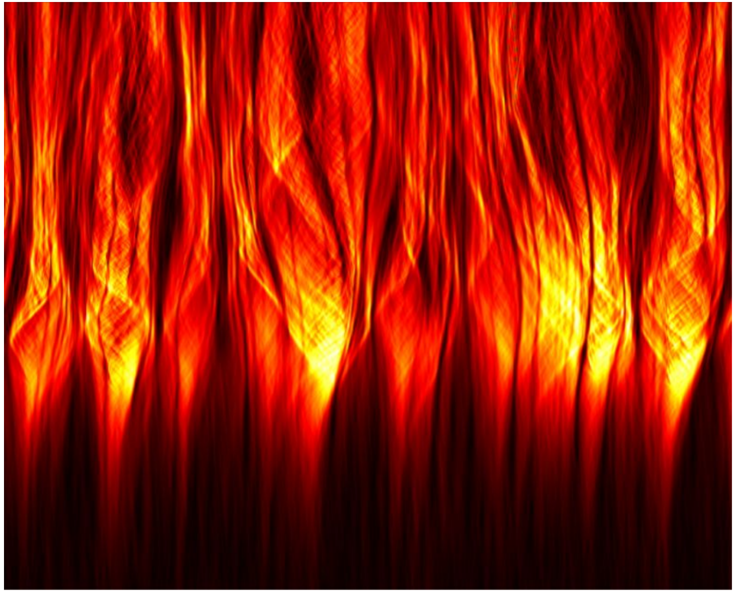
The non-resonant streaming instability: from theory to experiments



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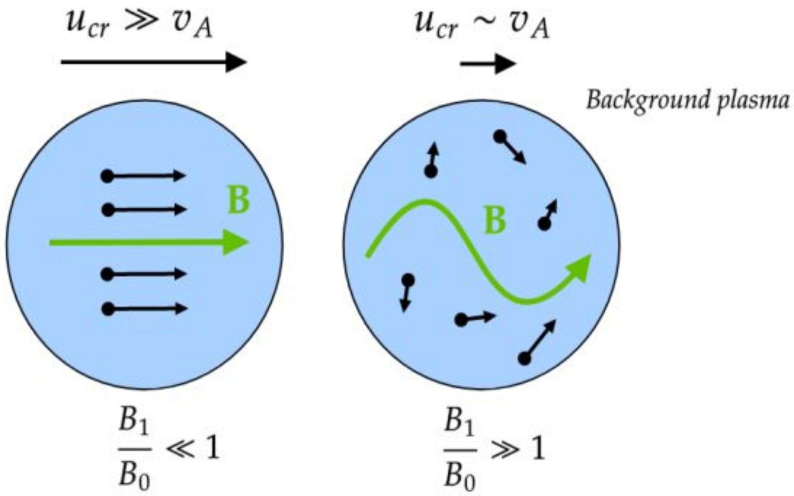
Summary

- What is it? Why does it matter?
- Modelling the non-resonant instability: fluid and kinetic approaches
- Hybrid-PIC (Particle In Cell) simulations results
- Collisional effects on the unstable waves
- Toward laboratory experiments
- Conclusions

The streaming instabilities: a basic physical picture

- Three modes can be distinguished: **left-hand resonant**, **right-hand resonant**, **non-resonant** (**NR**)
- The NR instability occurs when an population of **super-Alfvénic ions** traverses a **background plasma**, embedded in an **ambient magnetic field**



- Generates large amplitude parallel propagating electromagnetic waves

Supernova remnant shocks

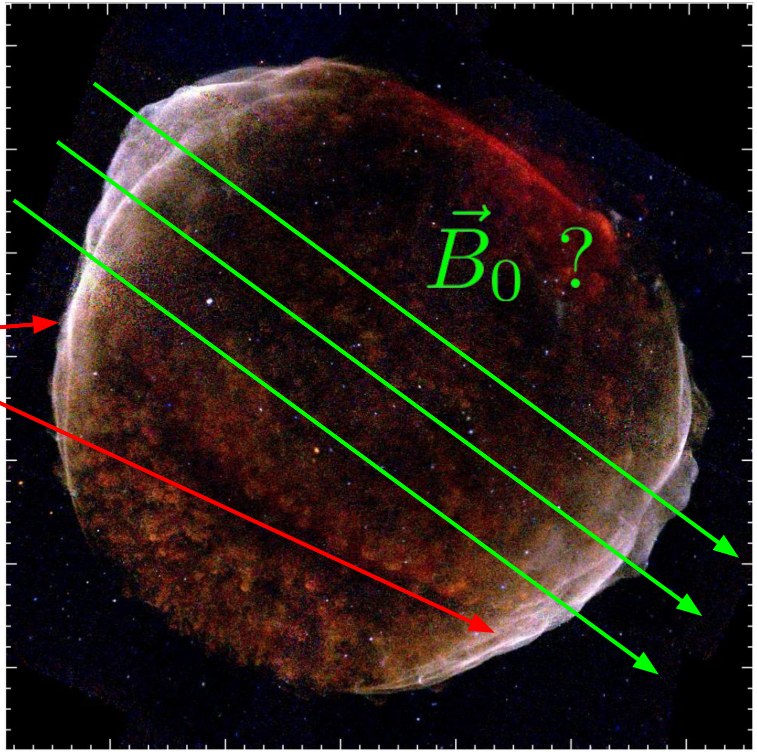
- Cosmic rays acceleration via **Diffusive Shock Acceleration**
- Multiple shock crossing
- Energies up to 10^6 GeV

Synchrotron emission, acceleration of electrons (and ions)

➡ Need large magnetic field fluctuations ahead of the shock front to obtain a **confinement** at shock boundary [Bell 2013]

$$E_{max} \approx 10^{14} (\lambda/r_g)^{-1} B_{\mu G} \tau_{1000} u_7^2 \text{ eV}$$

➡ The cosmic rays leaking from the shock regions can destabilize the non-resonant mode



SN 1006 seen in X-rays [Winkler+ 2014]

Modelling the instability

The instability may be described using either non-relativistic **Kinetic** or **Fluid** models

- **Fluid** model considering the main protons and electrons as a single background fluid, electrically charged:

$$\rho \frac{d\vec{u}}{dt} = -\nabla \cdot \vec{P} + \frac{1}{\mu_0}(\vec{\nabla} \times \vec{B}) \times \vec{B} - en_{cr}\vec{E} - \vec{j}_{cr} \times \vec{B}$$

$$\vec{E} = -(\vec{u} + \frac{n_{cr}}{n_m}\vec{u}_{cr}) \times \vec{B} \qquad \frac{\partial \vec{B}}{\partial t} = -\vec{\nabla} \times \vec{E}$$

- **Kinetic** theory, the dispersion relation includes finite Larmor radius effects

$$-k^2c^2 - \frac{1}{\sqrt{2}}\sum_\alpha \left[\frac{\omega_{p\alpha}^2}{v_{T\alpha}}\left(u_{\parallel\alpha} - \frac{\omega}{k}\right) Z(\zeta_\alpha^\pm)\right] = 0$$

$$\zeta_\alpha^\pm = \frac{1}{\sqrt{2}v_{T\alpha}k}(\omega - ku_{\parallel\alpha} \pm \Omega_\alpha)$$

→ Determines the response to the perturbation

Fluid model of the NR instability

[Marret+ 2021]

- **Momentum density conservation equation** of the background plasma

$$\frac{\partial \vec{u}_1}{\partial t} = \frac{(\vec{B}_0 \cdot \vec{\nabla})\vec{B}_1}{\mu_0 \rho} + \frac{n_{cr}}{n_m}\Omega_0 \left(\vec{u}_1 \times \frac{\vec{B}_0}{B_0} \right) - \frac{\vec{j}_{cr} \times \vec{B}_1}{\rho}$$

Magnetic tension — *Pseudo-cyclotronic motion* — *Cosmic rays induced magnetic force*

- **Maxwell-Ampère's equation** in conservative form

$$\frac{\partial \vec{B}_1}{\partial t} + \vec{\nabla} \cdot \left(\frac{n_{cr}}{n_m} \vec{u}_{cr} \vec{B}_1 \right) = (\vec{B}_0 \cdot \vec{\nabla})\vec{u}_1$$

Magnetic field advection — *Source term*

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Magnetic field advection — *Source term*

$k < \frac{n_{cr}}{n_m} \frac{u_{\parallel cr}}{v_{A0}^2} \Omega_0$ | $k > \frac{\Omega_0}{u_{\parallel cr}}$

$\gamma > \omega_r$

Environments for magnetic field amplification

Three regimes can be distinguished, depending on the **main ions thermal Larmor radius**:

$$r_{Lm} = \frac{v_{Tm}}{\Omega_0}$$

- **Cold regime** [Winske+ 1984, Bell 2004]
  Interstellar medium, Earth bow shock
  $$v_{Tm} \to 0 \qquad kr_{Lm} \ll 1$$

Fluid Model is sufficient

- **Warm, magnetized regime** [Reville+ 2008, Zweibel+ 2010]
  Superbubbles, shocks in galaxy clusters
  $$v_{Tm} \neq 0 \qquad kr_{Lm} \ll 1$$

- **Hot, demagnetized regime** [Marret+ 2021]
  Intergalactic medium
  $$v_{Tm} \neq 0 \qquad kr_{Lm} > 1$$

Kinetic Model is necessary

Hybrid-PIC simulations: system of equations

Simulations have been performed with the Hybrid-PIC code **HECKLE** [Smets+ 2011]

- The **ions** are considered as **macroparticles** as in PIC codes ⟶ Solve Vlasov equation

$$\frac{d\vec{v}_k}{dt} = \frac{q_k}{m_k}(\vec{E} + \vec{v}_k \times \vec{B})$$

$$\frac{\partial \vec{B}}{\partial t} = -\vec{\nabla} \times \vec{E}$$

- Ohm's law, neglected electron inertia (massless **electron fluid**)

$$\vec{E} = -\vec{u}_i \times \vec{B} + \frac{1}{en_e}(\vec{J} \times \vec{B} - \vec{\nabla} \cdot \vec{P}_e) + \sigma \vec{J} - \sigma' \Delta \vec{J}$$

- Poisson equation is not solved : **quasi-neutrality** is assumed at each time step

$$\vec{J} = \vec{\nabla} \times \vec{B}/\mu_0$$

- Ampère's law, non-relativistic

$$P_e = n_e k_B T_e \qquad T_e = \text{cste}$$

- Isothermal closure

Thermally modified NR instability

- **Cold regime**

$$\gamma_{\mathrm{cold}} = \frac{1}{2}\frac{n_{cr}}{n_m}\frac{u_{\parallel cr}}{v_{A0}}\Omega_0$$

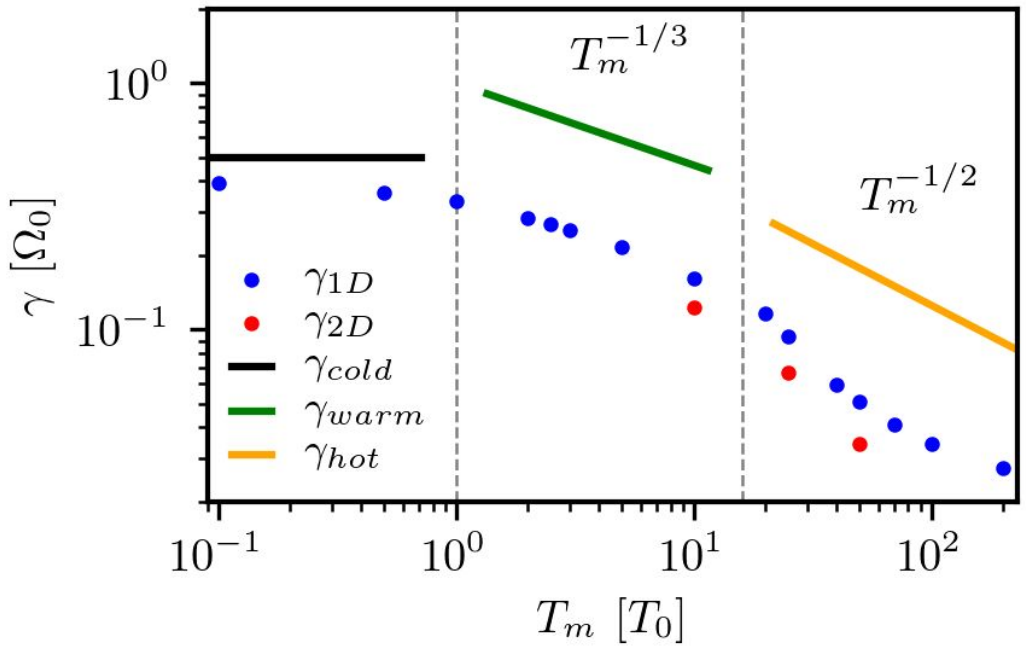
- **Warm, magnetized regime**

$$\gamma_{\mathrm{warm}} = \left(\frac{n_{cr}}{n_m}\frac{u_{\parallel cr}}{v_{Tm}}\right)^{2/3}\Omega_0$$

- **Hot, demagnetized regime**

$$\gamma_{\mathrm{hot}} = \left(\frac{\pi}{2}\right)^{1/2}\frac{n_{cr}}{n_m}\frac{u_{\parallel cr}}{v_{Tm}}\Omega_0$$

Interstellar medium, Earth bow shock — *Shocks in galaxy clusters, superbubbles* — *Intergalactic medium*

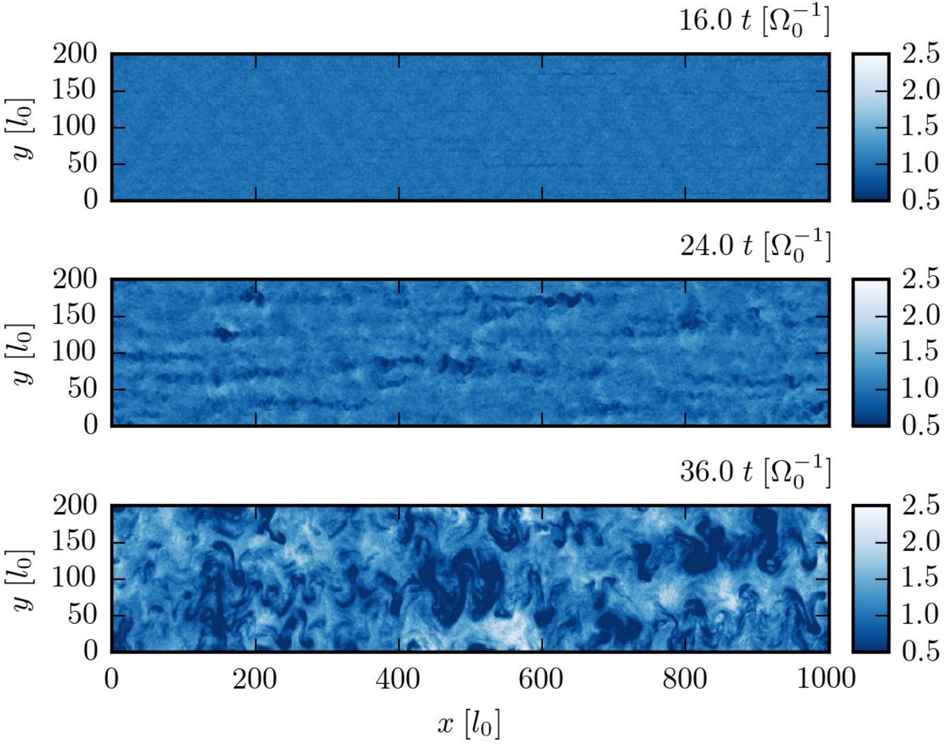


- No **B dependency** in the cold regime
- Unstable wavenumbers are also modified: Shift toward larger scales

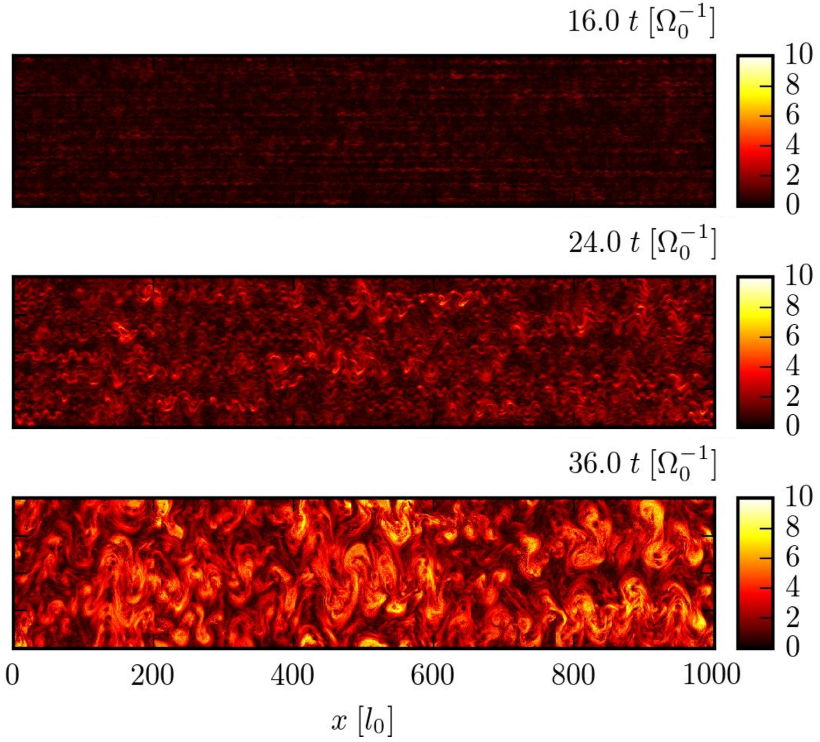
Density and Magnetic field perturbations

Generation of **density fluctuations** because of the **increasing magnetic pressure**

Background ions density



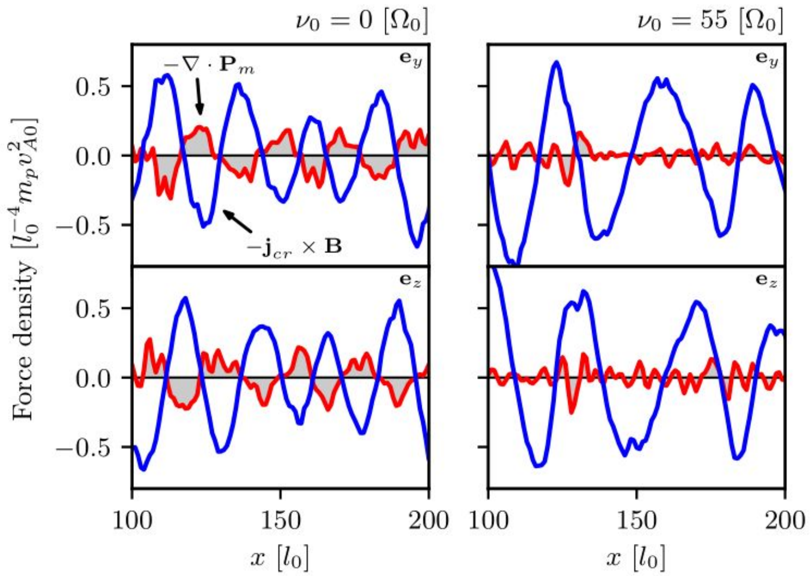
Perturbed magnetic field intensity

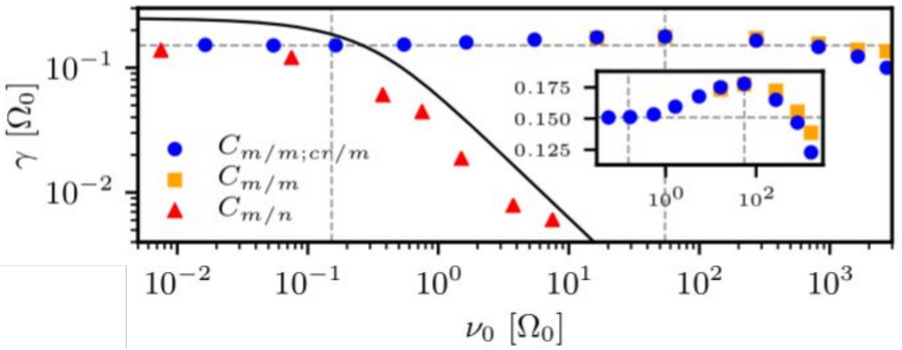


Effects of collisions on the NR mode

Collisions can be frequent in some astrophysical environments (HII regions, molecular clouds…), and in laboratory plasmas

- ▲ Ion-Neutral collisions damp the instability [Reville+ 2008]
- ● Ion-Ion Coulomb collisions reduce pressure gradients, favour the instability [Marret+ 2021]





Fluid momentum conservation equation

$$\rho \frac{\partial \vec{u}}{\partial t} = -\vec{j}_{cr} \times \vec{B} - \vec{\nabla} \cdot \bar{\bar{P}}$$

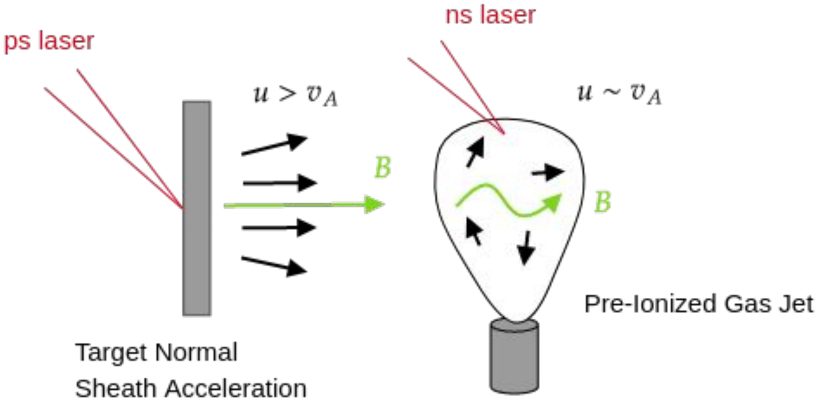
$$\vec{E} = -(\vec{u} + \frac{n_{cr}}{n_m} \vec{u}_{cr}) \times \vec{B}$$

Toward laboratory experiments

Two possible setups to obtain the non-resonant instability in the laboratory

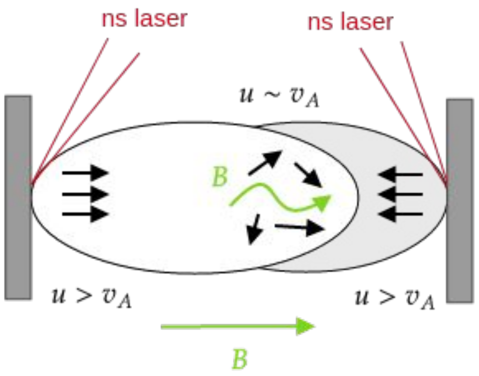
- **Target Normal Sheath Acceleration setup**

Streaming population obtained by irradiating a target with ultra short laser pulse



- **Counter-propagating plasma plumes**

Both the background and stream are generated by irradiating two opposed targets, collisionless interpenetration



The magnetic field B ~ 0.5 MG (50 T) can be produced with Helmholtz coils on ~cm^3 [Albertazzi+ 2013]

Need to take into account **thermal effects** and **collisions**

Conclusions

- The **NR instability** plays a central role in the acceleration and transport of cosmic rays
- It may be described by a fluid model in the cold limit
- It is modified for a finite background **ions temperature**, which requires a kinetic description
- **Ion-neutral collisions** damp the instability
- **Coulomb collisions** yield an unexpected enhancement of the instability
- Growing need for experimental verification of the theory and simulations predictions
- Temperature and collisional effects need to be taken into account to **design experiments**

References

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