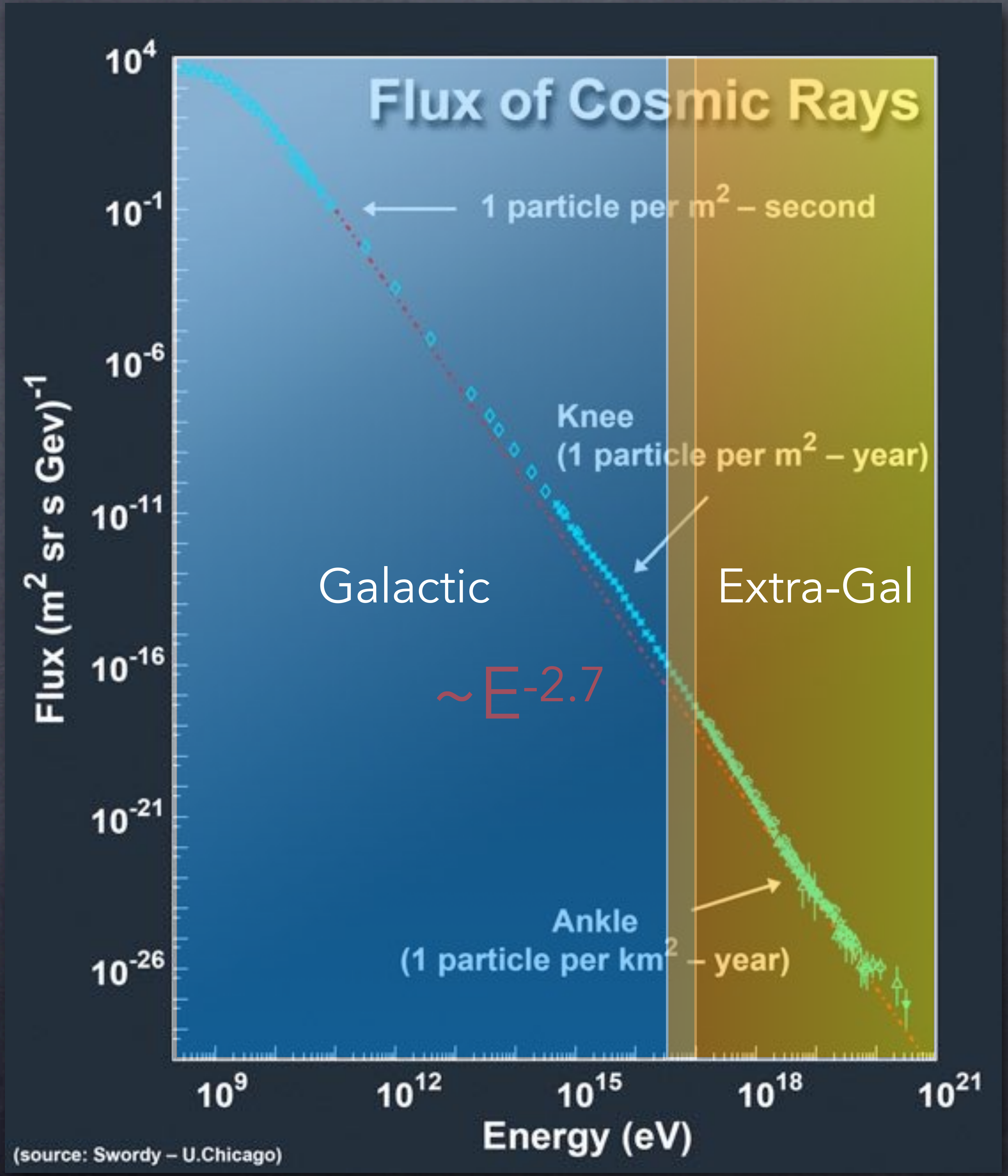
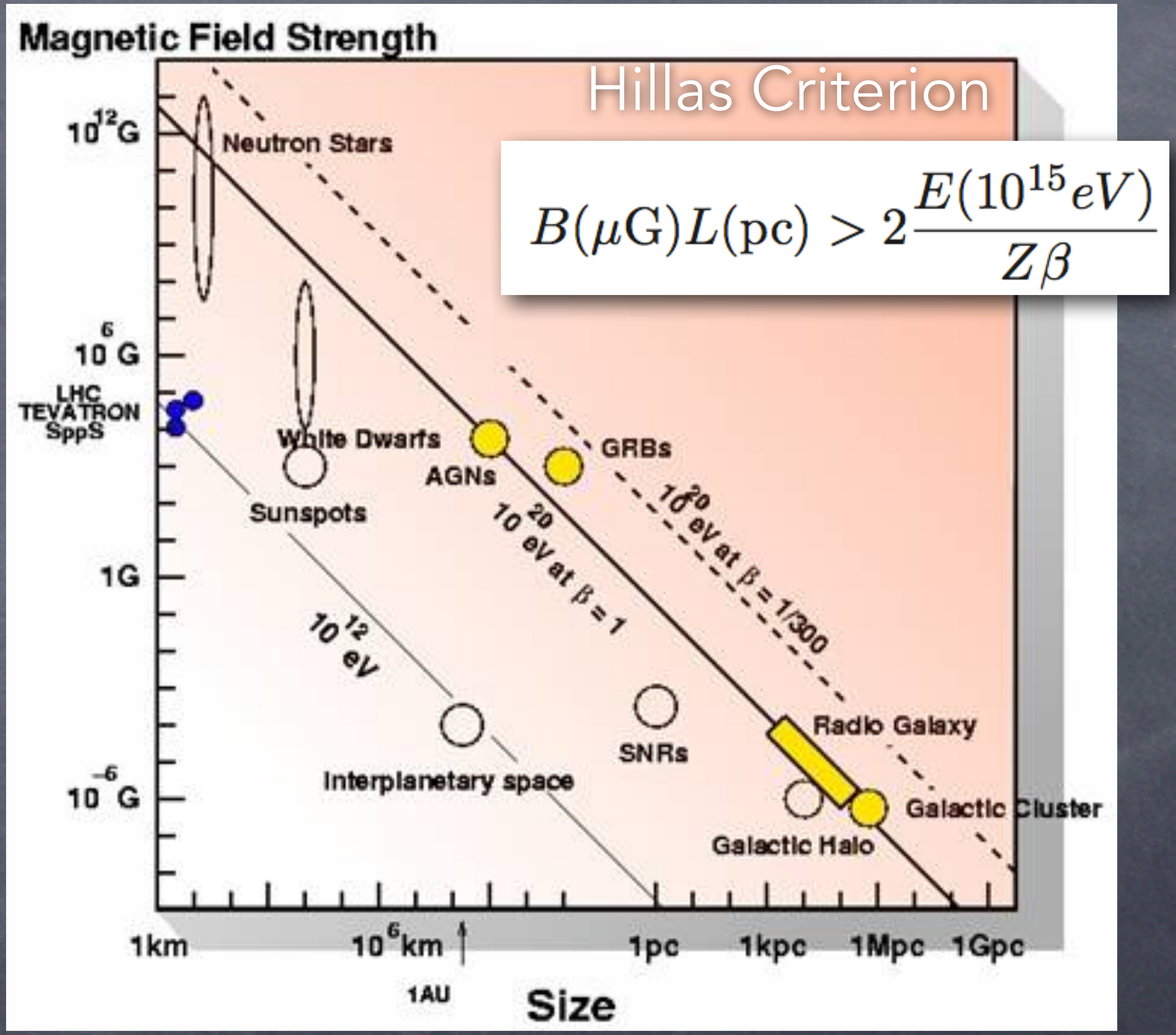
Cosmic Rays: Hunt for Sources



(source: Swordy – U.Chicago)

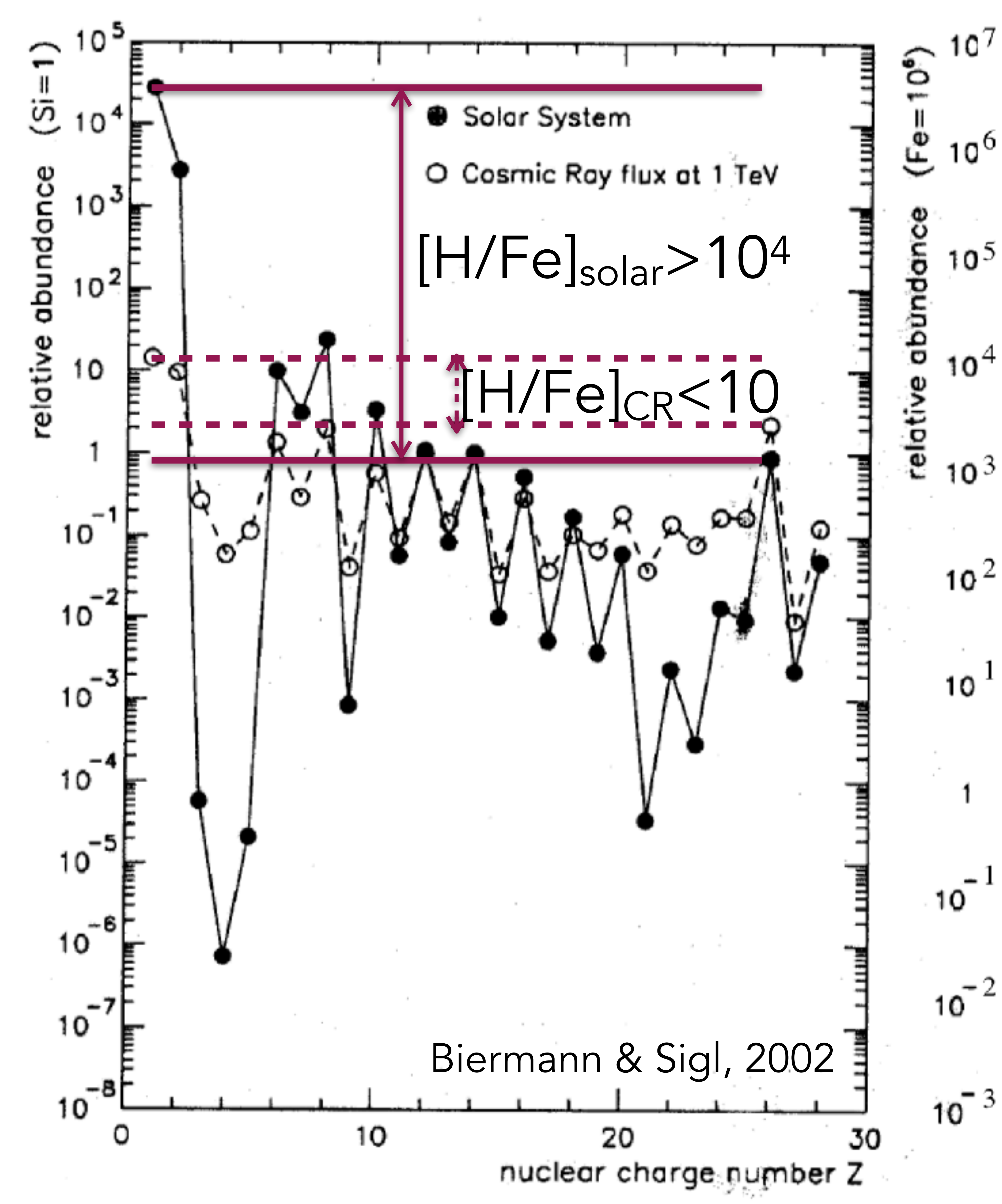


$$B(\mu\mathrm{G})L(\mathrm{pc}) > 2\frac{E(10^{15}eV)}{Z\beta}$$

- Remarkable power-law (plus "leg" features)
- The steepening at ~3PeV suggests a rigidity-dependent cut-off

Chemical Composition of Galactic CRs

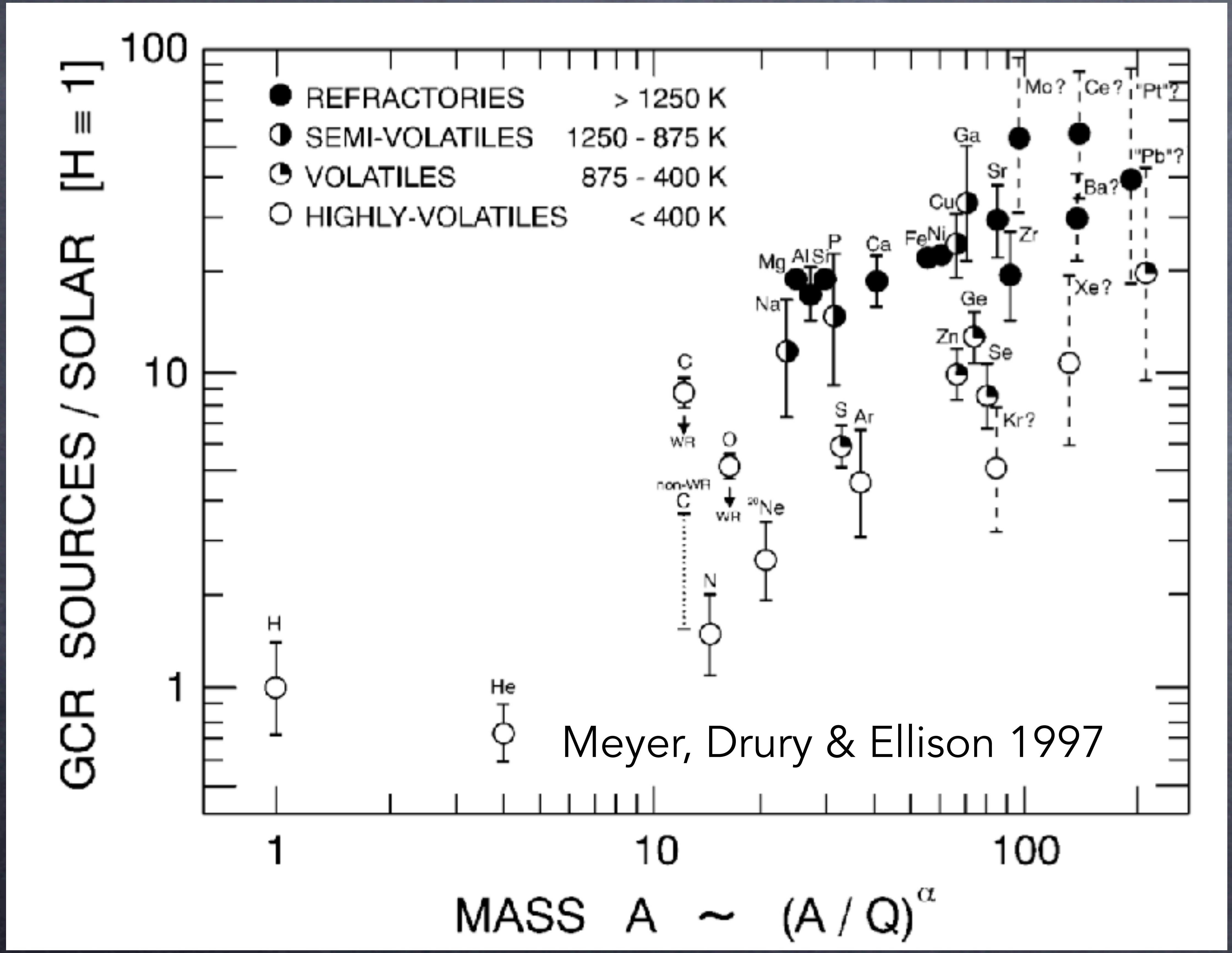
- "Urban legend": similar to solar at low energies (e.g., Simpson 1983)



Biermann & Sigl, 2002

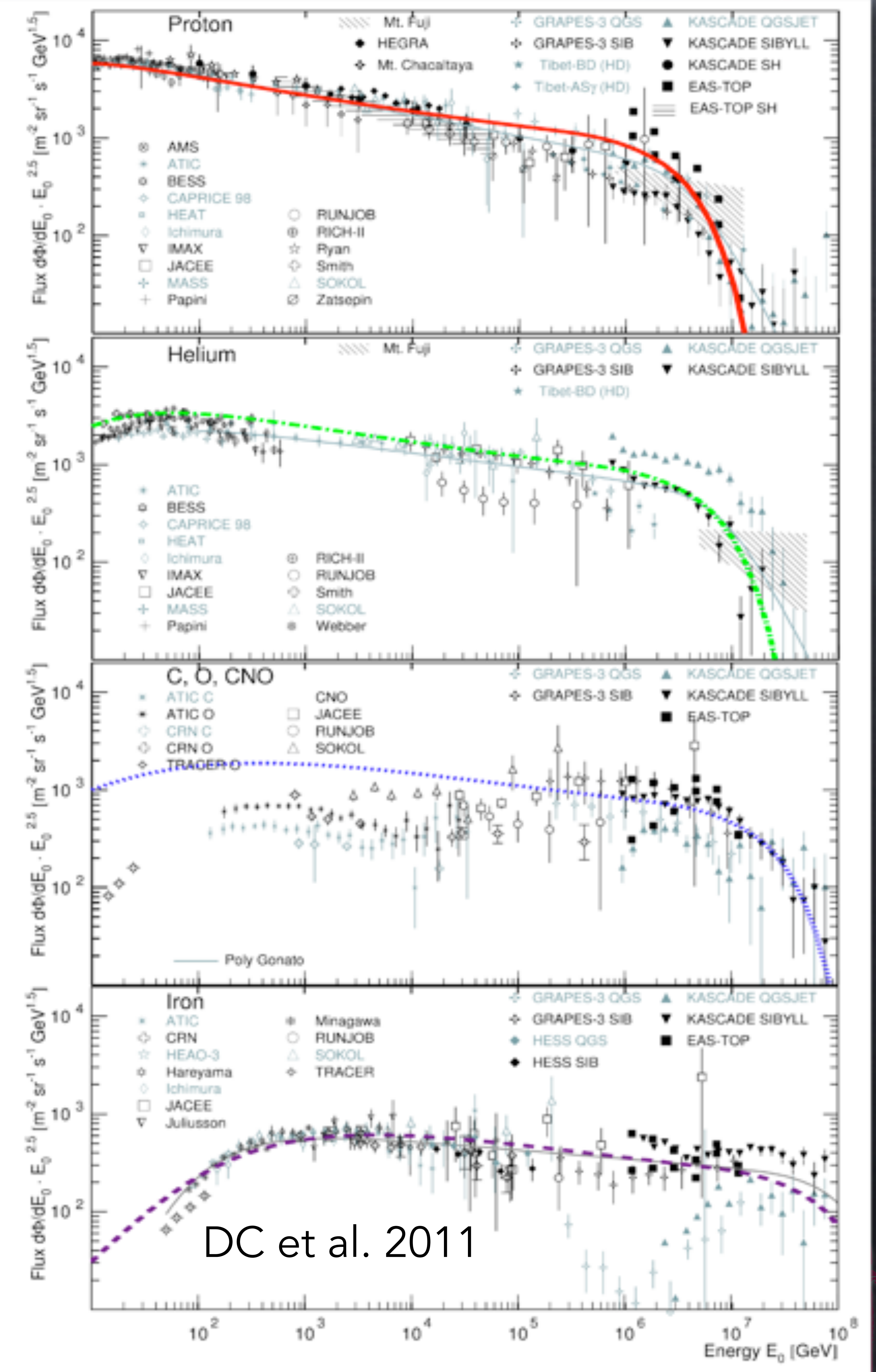
Chemical Composition of Galactic CRs

- “Urban legend”: similar to solar at low energies (e.g., Simpson 1983)
  - Depends on volatility, on atomic mass A, on first ionization potential…
- Above 1 TeV, fluxes of H, He, CNO, and Fe are comparable!



Meyer, Drury & Ellison 1997

Nuclei heavier than H must be injected more efficiently



DC et al. 2011

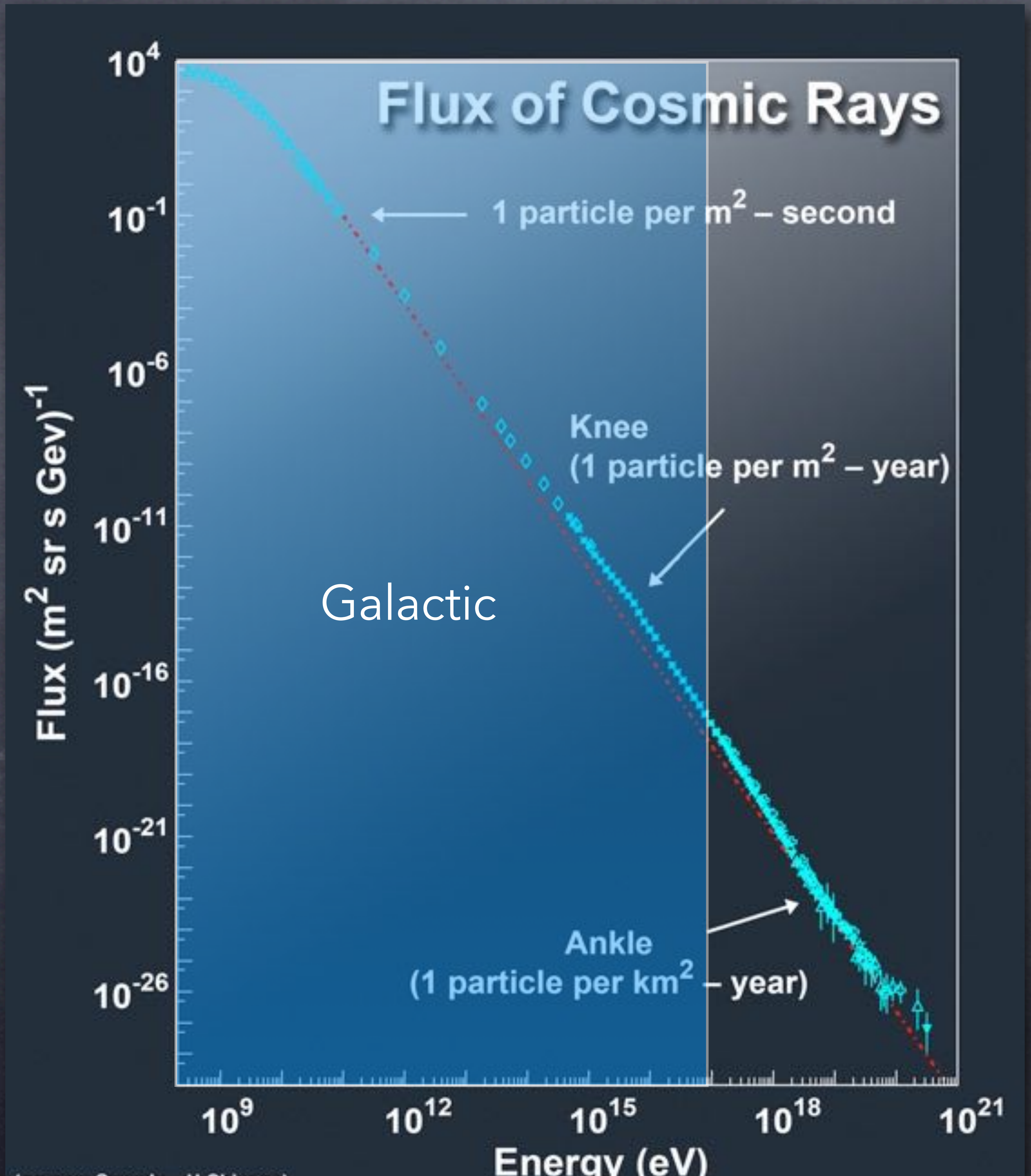
Outline

1) Origin of the elemental composition of Galactic CRs

2) Role of CRs in SNR evolution

3) *Espresso* acceleration of UHECRs

SNR Paradigm for Galactic Cosmic Rays



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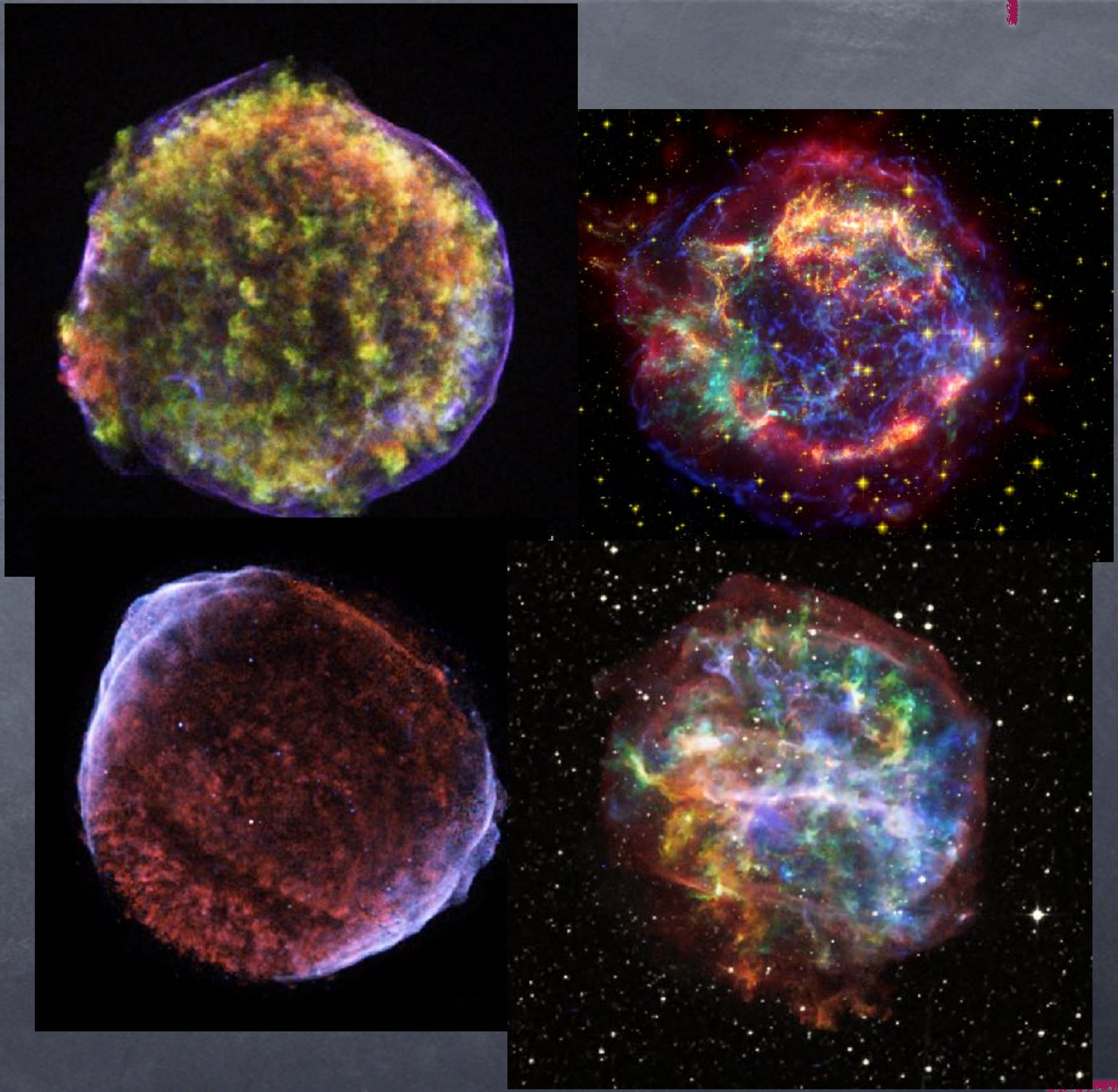
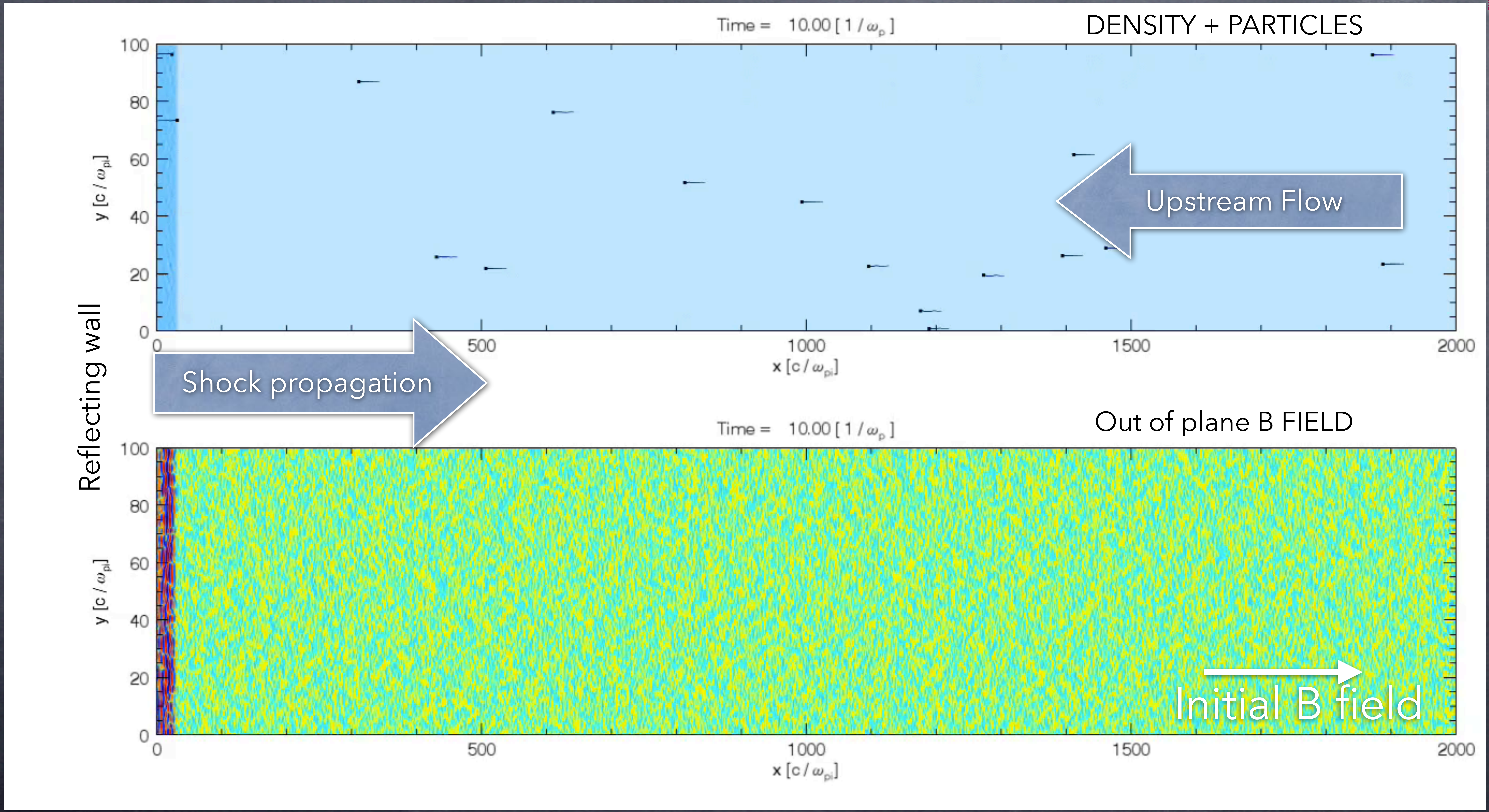


Hybrid simulations of collisionless shocks



DENSITY + PARTICLES

Upstream Flow

Reflecting wall

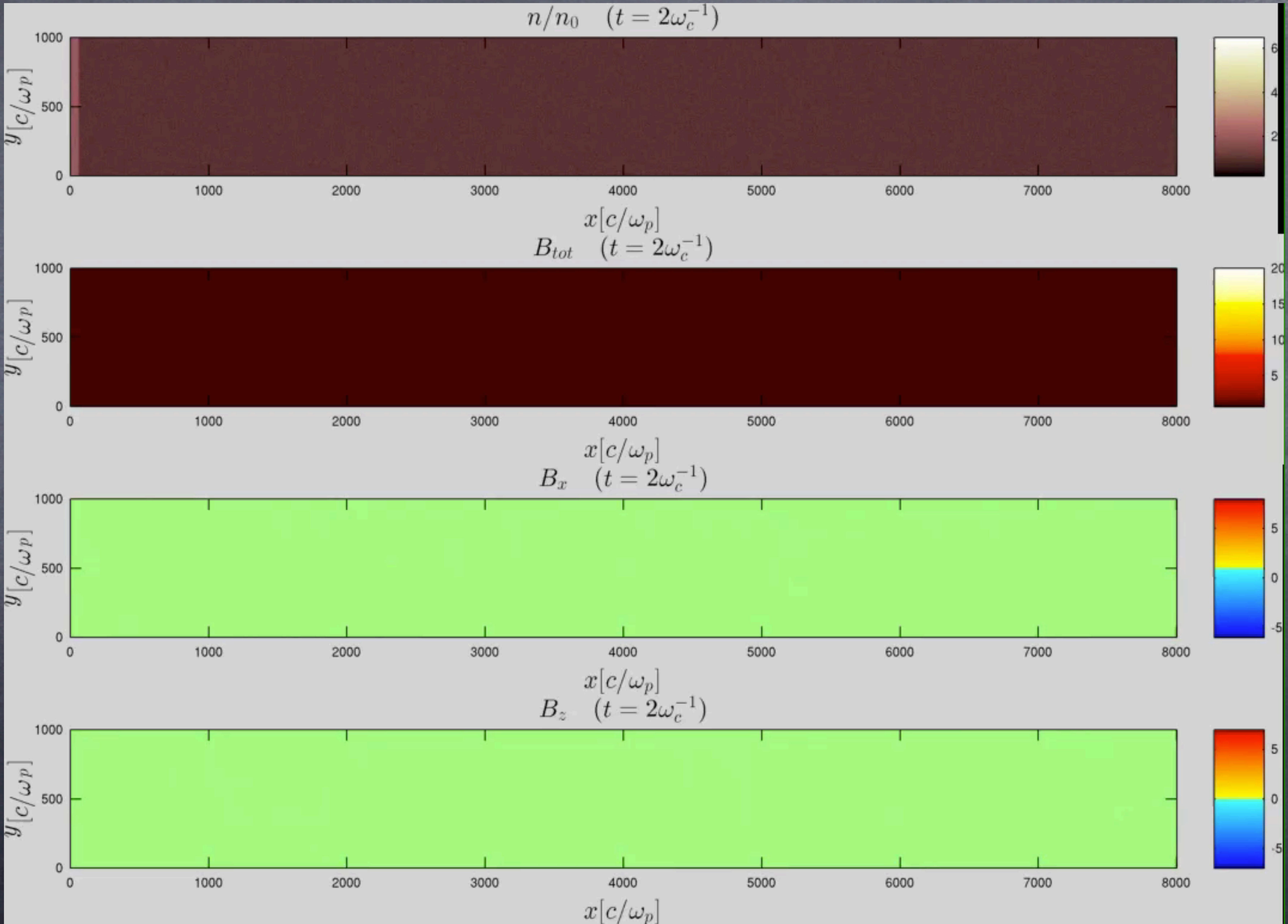
Shock propagation

Out of plane B FIELD

Initial B field

dHybrid code (Gargaté et al, 2007; DC & Spitkovsky 2014, **Haggerty & DC, see poster**)

CR-driven Magnetic-Field Amplification



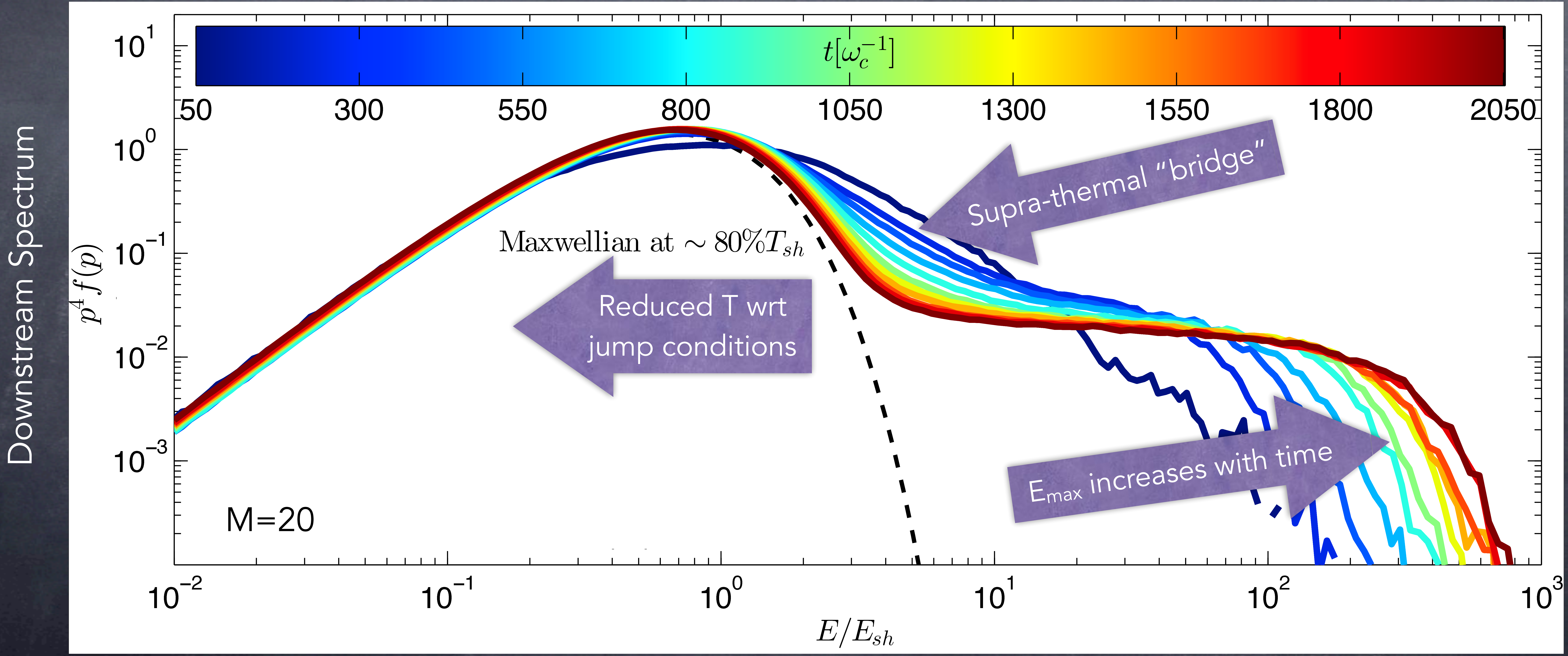
Initial B field

$M_s = M_A = 30$

DC & Spitkovsky, 2013

Spectrum evolution

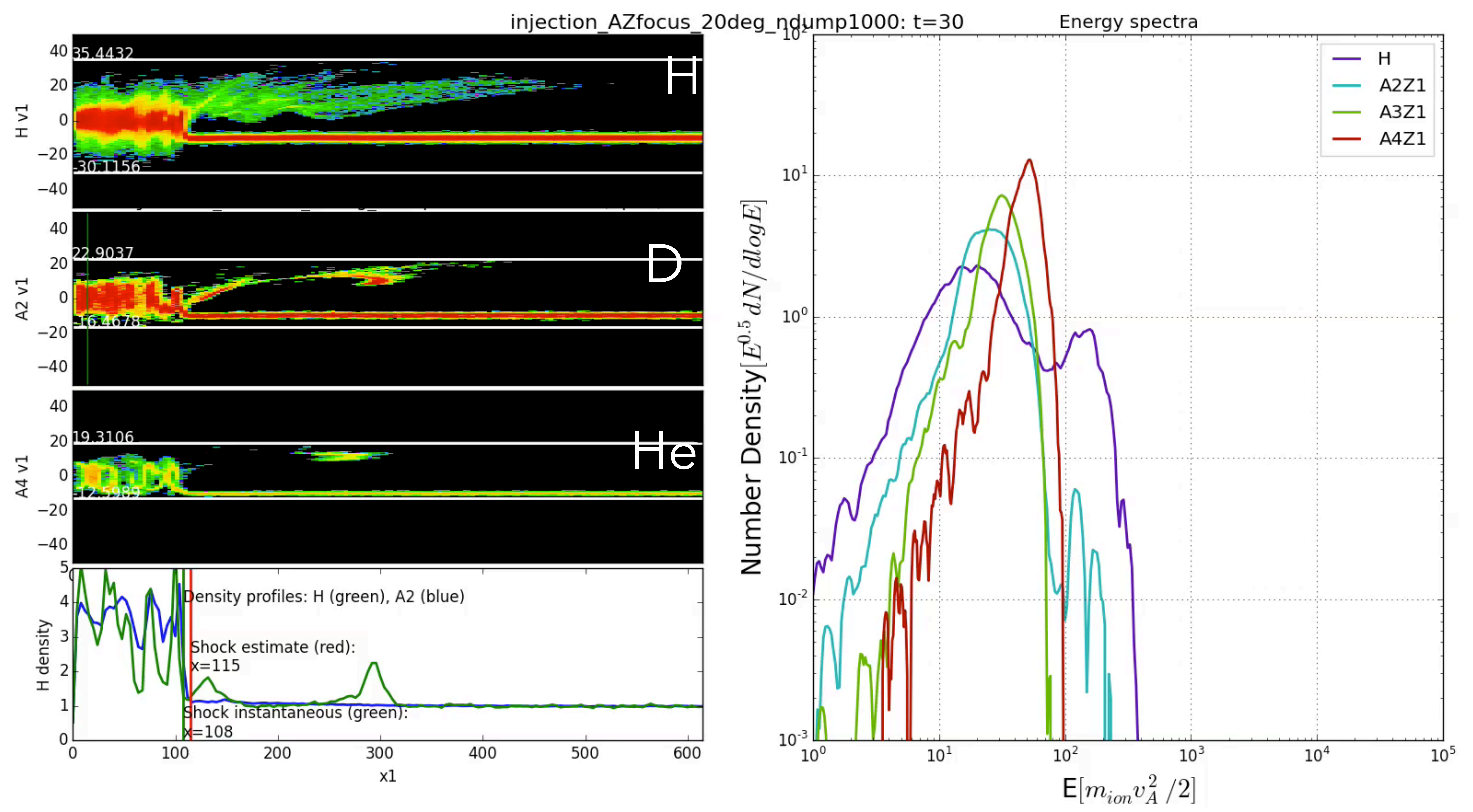
- Diffusive Shock Acceleration: non-thermal tail with universal spectrum $f(p) \propto p^{-4}$
- Efficiency: ~15% of the shock bulk energy in accelerated protons!



DC & Spitkovsky, 2014a

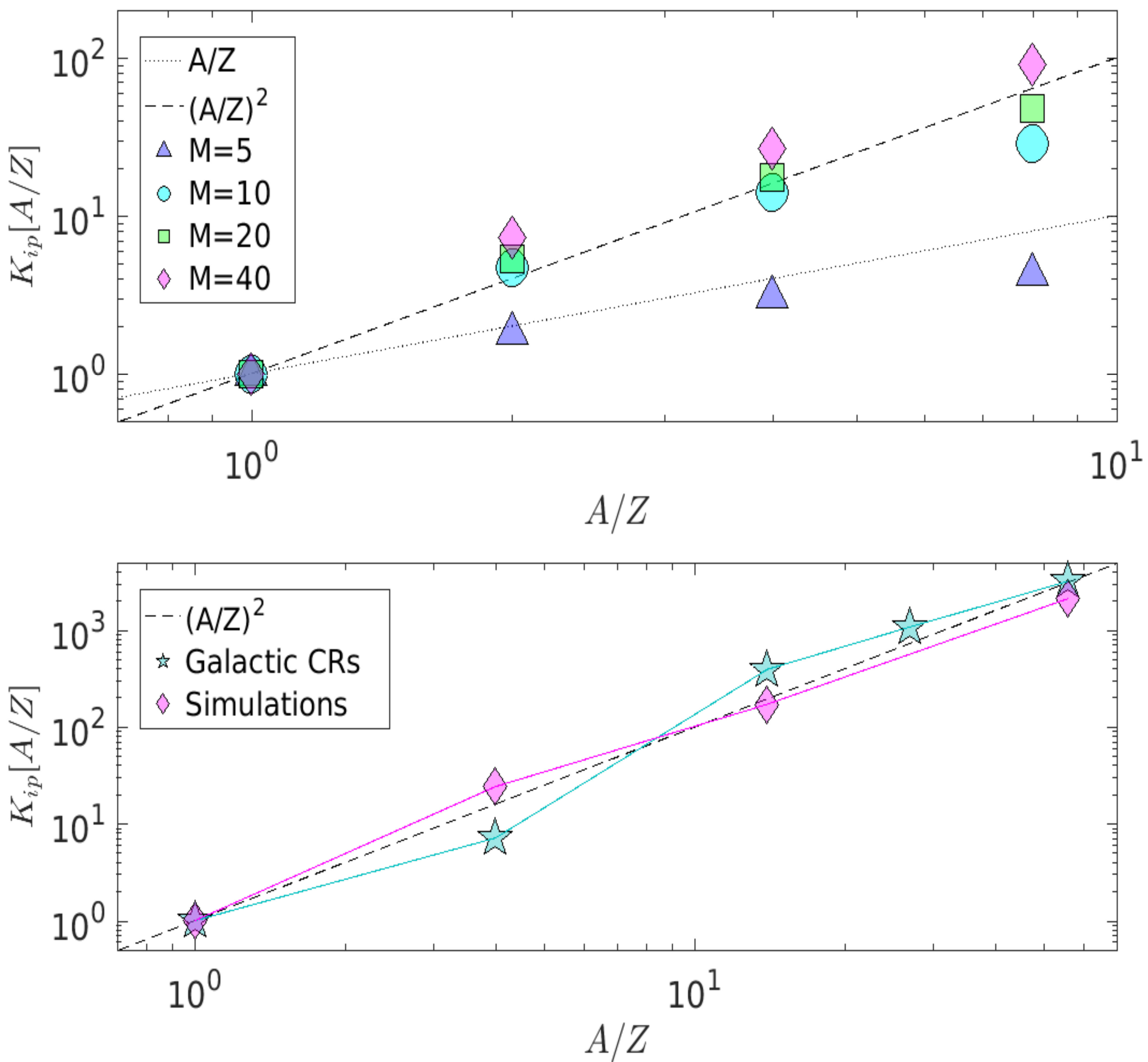
Hybrid Simulations

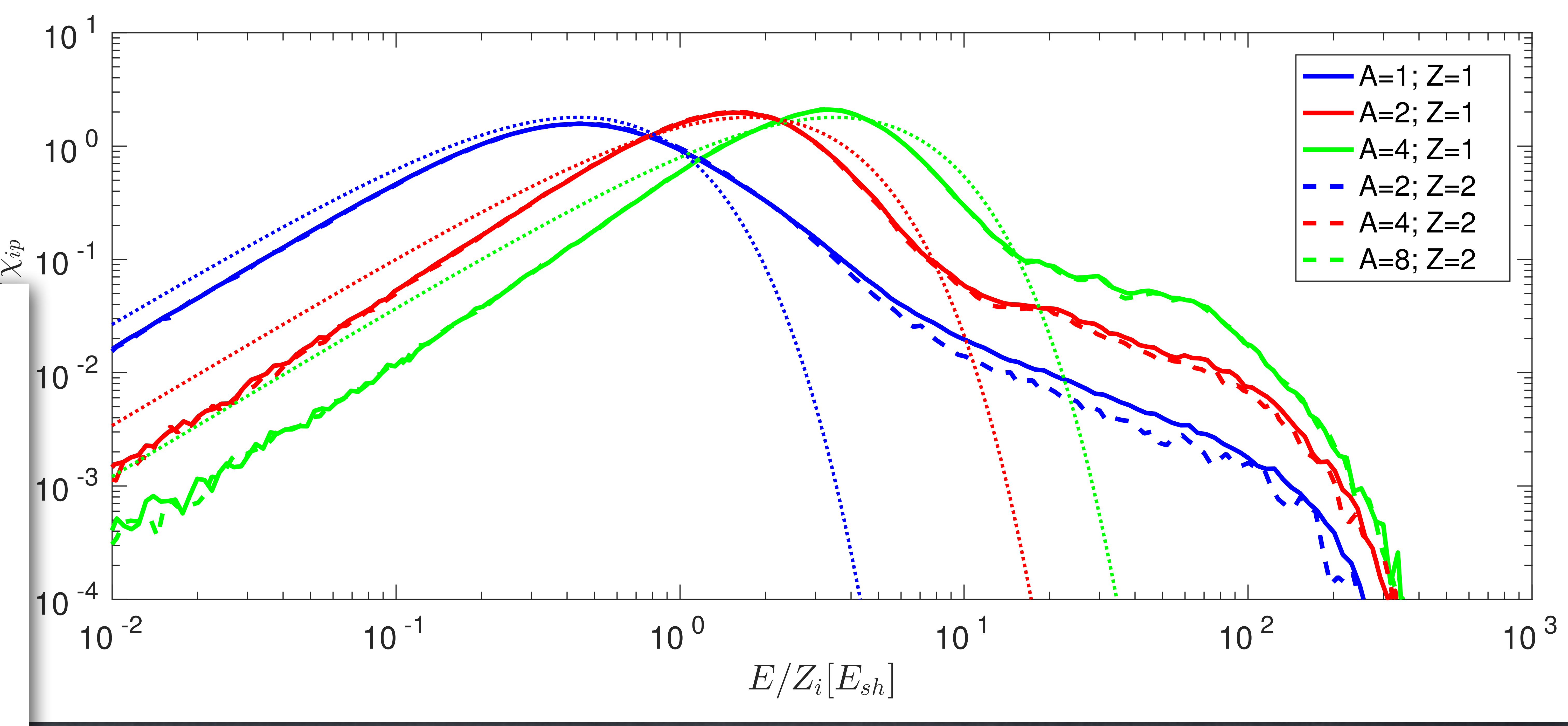
- M=10, parallel shock, with singly-ionized nuclei (DC, Yi, Spitkovsky 2017)



Hybrid Simulations with Heavy Ions

- Quasi-parallel shock, M=20
  Ion DSA when proton DSA!



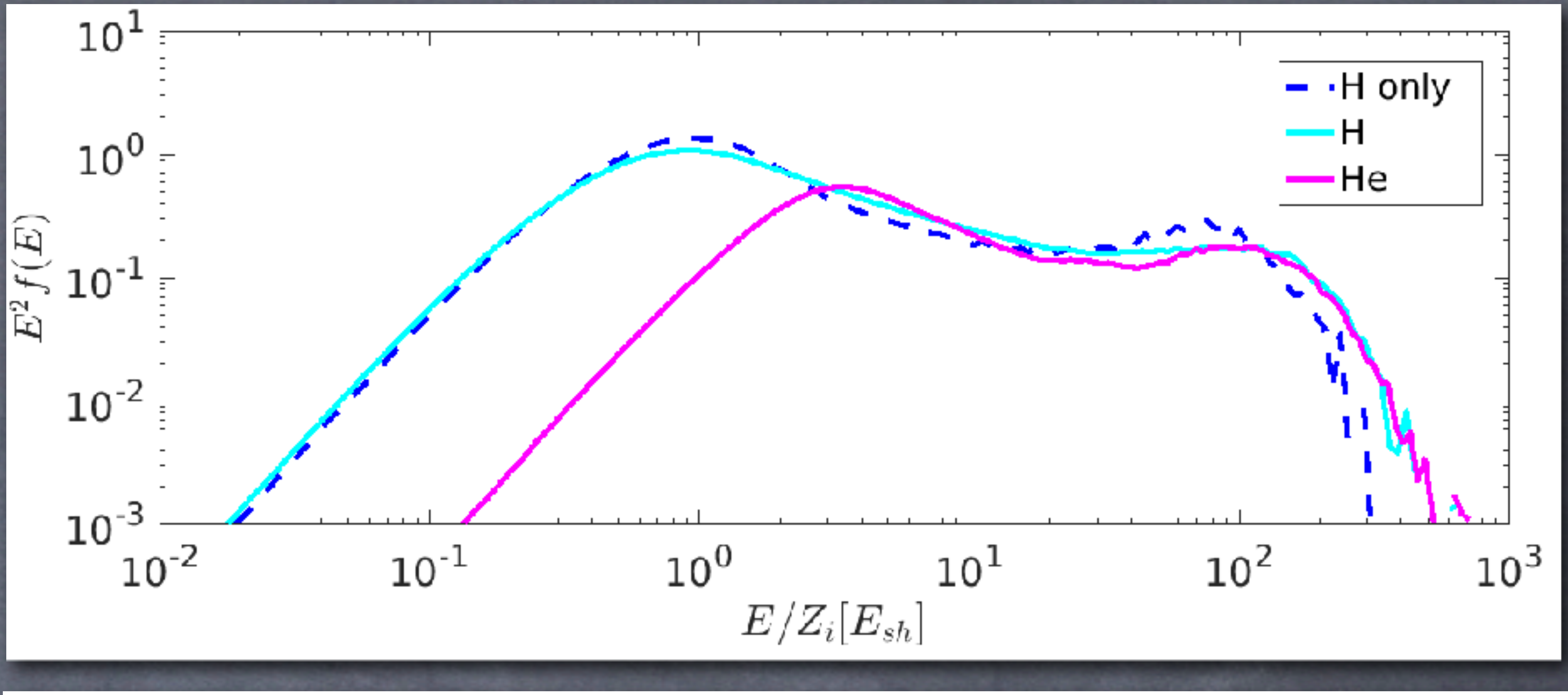


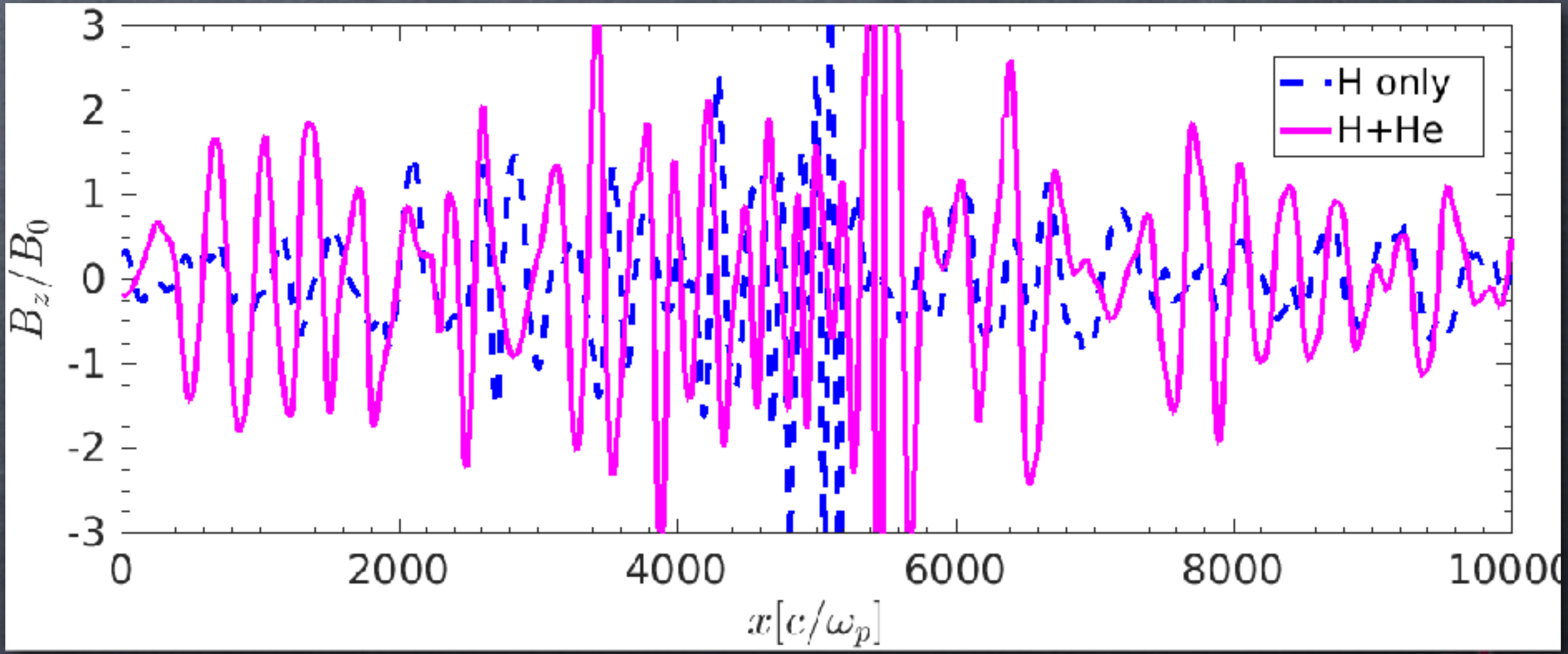
DC, Yi & Spitkovsky, 2017

- Post-shock T_i scales with A_i
- $E_{max,i}$ scales with Z_i
- The tail normalization scales with $(A_i/Z_i)^2$
  - Explains CR chemical enhancements!

Helium is *not* test-particle!

- With cosmological He abundance ~10% (DC & Roussi, in prog)
  - He acceleration efficiency ~15% (as H)
    - *Total* efficiency ~30%
    - Increases shock modification
  - He can drive waves as much as H
    - E_{max} 2x larger for both species
- Hadronic gamma-ray emission can be boosted by a factor ~5 (DC et al, 2011)

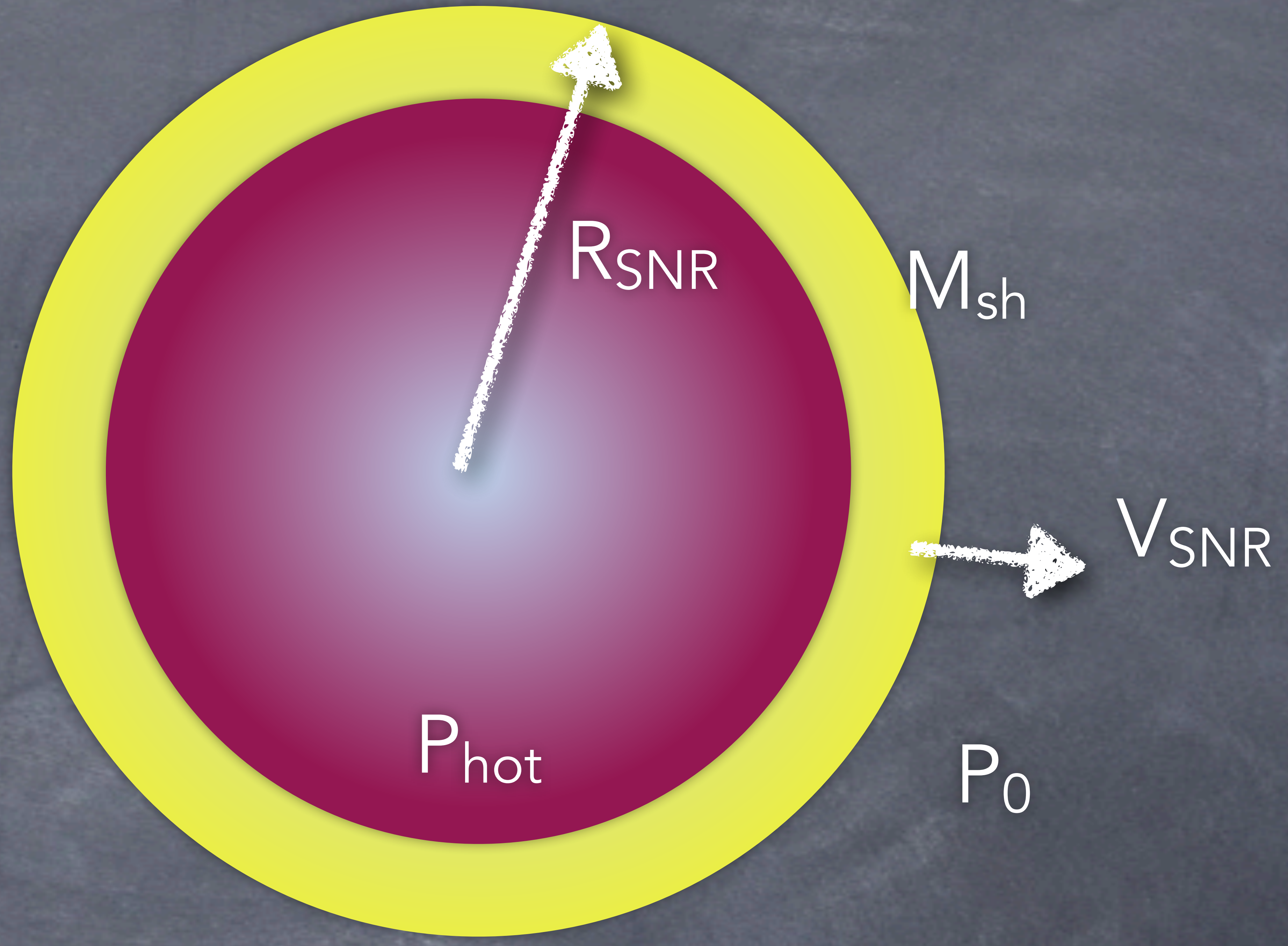




What is the feedback of
CRs on SNR evolution?
(and on galaxy formation?)

SNR Evolution in a Thin-Shell (Bisnovatyi-Kogan & Silich, 1995)

- **Ejecta-dominated** stage: $R_{SNR} \sim V_{SNR}\, t$
- **Sedov-Taylor** (adiabatic) stage: $R_{SNR} \sim t^{2/5}$
- **Radiative stage** ($T_{sh} <\sim 10^6$K)
  - Pressure-driven snowplow ($P_{hot} > P_0$)
  - Momentum-driven snowplow ($P_{hot} \sim P_0$)



$$\frac{d\left(M_{\rm sh} v_{\rm SNR}\right)}{dt} = 4\pi r_{\rm SNR}^2 \left(P_{\rm hot} - P_0\right)$$

SNRs deposit energy and momentum in the ISM
Crucial for feedback that can suppress star formation

SNR evolution with CRs

- CR acceleration efficiency ξ (in energy): CRs do not radiate their energy away: more effective expansion
- Thin-shell approximation reproduces the Sedov to radiative stage transition (first semi-analytical solution!)
- CRs can boost the momentum deposition by factors of 2-10 for typical ISM conditions

Diesing & DC, 2018

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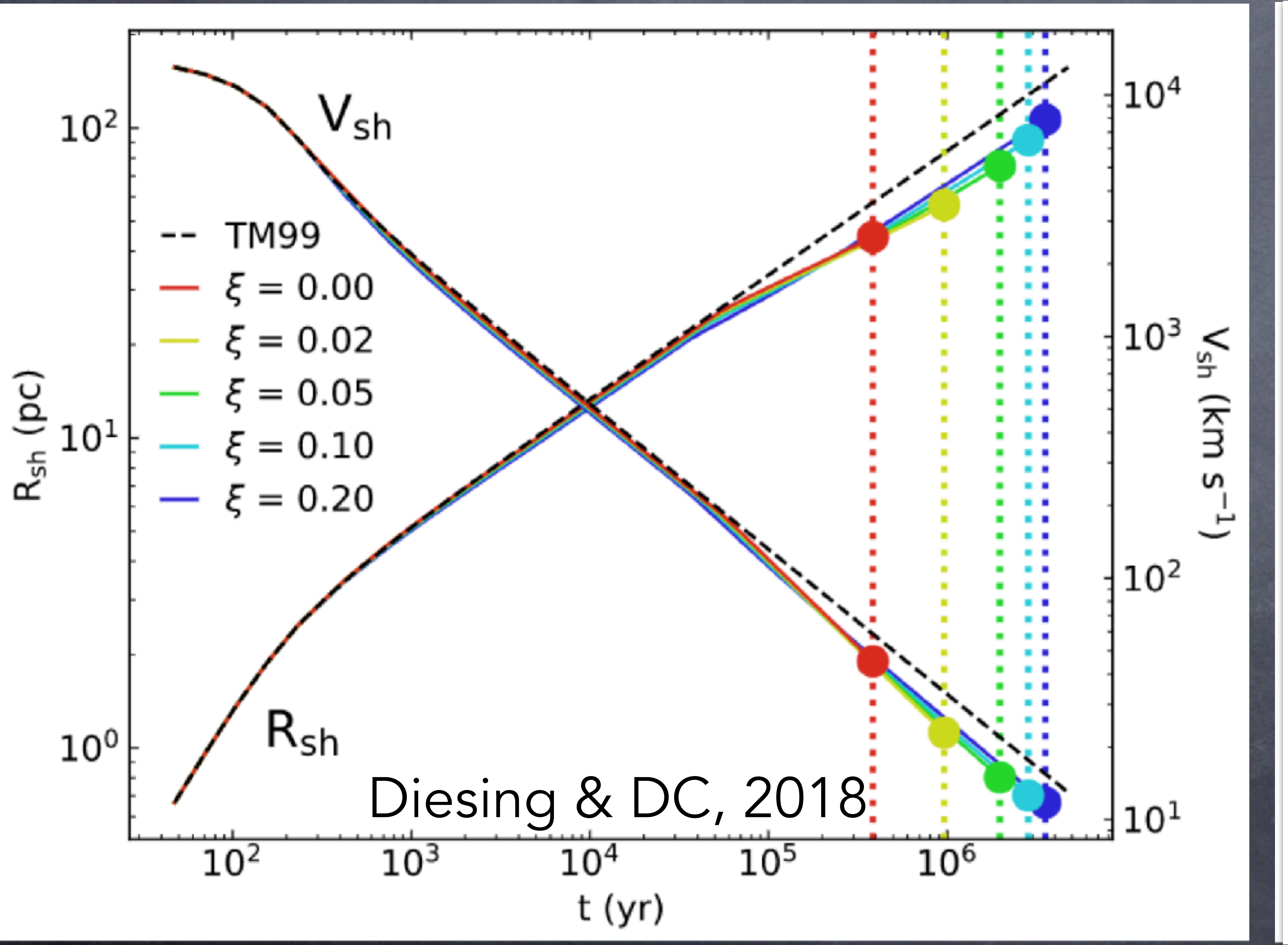
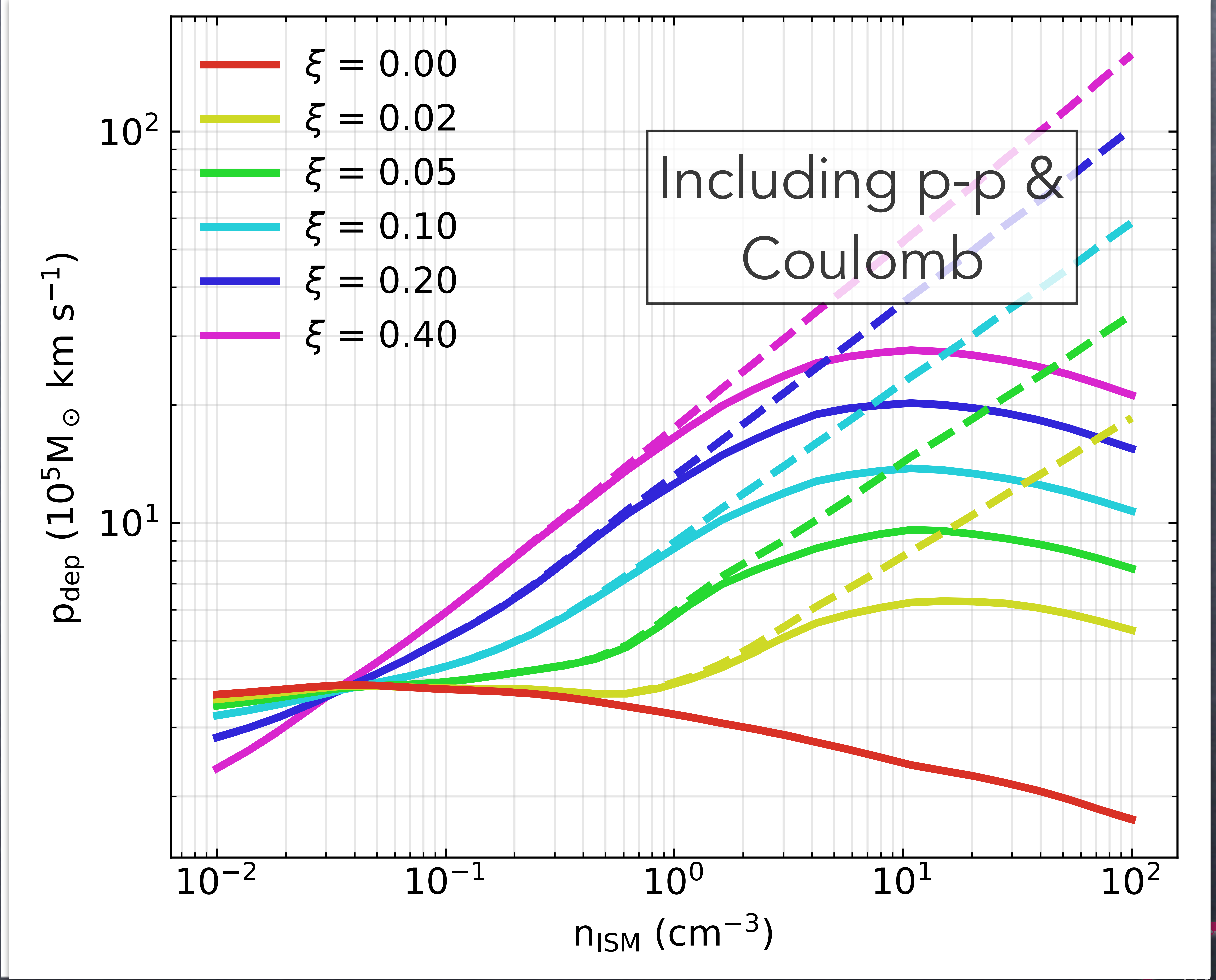


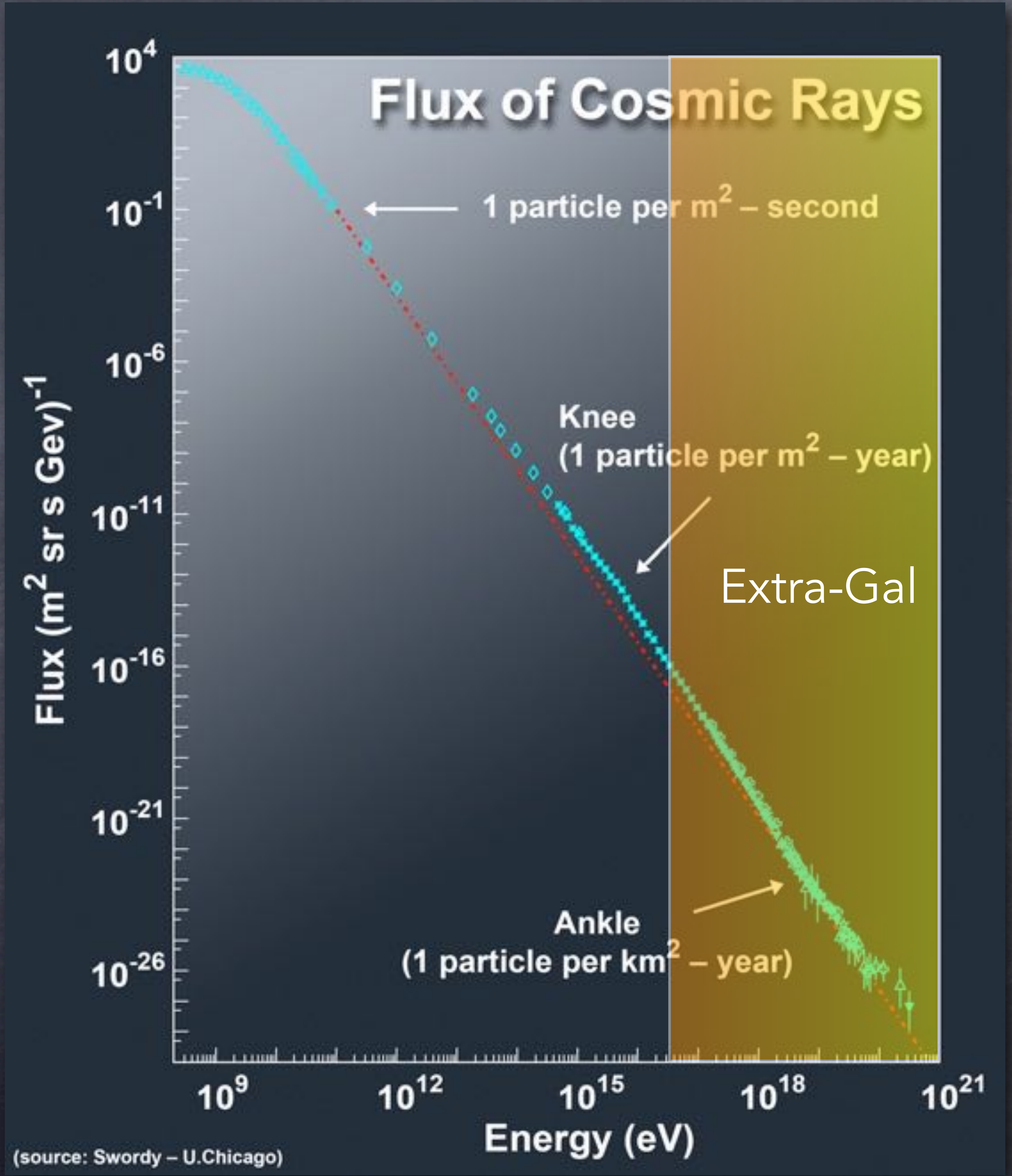
Diesing & DC, 2018



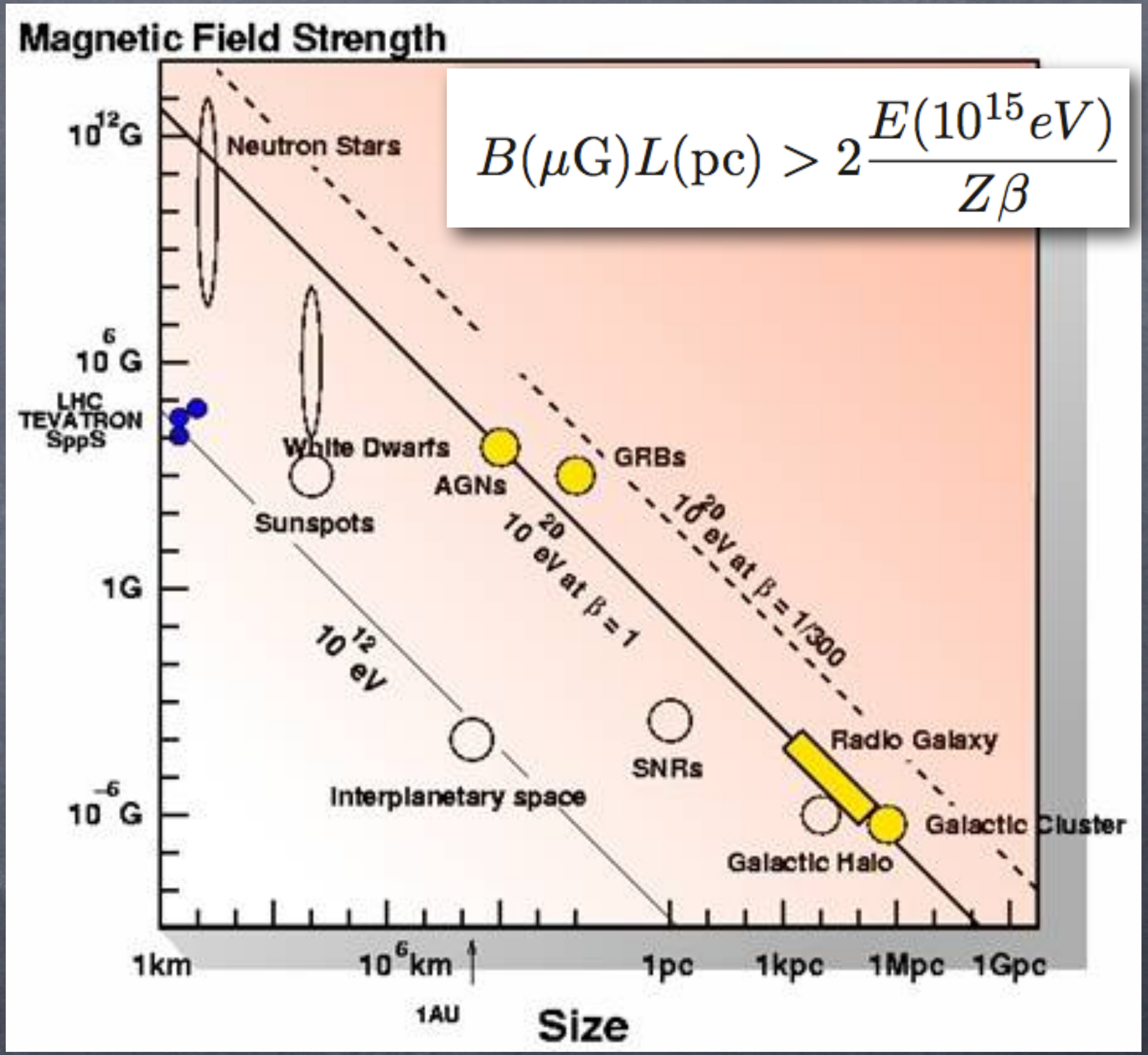
Including p-p & Coulomb

And now for something completely different…

Extra-galactic Cosmic Rays



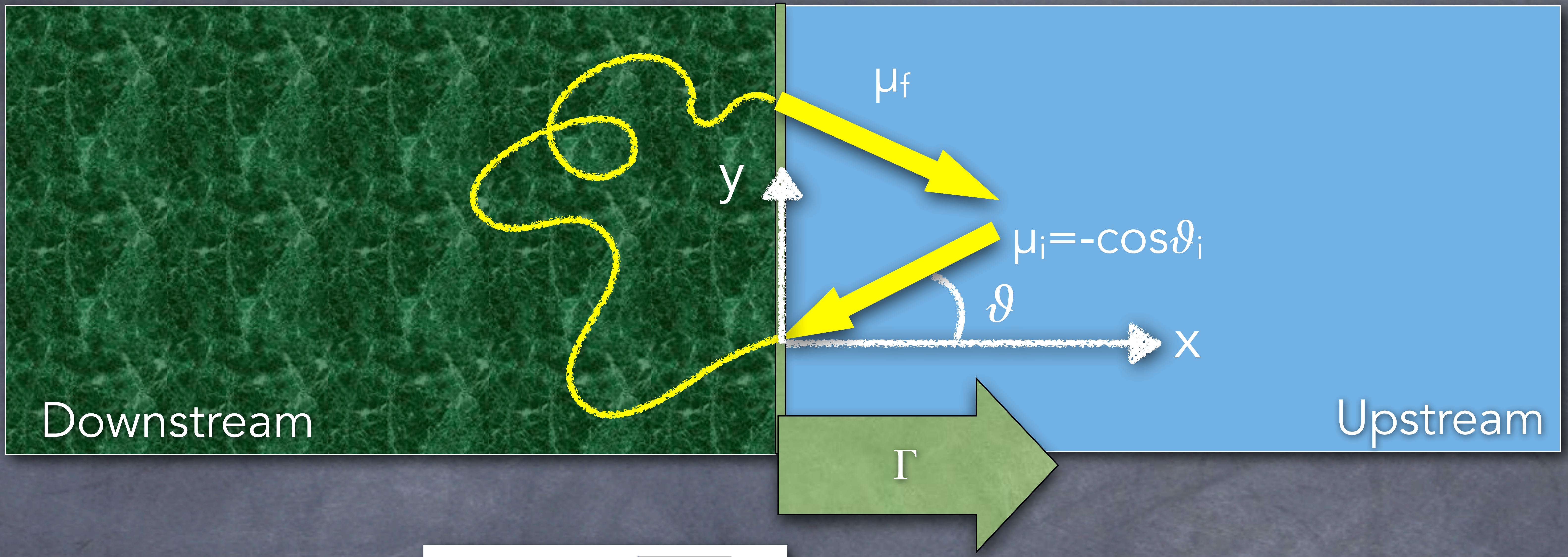
(source: Swordy – U.Chicago)



$$B(\mu\mathrm{G})L(\mathrm{pc}) > 2\frac{E(10^{15}eV)}{Z\beta}$$

- Sources typically involve relativistic flows

Acceleration at Relativistic Shocks



Encounter with the shock: $\mathbf{p}_\mathrm{i} \simeq E_\mathrm{i}(\mu_\mathrm{i}, \sqrt{1-\mu_\mathrm{i}^2}, 0),$

in the *downstream* frame:

$$E'_\mathrm{i} = \Gamma(E_\mathrm{i} - \beta p_{\mathrm{i},x}) = \Gamma E_\mathrm{i}(1-\beta\mu_\mathrm{i}),$$

Elastic scattering (e.g., gyration):

$$p'_{\mathrm{f},x} \equiv \mu'_\mathrm{f} E'_\mathrm{f}$$

$$\mu_\mathrm{f} = \frac{\mu'_\mathrm{f} + \beta}{1 + \beta\mu'_\mathrm{f}},$$

Back in the upstream:

$$E_\mathrm{f} = \Gamma(E'_\mathrm{f} + \beta p'_{\mathrm{f},x}) = \Gamma^2 E_\mathrm{i}(1-\beta\mu_\mathrm{i})(1+\beta\mu'_\mathrm{f}),$$

- Energy gain depends on $\mu_f - \mu_i$

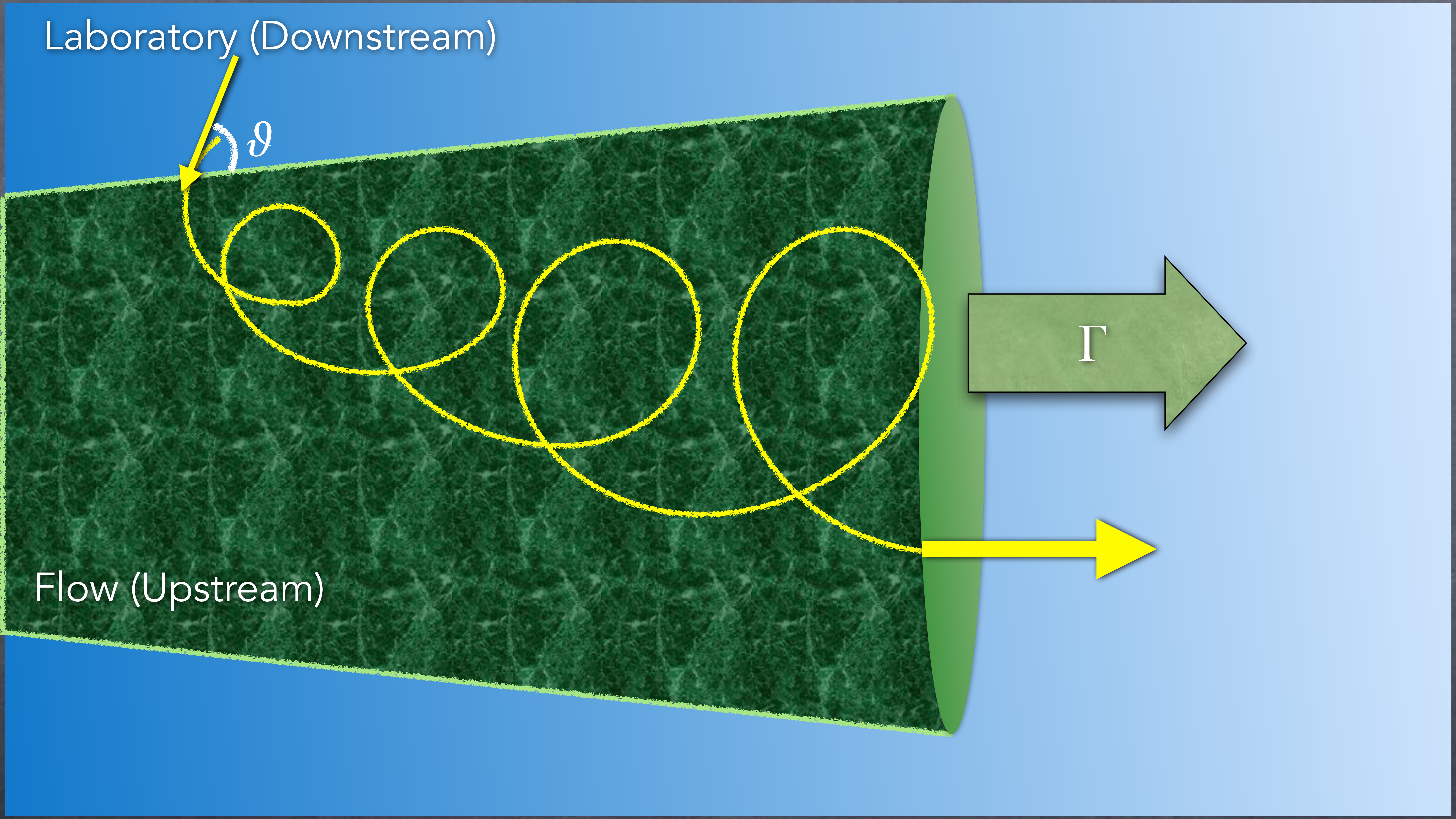
First cycle: $E_f \sim \Gamma^2 E_i$ (~Compton scattering)

- Following cycles: $E_f \sim 2 E_i$
- CAVEAT: return not guaranteed!

Vietri 1995; Achterberg et al. 2001

Acceleration in Relativistic FLOWS

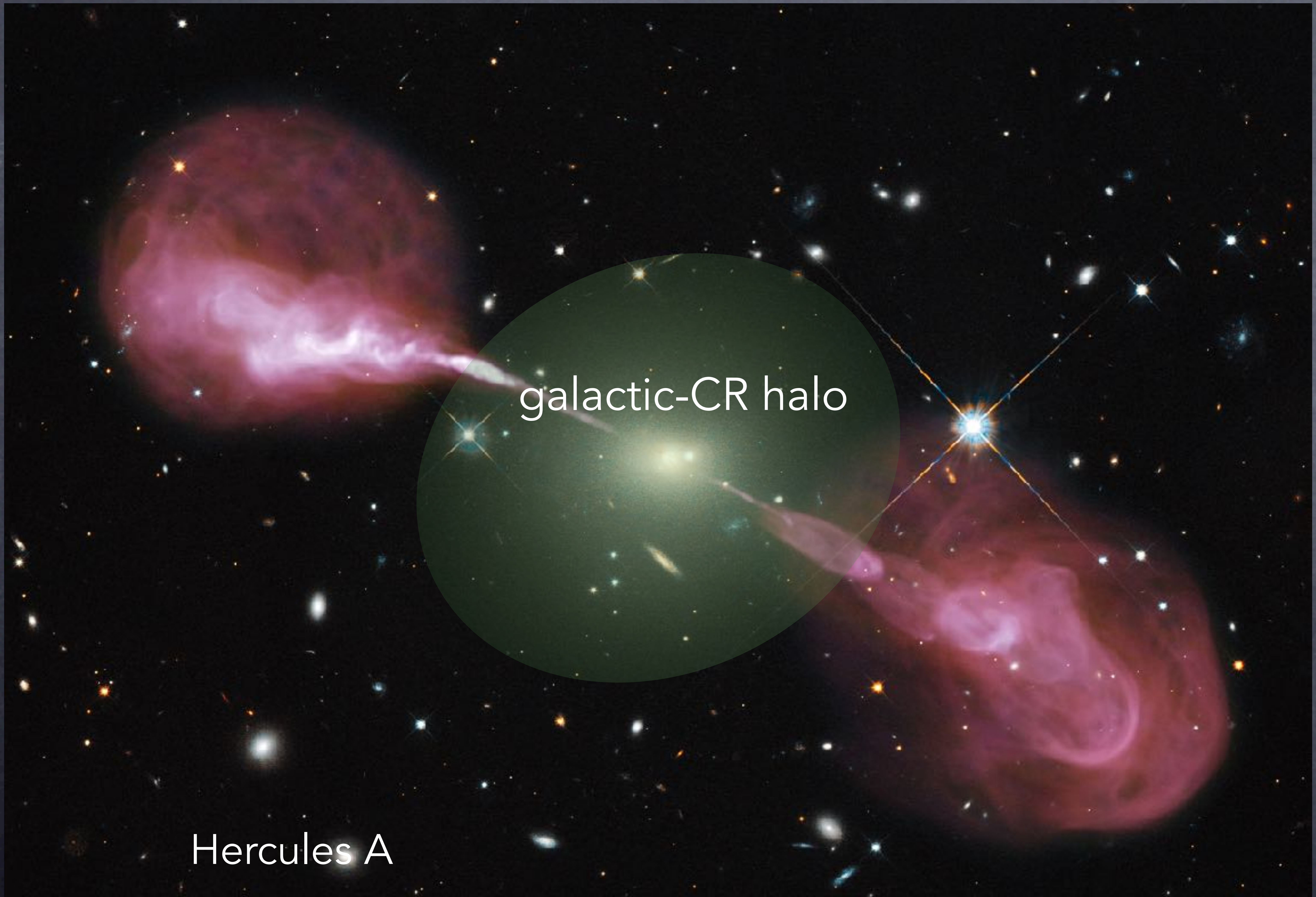
- Requirement: interface thickness << gyroradius << typical flow size



Most trajectories lead to a $\sim\Gamma^2$ energy gain!

Espresso Acceleration of UHECRs

- **SEEDS:** galactic CRs with energies up to ~3Z PeV
- **STEAM:** AGN jets with Γ up to 20-30



ONE-SHOT

reacceleration can produce UHECRs up to

$E_{max} \sim 2\Gamma^2\, 3Z$ PeV

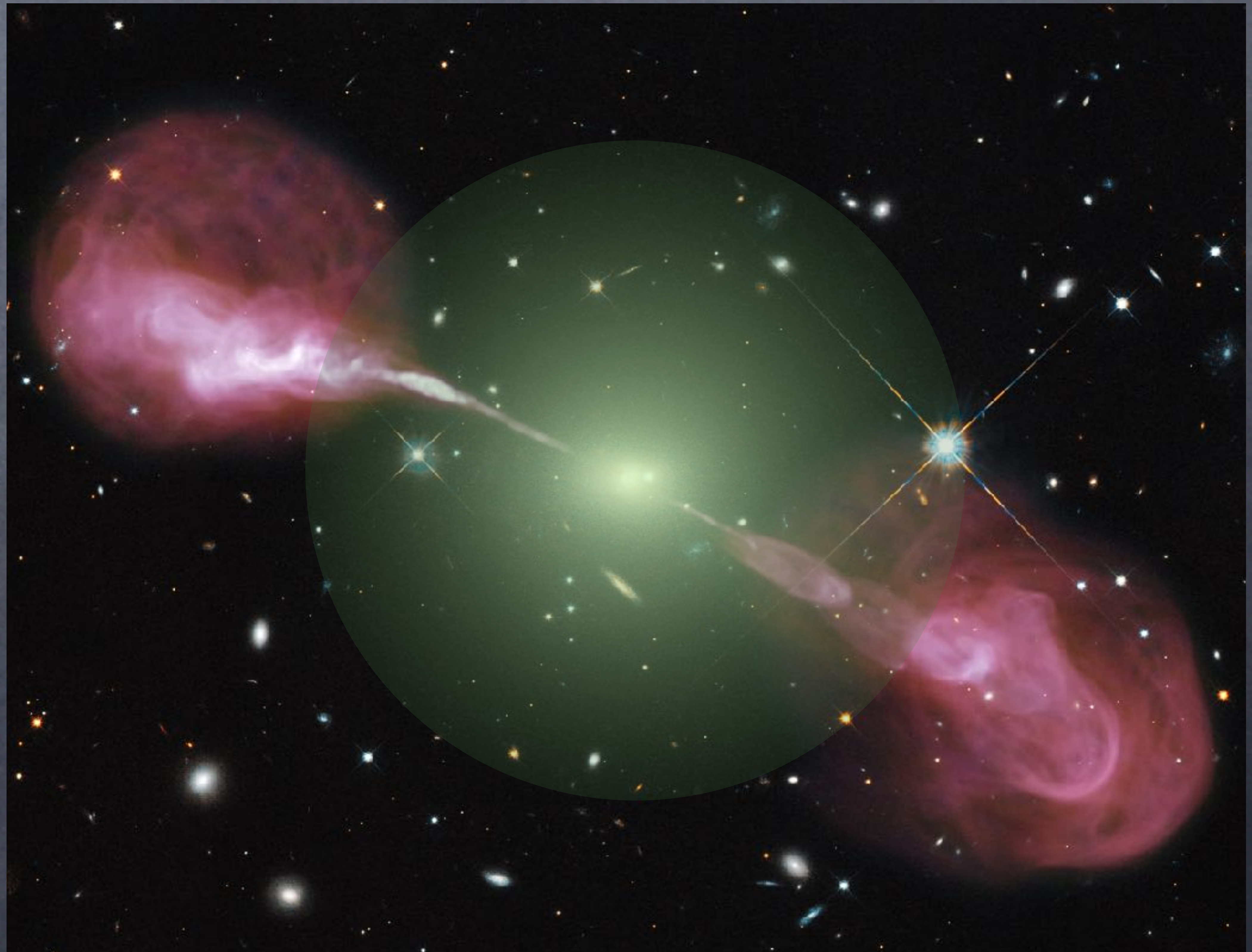
$E_{max} \sim 5Z\text{x}10^9$ GeV

UHECRs from AGN jets: constraints

- Confinement (Hillas Criterion): $B_{\mu G} D_{\rm kpc} \gtrsim \frac{4}{Z_{26}} \frac{E_{\max}}{10^{20}{\rm eV}}$ ✔
- Energetics: $Q_{\rm UHECR}(E \gtrsim 10^{18}{\rm eV}) \approx 5\times10^{45}$ erg/Mpc^3/yr

  $L_{\rm bol} \approx 10^{43}$-$10^{45}$ erg/s; $N_{\rm AGN} \approx 10^{-4}$/Mpc^3

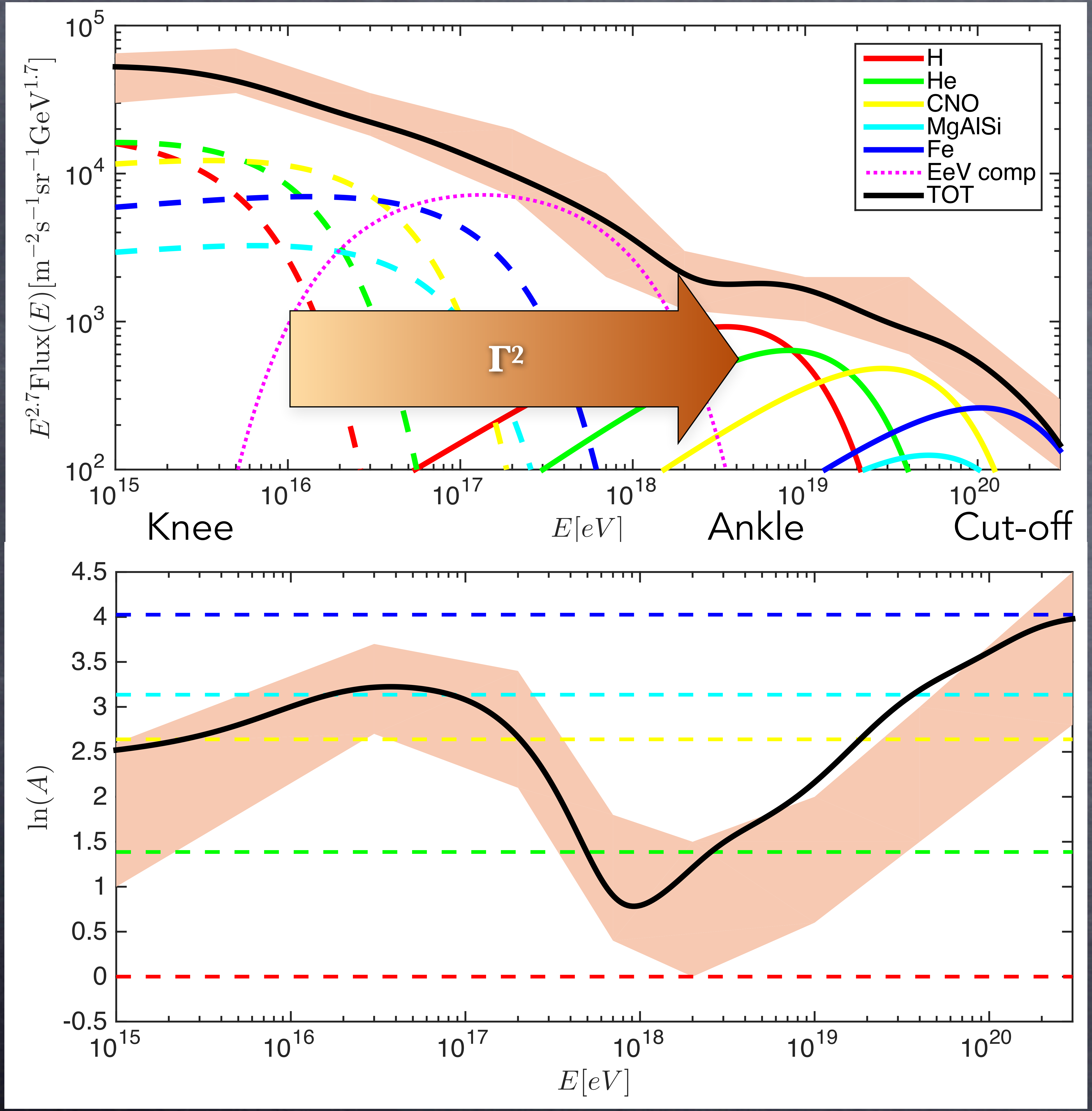
  $Q_{\rm AGN} \approx$ a few 10^{46}-10^{48} erg/Mpc^3/yr $\gg Q_{\rm UHECR}$ ✔



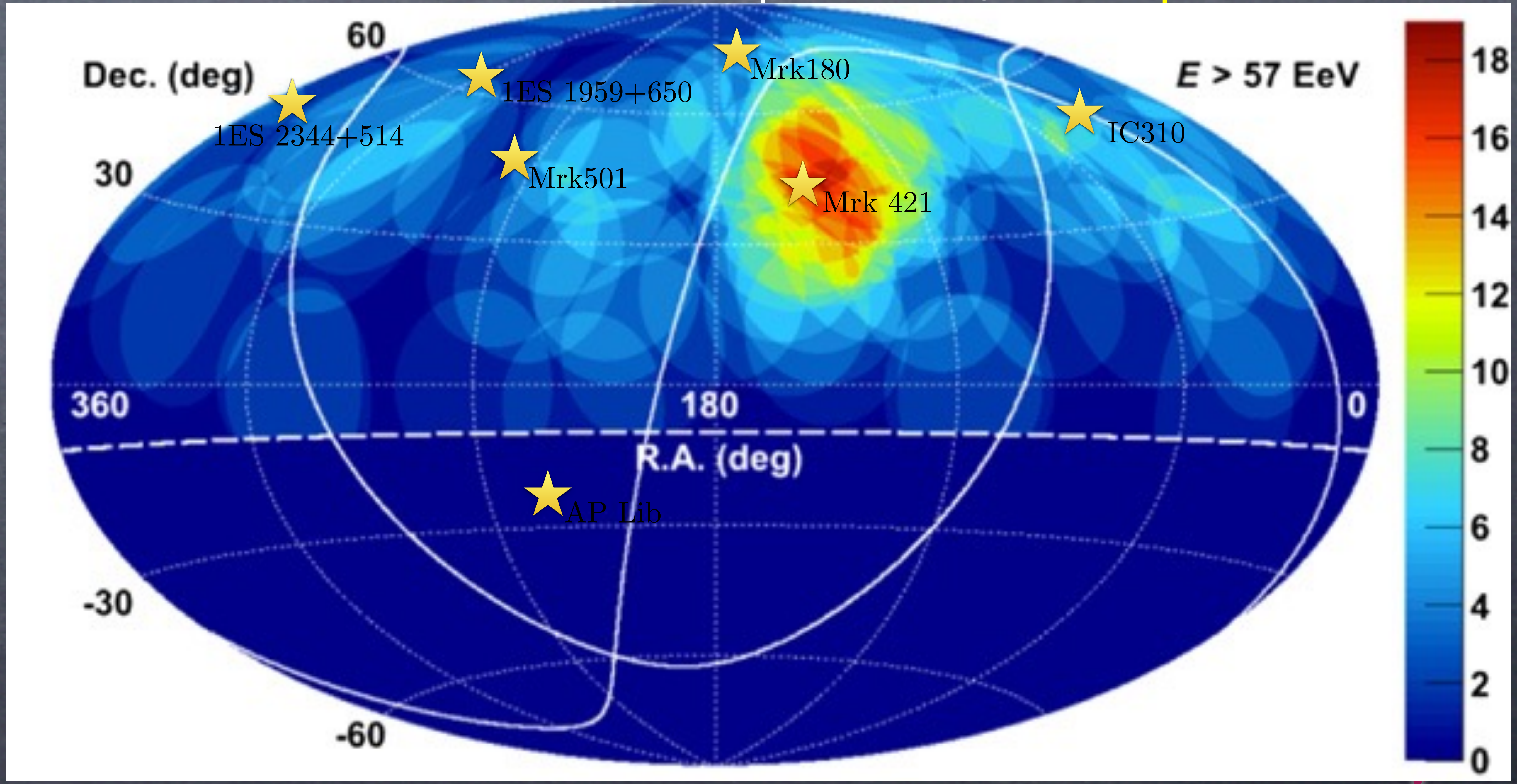
- Efficiency depends on:
  - Reacceleration efficiency ($\varepsilon > \sim 10^{-4}$)
  - Jet cross section

    (angle of a few degrees: $\varepsilon \sim 10^{-1}$-10^{-2})

Galactic CR + UHECR spectrum



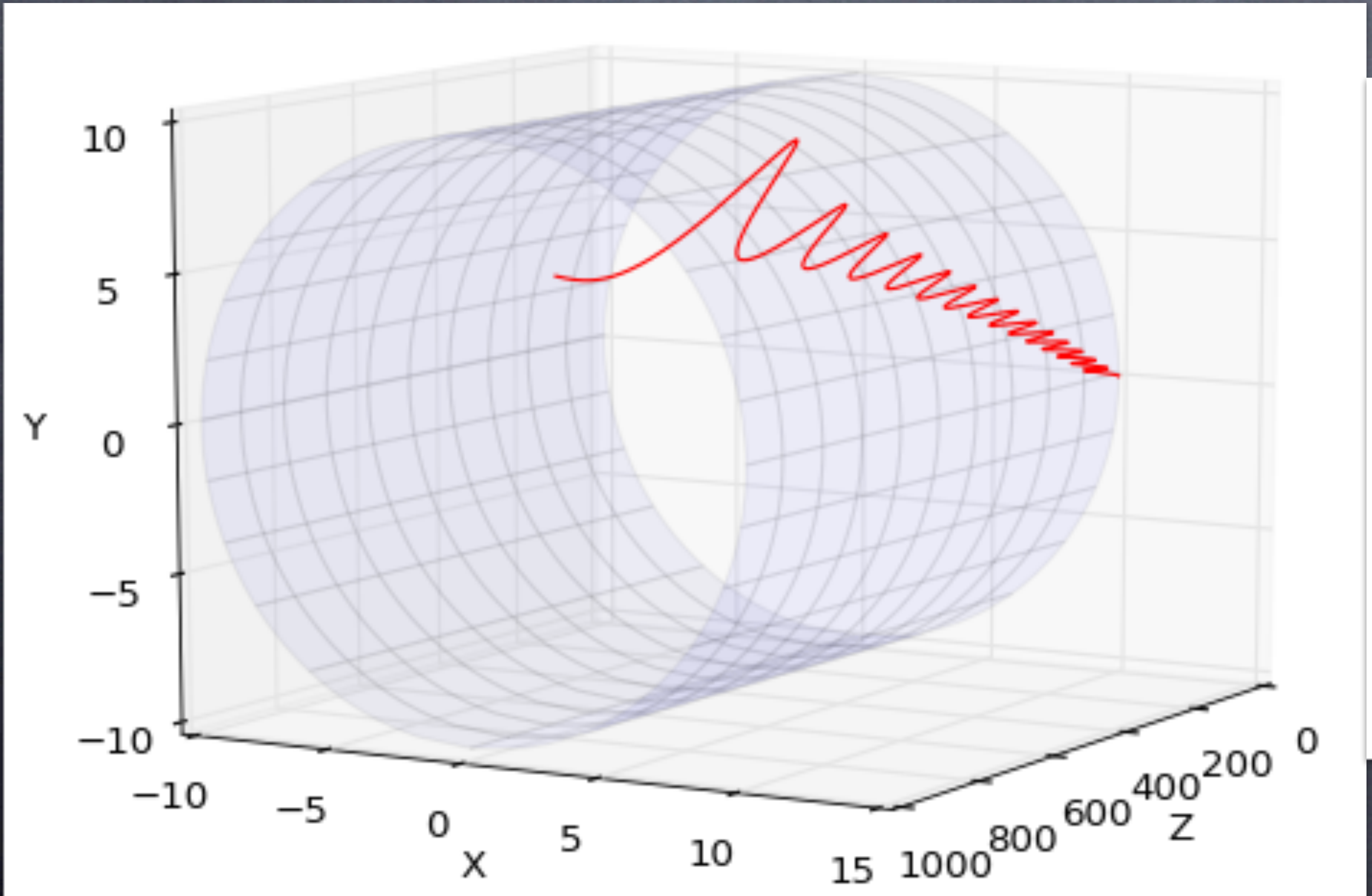
- Prediction of UHECR chemical composition!
  - UHECR spectra must be quite flat, ~$E^{-1.5}$ (Aloisio+13, Gaisser+13, Taylor 14,…)
- Different kinds of AGNs?
- Mrk 421 in the Telescope Array hotspot!

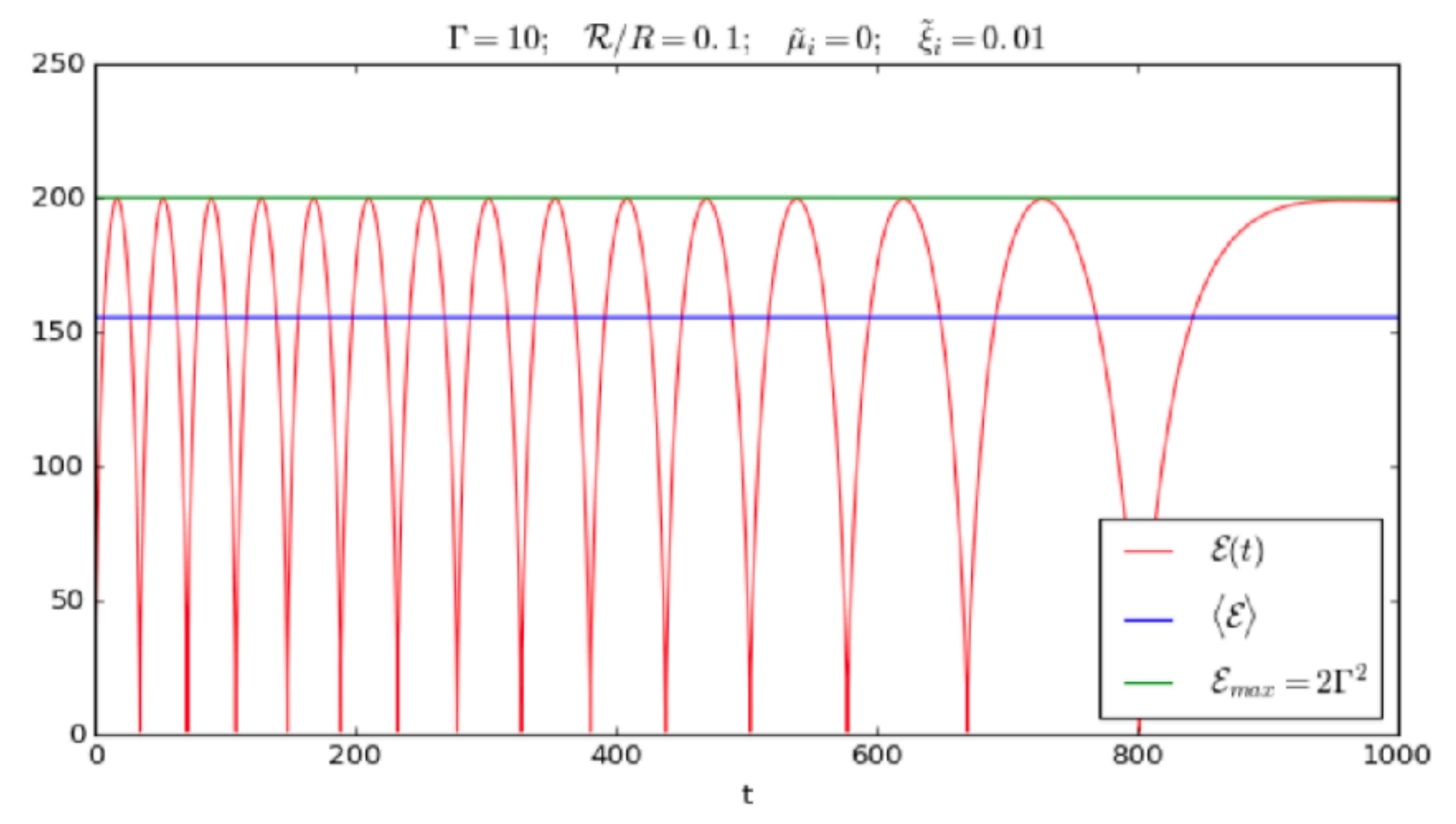


DC 2015, 2016

Testing *Espresso* Acceleration - I

- Propagation in synthetic jets with Hamiltonian formalism (DC 2016)
  - Γ^2 average energy gain independent on $B_\Phi(r)$; $\mathcal{E}_{\rm max}^{(\mathcal{R}<R/2)} = \Gamma^2(1-\beta\tilde{\mu}_{\rm i})(1+\beta) \simeq 2\Gamma^2$
  - Less than Γ^2 if gyroradius $\mathcal{R} > R_{\rm jet}/2$: $\mathcal{E}_{\rm max}^{(\mathcal{R}>R/2)} = (1-\beta\tilde{\mu}_{\rm i})\left[1+\Gamma^2\beta\frac{R}{\mathcal{R}}\right] \simeq \Gamma^2\frac{R}{\mathcal{R}}.$





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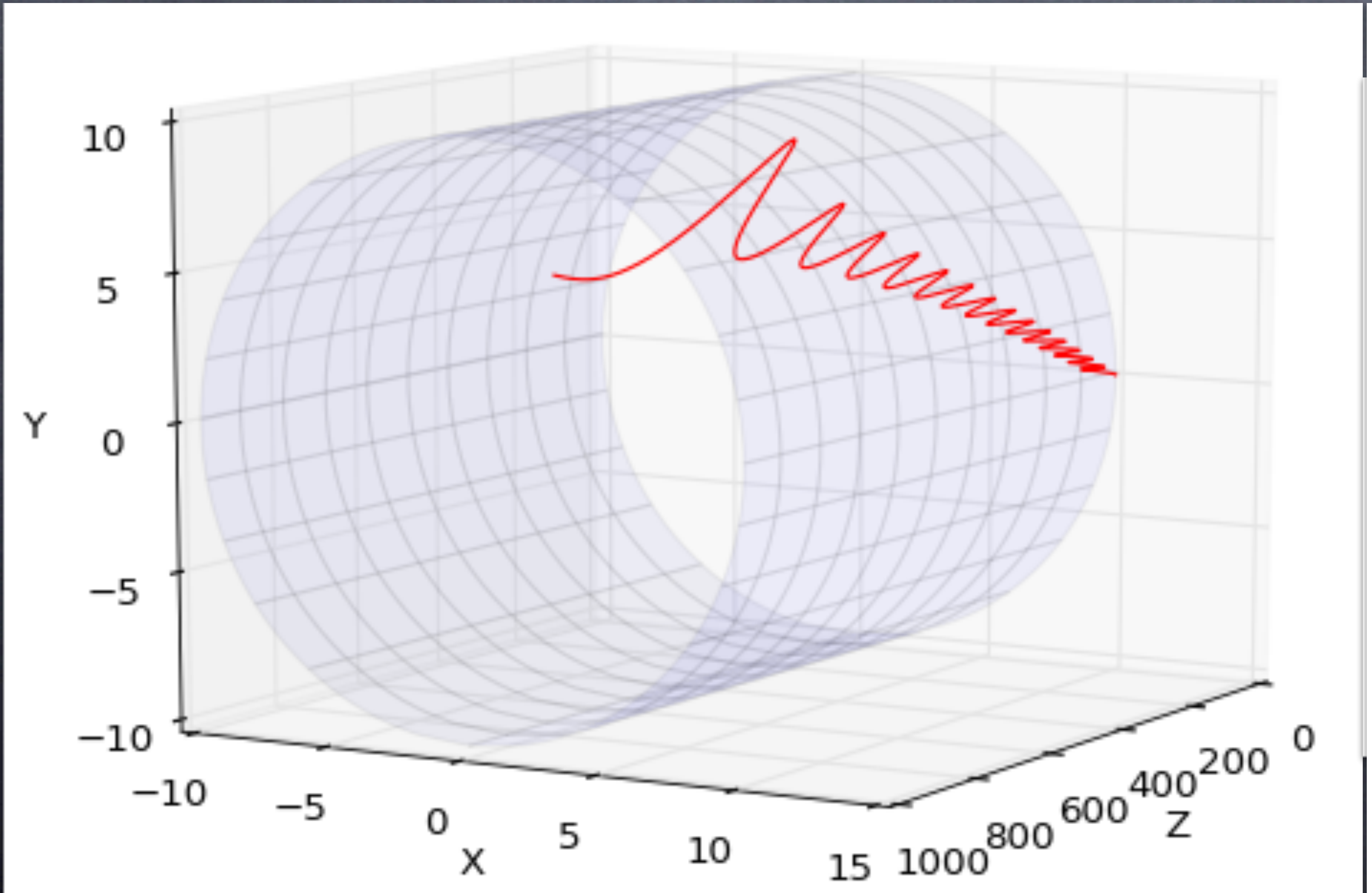
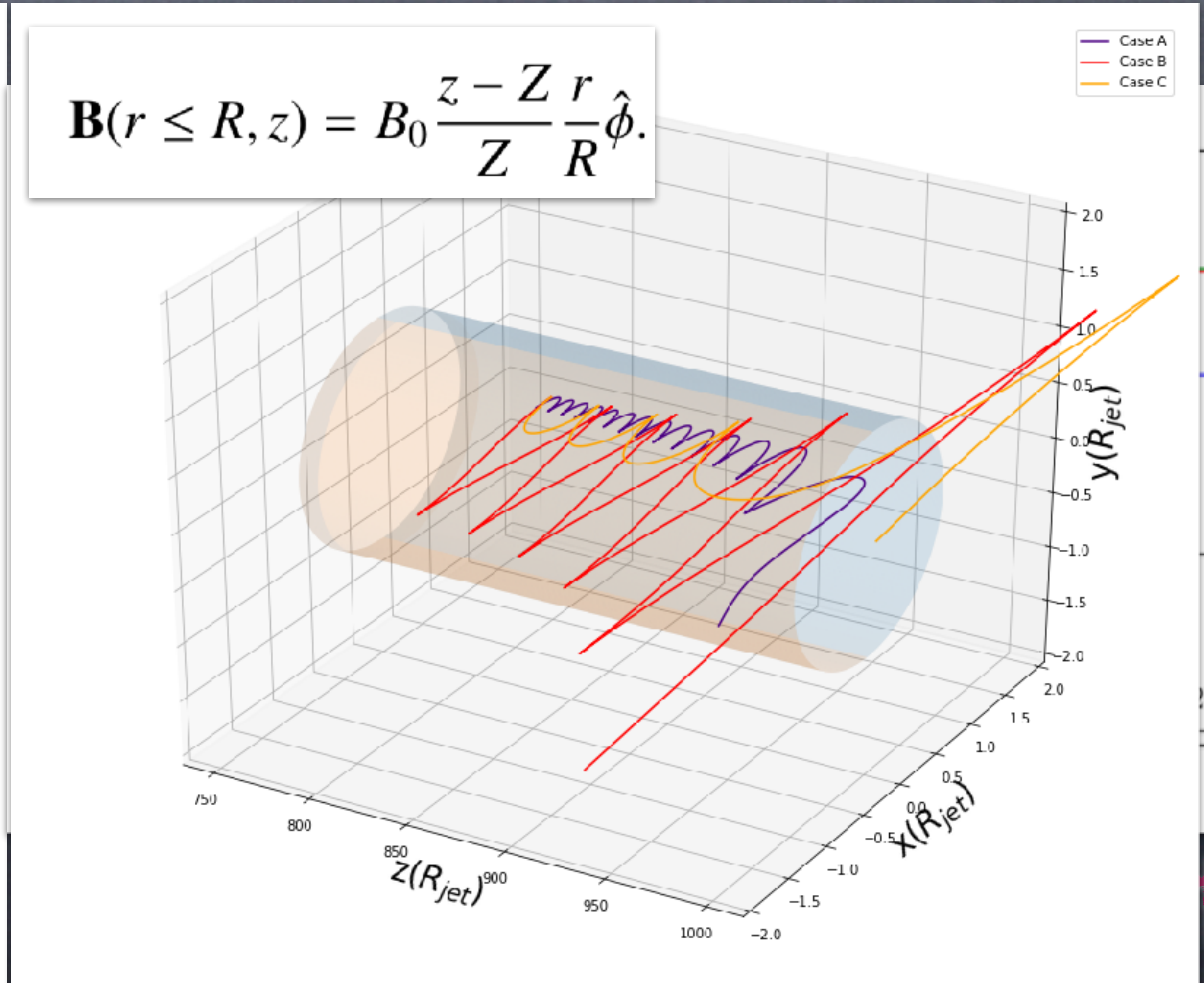
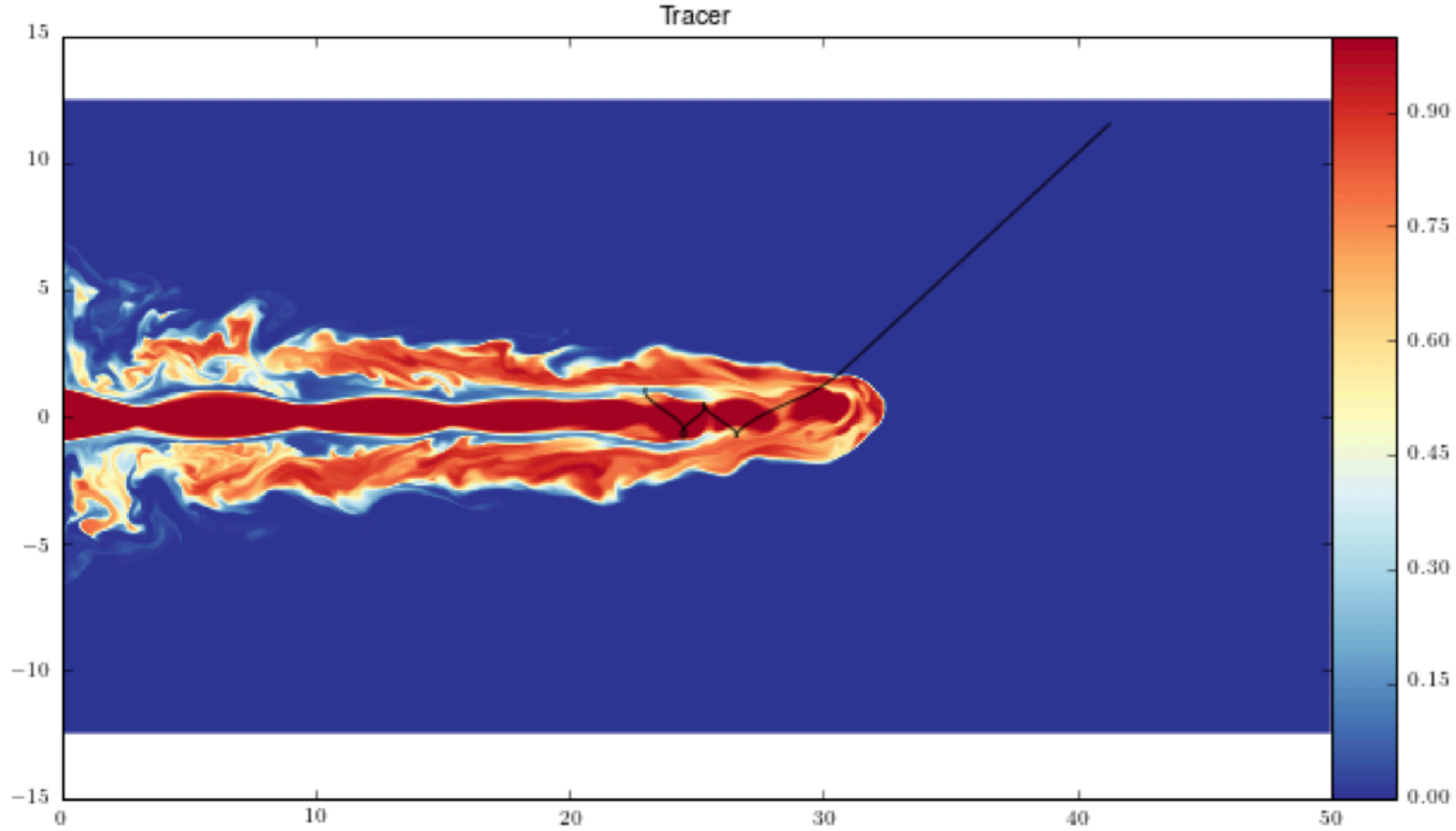


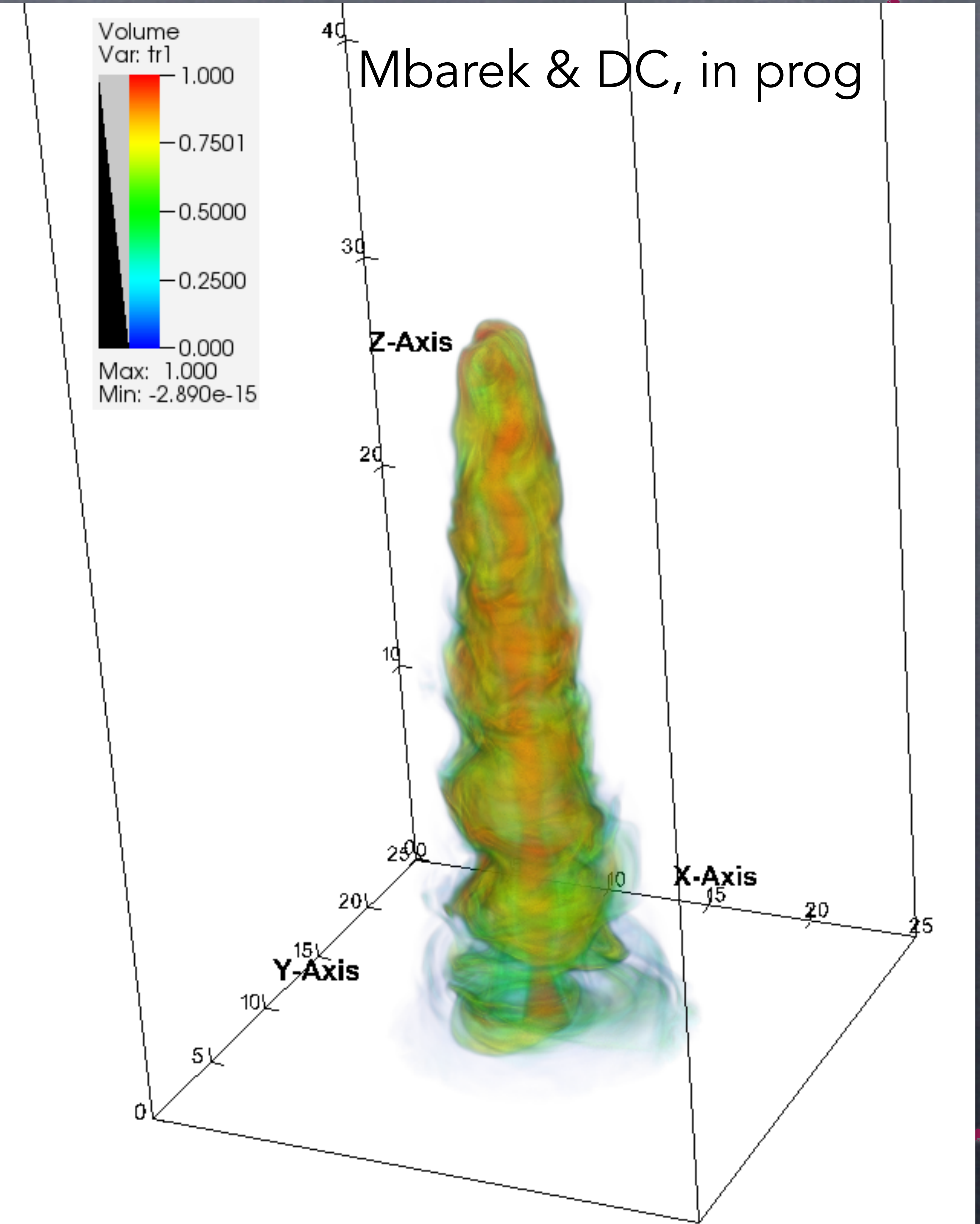


$$\mathbf{B}(r \le R, z) = B_0 \frac{z-Z}{Z}\frac{r}{R}\hat{\phi}.$$

Testing *Espresso* Acceleration - II

- *Pluto* 3D MHD sims, $\Gamma=10$ (e.g., Mignone+10)
  - Case A: $J_{jet}<0$; $E_r<0$; $B_\phi<0$ (Contopoulos-Kazanas 98)
  - Case B: $J_{jet}>0$; $E_r>0$; $B_\phi>0$

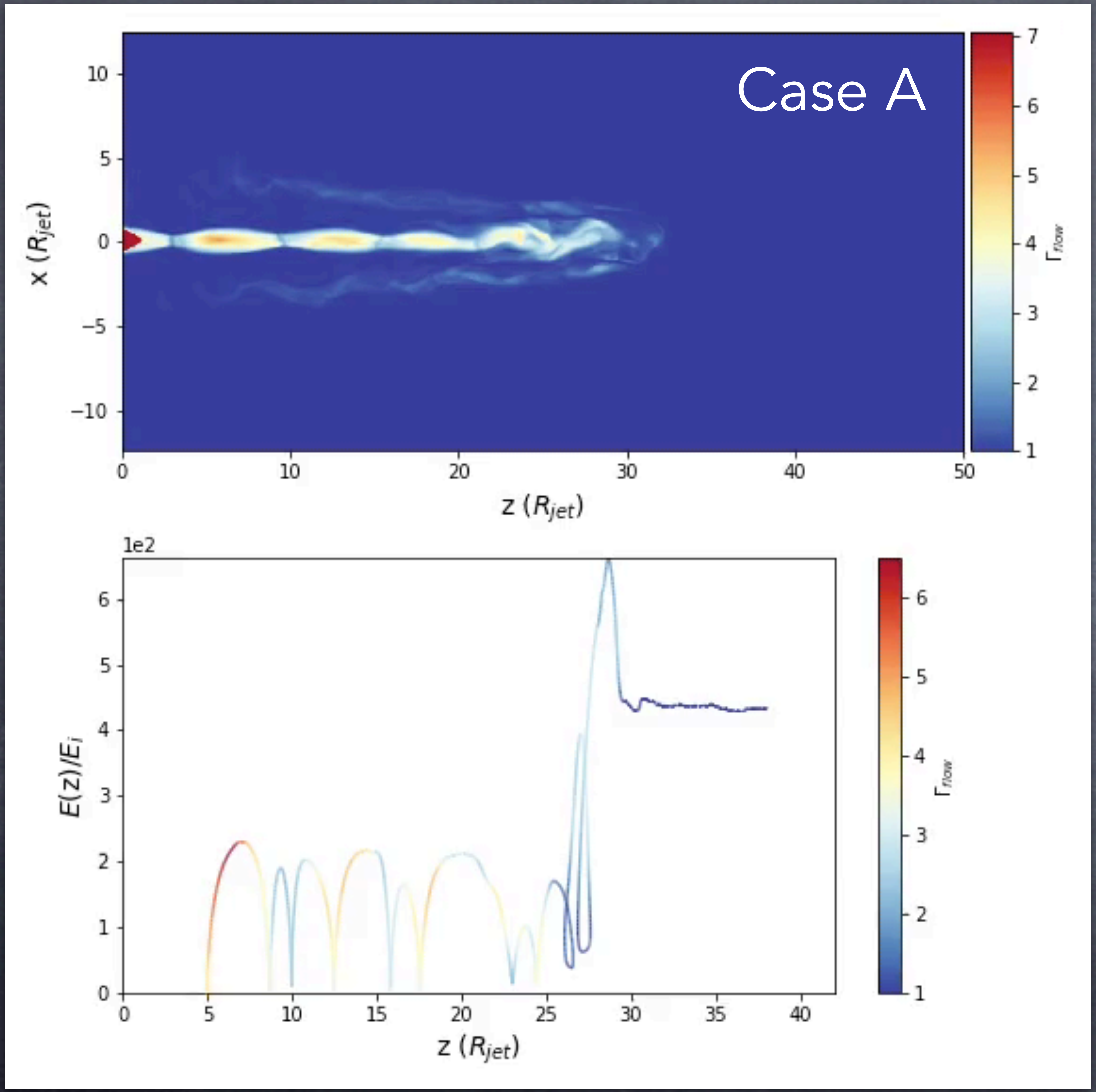


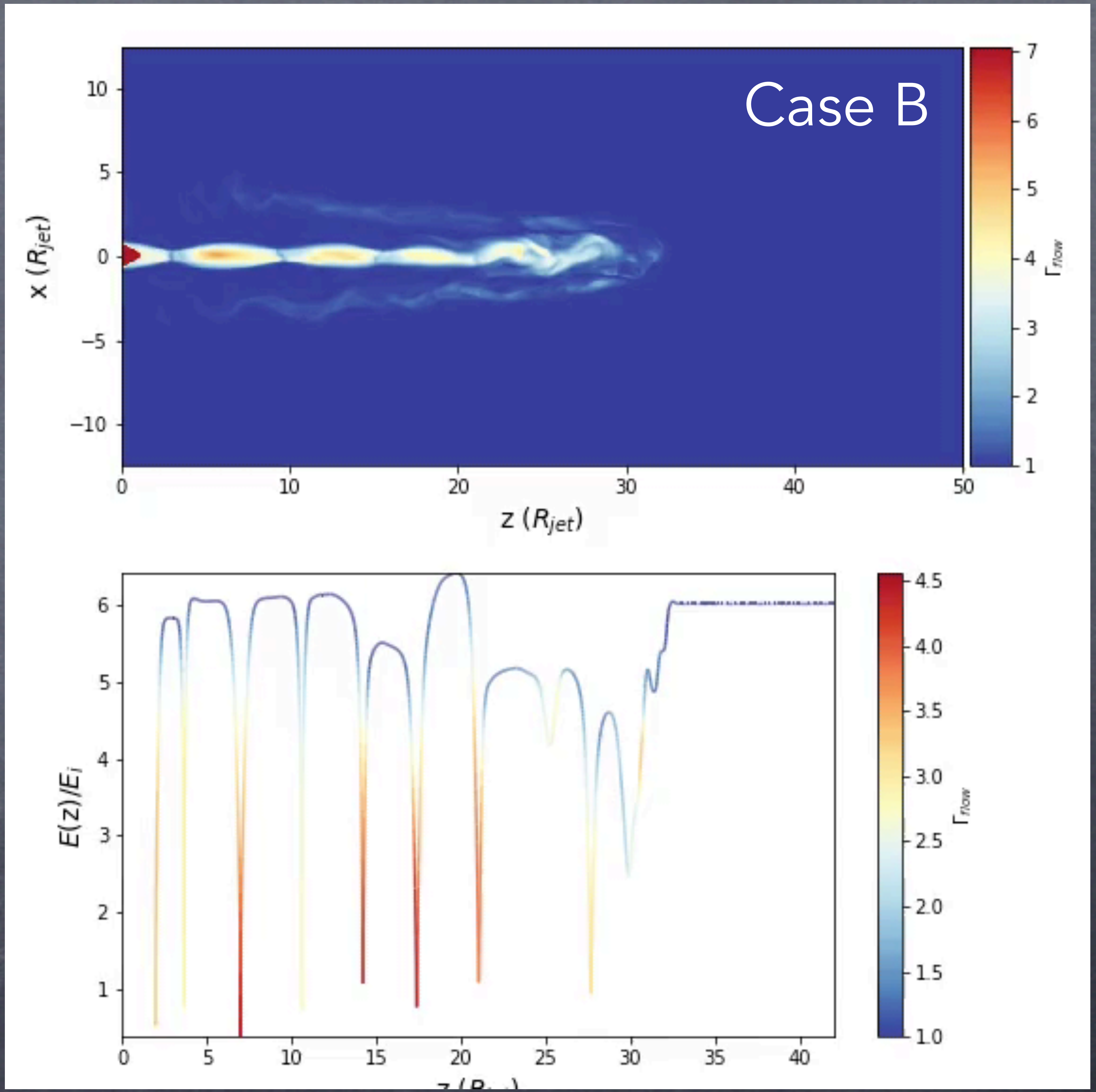


Mbarek & DC, in prog

Testing *Espresso* Acceleration - III

- Individual particle trajectories (Mbarek & DC, in prog)

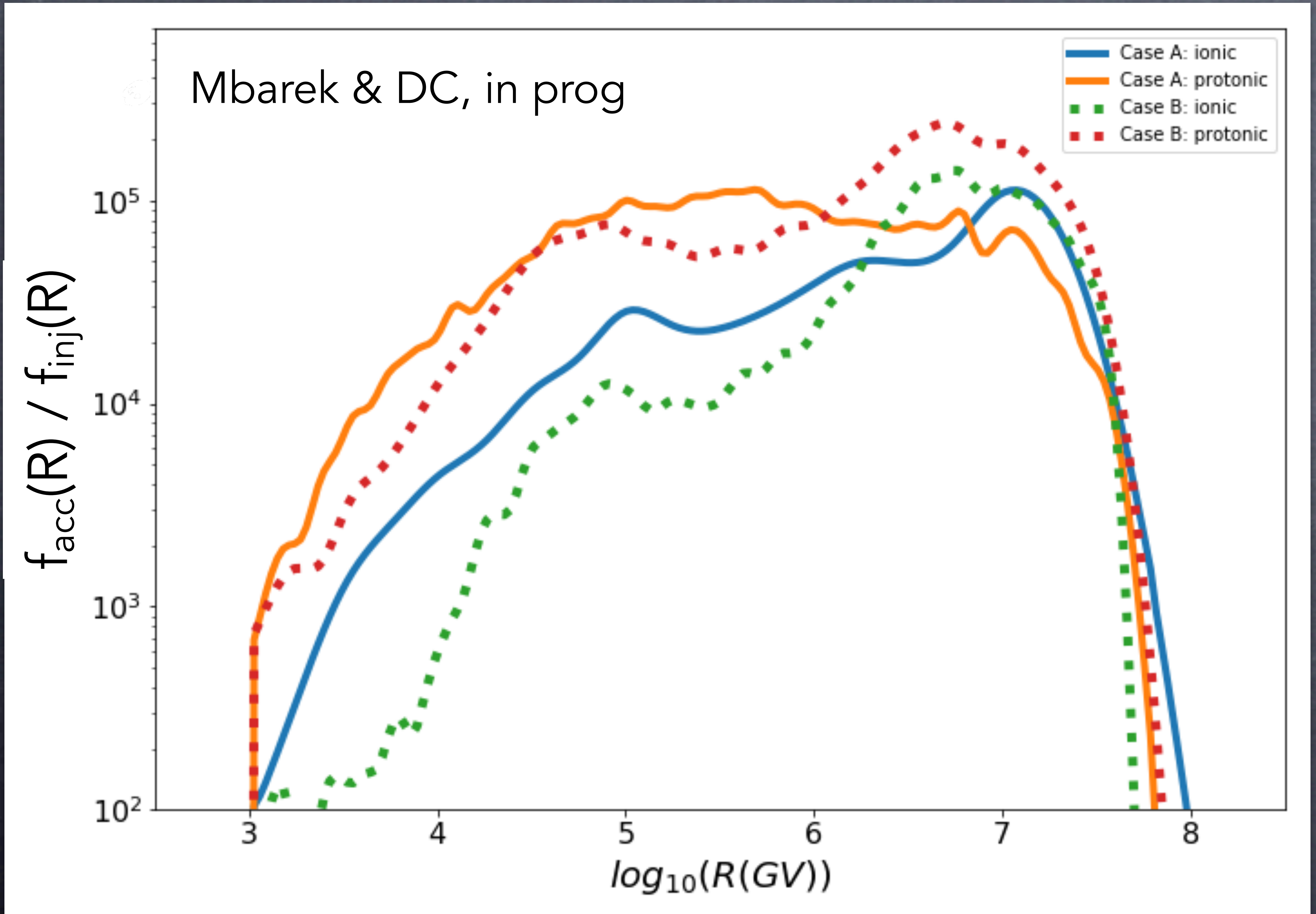


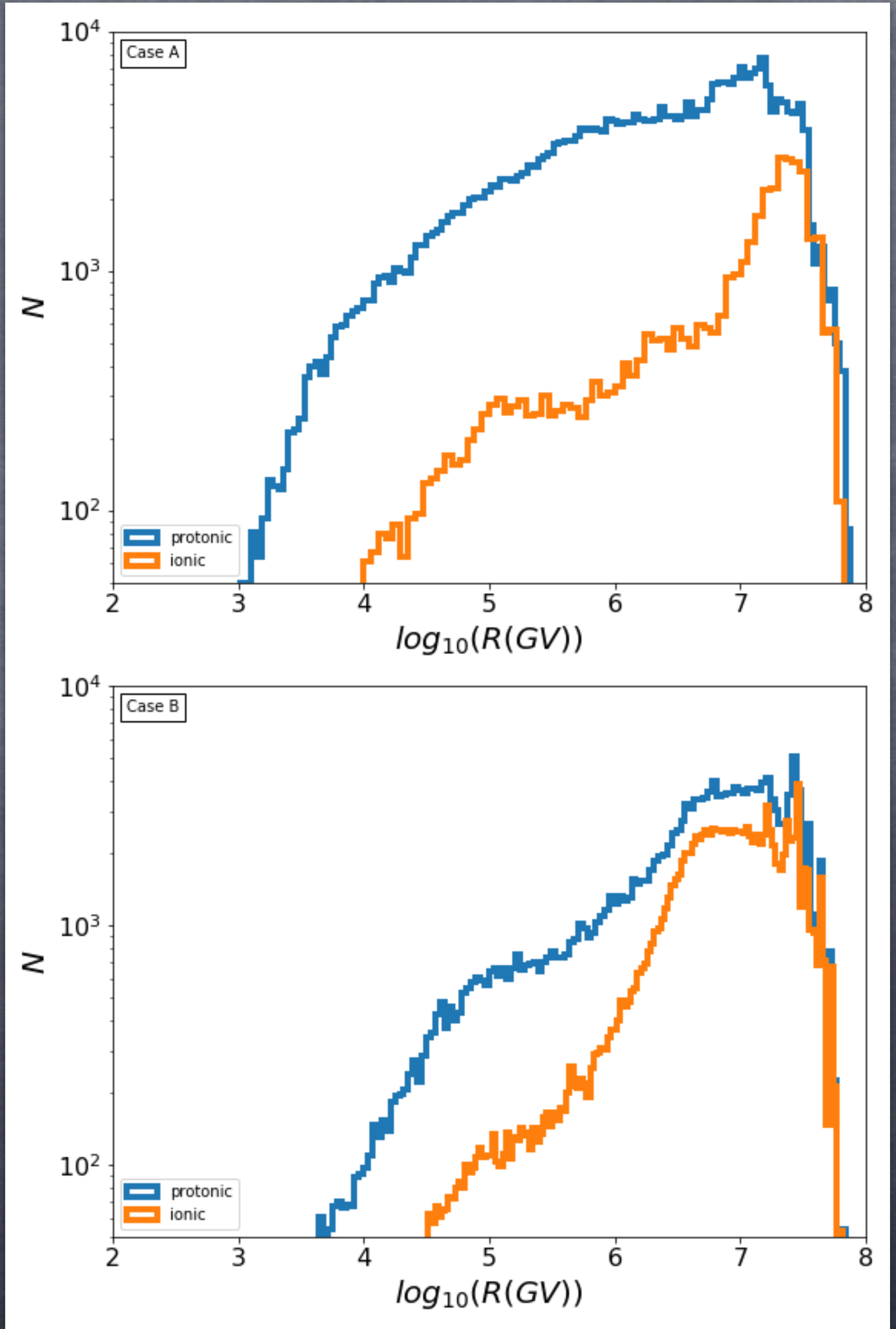


Espresso works! Even a few shots: $E_f/E_i>\Gamma^2$!

Implications for UHECRs

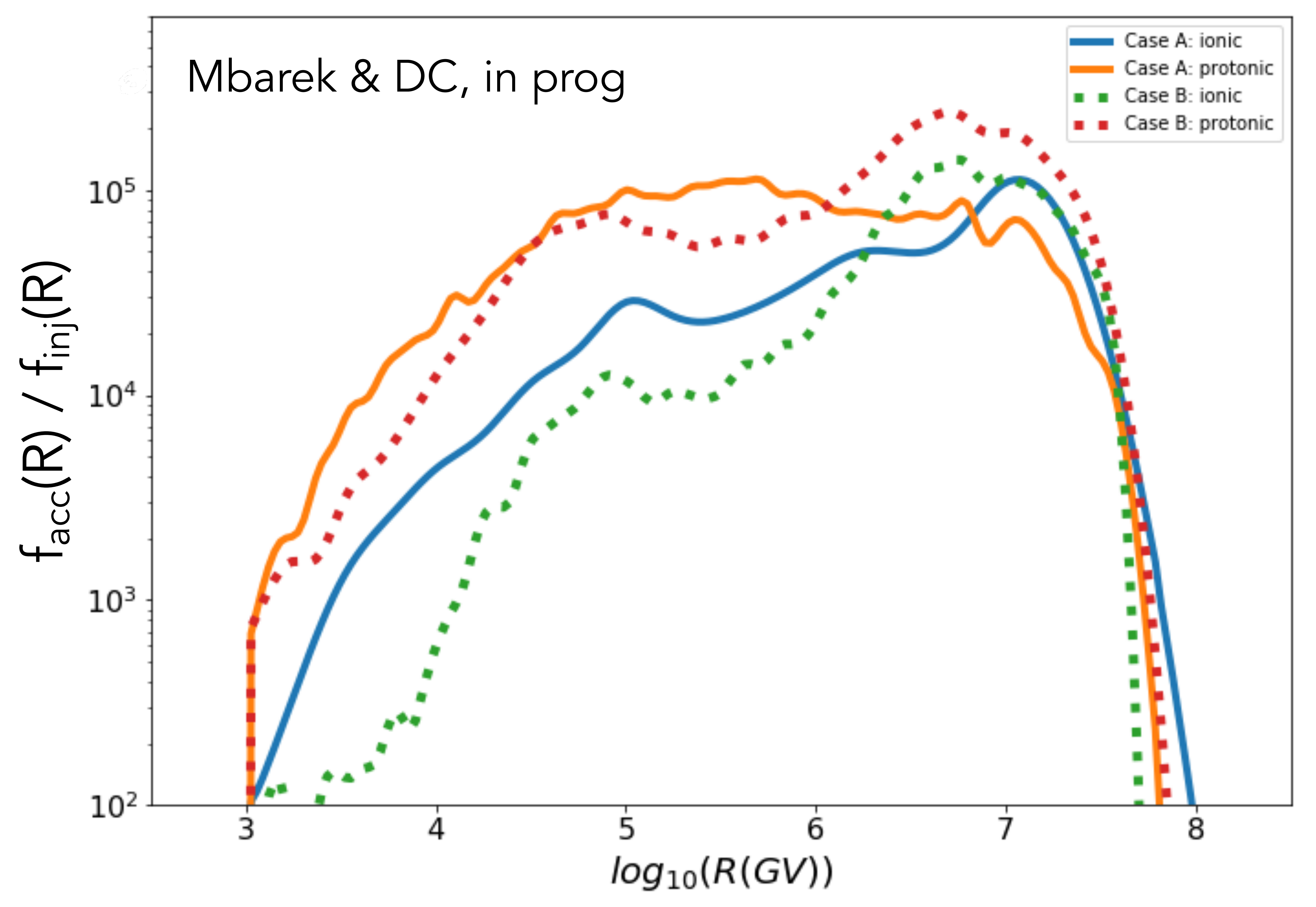
- Re-acceleration efficiency 10-20% in number
- Spectra flatter than injected ones (especially if ion photo-disintegration in the AGN is accounted for)



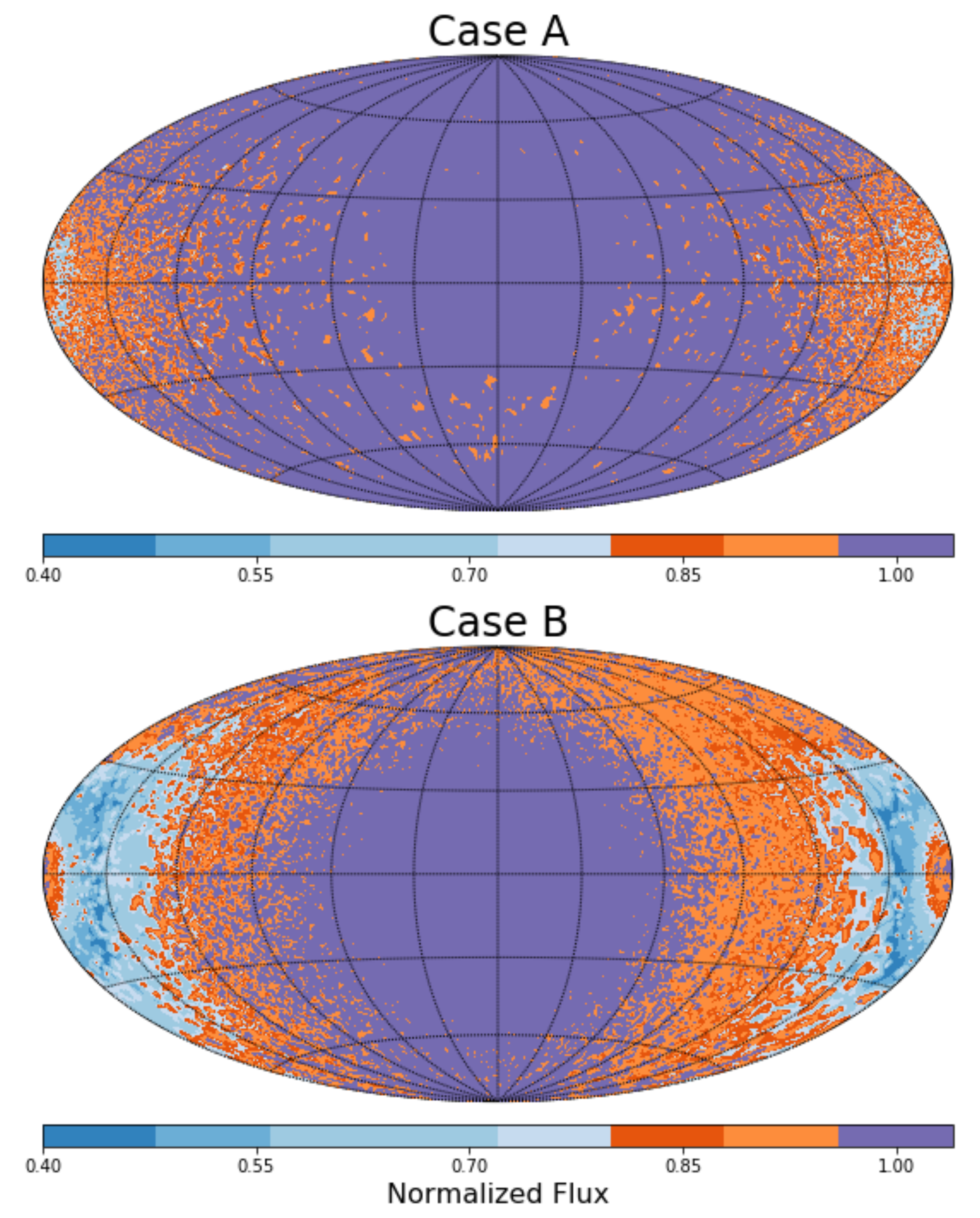


Implications for UHECRs

- Re-acceleration efficiency 10-20% in number
- Spectra flatter than injected ones (especially if ion photo-disintegration in the AGN is accounted for)
- UHECRs not very beamed!
  - Unlikely to point back to blazars



Mbarek & DC, in prog



A Summary

Origin	Source	Mechanism	E_{max}	Spectrum	Evidence
Galactic	SNRs	Diffusive Acceleration at non-rel shocks	$3Z\times10^{15}$ eV	Universal ~ E^{-2}	gamma rays e.g., Tycho
Extragal	AGNs	Espresso in rel flows?	$5Z\times10^{18}$ eV	Galactic, boosted	~Anisotropy~ Neutrinos?