EXTREME PARTICLE ACCELERATION AT (AGN) JET TERMINATION SHOCKS

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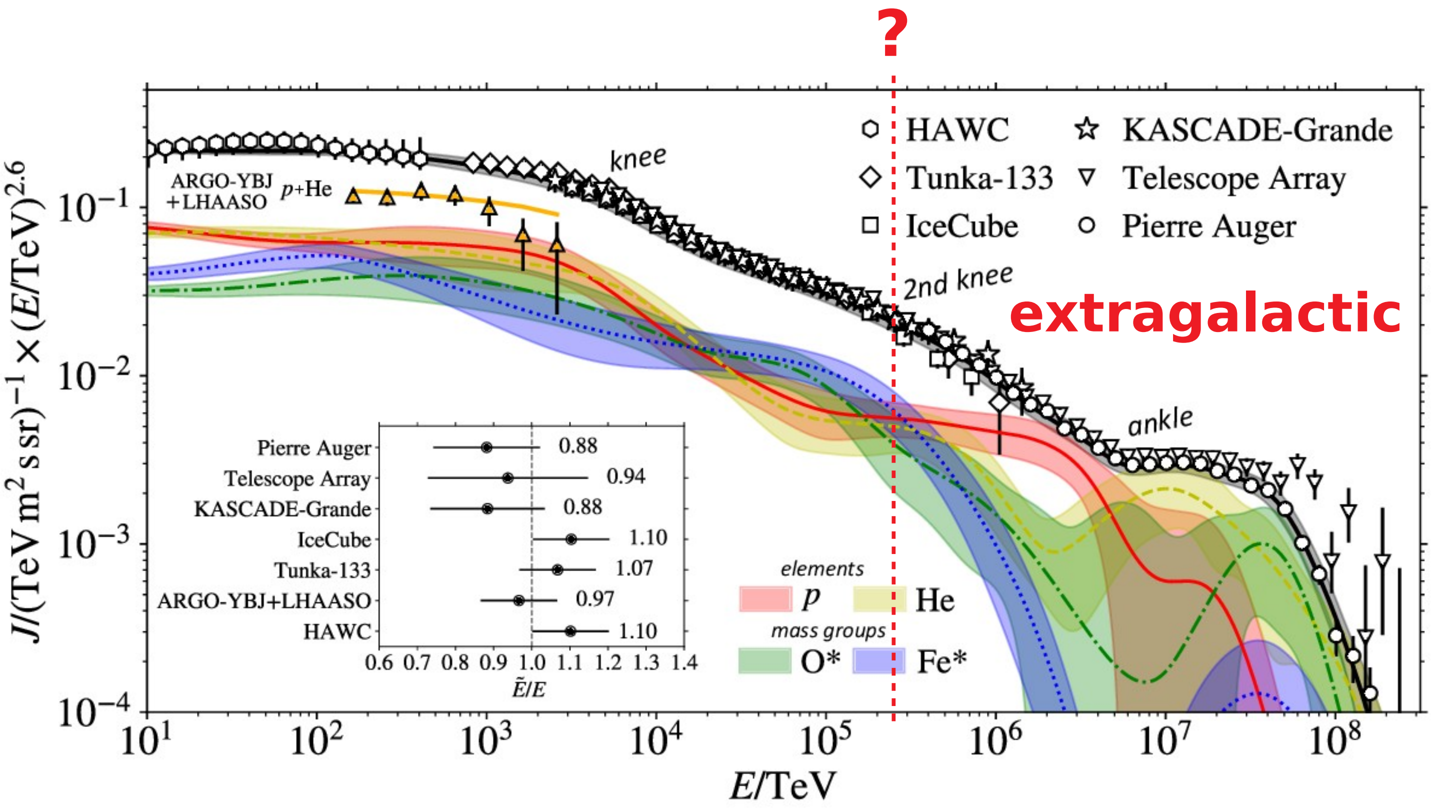
Ultra-High Energy Cosmic-Rays



Up to **~10^{20} eV**! Probably involve BHs: AGNs, GRBs

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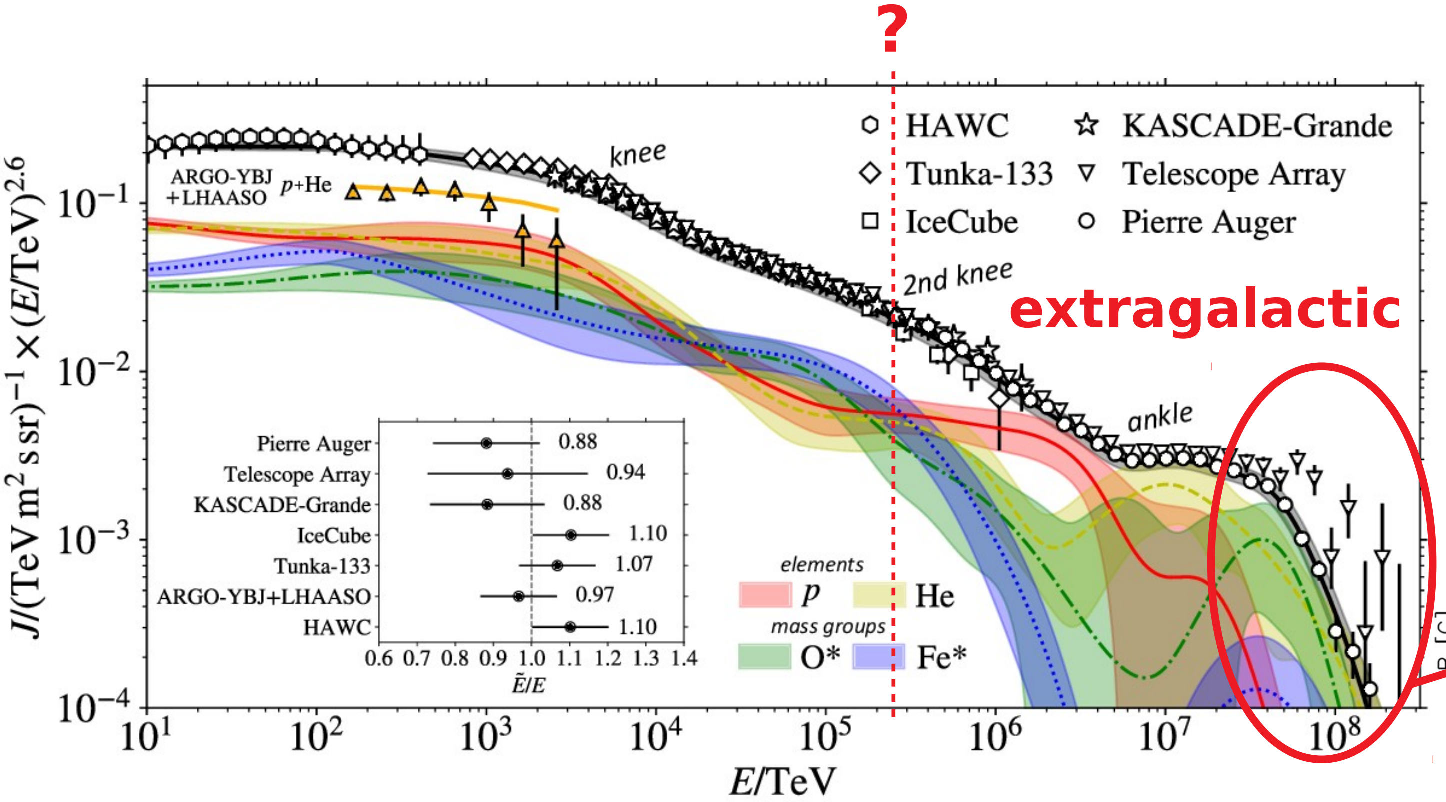
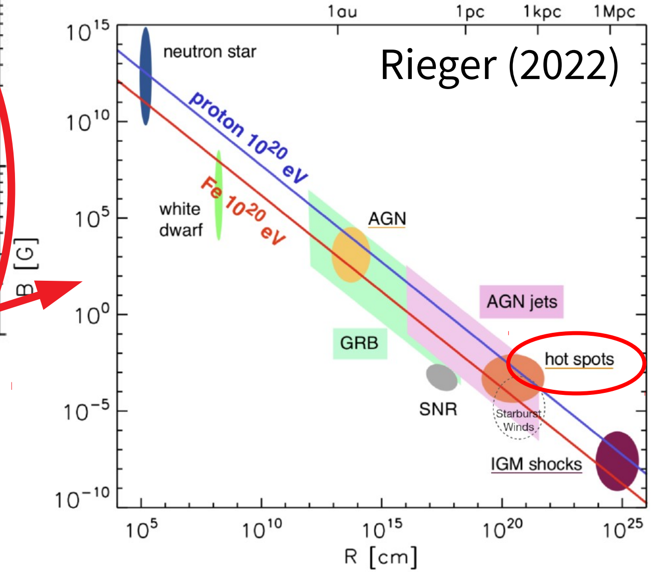


Hillas criterion (Hillas 1984):

R_g <~ size source

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

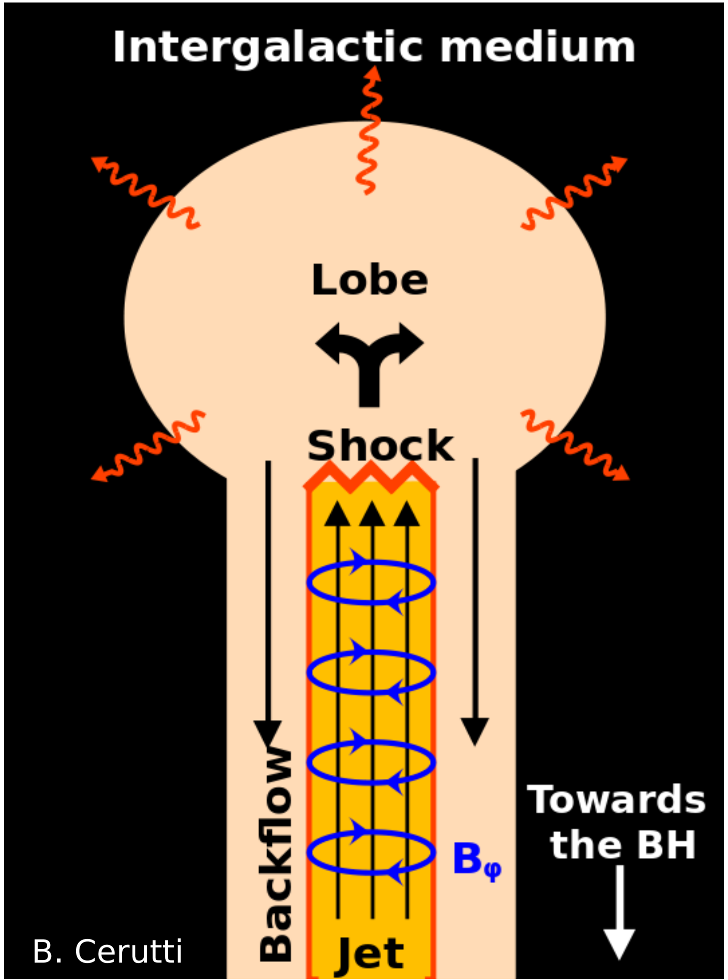


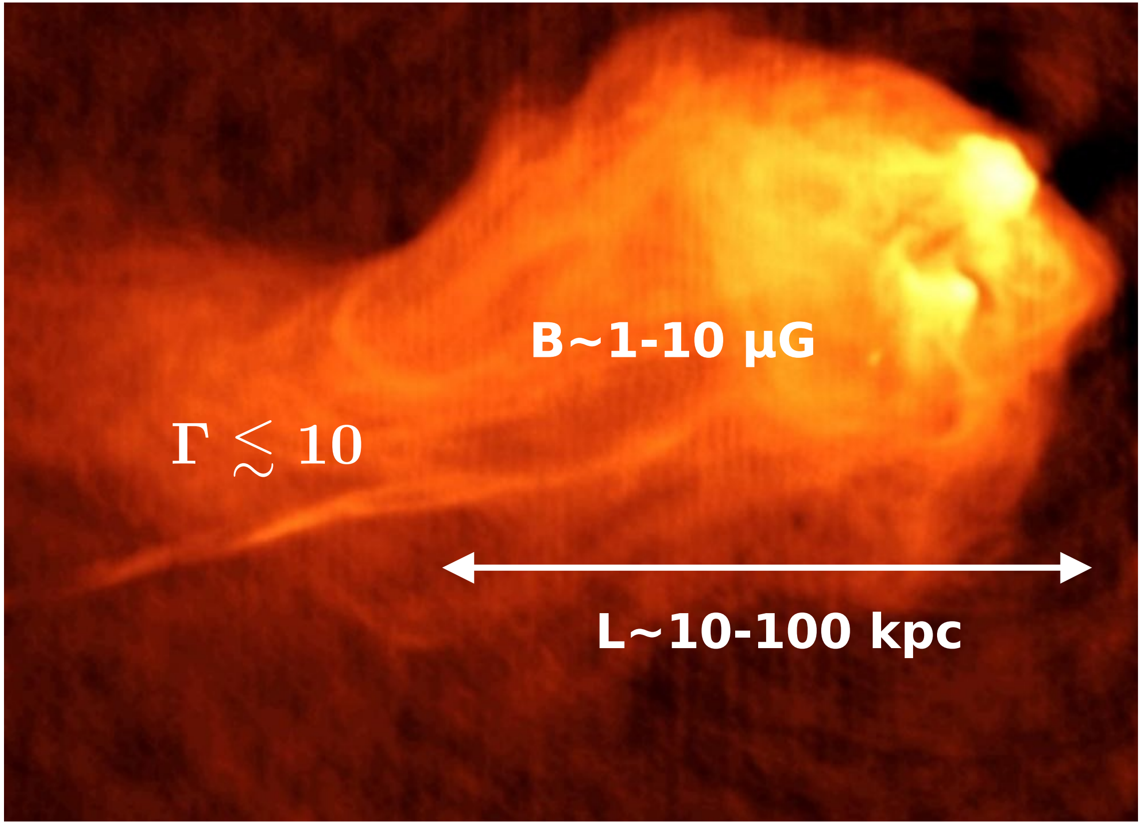
→ **AGN jet hotspots/lobes could confine UHECRs.**

→ **But can they be accelerated there?**

Jet Termination Shock Region

Blandford et al. 2019, Hardcastle & Croston 2020, Gabuzda 2021,...

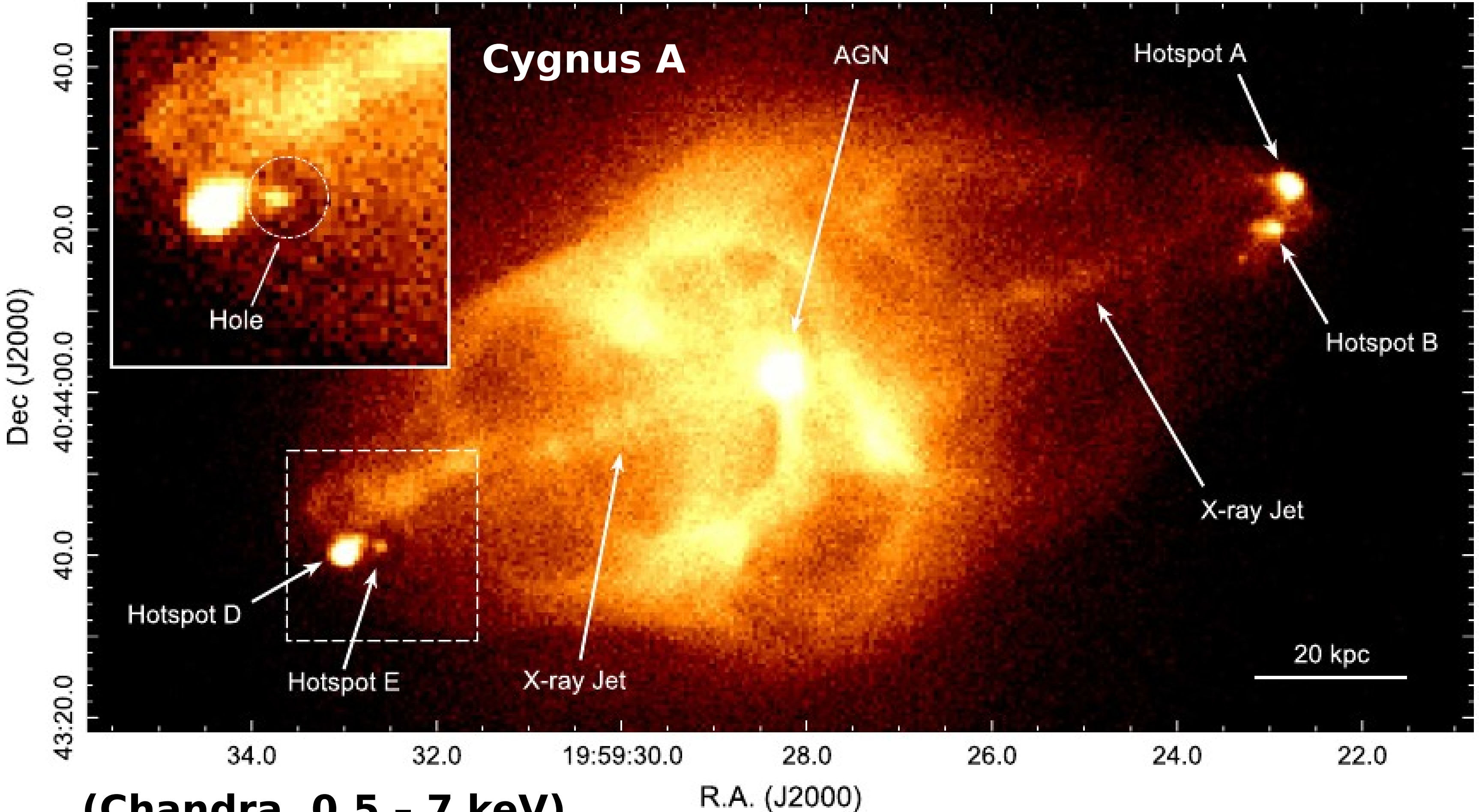




Magnetization: $\sigma \sim$ 0.01 – 1.

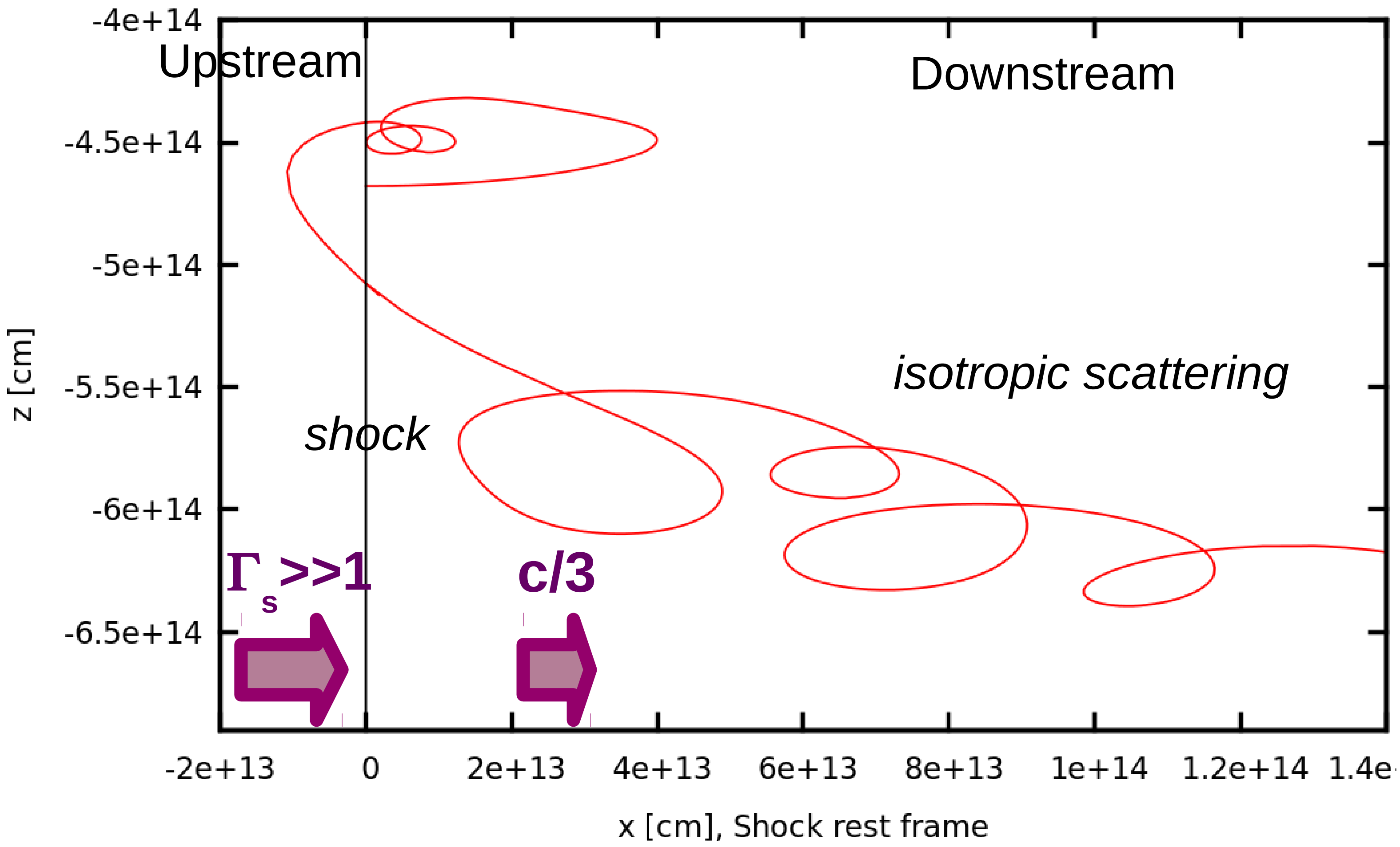
In-situ part. acceleration: Cygnus A hotspots

The Astrophysical Journal, 891:173 (10pp), 2020 March 10 Snios et al.



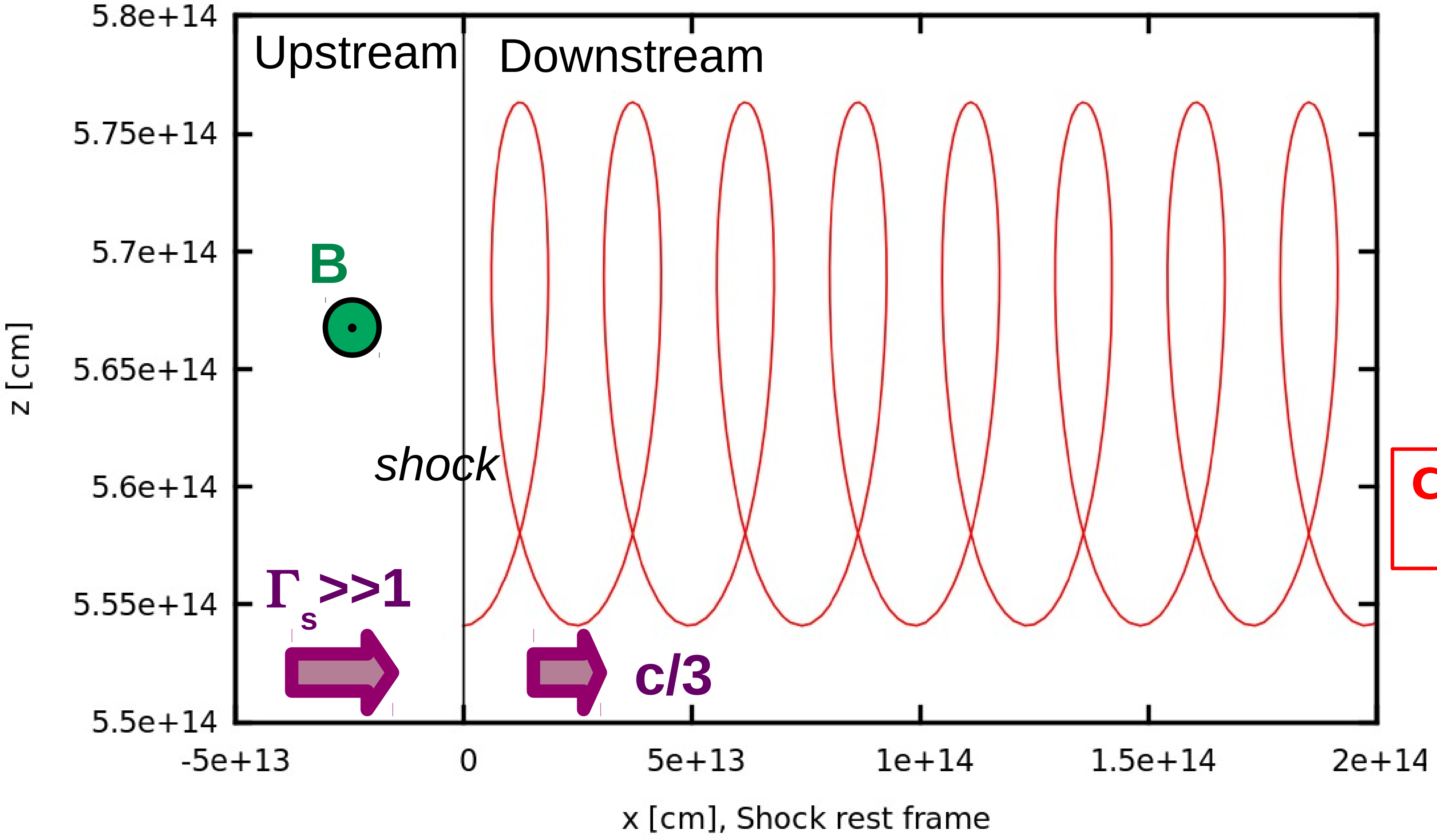
(Chandra, 0.5 – 7 keV)

Particle acceleration - relativistic shocks



$E^{-2.2}$ spectrum at ultra-relativistic shocks.

At relativistic perpendicular shocks...



1st-order Fermi inefficient !

Cannot accelerate CRs at jet TS !!

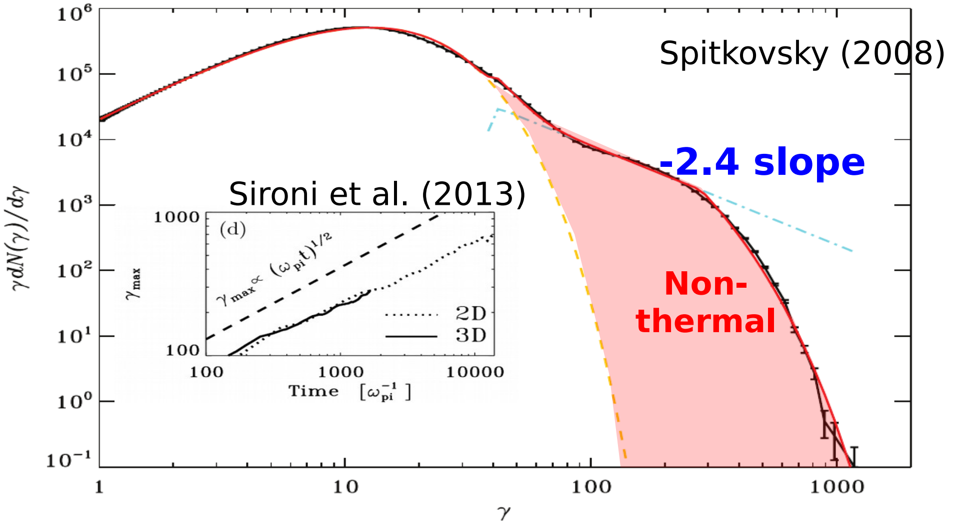
And particle-In-Cell (PIC) simulations ?

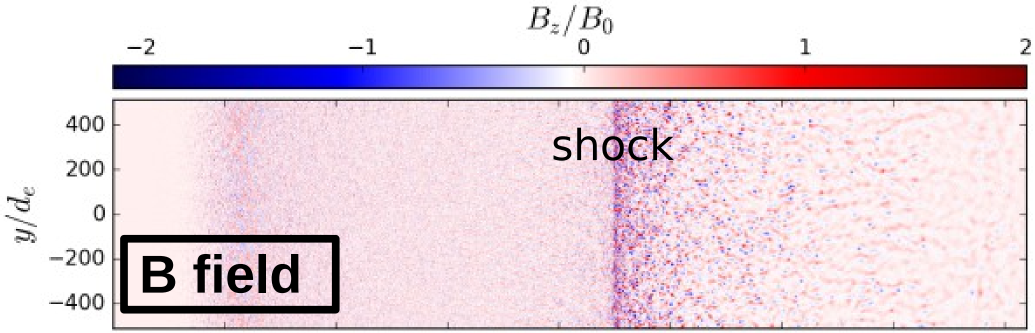
→ **Unmagnetized case (σ=0):**

Spitkovsky (2008), Sironi + (2013), Plotnikov+ (2018), Lemoine+ (2019)

Good but slow accelerators.

Maximum energy grows as $t^{1/2}$
(Reville & Kirk 2010, Plotnikov et al. 2013)





Weibel-dominated shock: Fermi-acceleration on small-scale plasma turbulence

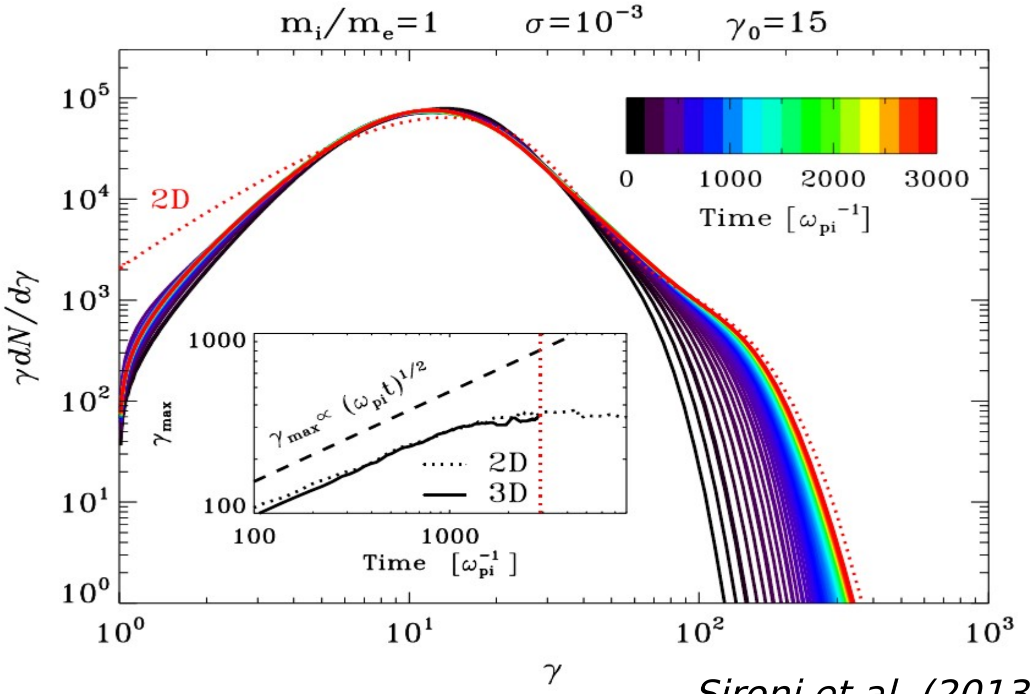
And particle-In-Cell (PIC) simulations ?

→ **<u>Magnetized case</u> (σ>10^{-3}):**

Even weak magnetization levels stop particle acceleration.

E_{max} quickly saturates.

Cannot accelerate CRs to UHE at jet TS !!



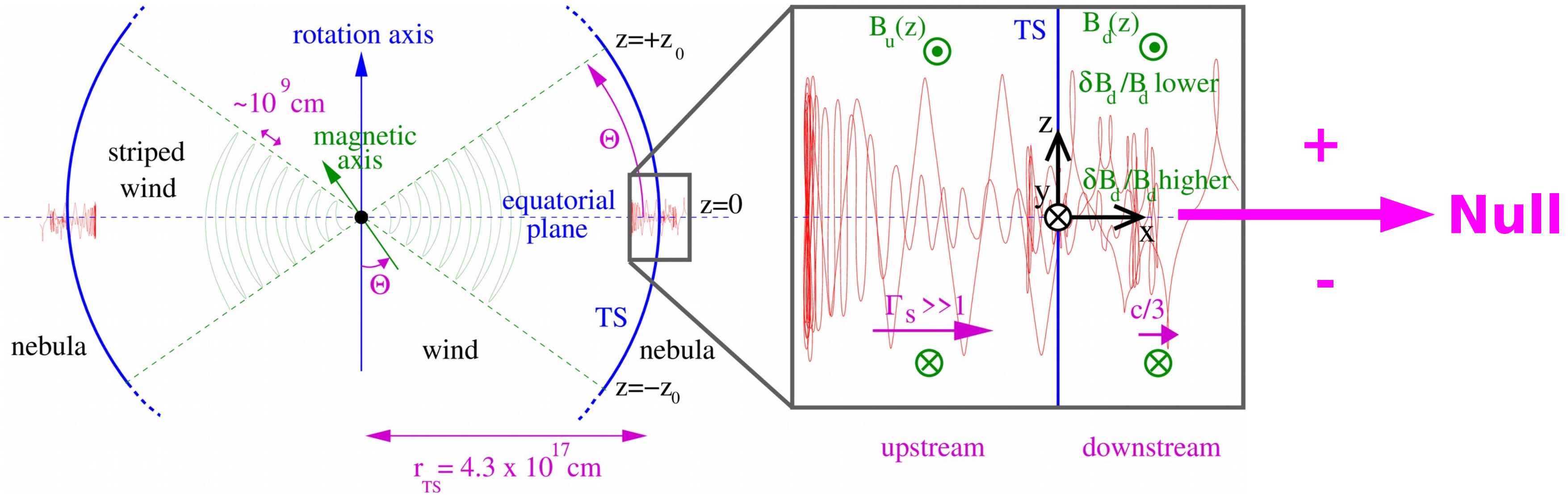
Sironi et al. (2013)

Our solution: Global B field geometry

This was for **plane-parallel**, **homogeneous** shocks…

GLOBAL GEOMETRY OF THE MAGNETIC FIELD CAN SOLVE THE PROBLEM!

See **Giacinti & Kirk (2018)** for Pulsar Wind Nebulae :



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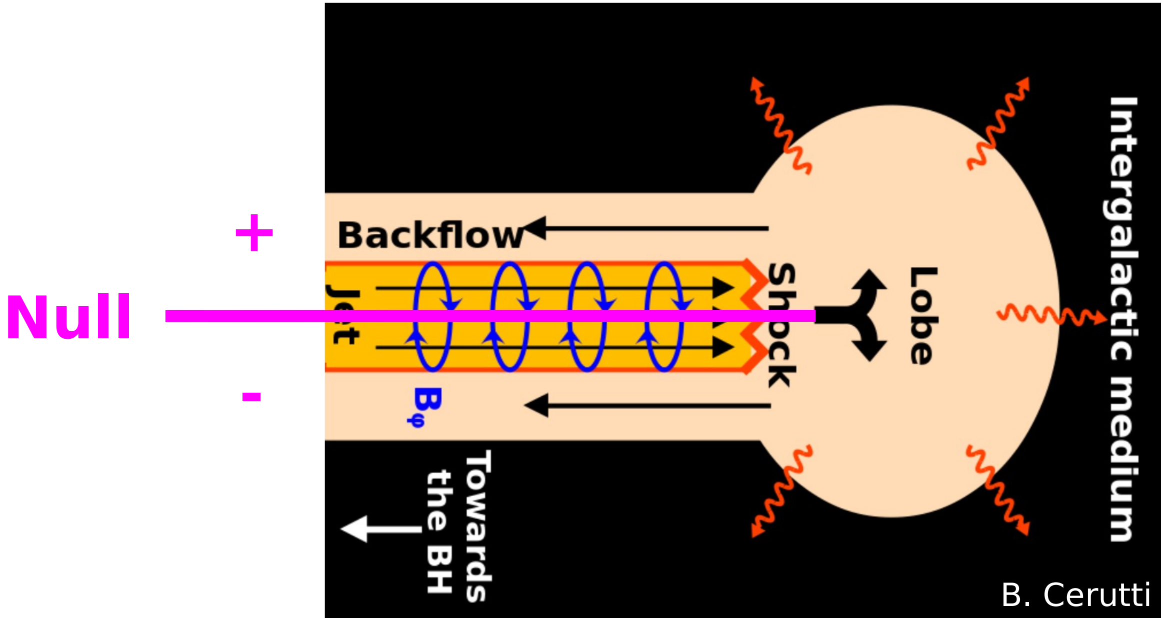
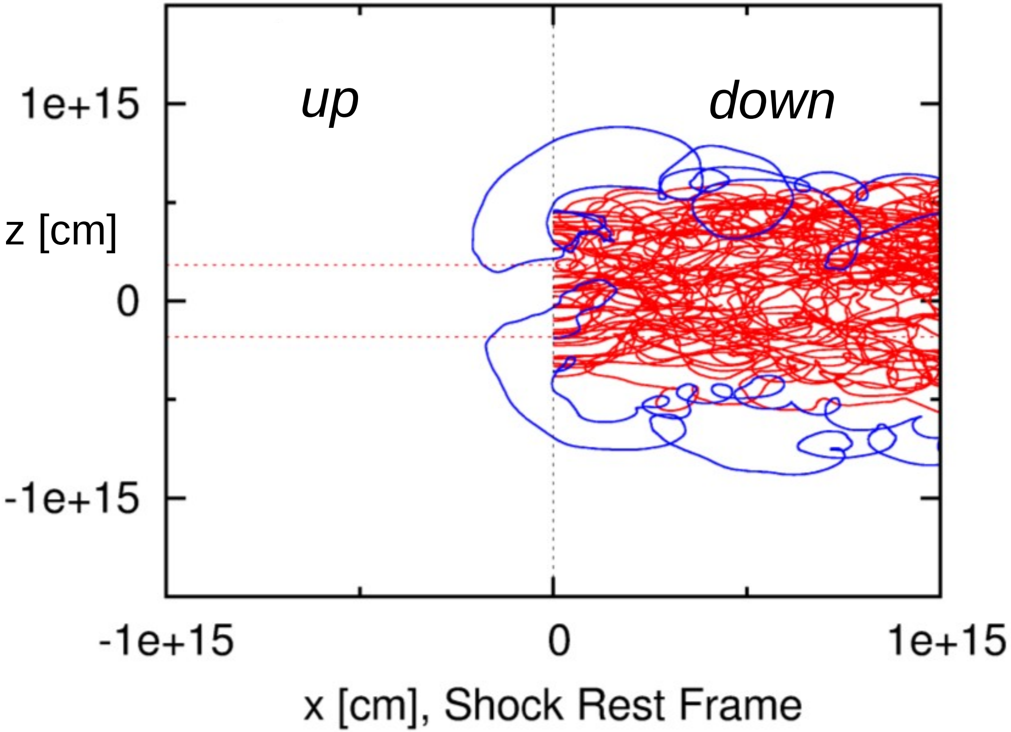


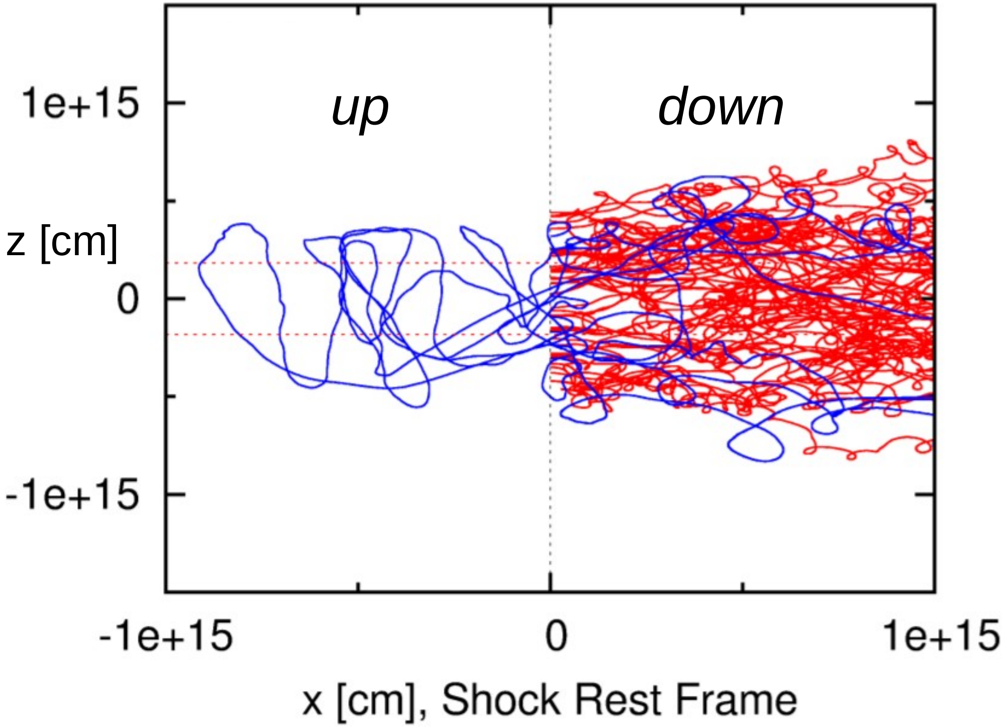
Numerical simulation (GG & Kirk 2018)

Positrons :



No/little acceleration

Electrons :



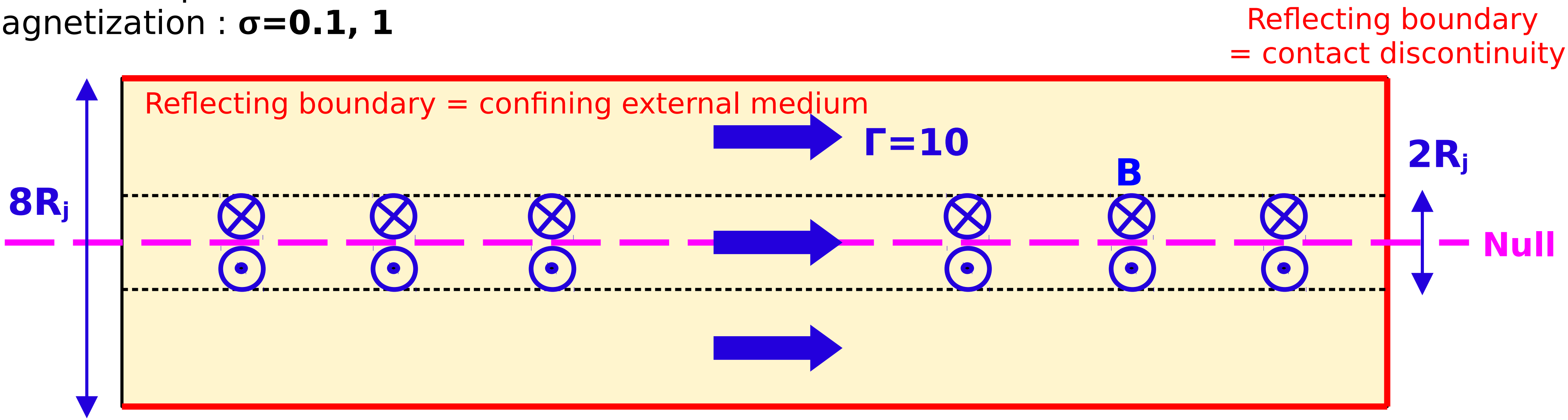
Acceleration

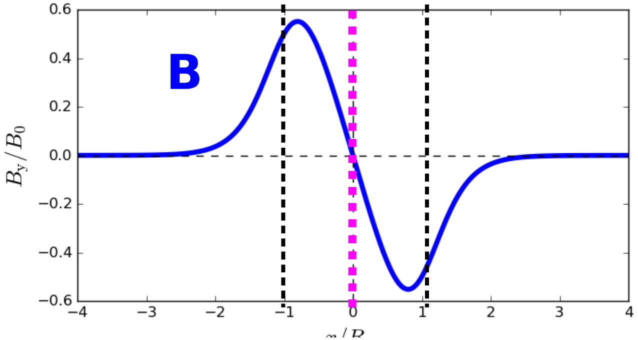
Particle-In-Cell (PIC) setup

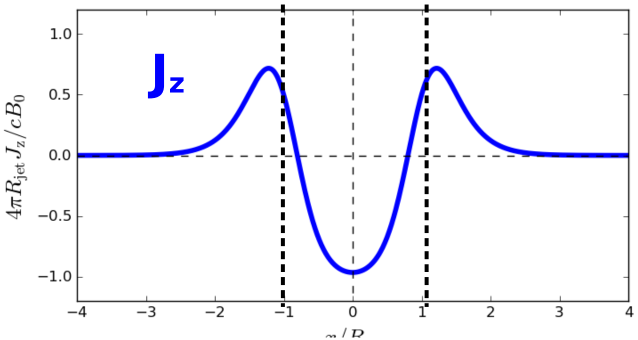
2D Cartesian box (xz-plane), **262,144×16,384 cells, or 6554x410 d_i (ion skin depth)**

Electron-ion plasma with **m_i/m_e=25**

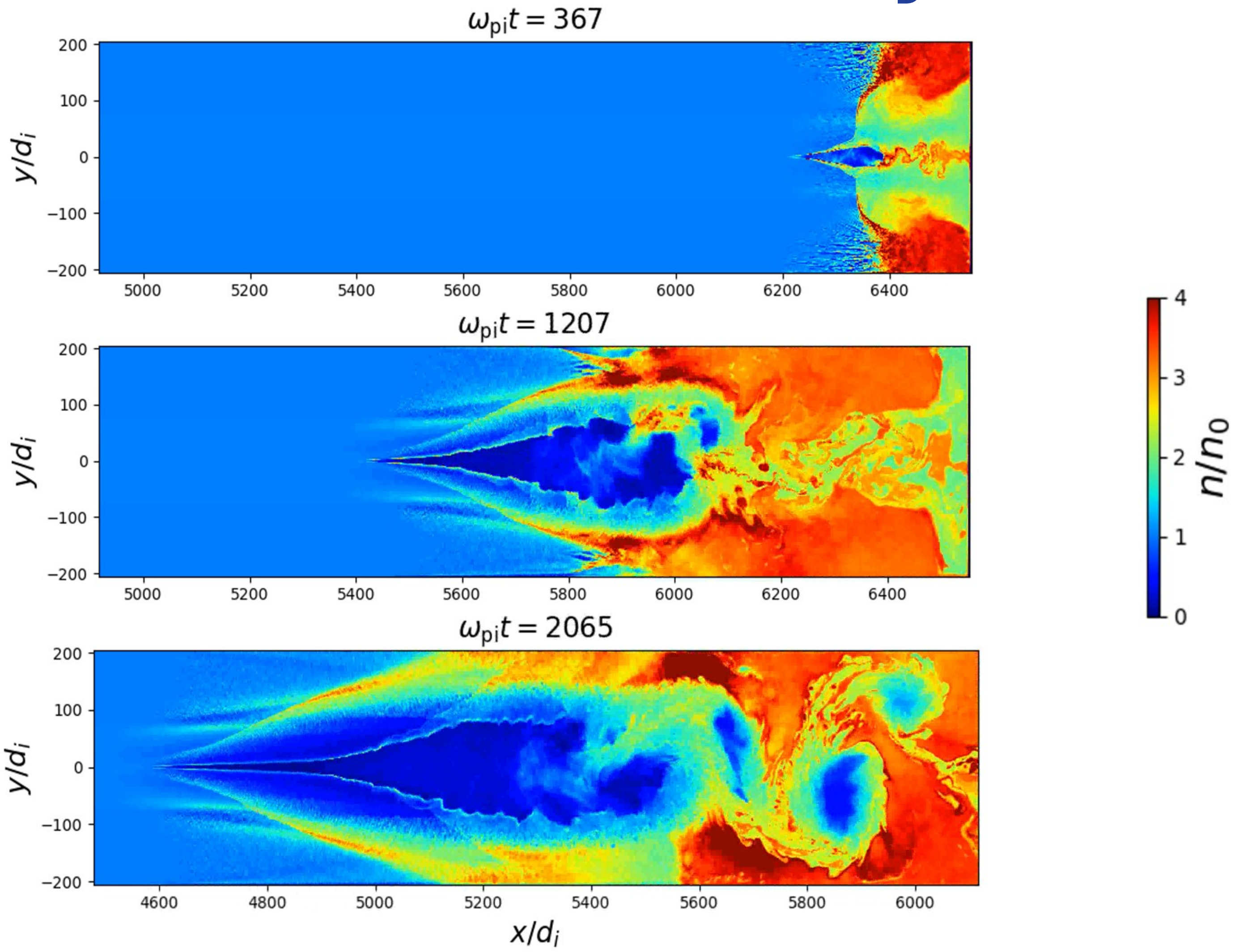
Magnetization : **σ=0.1, 1**



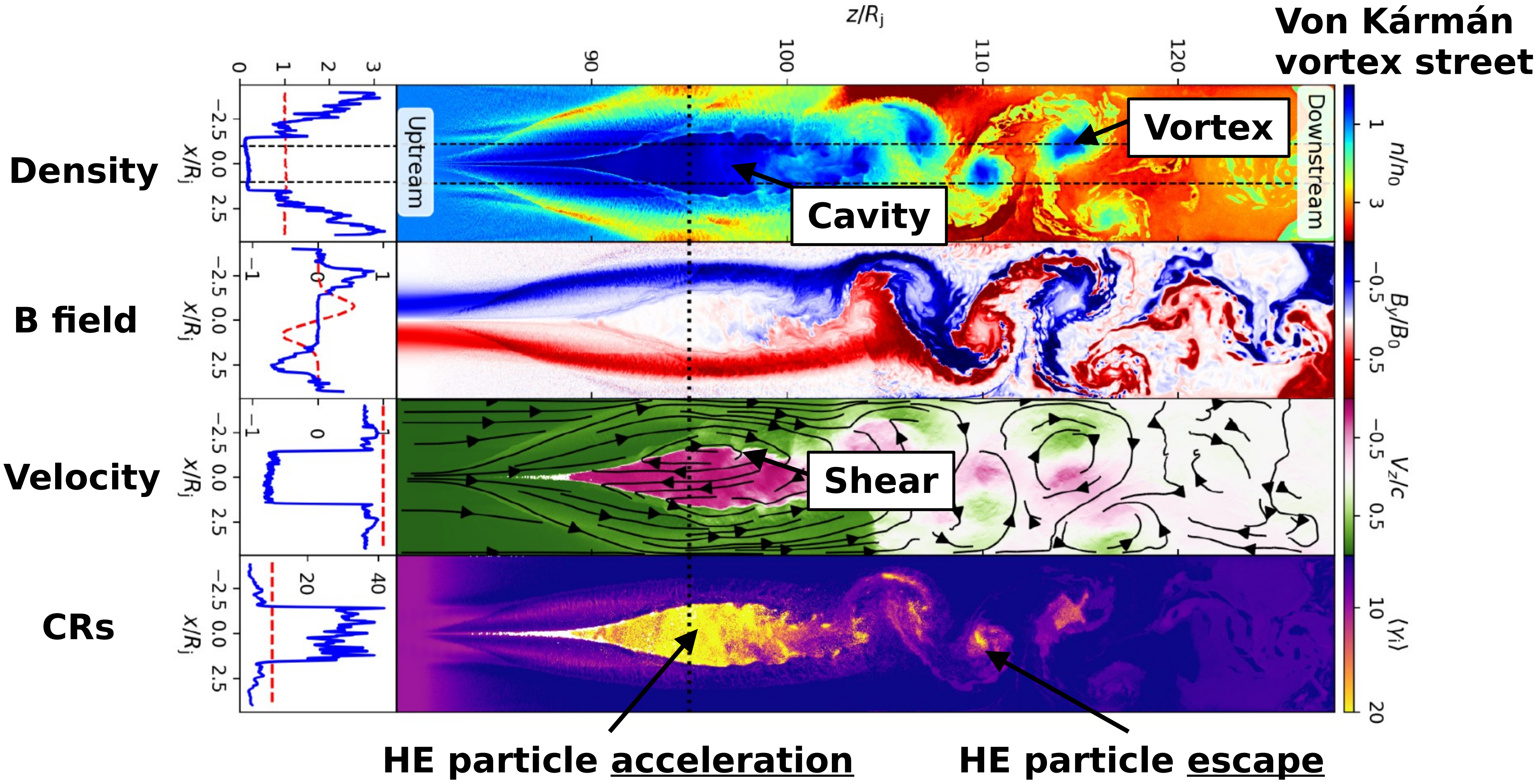




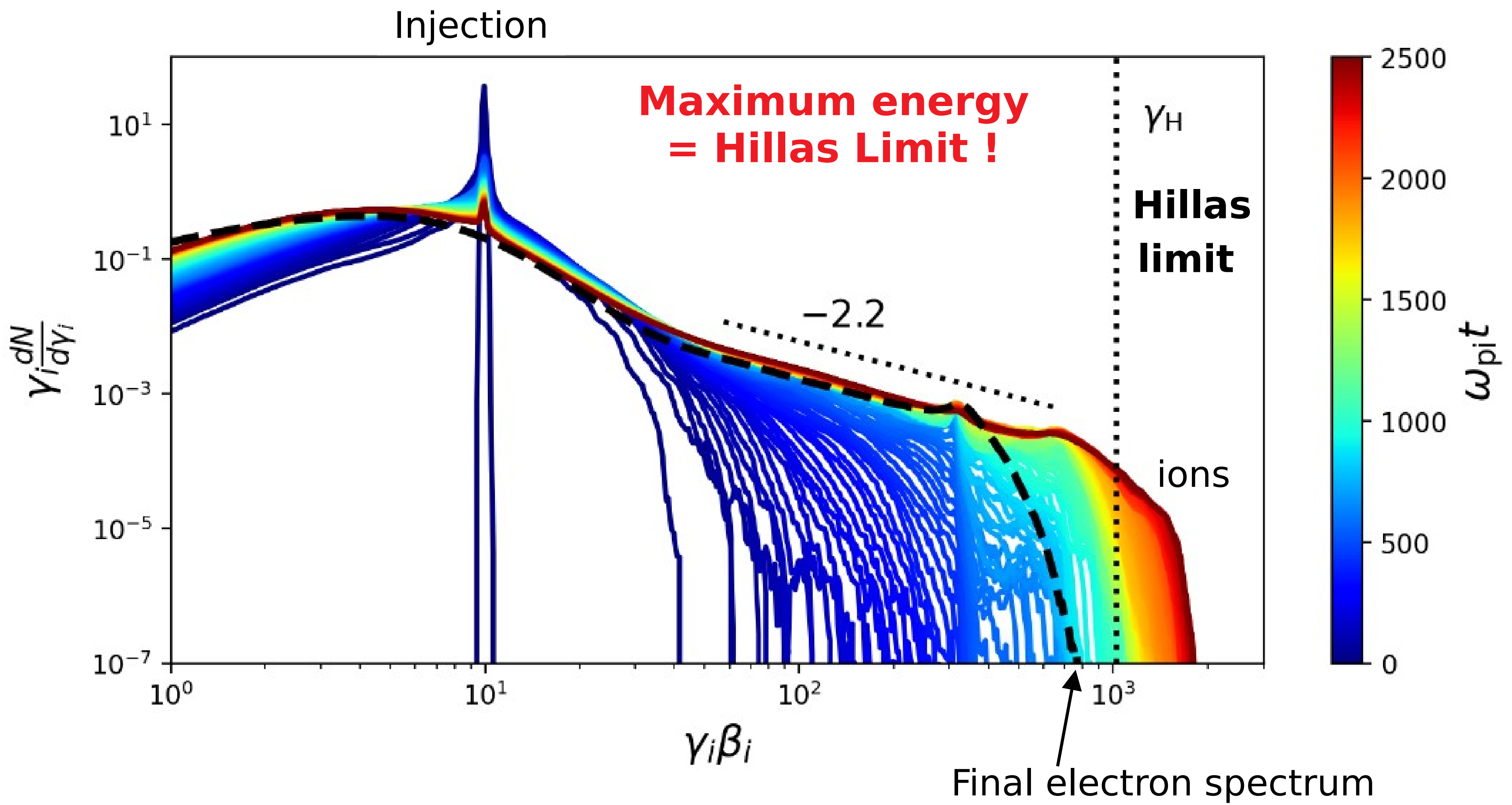
Results PIC Sim.: Density evolution



Results – PIC Simulations

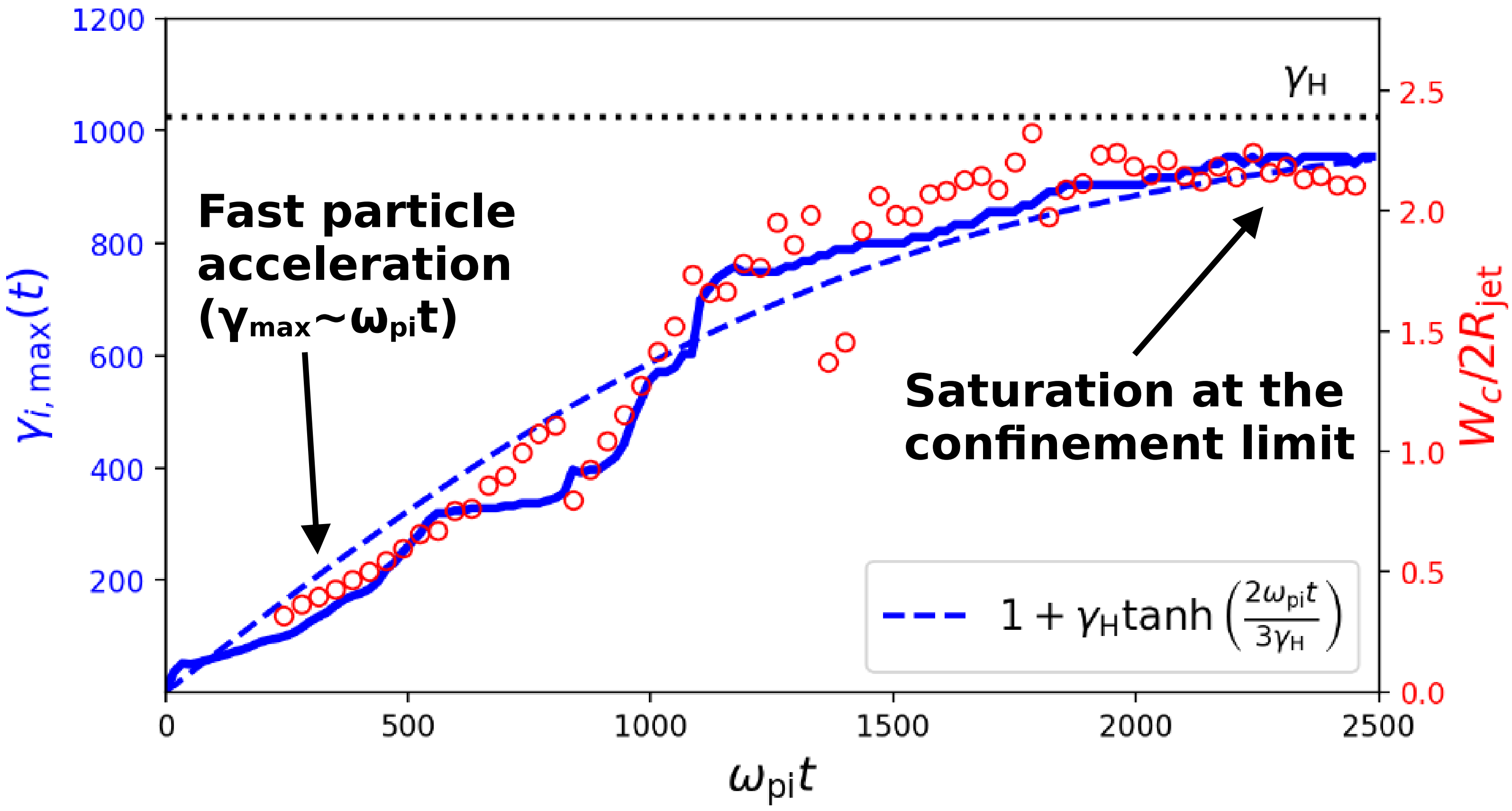


Ion spectrum: Time Evolution & E_{max}



E_{max} ions & Cavity size: Time Evolution

Max. particle energy



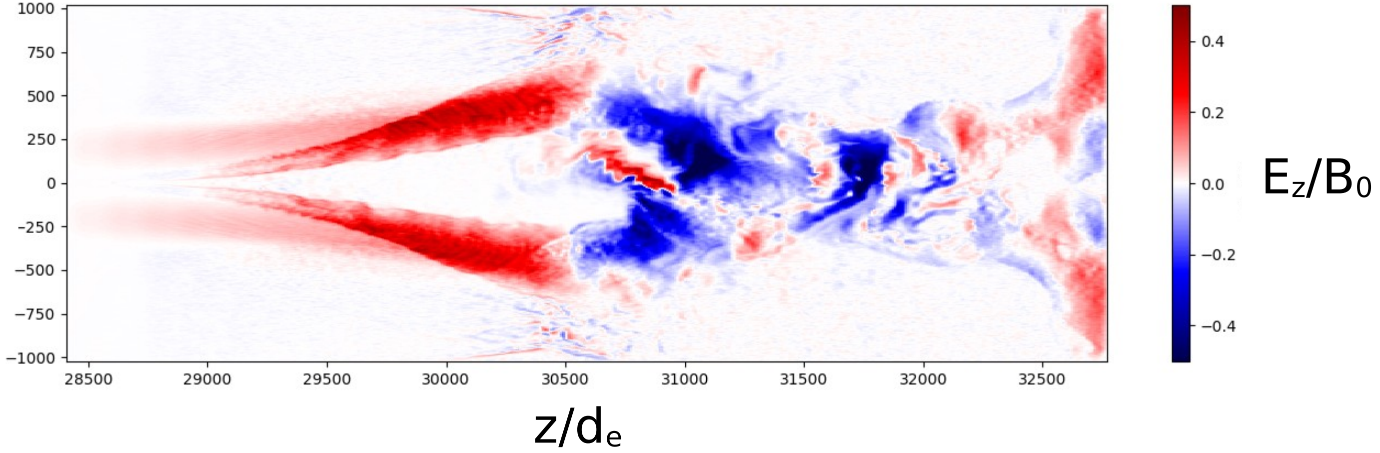
Width of the cavity

Maximum particle energy grows as the width of the cavity.
Cavity stops growing at ~ width jet => **Coincides w/ a naive Hillas criterion eval.**

Particle acceleration mechanism

→ Not standard shock acceleration mechanism here...
→ Shear-flow acceleration at the edges of the cavity instead

Ideal motion E field in the lab frame: $\mathbf{E} = -\dfrac{\mathbf{V}\times\mathbf{B}}{c}$



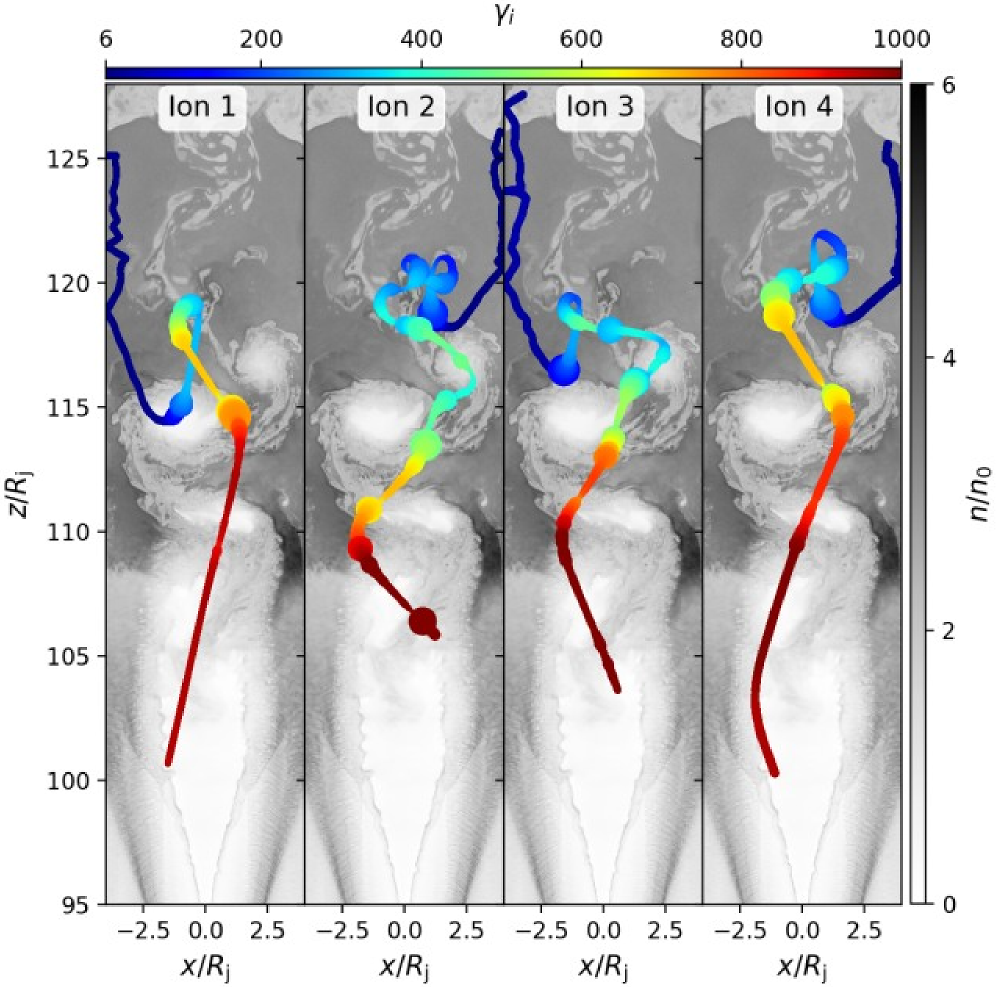
Acceleration rate:

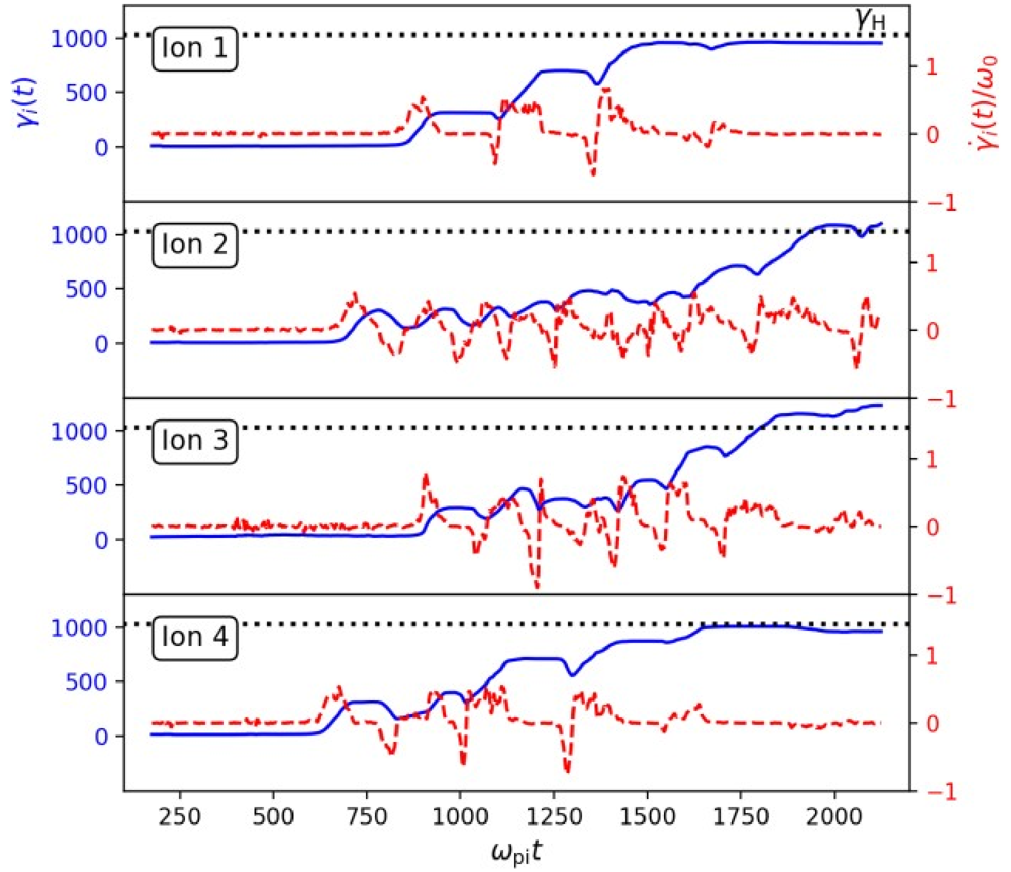
$$\dot{\gamma} = \frac{e}{m_i c}\mathbf{E}\cdot\boldsymbol{\beta} \approx 0.5\omega_0$$

$\sim$ cst (indpt of ene.)

$$\boxed{\gamma_{\mathrm{i}}(t) \propto t}$$

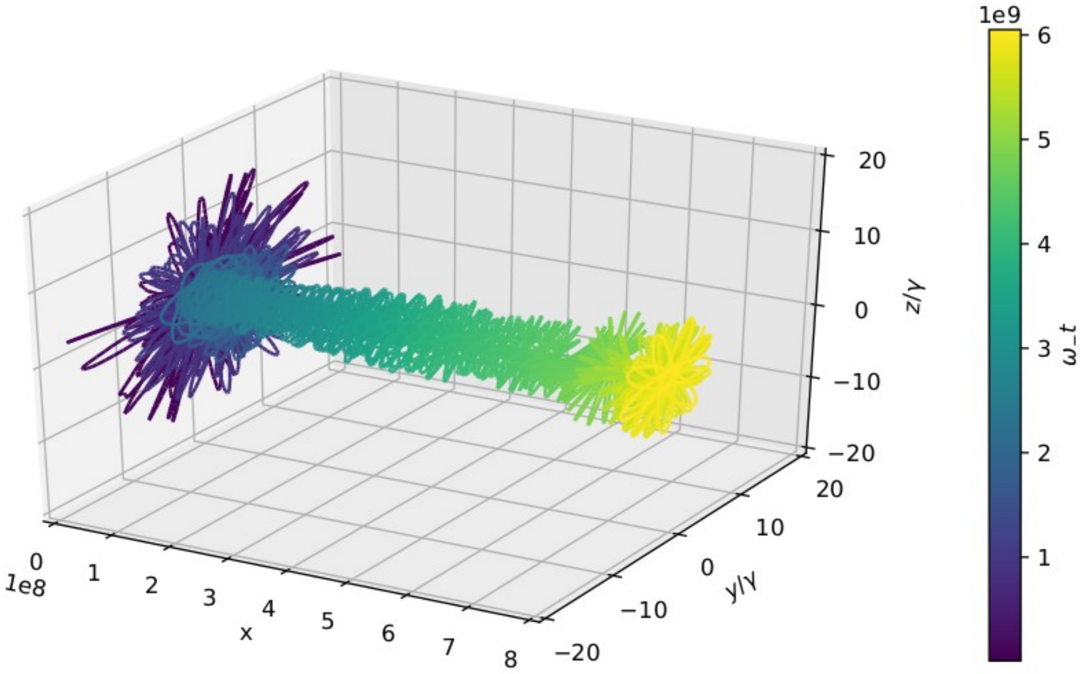
Particle acceleration mechanism

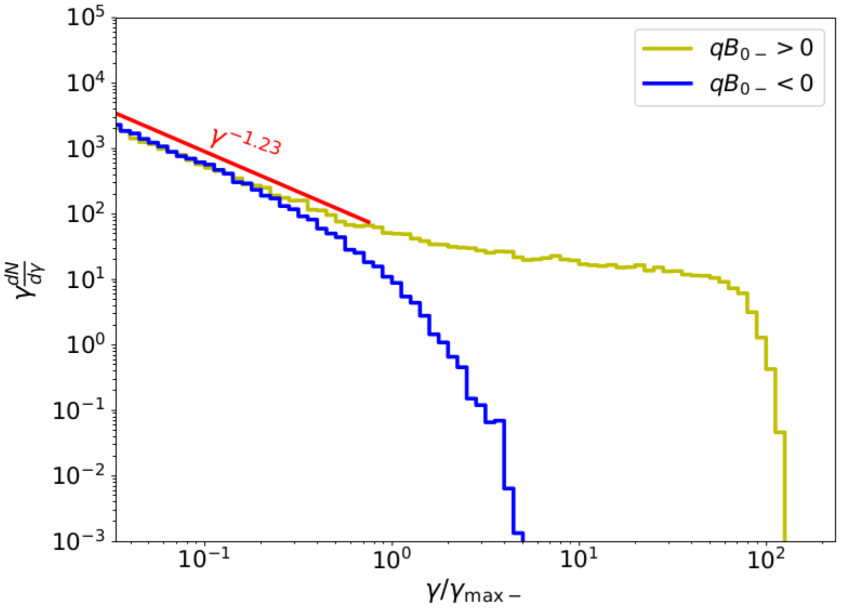




Particle acceleration mechanism

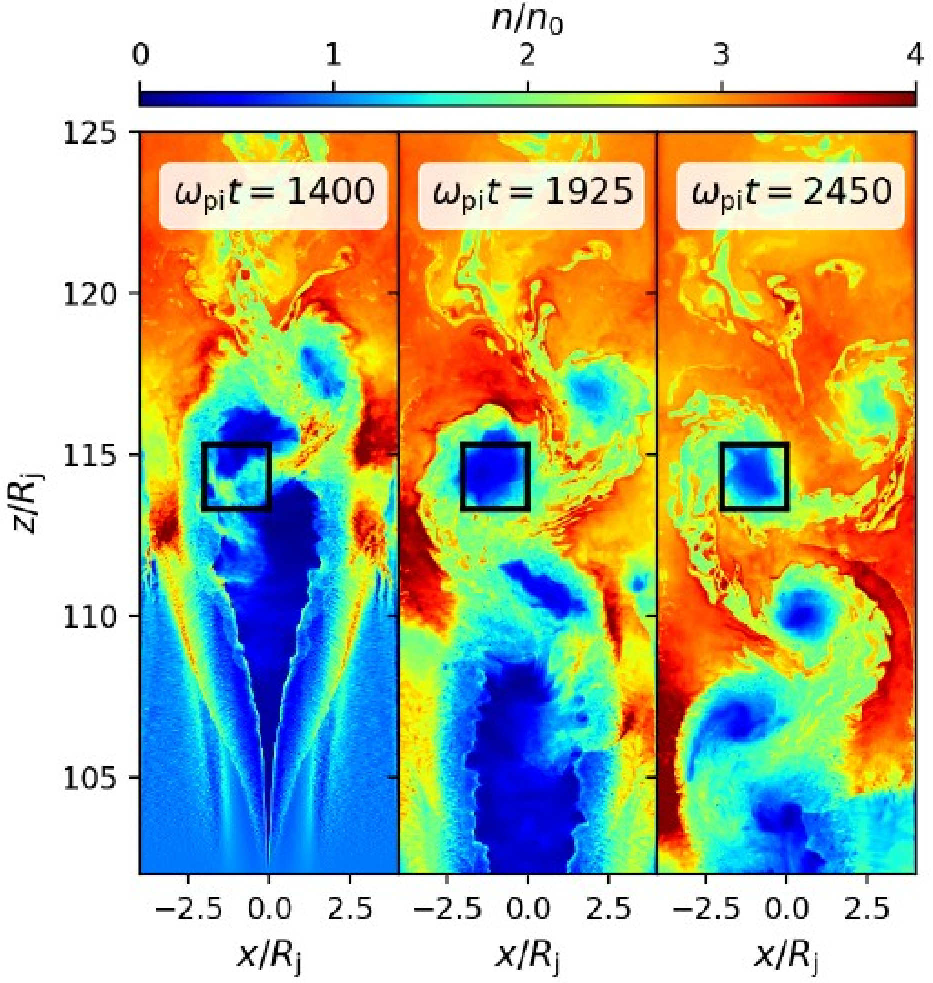
→ Though shock acceleration if CR pressure is not too large (i.e. in test-particle limit):
Huang, Reville, Kirk, GG, MNRAS 522, 4955 (2023)

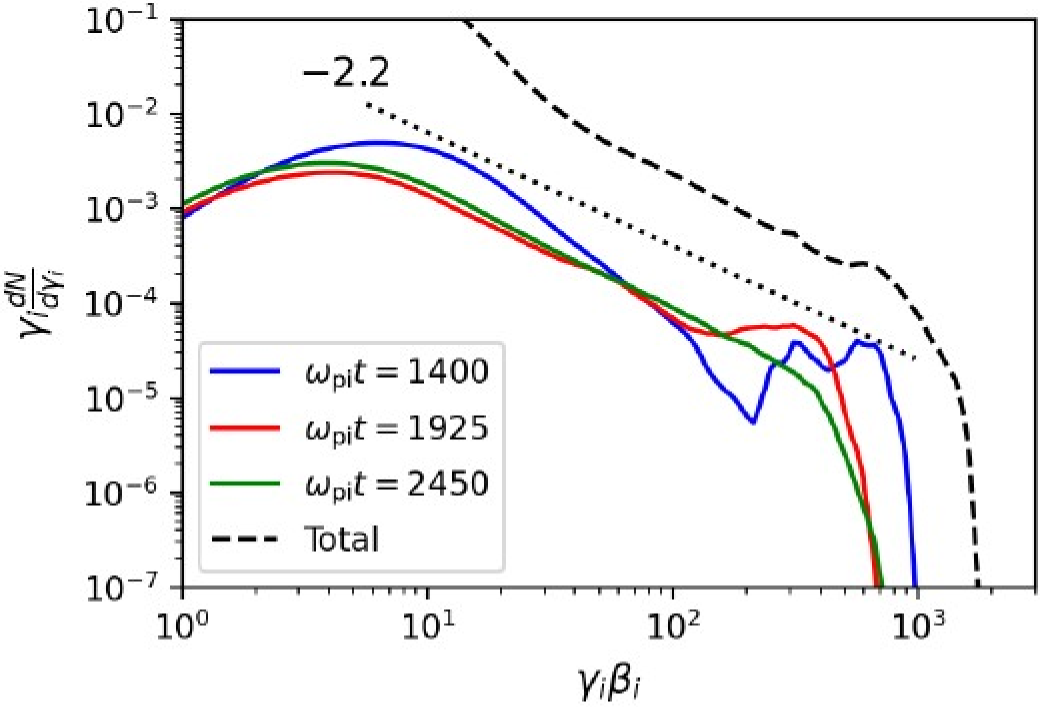




Key point: Particles (w/ correct sign of charge) remain around the null point

Mechanism for VHE particle escape



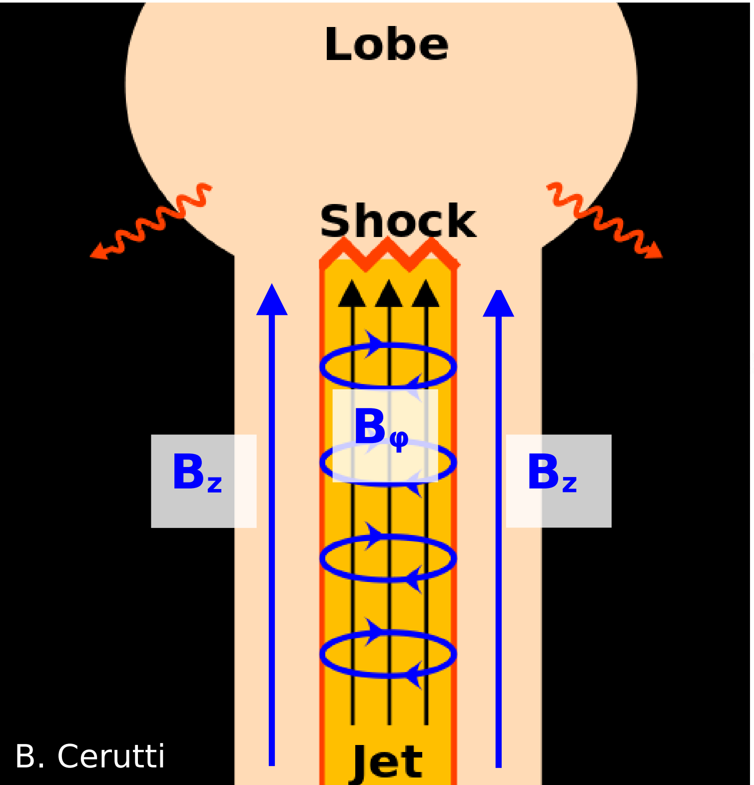


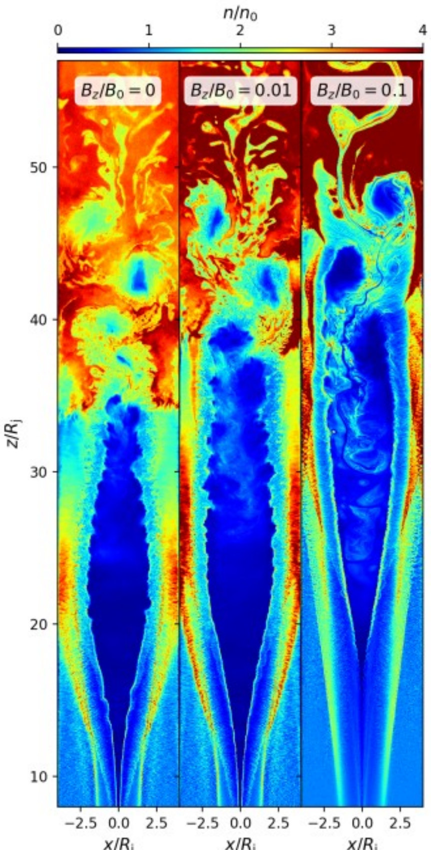
→ Particles **escape** (downstream) **in von Kármán vortices**.

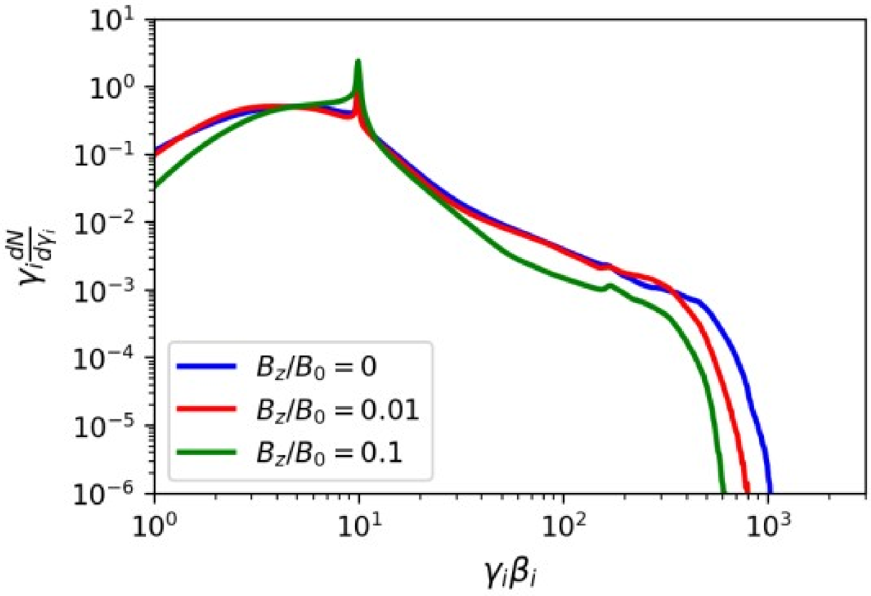
→ They suffer almost **no E losses**.

Effect of a poloidal B field component

If sub-dominant (**B_z<B_φ**), particle acceleration remains efficient
(as expected in the jet TS region)

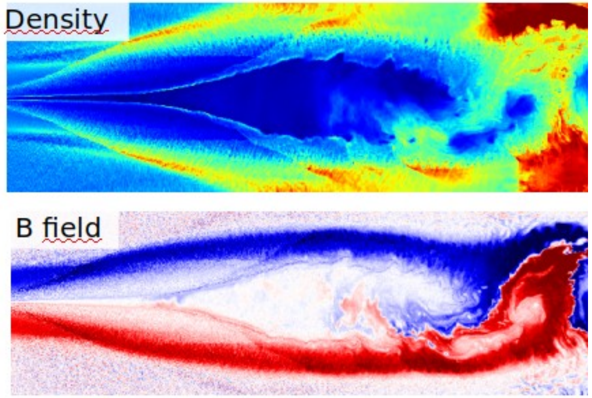




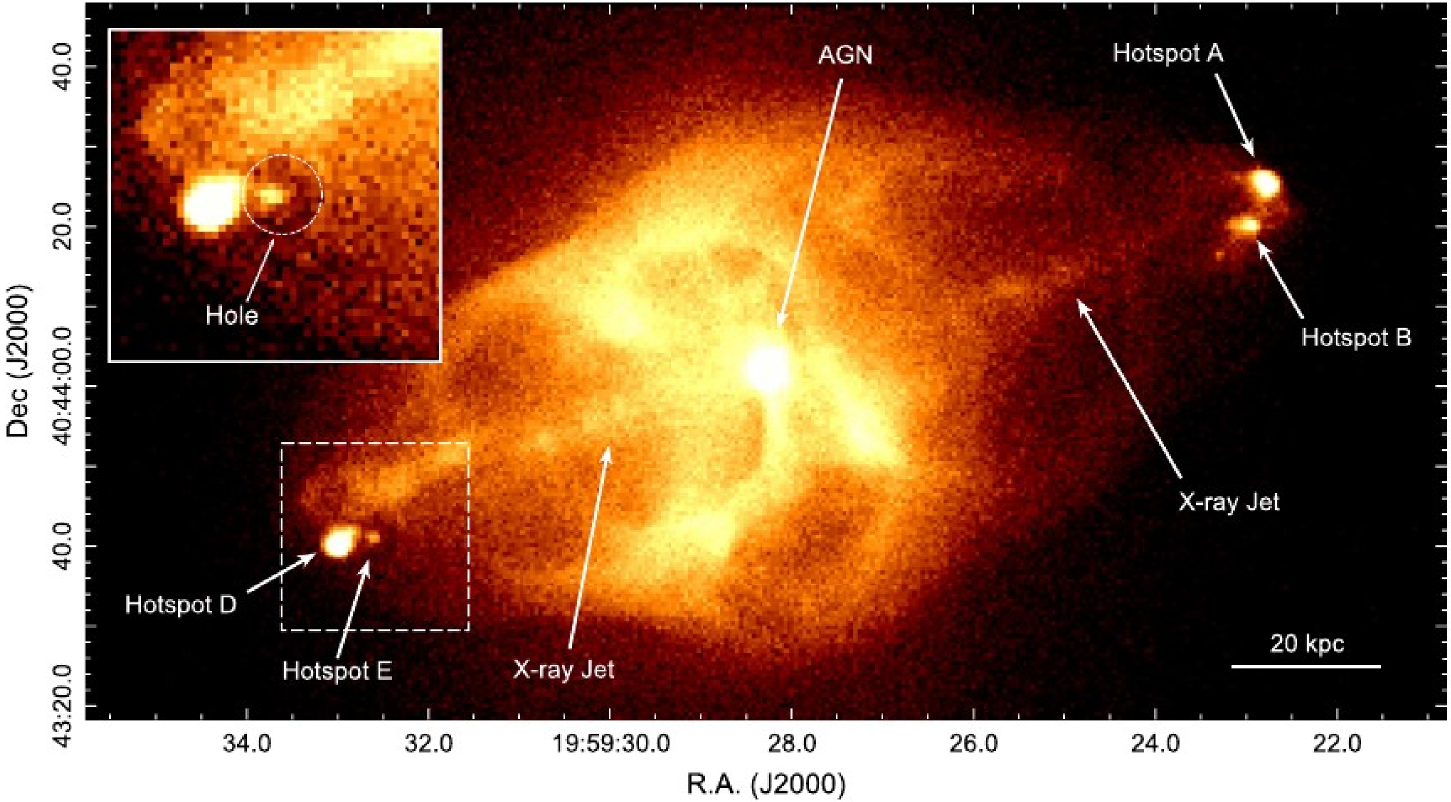


Observational test / evidence ?

Cavity might appear as under-luminous hole.



THE ASTROPHYSICAL JOURNAL, 891:173 (10pp), 2020 March 10 Snios et al.



Conclusions & Perspectives

- **Global structure of the magnetic field key to accelerating particles,**
- **A CR cavity forms at the shock front around the B field ‘null’ point,**
  => Look for cavities!
- **Particles are accelerated at the shear flows around the cavity,**
- **Particles are accelerated to the Hillas Limit!**
  This mechanism could accelerate hadrons to UHEs at AGN jet TSs!
  … and to PeV in stellar-mass BH jets, e.g. in SS433,
- **CRs escape in the downstream in von Kármán vortices.**