KITP - Santa Barbara, CA
September 12, 2019

A Novel Theory of Diffusive Shock Acceleration

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REVIEWS OF MODERN PHYSICS VOLUME 29, NUMBER 2 APRIL, 1957

On the Origins of Cosmic Rays

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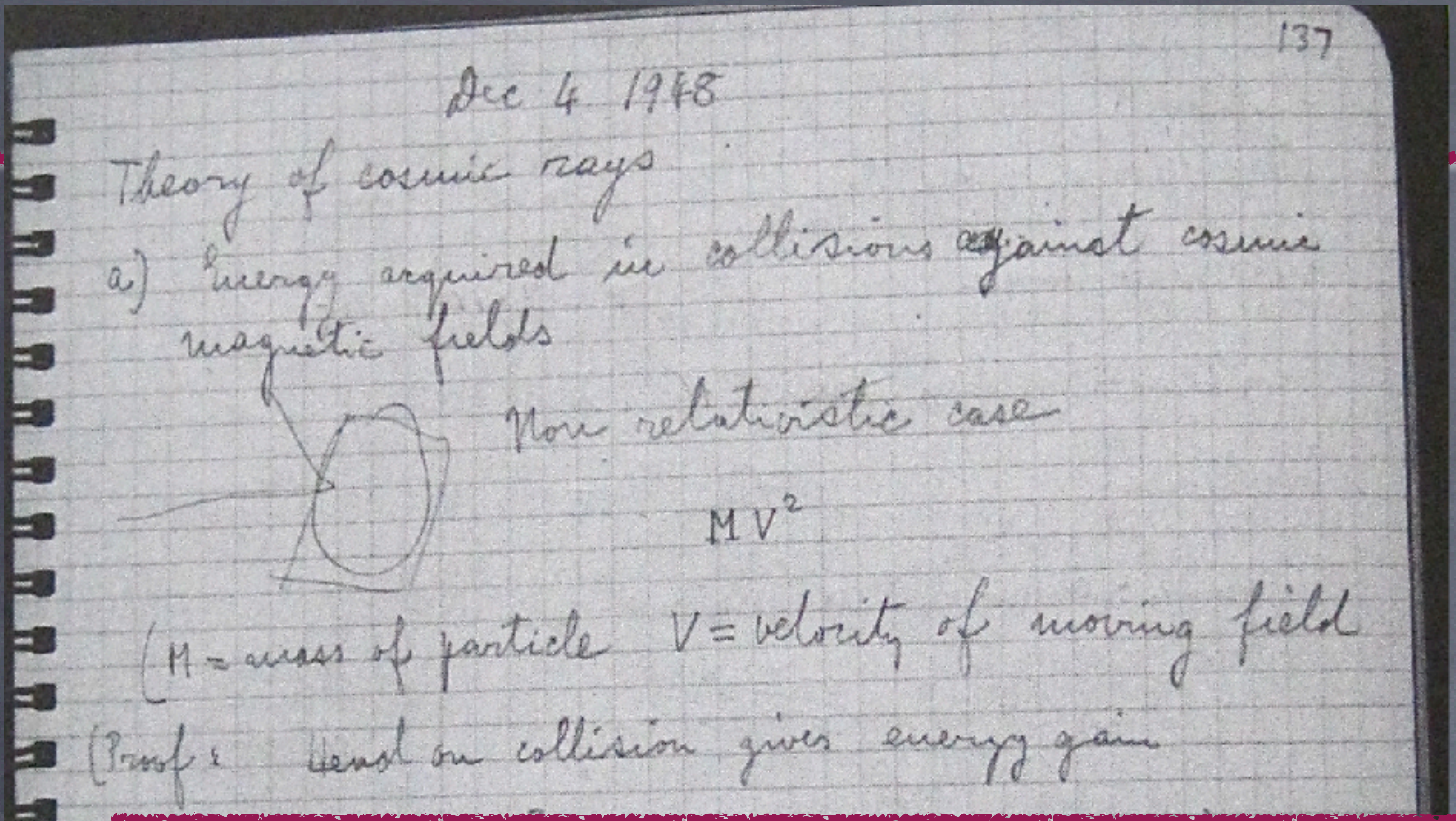
IN 1954, Professor Einstein once remarked that there were two easily observable phenomena that, in his opinion, showed a deep fundamental lack in our knowledge of the physical world. These, he said, were the cosmic rays, and the terrestrial magnetic field. We can

of, say, the latitude effect. The idea was gained, and given quantitative support, that the cosmic rays were not given and immutable, something whose origin could not be approached because they were so far beyond ordinary experience. This idea was aided by



Fermi Acceleration

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

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(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.

A *Universal* Acceleration Mechanism

- In shocks, particles gain energy at any interaction (Krymskii77; Blandford & Ostriker; Bell; Axford+78)

Diffusive Shock Acceleration (DSA)

Downstream (u_2) Upstream (u_1)

Test-particle squeezed between converging flows

- DSA returns power-law $N(p) \propto 4\pi p^2 p^{-q}$, function of the compression ratio $R = u_1/u_2$ only.

$$R = \frac{4M^2}{M^2+3}; \quad q = \frac{3R}{R-1}$$

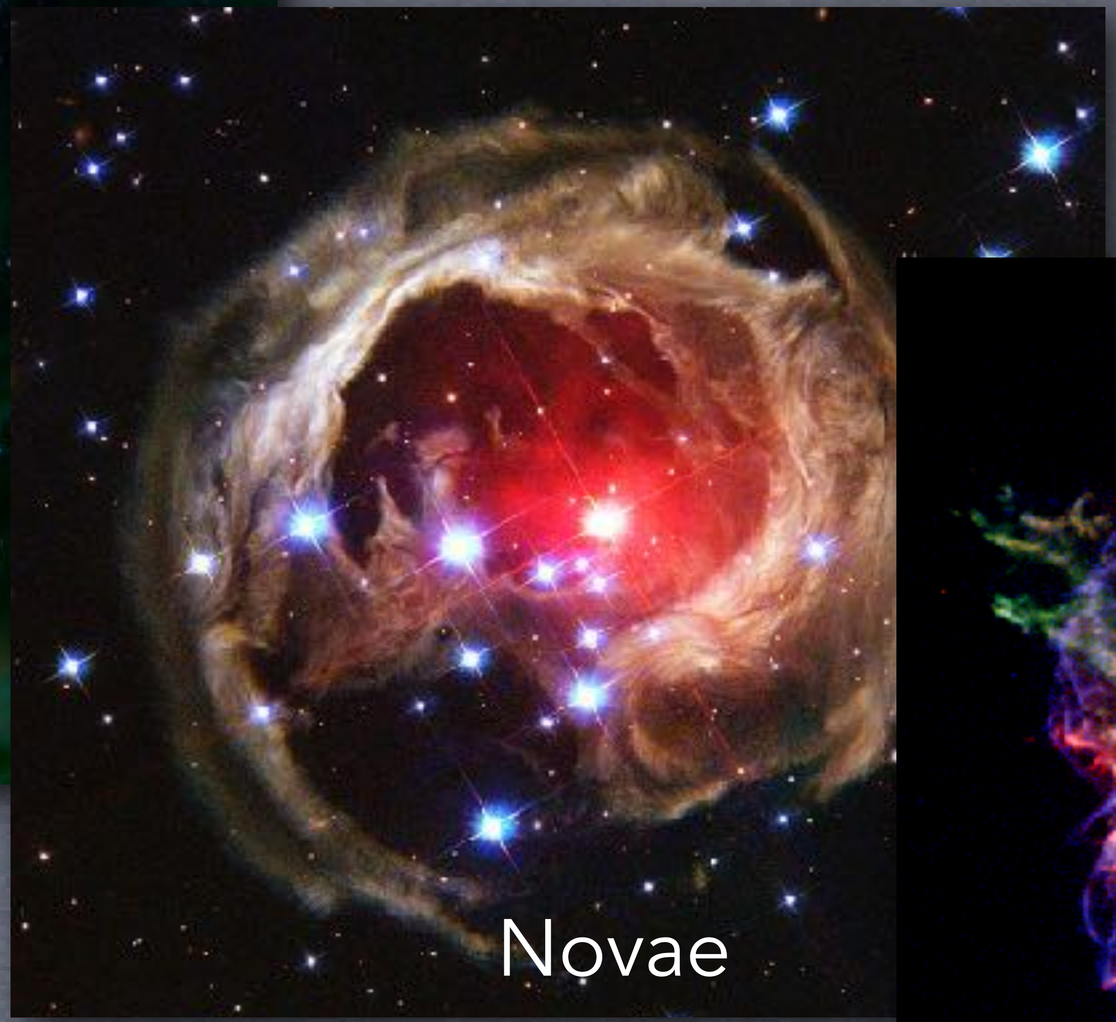
  - For strong shocks: Mach number $M = v_{sh}/c_s \gg 1 \rightarrow R = 4$ and $q = 4$ (in energy, $q_E = 2$)

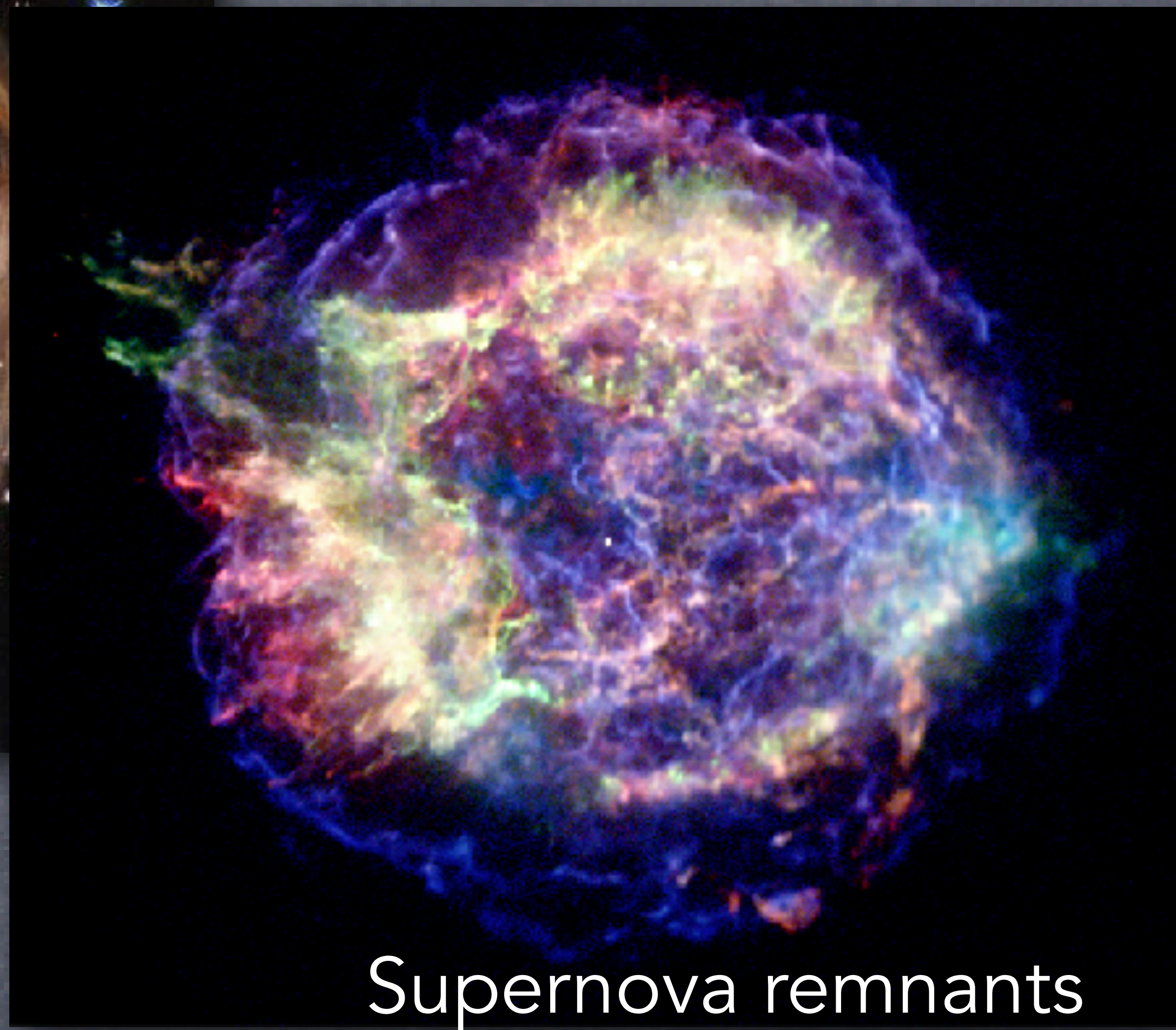
Non-Relativistic Collisionless Shocks

- Prominent sites of non-thermal particles and emission

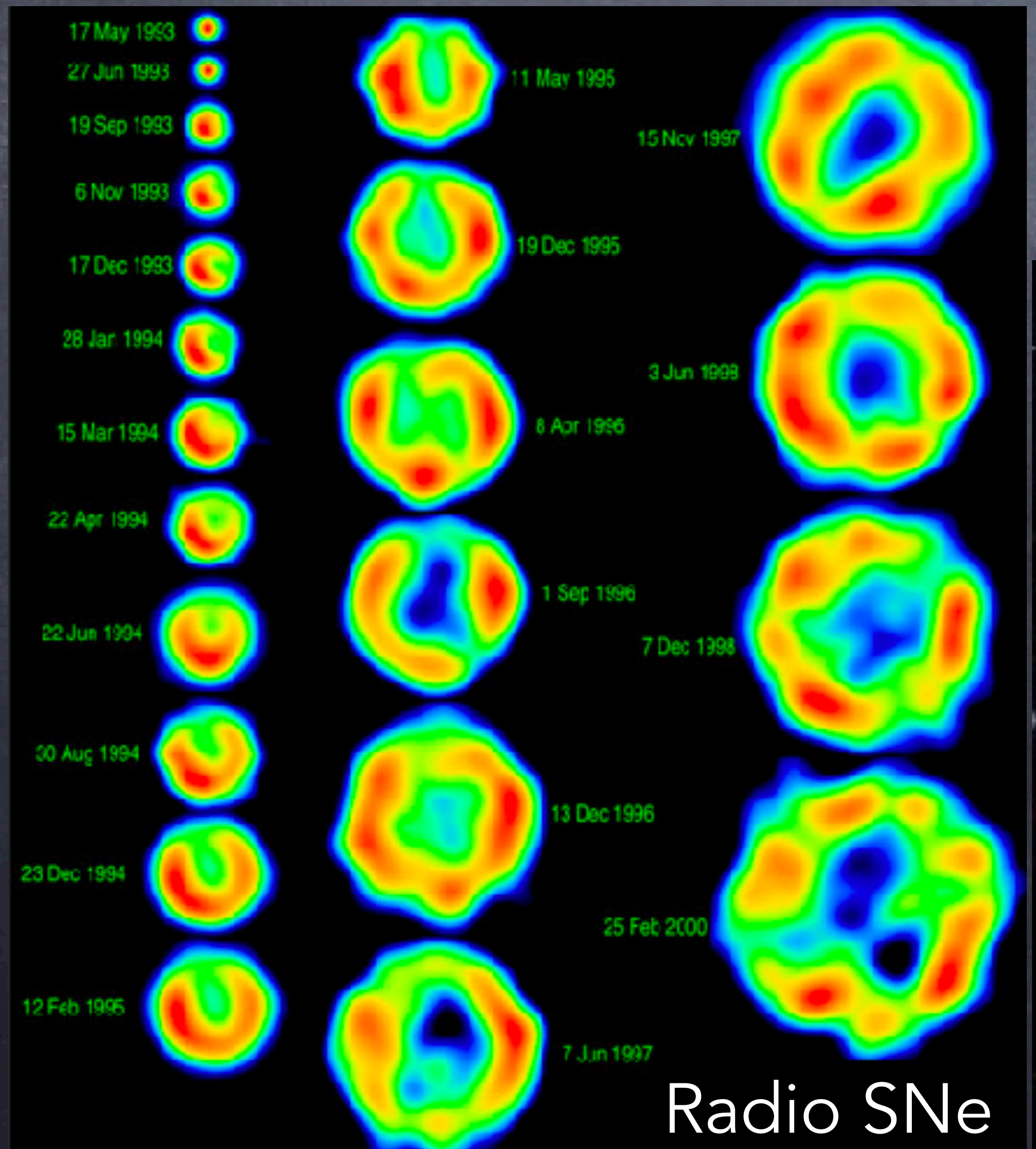
Heliospheric

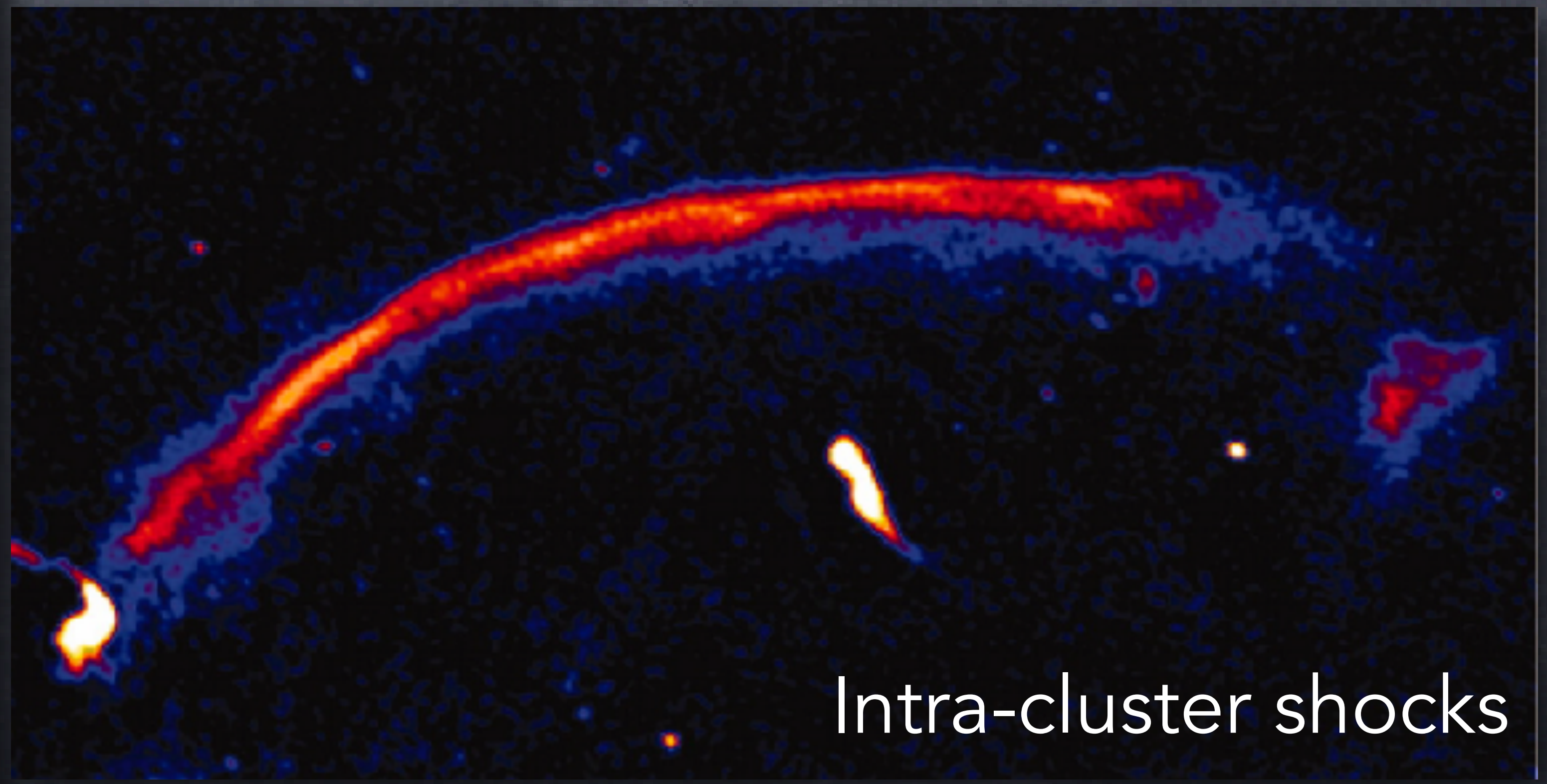
Galactic





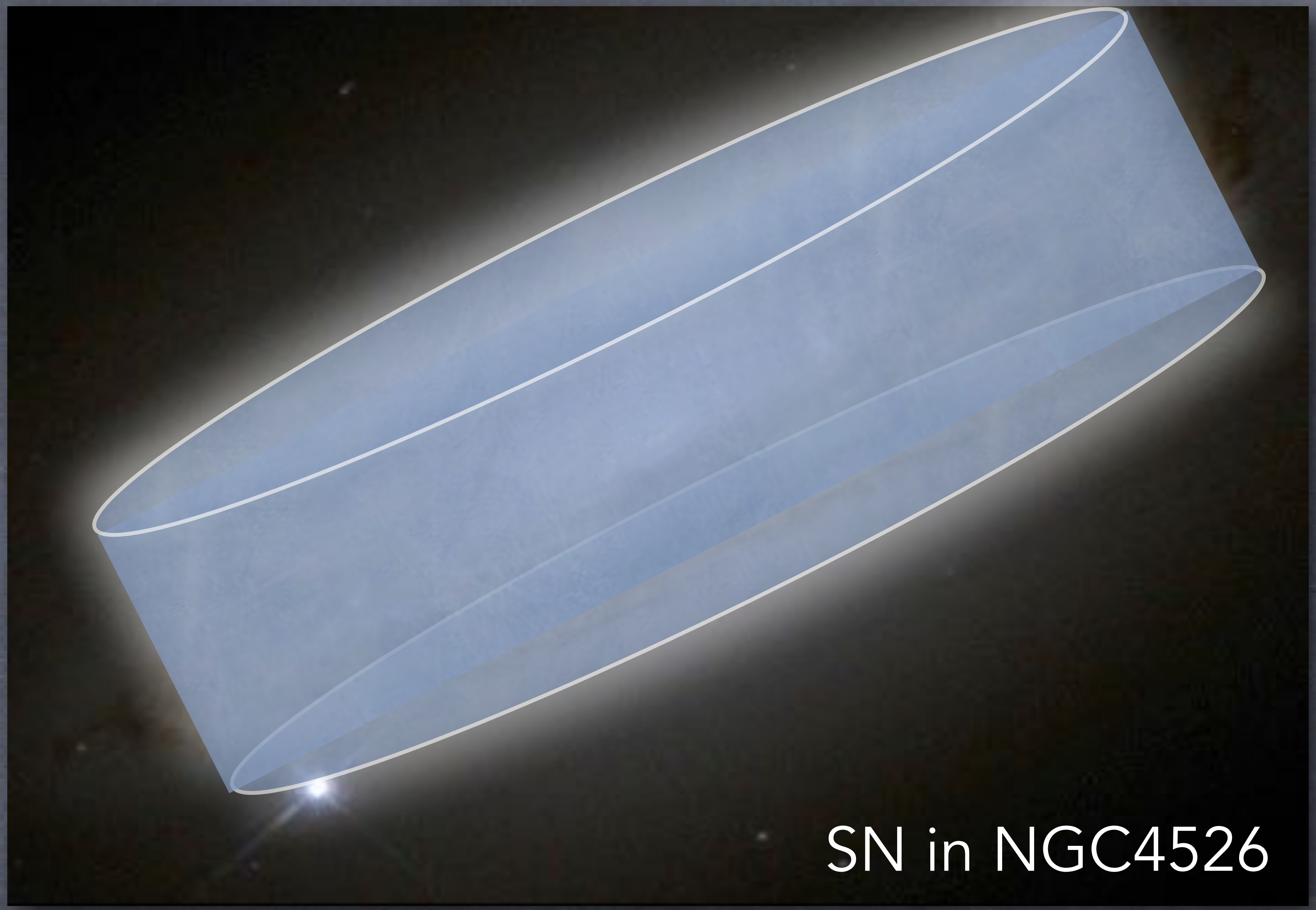
Extra-Galactic





Acceleration in SN Remnants: energetics

- Baade-Zwicky (1934) energetic argument, updated



$$\varepsilon_{CR} = 0.5 eV cm^{-3}$$

$$V_{conf} = \pi R^2 h = 2 \times 10^{67} \text{ cm}^3$$

$$W_{CR} = \varepsilon_{CR} V_{conf} \approx 2 \times 10^{55} \text{ erg}$$

$$L_{CR} \approx \frac{W_{CR}}{\tau_{conf}} \approx 5 \times 10^{40} \text{ erg s}^{-1}$$

$$L_{SN} = R_{SN} E_{kin} \approx 3 \times 10^{41} \text{ erg s}^{-1}$$

~10% of SN ejecta kinetic energy converted into CRs can account for the energetics

Non-Linear Diffusive Shock Acceleration

- The momentum spectral index depends only on the compression ratio

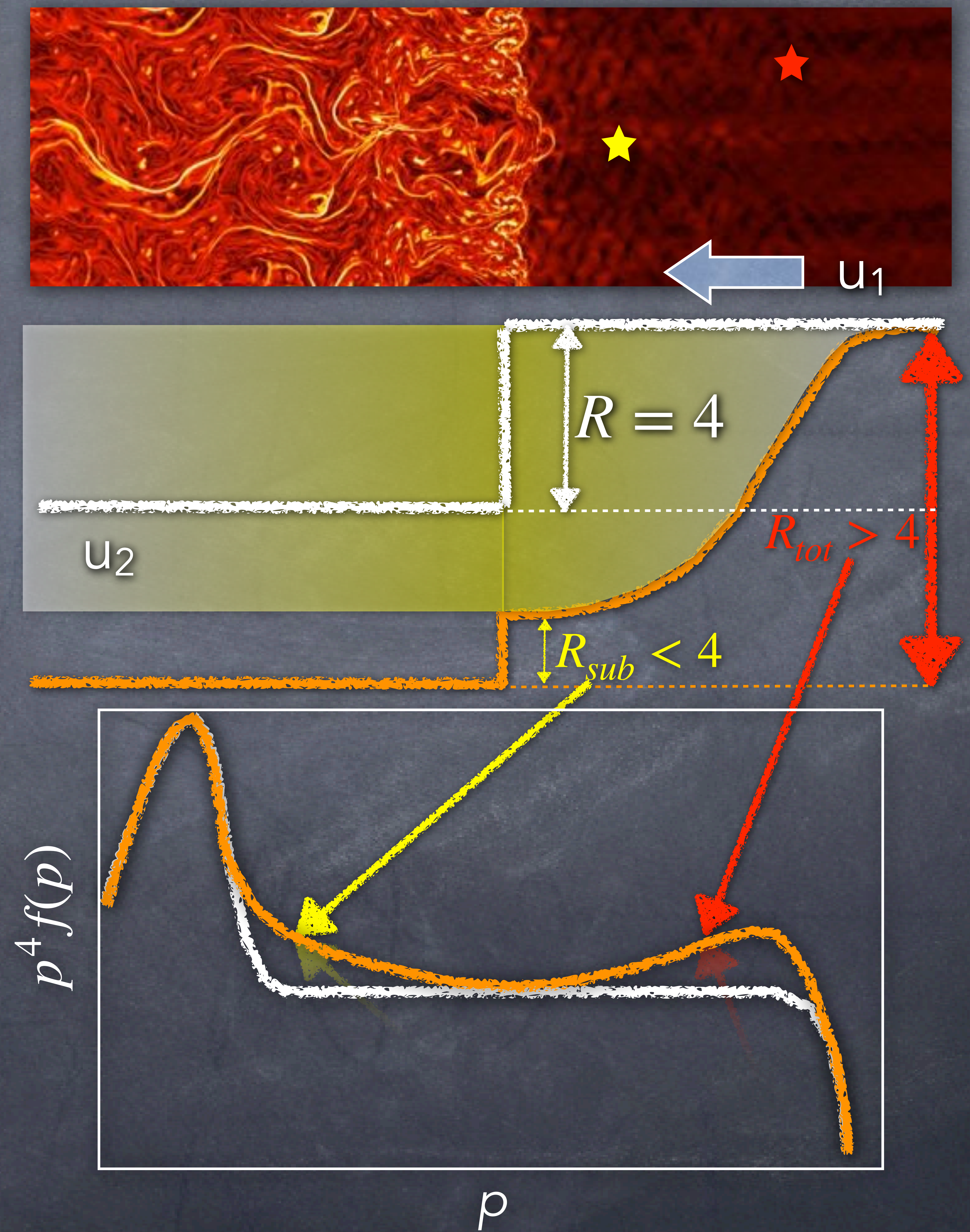
$$q = \frac{3R}{R-1}; \qquad R = \frac{\gamma+1}{\gamma-1}$$

- The CR pressure makes the adiabatic index smaller and induce a shock precursor

- Particles "feel" different compression ratios: spectra should become concave

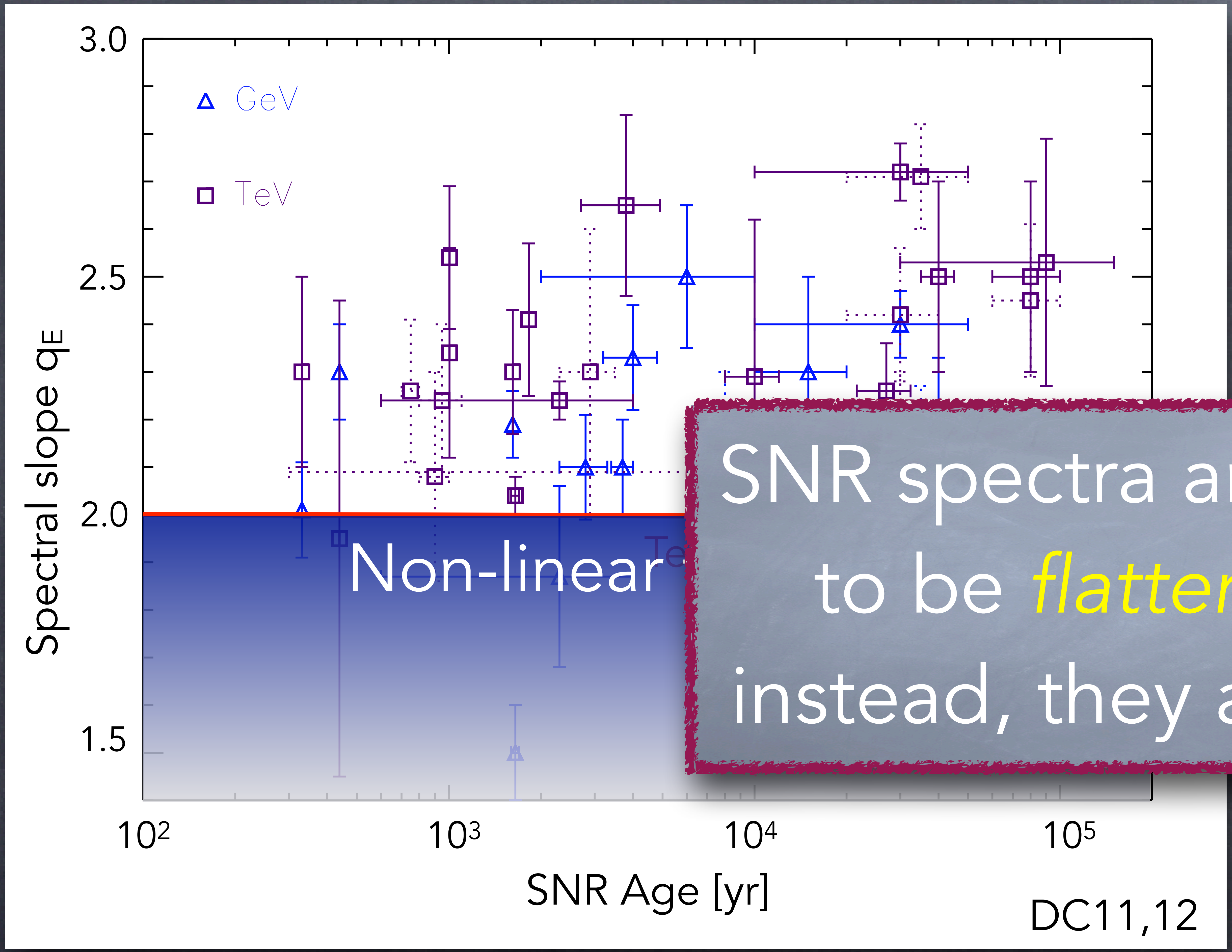
- If acceleration is efficient, at energies >1 GeV: $q < 4$ (flat spectra!)

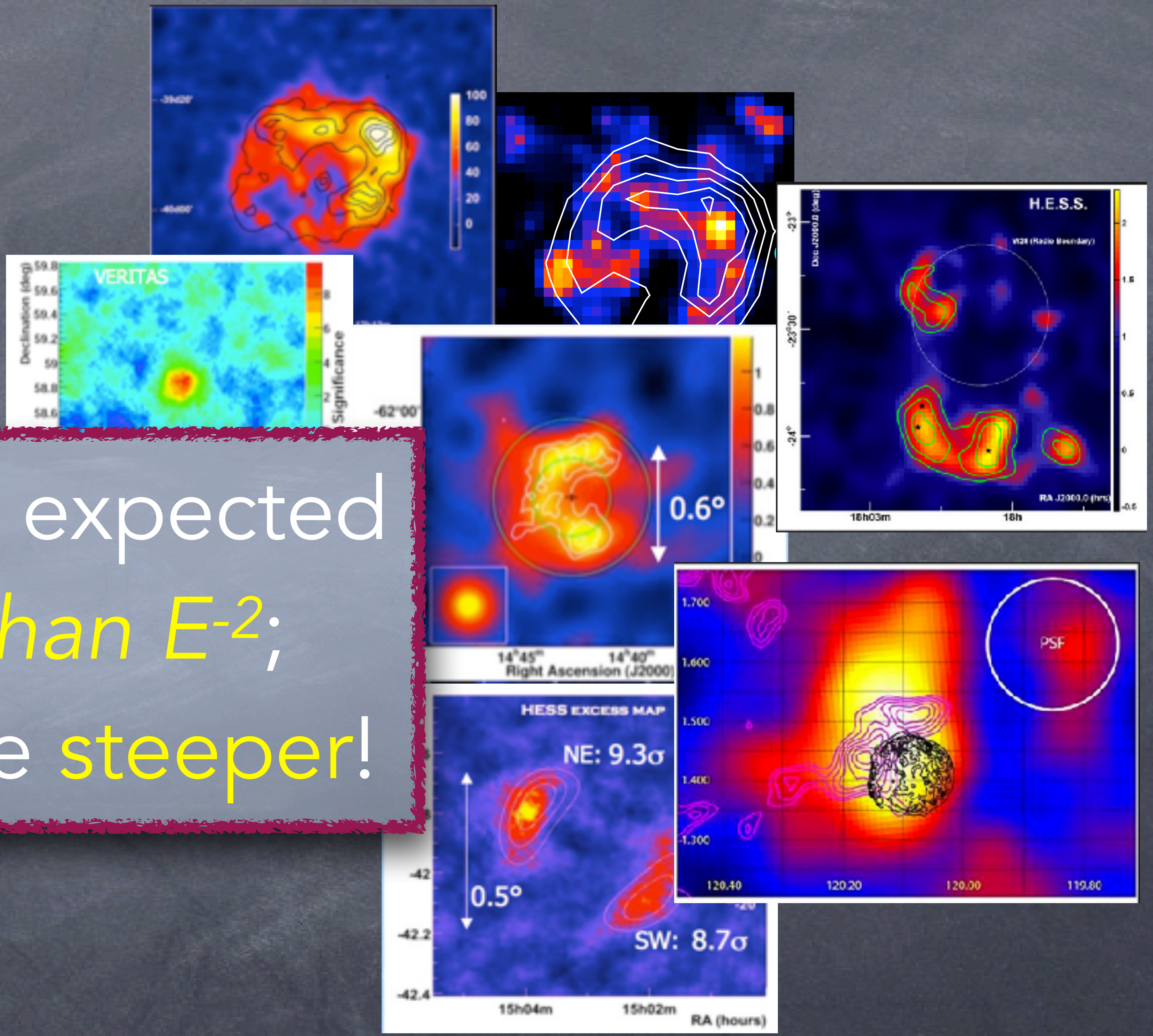
(e.g., Jones-Ellison91, Malkov-Drury01 for reviews)



This was the state of the art at the first Astroplasmas KITP Program in 2009

I) Gamma-Rays from SNRs





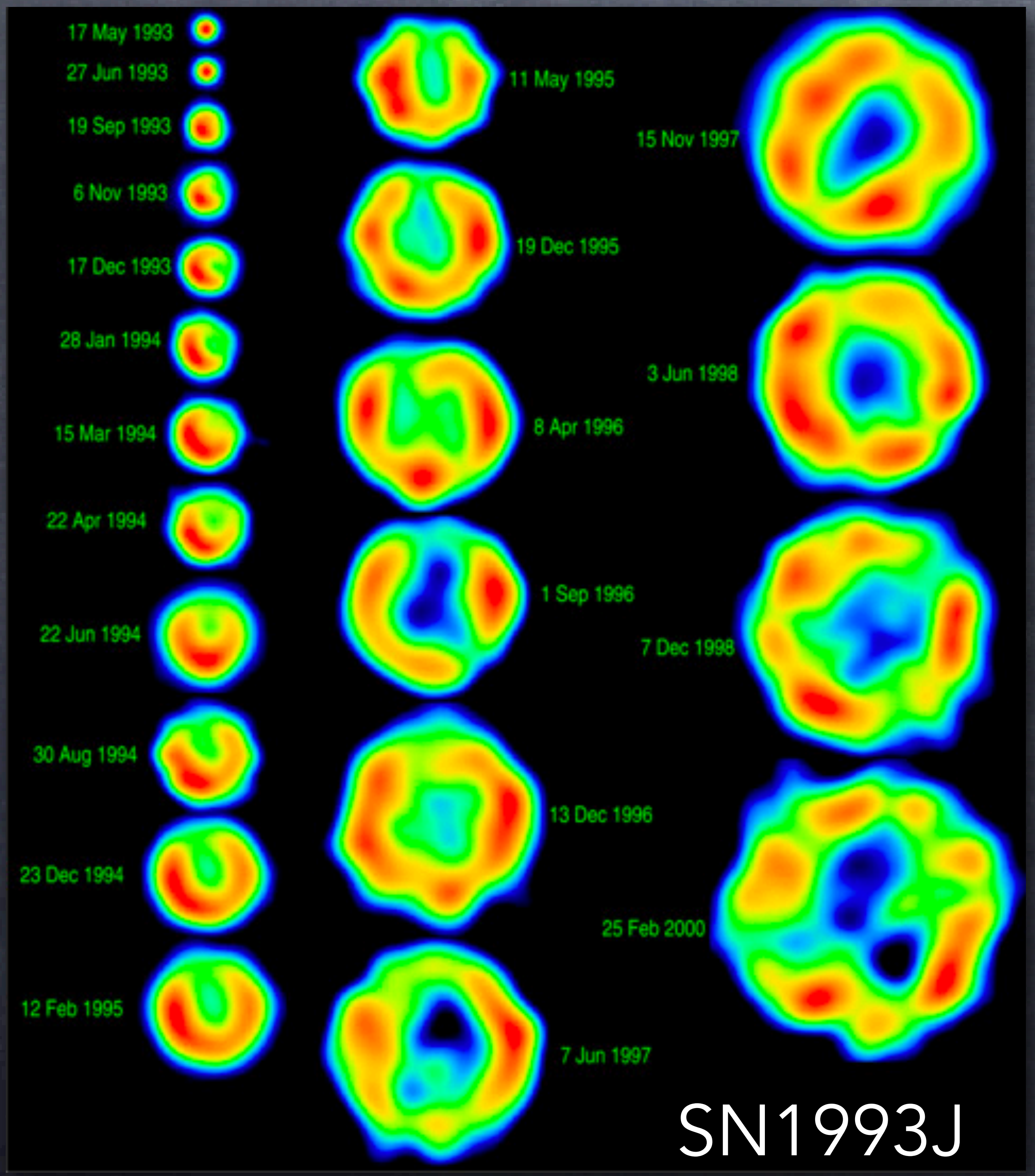
SNR spectra are expected to be *flatter than E^{-2}*; instead, they are steeper!

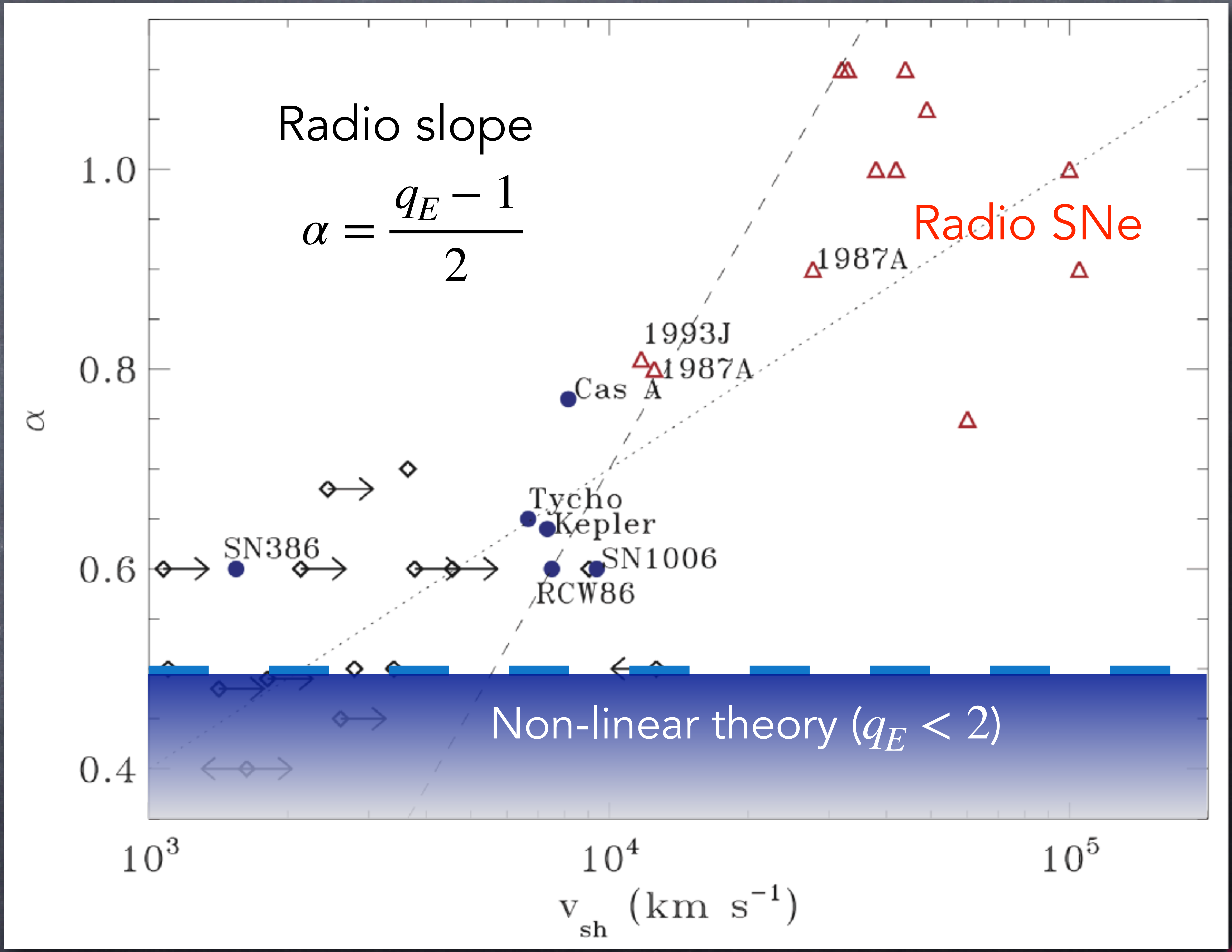
- Too steep to be leptonic: hadronic emission
- Not consistent with non-linear DSA theory!

II) Extra-galactic SNe

- Fast shocks in young SNRs
- Radio emission requires (e.g., Chevalier-Fransson06)

$f(E) \propto E^{-3} \quad \rightarrow \quad q_E \approx 3; q \simeq 5$

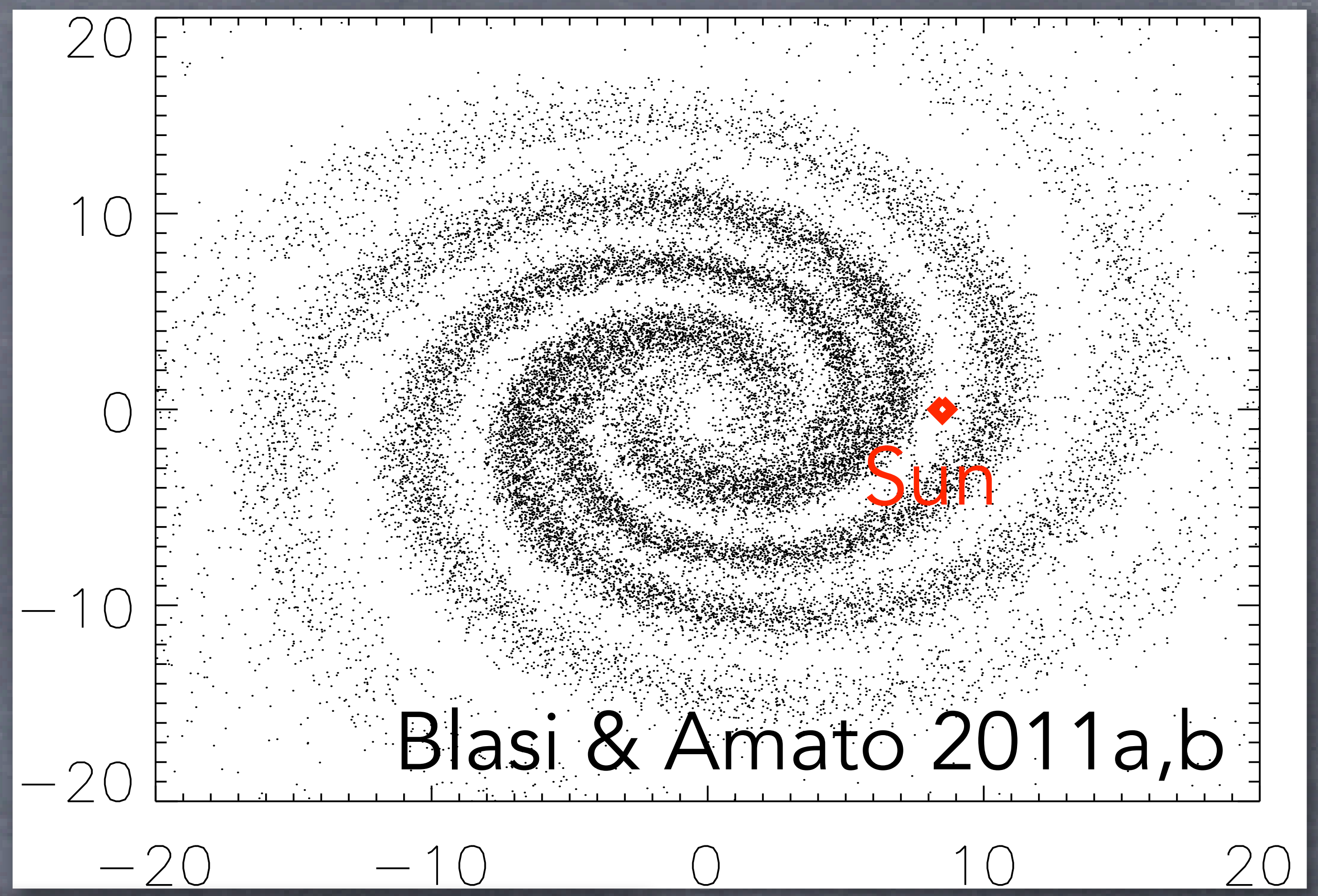


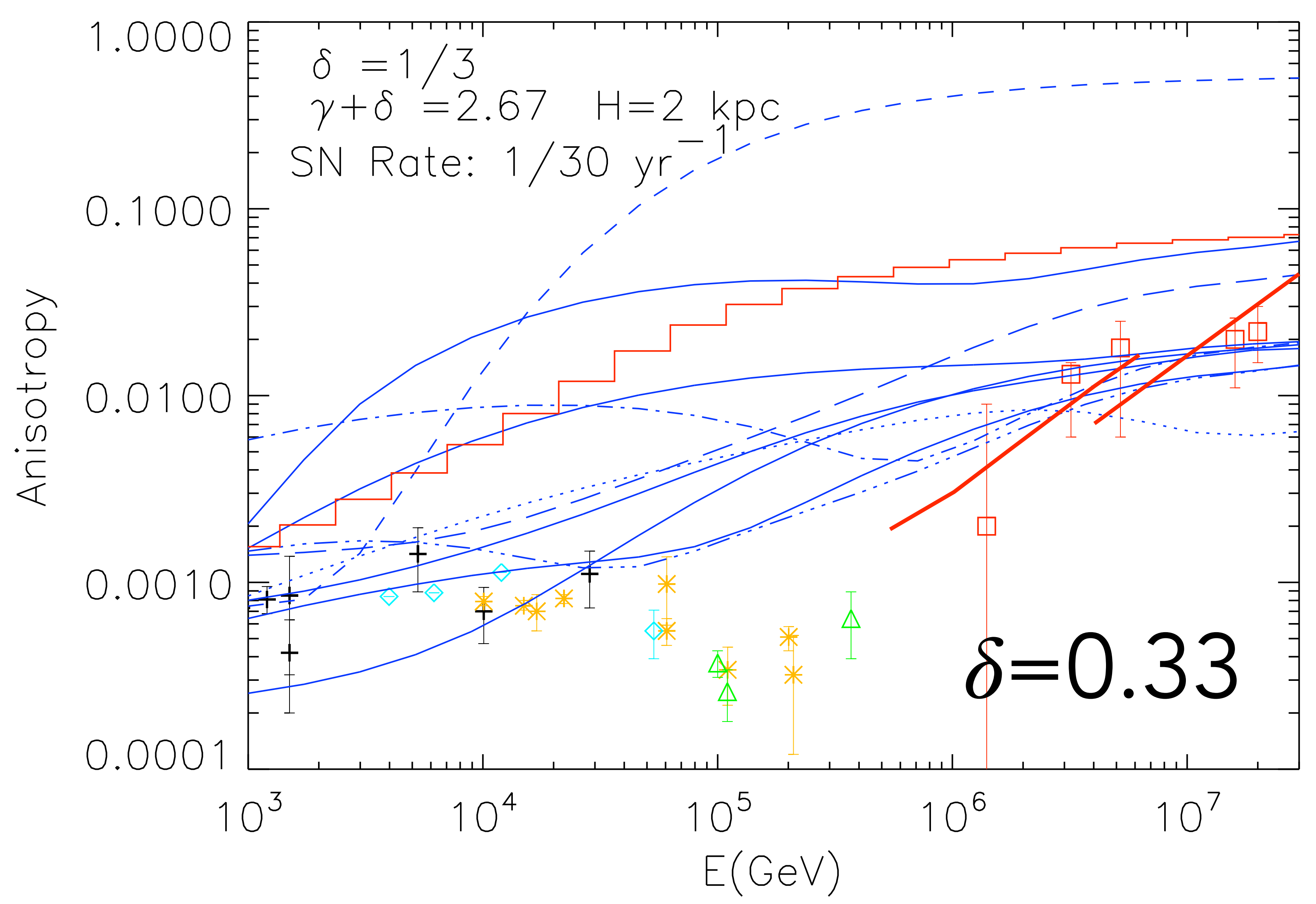


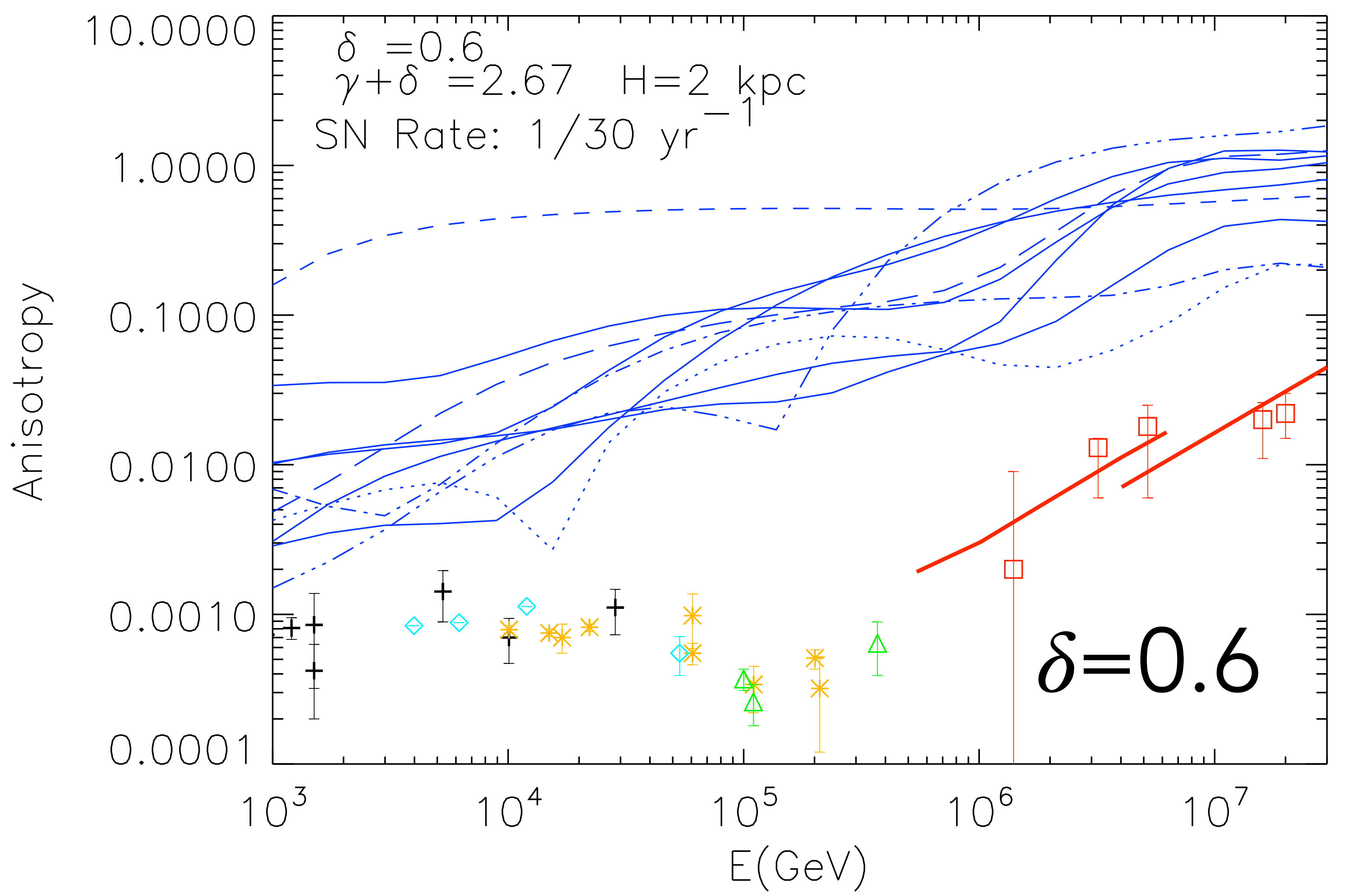
Adapted from Bell+11

III) CR spectrum and anisotropy

- Injection spectrum: $\sim E^{-\gamma}$
- Residence time in the Galaxy: $\sim E^{-\delta}$
  - Constraint: $\delta + \gamma \sim 2.7$
- Monte Carlo simulations of SNRs + CR transport







- δ=0.33 returns:
  - more universal CR spectra
  - less anisotropy
  - the measured B/C (AMS-II, 2016)

An injection slope of $\gamma \simeq 2.7 - 0.33 \simeq 2.37$ is preferred

Tension between theory and observations

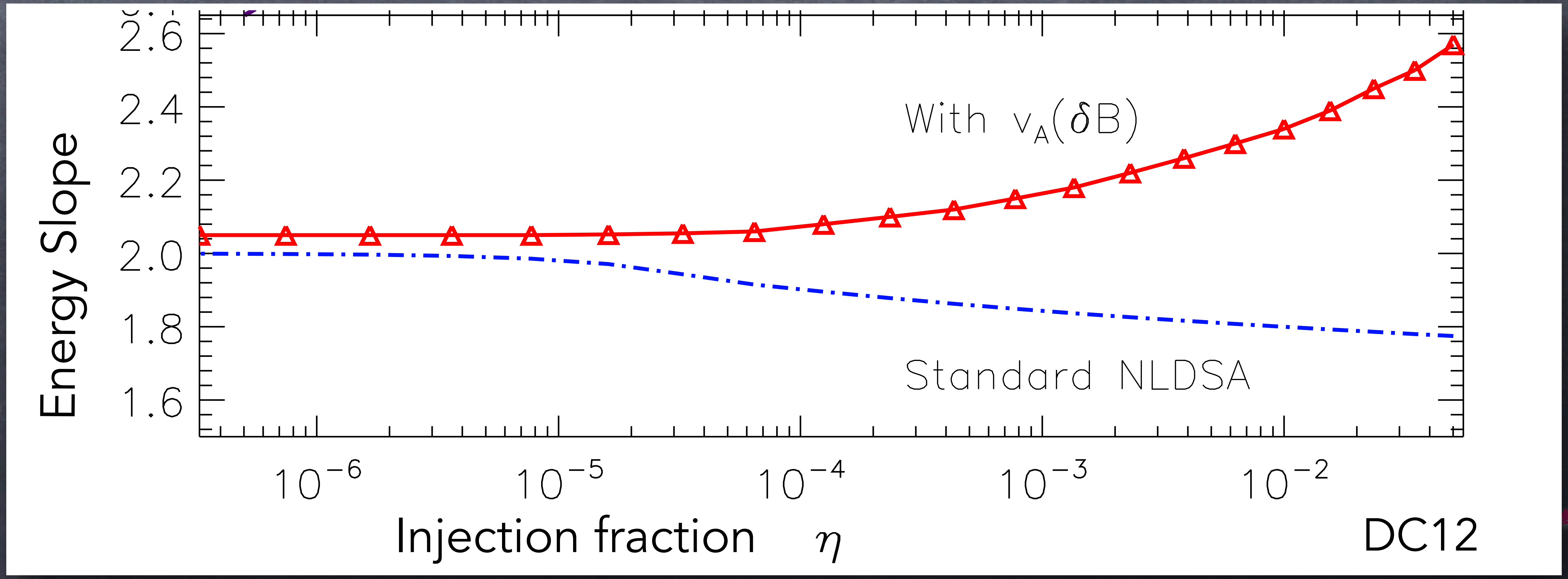
A Theoretical Challenge

- Shocks in partially-neutral media (Blasi+12; Morlino+13; Ohira14, …)
- Oblique trans-relativistic shocks (Kirk+96; Morlino+07; Bell+11, …)
- Geometry effects (Malkov-Aharonian19, Hanusch+19)
- Ion "losses" du
- Feedback of amp … C+09; DC11,12,…)

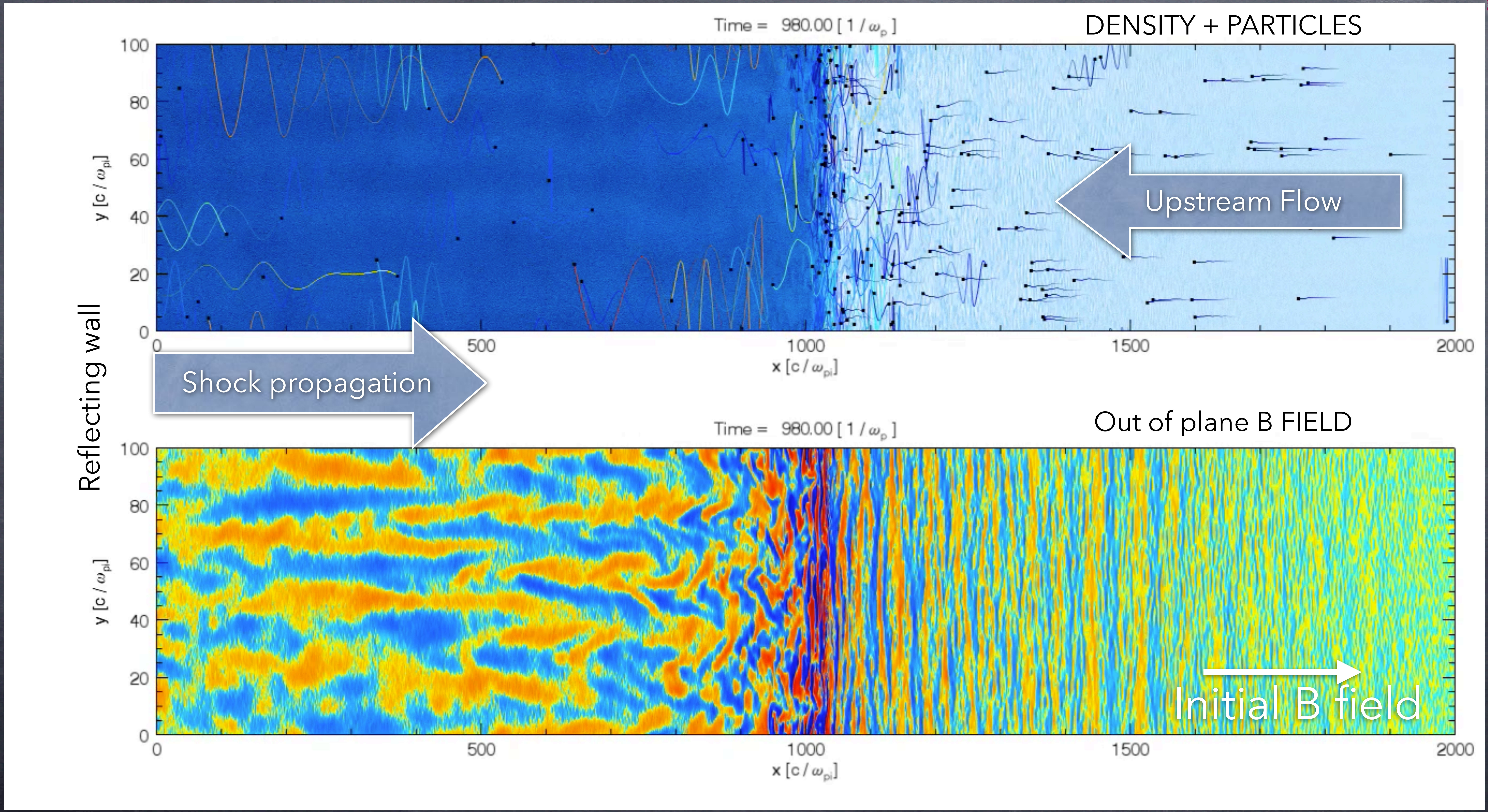
None of these ideas has been tested from *first principles*!

The large velocity of *scattering centers* $v_{waves} \approx v_A(\delta B)$ leads to an effective ratio:

$$R_{cr} \simeq \frac{u_1 \pm v_{A,1}}{u_2 \pm v_{A,2}} \lesssim R_{gas}$$

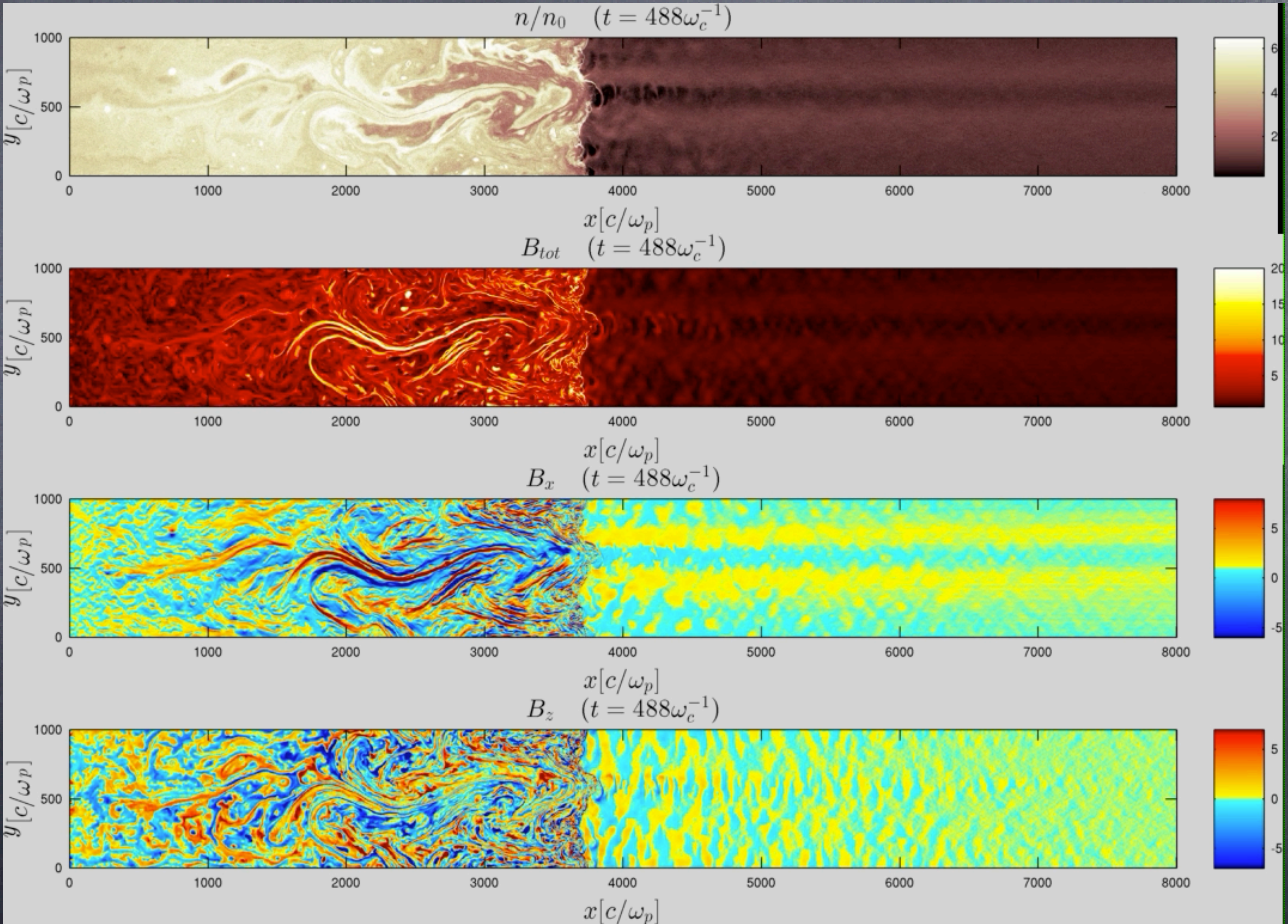


Hybrid Simulations of Collisionless Shocks



dHybrid code (Gargaté+07; DC & Spitkovsky 2013…2017), Haggerty & DC19

CR-driven Magnetic Field Amplification

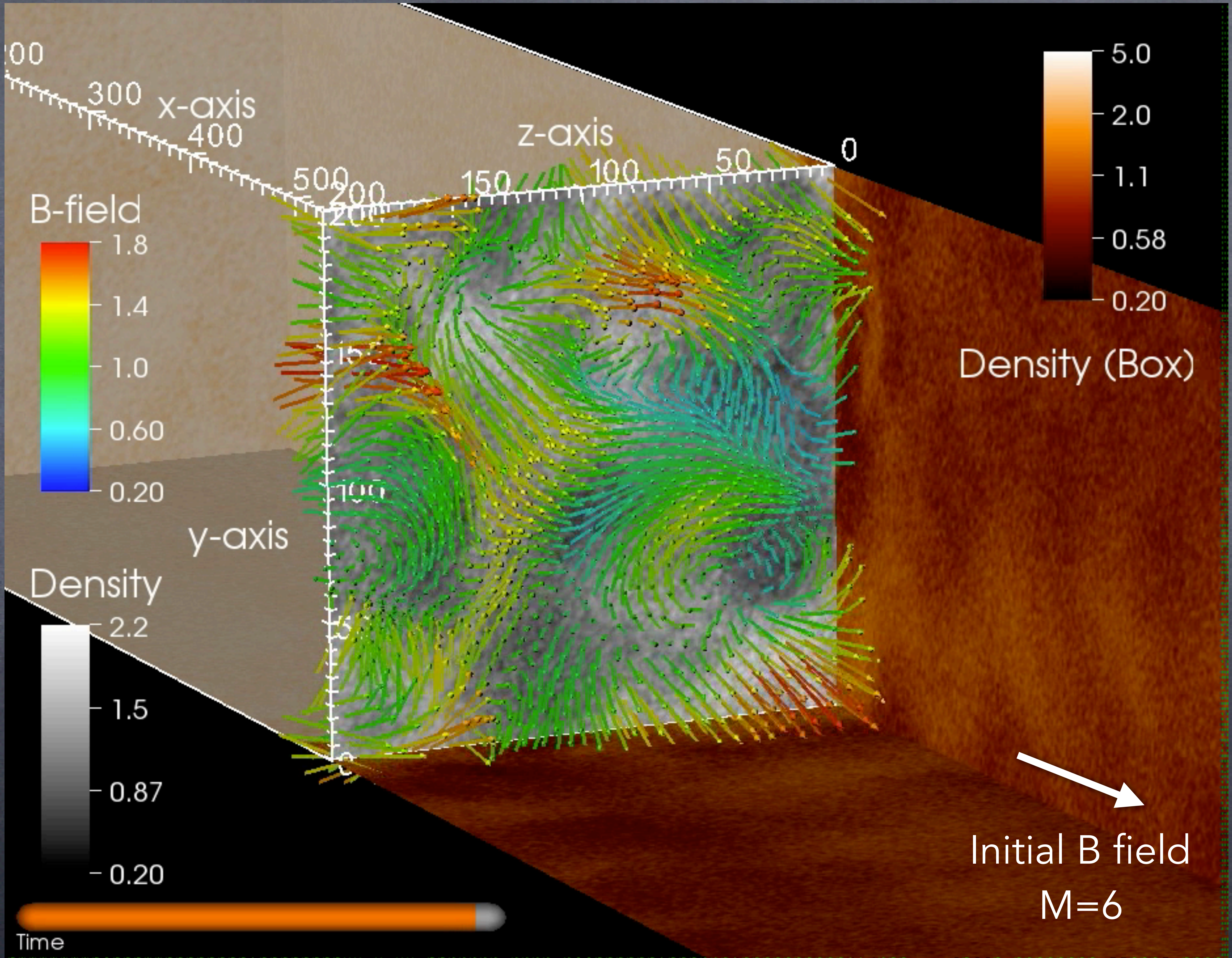


Initial B field

$M_s = M_A = 30$

DC & Spitkovsky, 2013

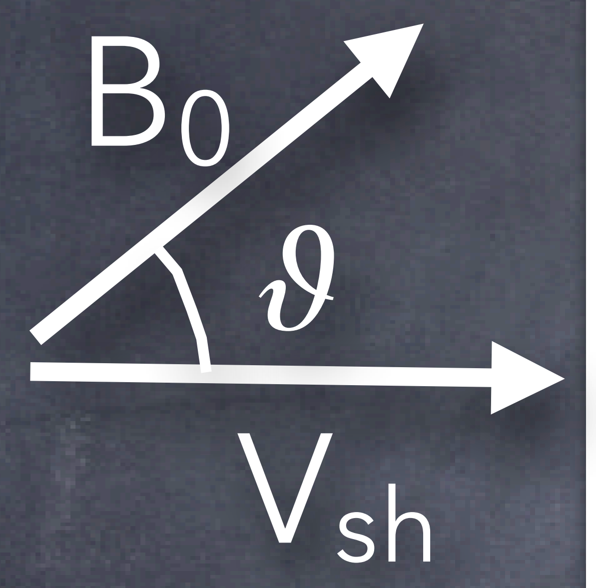
3D simulations of a parallel shock

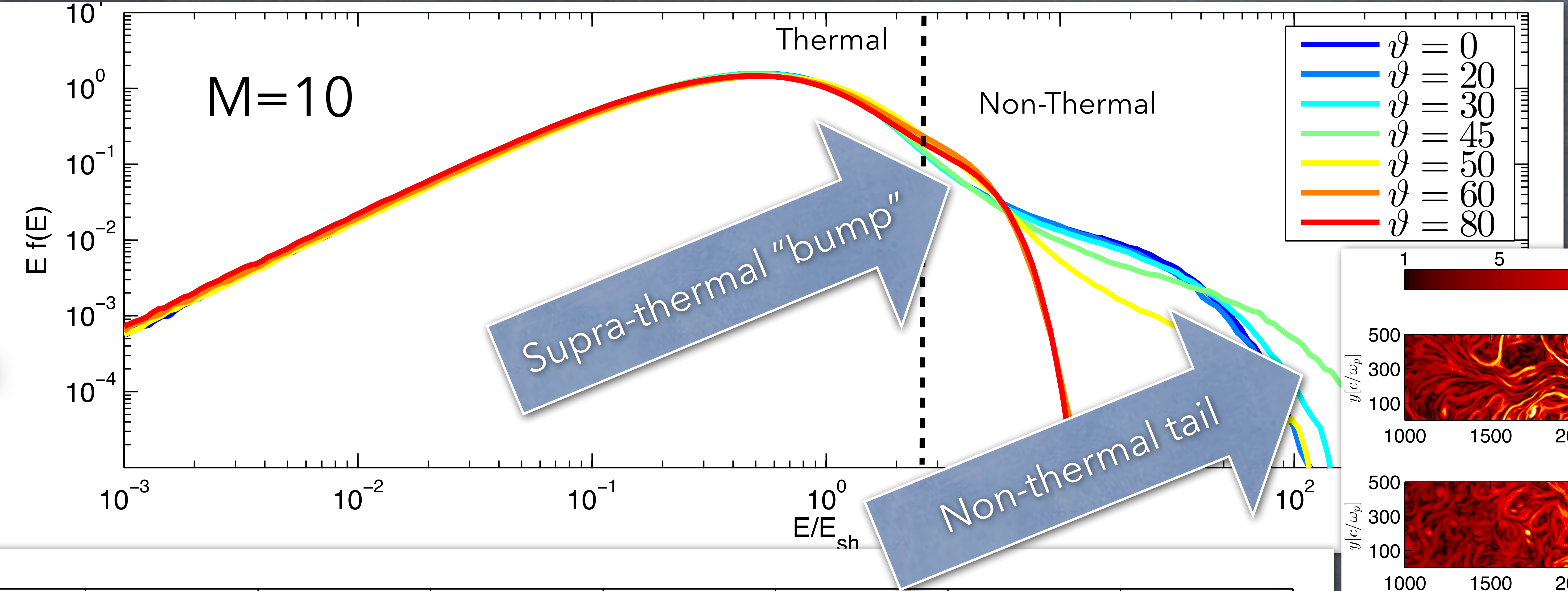


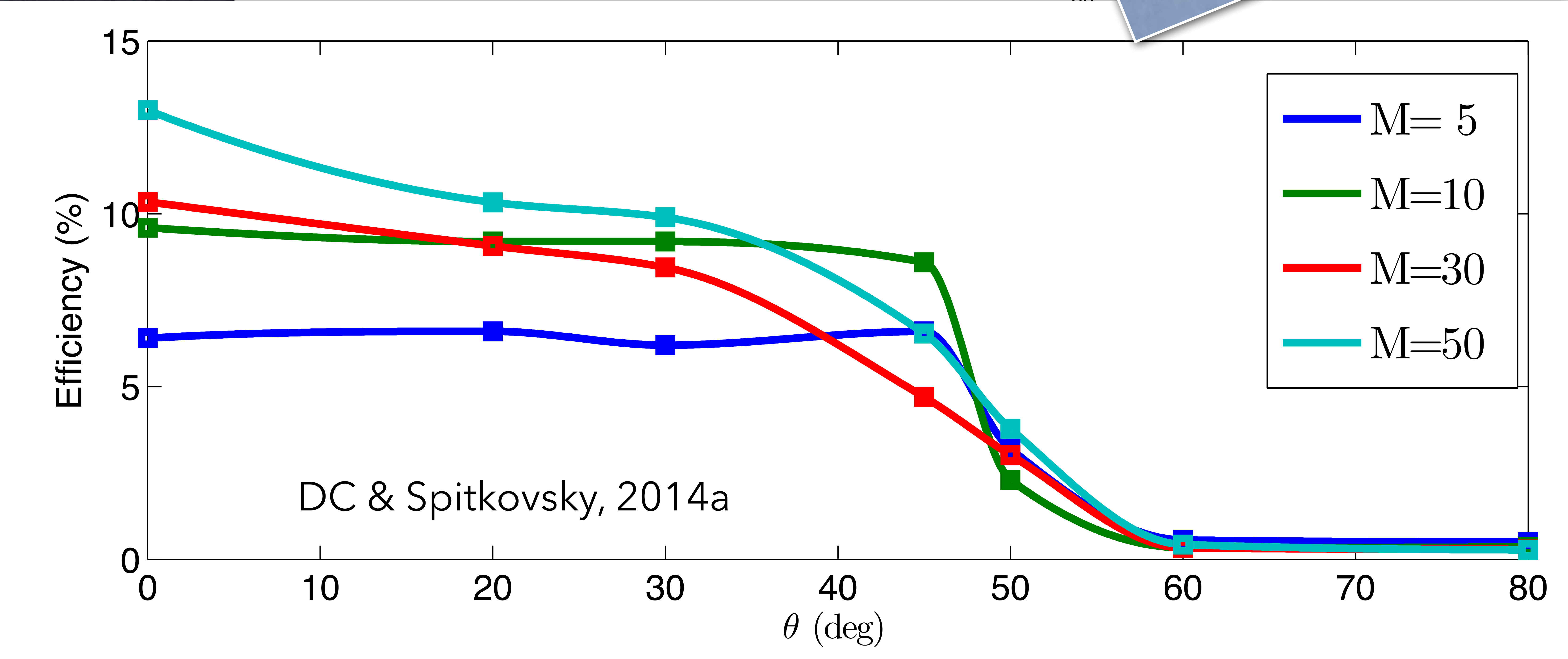
DC & Spitkovsky, 2014a

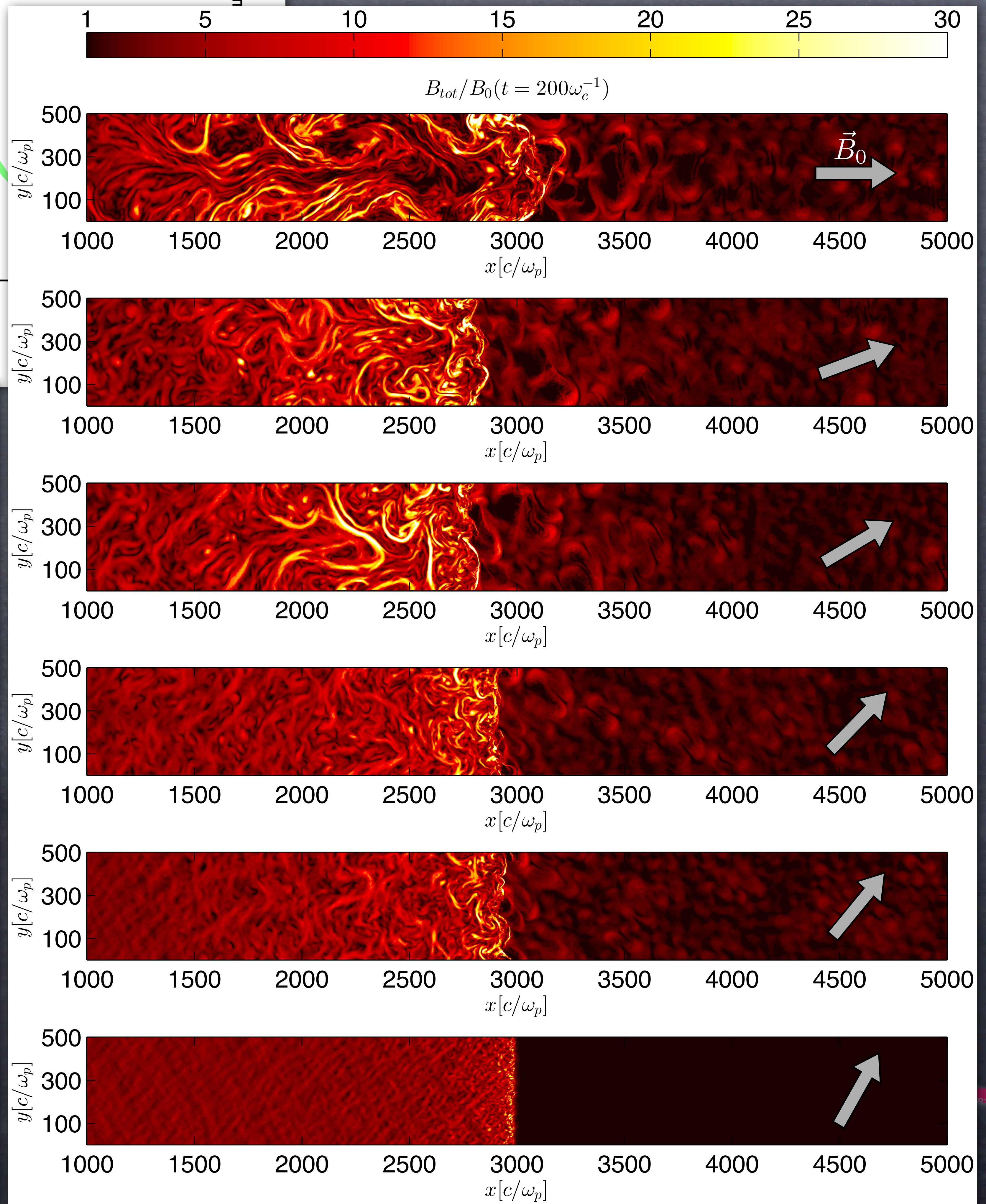
Parallel vs Oblique shocks

Shock inclination



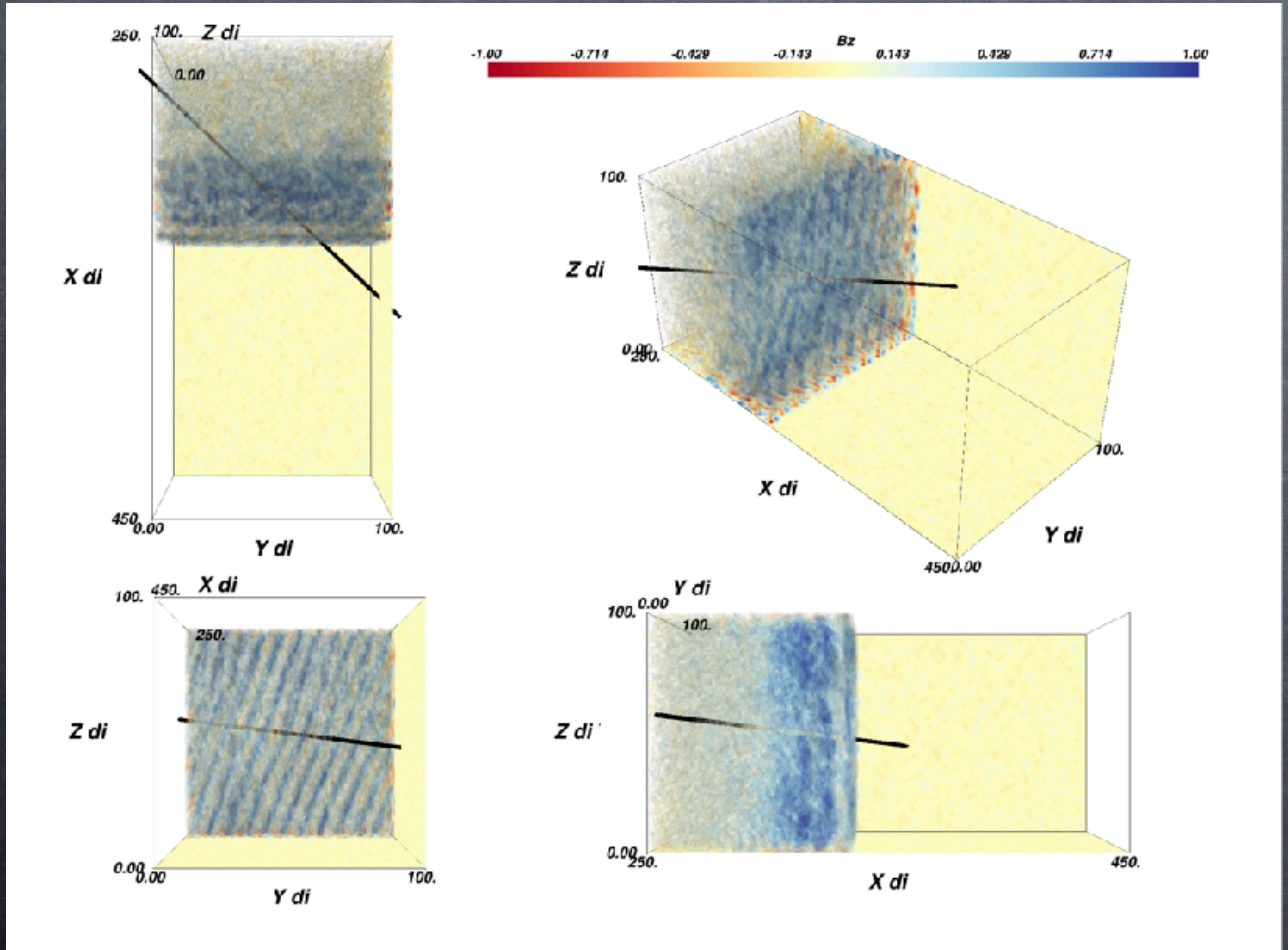


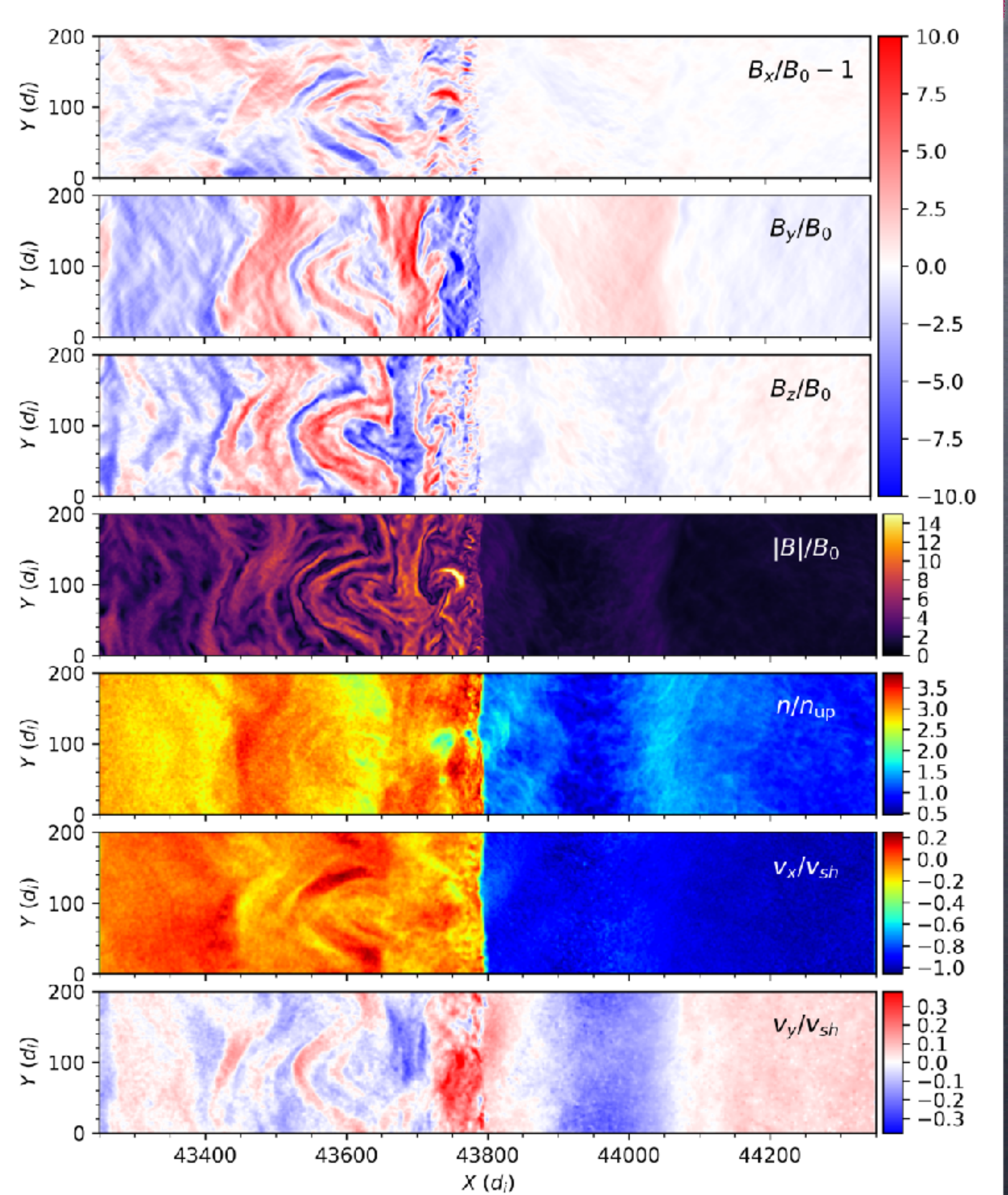




Hybrid Simulations with Relativistic Ions: dHybridR

- Approximation valid if $u \ll c, n_{cr} \ll n_{gas}$
- Time-step fixed a priori by c
- Unprecedentedly-long simulations
  (Haggerty & DC19)





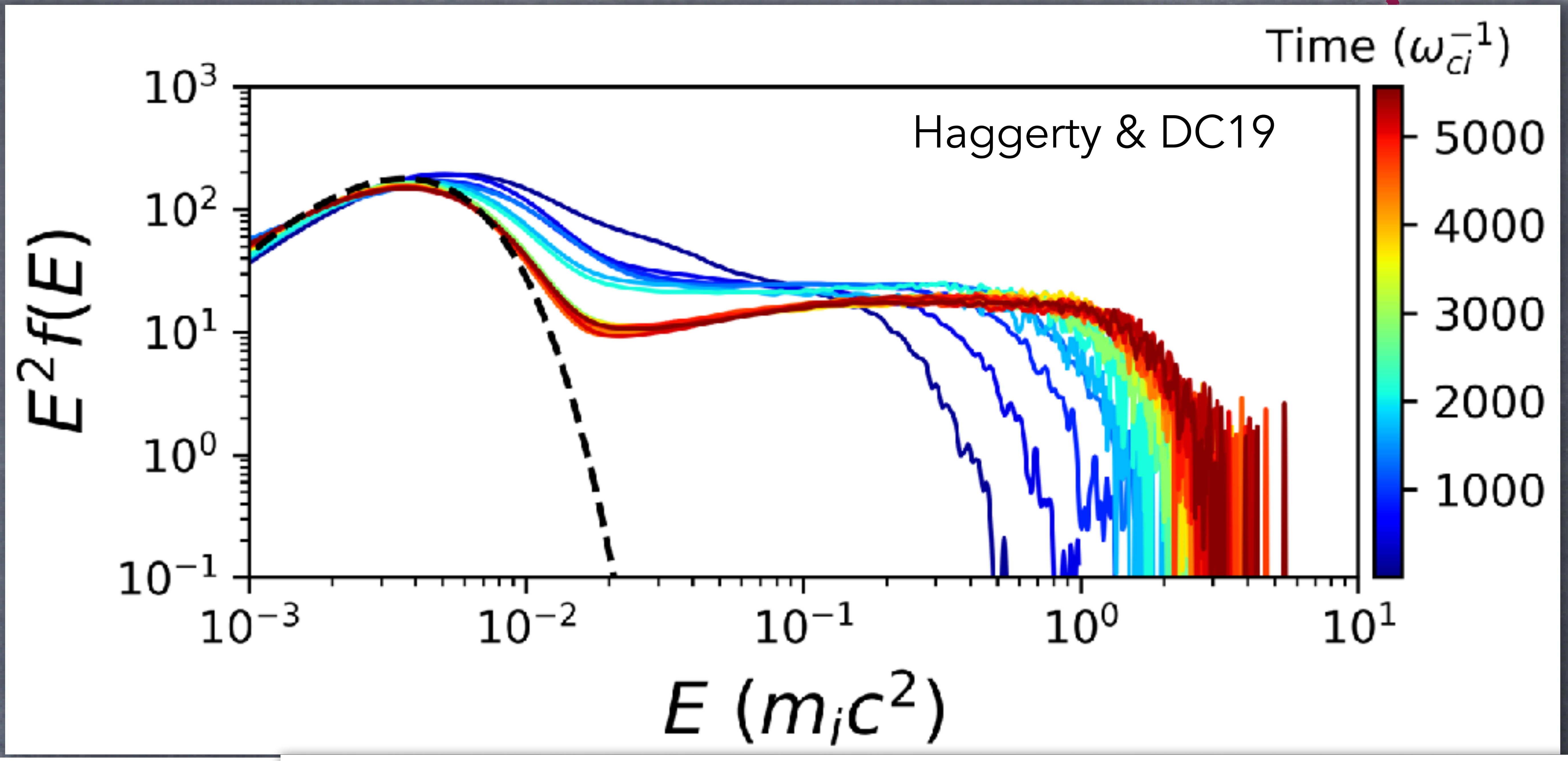
Hybrid Simulations with Relativistic Ions: dHybridR

DSA: $f(p) \propto p^{-4}$;

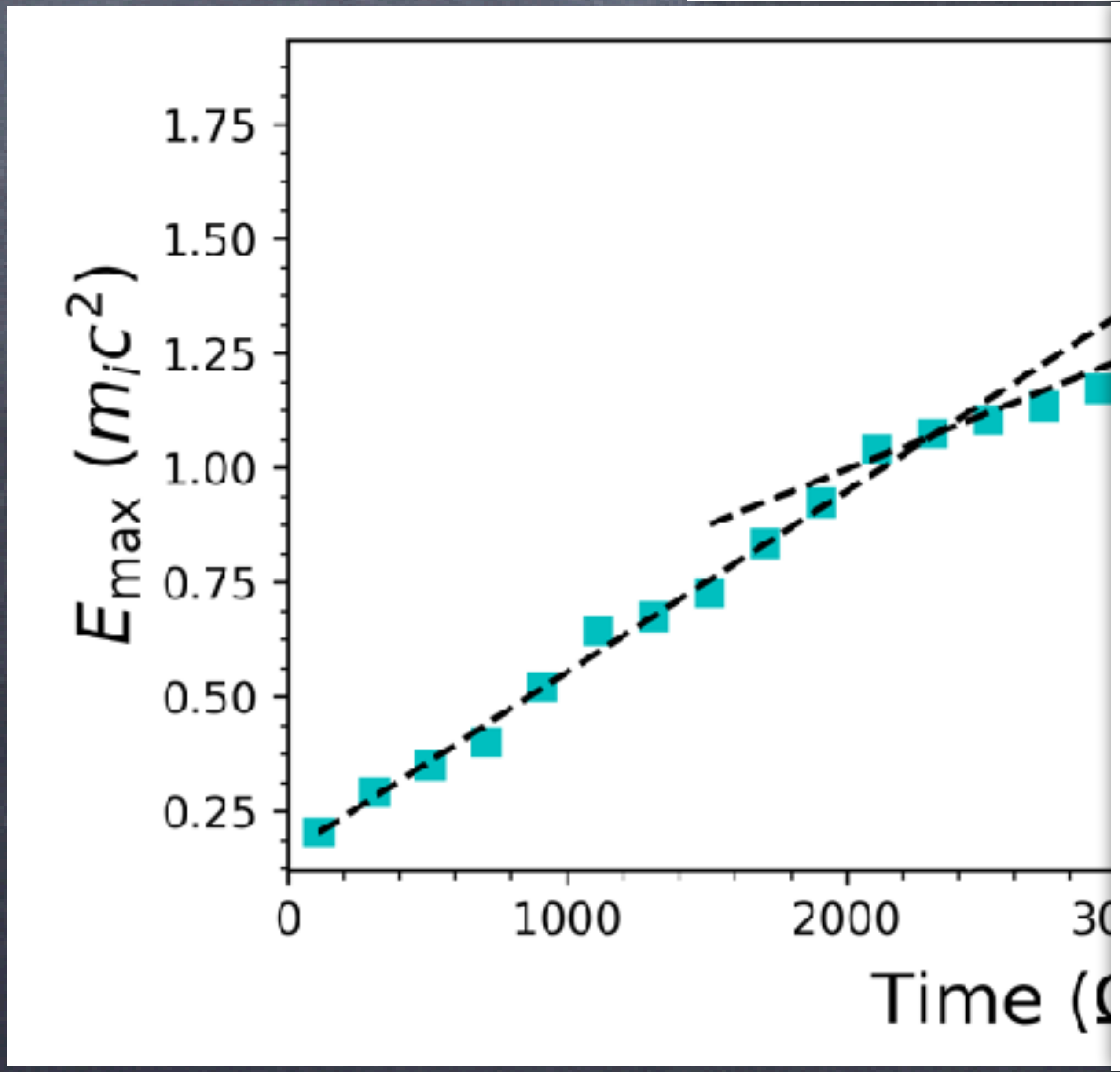
$$4\pi p^2 f(p)dp = f(E)dE$$

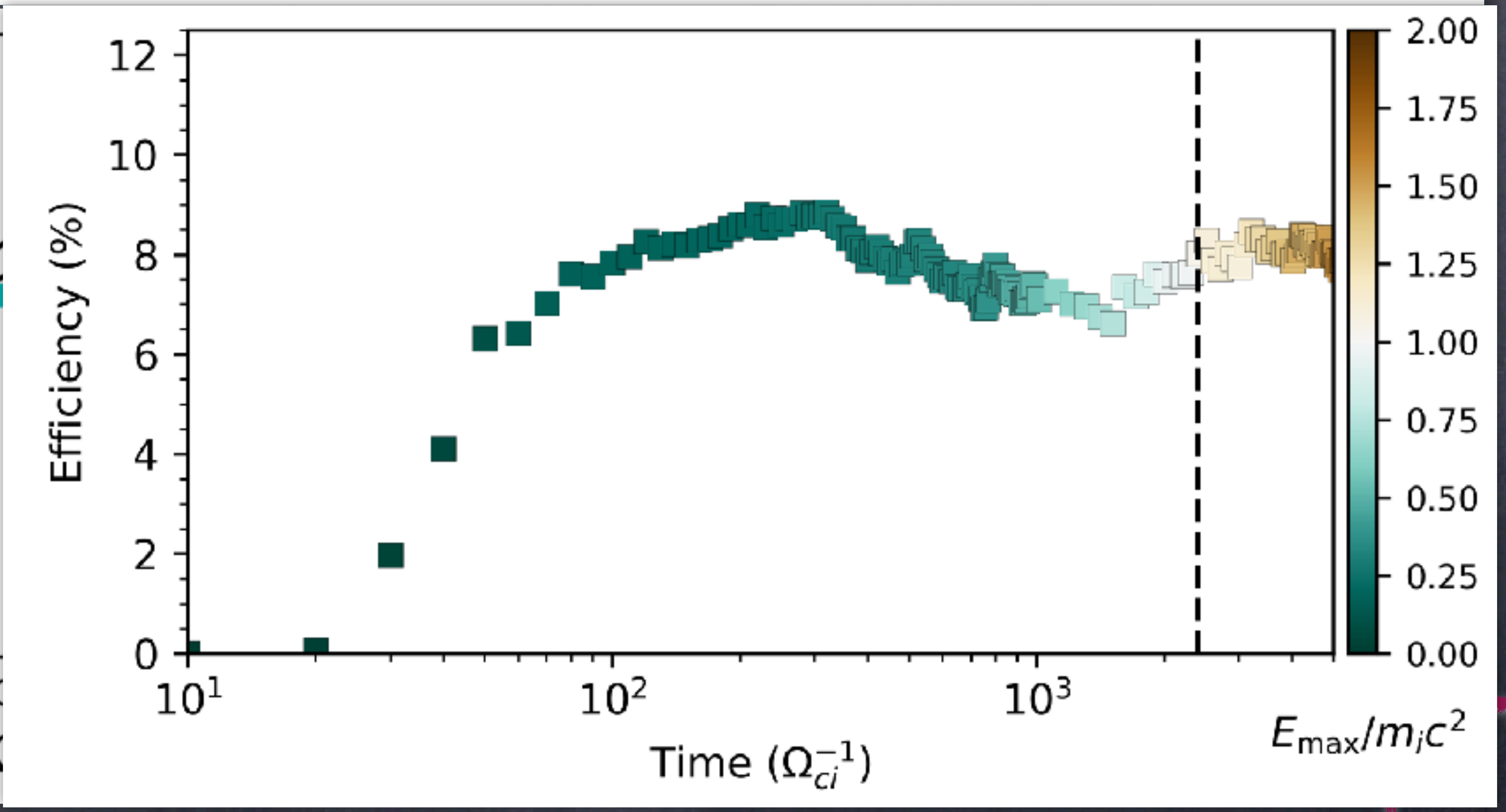
$f(E) \propto E^{-1.5}$ (non rel.)

$f(E) \propto E^{-2}$ (relativ.)



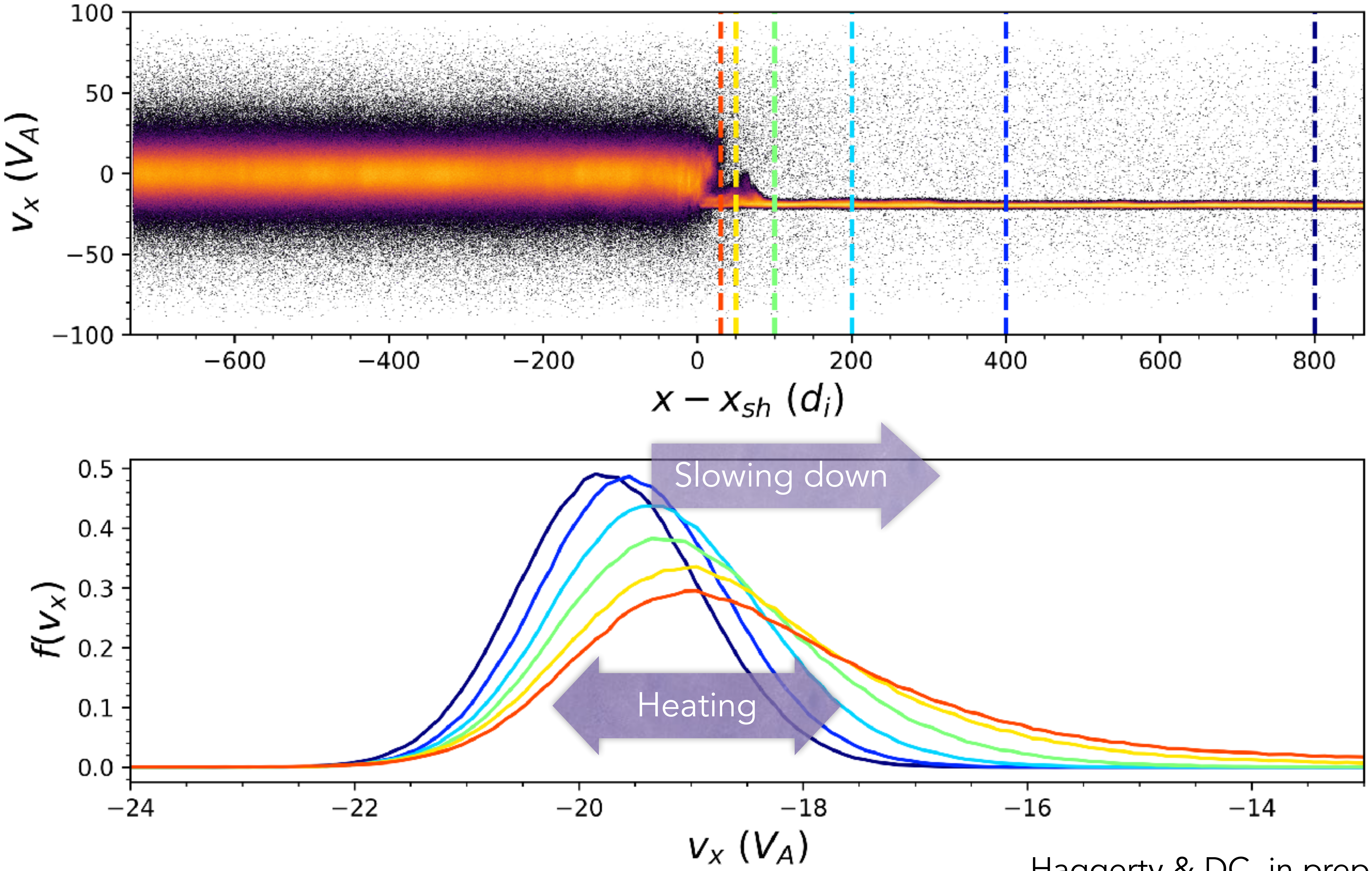
- Long-term evolution
  - $E_{max}(t) \propto t$
  - Efficiency $\sim 10\,\%$





CR-modified Shocks: I) Precursor

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

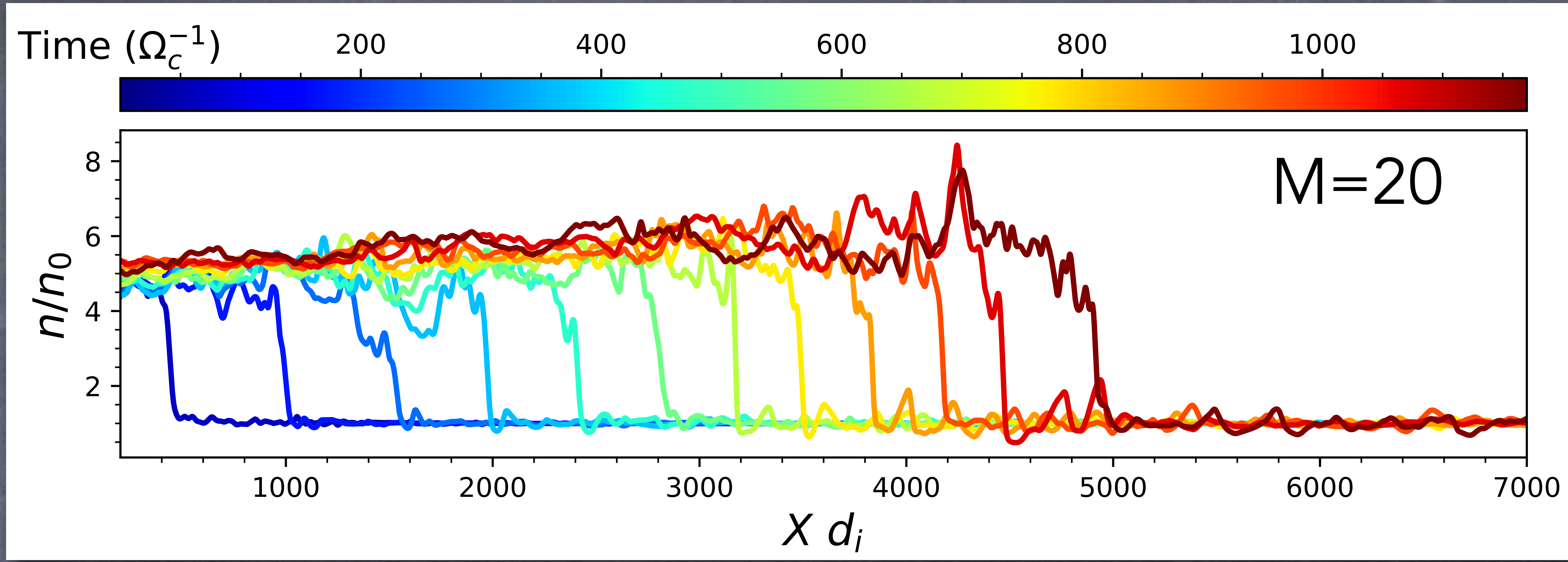


Haggerty & DC, in prep

- B damping leads to non-adiabatic heating
  - ~ equipartition between gas and B pressures
- Compression ~1.3 upstream (also due to supra-thermal ions)

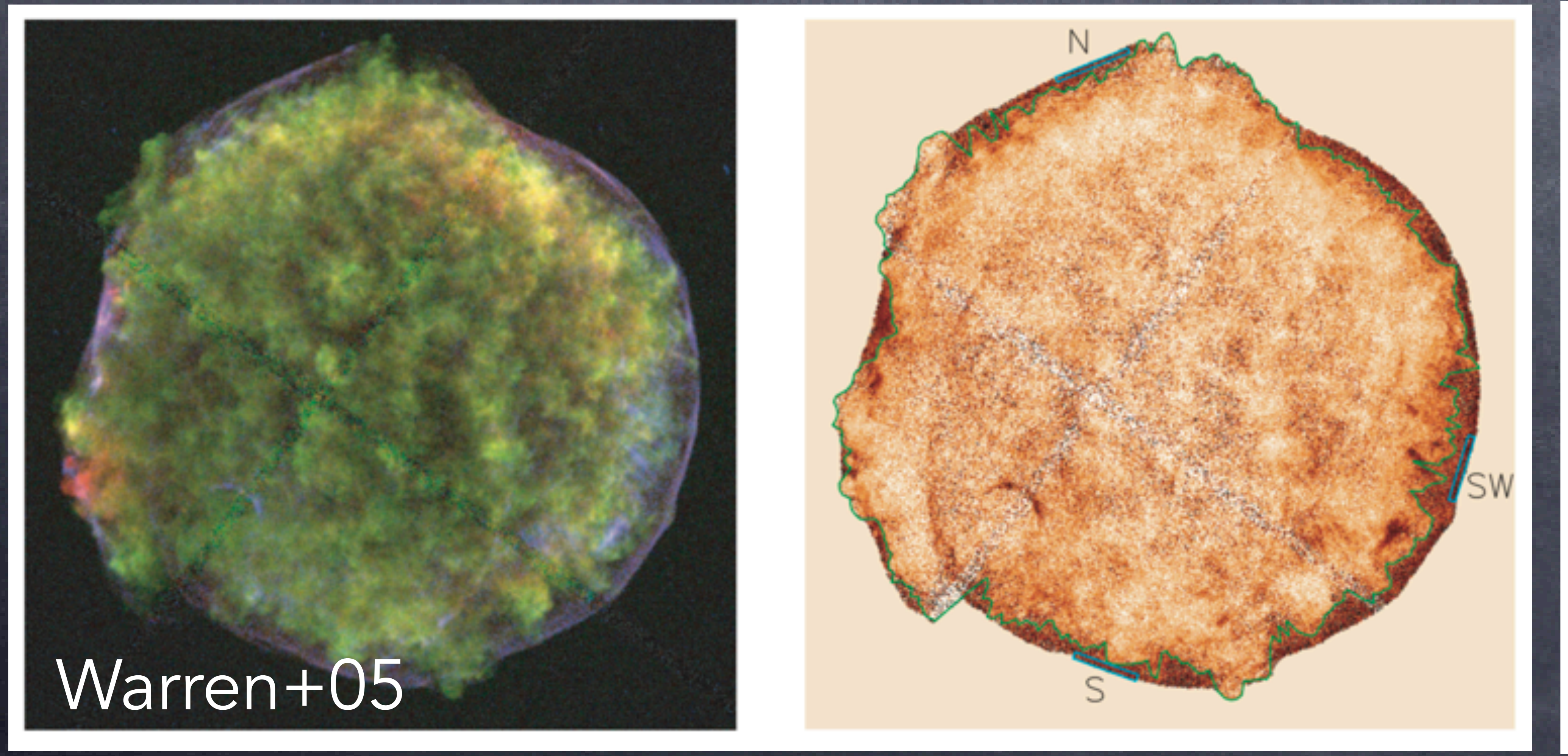
CR-modified Shocks: II) Enhanced compression

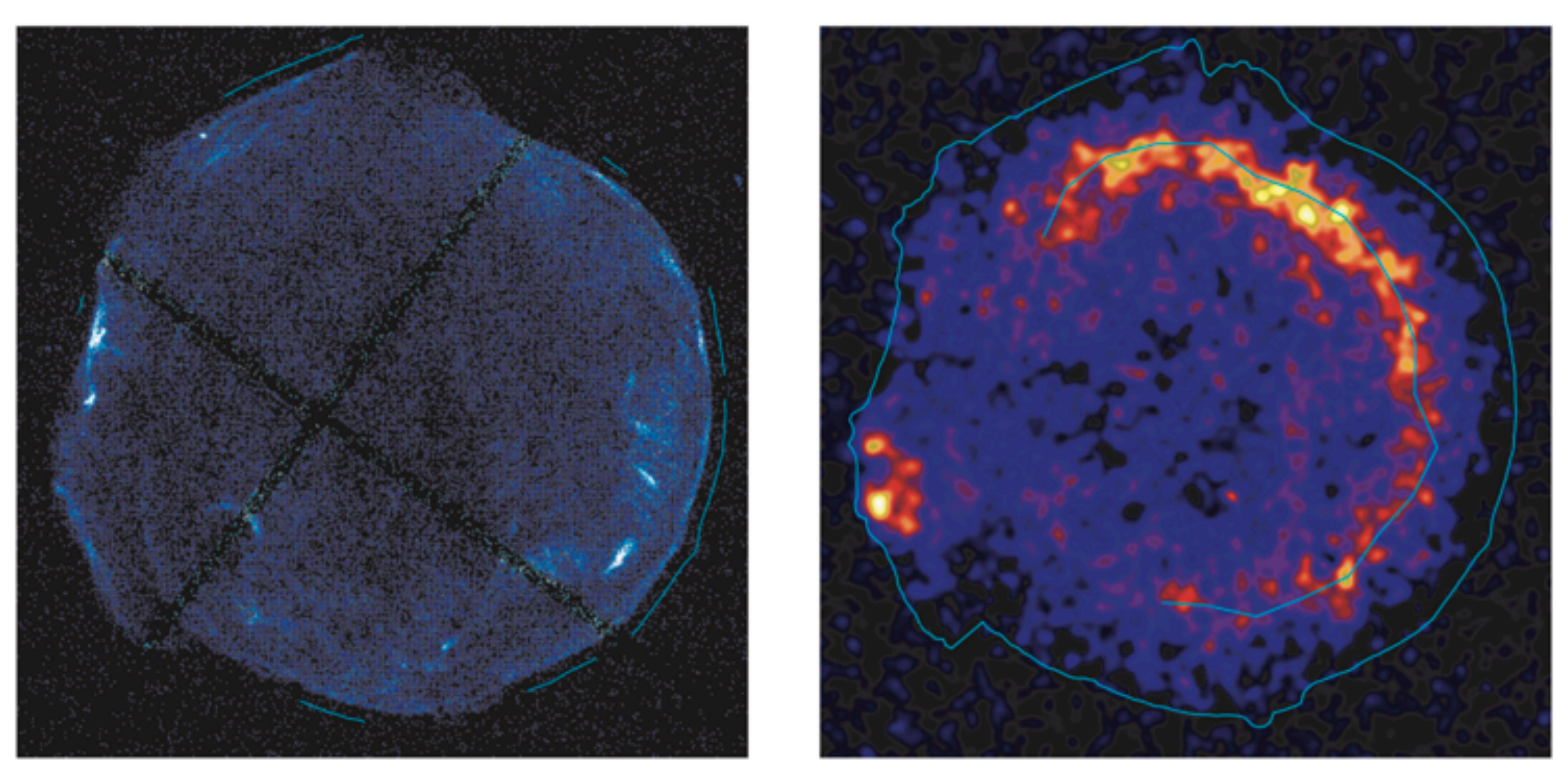
- *R* increases with time, up to ~7!



- *R*~6-7 inferred in Tycho by measuring the distance between forward shock and contact discontinuity

$$R \simeq 7 \rightarrow q_{expected} \simeq 3.5$$

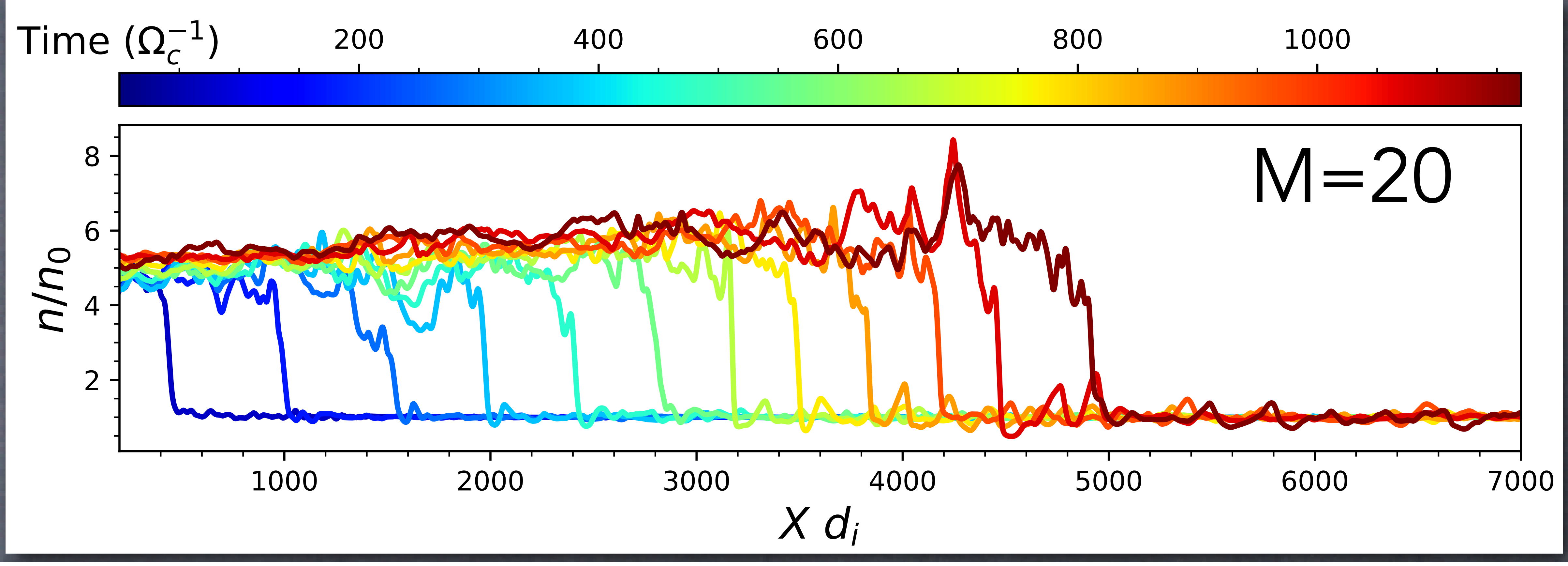




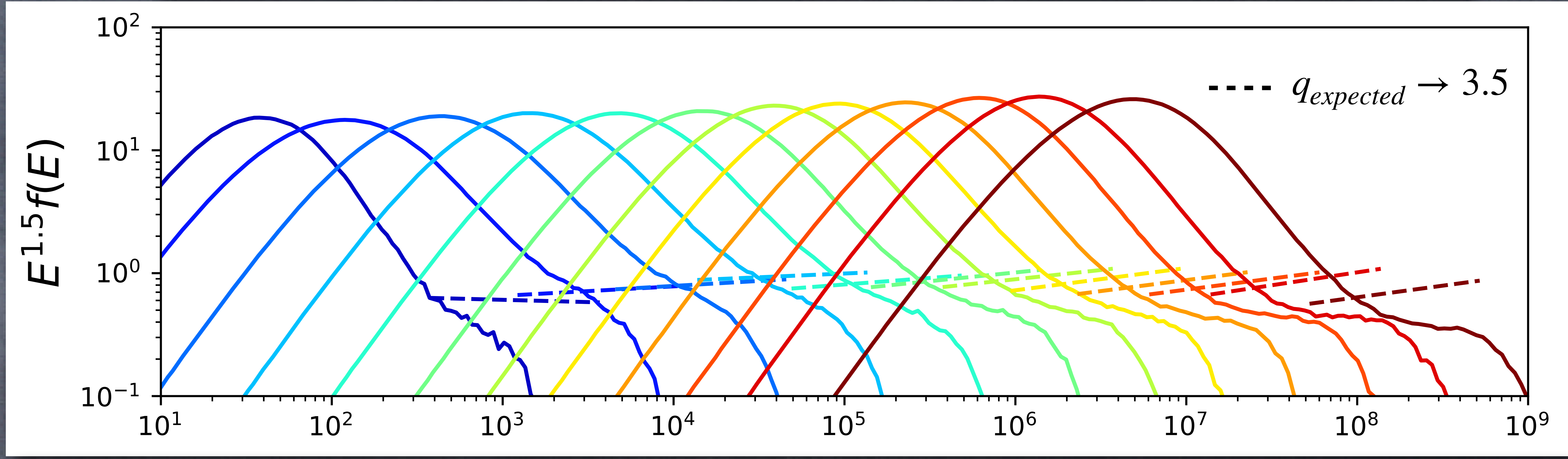
Need to Revise the Theory of Non-Linear DSA

- *R* increases with time, up to ~7!

$$R \simeq 7 \rightarrow q_{expected} \simeq 3.5$$

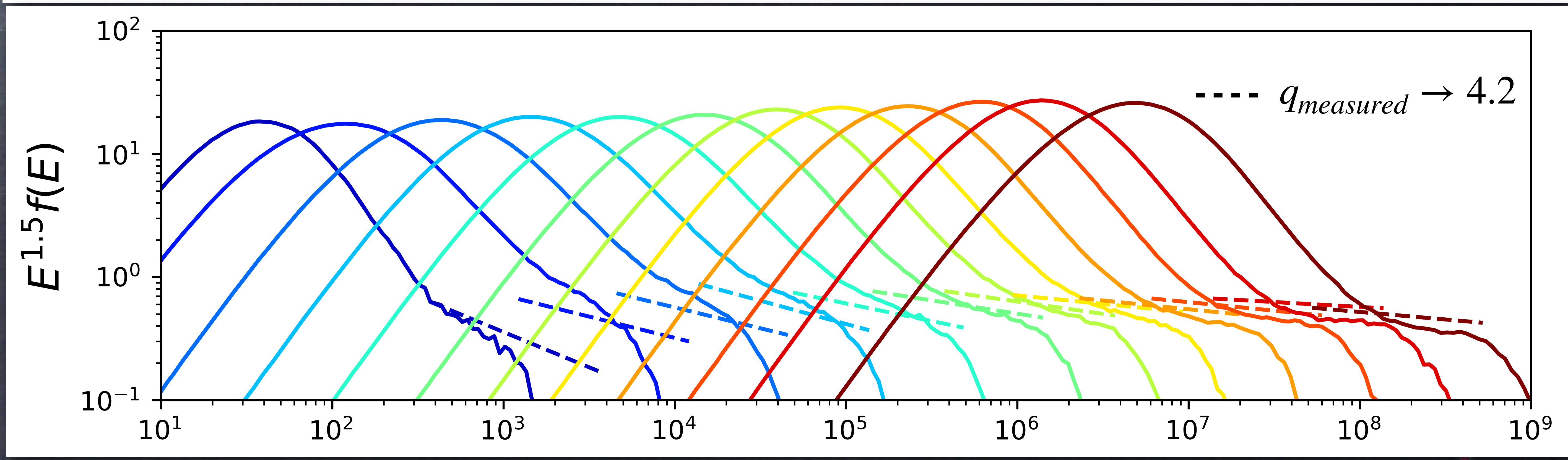


- CR spectra do not agree with DSA
  - They rather have $q \simeq 4.2$



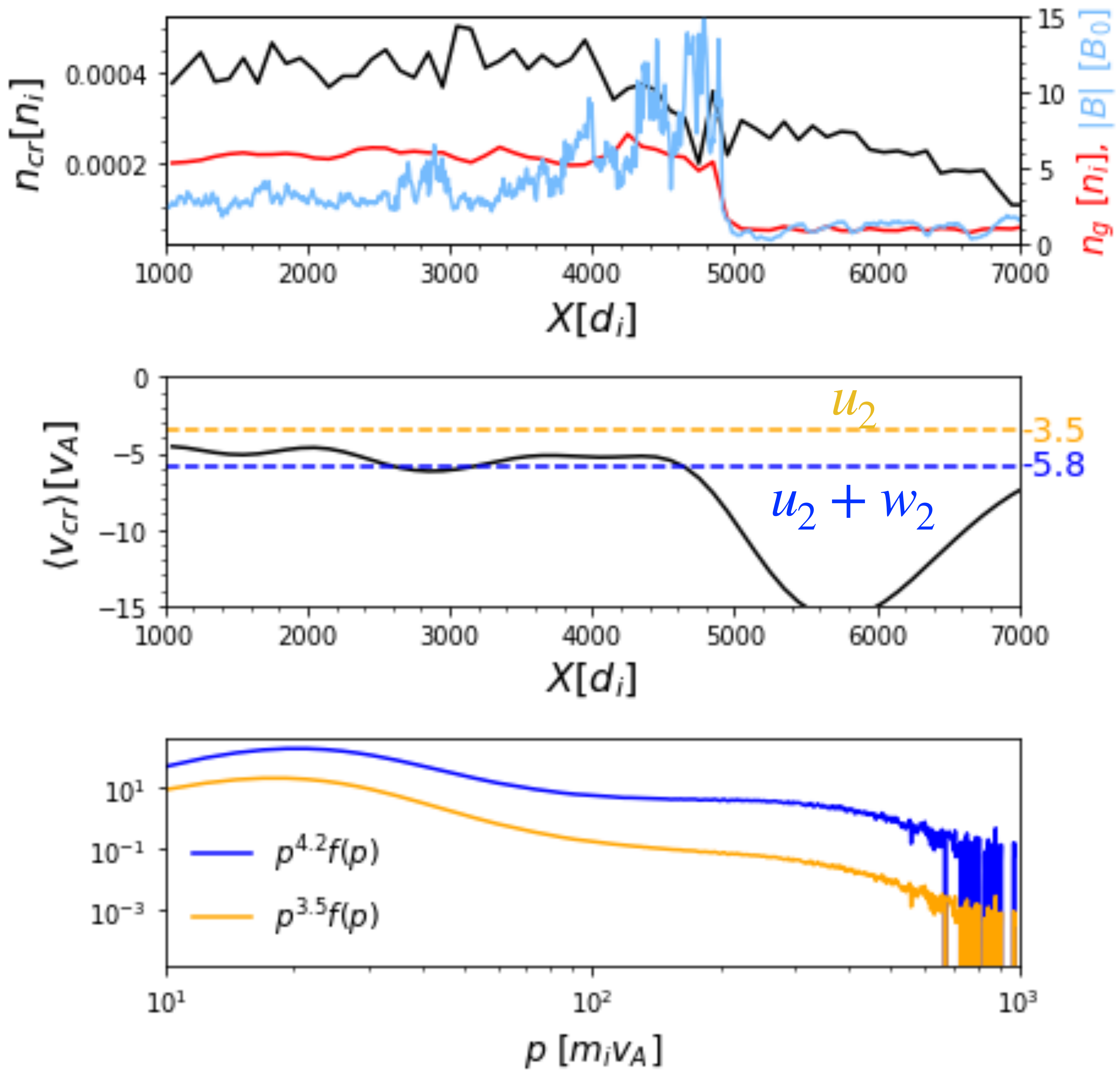
- Evidence for decoupling between

$$R_{gas} \simeq 7 \quad \text{vs} \quad R_{cr} \simeq 3.5$$



DC, Haggerty, Blasi, in prog.

Velocity of the CR Scattering Centers



- CR feel an effective compression

$$R_{cr} = \frac{u_1 + w_1}{u_2 + w_2}$$

- We can measure the effective CR speed $\langle v_{cr}\rangle = u + w$
- Upst: $w_1 \ll u_1 \simeq 21.5 v_A \sim 0.9 v_{sh}$
- Downst: $u_2 \simeq 3.5 v_A; w_2 \simeq 2.3 v_A$

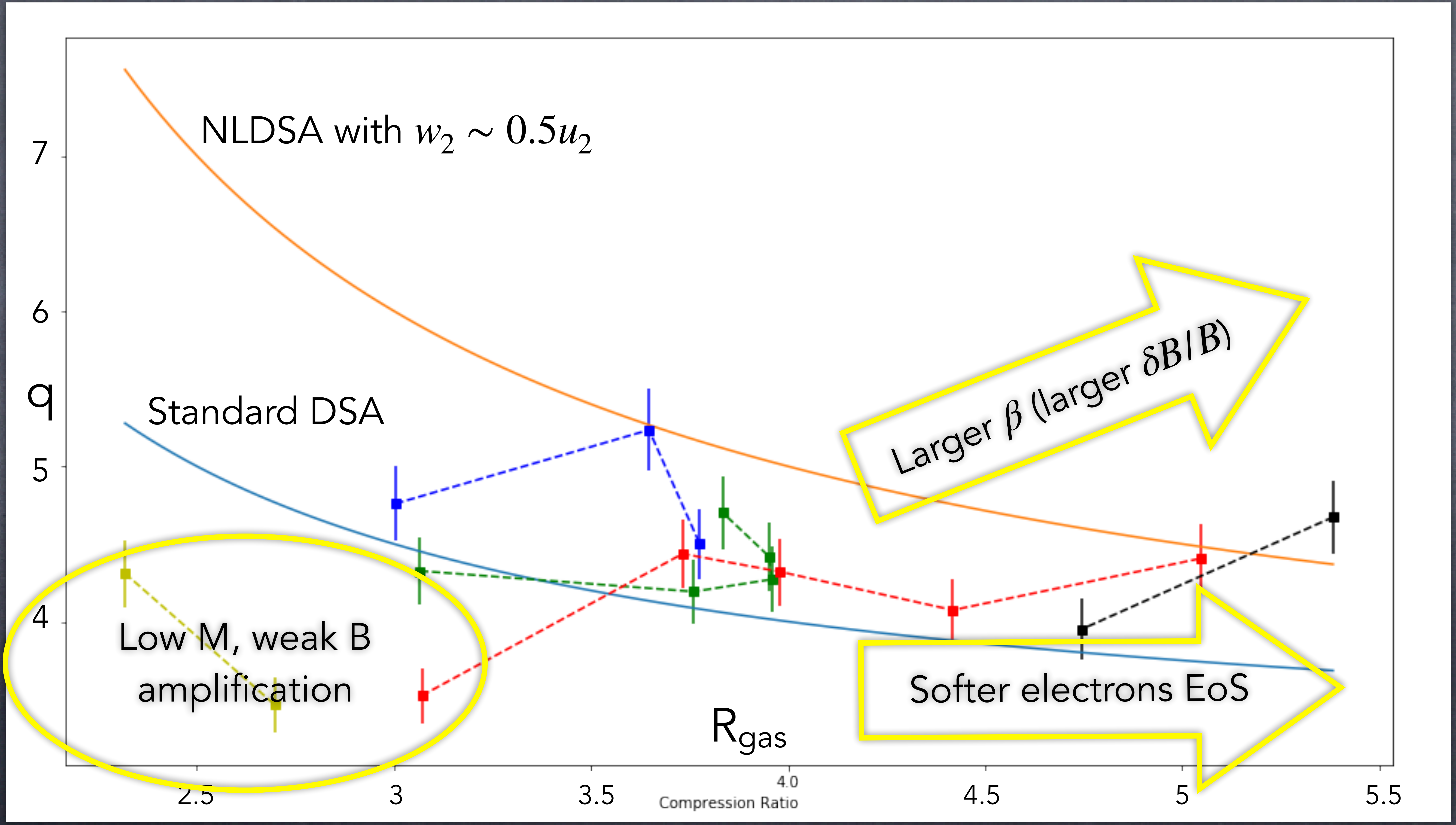
$$R_{gas} \simeq \frac{v_{sh}}{u_2} \simeq 6.7; \quad R_{cr} \simeq \frac{u_1}{u_2 + w_2} \simeq 3.6$$

- Slope $q = \dfrac{3R_{cr}}{R_{cr} - 1}$ fits the spectrum!

DC, Haggerty, Blasi, in prog.

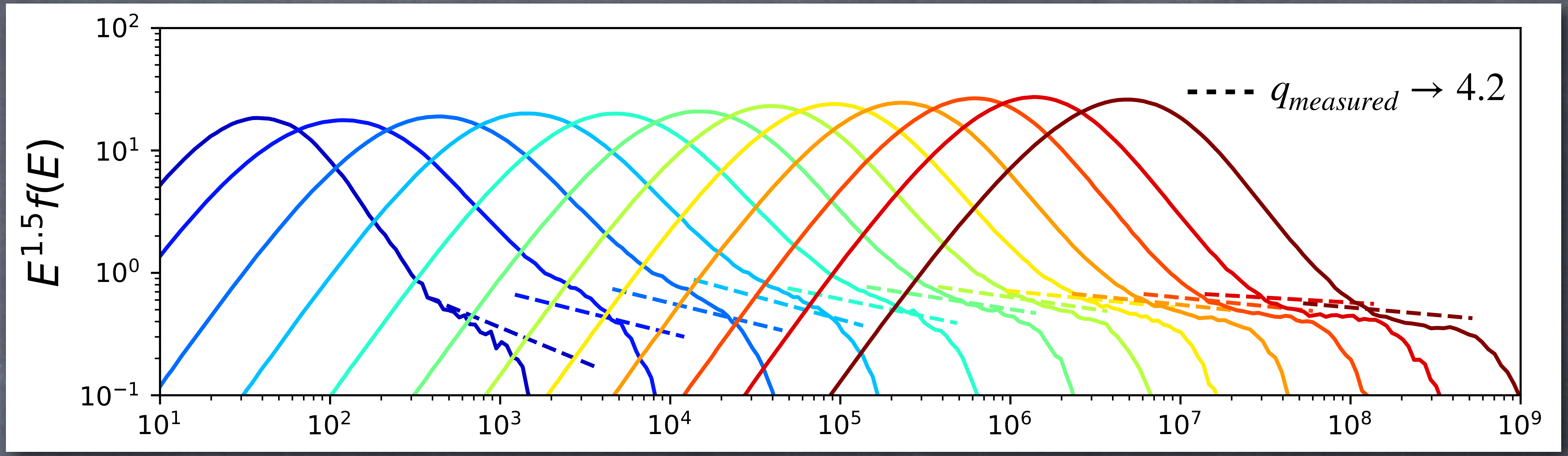
NLDSA Non-Universality

- Several runs with different Mach numbers, plasma β, electron EoS



DC, Haggerty, Blasi, in prog.

Conclusions



- Hybrid simulations with relativistic ions
  - DSA produces power laws in momentum
  - Acceleration efficiency ~10% for large M
- Evidence of CR-modified shocks: upstream precursor and increased $R_{gas} \simeq 7$
  - CRs feel a compression ratio $R_{cr} < R_{gas}$ due to net velocity of amplified magnetic structures *downstream*: in Non-Linear DSA, the power-law index is *not universal*
- First-principle explanation for the observed steep DSA spectra, e.g., in SNRs
  - More scalings with shock parameters are being worked out