PARTICLE ACCELERATION AT RELATIVISTIC SHOCKS: AGN JET TSs & PW TSs

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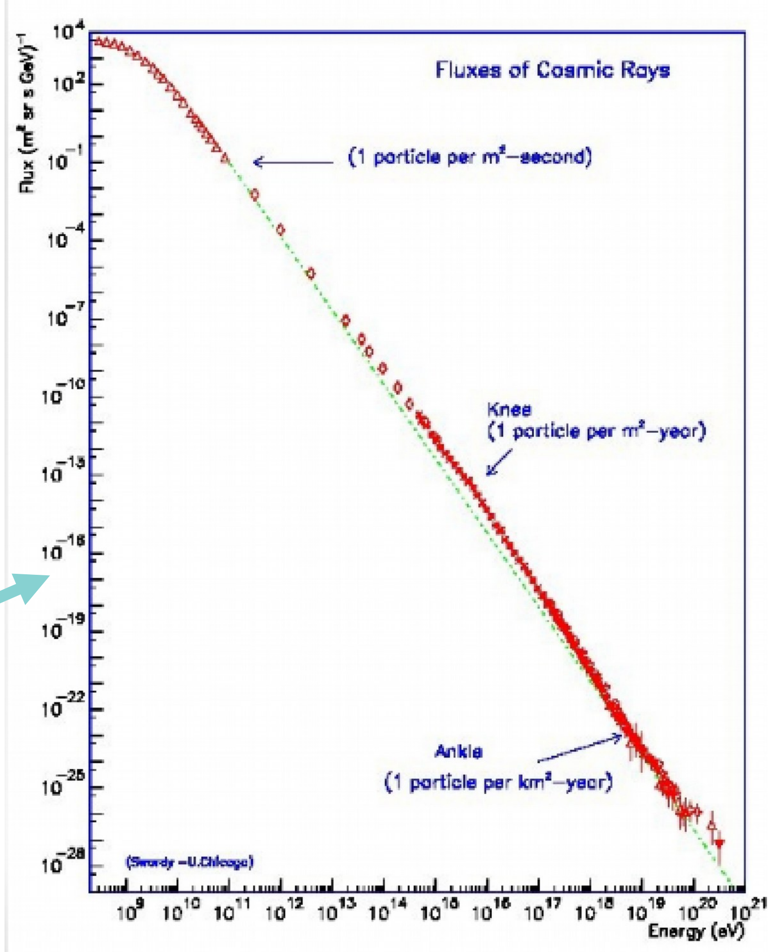
A&A 676, A23 (2023); arXiv:2303.12636

Cosmic-rays & their secondaries :

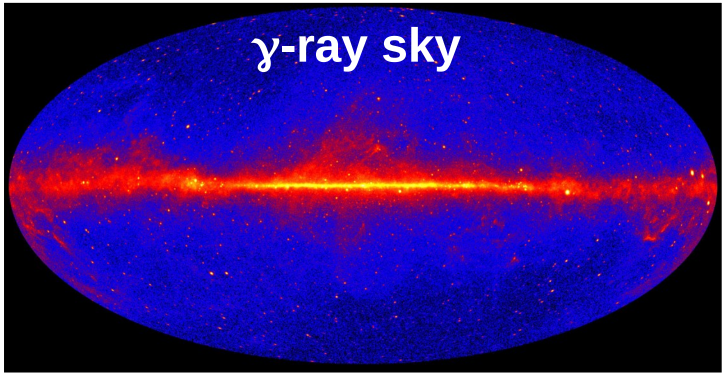
High-energy **particles (p^+,e^-,...) up** to **10^{20} eV.**



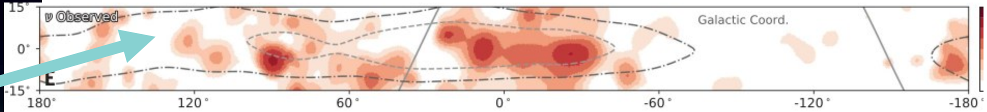
Cosmic-rays & their secondaries :

High-energy **particles (p^+,e^-,...) up to 10^{20} eV.**

Produce γ-rays, neutrinos:



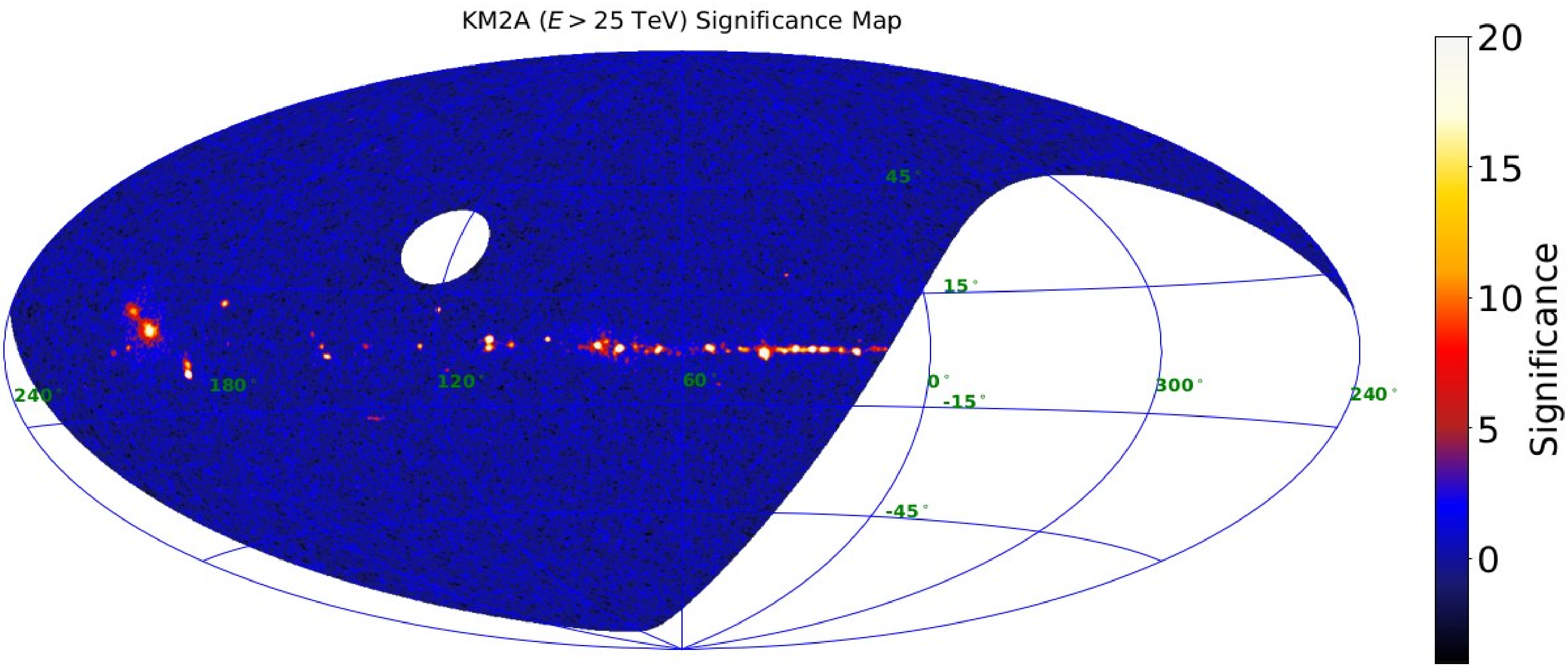
ν sky



PeV Gamma-Ray Astronomy: LHAASO

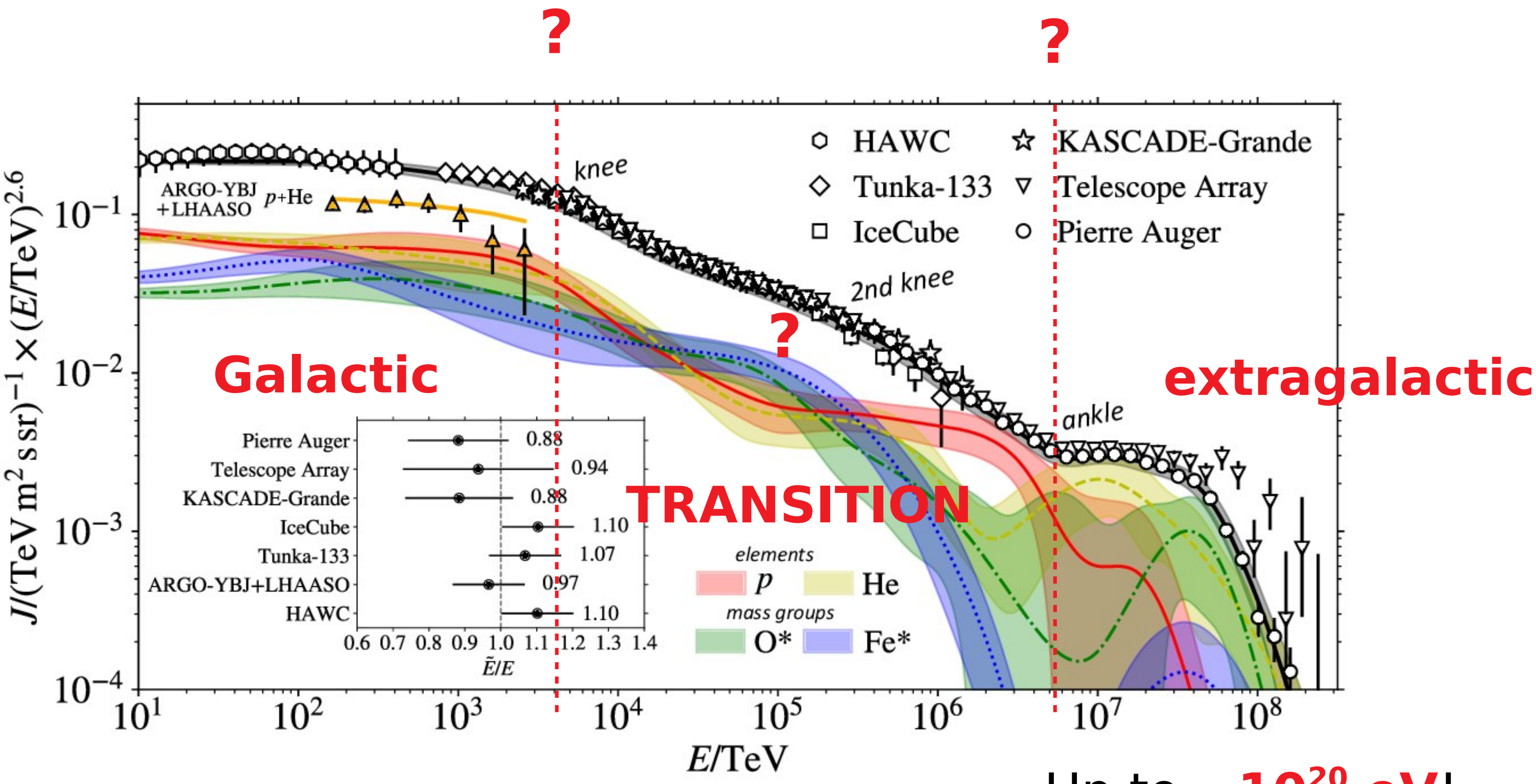
Sky at 25 TeV – 1 PeV with LHAASO

LHAASO Collaboration



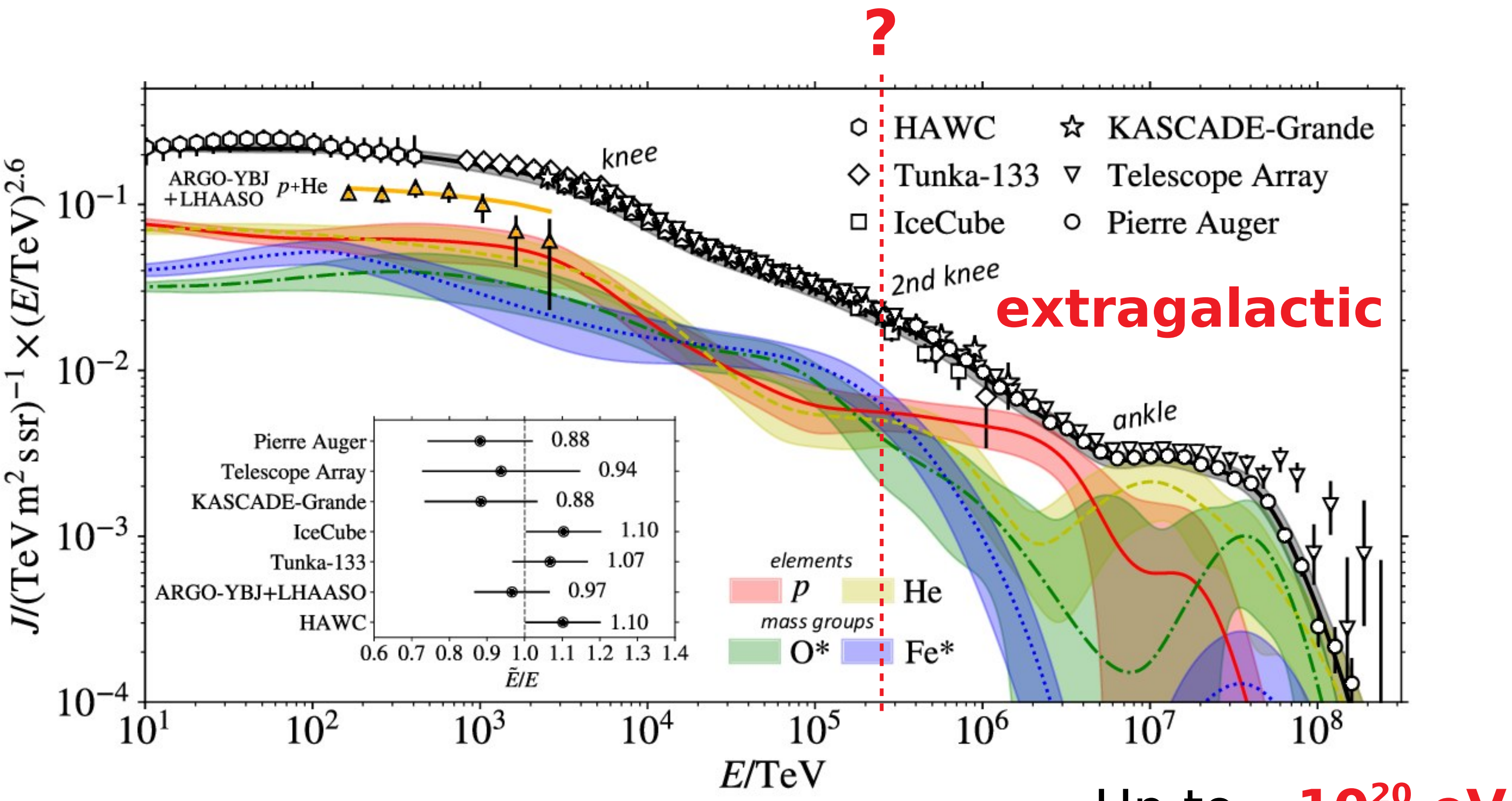
Hadronic PeVatrons: Stellar clusters ?; Many PWNe (leptonic) → Relativistic shock

Cosmic-Ray Spectrum



Up to **~10^{20} eV**!

Ultra-High Energy Cosmic-Rays



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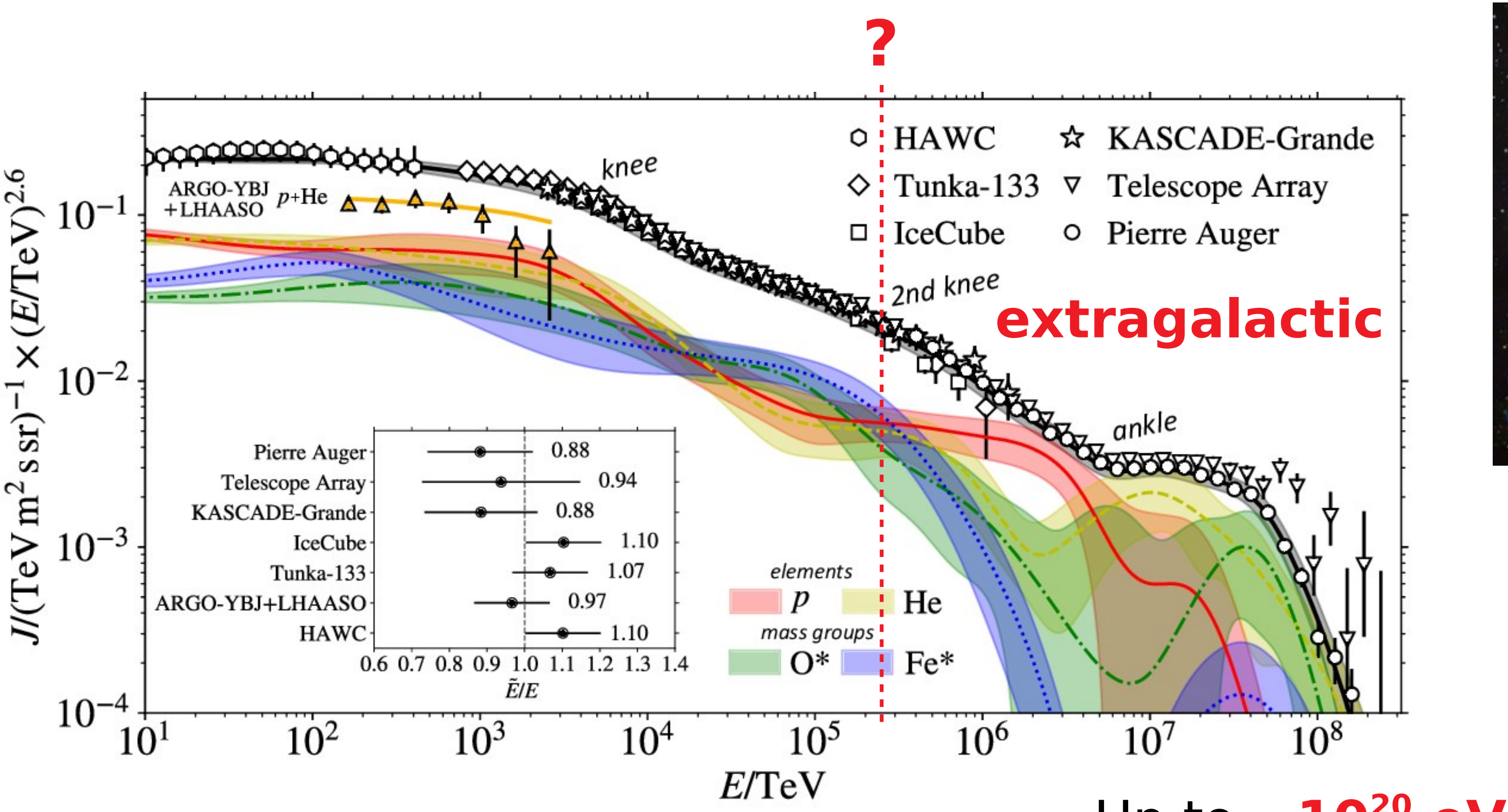
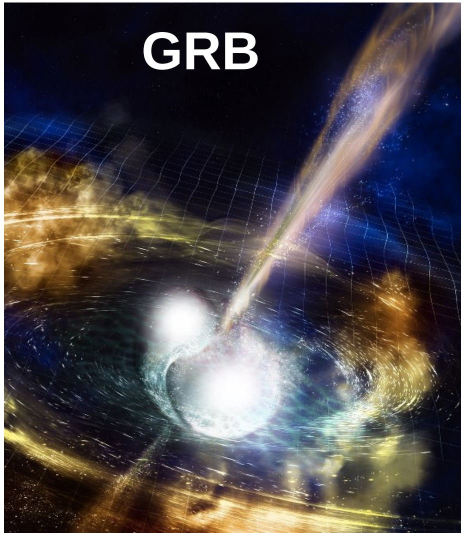
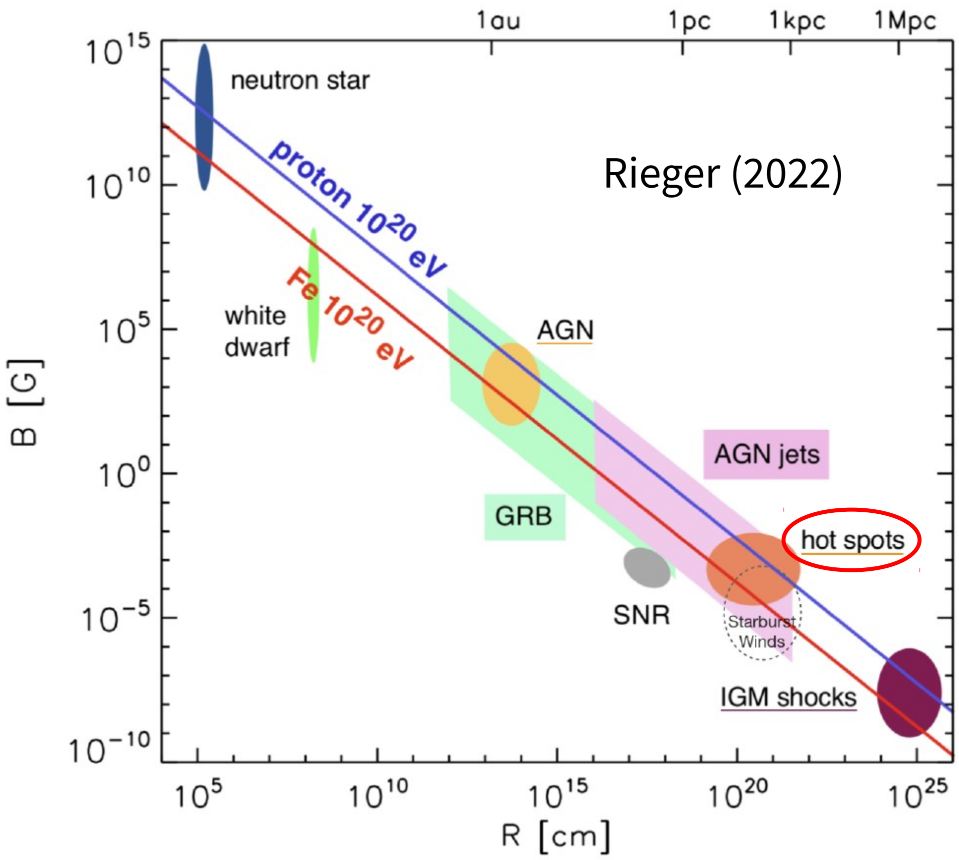




Up to **~10^{20} eV**!

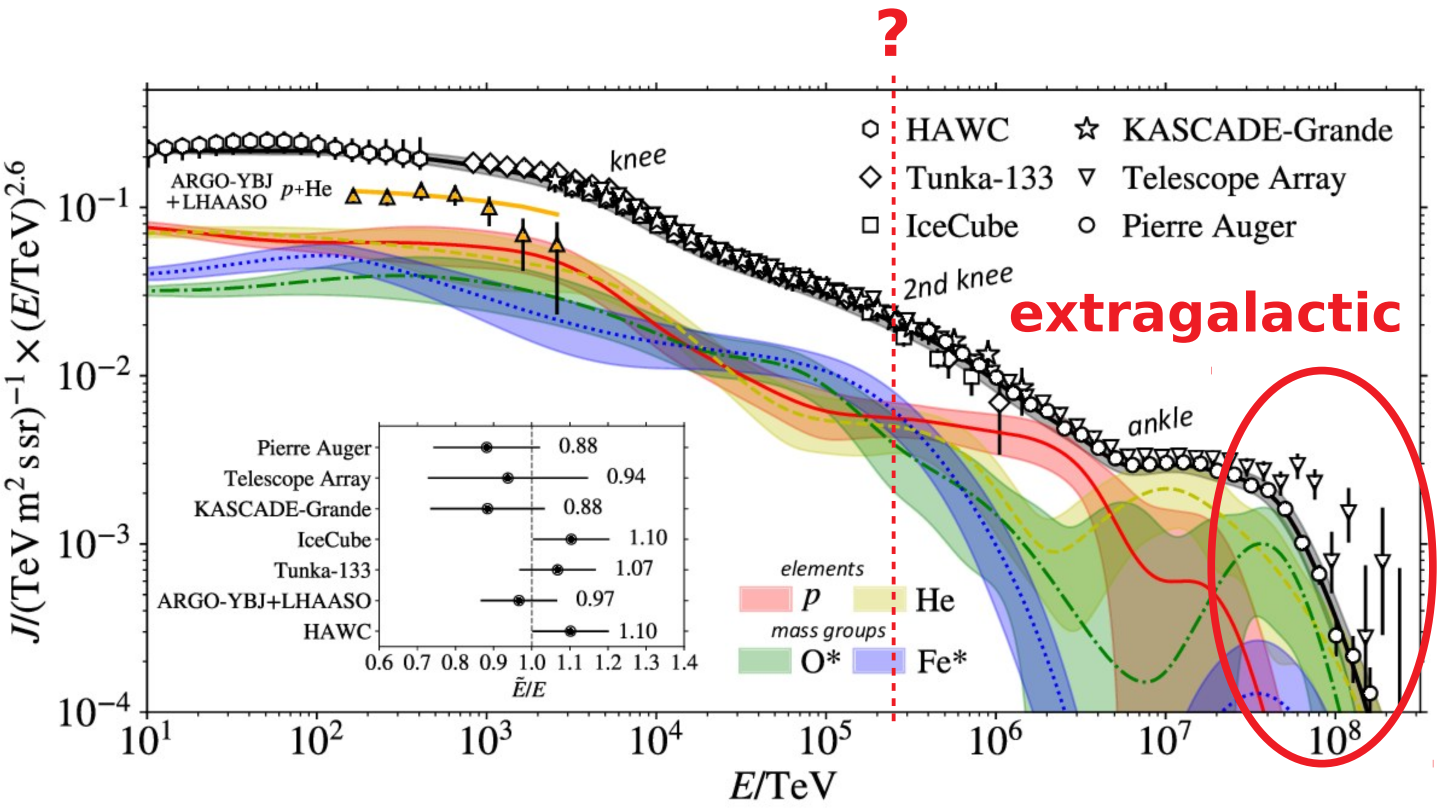
Ultra-High Energy Cosmic-Rays



Hillas criterion (Hillas 1984):
R_g <~ size source

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

Ultra-High Energy Cosmic-Rays



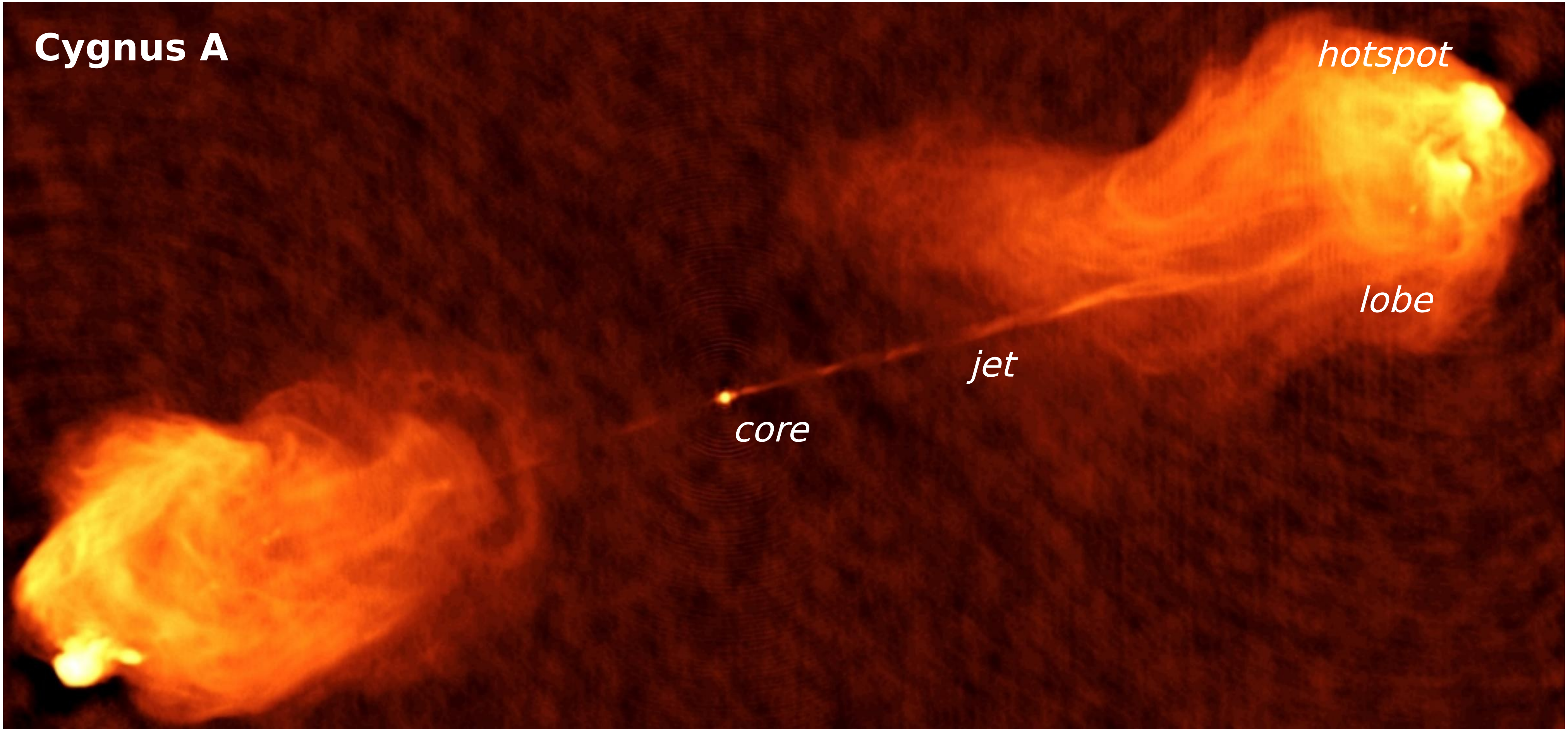
→ AGN jet hotspots/ lobes could confine UHECRs.

Hillas criterion (Hillas 1984):
R_g <~ size source

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

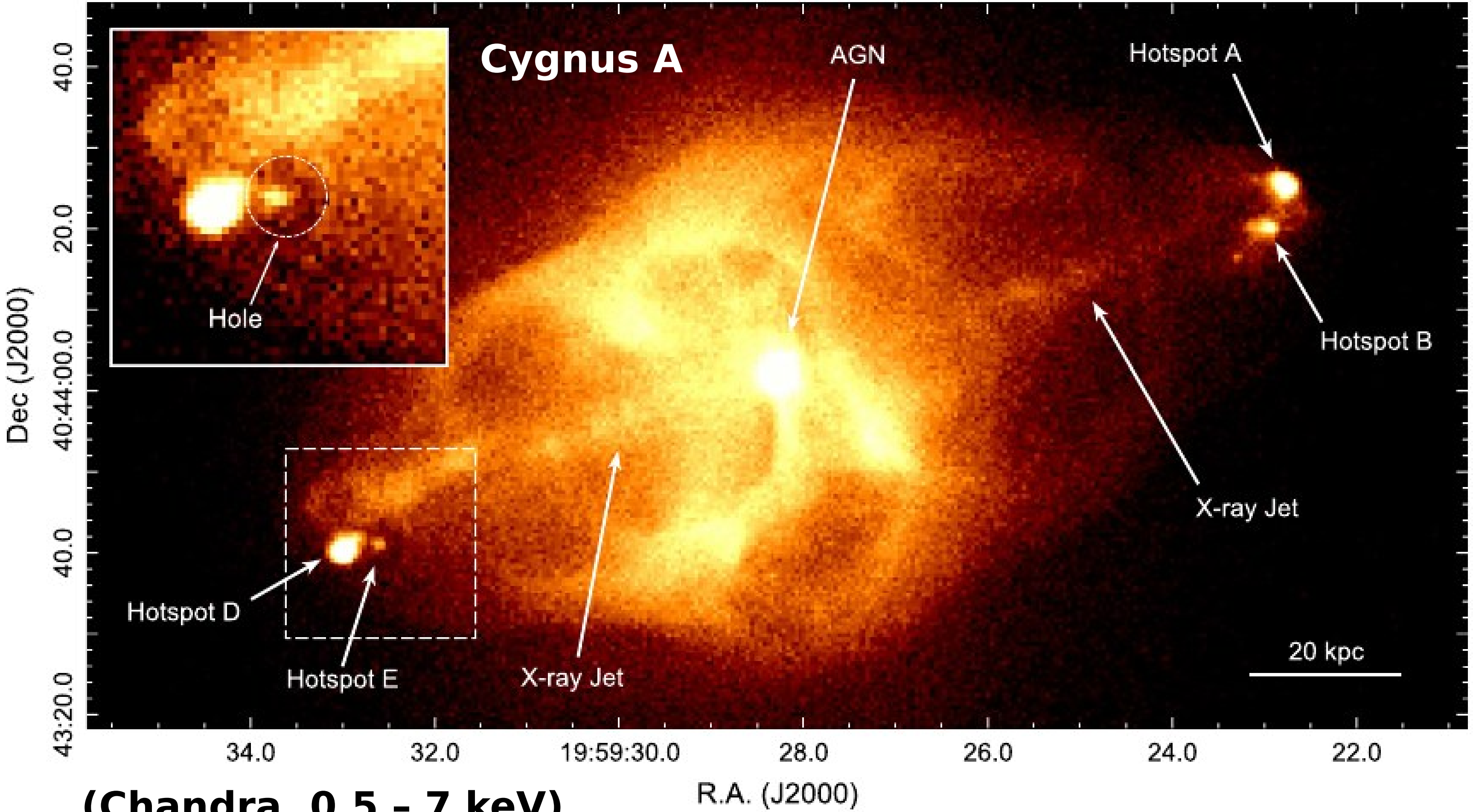
→ … But can they be accelerated there?

FR II jets



In-situ part. acceleration: Cygnus A hotspots

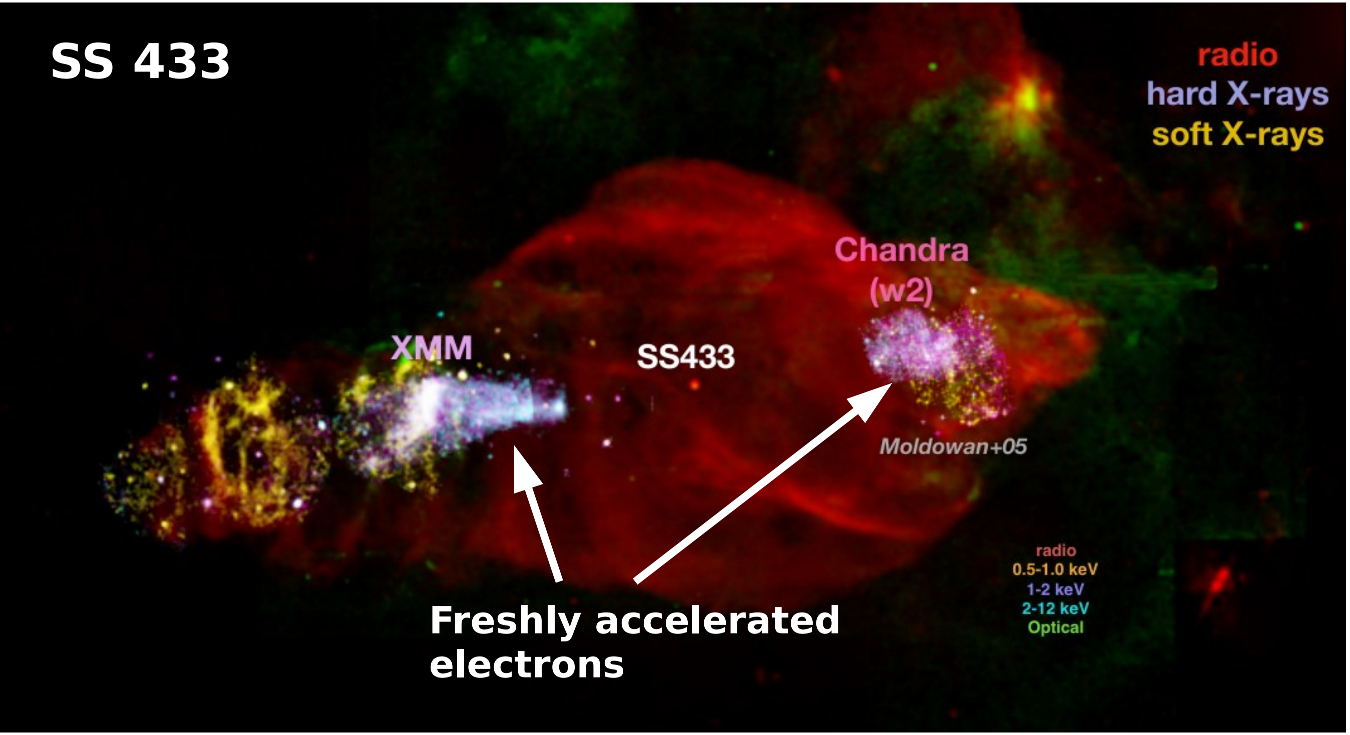
THE ASTROPHYSICAL JOURNAL, 891:173 (10pp), 2020 March 10 Snios et al.



(Chandra, 0.5 – 7 keV)

Same mechanism (for e^-) in microquasars?

Safi-Harb et al. (2022)



Detected by H.E.S.S. and HAWC.

In-situ particle acceleration,
to > 100 TeV.

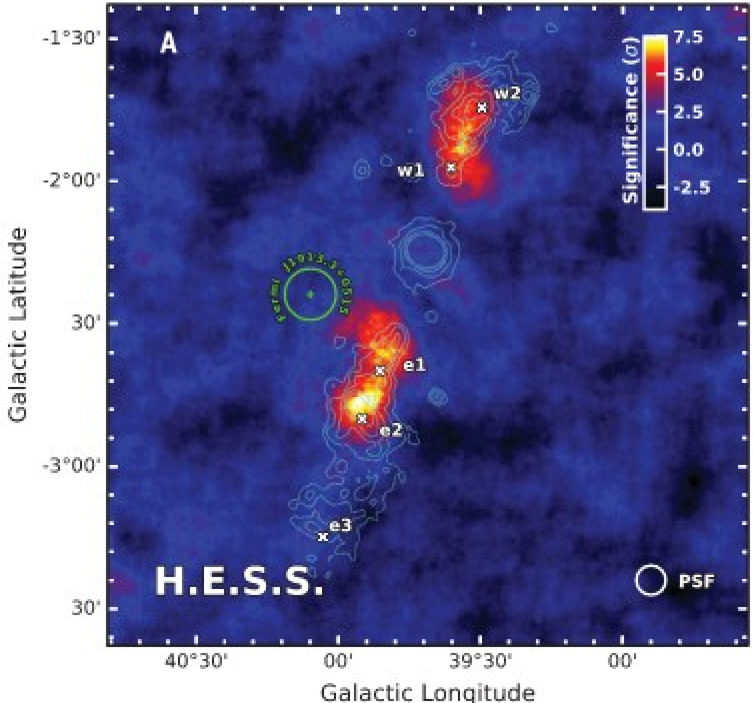
Same mechanism (for e^-) in microquasars?

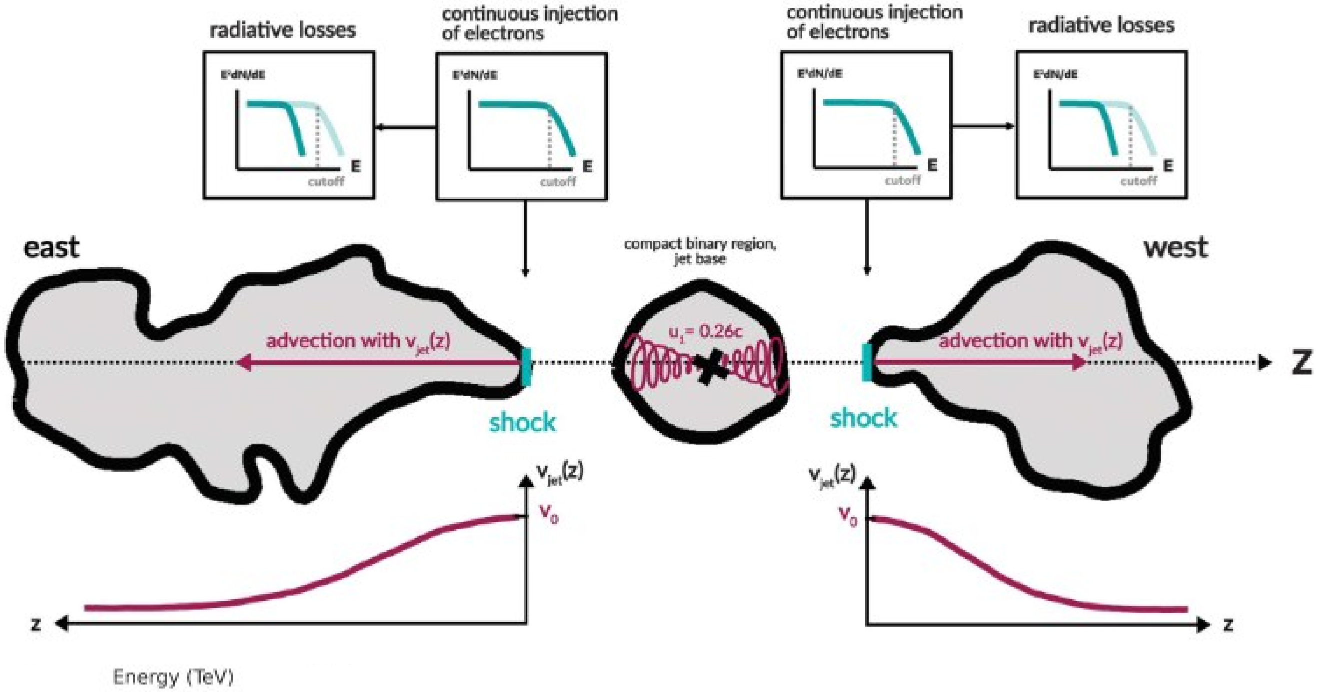
RESEARCH

GAMMA-RAY ASTRONOMY

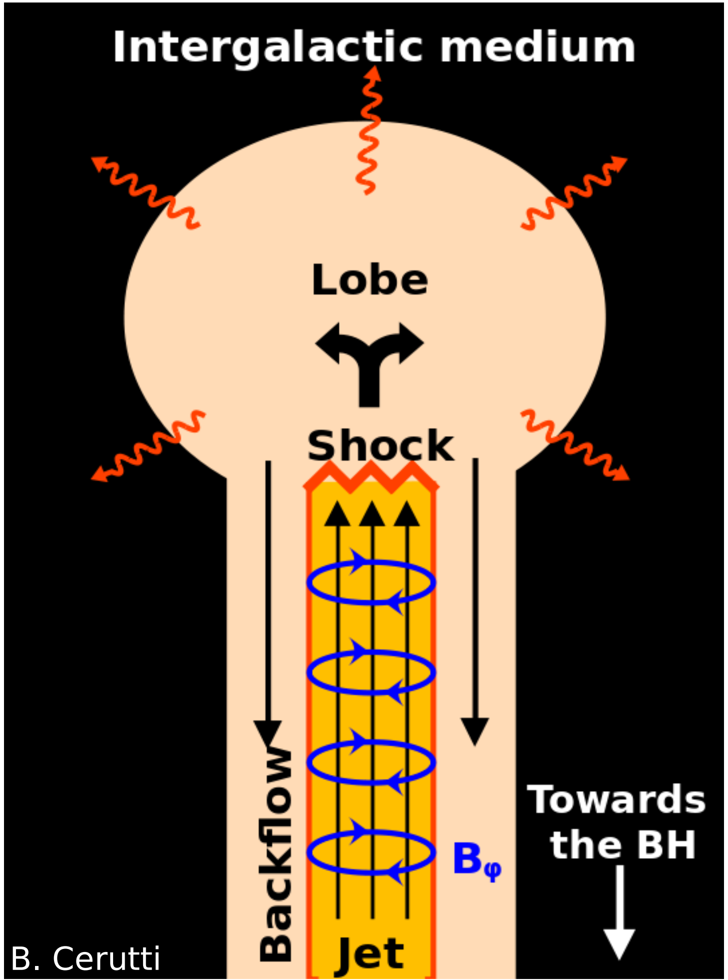
Acceleration and transport of relativistic electrons in the jets of the microquasar SS 433

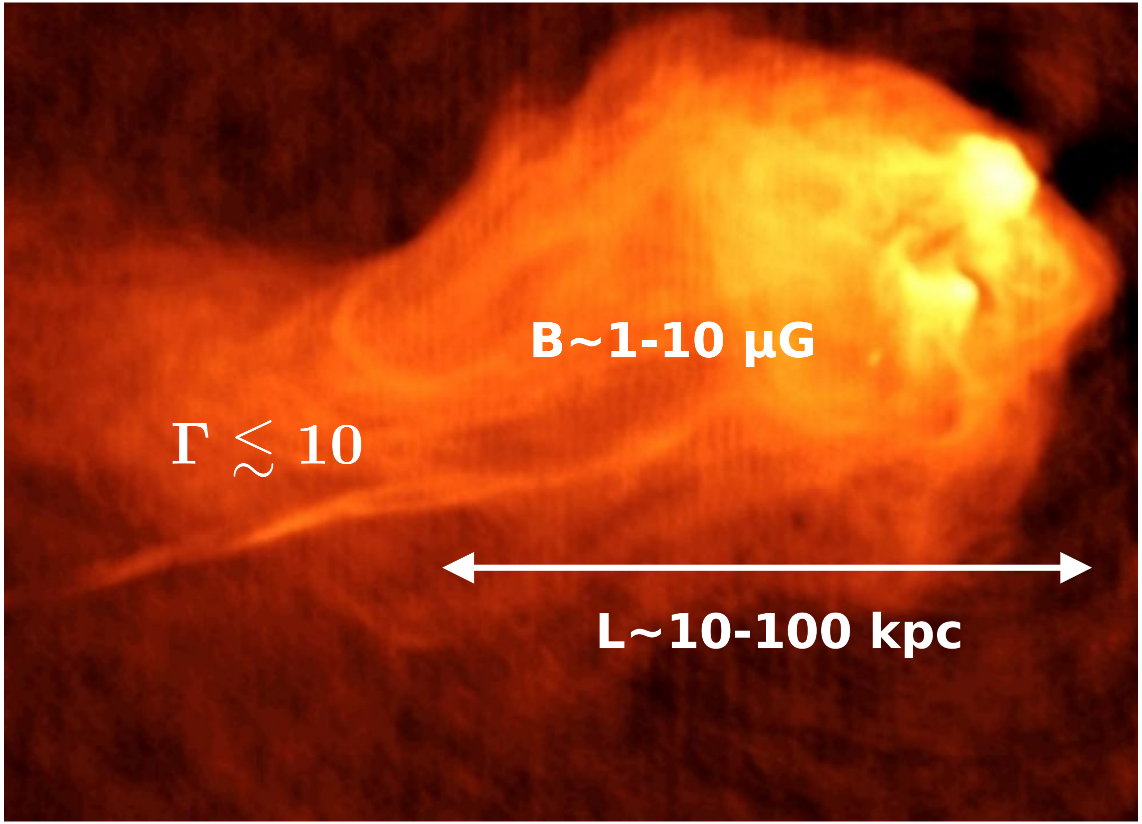
H.E.S.S. Collaboration,
Science **383**, 402–406 (2024)





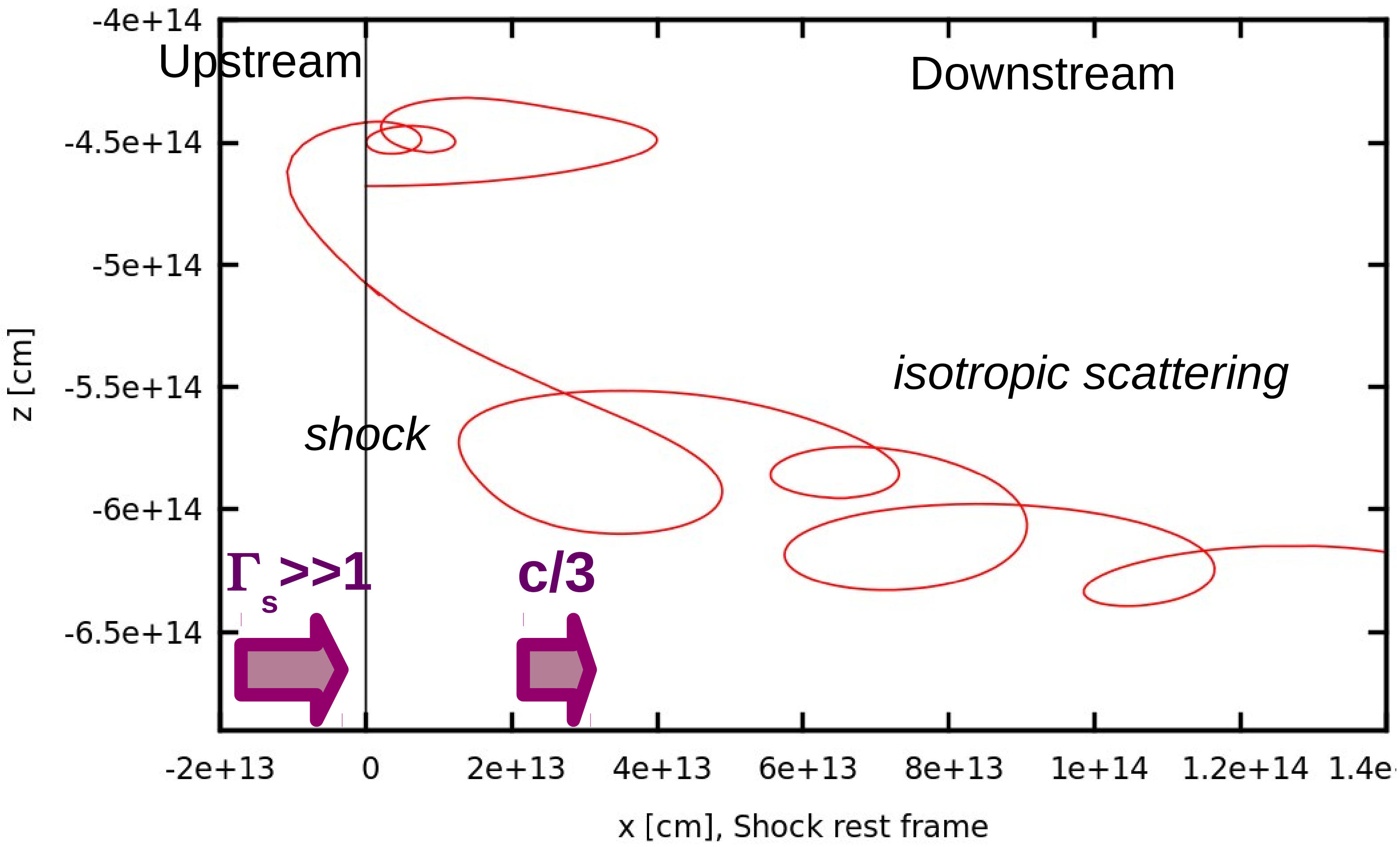
Jet Termination Shock Region





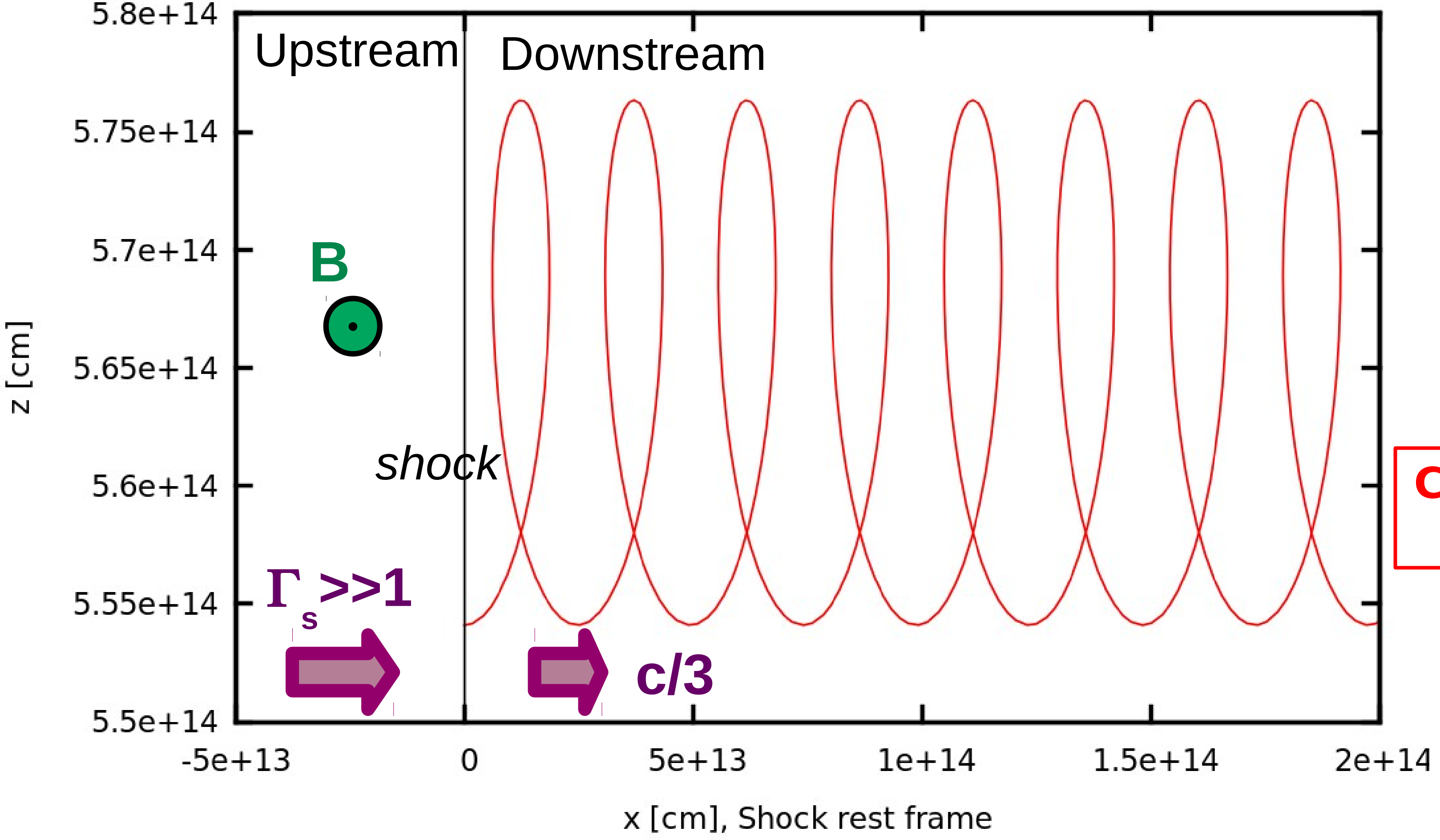
Magnetization: $\sigma_0 = \dfrac{B_0^2}{8\pi\Gamma_0 n_0 m_p c^2}$ ~ **0.01 – 1.**

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 !!

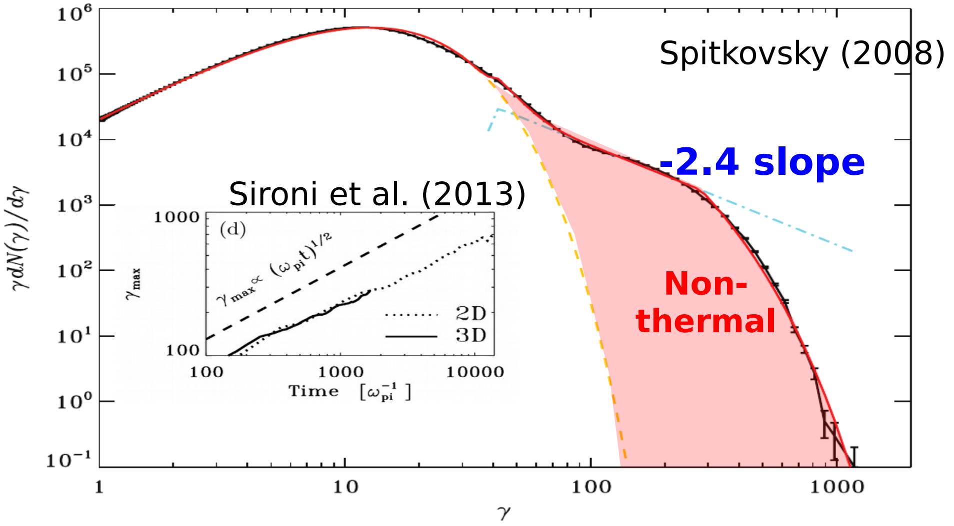
Particle-In-Cell (PIC) simulations

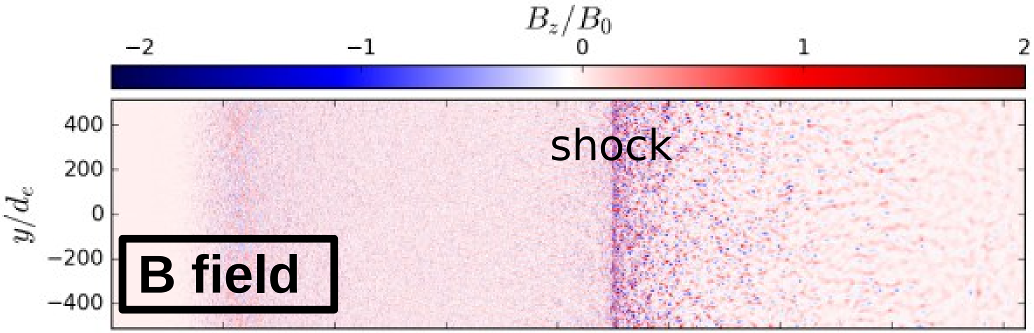
→ **Unmagnetized case (σ=0):**

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

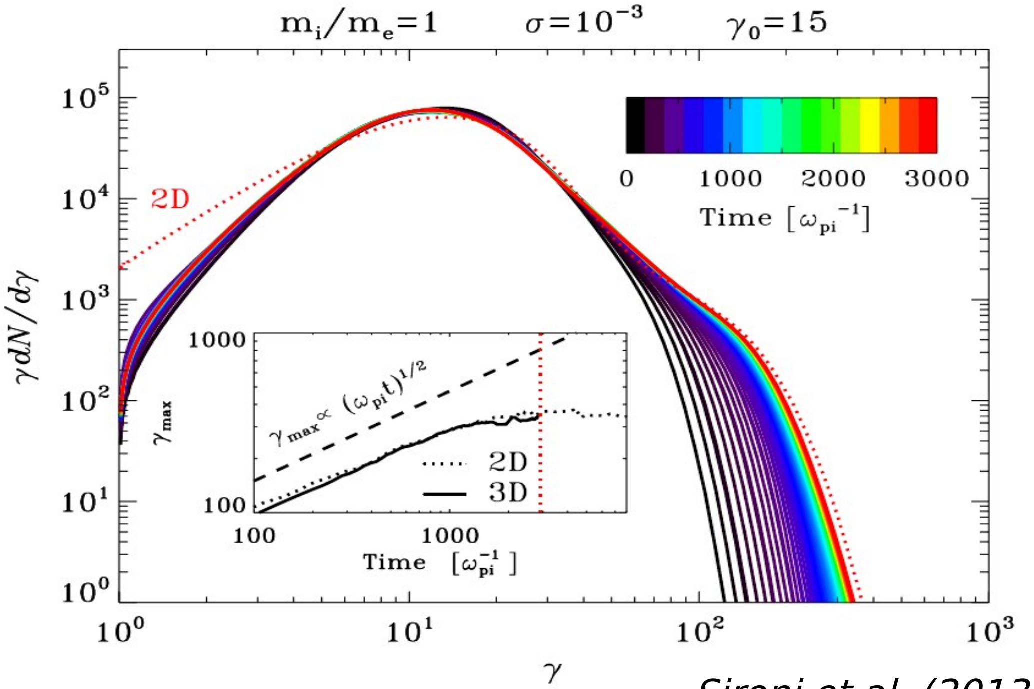
Particle-In-Cell (PIC) simulations

→ **<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 !!

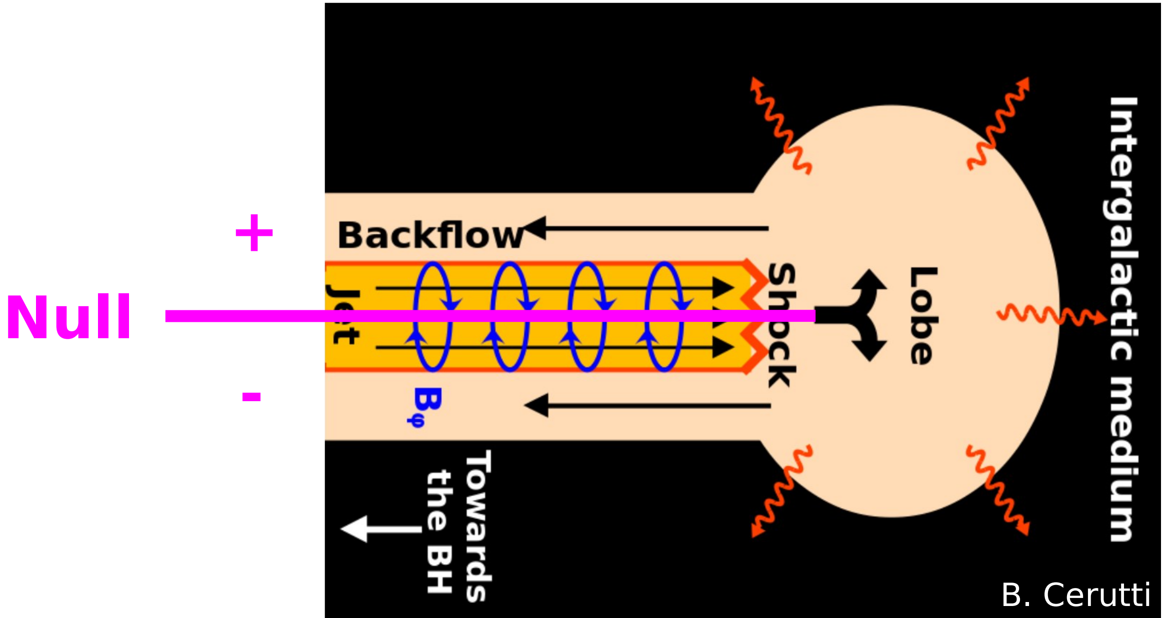


Sironi et al. (2013)

Solution: Global B field geometry

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

LARGE-SCALE GEOMETRY OF THE MAGNETIC FIELD MAY SOLVE THE PROBLEM!



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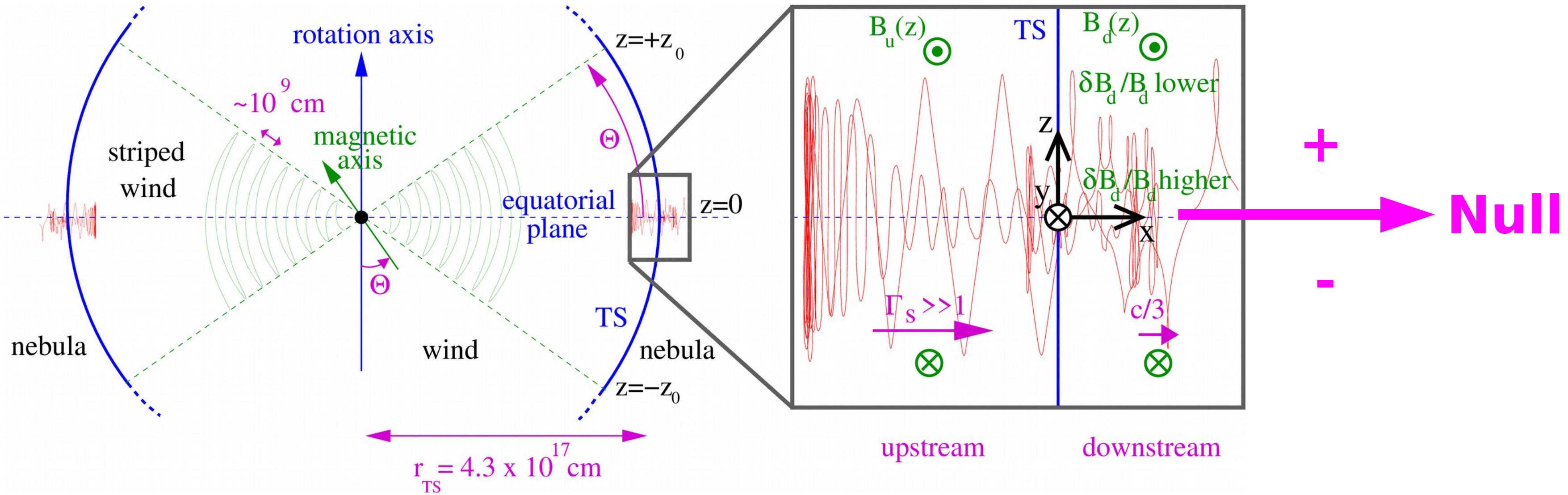
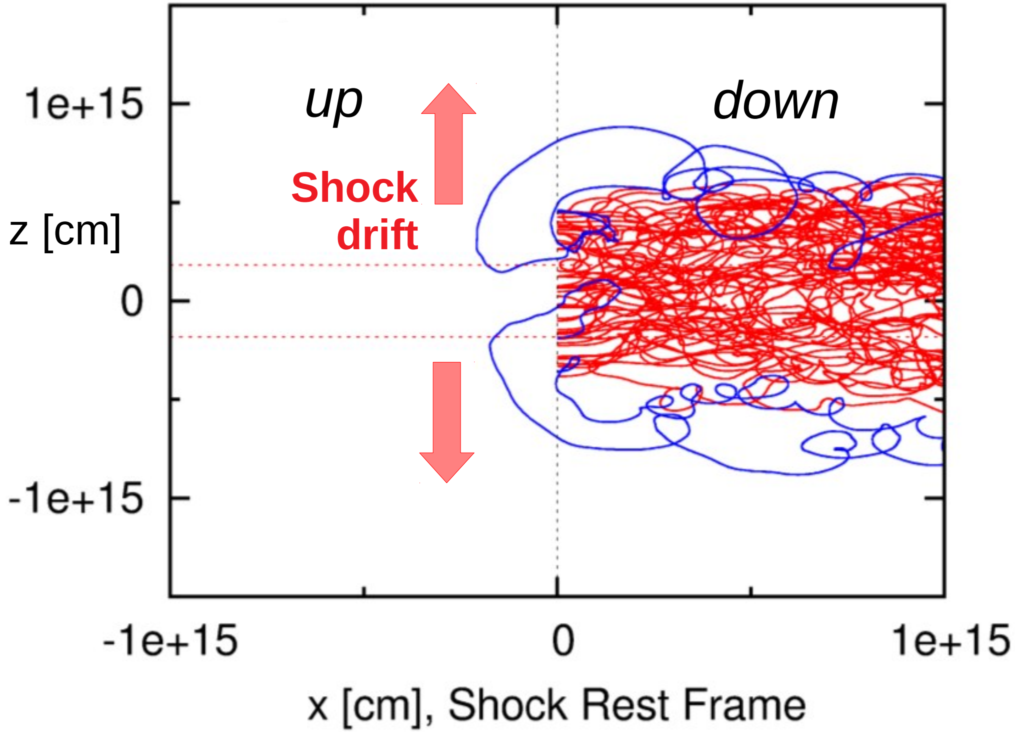
LARGE-SCALE GEOMETRY OF THE MAGNETIC FIELD MAY SOLVE THE PROBLEM!

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



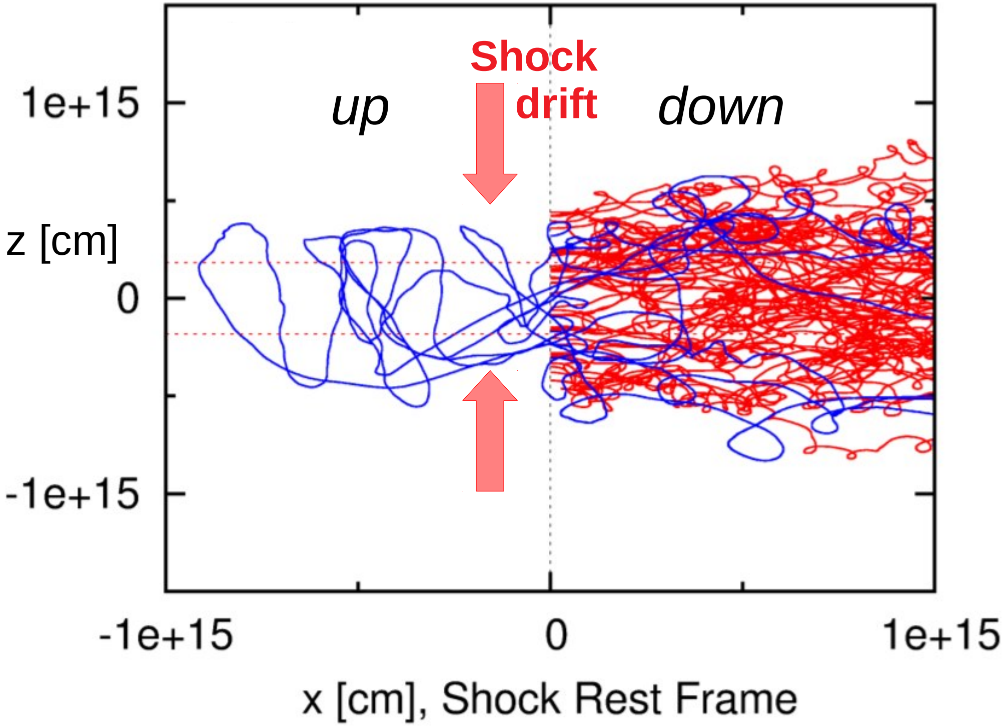
See **Giacinti & Kirk (2018)** for Pulsar Wind Nebulae :

Positrons :



No/little acceleration

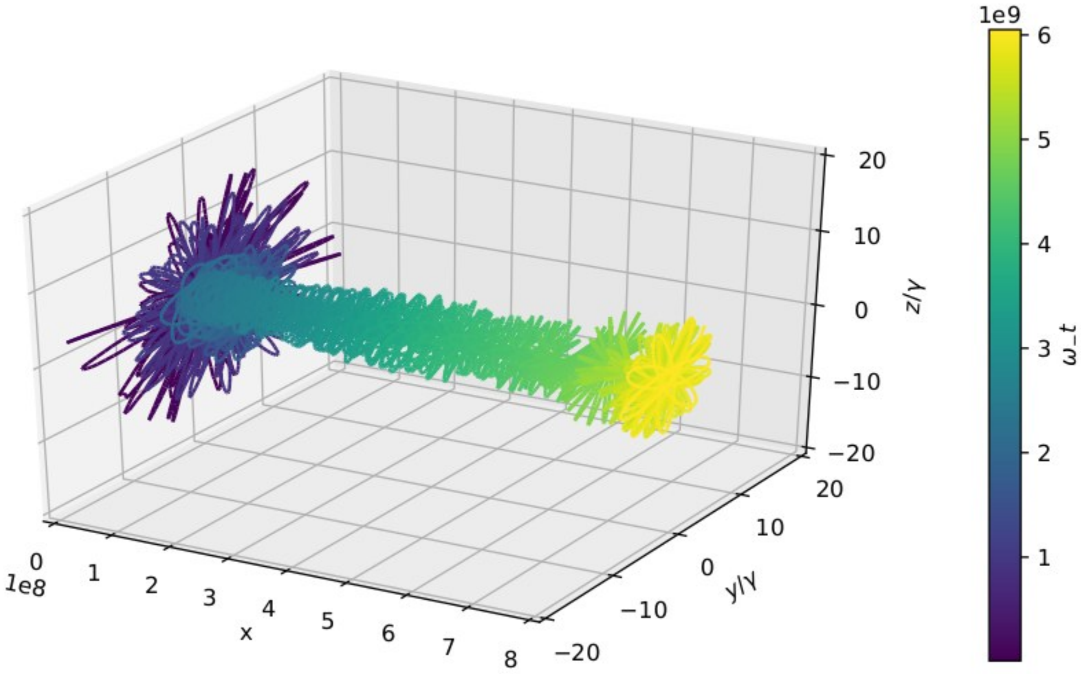
Electrons :

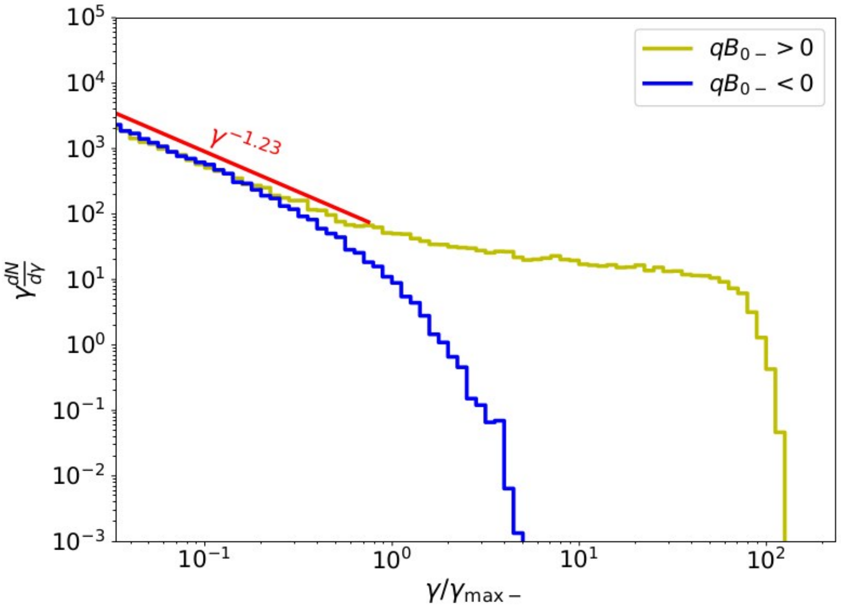


Acceleration

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)





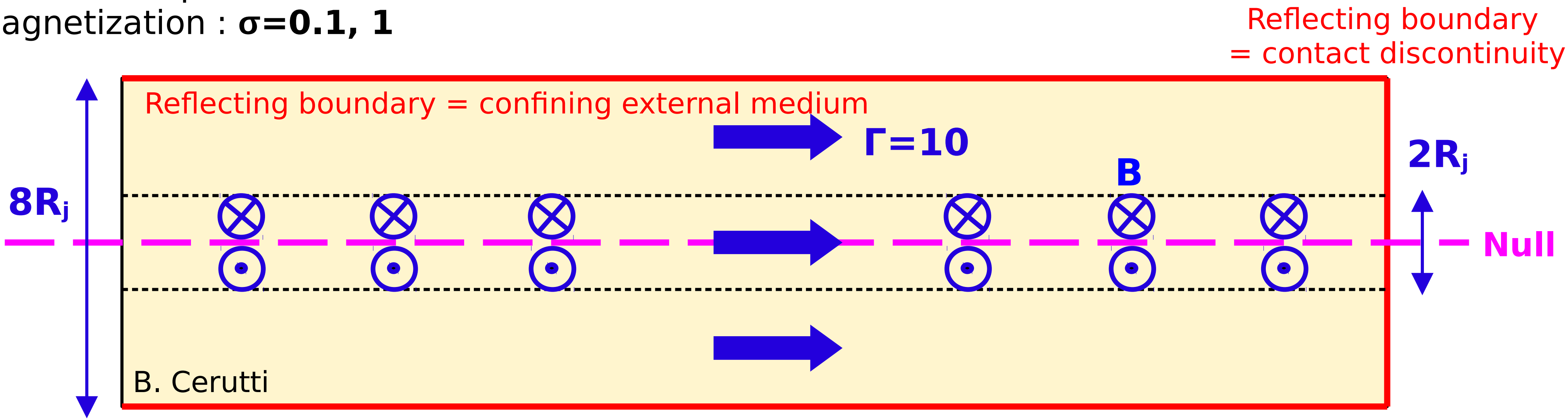
Key point: Particles (w/ correct sign of charge) remain around the null point

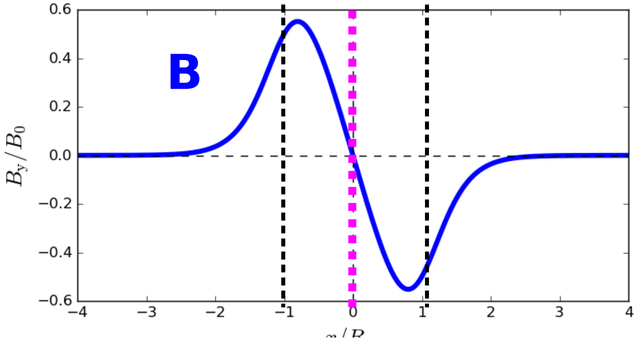
Particle-In-Cell (PIC) setup

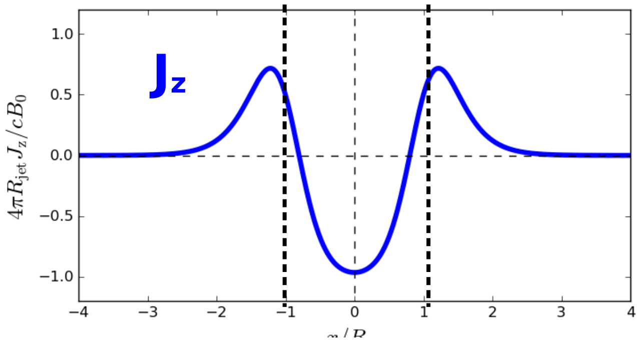
2D Cartesian box (xz-plane), **262,144×16,384 cells, or 6554x410 d_i (ion skin depth)**

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

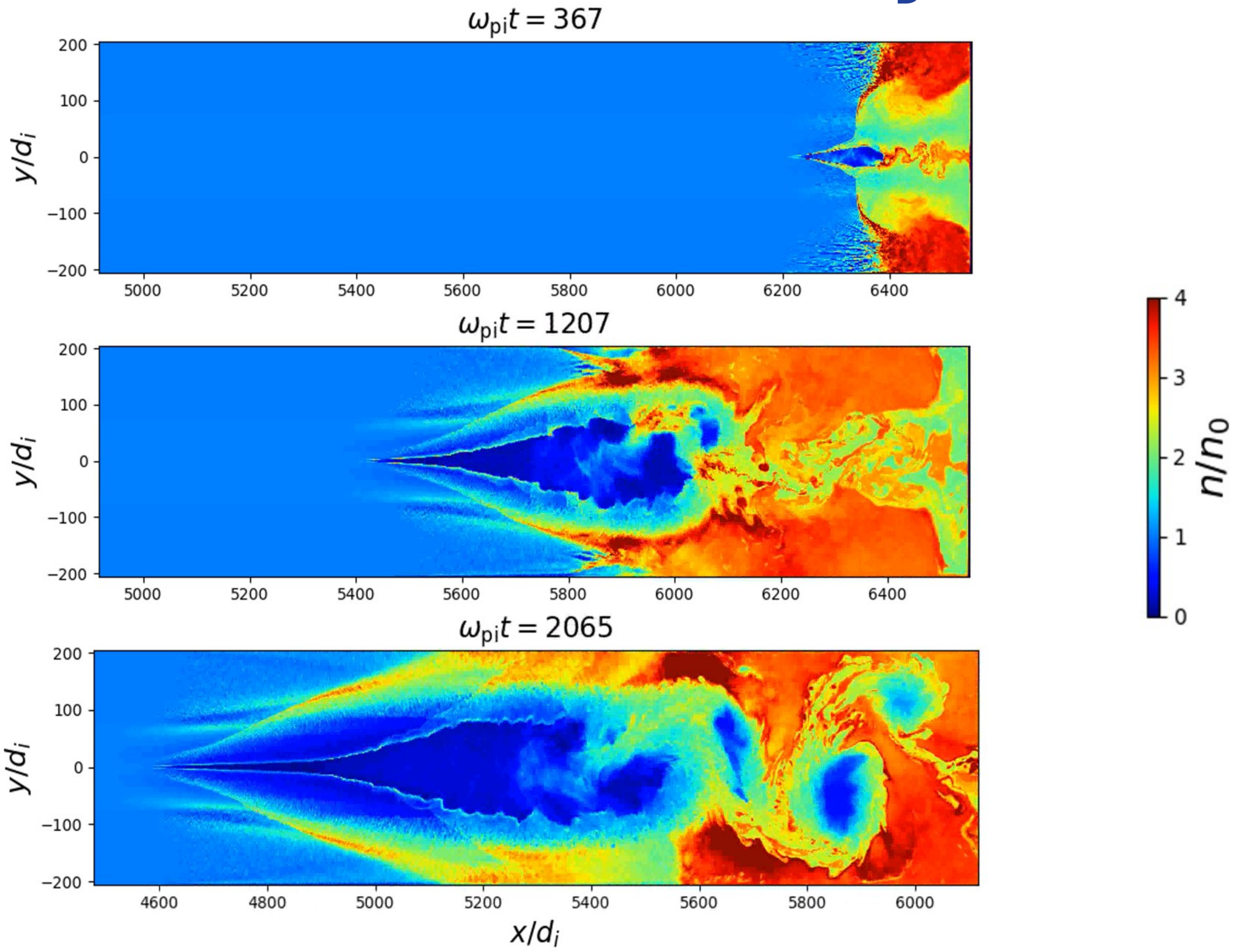
Magnetization : **σ=0.1, 1**



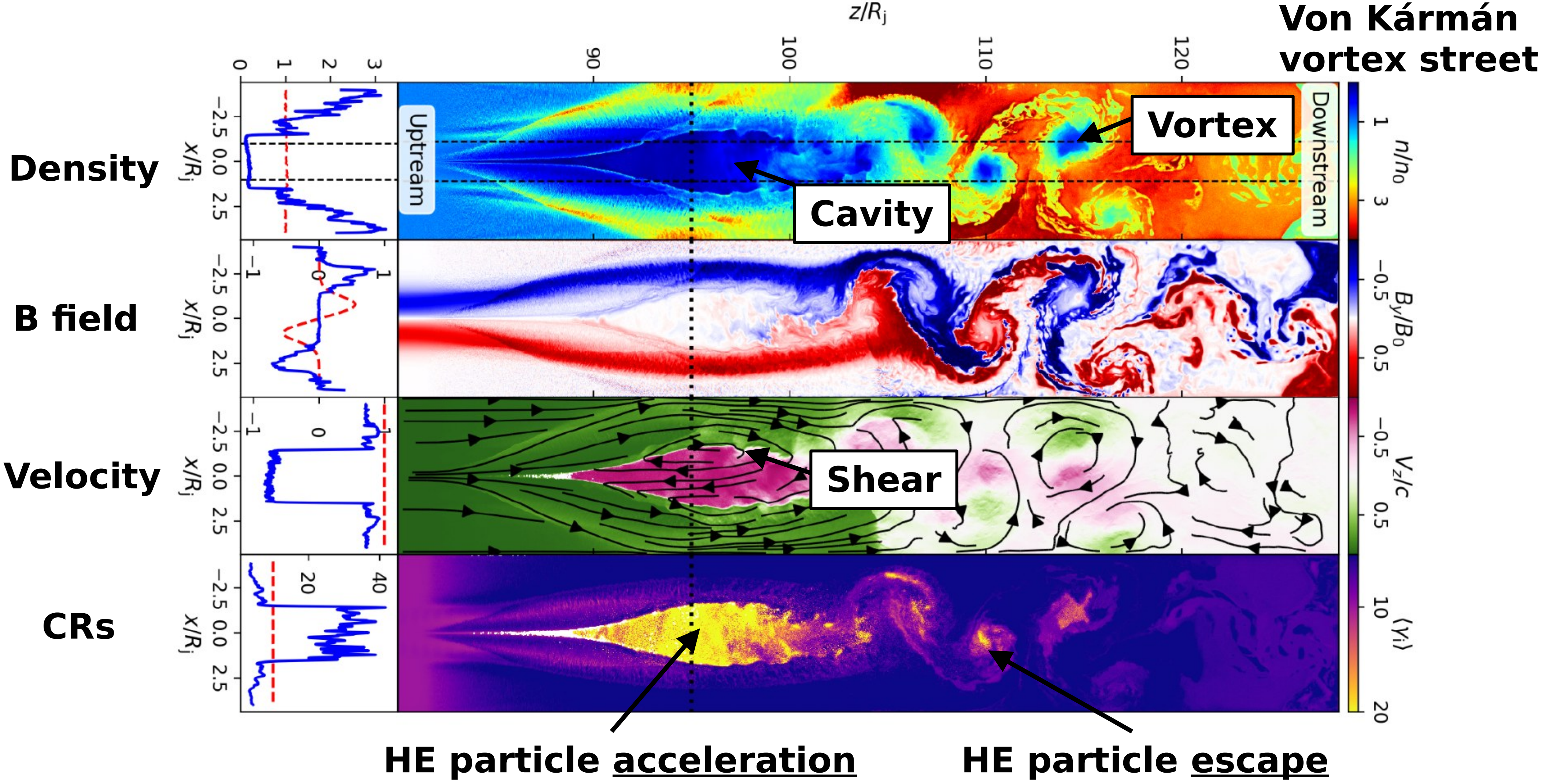




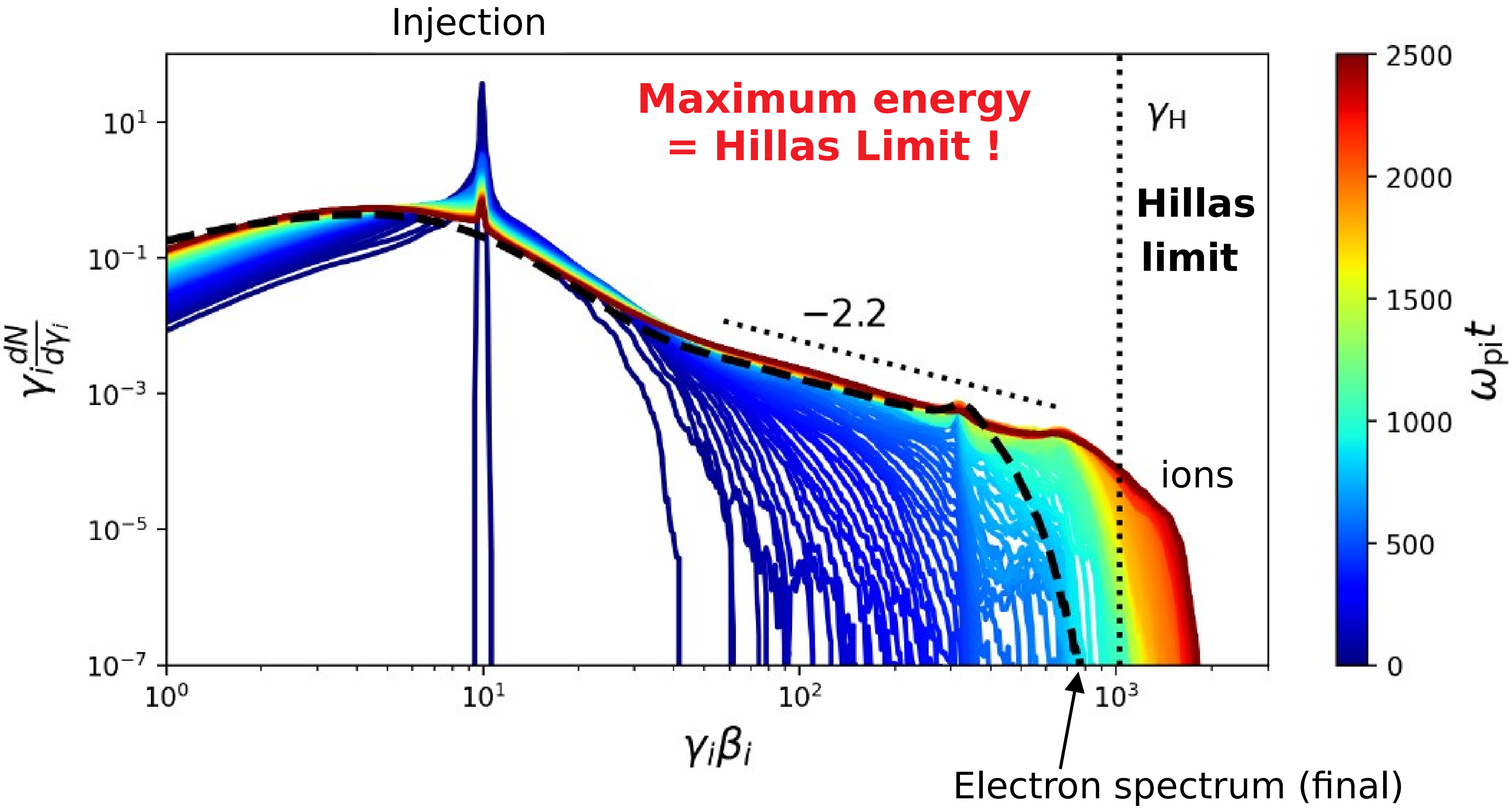
Results PIC Sim.: Density evolution



Results – PIC Simulations

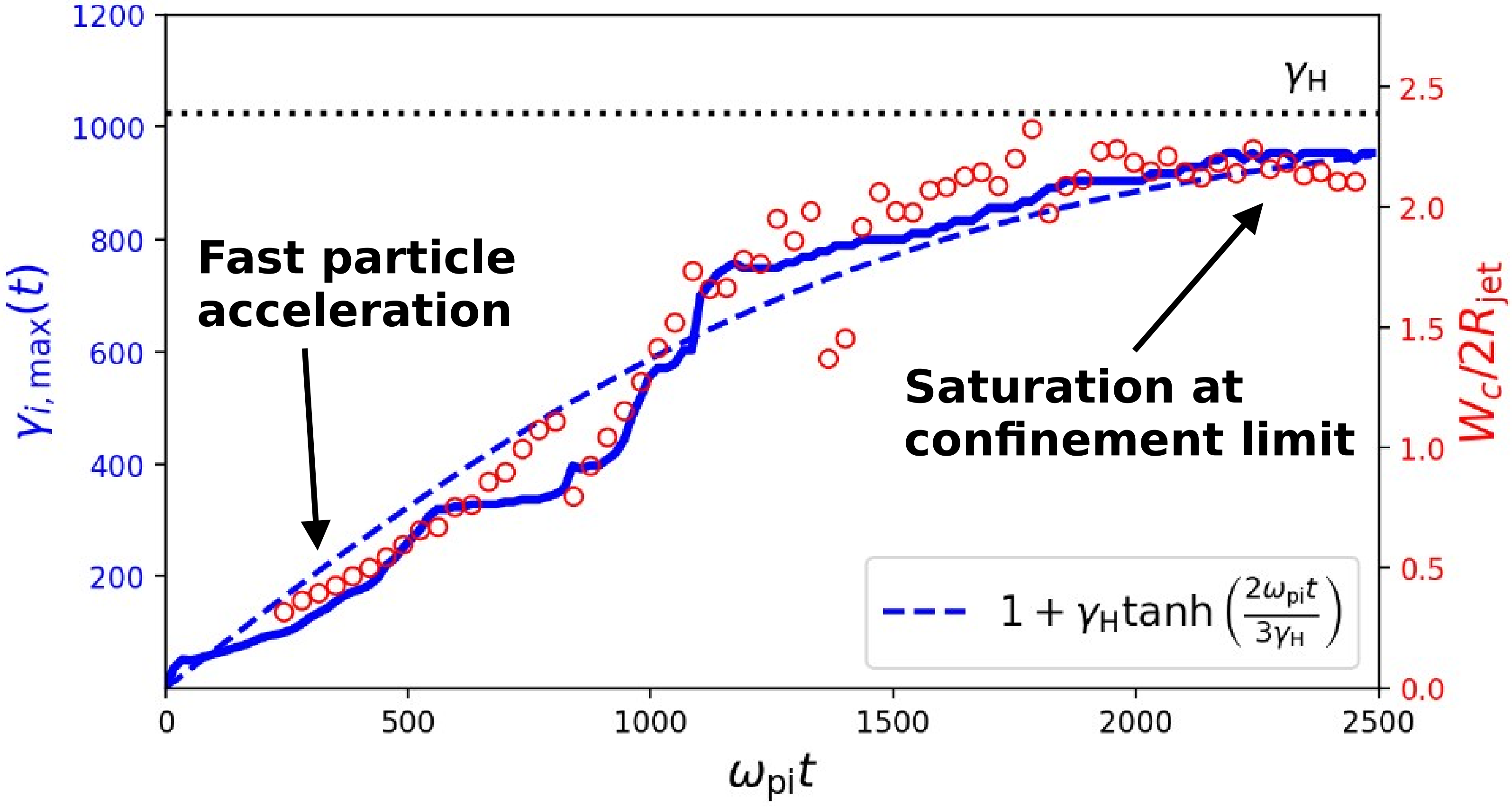


Ion spectrum: Time Evolution & E_{max}



E_{max} ions & Cavity size: Time Evolution

Max. particle energy



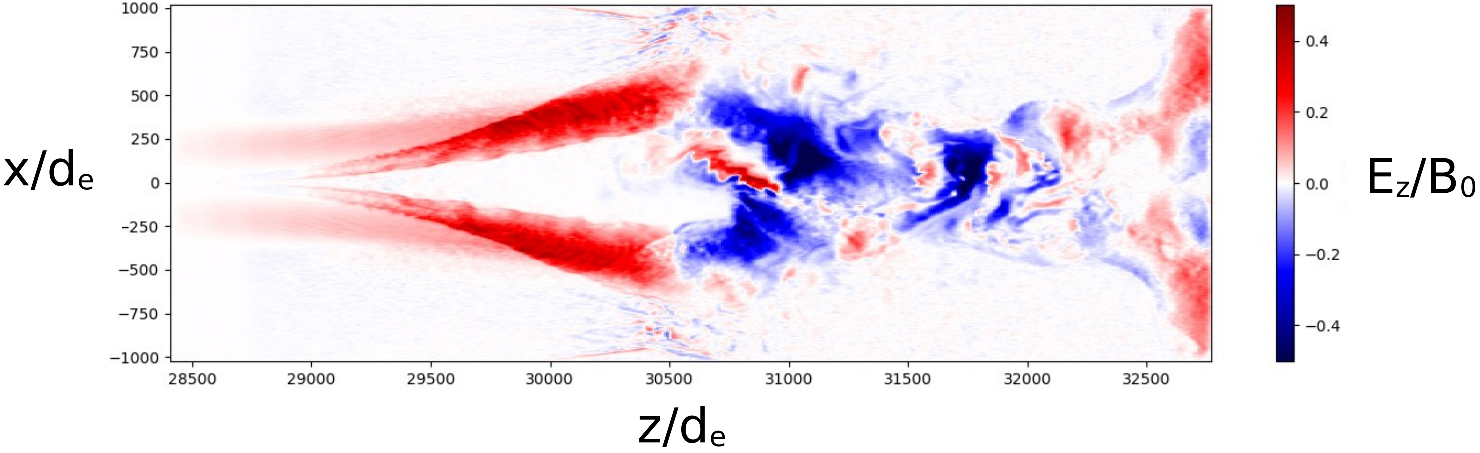
Width of the cavity

Maximum particle energy grows as cavity width.
Cavity stops growing at ~ width jet => **Hillas criterion.**

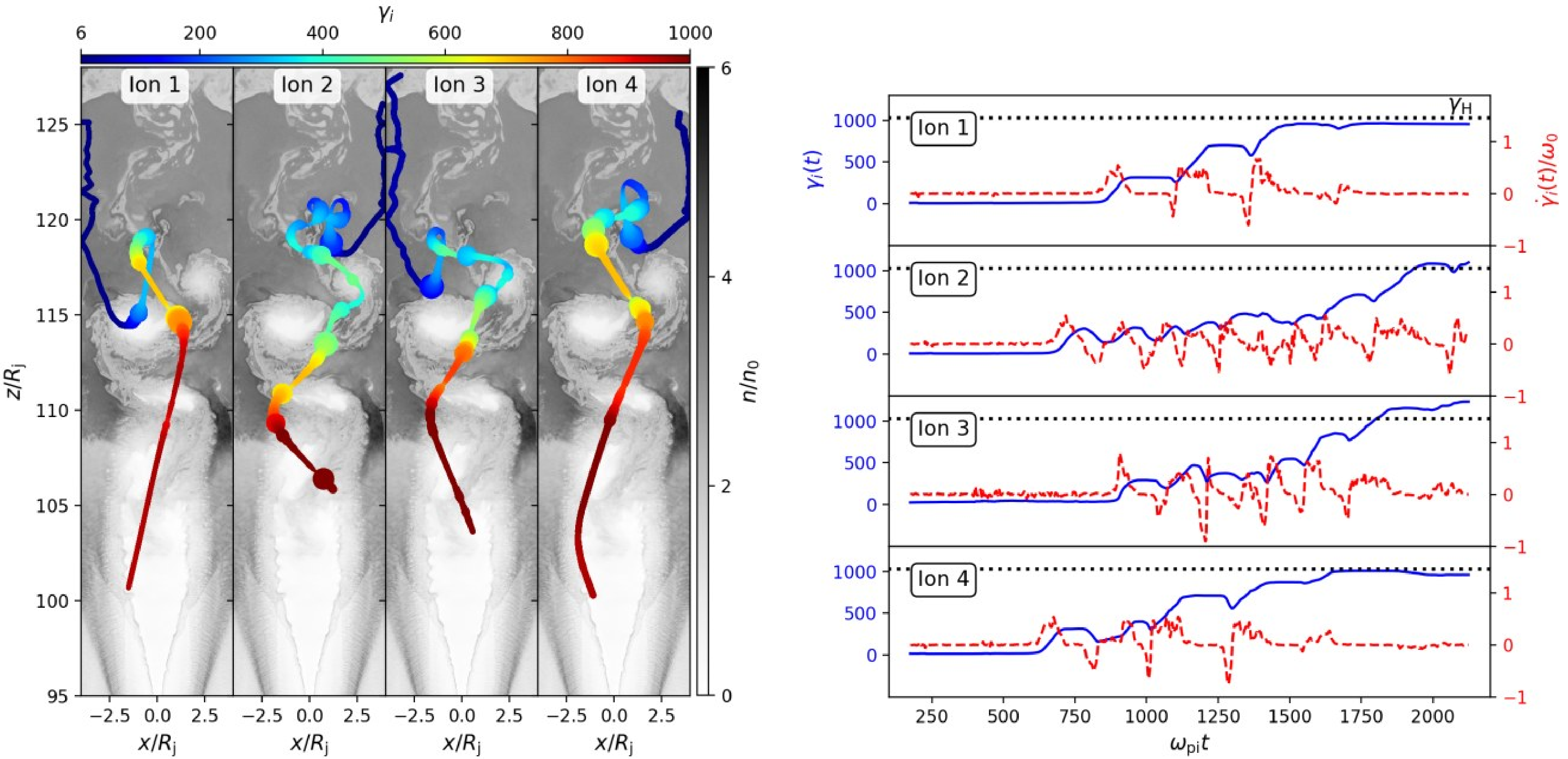
Particle acceleration mechanism

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

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

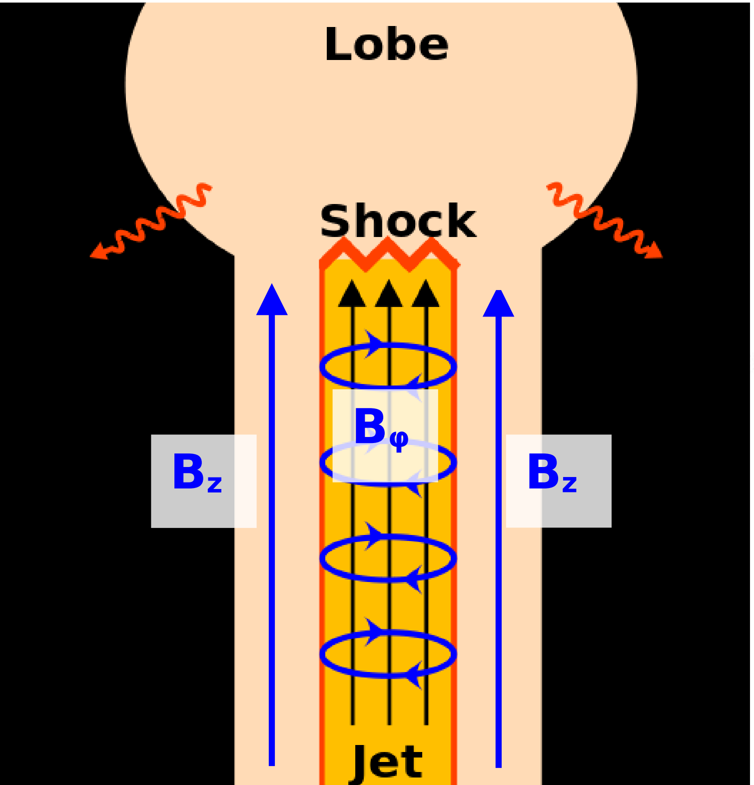


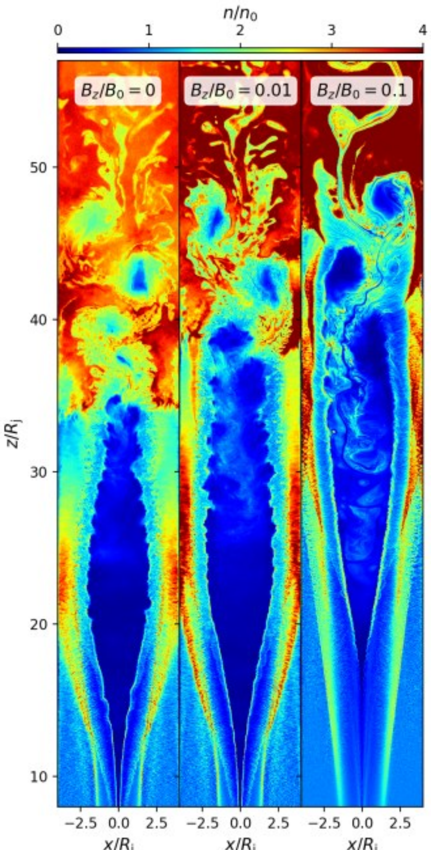
Particle acceleration mechanism

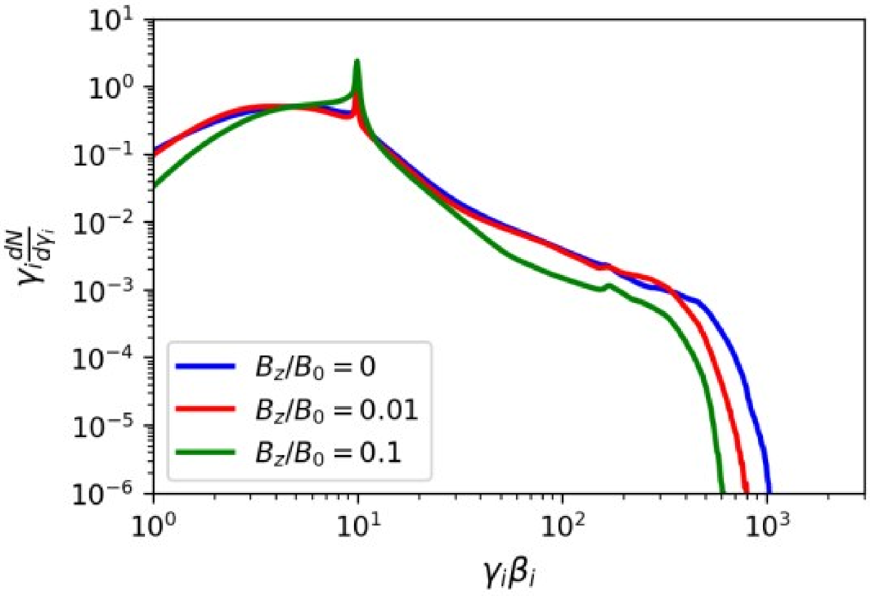


Effect of a poloidal B field component

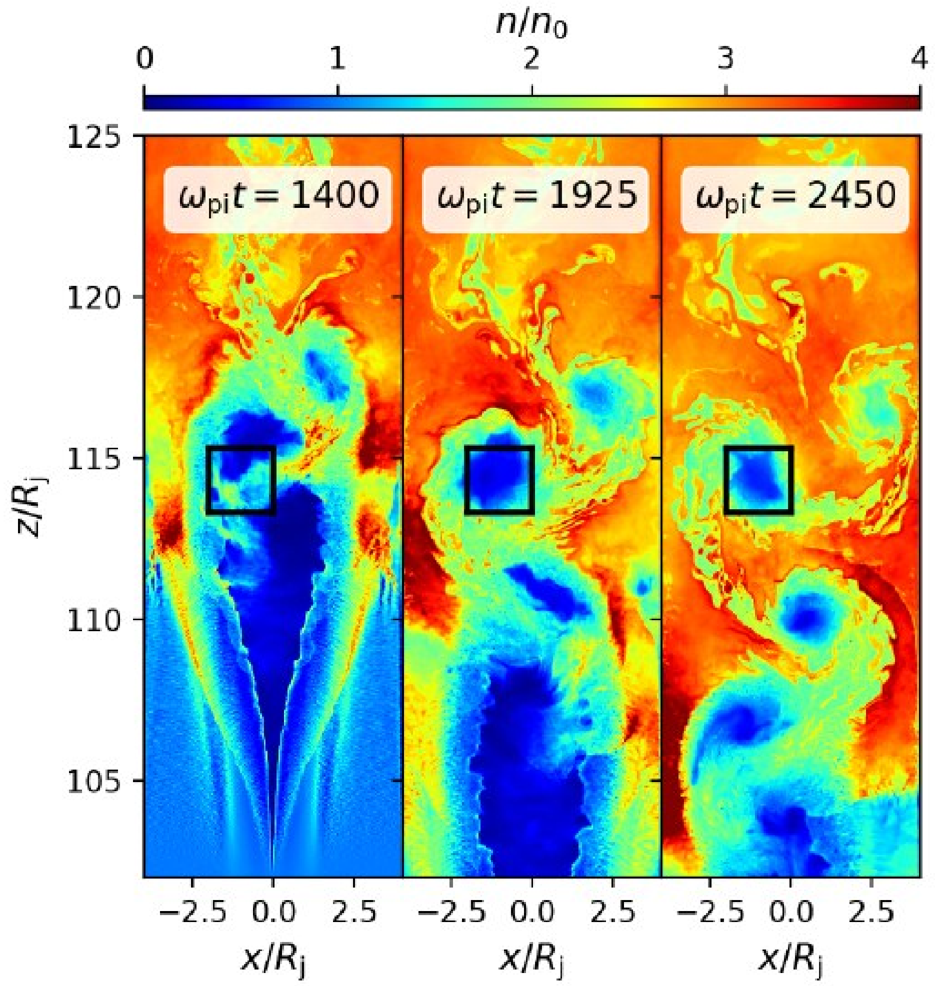
If **B_z<B_φ (expectation in jet TS region)**, particle acceleration remains efficient

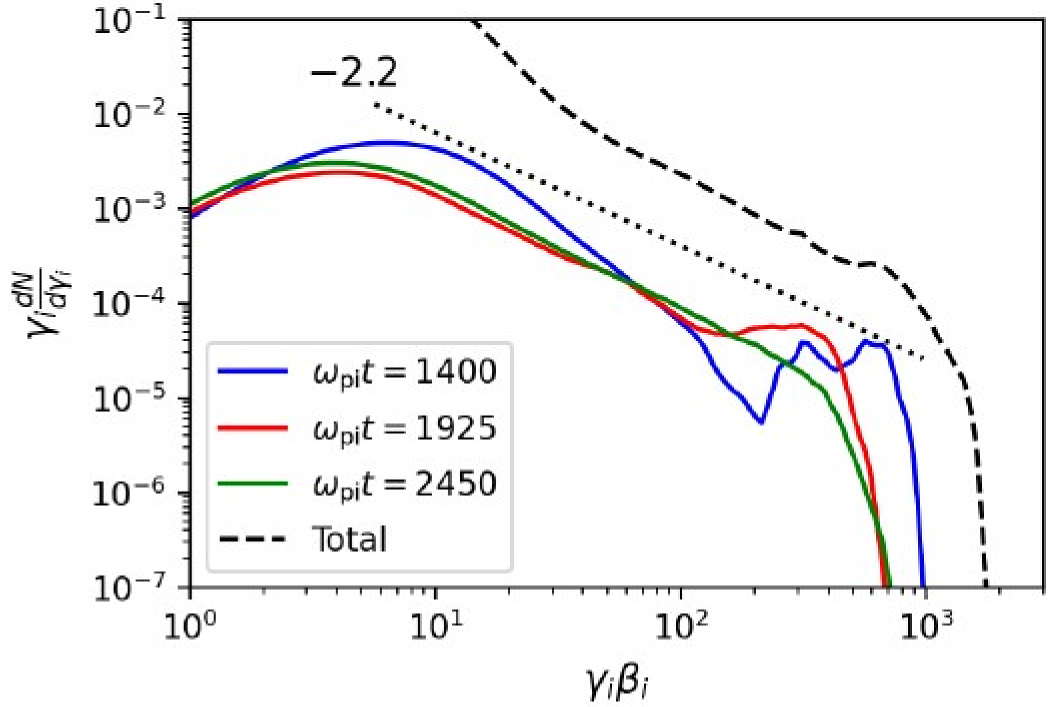






Mechanism for VHE particle escape



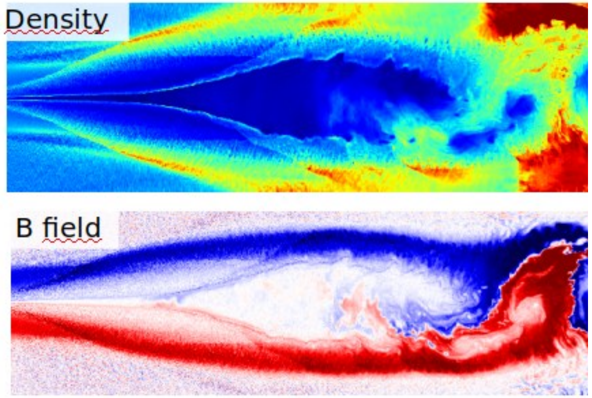


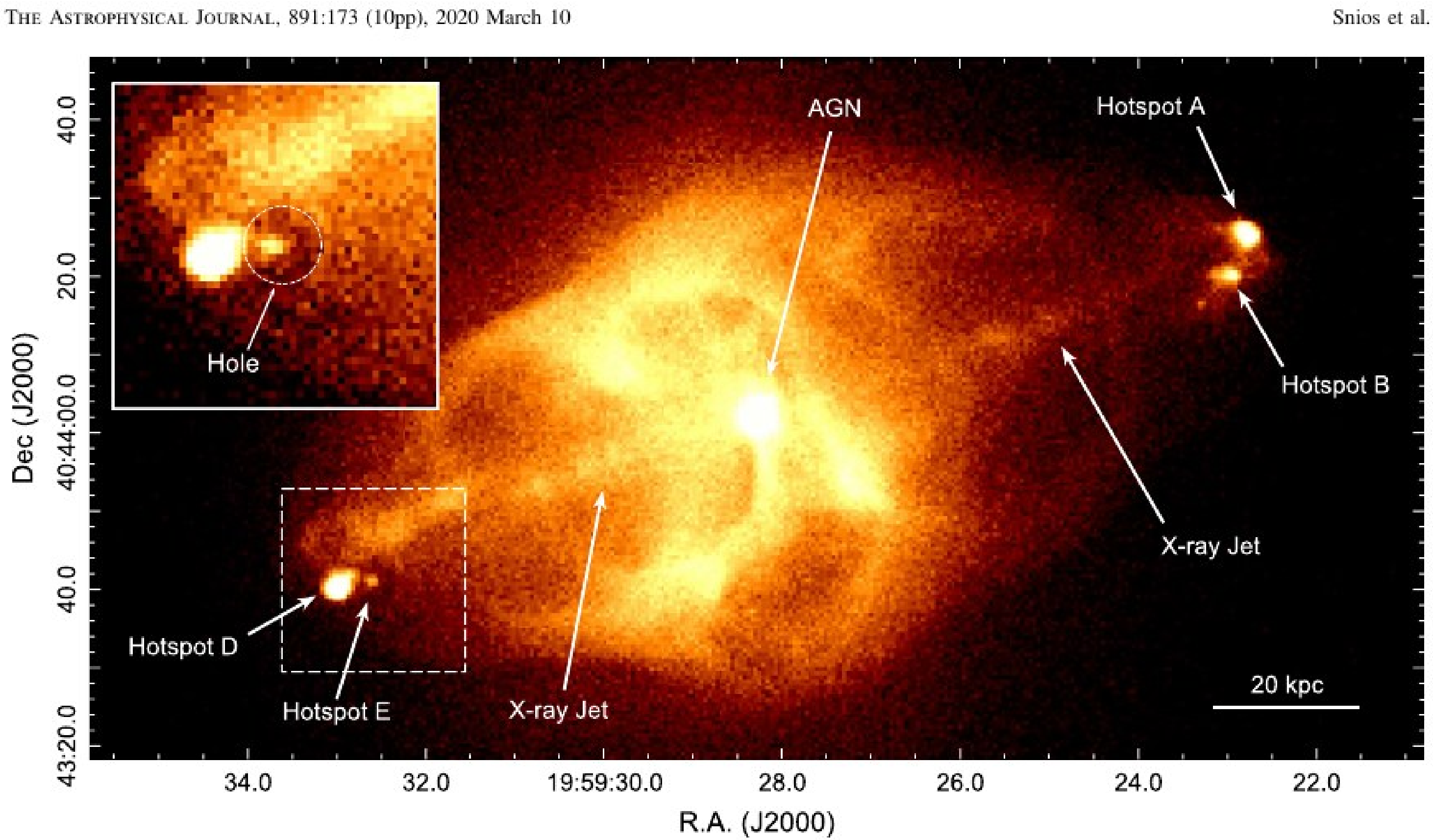
→ Particles escape in von Kármán vortices.

→ **No E losses**.

Observational test / evidence ?

Cavity → under-luminous holes?





Conclusions & Perspectives

- **Large-scale structure of the B fields key for having particle acceleration,**
  → Very generic: May apply for GRBs, microquasars, PWNe, …

- **CR-dominated cavity at the shock front around the B field null point,**
  → Search for cavities.

- **Particles accelerated at the shear flows around the cavity,**

- **Particles accelerated to the Hillas Limit (at least in the simulations)**
  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 inside von Kármán vortices.**

- **Next step: Study this problem with PIC-MHD simulations.**