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The Theory of Efficient Particle Acceleration at Shocks

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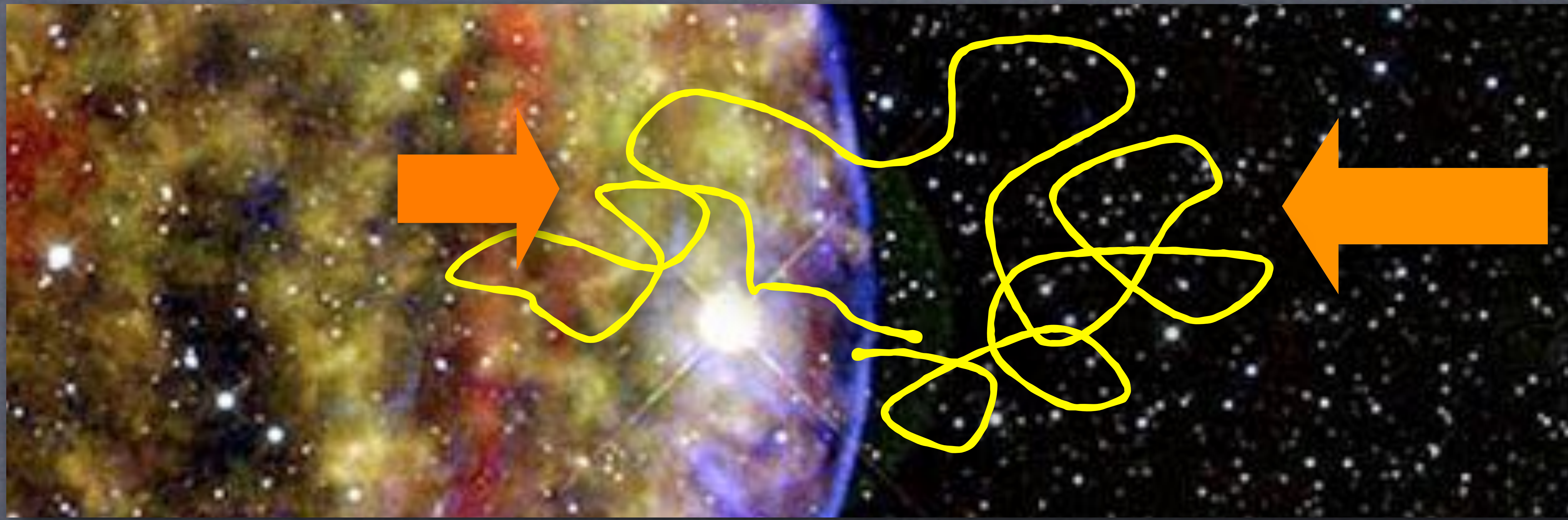
The SNR paradigm for the origin of CRs

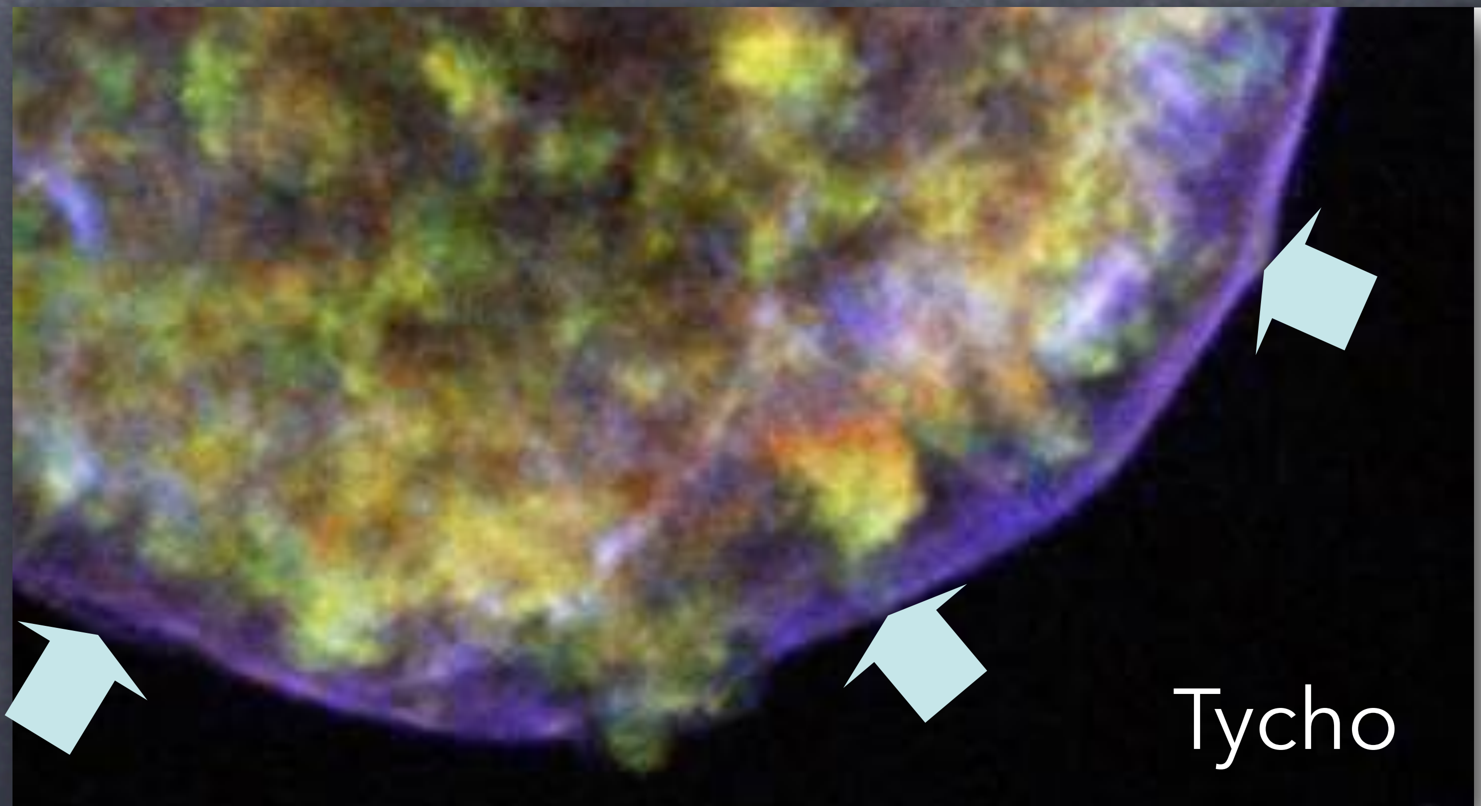
- **Energetics**: ~10% of SN kinetic energy can account for Galactic CRs (Baade-Zwicky34)

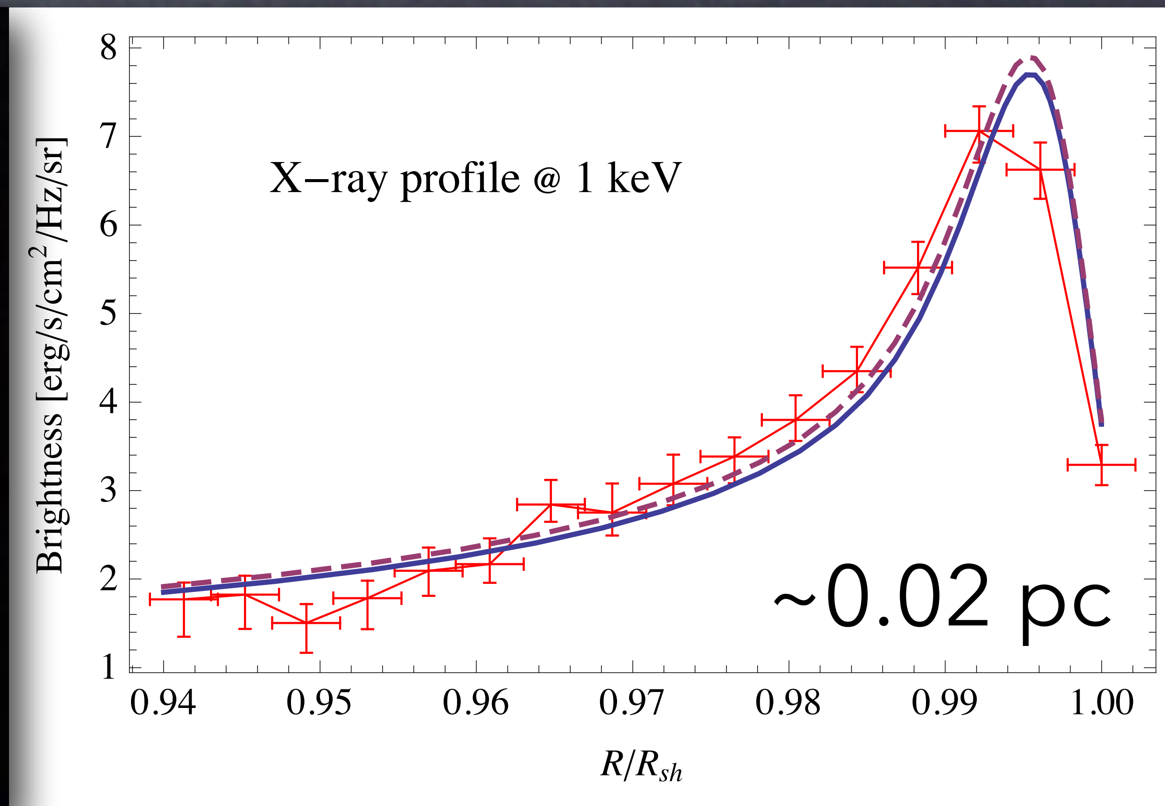
- **Mechanism**: Fermi acceleration at SNR shocks is *first-order* and produces power-laws. Diffusive Shock Acceleration (DSA) (Krimskii77,Axford+78,Bell78,Blandford-Ostriker78)



Downstream Upstream

- Evidence of **B field amplification**: self-generated scattering enhances the energization rate (e.g., Bamba+05, Völk+05, Parizot+06, Morlino+12, Ressler+14, etc)



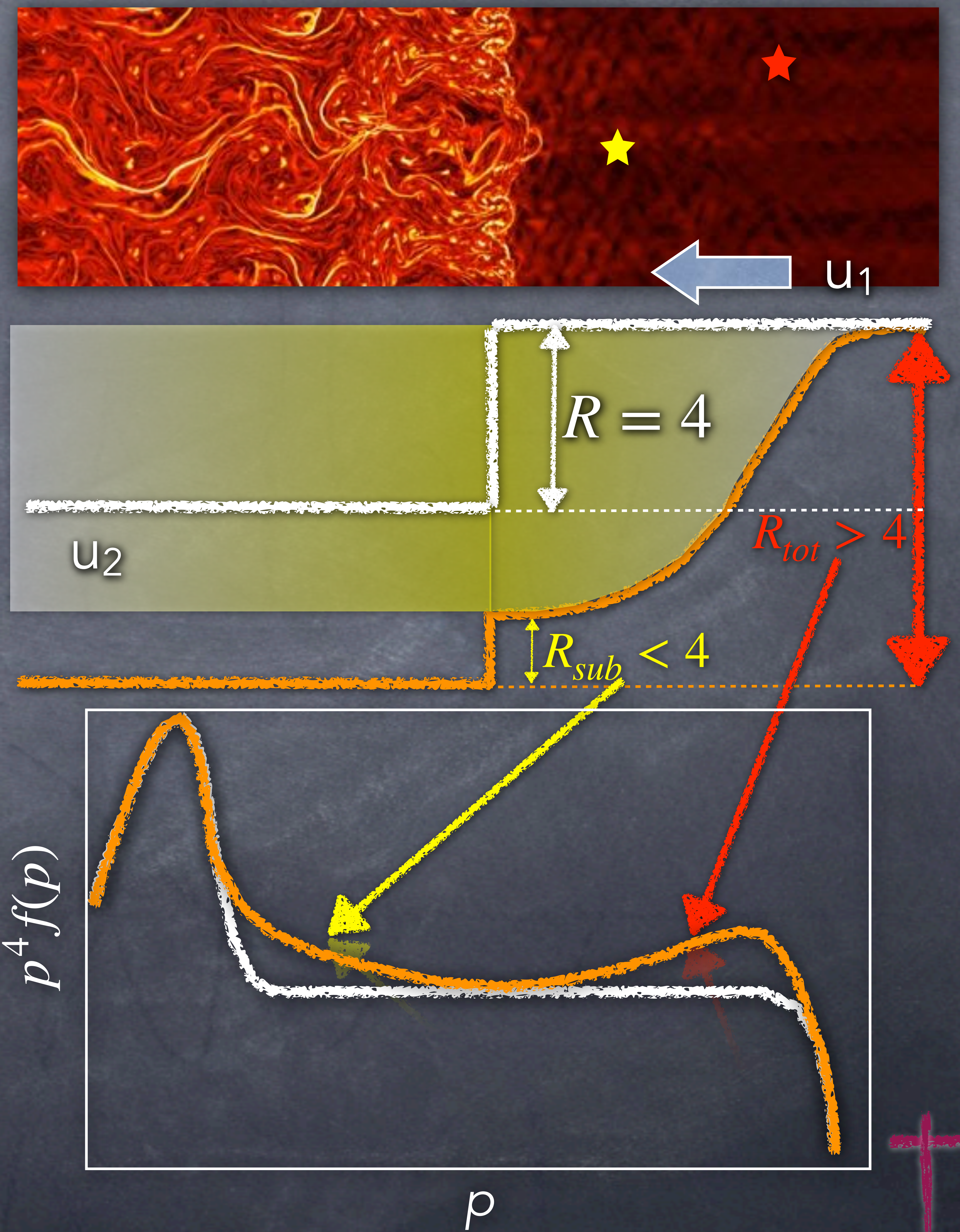


Non-Linear Diffusive Shock Acceleration

- DSA yields *momentum* power laws $f(p) \propto 4\pi p^2 p^{-q}$
- The slope q depends only on the shock compression

$$q = \frac{3R}{R-1}; \quad R = \frac{\gamma+1}{\gamma-1} \simeq 4; \rightarrow q = 4 \text{ for strong shocks}$$

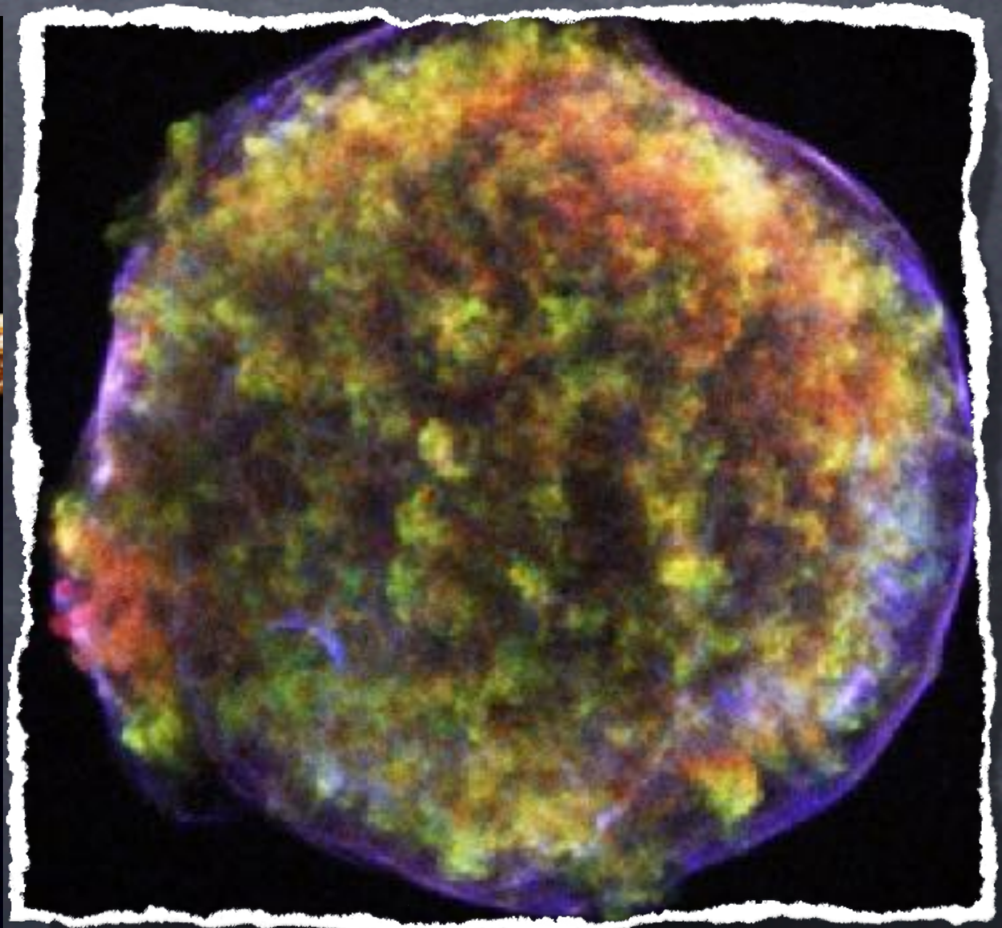
- The CR pressure makes the adiabatic index γ smaller and induces a shock precursor
- Particles "feel" different compression ratios: spectra should become concave
- If acceleration is efficient, high-energy particles feel $R_{tot} > 4$ and their spectra must be flat, i.e., $q < 4$



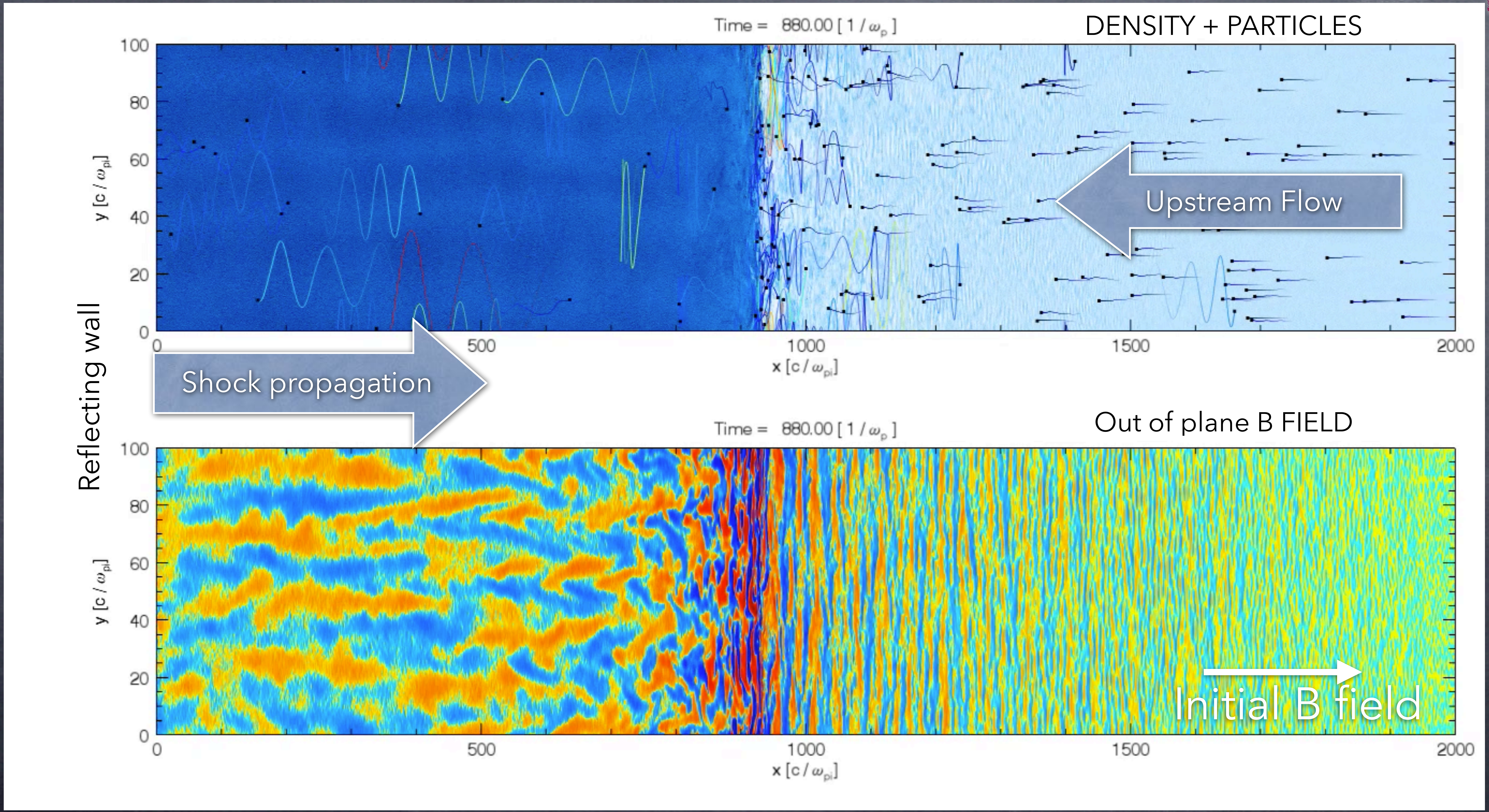
(e.g., Jones-Ellison91, Malkov-Drury01 for reviews)

Theory vs Observations

- ***Efficient DSA*** should return:
  - Compression ratios $R > 4$;
  - CR spectra flatter than p^{-4} (flatter than E^{-2} for relativistic particles)
- **Observations**, instead, point to significantly steeper spectra:
  - Hadronic γ-rays from historical and middle-age SNRs: $q \sim 4.3 - 4.7$ (e.g., Caprioli11,12; Aharonian+19);
  - Synchrotron emission from radio SNe: $q \sim 5$ (e.g., Chevalier-Fransson06, Bell+11);
  - Propagation of Galactic CRs suggests source spectra with $q \sim 4.3 - 4.4$ (e.g., Blasi-Amato11a,b; Evoli+19).



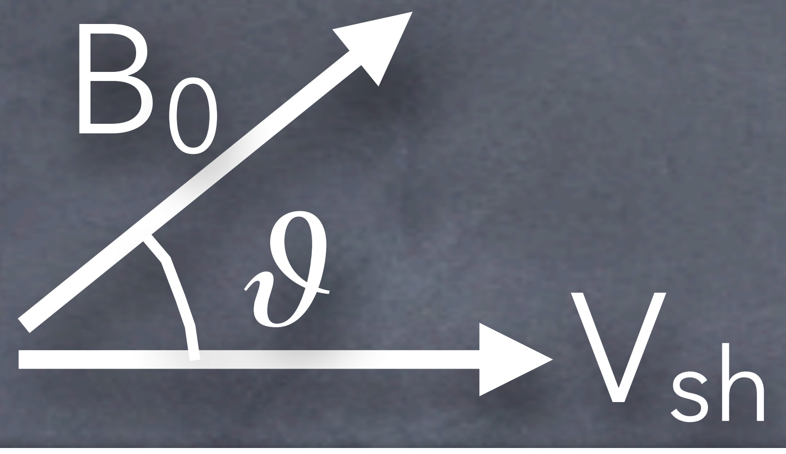
Hybrid Simulations of Collisionless Shocks

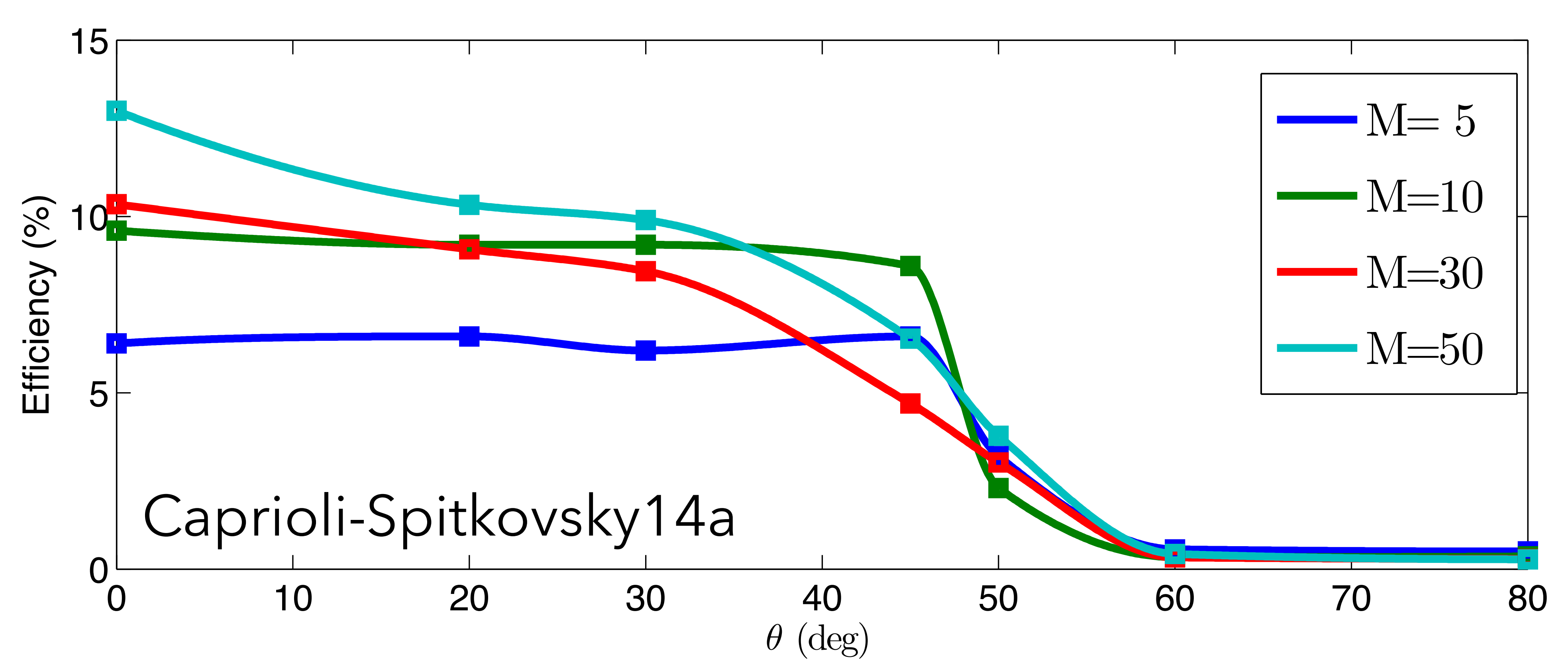


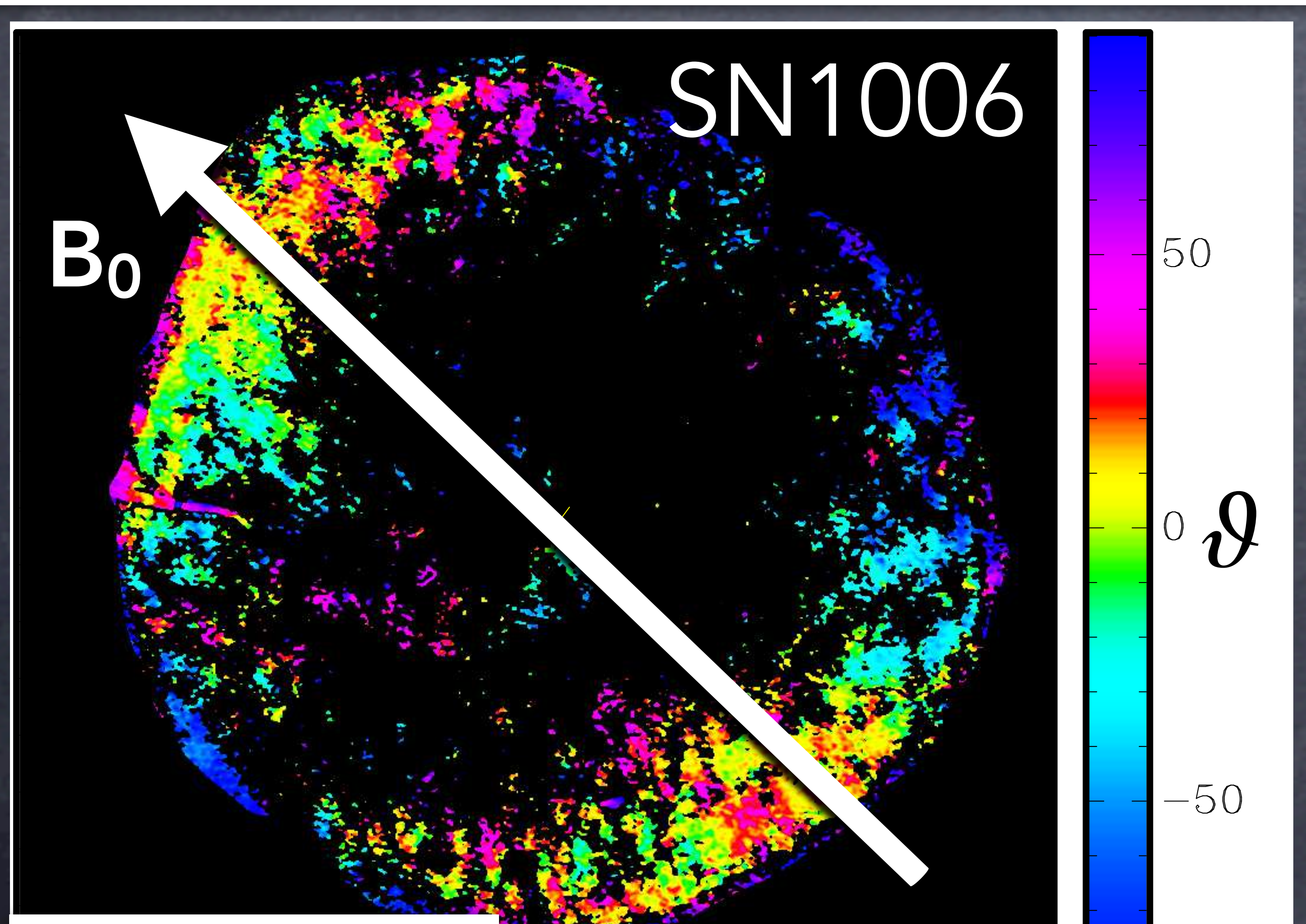
dHybrid code (Gargaté+07; Caprioli-Spitkovsky13-18), now ***dHybridR*** (+relativity; Haggerty-Caprioli19)

DSA Efficiency

Acceleration depends on the shock inclination

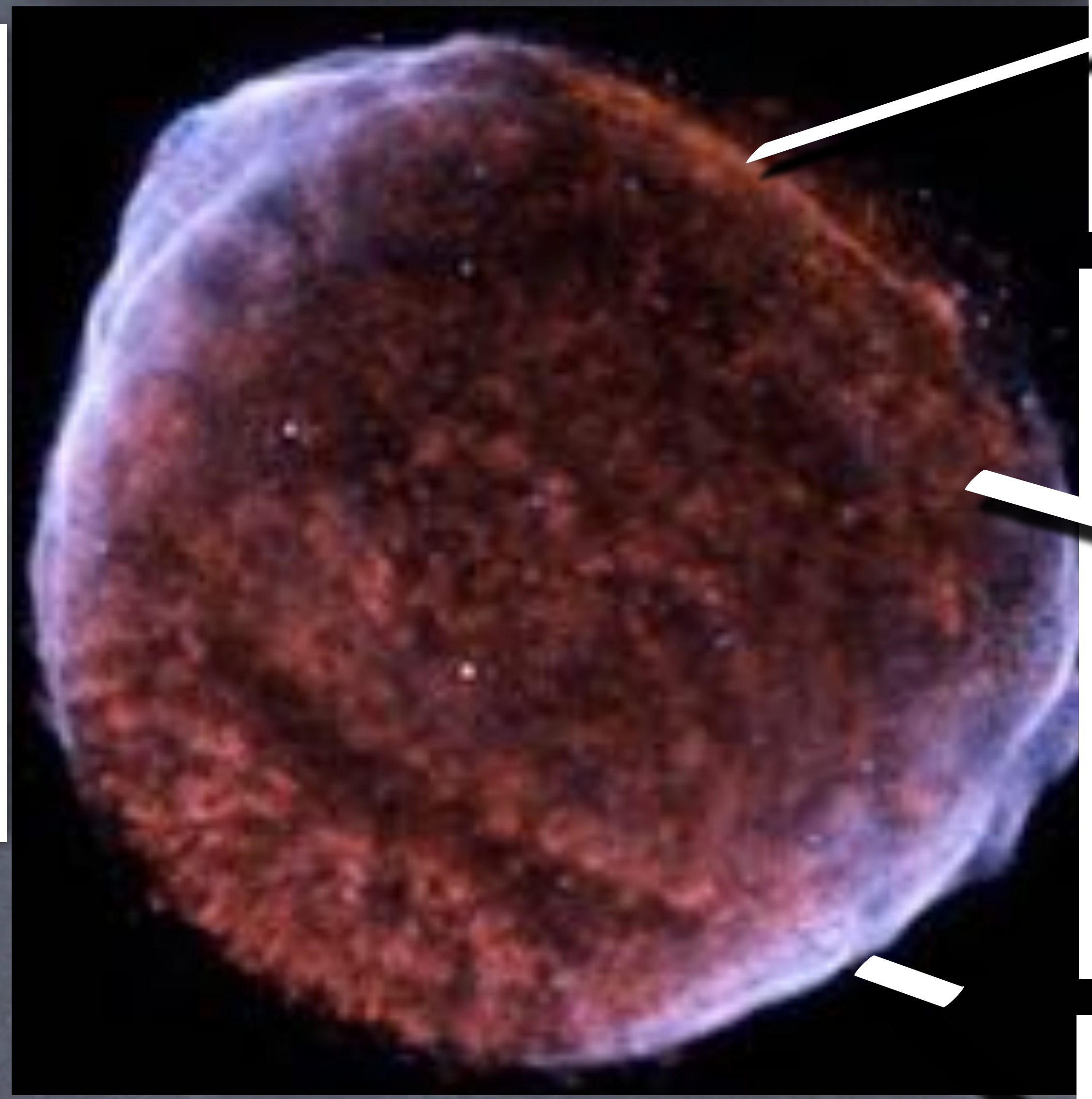




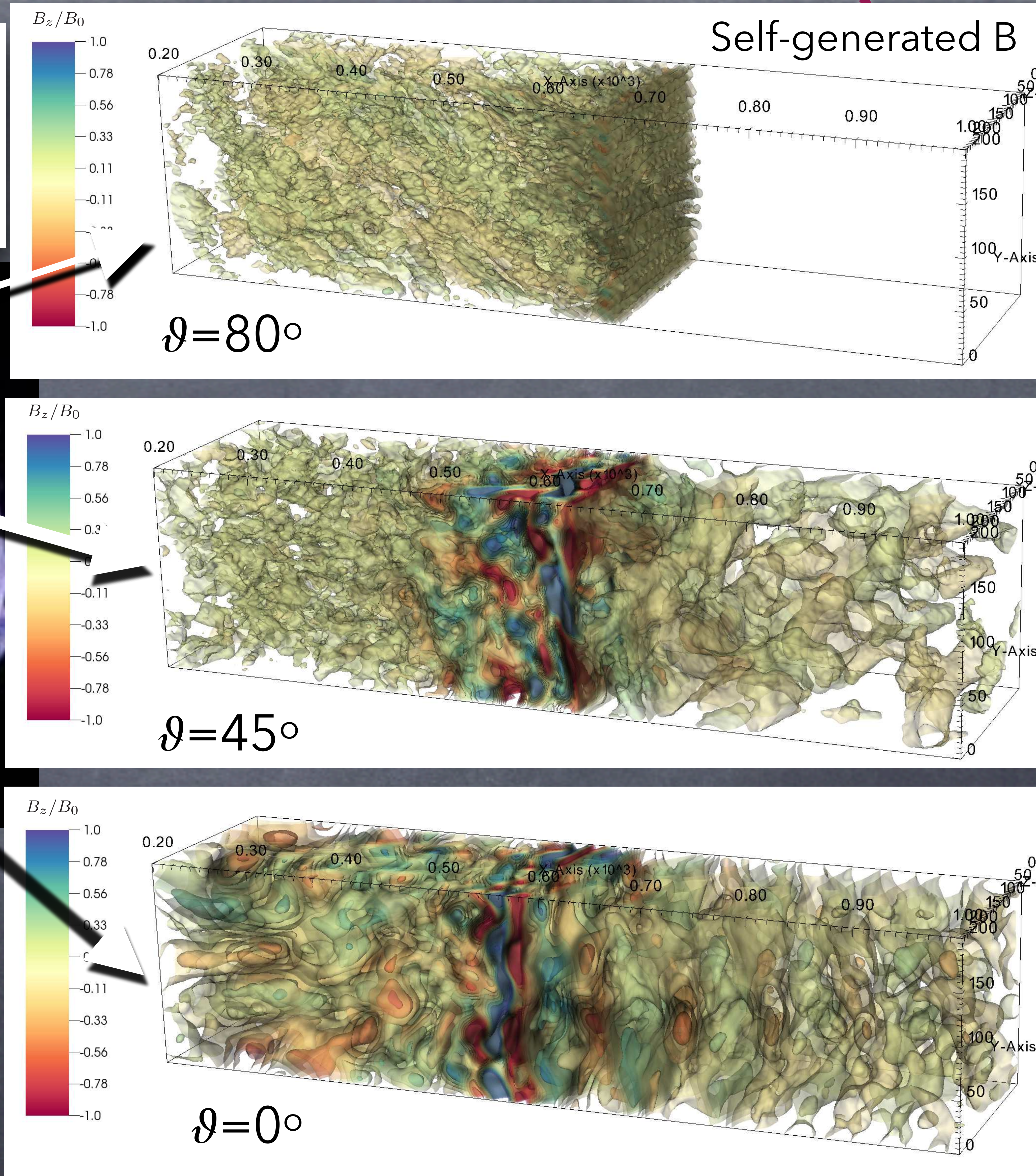


Reynoso+13

X-ray emission:
red=thermal
white=synchrotron



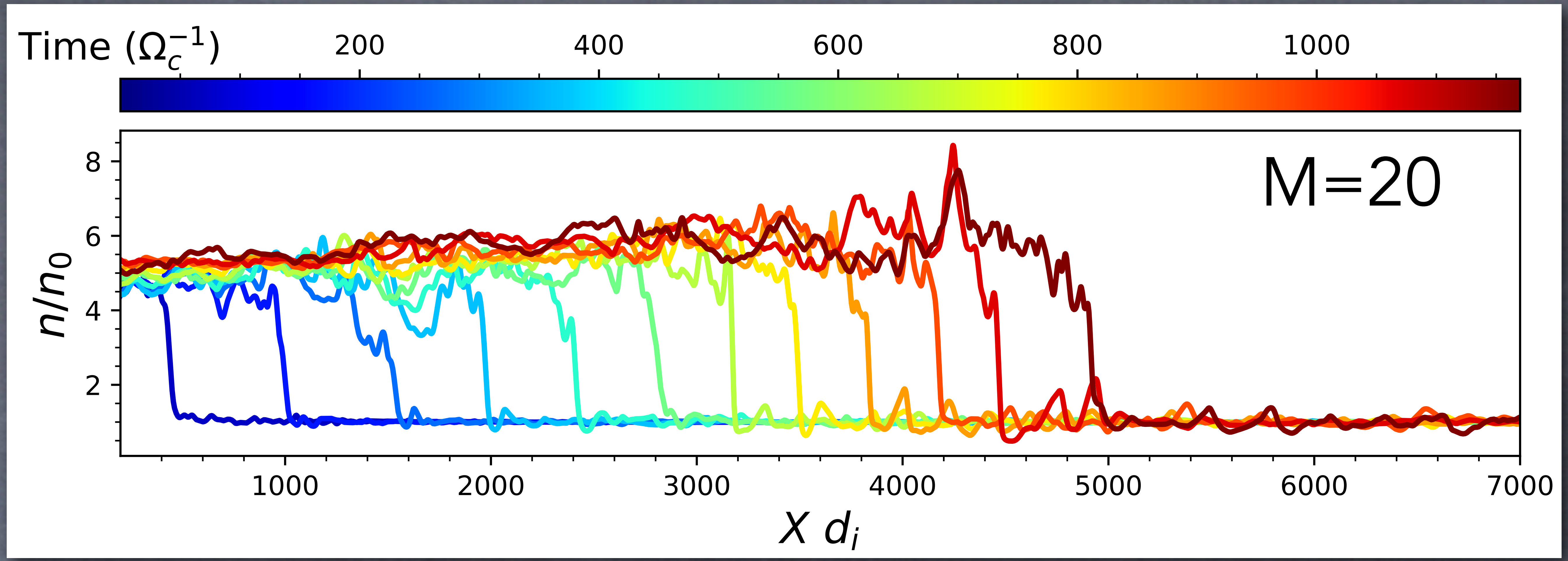
B amplification and ion acceleration where the shock is parallel



Caprioli-Spitkovsky14a,b,c

CR-modified Shocks: Enhanced compression!

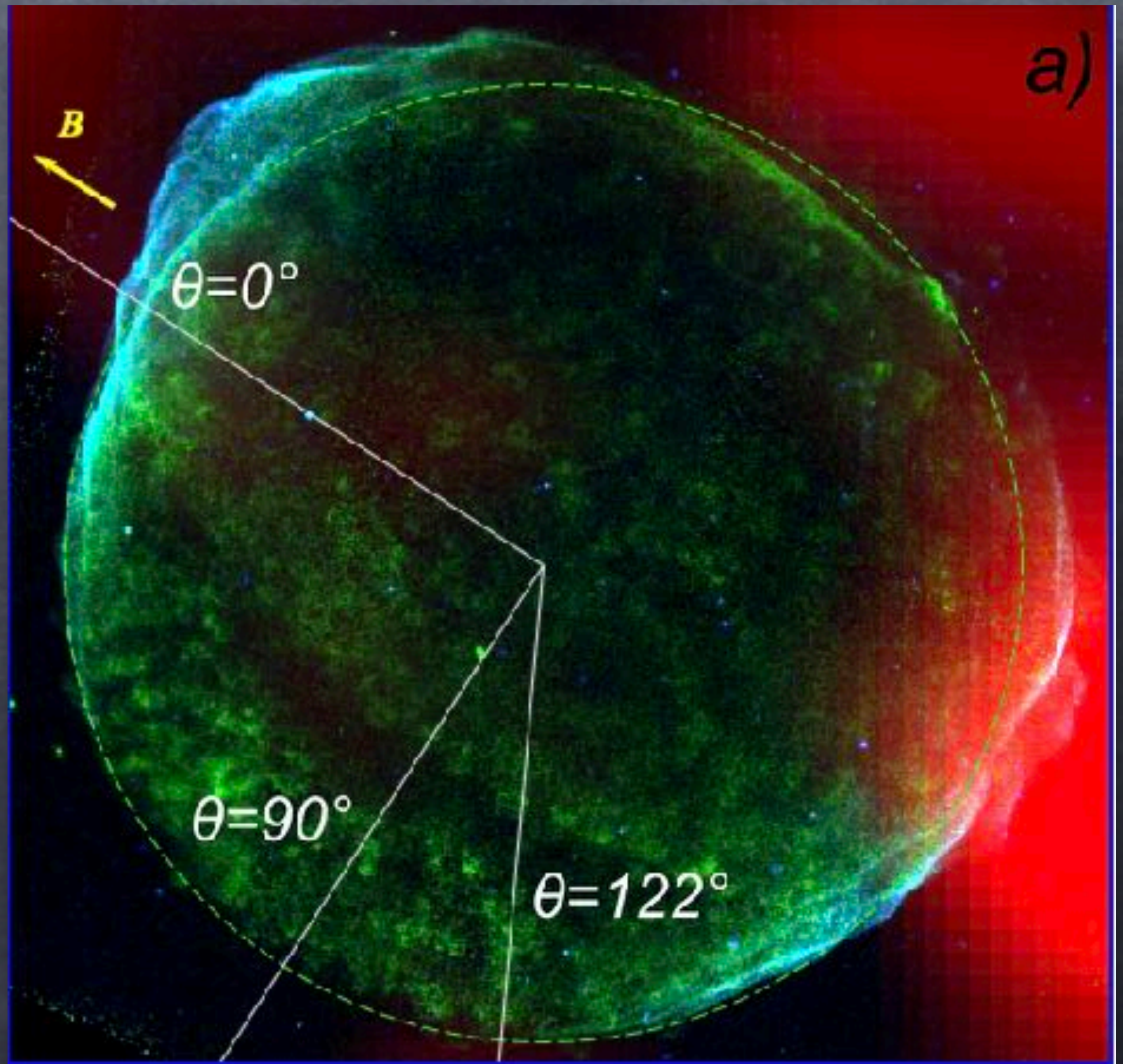
- Hybrid simulations (Haggerty-Caprioli20)
  - Efficiency $\lesssim 15\,\%$ at parallel shocks
  - Formation of upstream precursor
  - R increases with time, up to ~ 6

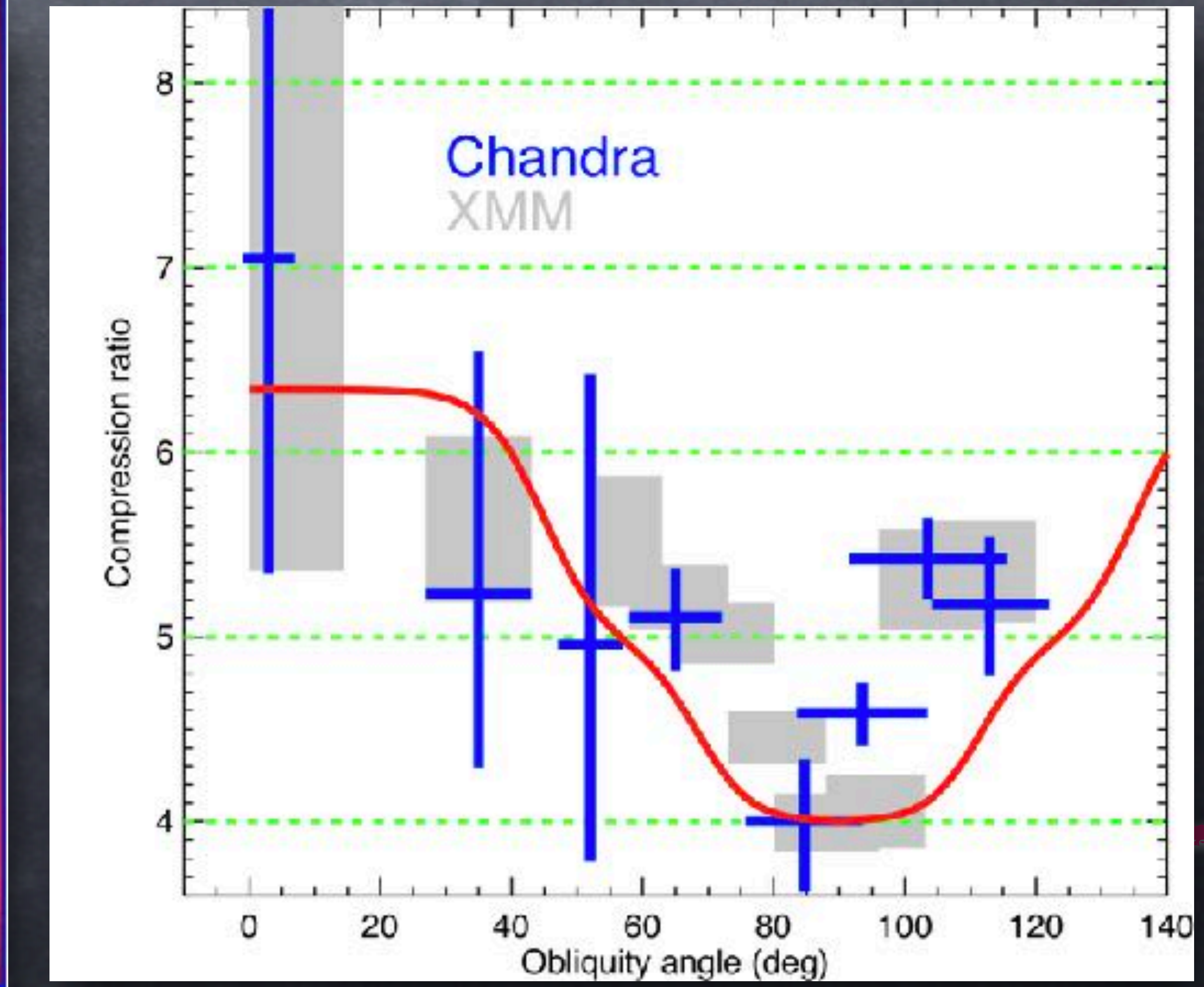


- $R \sim 6-7$ inferred in Tycho (Warren+05). In SN1006: $R \sim 4-7$, modulated with the azimuth/shock inclination (Giuffrida, Miceli, Caprioli+21, submitted to NatComm.)
  - If $R \simeq 7 \rightarrow q_{\rm expected} \simeq 3.5$
  - Tycho: radio to γ-ray observations:

$$q_{\rm inferred} \simeq 4.3$$

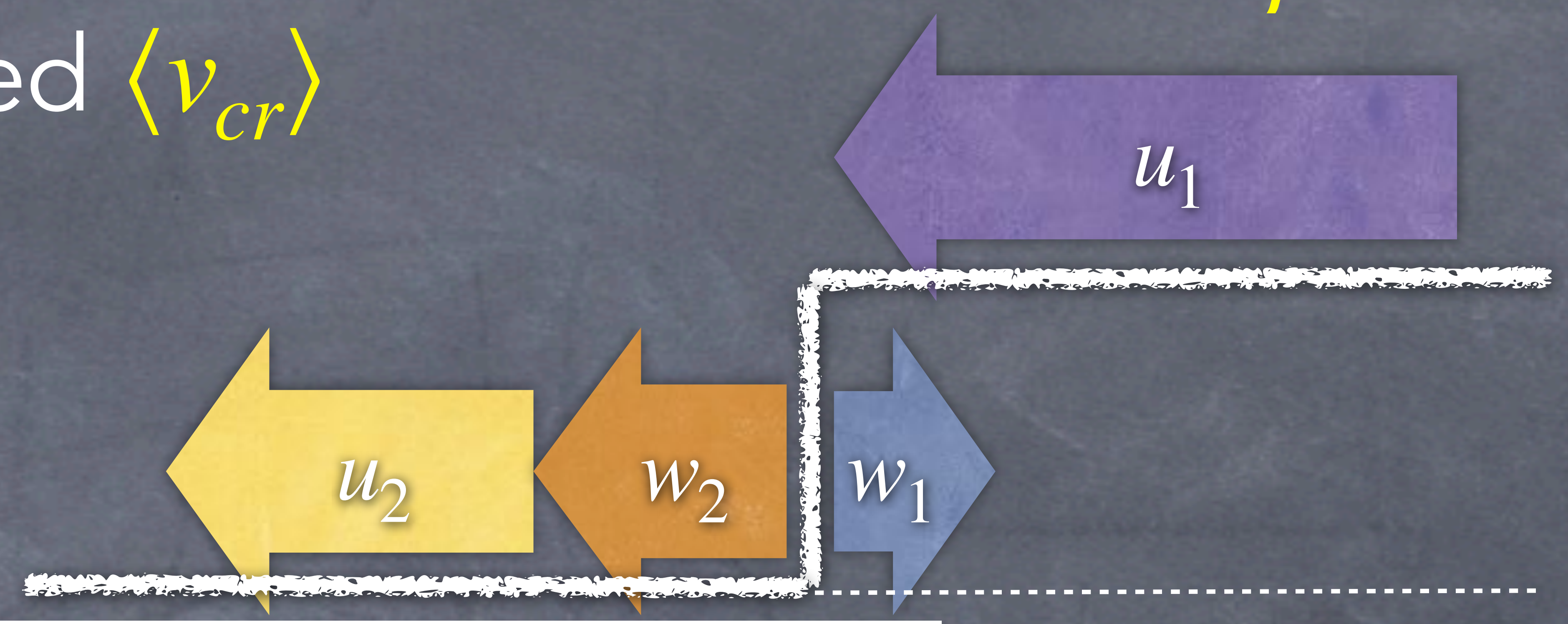
A challenge to DSA theory!

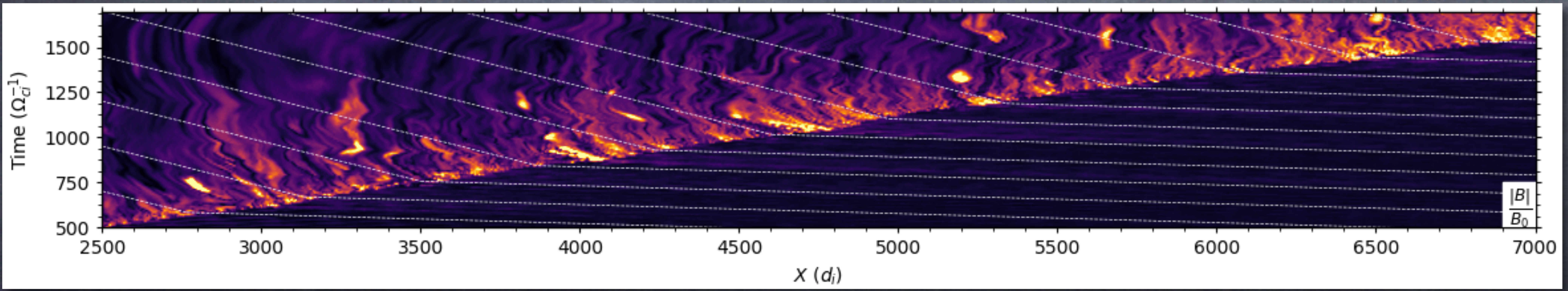




The Role of Amplified Magnetic Fields

- CRs feel an effective compression $R_{cr} = \frac{u_1 + w_1}{u_2 + w_2}$; $w = \text{wave speed} \approx v_A = \frac{B}{4\pi\rho}$
- We can measure both w and the effective CR speed $\langle v_{cr} \rangle$
  - Upstream: $w_1 \simeq -v_{A,1}(\delta B_1) \ll u_1$
  - Downstream: $\langle v_{cr} \rangle \simeq w_2 \simeq +v_{A,2}(\delta B_2) \equiv \alpha\, u_2$



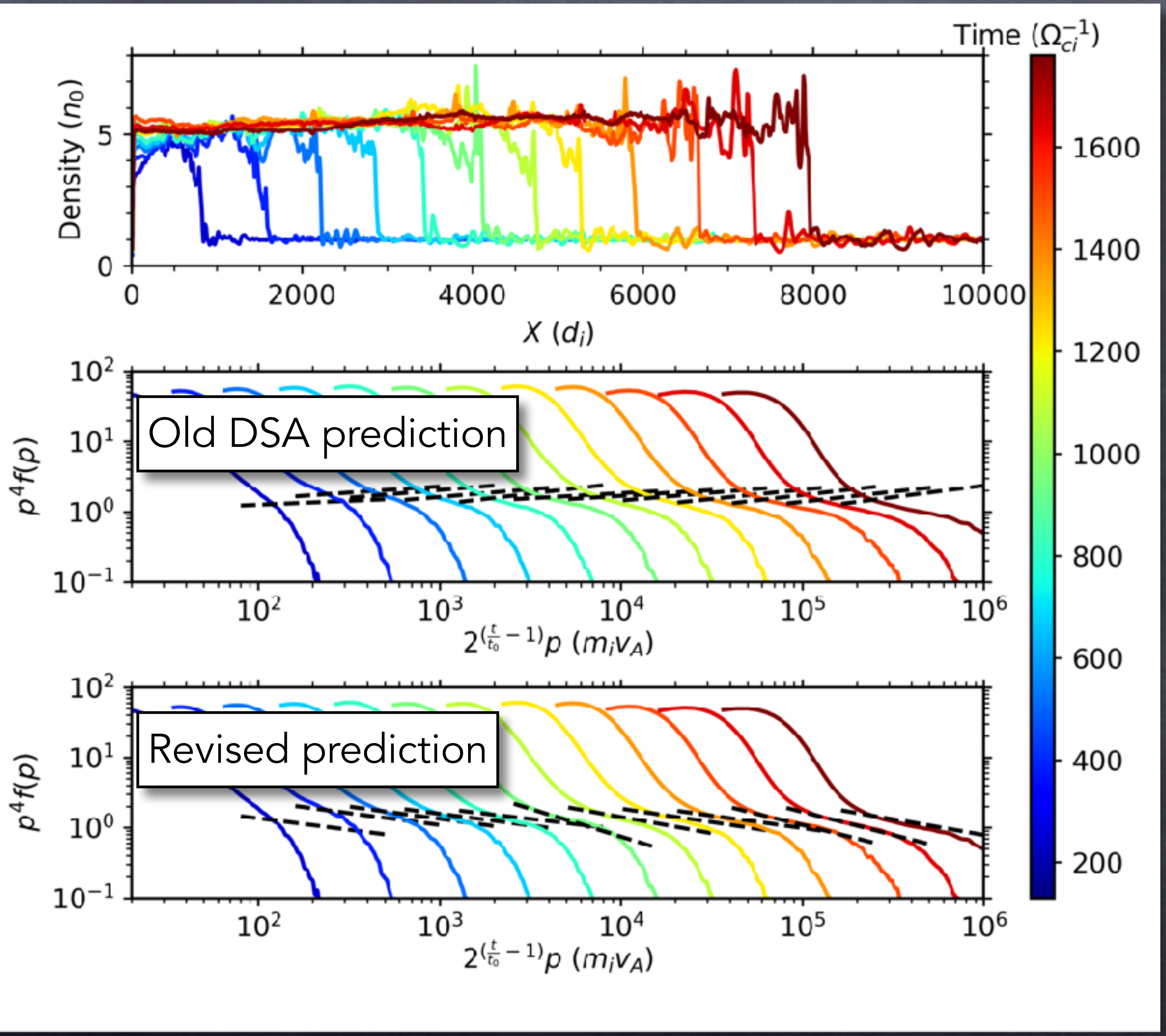


Haggerty-Caprioli20

- B fields (and hence CRs) drift downstream with respect to the thermal gas
  - First evidence of the formation of a *postcursor*
  - CRs *feel* a compression ratio *smaller* than the gas

$$R_{cr} \simeq \frac{u_1}{u_2(1+\alpha)} < R_{gas}$$

A Revised Theory of Diffusive Shock Acceleration



Caprioli, Haggerty & Blasi 2020

- With the effective compression felt by CRs

$$q = \frac{3R_{cr}}{R_{cr} - 1} = \frac{3R_{gas}}{R_{gas} - 1 - \alpha} > q_{DSA}$$

- CRs feel $R_{cr} < R_{gas}$: the power-law index is *not universal, but depends on B field*
- *Ab-initio* explanation for the steep spectra observed in SNRs, radio SNe, CRs…
    - Also see Highlight Talk by R. Diesing (ID:488)