ICRC19 - Madison, WI

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The Issue With Diffusive Shock Acceleration

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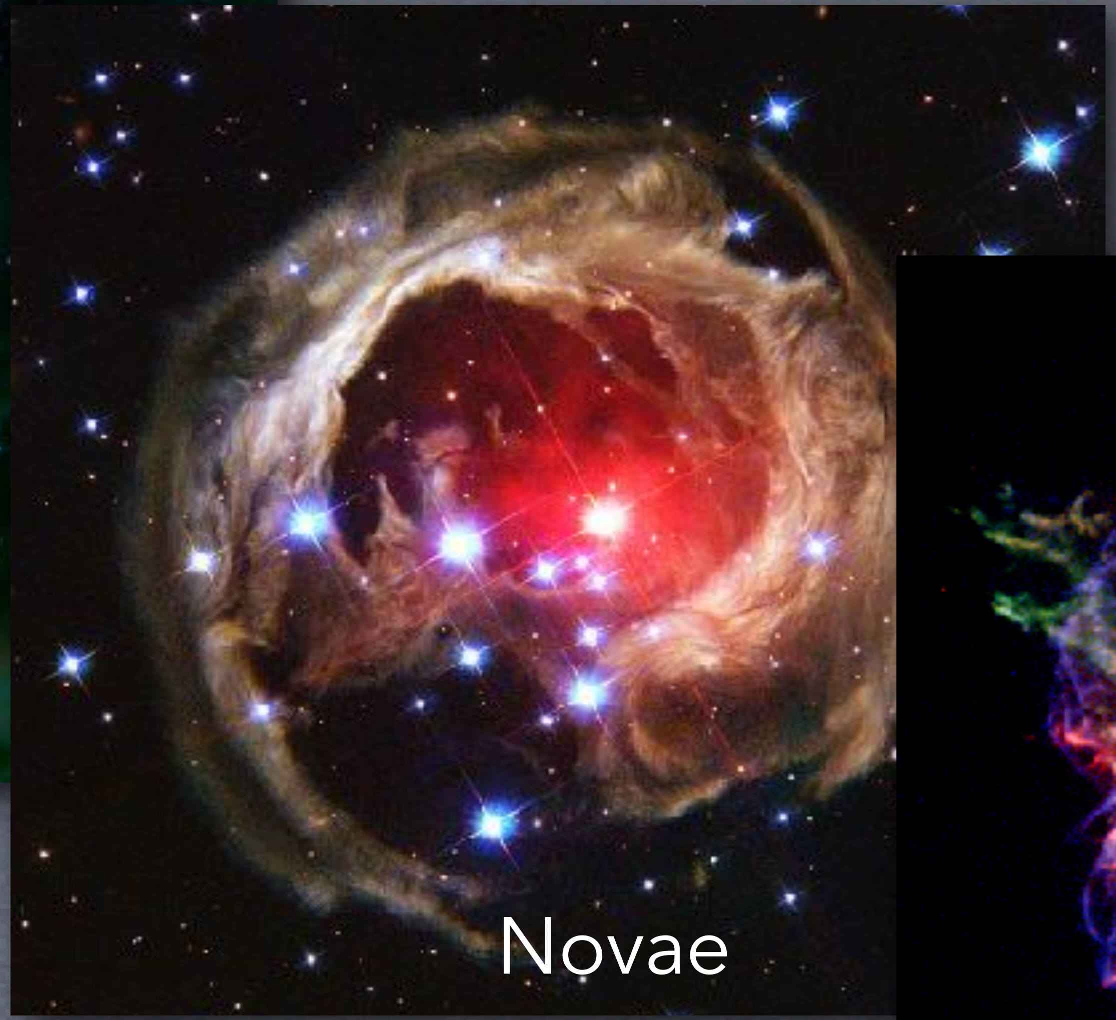
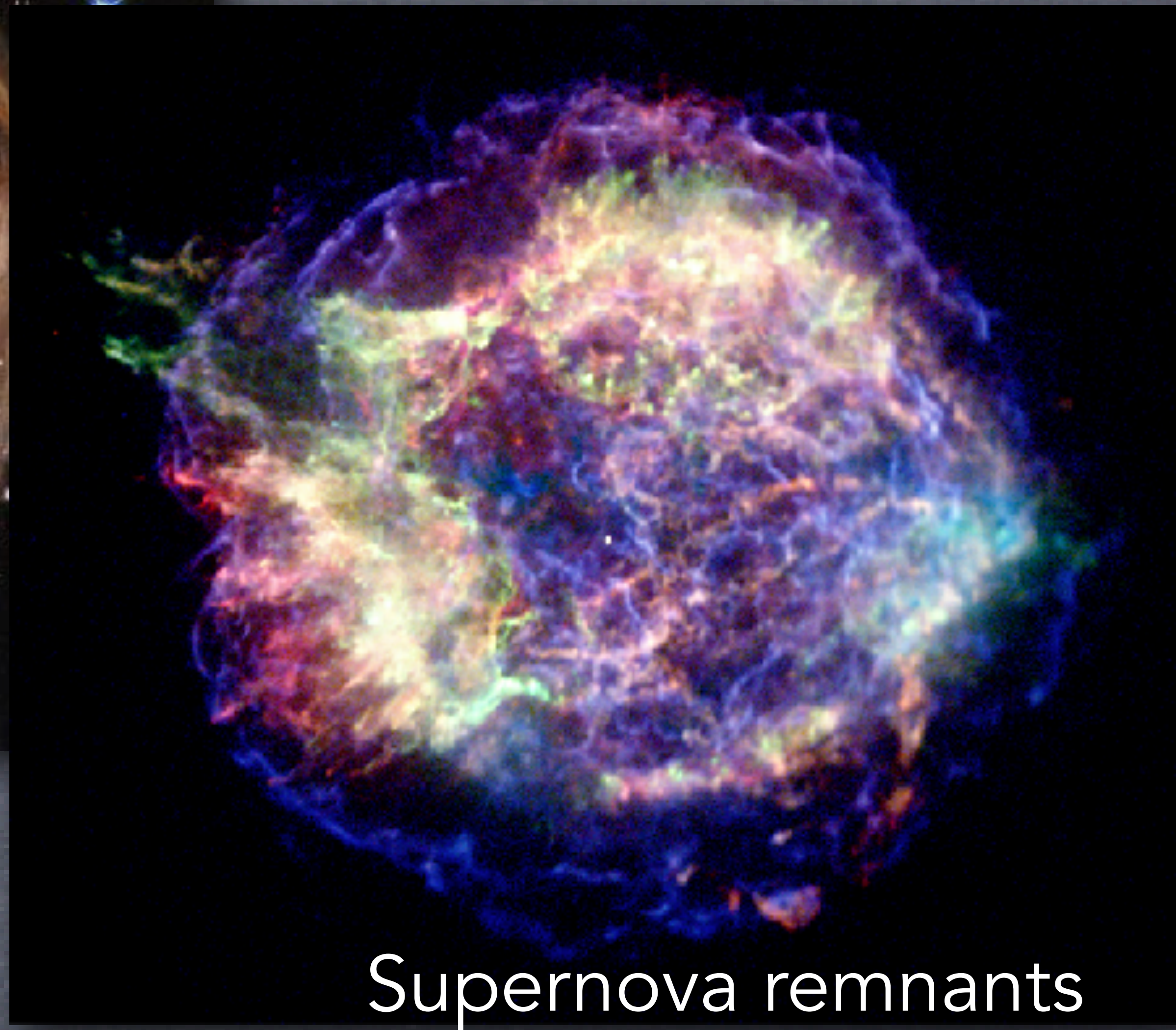
Non-Relativistic Collisionless Shocks

- Prominent sites of non-thermal particles and emission

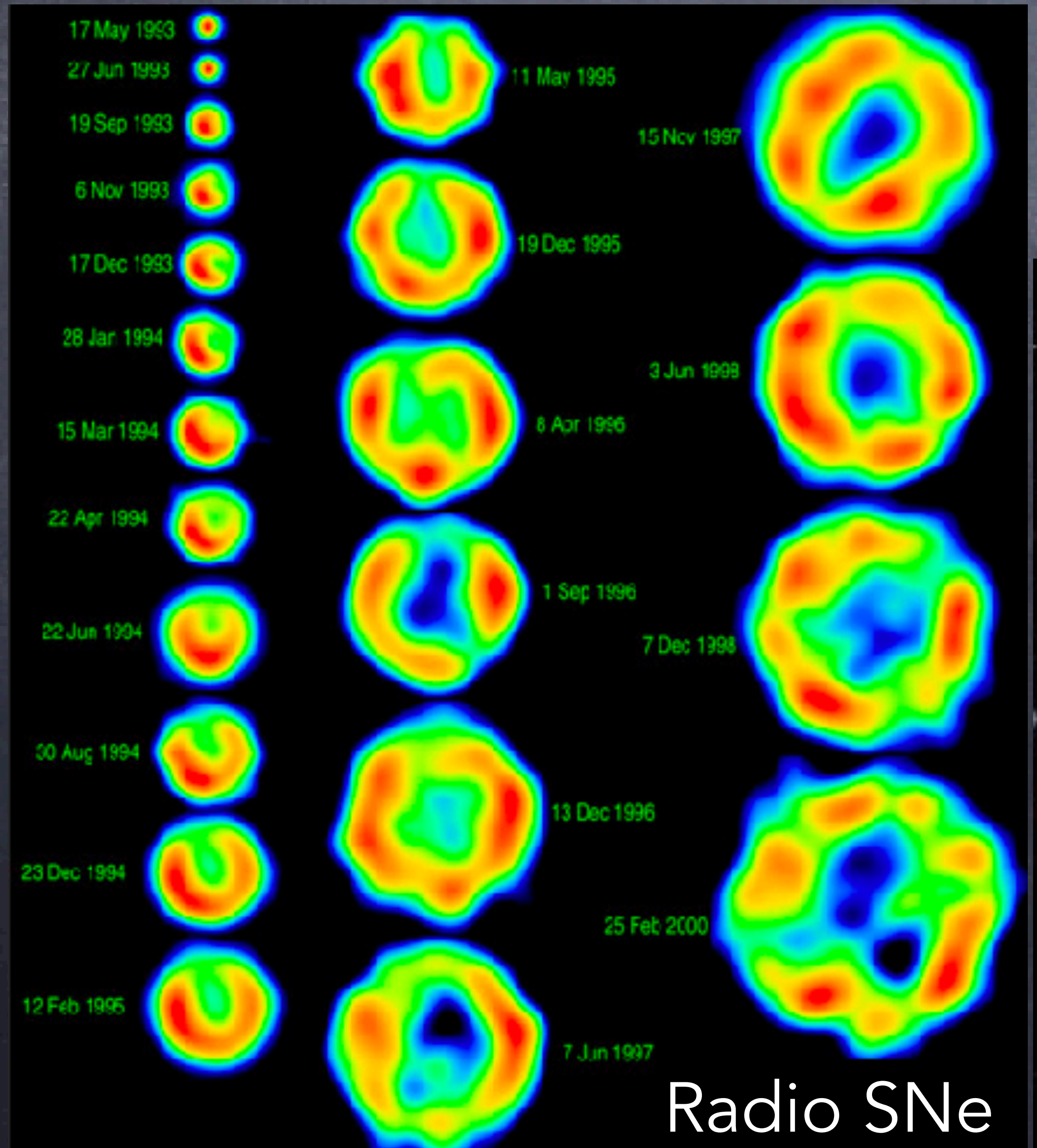
Heliospheric

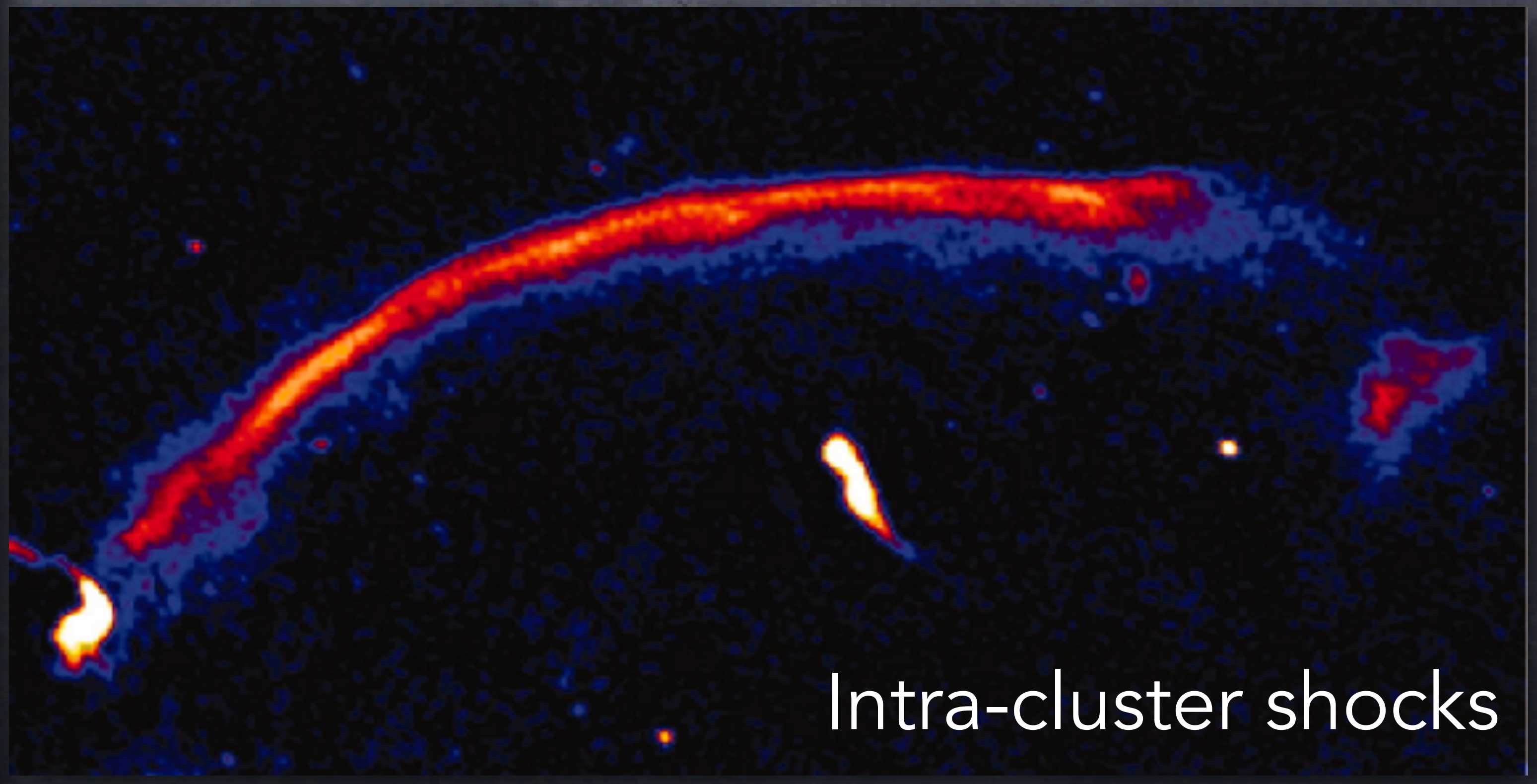
Galactic





Extra-Galactic





A universal acceleration mechanism

- Fermi mechanism (Fermi, 1949): random elastic collisions lead to energy gain
- In shocks, particles gain energy at any interaction (Krymskii77; Blandford & Ostriker; Bell; Axford+78)

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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.

- … 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, $q_E = 2$)

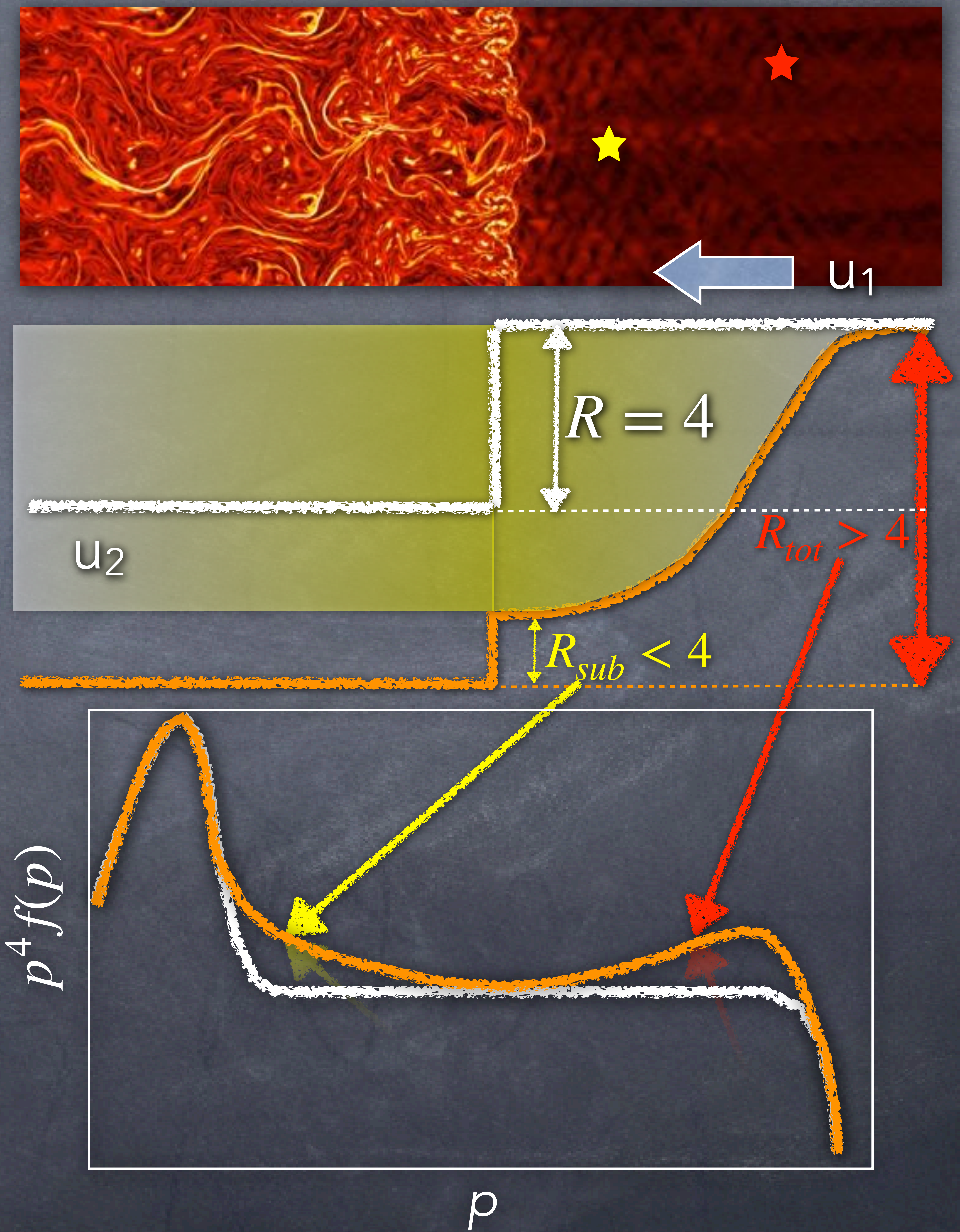
Non-Linear Diffusive Shock Acceleration

- The momentum spectral index depends only on the compression ratio

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

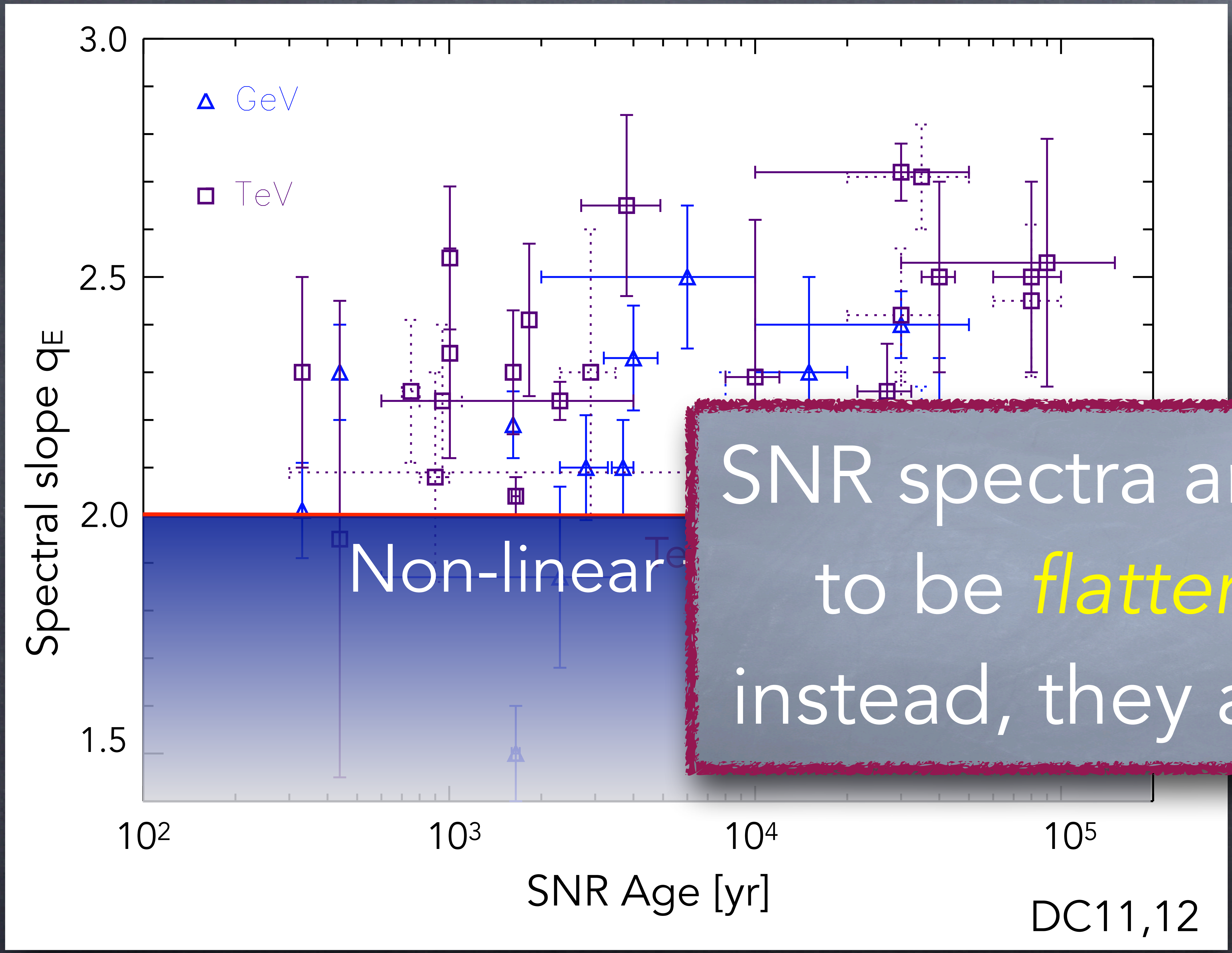
- The CR pressure makes the adiabatic index smaller and hence *R* larger
- Particles "feel" different compression ratios: spectra should become concave
- If acceleration is efficient, at energies >1 GeV: $q < 4$ (flat spectra!)

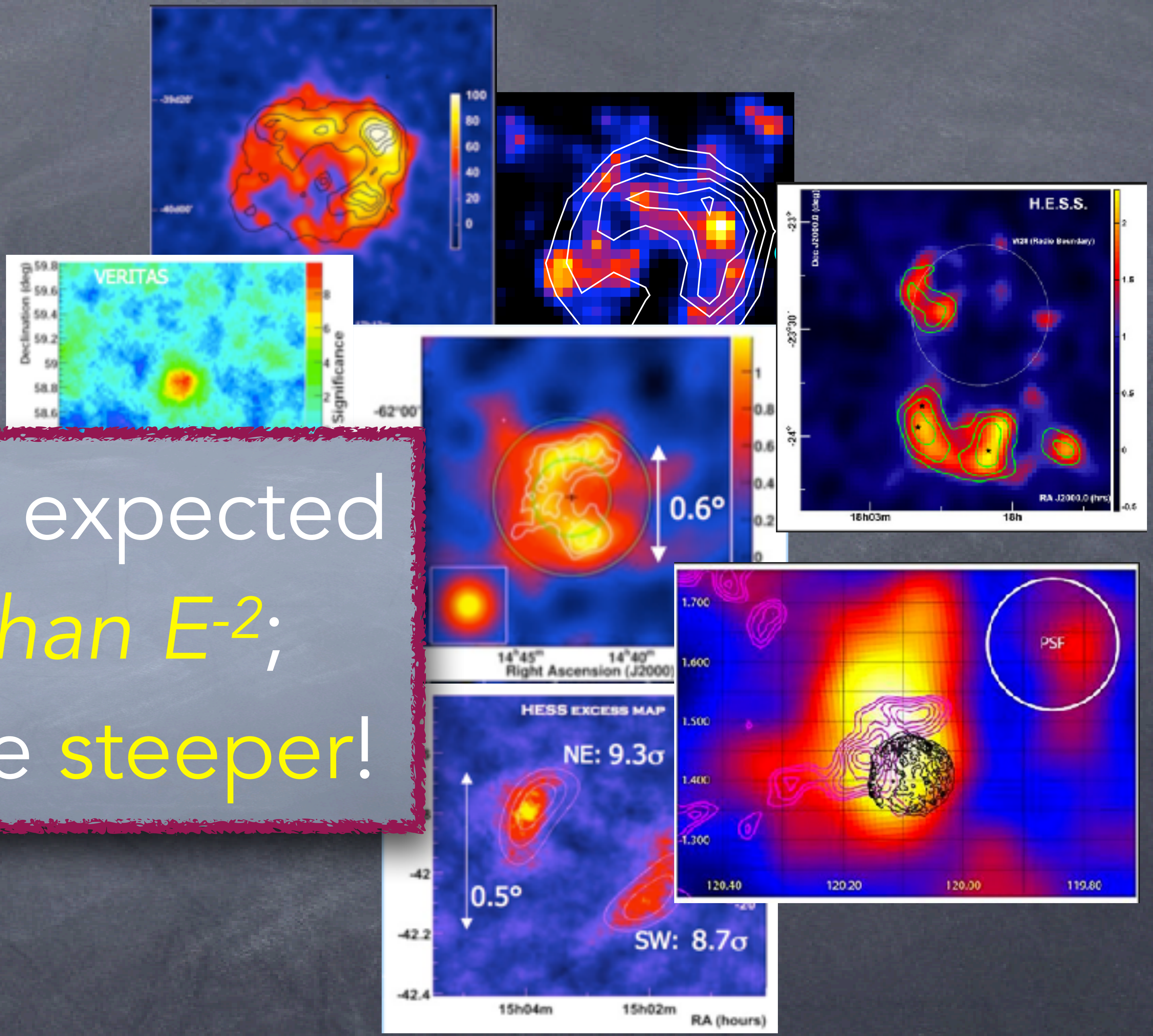
(e.g., Jones-Ellison91, Malkov-Drury01 for reviews)



What Do Observations Say?

Gamma-Rays from SNRs





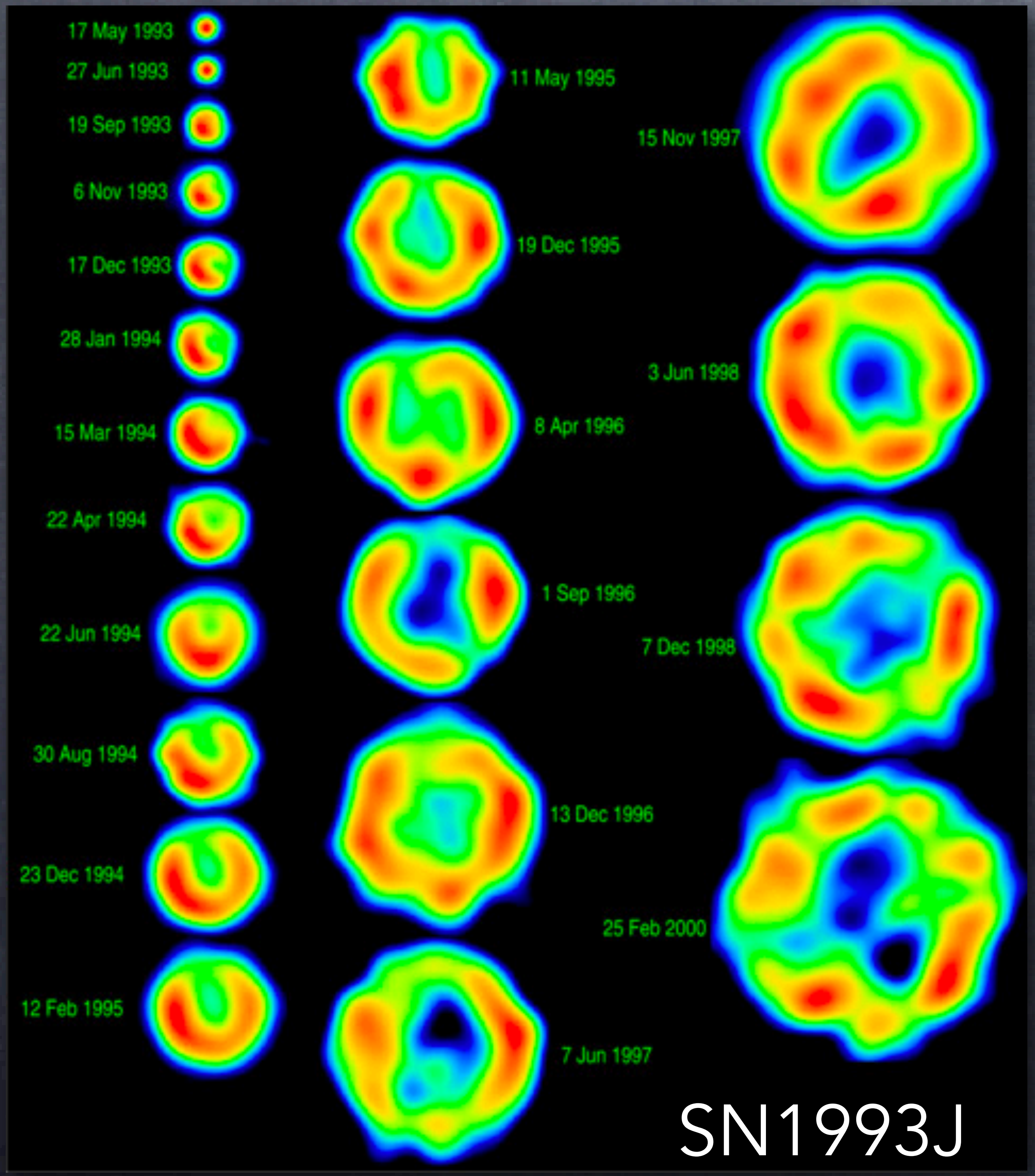
SNR spectra are expected to be *flatter than E^{-2}*; instead, they are steeper!

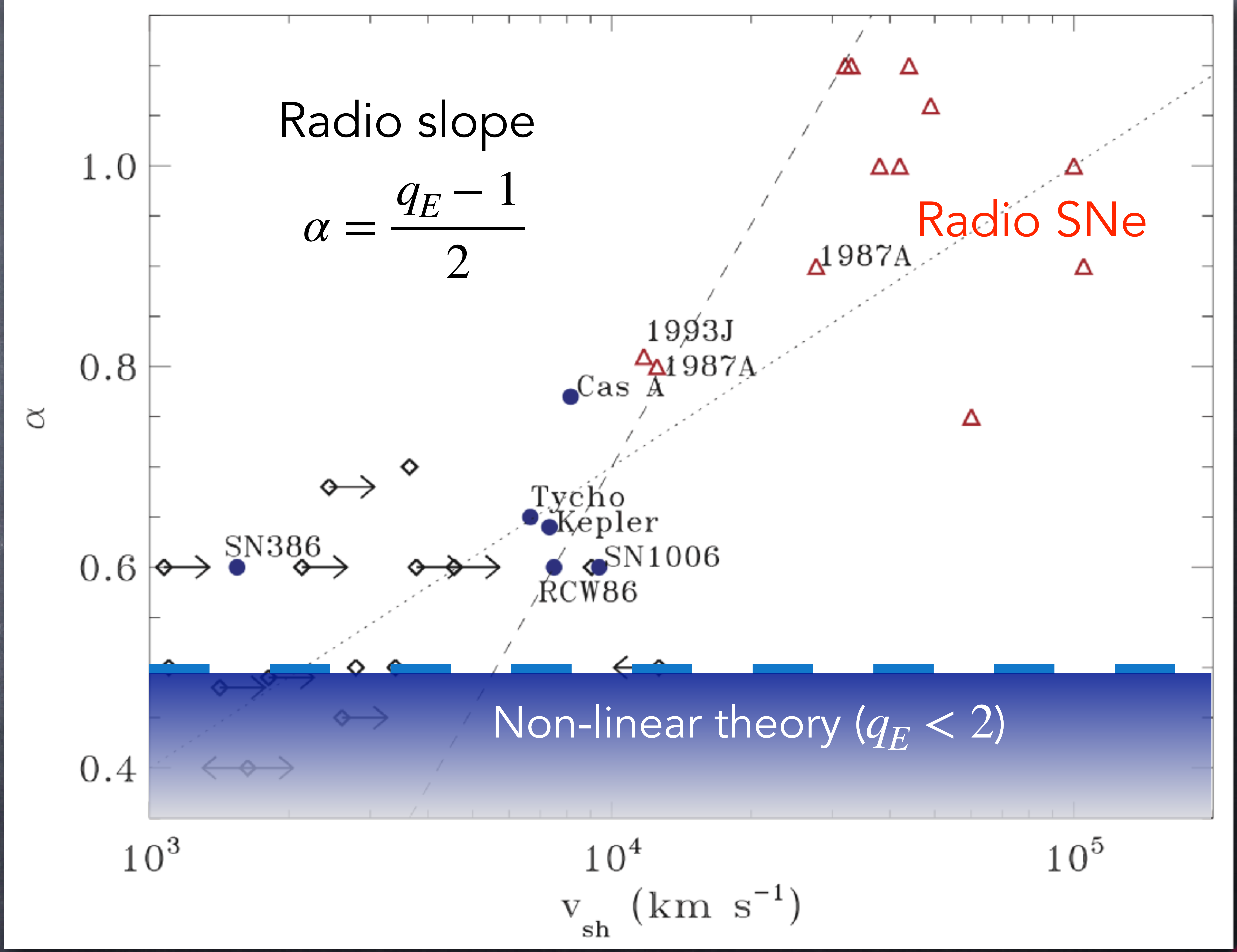
- Too steep to be leptonic: hadronic emission
- Not consistent with non-linear DSA theory!

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

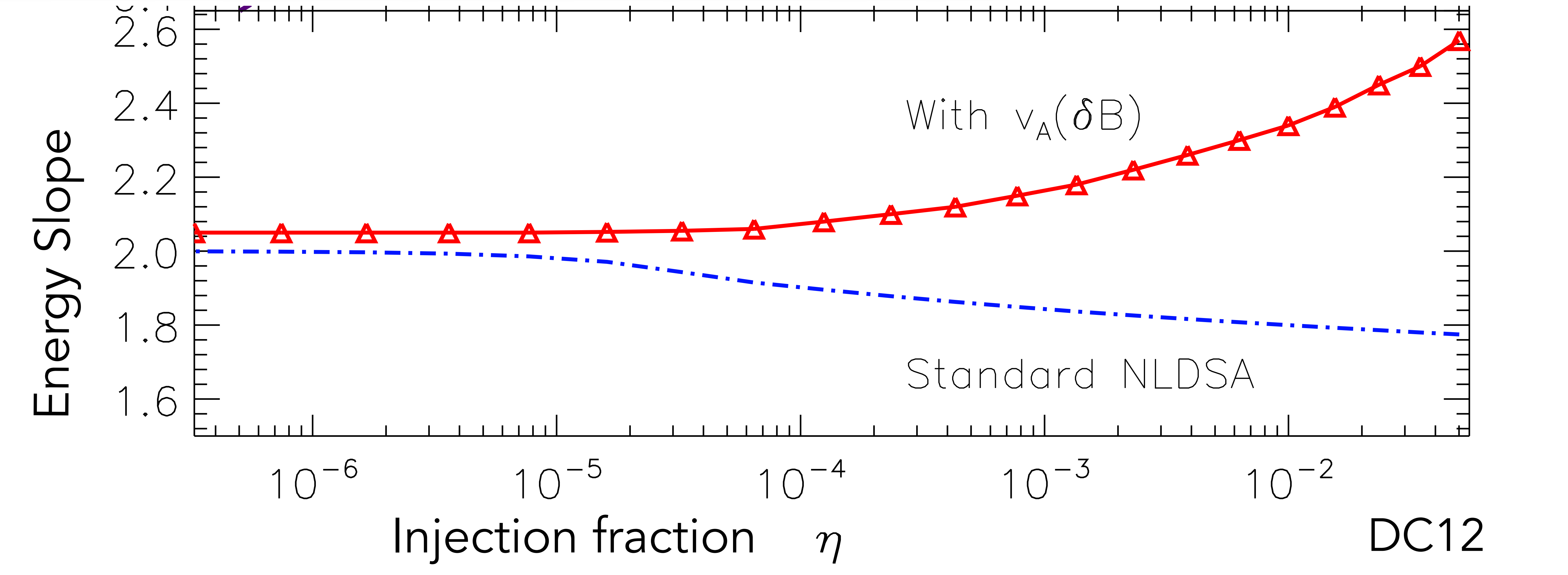
A Theoretical Challenge

- 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*!

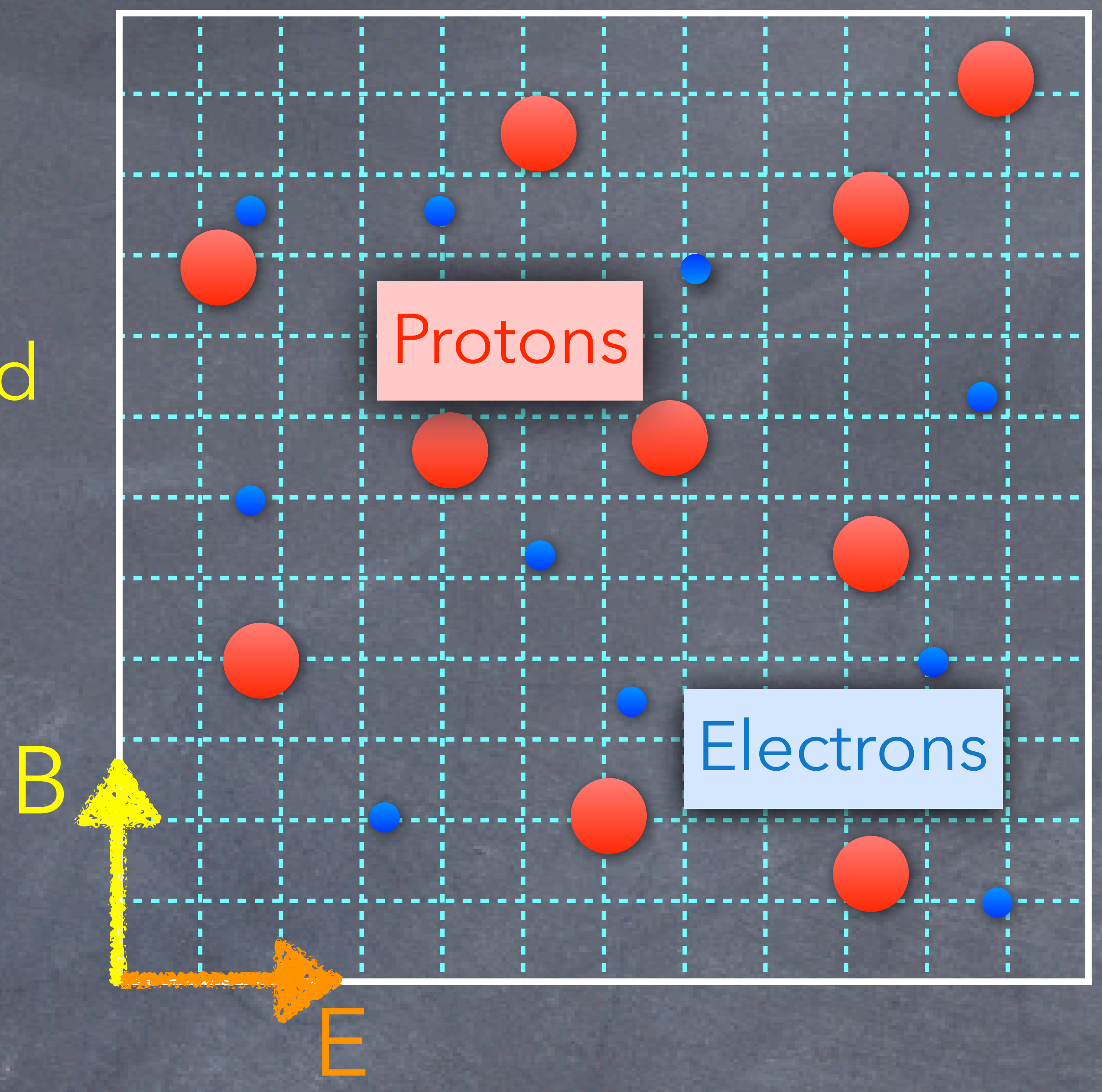
The large velocity of *scattering centers* $v_{waves} \approx v_A(\delta B)$ leads to an effective ratio:

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



Astroplasmas from first principles

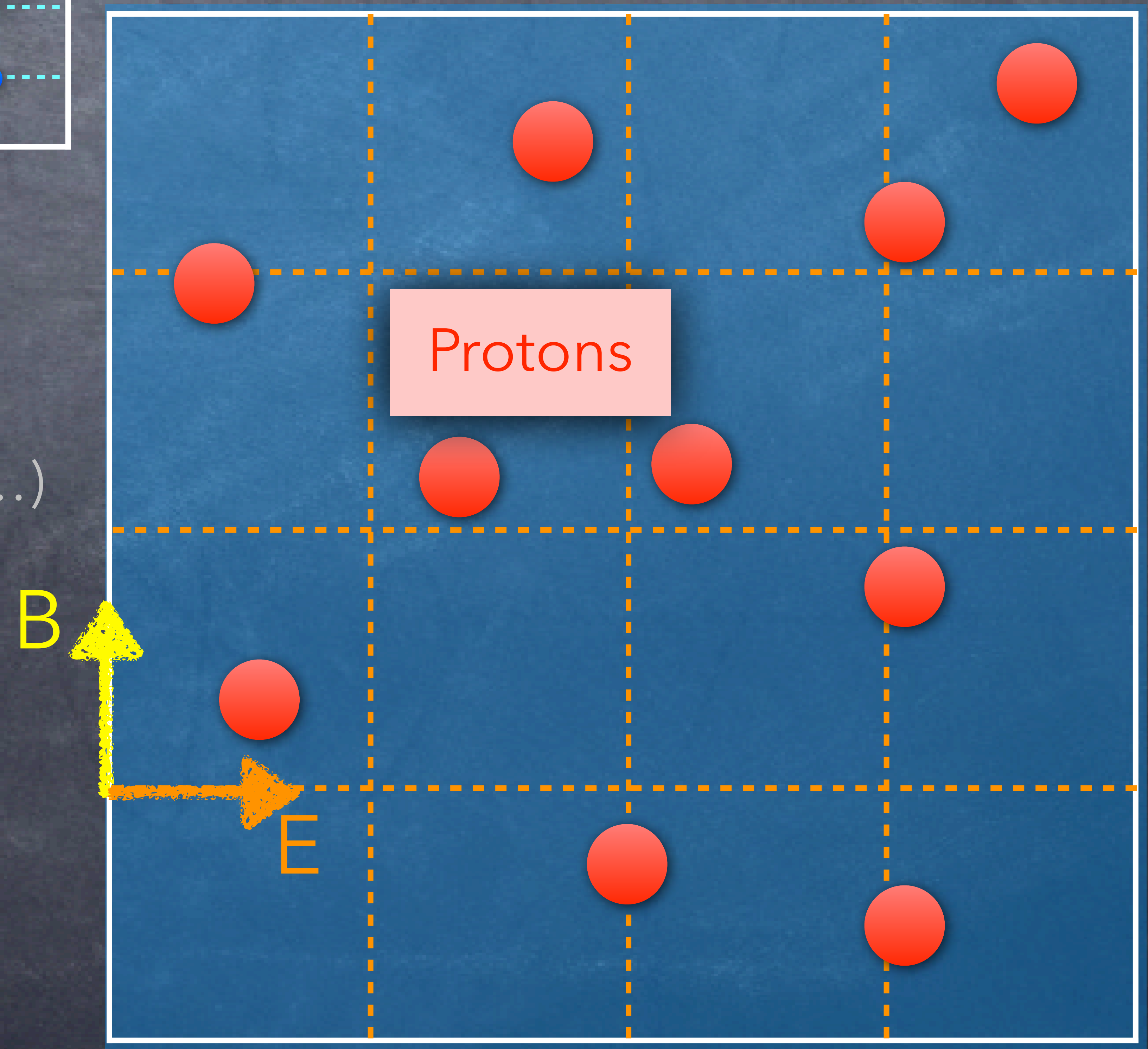
- Full-PIC approach
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



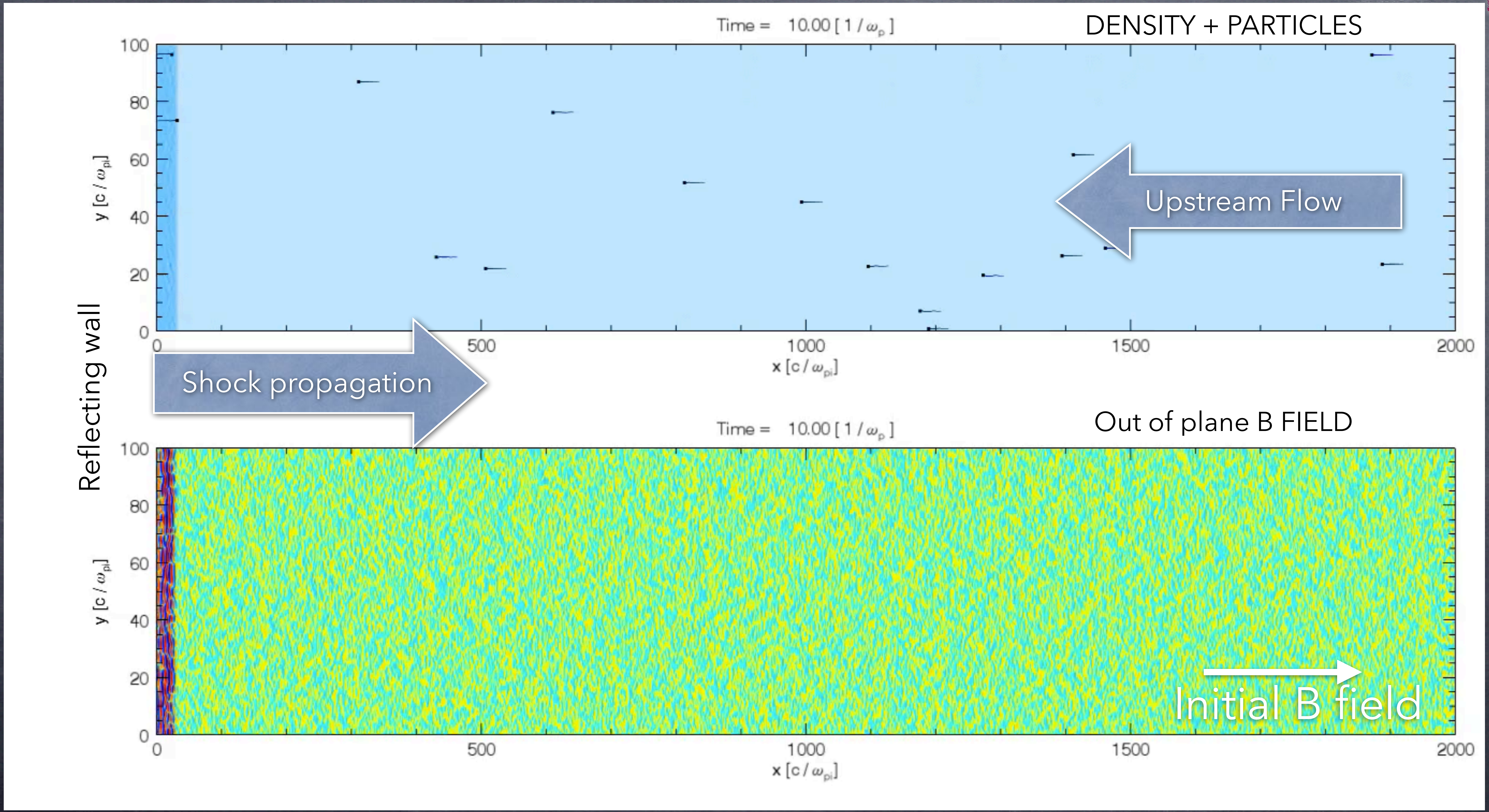
- Hybrid approach: Fluid electrons - Kinetic protons

(Winske-Omidi; Burgess+, Lipatov02; Giacalone+; DC-Spitkovsky+; Haggerty-DC,…)

  - massless electrons for more macroscopical time/length scales



Hybrid Simulations of Collisionless Shocks



dHybrid code (Gargaté et al, 2007; DC & Spitkovsky 2014, Haggerty & DC, in prog.)

A Revised Theory of Non-Linear DSA

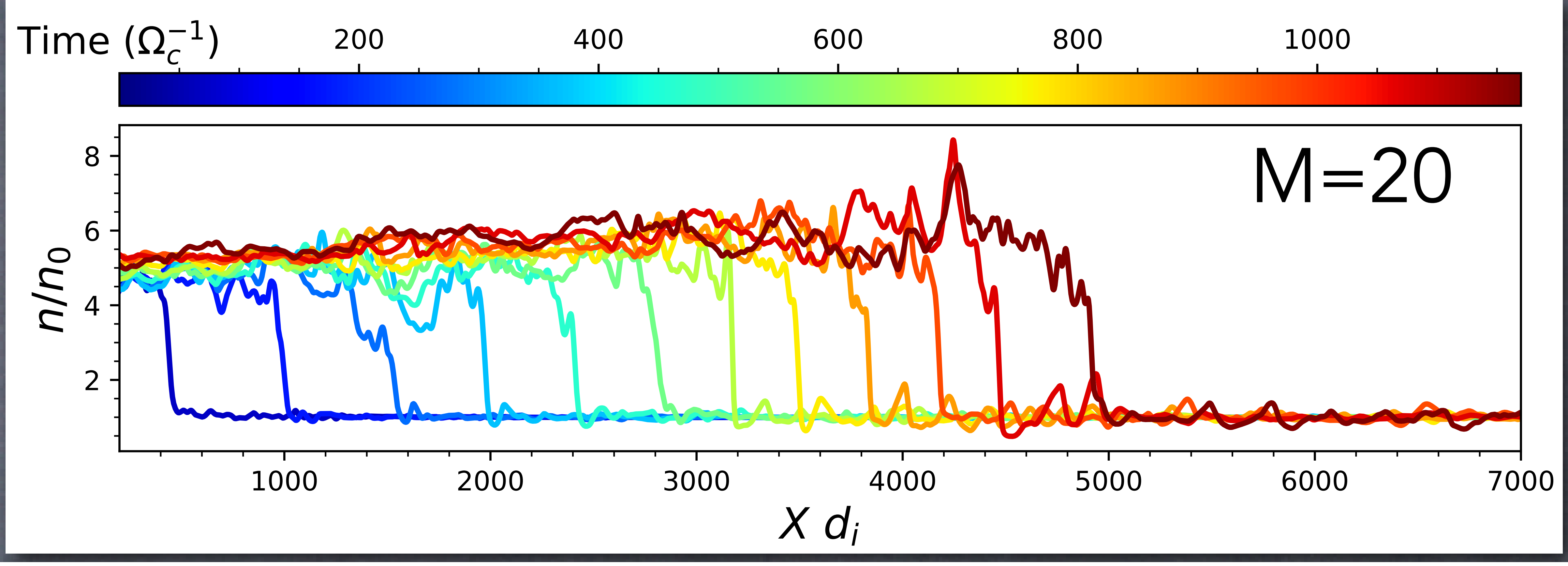
- Unprecedentedly-long hybrid sims with *dHybridR*, including relativistic ion dynamics (Haggerty-DC, soon)
- *R* increases with time, up to ~7!
  - *R*~6-7 inferred in Tycho (Warren+05)

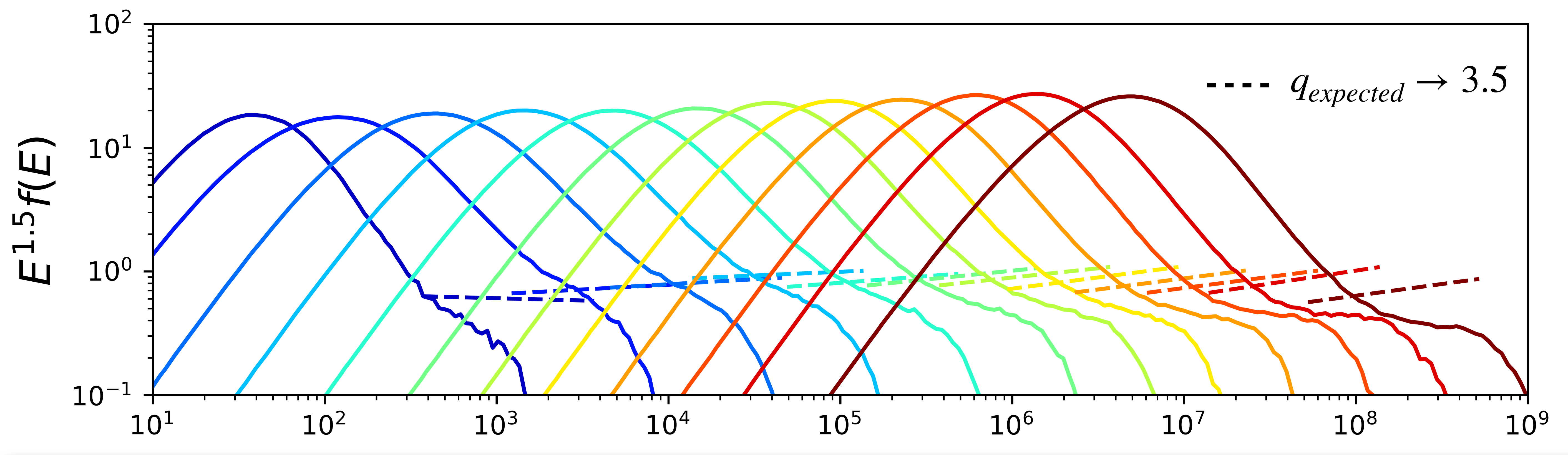
$$R \simeq 7 \rightarrow q_{expected} \simeq 3.5$$

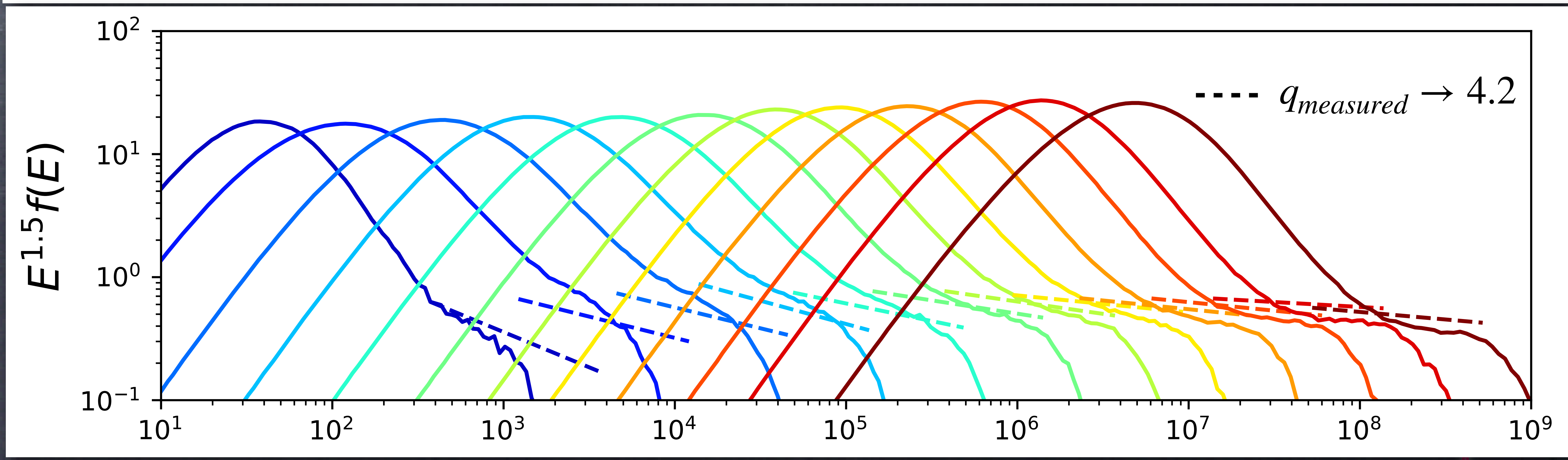
- CR spectra fitted with $q \simeq 4.2$
- Evidence for decoupling between

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

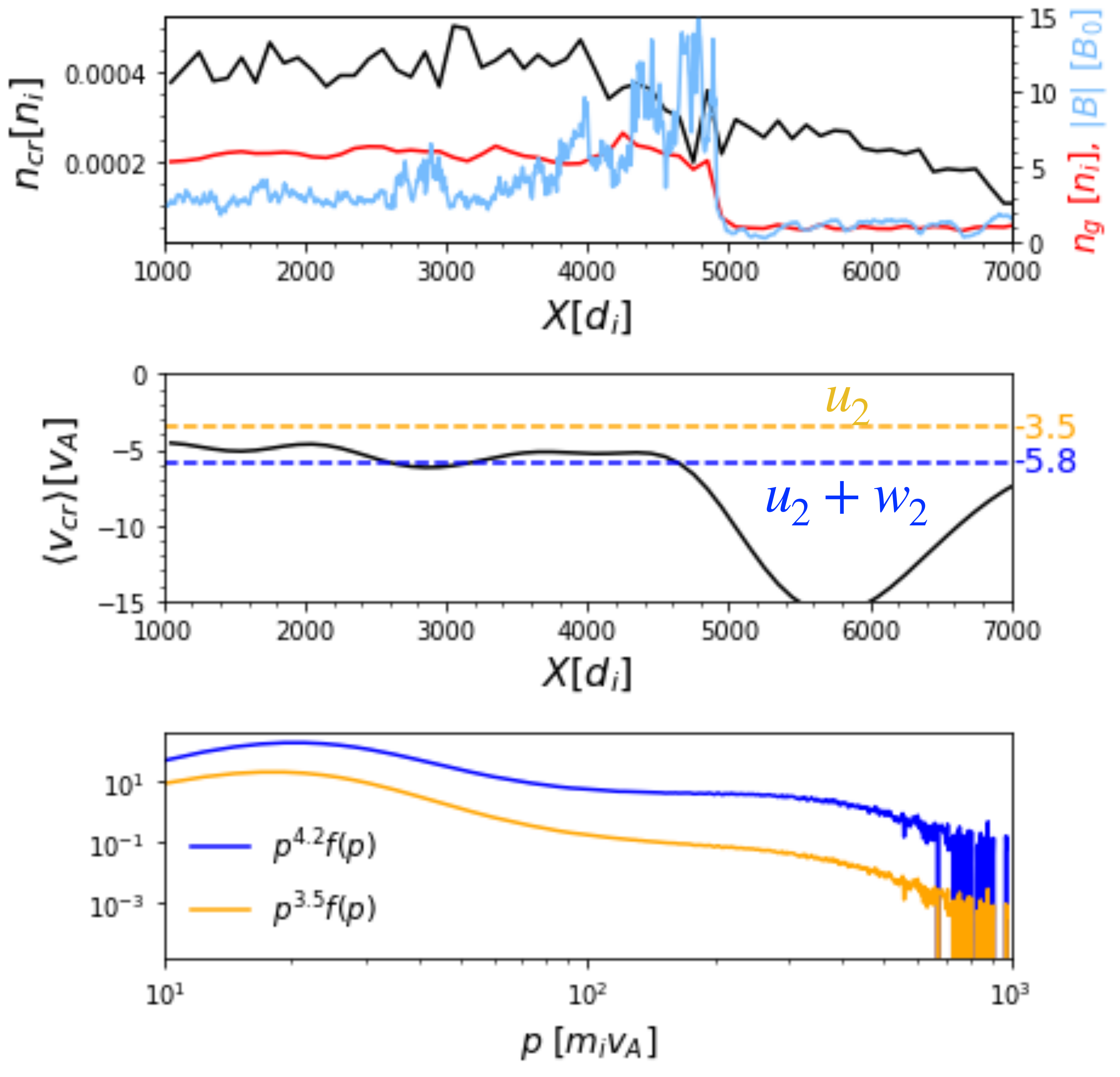
DC, Haggerty, Blasi, in prog.







Velocity of the CR Scattering Centers



- CR feel an effective compression:

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

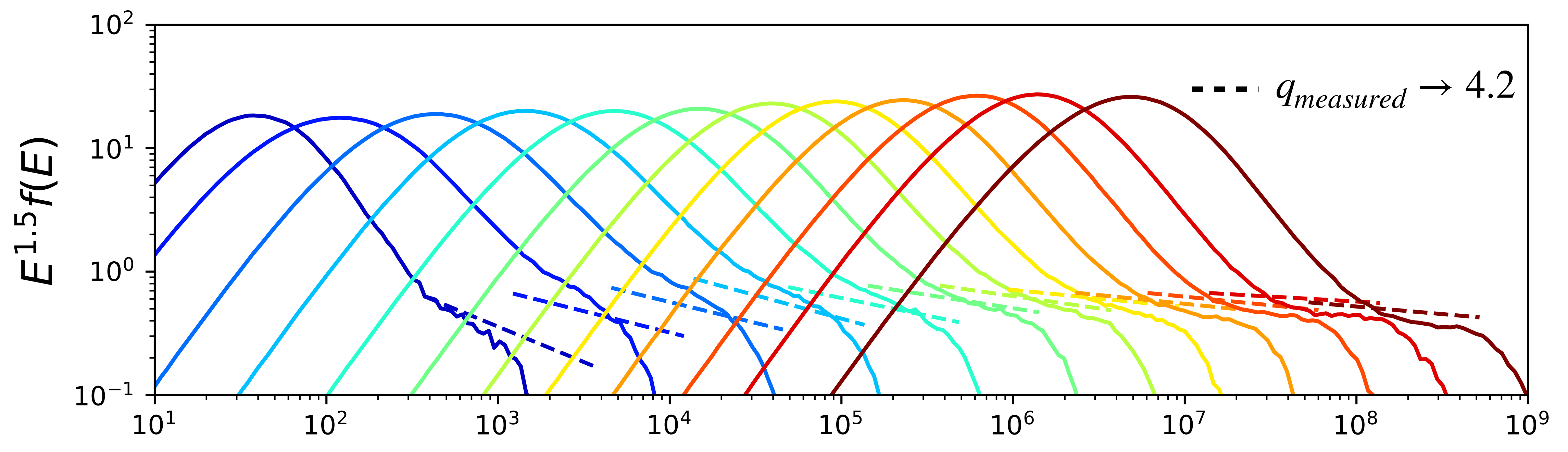
- We can measure the effective CR speed $\langle v_{cr} \rangle = u + w$
- Upst: $w_1 \ll u_1 \simeq 21.5 v_A \sim 0.9 v_{sh}$
- Downst: $u_2 \simeq 3.5 v_A; w_2 \simeq 2.3 v_A$

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

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

DC, Haggerty, Blasi, in prog.

Conclusions



- Hybrid simulations with relativistic ions
  - Acceleration efficiency ~10% for large M
  - Evidence of CR-modified shocks: upstream precursor and increased $R_{gas} \simeq 7$
  - CRs feel a $R_{cr} < R_{gas}$ due to net velocity of amplified magnetic structures *downstream* (different from anything in the literature,…)

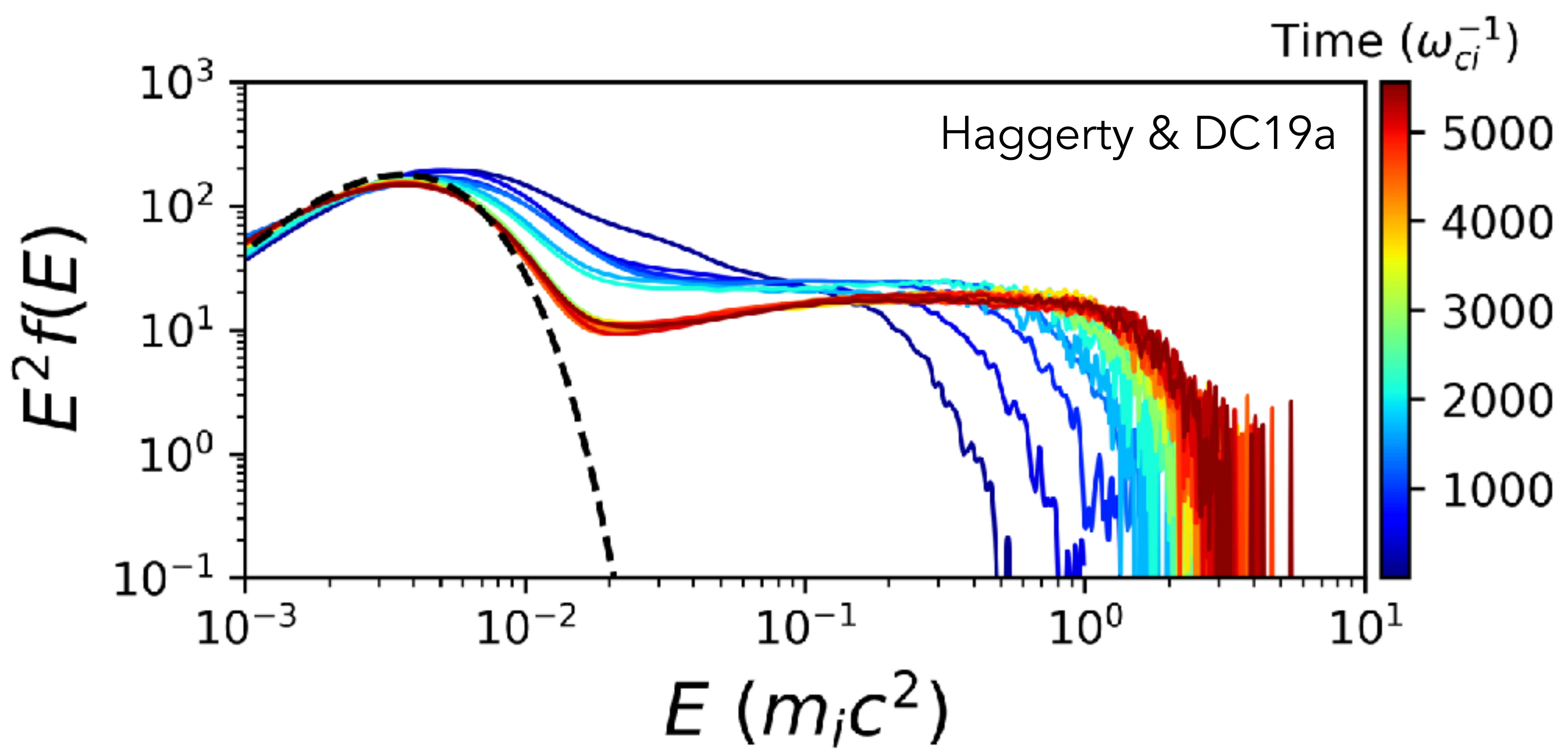
- First-principle explanation for the observed steep DSA spectra, e.g., in SNRs
  - More scalings with shock parameters are being worked out

Hybrid Simulations with Relativistic Ions: dHybridR

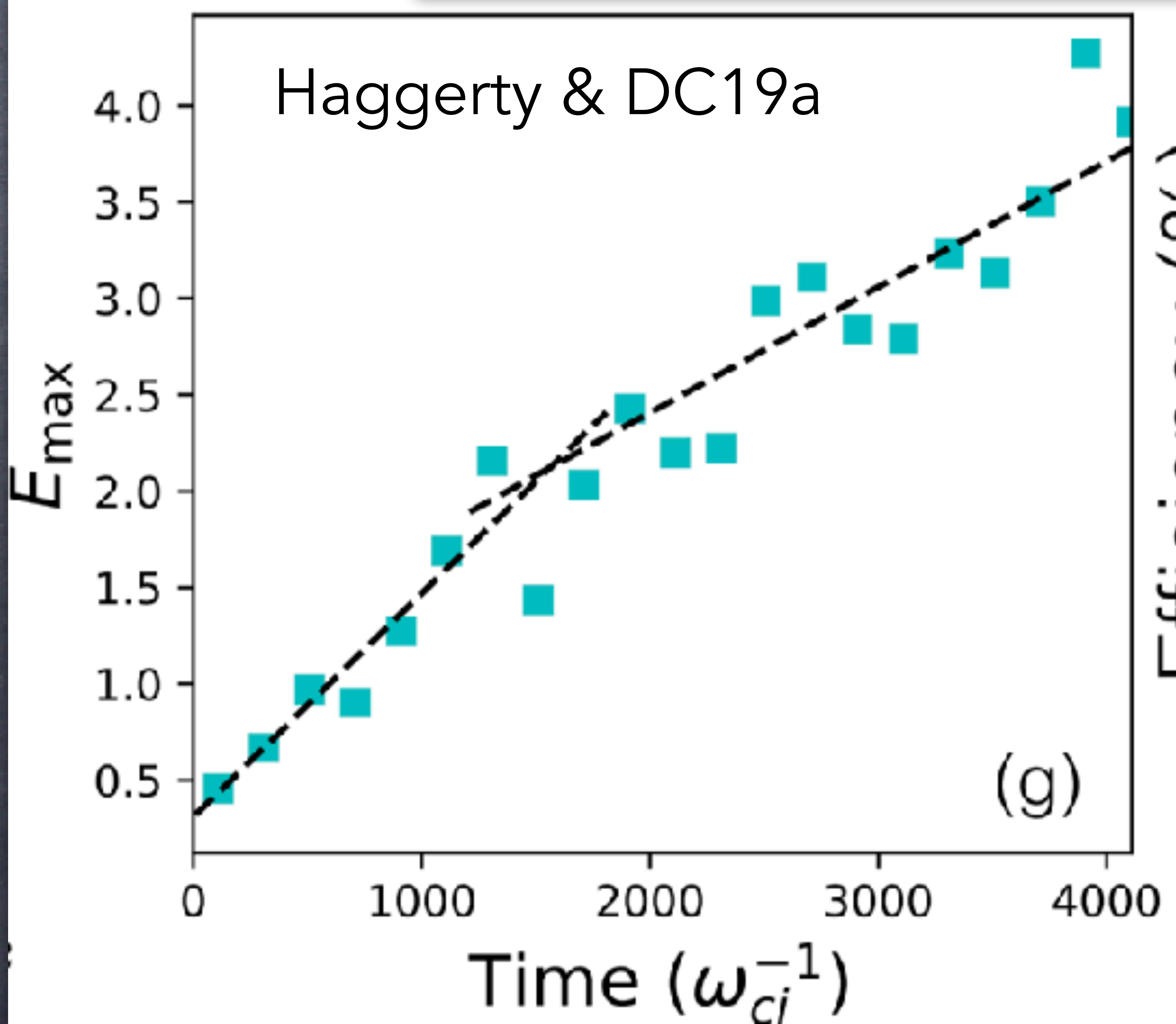
- Hybrid limit requires $v_{bulk} << c$

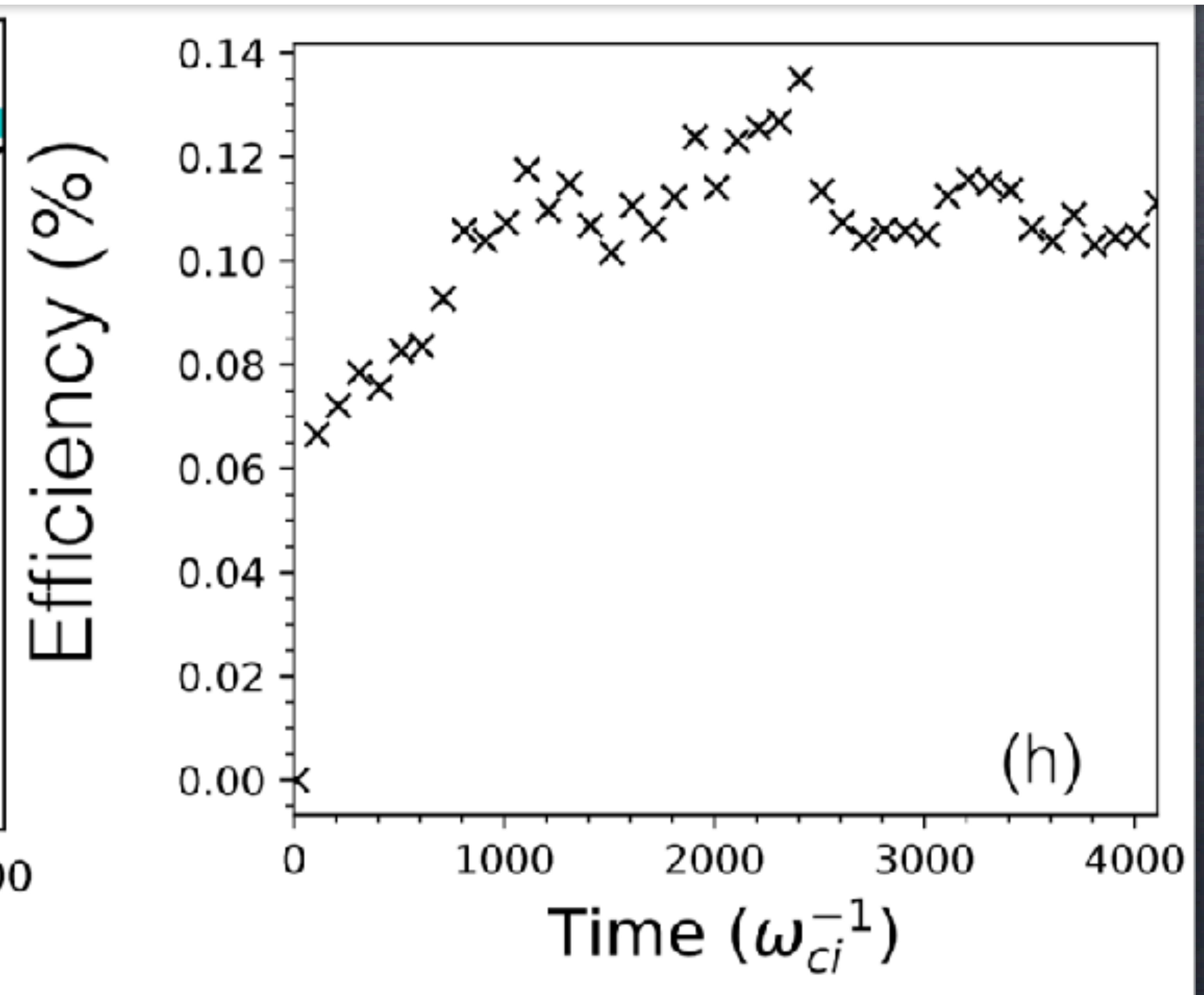
DSA: $f(p) \propto p^{-4}$; $4\pi p^2 f(p) dp = f(E) dE$

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



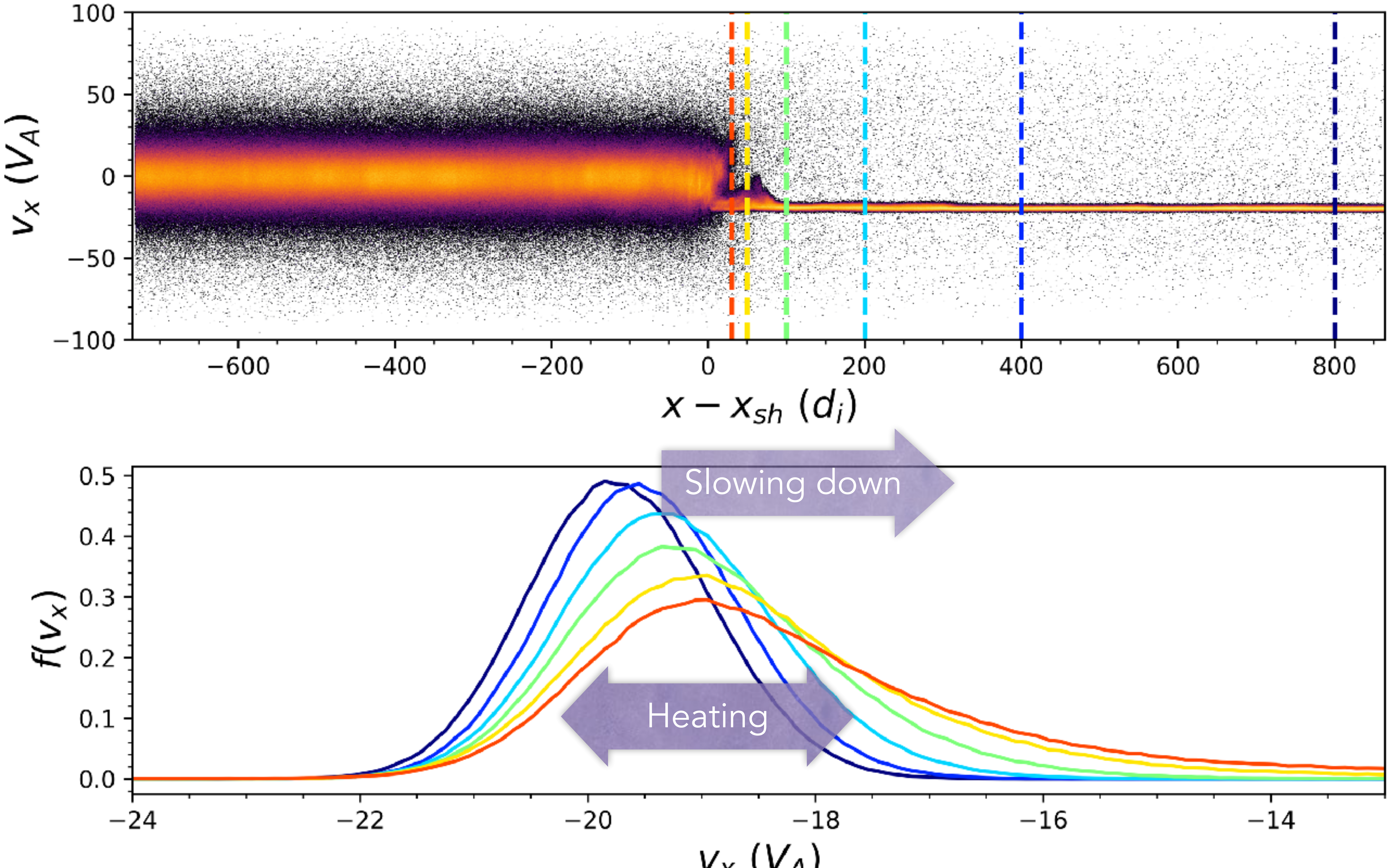
- Long-term evolution
  - $E_{max}(t) \propto t$
  - Efficiency 10-12%





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!