THE UNIVERSITY OF CHICAGO

Espresso acceleration of UHECRs in relativistic MHD Jets

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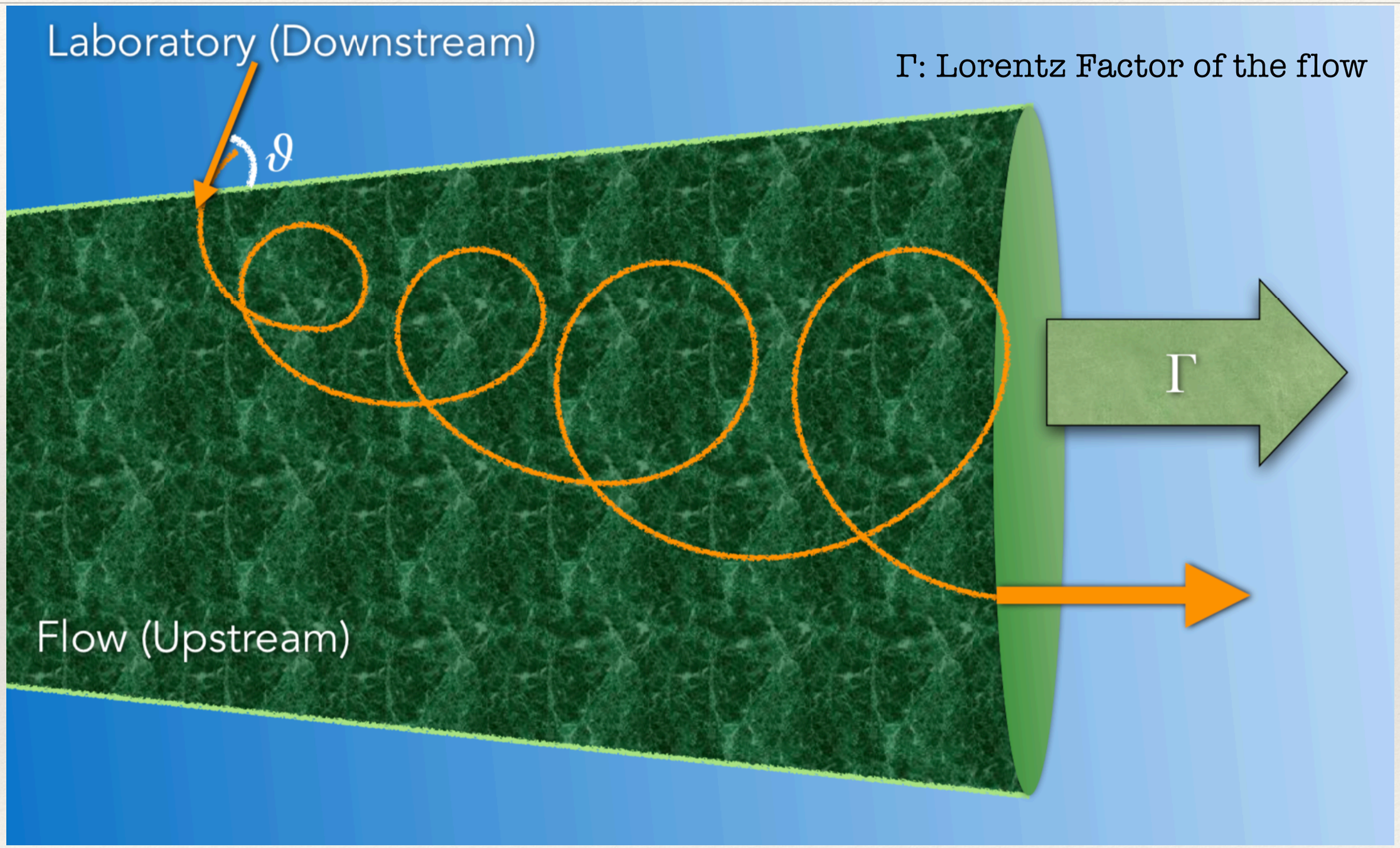
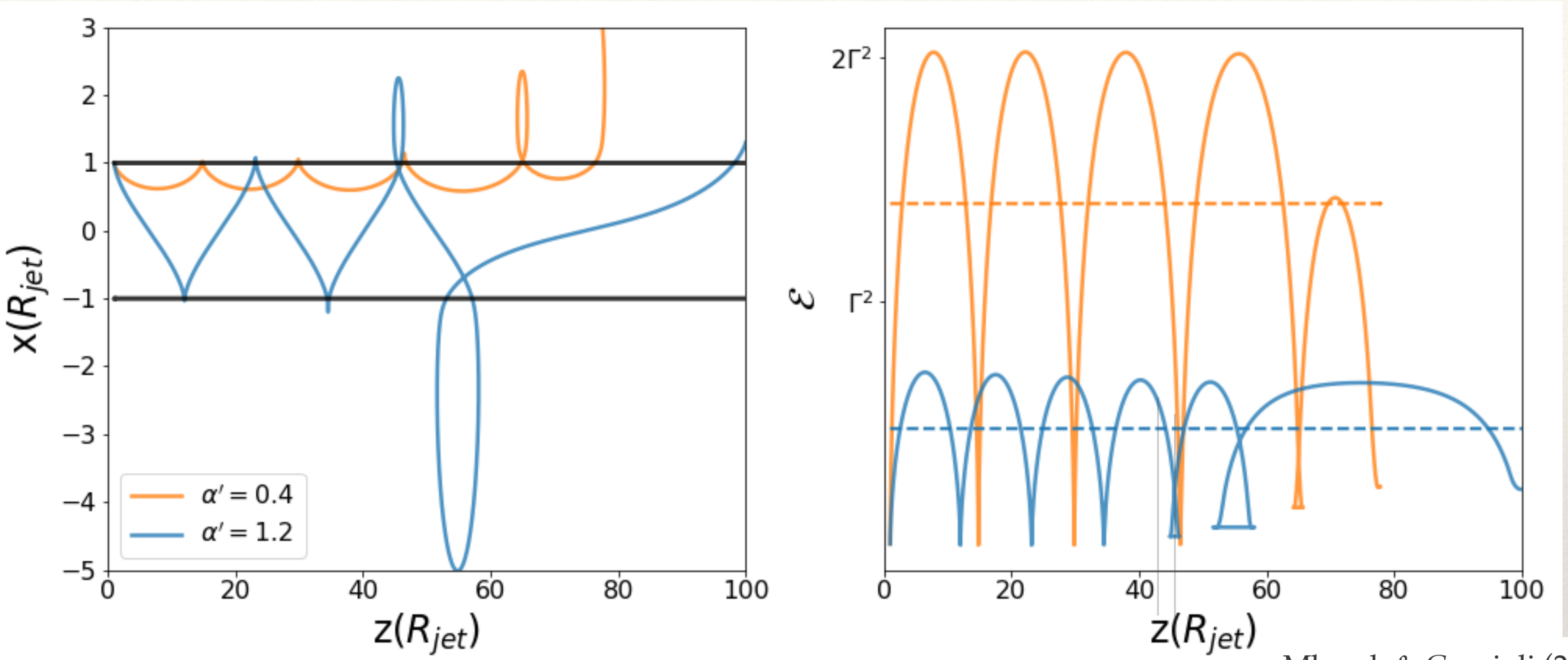
The *espresso* mechanism: A brief Introduction



SEEDS: galactic CRs with energies up to ~ 3Z PeV

STEAM: AGN jets with Lorentz factors Γ up to ~ 20-30

Espresso Acceleration in Idealized Cylindrical Jet Models

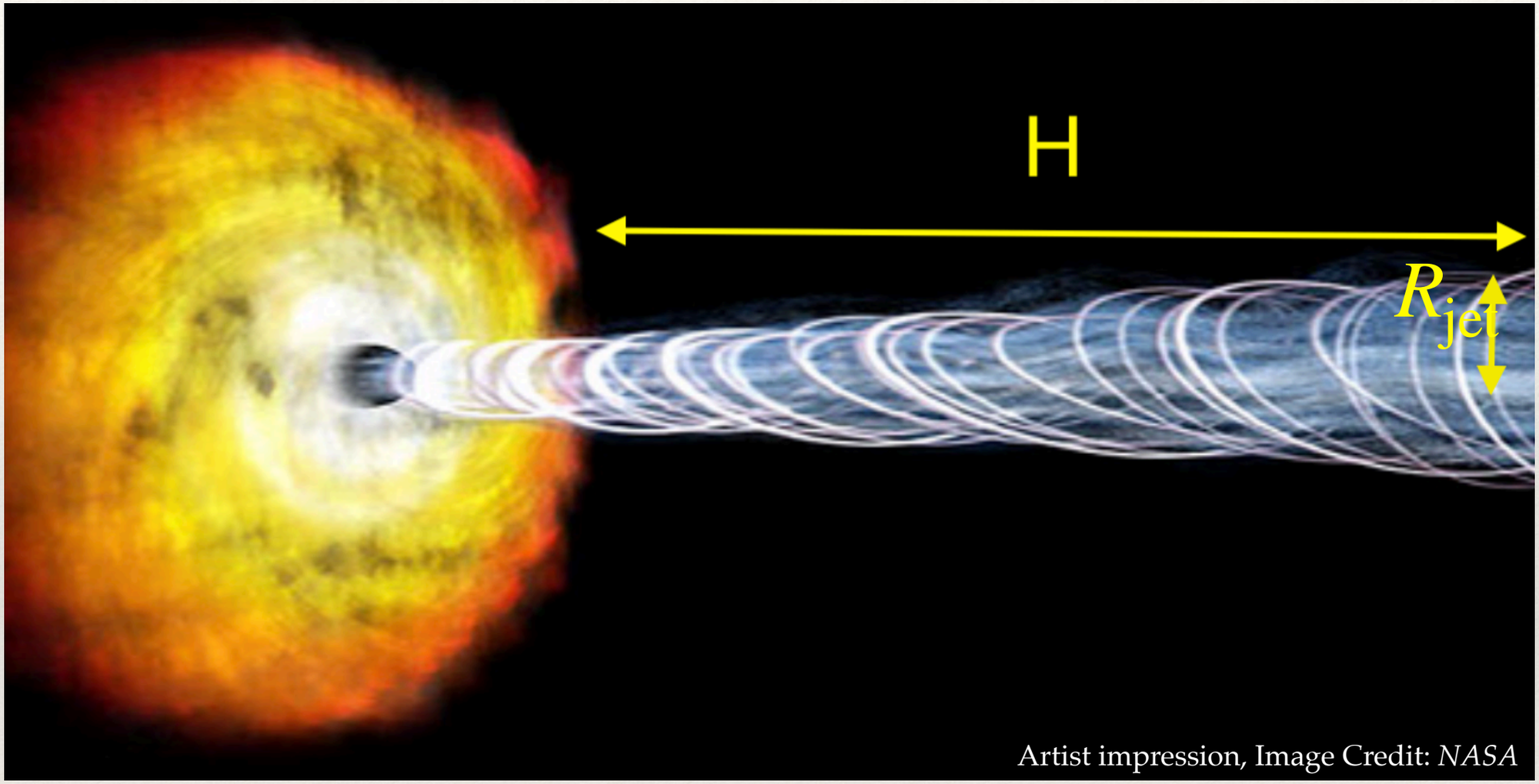


Mbarek & Caprioli (2019)

- α' is the Larmor radius in the flow frame
- $\mathscr{E}$ is the energy gain in the lab frame

$$\alpha' \equiv \frac{\mathscr{R}'}{R_{\rm jet}} = \frac{E'}{q\langle B'\rangle_r R_{\rm jet}} = \Gamma^2 \alpha_{\rm i} = \alpha_{\rm f}$$

Espresso Acceleration in Idealized Cylindrical Jet Models

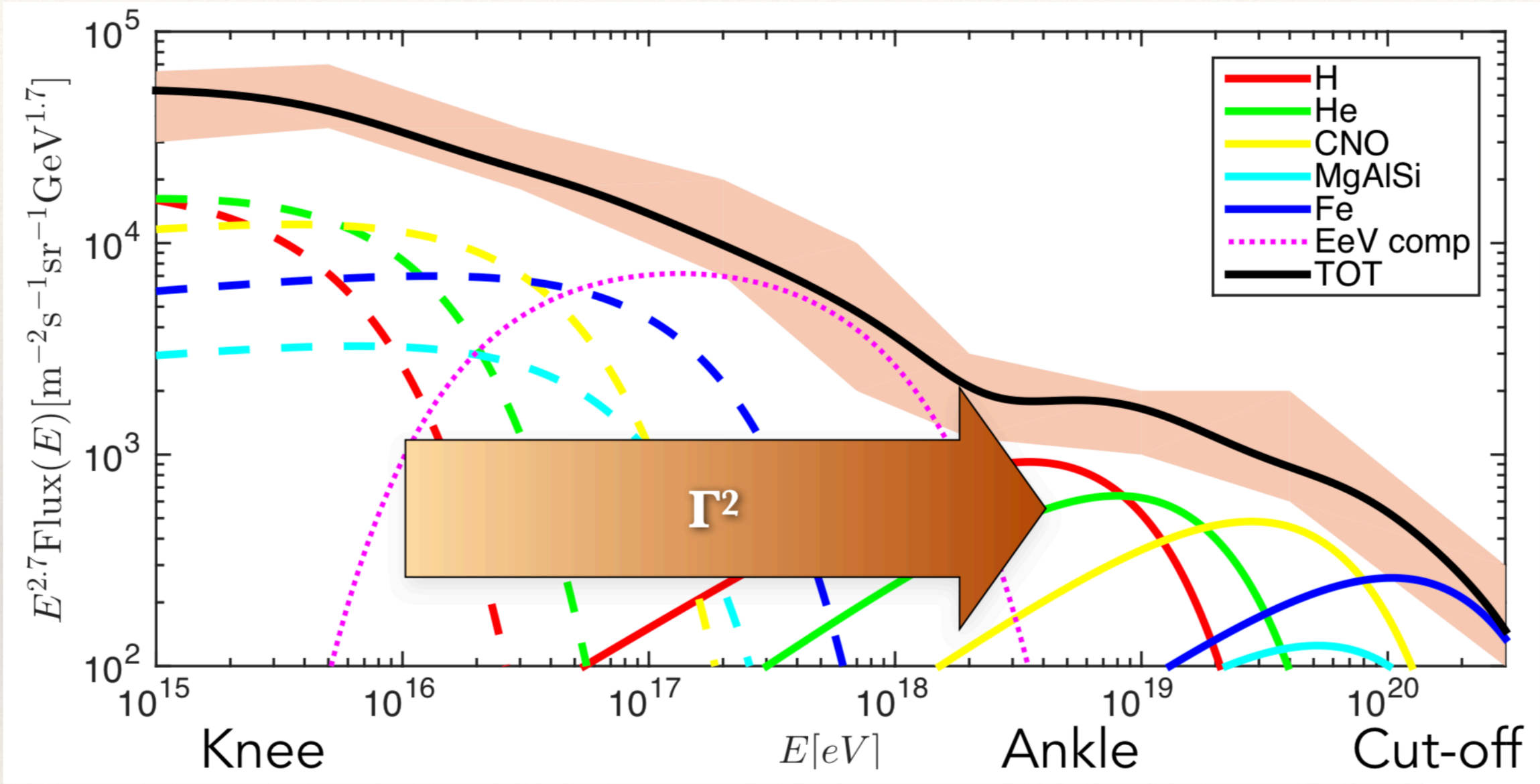


Artist impression, Image Credit: *NASA*

Manifestation of the Hillas criterion:

$$\mathscr{R}_{\rm i} \lesssim \frac{R_{\rm jet}}{2\Gamma^2}; \qquad \mathscr{R}_{\rm i} \lesssim \frac{H}{\Gamma^3}$$

The *espresso* mechanism and the chemical composition



Caprioli 2015

Fluxes and chemical composition above 10^{15} eV from *espresso* model compared with UHECR data.

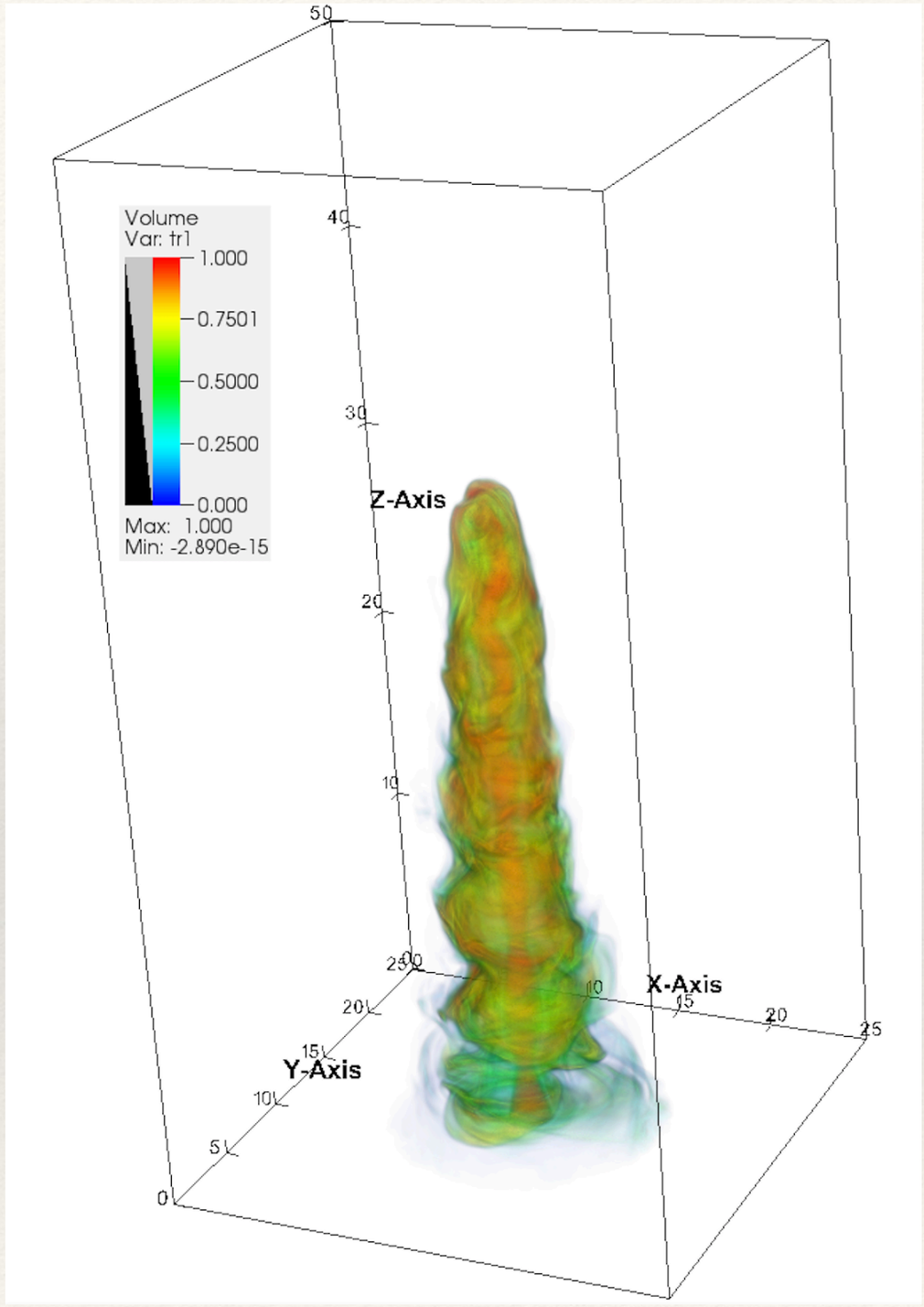
In Mbarek & Caprioli (2019), we test *espresso* in MHD jets

- Do particles typically get a boost of Γ^2? Can we get more than one *espresso* shot?
- Is acceleration up to the Hillas limit generally achievable?
- What is the fraction of CR seeds that can undergo *espresso* acceleration in a realistic jet?
- Are reaccelerated particles released isotropically?

Espresso in relativistic MHD Jet Simulations

3D Simulation with PLUTO (Mignone et al. 2010)

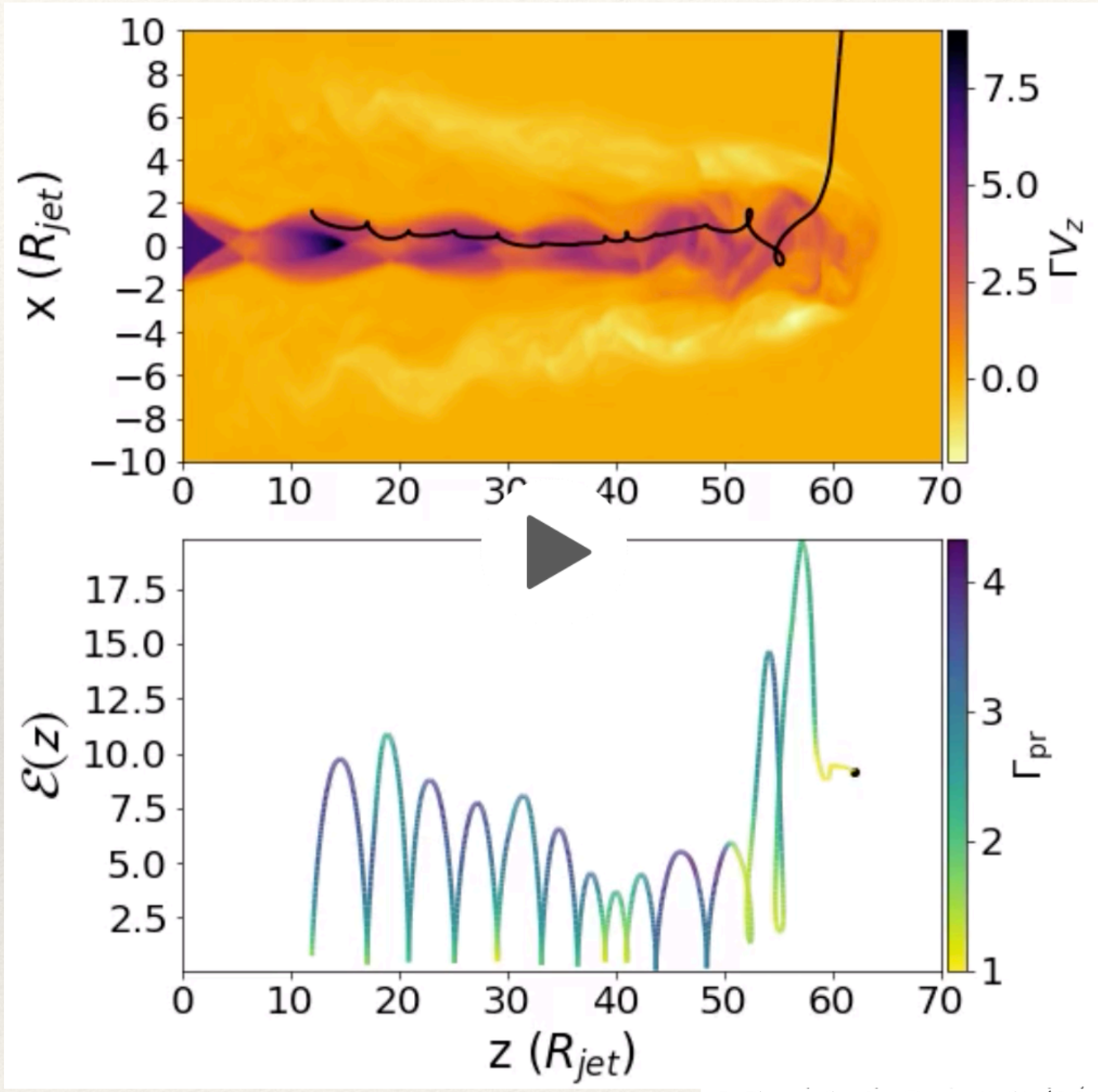
Jet is initialized with $\Gamma = 7$, but the effective value $\Gamma_{\text{eff}} = 3.2$



Espresso in relativistic MHD Jet Simulations

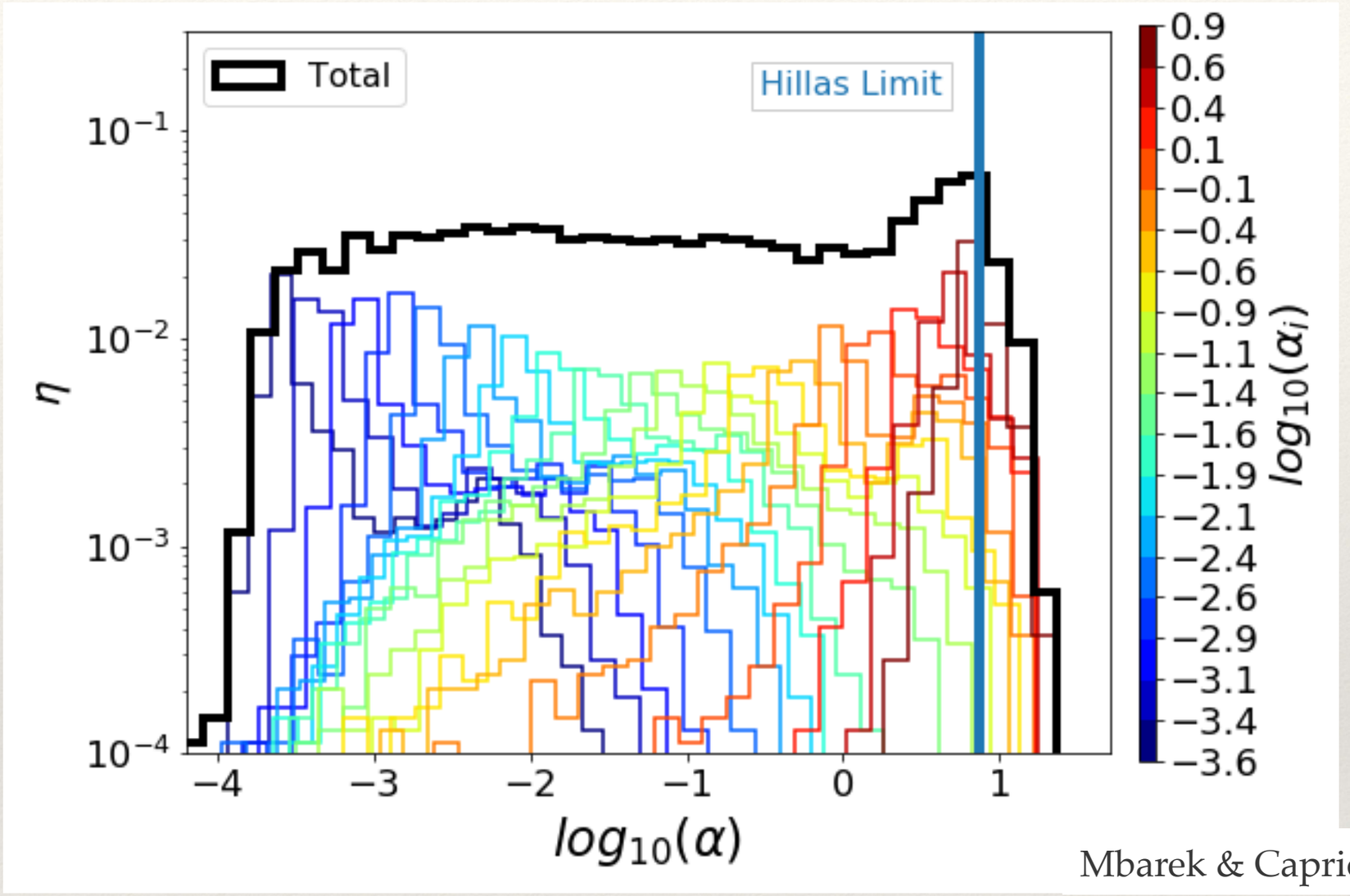
The trajectory agrees very well with analytical results!

Double *espresso* shot !!



Mbarek & Caprioli (2019)

Acceleration up to the Hillas limit

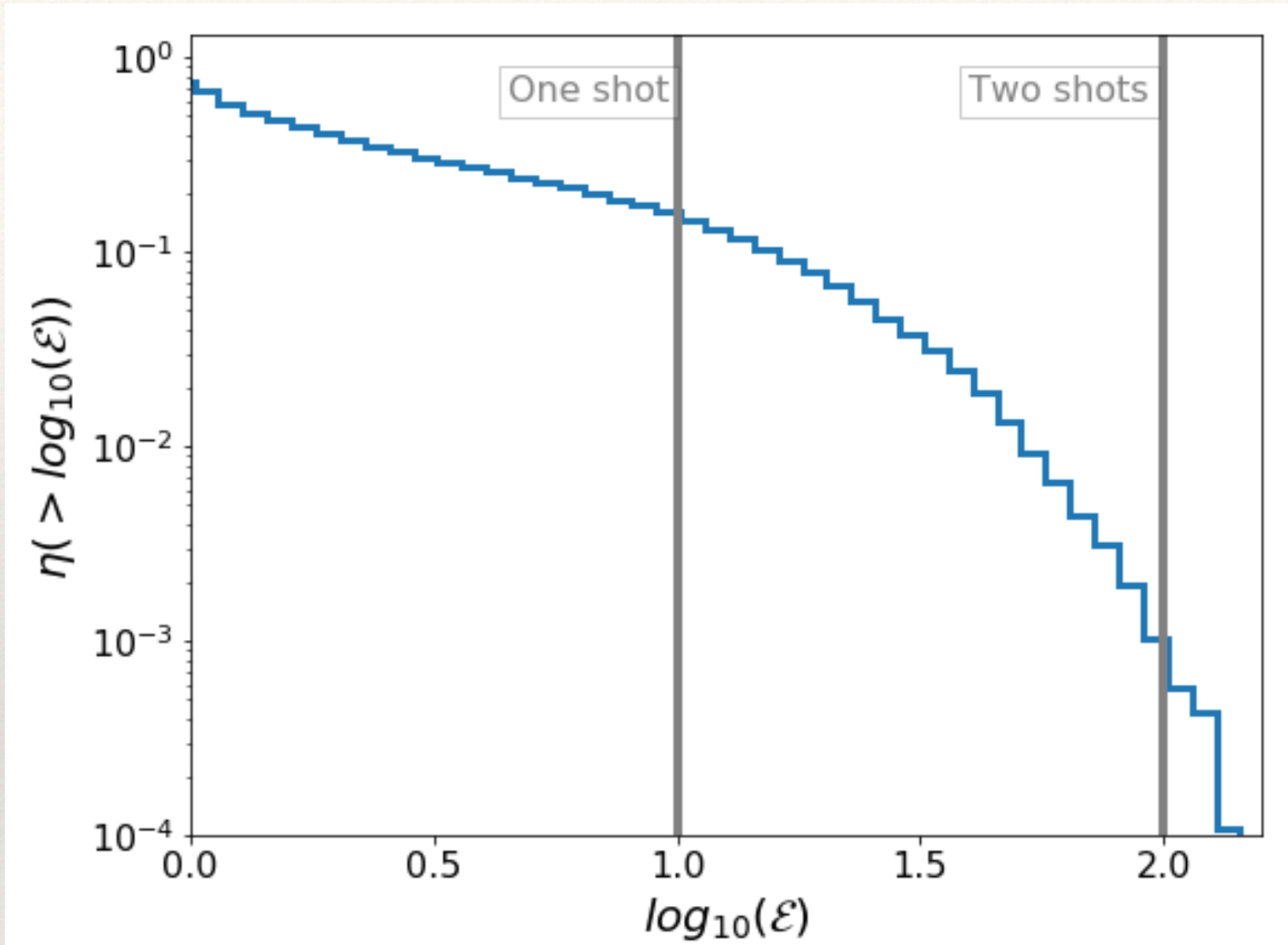


Mbarek & Caprioli (2019)

- Seeds with $\alpha_i \lesssim 1$ can undergo boosts as large as $\sim 50 - 100 \gg \Gamma^2_{\rm eff}$!!
  - Energy gain saturates at the Hillas limit

Fraction of accelerated CR seeds

- **10%** of the seeds are boosted by a factor of $\Gamma_{\rm eff}^2 \approx 10$ in energy (One *espresso* shot)
- **0.1%** of the seeds gain more than $\Gamma_{\rm eff}^4 \sim 100$ (two *espresso* shots)

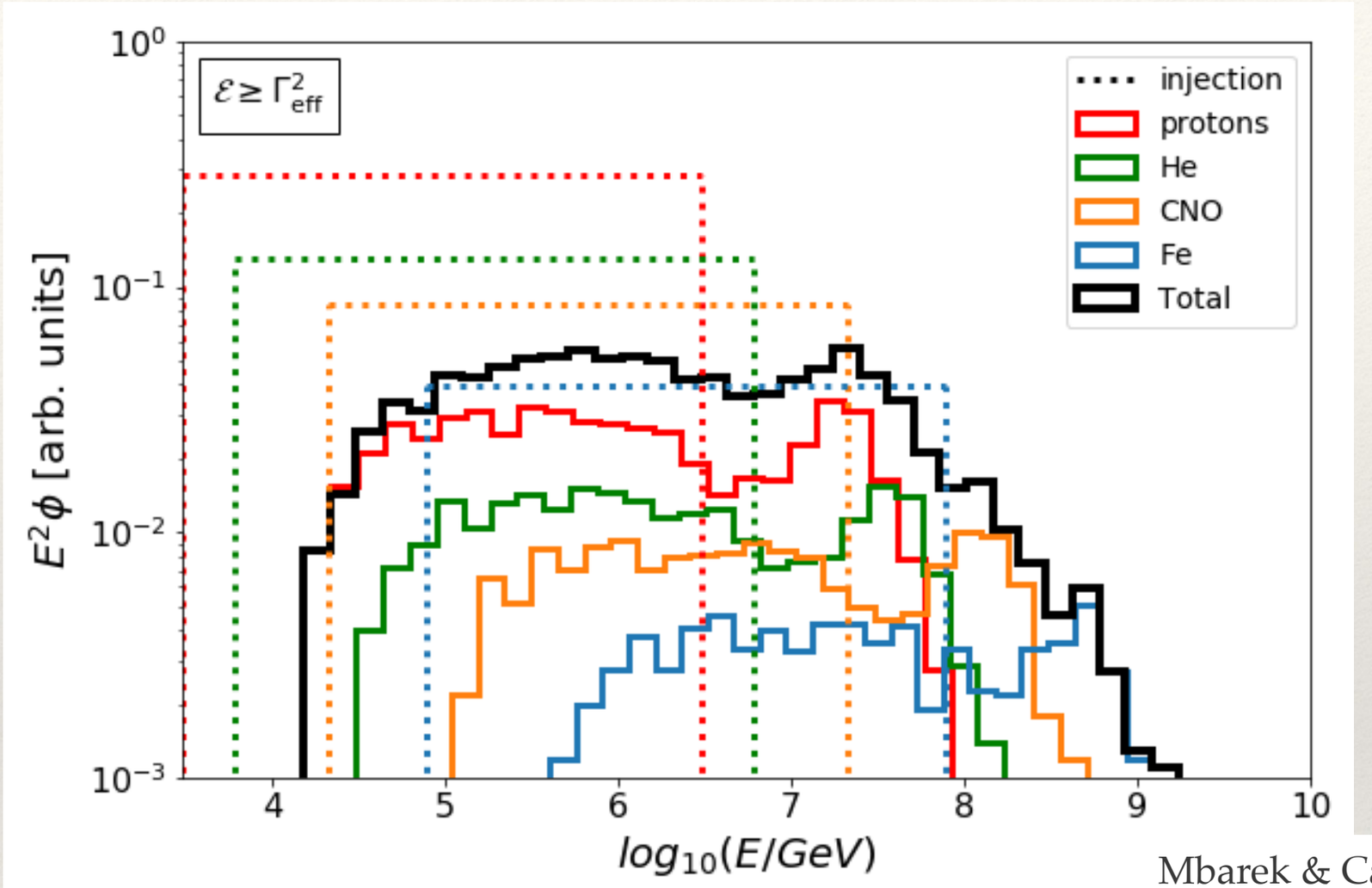


Mbarek & Caprioli (2019)

Cumulative distribution of the energy gains of particles

Released spectrum

Injection spectrum:
$\phi_s(E) \propto E^{-2}$



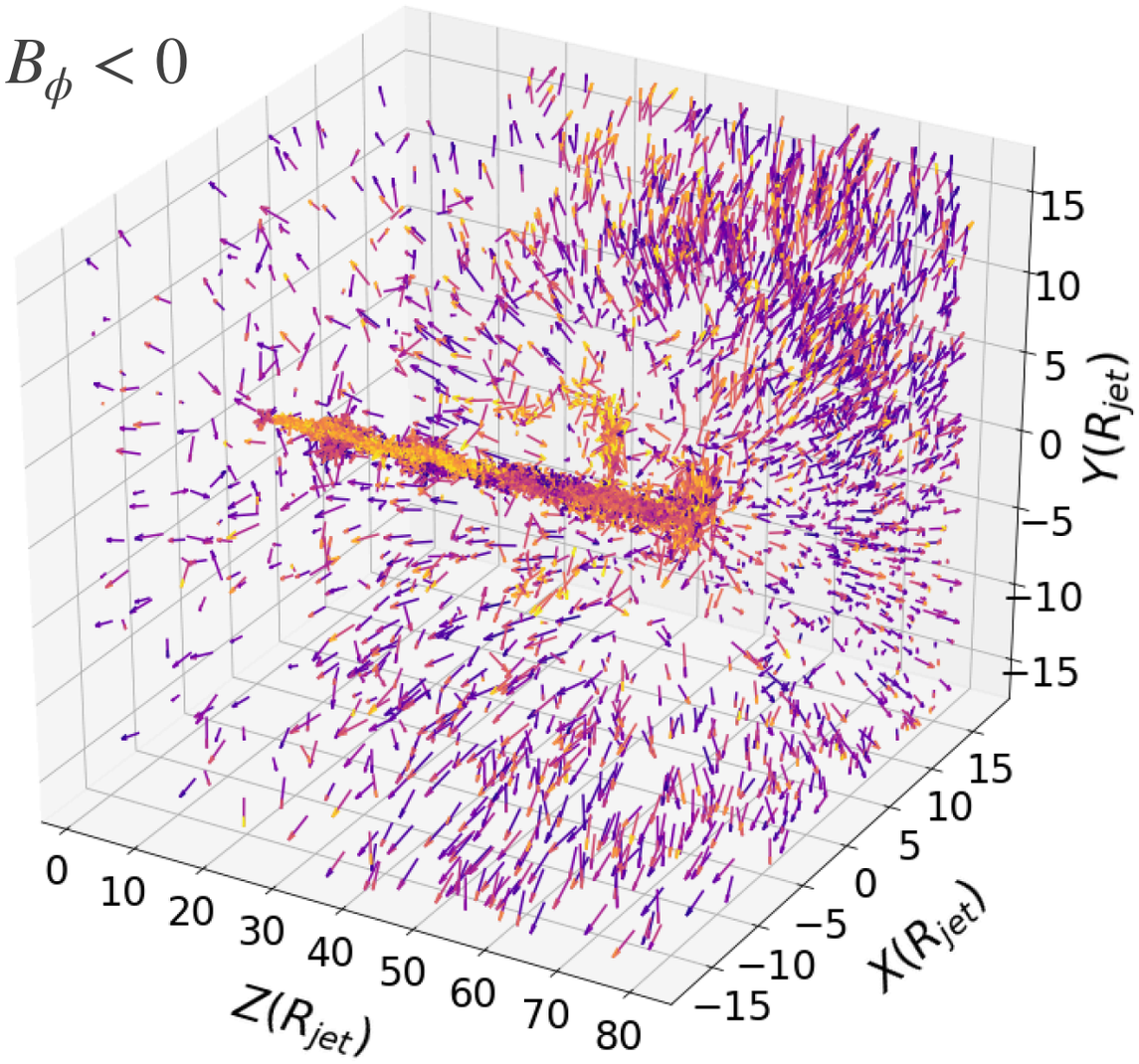
Mbarek & Caprioli (2019)

- The cutoffs of seed species are boosted up in energy by a factor of $\Gamma_{\rm eff}^2 \sim 10$
- Spectra exhibit a high-energy tail because of the particles that underwent multiple acceleration cycles.

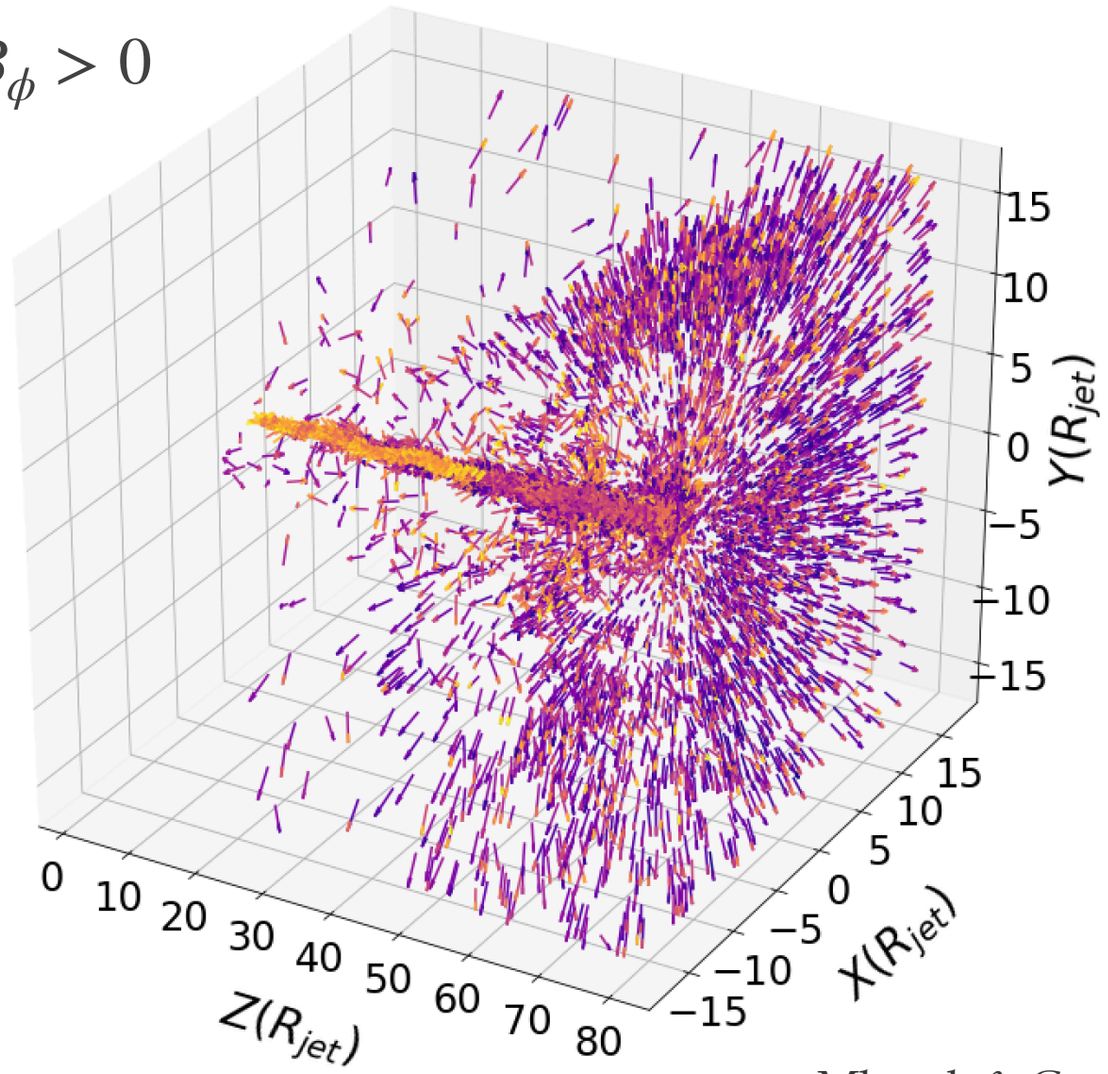
Angular Distribution of Reaccelerated Particles

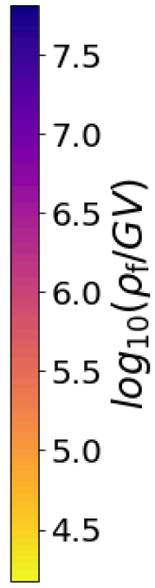
ρ_f is the rigidity of the escaping particles

$B_\phi < 0$



$B_\phi > 0$



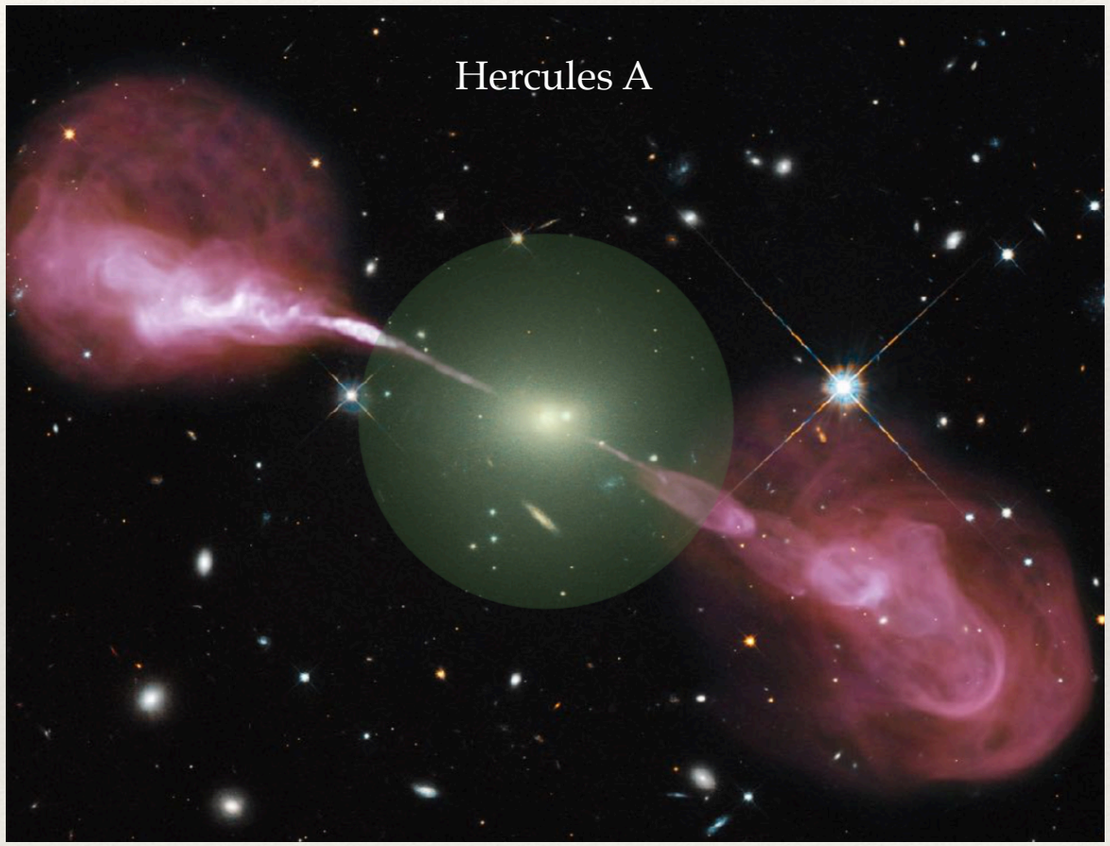


Mbarek & Caprioli (2019)

- For $B_\phi < 0$, particles are released quasi isotropically,
- For $B_\phi > 0$, particles are preferentially beamed along the jet axis

Potential jet candidates

radio-loud FRIIs	radio-loud FRIs
• show $\Gamma \geq 10$ at kpc scales and above	• decelerated to non-relativistic bulk flows within 1 kpc
Conclusion: They are excellent candidates	**Conclusion:** marginally satisfy the constraints, but..



Conclusions

- We find no particles that go through stochastic acceleration
- Espresso relies on **very general assumptions** and is quantitatively verified **bottom-up** in state-of-the-art MHD simulations.
- The espresso model could account for all of the **UHECR observables** (**spectrum, maximum energy, energetics, composition, anisotropy**).