Particle acceleration in relativistic magnetized shocks revisited : the role of global magnetic nulls

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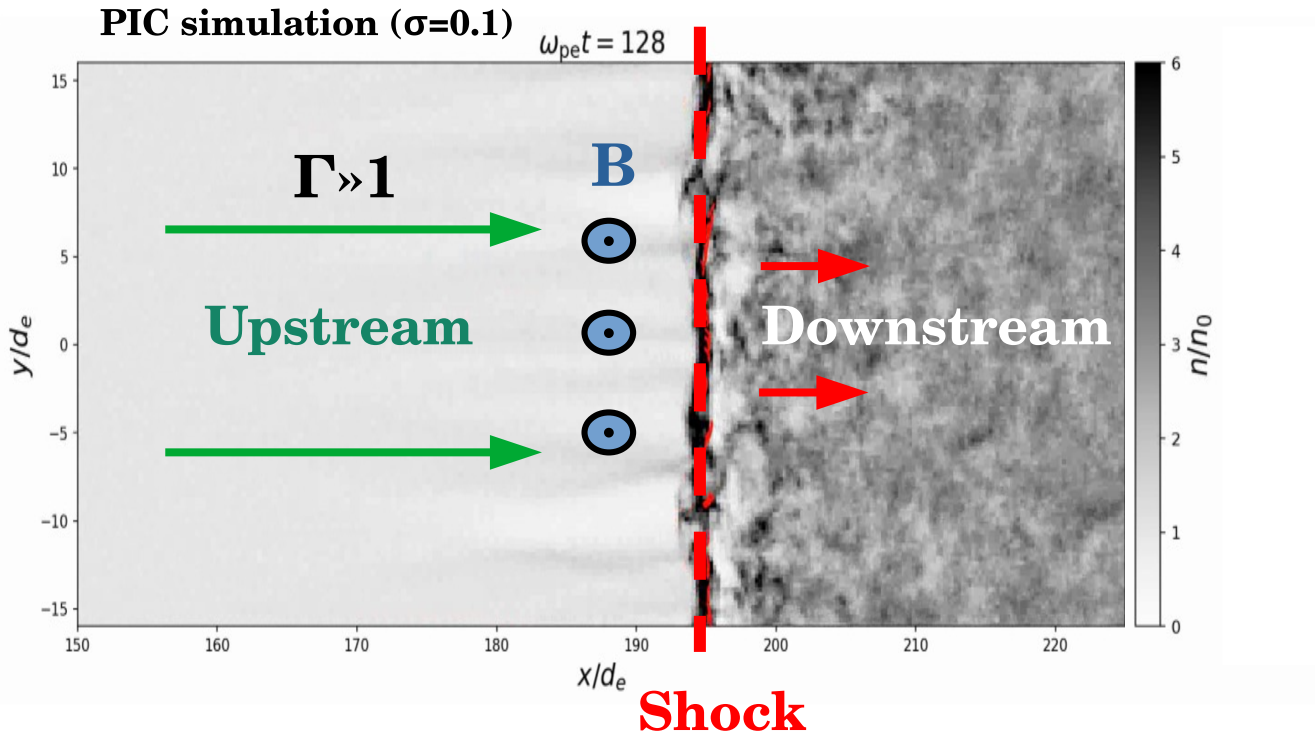
Relativistic magnetized shocks are poor accelerators

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

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



Magnetic reflection at the shock => No acceleration

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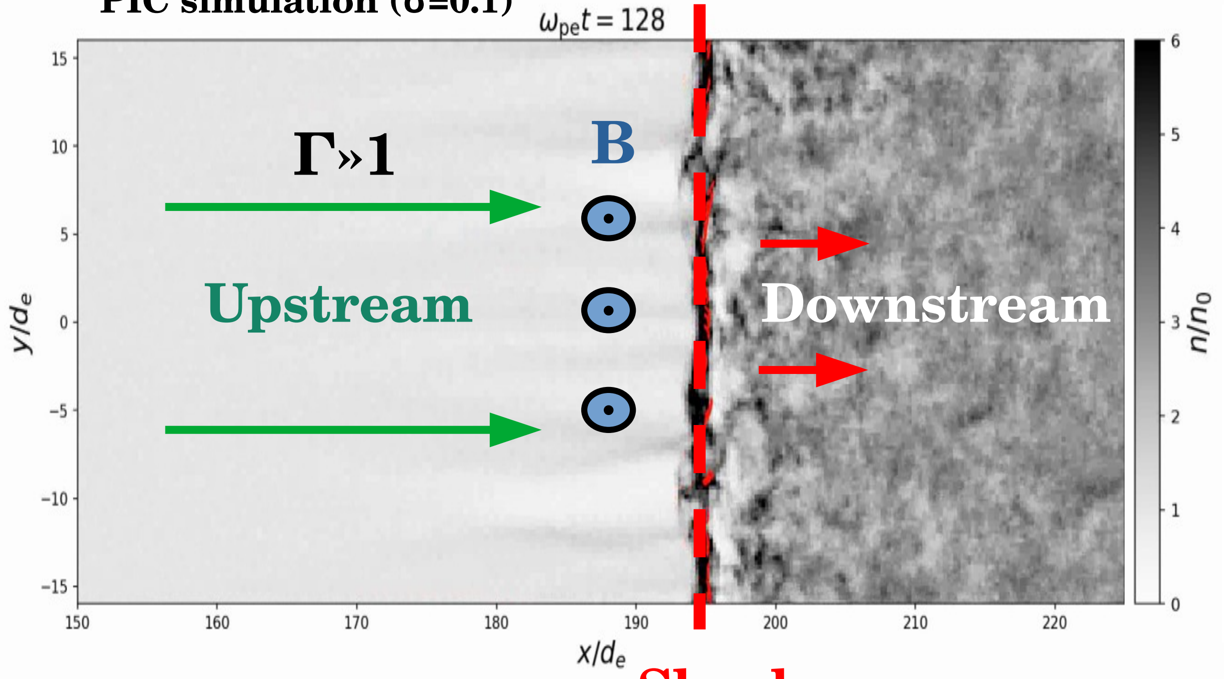
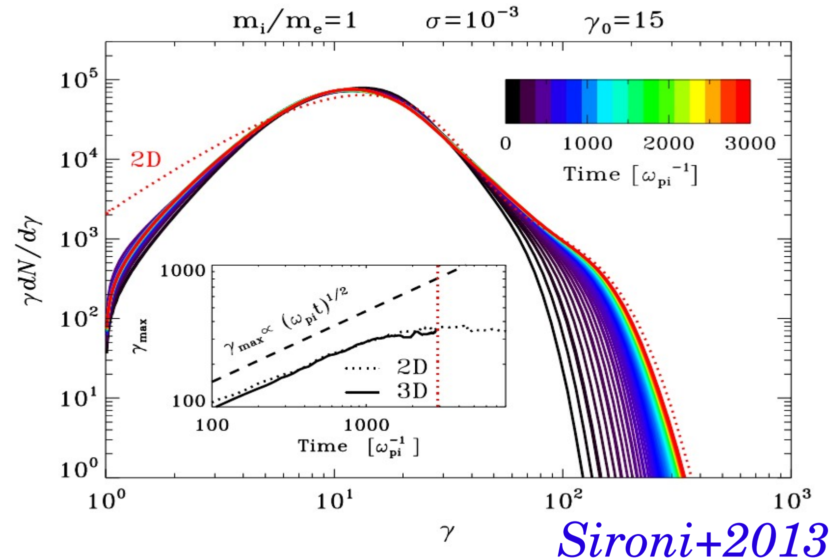
PIC simulation (σ=0.1)





Sironi+2013

Magnetic reflection at the shock => <u>No acceleration</u>

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

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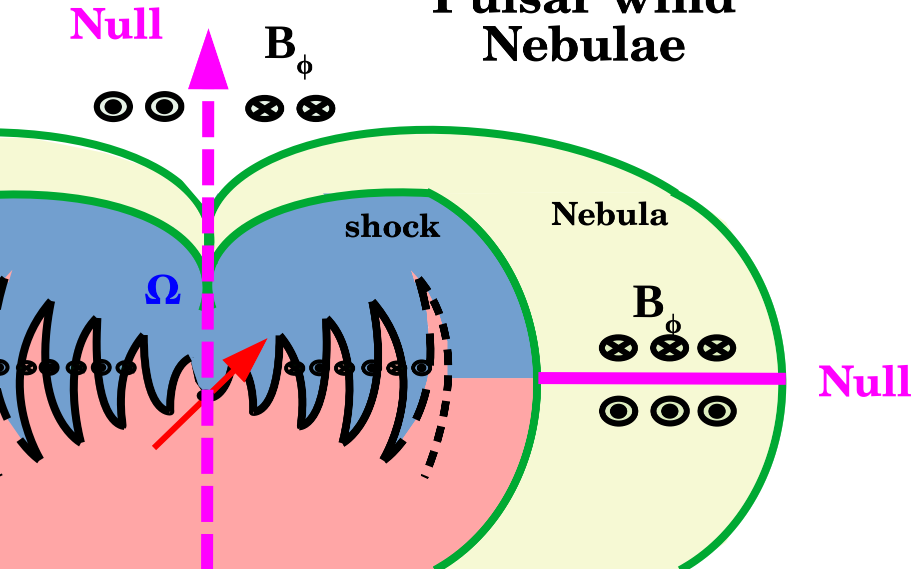
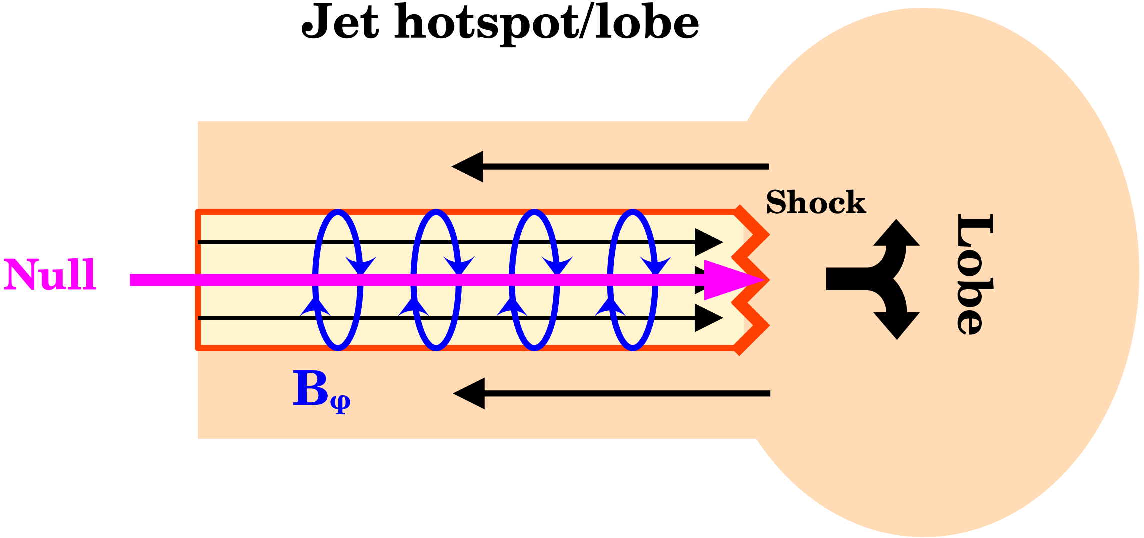
Cerutti & Giacinti 2020

Pulsar wind Nebulae

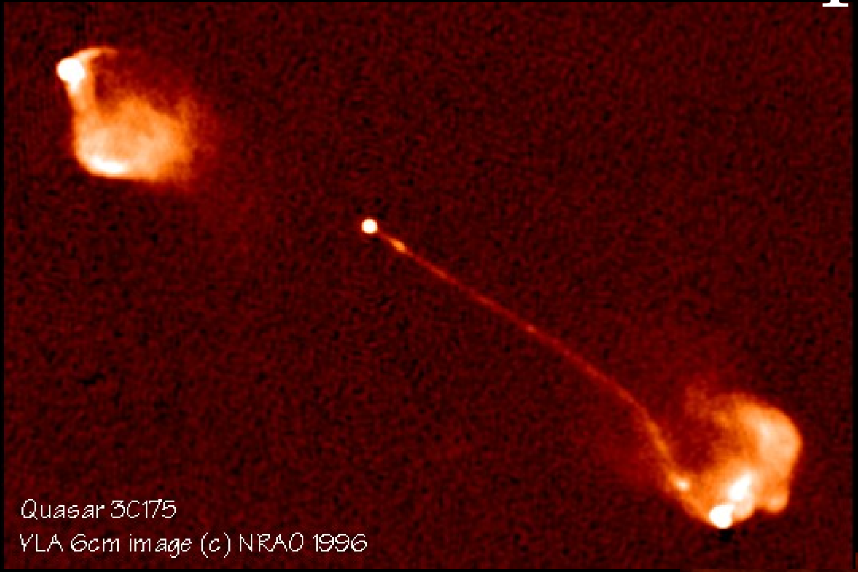


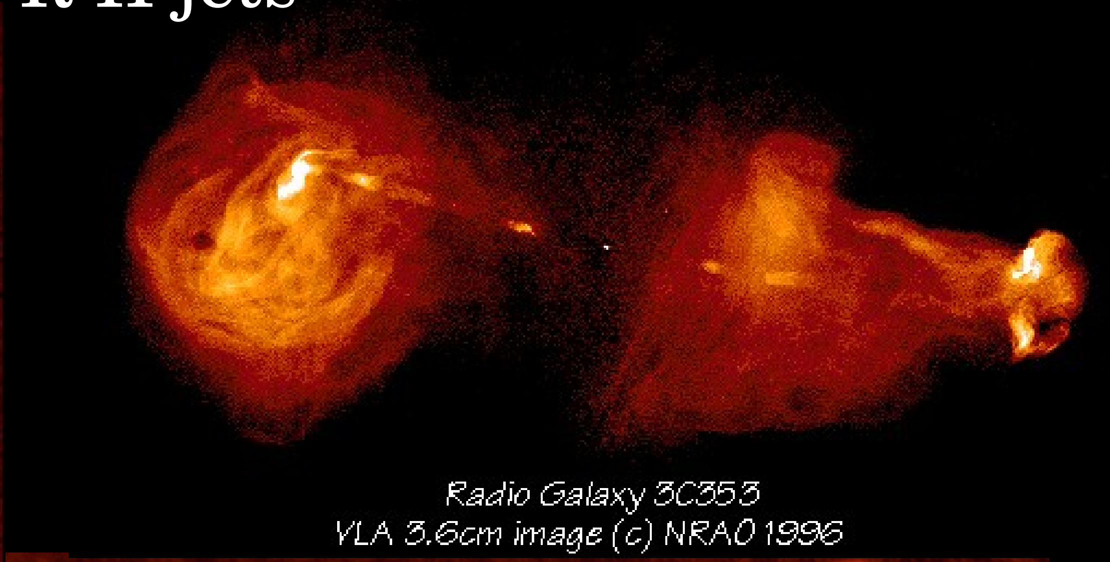
Cerutti & Giacinti 2023

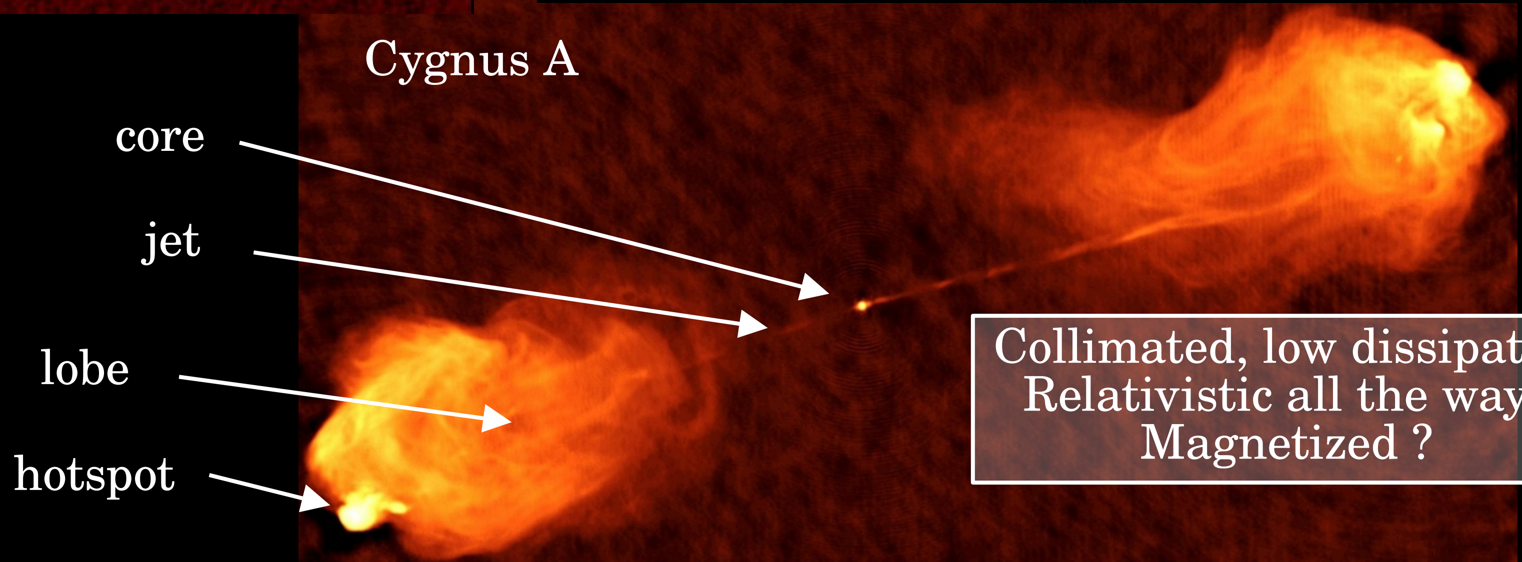
Jet hotspot/lobe



FR II jets



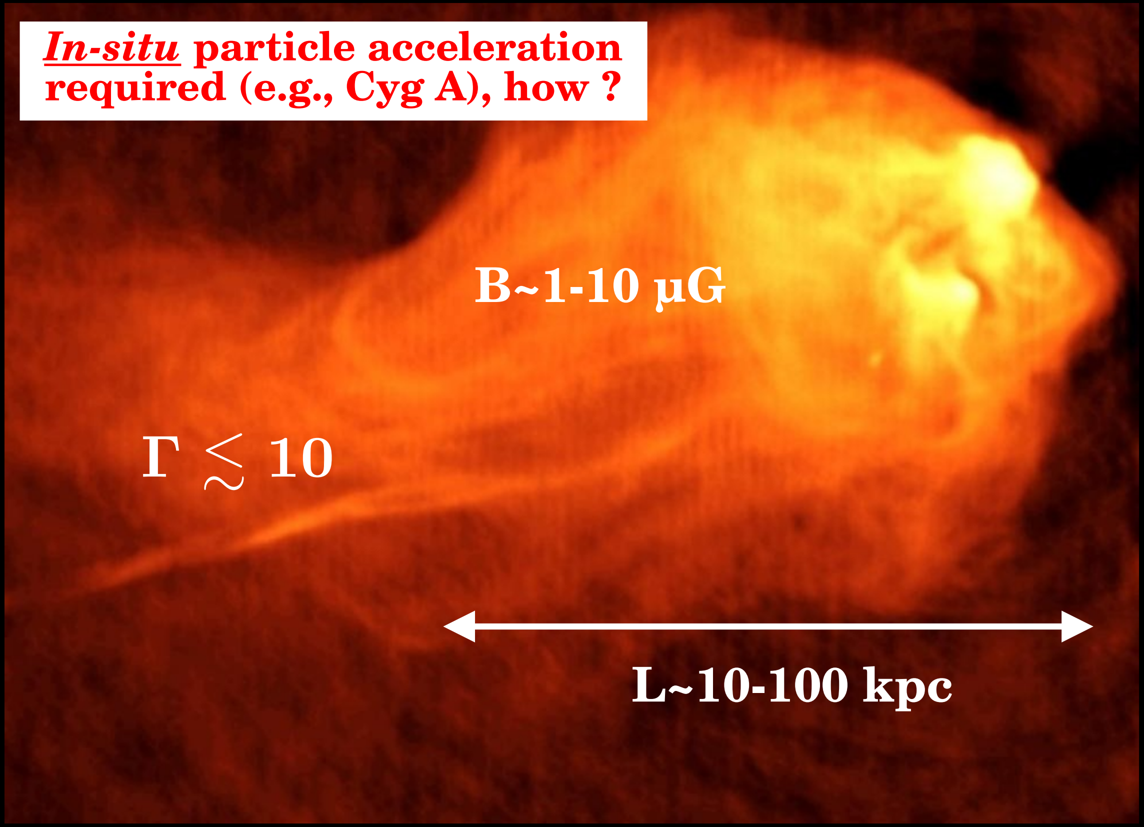




Collimated, low dissipation
Relativistic all the way ?
Magnetized ?

Physical conditions @ extragalactic jet termination shock

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



Ambient plasma magnetization ~ equipartition ?

$$\sigma = \frac{B_0^2}{4\pi\Gamma n m_i c^2} \sim 0.01 - 1$$

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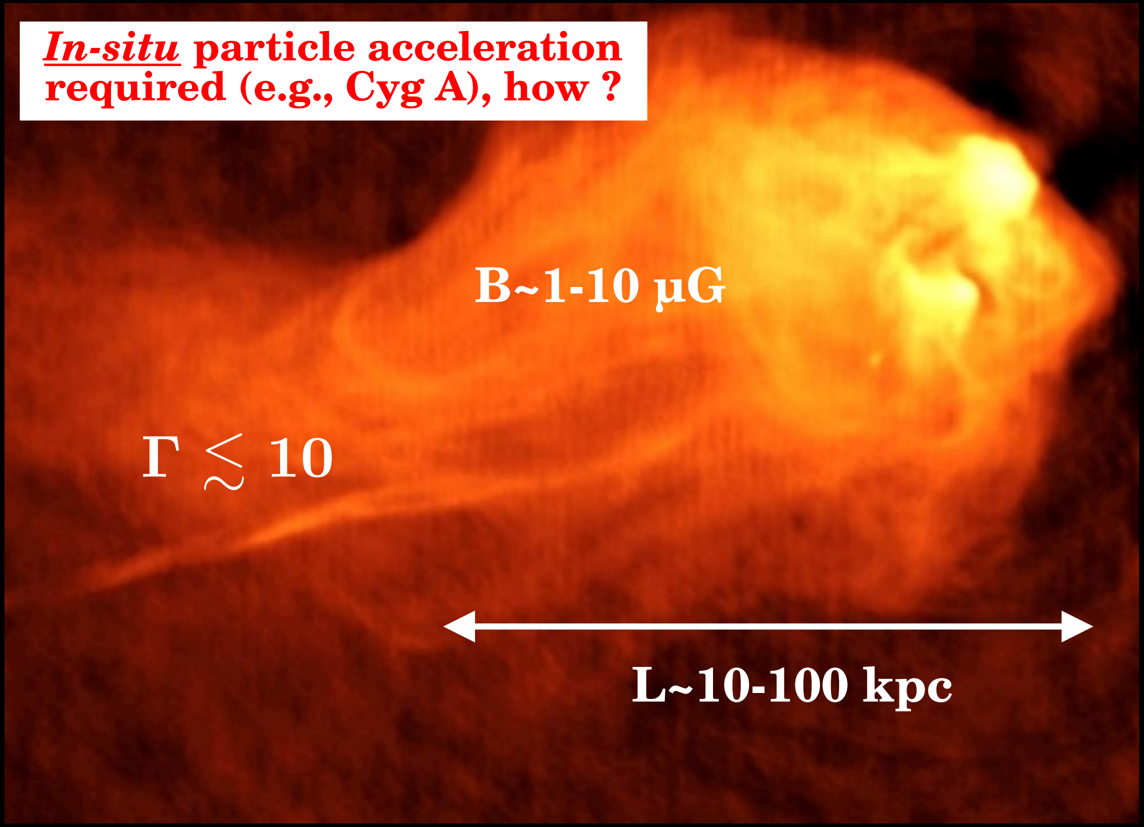

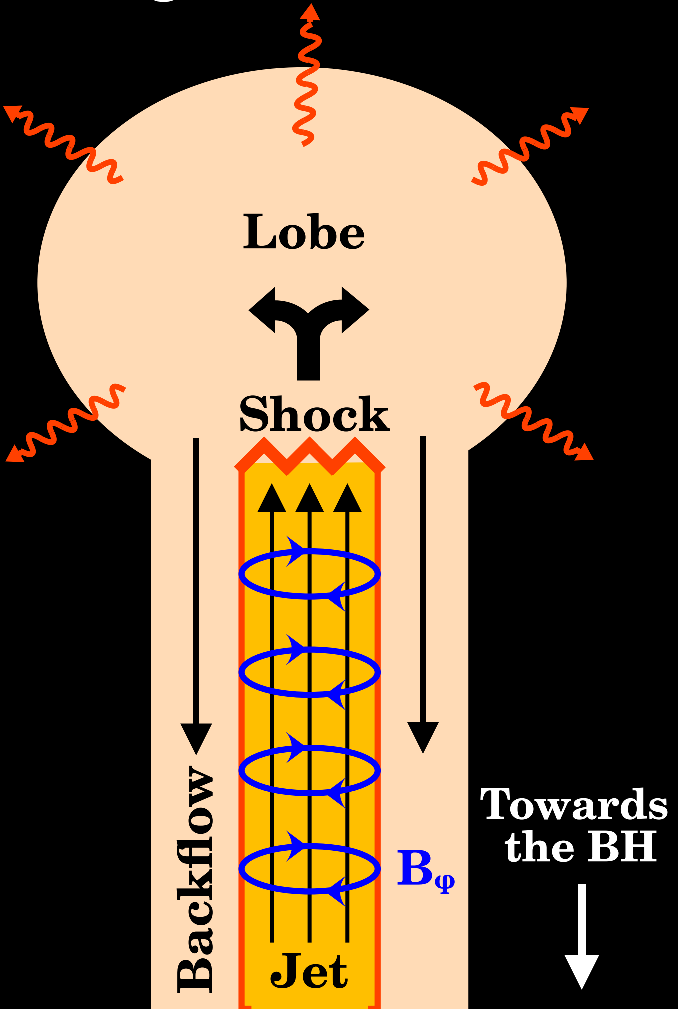

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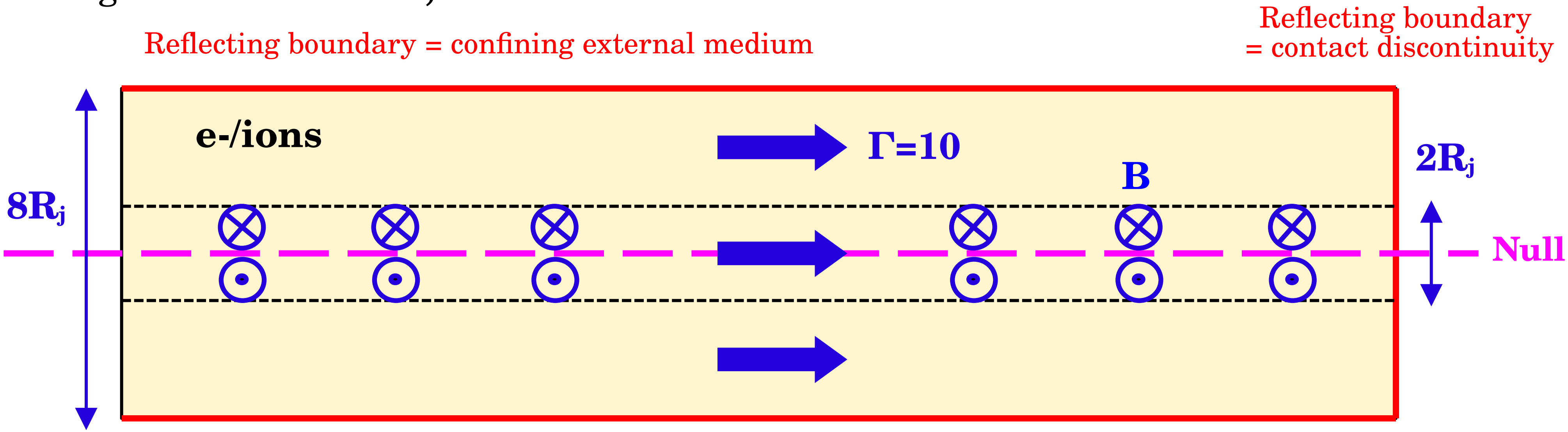
Our PIC setup

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

PIC code : Zeltron



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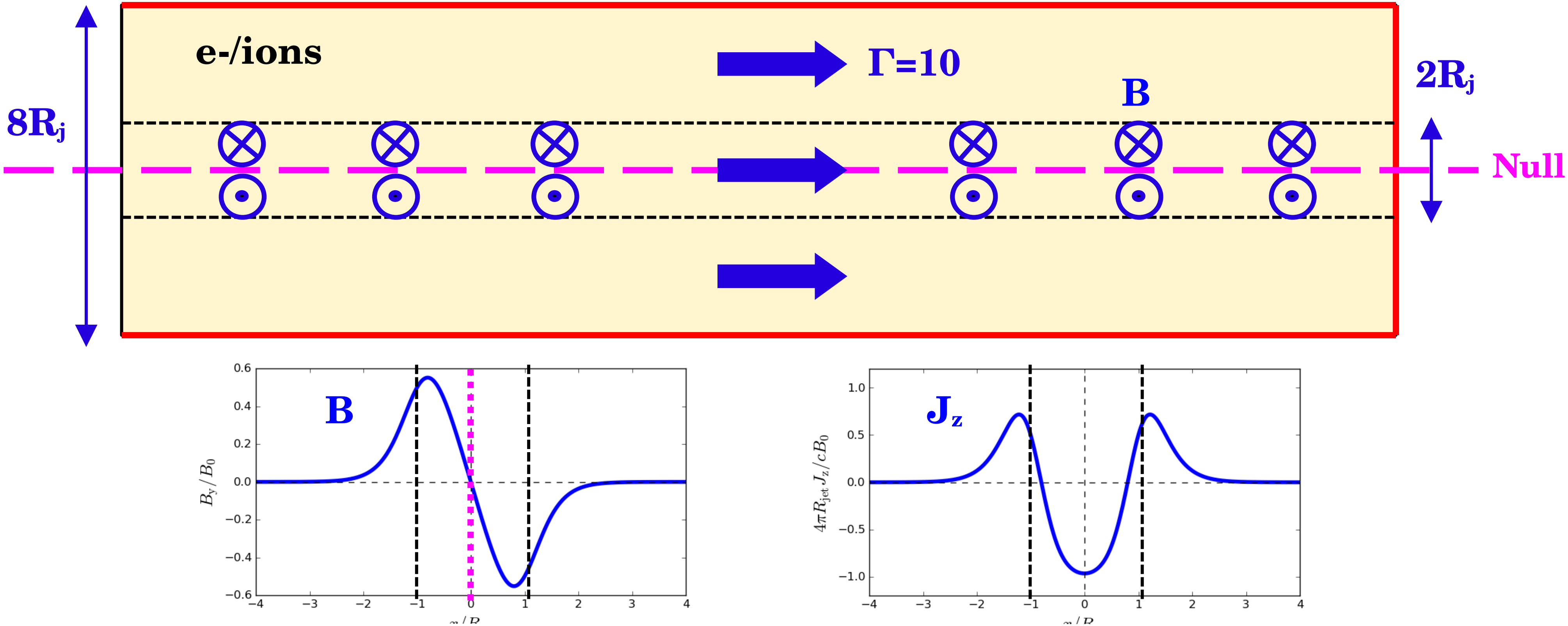
Reflecting boundary = confining external medium

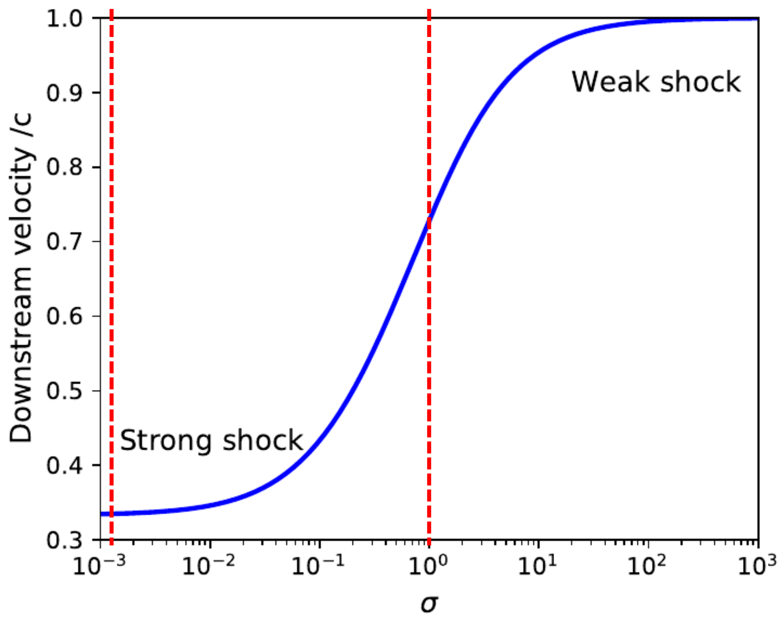
Reflecting boundary
= contact discontinuity



Variations in the downstream bulk flow velocity

Kennel & Coroniti 1984

Rankine-Hugoniot MHD
perpendicular shock



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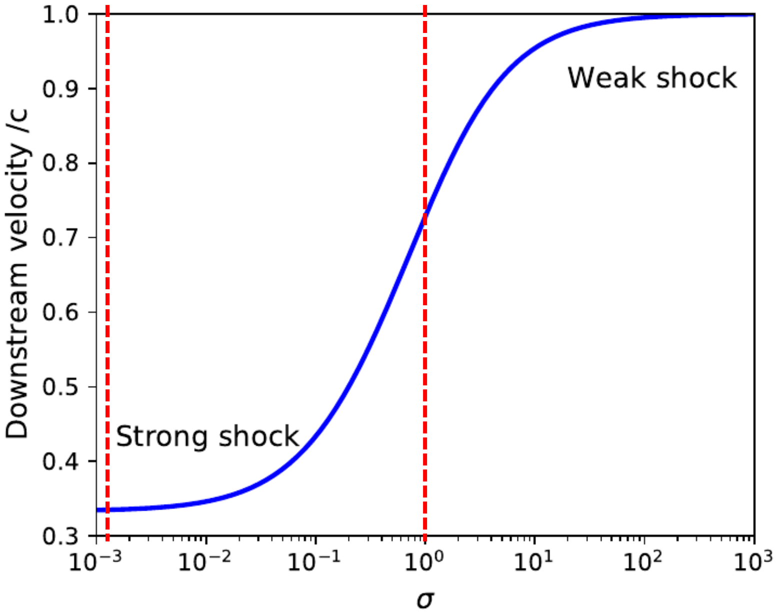

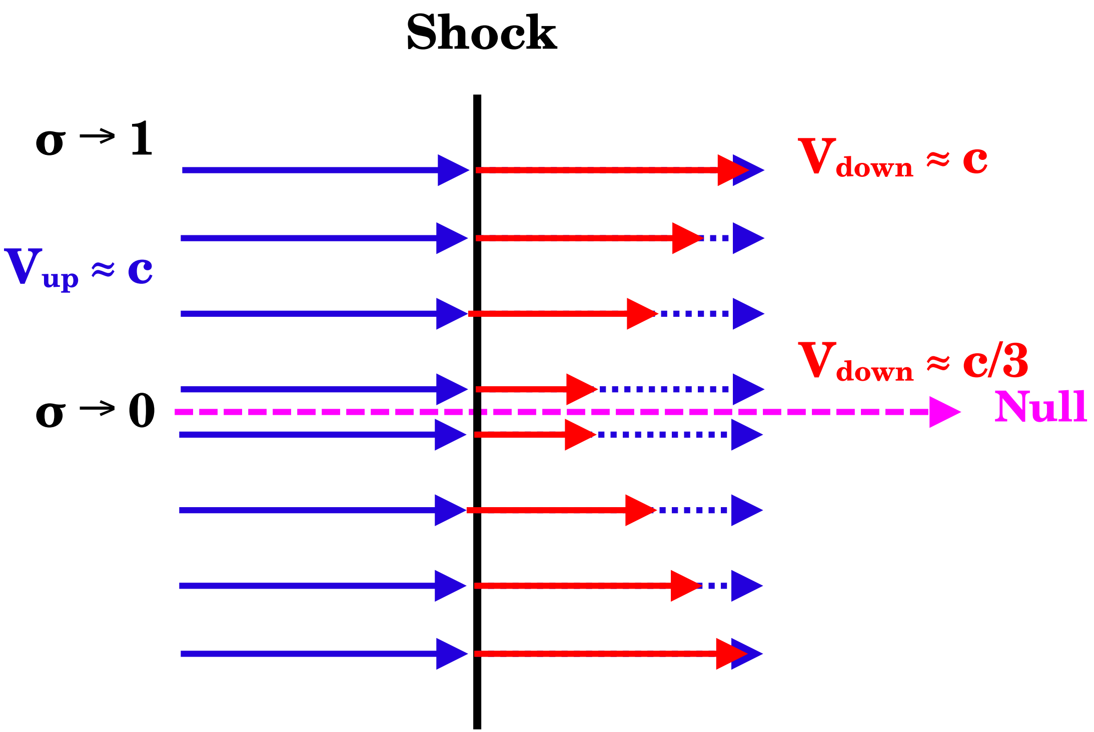

=> Formation of a strong velocity shear in the downstream medium

Variations in the downstream bulk flow velocity

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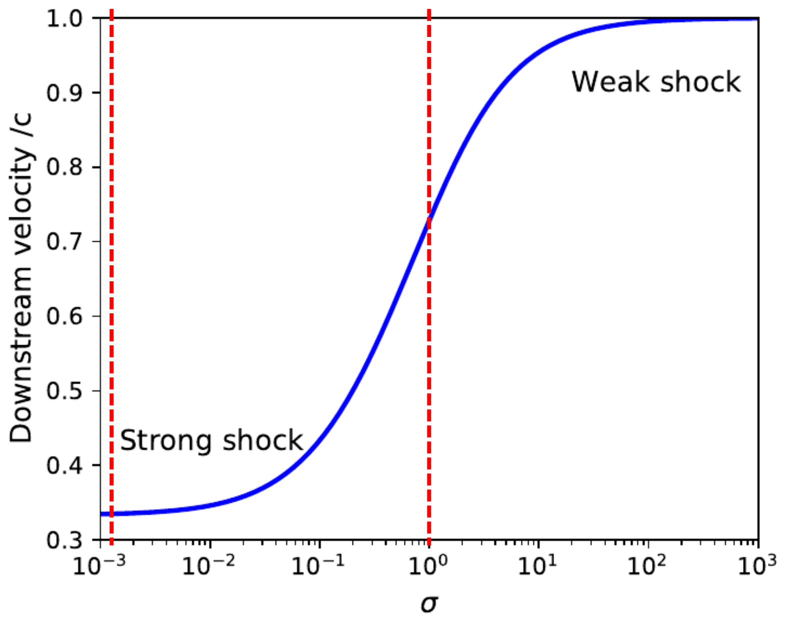
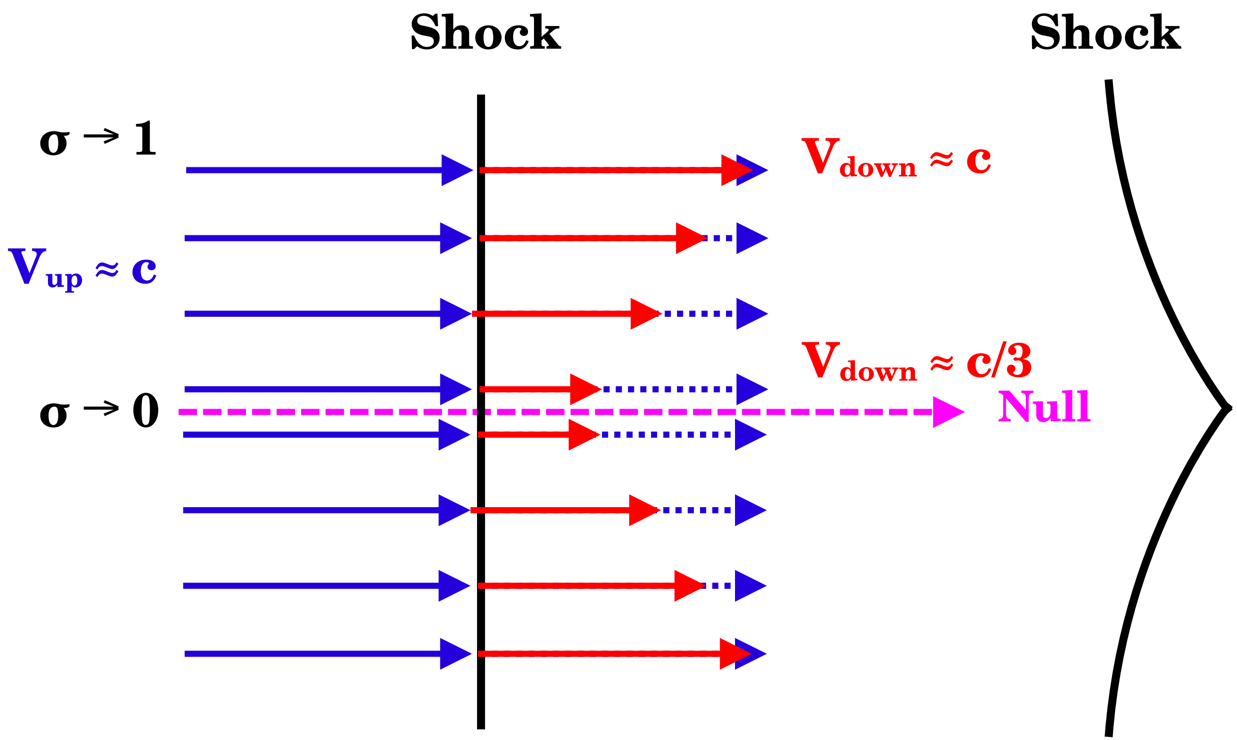
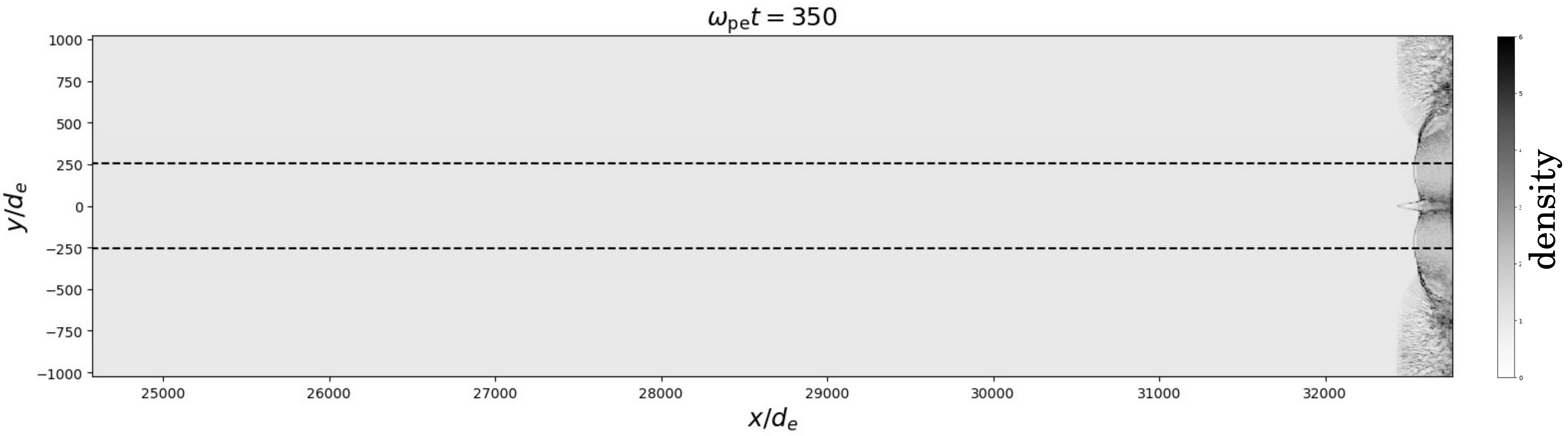




=> Formation of a strong velocity shear in the downstream medium

Plasma density evolution

Early phases



Plasma density evolution

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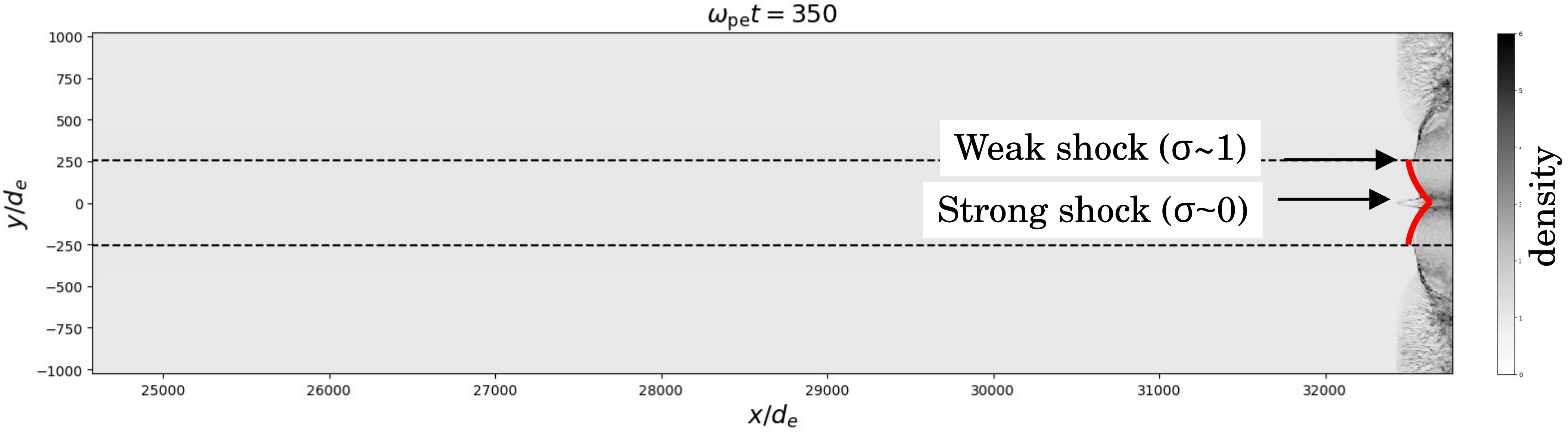

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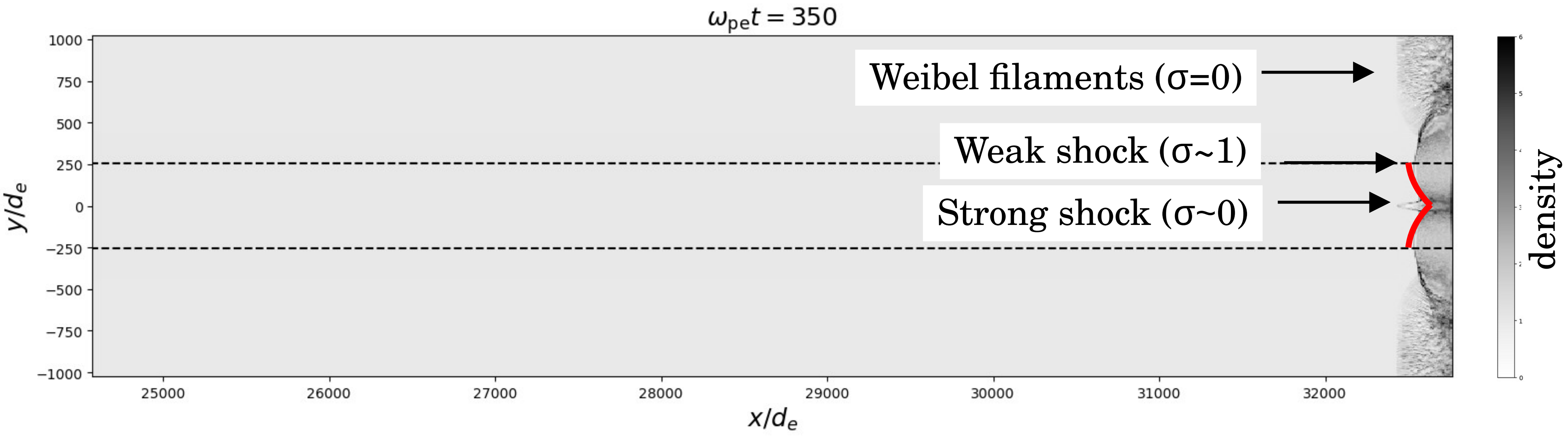

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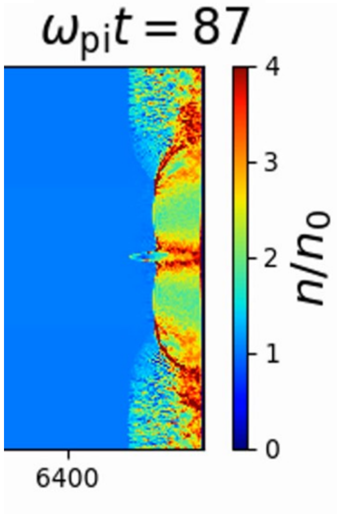

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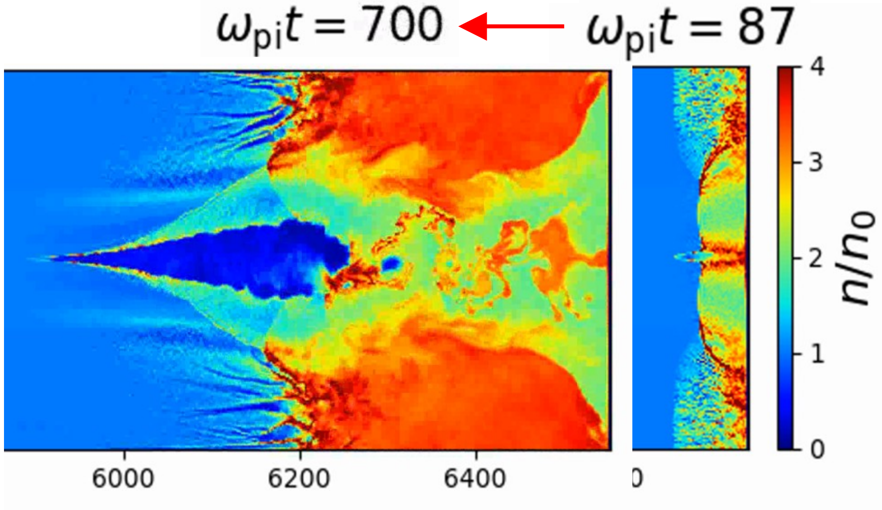

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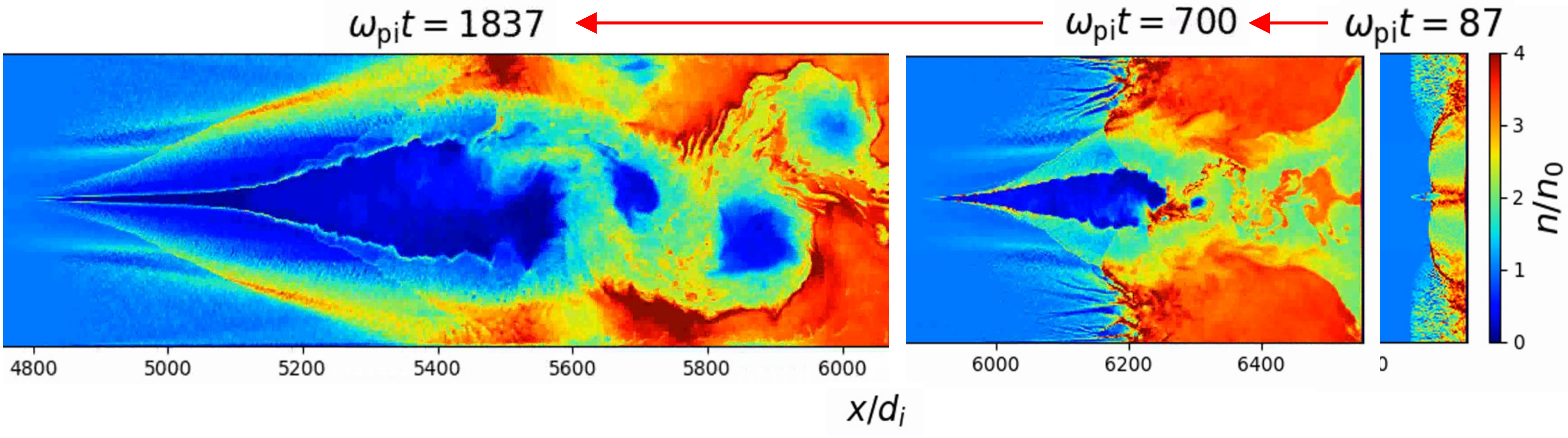

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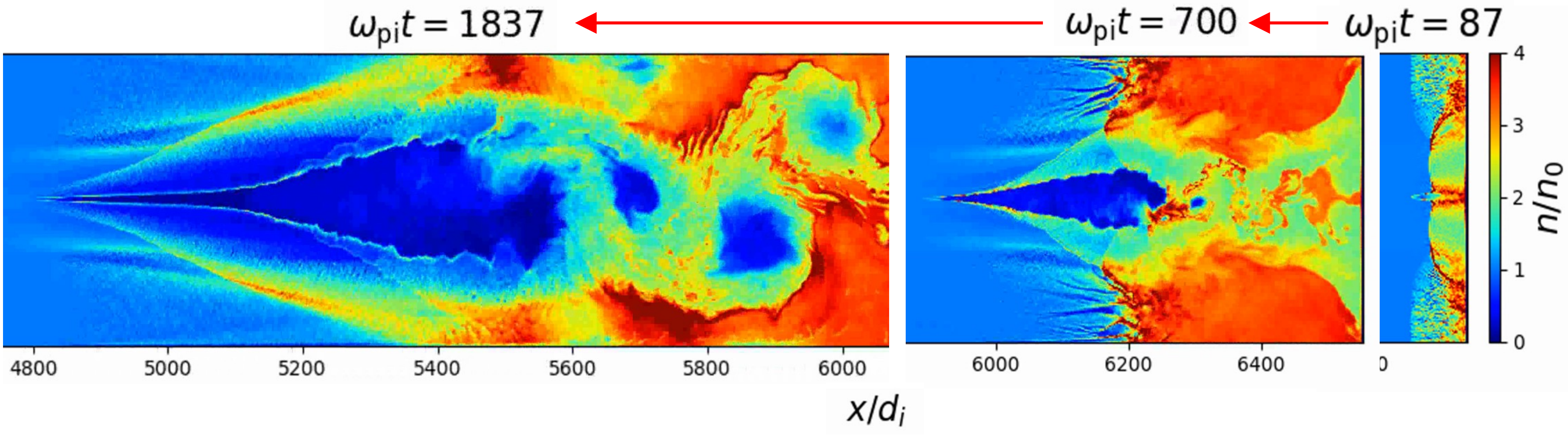
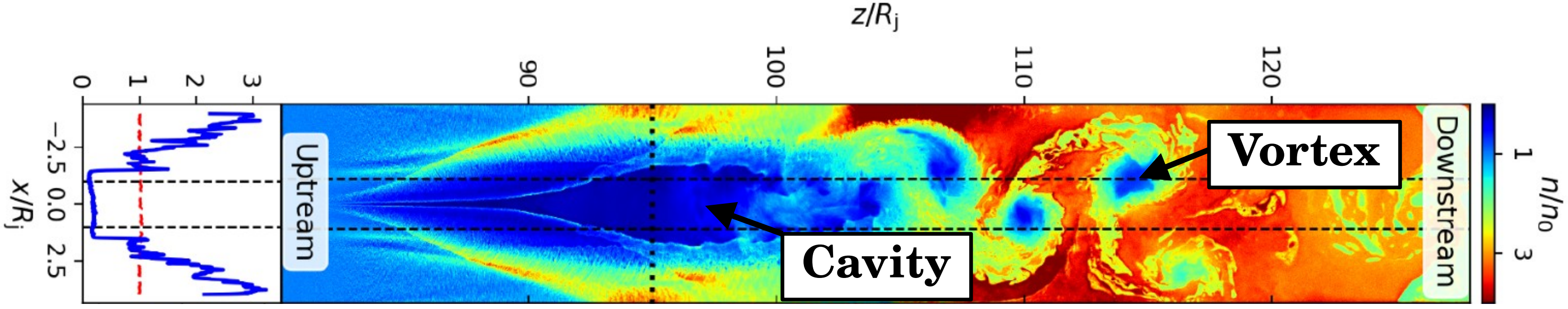


von Kármán vortices

Large over-pressured cavity

=> obstacle to the incoming flow

Cavity, shear, vortices, particle acceleration !



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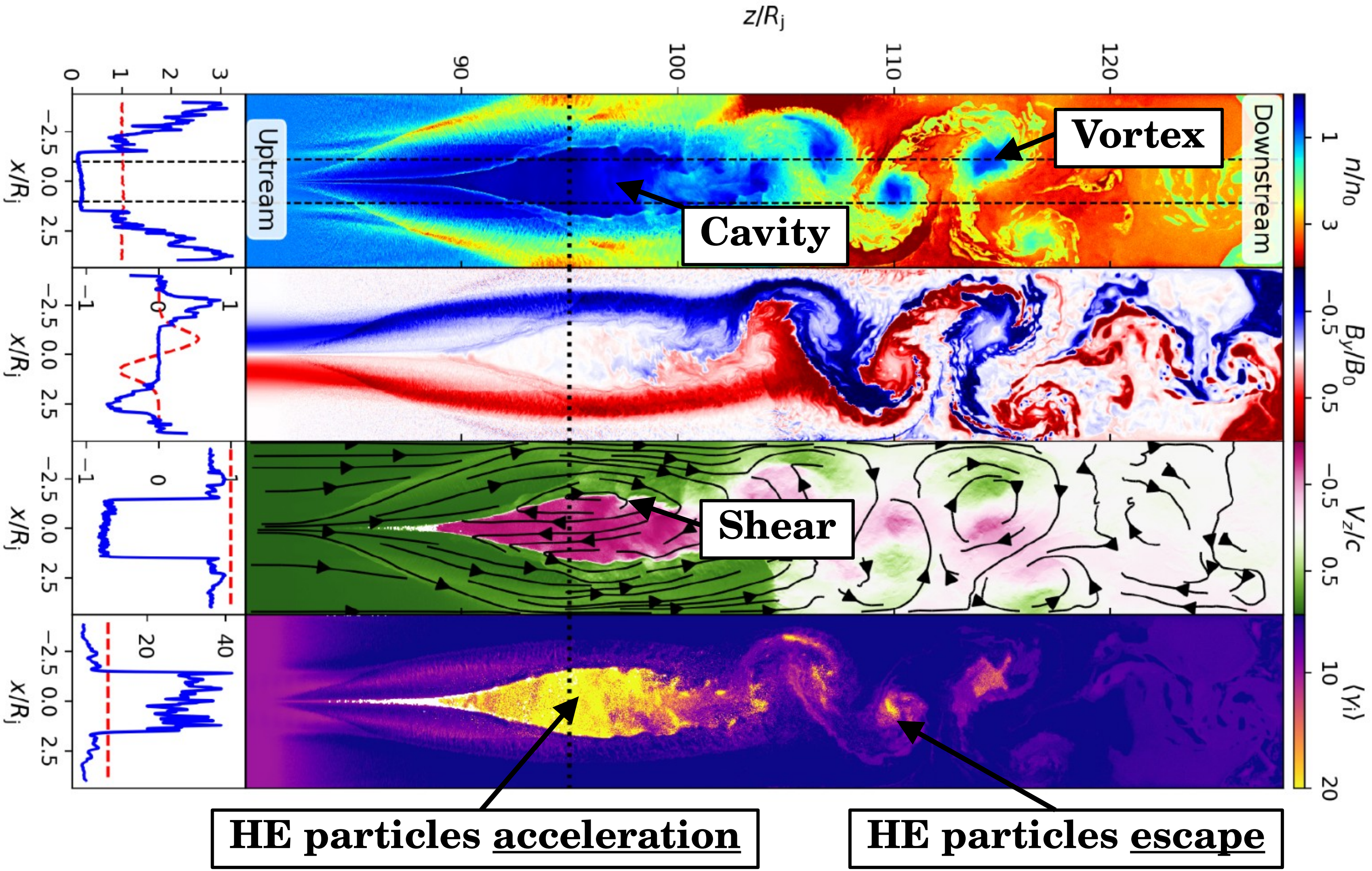
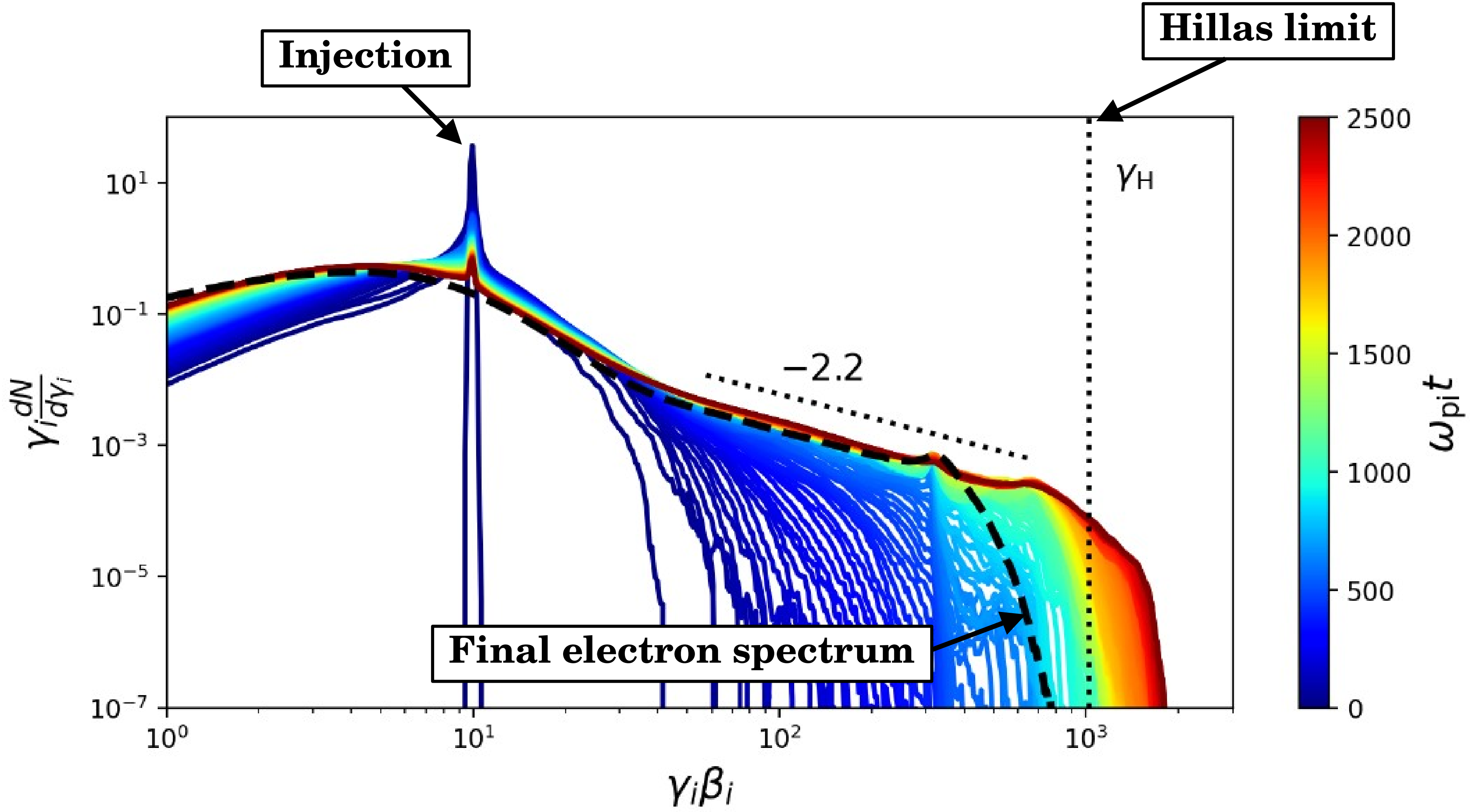
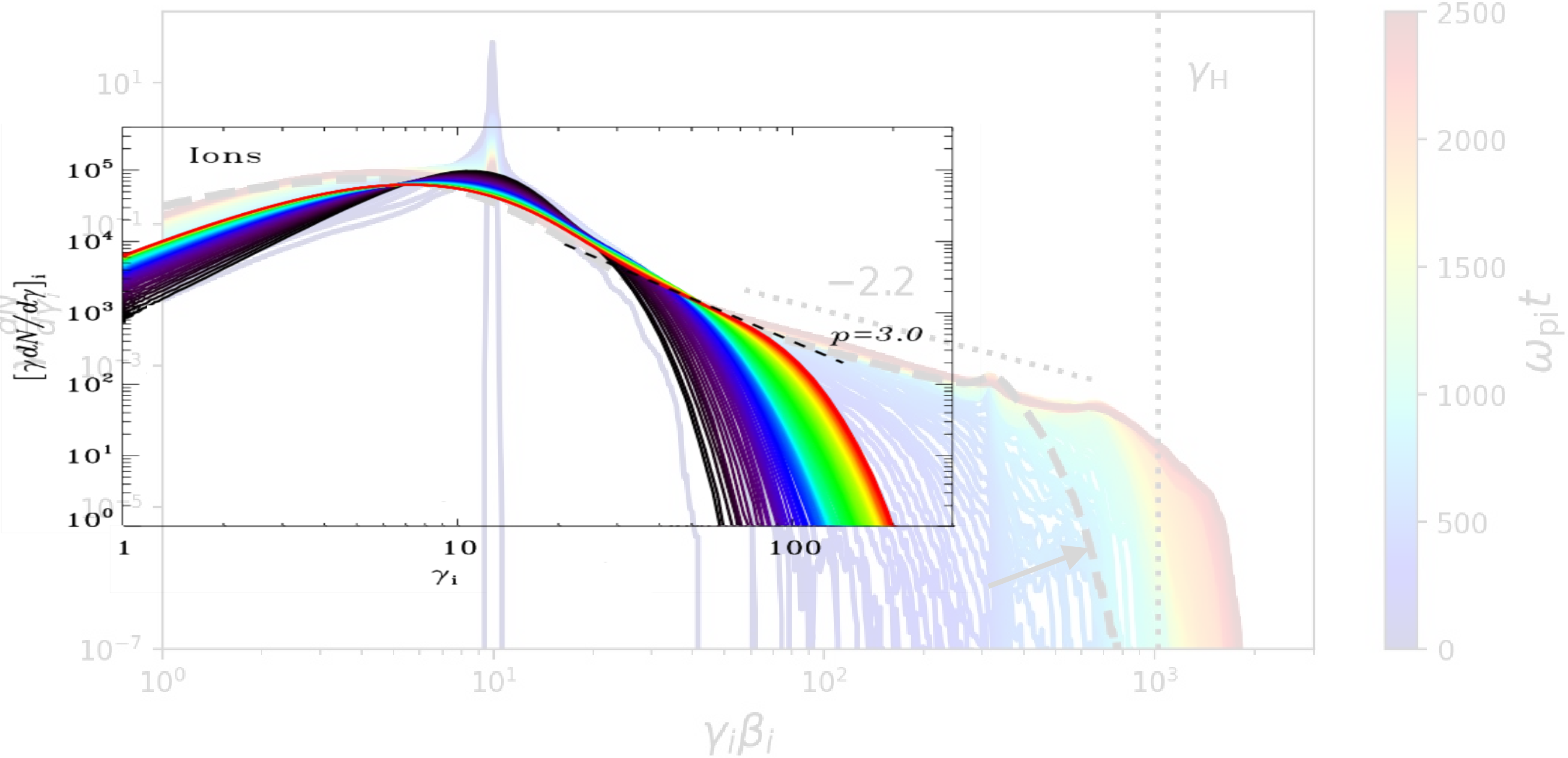


Ion spectrum temporal evolution

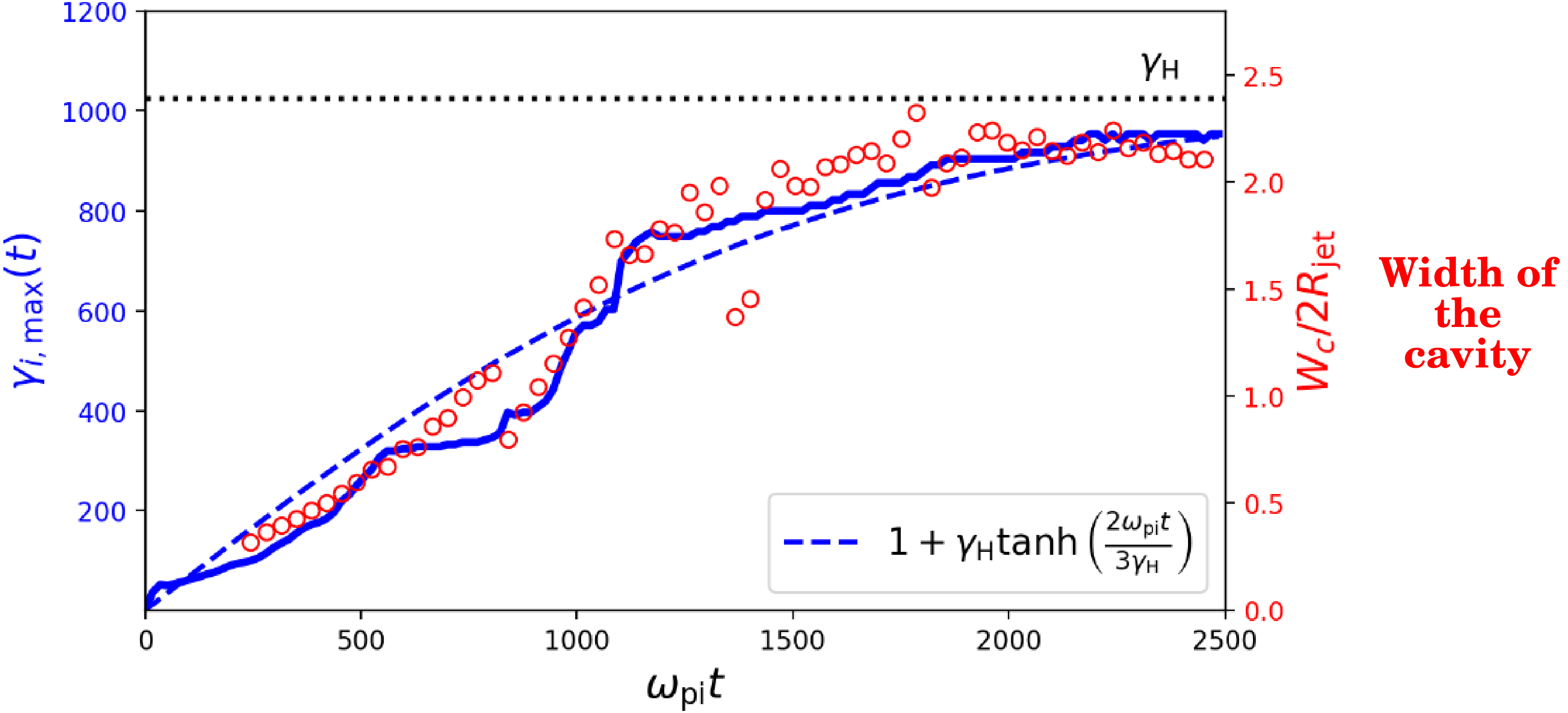


Ion spectrum temporal evolution

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



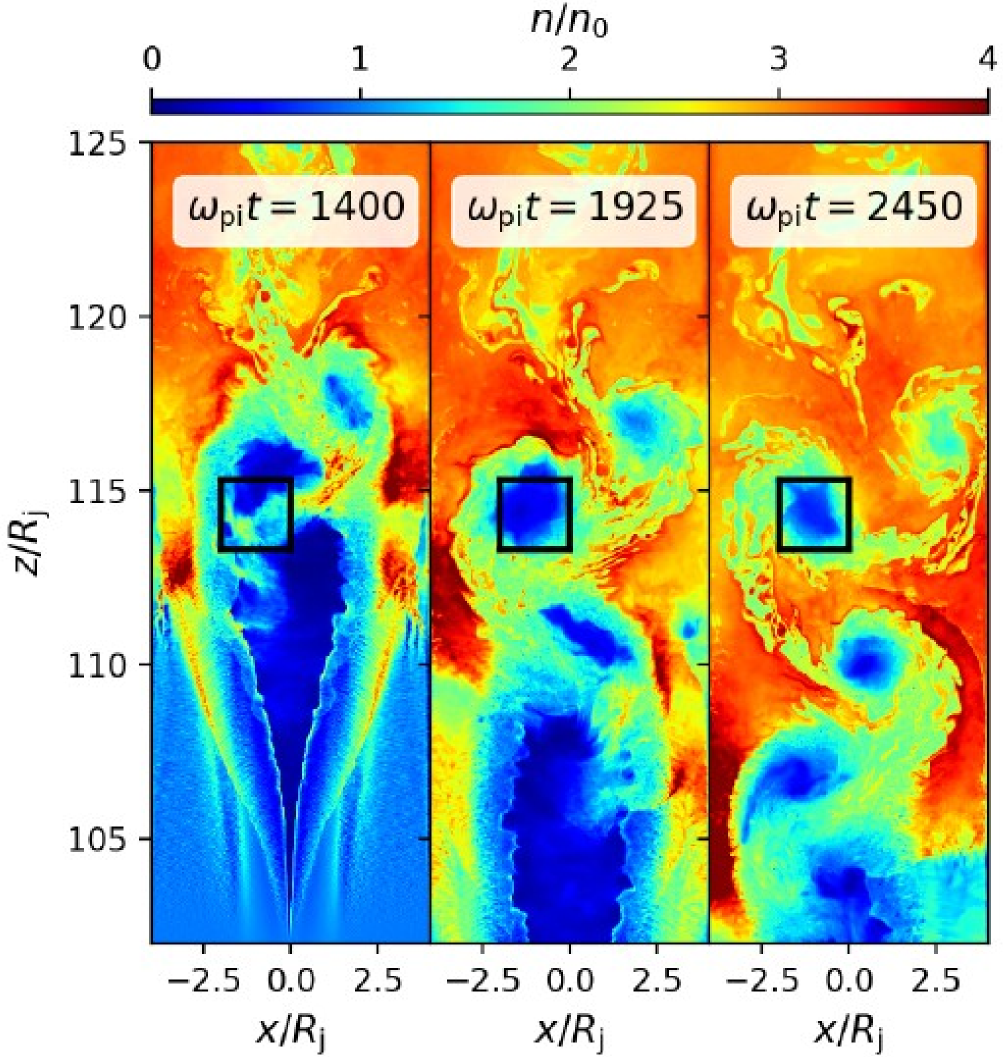
Saturation

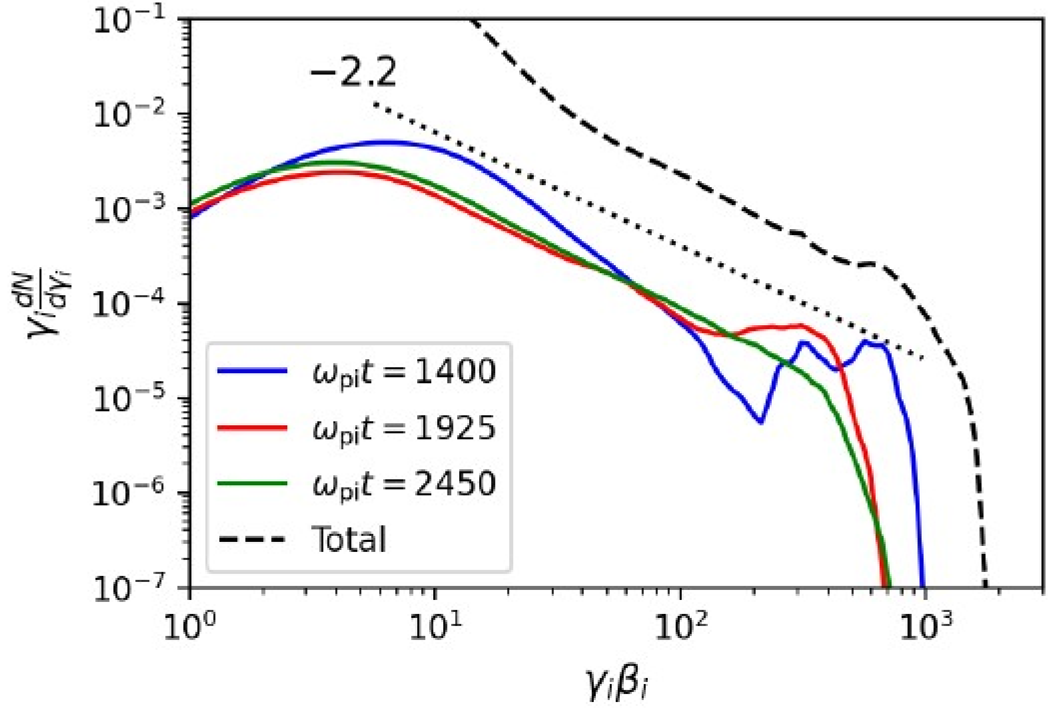


Fast particle acceleration ($\gamma_{max} \sim \omega_{pi}t$) followed by a **saturation at the confinment limit**

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

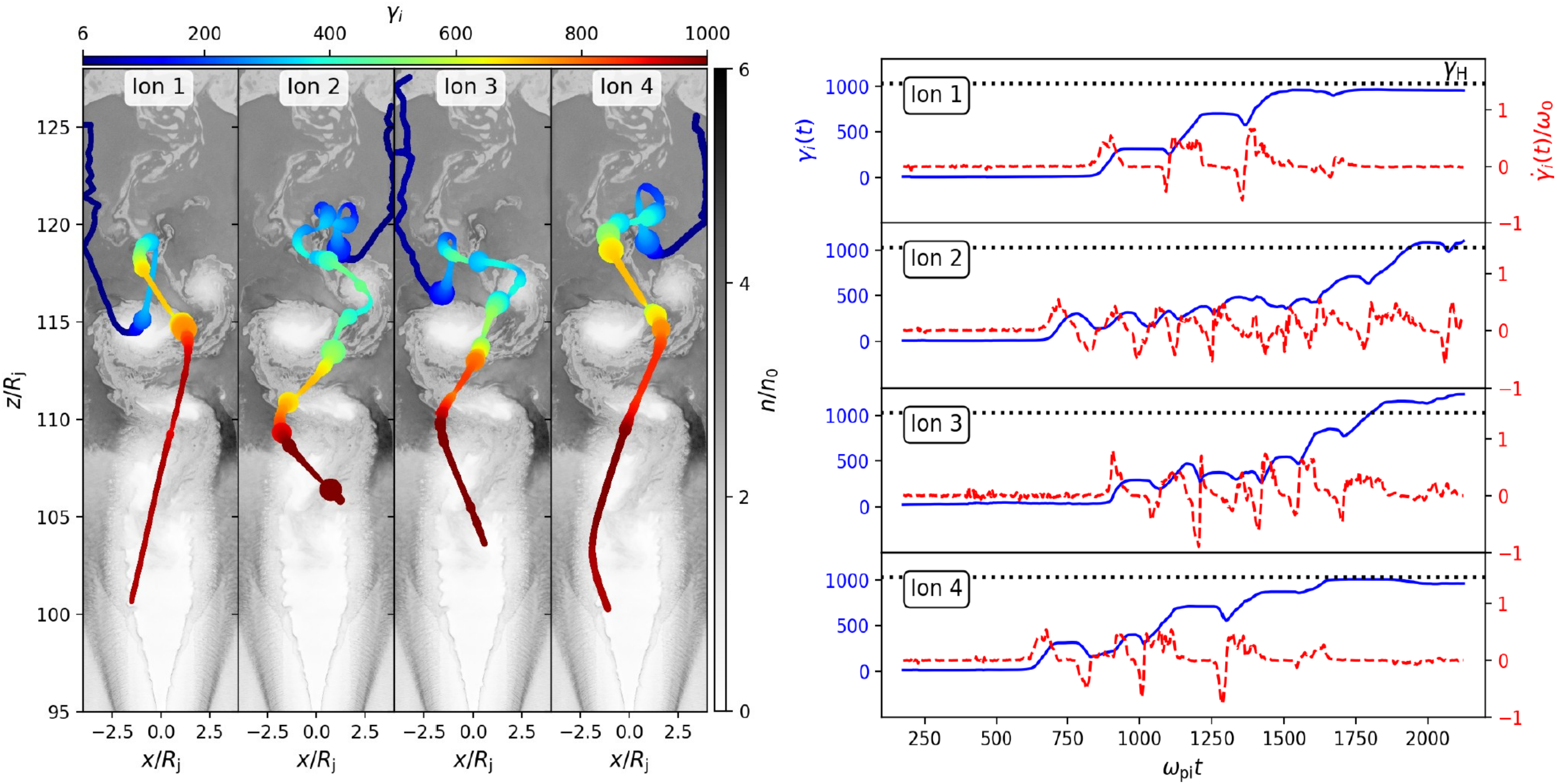
High-energy particle escape





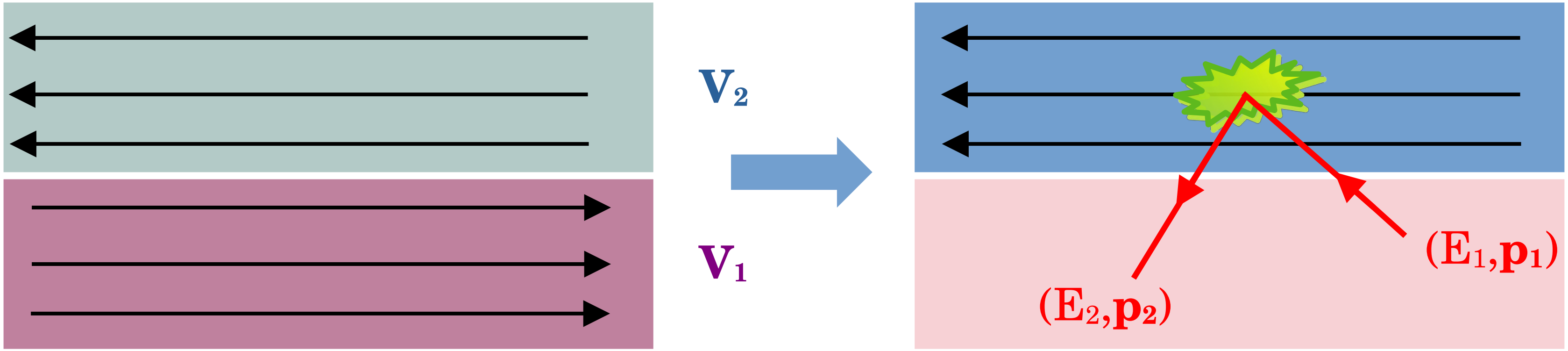
Particle escape with little energy losses

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



Shear-flow acceleration

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



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

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

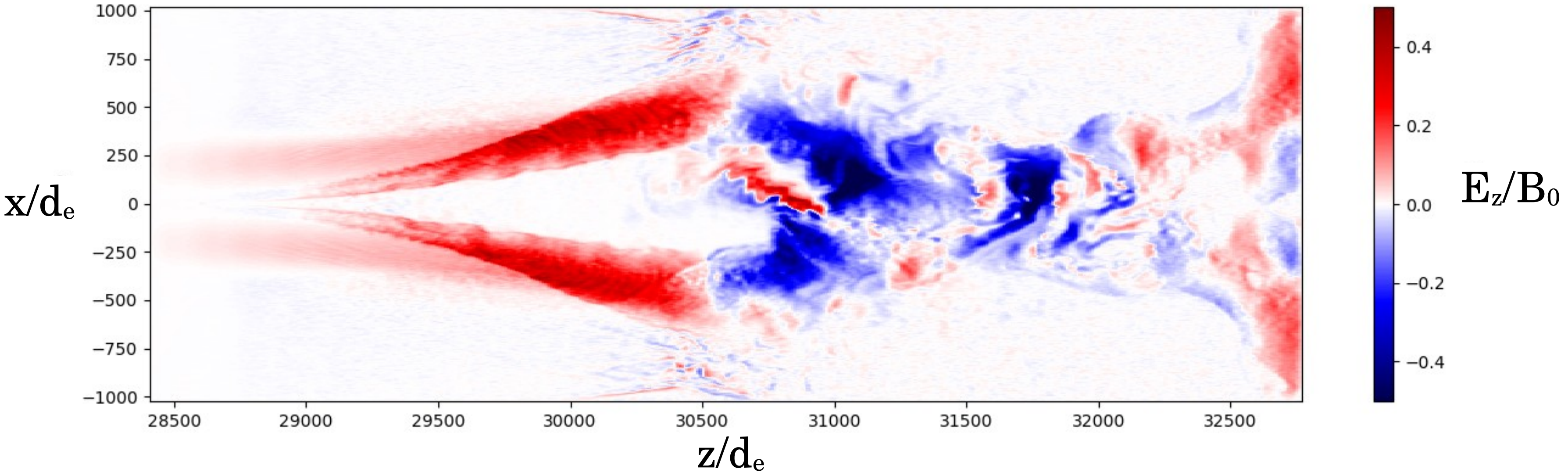
$$E_2 - E_1 = 2\Gamma^2 \left(E_1 \frac{U^2}{c^2} - \mathbf{p_1} \cdot \frac{\mathbf{U}}{c} \right)$$

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 $\mathbf{E} = -\frac{\mathbf{V} \times \mathbf{B}}{c}$

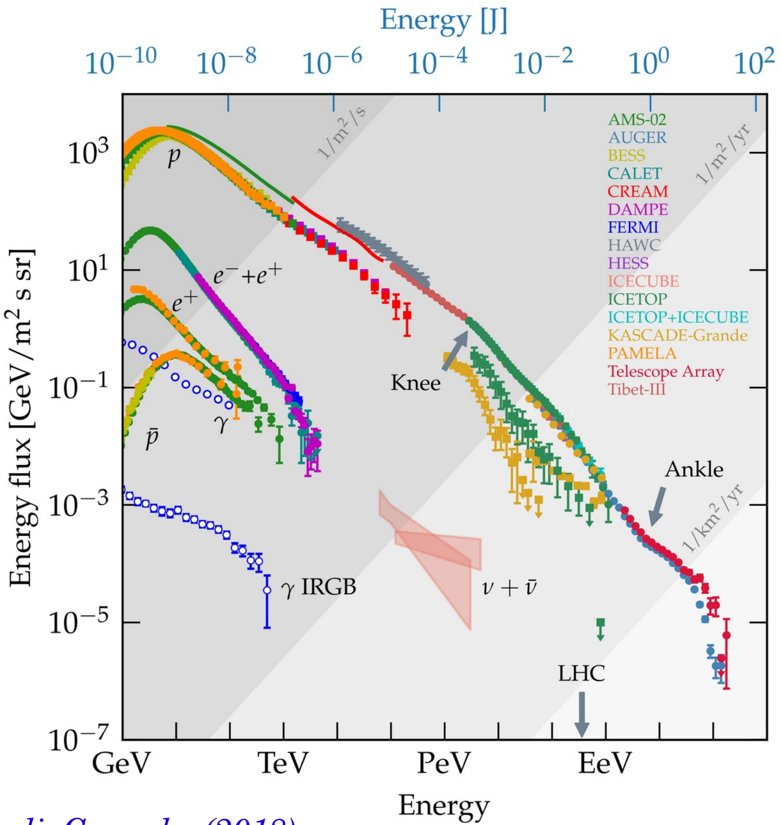


Acceleration rate : $\dot{\gamma} = \frac{e}{m_i c}\mathbf{E} \cdot \boldsymbol{\beta} \approx 0.5\omega_0$ ~constant, independant of energy $\gamma_\mathrm{i}(t) \propto t$

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

Ultra-high energy cosmic rays (UHECR) & Hillas criterion

Cosmic-ray spectrum



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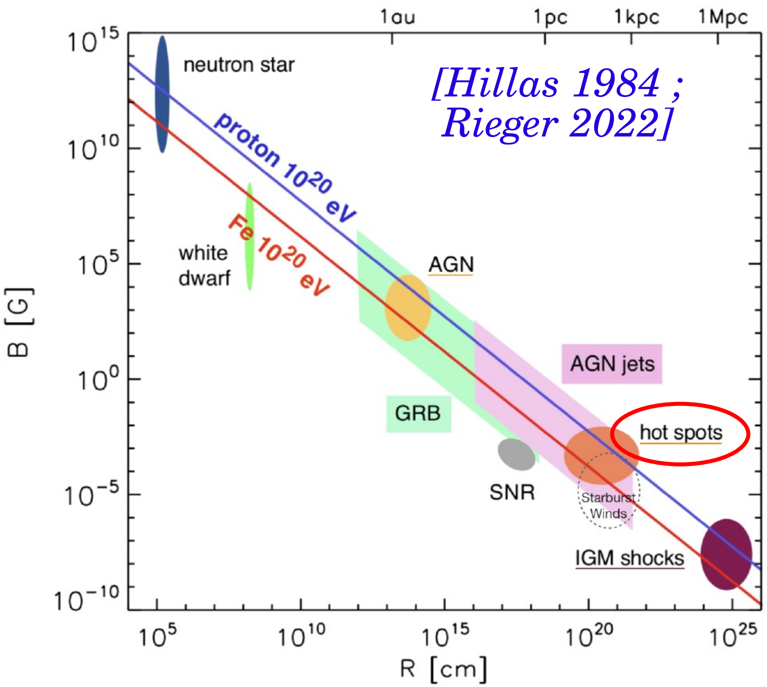
Cosmic-ray confinment limit :
Larmor radius = source

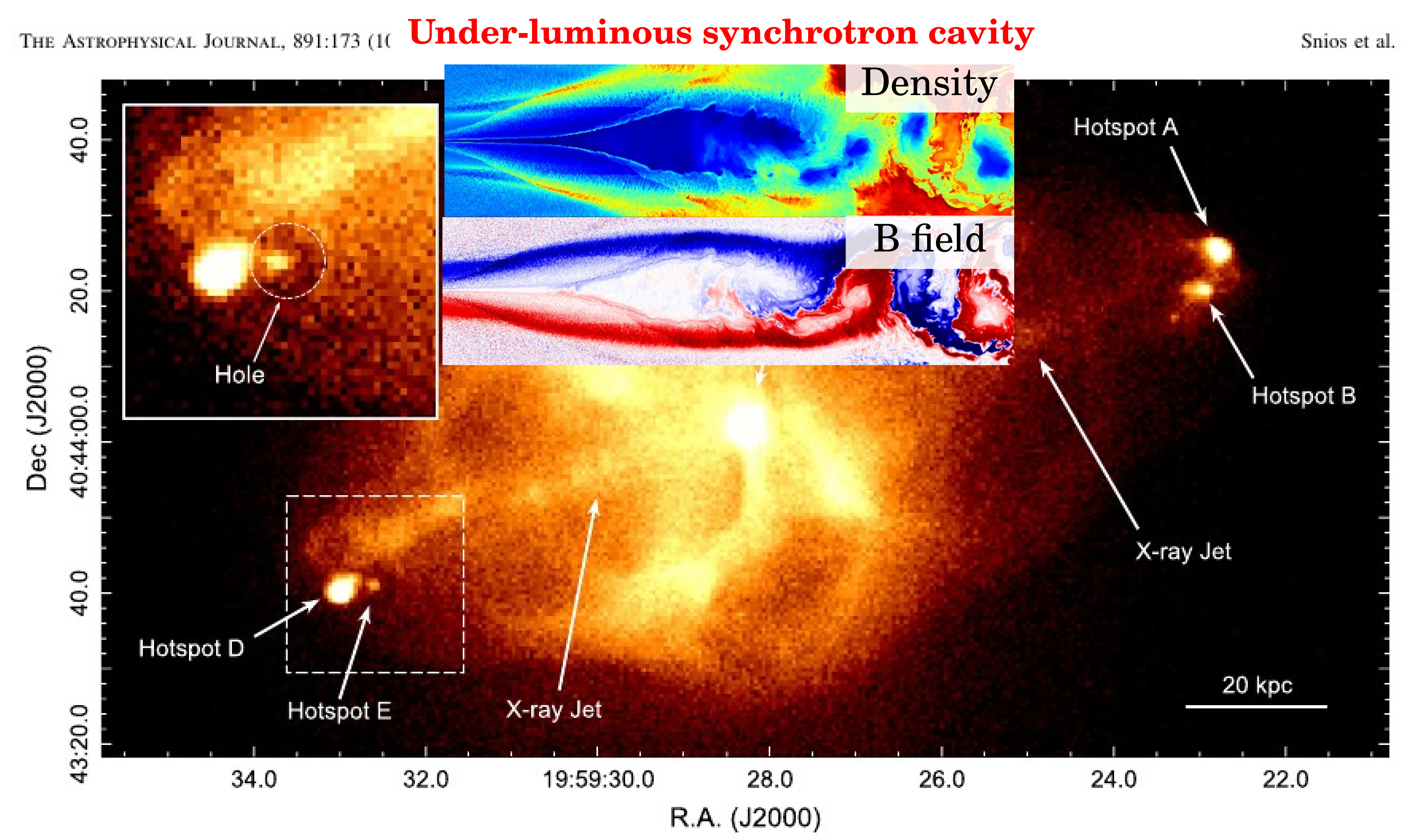
$$E \leq 10^{20}\, Z \left(\frac{B}{10\mu\,\mathrm{G}}\right)\left(\frac{L}{10\ \mathrm{kpc}}\right)\ \mathrm{eV}$$



[Hillas 1984 ; Rieger 2022]

Via this mechanism, jet hotspots/lobes could accelerate (and confine) UHECR !

Observational evidence ?



Take-away messages, implications & perspectives

- The global structure of the magnetic field (presence of nulls) 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. PeV particle acceleration in PWN (+ Crab flares).
- Caveats : Full 3D effects, role of curvature drift, role of external medium ?