GSSI - L'Aquila
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UHE Cosmic Rays and Neutrinos From AGN Jets

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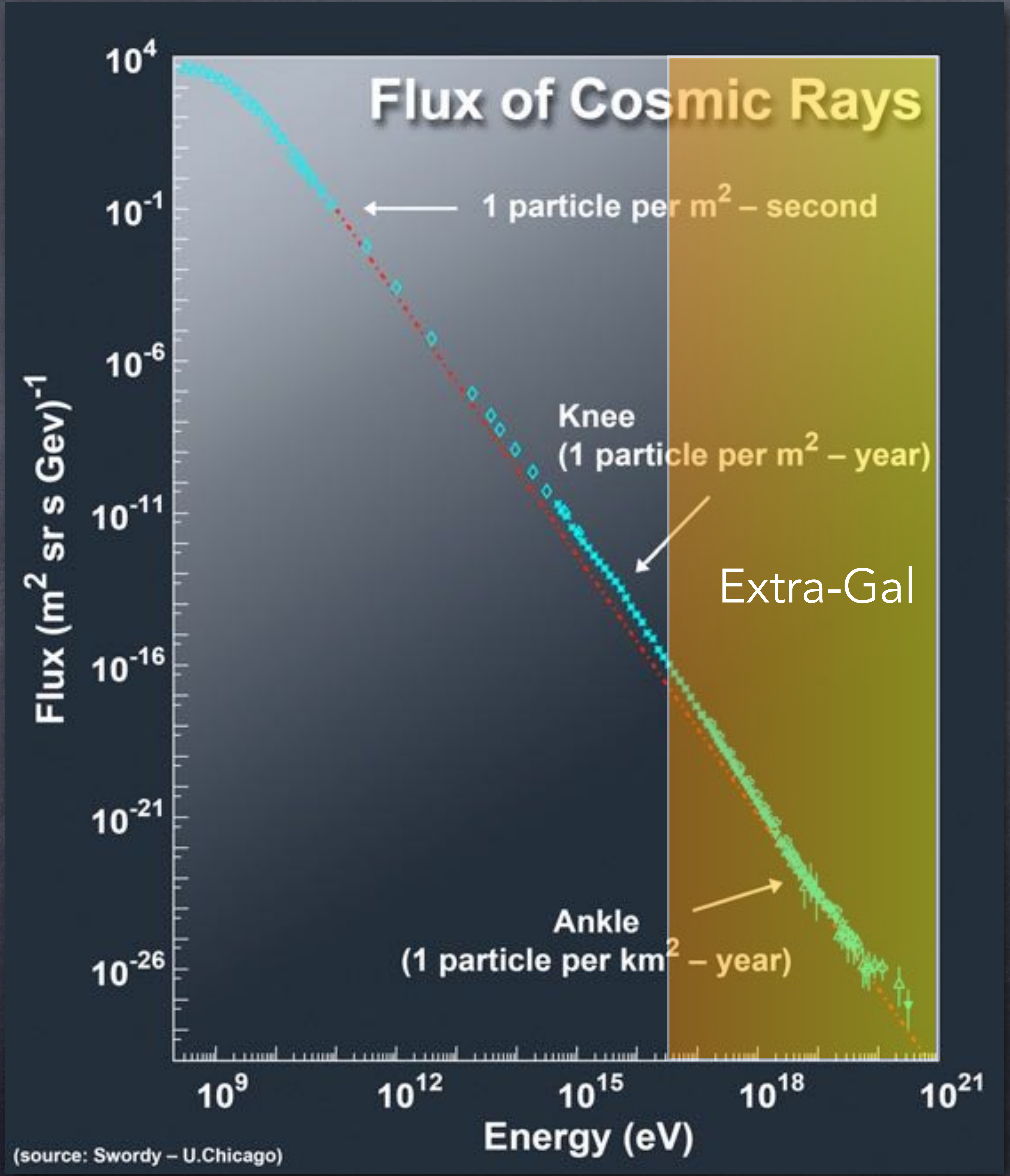
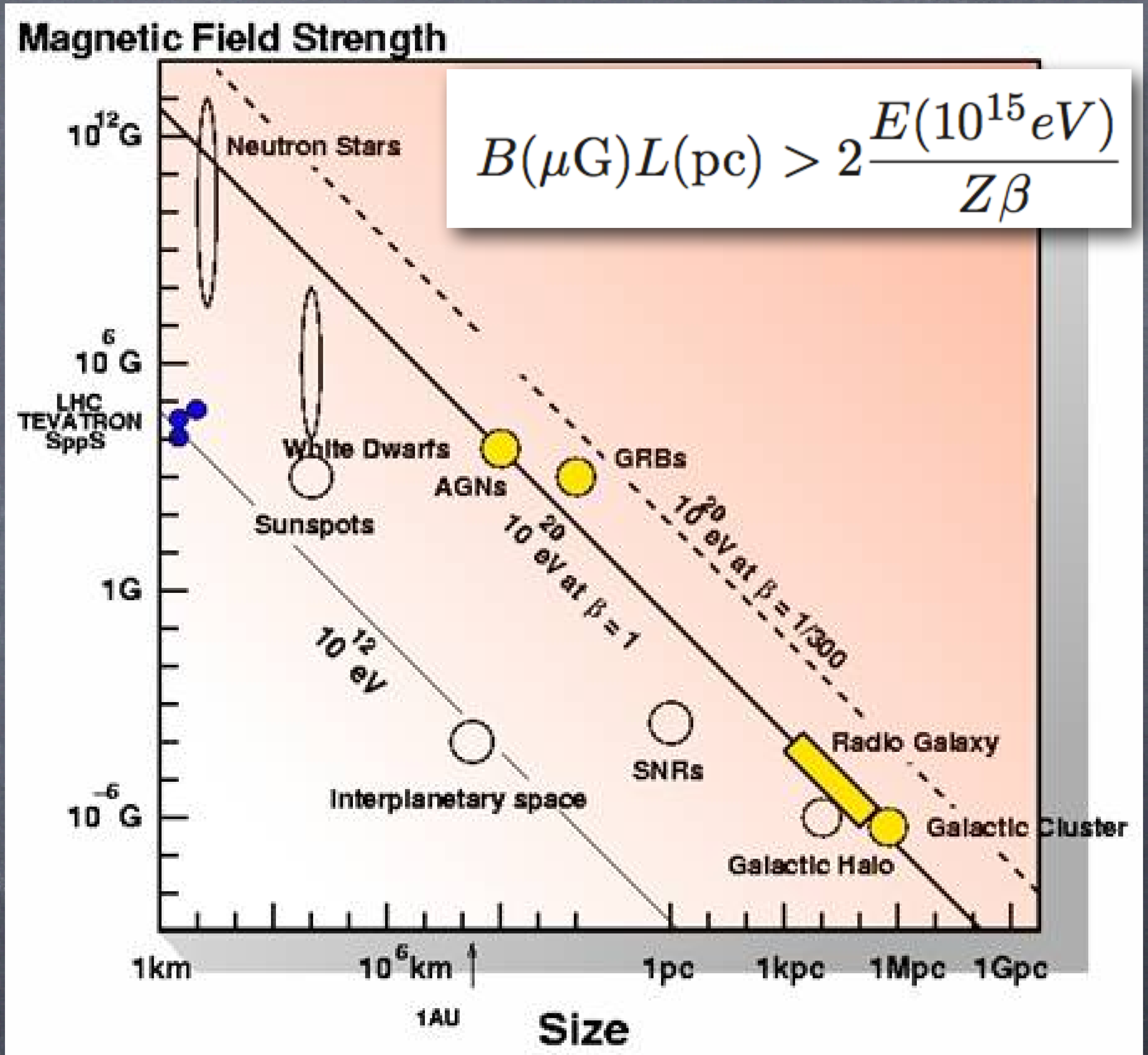
with: R. Mbarek (UMaryland), K. Murase (Penn State)

Extra-galactic Cosmic Rays

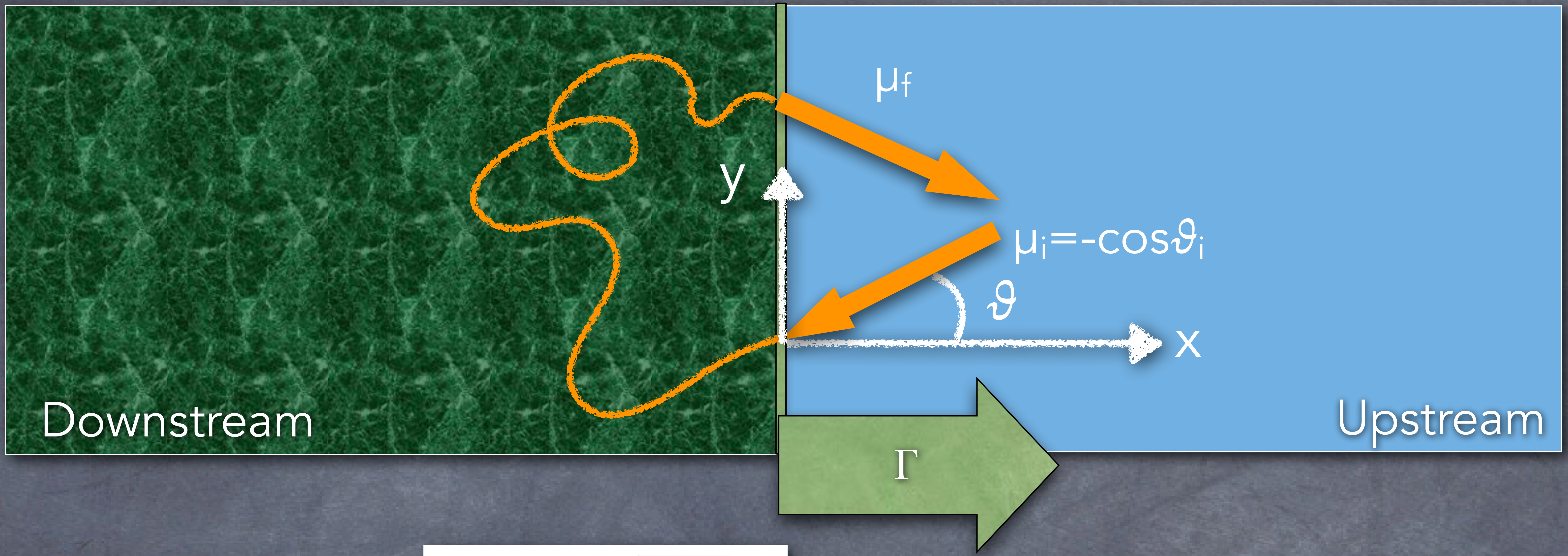




$$B(\mu\mathrm{G})L(\mathrm{pc}) > 2\frac{E(10^{15}eV)}{Z\beta}$$

- Hillas criterion favors the origin of UHECRs in relativistic objects

Acceleration at Relativistic Shocks



E.g., Vietri 1995

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

in the *downstream* frame:

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

Elastic scattering (e.g., gyration): $p'_{{\rm f},x} = \mu'_{\rm f} E'_{\rm f}$ $\quad \mu_{\rm f} = \frac{\mu'_{\rm f}+\beta}{1+\beta\mu'_{\rm f}},$

Back in the upstream:

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

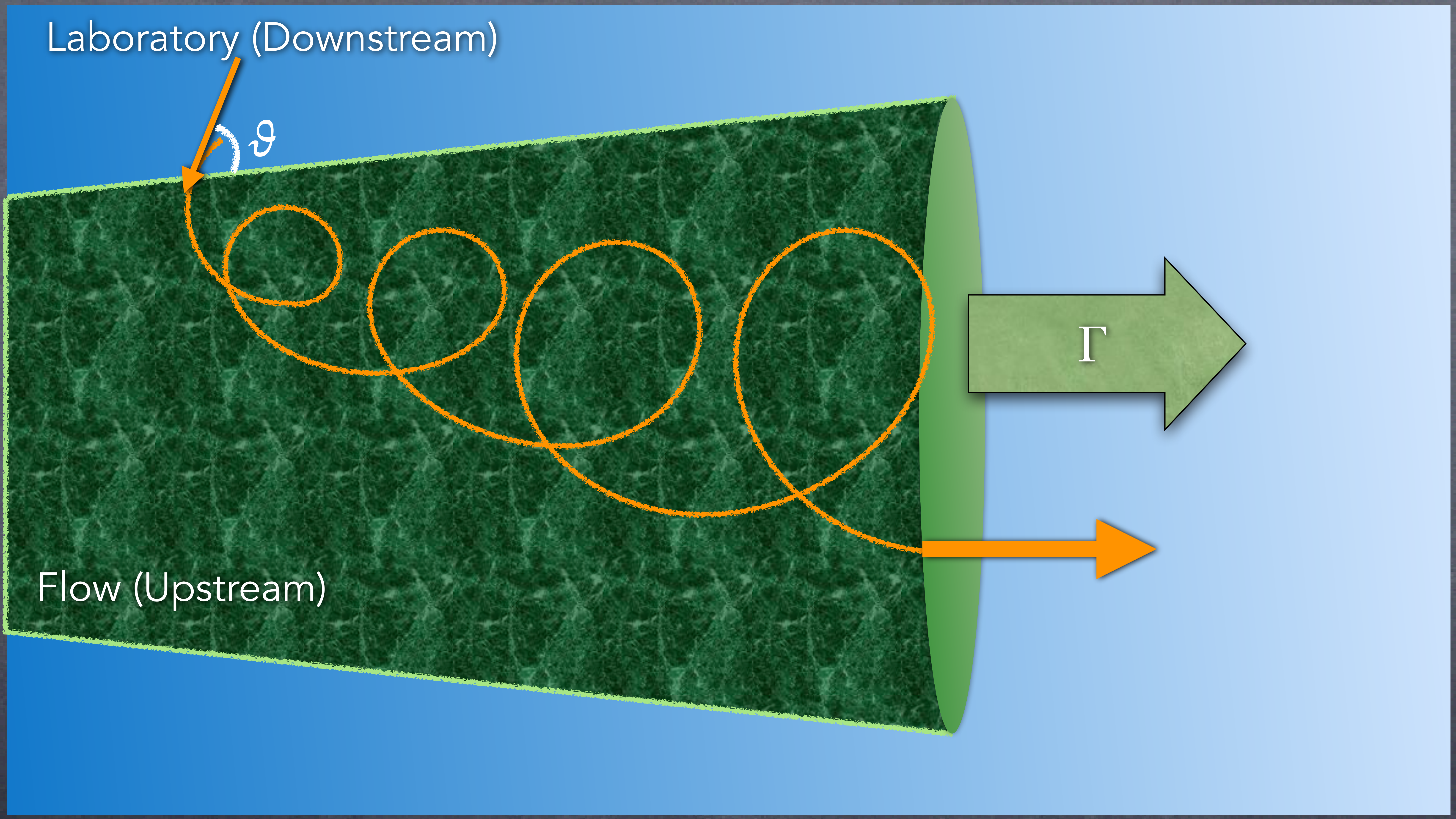
- Energy gain depends on μ_i, μ_f

First cycle: $\mathscr{E} \equiv \frac{E_f}{E_i} \sim \Gamma^2$ (~Compton scattering)

- Following cycles: $\mathscr{E} \sim 2$
- CAVEAT: return not guaranteed!

Acceleration in Relativistic Flows

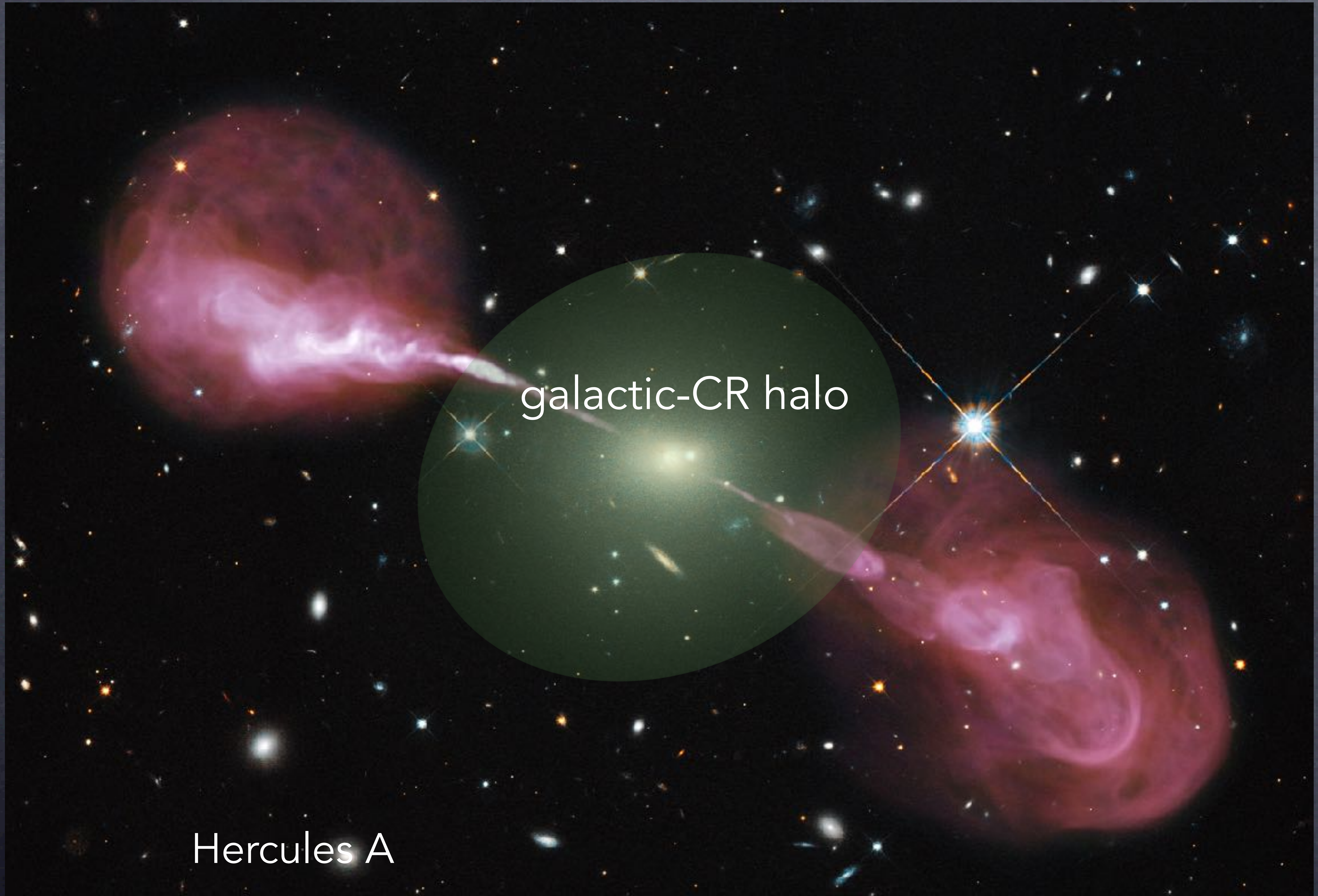
- Requirement: interface thickness << gyroradius << typical flow size



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

Espresso Acceleration of UHECRs

- **SEEDS:** galactic CRs up to $E_{knee} \sim 3Z \times 10^{15}\mathrm{eV}$
- **STEAM:** AGN jets with Γ up to 20-30



ONE-SHOT
reacceleration can produce UHECRs up to

$$E_{max} \sim 2\Gamma^2 \, E_{knee}$$

$$E_{max} \sim 5Z \times 10^{18}\mathrm{eV}$$

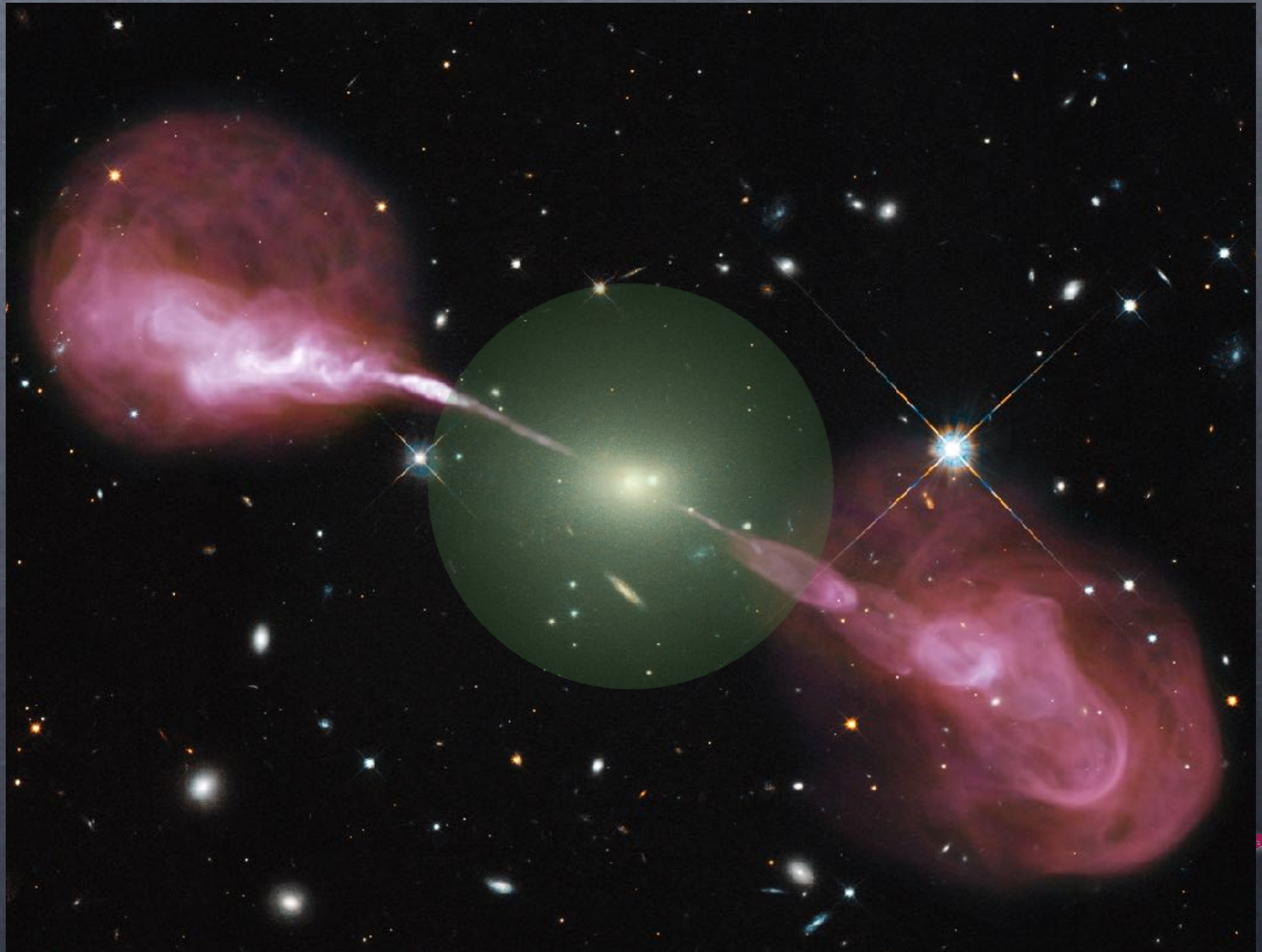
Caprioli 2015

UHECRs from AGN jets: constraints

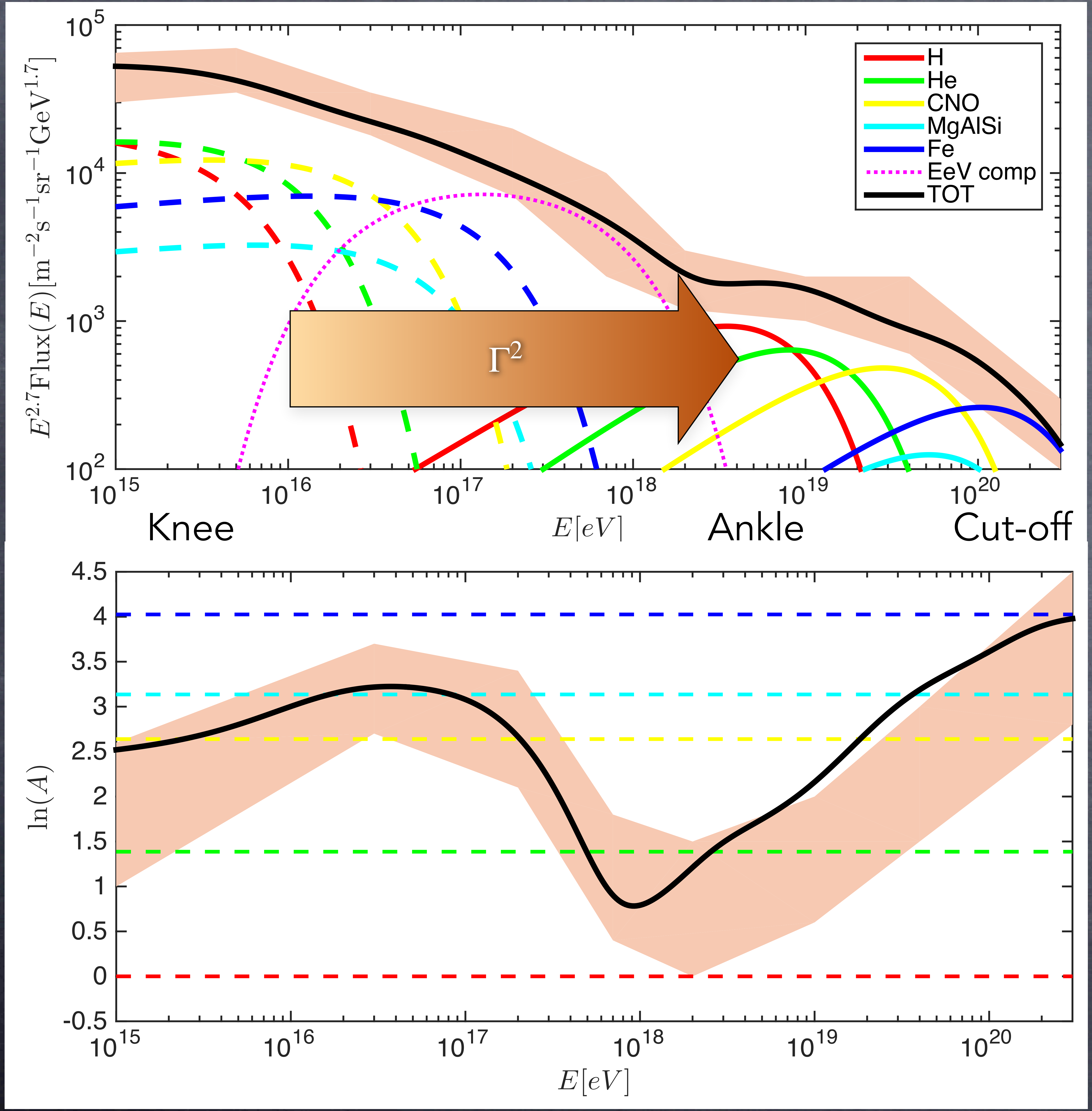
- Confinement (Hillas Criterion): $B_{\mu G} D_{\rm kpc} \gtrsim \frac{4}{Z_{26}} \frac{E_{\rm max}}{10^{20}{\rm eV}}$ ✔
- Energetics: $Q_{UHECR}(E \gtrsim 10^{18}eV) \approx 5 \times 10^{45} erg/Mpc^3/yr$

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

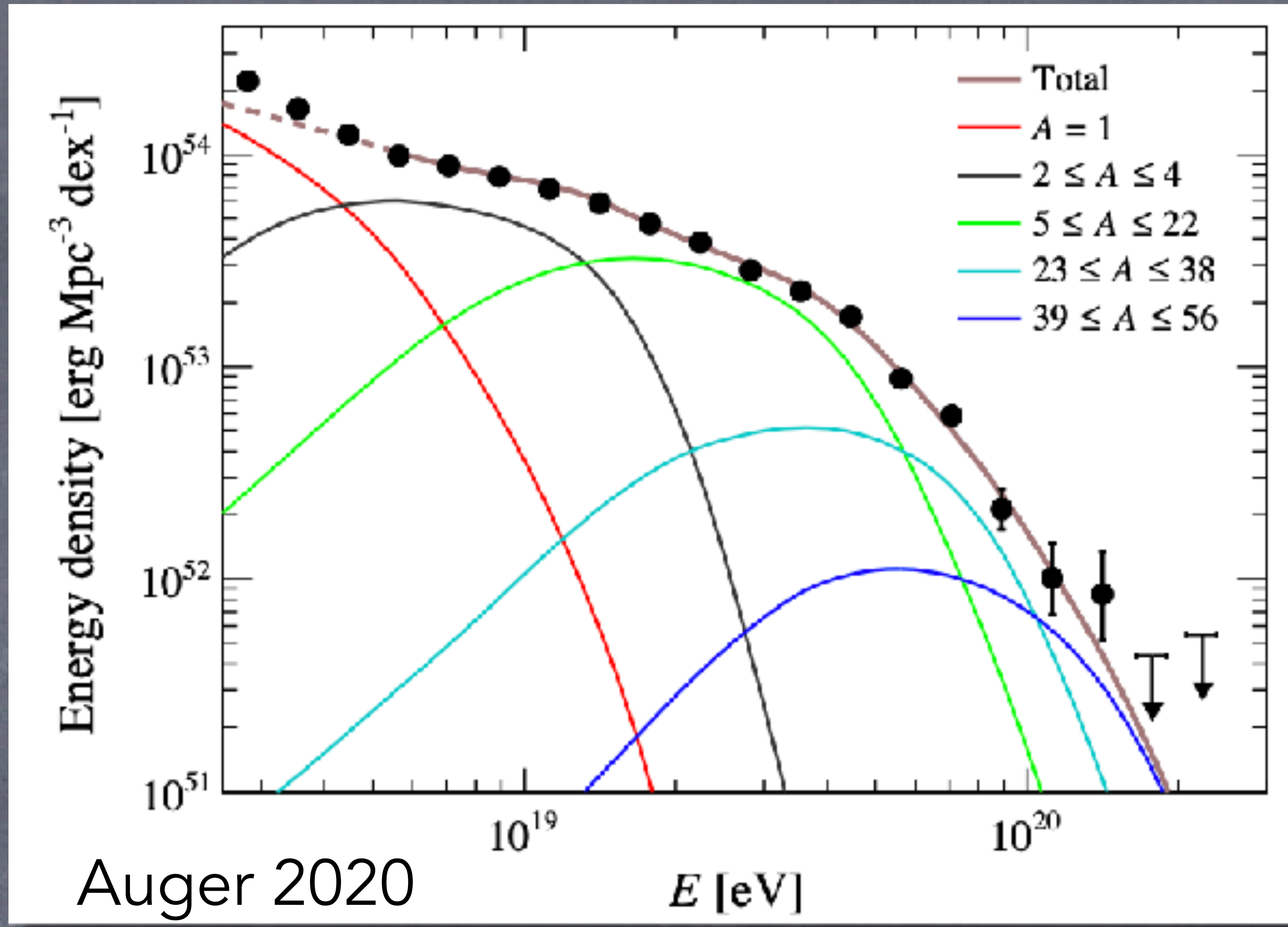
  $Q_{AGN} \approx$ a few 10^{46}-$10^{48} erg/Mpc^3/yr$ >> Q_{UHECR} ✔
- Reacceleration efficiency required:
  - $\eta \gtrsim 10^{-4}$ in energy;
  - A jet with opening angle of a few degrees reprocesses $\sim 1\ \%$ of the seeds
- Contributing AGNs
  - Likely radio-loud quasars, blazars, FR-I,…



Galactic CR + UHECR spectrum



- Prediction for UHECR chemical composition!

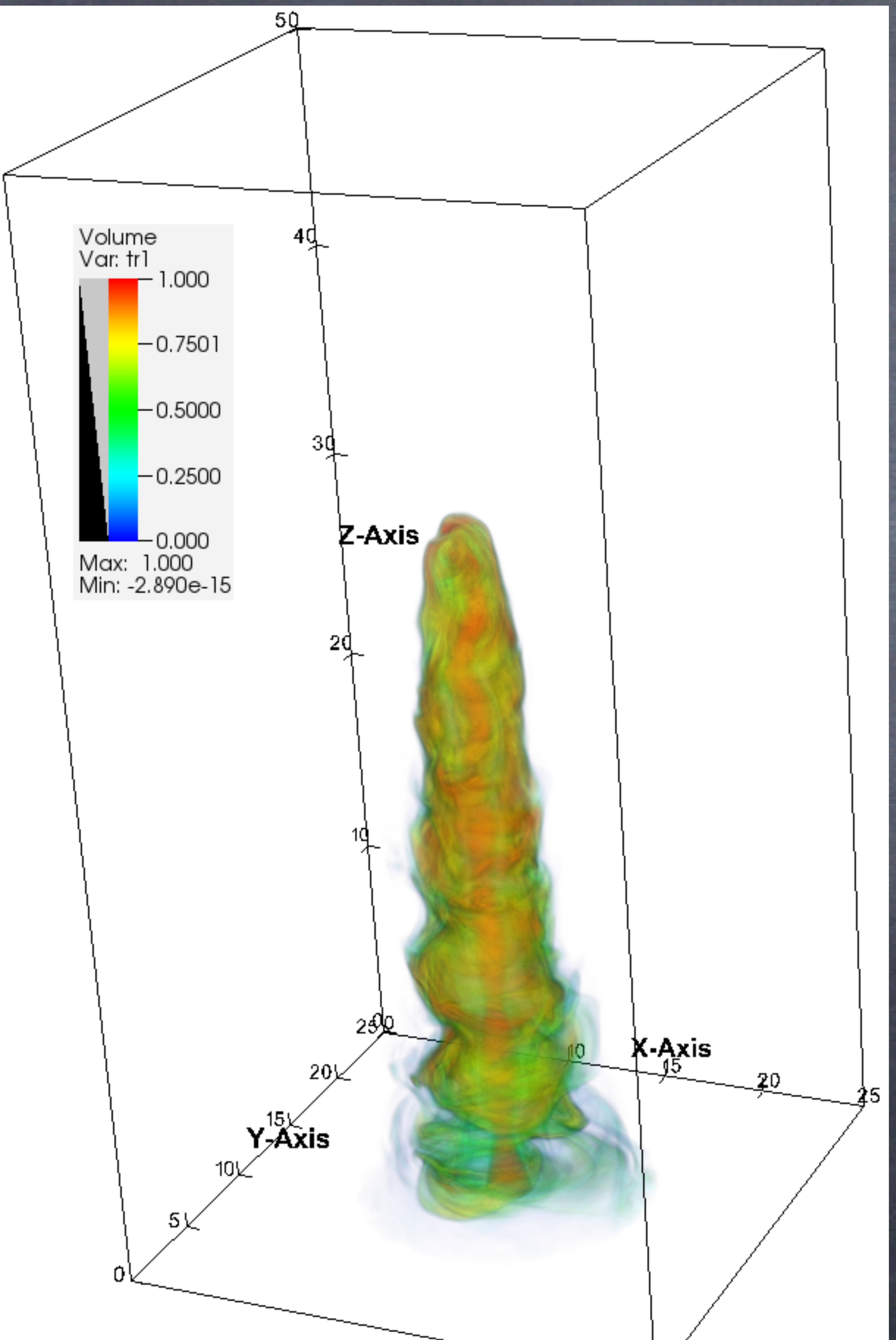


- What kind of AGN can contribute?
  - Enough sources within the horizon?
  - What if $\Gamma \sim$ a few (e.g., FR-I galaxies) ?
  - Expected anisotropy?

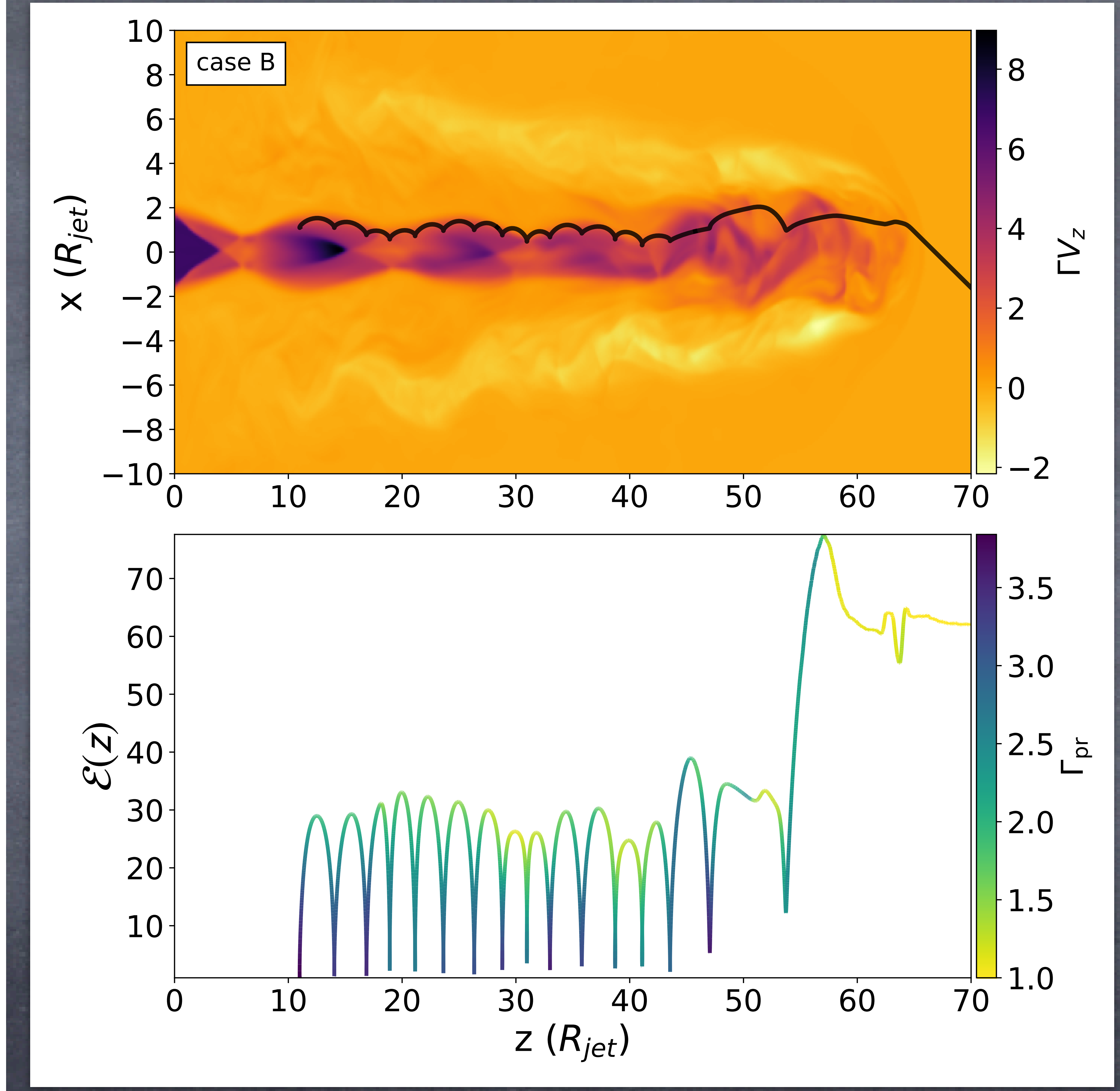
Caprioli 2015, 2018

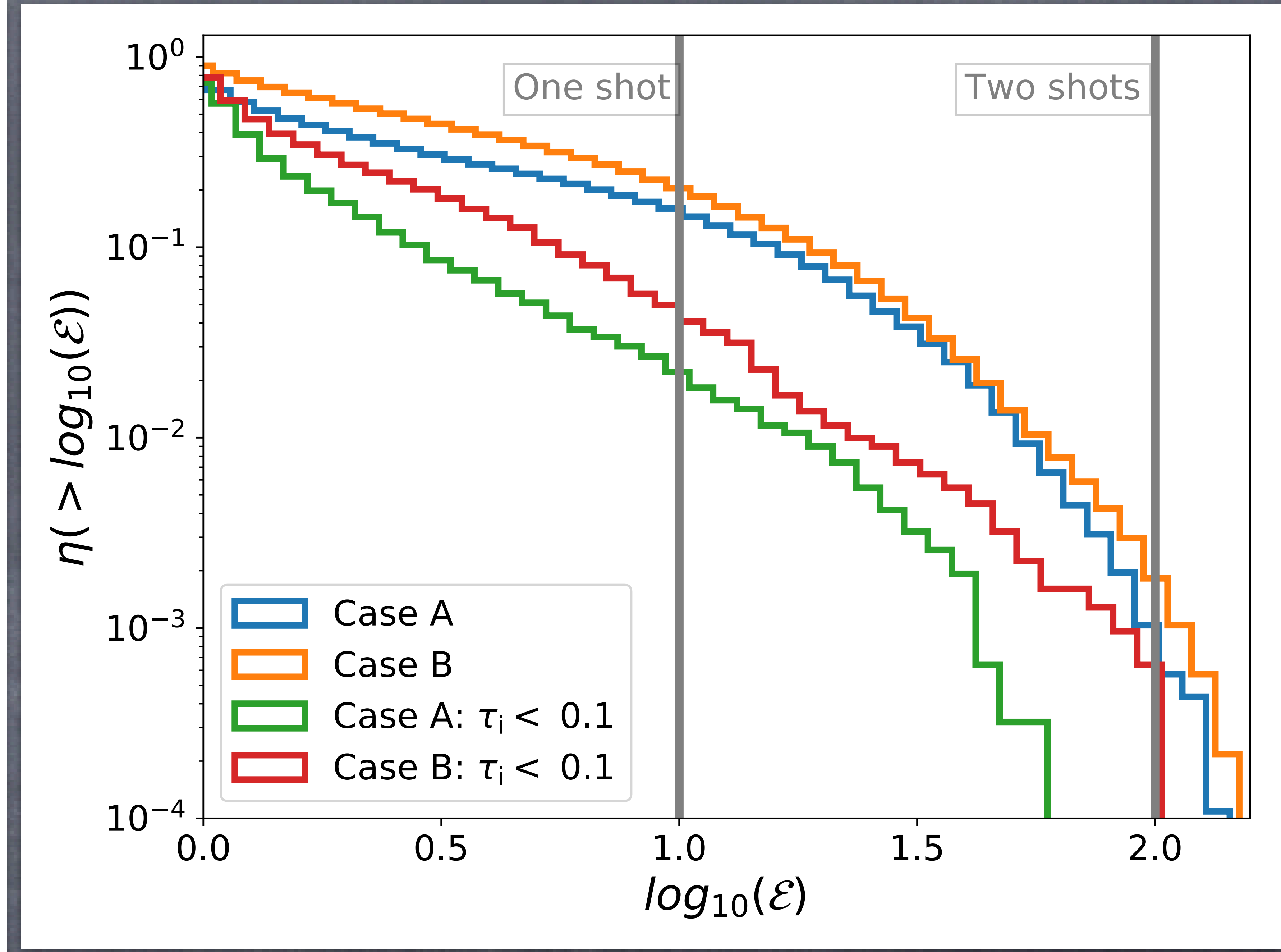
Testing *Espresso* Acceleration

- Propagation of test particles in 3D RMHD simulations with *Pluto* (Mbarek & Caprioli19)



Mbarek & DC 2019



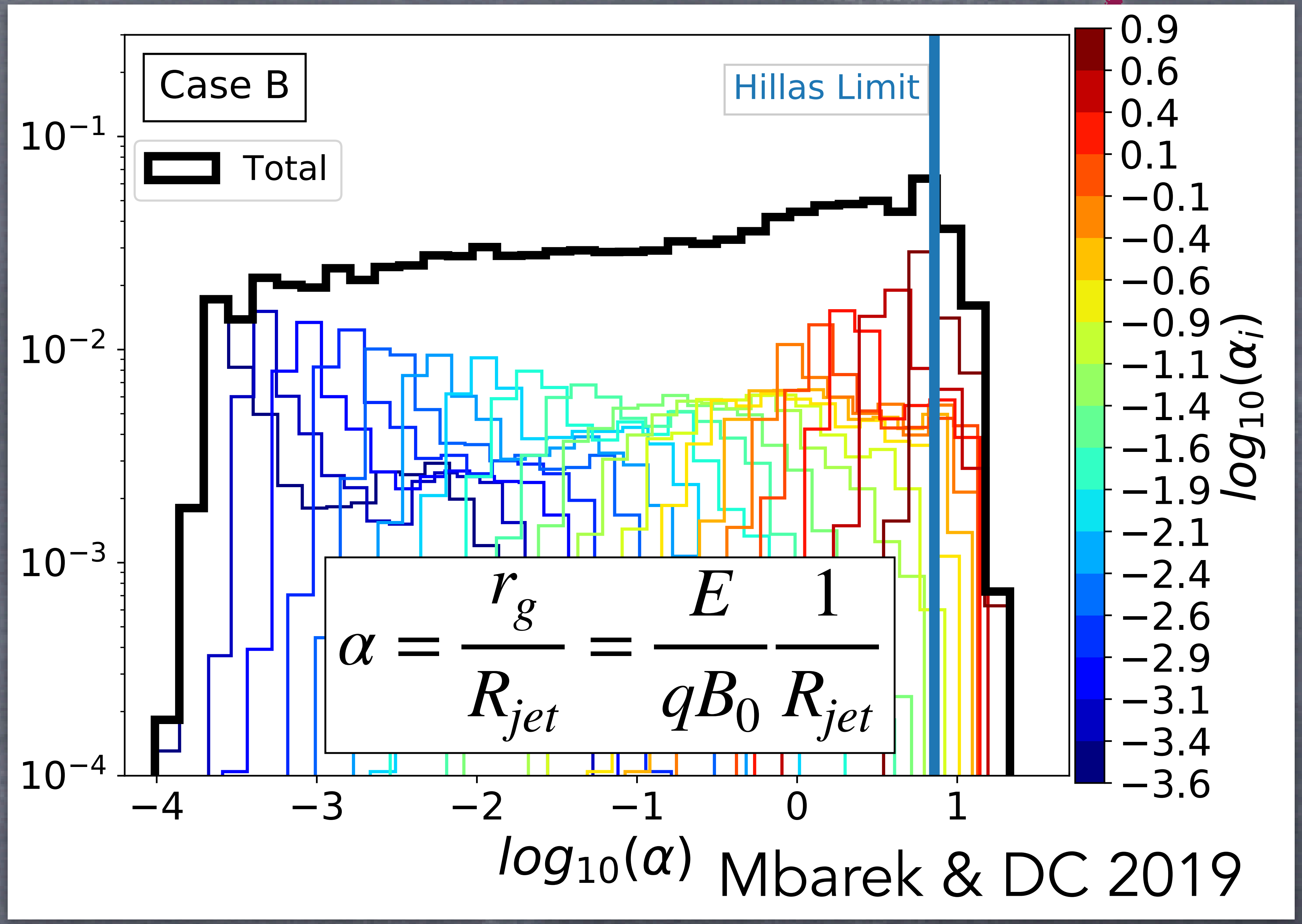


Effective Lorentz factor: $\Gamma_{eff} \approx 3.2$

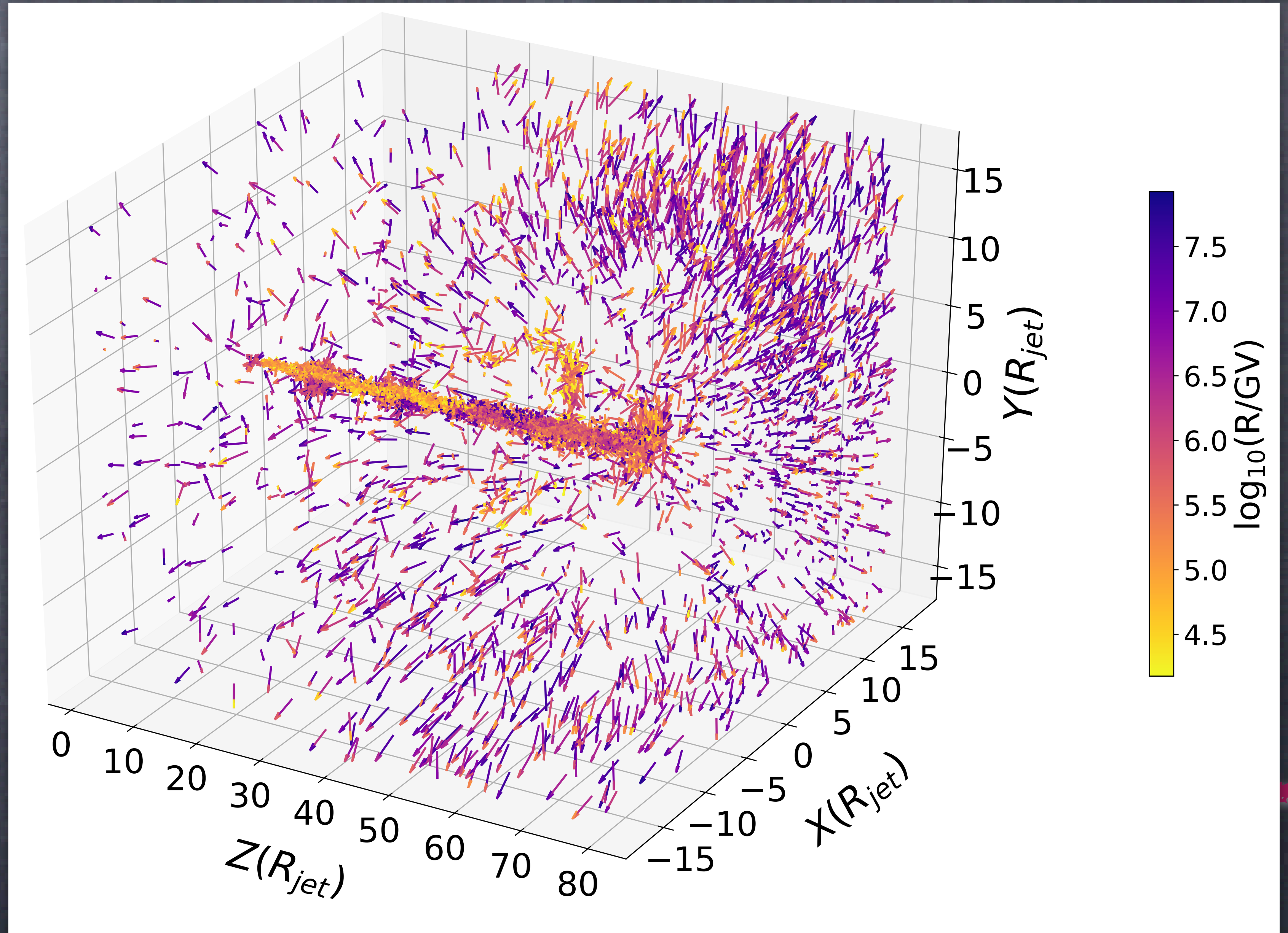
- *Espresso* works for $> 1\,\%$ of the Galactic CR seeds
- *Two-shot acceleration* ($\mathcal{E} \gtrsim \Gamma^4$) is also possible!

Spectra and Anisotropy

- *Espresso* acceleration occurs up to the Hillas limit
  - *First* tested *bottom-up mechanism for UHECRs*
- Re-accelerated UHECRs released almost isotropically
  - Weak dependence on the sign of B_ϕ
- Astro implications of 3D RMHD simulations:
  - Multiple *espresso* shots allow FR-I galaxies with $\Gamma \sim$ few (e.g., Cen A) to be UHECR sources, too
  - Even non-blazar AGNs may contribute to the UHECR flux at Earth

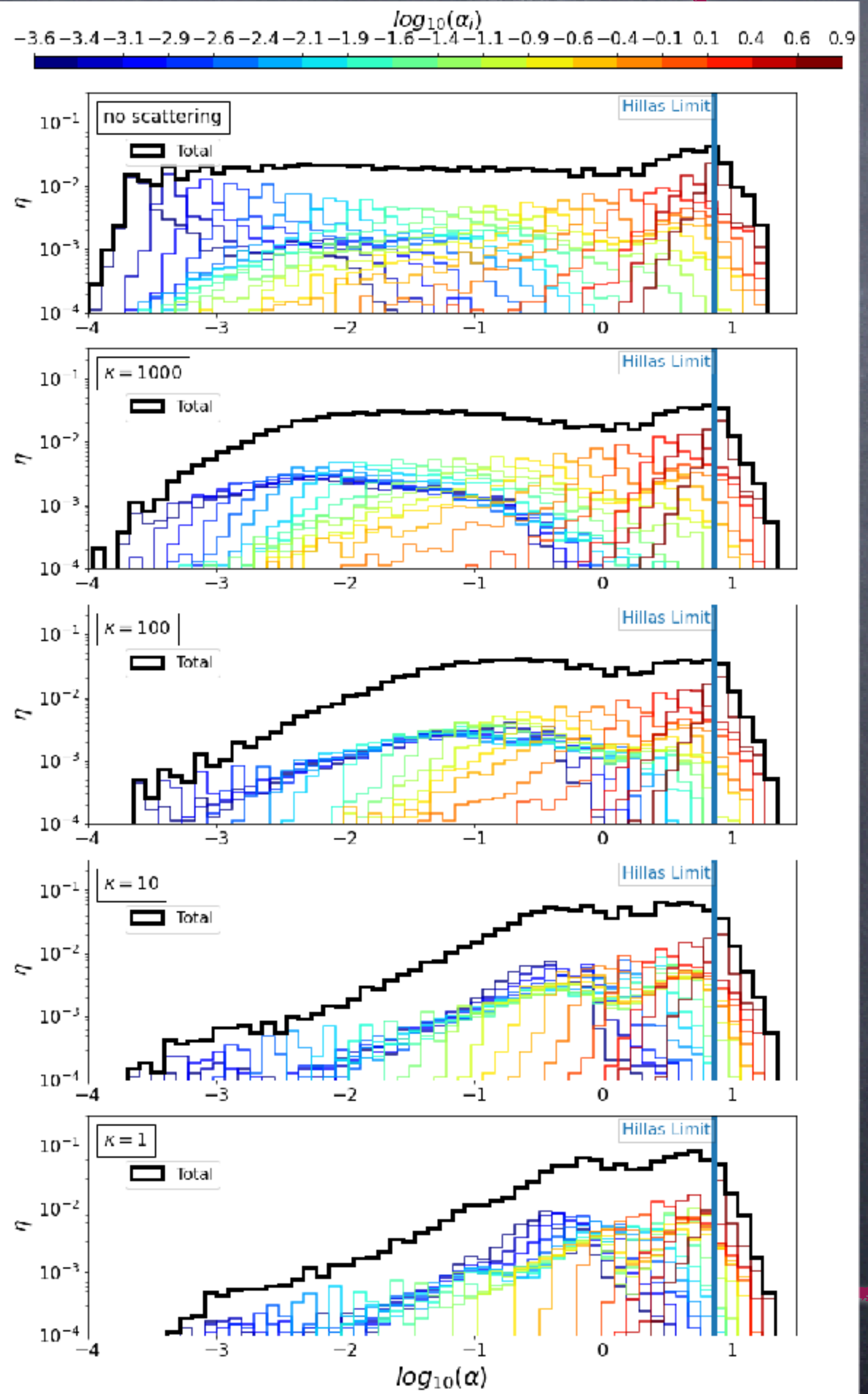


Mbarek & DC 2019



Espresso vs Stochastic Shear Acceleration

- Shear acceleration at the jet-cocoon layer proposed as source of UHECRs (e.g., Ostrowski 1998, 2000; Kimura+2018)
  - depends on *poorly-know* scattering rate
- Added sub-grid Monte Carlo scattering to our RMHD jet with $\tau_{scatt} = \frac{\kappa}{\Omega_c}$ ($\kappa = 1 \rightarrow$ *Bohm* diffusion)
- Scattering fosters acceleration of *low-energy seeds*
  - The Hillas limit only achieved via *espresso*!
  - Overall spectrum becomes flatter



Mbarek & Caprioli 2021

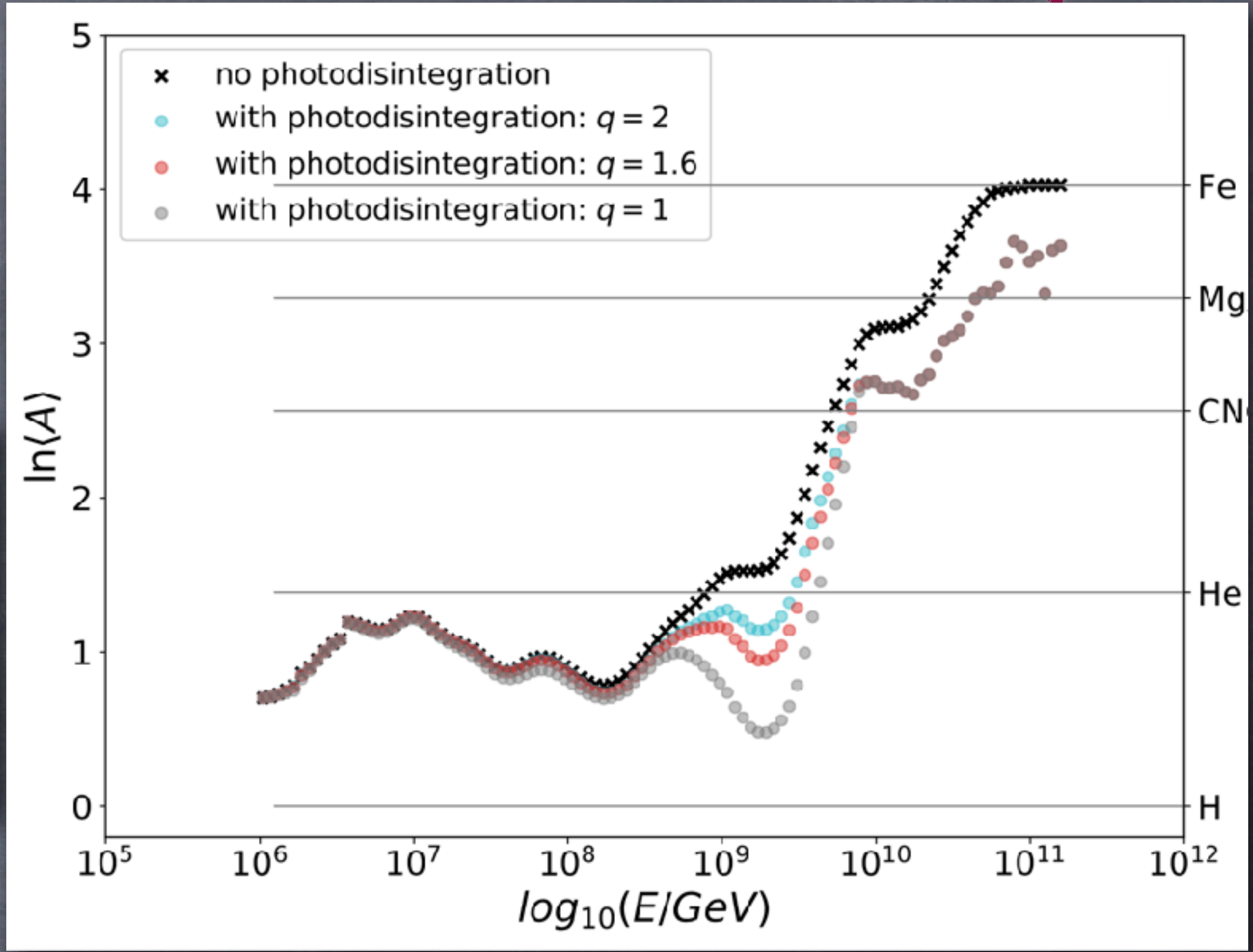
ESPRESSO ACCELERATION and UHE neutrinos

UHECR attenuation in realistic AGNs

- Included loss mechanisms for UHE protons and nuclei:
  - CR - p collisions
  - CR - γ collisions (nuclei photodisintegration)

Particle	Process	Reactions
Proton (p)	proton-proton (pp) photomeson ($p\gamma$)	$\mathrm{p}+\mathrm{p}\rightarrow \mathrm{p}+\mathrm{n}+\pi^{+}\rightarrow \mathrm{p}+\mathrm{n}+e^{+}+\nu_e+\nu_\mu+\bar{\nu}_\mu$ $\mathrm{p}+\gamma\rightarrow \mathrm{n}+\pi^{+}\rightarrow \mathrm{n}+e^{+}+\nu_e+\nu_\mu+\bar{\nu}_\mu$
Nucleus (N)	photomeson ($N\gamma$) photodisintegration & neutron decay	$\mathrm{N}+\gamma\rightarrow {}^{A-1}\mathrm{N}+\mathrm{n}+\pi^{+}\rightarrow {}^{A-1}\mathrm{N}+\mathrm{n}+e^{+}+\nu_e+\nu_\mu+\bar{\nu}_\mu$ ${}^{A}\mathrm{N}+\gamma\rightarrow {}^{A-1}\mathrm{N}+\mathrm{n}\rightarrow {}^{A-1}\mathrm{N}+\mathrm{p}+e^{-}+\bar{\nu}_e$ ${}^{A}\mathrm{N}+\gamma\rightarrow {}^{A-1}\mathrm{N}+\mathrm{p}$

Mbarek, Caprioli & Murase 2022



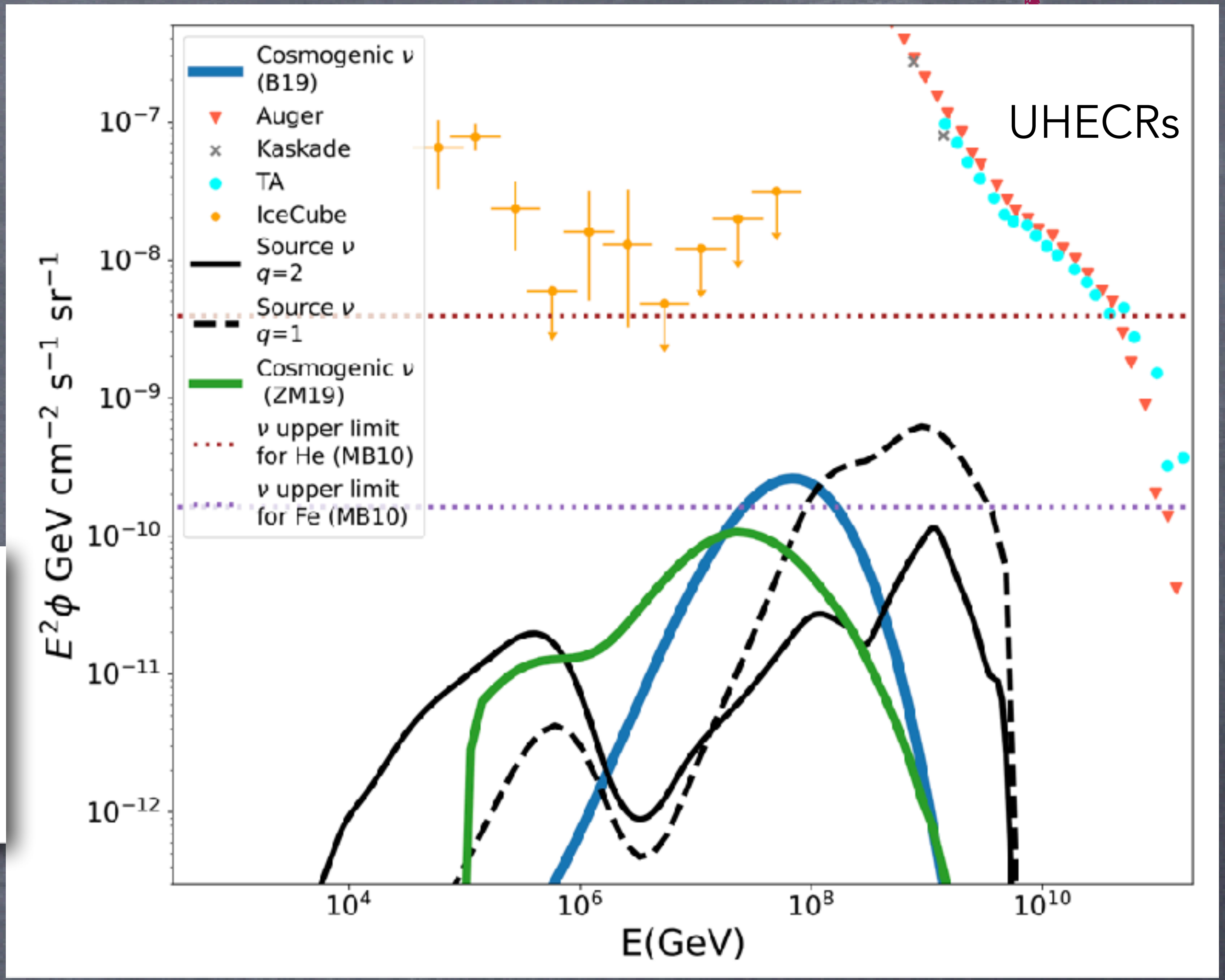
- Technically challenging & dependent on the AGN photon fields
  - Non-thermal emission (dominant), Broad-Line Region, dusty torus IR, CMB, starlight, …
- Even maximizing losses, UHECR composition should remain heavy at the highest energies
  - because espresso acceleration happens far from the jet basis

Expected Flux of UHE Neutrinos from AGNs

- 3 channels for UHE neutrinos:
  - CR - p collisions
  - CR - γ collisions (nuclei photodisintegration)
  - β-decay of secondary nuclei (novel)

Particle	Process	Reactions	Neutrino Energy fraction
Proton (p)	proton-proton (pp)	$\mathrm{p}+\mathrm{p}\rightarrow \mathrm{p}+\mathrm{n}+\pi^{+}\rightarrow \mathrm{p}+\mathrm{n}+e^{+}+\nu_e+\nu_\mu+\bar{\nu}_\mu$	p:$\nu\sim$ 20:1
	photomeson ($p\gamma$)	$\mathrm{p}+\gamma\rightarrow \mathrm{n}+\pi^{+}\rightarrow \mathrm{n}+e^{+}+\nu_e+\nu_\mu+\bar{\nu}_\mu$	p:$\nu\sim$ 20:1
Nucleus (N)	photomeson ($N\gamma$)	$\mathrm{N}+\gamma\rightarrow {}^{A-1}\mathrm{N}+\mathrm{n}+\pi^{+}\rightarrow {}^{A-1}\mathrm{N}+\mathrm{n}+e^{+}+\nu_e+\nu_\mu+\bar{\nu}_\mu$	N:$\nu\sim$ 20:1
	photodisintegration	${}^{A}\mathrm{N}+\gamma\rightarrow {}^{A-1}\mathrm{N}+\mathrm{n}\rightarrow {}^{A-1}\mathrm{N}+\mathrm{p}+e^{-}+\bar{\nu}_e$	N:$\nu\sim 10^{3}$A:1
	& neutron decay	${}^{A}\mathrm{N}+\gamma\rightarrow {}^{A-1}\mathrm{N}+\mathrm{p}$	—

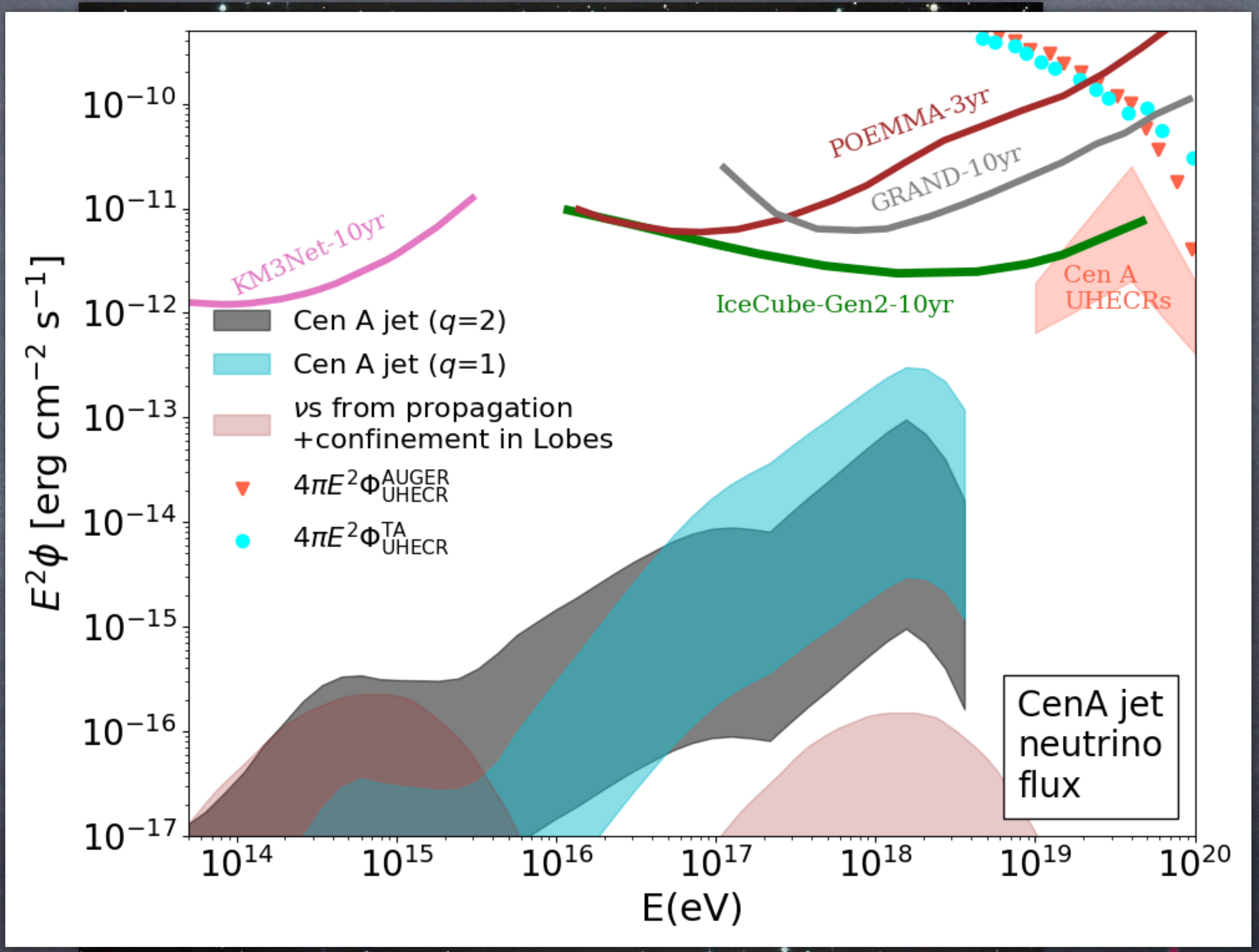
Mbarek, Caprioli & Murase 2023



- AGN contribution *may* dominate cosmogenic neutrino flux for $E > 10^7$GeV (ANITA, ARA, POEMMA)
- IceCube neutrinos ($E \sim 10^3 - 10^6$ GeV) may come from β-decay of secondary nuclei
  - Due to the role of non-thermal γ, possible correlation with AGN flares (e.g., TXS0506+056)

UHE CRs and Neutrinos from Cen A

- Centaurus A: closest AGN (FR-I, ~4Mpc, $L_{\rm bol} \lesssim 10^{44}$ erg/s)
- Auger24: 3-25% of UHECR flux from Cen A consistent with observed spectrum + composition + anisotropy
- Cen A can be a UHECR source, but not *powerful* enough to be typical
- Estimated source neutrino flux from such UHECRs quite low



Mbarek, Caprioli & Murase, subm.

Origin of CR Chemical Composition

Injection and Acceleration of Heavy Nuclei

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

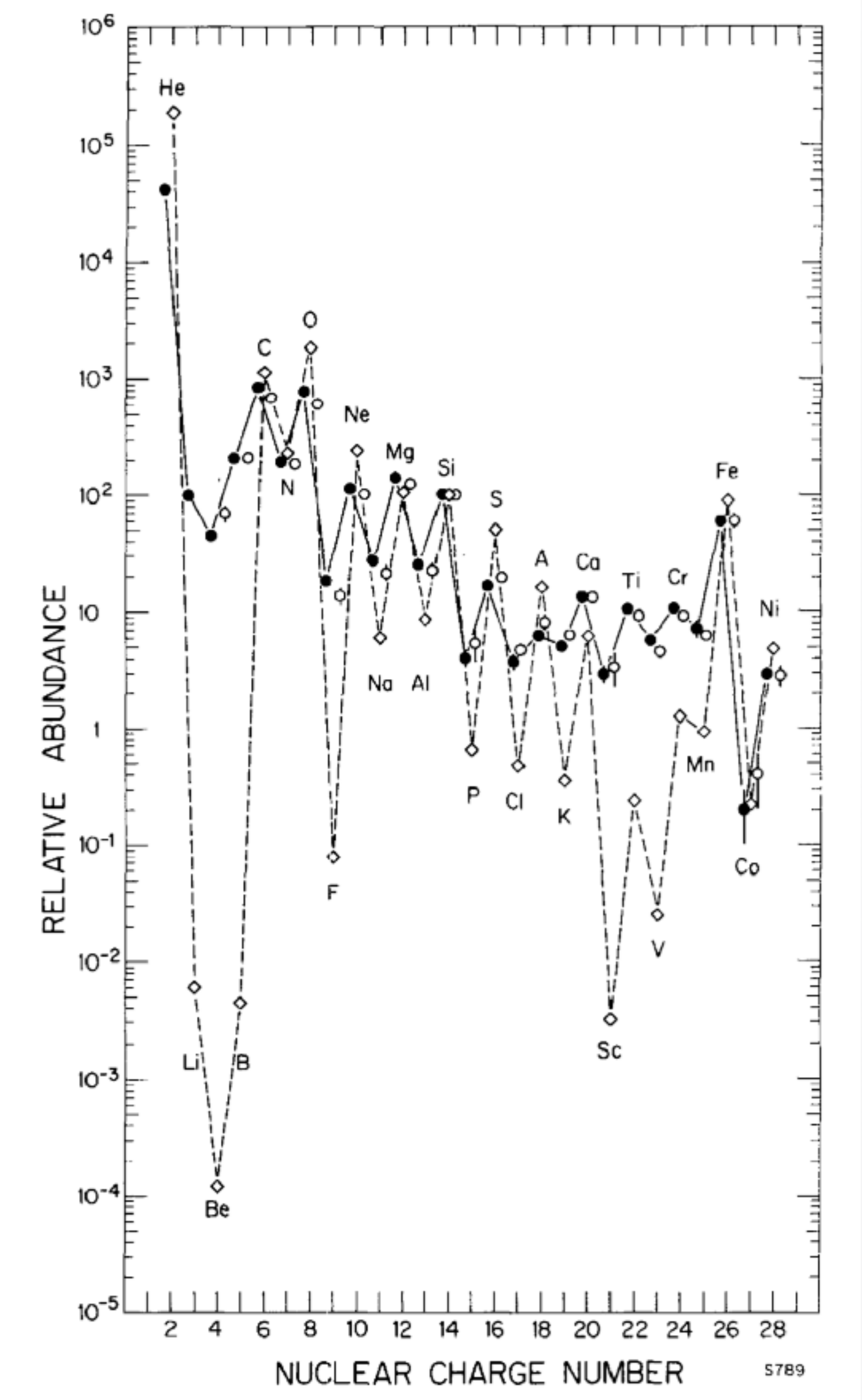
A theory of the origin of cosmic radiation is proposed according to which cosmic rays are originated and accelerated primarily in the interstellar space of the galaxy by collisions against moving magnetic fields. One of the features of the theory is that it yields naturally an inverse power law for the spectral distribution of the cosmic rays. The chief difficulty is that it fails to explain in a straightforward way the heavy nuclei observed in the primary radiation.

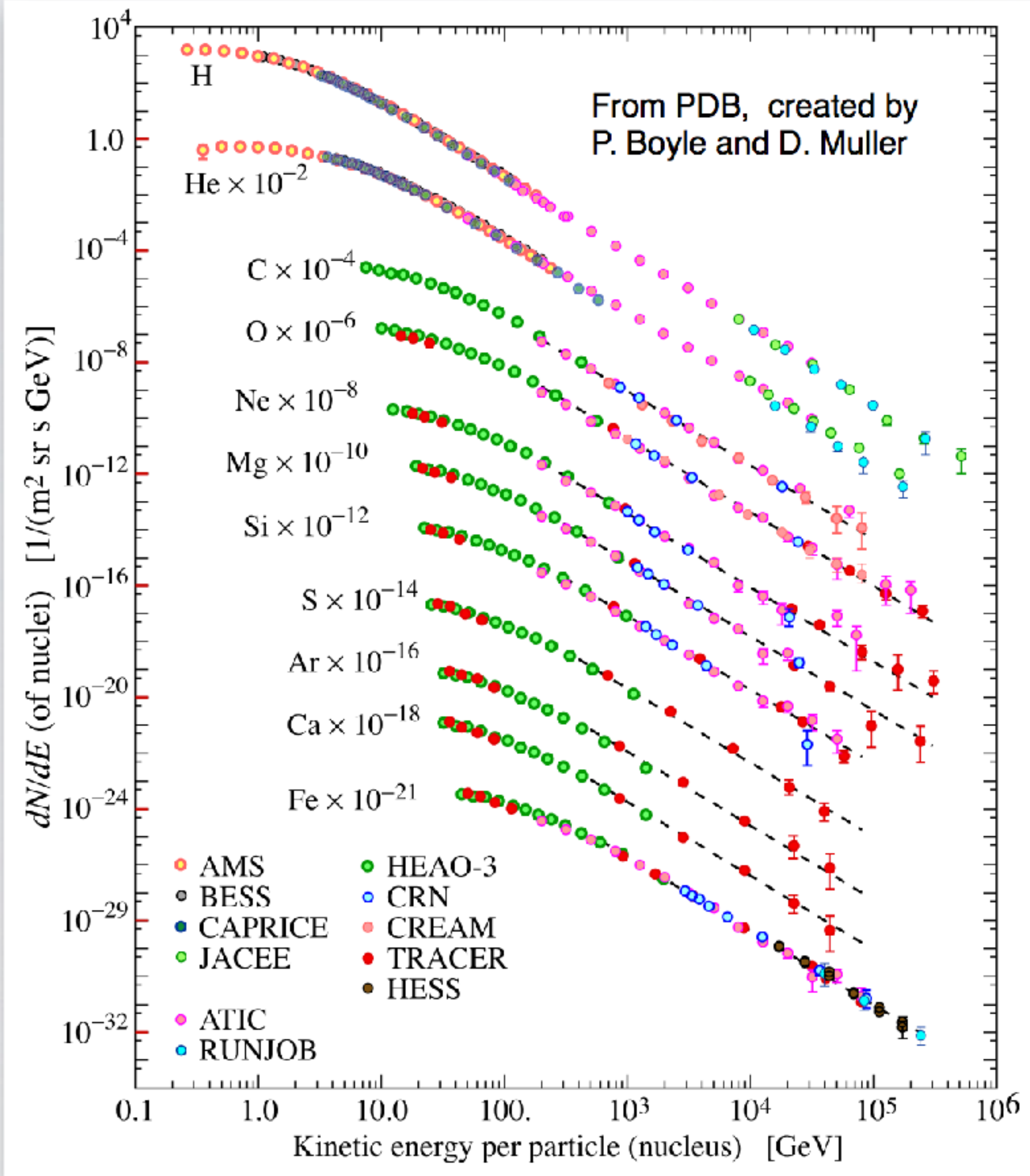
Spectra result from balance between acceleration and *collisional* losses: heavy ions should have *steeper* spectra!

$$\frac{dN}{dE} \propto E^{-(1+\tau_a/\tau_L)}$$

Chemical Composition of Galactic CRs - I

- *Similar* to solar at low energies (Simpson 1983); All species have the same spectral slope

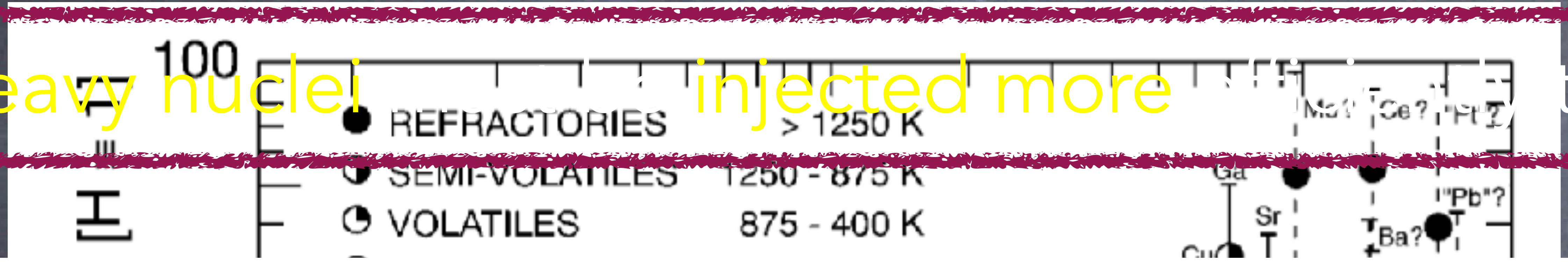


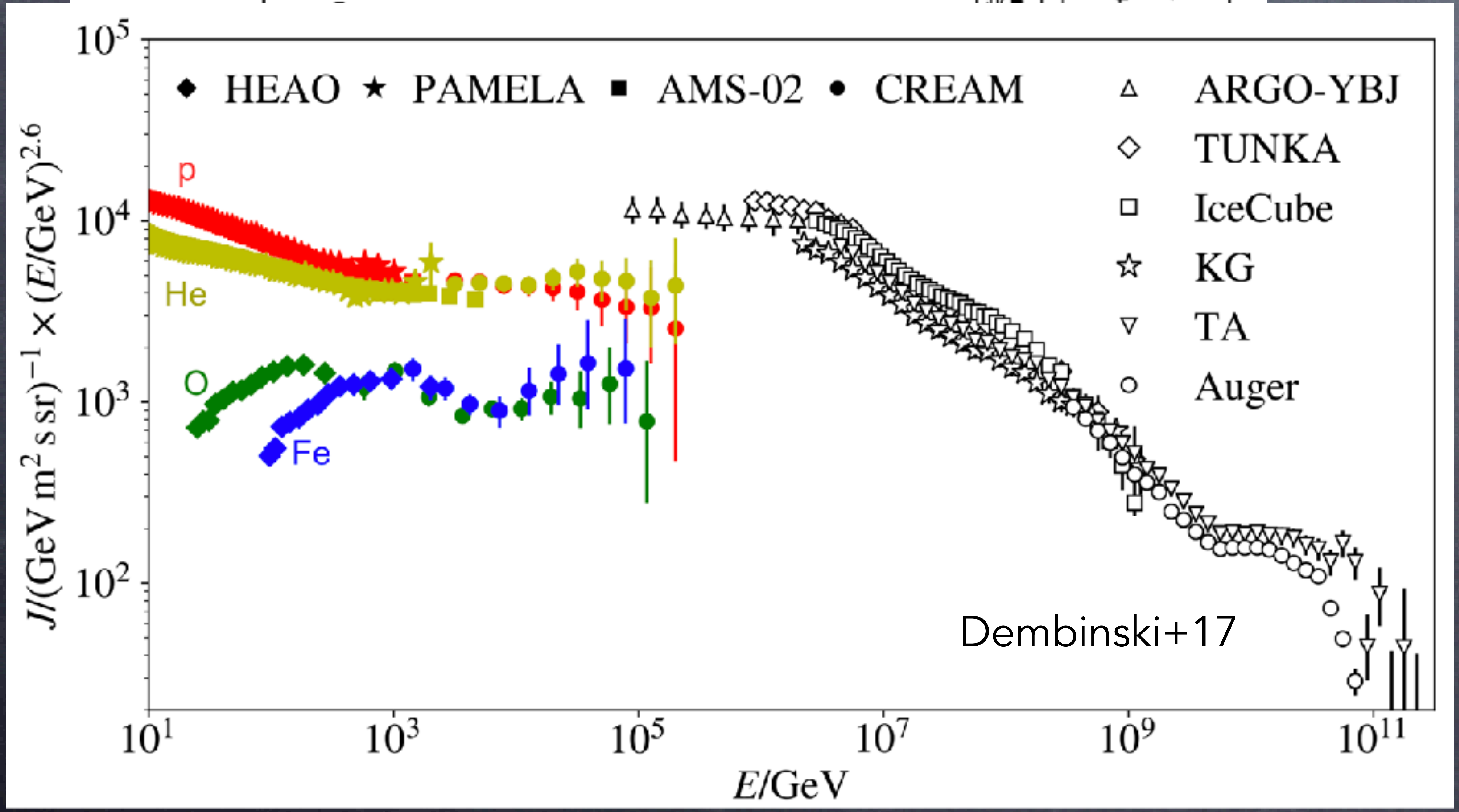


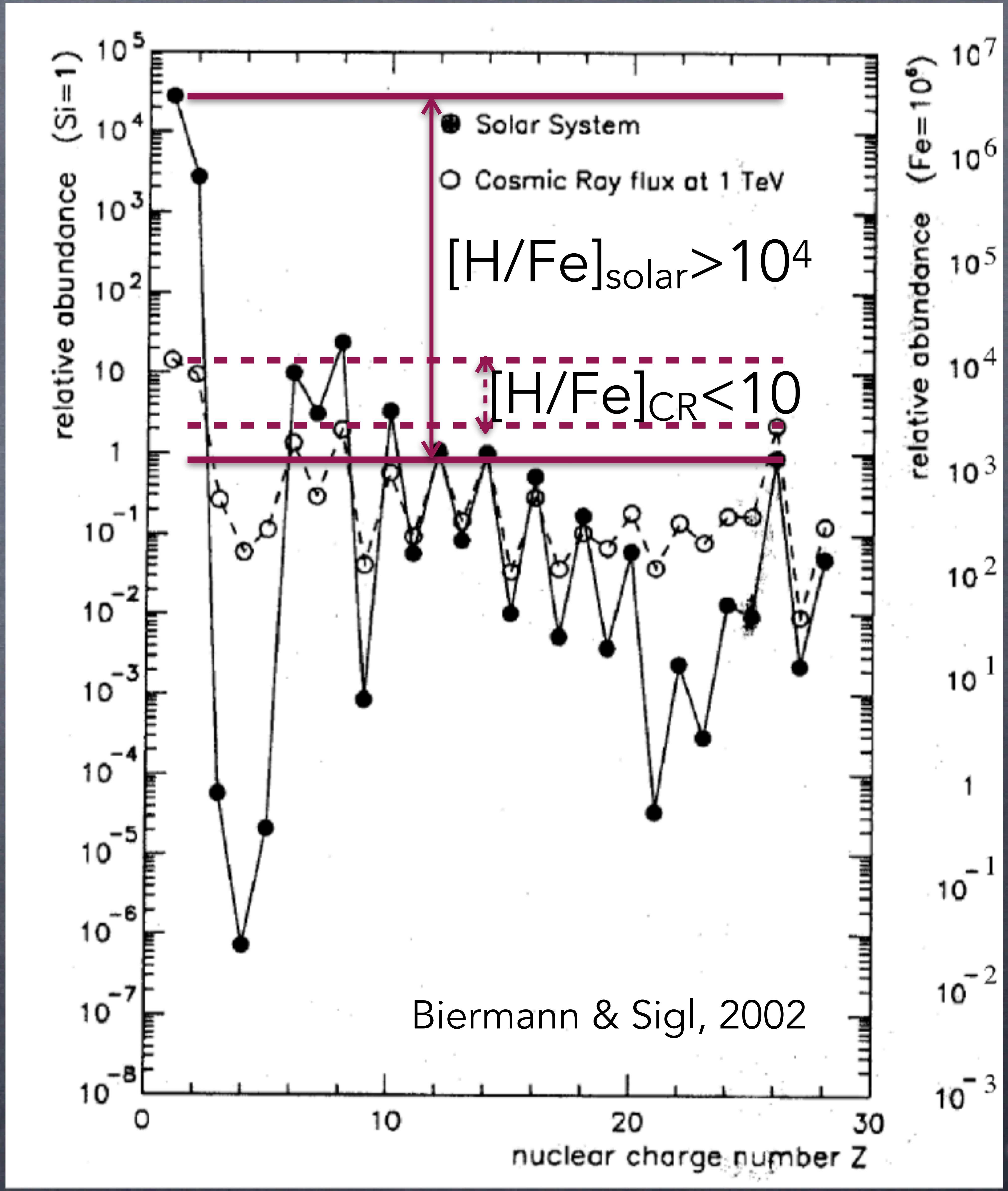
Chemical Composition of Galactic CRs - II

- Depends on volatility (refractory vs volatile elements), on atomic mass A, on first ionization potential…
- Above ~1 TeV, fluxes of H, He, CNO, and Fe are comparable

Heavy nuclei … injected more … than H!

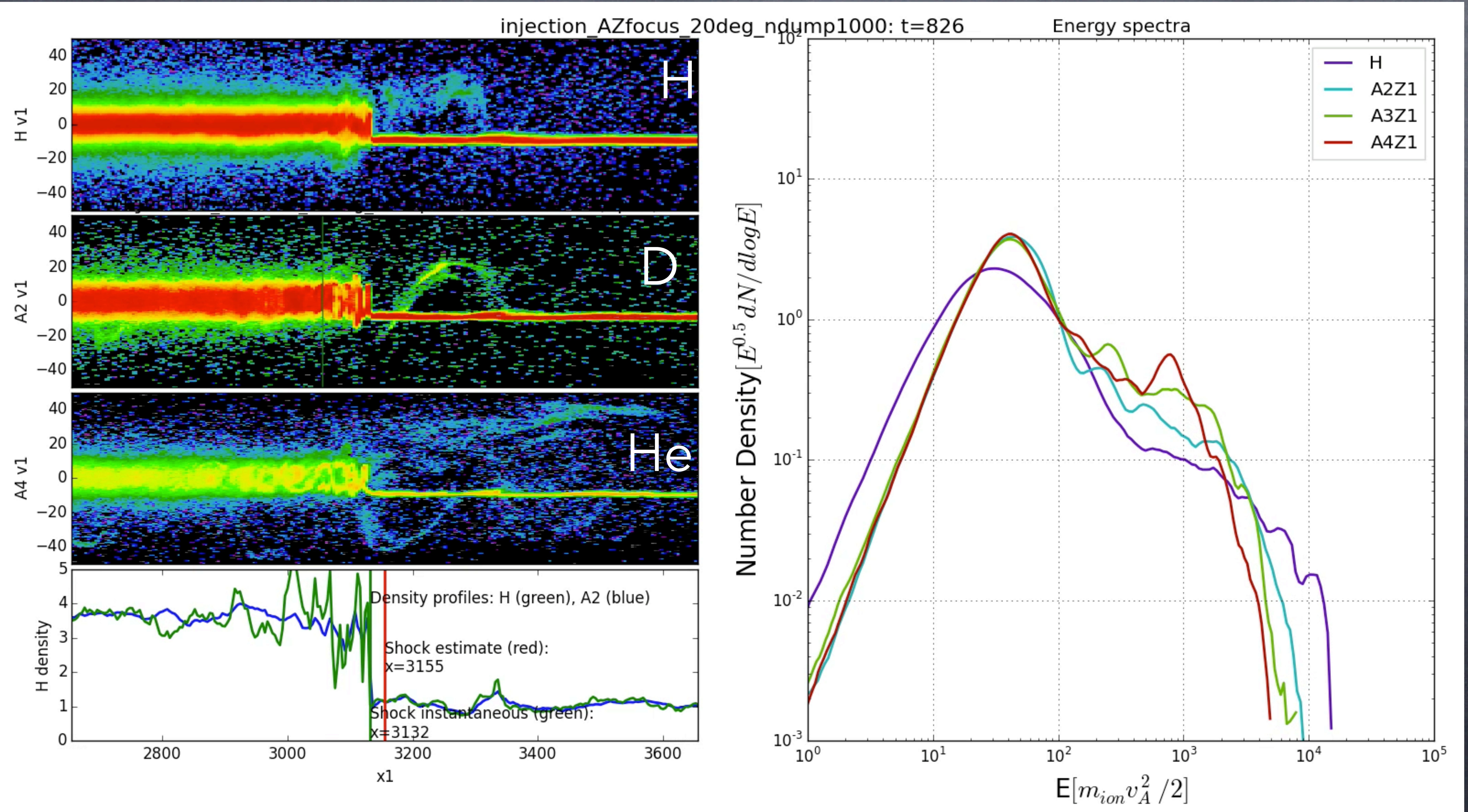






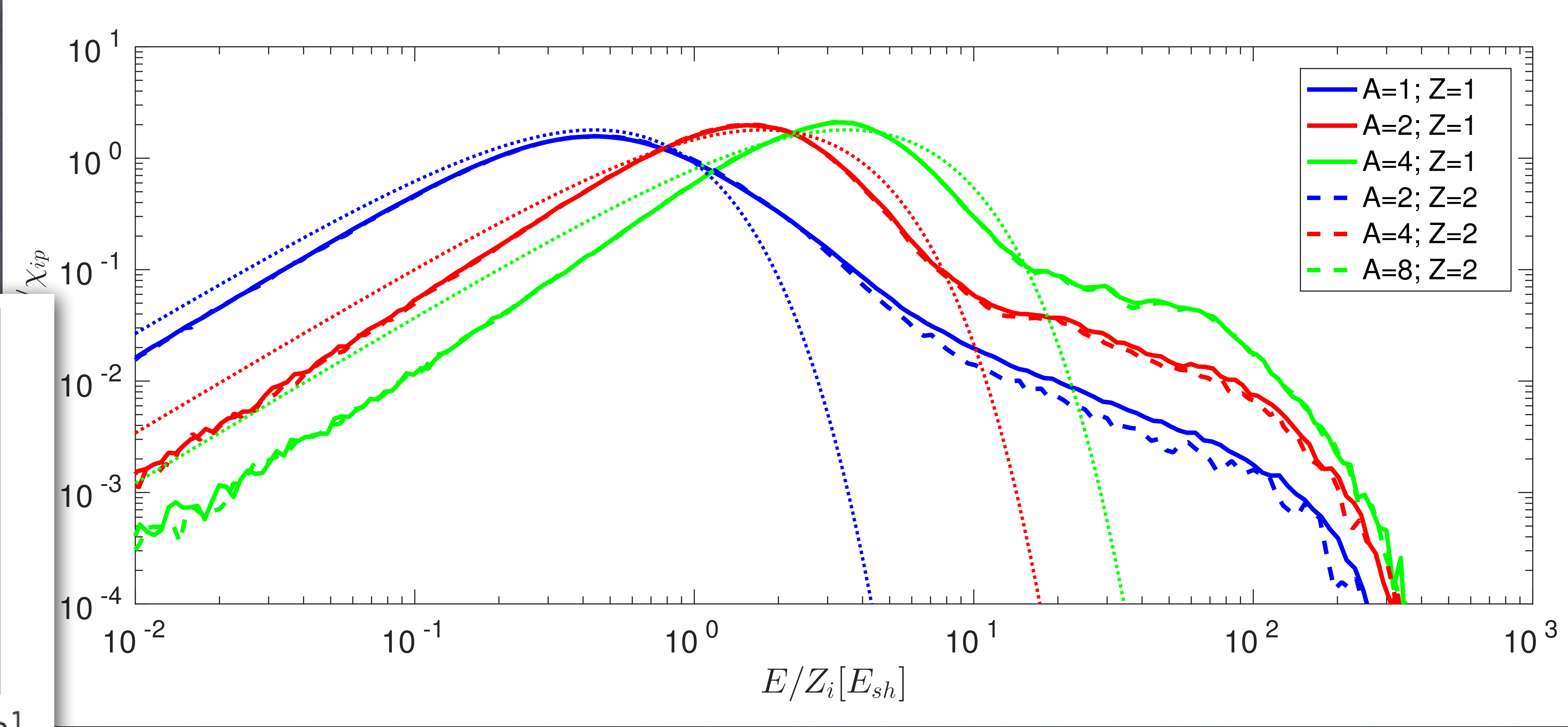
Hybrid Simulations

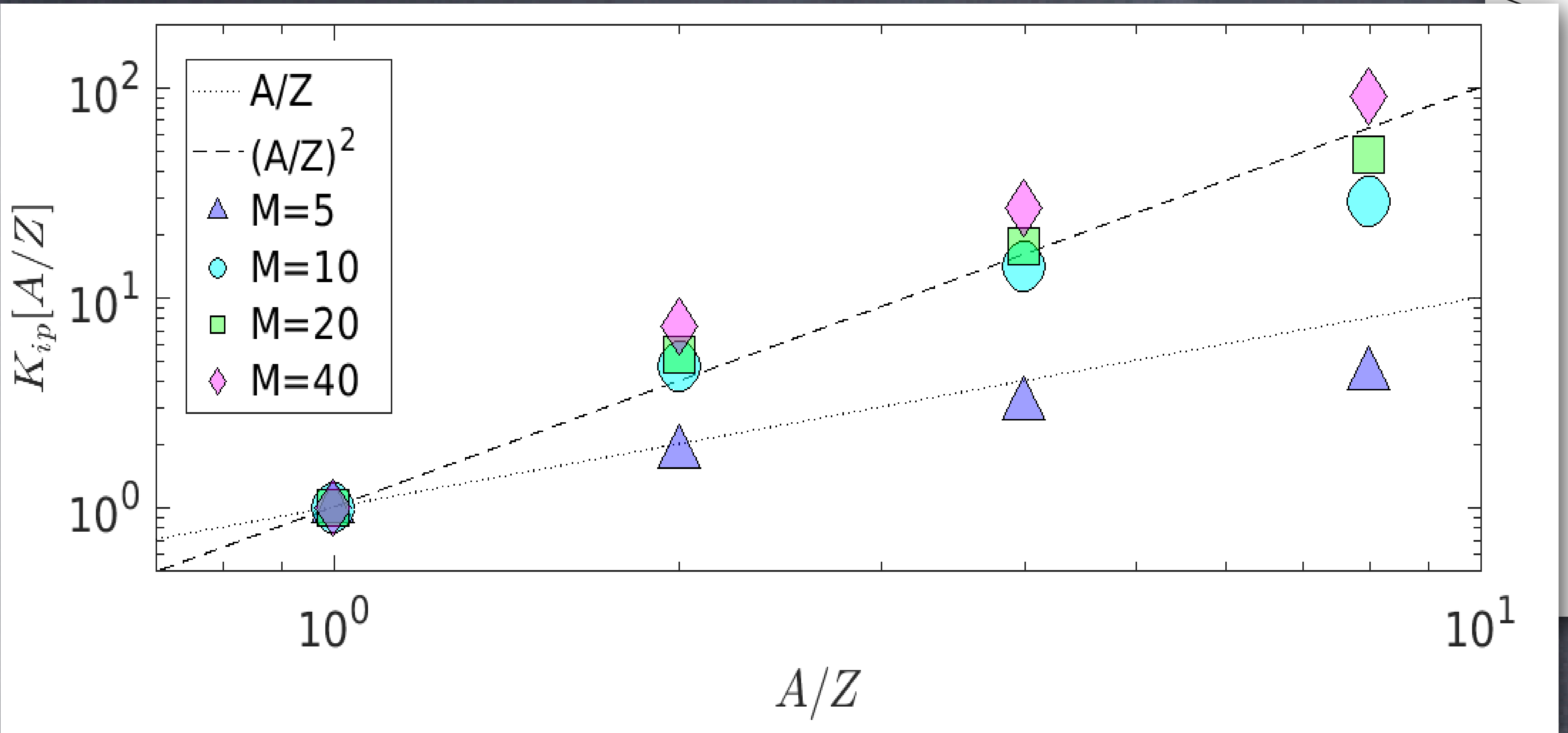
- M=10, parallel shock, with singly-ionized nuclei (DC, Yi, Spitkovsky 2017)

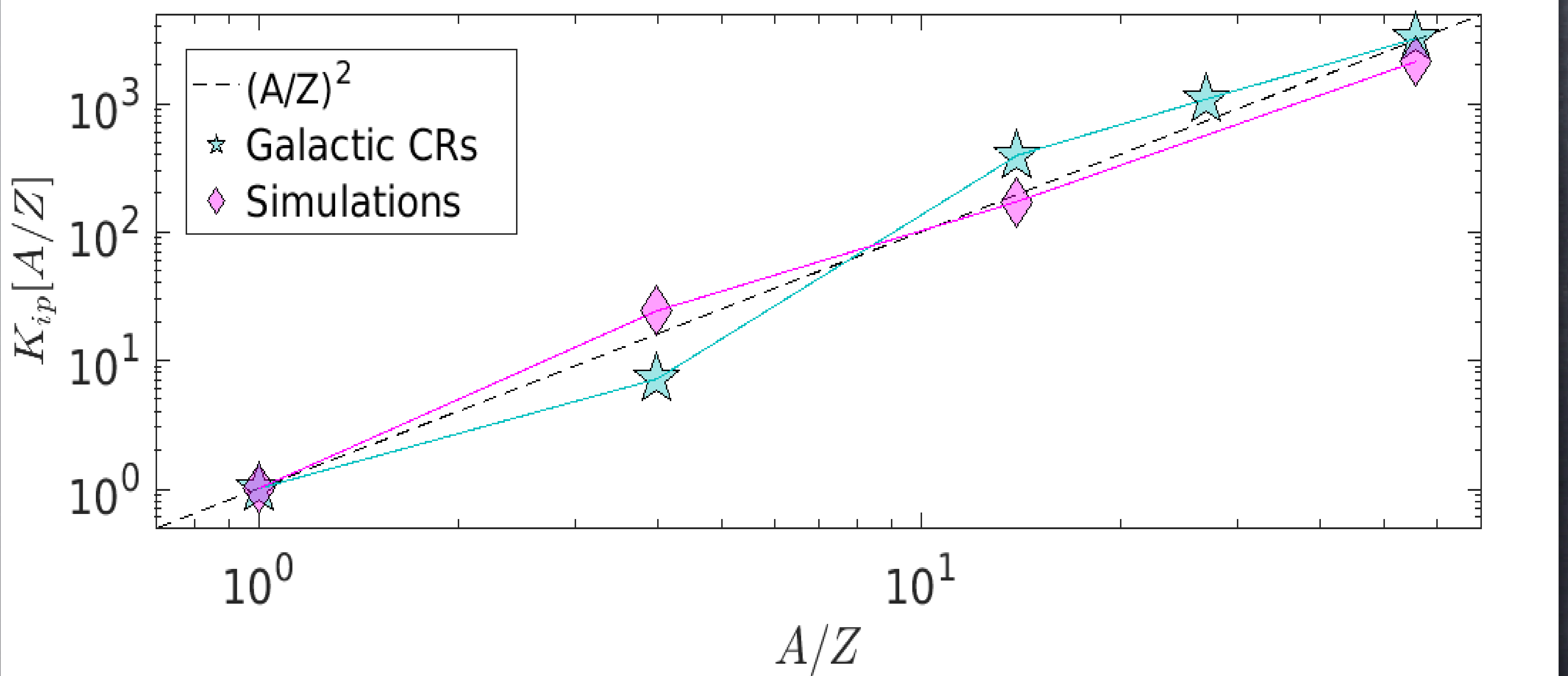


Hybrid Simulations with Heavy Ions

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





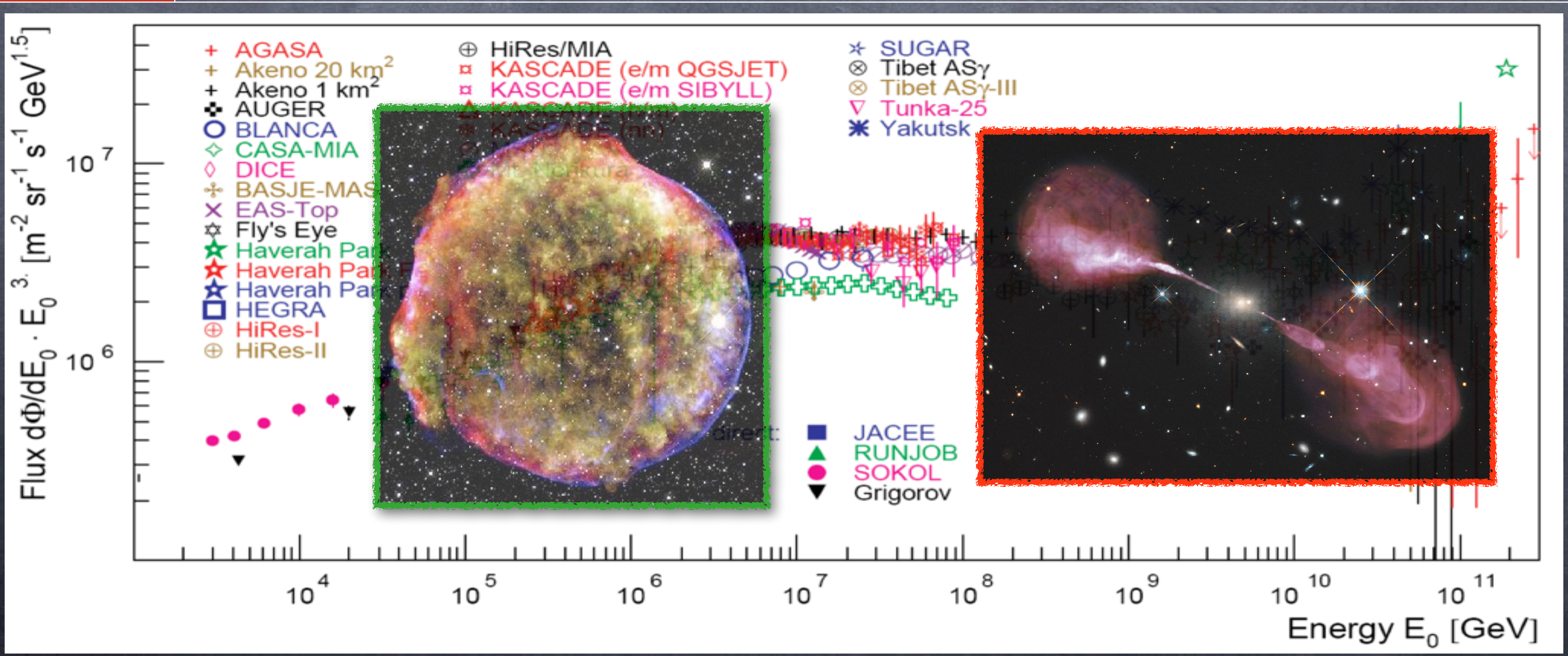


DC, Yi & Spitkovsky, 2017

- 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!

A Summary

Origin	Sources	Mechanism	E_{max}	Spectrum	Evidence
Galactic	SNRs; Star clusters?	Diffusive Acceleration at non-rel shocks	3Zx10^6 GeV?	Universal ~E^{-2}	gamma rays e.g., Tycho
Extragal	AGNs	Espresso in rel flows?	5Zx10^9 GeV	Galactic, boosted	Anisotropy? Neutrinos?



Honoring Venia Berezinsky

- No Wikipedia page, except a very simple one in German: *This is ridiculous!*

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Weniamin Sergejewitsch Beresinski

Weniamin Sergejewitsch Beresinski (russisch Вениамин Сергеевич Березинский, englische Transkription Veniamin Berezinsky; * 17. April 1934 in Stalingrad, Sowjetunion; † 16. April 2023[1] in L'Aquila, Italien[2]) war ein russischer Physiker, der sich mit kosmischer Höhenstrahlung und Astro-Teilchenphysik befasste.

Inhaltsverzeichnis [Verbergen]

Werdegang [Bearbeiten | Quelltext bearbeiten]

Beresinski studierte an der Lomonossow-Universität mit dem Abschluss 1962 und wurde 1965 am Lebedew-Institut promoviert (Aspirantur). 1975 habilitierte er sich dort (russischer Doktortitel). 1962 bis 1971 war er am Lebedew-Institut und 1971 bis 1991 war er leitender Wissenschaftler im Institut für Kernforschung (INR) der Russischen Akademie der Wissenschaften.

Er war 1979 bis 1992 im Rat für Neutrinophysik (Leitung Bruno Pontecorvo) der Russischen Akademie der Wissenschaften und 1989 bis 1992 im Rat für Teilchen und Kosmologie (Leitung Andrei Sacharow).

1992 bis 1997 war er von italienischer Seite Koordinator des European Network Astroparticle Physics. Ab 1995 leitete er die Astroteilchenphysik-Gruppe am INFN (Istituto Nazionale di Fisica Nucleare) im Laboratori Nazionali del Gran Sasso, wo er seit 1991 Forschungsdirektor war.

2010 erhielt er den Markow-Preis[3] insbesondere für die Entwicklung einer Theorie der Entstehung kosmischer Neutrinos sehr hoher Energien. 1991 erhielt er den Humboldt-Forschungspreis. Für 2017 wurde Beresinski der Premio Enrico Fermi zugesprochen.

Beresinski arbeitete überwiegend als Theoretiker.

1983 bis 1997 war er im Herausgeber-Gremium von Astronomy Letters und ab 1992 Herausgeber bei Astroparticle Physics.

Er war Mitglied des Istituto Veneto di Scienze, Lettere ed Arti.

Schriften [Bearbeiten | Quelltext bearbeiten]

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- mit S. V. Bulanov, V. A. Dogiel, V. L. Ginzburg, V. S. Ptuskin: *Astrophysics of cosmic rays*, Elsevier 1990
- *Ultrahigh energy neutrino astrophysics*, Nuclear Physics B, Proc. Suppl., 151 (2006) 260-269