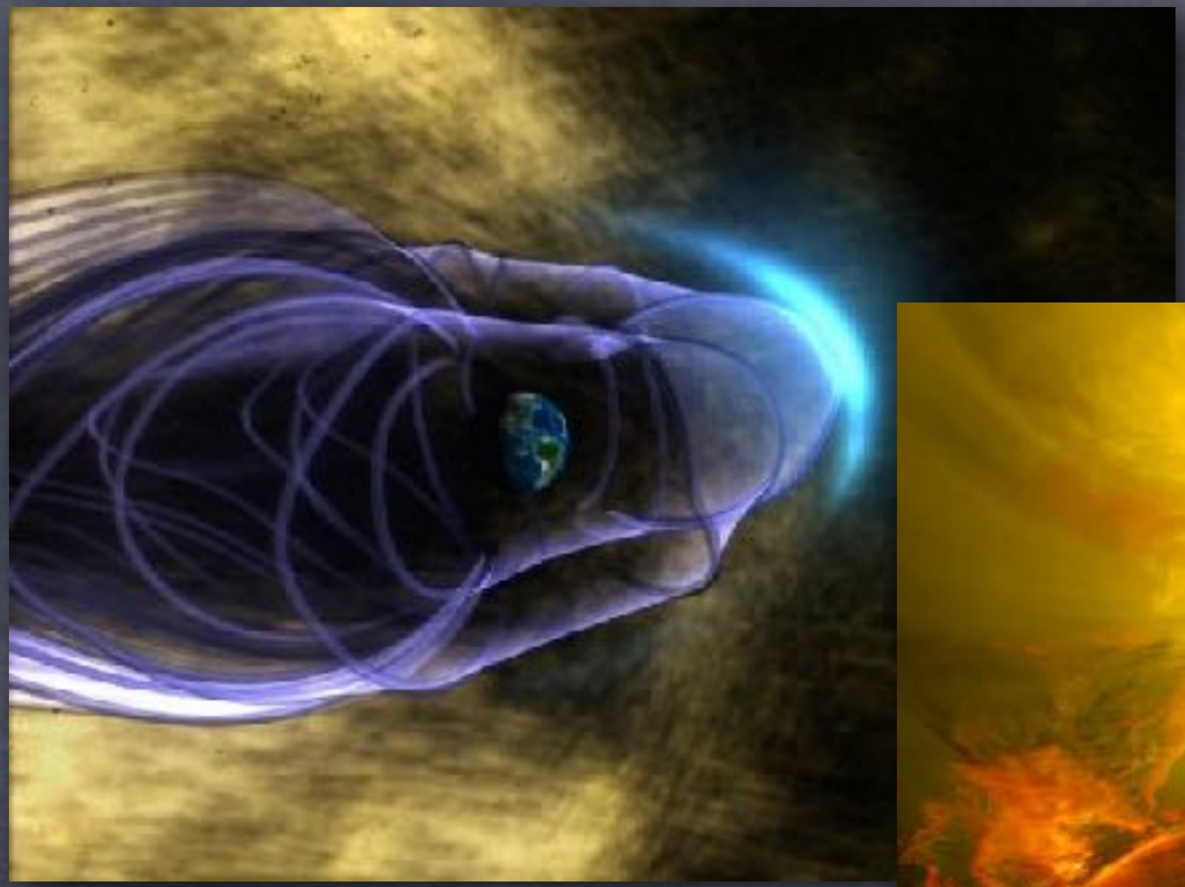
Chania, Crete, Greece
June 4, 2019

Acceleration at SNR Shocks: State of the Art And Challenges

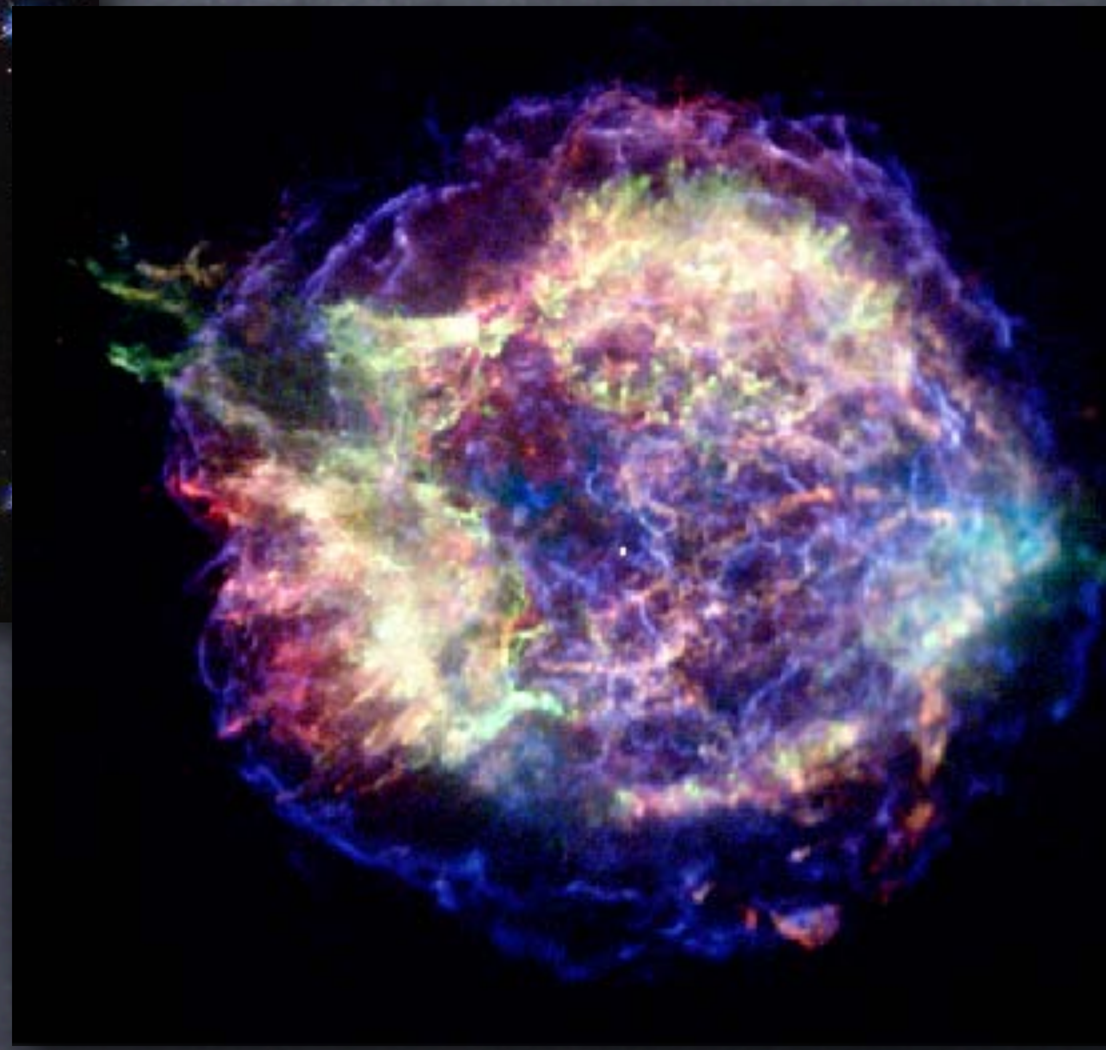
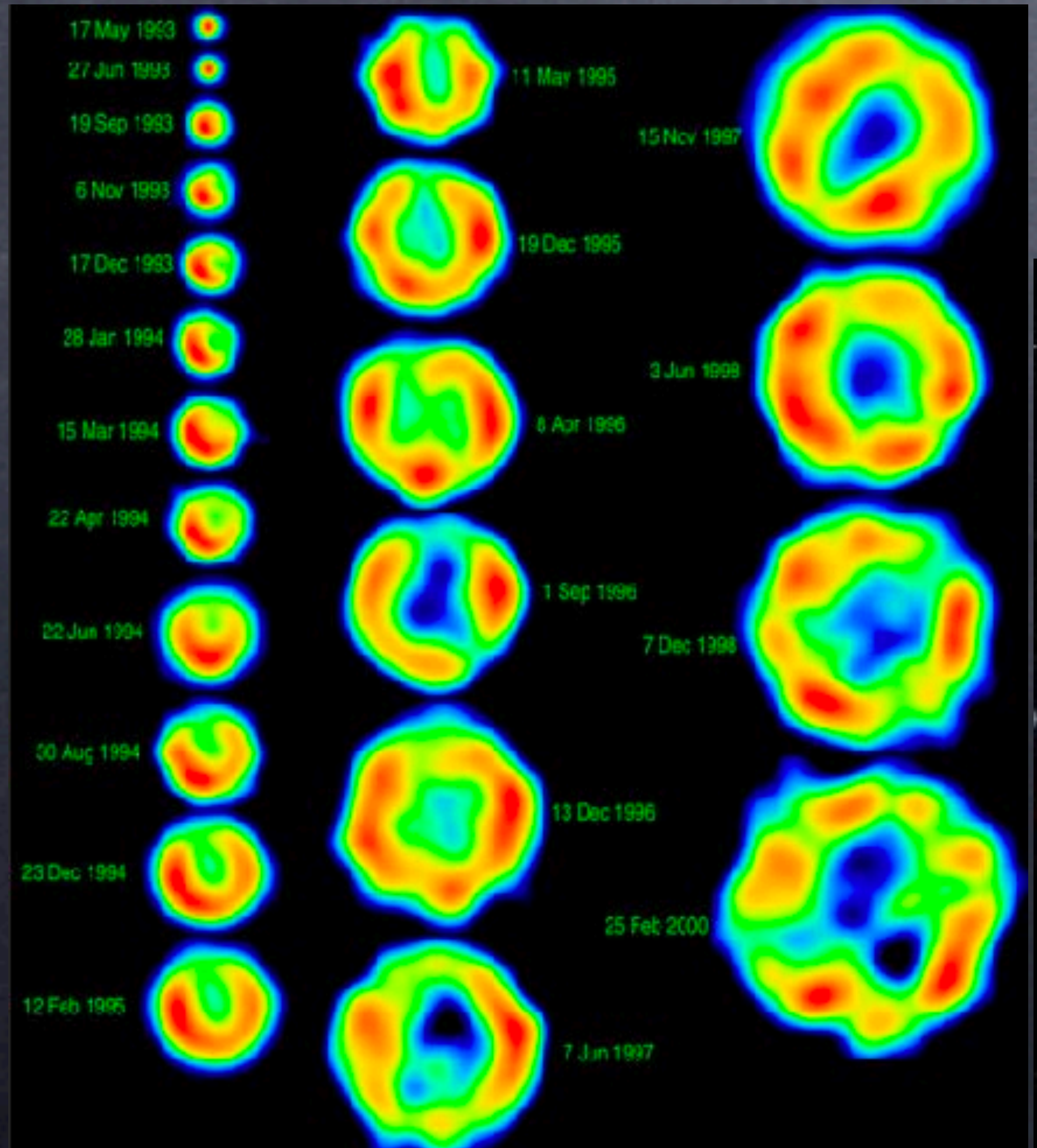
Damiano Caprioli
University of Chicago

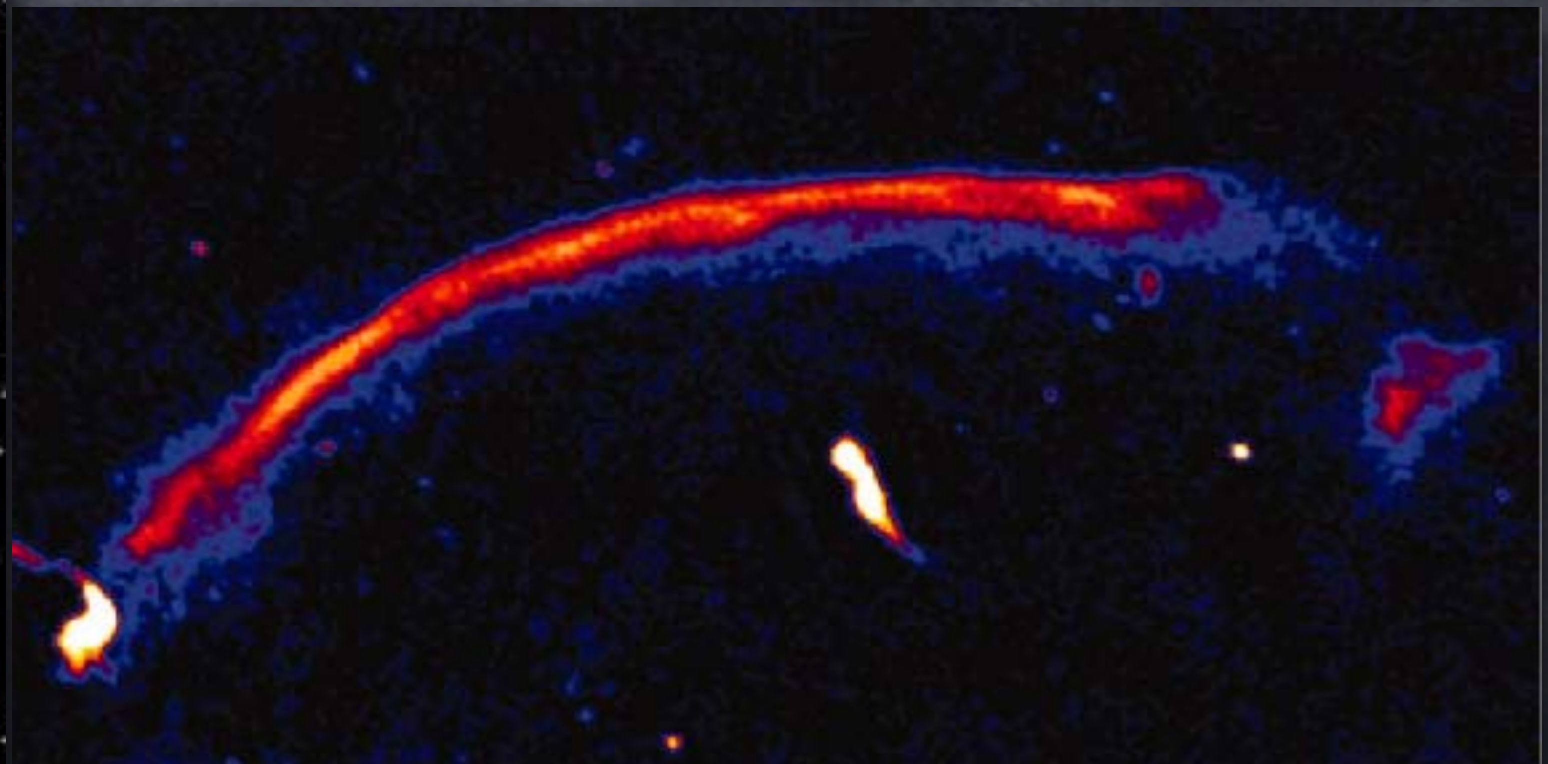
Non-Relativistic Collisionless Shocks

- Mediated by collective electromagnetic interactions
- Show prominent non-thermal activity





A universal acceleration mechanism

- Fermi mechanism (Fermi, 1949): random elastic collisions lead to energy gain

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.

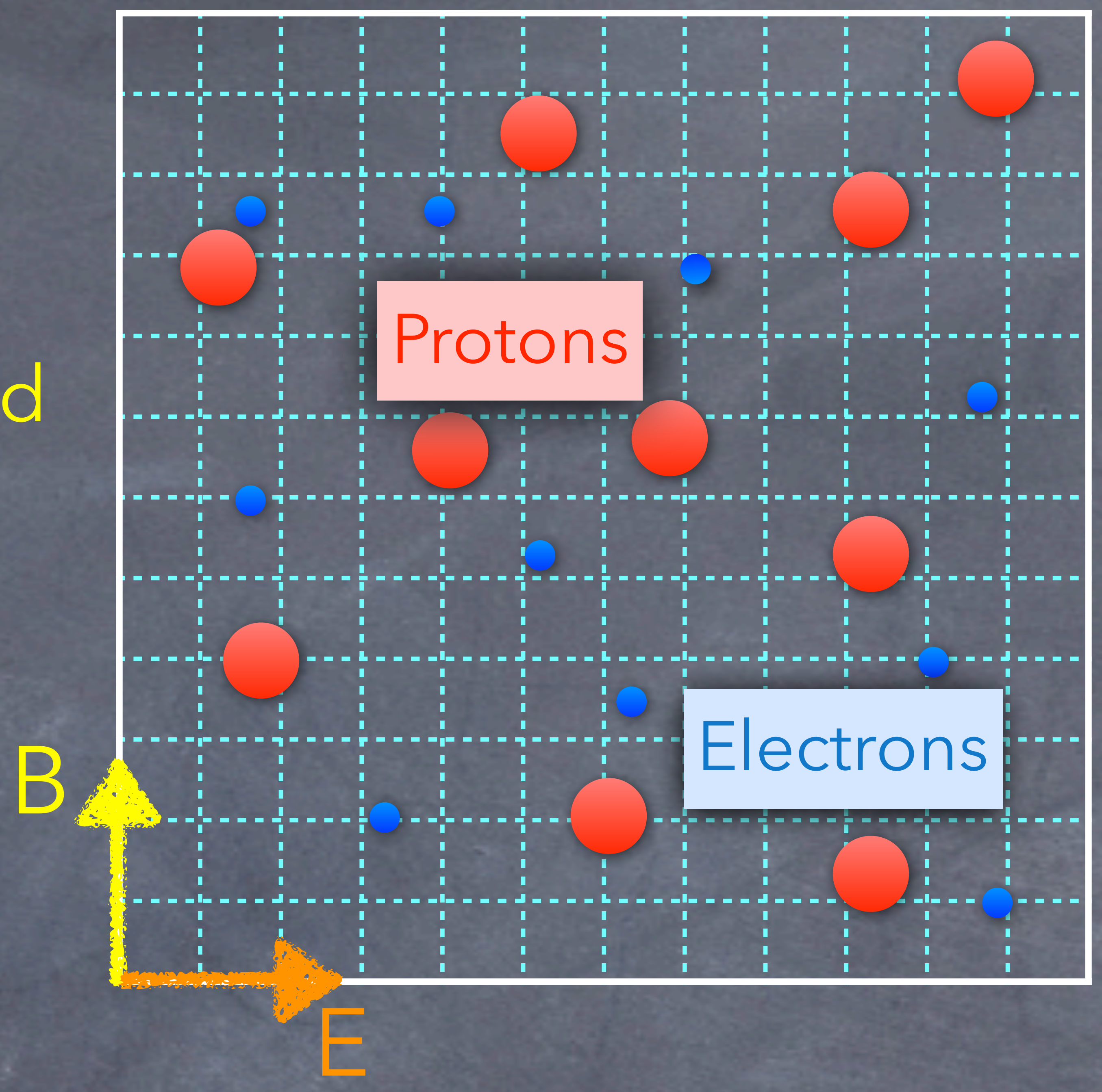
- DSA produces power-laws $N(p) \propto 4\pi p^2 p^{-\alpha}$, depending on the compression ratio $R=\rho_d/\rho_u$ only.

$$\boxed{R = \frac{4M_s^2}{M_s^2+3} \qquad \alpha = \frac{3R}{R-1}}$$

  - For strong shocks (Mach number $M_s=V_{sh}/c_s>>1$): $R=4$ and $\alpha=4$

Astroplasmas from first principles

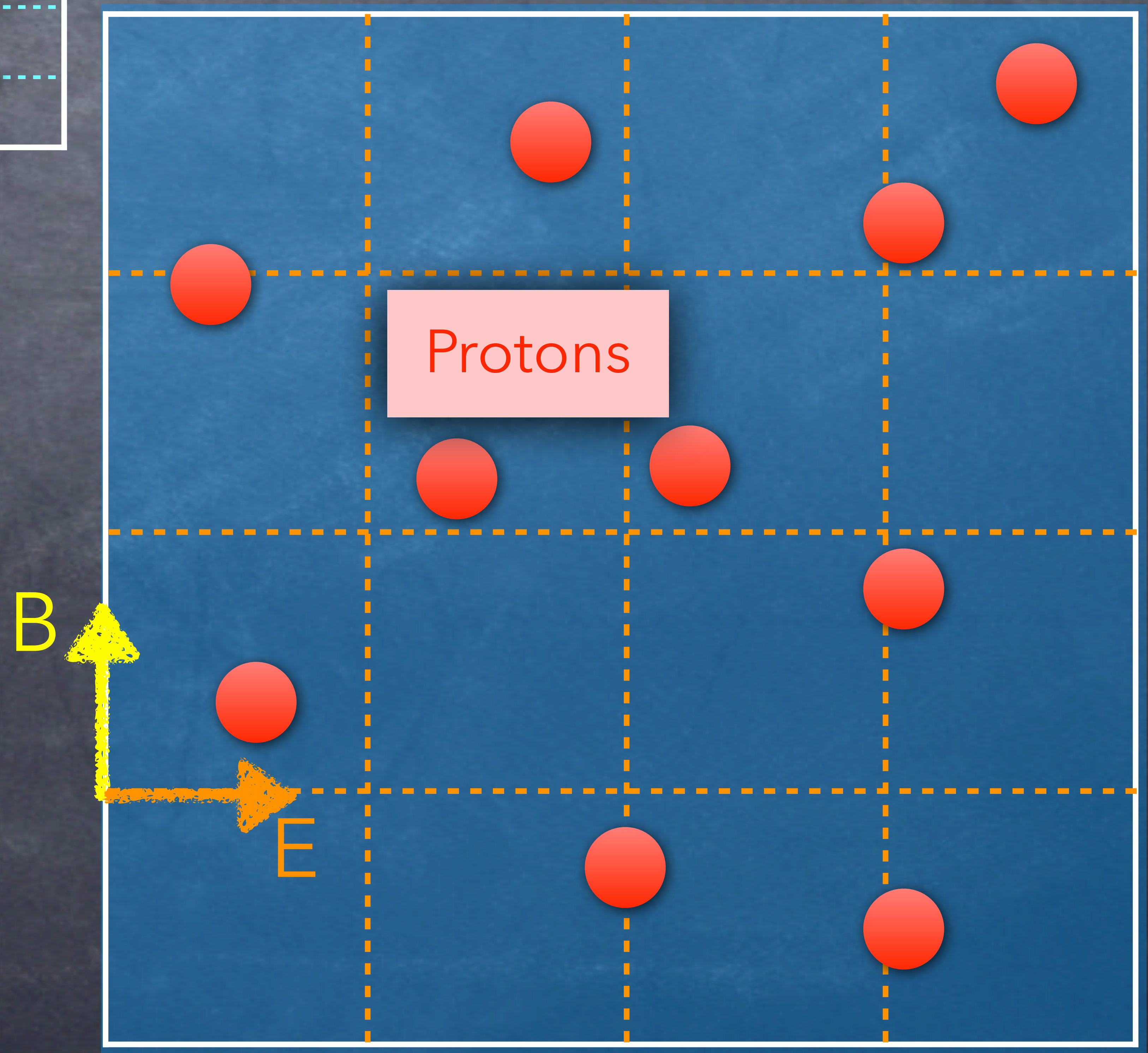
- Full-PIC approach
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



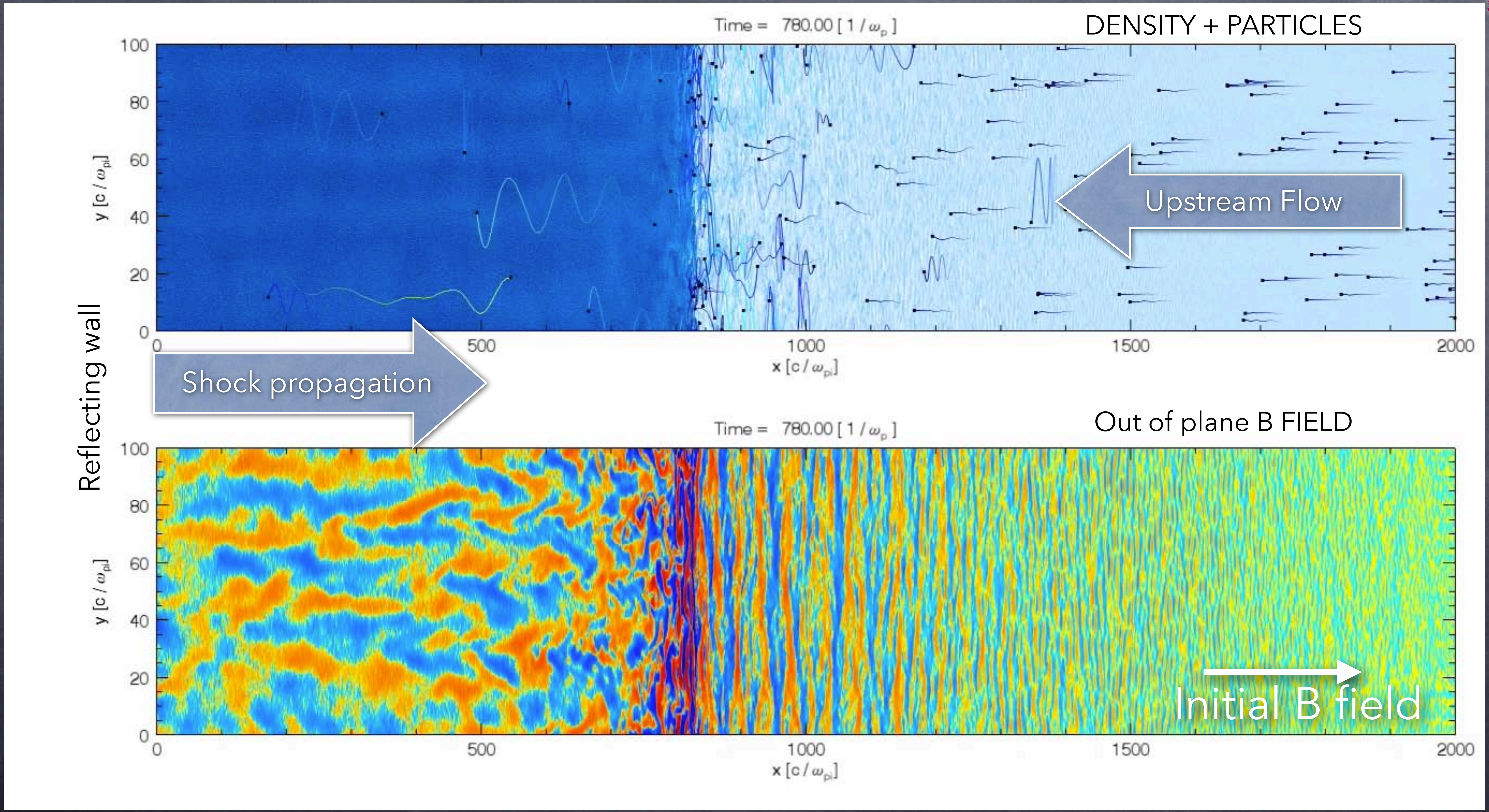
- Hybrid approach: Fluid electrons - Kinetic protons

(Winske & Omidi; Burgess +., Lipatov02; Giacalone+93-; DC & Spitkovsky 13-18, Haggerty & DC 19…)

  - massless electrons for more macroscopical time/length scales



Hybrid simulations of collisionless shocks

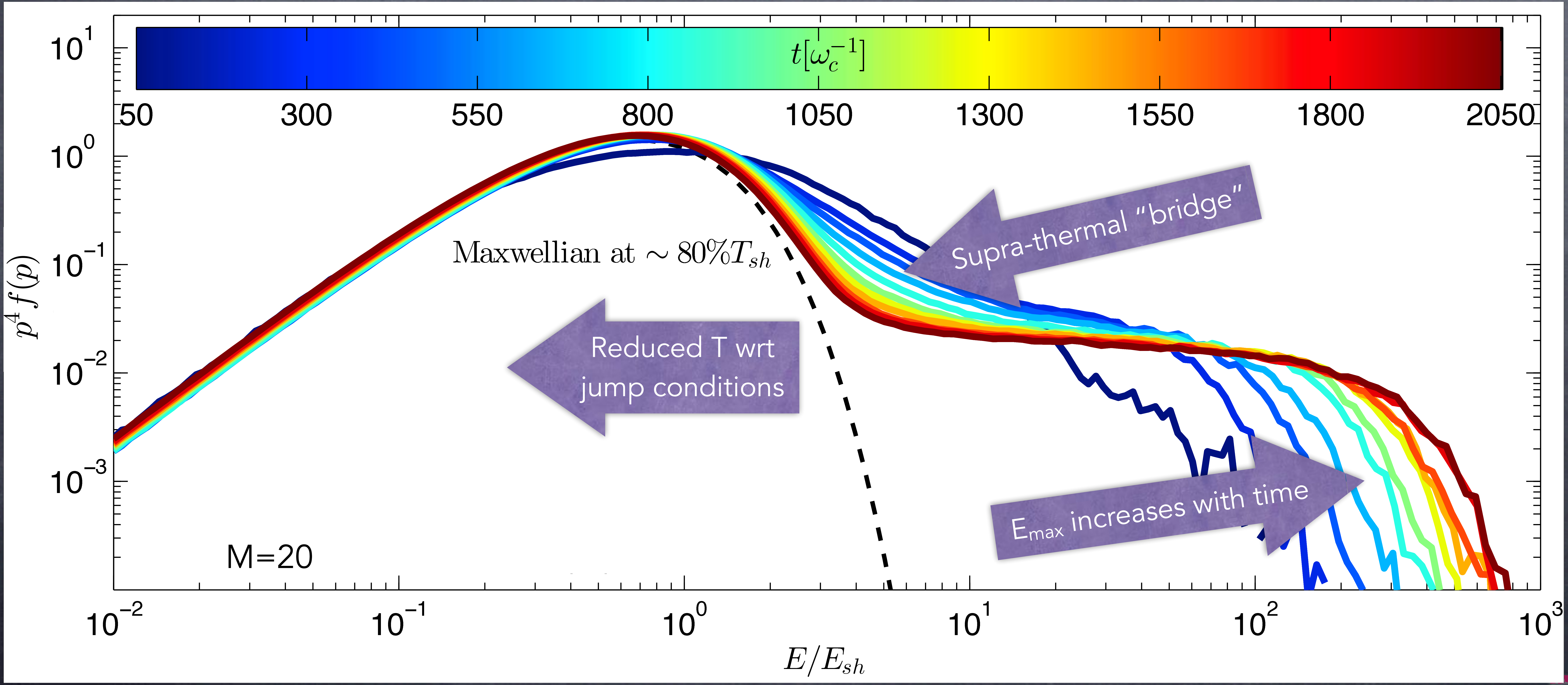


dHybrid code (Gargaté+07; DC & Spitkovsky14); **dHybridR** (Haggerty & DC 19)

Spectrum evolution

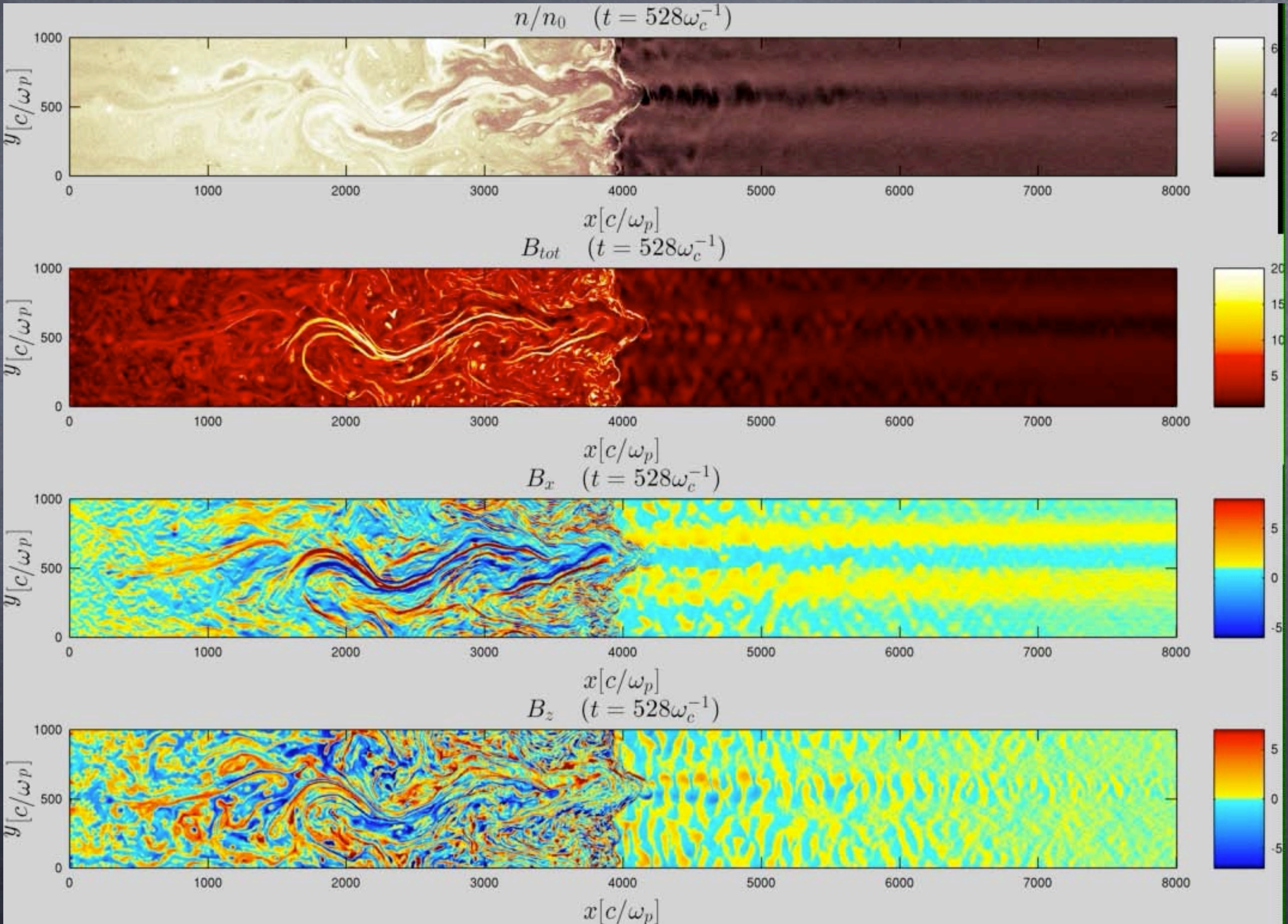
- Diffusive Shock Acceleration (DSA): non-thermal power-law tail
  Acceleration efficiency: ~15% of the shock bulk energy!

Downstream Spectrum



DC & Spitkovsky14a

CR-driven Magnetic-Field Amplification



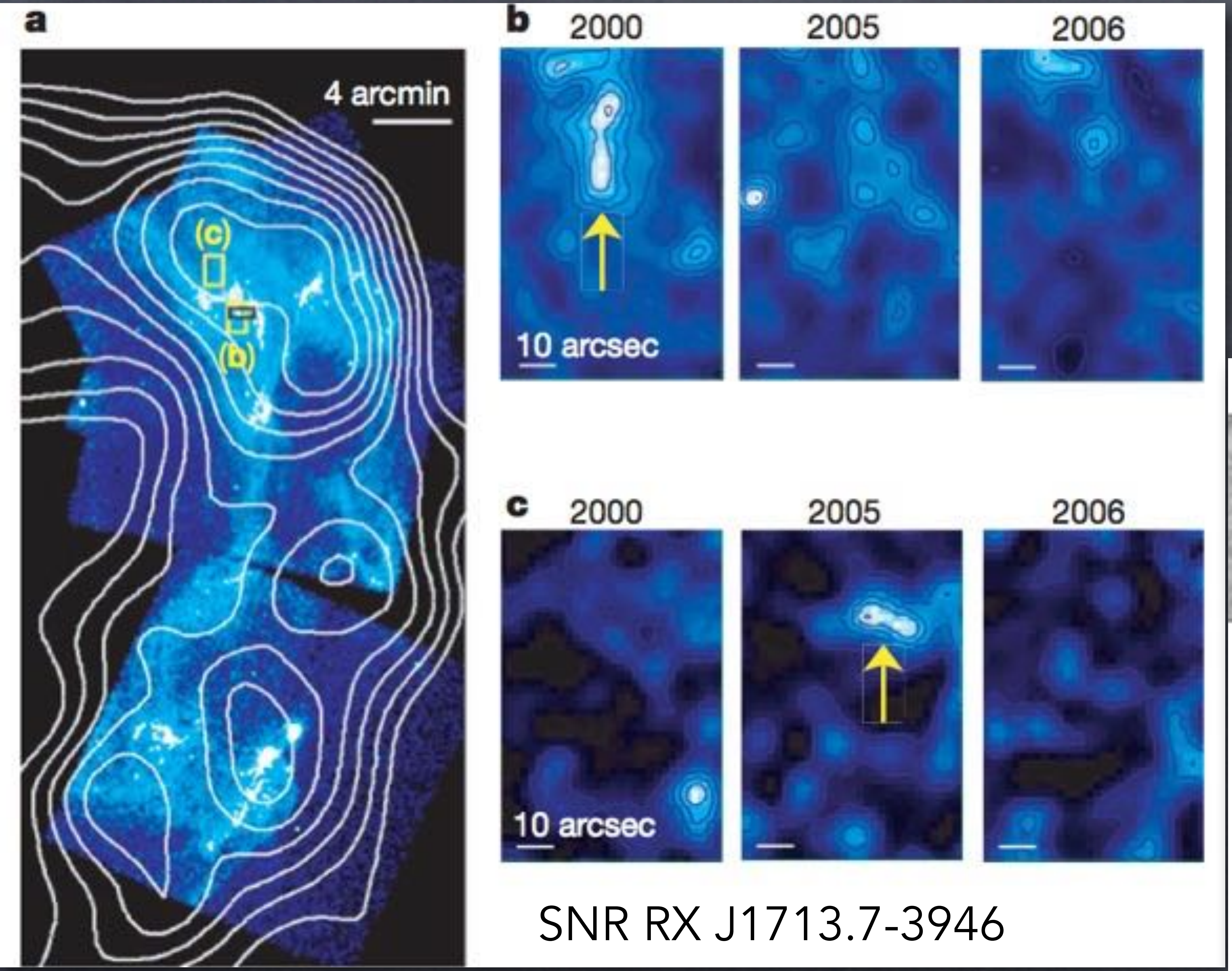
Initial B field

$M_s = M_A = 30$

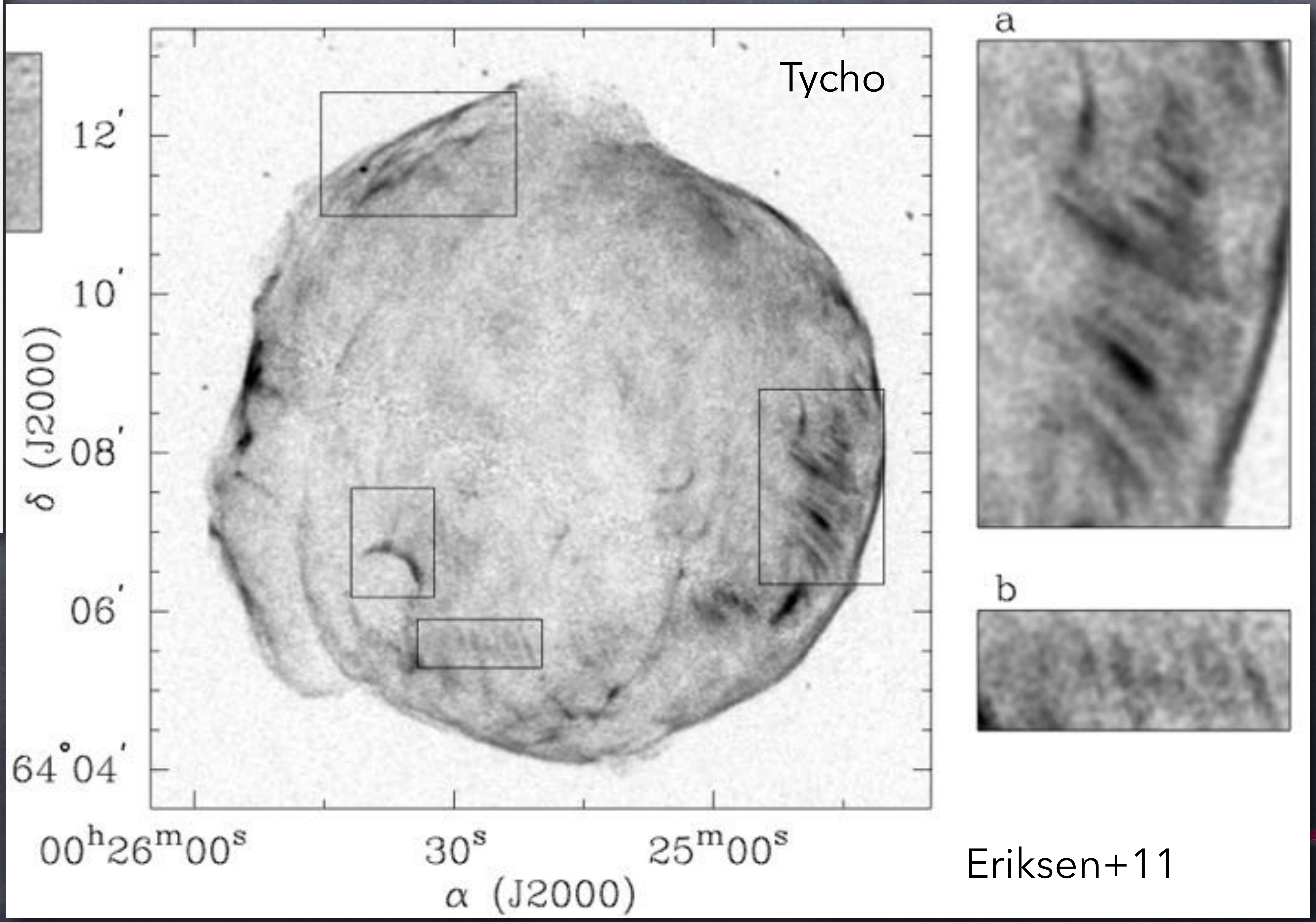
DC & Spitkovsky13

X-ray observations of young SNRs

- Rapidly-variable knots with δB/B~100
- Radial filaments with ~ gyroradius spacing



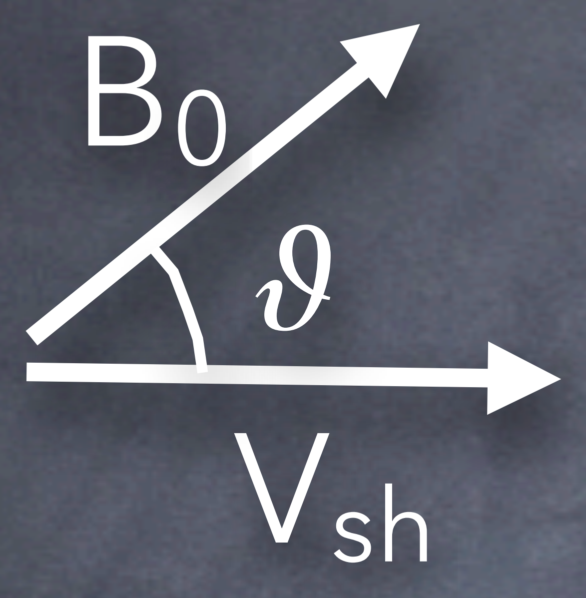
Uchiyama+07

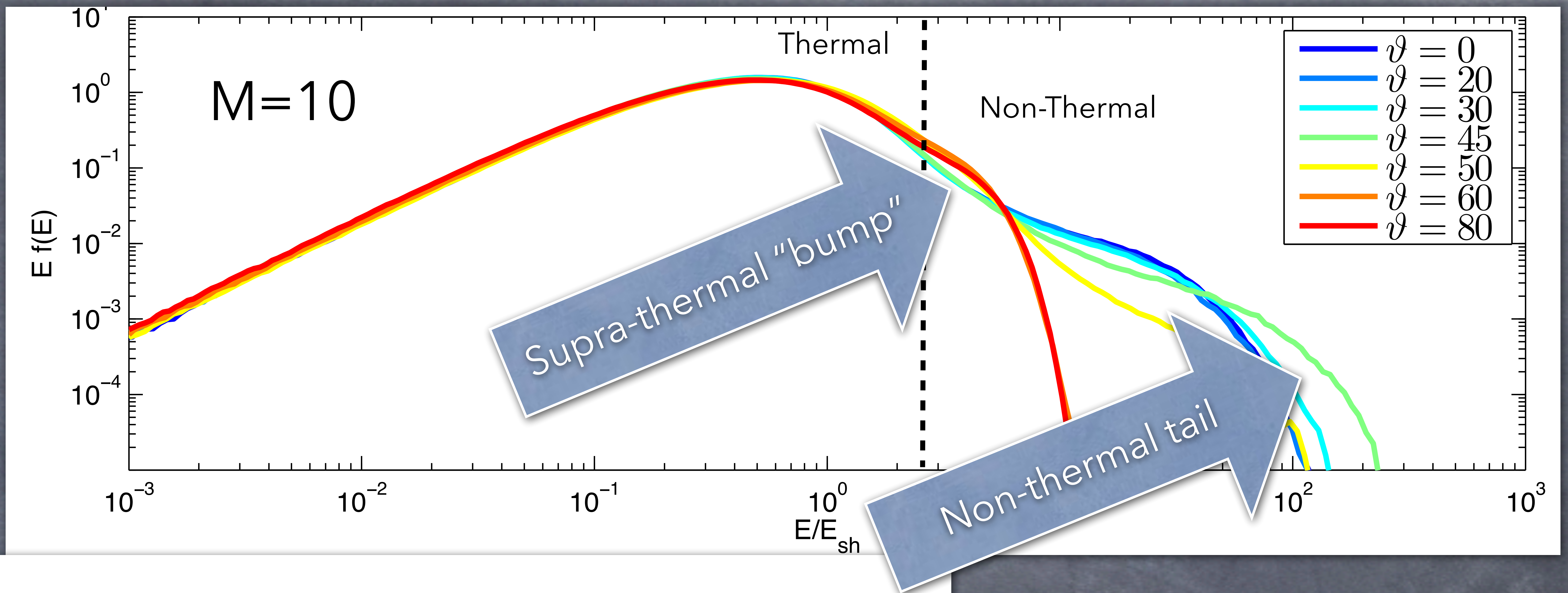


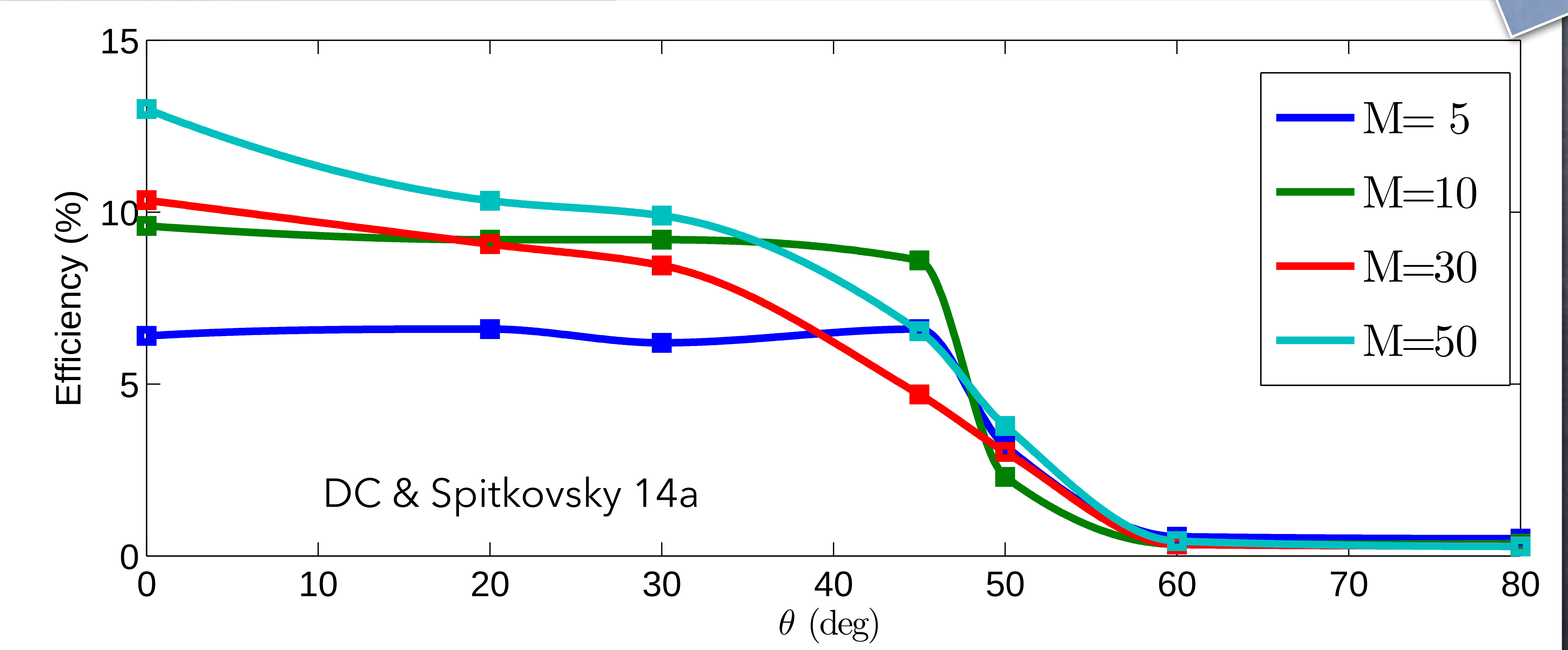
TALK BY D. CASTRO LATER TODAY

Parallel vs Oblique shocks

Shock inclination

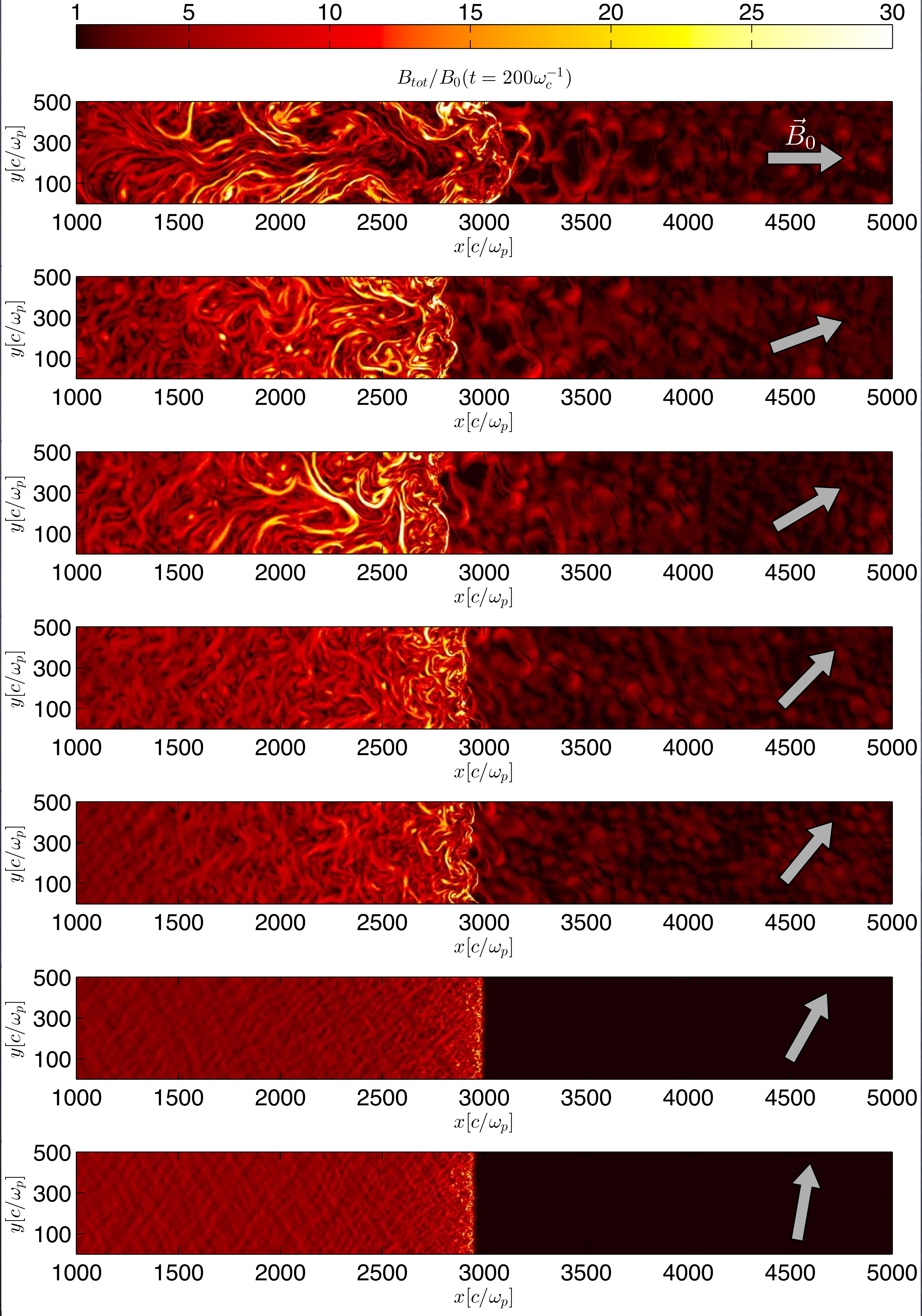


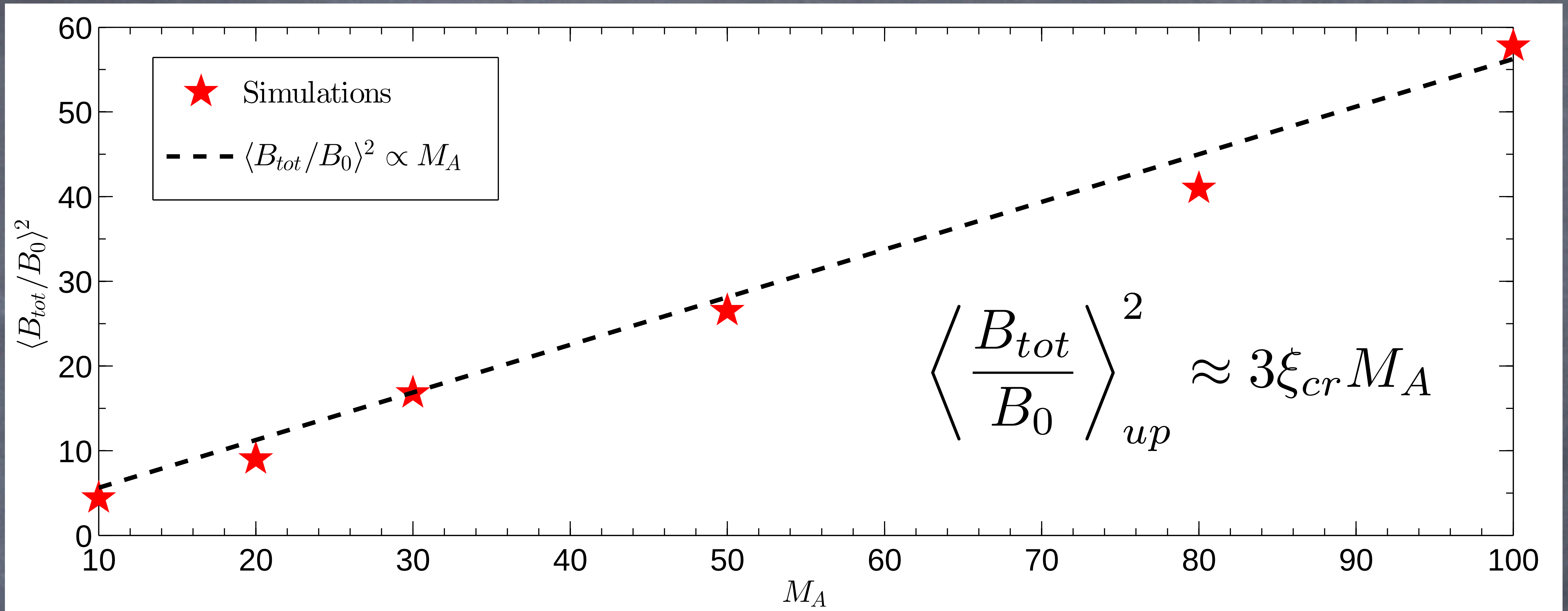




Spontaneous injection of thermal protons only at quasi-parallel shocks

Dependence on shock strength (M_A) and inclination

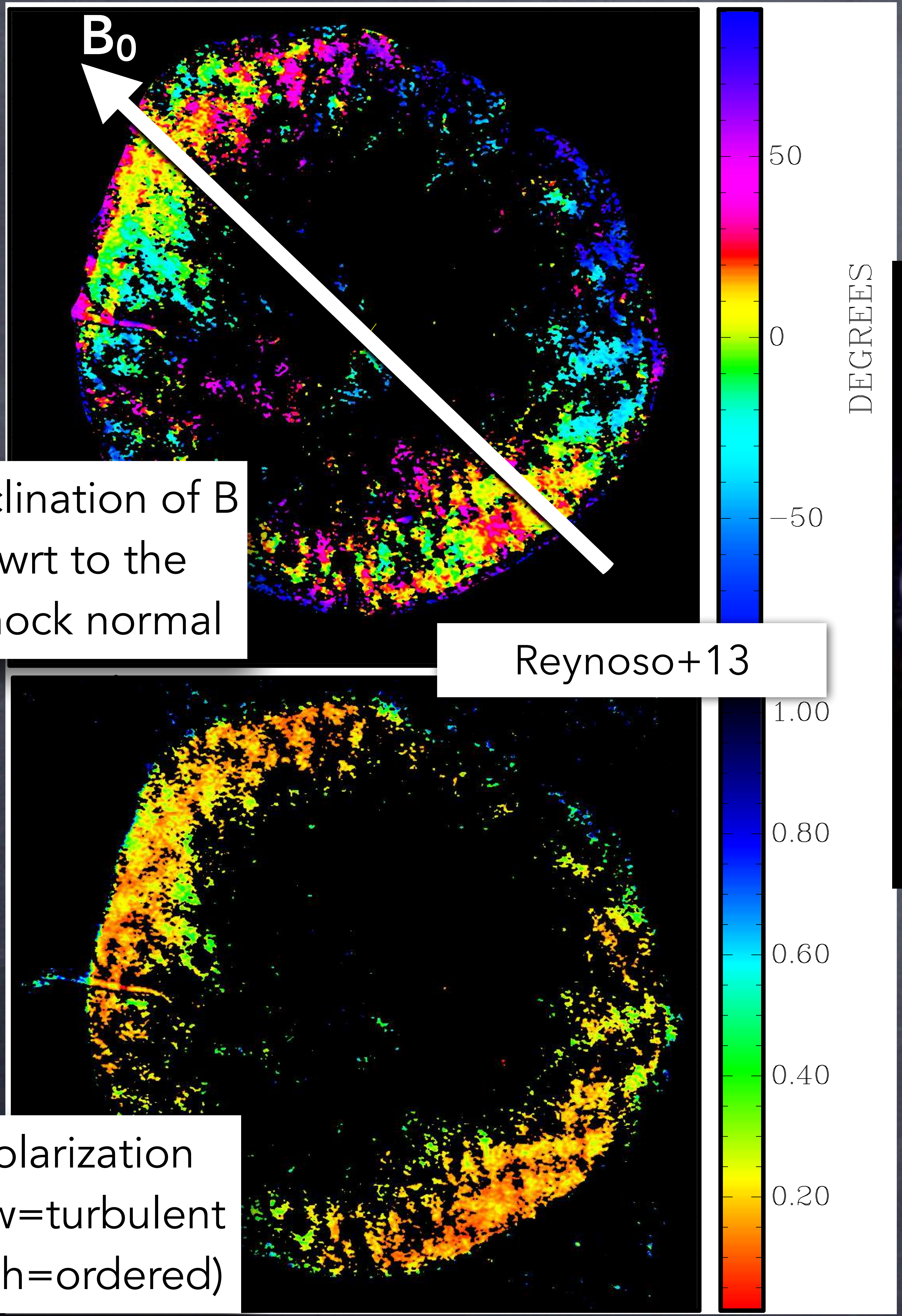




More B amplification for stronger (higher M_A) shocks

- Different flavors of CR-driven streaming instabilities (Amato & Blasi 09; DC & Spitkovsky 14b)
- Study how CRs diffuse in the self-generated turbulence Bohm-like diffusion (DC & Spitkovsky 14c)

SN 1006: a parallel accelerator



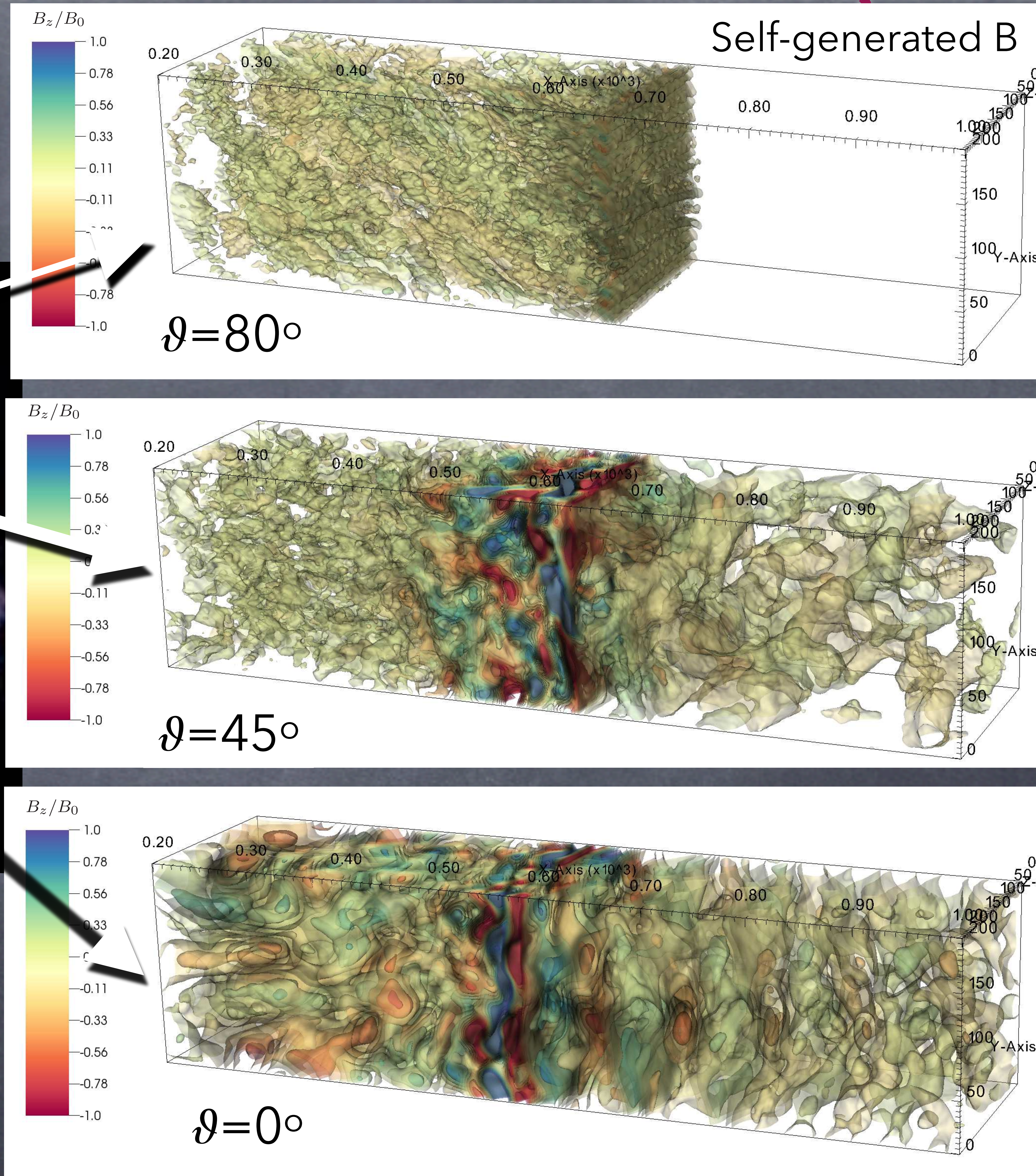
Inclination of B wrt to the shock normal

Reynoso+13

Polarization (low=turbulent high=ordered)

X-ray emission:
red=thermal
white=synchrotron

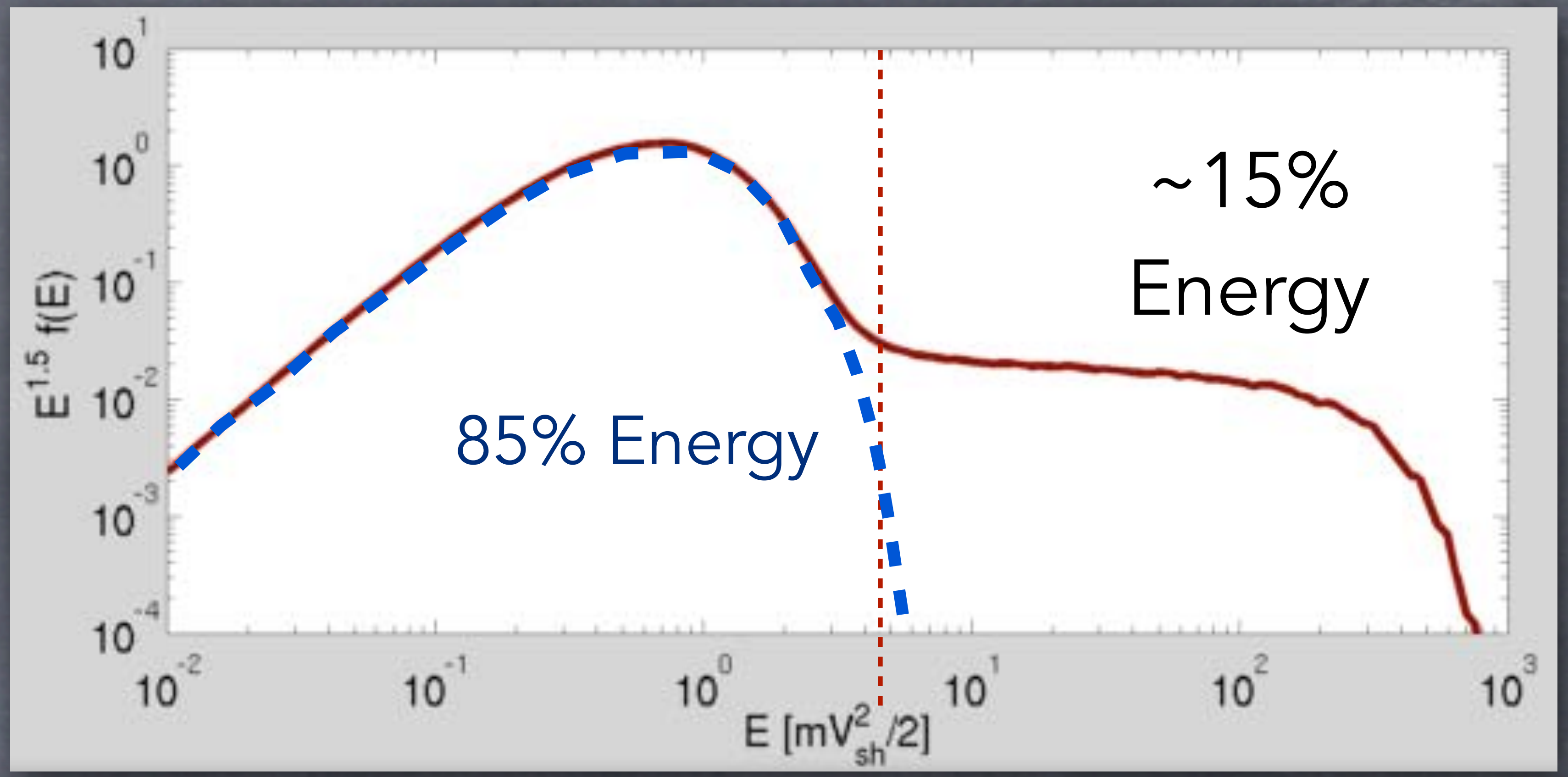
B amplification and ion acceleration where the shock is parallel

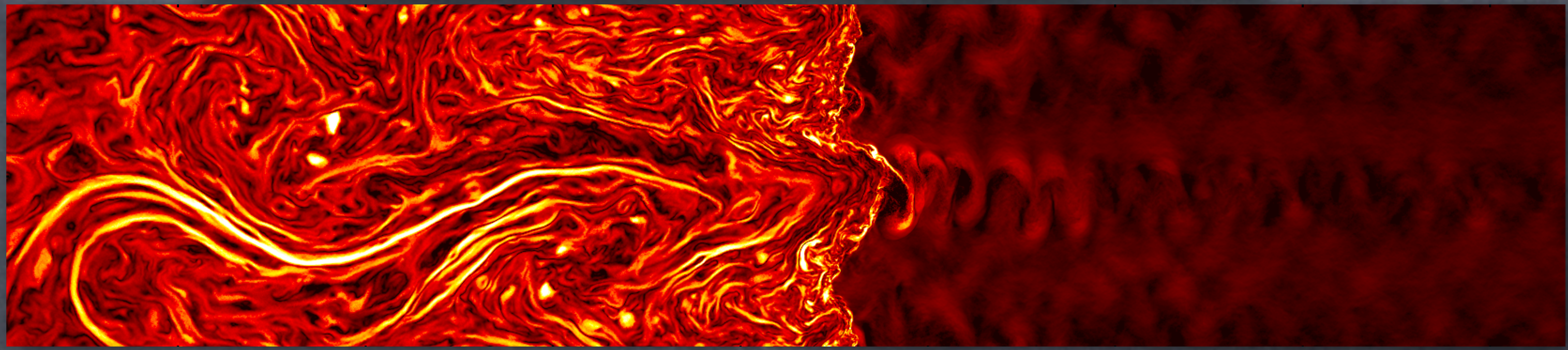


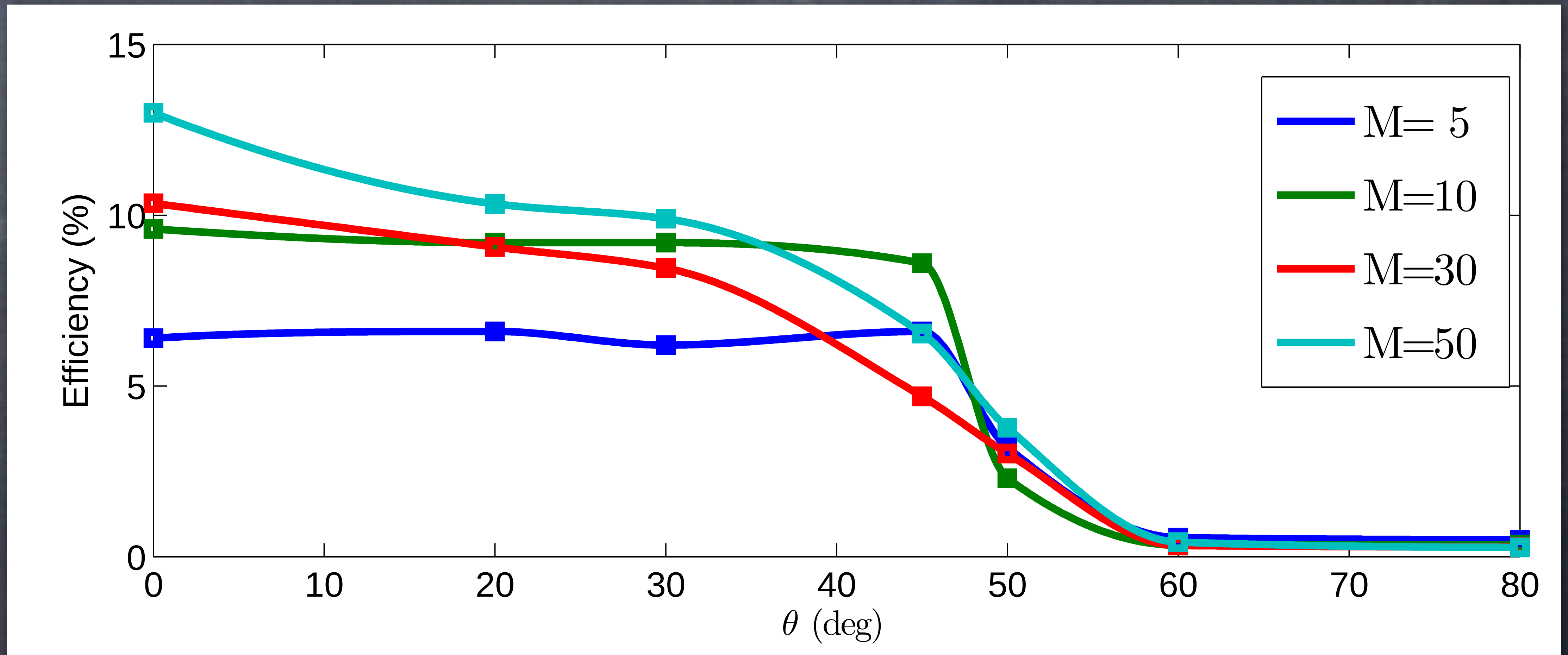
DC & Spitkovsky 14a

Proton DSA: Summary

- Shock acceleration can be efficient
- CRs amplify B via streaming instability
- DSA efficient at parallel, strong shocks
    - Injection of thermal ions at parallel shocks (DC+15)
    - *Seed* reacceleration may occur also at oblique shocks (DC+18)







What about Heavy Nuclei?

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

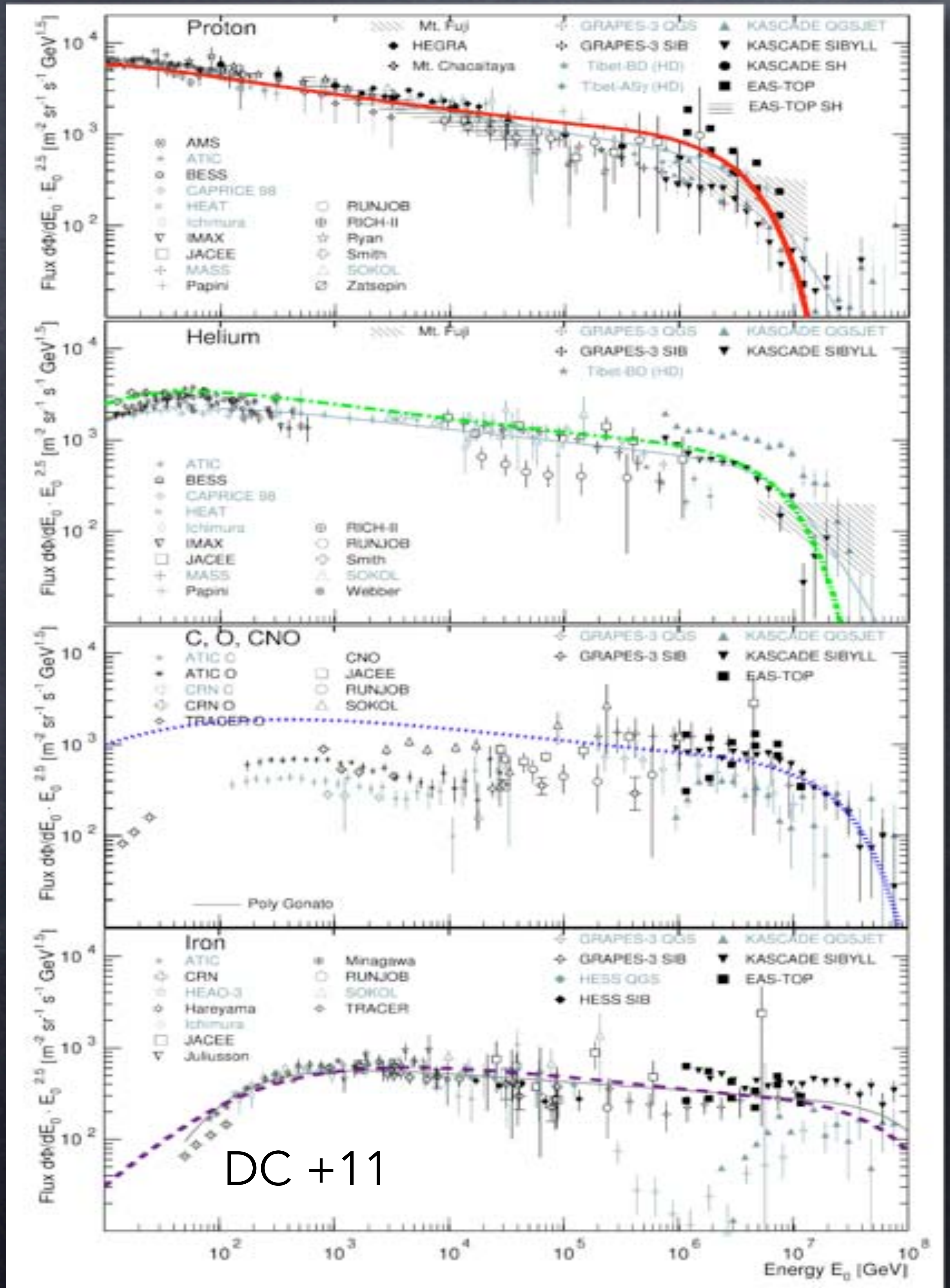
On the Origin of the Cosmic Radiation

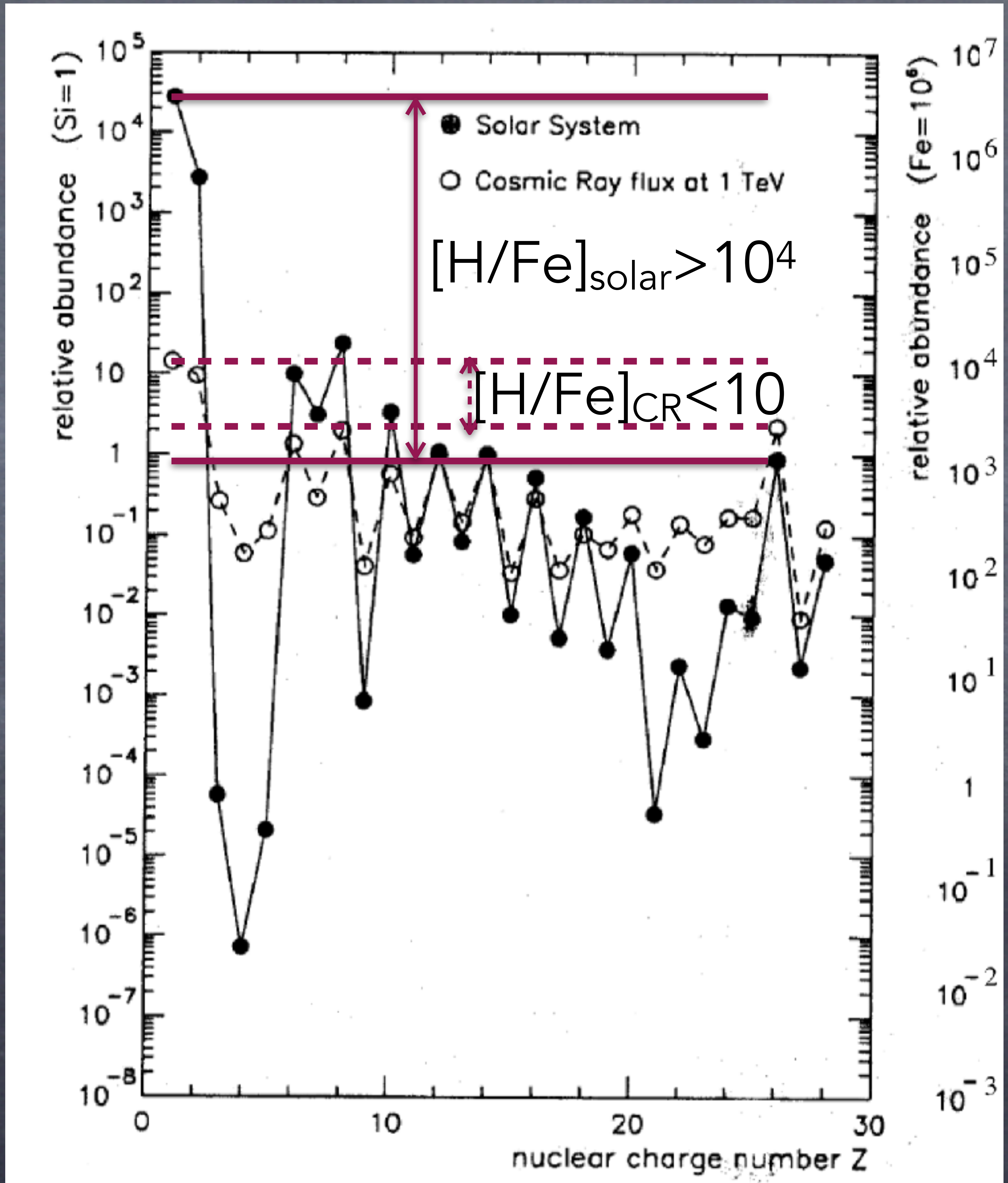
ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 3, 1949)

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.

Chemical Composition of Galactic CRs

- Similar to solar…*at ~GeV energies* (Simpson83);
- However, at ~1 TeV:

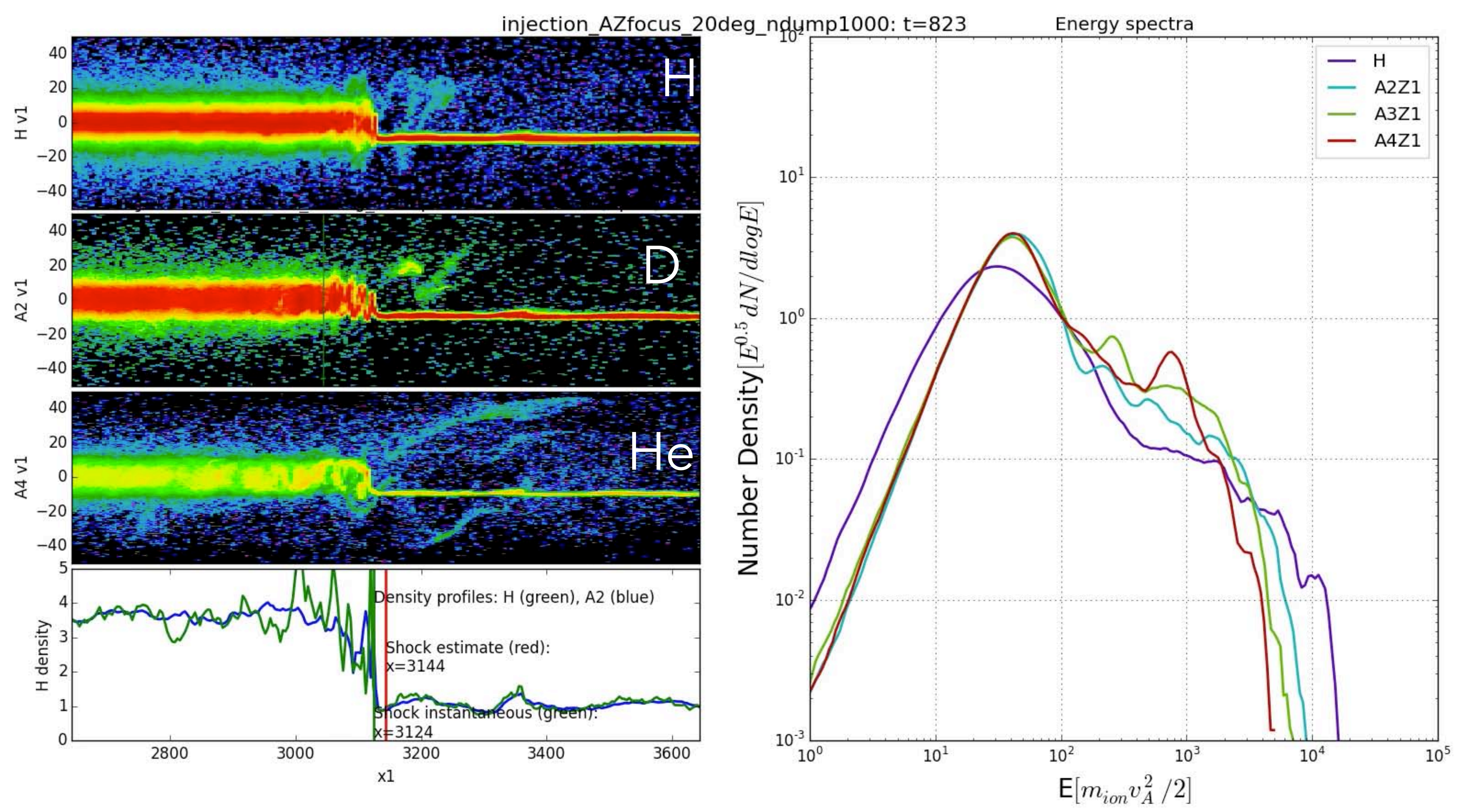




Nuclei heavier than H must be injected more efficiently!

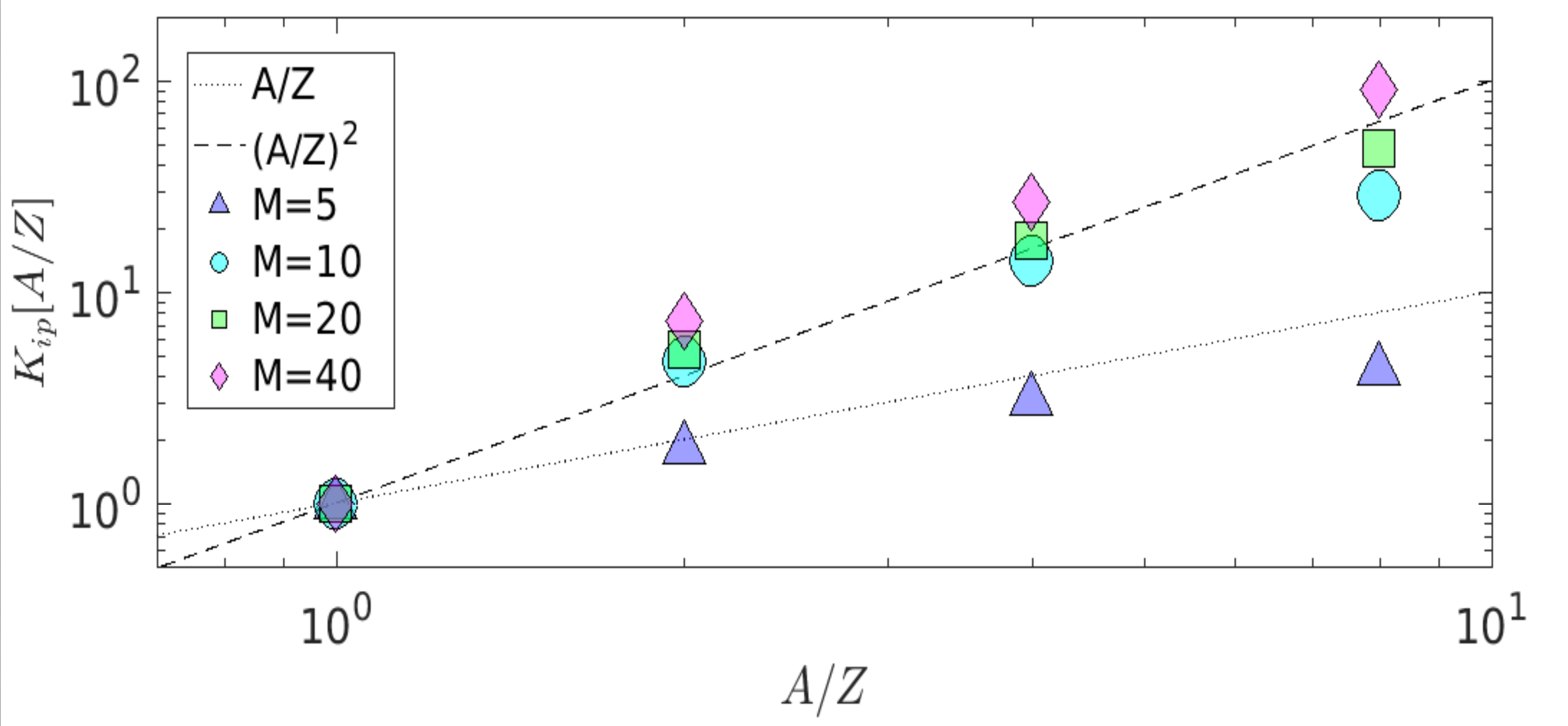
Hybrid Simulations

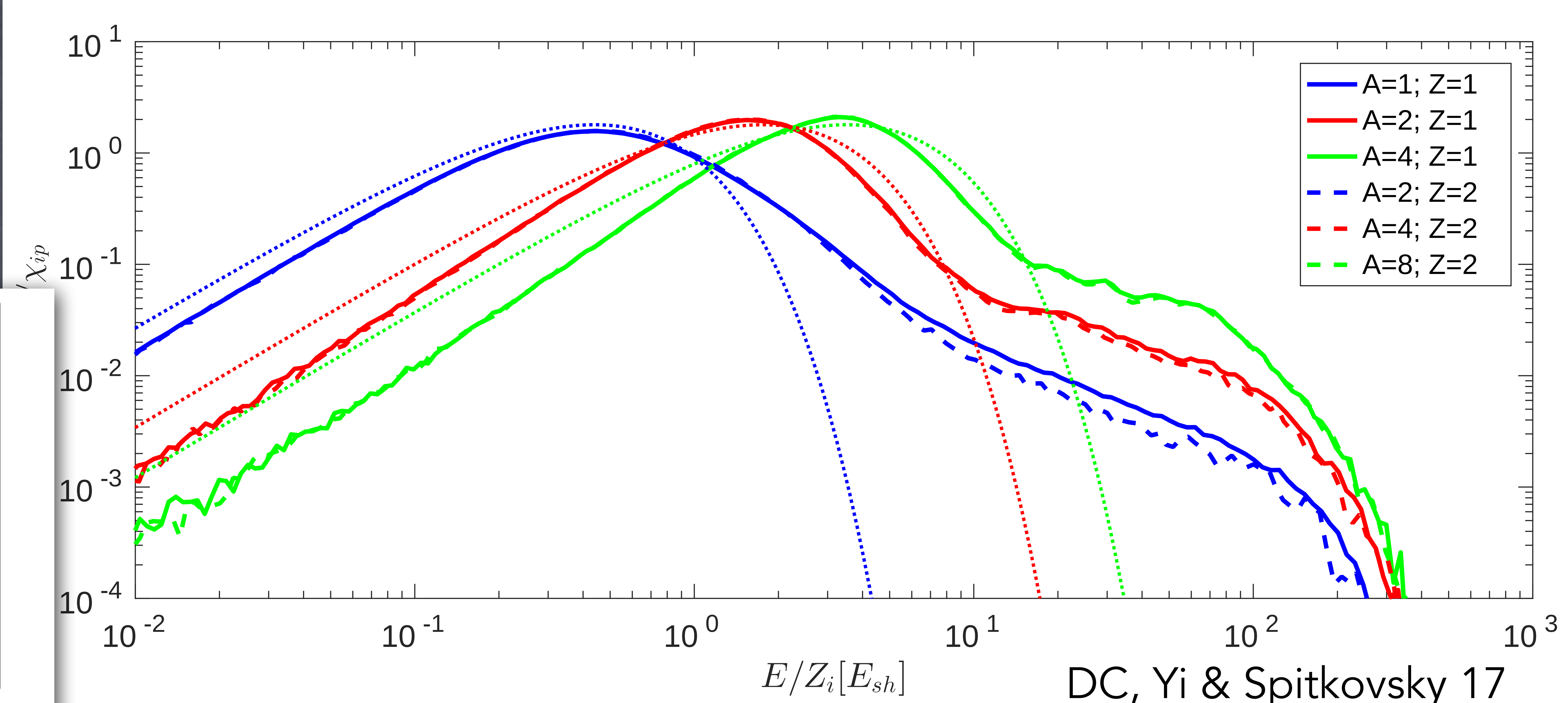
- M=10, parallel shock, with singly-ionized nuclei (DC, Yi, Spitkovsky 17)



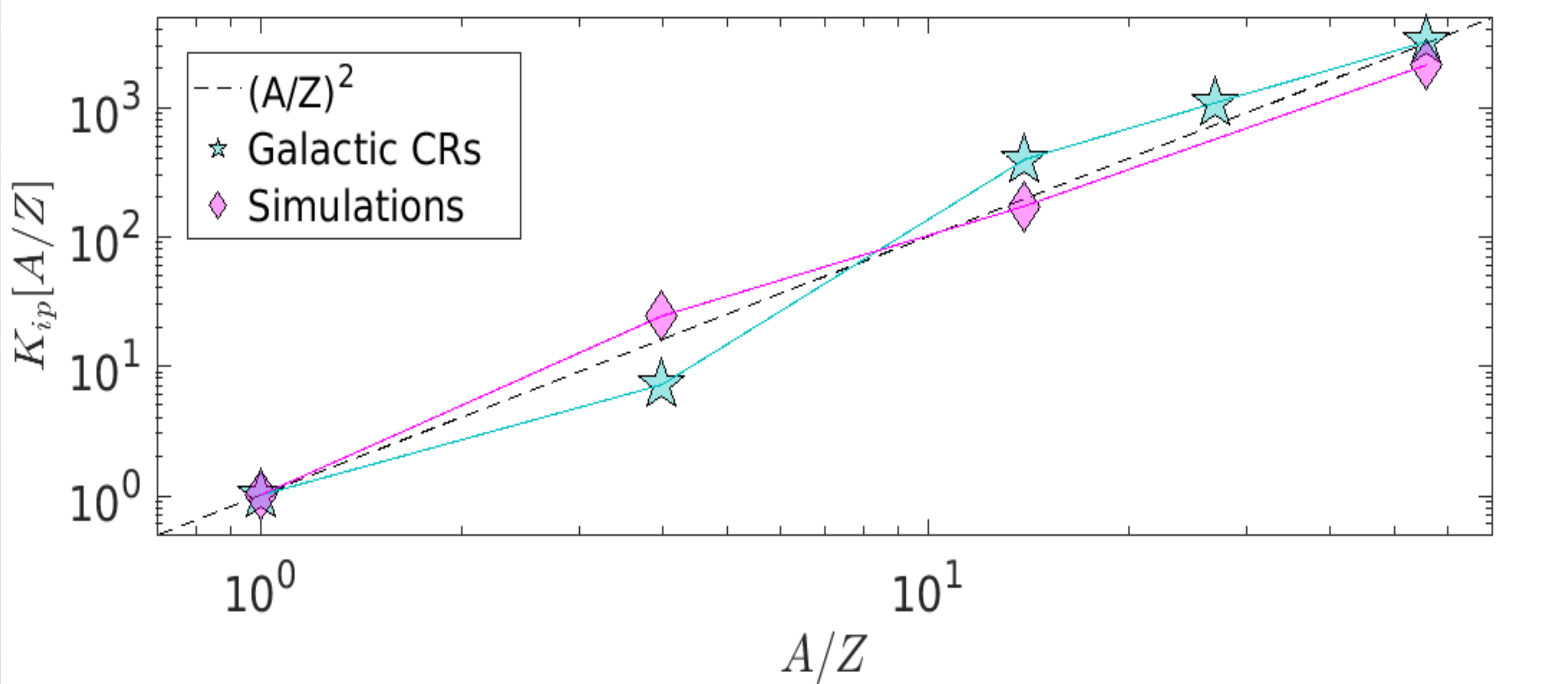
Hybrid Simulations with Heavy Ions

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





DC, Yi & Spitkovsky 17



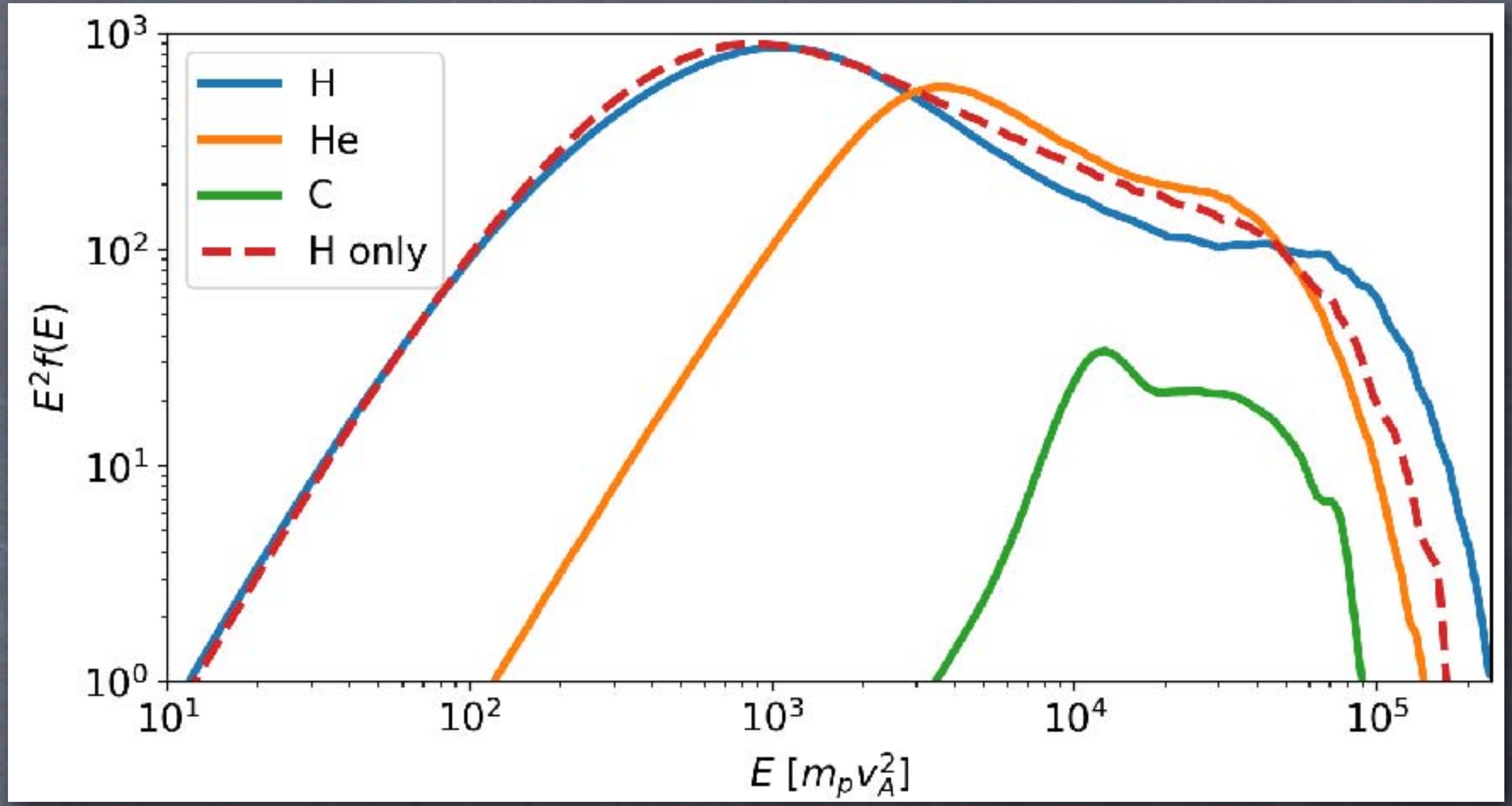
- Post-shock T_i scales with A_i

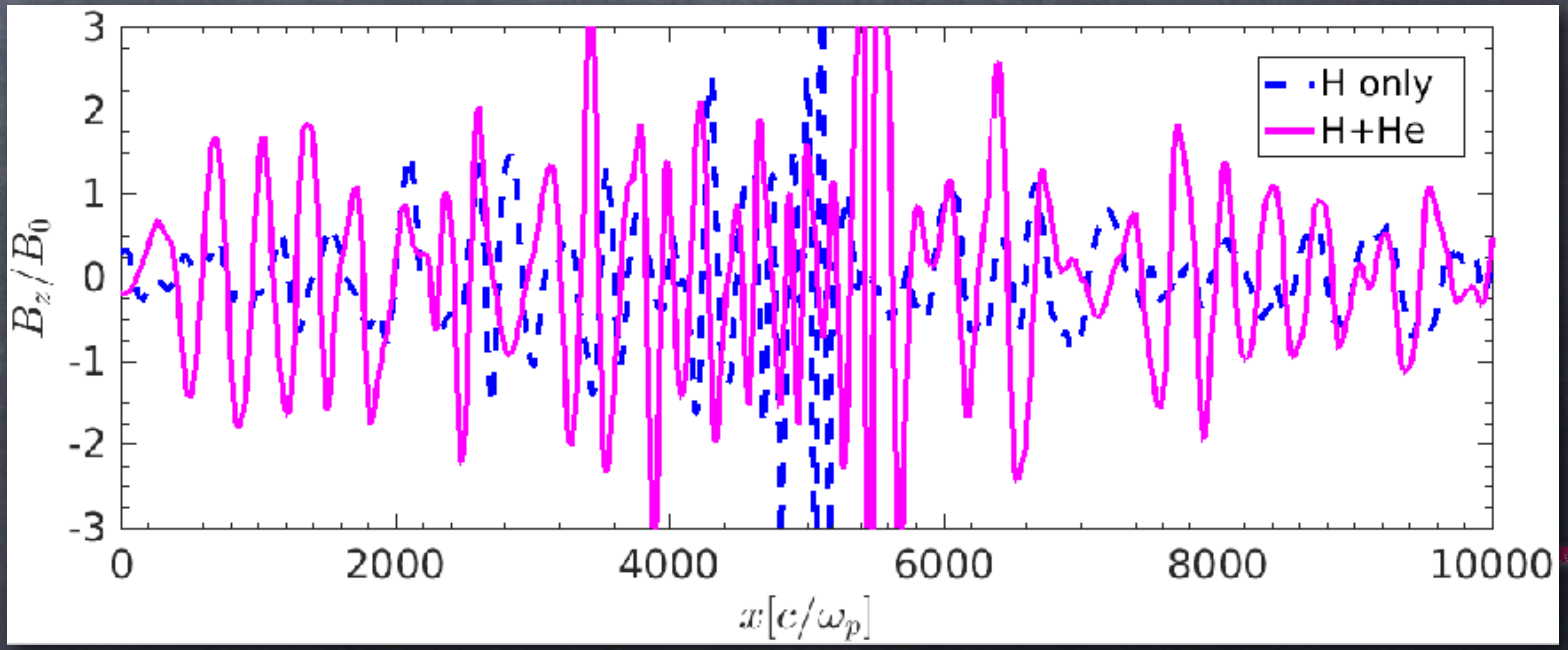
TALK BY M. MICELI

- $E_{max,i}$ scales with Z_i
- The tail normalization scales with $(A_i/Z_i)^2$
  - Explains CR abundances!

Helium is *not* test-particle!

- With cosmological He abundance ~10% (DC, Cotter, Roussi, in prog; Hanusch+19)
  - He acceleration efficiency ~15% (as H)
    - *Total* efficiency ~30%
  - He can drive waves as much as H
    - E_{max} 2x larger for both species
  - Hadronic γ-ray emission can be by a factor ~5 (DC+11)





Multi-Scale Approach to Shock Acceleration

Micro

Meso

(Space-Physics)

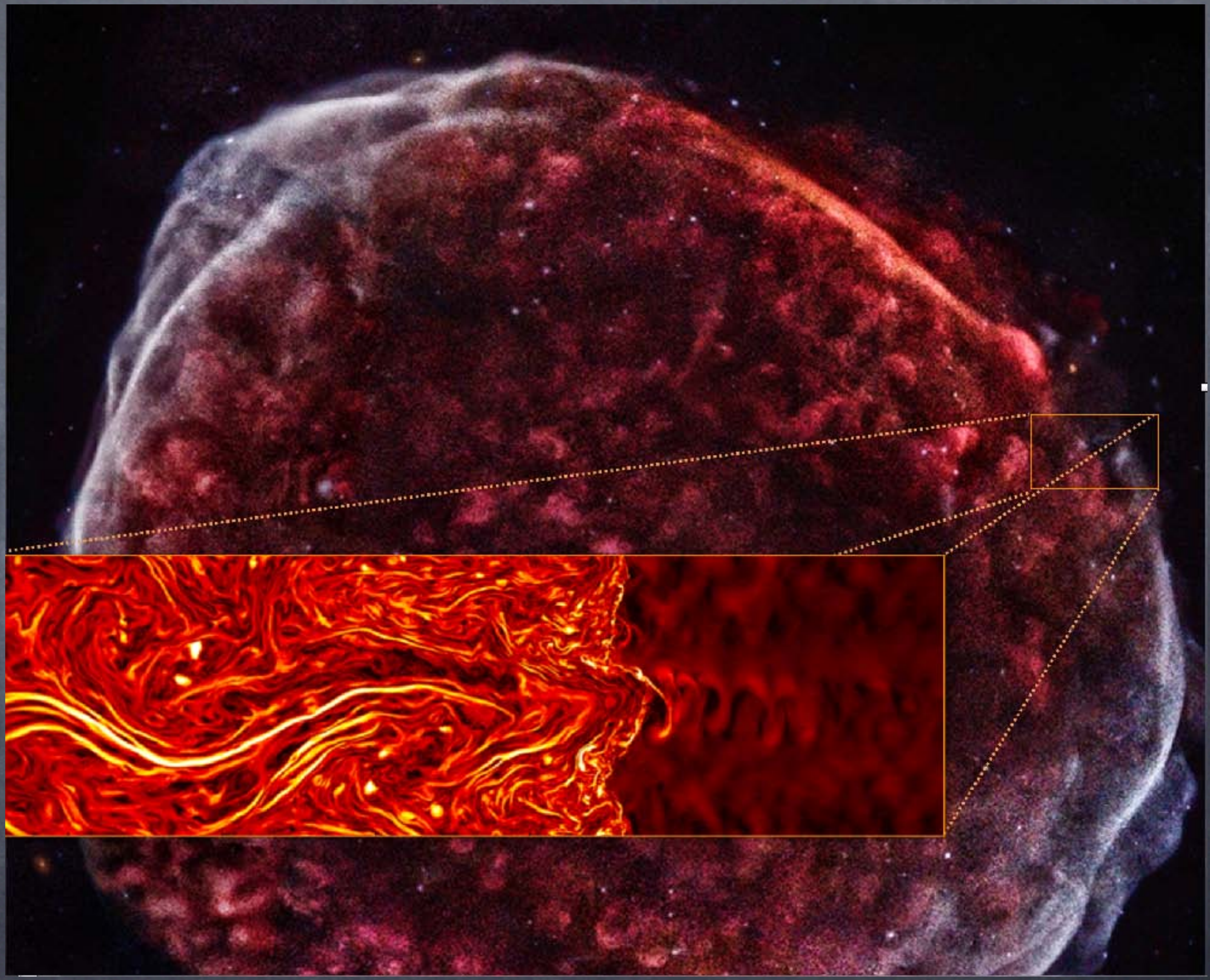
Astro

PIC Simulations
electron + ion dynamics

Hybrid: ion dynamics, magnetic field amplification

Super-Hybrid (MHD+hybrid)
Large/long scales
High-Mach numbers
(Bai+15, Mignone+18, Casse+18)

Semi-Analytical
CRAFT = *Cosmic Ray Analytical Fast Tool*



Large-scale kinetic approaches to non-linear DSA

- Solve shock hydrodynamics self-consistently with CR Diffusion-Convection eq.:

$$\tilde{u}(x)\frac{\partial f(x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(x,p)}{\partial x}\right] + \frac{p}{3}\frac{\mathrm{d}\tilde{u}(x)}{\mathrm{d}x}\frac{\partial f(x,p)}{\partial p} + Q(x,p),$$

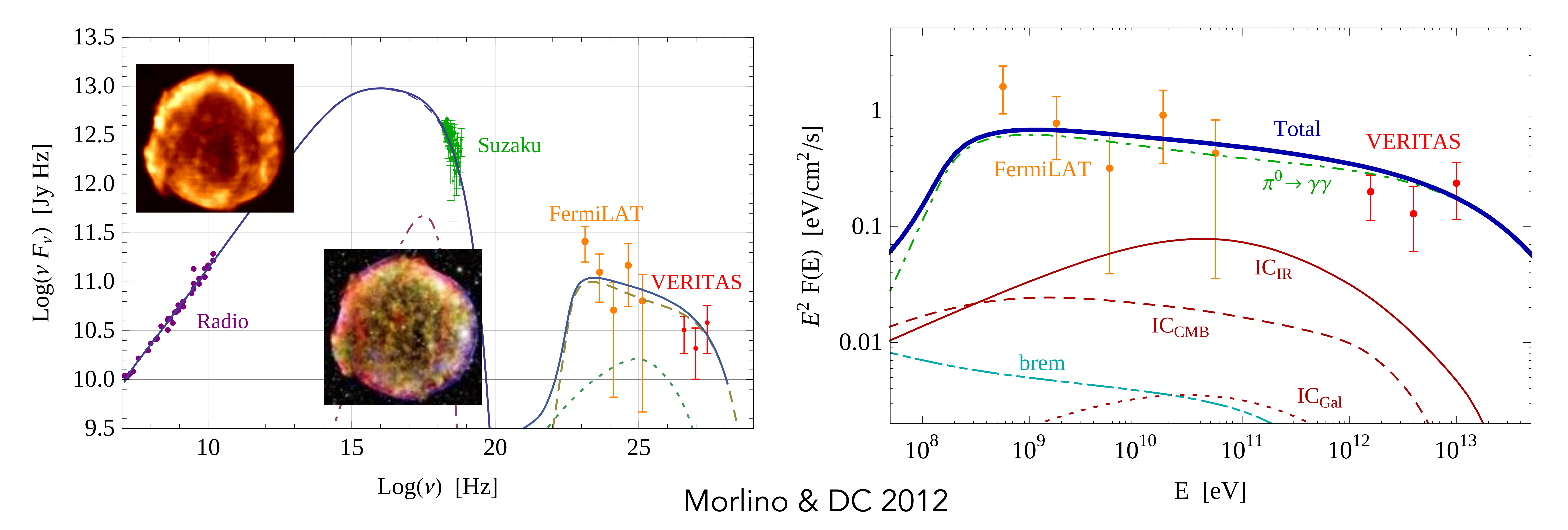
ADVECTION DIFFUSION ACCELERATION INJECTION

  - **FULLY NUMERICAL**: time-dependent (Kang & Jones97-…; Berezhko & Völk97-…; Zirakashvili & Aharonian09…)
  - **MONTE CARLO:** account for anisotropic distributions (Jones & Ellison+91; Baring+95-…, Ellison+90-…)
  - **SEMI-ANALYTICAL**: versatile, computationally fast (Malkov97; Blasi02; Amato & Blasi05-…, DC+09-…,)
    - CRAFT: *CR Analytical Fast Tool*, which will be publicly released (Diesing, DC+19)
- Require an a priori description of
  - Magnetic field generation, Particle scattering, D(x,p), CR injection, Q(x,p)

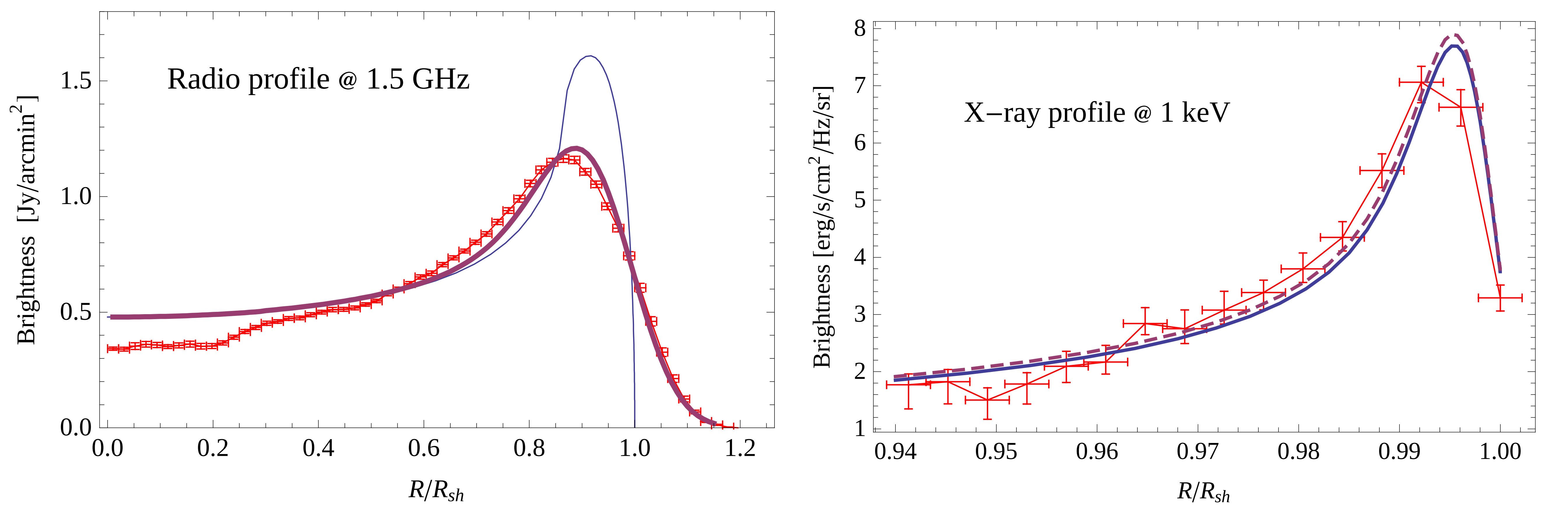
Provided only by kinetic simulations!

Tycho: the smoking gun for hadron acceleration

Type Ia SN
Age=447yr
Distance~3kpc



Morlino & DC 2012



- Spectra and maps from CRAFT
- Acceleration efficiency. ~10%
- Protons up to ~0.5 PeV

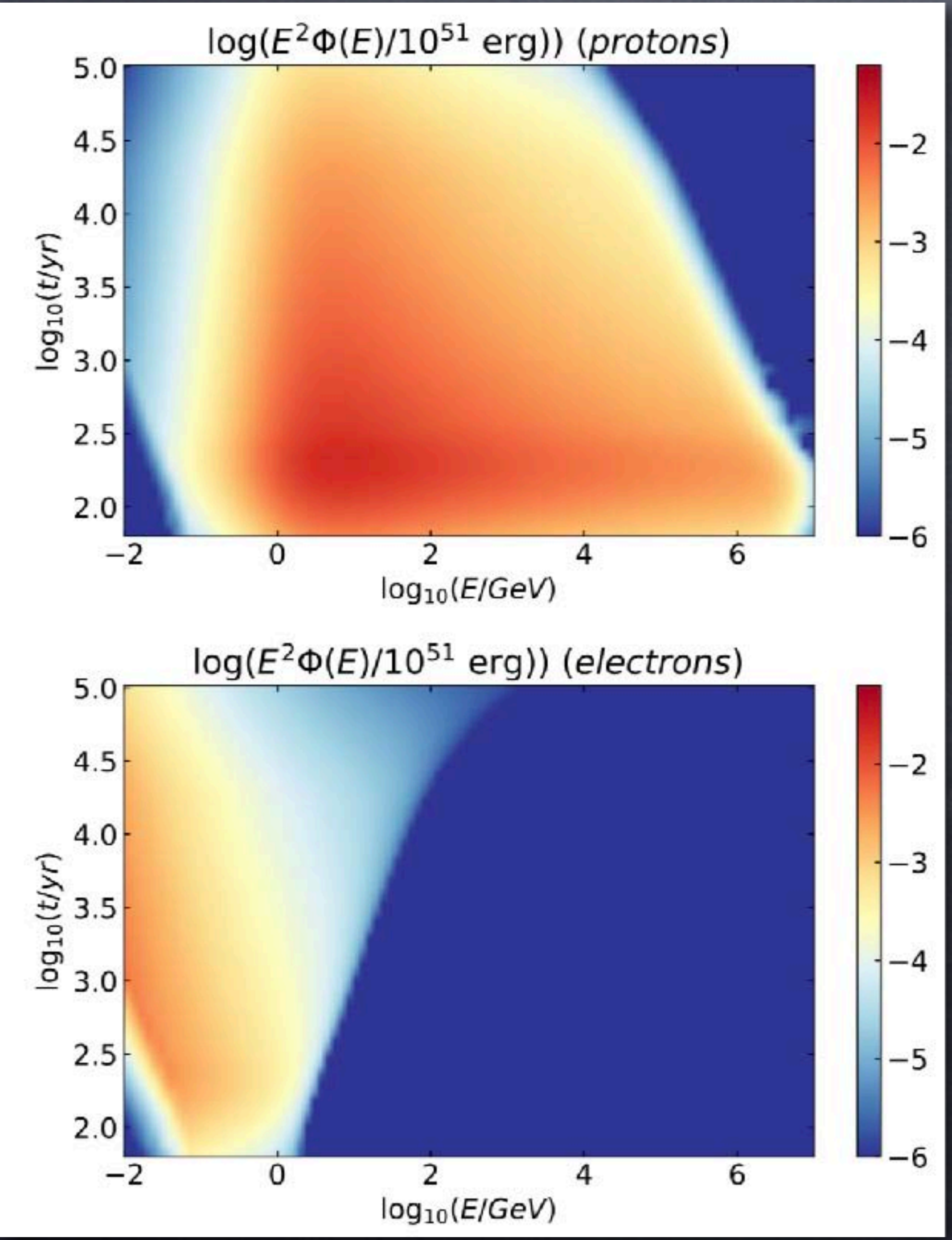
- Only two free parameters: electron/proton ratio and injection (now constrained with PIC!)

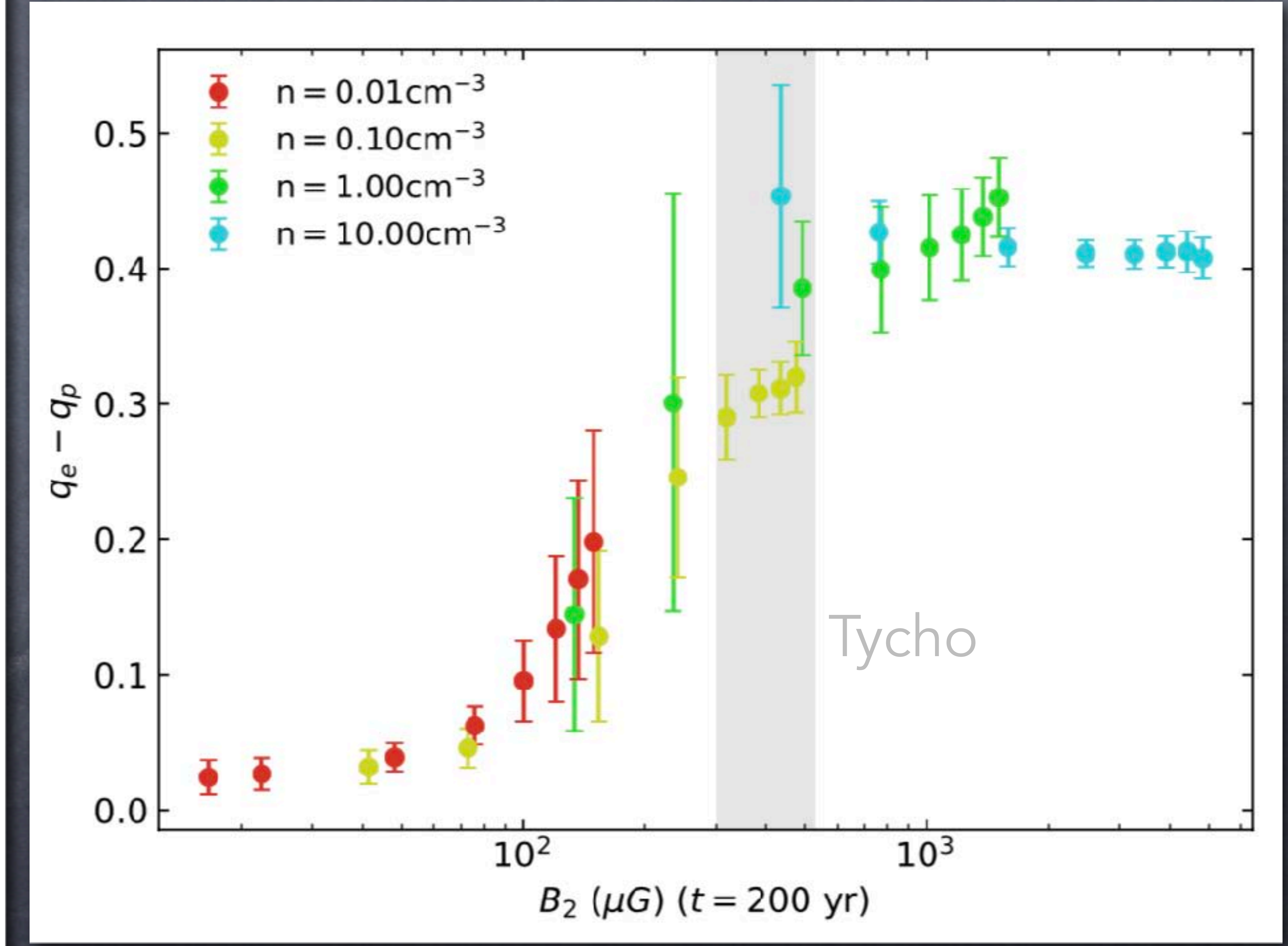
The spectrum of electrons produced by SNRs

- SNR evolution into radiative stage (Diesing & DC, 2018)

TALK BY R. DIESING ON THURSDAY

- Calculation of electron spectrum including synchrotron losses in self-generated B:





Cooling makes the electron spectrum steeper by Δq~0.3-0.4

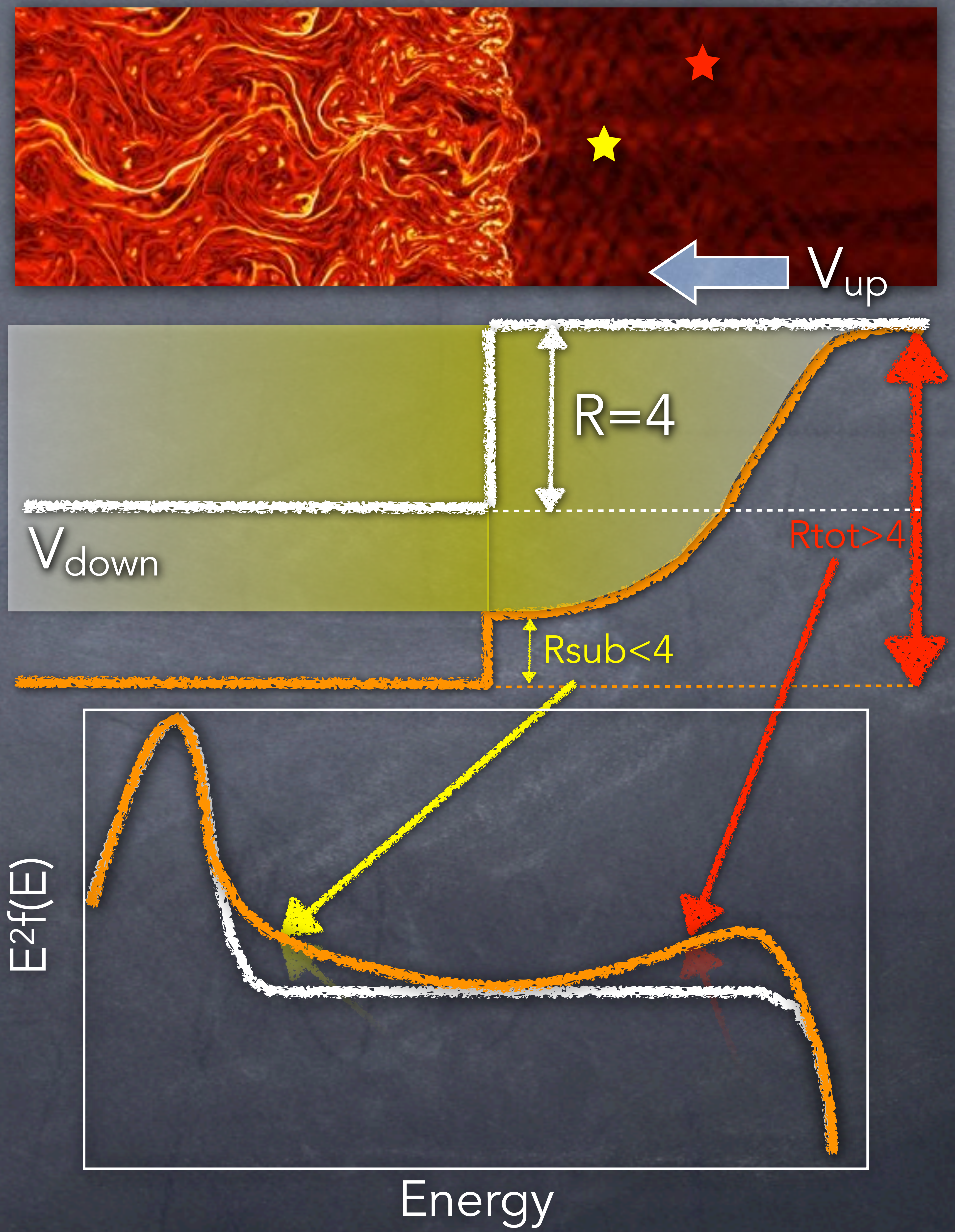
- May explain the *positron excess* as an *electron deficit*!

Non-Linear Diffusive Shock Acceleration

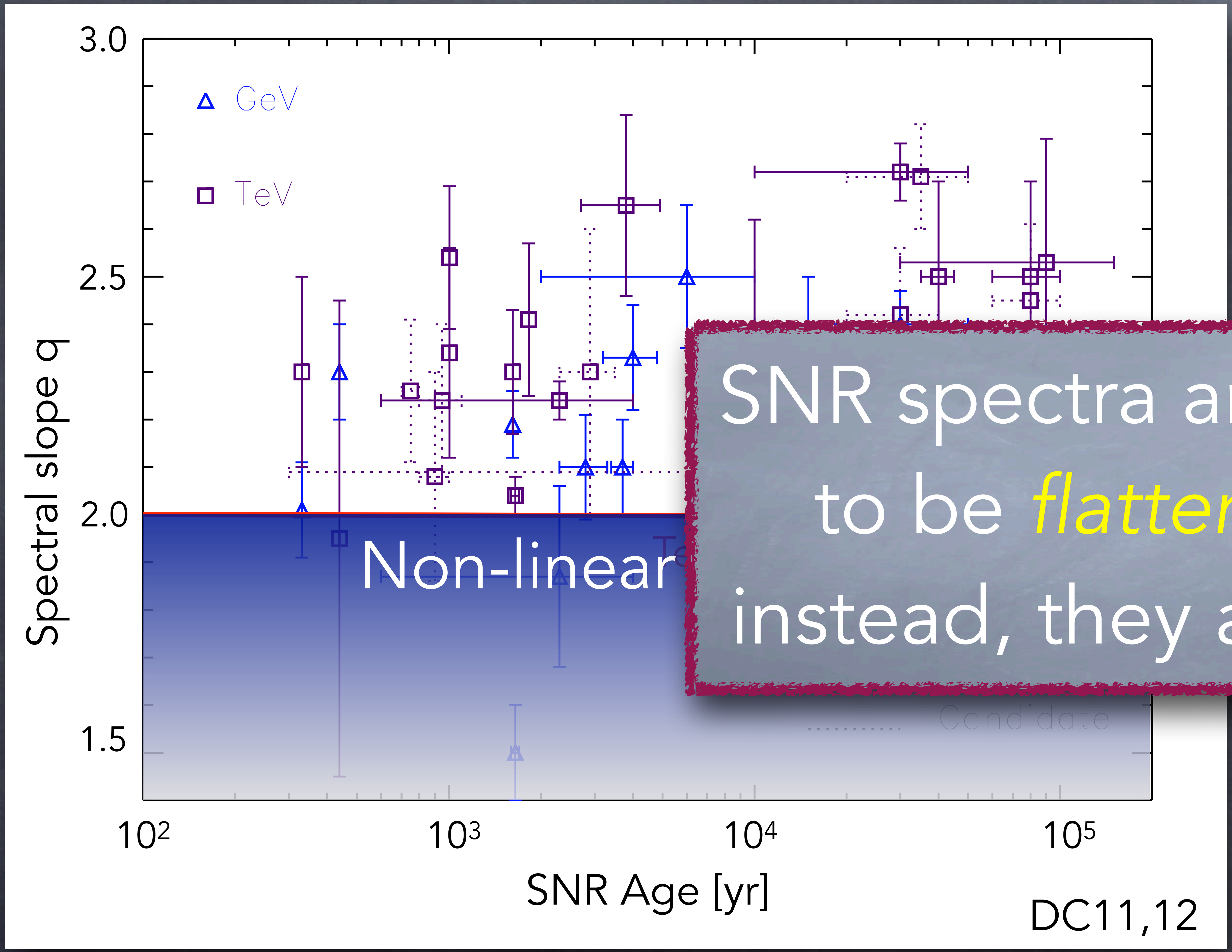
- The spectral index depends only on the compression ratio

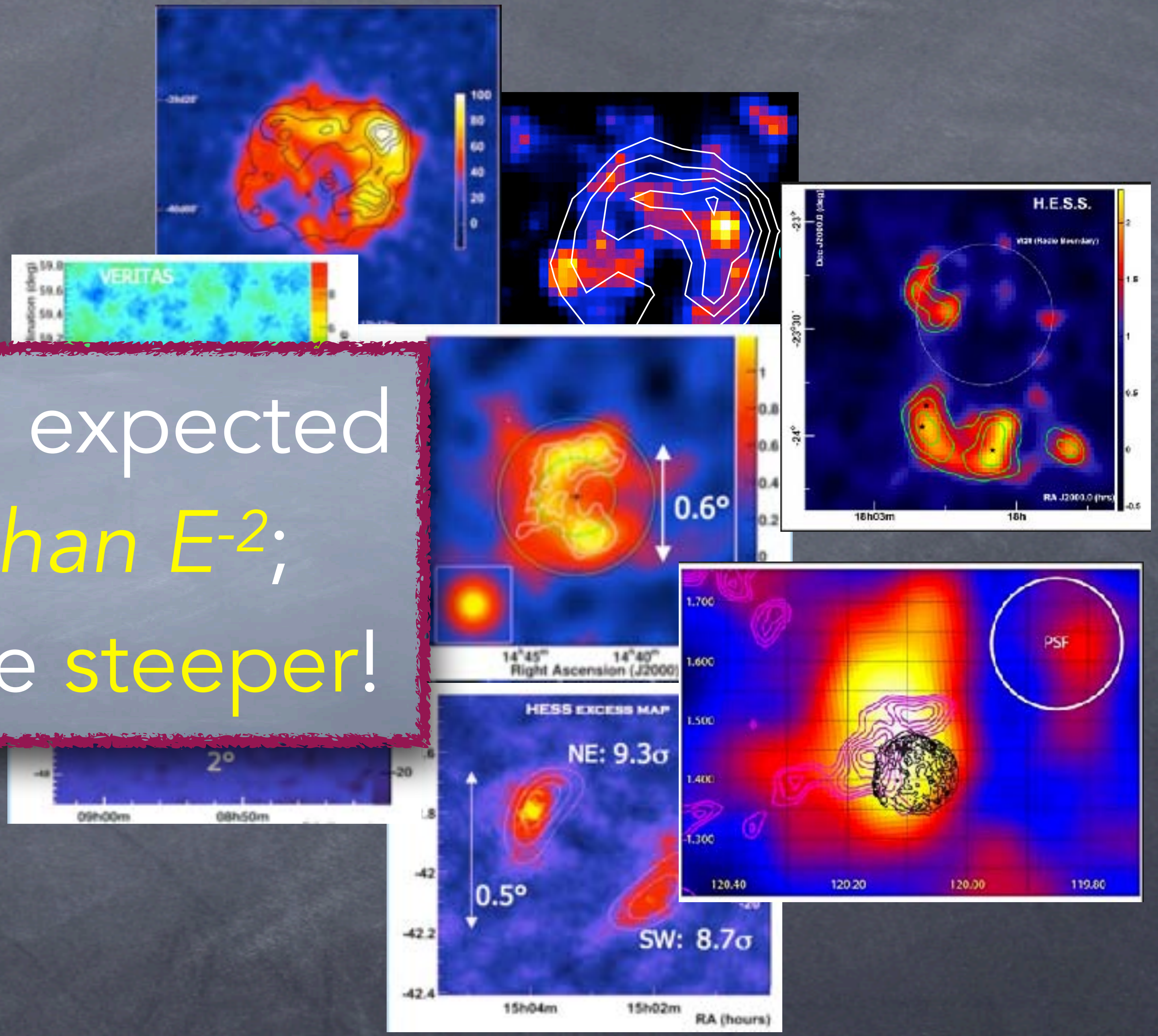
$$q = \frac{R+2}{R-1}; \qquad R = \frac{\gamma+1}{\gamma-1};$$

- The CR pressure makes the adiabatic index smaller (R becomes larger)
- Particles "feel" different compression ratios: spectra become concave
- If acceleration is efficient, at energies >1 GeV: q < 2 (flat spectra!)



With Fermi, HESS, VERITAS, MAGIC, HAWC,...





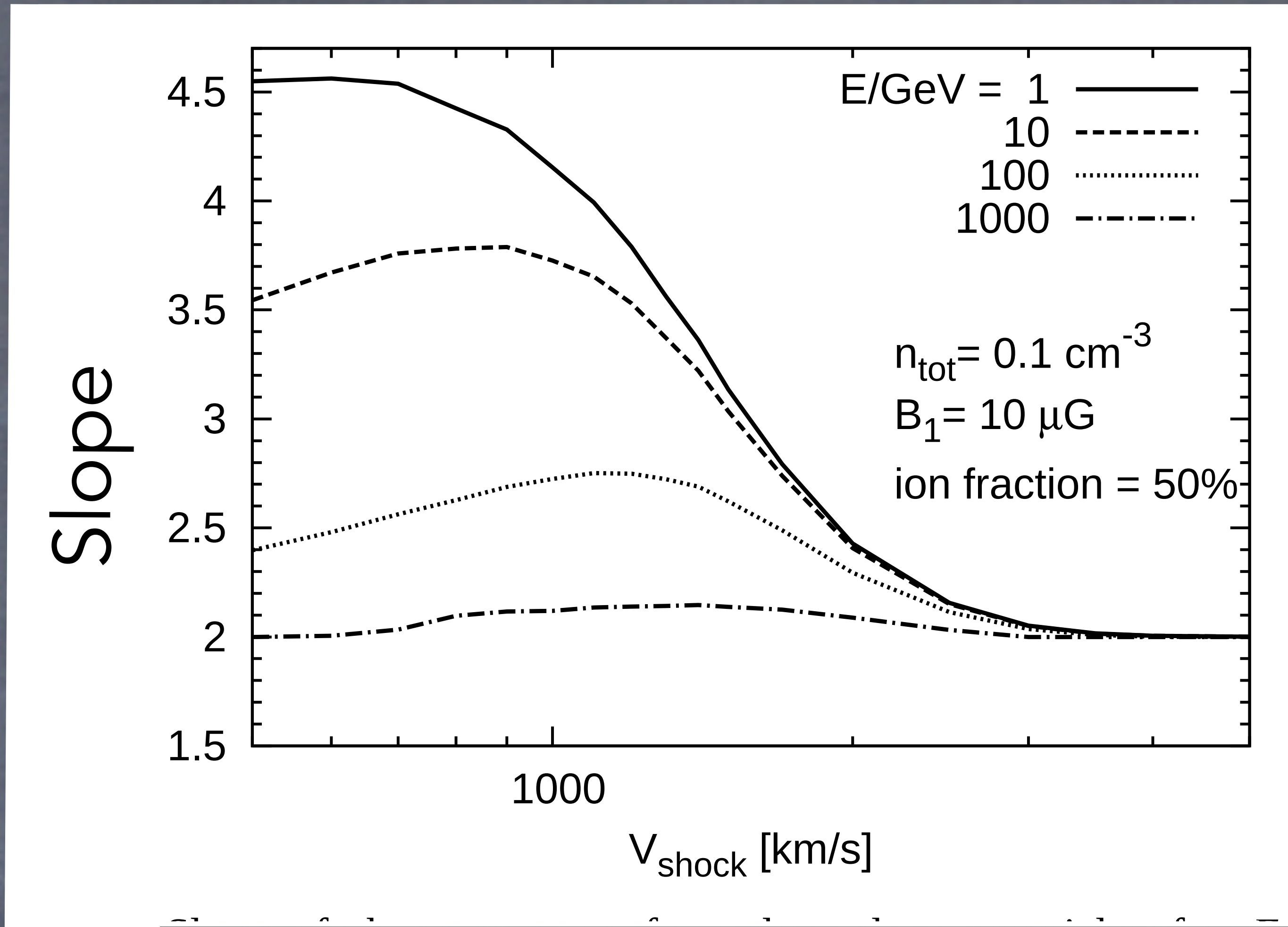
SNR spectra are expected to be *flatter than E^{-2}*; instead, they are steeper!

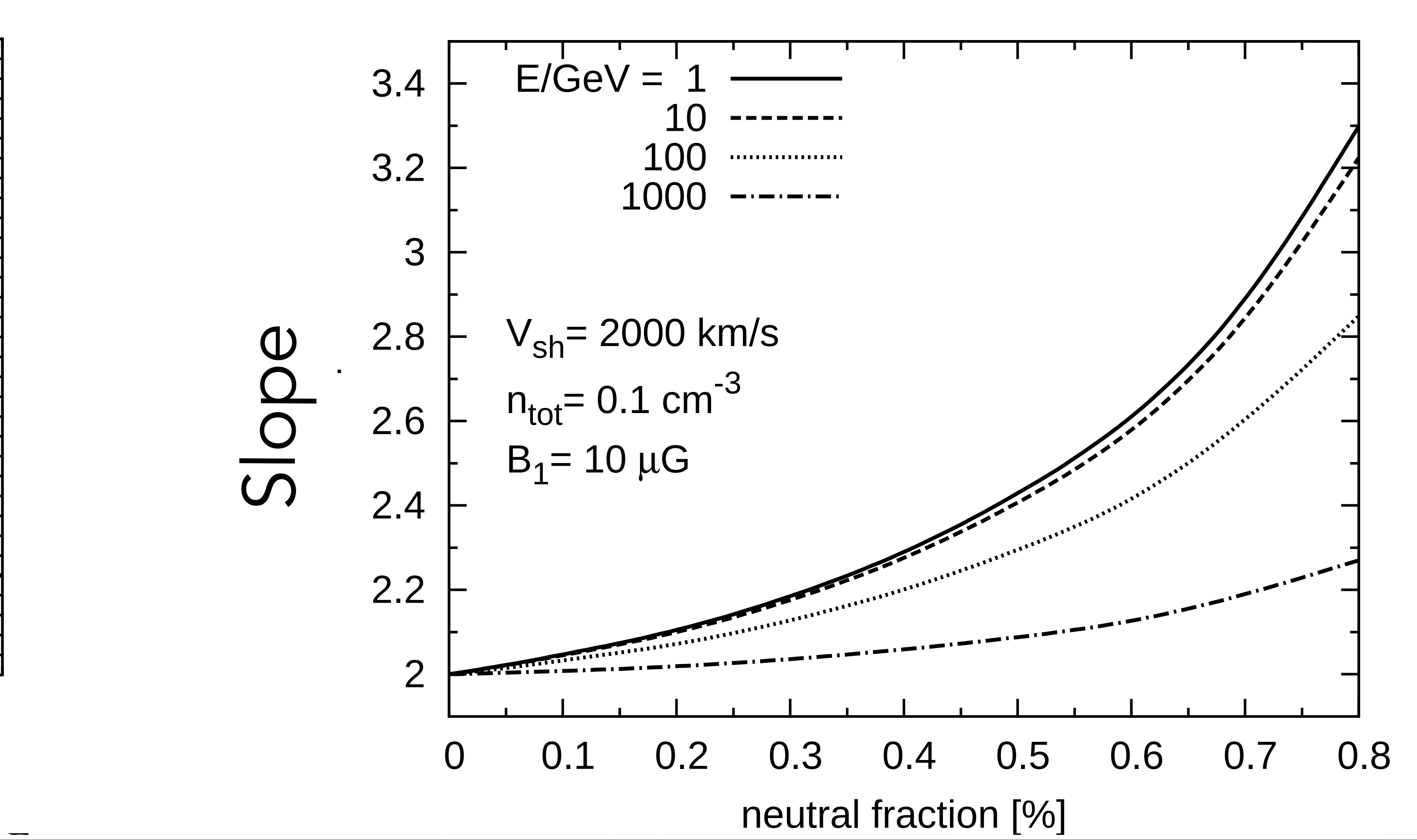
- Evidence of ion acceleration: spectra too steep to be leptonic...
- ...and to be consistent with non-linear DSA theory! (e.g., Jones & Ellison91, Malkov & Drury01)

The Origin of Steep Spectra

- Shocks in partially-neutral media (Blasi+12; Morlino+13; Ohira14)
  - Charge-exchange may induce a neutral return flux that makes the shock weaker
  - Balmer lines probe CR acceleration (Helder+09; Raymond+10; Morlino+14)

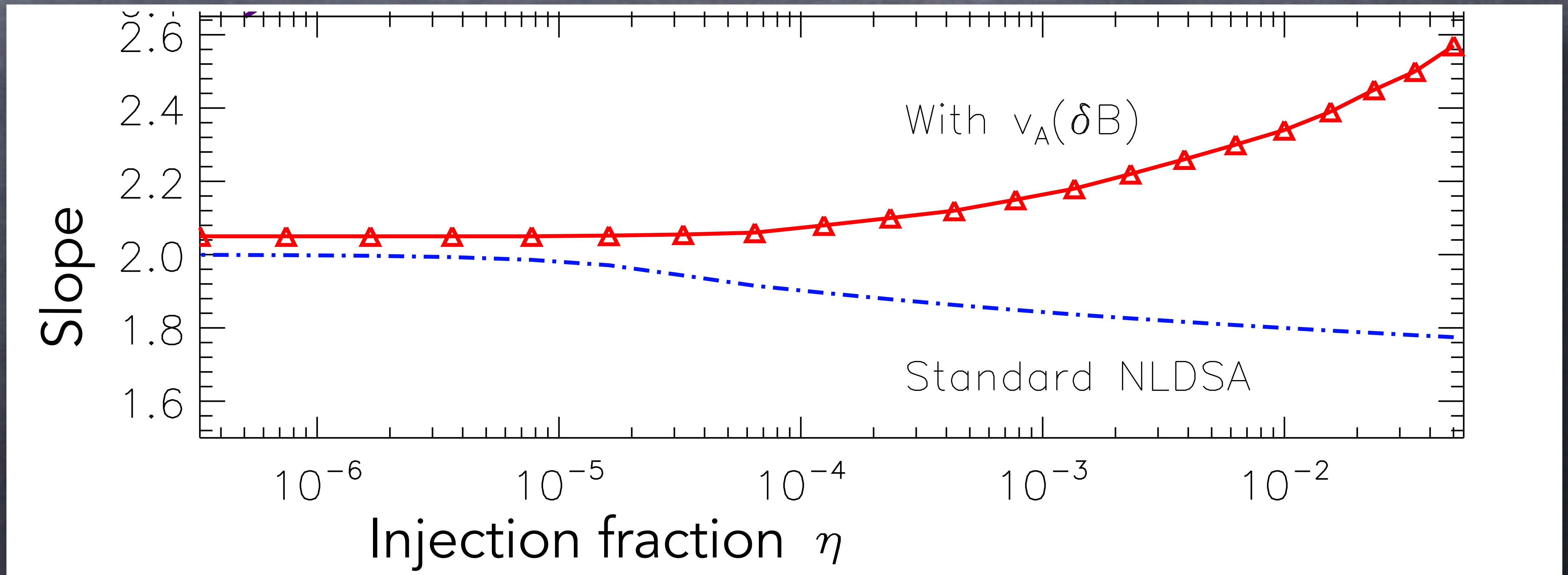
TALK BY R. BANDIERA





- Magnetic feedback (Bell78; Zirakashvili & Ptuskin 08; DC+09; DC11,12,...)
  - The large velocity of scattering centers ($v_A \sim \delta B$) leads to an effective ratio:

$$R_{\rm CR} \simeq \frac{U_{\rm up} - v_A(\delta B)}{U_{\rm down}} \lesssim R_{\rm gas}$$



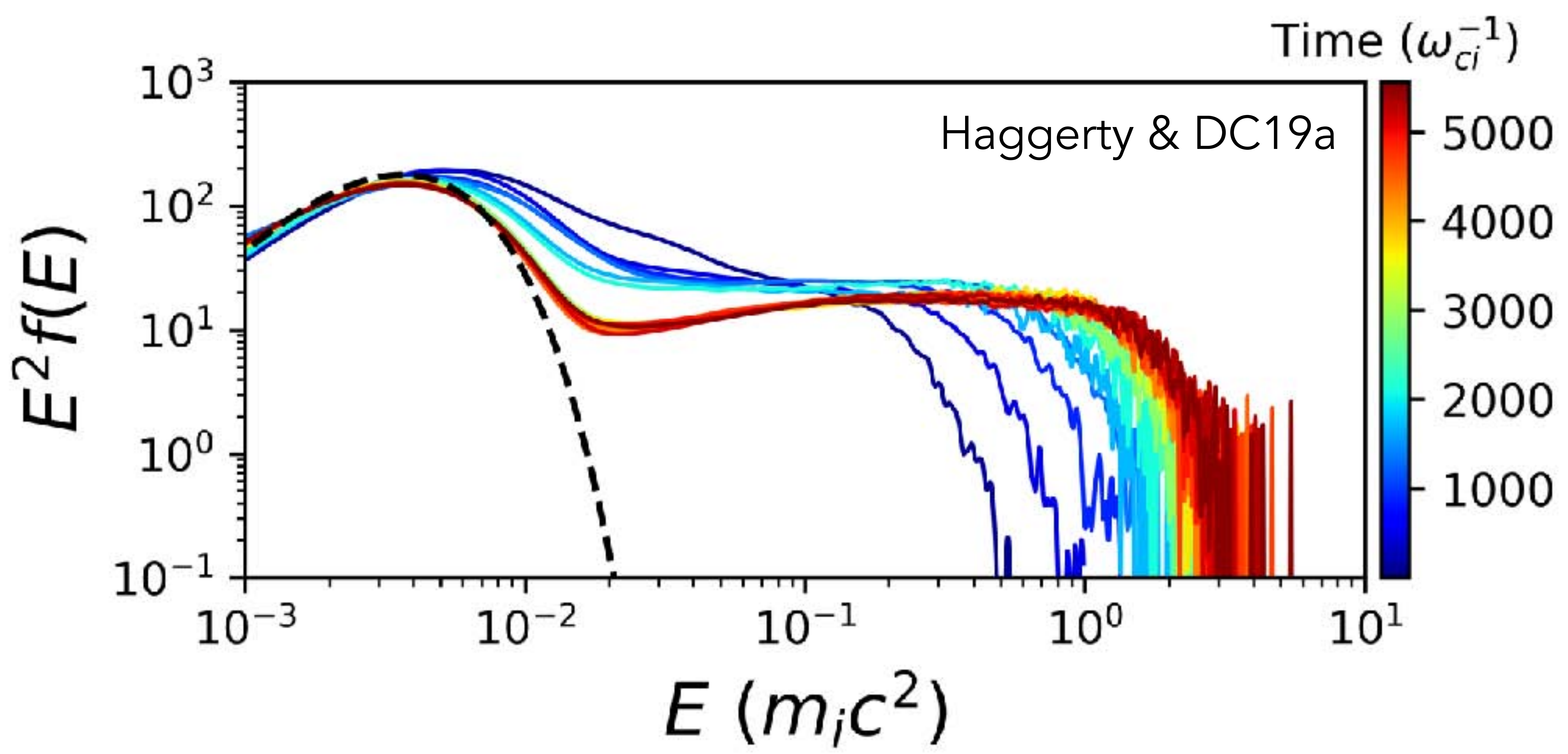
- Oblique shocks/modified diffusion (Kirk+96; Morlino+07; Bell+11, Malkov & Aharonian19,...)

Hybrid Simulations with Relativistic Ions: dHybridR

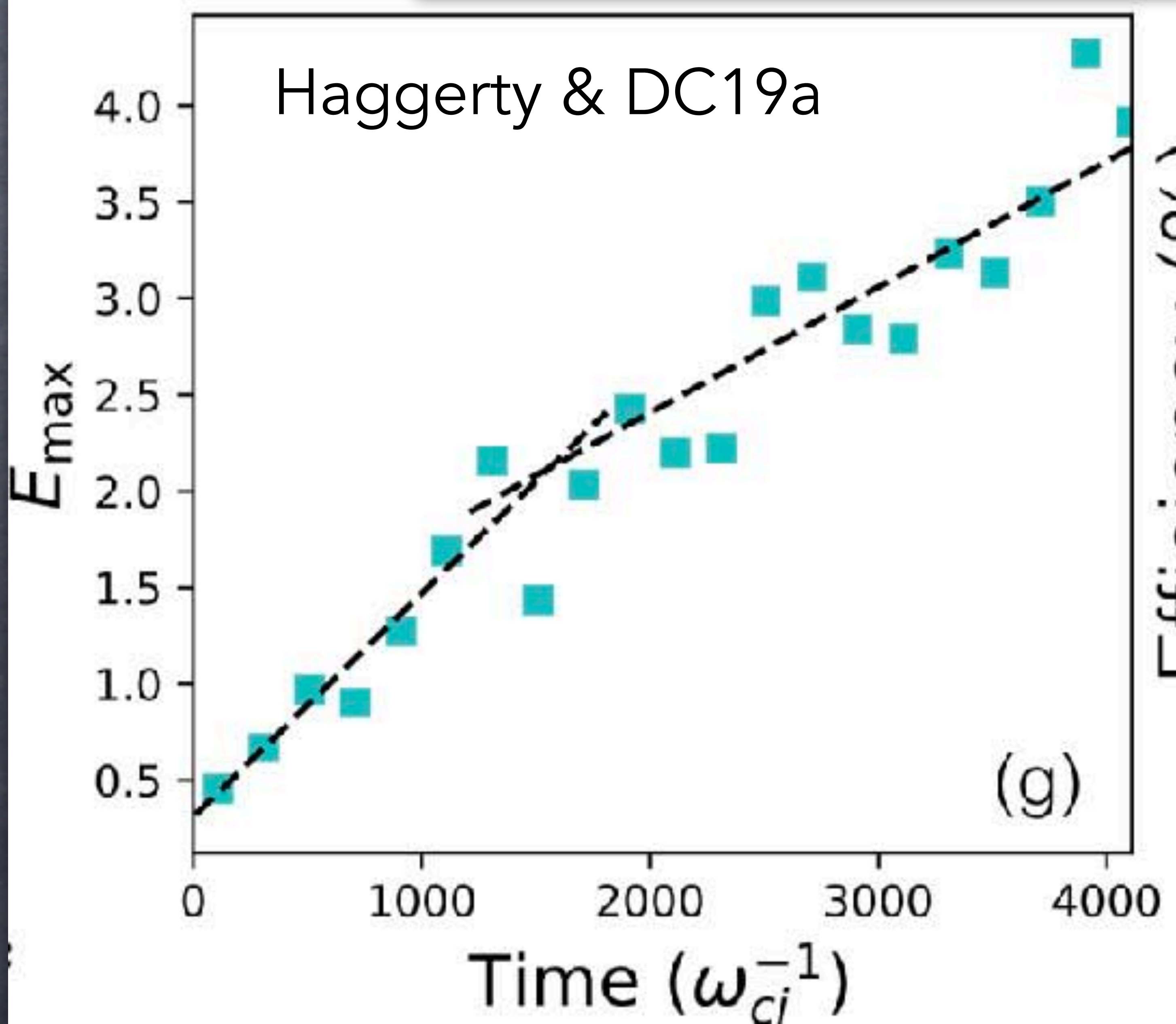
- Hybrid limit requires $v_{bulk} << c$

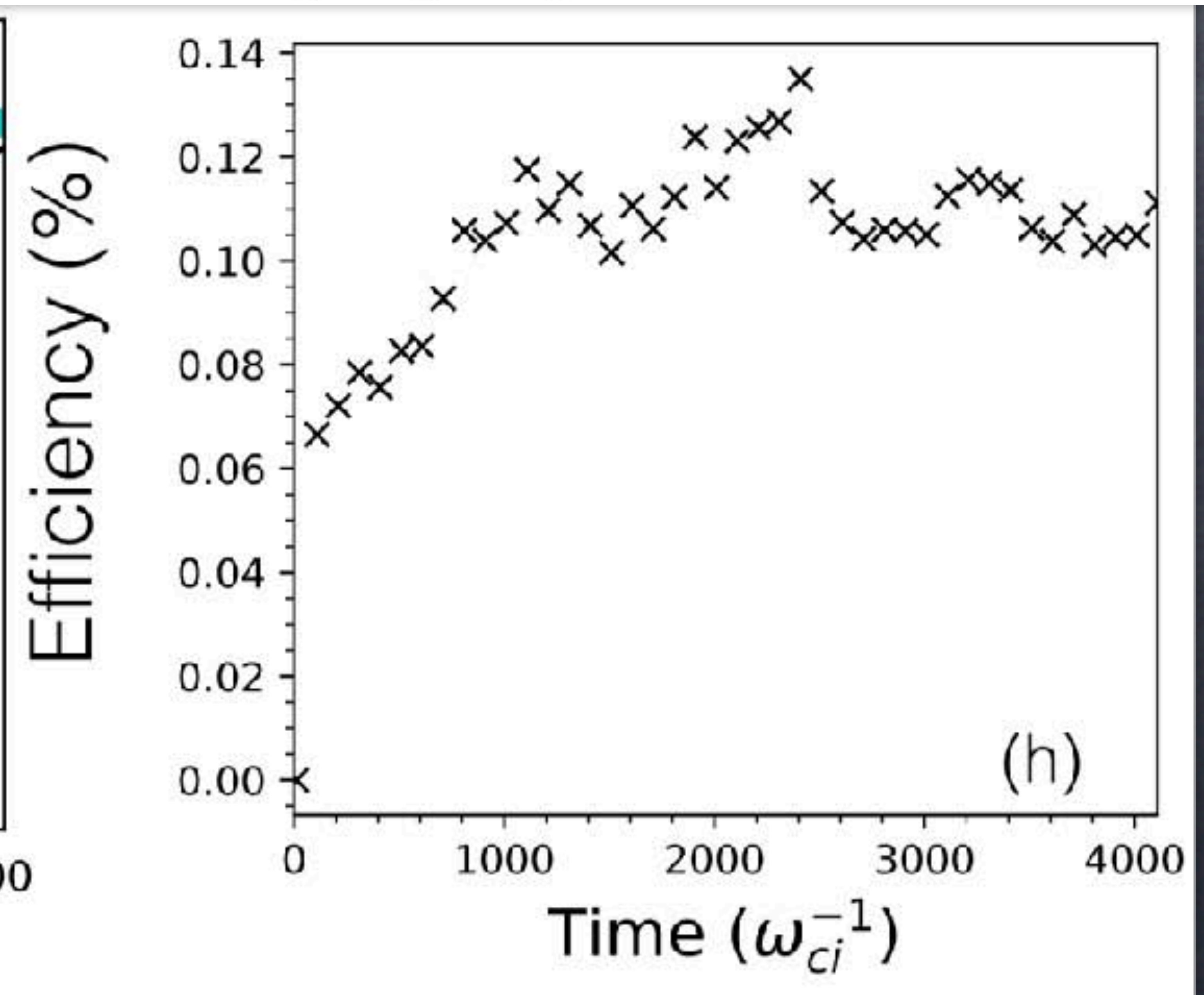
DSA: $f(p) \propto p^{-4}$; $4\pi p^2 f(p)dp = f(E)dE$

$f(E) \propto E^{-1.5}$ (non rel.) -> $f(E) \propto E^{-2}$ (relativ.)



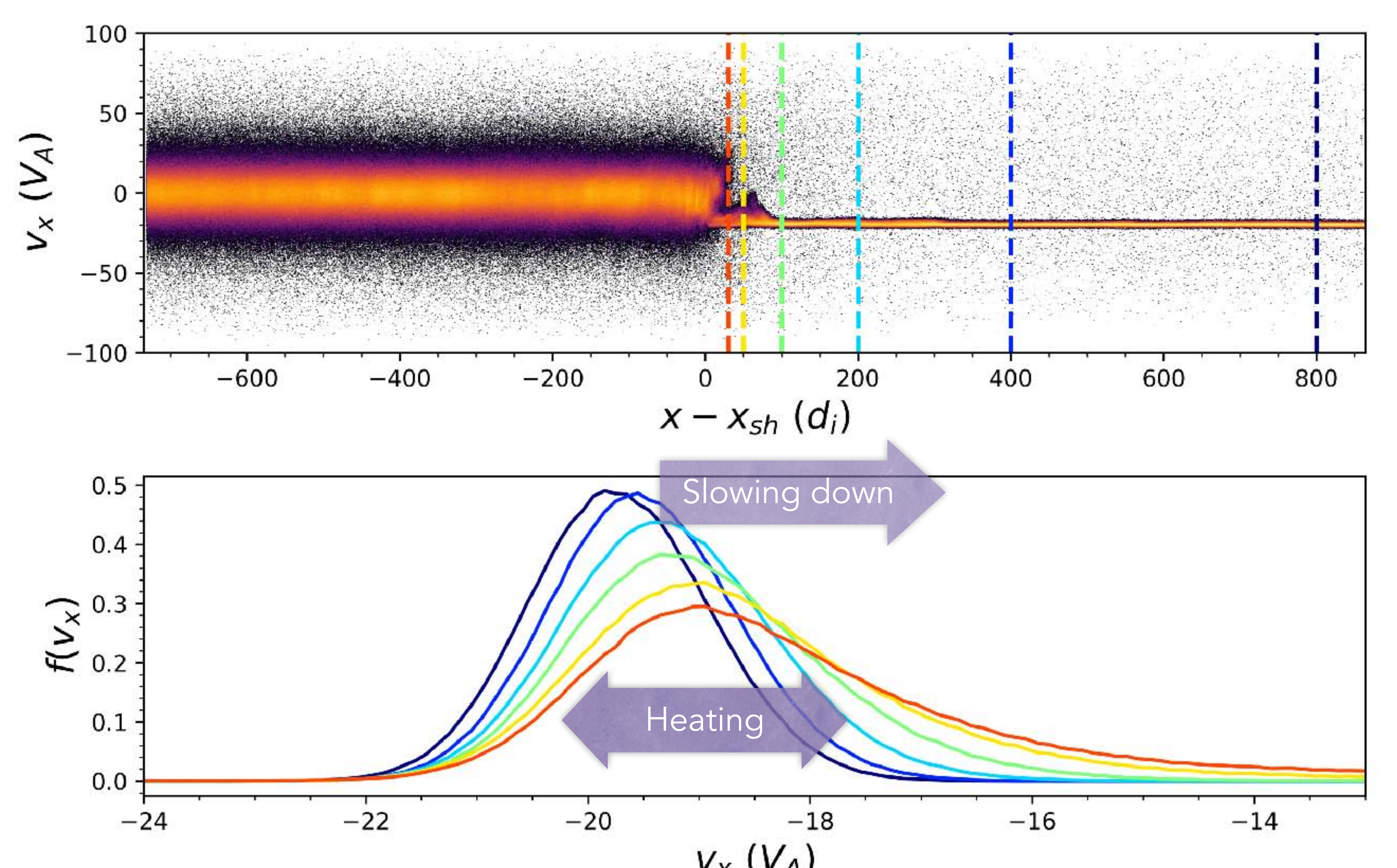
- Long-term evolution
  - $E_{max}(t) \propto t$
  - Efficiency 10-12%





Evidence of a CR Precursor

- The CR pressure slows the upstream flow down and heats it up



Haggerty & DC, in prep

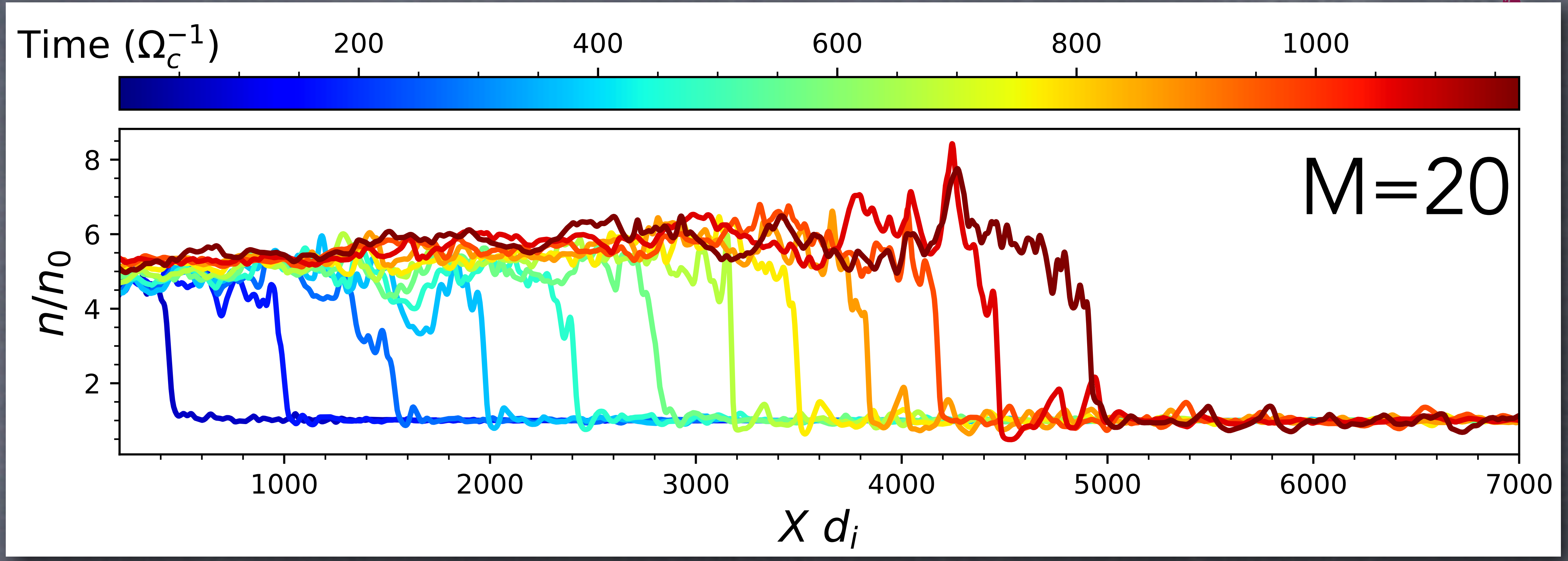
- B damping leads to non-adiabatic heating
  - ~ equipartition between gas and B pressures
- Compression ~1.3 upstream and $R_{TOT} > 4$ overall!

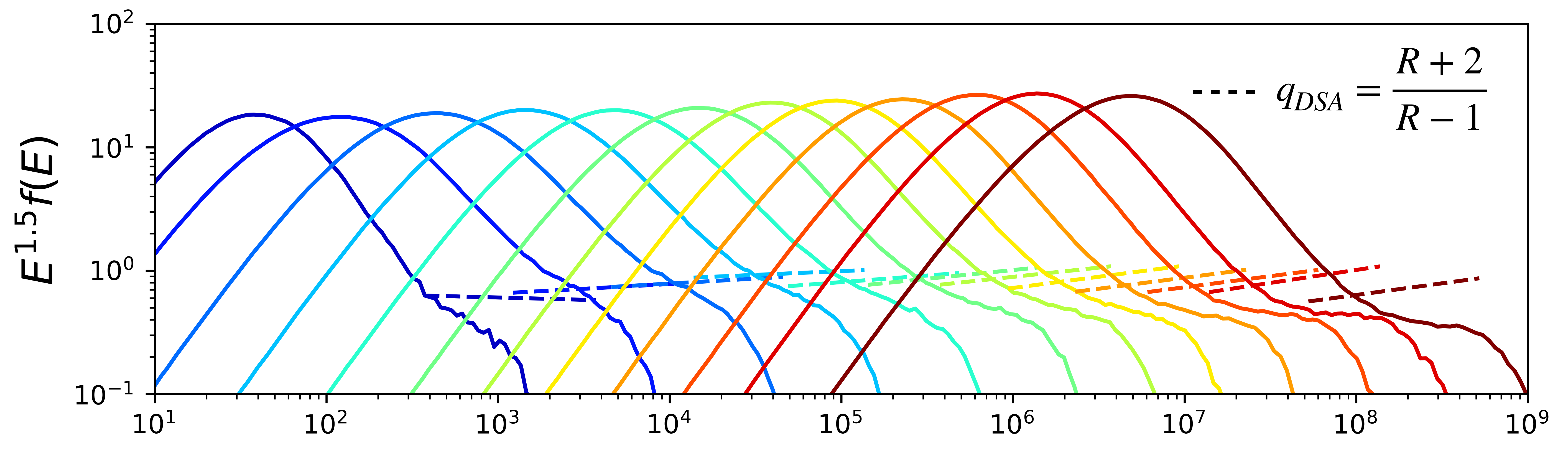
A Revised Theory of Non-Linear DSA

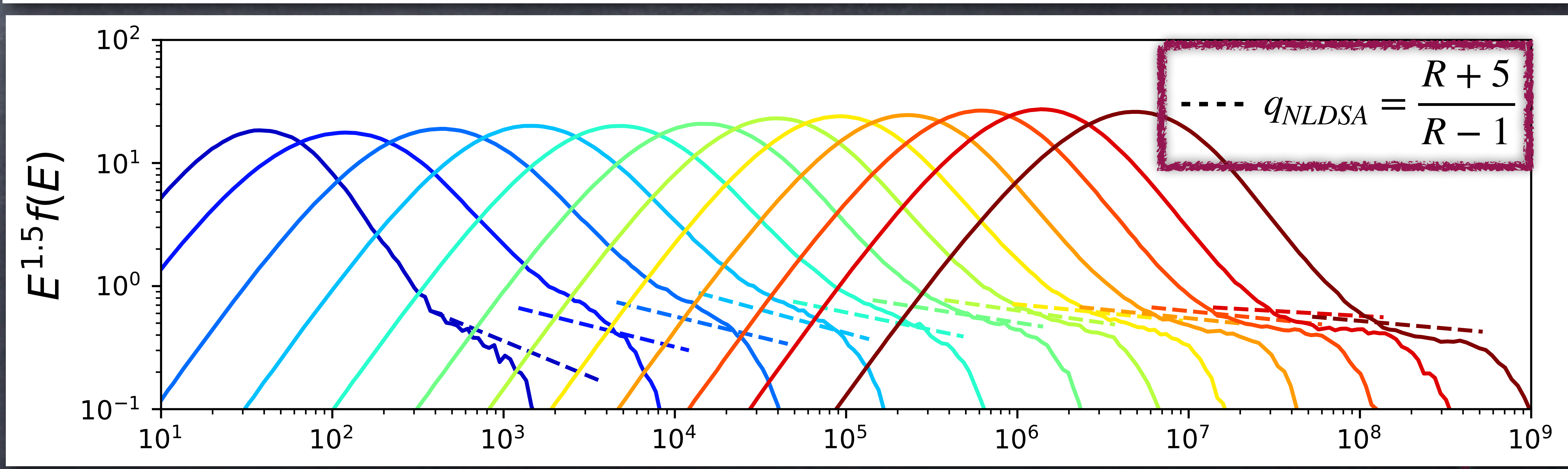
- *R* increases with time, up to ~6
- Spectra *inconsistent* with $q_{\mathrm{DSA}} = \dfrac{R+2}{R-1}$
- They rather obey

$$\boxed{q_{\mathrm{NLDSA}} = \frac{R+5}{R-1}}$$

  - *R*~6, *q*~2.2 Explains Tycho (Warren+05, Morlino & DC12, Slane+14)
  - *R*~4-7 account for γ-ray observations
- Crucial role of a B-dominated post-cursor (stay tuned…)







GLOBAL SUMMARY

- Ion injection and DSA efficiency ✔
  - DC & Spitkovsky14a, DC+15,17,18, Haggerty & DC19a
- Magnetic field amplification ✔
  - DC & Spitkovsky14bc, DC+18
- Spectral indexes of ions and electrons ~✔
  - DC & Haggerty19, Diesing & DC19
- Electron injection and DSA efficiency ~?
  - Park+15, Crumley+19, Xu+19
- Saturation of the Bell instability and maximum E_{max} ~?
- Escape from SNRs ?