Cosmic-ray driven plasma instabilities

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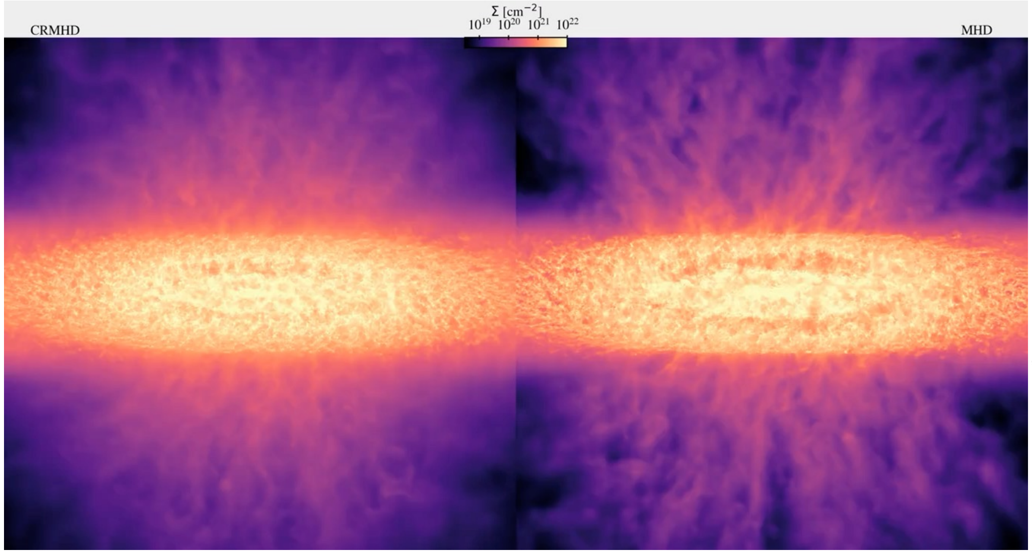
Cosmic Rays Impact Galaxies

with CRs without CRs



Thomas, CP, Pakmor 2025

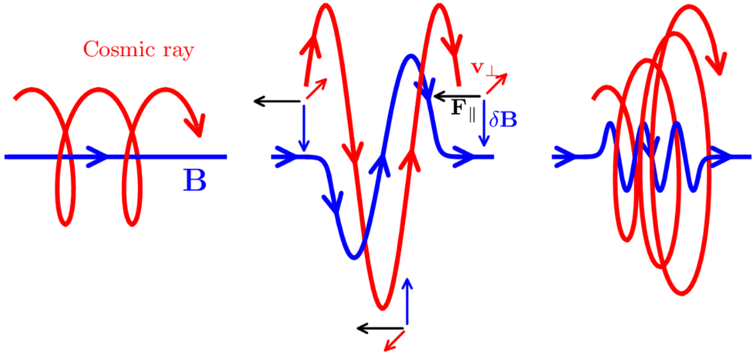
Cosmic rays

- drive galactic winds
- regulate star formation
- amplify magnetic fields

through microphysical interactions

Connecting the Scales

Gyroresonant instabilites



Jacob & CP

Scale ~ AU

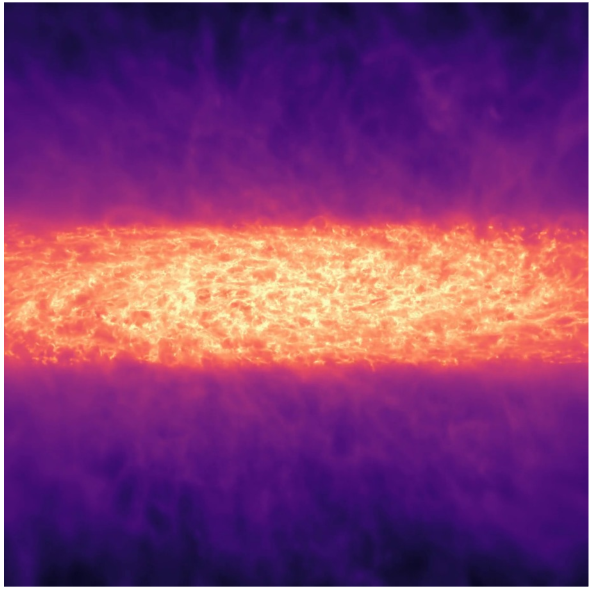
Impact of cosmic ray interactions

CR model

Diffusion

Mean velocity

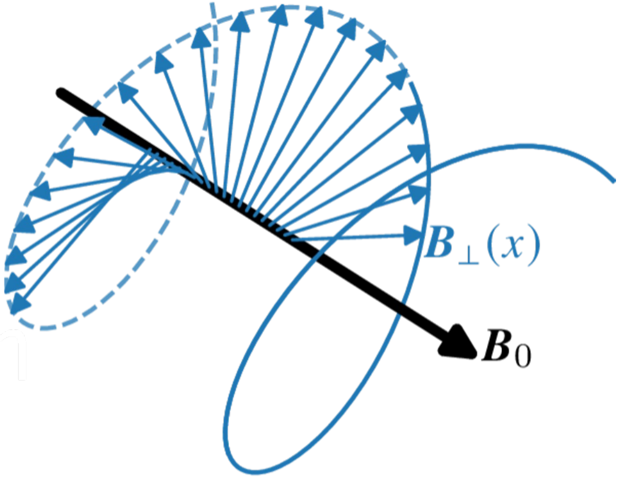
Pressure



Scale $\gtrsim$ kpc (10^8 AU)

What is Gyroresonance?

Plane wave: $\exp(-ik(x - v_{\mathrm{wave}} t))$



Lemmerz+ 2025

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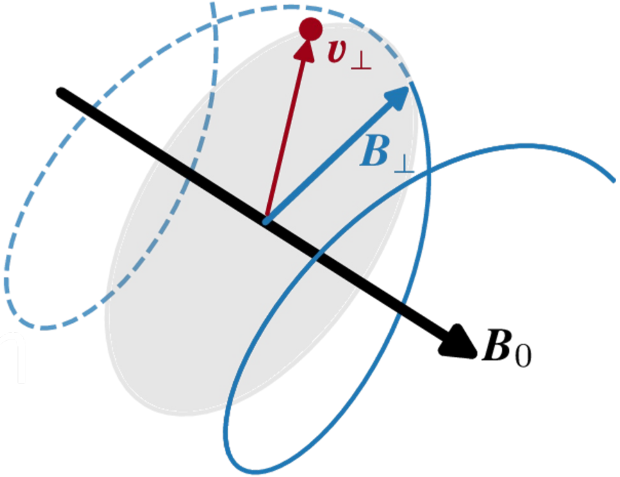
Cosmic ray: $v_{\|}$ movement along B_0

Ω_{cr} gyration frequency



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What is Gyroresonance?

Plane wave: $\exp(-ik(x - v_{\rm wave} t))$

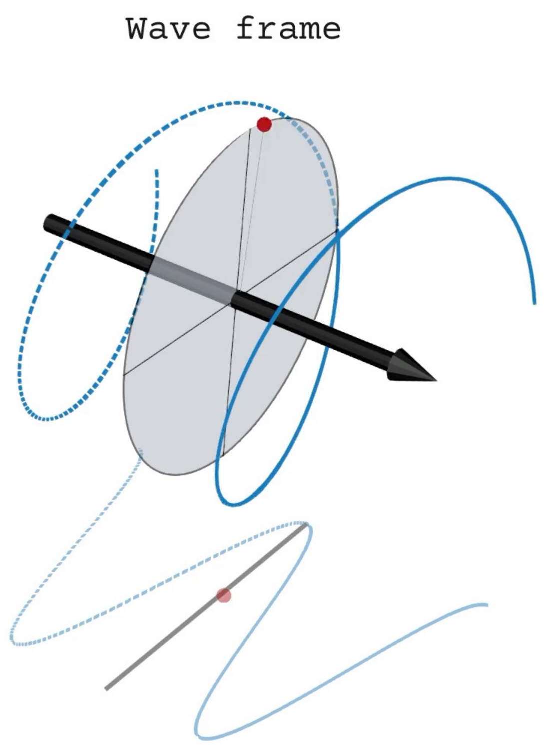
Cosmic ray: $v_{||}$ movement along B_0

$\Omega_{\rm cr}$ gyration frequency

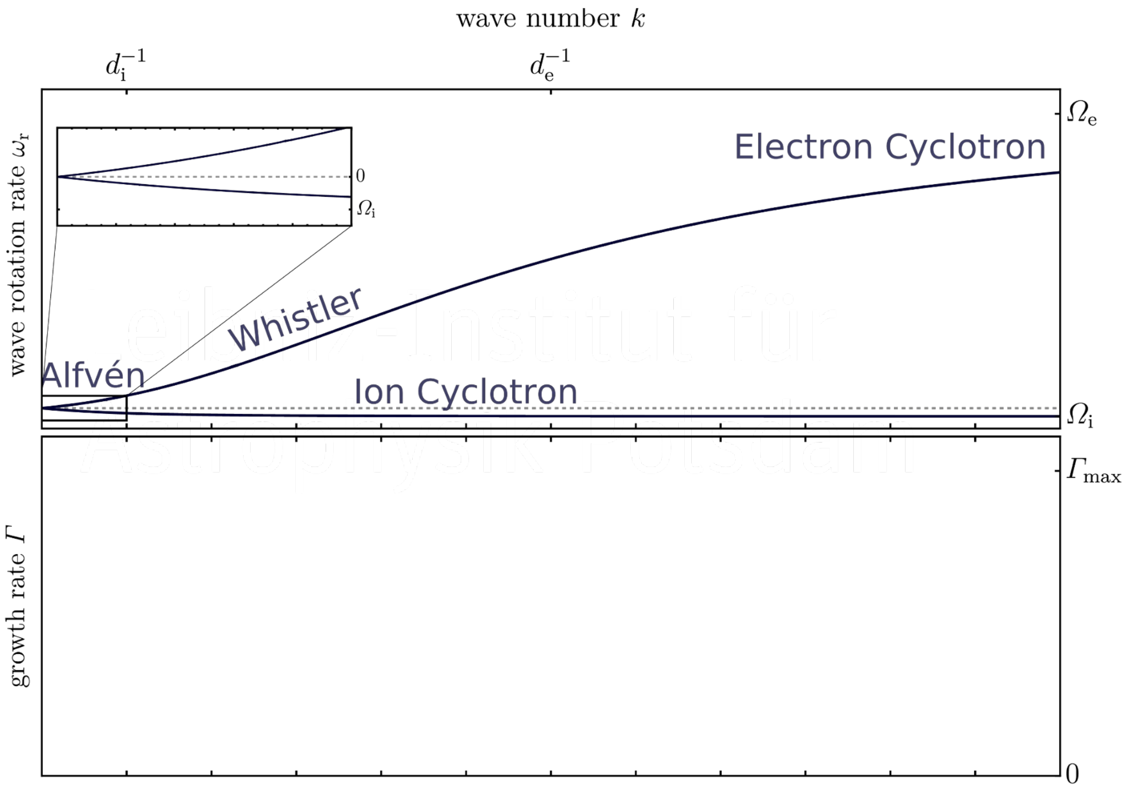
Resonance condition:

$$\overbrace{\Omega_{\rm cr}}^{\text{Gyration}} + \overbrace{k v_{||}}^{\text{Dopplershift}} = \overbrace{k v_{\rm wave}}^{\text{wave frequency}}$$

Resonant wave appears **static** to CR



Gyroresonance in Dispersion Relation



Shalaby+ 2023

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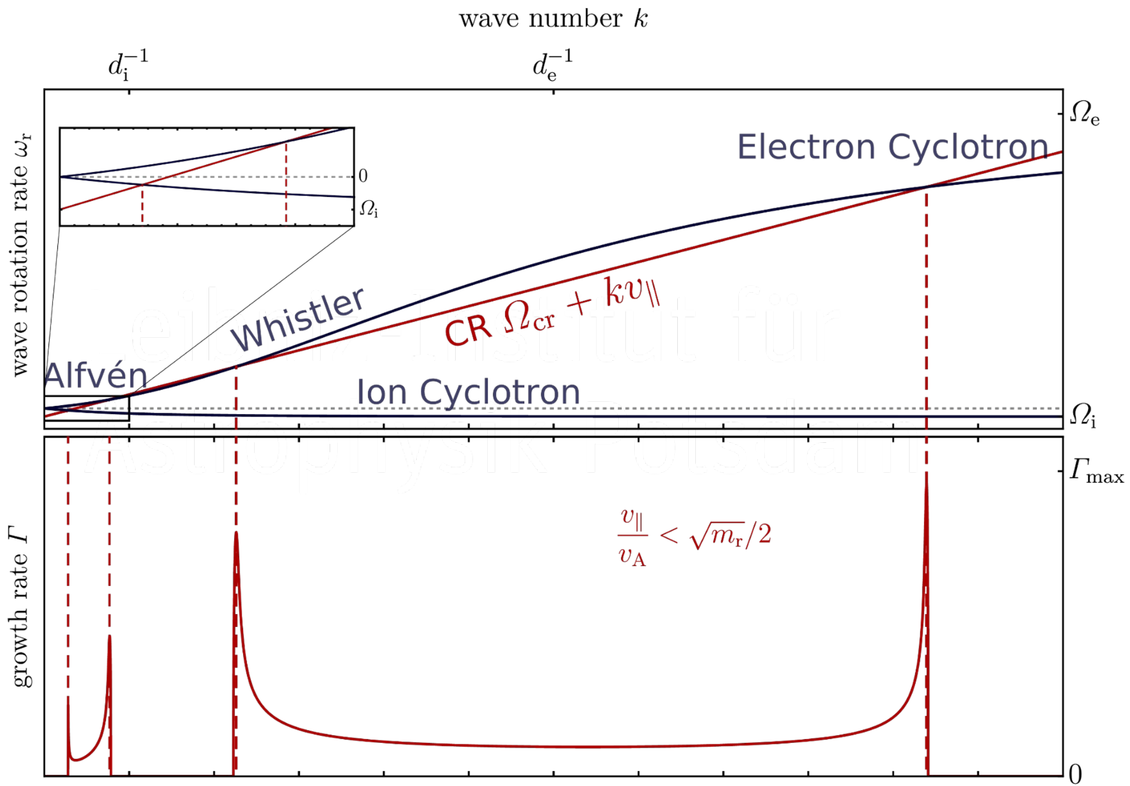

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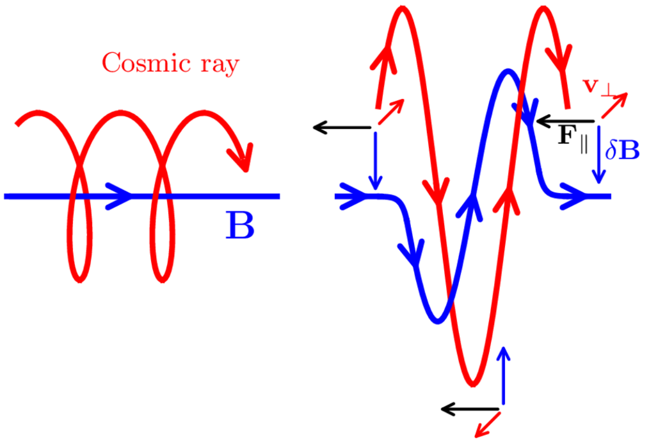
Particle-Wave Interactions



Jacob & CP

- electric fields vanish in the Alfvén wave frame:

$$\nabla \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t}$$

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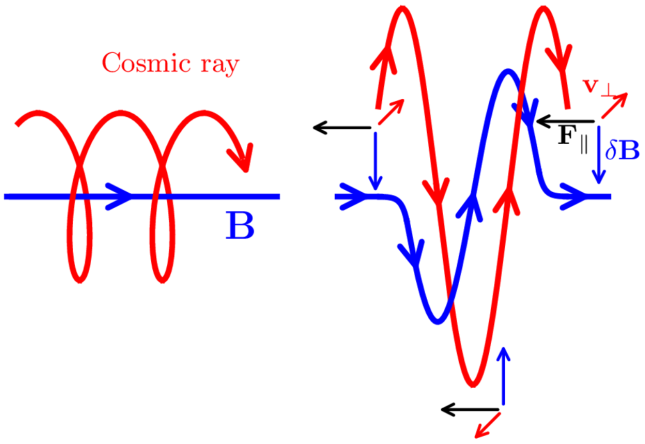

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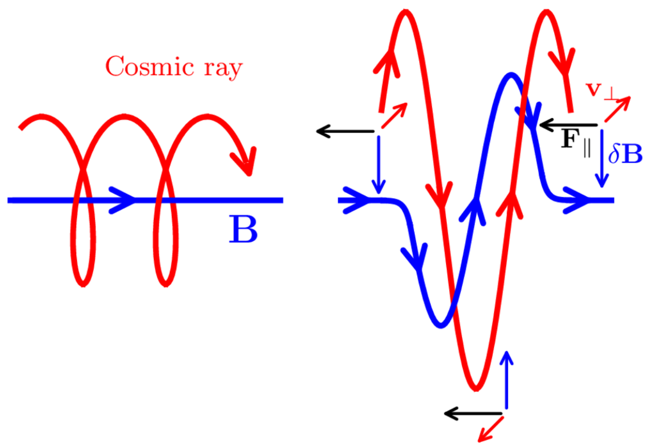

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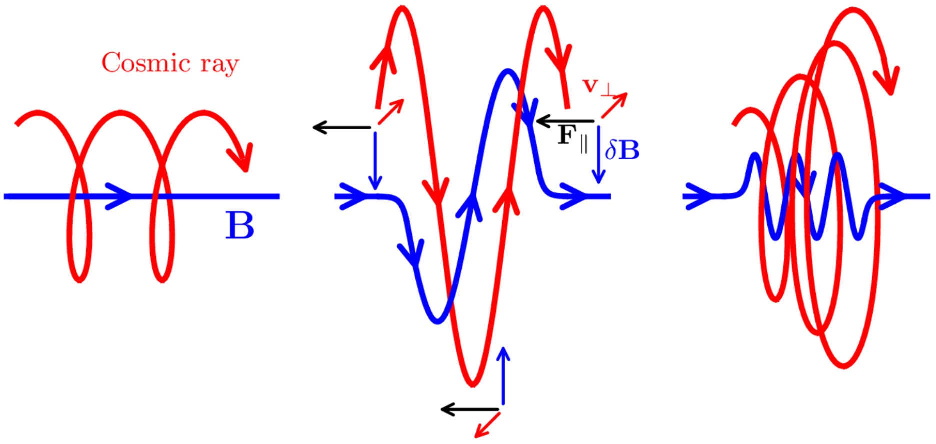

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- which changes $p_\parallel$ and thereby the pitch-angle cosine
$$\mu = \cos\theta = \frac{\mathbf{B}}{|\mathbf{B}|}\cdot\frac{\mathbf{p}}{|\mathbf{p}|}$$

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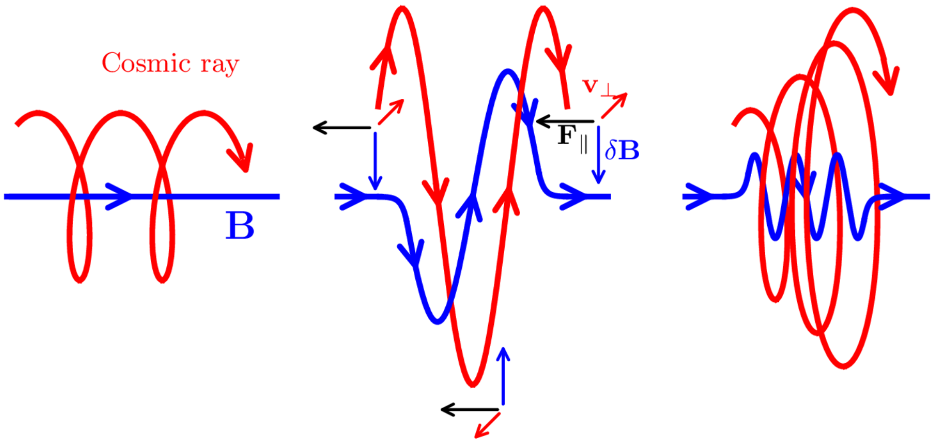

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=> But why do waves grow?

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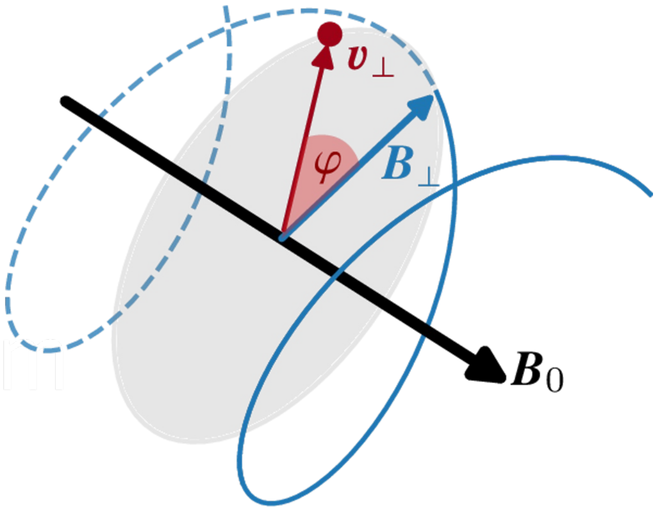
From Particle-Wave to Wave-Wave

- Goal: understand collective behaviour of many CRs



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From Particle-Wave to Wave-Wave

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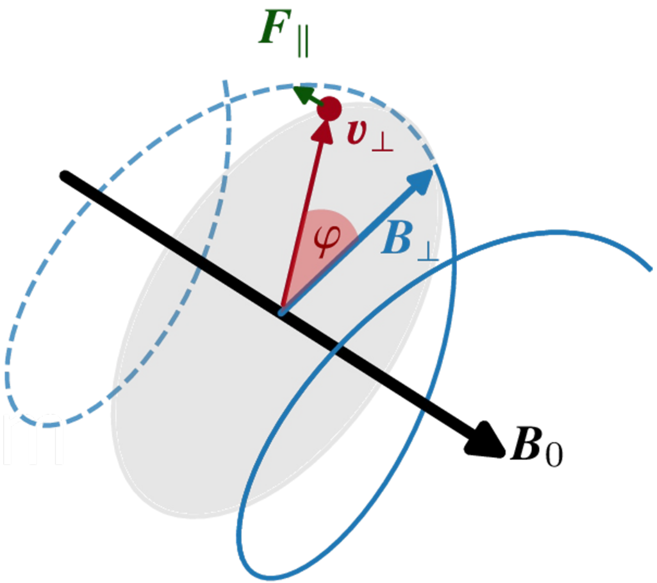

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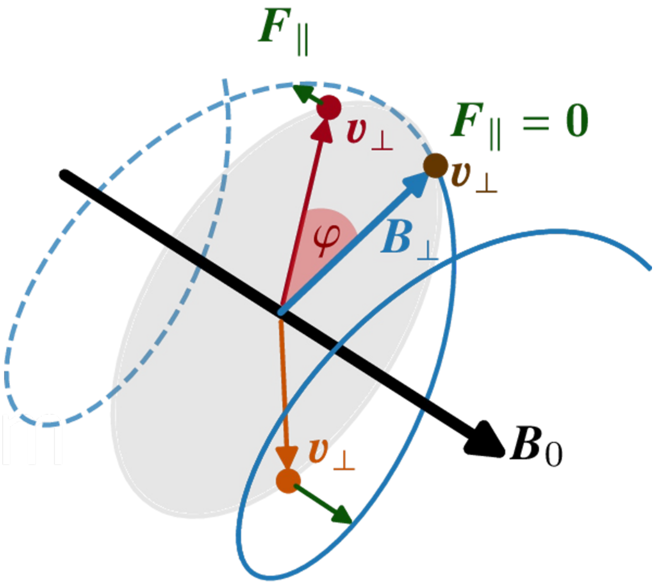

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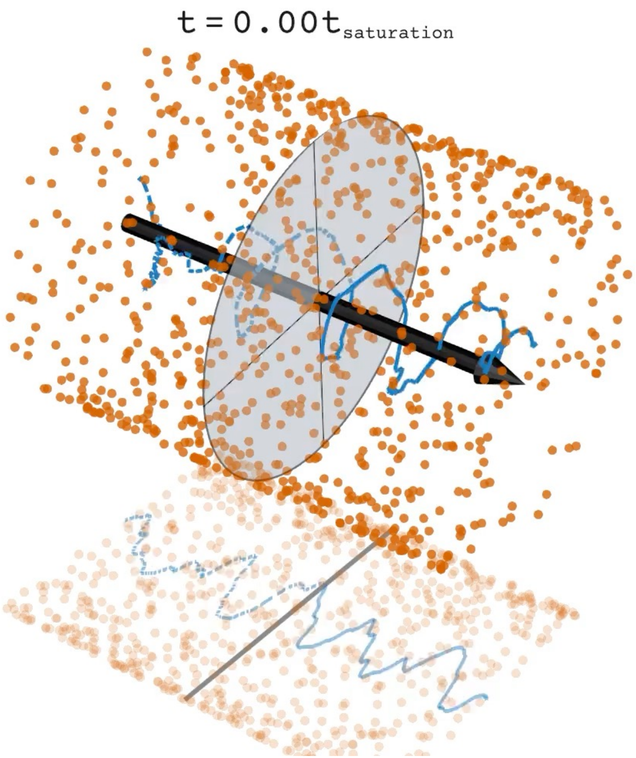

fluid-PIC simulation (Lemmerz+ 2025)

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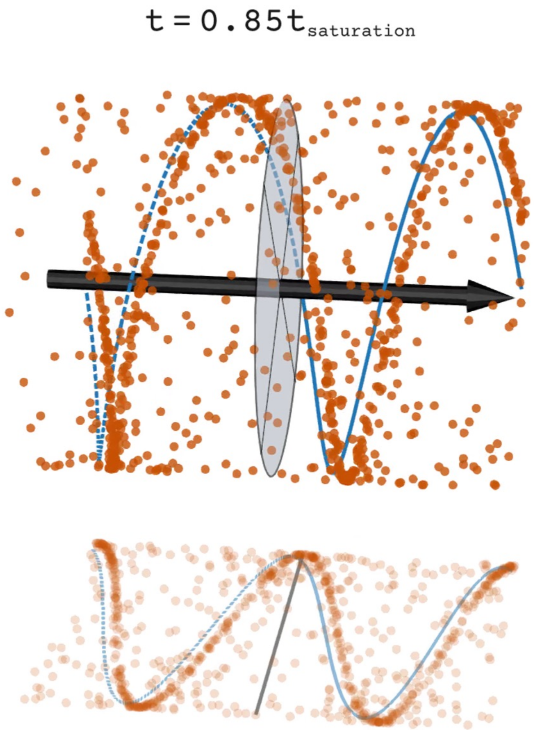

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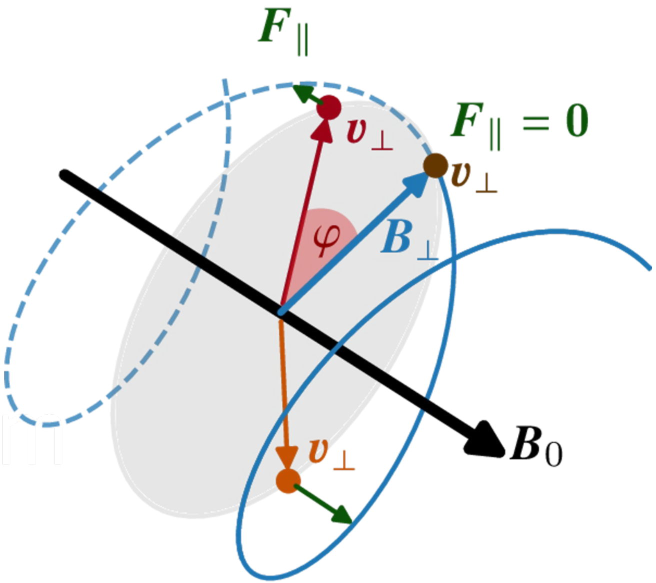

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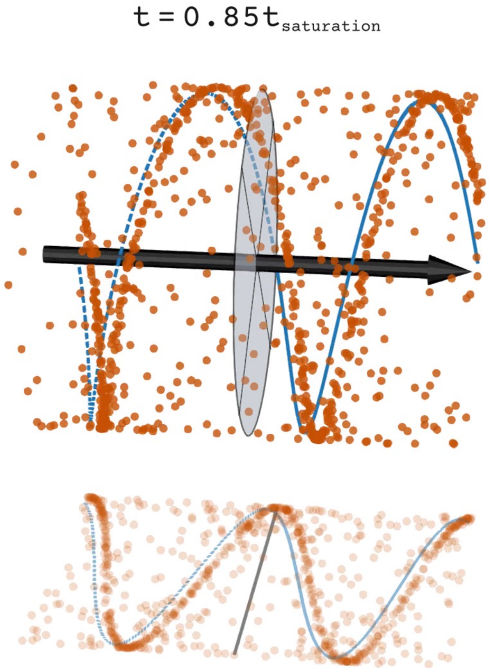
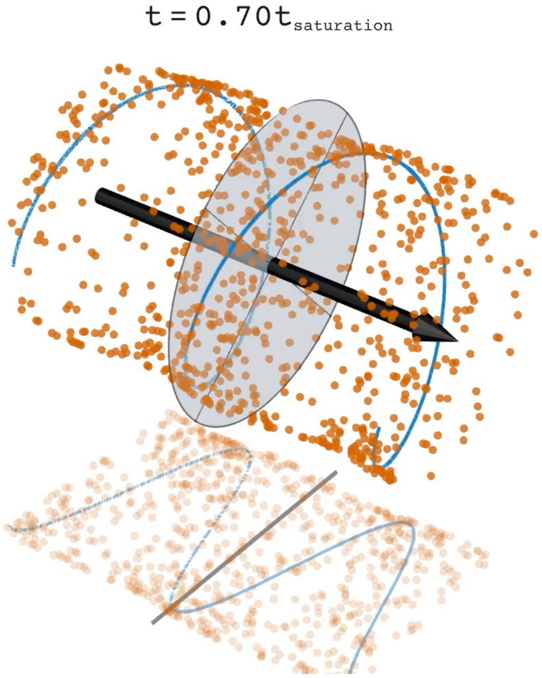
Gyroresonance with different waves

fluid-PIC simulation

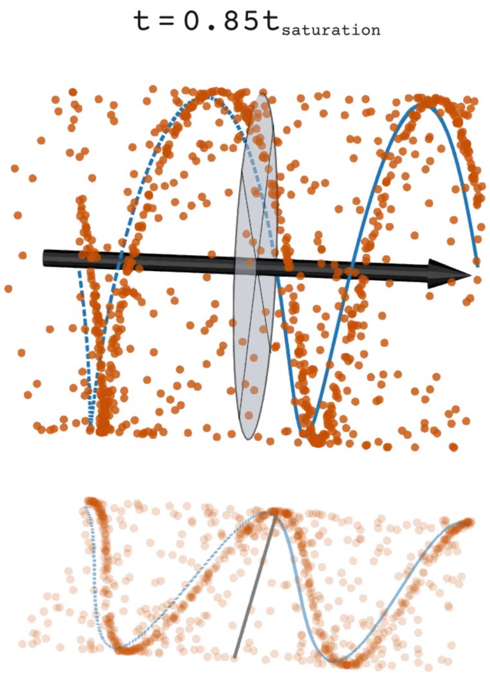




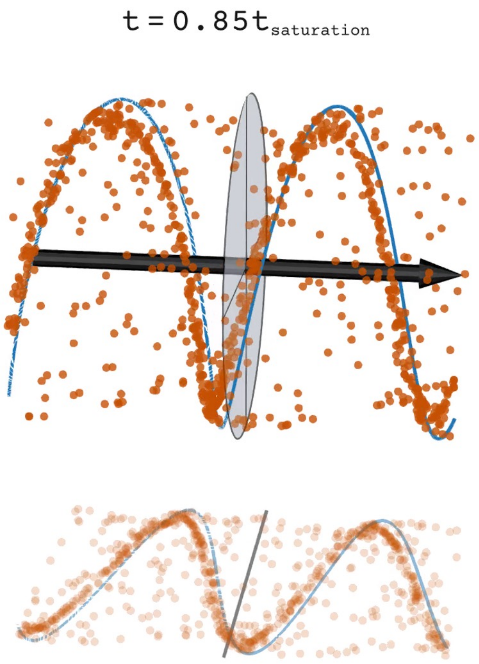
Forward Alfvén, Whistler

Backward Alfvén

Gyroresonance with different waves



Forward Alfvén, Whistler



Backward Alfvén

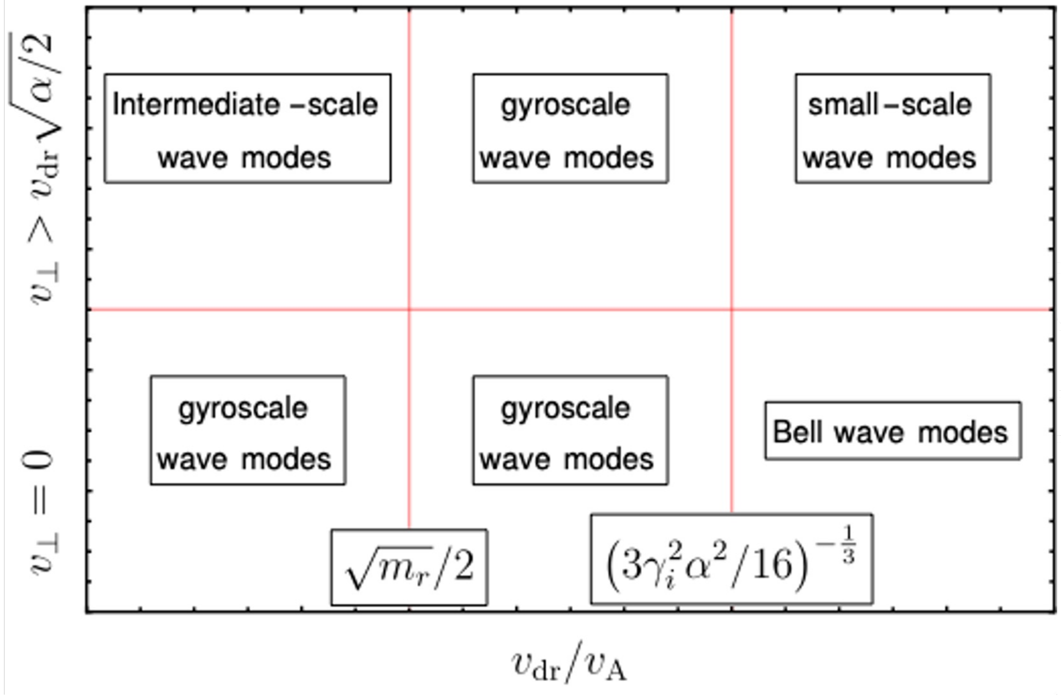
Bunching theory

- ➔ Bunching in gyrophase
- ➔ Biased scattering, favors wave growth

Traditional, Quasilinear theory

- ➔ Assumes uniform φ
- ➔ Diffusive scattering, no backward wave

Graphical classification of CR instabilities

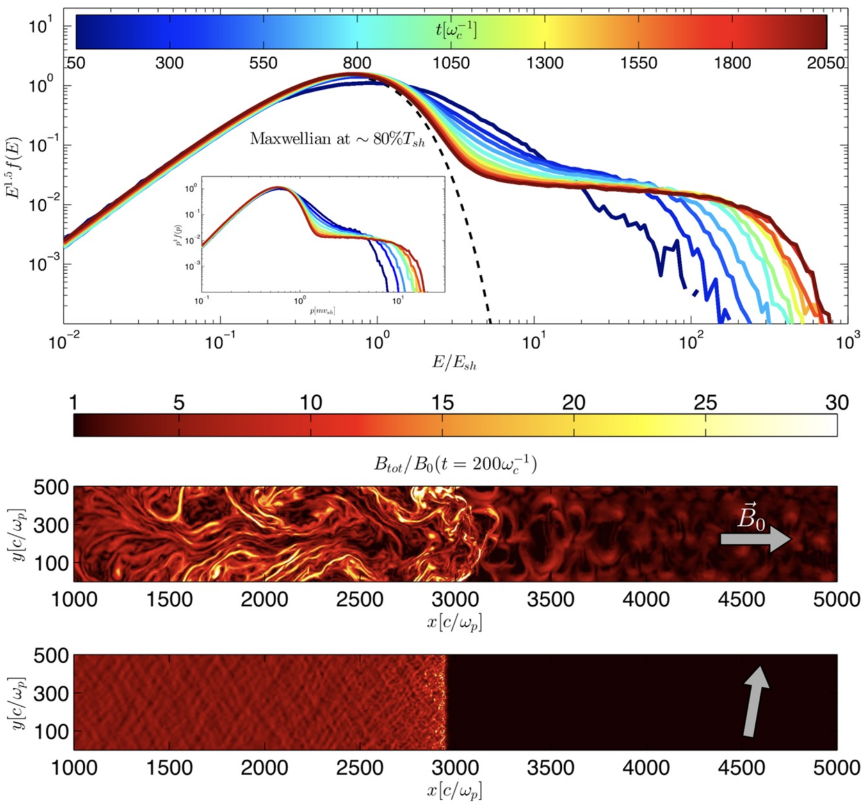


Shalaby+ 2021

CR-driven instabilities in the linear regime (low density, gyrotropic CRs with a cold momentum distribution):

- ➔ the fastest wave modes depend on the CR flux and pitch angle
- ➔ because CRs will typically have a finite pitch angle, the typical dominant unstable wave modes occupy the top region

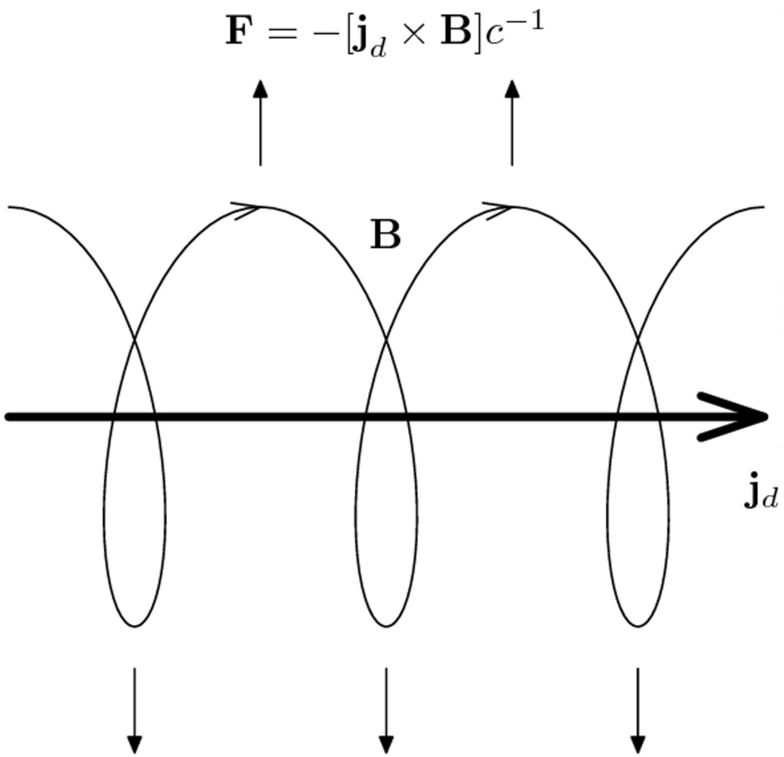
Non-resonant hybrid (Bell's) instability



Hybrid-PIC simulation of CR ion acceleration at a collisionless, non-relativistic strong shock (Caprioli & Spitkowski 2014).

- top panel: downstream ion energy spectrum of a quasi-parallel shock, color coded by different times – thermal Maxwellian & CR power law that shows an increasing maximum energy with time
- bottom panels: magnitude of the total magnetic field for strong shocks with different obliquity, implying that magnetic field amplification and CR acceleration only works in quasi-parallel shocks

Non-resonant hybrid (Bell's) instability



Visualization of the underlying principle of Bell's streaming instability:

- The CR current, $\mathbf{j}_\mathrm{d}$, induces a return current in the background electrons, $-\mathbf{j}_\mathrm{d}$, which amplifies a helical magnetic perturbation and stretches it via the Lorentz force $\mathbf{F} = -(\mathbf{j}_\mathrm{d} \times \mathbf{B})c^{-1}$ (Zirakashvili+ 2008)
- Saturation once CRs get magnetized:

$$\varepsilon_{B,\mathrm{sat}} \sim \frac{1}{2}\frac{\upsilon_\mathrm{s}}{c}\,\varepsilon_\mathrm{cr}$$

Main questions

- ➔ Physics of instability saturation
  - ◆ Saturation as growth = damping or through particle trapping in Lorentz force potential?
  - ◆ Growth: which instability dominates? Forward/backward Alfvén, Whistler modes? Is MHD sufficient or do we need full dispersion relation?
  - ◆ Damping: Ion-neutral, nonlinear Landau damping, turbulent damping?
- ➔ Effect of inhomogeneities in $\rho, \mathbf{B}, \ldots$
- ➔ Multi-D effects: turbulence, cascades, oblique waves