San Vito di Cadore
September 2016

Espresso Acceleration of UHECRs (and more)

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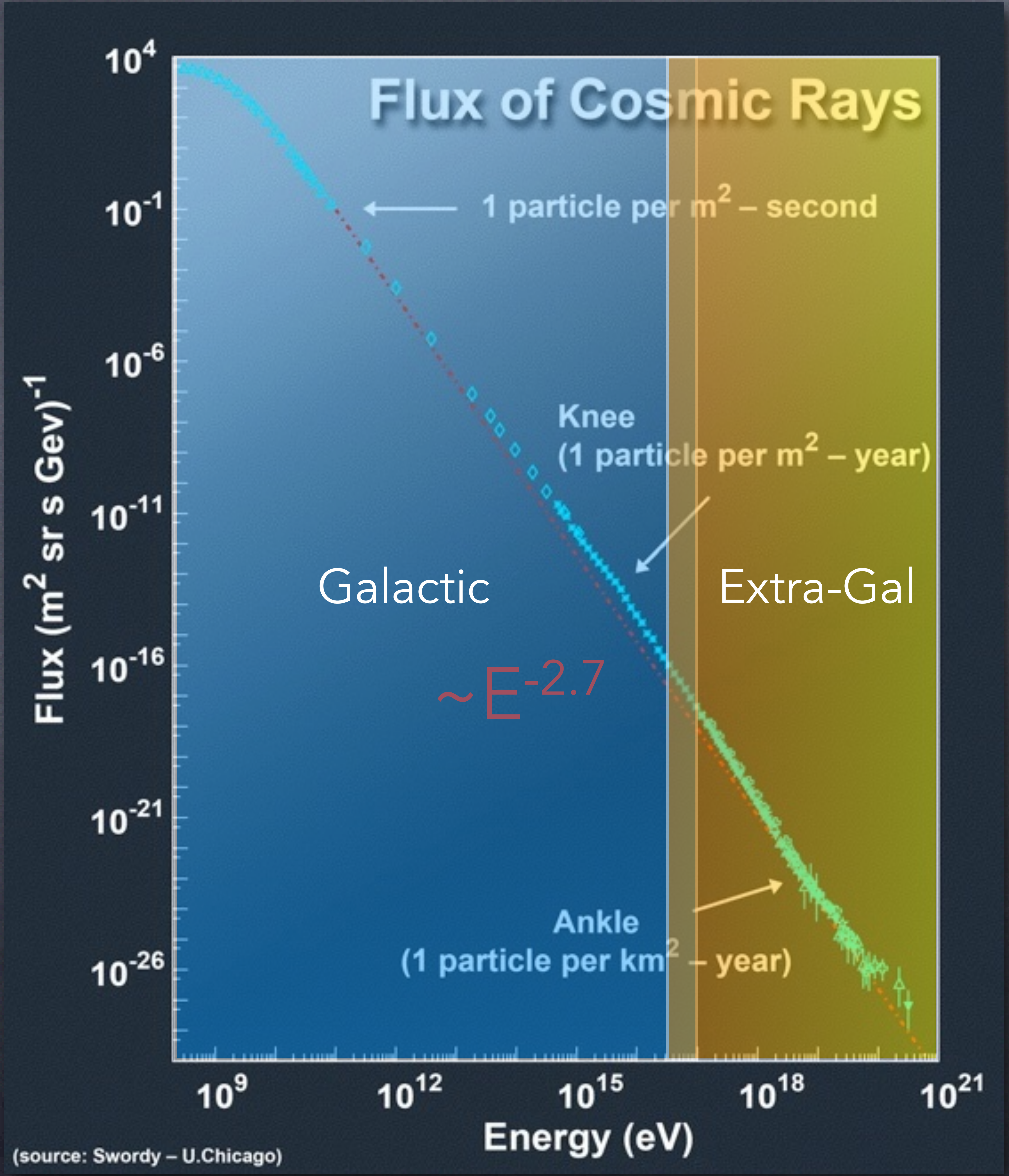
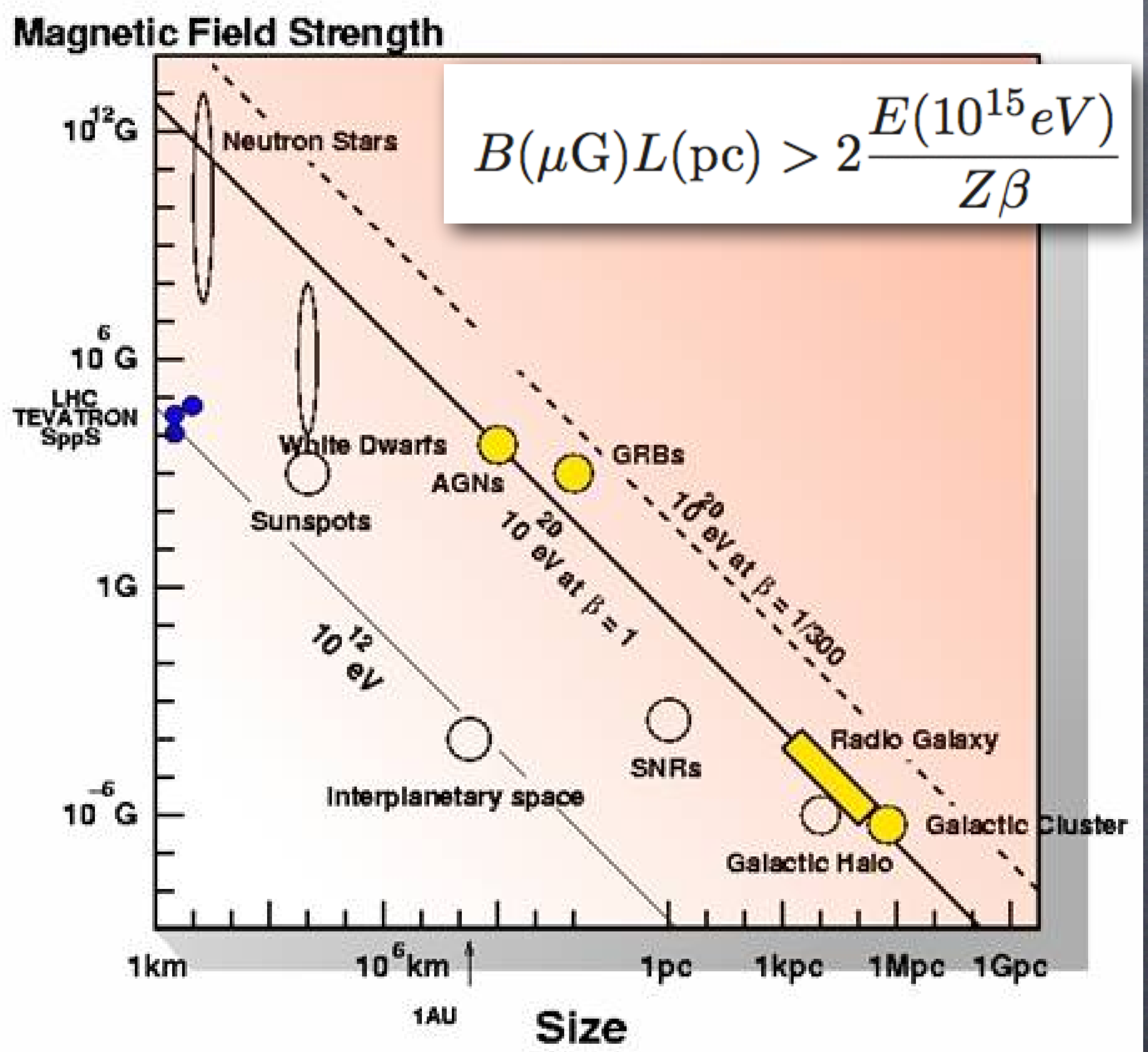
soon at the University of Chicago

Cosmic Rays

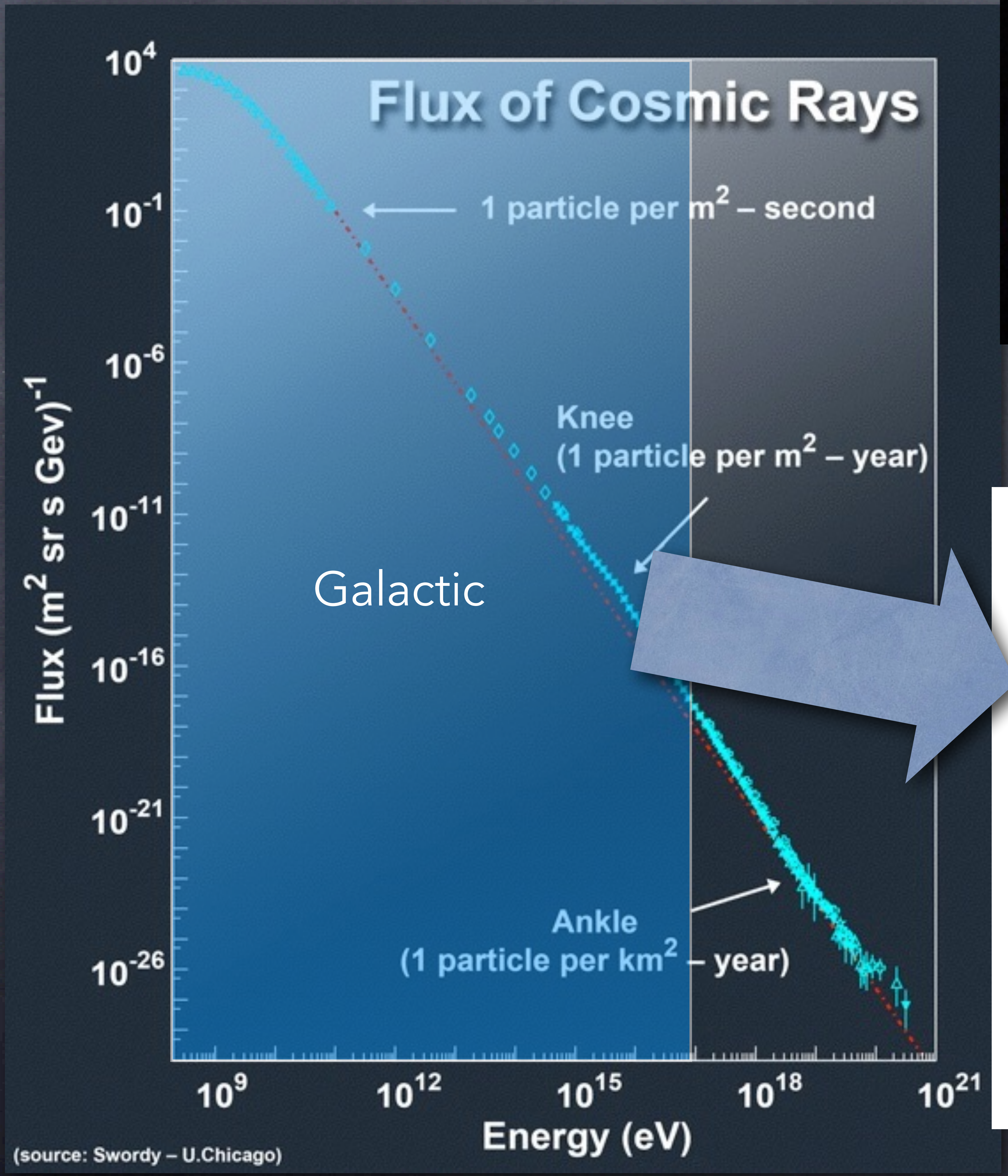




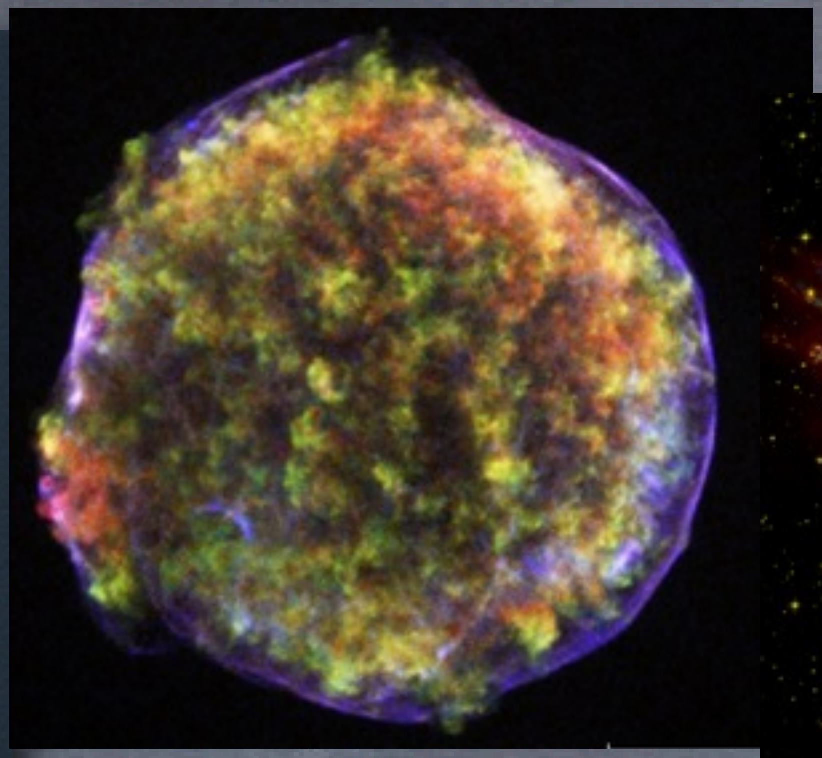
$$B(\mu\mathrm{G})L(\mathrm{pc}) > 2\frac{E(10^{15}eV)}{Z\beta}$$

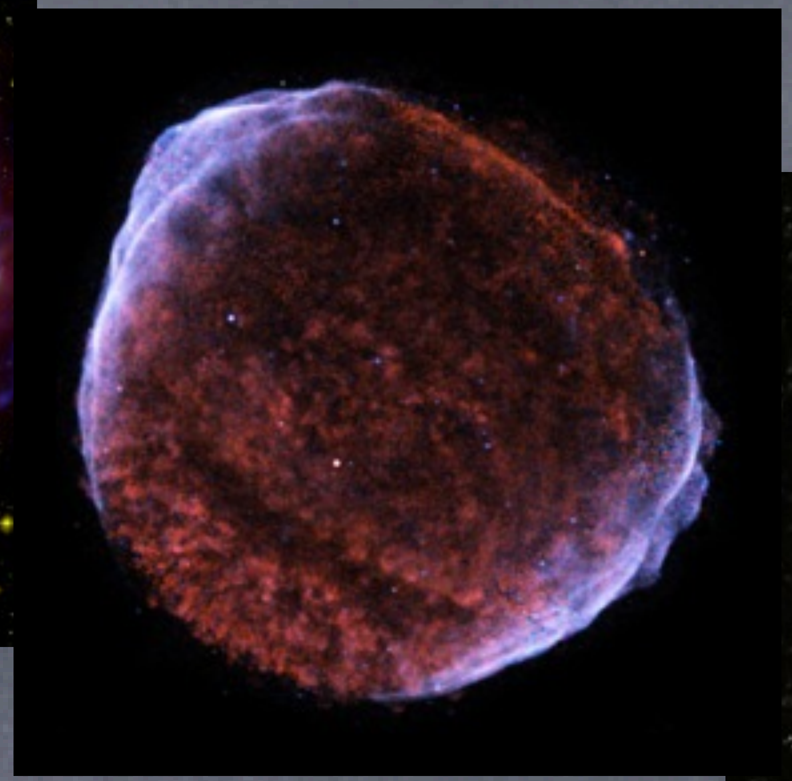
- Remarkable power-law (plus “leg” features)

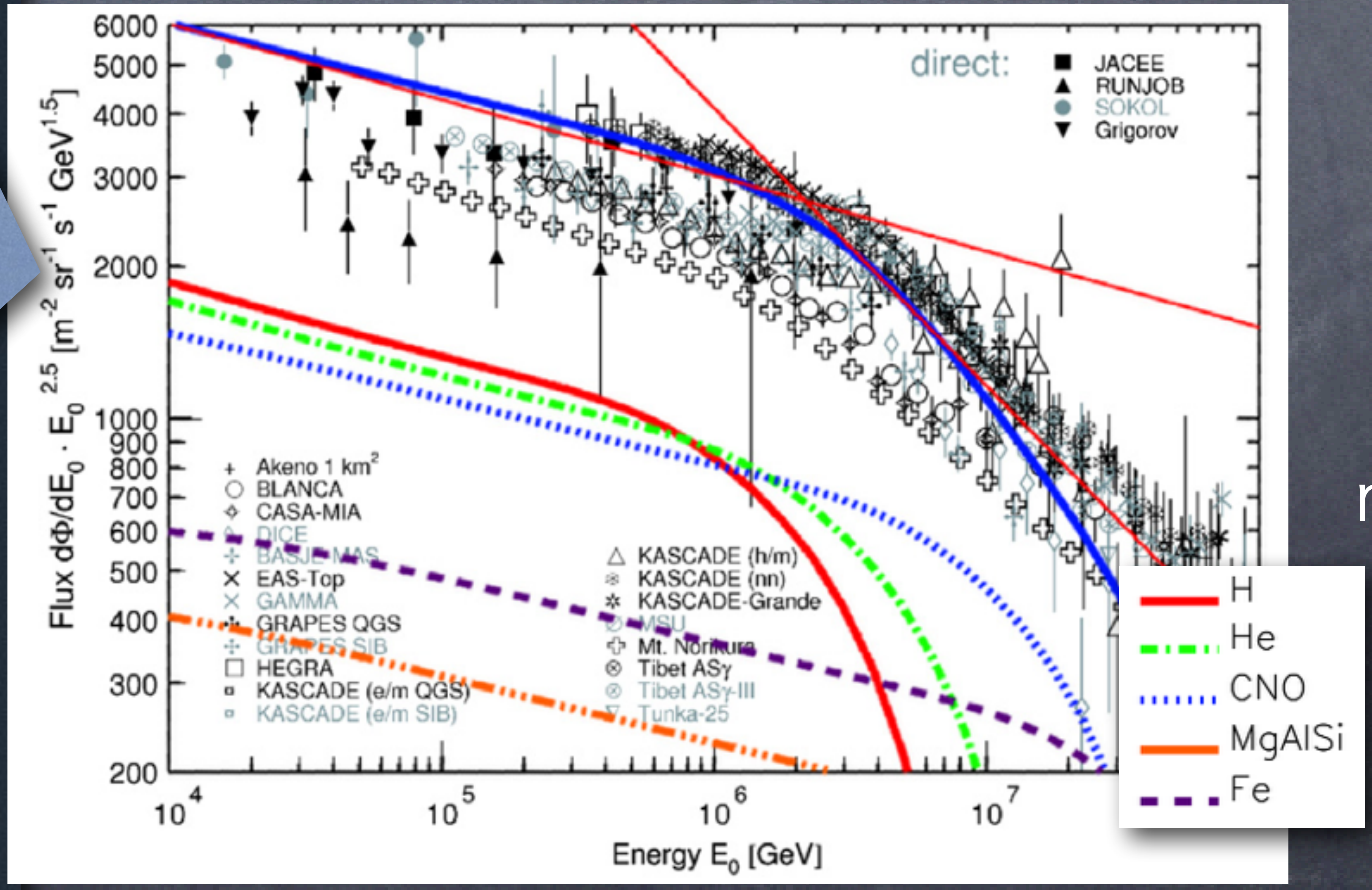
SNR Paradigm for Galactic Cosmic Rays



Galactic



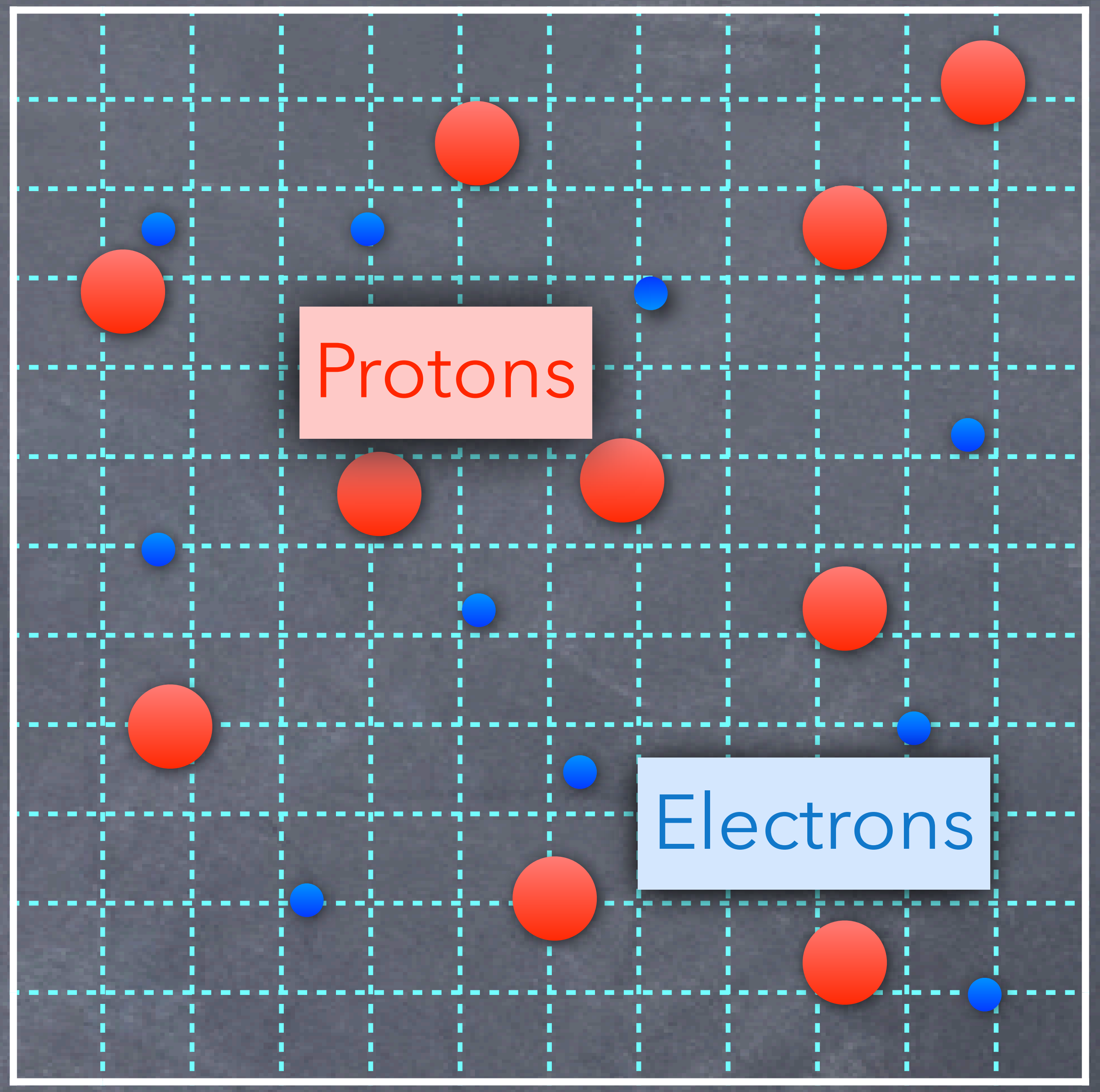


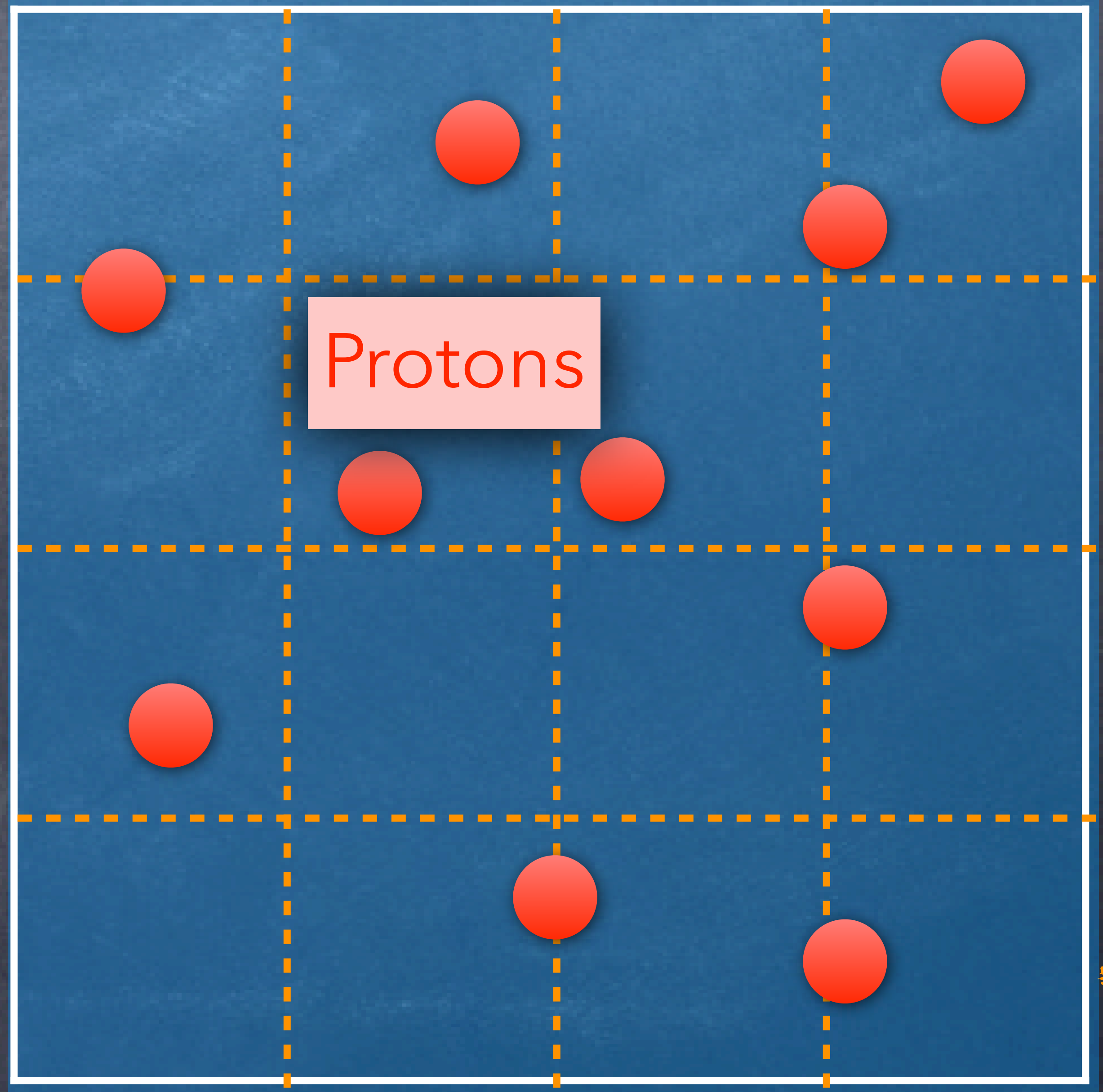
A rigidity-dependent acceleration mechanism up to the knee (a few 10^6 GV)

Astroplasmas from first principles

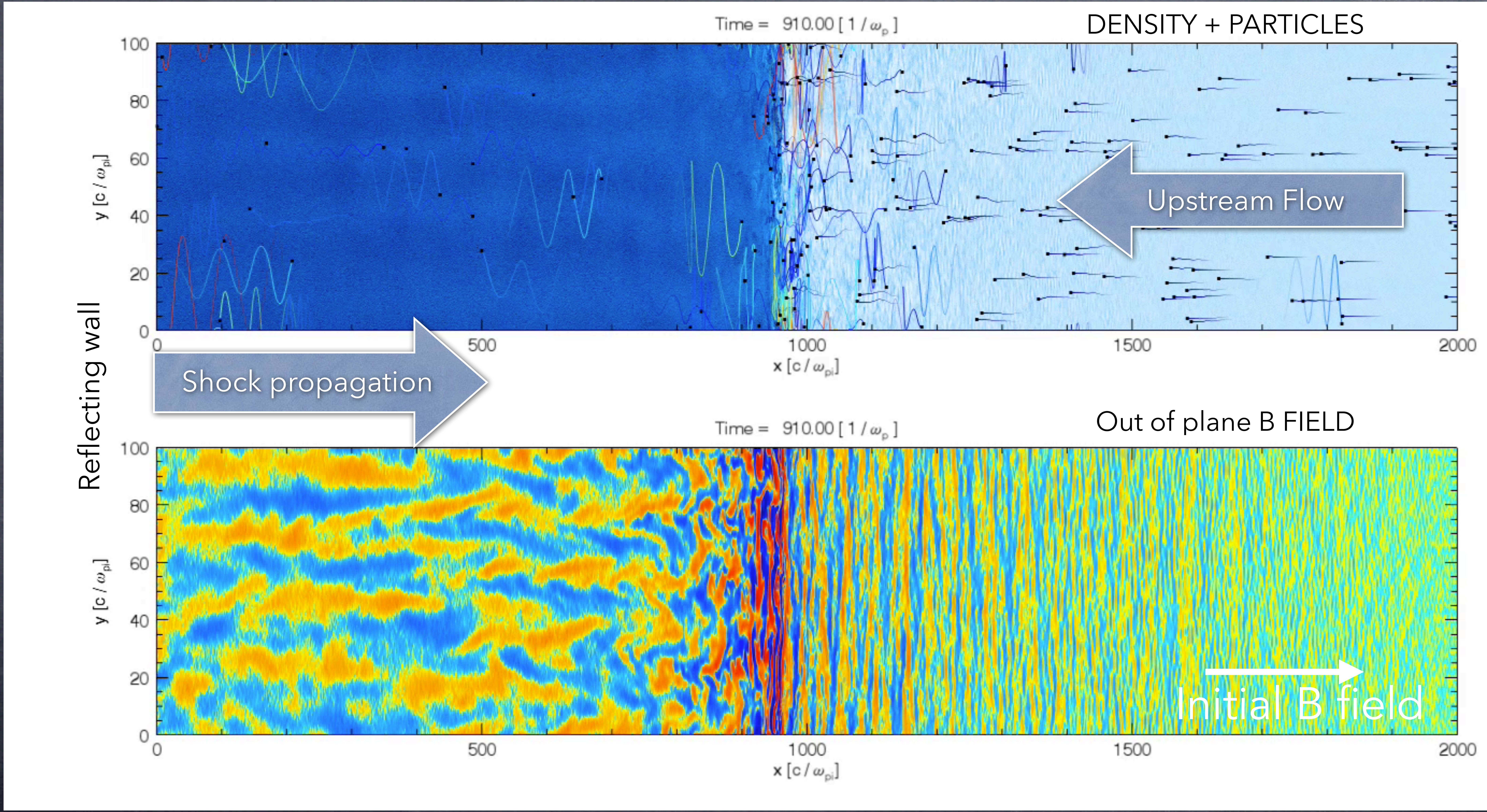
- Full particle in cell approach
  (…, Spitkovsky 2008; Amano & Hoshino 2007, 2010; Niemiec et al. 2008, 2012; Stroman et al. 2009; Riquelme & Spitkovsky 2010; Park et al. 2012; Guo et al. 2014; DC et al. 2015…)
  - Put particles and electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



- Hybrid approach: Fluid electrons - Kinetic protons
  (Winske & Omidi; Burgess et al., Lipatov 2002; Giacalone et al. 1993,1997,2004-2013; DC & Spitkovsky 2013-2015,…)
  - massless electrons for more macroscopical time/length scales



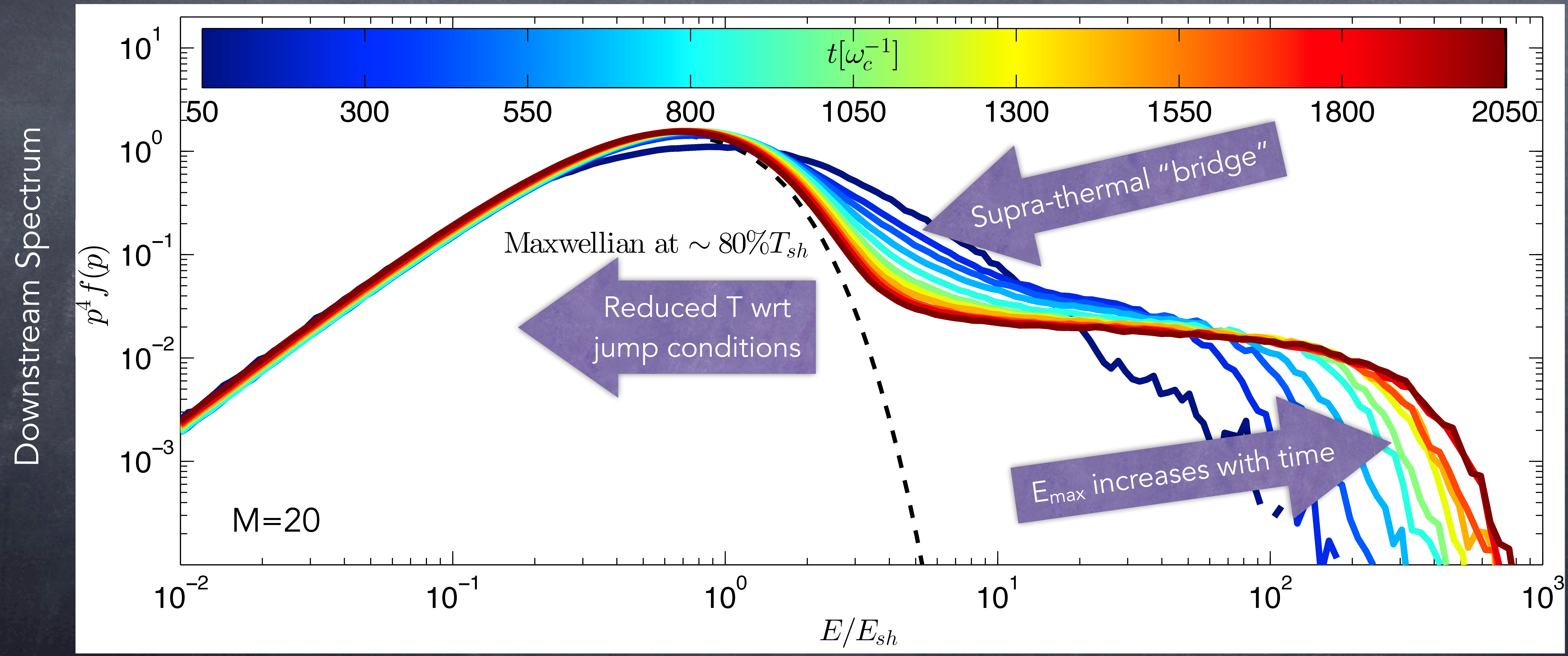
Hybrid simulations of collisionless shocks



dHybrid code (Gargaté et al, 2007; DC & Spitkovsky 2014)

Spectrum evolution

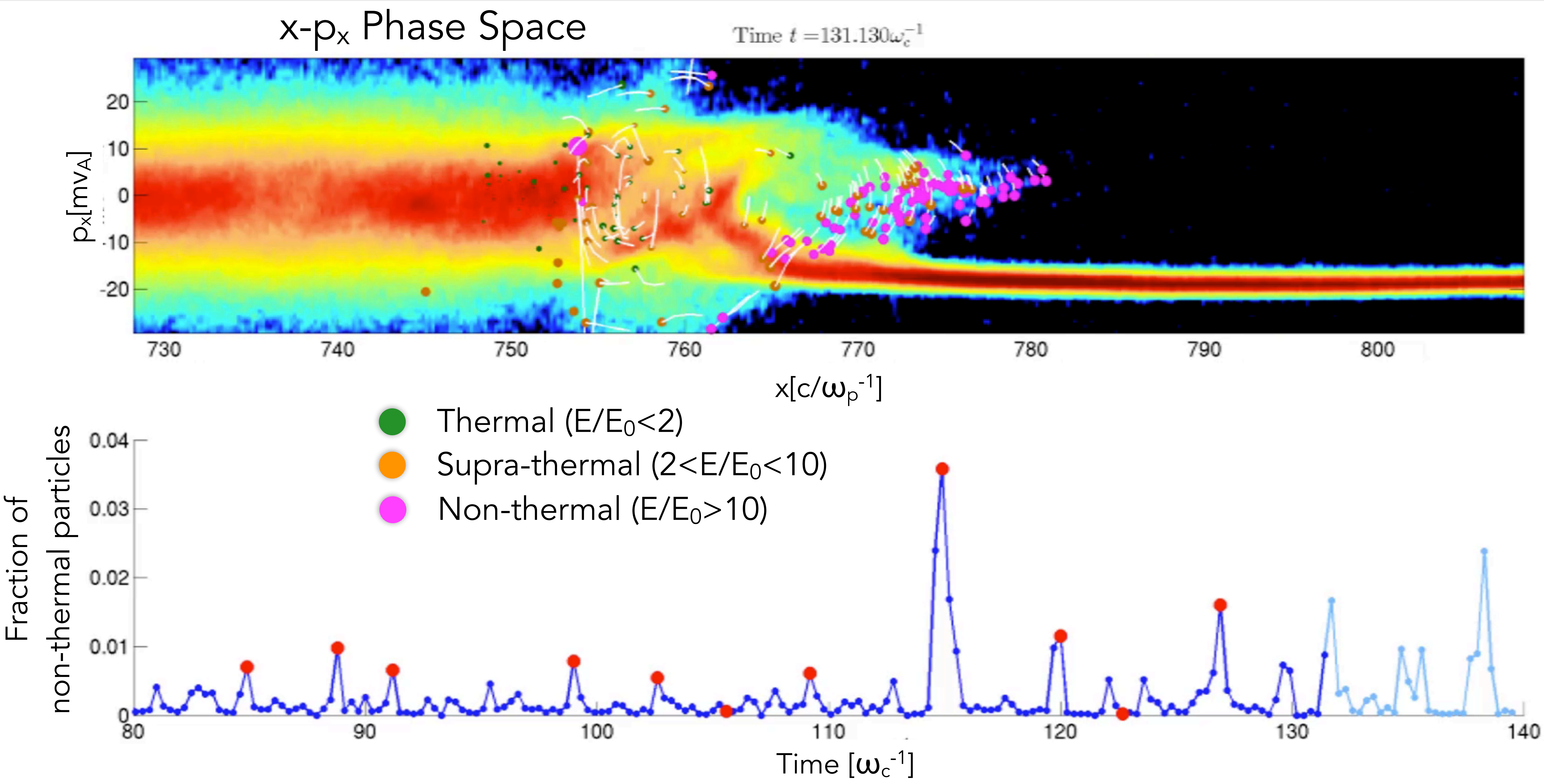
- Diffusive Shock Acceleration: non-thermal tail with universal spectrum $f(p) \propto p^{-4}$
- Acceleration efficiency: ~15% of the shock bulk energy!



DC & Spitkovsky, 2014a

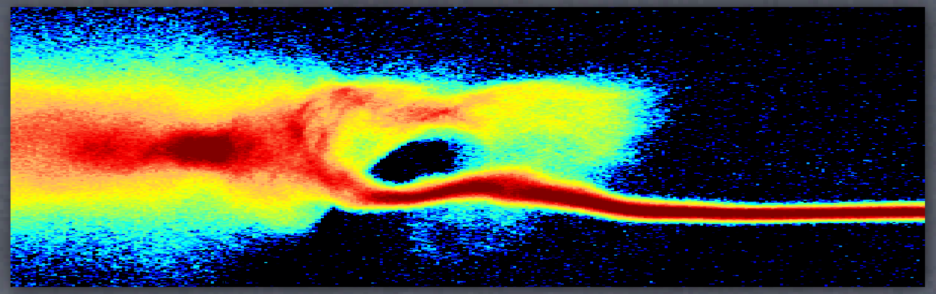
Particle Injection - Simulations

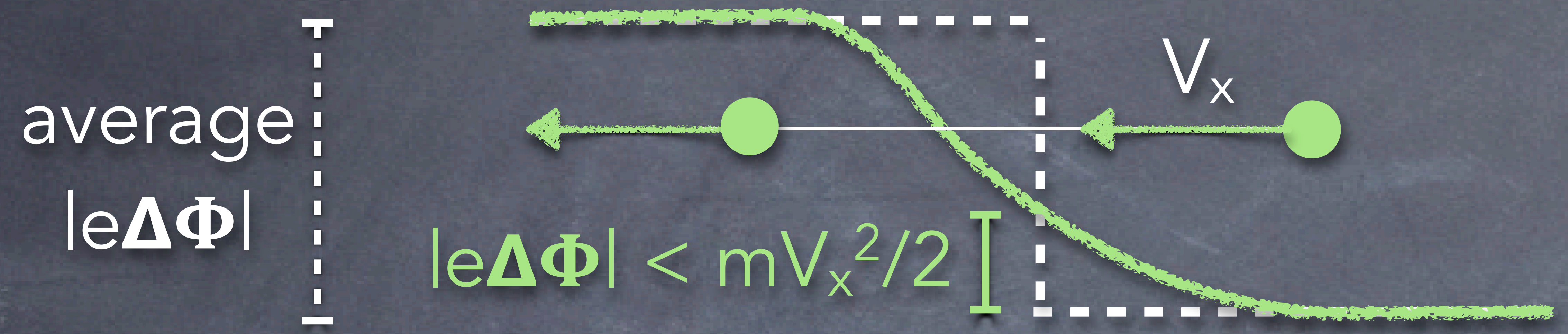
DC, Pop & Spitkovsky, 2015



Encounter with the shock barrier

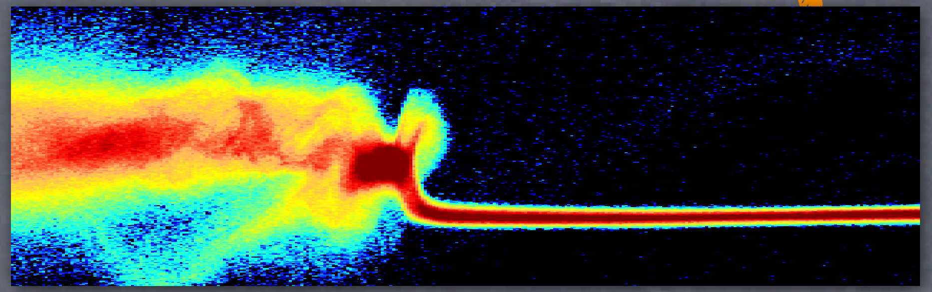
- Low barrier (reformation)

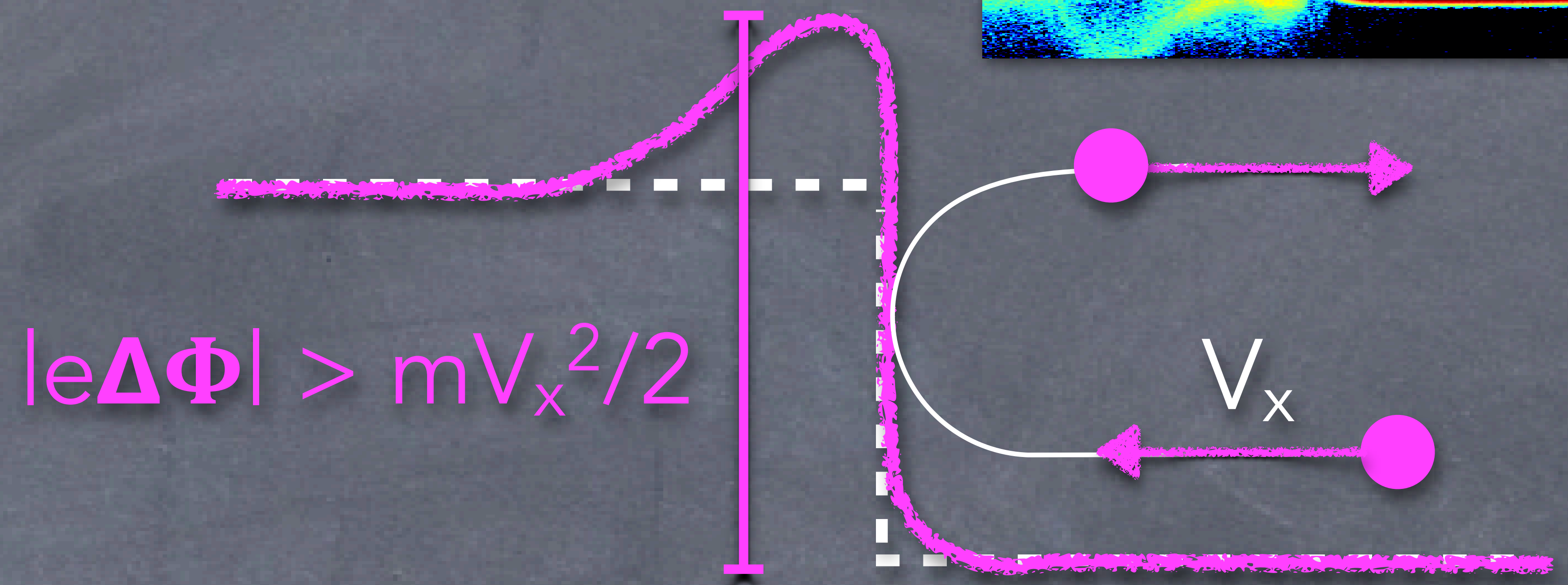




Ions advected downstream, and thermalized

- High barrier (overshoot)





Ions reflected upstream, and energized via Shock Drift Acceleration

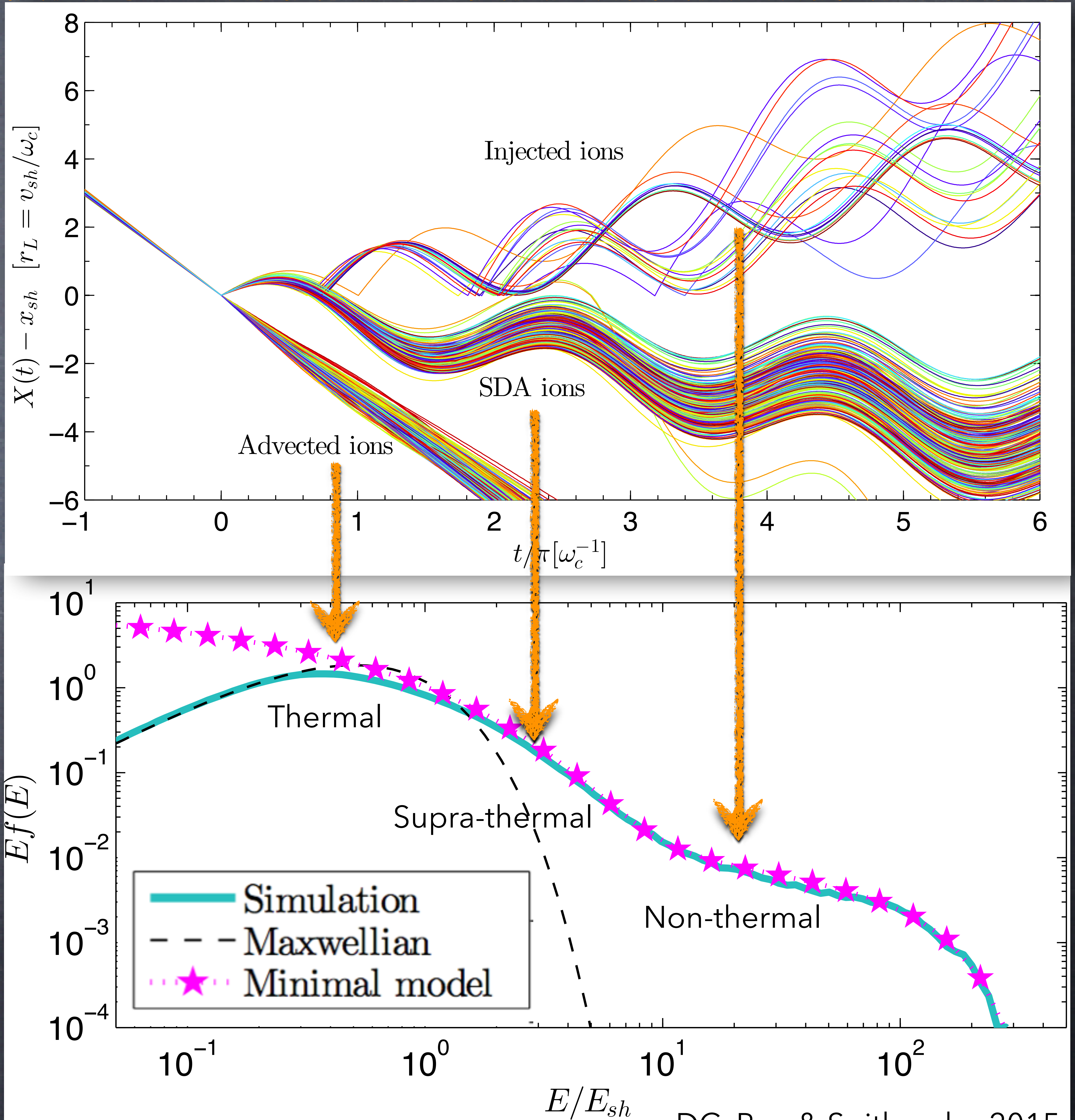
- To overrun the shock, ions need a minimum E_{inj}, increasing with ϑ (DC, Pop & Spitkovsky 15)
  - Ion fate determined by barrier duty cycle (~25%) and shock inclination
- After N SDA cycles, only a fraction $\eta \sim 0.25^N$ has not been advected
  - For $\vartheta=45^\circ$, $E_{inj} \sim 10E_0$, which requires N~3 -> $\eta \sim 1\%$

Minimal Model for Ion Injection

- Time-varying potential barrier
  - **High state** (duty cycle ~25%)
    - Reflection + SDA
  - **Low-state** (~75%)
    - Thermalization
- Spectrum à la Bell (1978)

$$f(E) \propto E^{-1-\gamma}; \quad \gamma \equiv -\frac{\ln(1-\mathcal{P})}{\ln(1+\mathcal{E})}$$

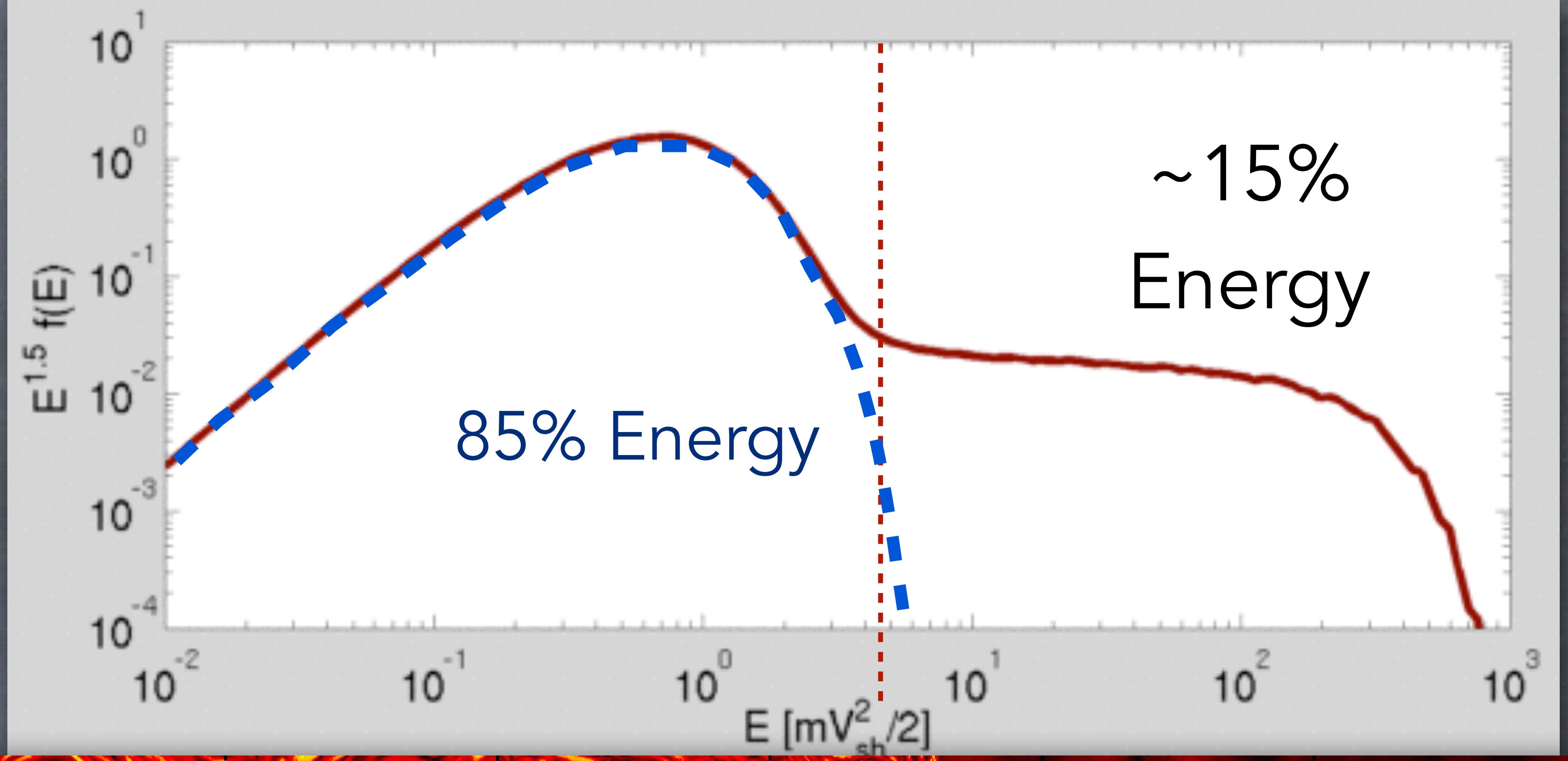
- P=probability of being advected
- ε=fractional energy gain/cycle

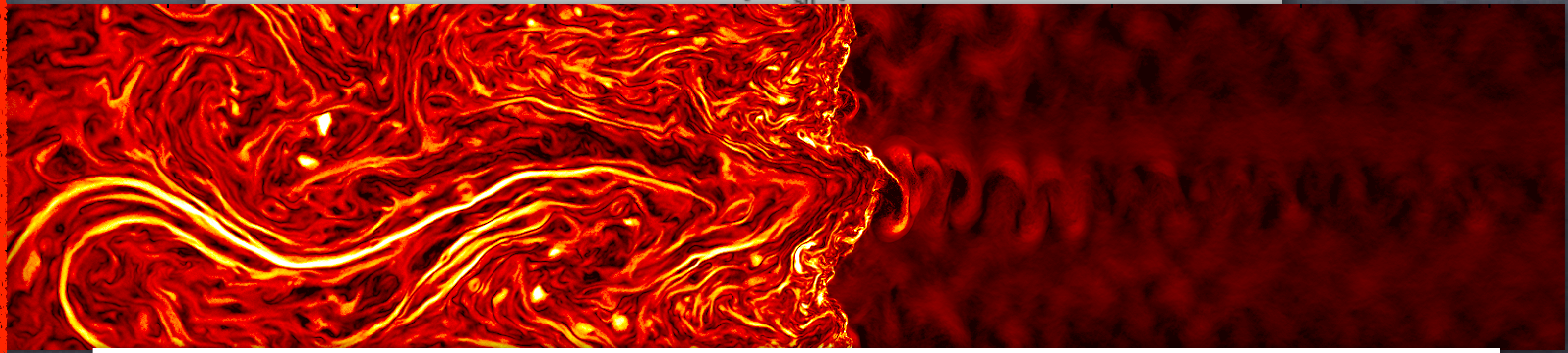


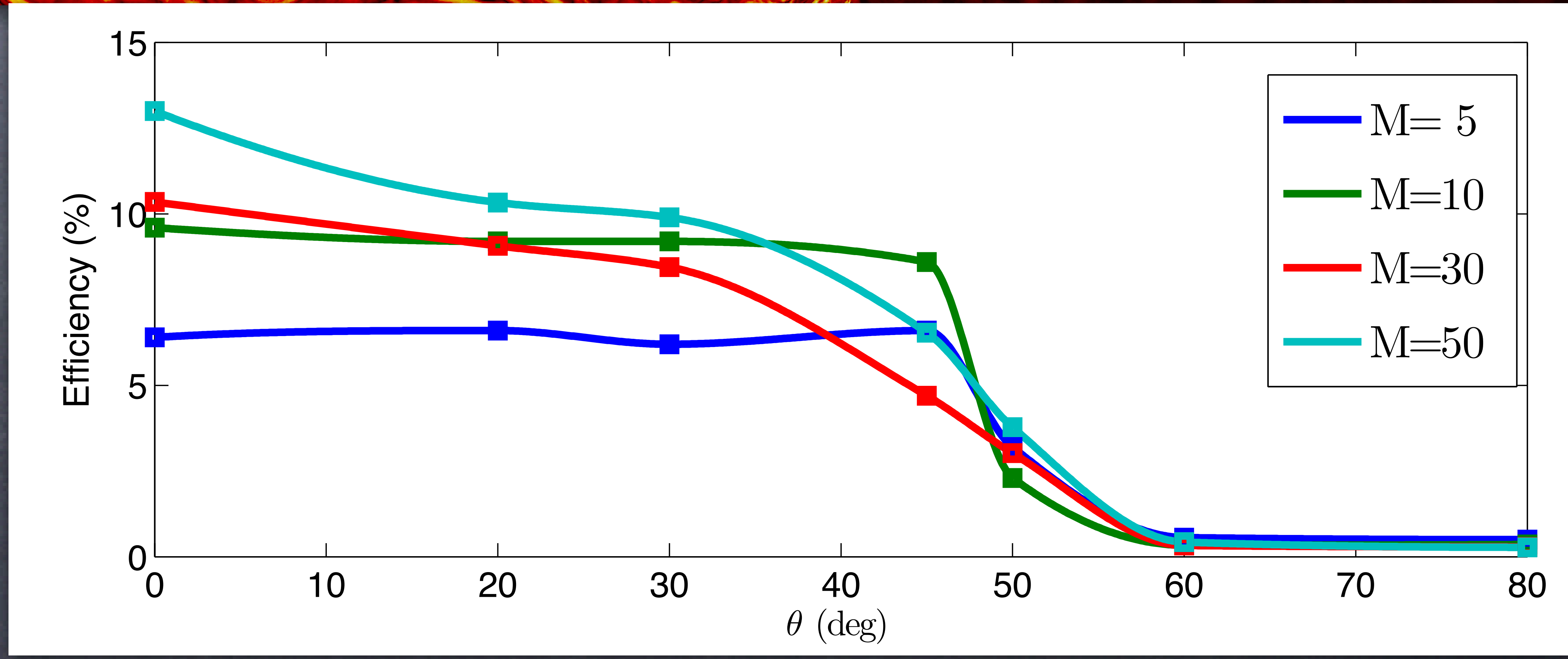
DC, Pop & Spitkovsky, 2015

Hybrid Simulations: Summary

- Shock Acceleration can be efficient
- CRs amplify B via streaming instability
- DSA efficient at parallel, strong shocks (DC & Spitkovsky 2014a,b,c)
- Injection via specular reflection and shock-drift acceleration (DC et al. 2015)







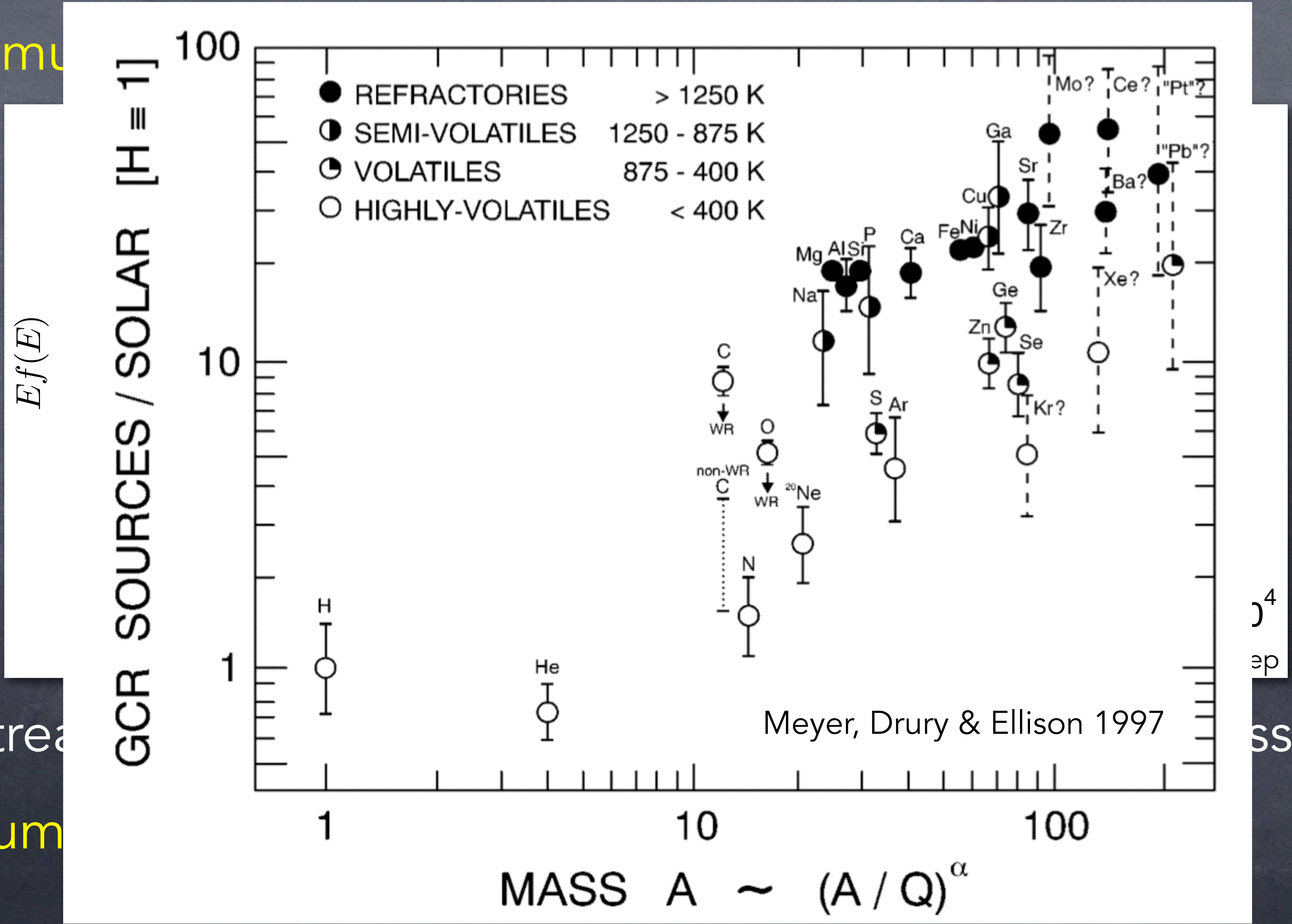
- What about electrons? (Park et al. 2015)
- Toward space/astrophysical scales (Bai et al. 2015)

PART I
(The one you should trust)


Acceleration of Nuclei
Heavier than Hydrogen

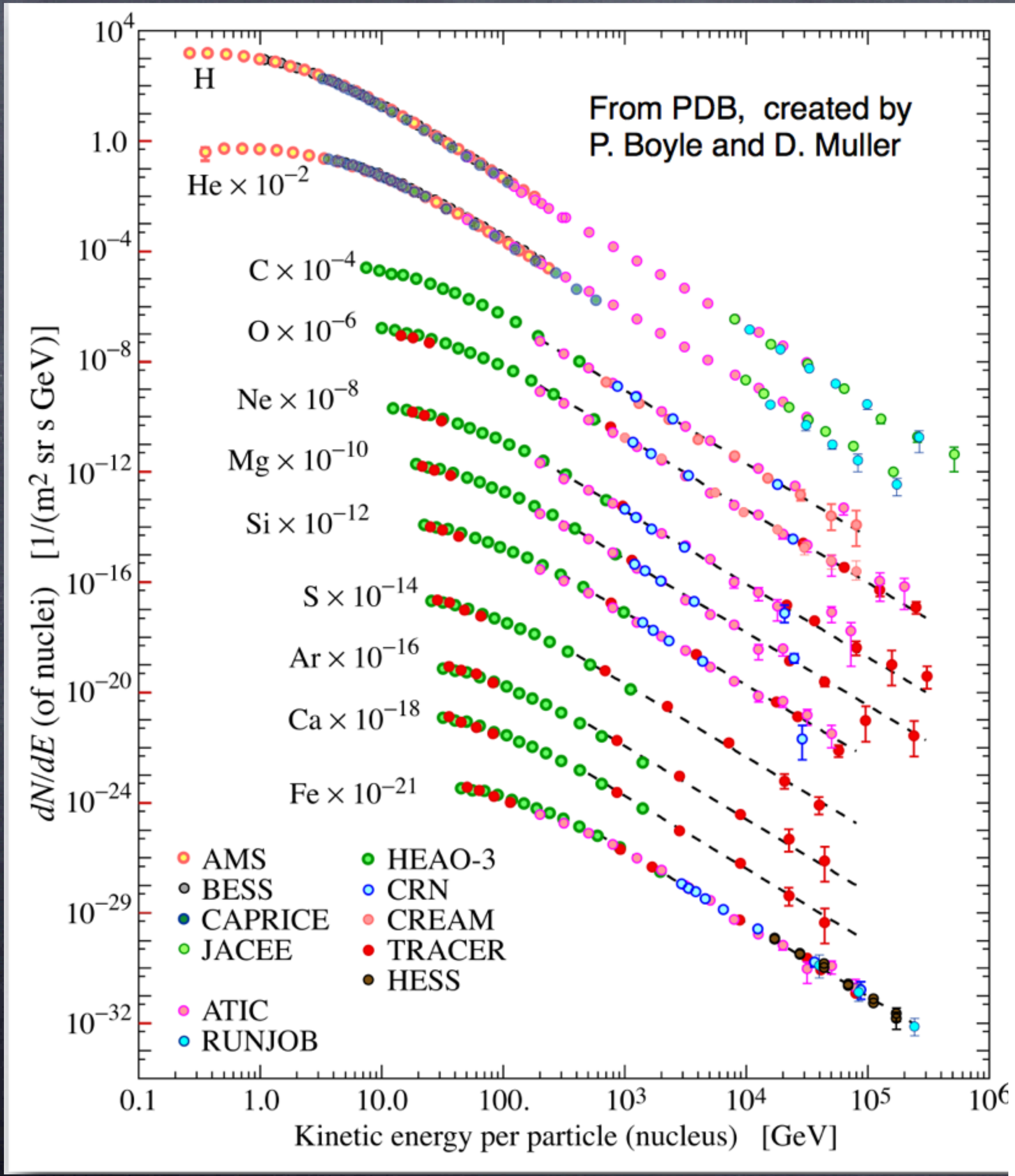
Acceleration of Heavy Nuclei

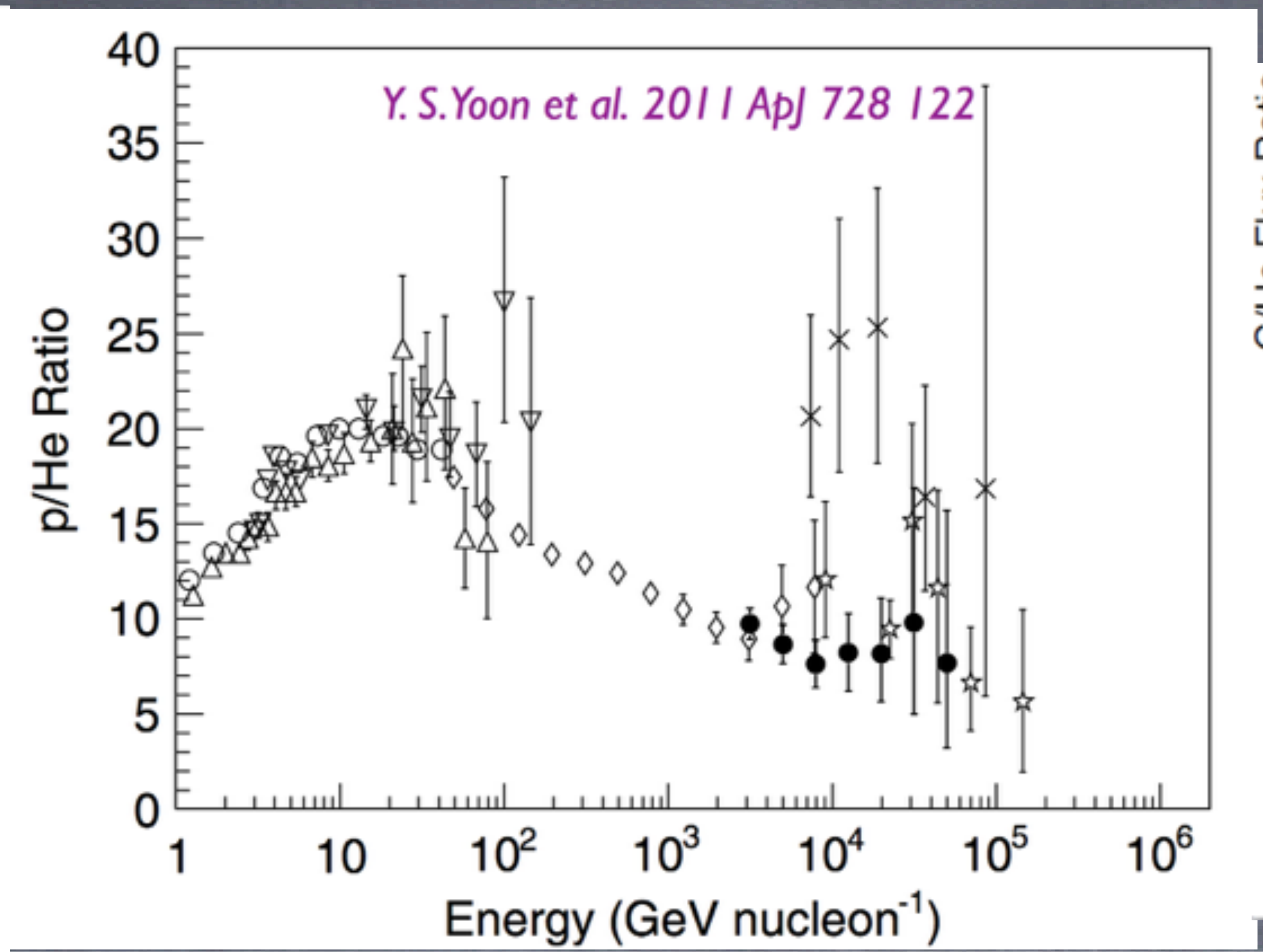
- Nuclei heavier than H must be injected more efficiently (Meyer, Drury & Ellison 1997a,b)
- Studied via mu

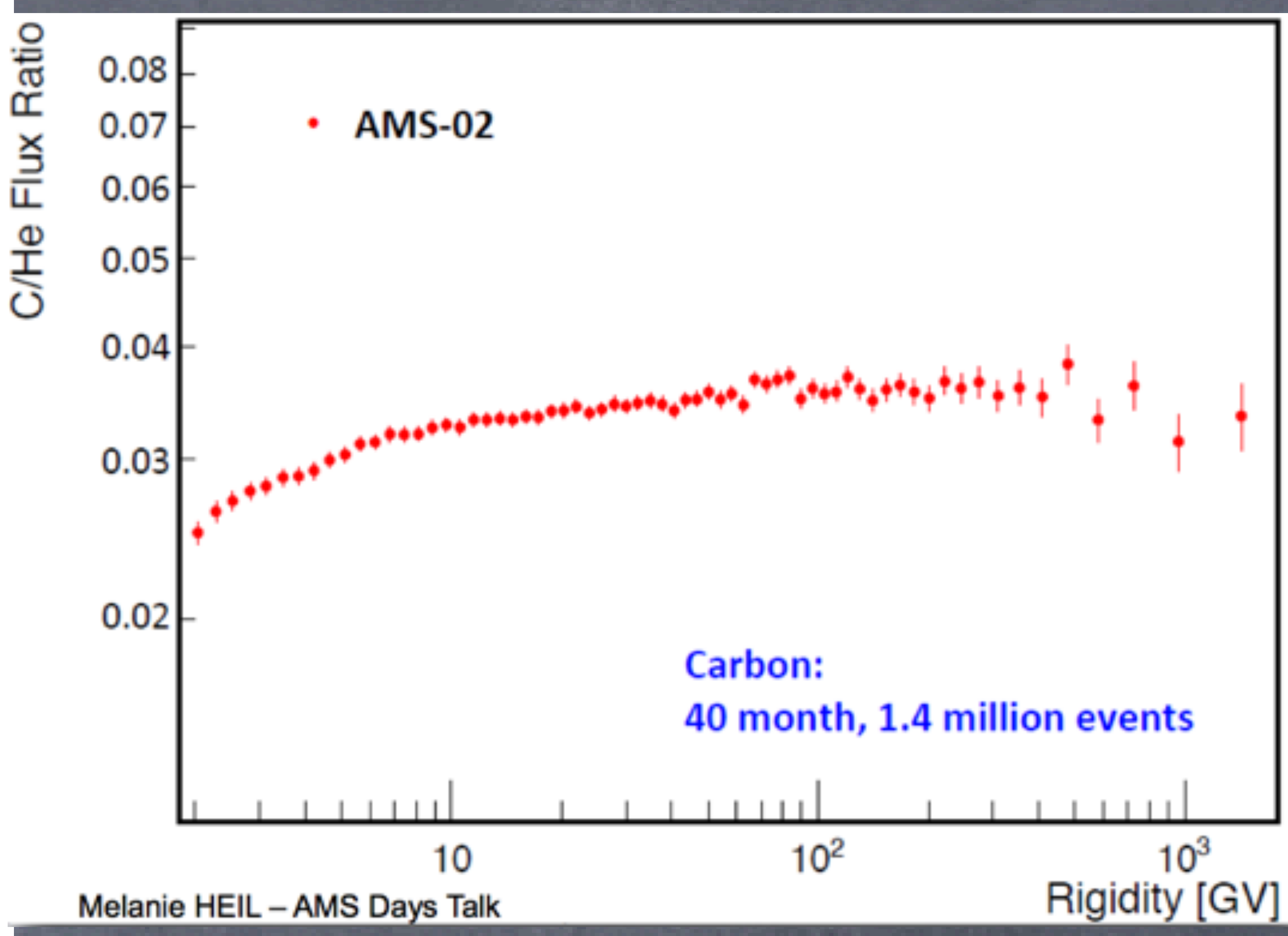


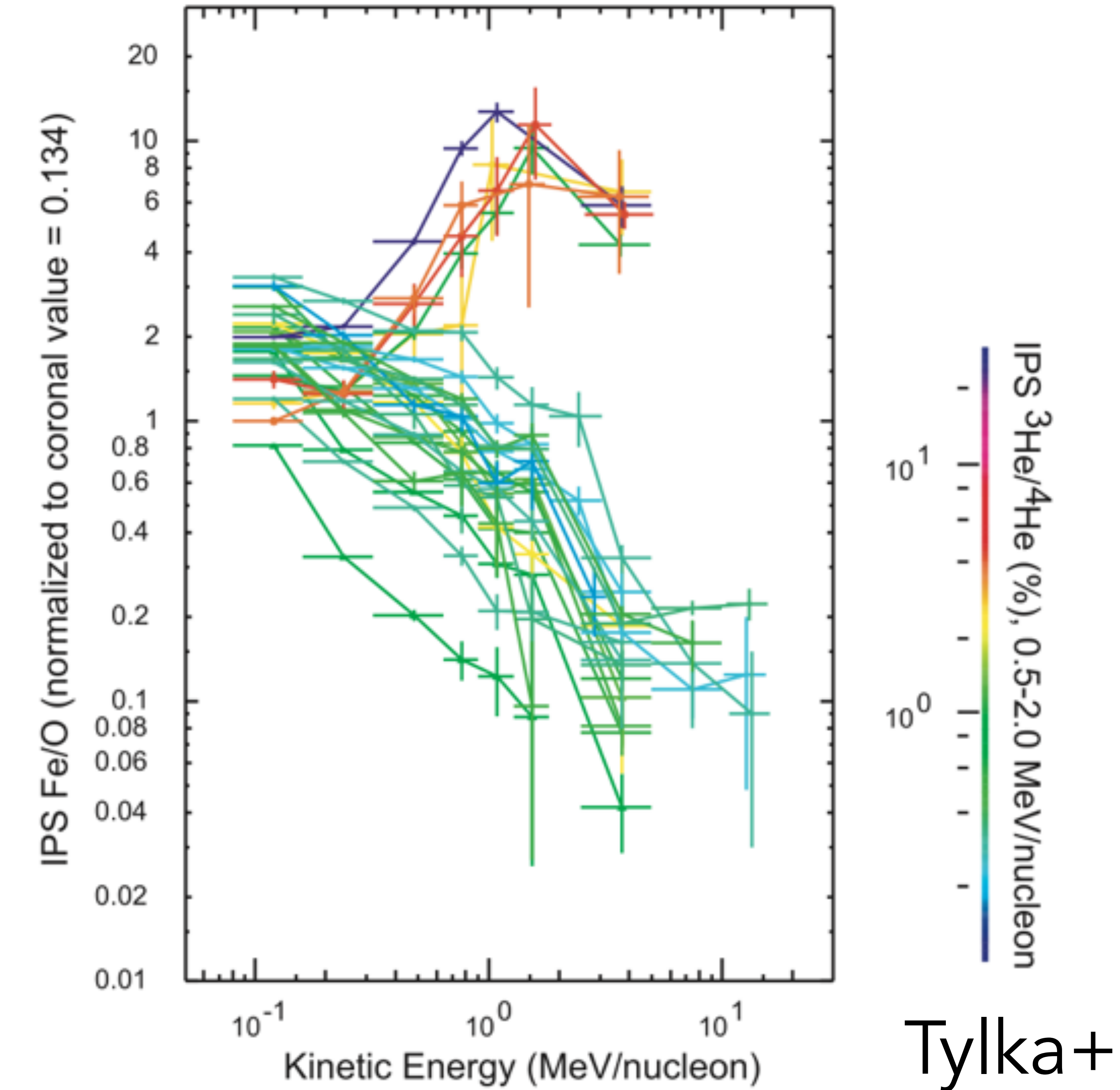
- The downstrea ss A (Kropotina+16)
- The maximum

Anomalous Abundances in CRs and SEPs

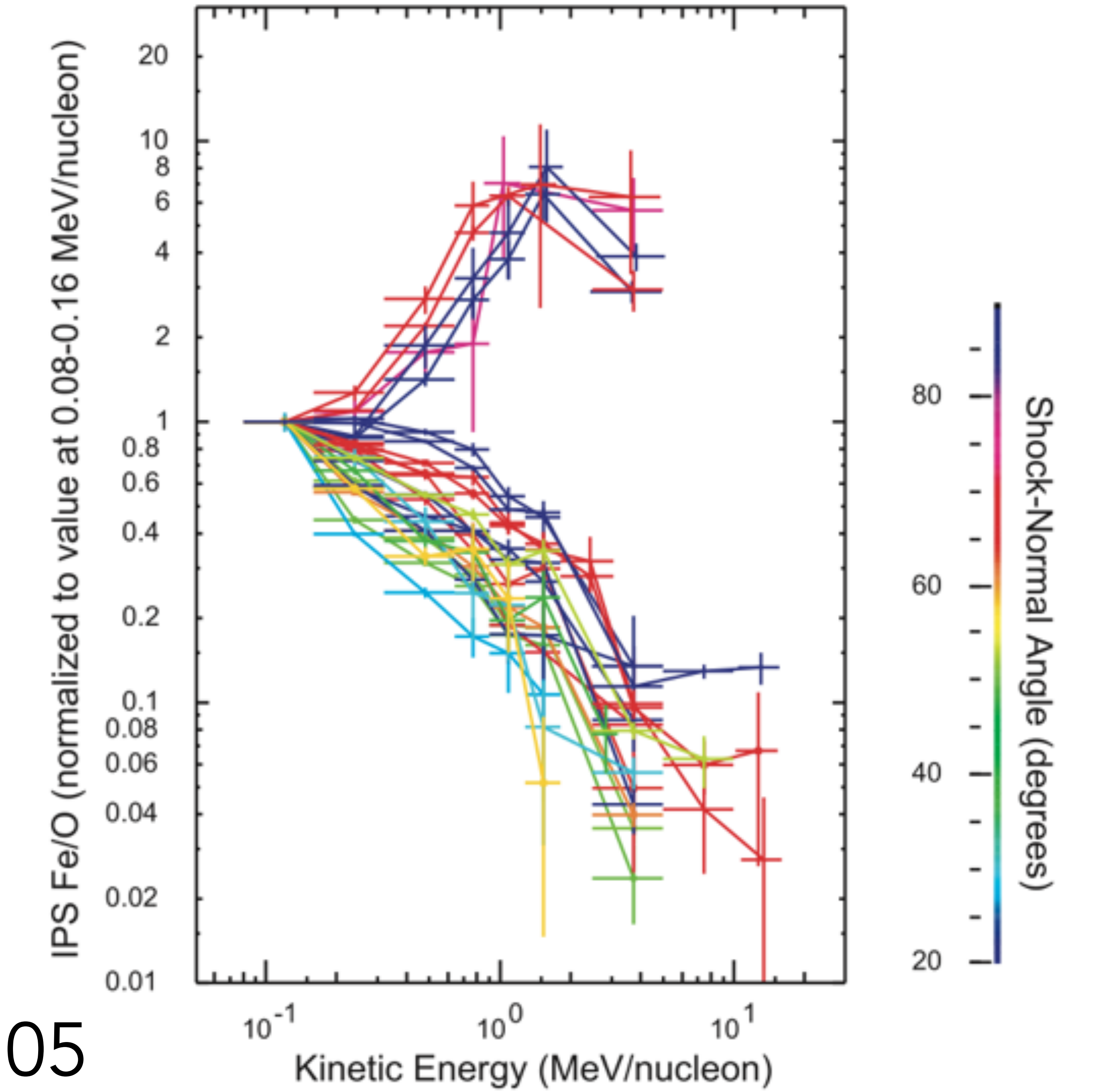






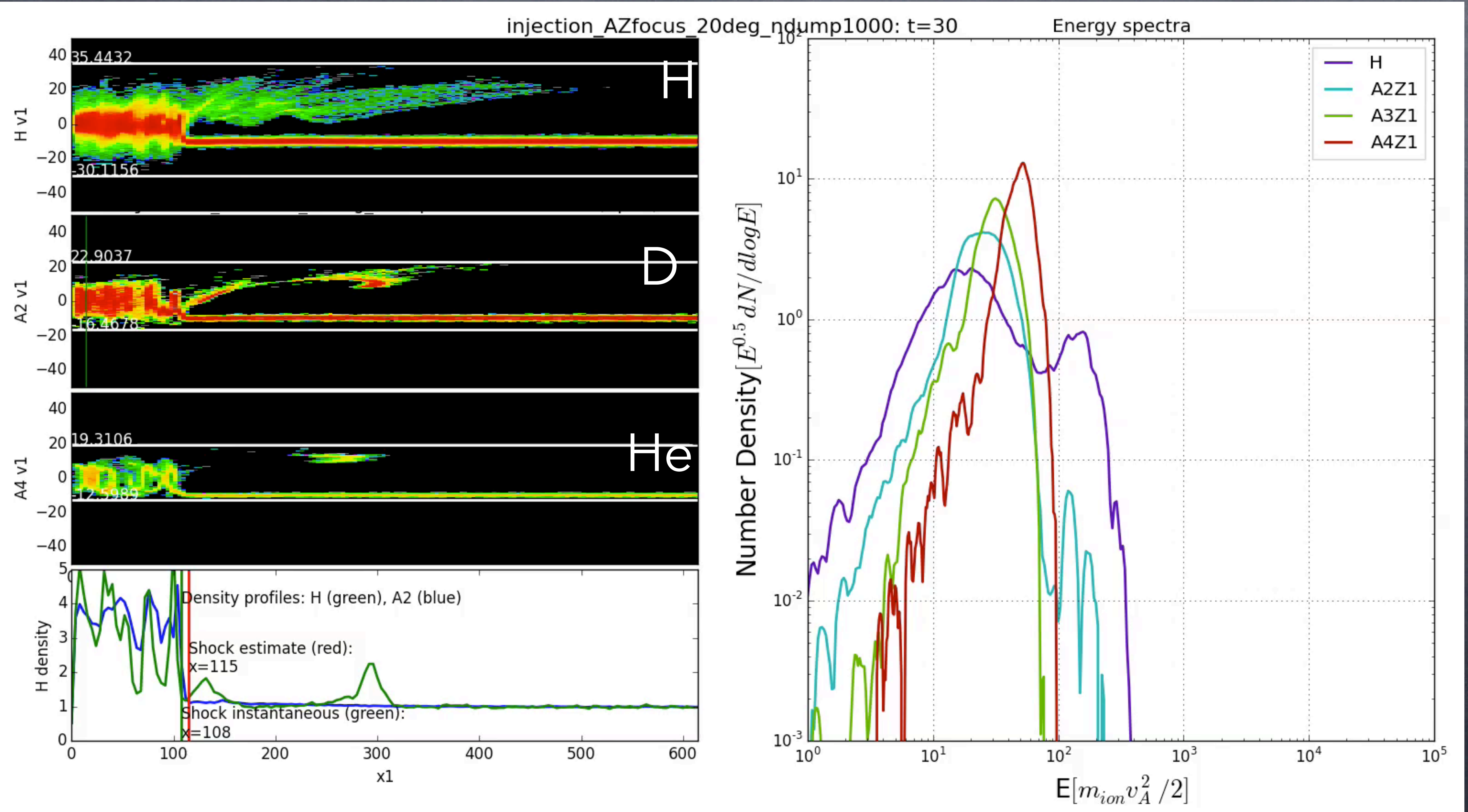


Tylka+05



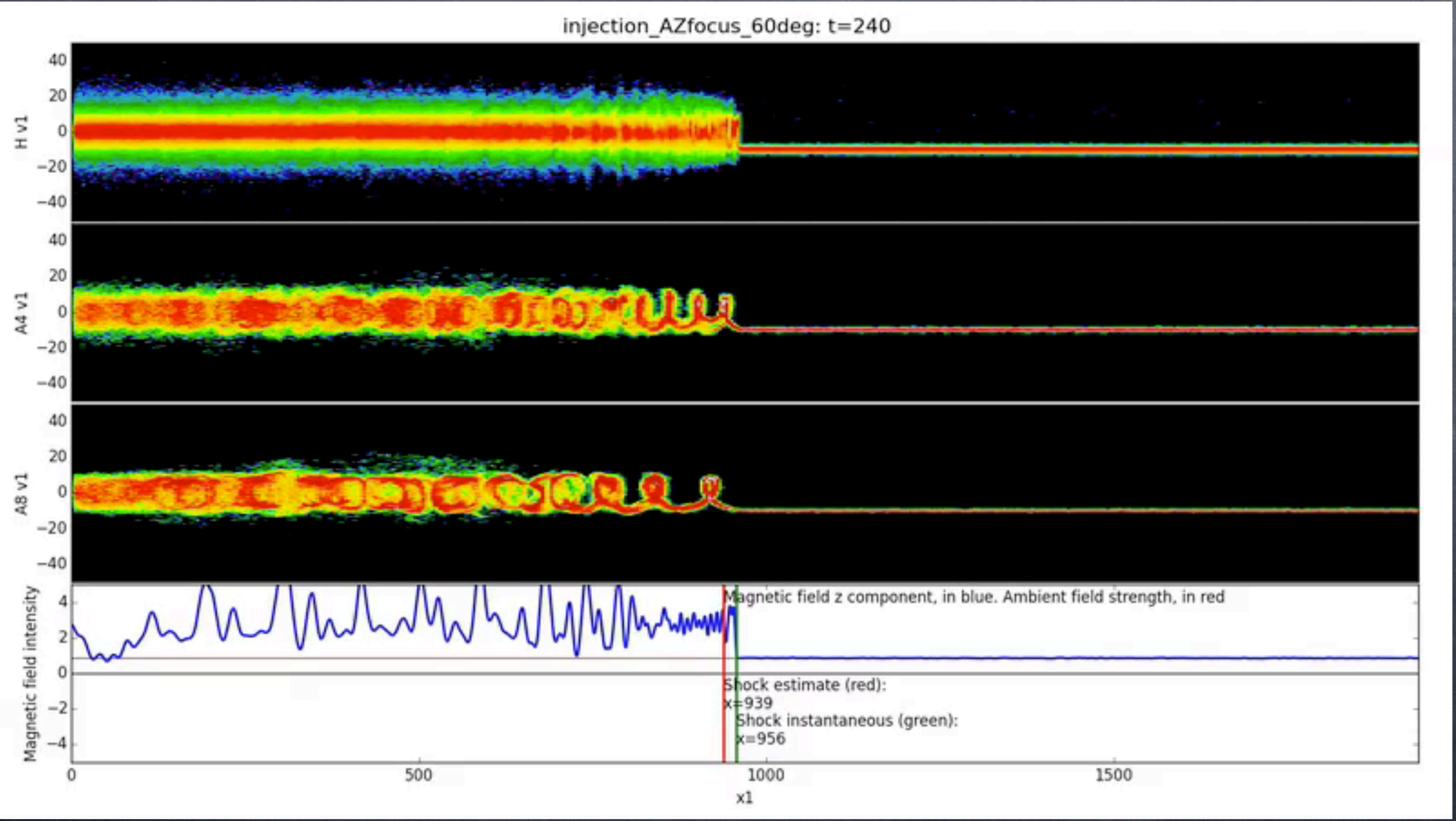
Hybrid Simulations

- M=10, parallel shock, with singly-ionized nuclei (DC, Li, Spitkovsky, ~submitted)



Not Always!

- M=10, oblique (ϑ=60°) shock, (DC, Li, Spitkovsky, ~subm.)



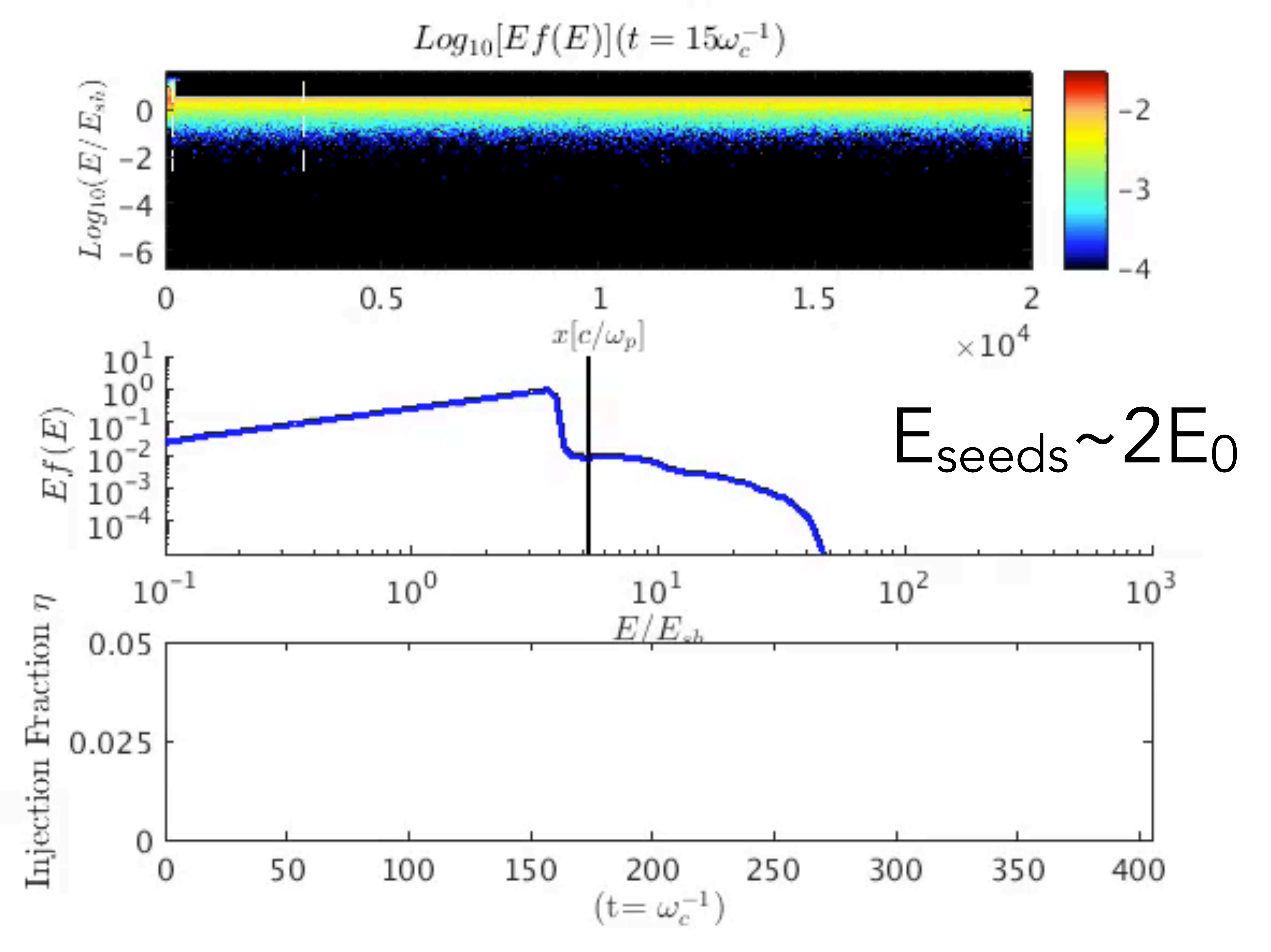
Nuclei Injection

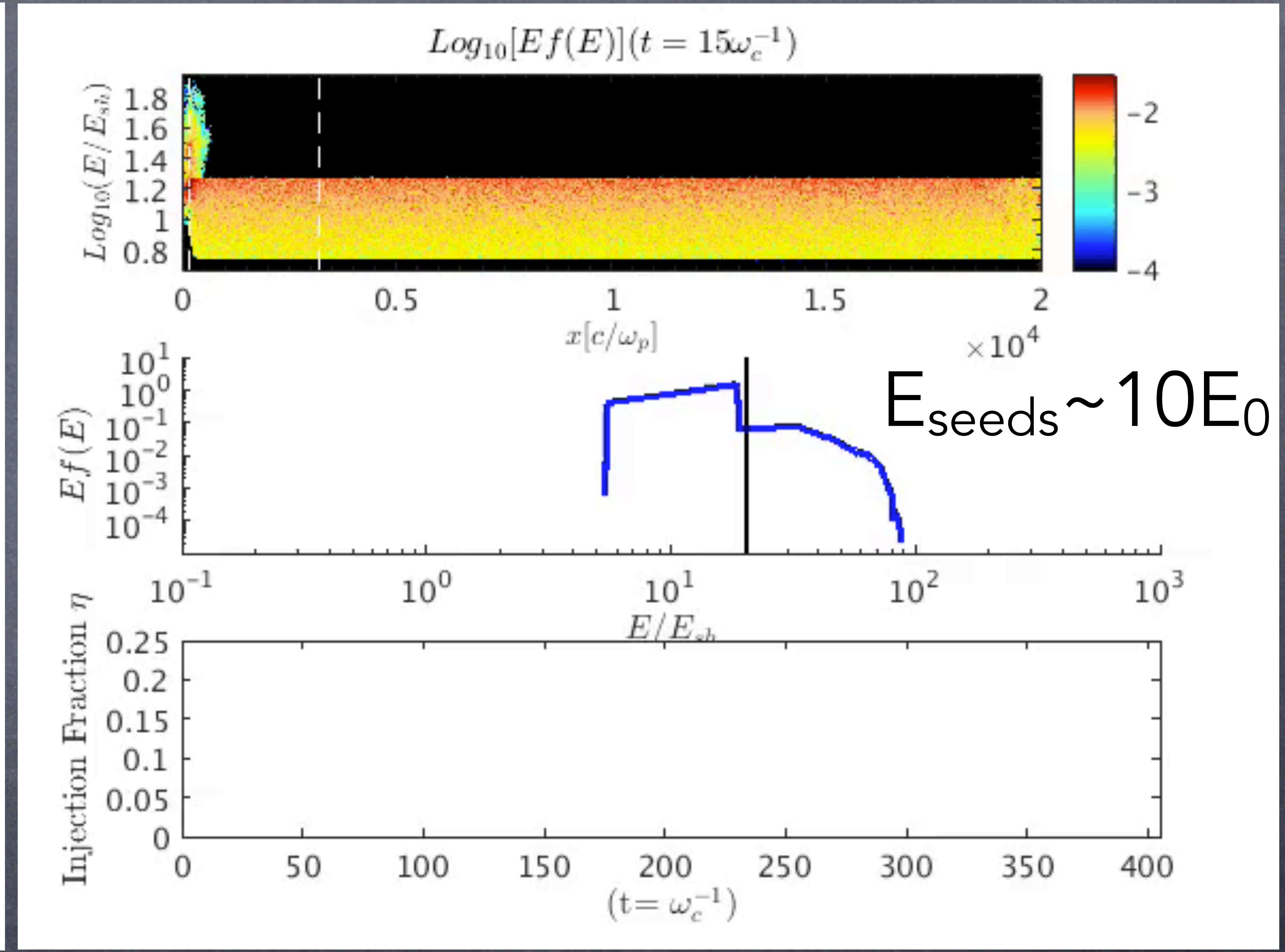
- In the absence of H-driven turbulence, heavies are thermalized far downstream
  - Early times at parallel shocks
  - Oblique shocks
- When B amplification is effective, heavies are heated up very quickly and can recross the shock because of their large gyroradii (~thermal leakage).
- Nuclei enhancement depends on A/Z and on the shock Mach number
- Peculiar ^{3}He/ ^{4}He and Fe/C enhancements in solar energetic particles
  - Correlations with shock inclination (Tylka & Lee 06; Reames 12; …)
  - Role of suprathermal ions pre-accelerated in solar flares (e.g., Tylka+05)

Pre-existing Energetic Particles

Energetic Particle Seeds

- Oblique shock with pre-existing energetic particles (DC, Zhang, Spitkovsky, in prep.)





- Seeds can be reaccelerated! The more energetic the better…

More on Reacceleration

- Maximum injection fraction ~25%
- Naturally comes from seeds retaining their anisotropy in the shock frame!

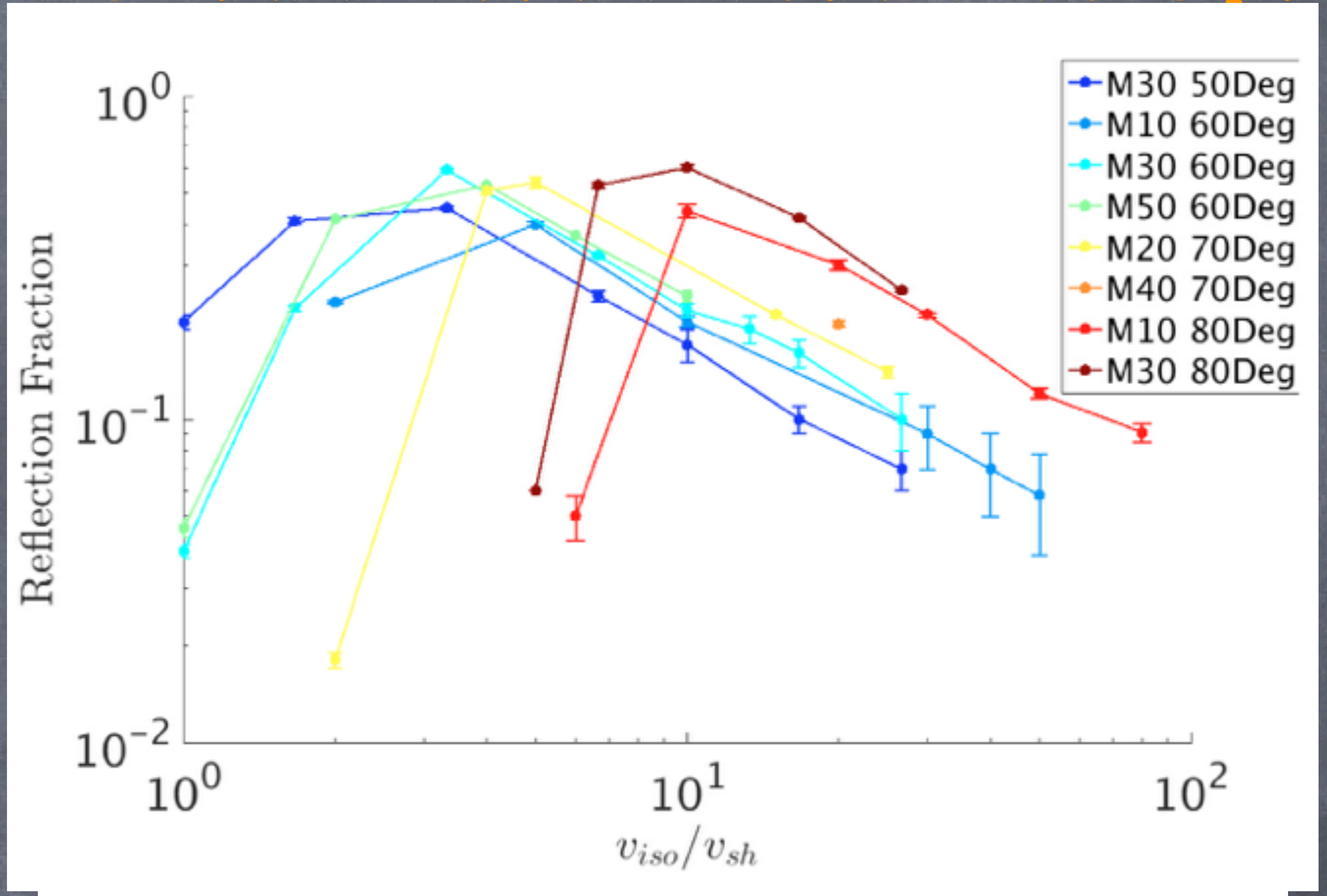
$J_{in}+J_{ref} = J_{out}$ $J_{in}=n_{CR}v_{sh}=J_{out}$ $\Rightarrow J_{ref} = 0$

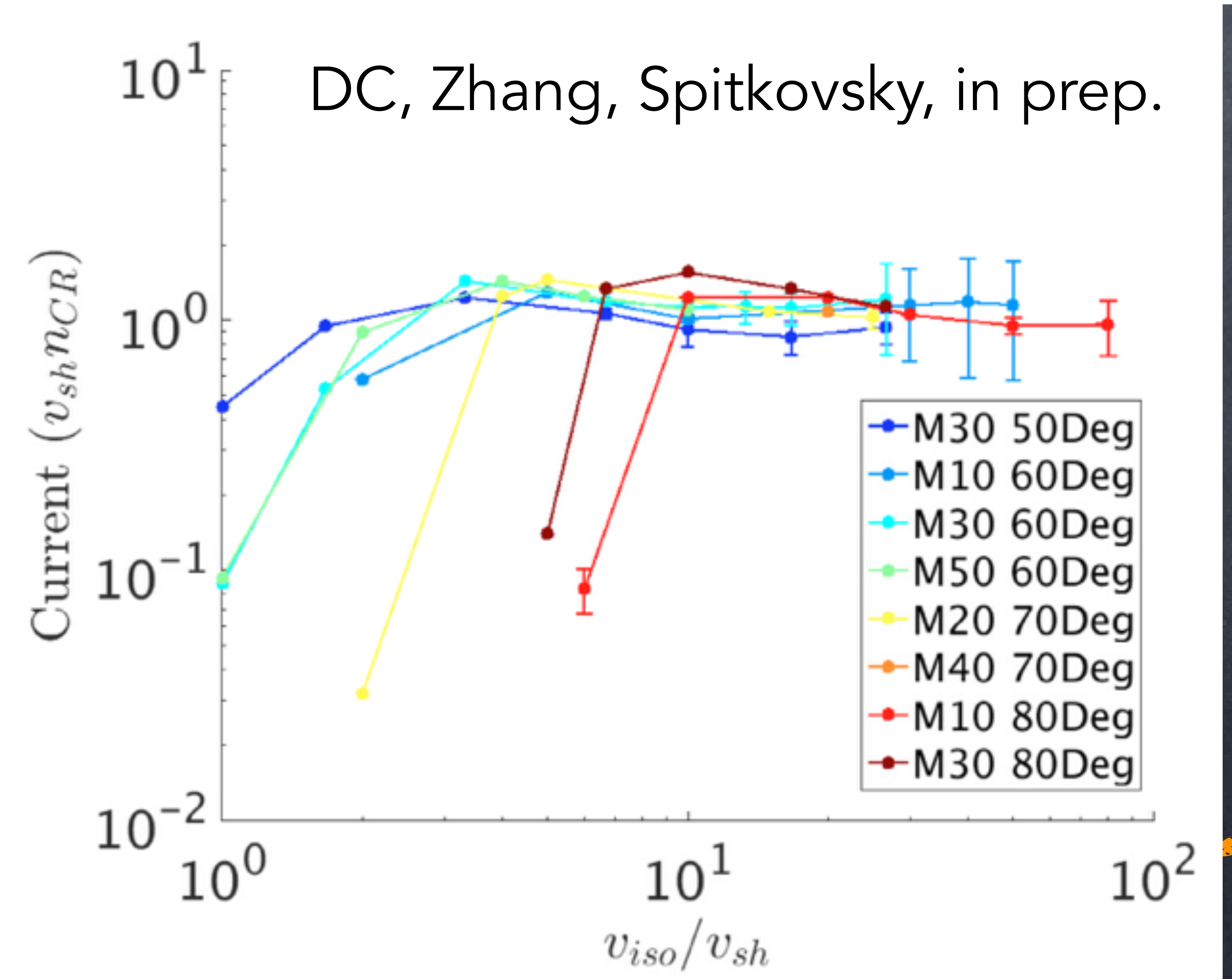
In the upstream frame $J'_{ref} = J_{ref} - n_{CR}v_{sh} = - n_{CR}v_{sh}$

- Current driven by reaccelerated Galactic CRs (~GeV protons from Voyager I data)

$$\tau_{\rm Bell} = 3\times 10^8 s \left(\frac{v_{\rm sh}}{5000{\rm km/s}}\right)^{-1}$$

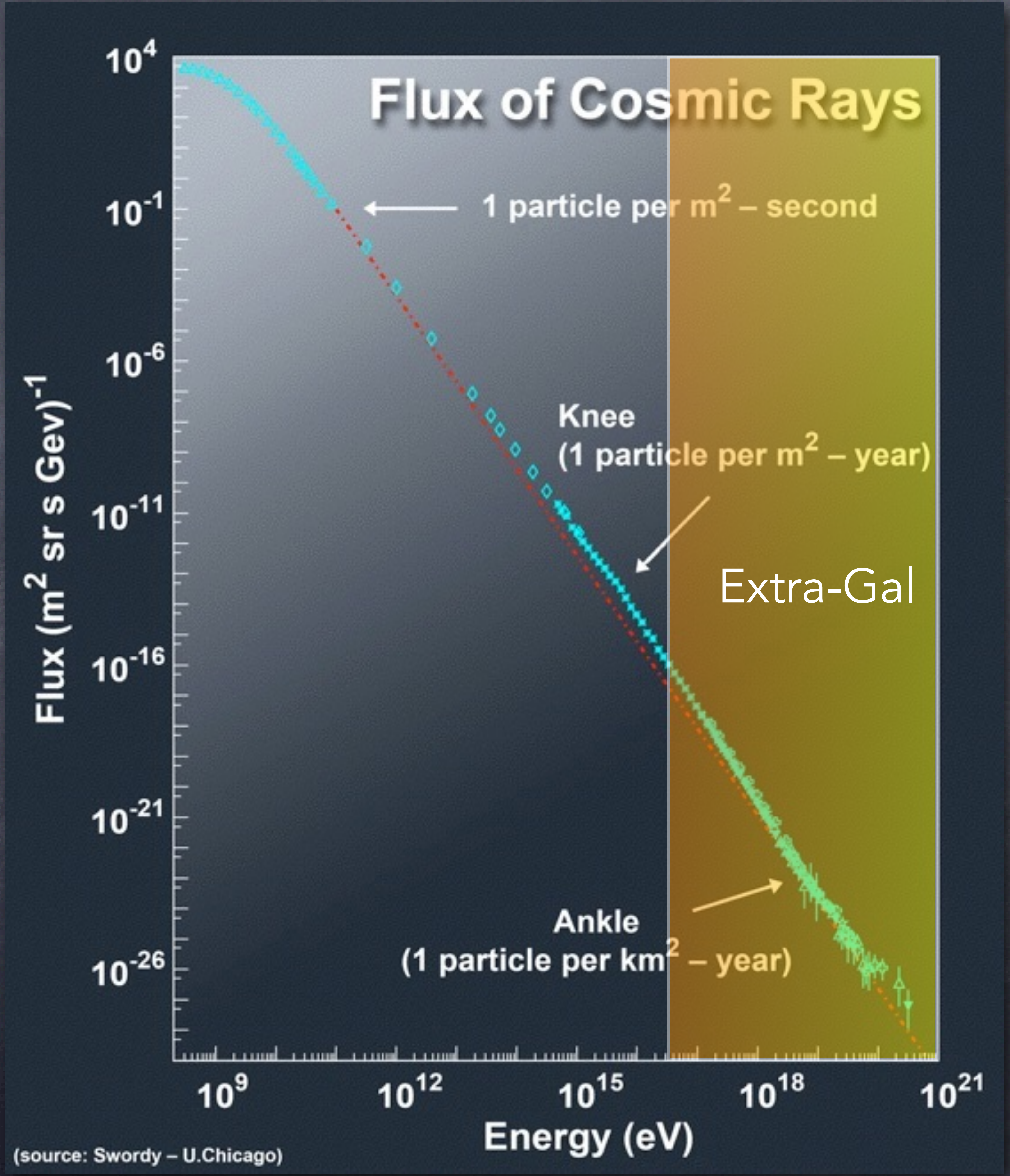
- Potentially important for the PeV problem!!

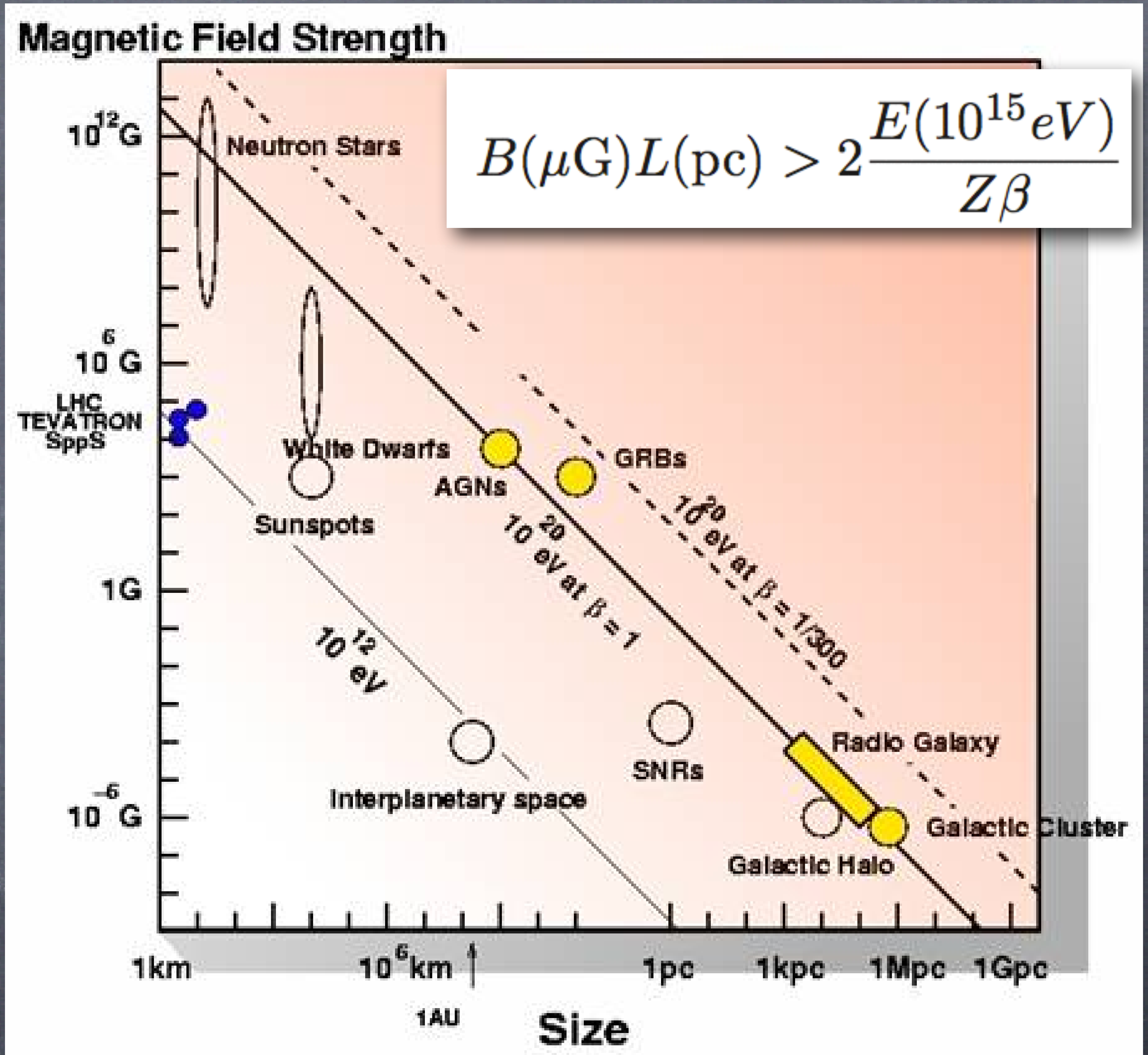




PART II
(The one you *may* trust)

Extra-galactic Cosmic Rays

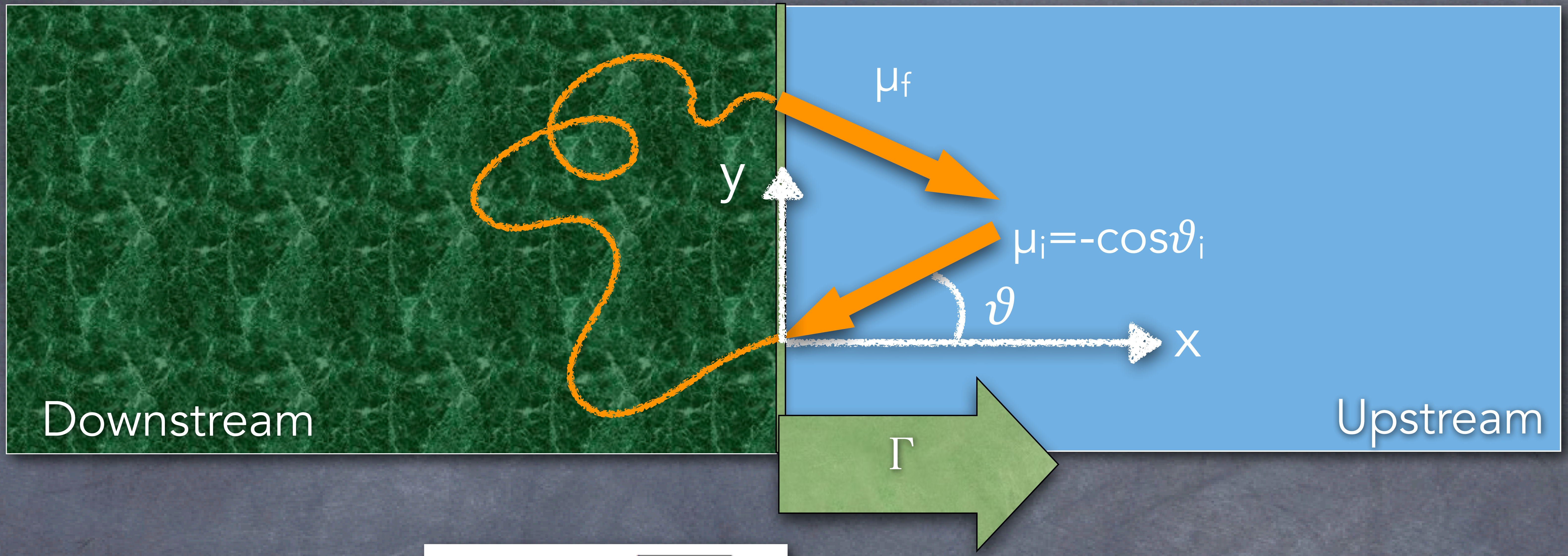




$$B(\mu\mathrm{G})L(\mathrm{pc}) > 2\frac{E(10^{15}eV)}{Z\beta}$$

- 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:

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

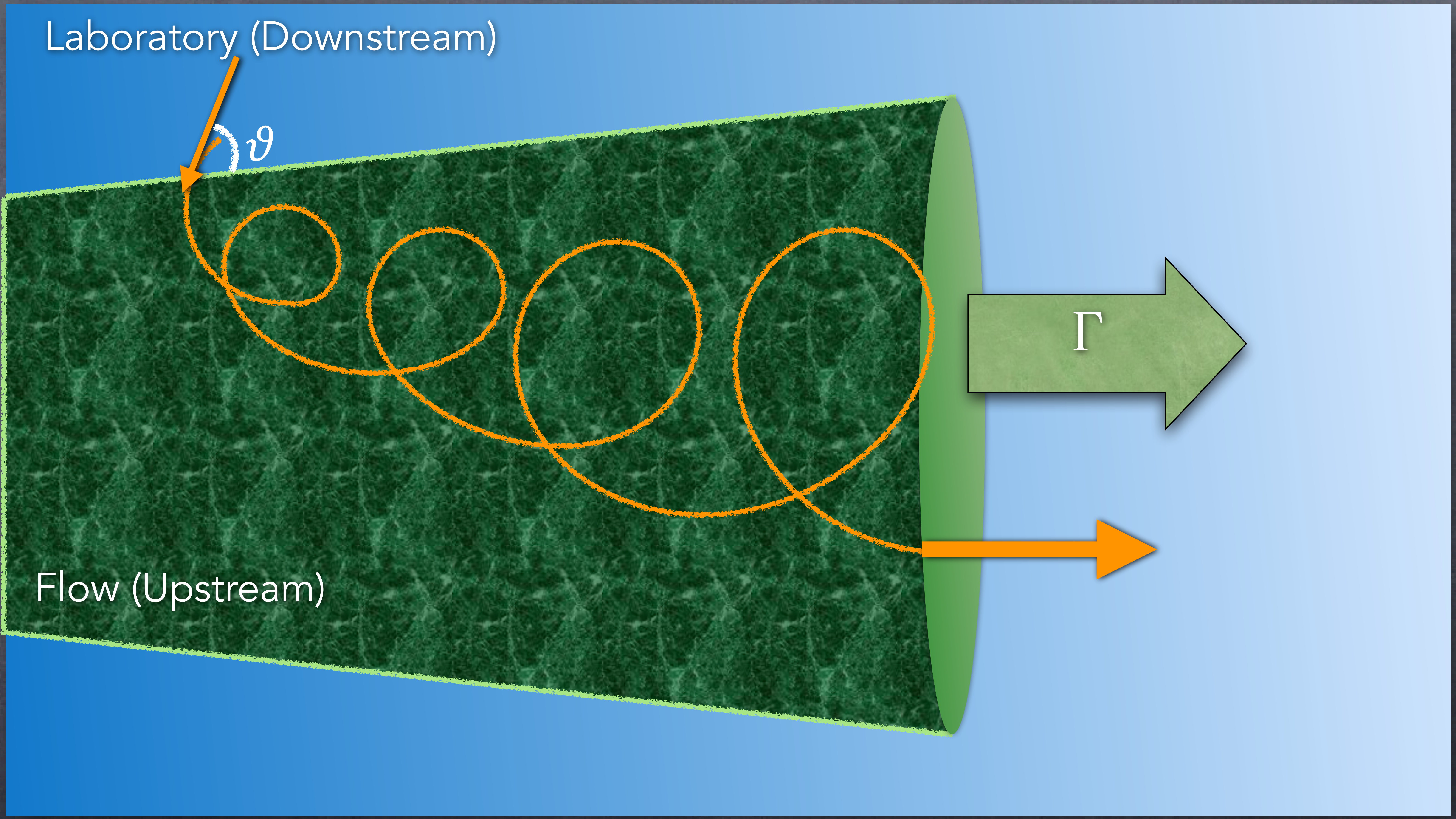
- Energy gain depends on $\mu_f - \mu_i$

First cycle: $E_f \sim \Gamma^2 E_i$

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

Acceleration in Relativistic FLOWS

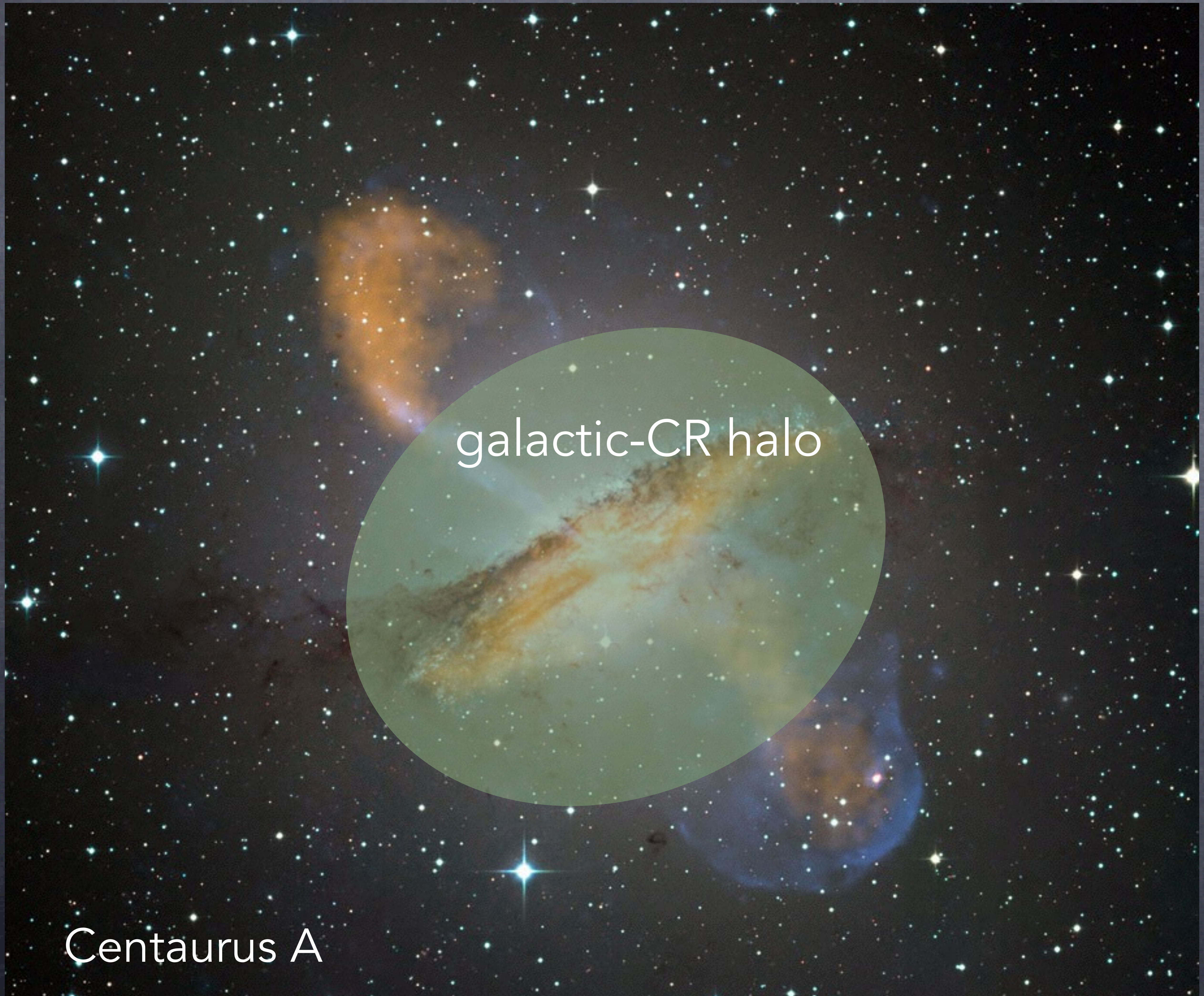
- Requirement: interface thickness << gyroradius << typical flow size



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

Espresso Acceleration of UHECRs

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



ONE-SHOT
reacceleration can produce UHECRs up to
$E_{max} \sim 2\Gamma^2\, 3Z$ PeV

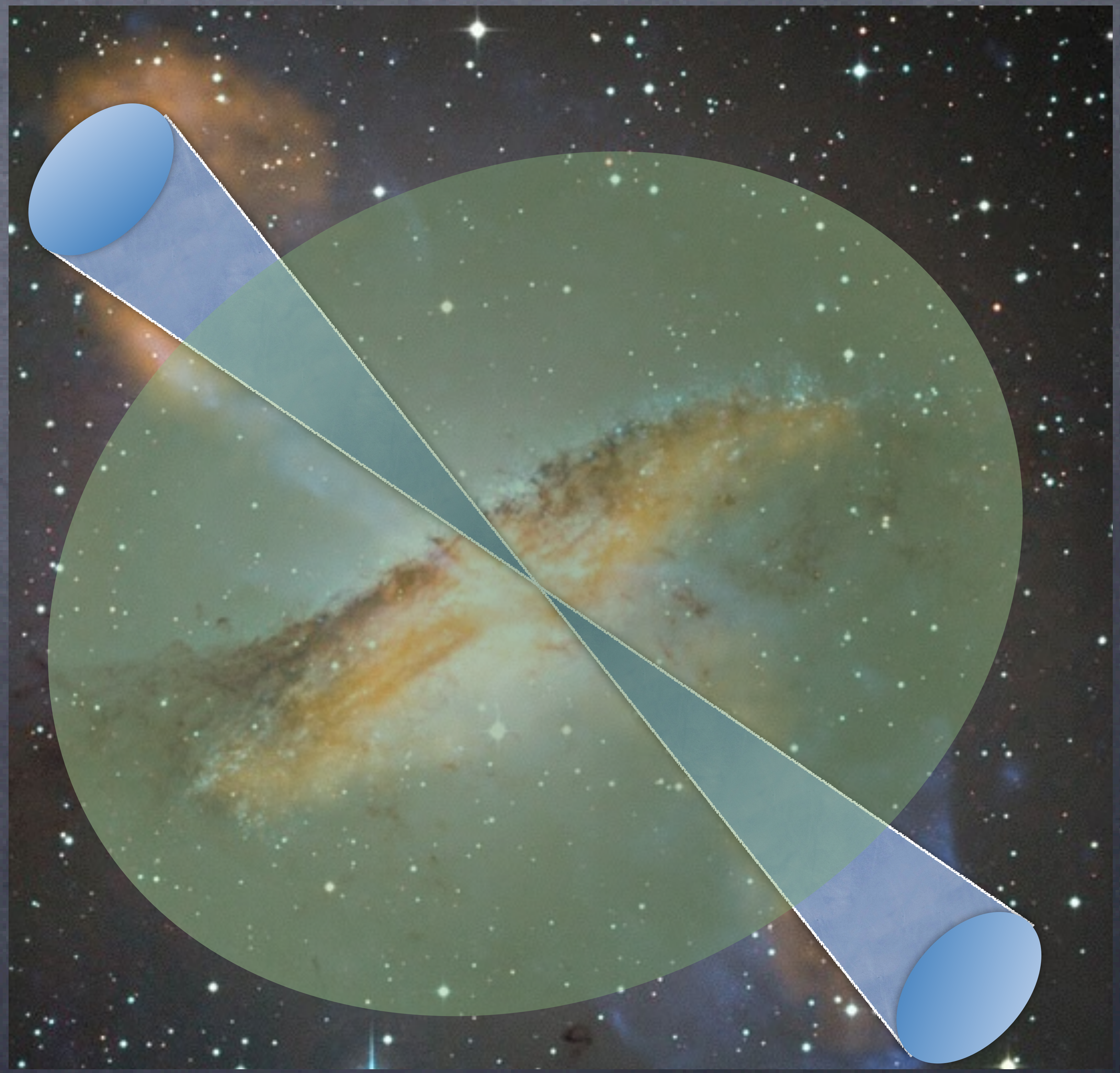
$E_{max} \sim 5Z \times 10^9$ GeV

UHECRs from AGN jets: constraints

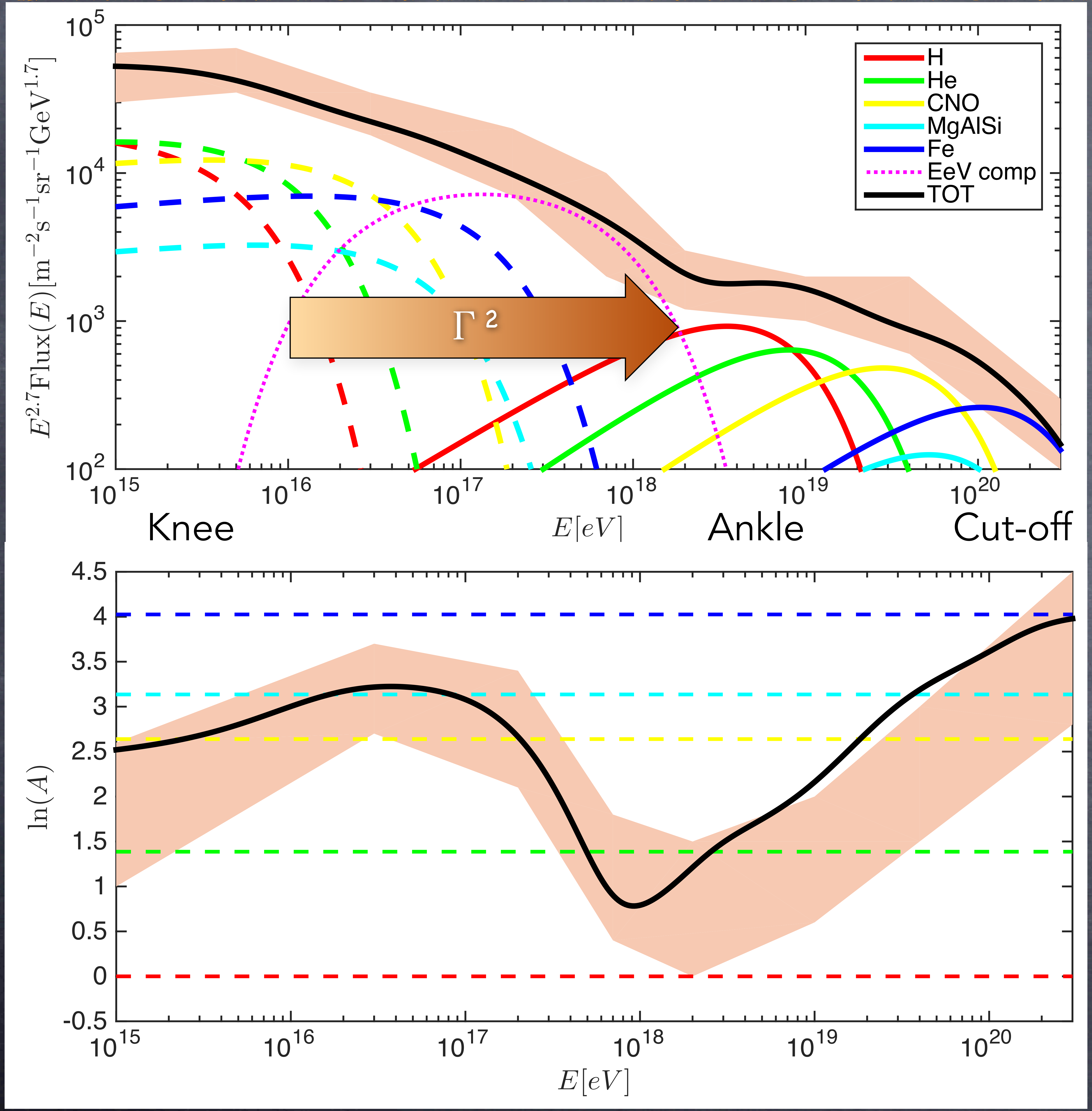
- Confinement (Hillas Criterion): $B_{\mu G} D_{\rm kpc} \gtrsim \frac{4}{Z_{26}} \frac{E_{\rm max}}{10^{20}{\rm eV}}$ ✔
- Energetics: $Q_{\rm UHECR}(E \gtrsim 10^{18}{\rm eV}) \approx 5{\rm x}10^{45}{\rm erg/Mpc^3/yr}$

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

  $Q_{\rm AGN} \approx$ a few 10^{46}-10^{48}erg/Mpc^3/yr >> $Q_{\rm UHECR}$ ✔
- Efficiency depends on:
  - Reacceleration efficiency (ε>~10^{-4})
  - Jet cross section
    (angle of a few degrees: $\varepsilon \sim 10^{-1}$-10^{-2})
  - Contributing AGNs
    - Likely radio-loud quasars, blazars, FR-I,…



Galactic CR + UHECR spectrum

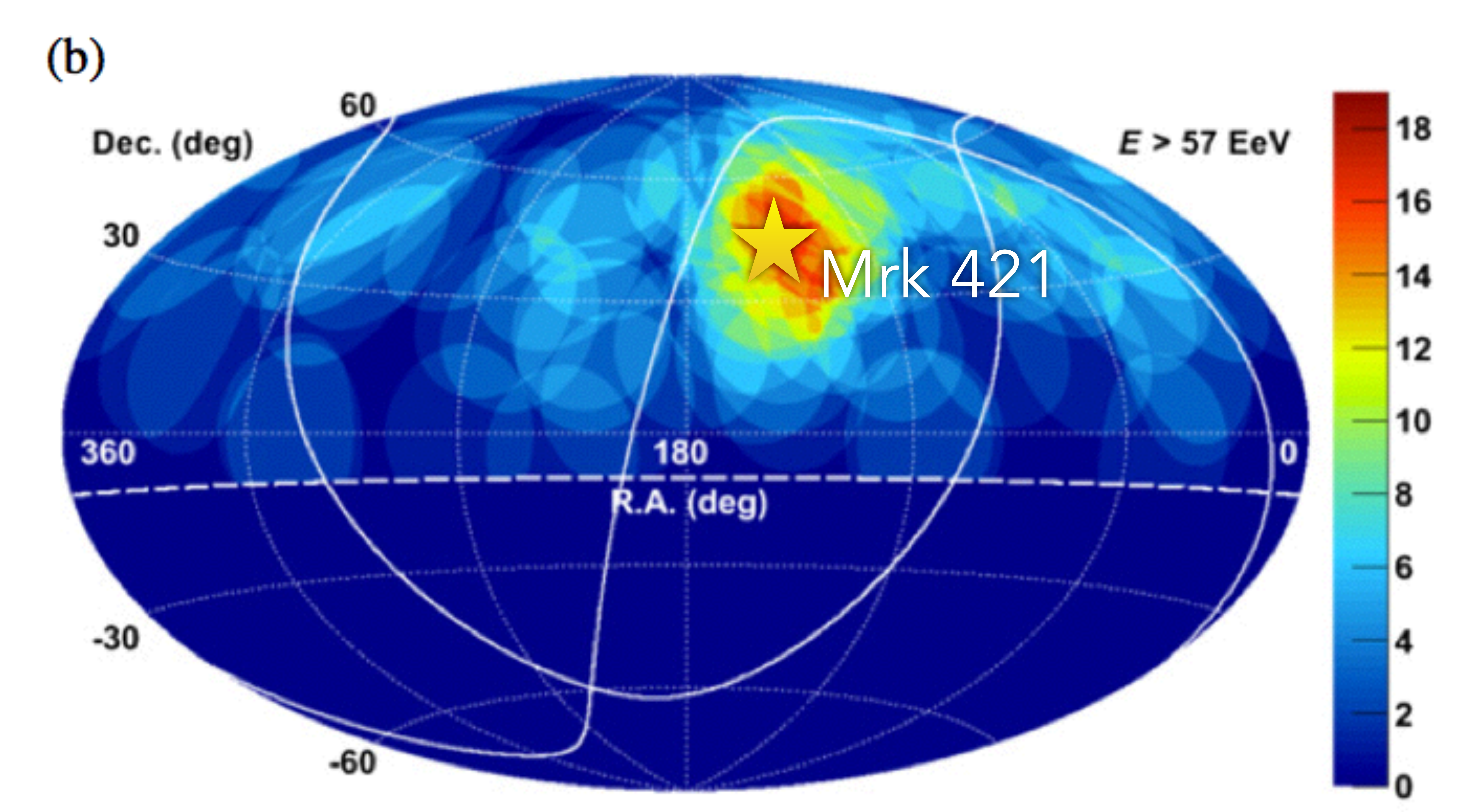


- CR spectral features
- Prediction of UHECR chemical composition!
  - UHECR spectra must be quite flat, ~$E^{-1.5}$ (Aloisio+13, Gaisser+13, Taylor 14,…)
  - An additional steep/light component must fill the gal-extragal transition
- Different kinds of AGNs?

DC, 2015

Pointing to Sources?

- Nearby (z<0.03) *known* powerful blazars: Mrk 421, Mrk 501
- Telescope Array hotspot (only at 3.4σ…)



CR Summary

Origin	Source	Mechanism	E	Spectrum	Evidence
Galactic	SNRs	Diffusive Acceleration non-rel shocks	3Zx10	Universal	gamma rays e.g., Tycho
Extragal	AGNs	Espresso in rel	5Zx10	Galactic, boosted	Anisotropy? Neutrinos?