TeVPA 2017
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New Insights on Particle Acceleration at Non-relativistic Shocks

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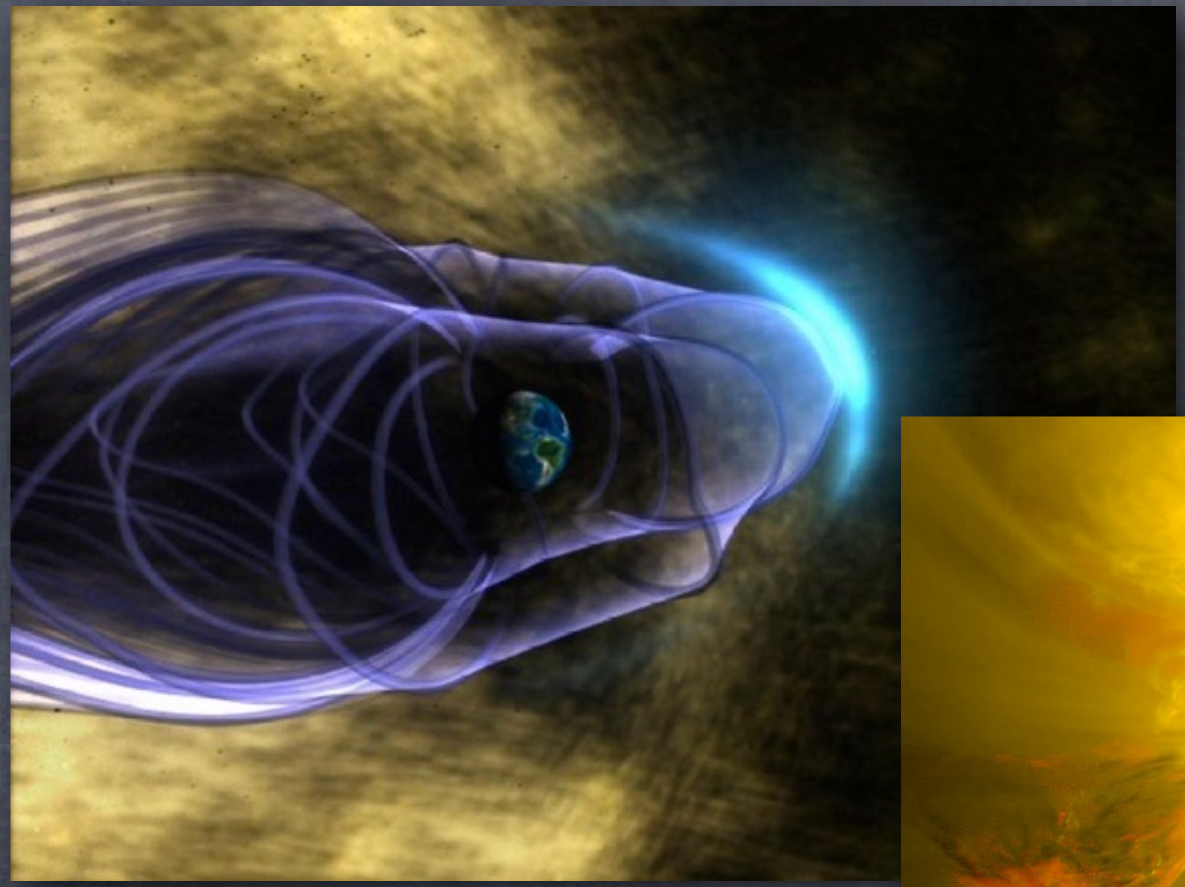
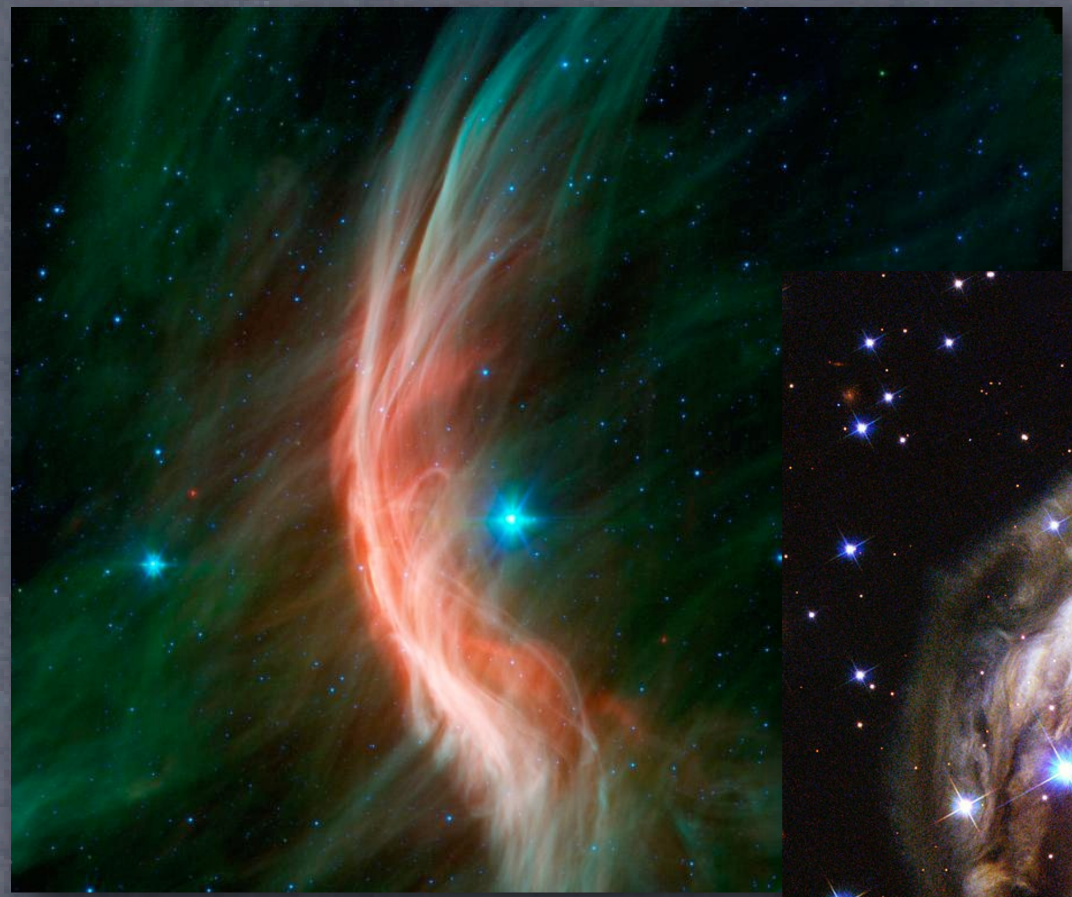
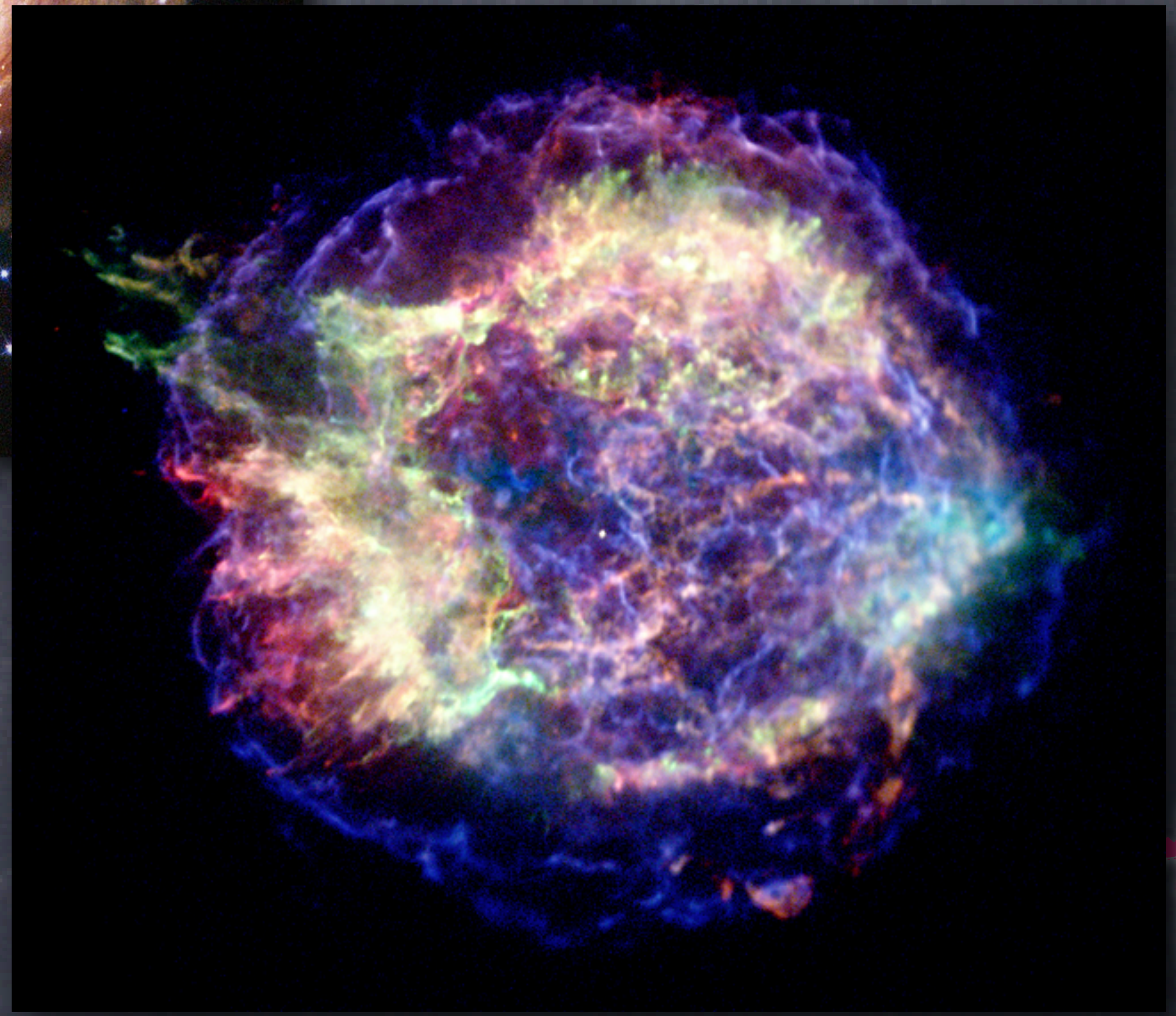
Non-Relativistic Collisionless Shocks

- Mediated by collective electromagnetic interactions
- Show prominent non-thermal activity
- Propagate in environments likely rich in energetic particles (seeds)

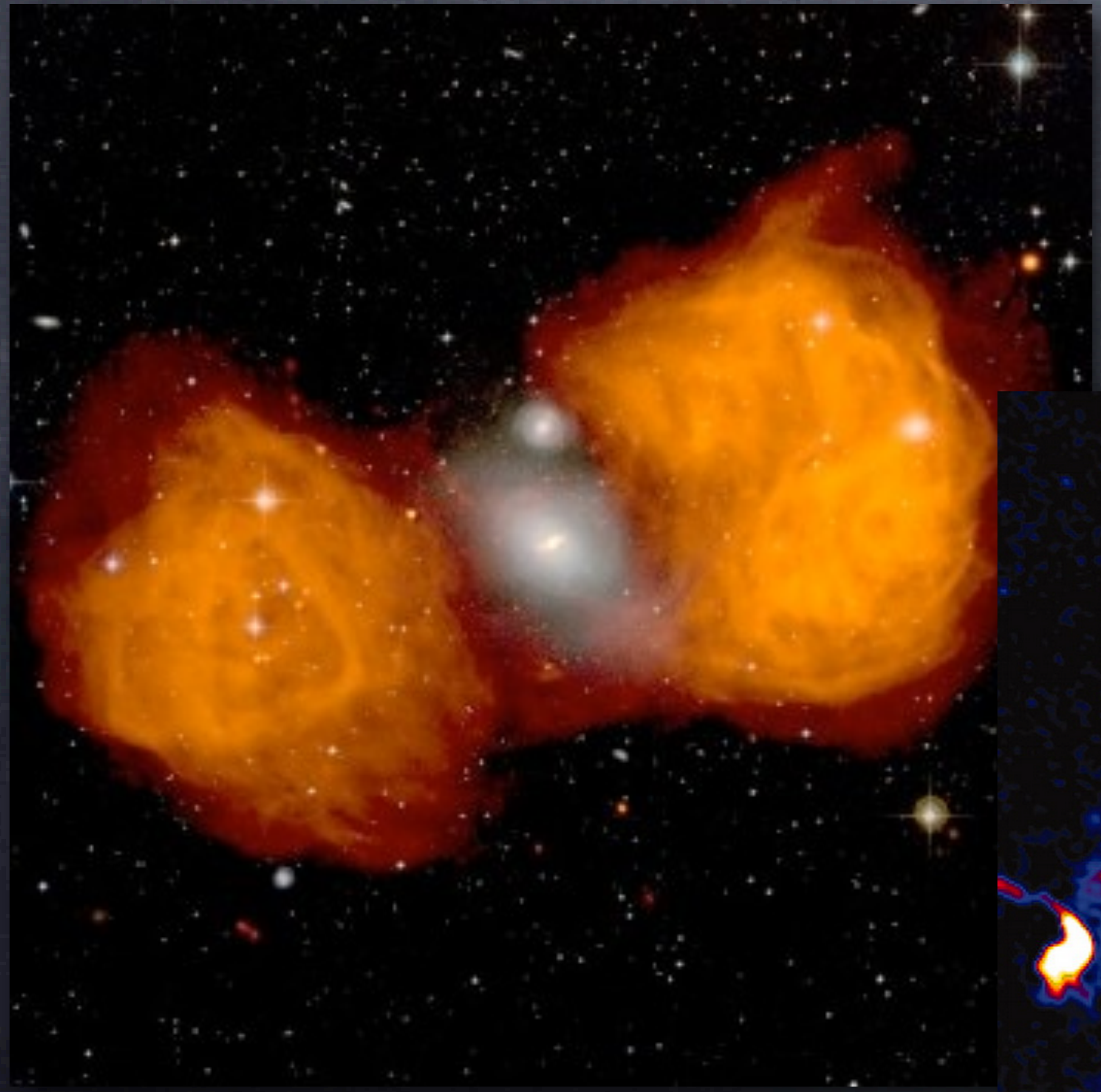
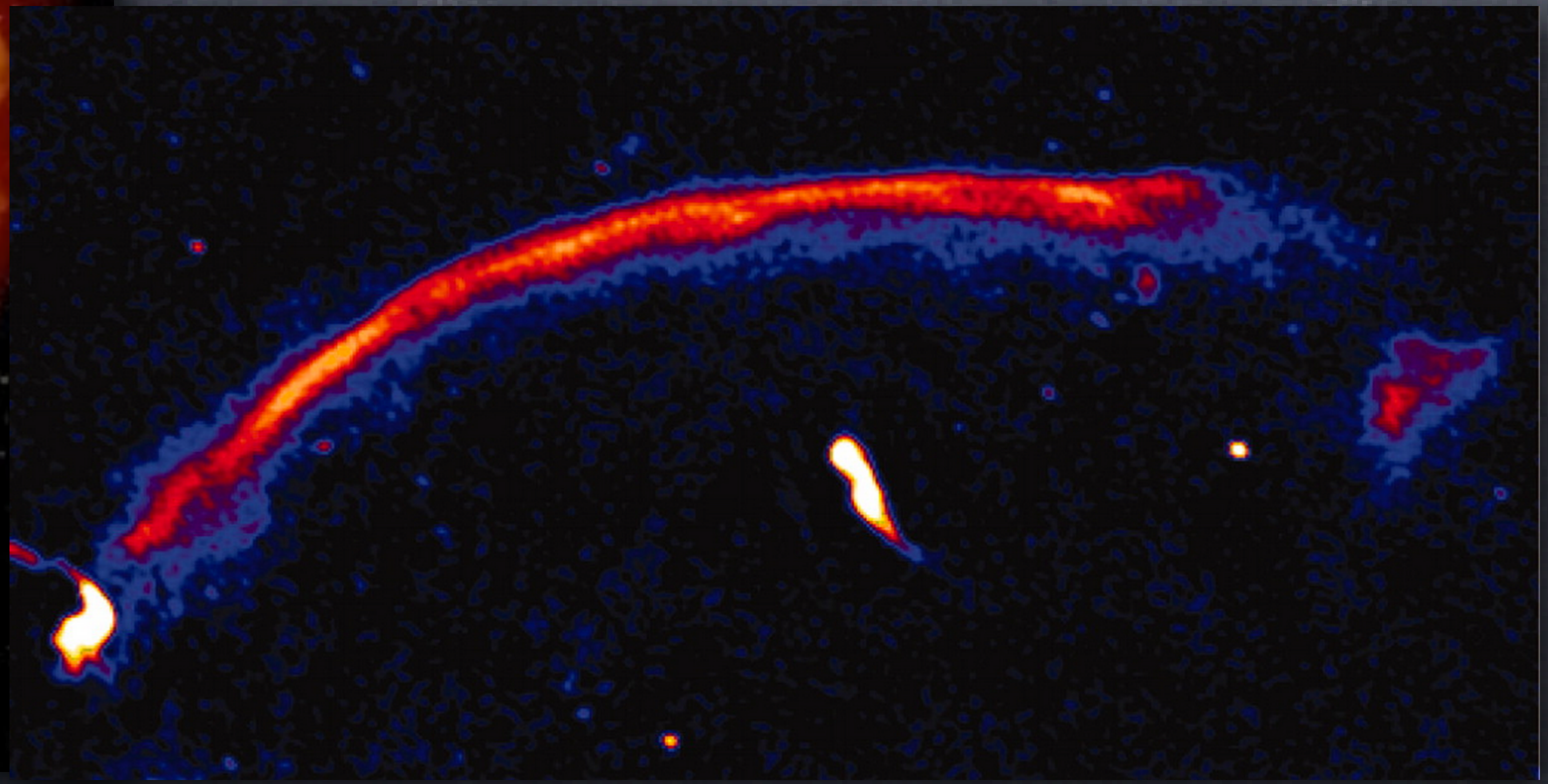



Heliospheric





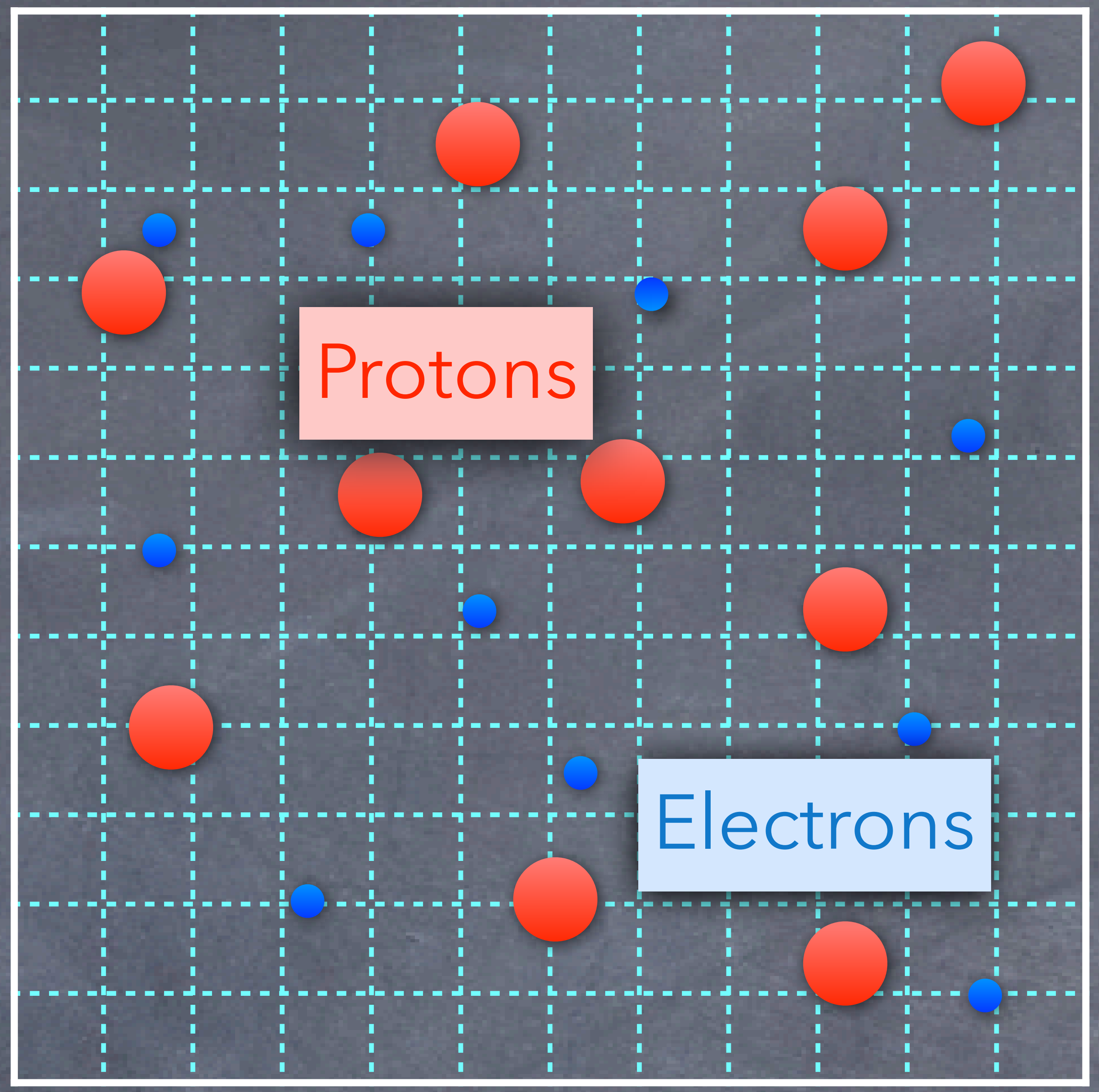
Galactic

Extra-Galactic

Astroplasmas from first principles

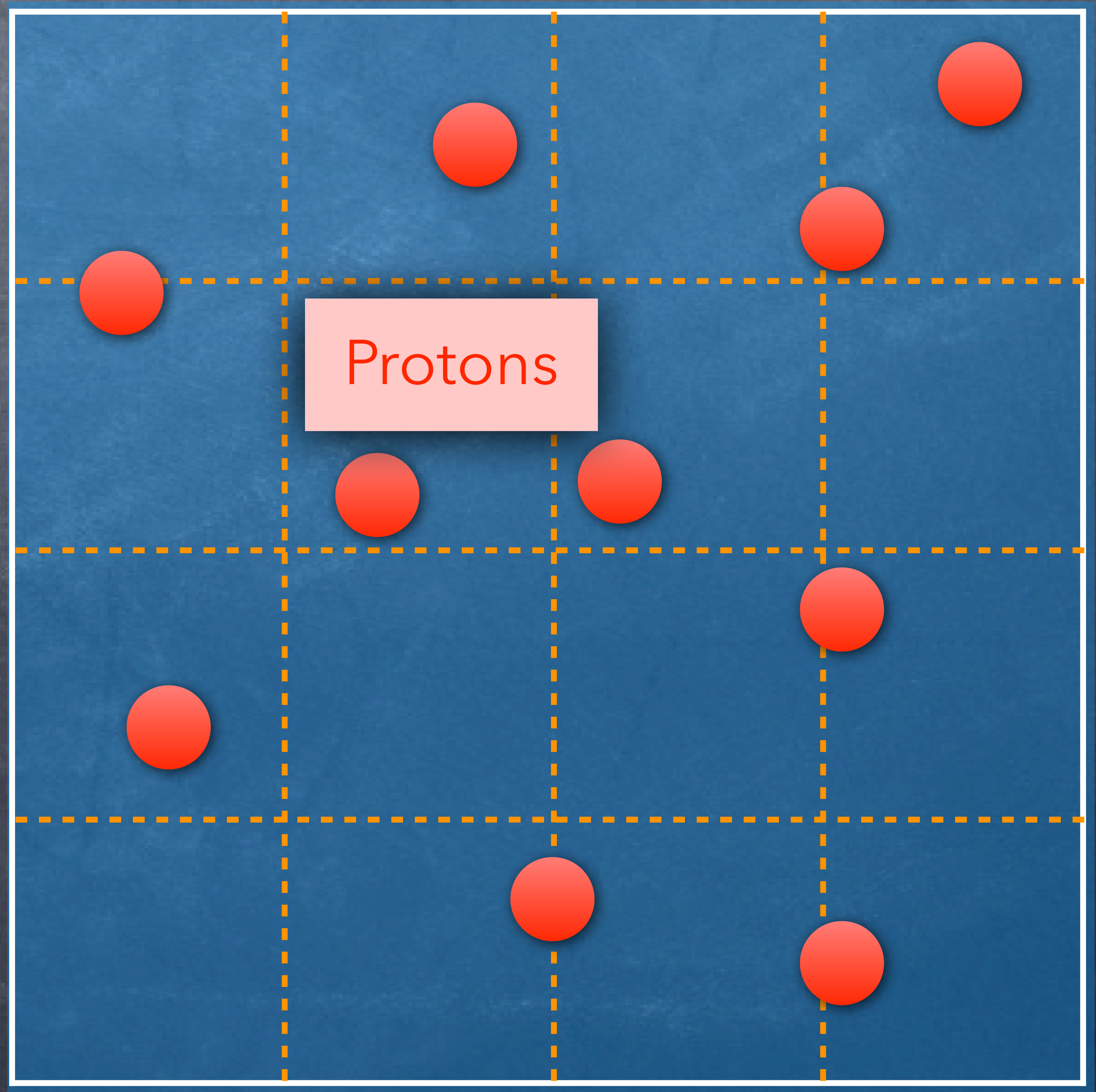
- Full-PIC approach
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



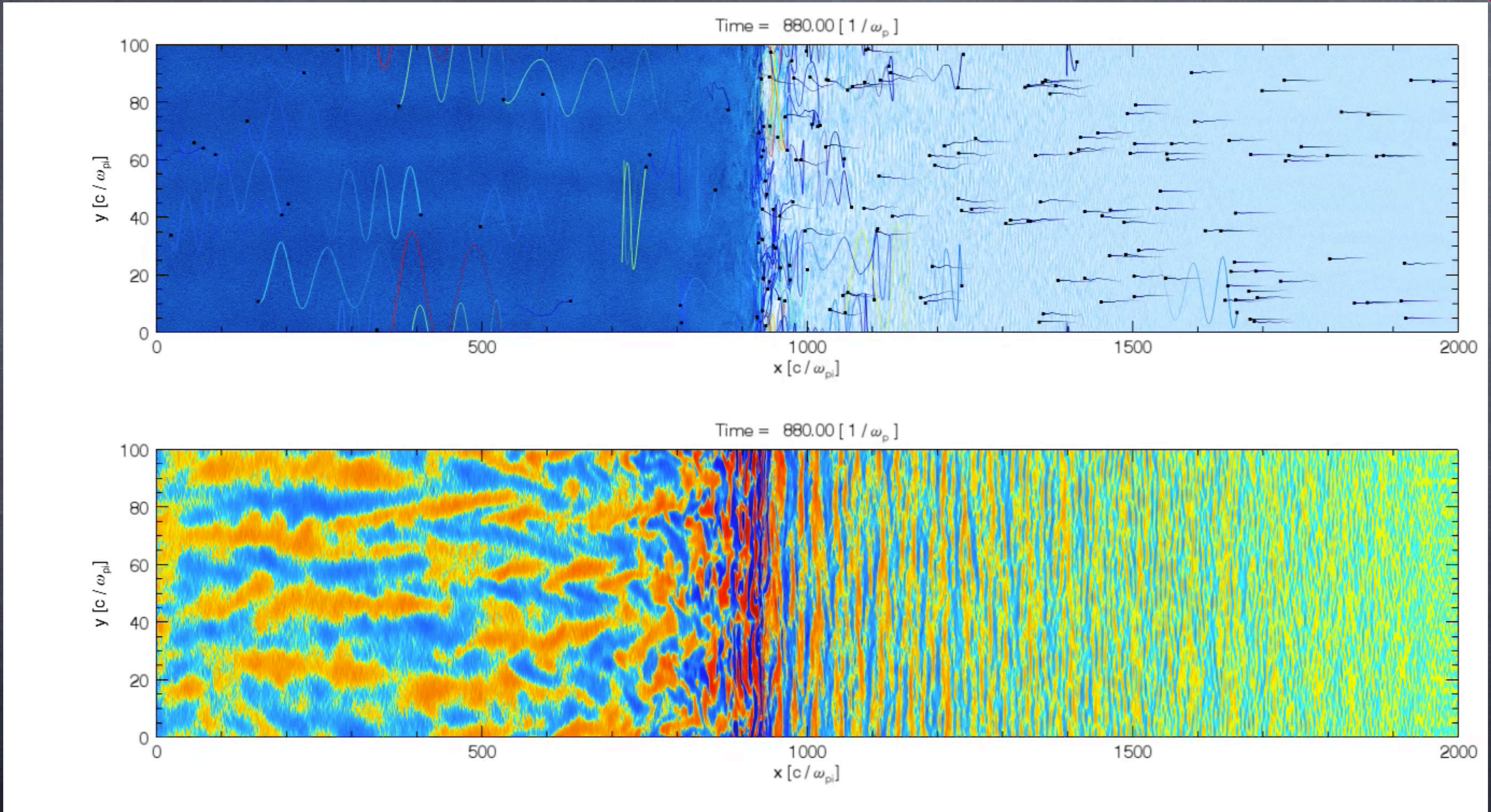
- Hybrid approach: Fluid electrons - Kinetic protons

(Winske & Omidi; Burgess et al., Lipatov; Giacalone et al.; DC & Spitkovsky,….)

  - massless electrons for more macroscopical time/length scales

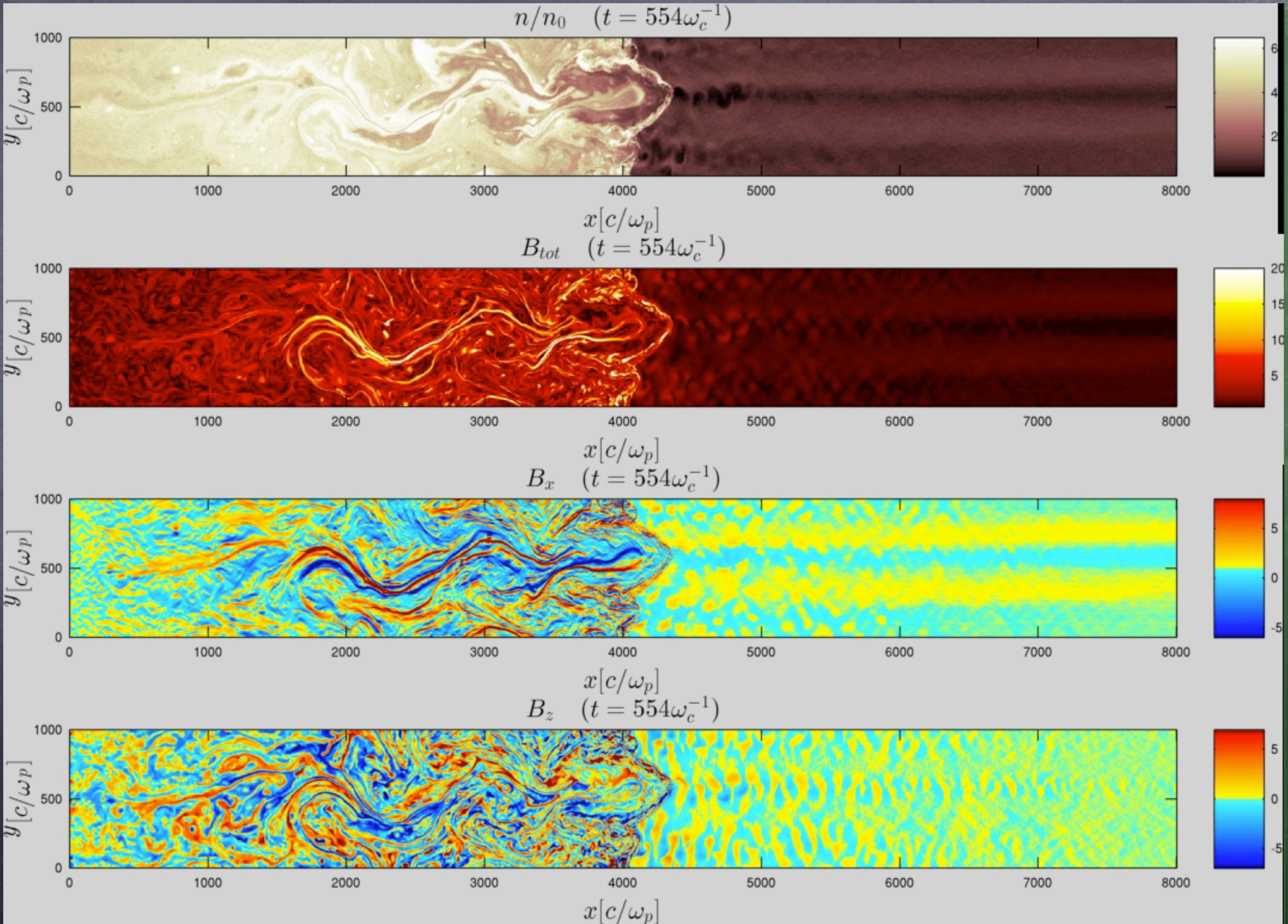


Hybrid simulations of collisionless shocks



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

CR-induced Magnetic Field Amplification



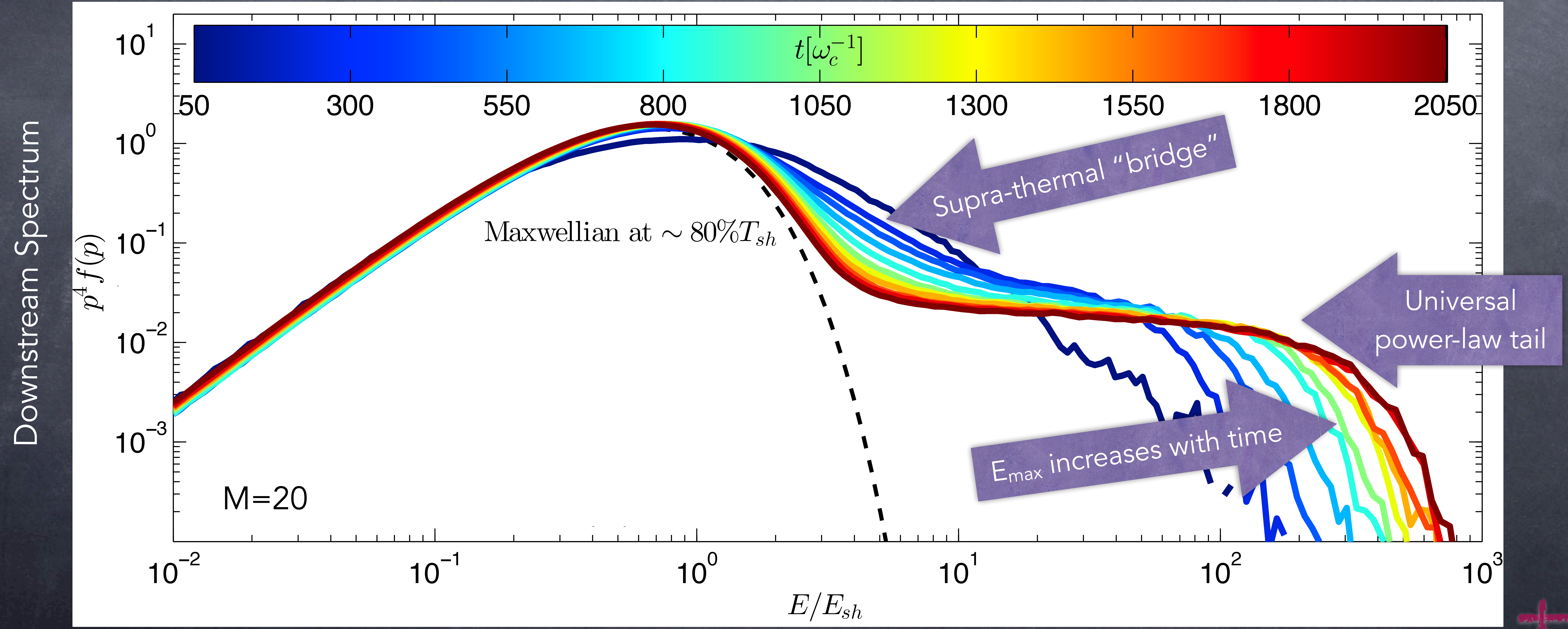
Initial B field

$M_s = M_A = 30$

DC & Spitkovsky, 2013

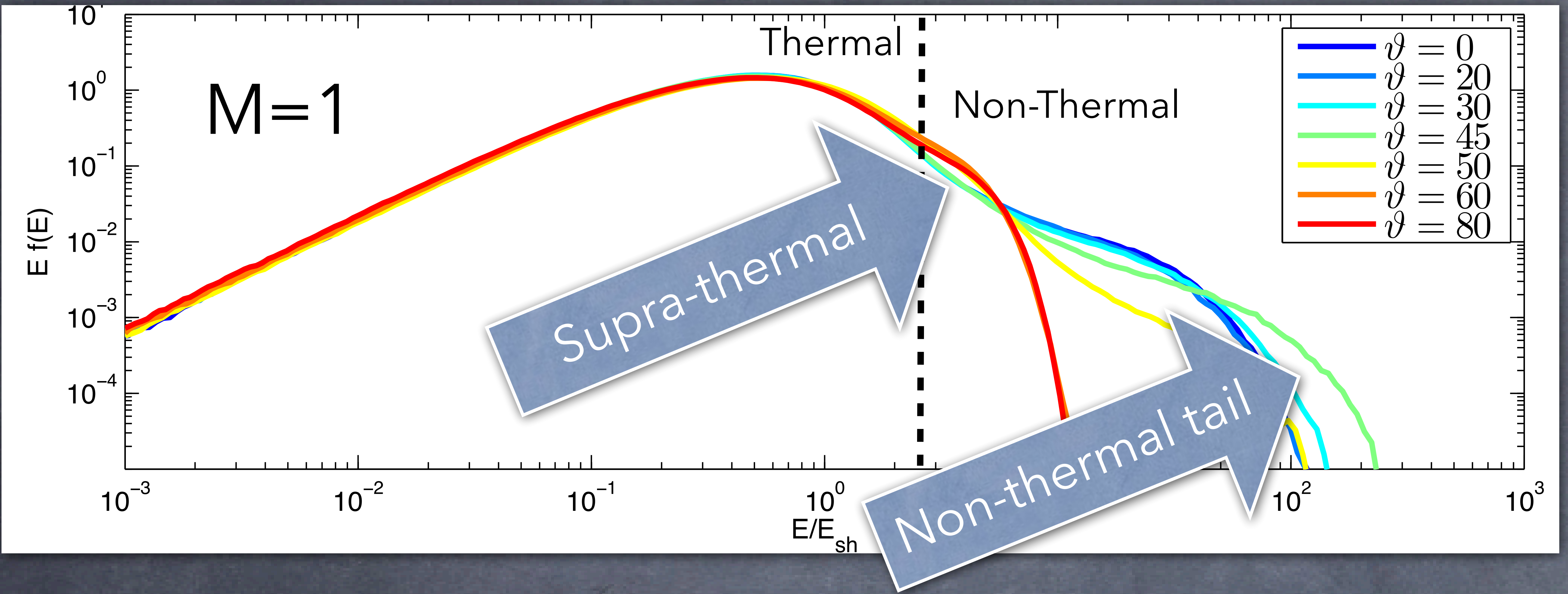
Spectrum evolution

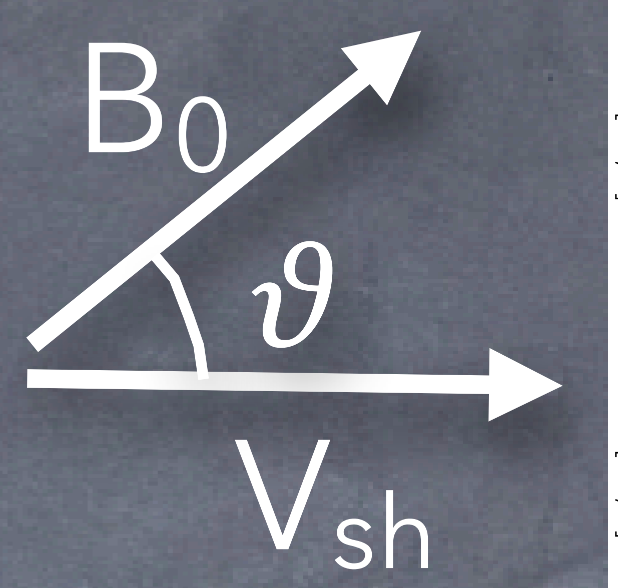
- Diffusive Shock Acceleration: non-thermal tail with universal spectrum $f(p) \propto p^{-4}$
- Acceleration efficiency: ~15% of the shock bulk energy!

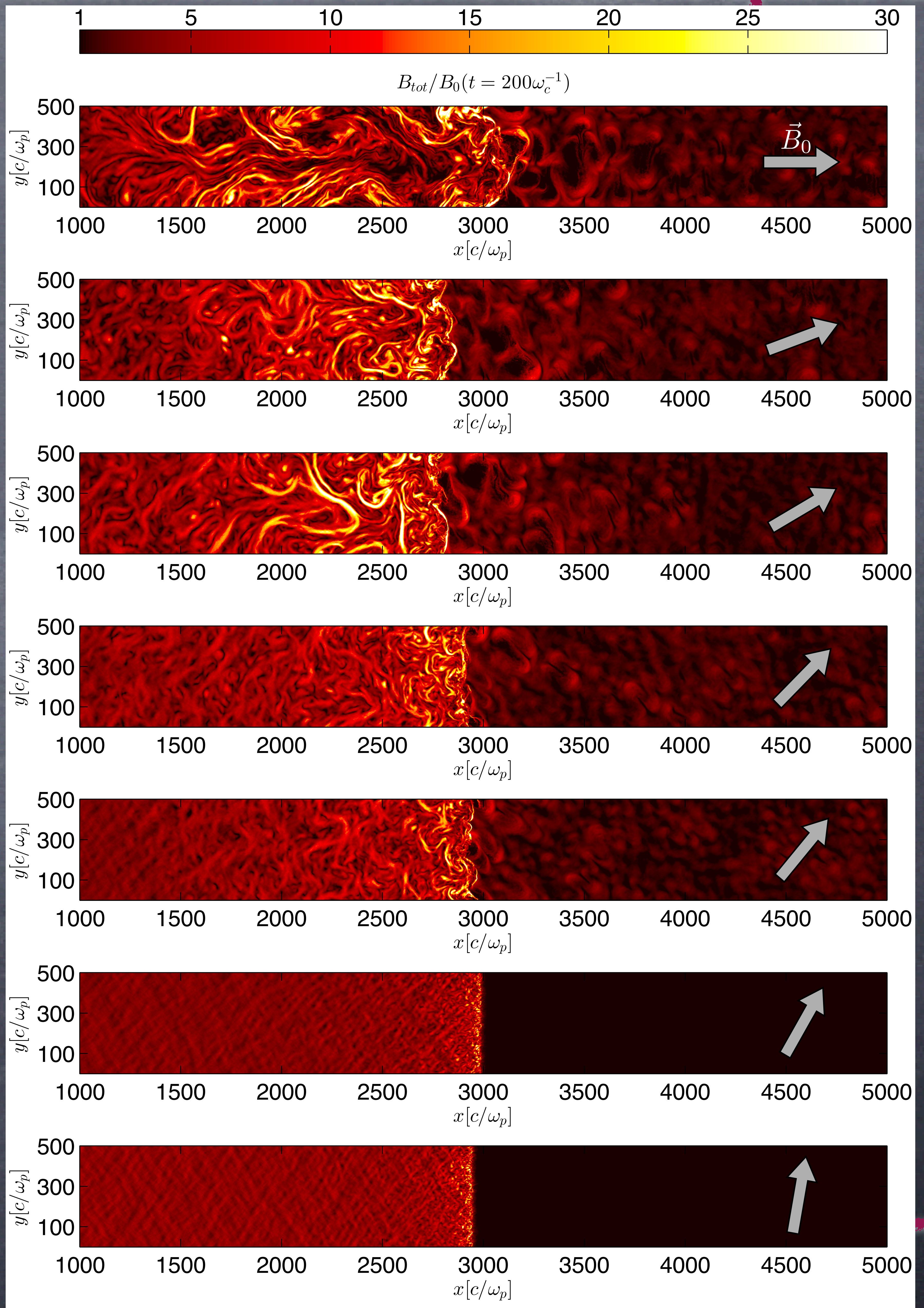


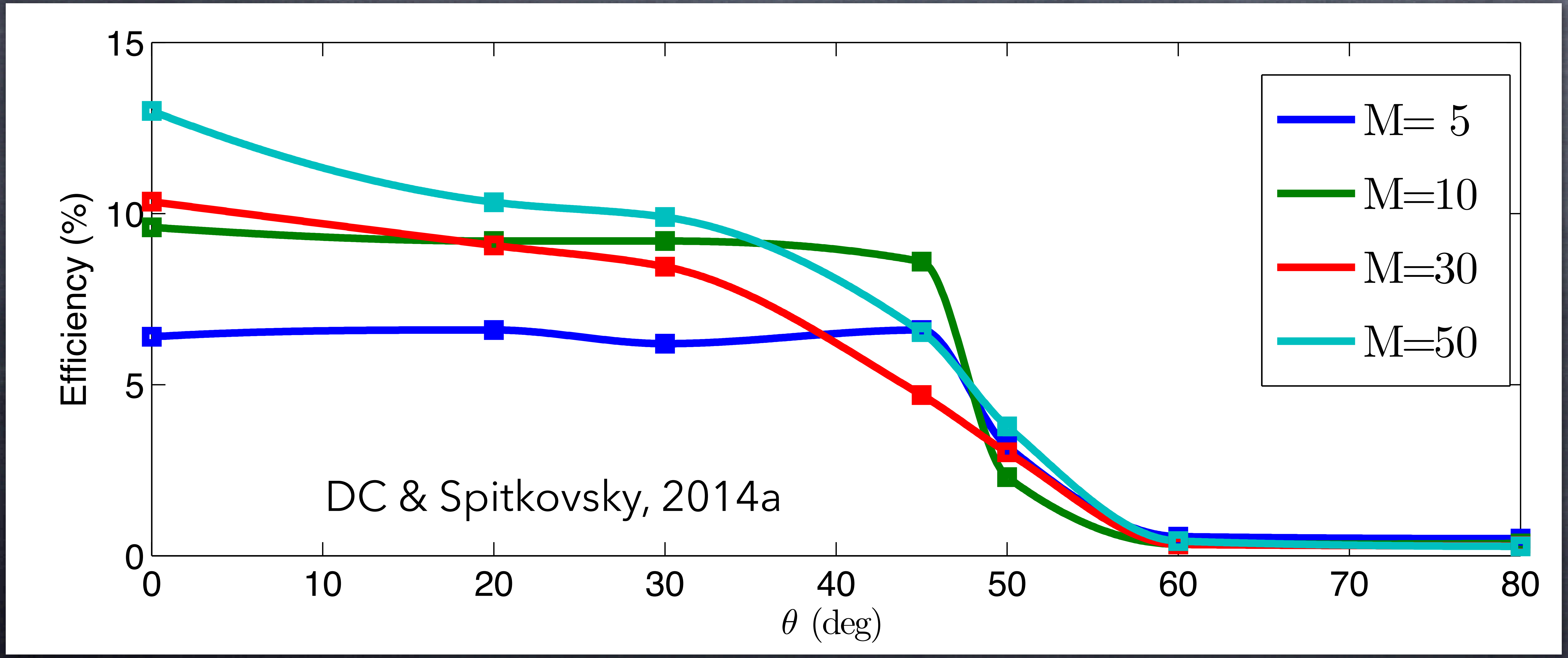
DC & Spitkovsky, 2014a

Parallel vs Oblique shocks



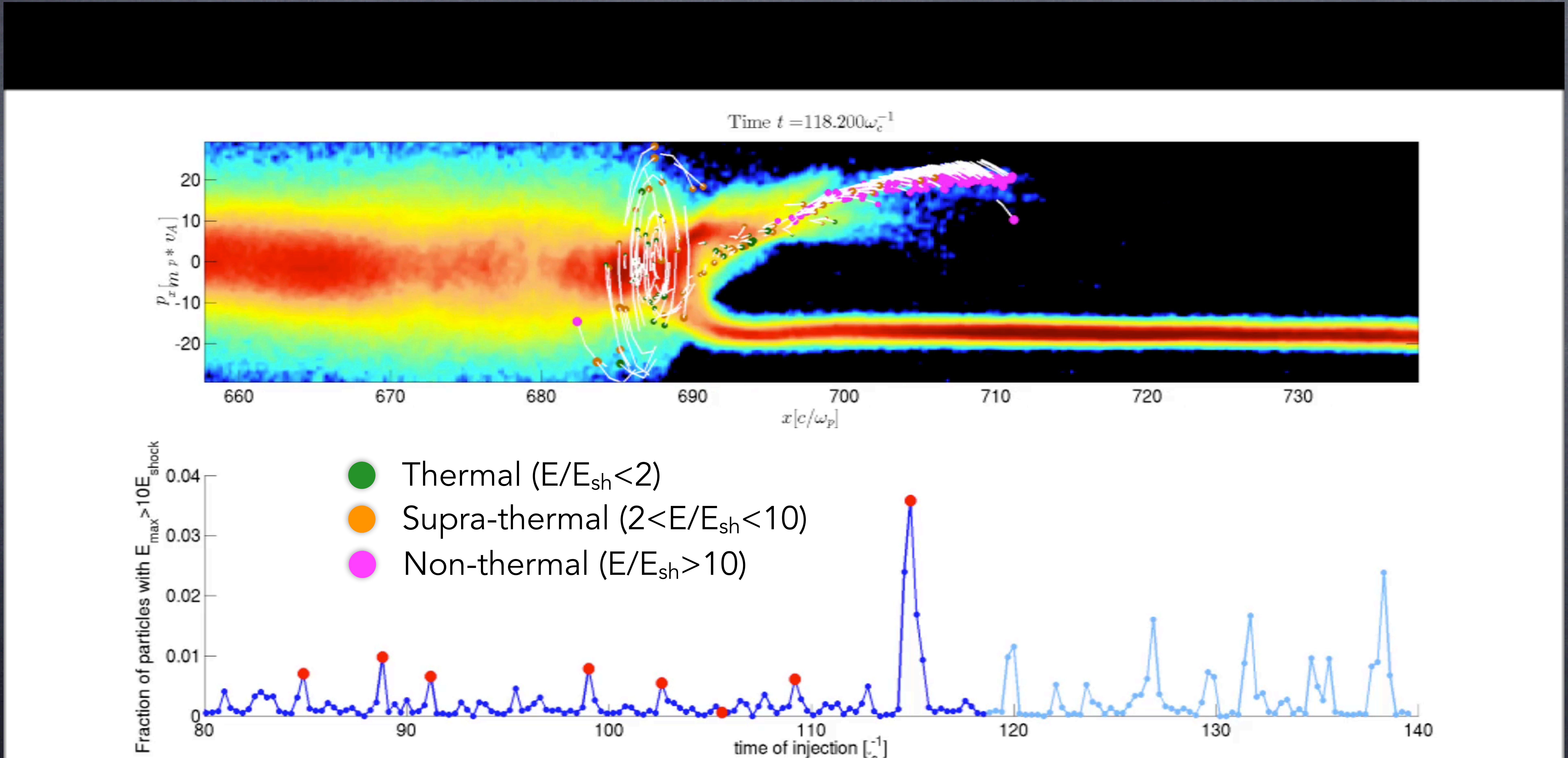






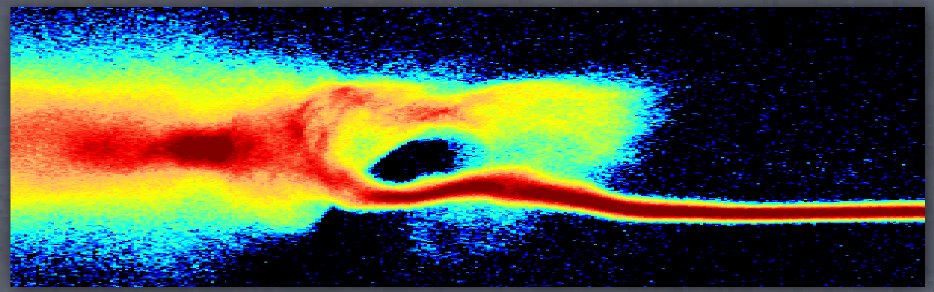
Ion Injection at Shocks

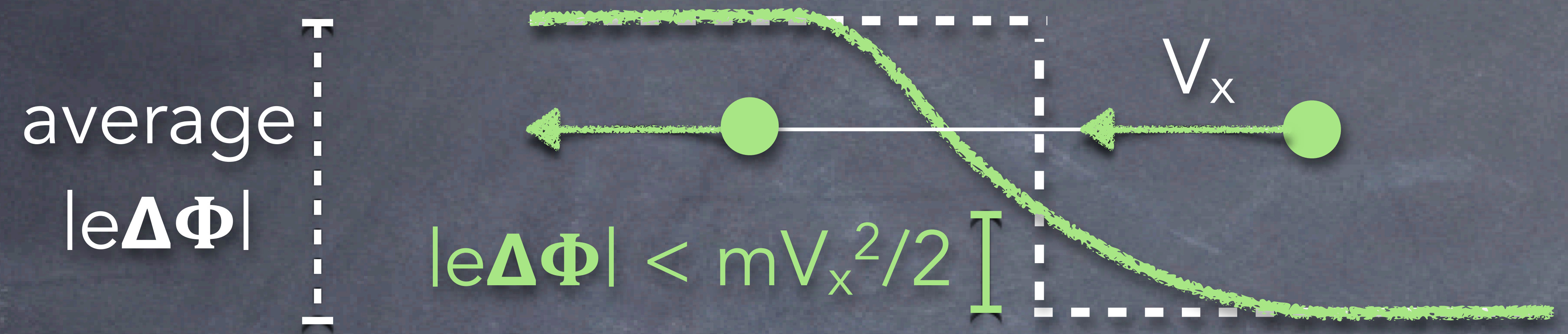
- Ions injected into DSA undergo specular reflection at the reforming shock barrier and shock drift acceleration
- The fraction of injected particles depends on v_{in} and ϑ (DC, Pop & Spitkovsky, 2015)



Injection via Shock-Drift Acceleration (SDA)

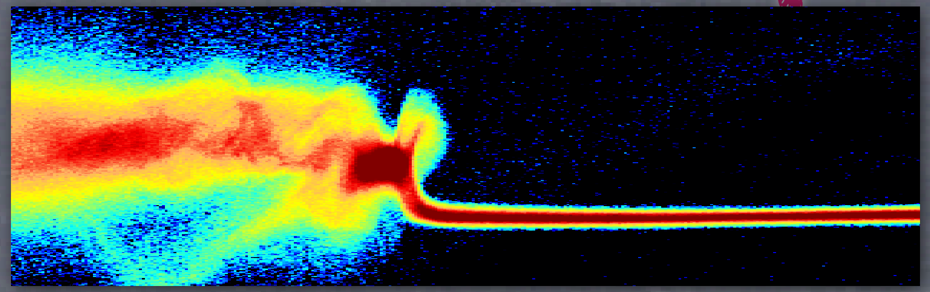
- Low barrier (reformation)

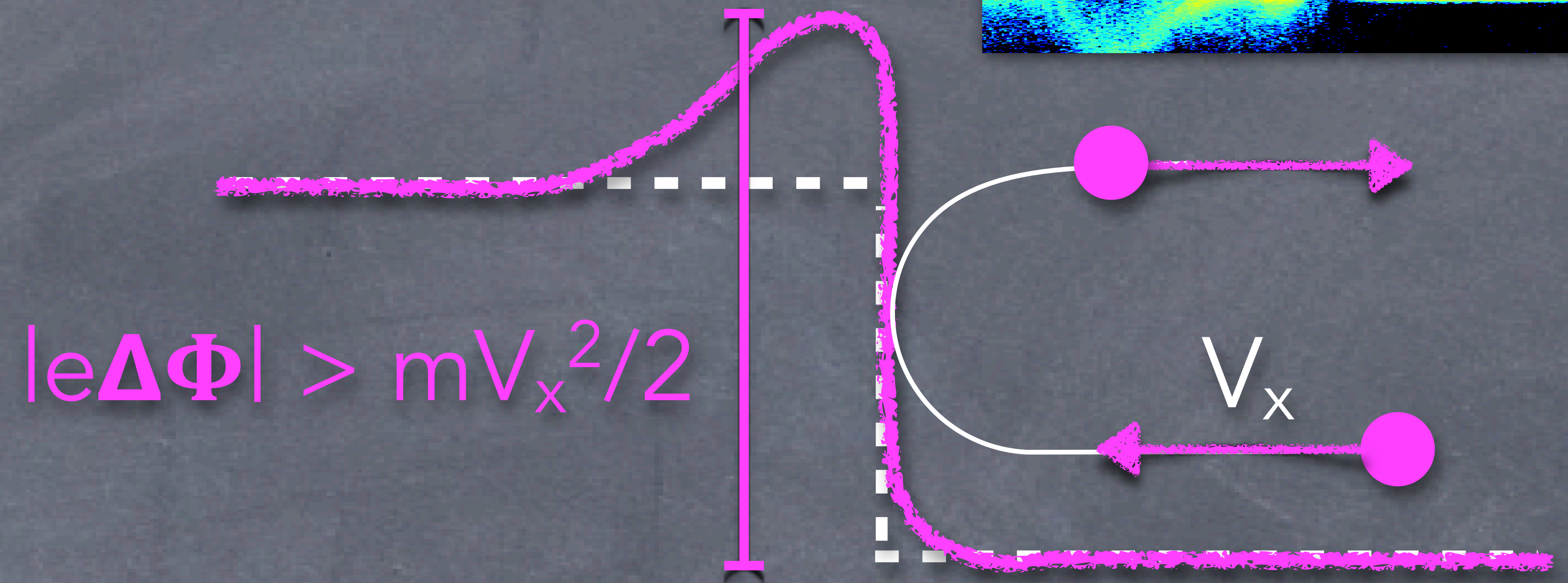




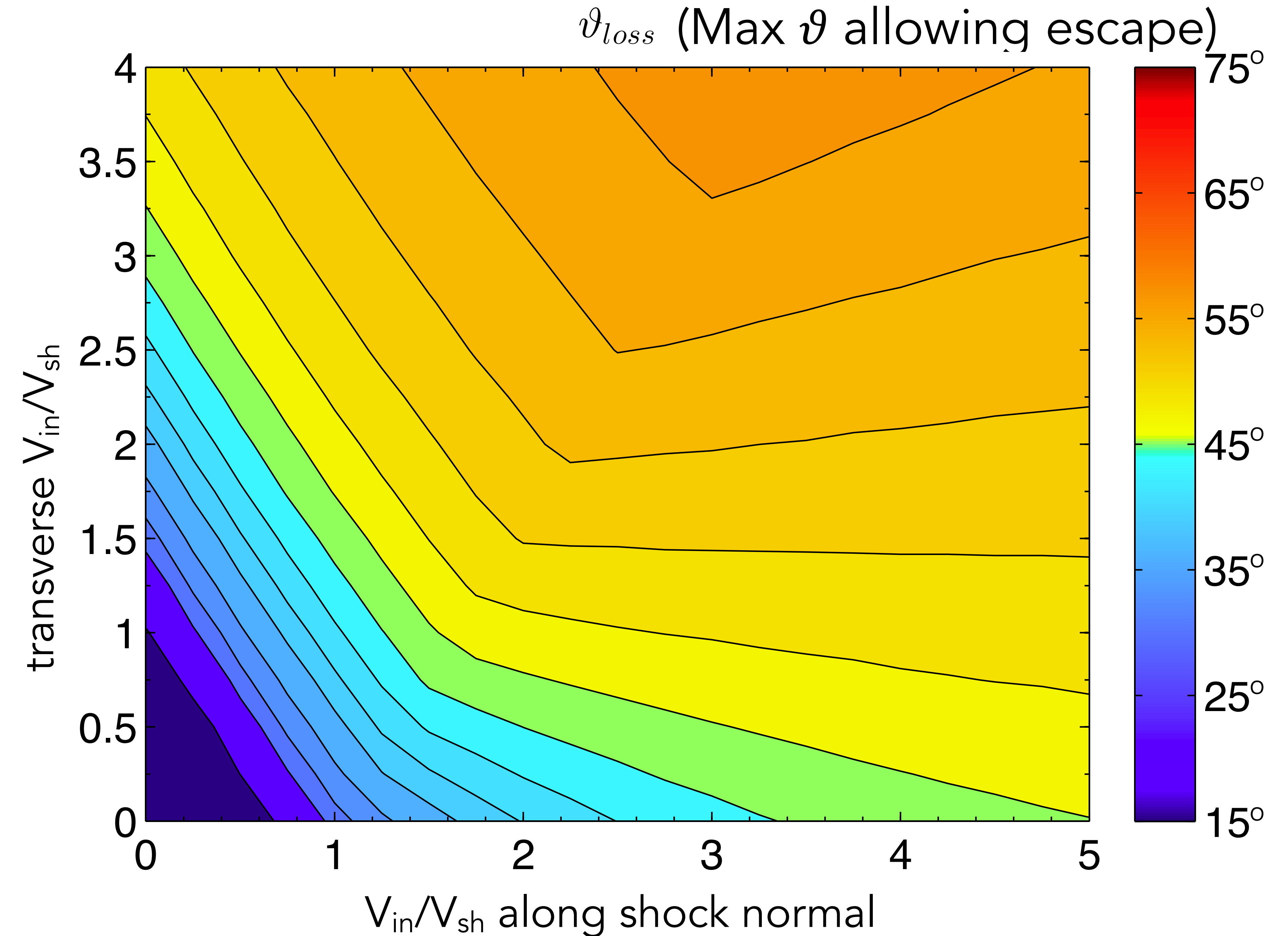
Ions advected downstream, and thermalized

- High barrier (overshoot)





Ions reflected upstream, and energized via SDA

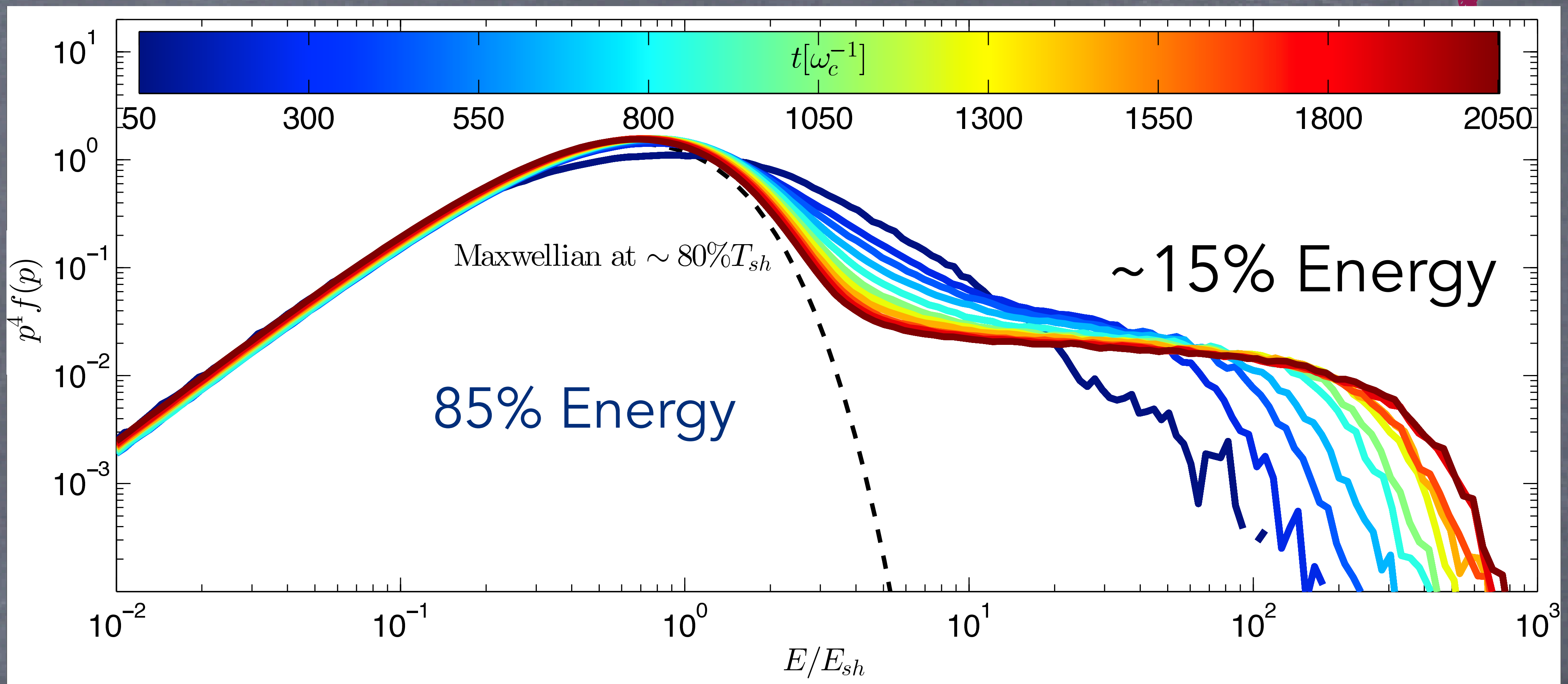


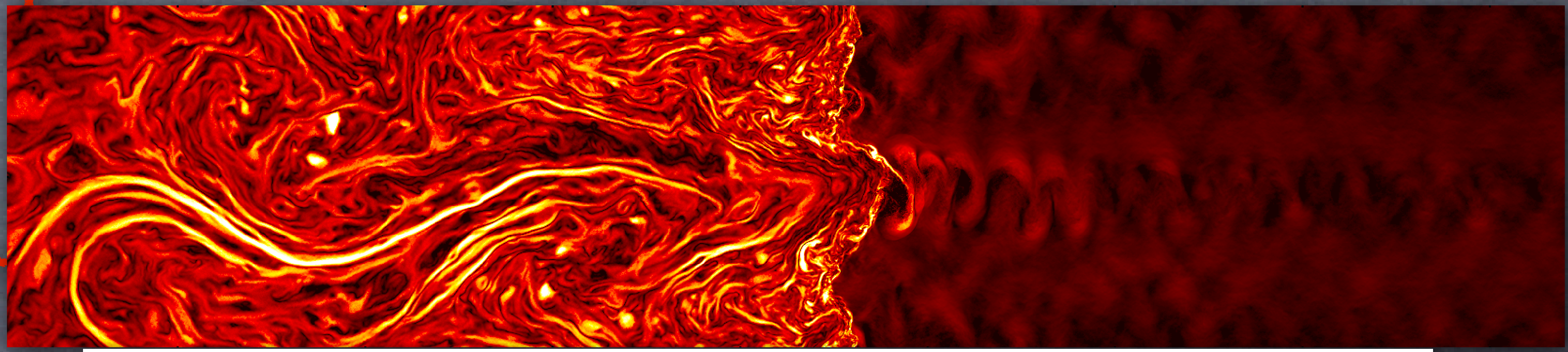
- Reflection probability ~ barrier duty cycle (~25%)
- To overrun the shock, ions need a minimum energy E_{inj}, increasing with ϑ, which they may achieve via multiple SDA cycles
- After N cycles, only a fraction $\eta \sim 0.25^N$ has not been advected
  - For $\vartheta \lesssim 45^\circ$, $E_{inj} \lesssim 10E_{sh}$, which requires $N \lesssim 3 \rightarrow \eta \sim 1\%$
  - For $\vartheta > 45^\circ$, $E_{inj} > 10E_{sh}$, hence $N > 3$ and $\eta << 1\%$

DC, Pop & Spitkovsky, 2015

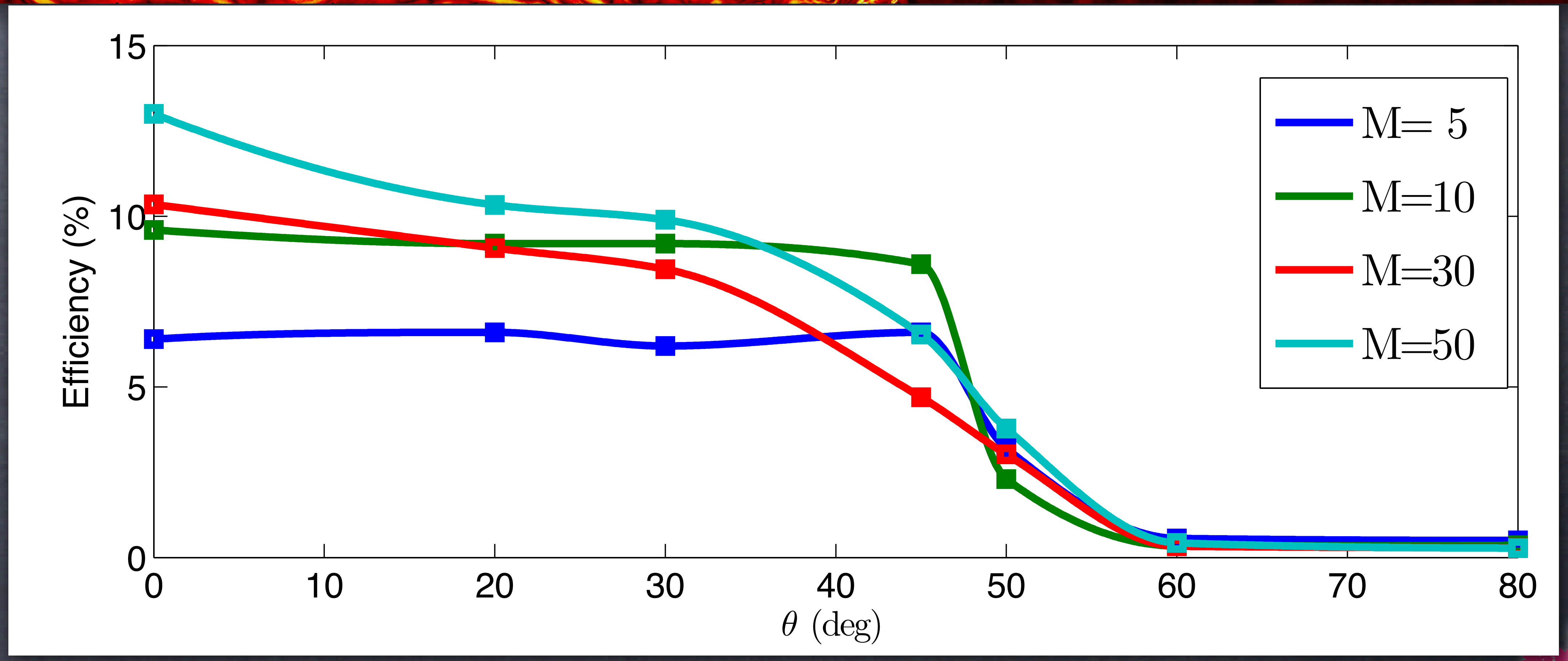
Hybrid Simulations: Summary

- DSA efficient at q-parallel, strong shocks
- CRs amplify B via streaming instability
- Injection of thermal ions at q-parallel shocks via specular reflection and SDA





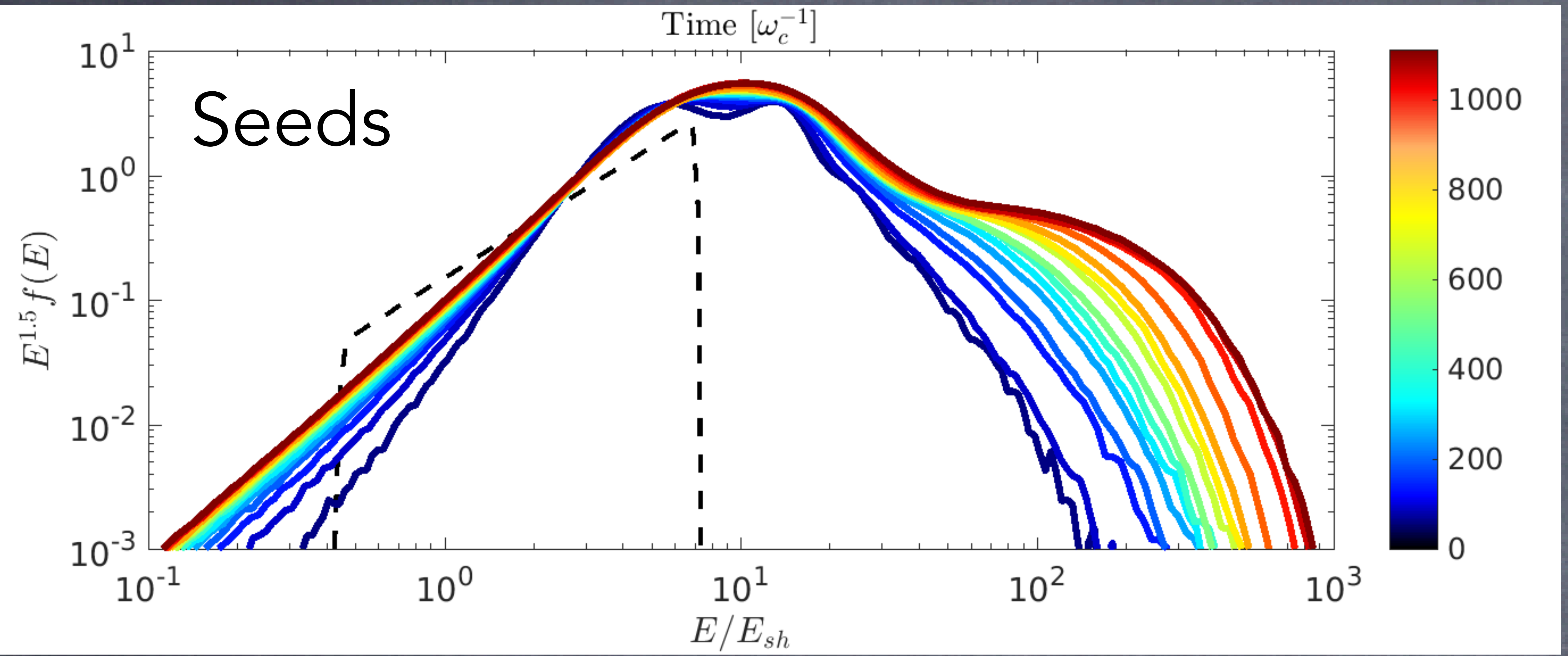
- What if there are already energetic seeds?
- How does injection depend on mass/charge?

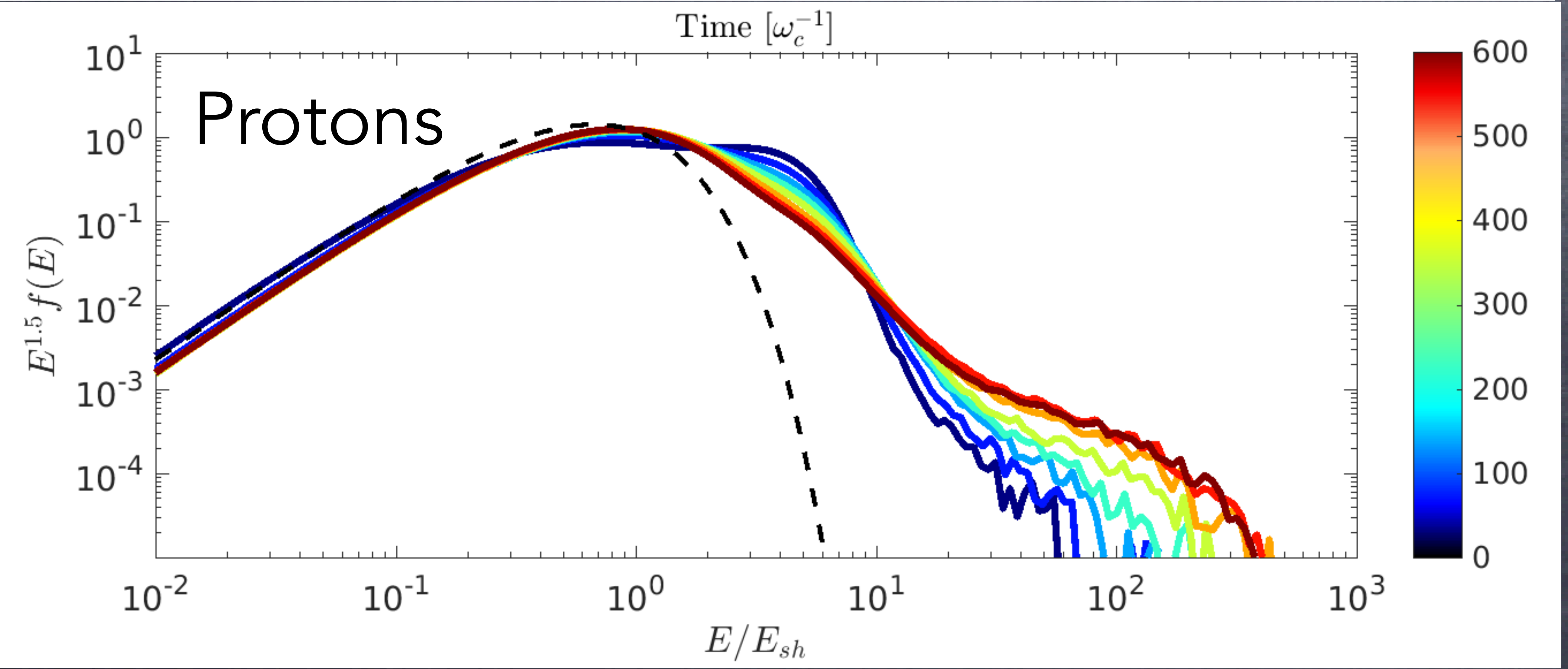


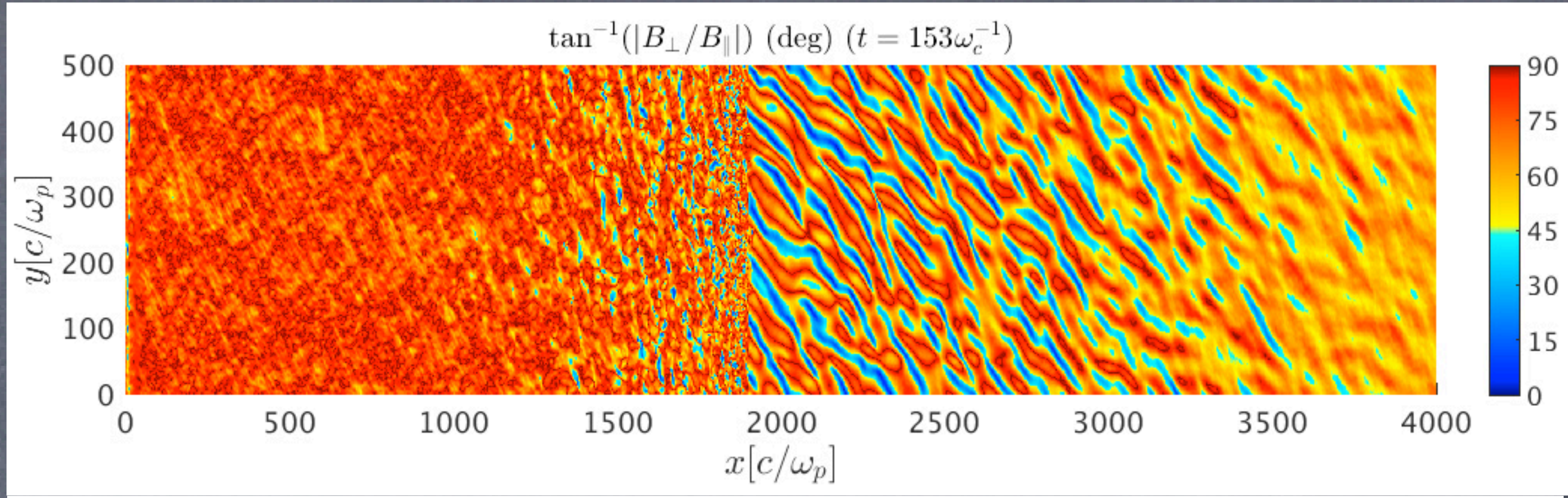
What if there are already energetic particles (seeds)?

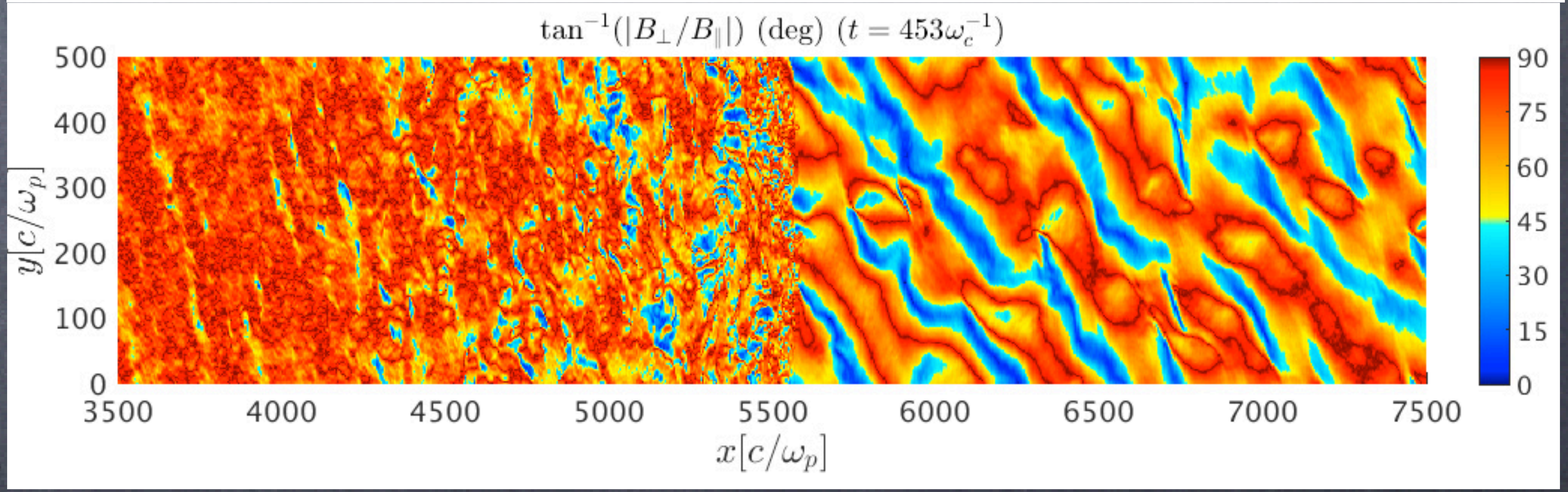
Diffusive Shock Re-Acceleration

- ϑ=60° shock with isotropic seeds E_{CR}=10E_{sh} ; n_{CR}=0.01 (DC, Zhang, Spitkovsky, JPP submitted)
  - Seeds are effectively reflected at the shock, amplify the upstream B, and undergo DSA: DSRA!



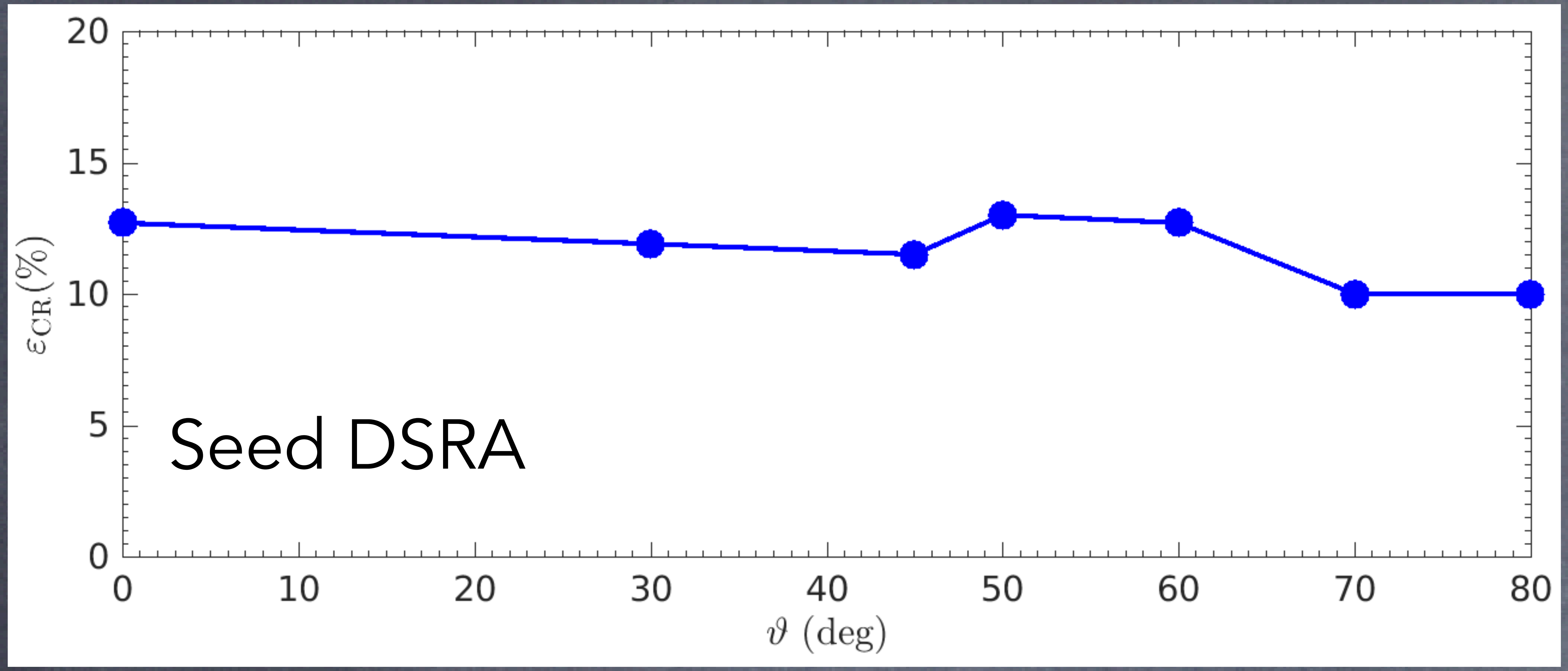


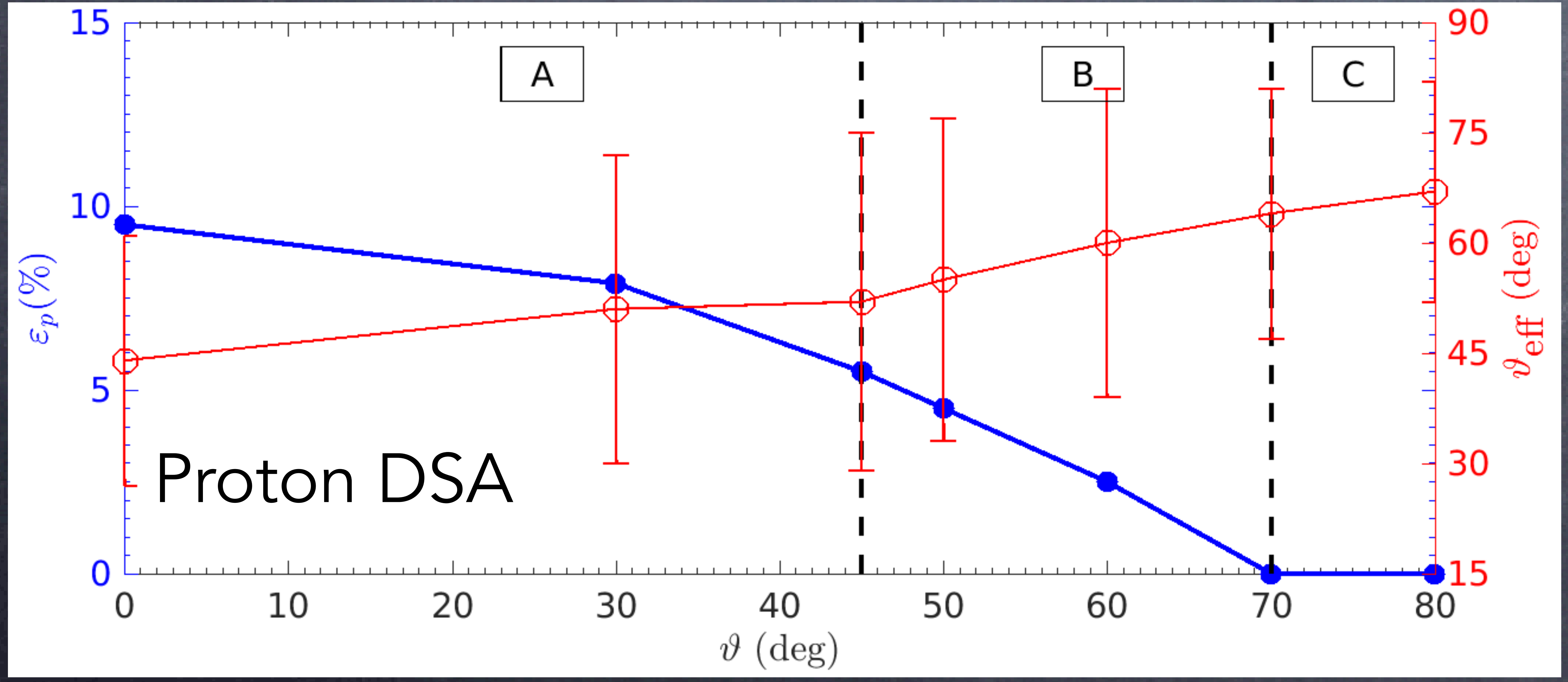




B-amplification opens up quasi-parallel patches at the shock where protons can be injected

Efficiency



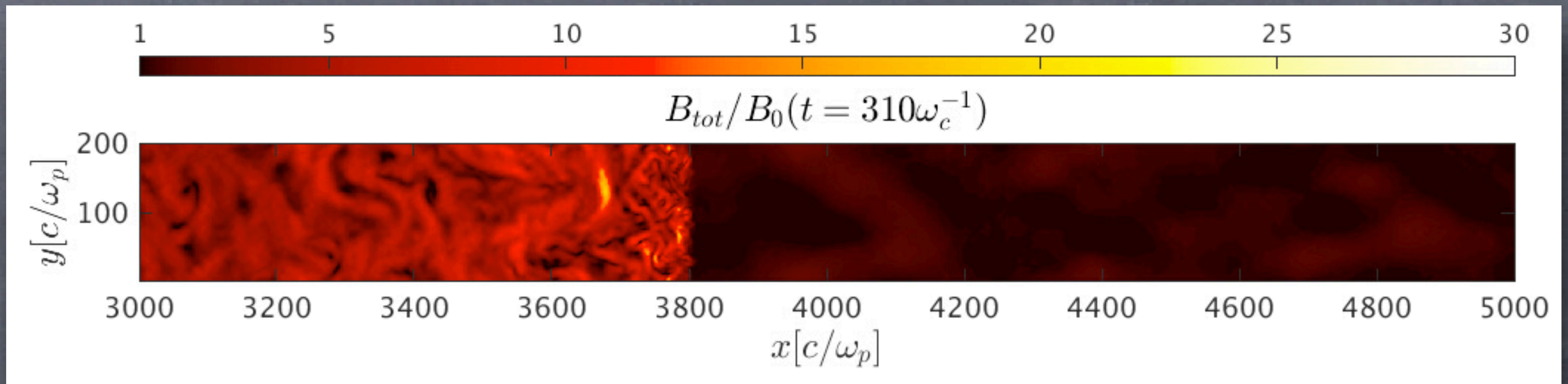


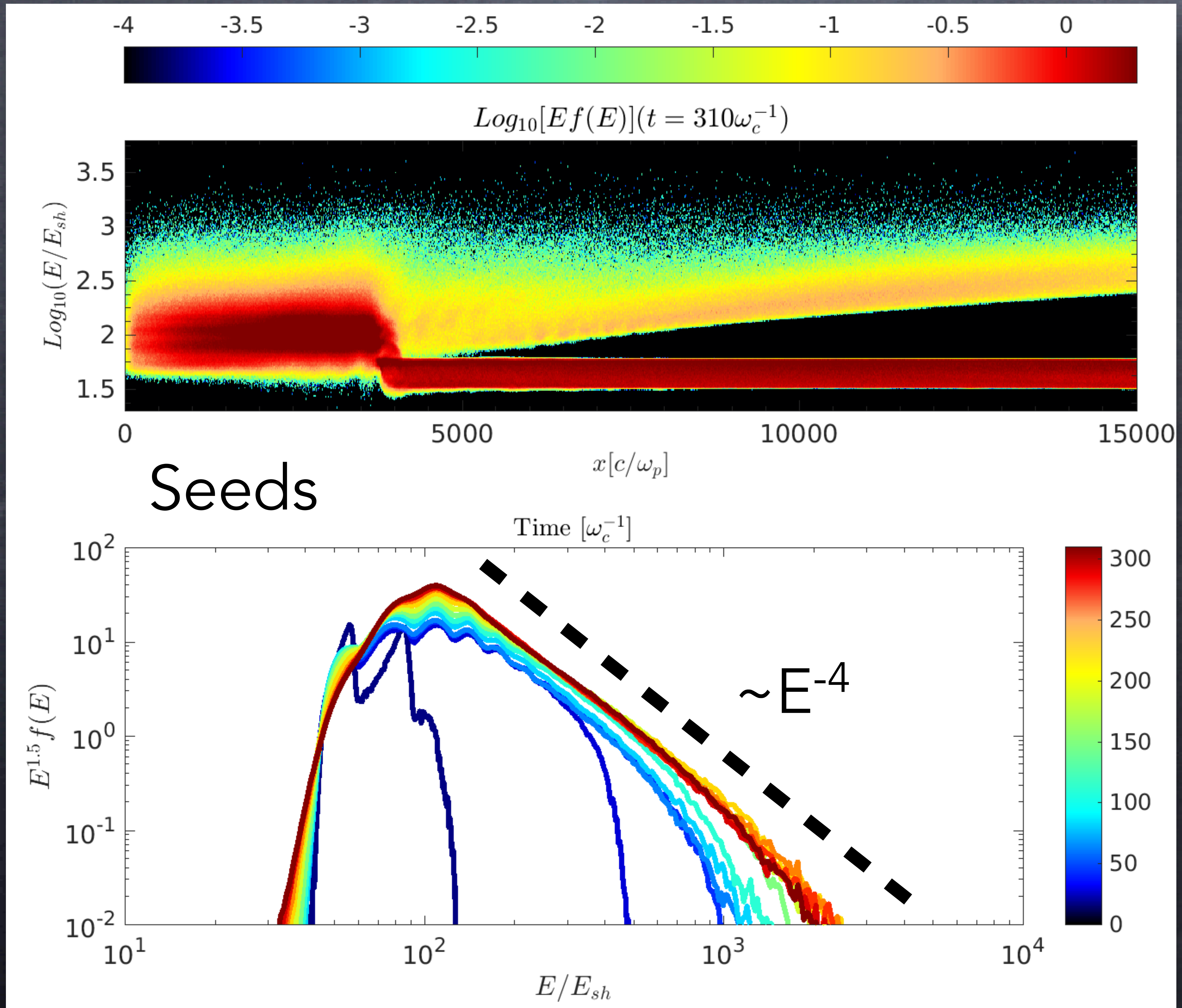
- Seed DSRA independent of ϑ, about 4x the initial energy density
- Also electrons are reaccelerated!

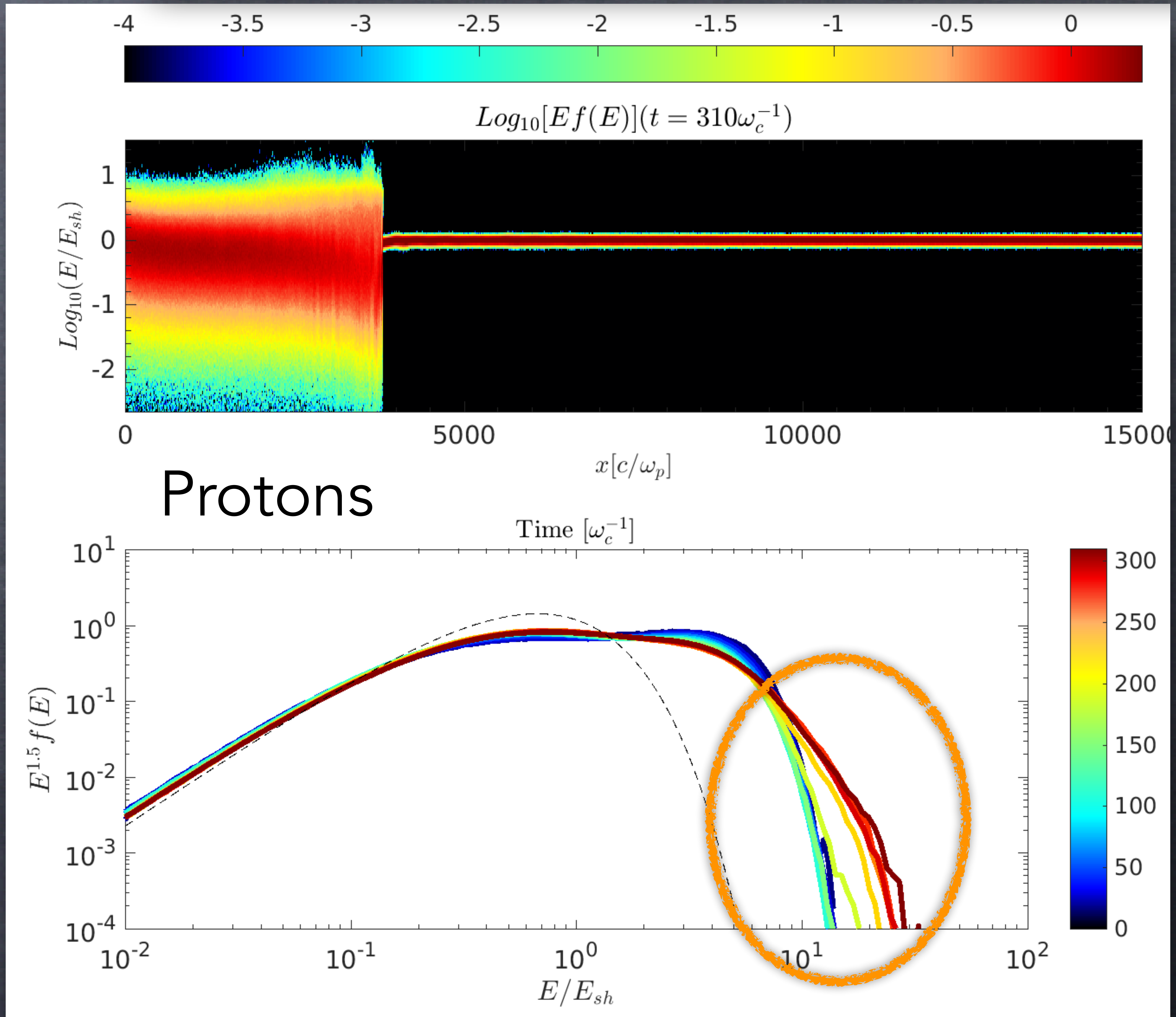
- A ($\vartheta<45°$): As without seeds
- B ($45°<\vartheta<70°$): Boosted to few %
- C ($\vartheta>70°$): No proton DSA

Quasi-Perpendicular SEEDED Shocks

- ϑ=80° quasi-perp shock with seeds E_{CR}=10E_{sh}
  - Seeds diffuse but their spectrum is steeper than DSA
  - Non-thermal protons only downstream







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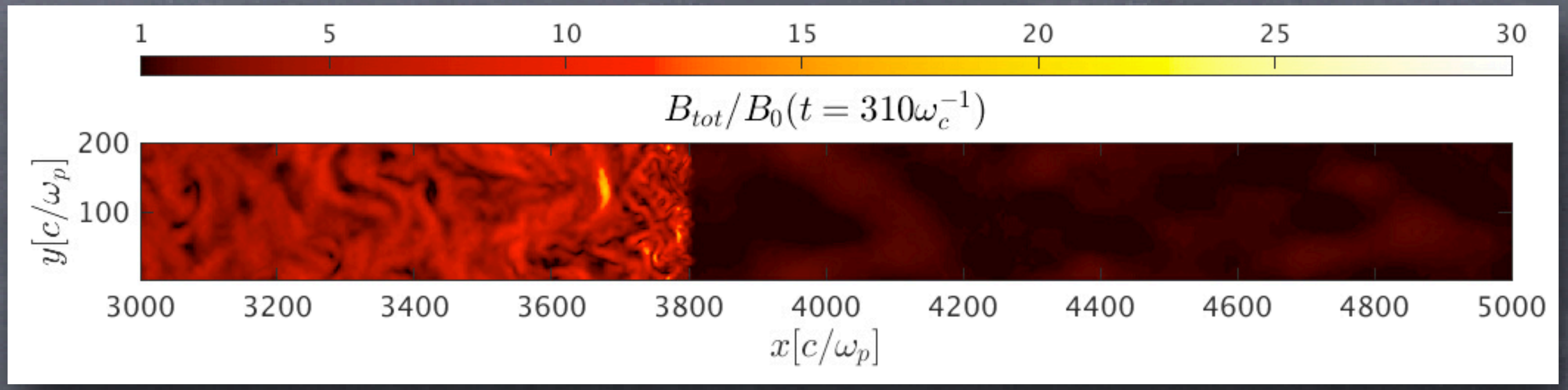
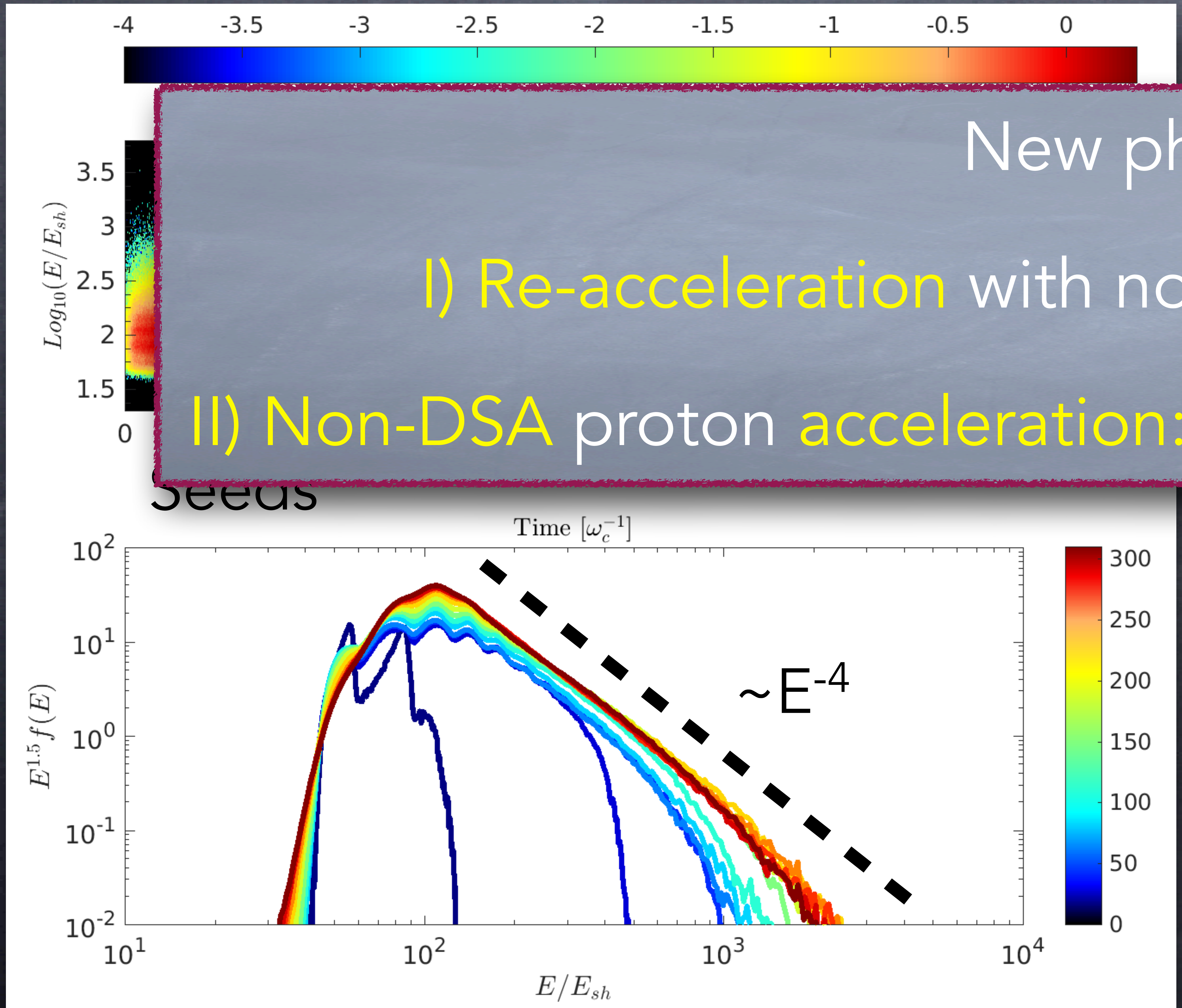
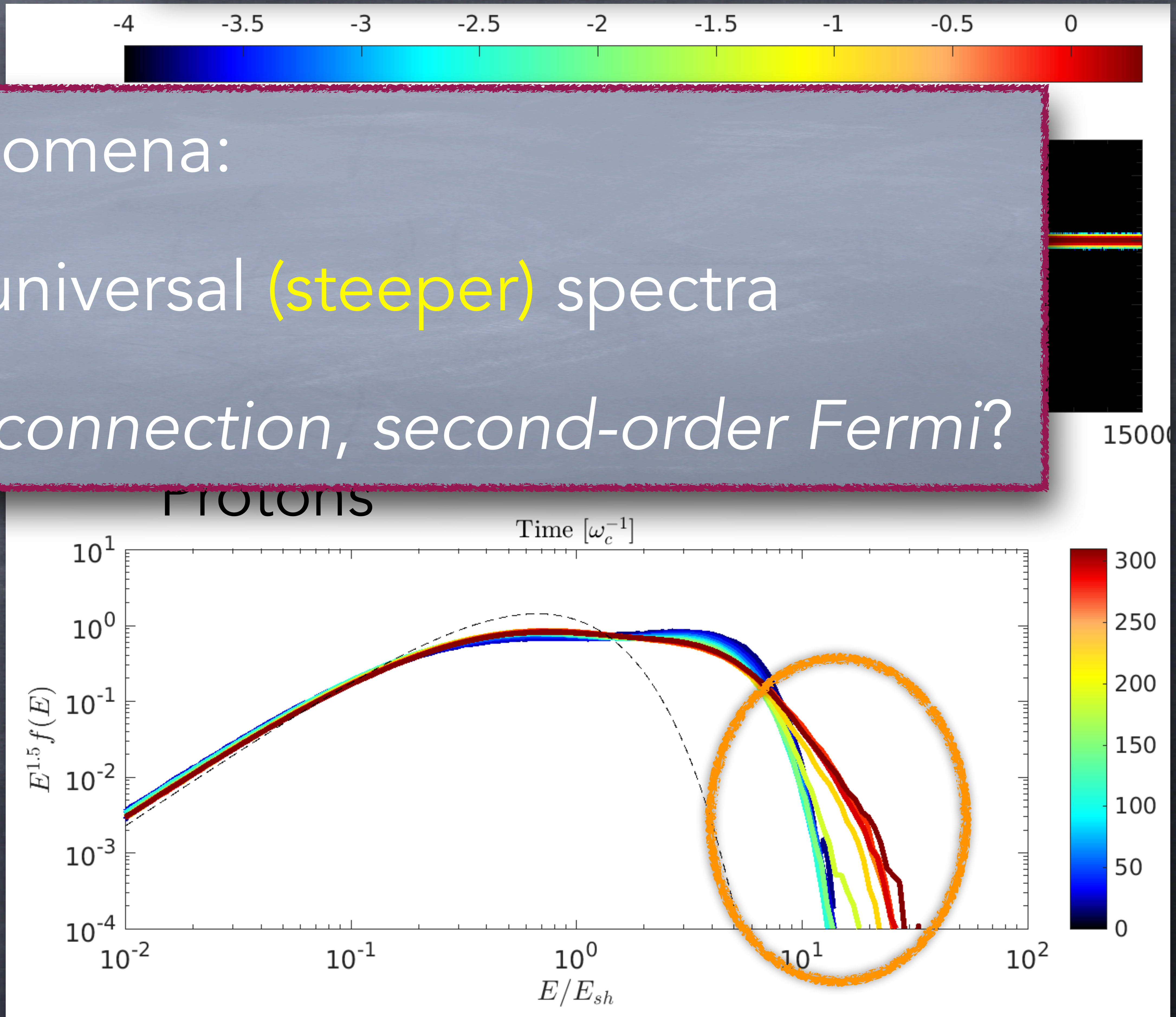






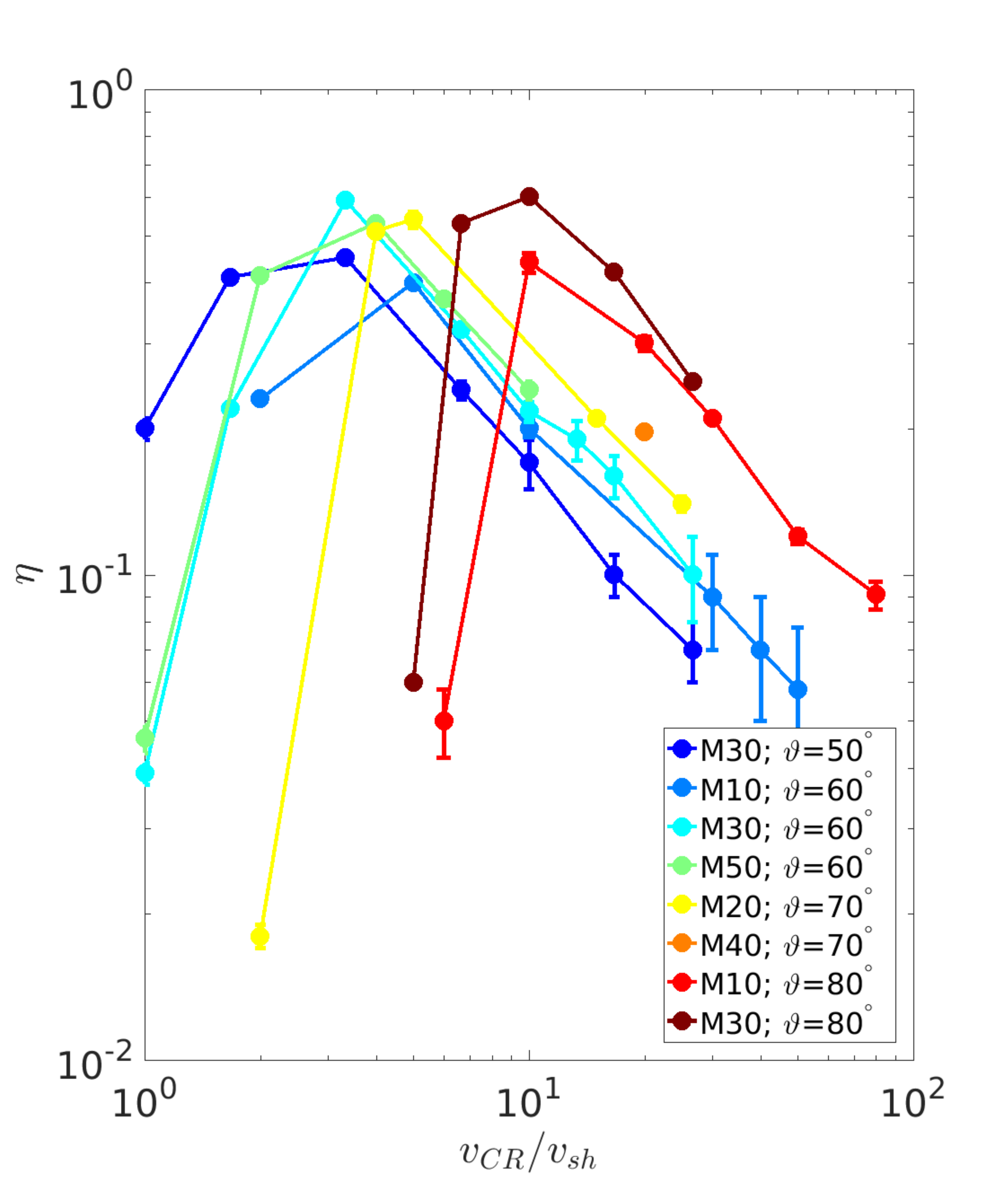
New phenomena:

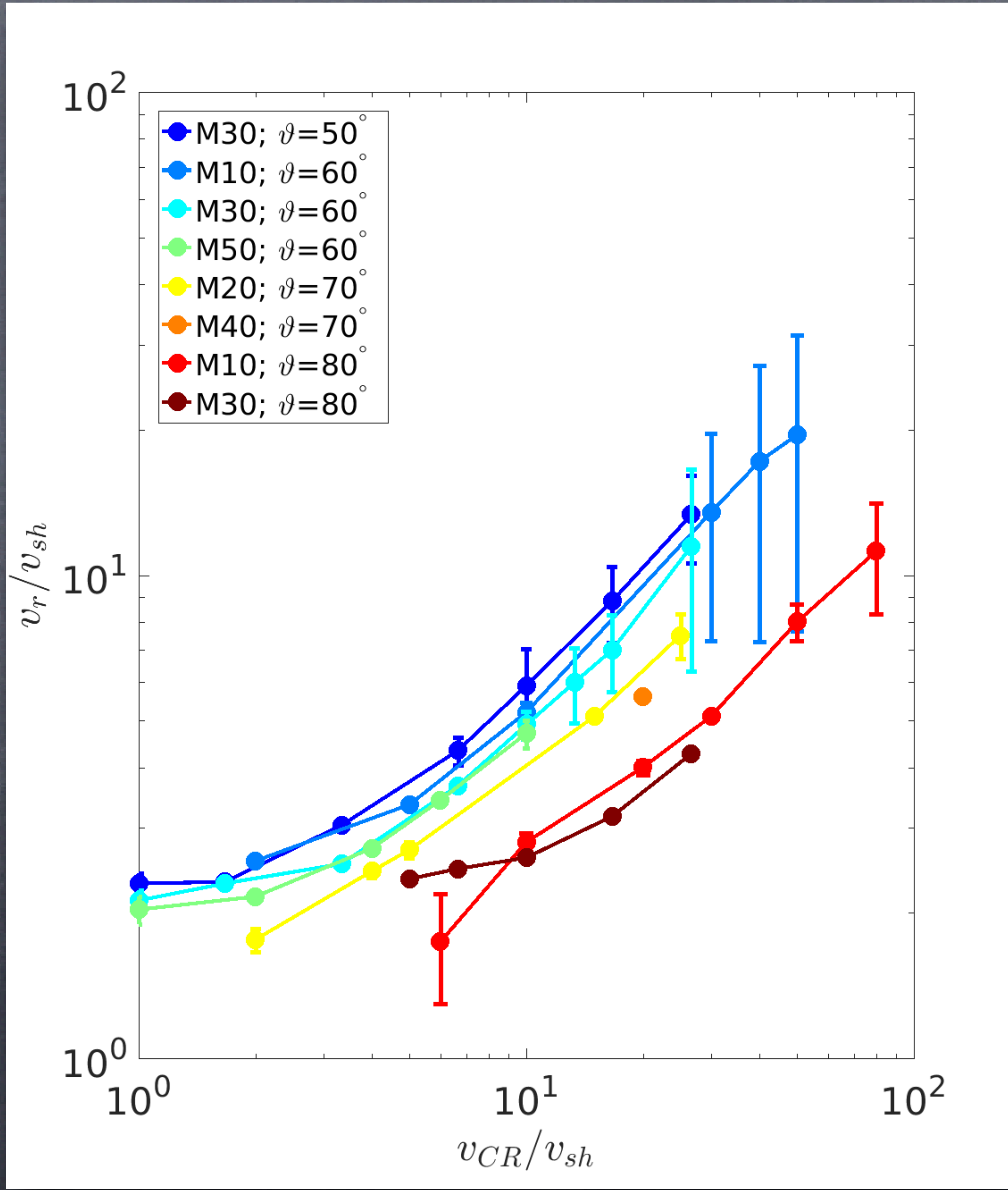
I) Re-acceleration with non-universal (steeper) spectra

II) Non-DSA proton acceleration: *reconnection, second-order Fermi*?

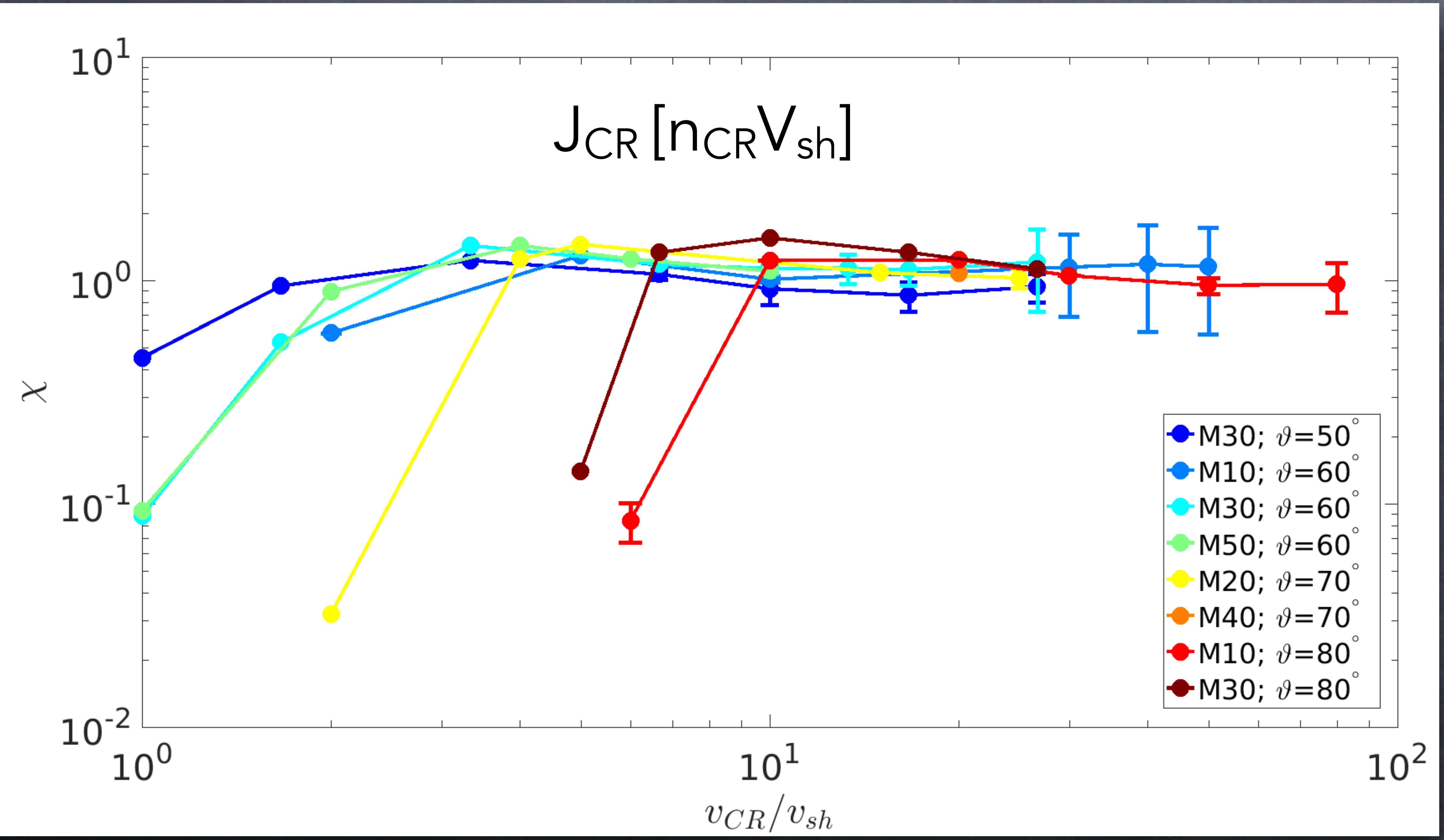
The Current in Reflected CRs

- It depends on the fraction of reflected seeds, η, and their speed, v_r





A *Universal* Current in Reflected CRs



- η and v_r balance their dependence on ϑ and M exactly:

$$J_{CR} = n_{CR}V_{sh}$$

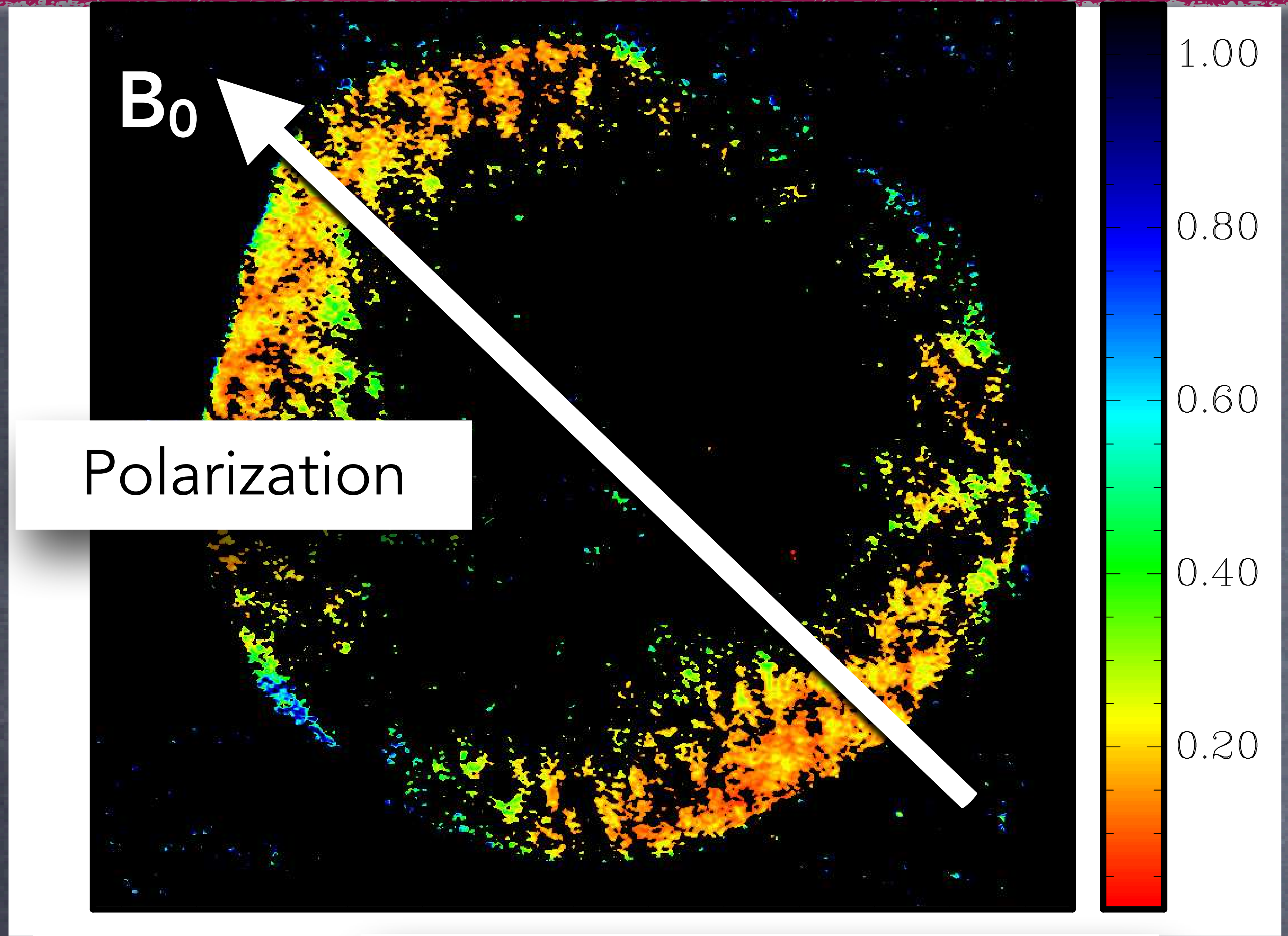
- Easy explanation: CR anisotropy conserved at the shock crossing, in the shock frame

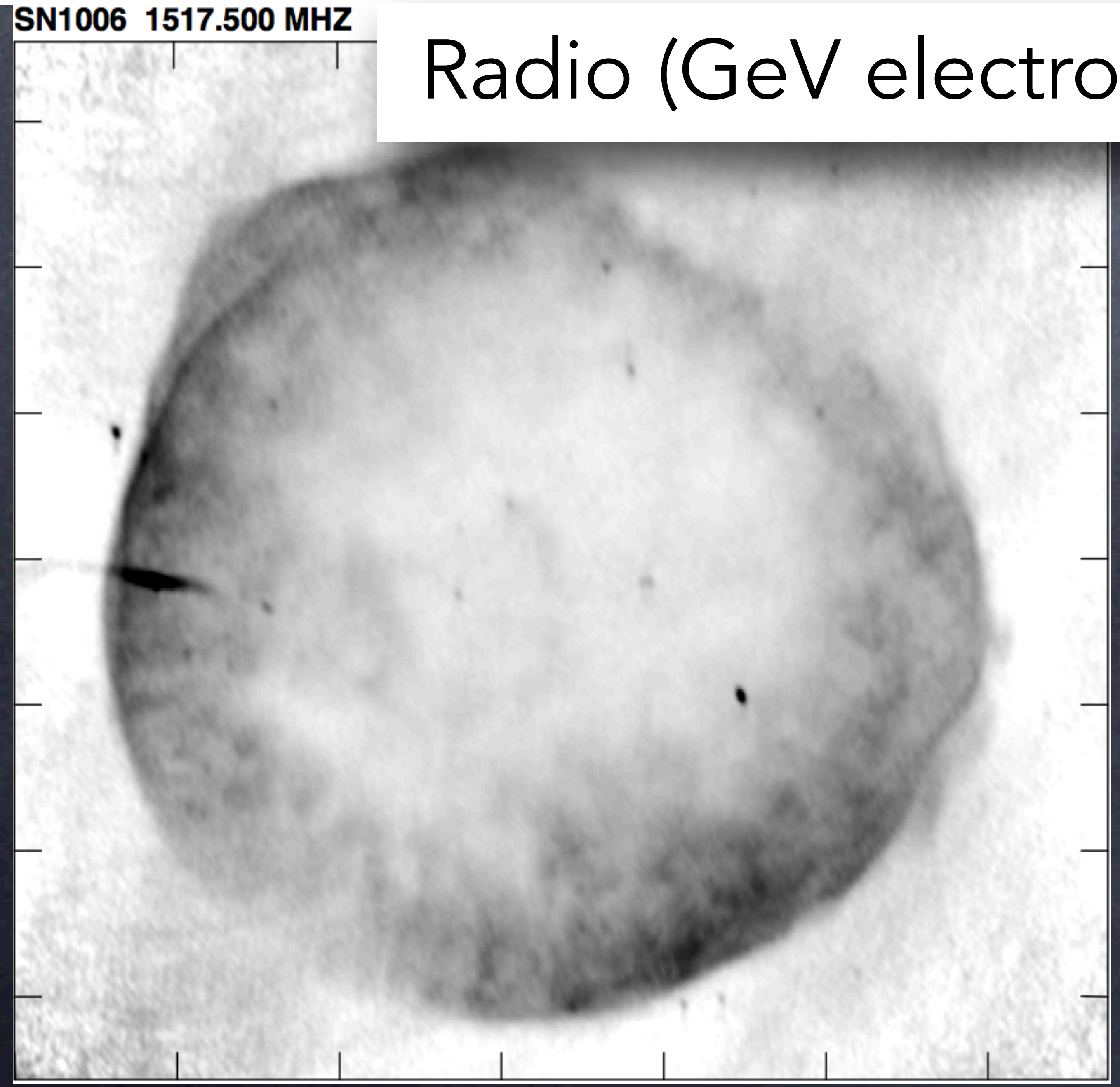
- For SNRs and Galactic CRs:

$$T_{Bell} \sim 10\text{yr}$$

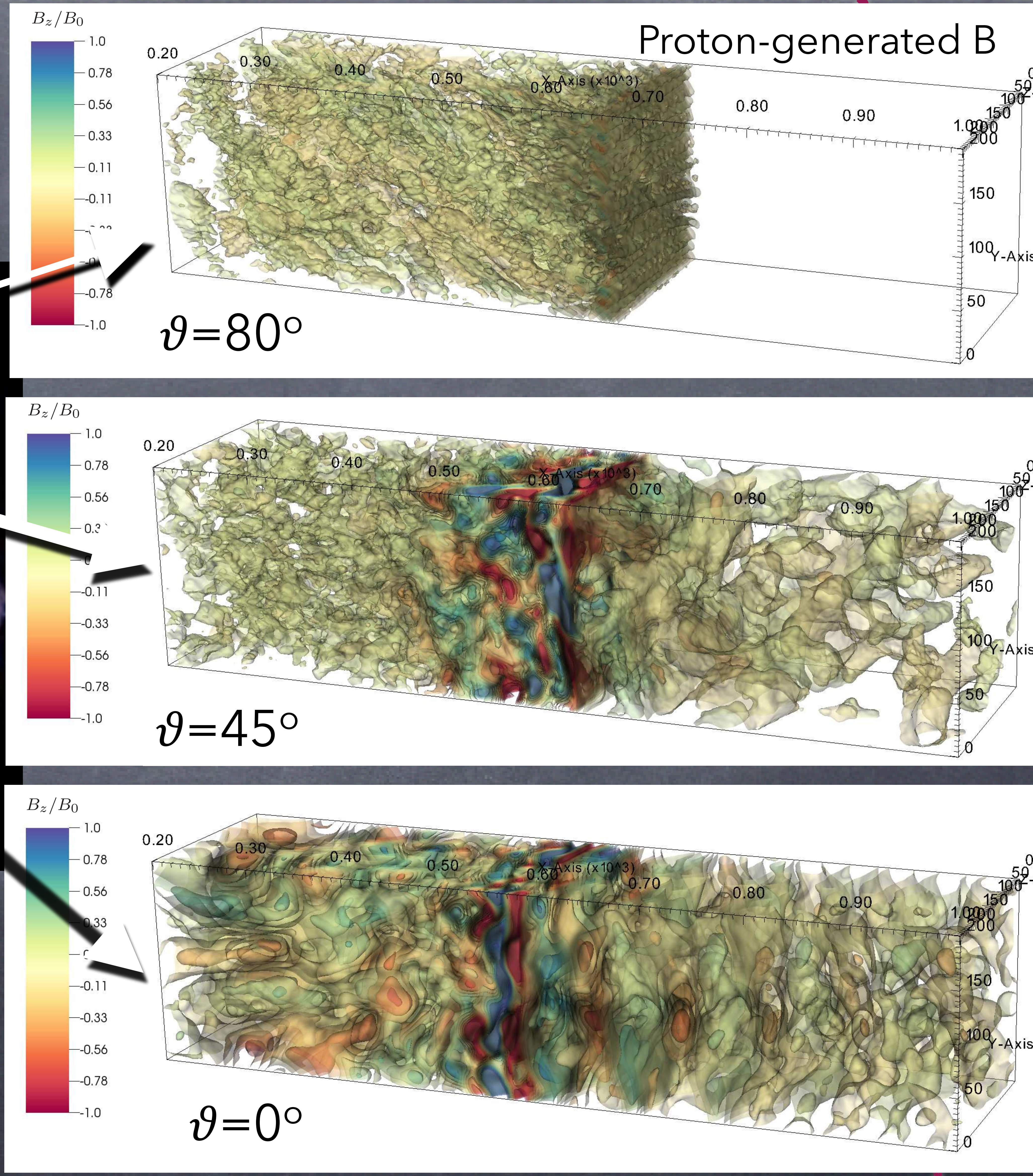
Minimum level of B-amplification for shocks in the ISM

SN 1006





X-rays. Red: thermal
White: synchrotron
(TeV electrons)



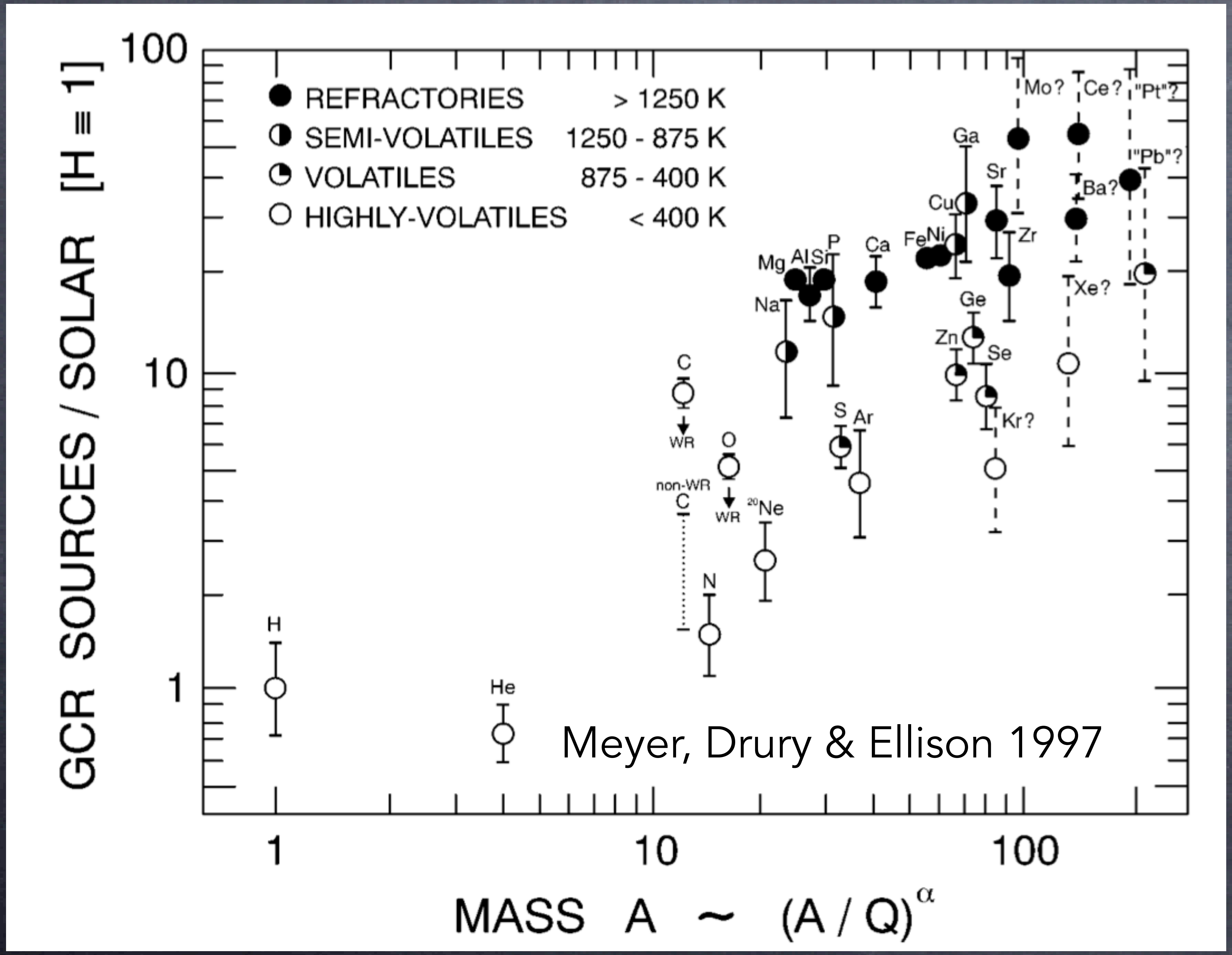
TeV acceleration only where quasi-par, but seed DSRA can produce *GeV* electrons where oblique/quasi-perp

DC & Spitkovsky, 2014a

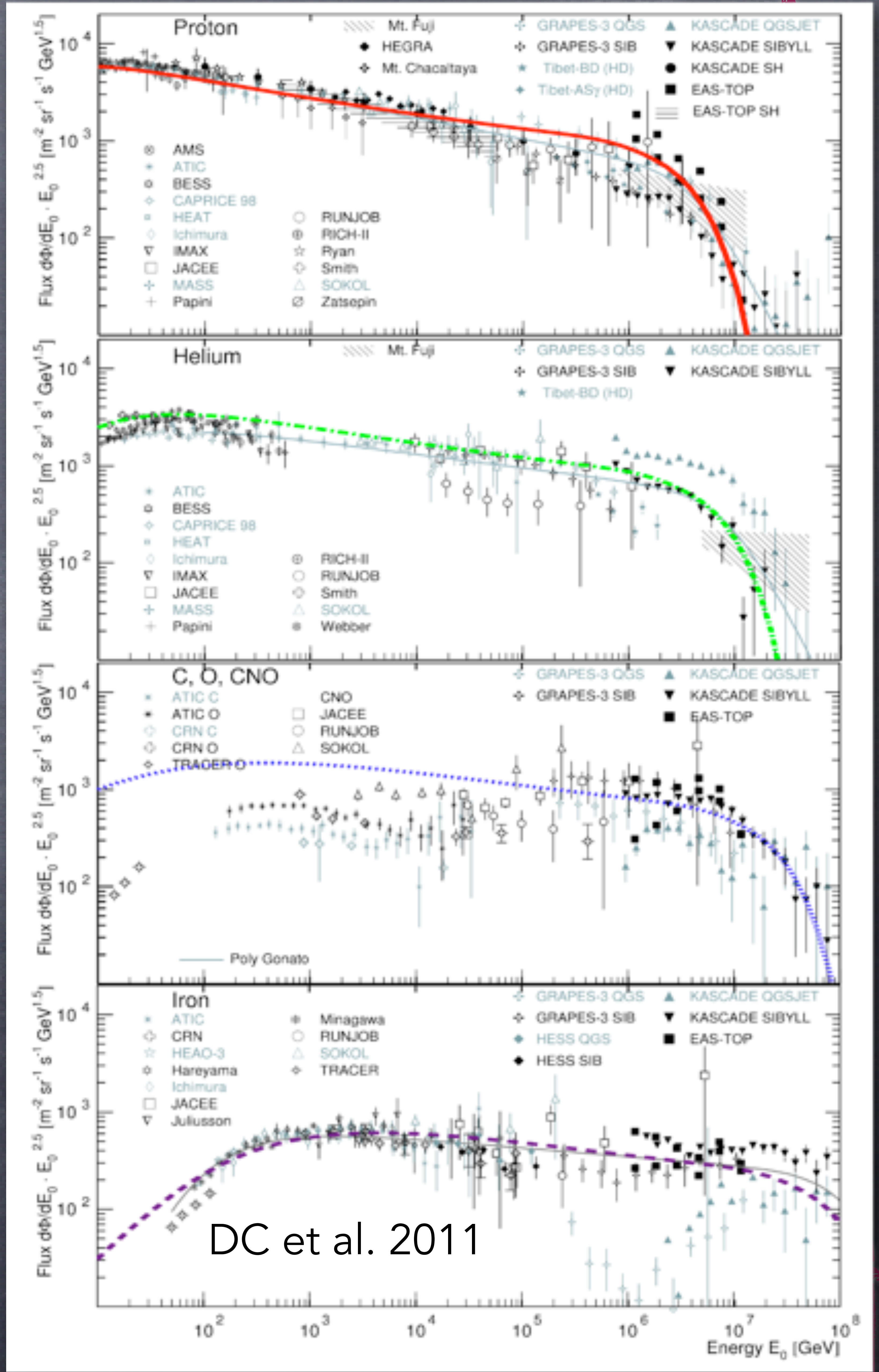
How does DSA depend on the ion mass/charge ratio?

Chemical Composition of Galactic CRs

- “Urban legend”: similar to solar (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!

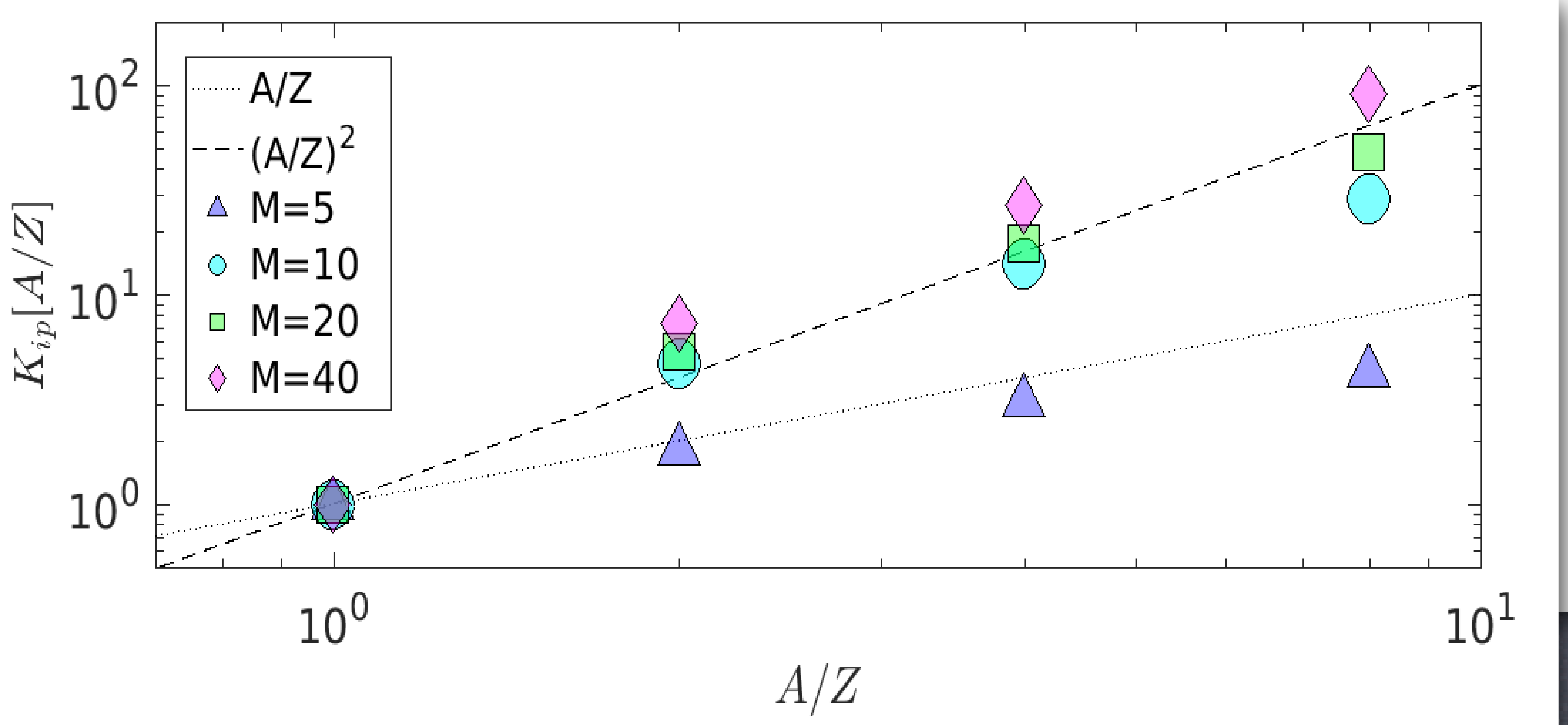


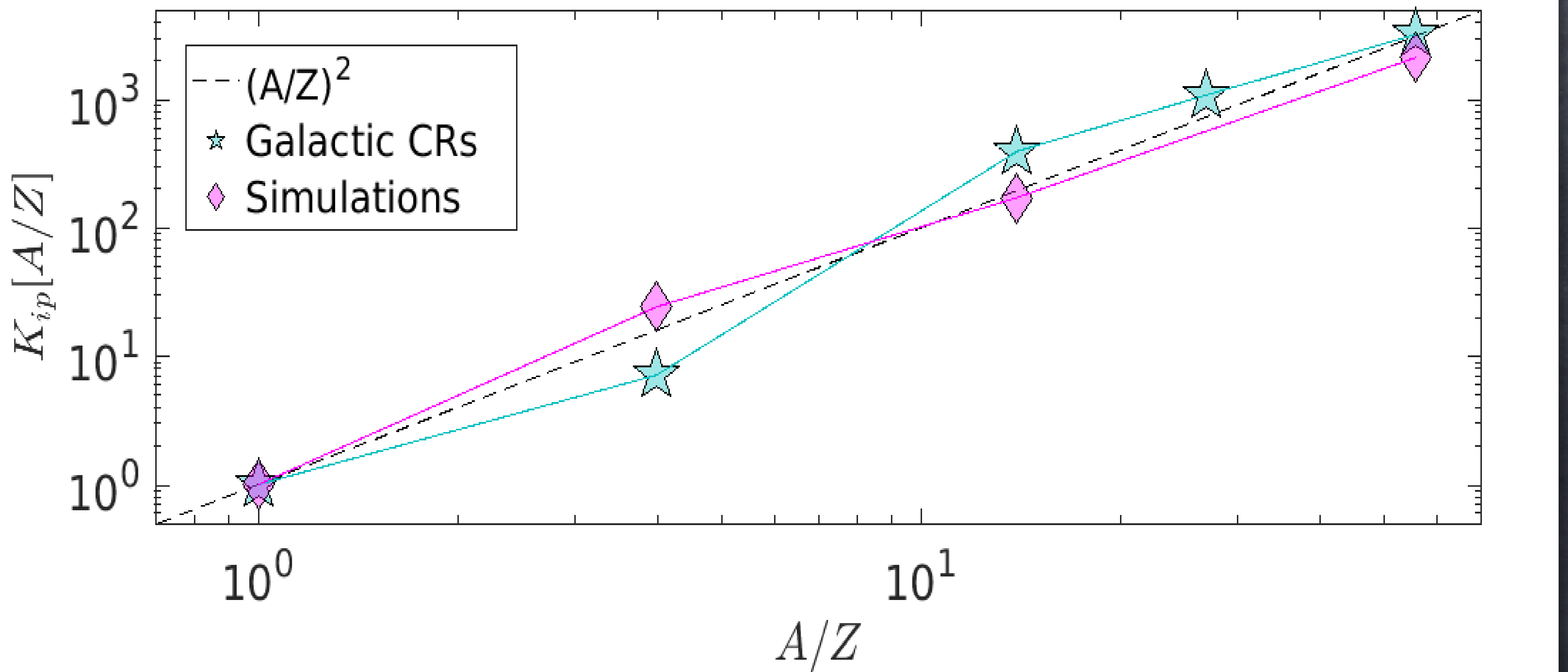
Nuclei heavier than H must be injected more efficiently

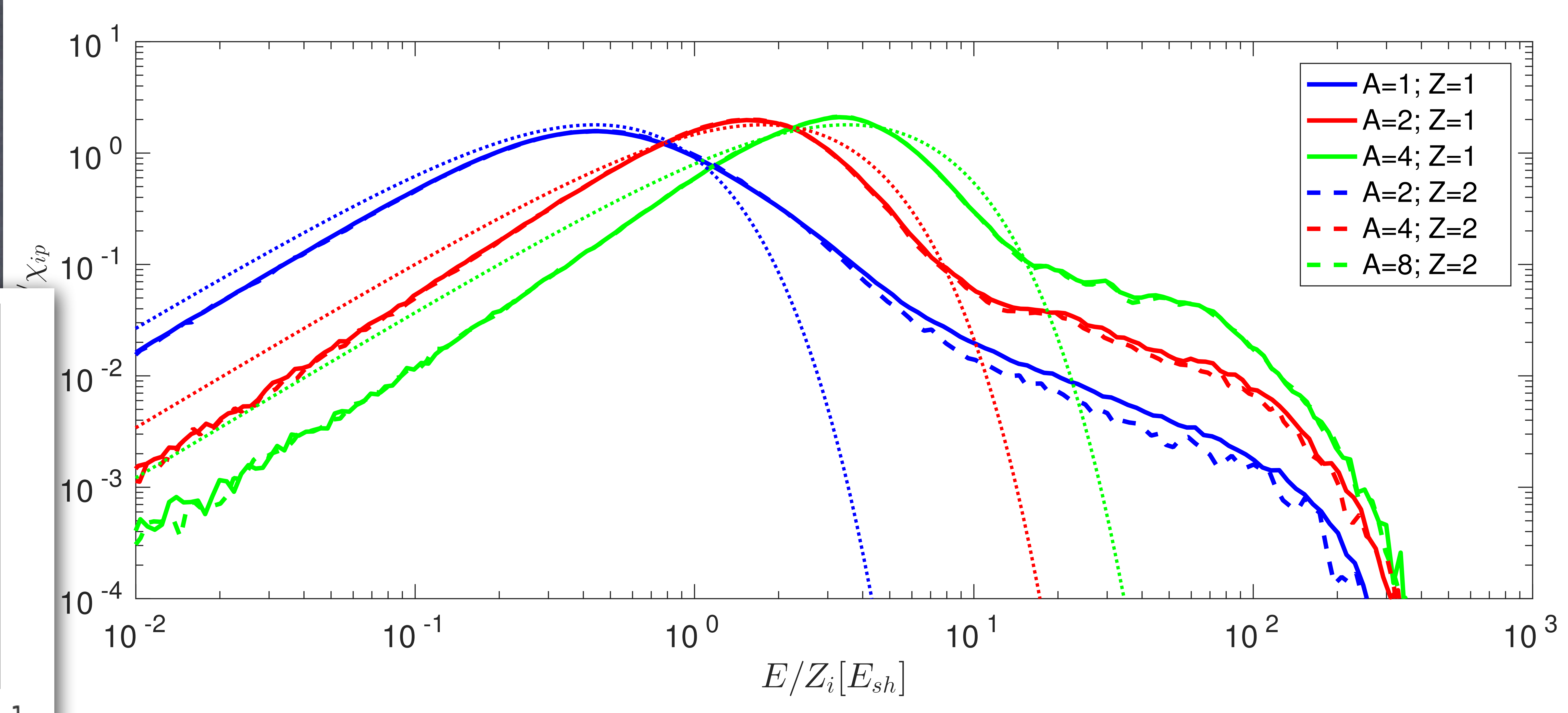


Hybrid Simulations: Acceleration of Heavy Ions

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



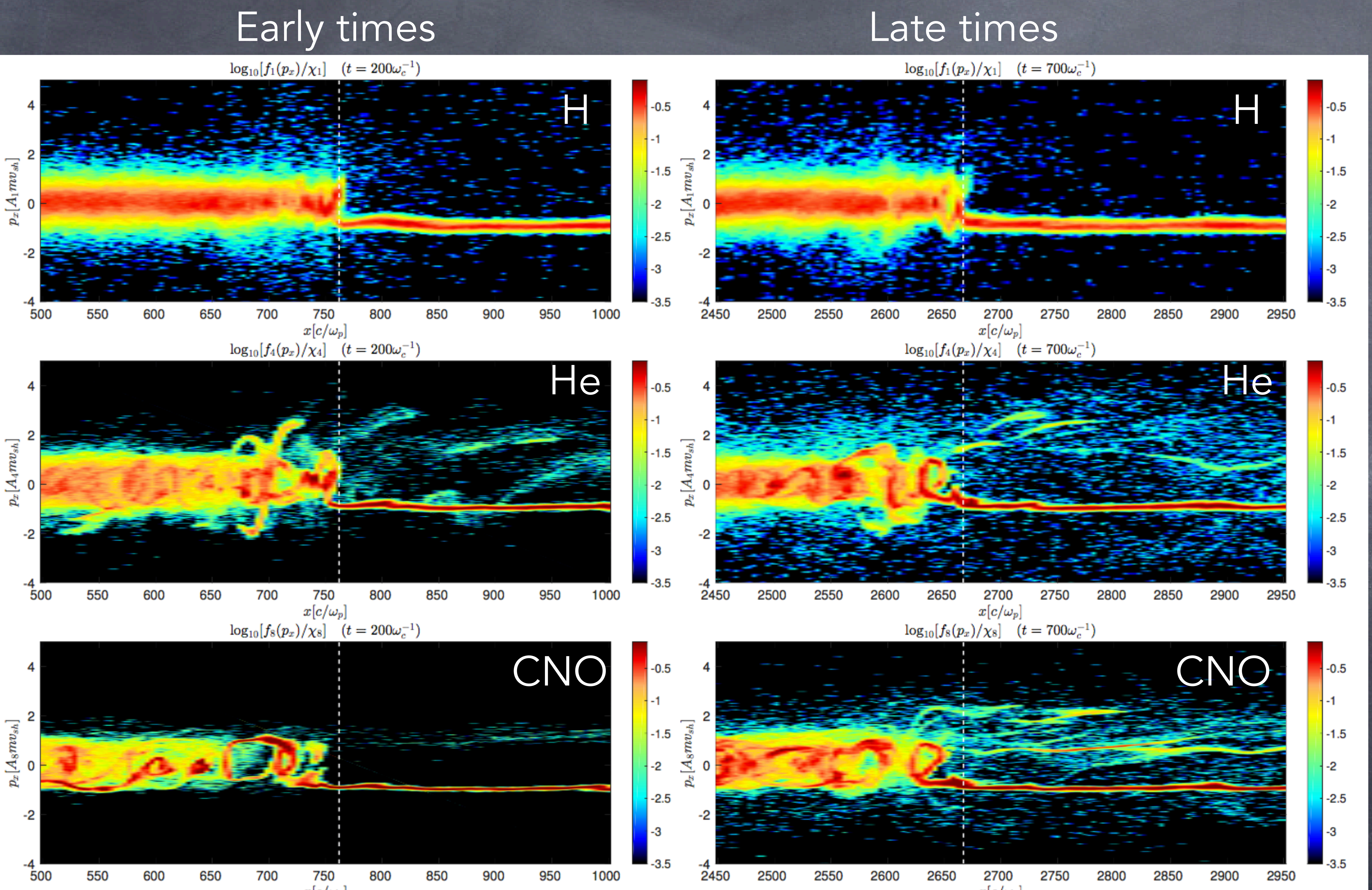




DC, Yi & Spitkovsky, 2017

- 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 GCR chemical enhancements

The Onset of Ion Acceleration

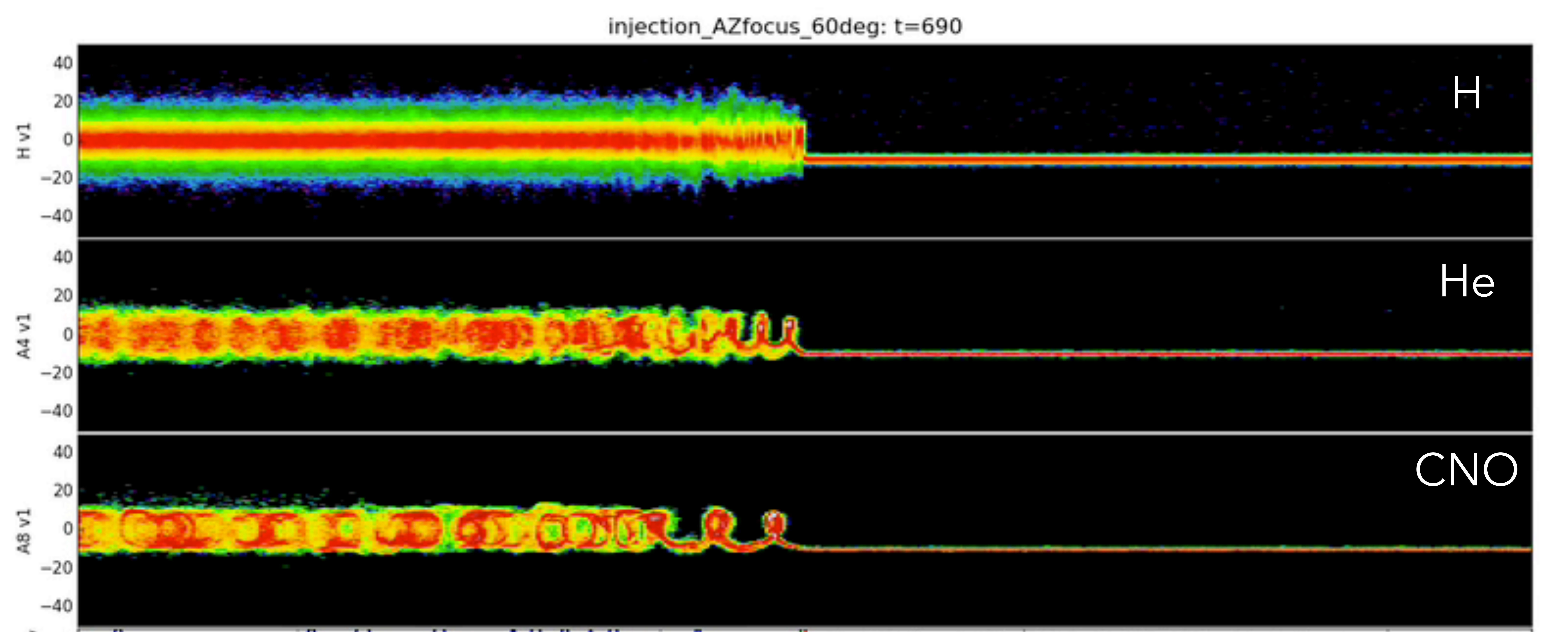


- M=20, parallel, with singly-ionized nuclei
- Ions injected by being isotropized just downstream: no shock reflection!
- Heavy ion injection after the onset of self-generated B turbulence

DC, Yi, Spitkovsky 2017

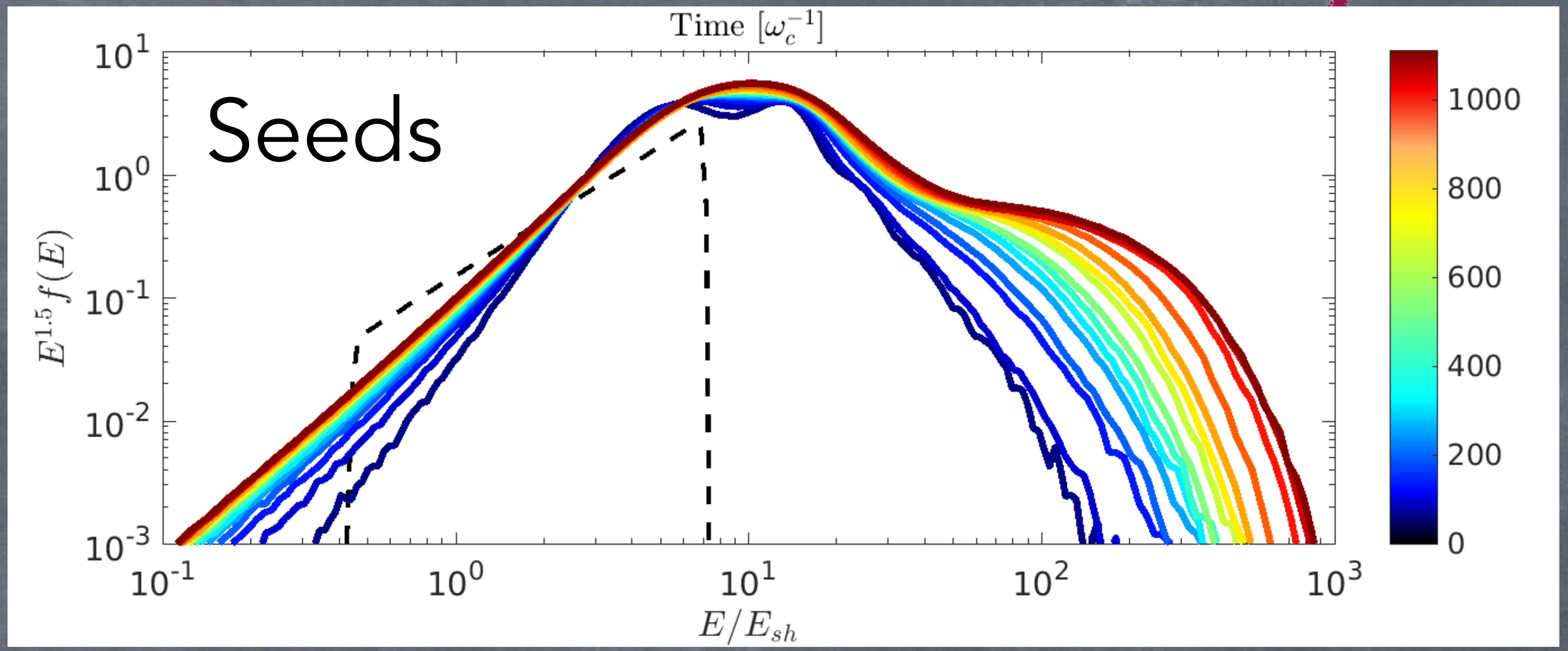
No Injection at Quasi-perpendicular Shocks

- M=20, oblique (ϑ=60°) shock: no injection into DSA!
  - Having a large gyroradius (large A/Z) is not sufficient for injection
  - Seed ions can still enter DSA (e.g., solar energetic particles/solar flares Tylka+05)

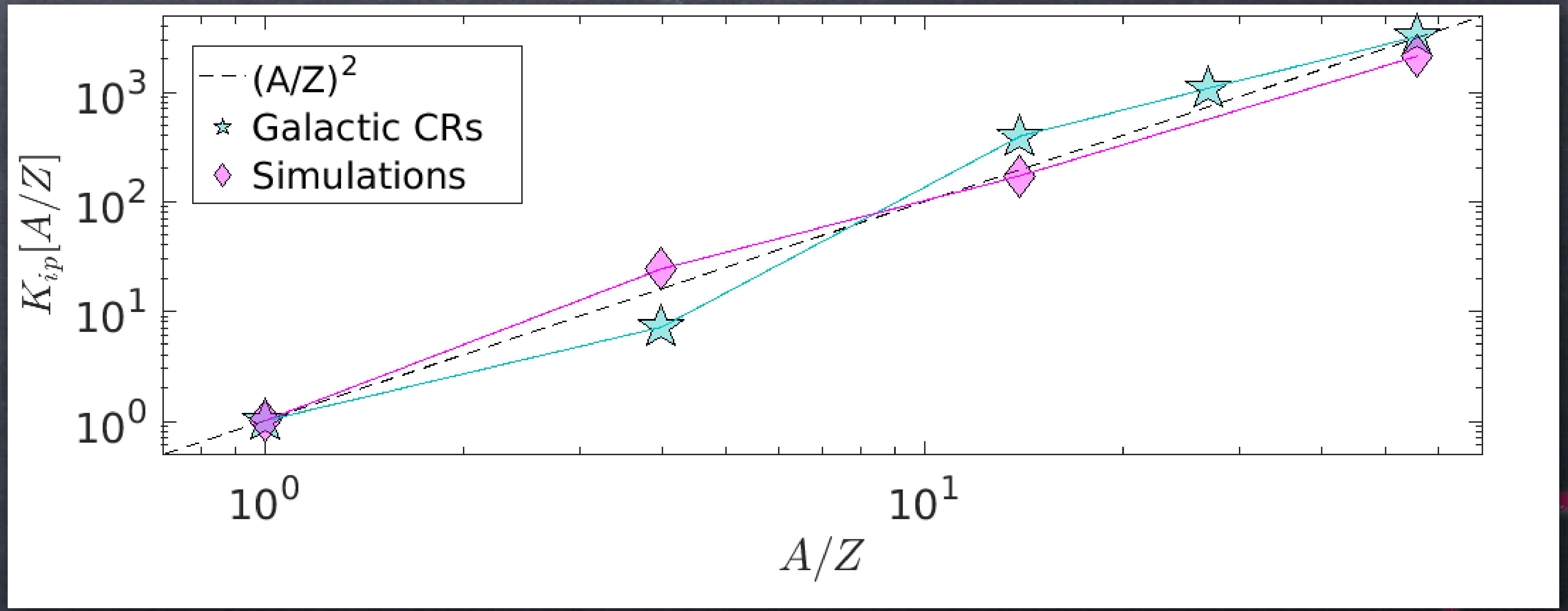


Summary

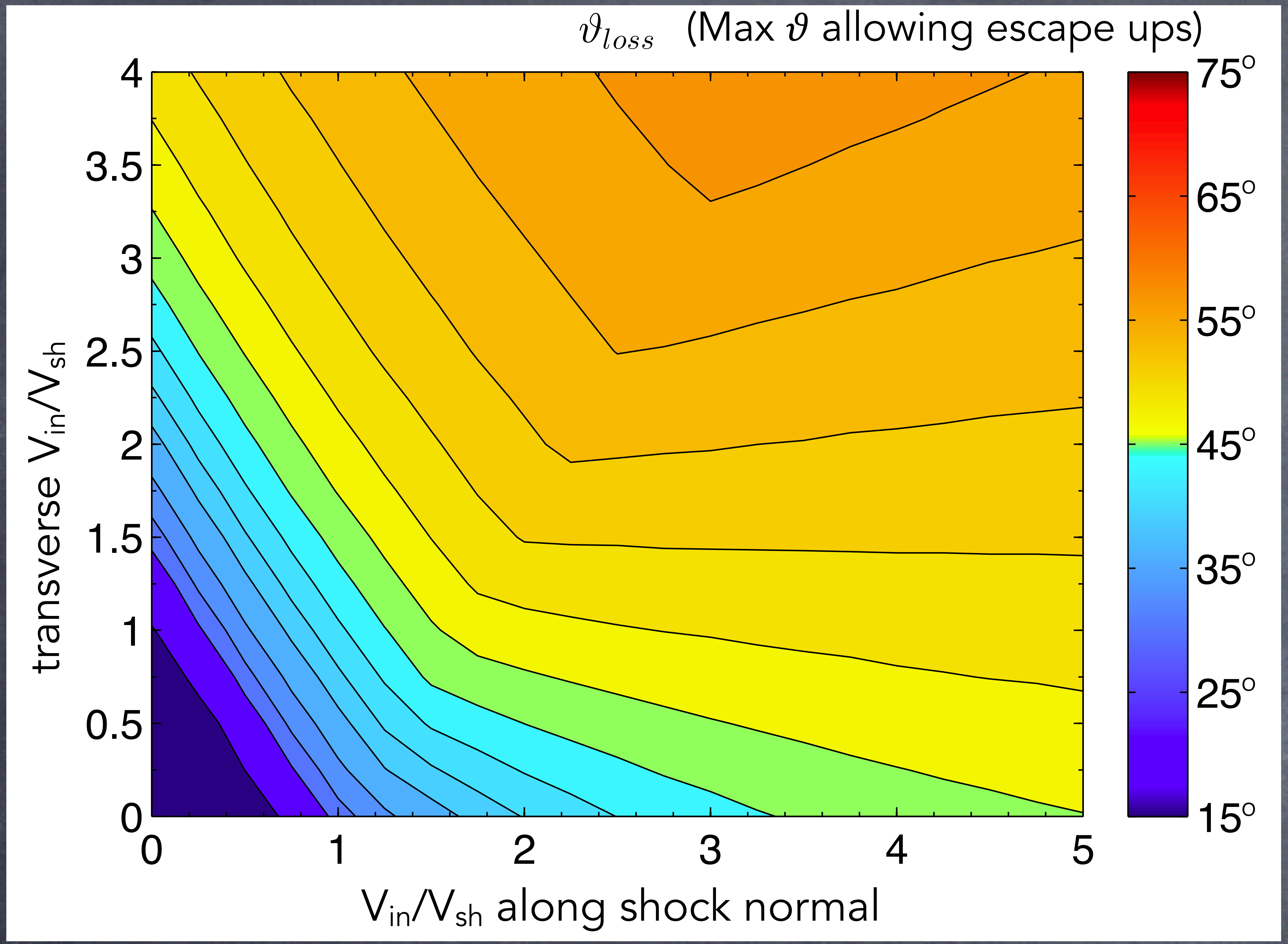
- Seed Diffusive Shock Re-Acceleration effective
  - Streaming instability with universal current $J_{CR} = n_{CR}V_{sh}$
  - Can trigger proton DSA for oblique shocks
  - New phenomena at quasi-perpendicular shocks: *steep seed spectra* & proton acceleration *downstream*!
  - CR reacceleration must happen in SNRs (e.g., W44, IC443, see Uchiyama+10, Cardillo+16)
- When proton DSA and B amplification are effective, heavy ions are preferentially injected
  - Nuclei enhancement depends on A/Z and on the shock Mach number



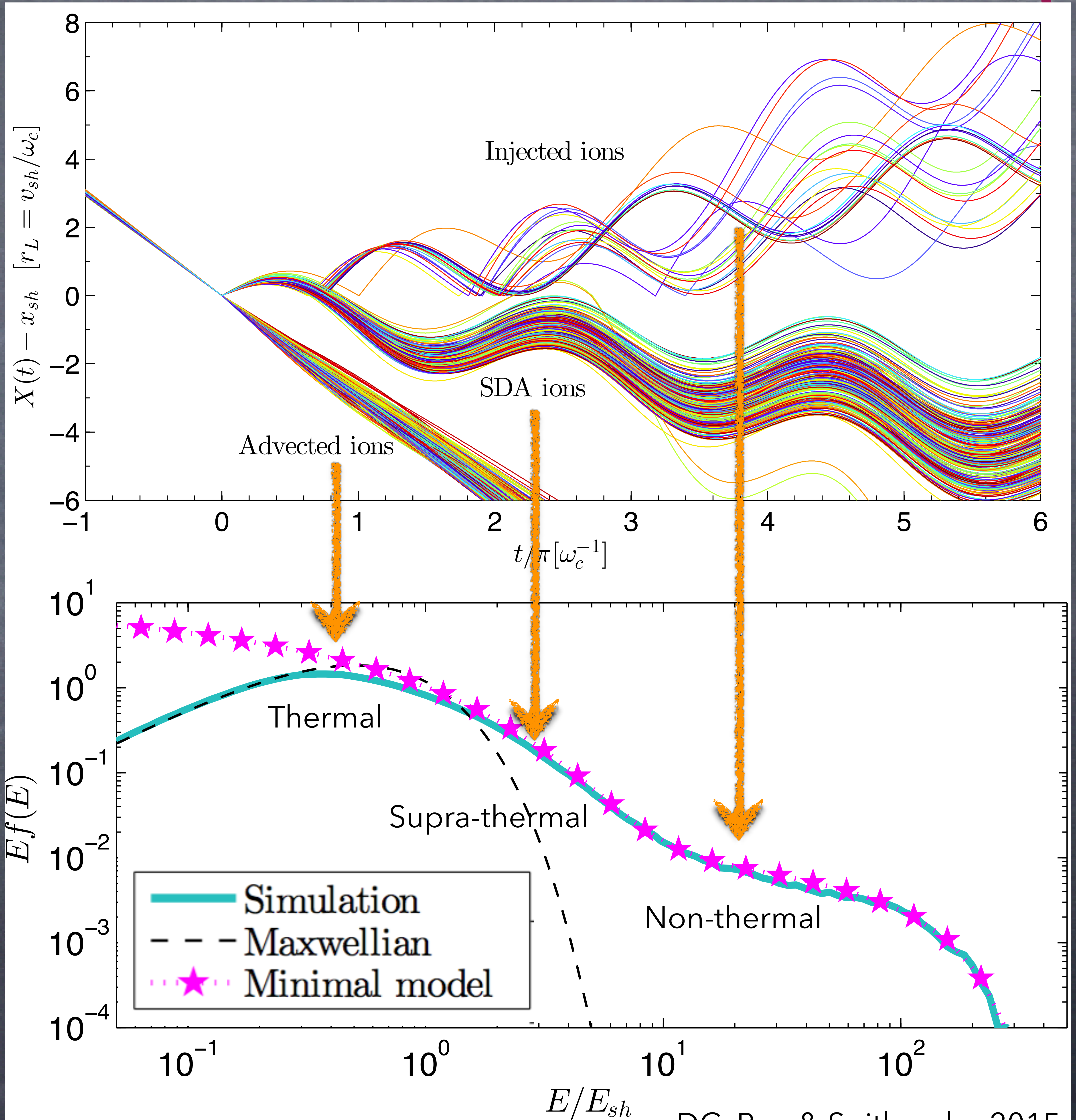
Similar phenomenology may be triggered by pre-existing magnetic turbulence



Ion Injection at Shocks: a Minimal Model



DC, Pop & Spitkovsky, 2015

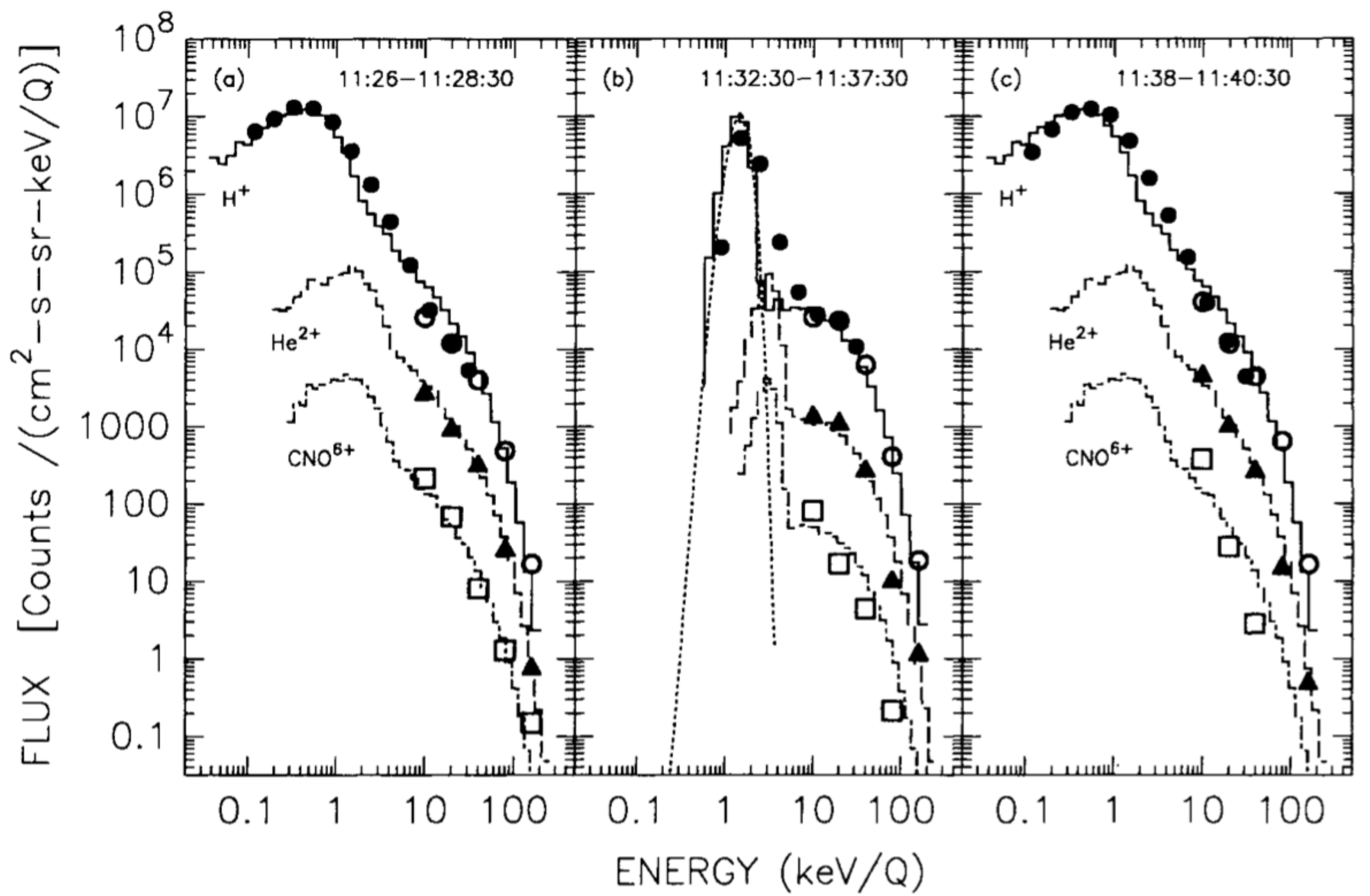


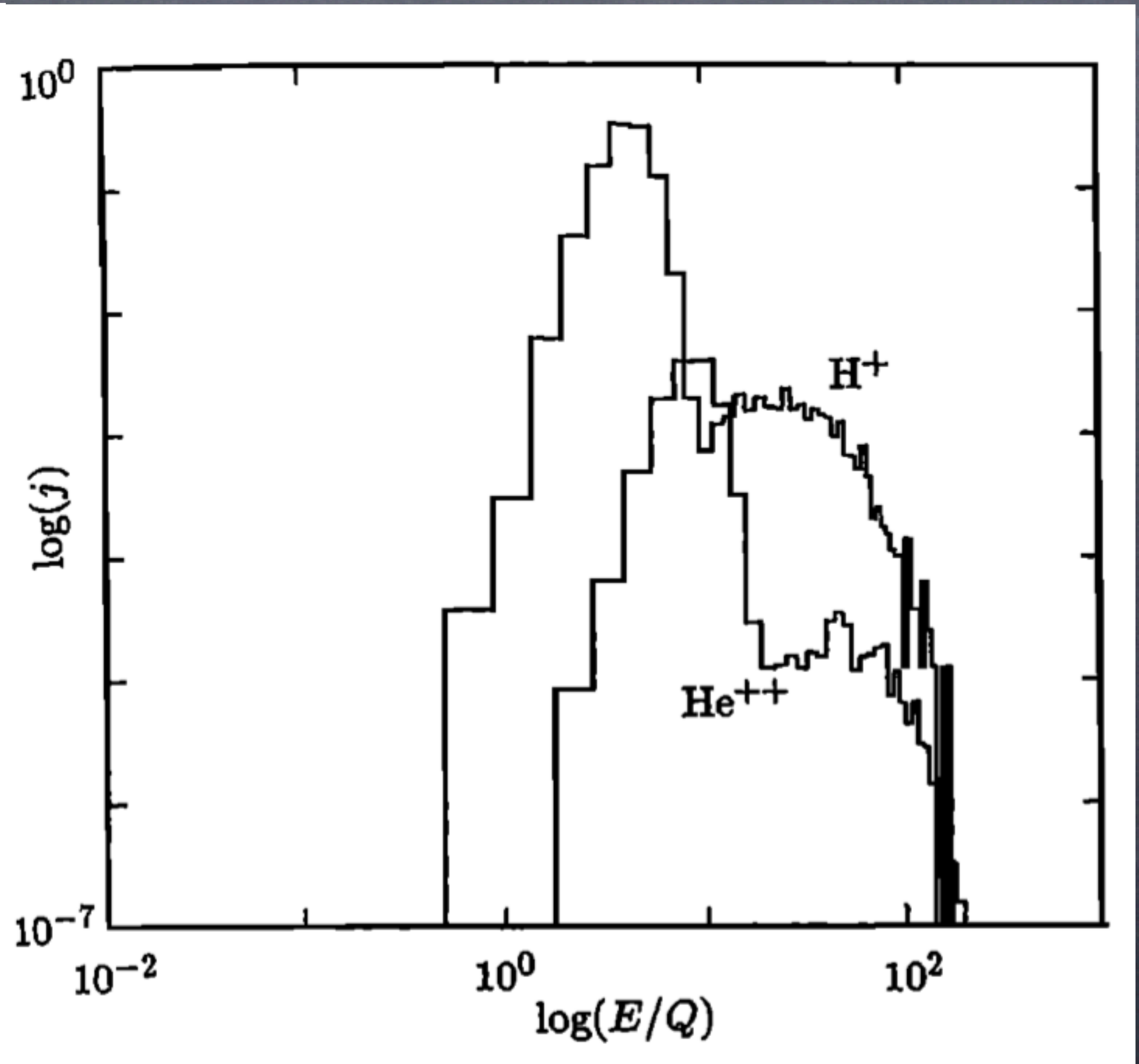
DC, Pop & Spitkovsky, 2015

E_{inj} is larger at oblique shocks: injection requires more SDA cycles, and fewer particles can achieve E_{inj}

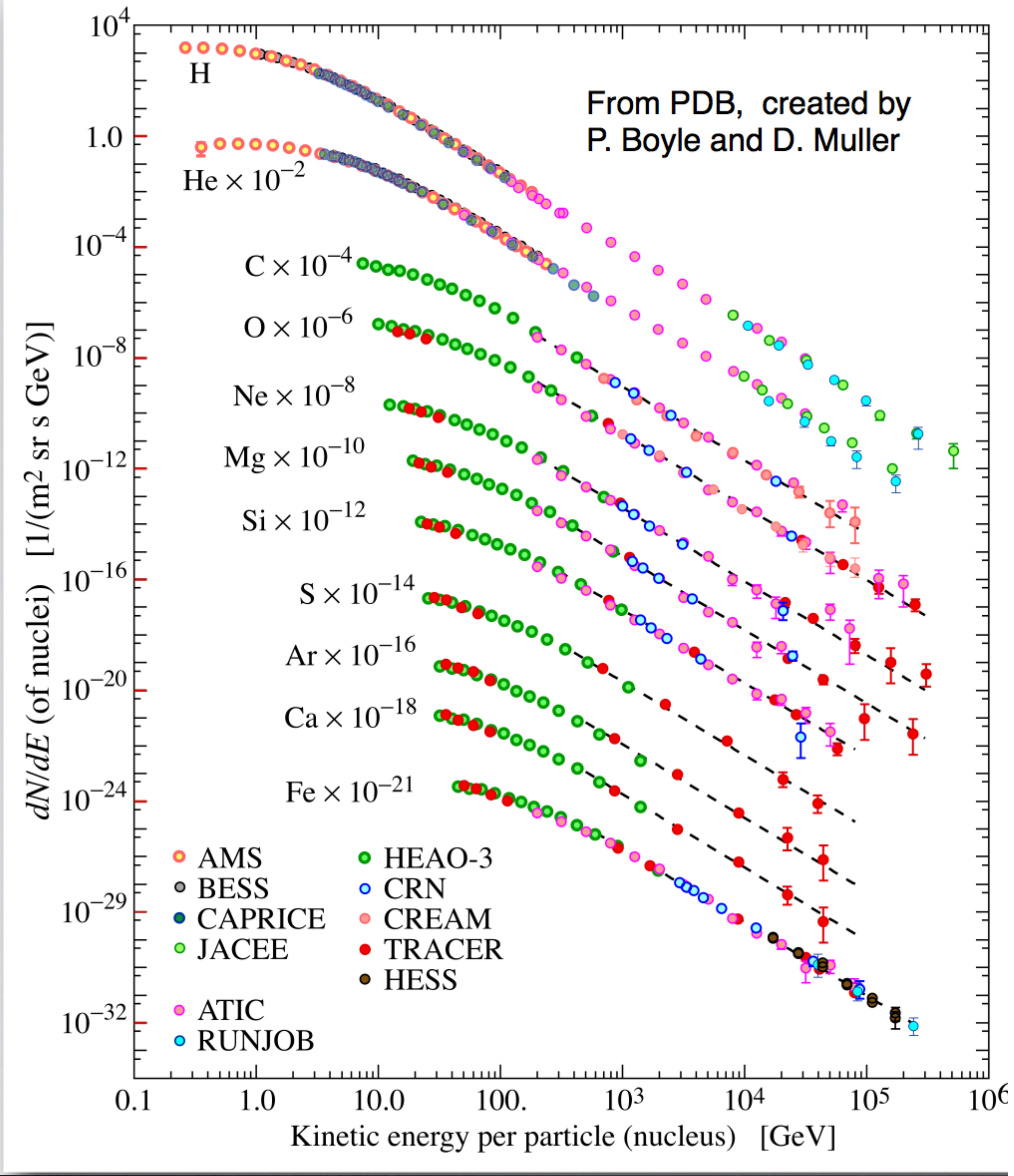
Early Heavy Theory

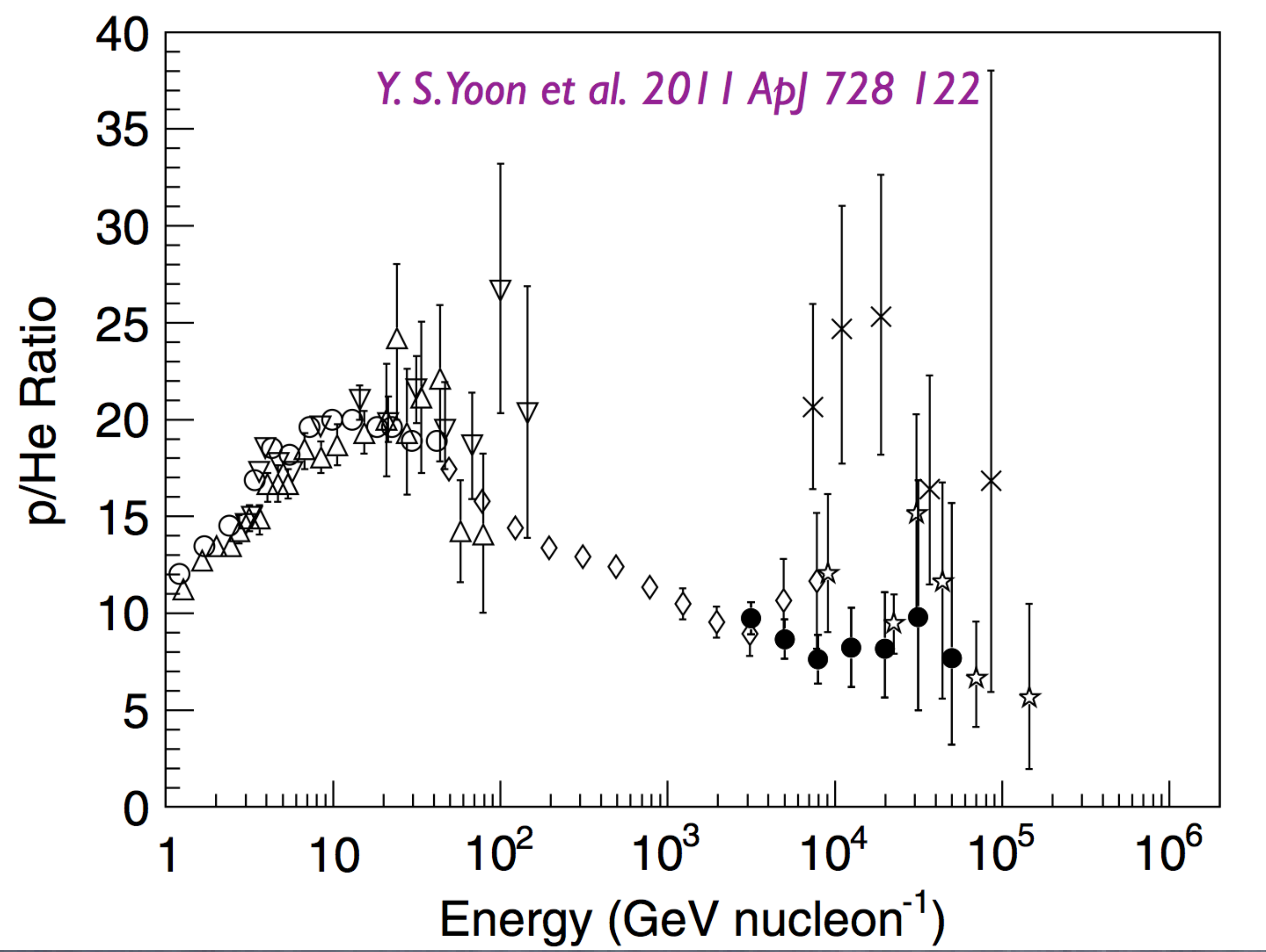
- Earth's bow shock (AMPTE/IRM): Monte Carlo (Ellison, Möbius, Paschmann 1990)
- Hybrid simulations with alpha-particles (Trattner & Scholer 1991, more recently Kropotina+2016)





Anomalous Abundances in CRs and SEPs





CR discrepant hardening (CREAM10)

Chemical composition of gradual SEPs (e.g., Mason+04, Tylka+05, Reames15 Desai+16a,b)