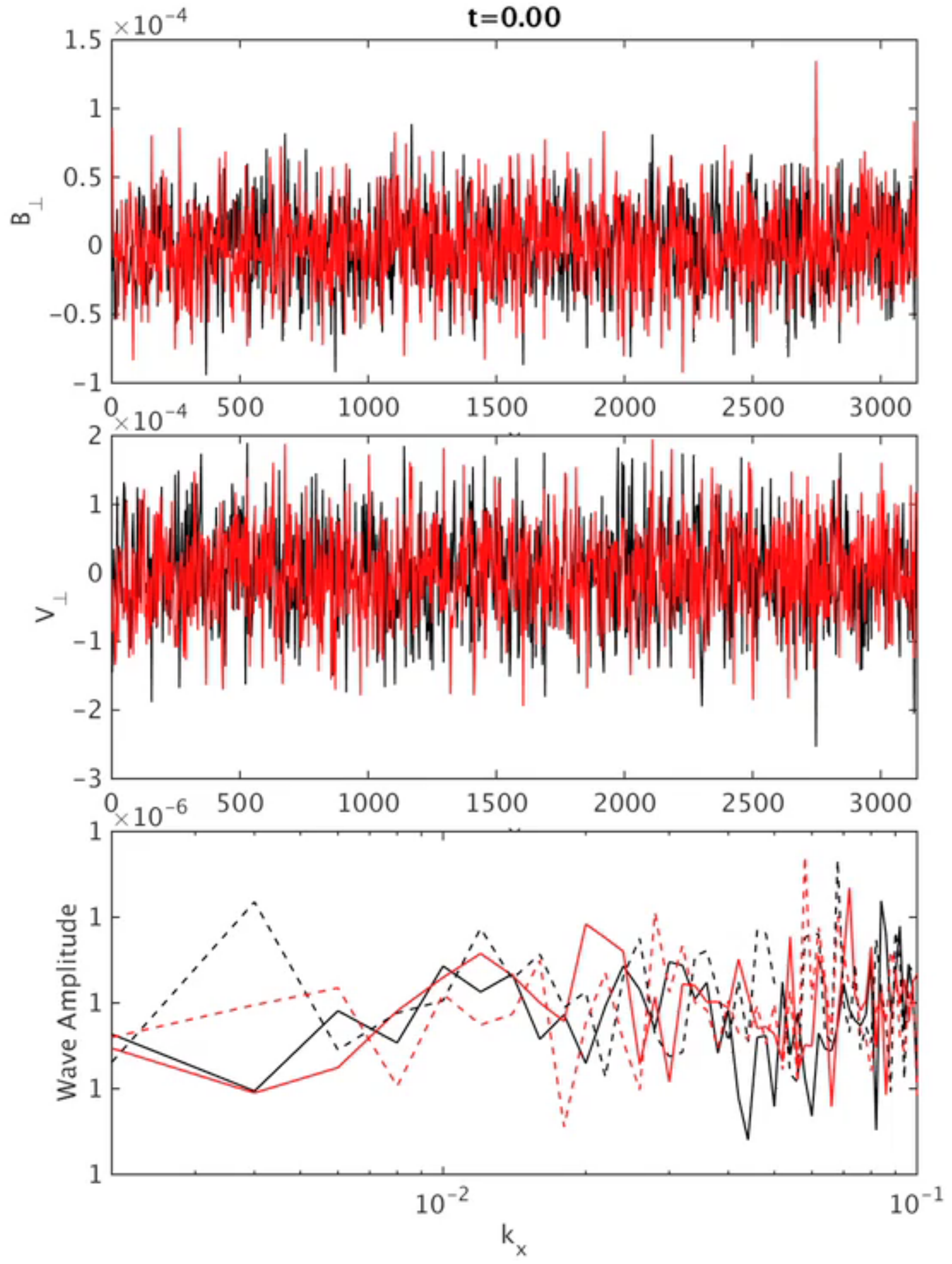
Anisotropy level ~$v_A/c$

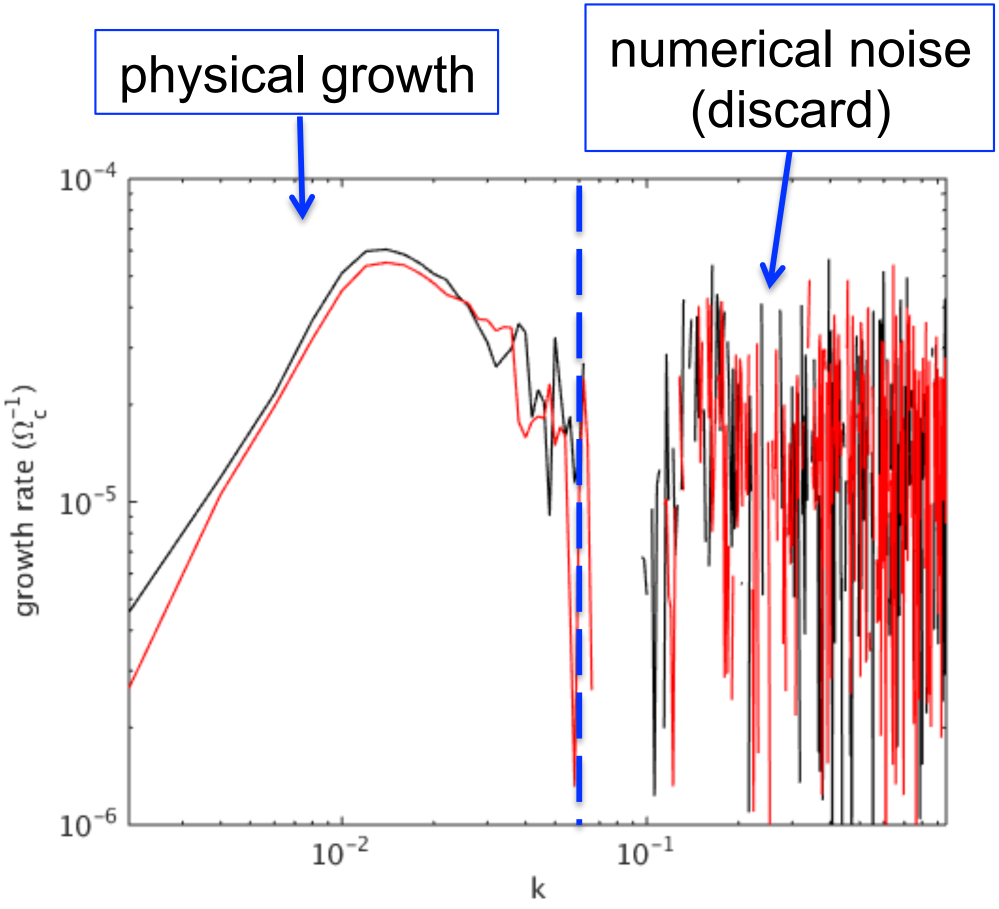
Generally requires huge (~$10^4$) # of particles per cell => extremely expensive

The problem can be alleviated by the $\delta f$ method: can do well with $10^3$ particles per cell.



# CR streaming instability: 1D simulations

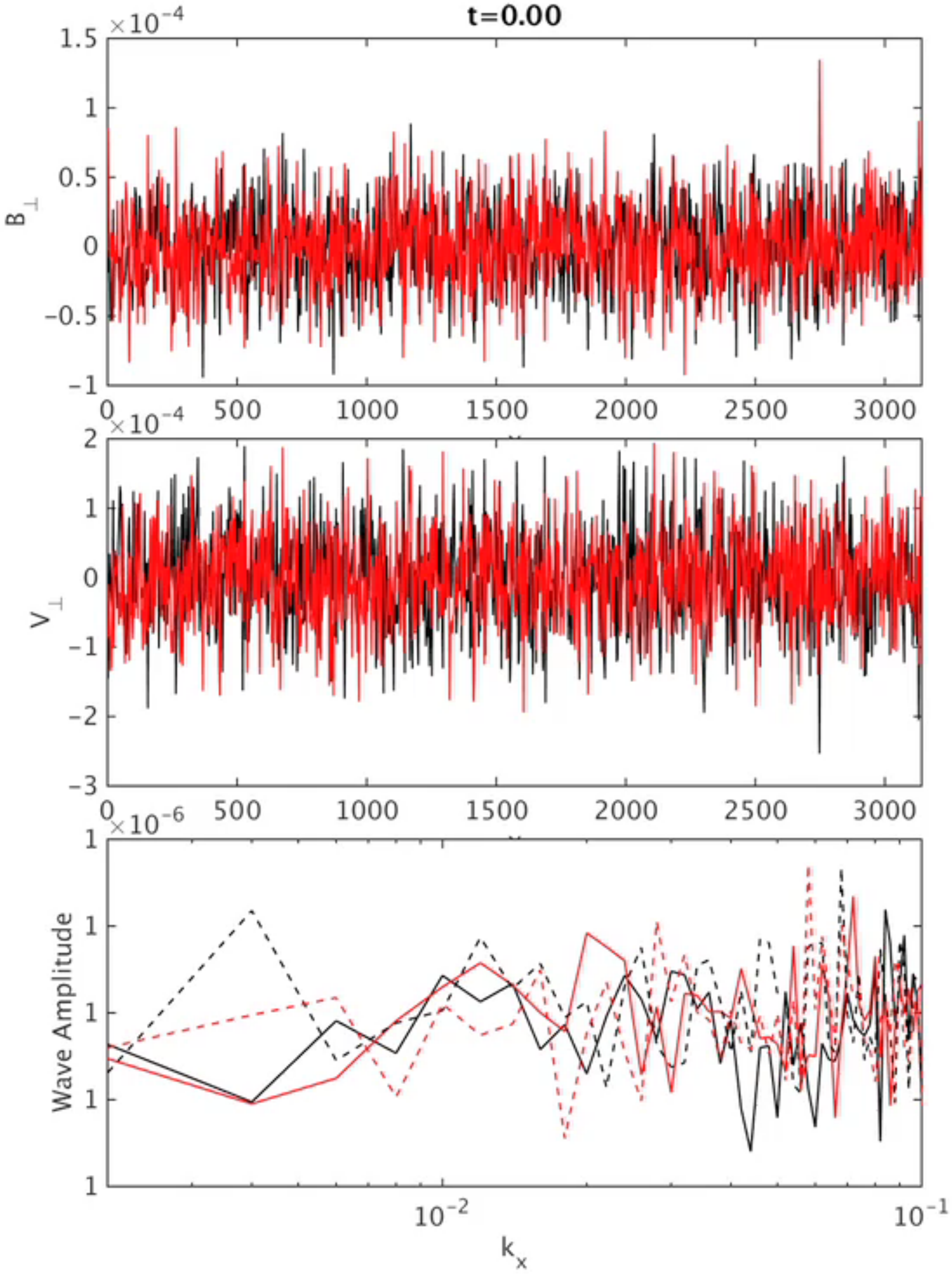



physical growth

numerical noise
(discard)

Maximum growth rate at k resonant with lowest-energy CRs, consistent with theoretical expectations.

# Toward non-linear regime



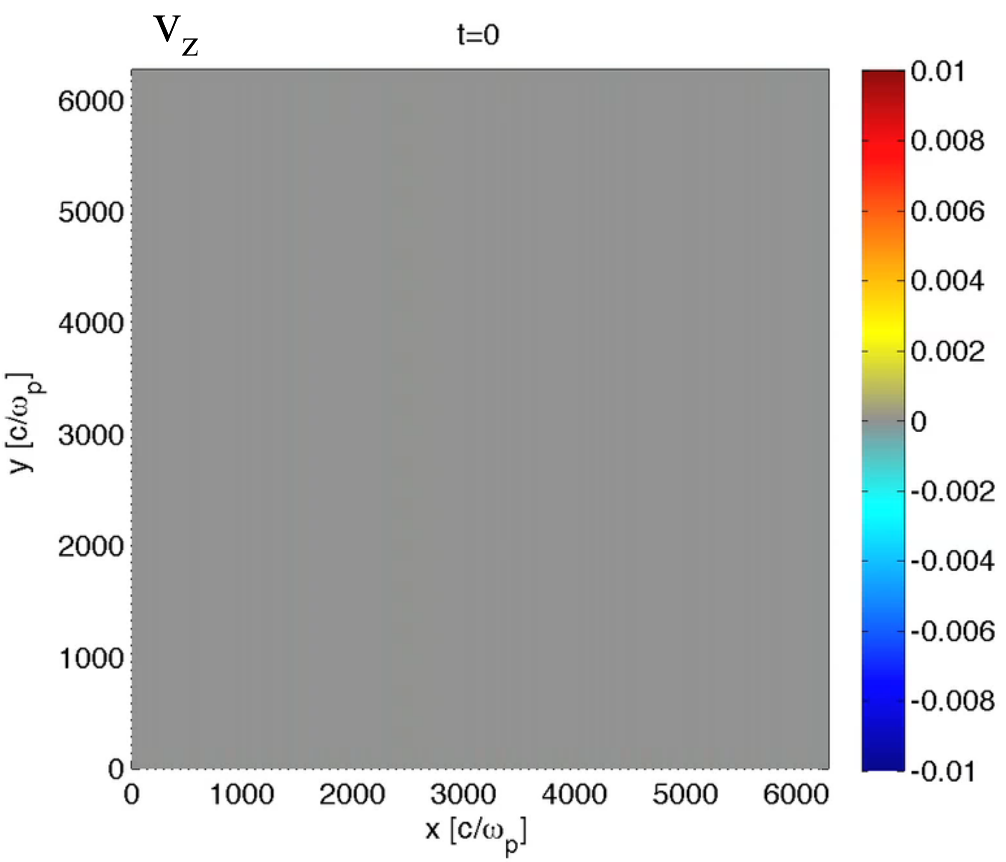
Achieved with “inflow-outflow” particle boundary condition:

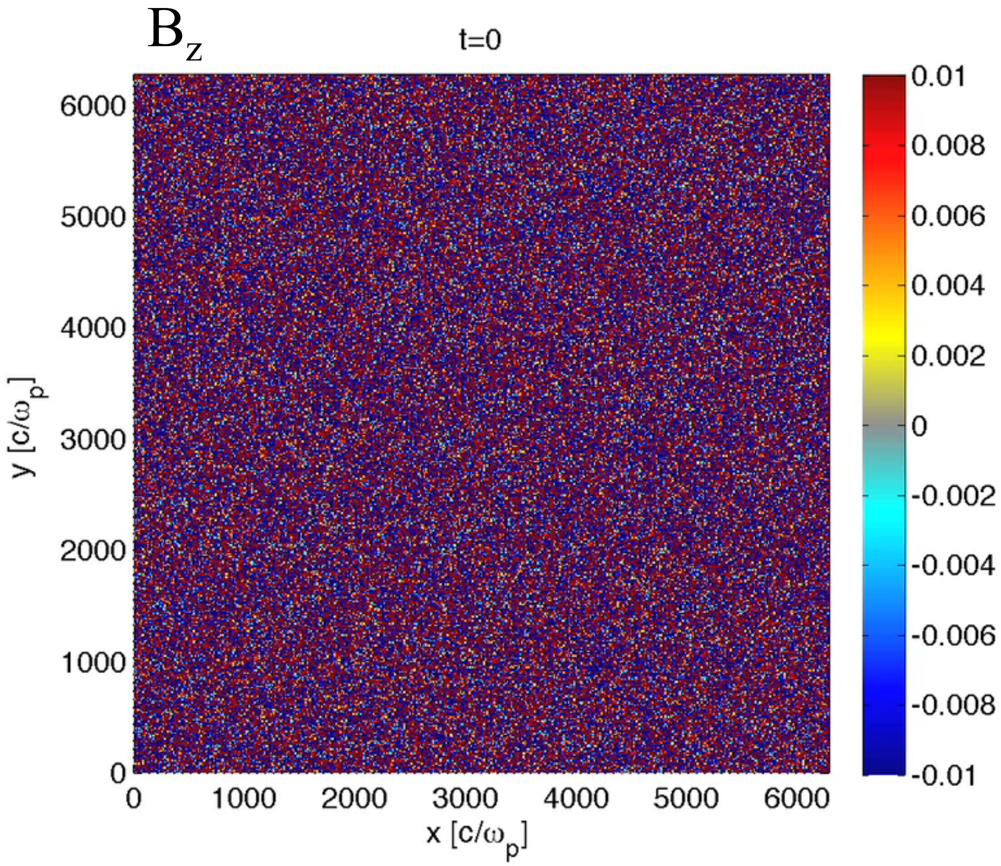
Particles are continuously replenished from boundaries to feed continued growth.

Wave steepening into shocks, conversion into compressible modes, etc.

Setup is still unrealistic especially towards non-linear stage but is useful for test purpose.

# Test simulation in 2D





Instability largely proceeds in parallel manner:

1D approach is probably OK.

Results still very preliminary, work still in active progress.

# Summary

- Development of the MHD-PIC method/code
  - Valid on scales > ion skin depth, fully conservative, well tested.
- MHD-PIC simulations of particle acceleration in shocks
  - Proof-of-concept study: general results agree with hybrid-PIC studies (shock structure/evolution, particle accel. rate/efficiency/spectral slope).
  - New advances: easily run large-box simulation to follow long-term evolution; follow particle acceleration into the relativistic regime.
  - Future work: improve injection recipes and toward realistic parameters.
- MHD-PIC simulations of resonant CR streaming instability
  - First numerical study: overcome technical challenges with confirmation of linear growth rates. 2D behavior very similar to 1D.
  - Future work: CR diffusion and self-confinement, towards global scales, closure relations for fluid treatment of CRs.