Extreme particle acceleration at jet termination shocks

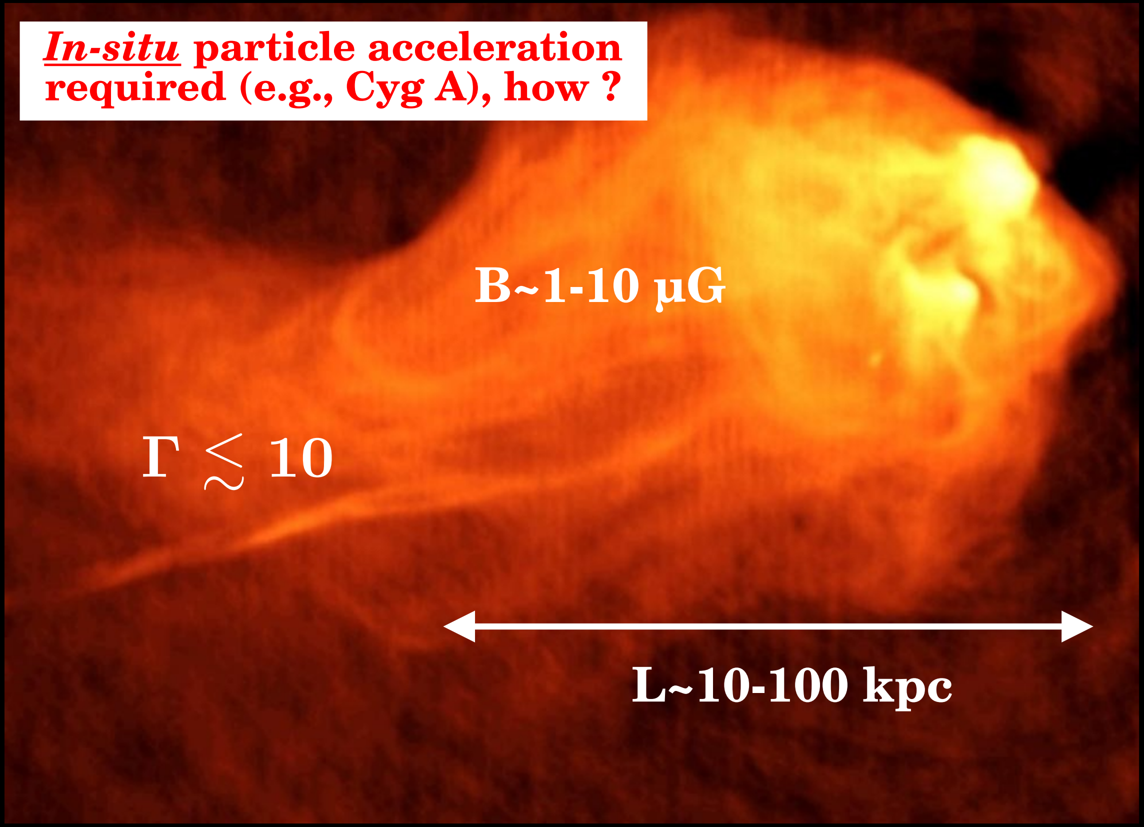
Benoît Cerutti, *Univ. Grenoble Alpes, CNRS, IPAG*
Gwenaël Giacinti, *Tsung-Dao Lee Institute, Shanghai*

A&A 2023, arXiv:2303.12636

HEPRO VIII, Paris, Oct. 23-26, 2023

Physical conditions @ extragalactic jet termination shock

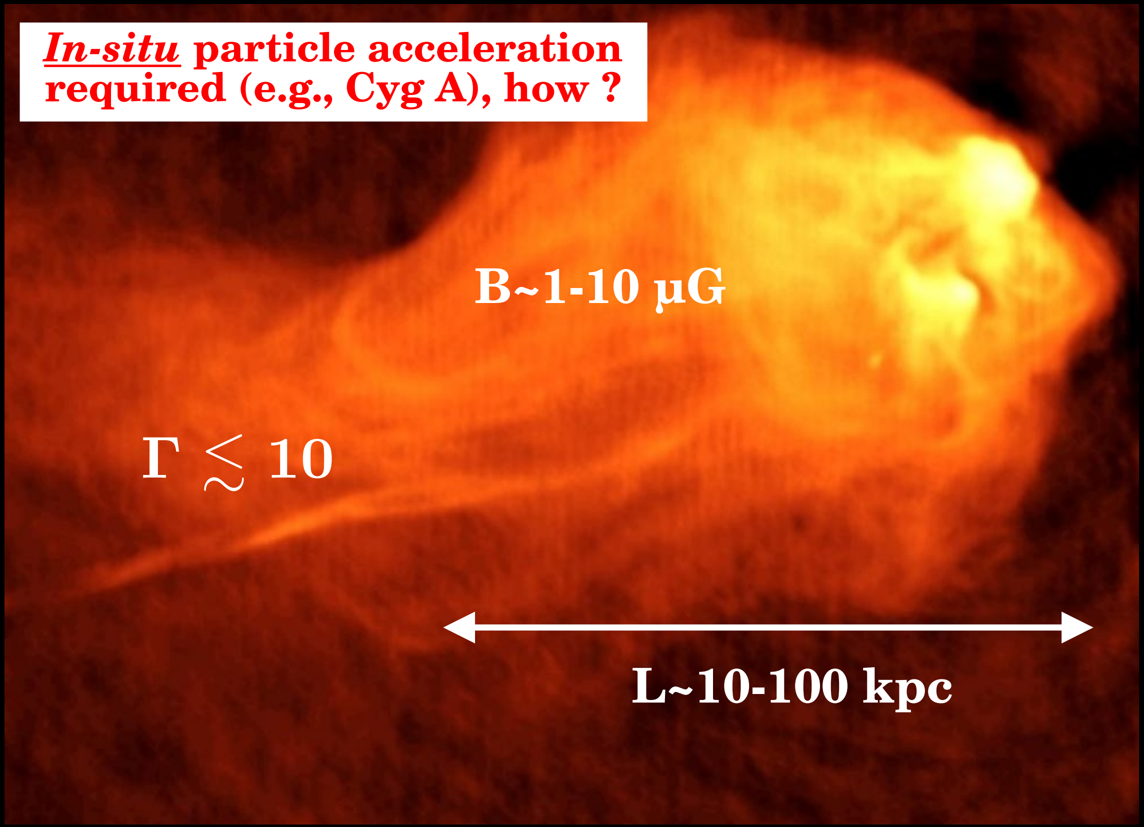
[e.g., Blandford et al. 2019 ; Hardcastle & Croston 2020 ; Gabuzda 2021]



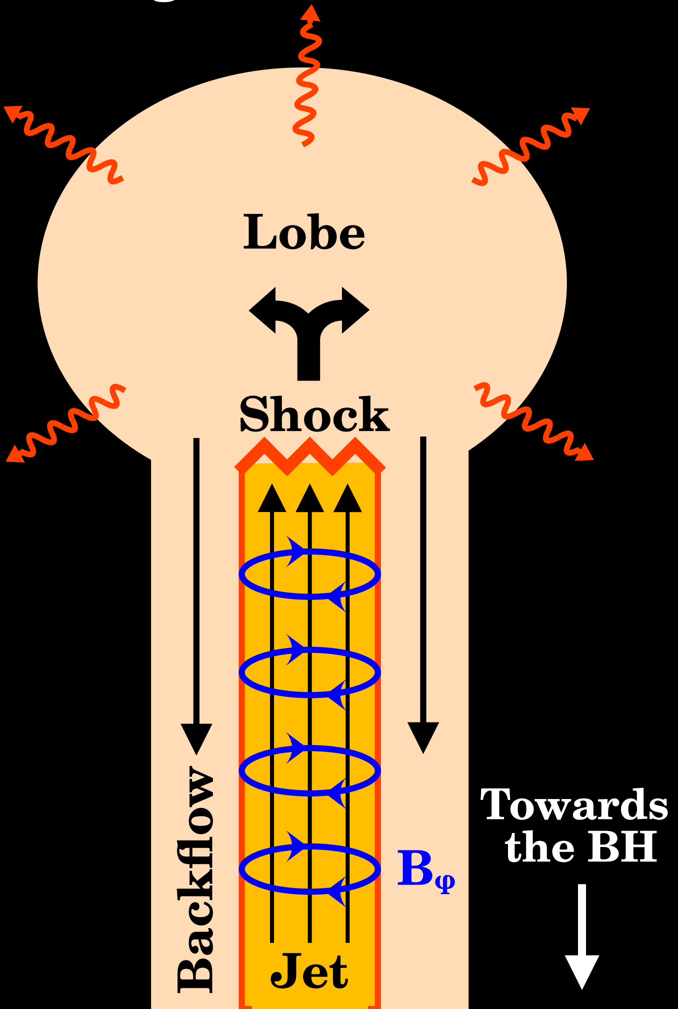
Ambient plasma magnetization $\sigma = \dfrac{B_0^2}{4\pi\Gamma n m_i c^2} \sim 0.01 - 1$

Physical conditions @ extragalactic jet termination shock

[e.g., Blandford et al. 2019 ; Hardcastle & Croston 2020 ; Gabuzda 2021]



Intergalactic medium



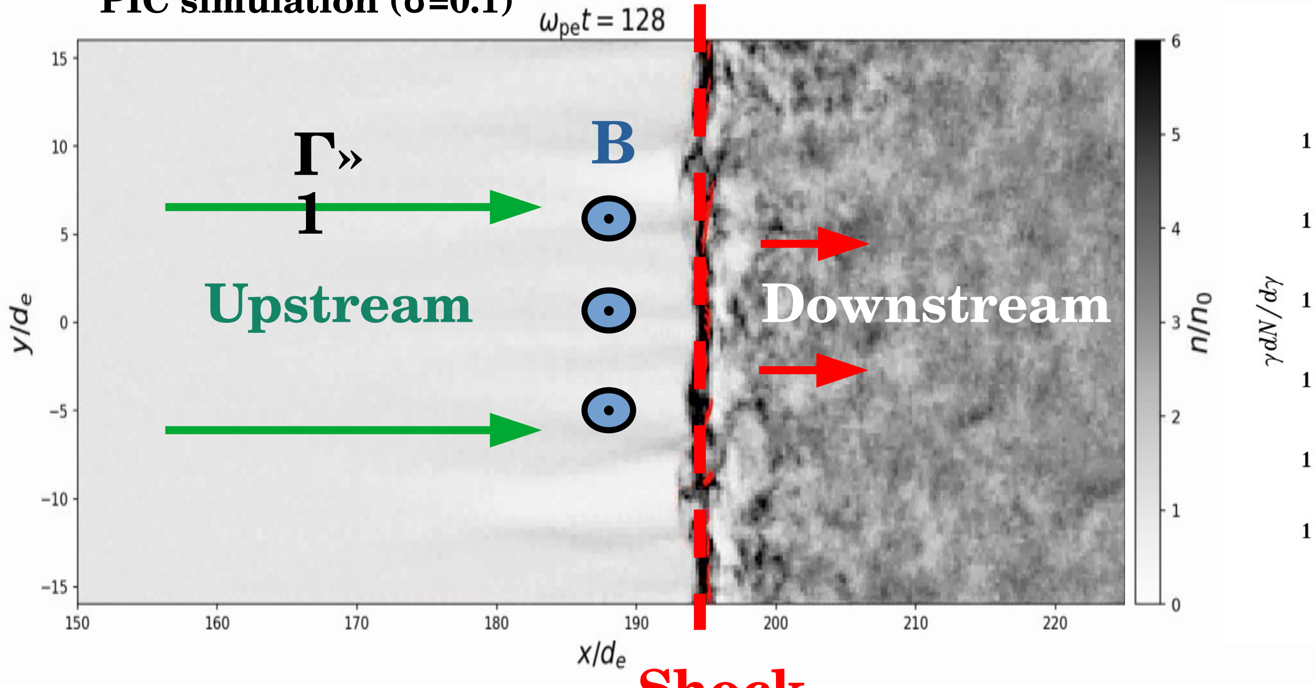
Ambient plasma magnetization $\sigma = \dfrac{B_0^2}{4\pi\Gamma n m_i c^2} \sim 0.01 - 1$

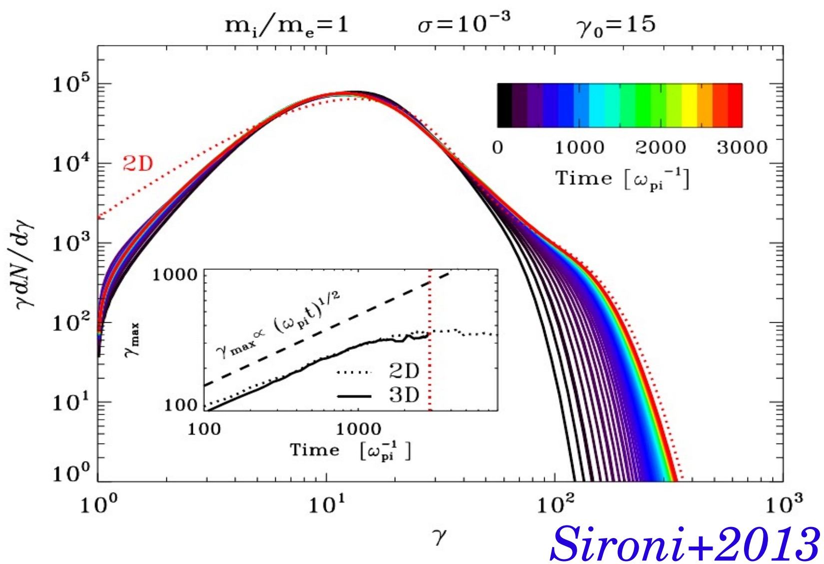
Relativistic magnetized shocks are poor accelerators

[e.g. Gallant+1992; Sironi+2013 ; Plotnikov+2018 ; Lemoine+2019]

Even **modest magnetization** (**σ>~10^{-3}**) is enough to **quench** particle acceleration.

PIC simulation (σ=0.1)





Sironi+2013

At best they are slow : $\gamma_{max} \propto t^{1/2}$
And quickly reaches saturation $\gamma_{max}/\Gamma \sim \sigma^{-1/4}$

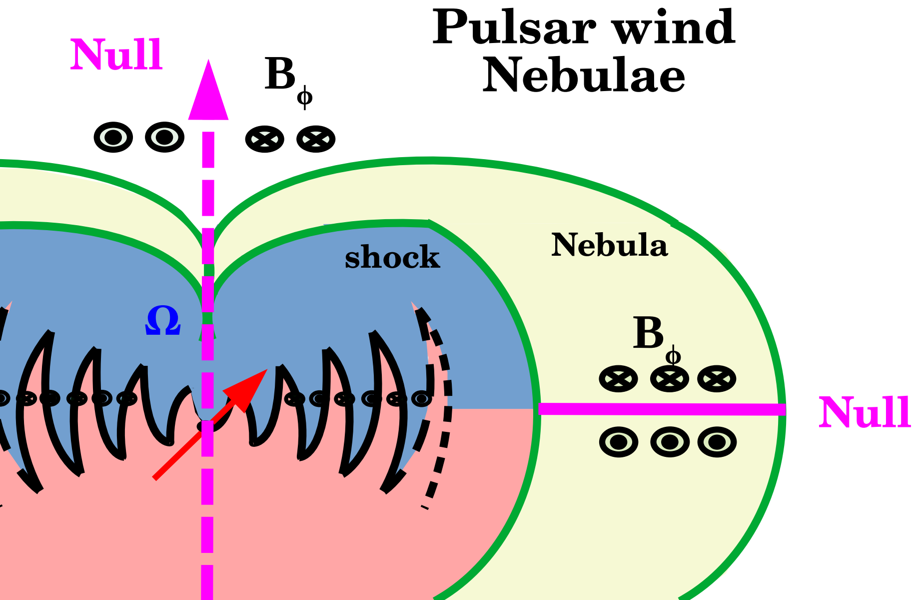
But what if this was not the end of the story ?

These conclusions are valid for a **local**, **plane-parallel**, and **homogeneous** shock.

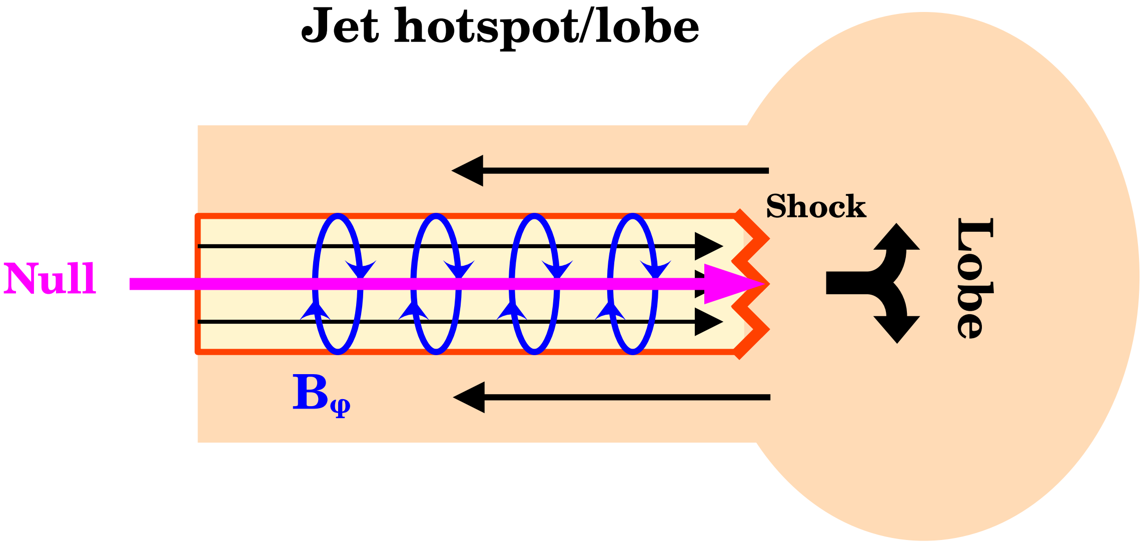
Here, we argue that one must take the **global aspect** of the shock into account.
=> The local approach is not a good approximation

Particularly true for a relativistic magnetized shock where B => B_φ
It must vary and go through a null

Cerutti & Giacinti 2020



Cerutti & Giacinti 2023



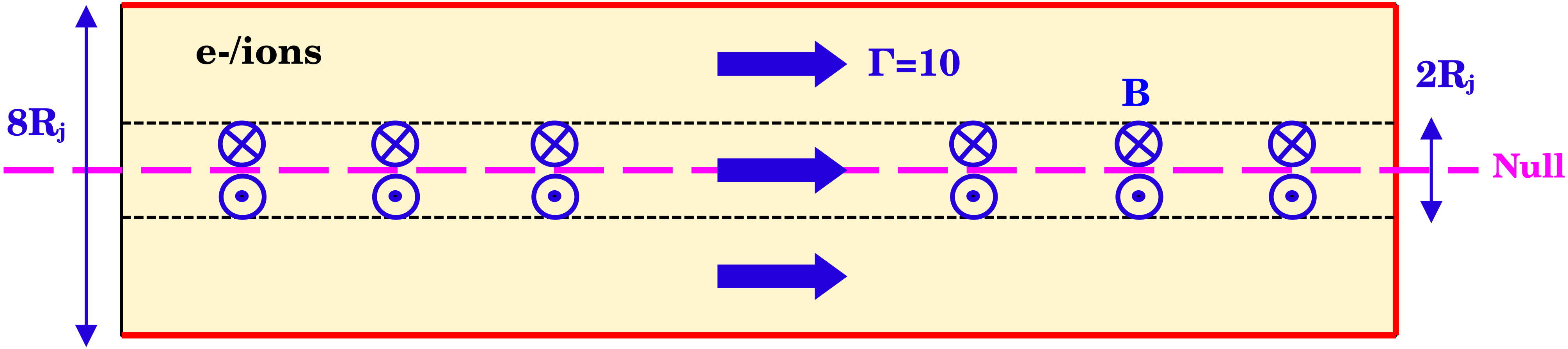
Our PIC setup

2D Cartesian box (xz-plane), **262,144×16,384 cells**
Electron-ion plasma : $\mathbf{m_i/m_e=25}$
Magnetization : **σ=0.1, 1**

PIC code : Zeltron

Reflecting boundary = confining external medium

Reflecting boundary
= contact discontinuity



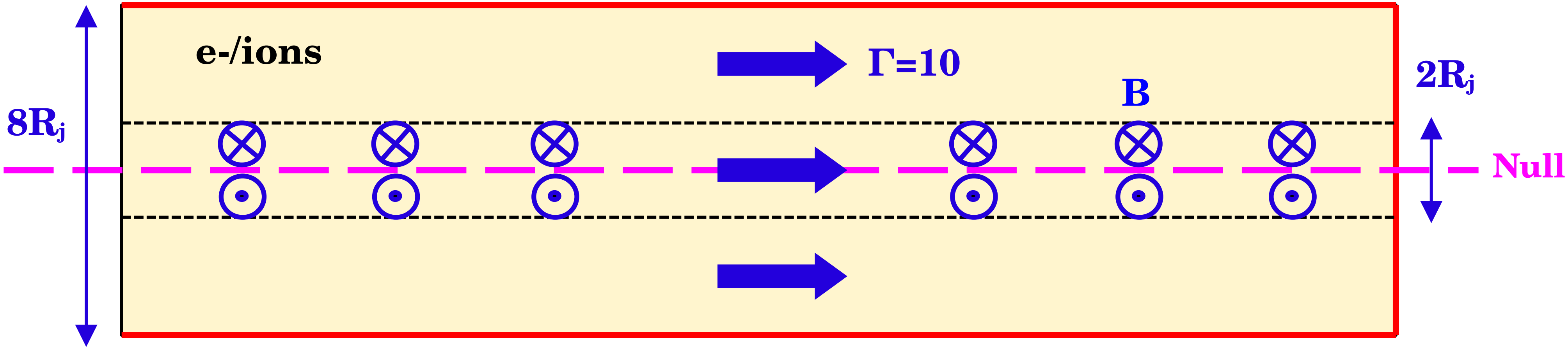
Our PIC setup

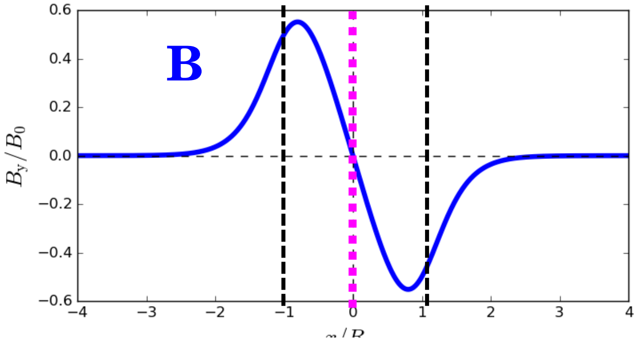
2D Cartesian box (xz-plane), **262,144×16,384 cells**
Electron-ion plasma : **m_i/m_e=25**
Magnetization : **σ=0.1, 1**

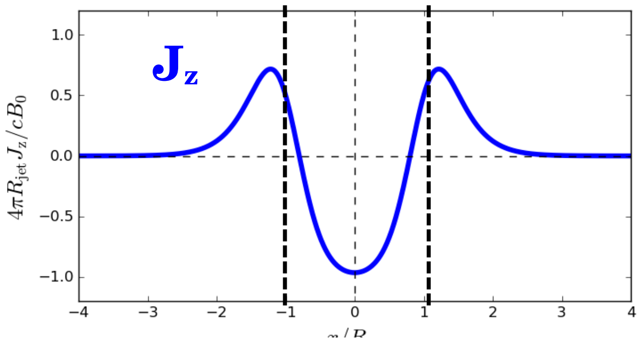
PIC code : Zeltron

Reflecting boundary = confining external medium

Reflecting boundary
= contact discontinuity



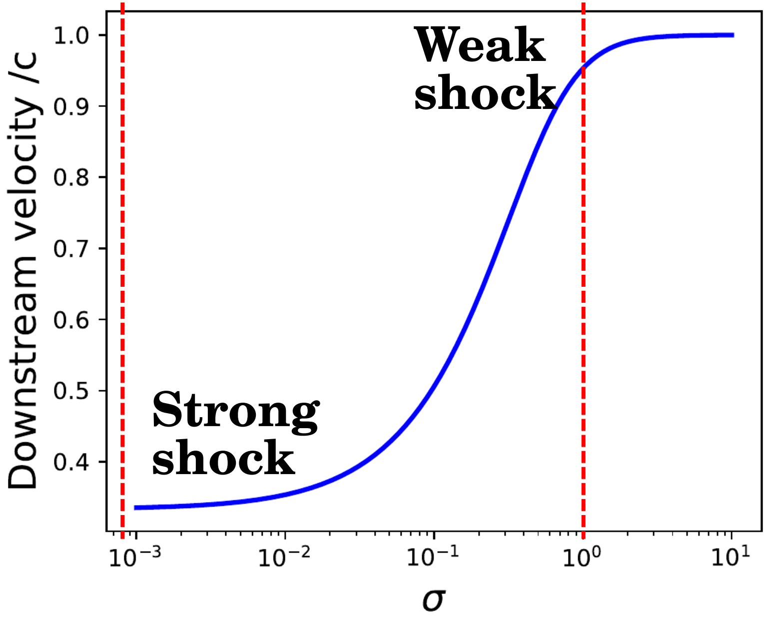




Variations in the downstream bulk flow velocity

Kennel & Coroniti 1984

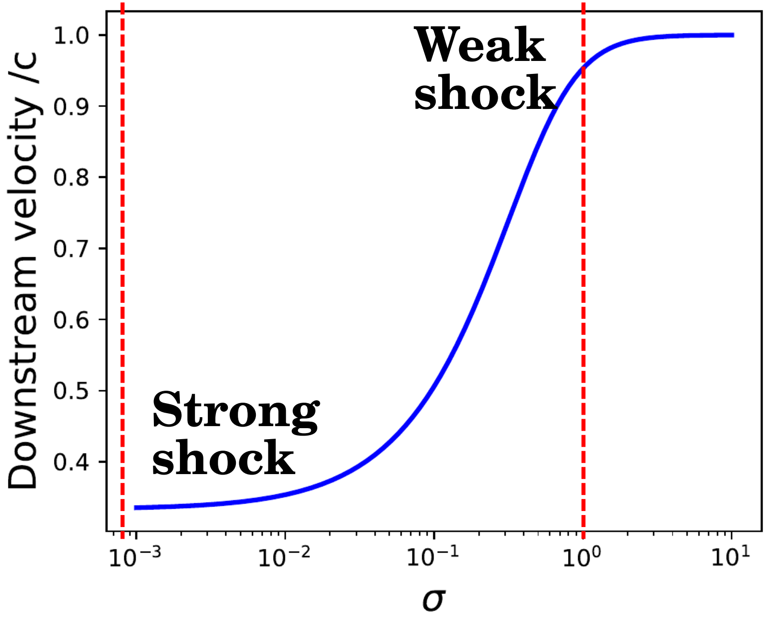
Rankine-Hugoniot MHD
perpendicular shock

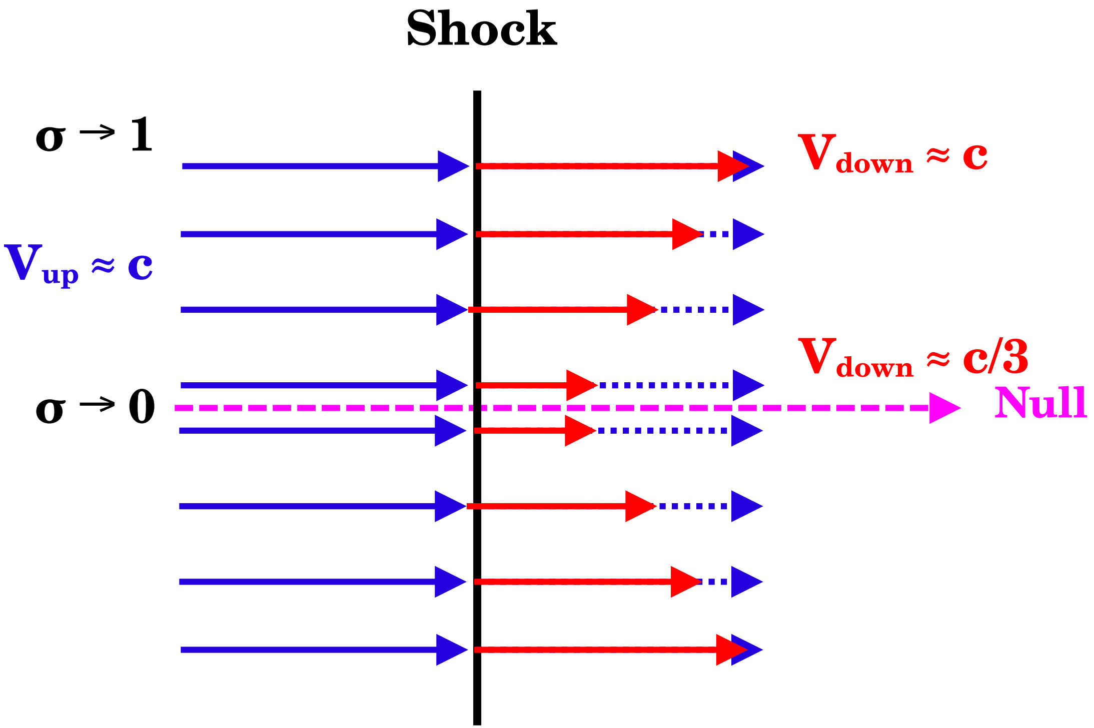


Variations in the downstream bulk flow velocity

Kennel & Coroniti 1984

Rankine-Hugoniot MHD
perpendicular shock



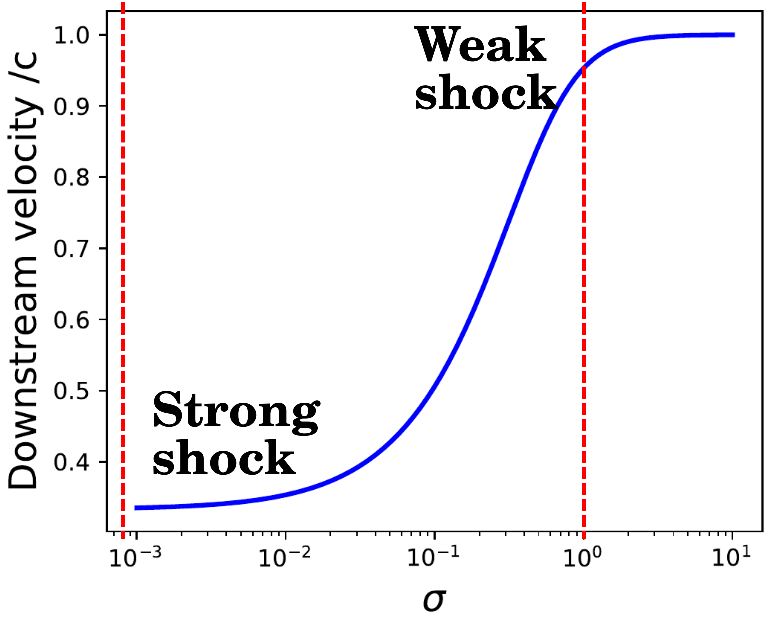


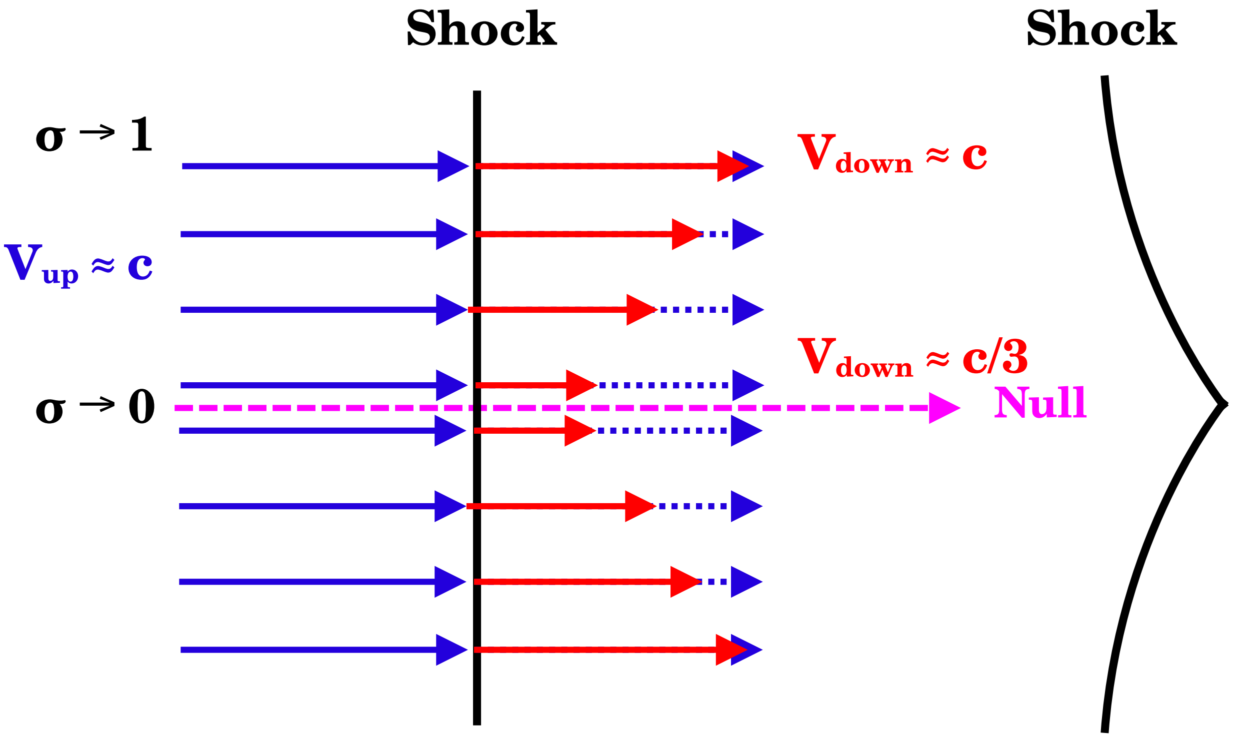
=> Formation of a strong velocity shear in the downstream medium

Variations in the downstream bulk flow velocity

Kennel & Coroniti 1984

Rankine-Hugoniot MHD
perpendicular shock

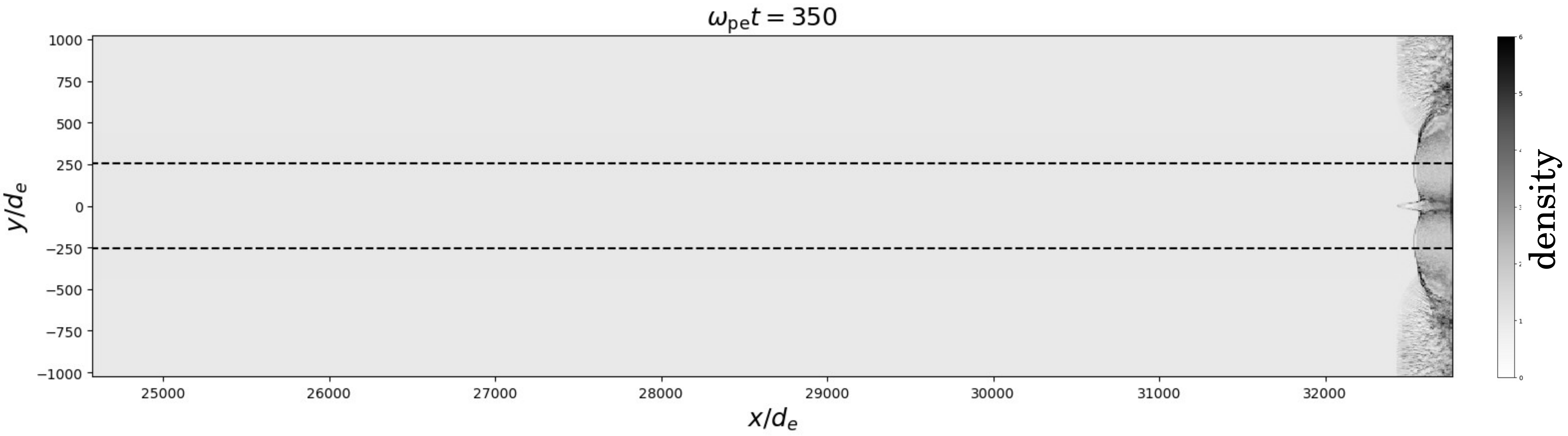




=> Formation of a strong velocity shear in the downstream medium

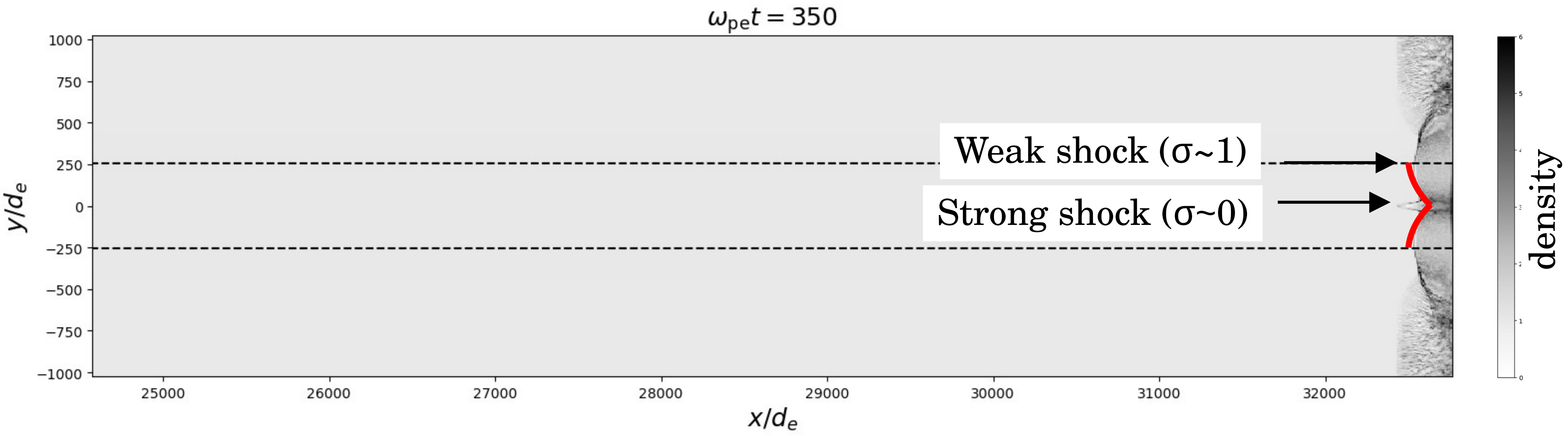
Plasma density evolution

Early phases



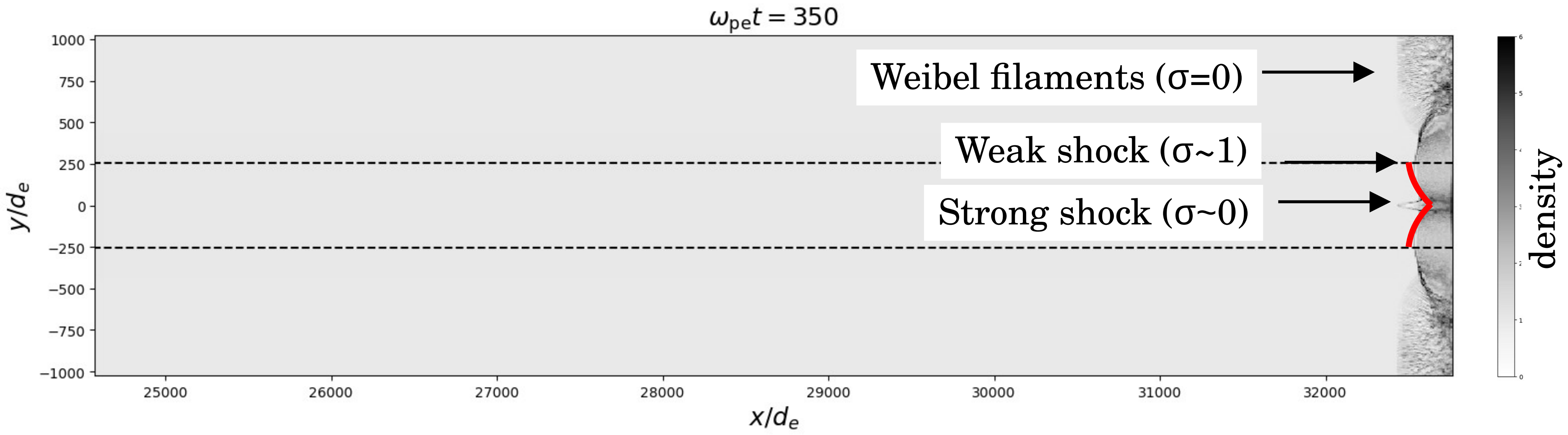
Plasma density evolution

Early phases

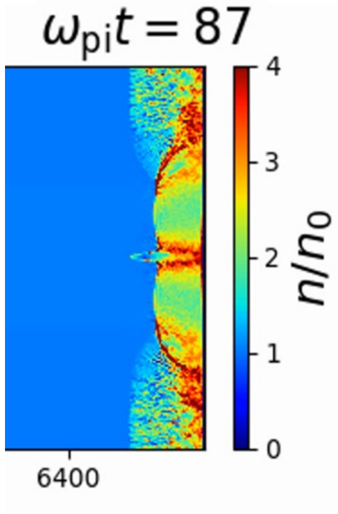


Plasma density evolution

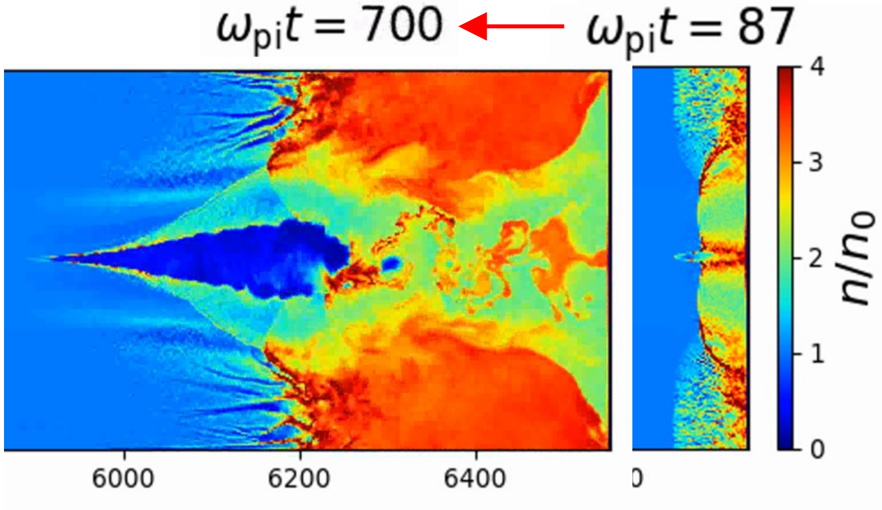
Early phases



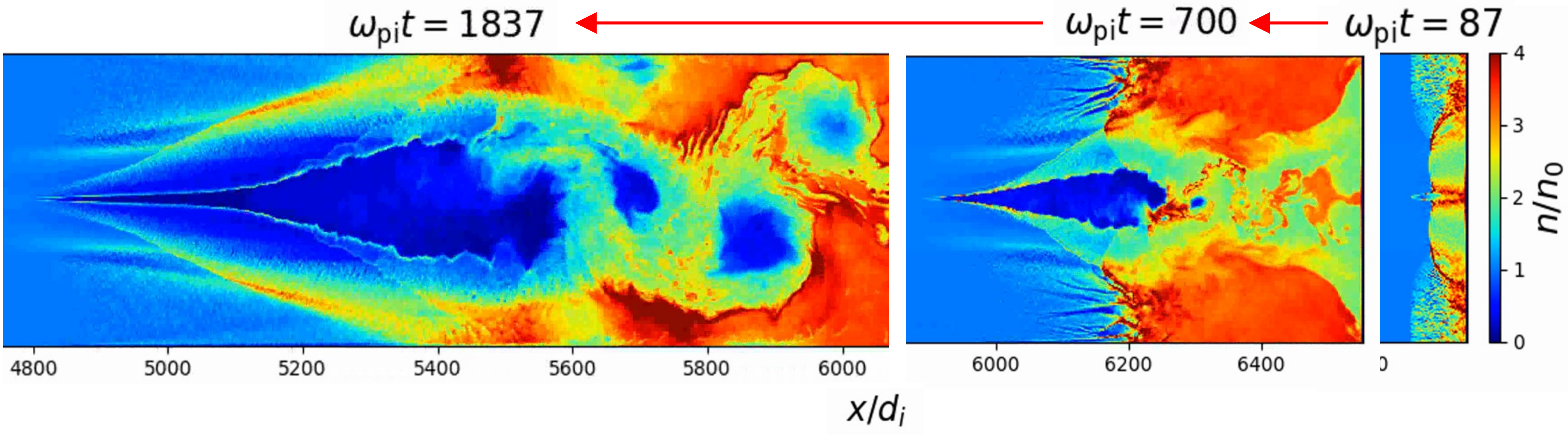
Plasma density evolution



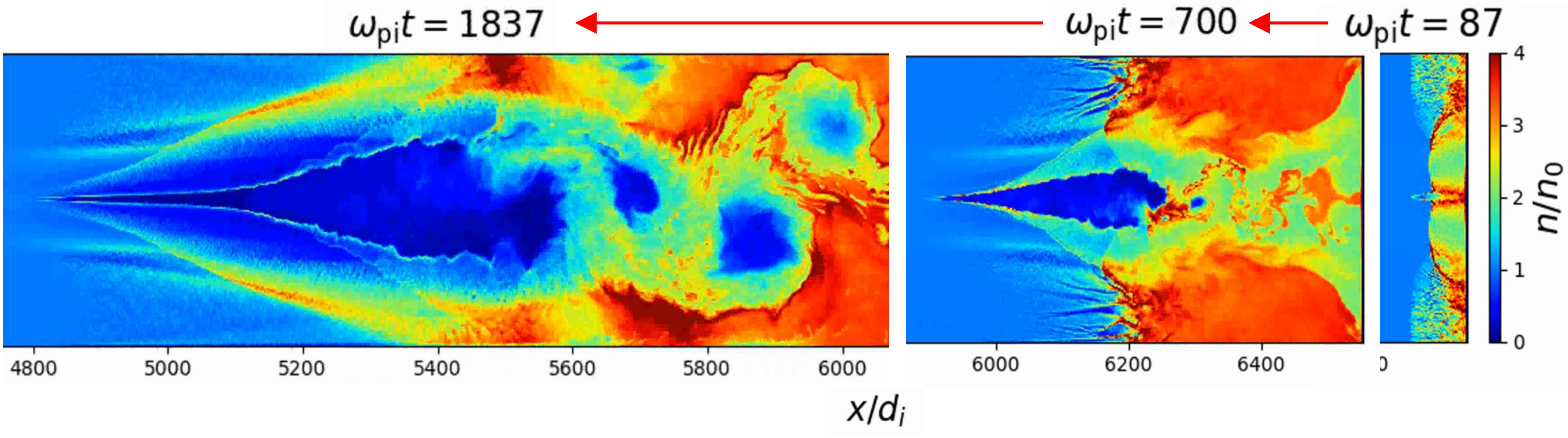
Plasma density evolution



Plasma density evolution



Plasma density evolution

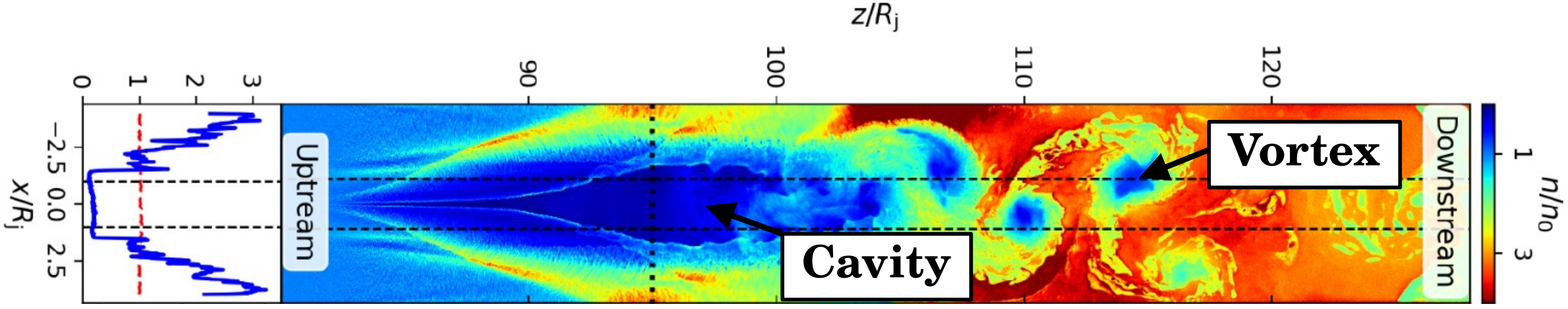


von Kármán vortices

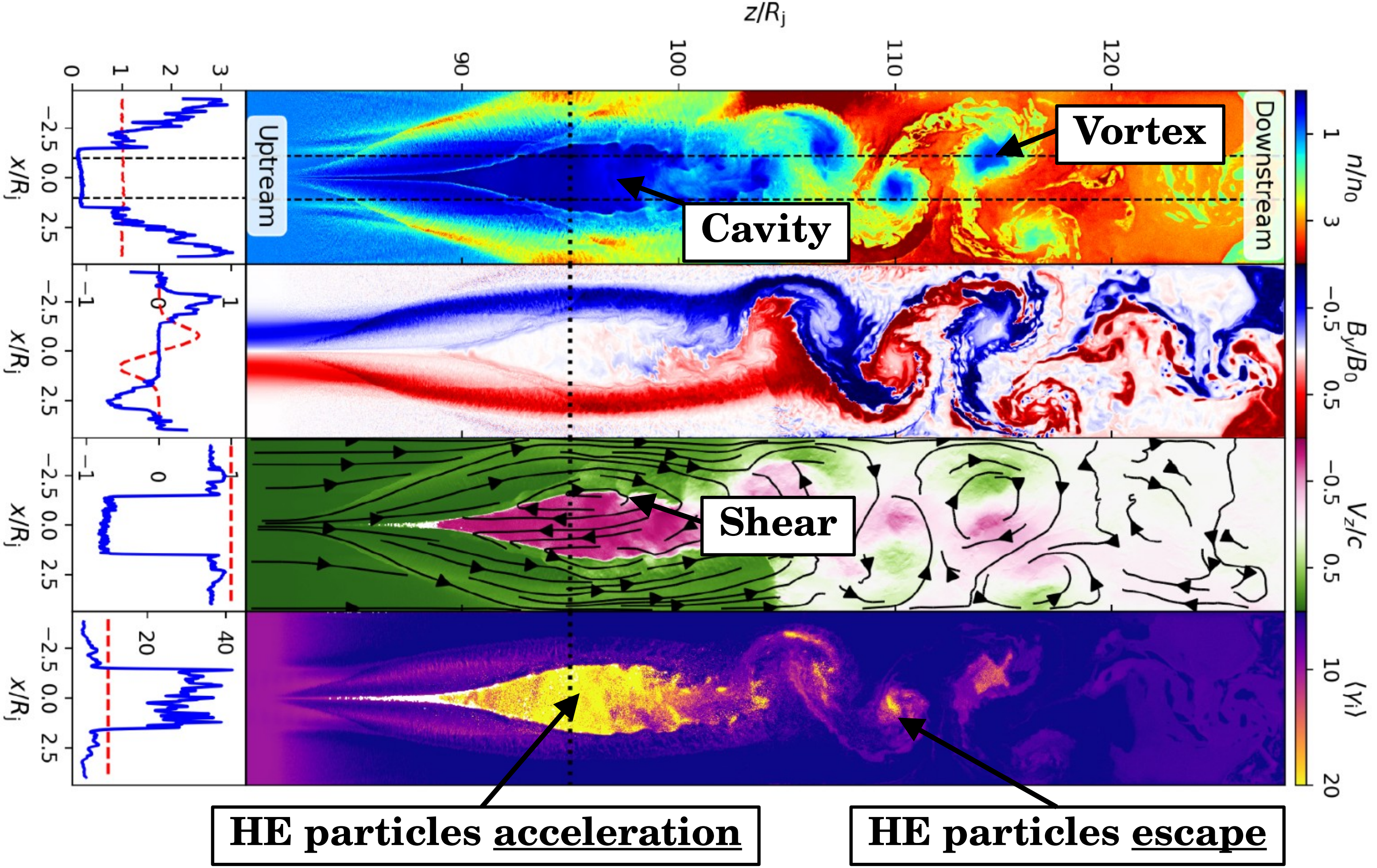
Large over-pressured cavity

=> obstacle to the incoming flow

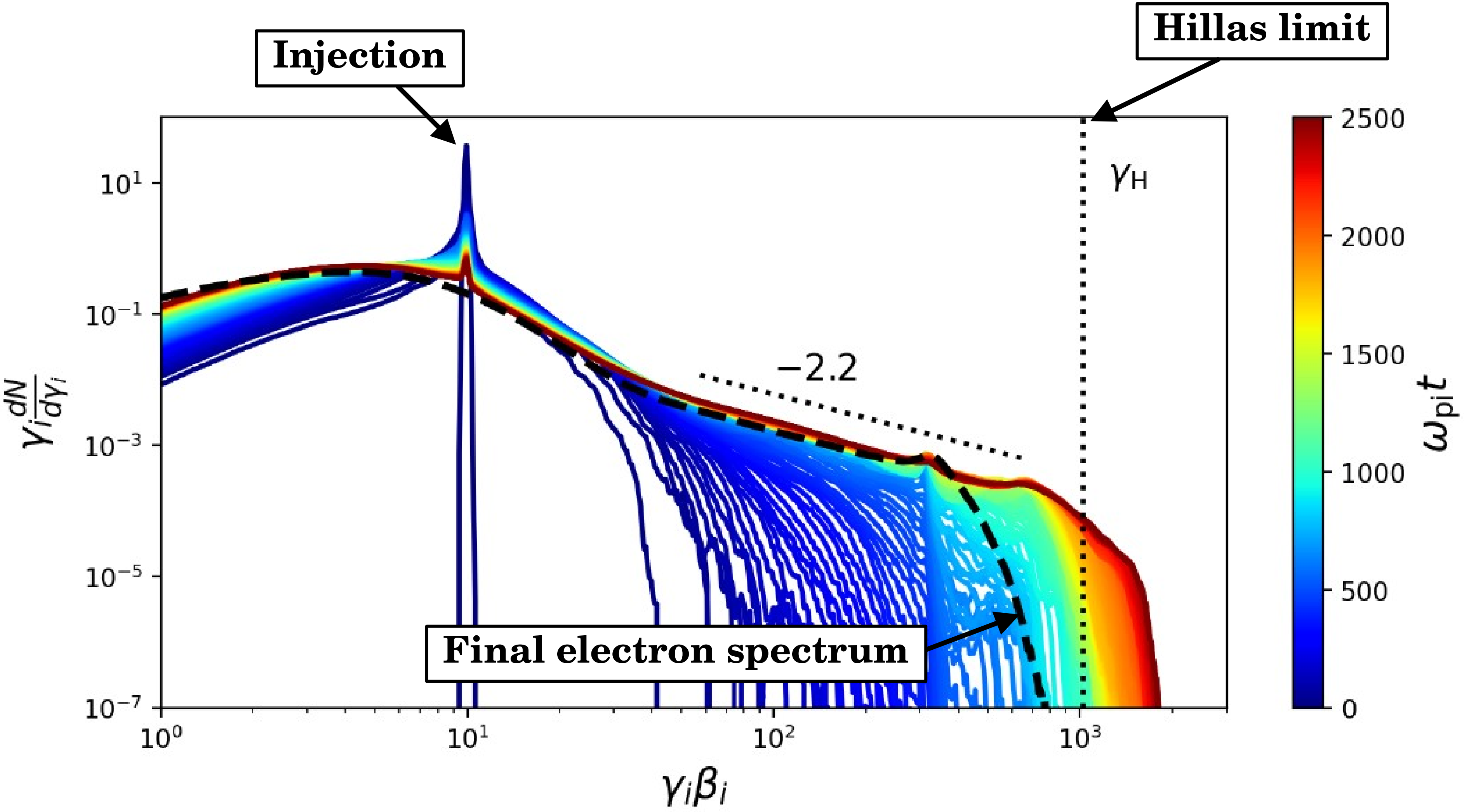
Cavity, shear, vortices, particle acceleration !



Cavity, shear, vortices, particle acceleration !

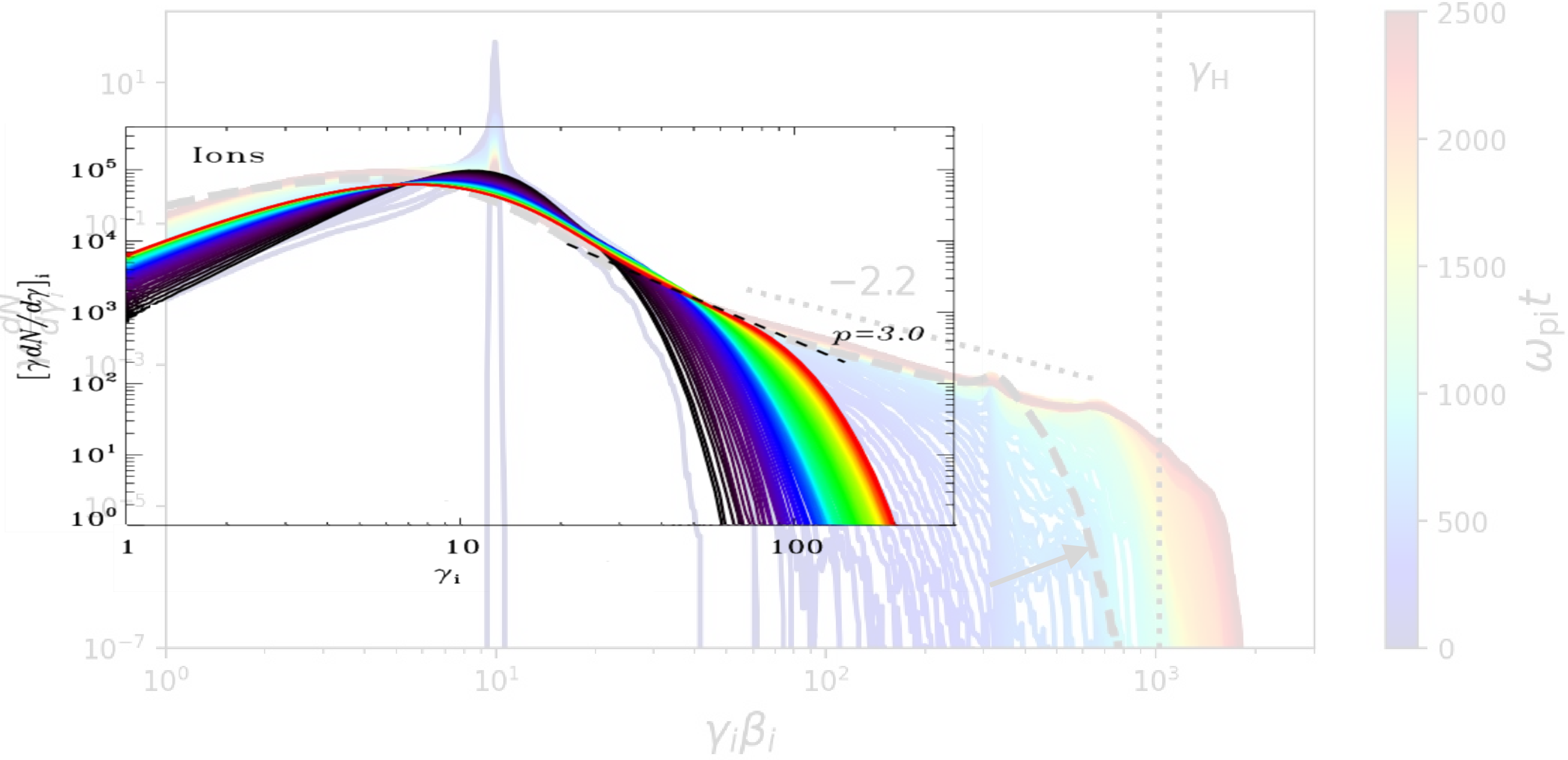


Ion spectrum temporal evolution

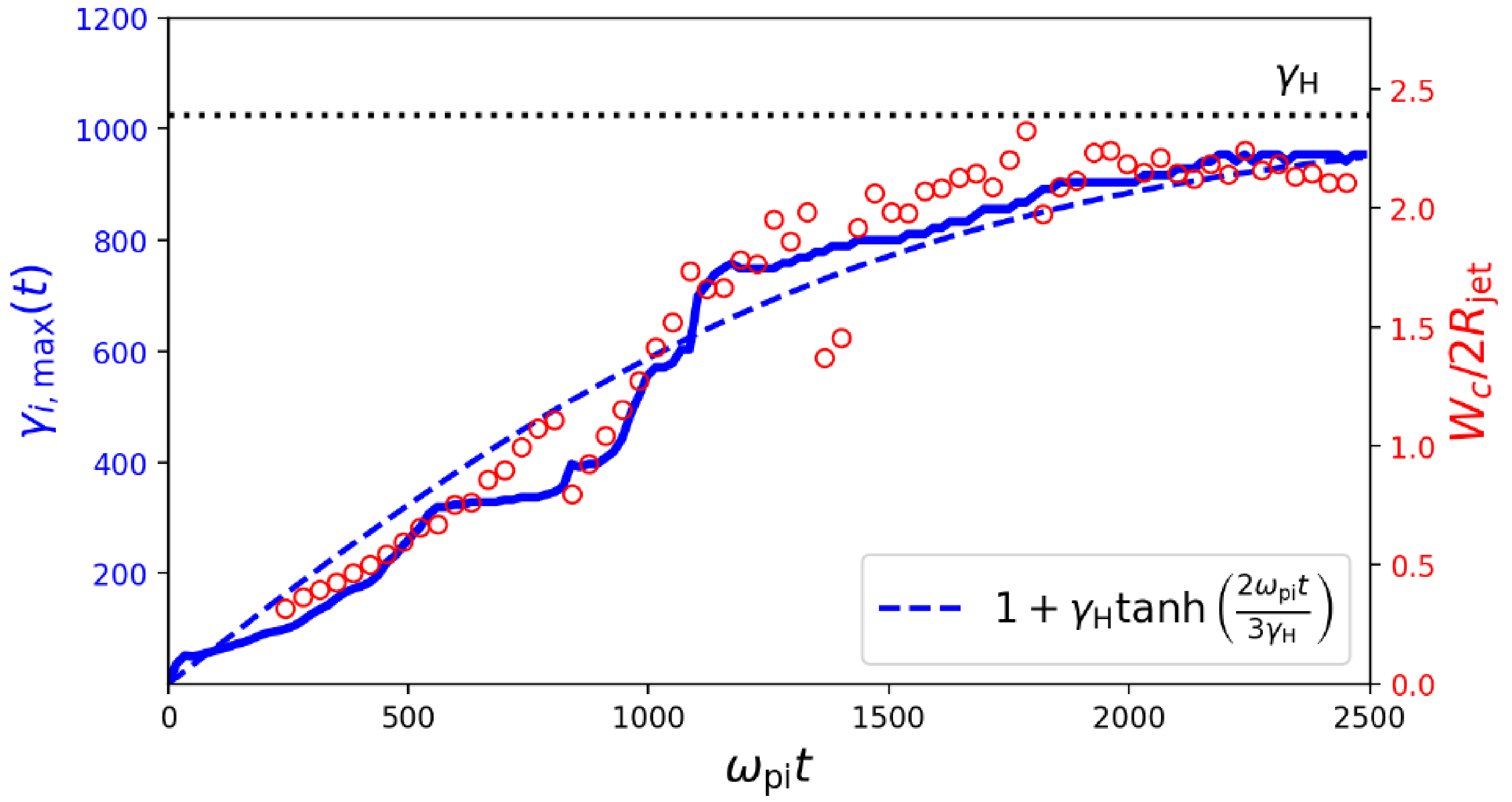


Ion spectrum temporal evolution

Comparison with the unmagnetized isotropic case (from *Sironi+2013*)



Saturation

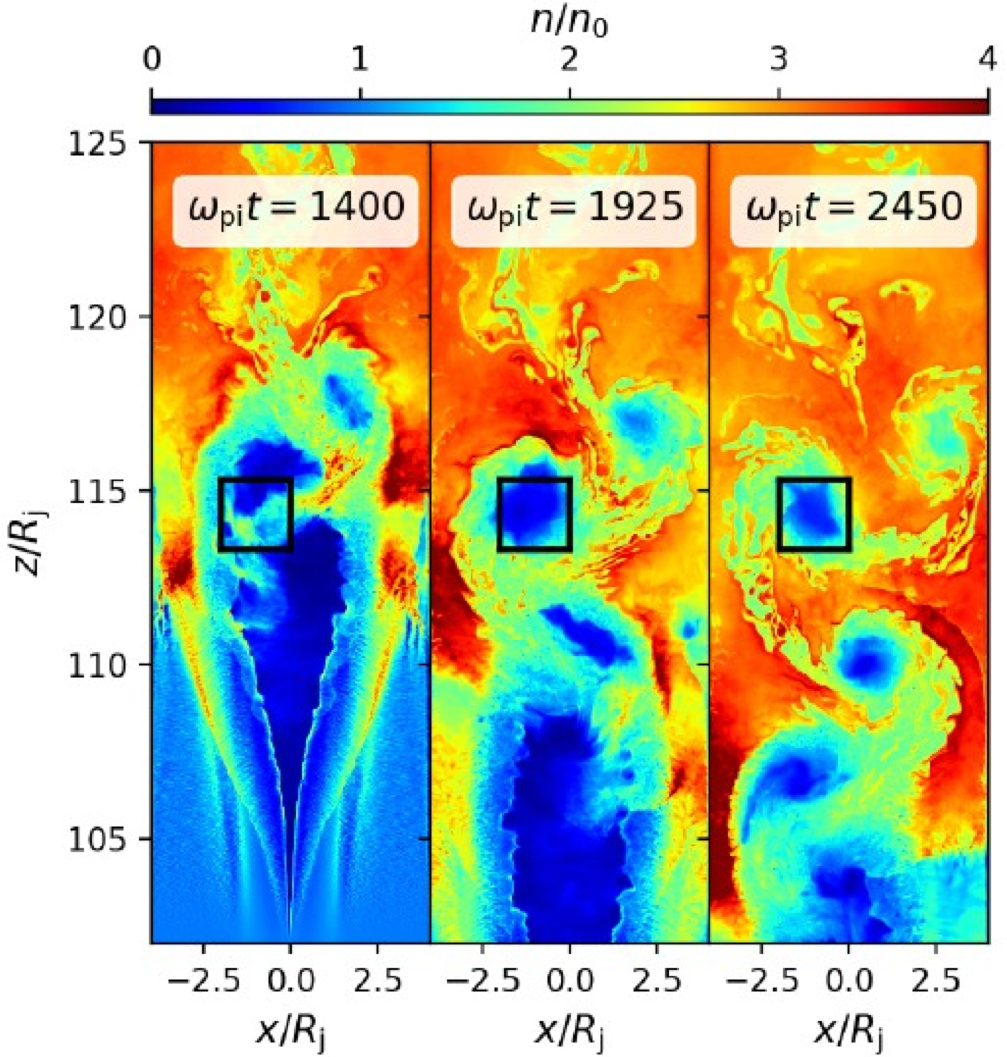


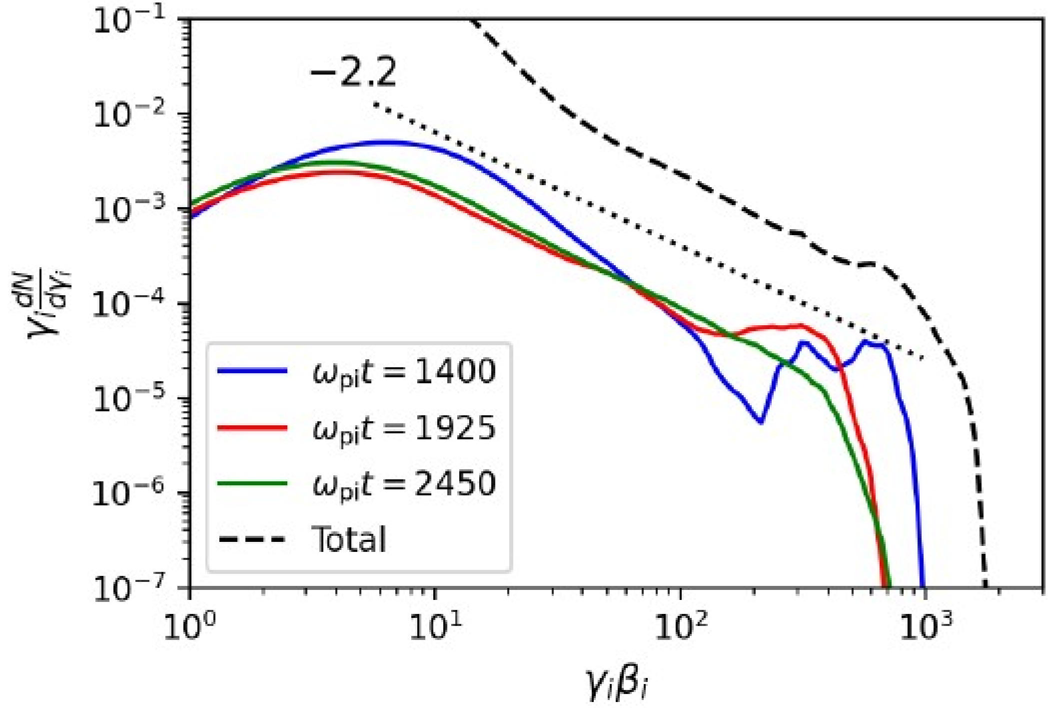
Width of the cavity

Fast particle acceleration ($\gamma_{max}\sim\omega_{pi}t$) followed by a **saturation** at the confinment limit

Co-evolution of the maximum particle energy and the width of the cavity

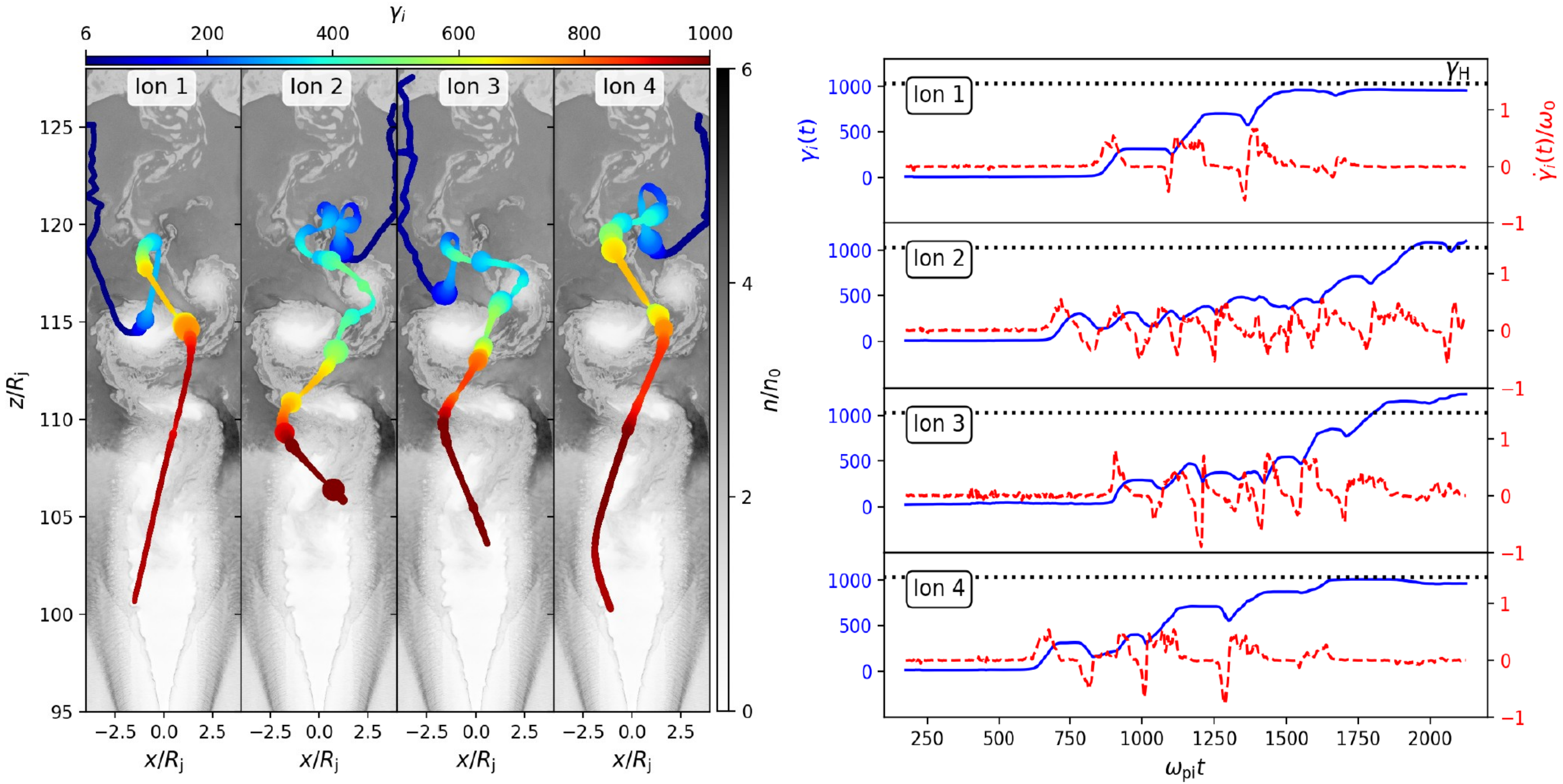
High-energy particle escape





Particle escape with little energy losses

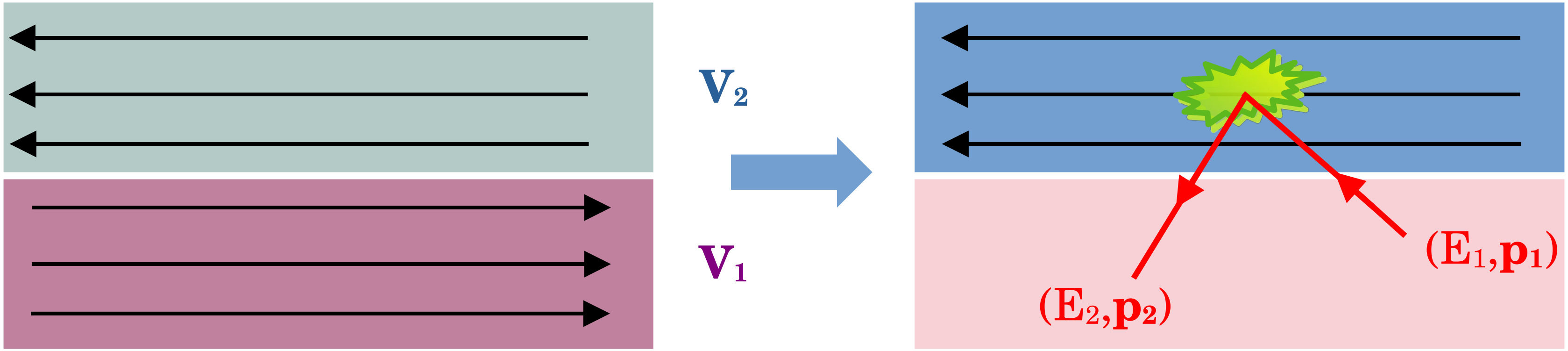
High-energy ion trajectories $\gamma \sim \gamma_H$



Shear-flow acceleration

[e.g., Ostrowski 1990, 1998; Rieger & Duffy 2004, 2006]

Cf. Frank talk



$$U = \frac{V_2 - V_1}{1 - V_1 V_2/c^2}$$

Elastic scattering in the magnetic mirror frame: $E'_1=E'_2$, $p'_{//,1}=-p'_{//,2}$

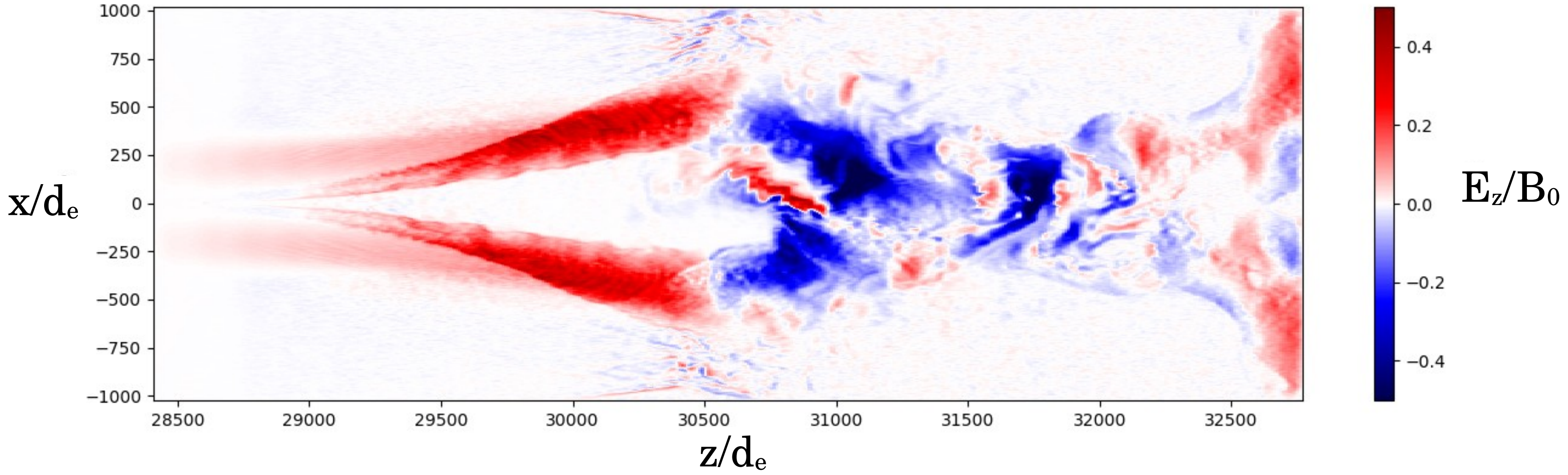
$$E_2 - E_1 = 2\Gamma^2 \left(E_1 \frac{U^2}{c^2} - \mathbf{p_1} \cdot \frac{\mathbf{U}}{c} \right)$$

Isotropic pitch angle distribution $\langle \frac{\Delta E}{E} \rangle = 2\left(\Gamma^2 - 1\right) \sim 1$

Particle acceleration by change of Lorentz frame => Fermi mechanism

Ideal motion electric field in the laboratory frame

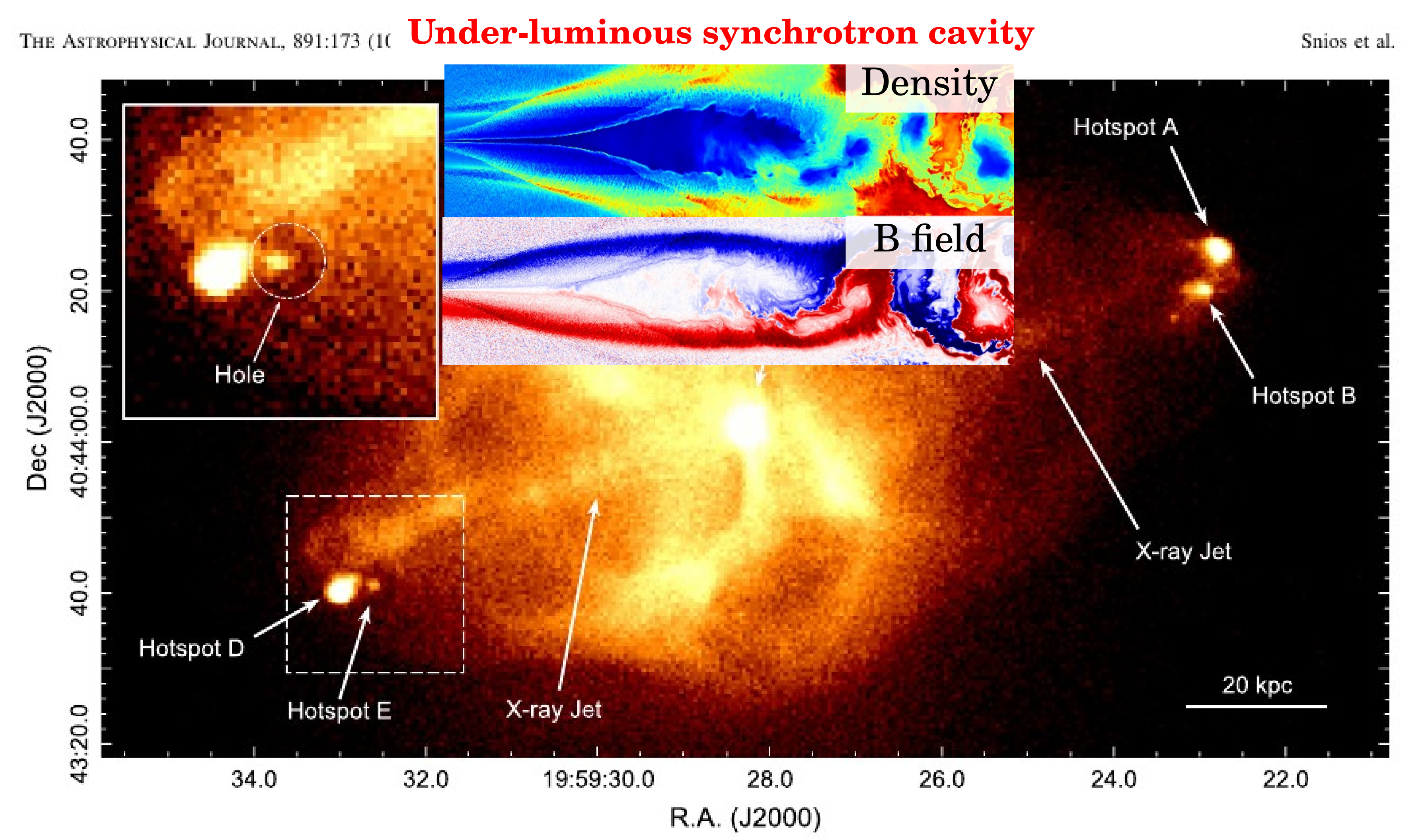
Macroscopic ideal electric field $\mathbf{E} = -\frac{\mathbf{V} \times \mathbf{B}}{c}$



Acceleration rate : $\dot{\gamma} = \frac{e}{m_i c}\mathbf{E} \cdot \boldsymbol{\beta} \approx 0.5\omega_0$ ~constant, independant of energy $\gamma_{\rm i}(t) \propto t$

In contrast to previous studies where small-scale turbulence leads to a diffusive process

Observational evidence ?

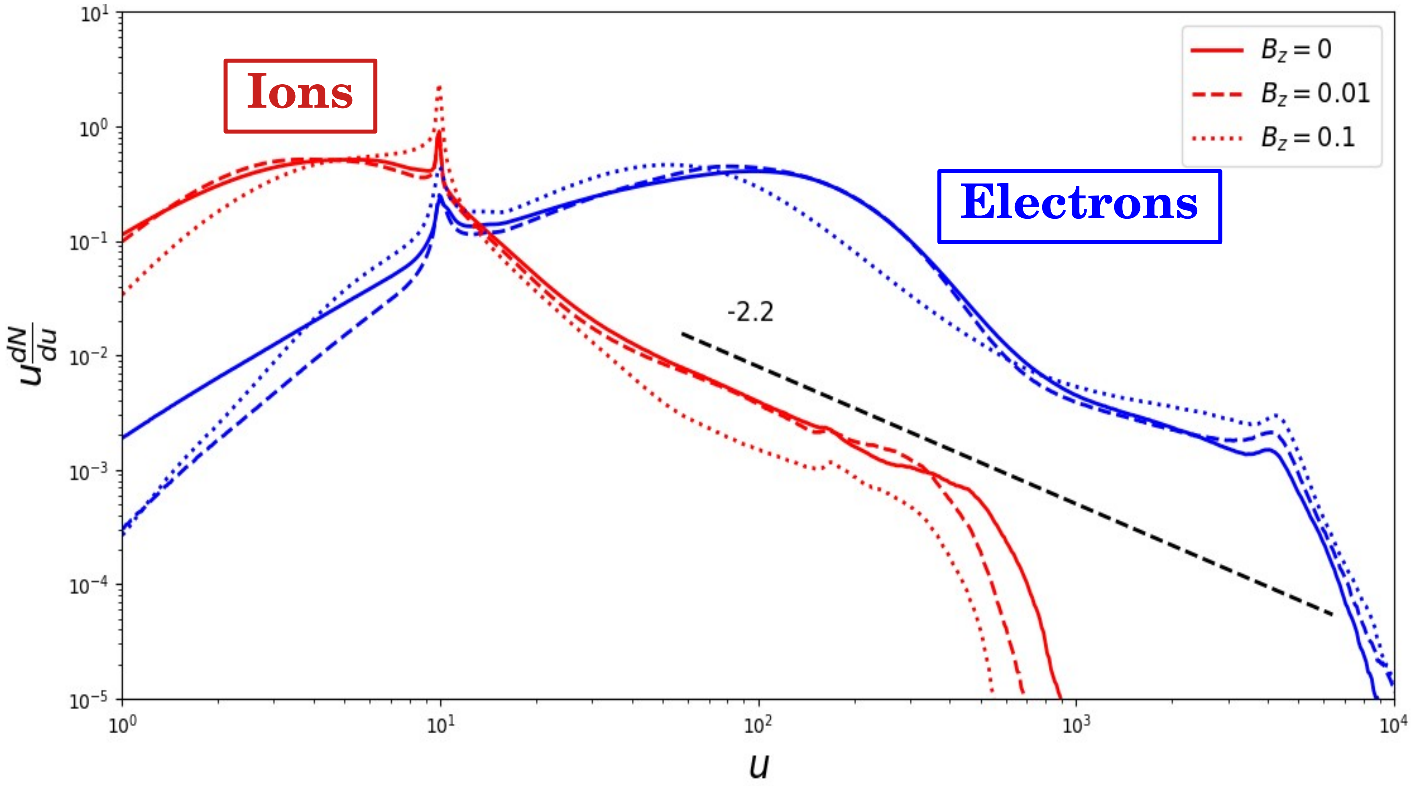


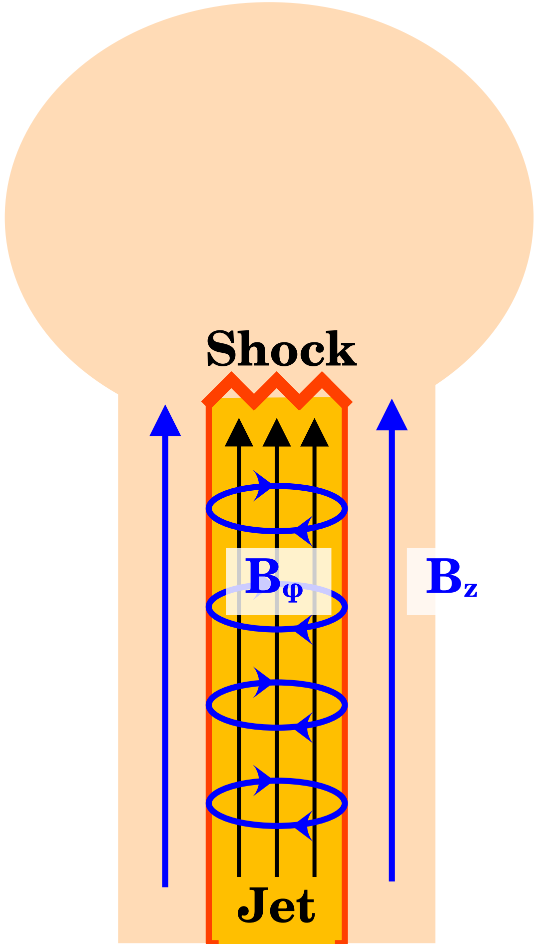
Take-away messages, implications & perspectives

- The **global structure** of the magnetic field is key in accelerating particles
- Particle acceleration proceeds via **shear flows** near the shock front **cavity**
- Particle acceleration is **fast** and reaches the **confinment limit** (Hillas)
- **Cosmic ray escape** in the downstream proceeds via **von Kármán vortices**
- Scaled to extragalactic jets, this mechanism could accelerate **UHECR**, and possibly **PeV cosmic rays** in stellar-mass black hole jets such as SS 433.
- **Caveats** : Full 3D effects, role of curvature drift (see Huang+2023, Poster), role of external medium ?

Effect of a (sub-dominant) poloidal field component

A poloidal component is important for **stabilizing** the jet against kink instabilities





Particle acceleration remains efficient if $B_z < B_\varphi$
(expected in jets this far from the launching regions)