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Particle Acceleration at SNR Shocks: Bridging Simulations and Observations

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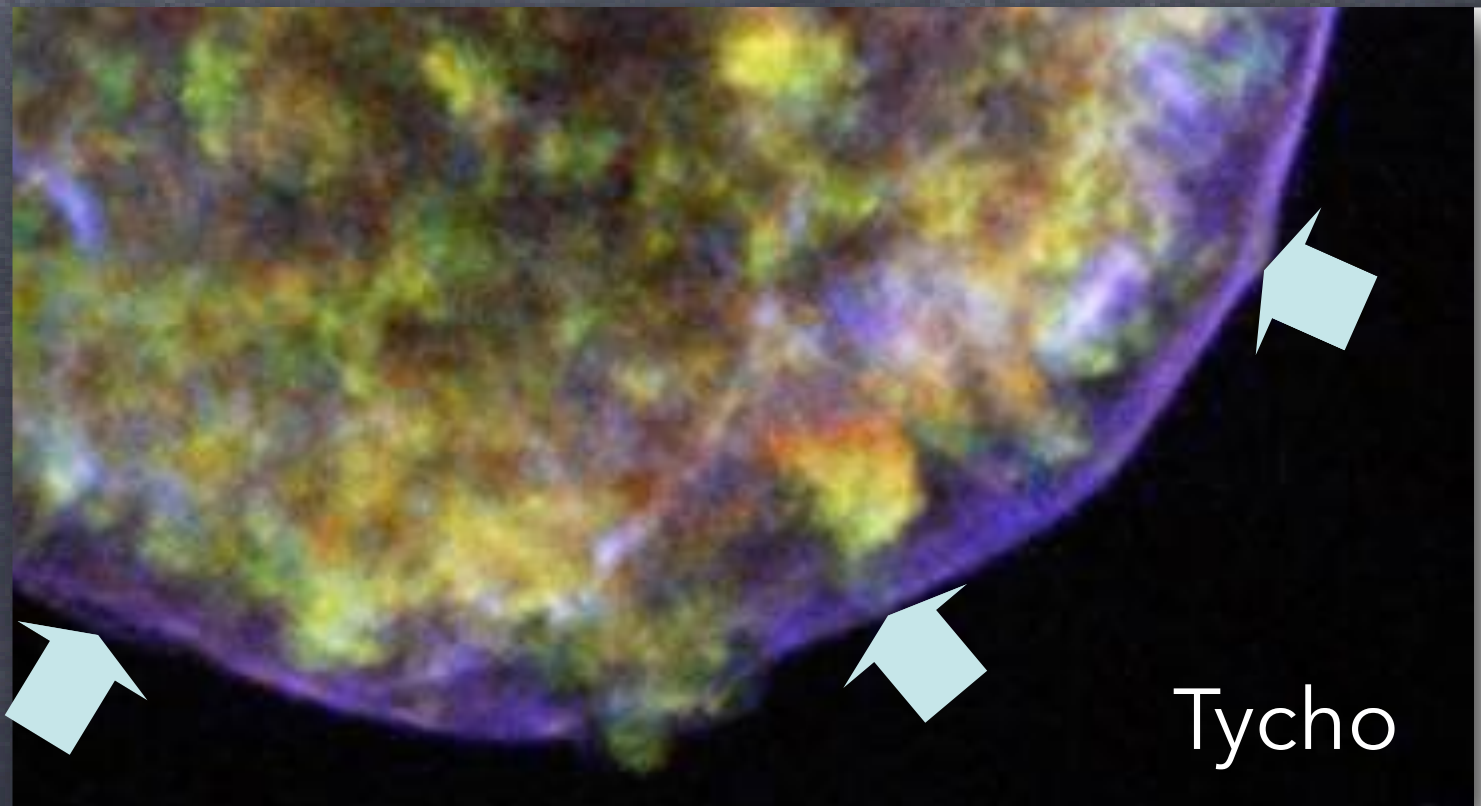
The SNR paradigm for the origin of CRs

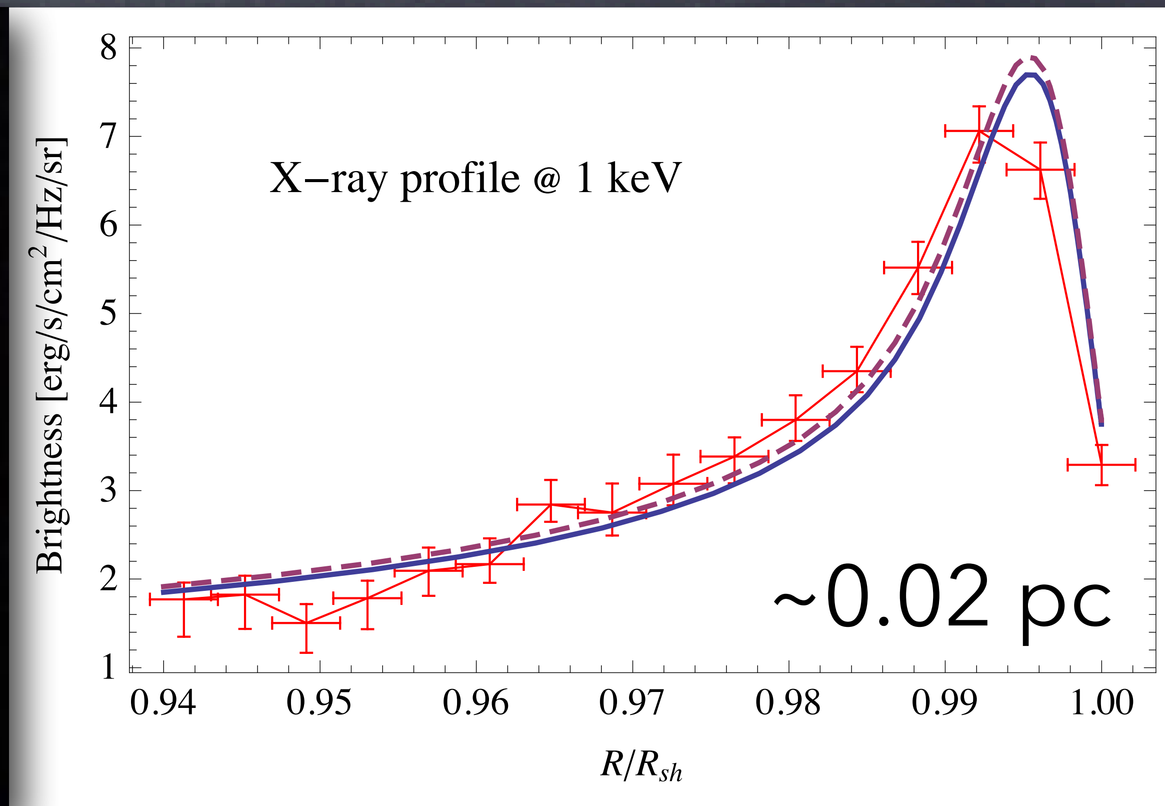
- **Energetics**: ~10% of SN kinetic energy can account for Galactic CRs (Baade-Zwicky34)

- **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)



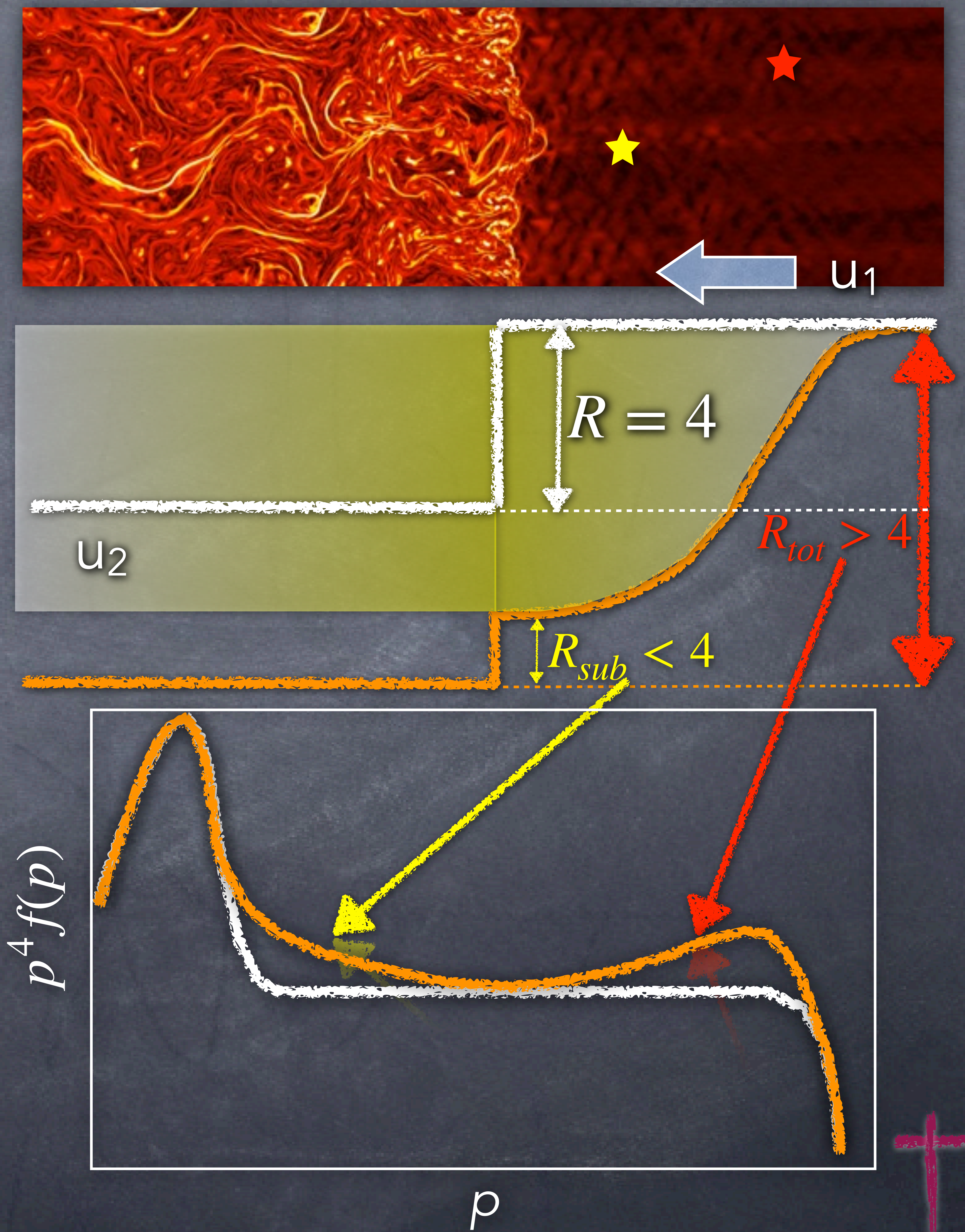


Non-Linear Diffusive Shock Acceleration

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

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

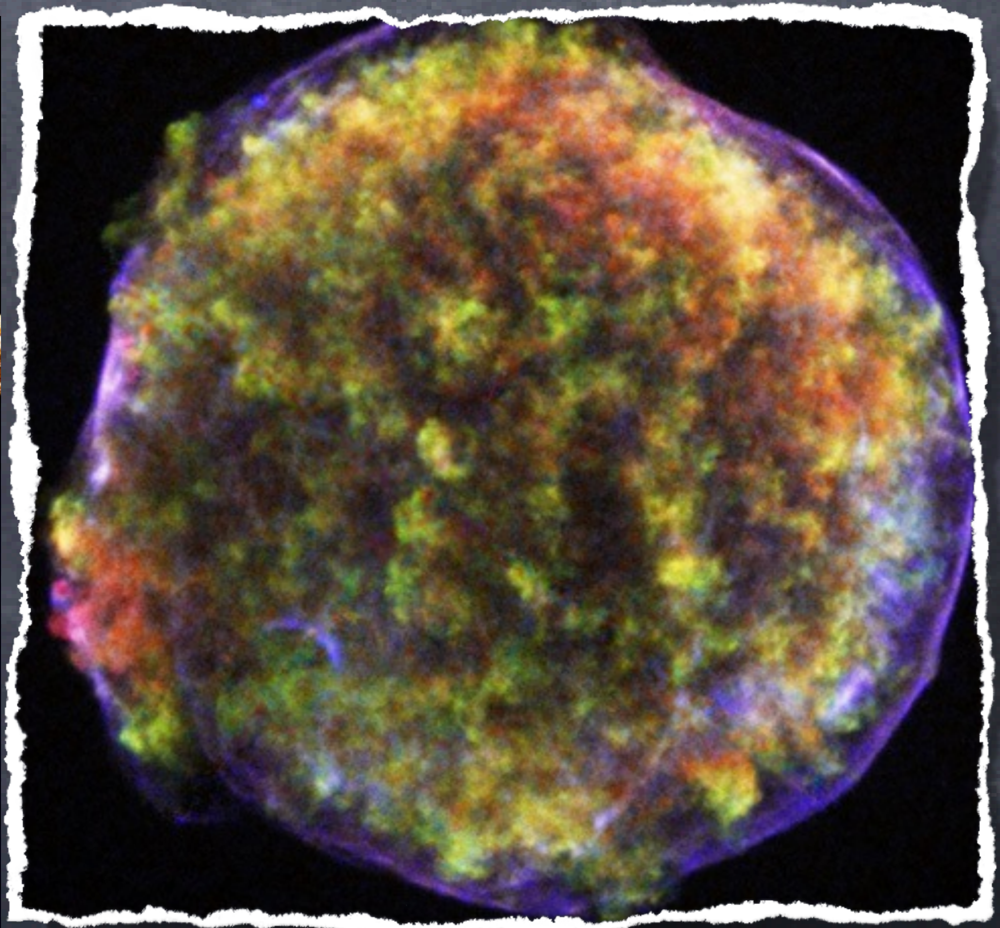
- The CR pressure makes the adiabatic index γ smaller and induces a shock precursor
- Particles "feel" different compression ratios: spectra should become concave
- If acceleration is efficient, high-energy particles feel $R_{tot} > 4$ and their spectra must be flat, i.e., $q < 4$



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

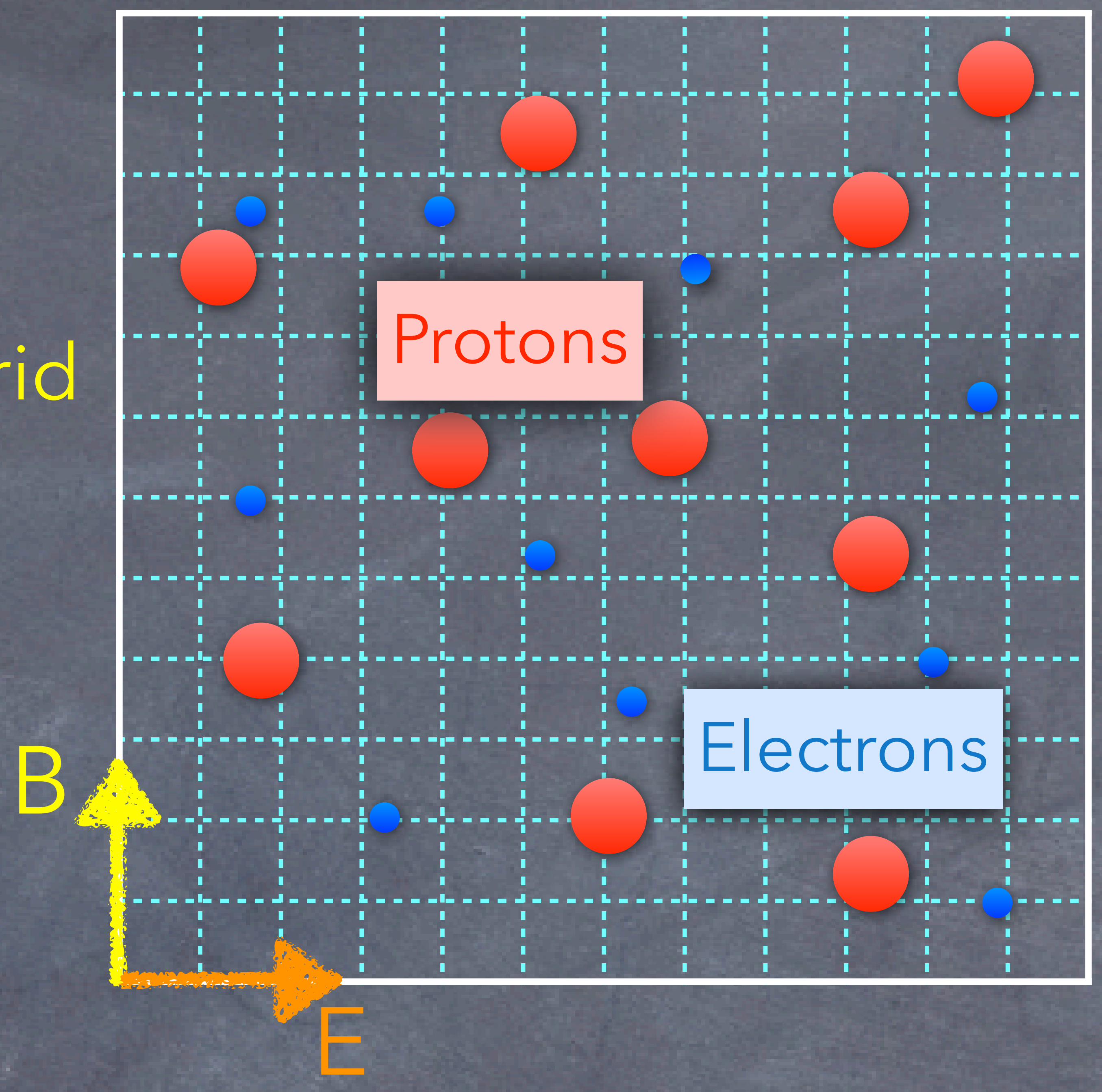
Theory vs Observations

- ***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).



Astroplasmas from first principles

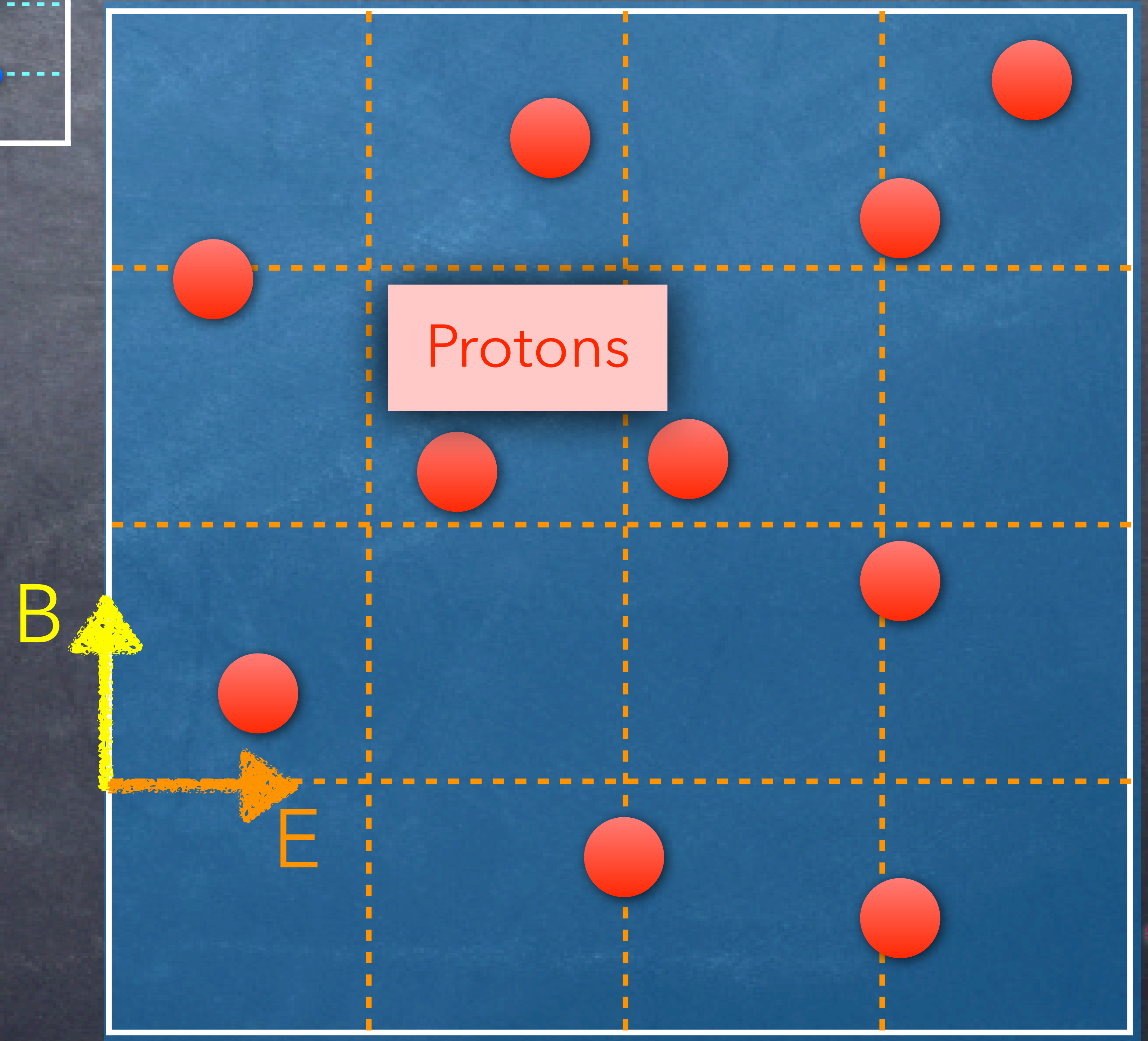
- Full-PIC approach
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



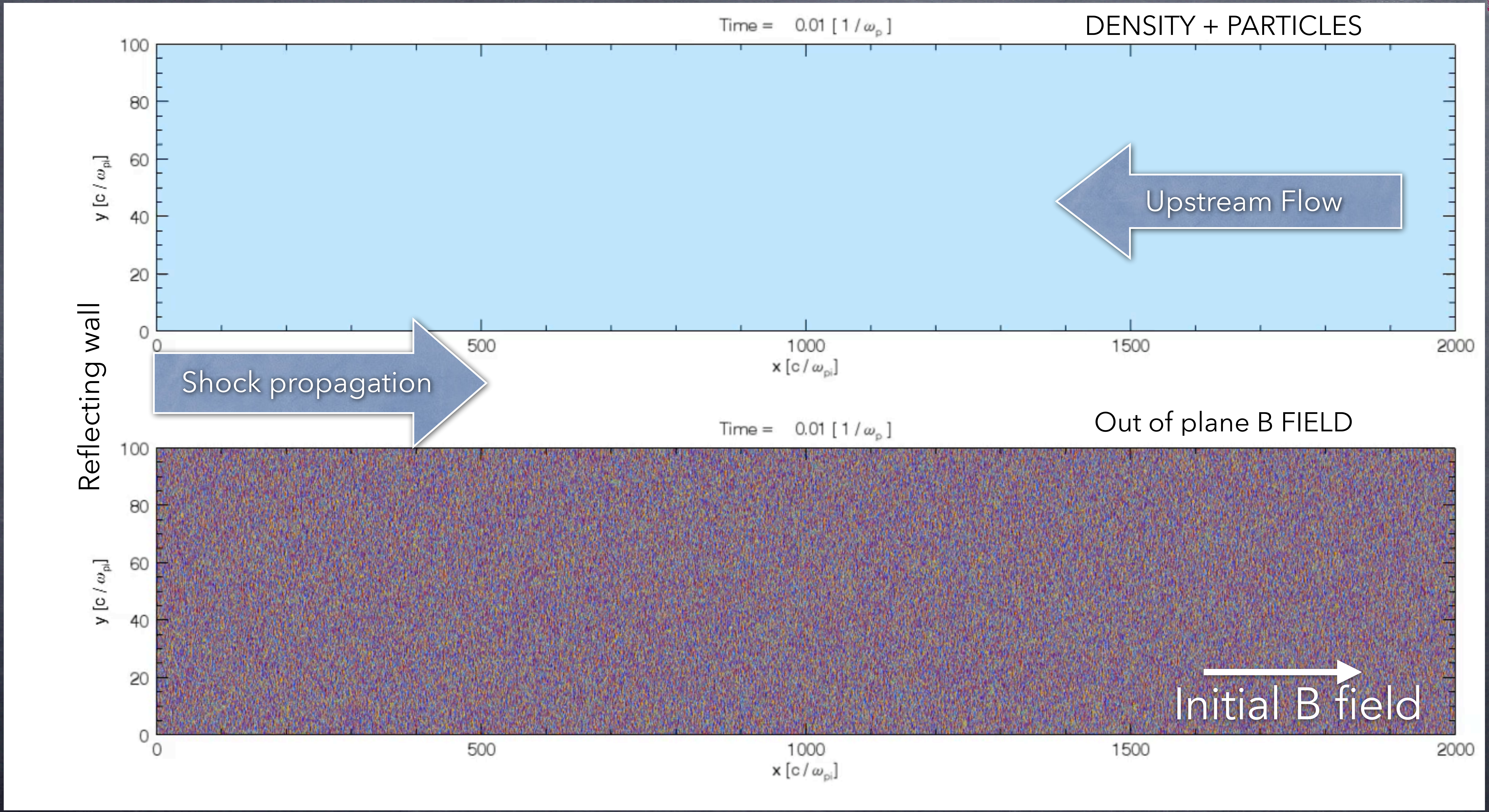
- Hybrid approach: Fluid electrons - Kinetic protons

(Winske & Omidi; Burgess et al., Lipatov 2002; Giacalone et al. 1993,1997,2004-2013; DC & Spitkovsky 2013-2015, Haggerty & DC 2019…)

  - massless electrons for more macroscopical time/length scales



Hybrid Simulations of Collisionless Shocks

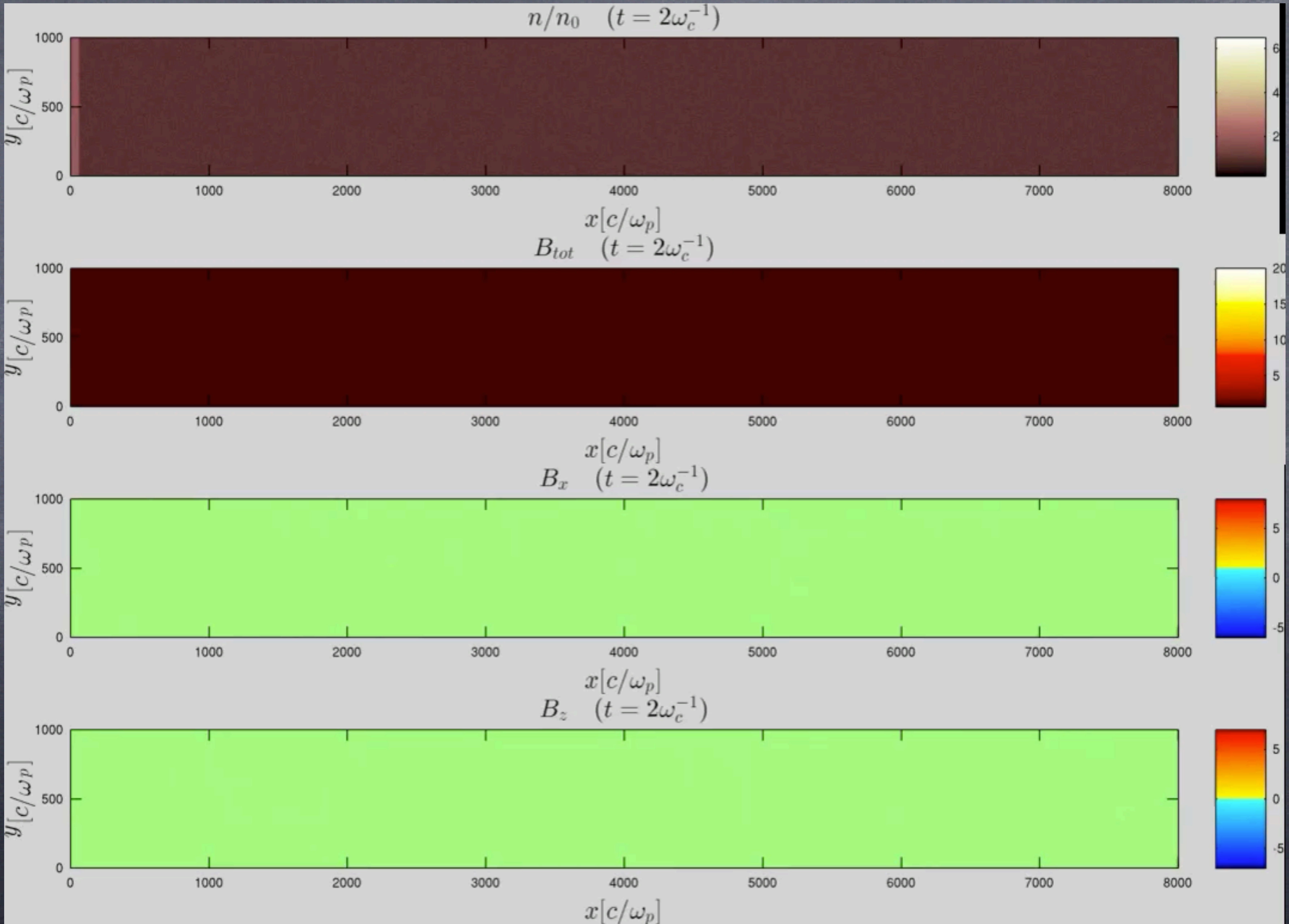


dHybridR code (+relativity; Haggerty-Caprioli19)

CR-driven Magnetic-Field Amplification

Initial B field

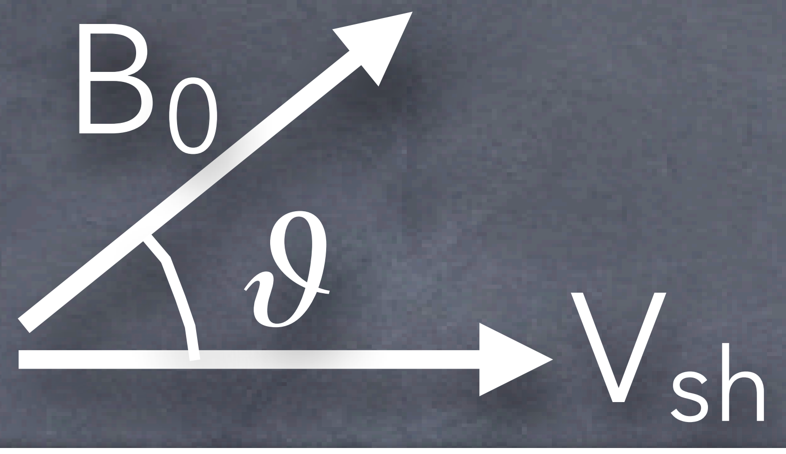
$M_s = M_A = 30$

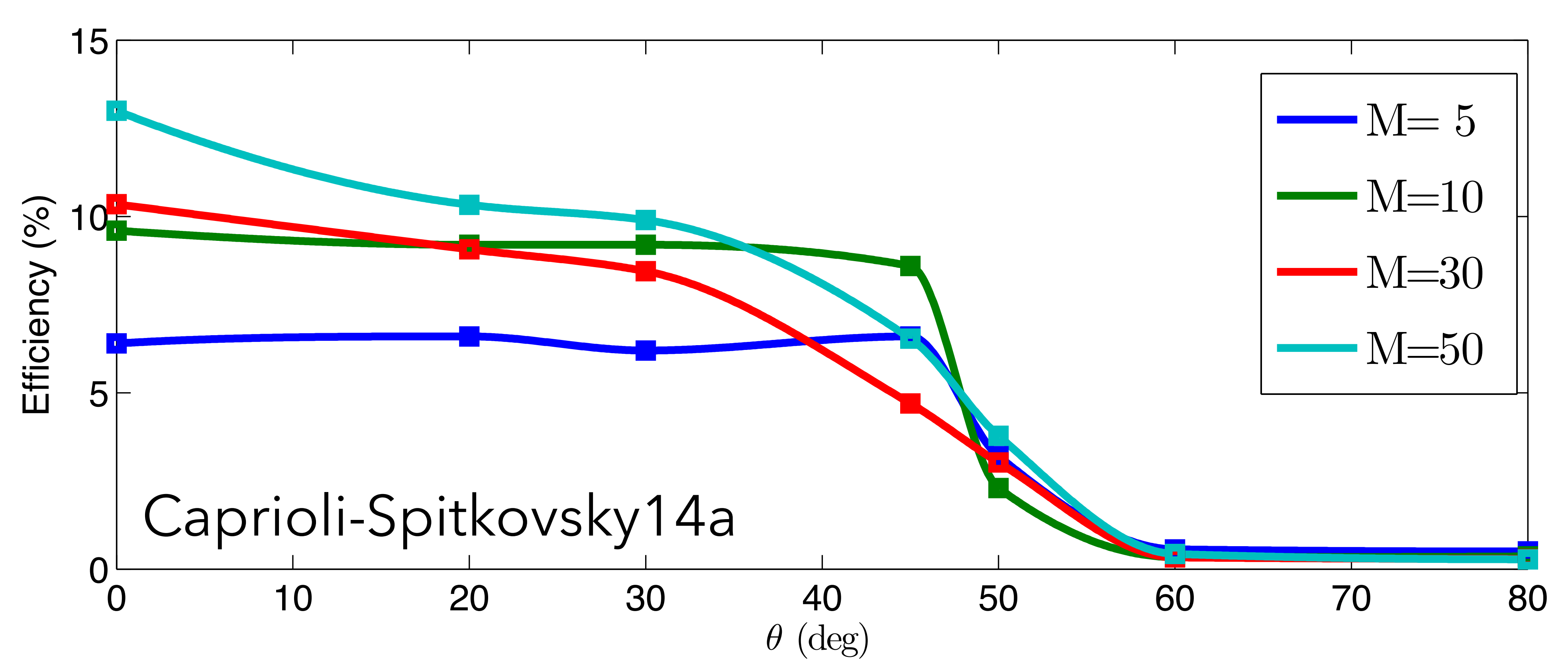


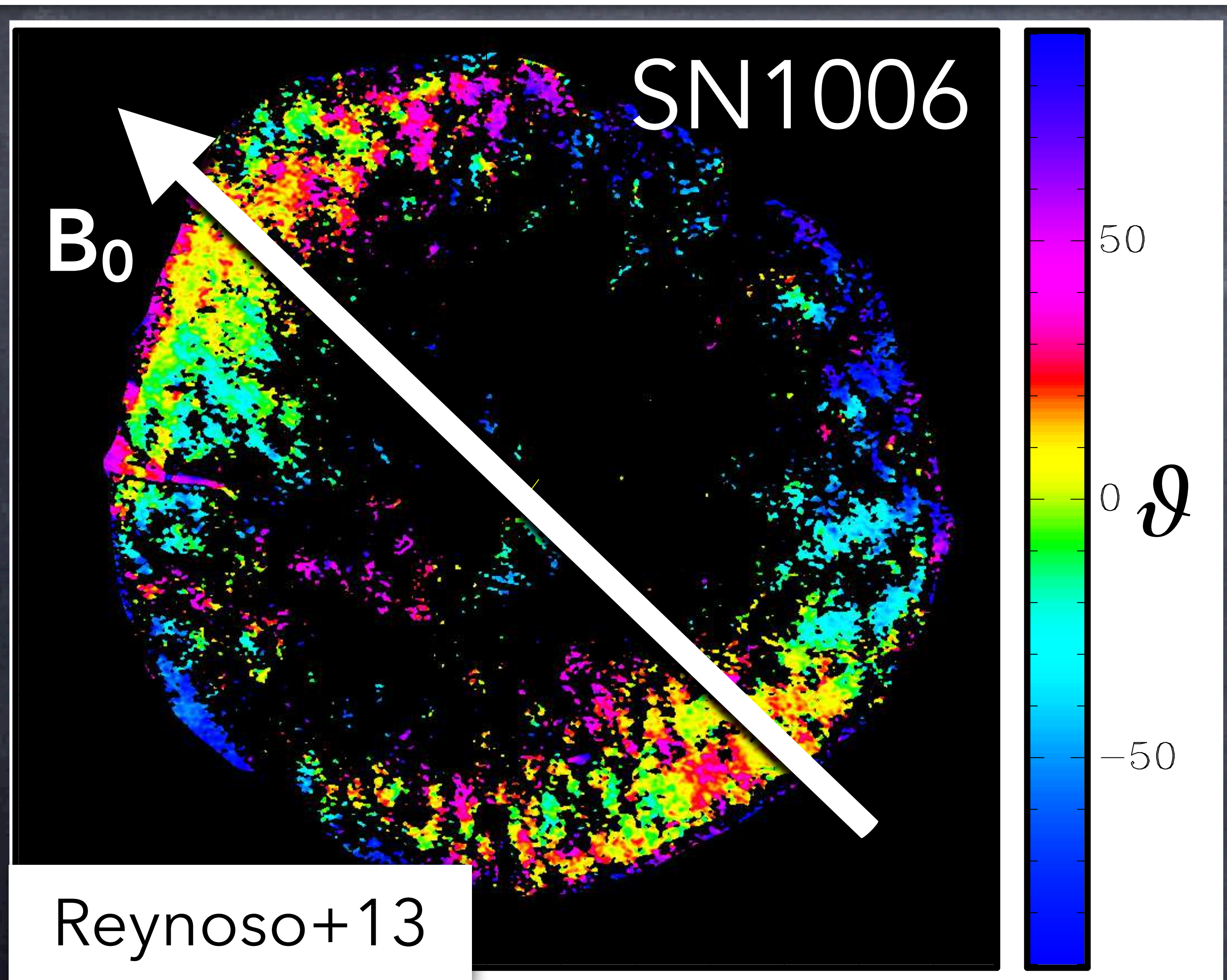
Caprioli & Spitkovsky, 2013

DSA Efficiency

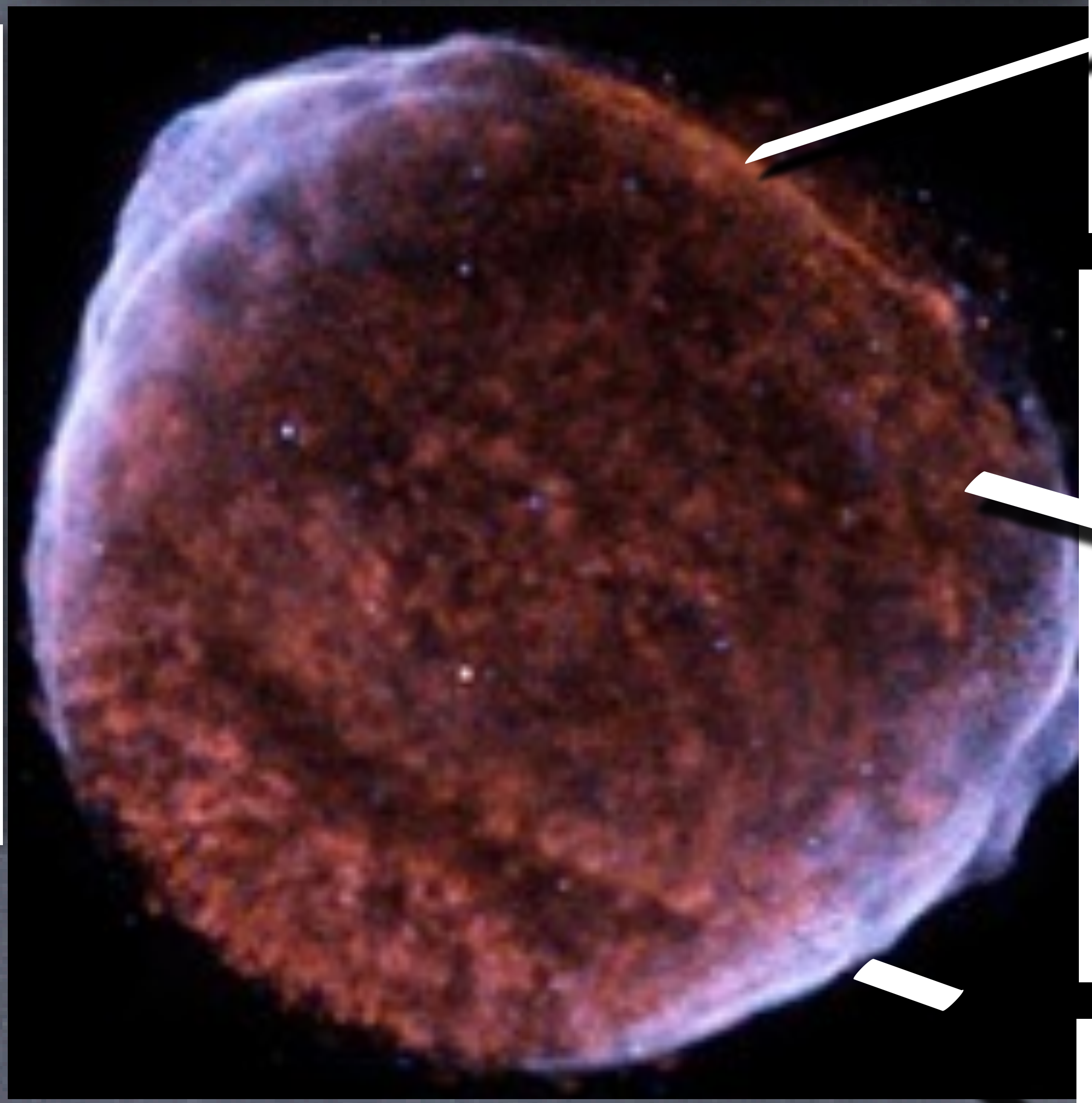
Acceleration depends on the shock inclination



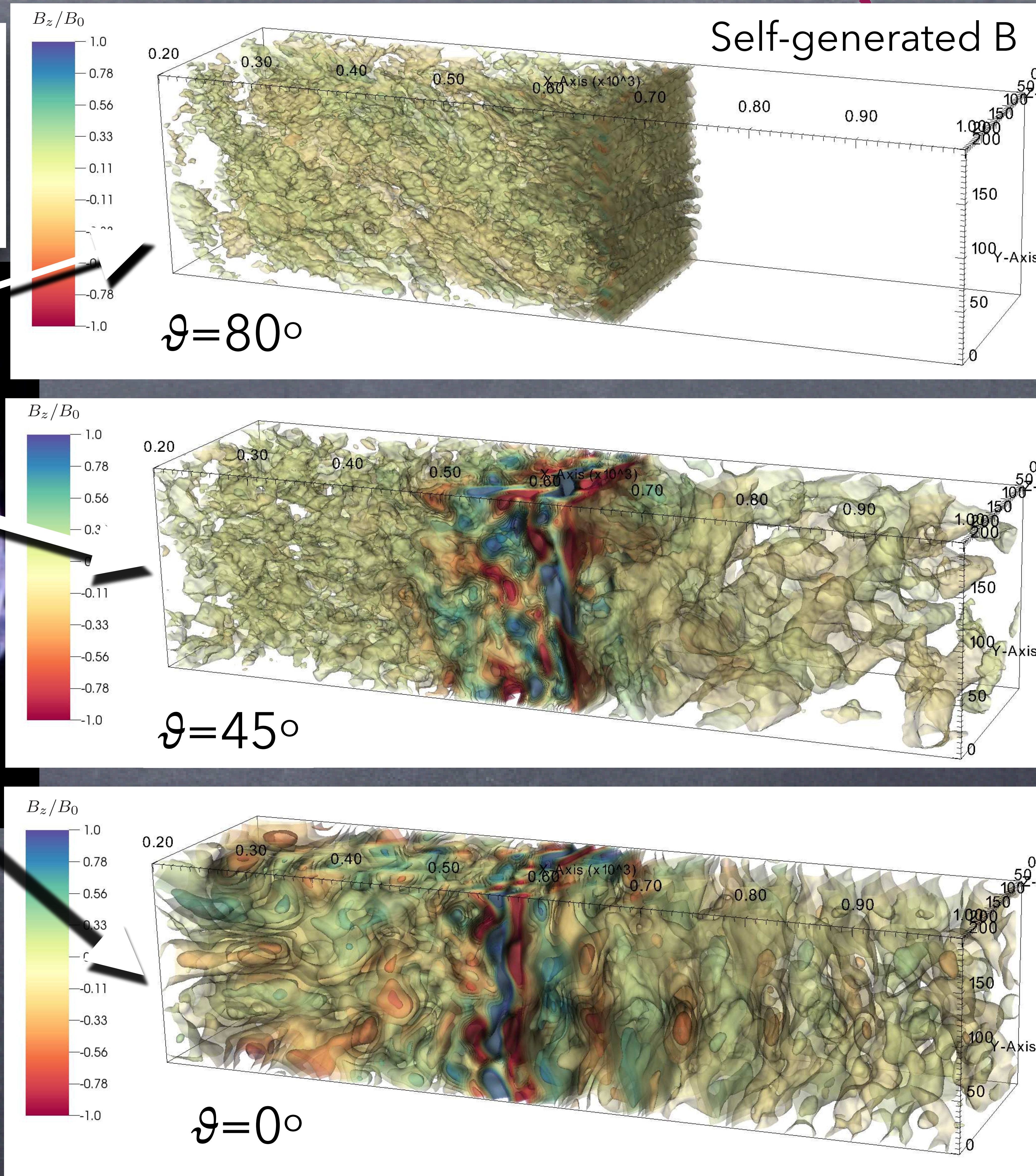




X-ray emission:
red=thermal
white=synchrotron



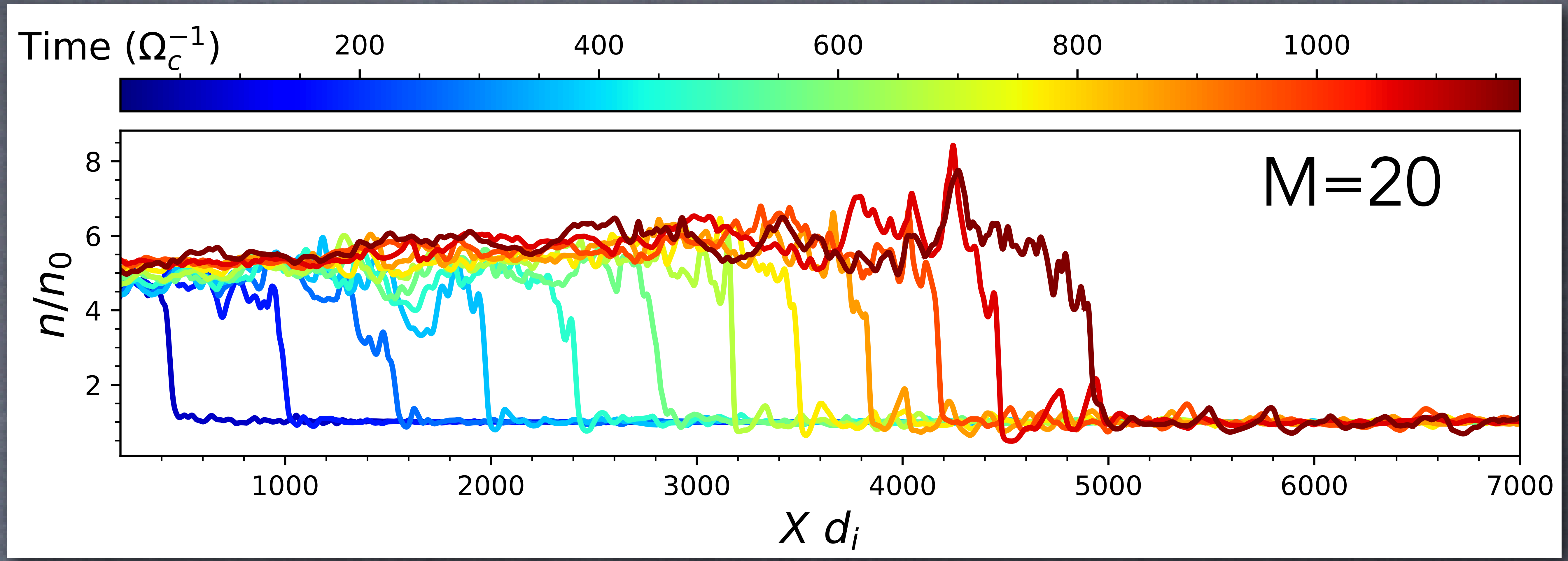
B amplification and ion acceleration where the shock is parallel



Caprioli-Spitkovsky14a,b,c

CR-modified Shocks: Enhanced compression!

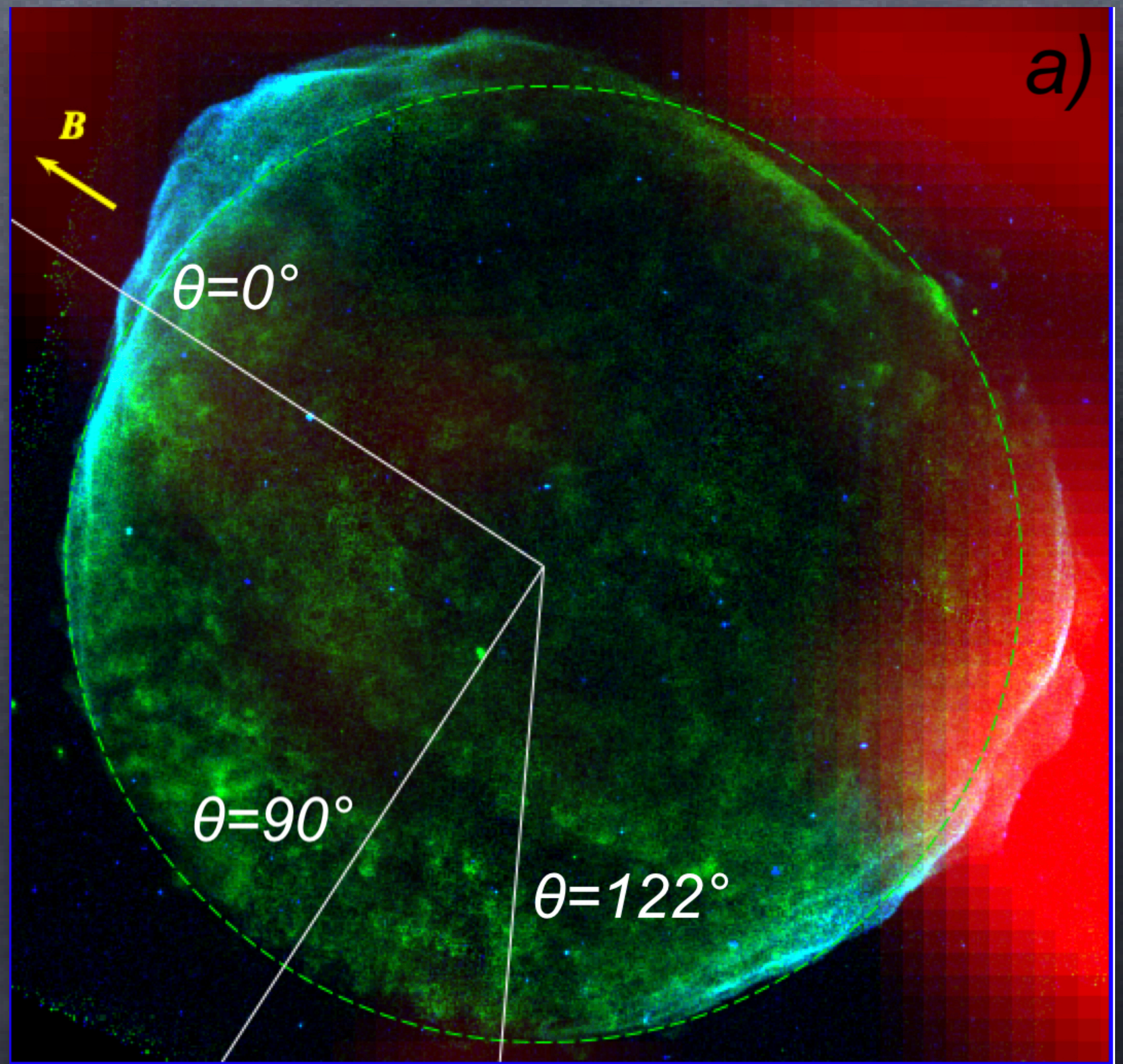
- Hybrid simulations (Haggerty-Caprioli20)
  - Efficiency $\lesssim 15\,\%$ at parallel shocks
  - Formation of upstream precursor
  - R increases with time, up to ~ 6

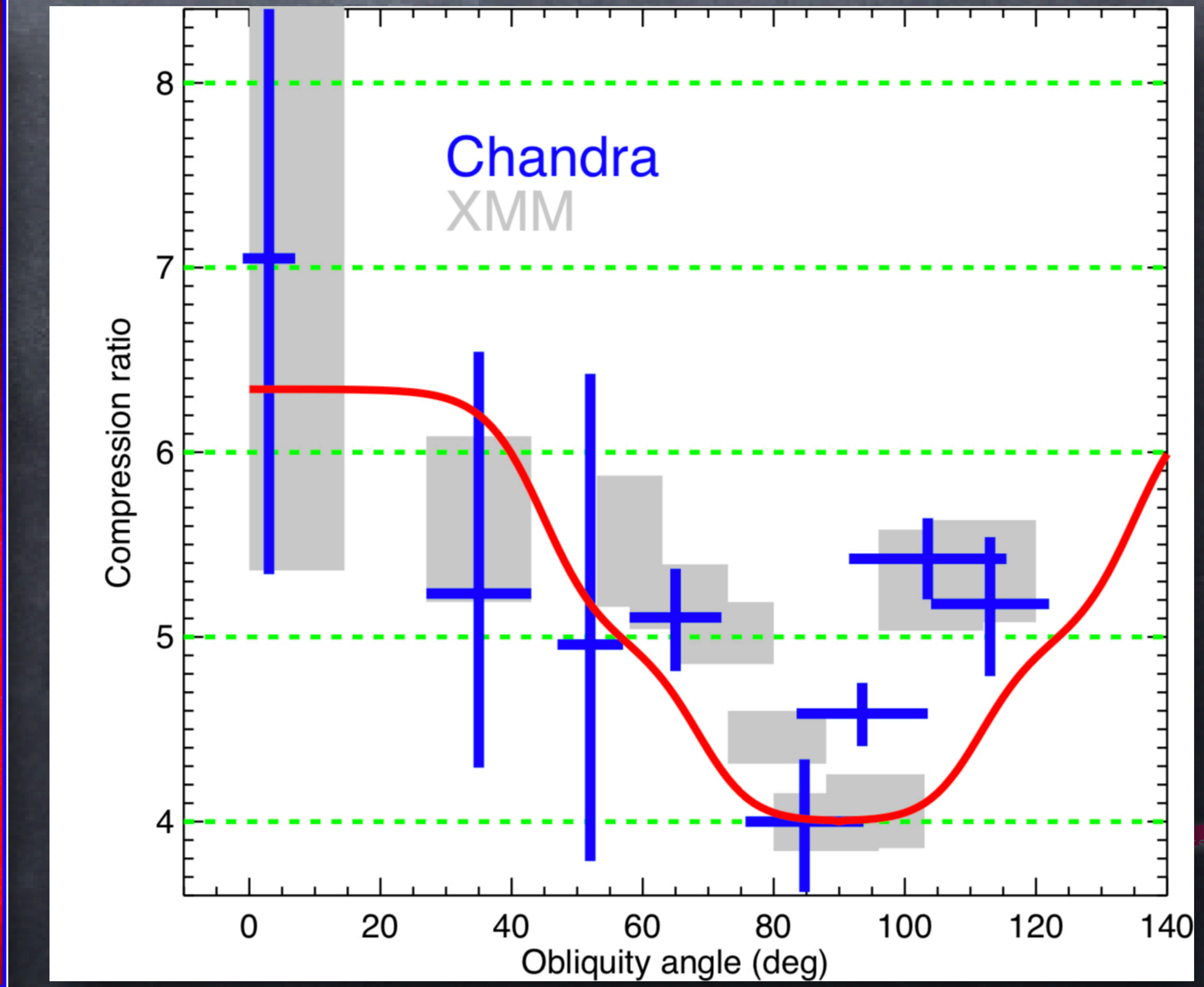


- $R \sim 6-7$ inferred in Tycho (Warren+05). In SN1006: $R \sim 4-7$, modulated with the azimuth/shock inclination (Giuffrida+21)
  - If $R \simeq 7 \rightarrow q_{\text{expected}} \simeq 3.5$
  - Tycho: radio to γ-ray observations:

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

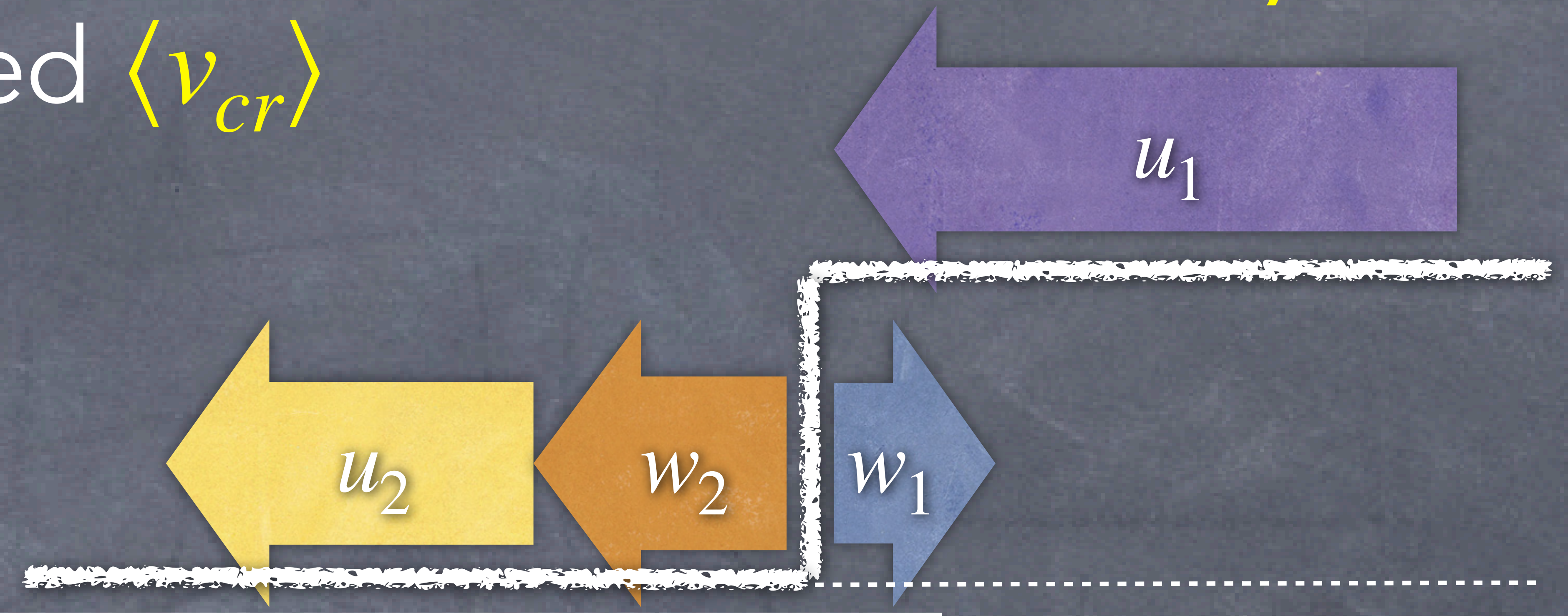
A challenge to DSA theory!

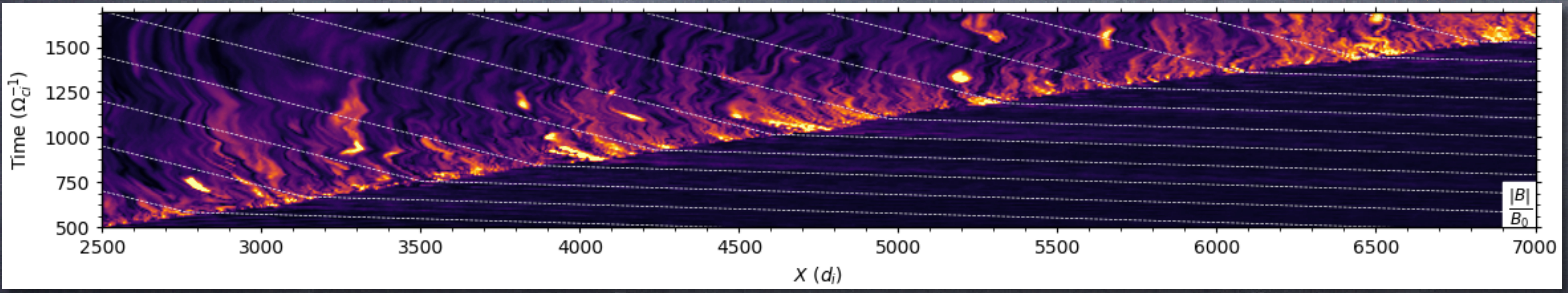




The Role of Amplified Magnetic Fields

- CRs feel an effective compression $R_{cr} = \dfrac{u_1 + w_1}{u_2 + w_2}$; w = wave speed $\approx v_A = \dfrac{B}{4\pi\rho}$
- 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: $\langle v_{cr} \rangle \simeq w_2 \simeq +v_{A,2}(\delta B_2) \equiv \alpha\ u_2$



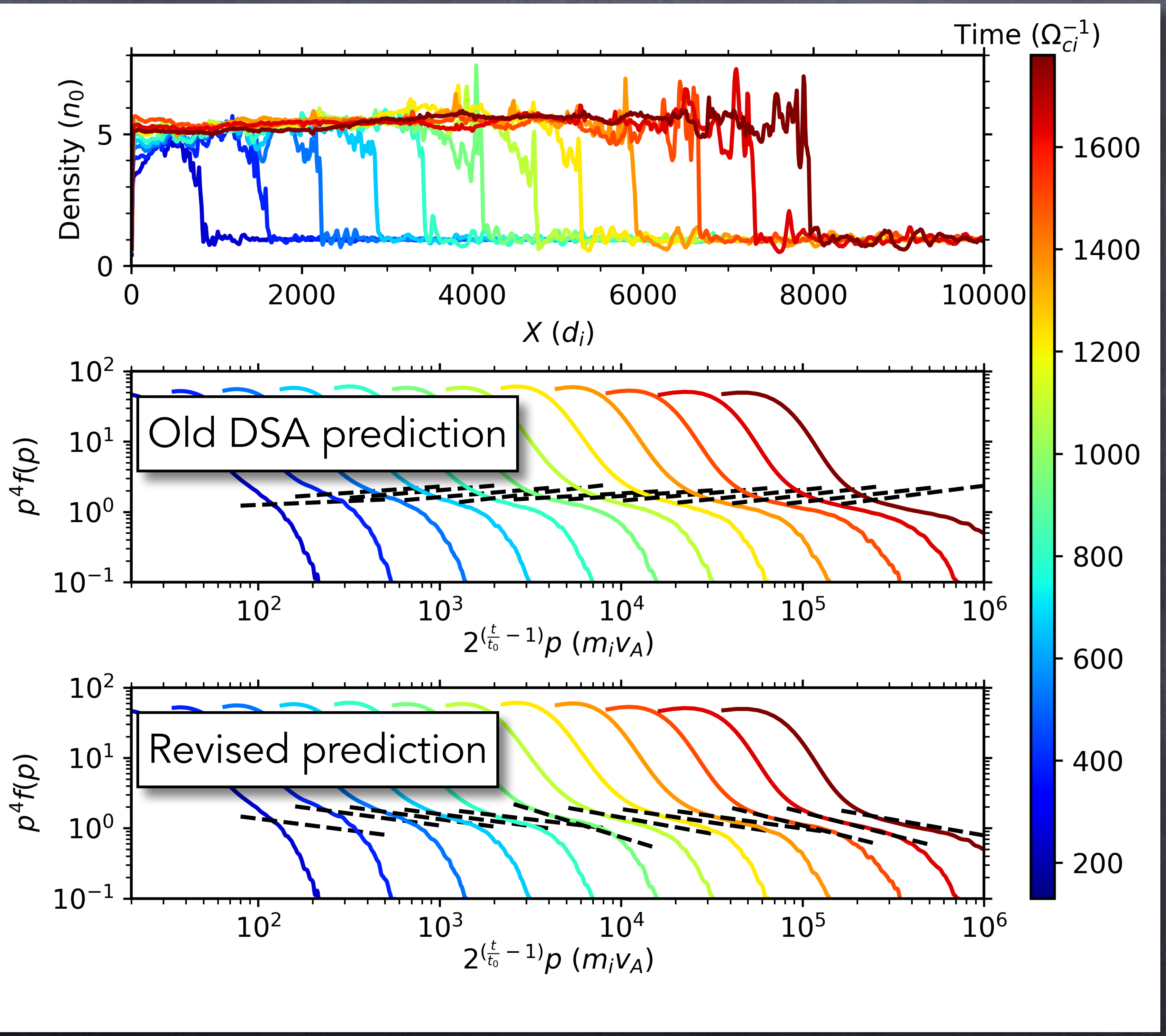


Haggerty-Caprioli20

- 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

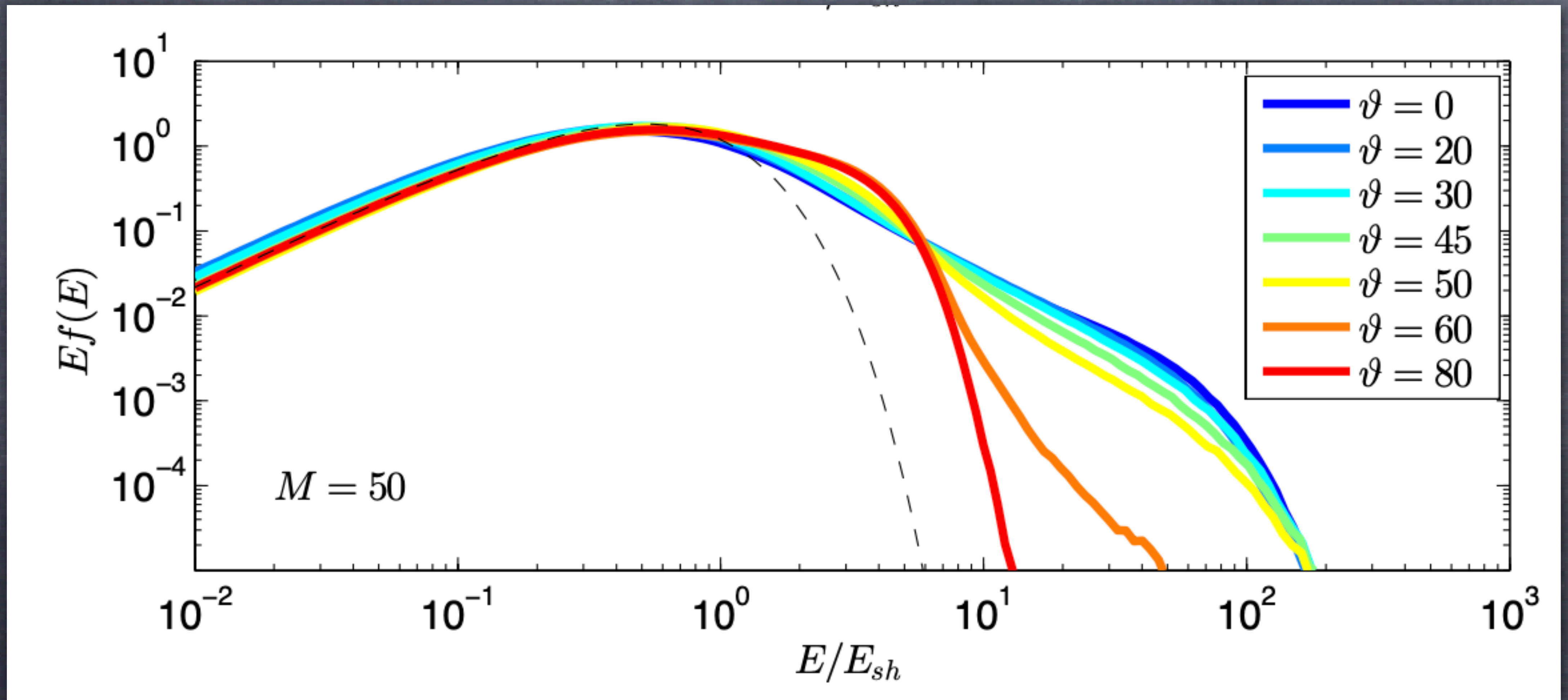


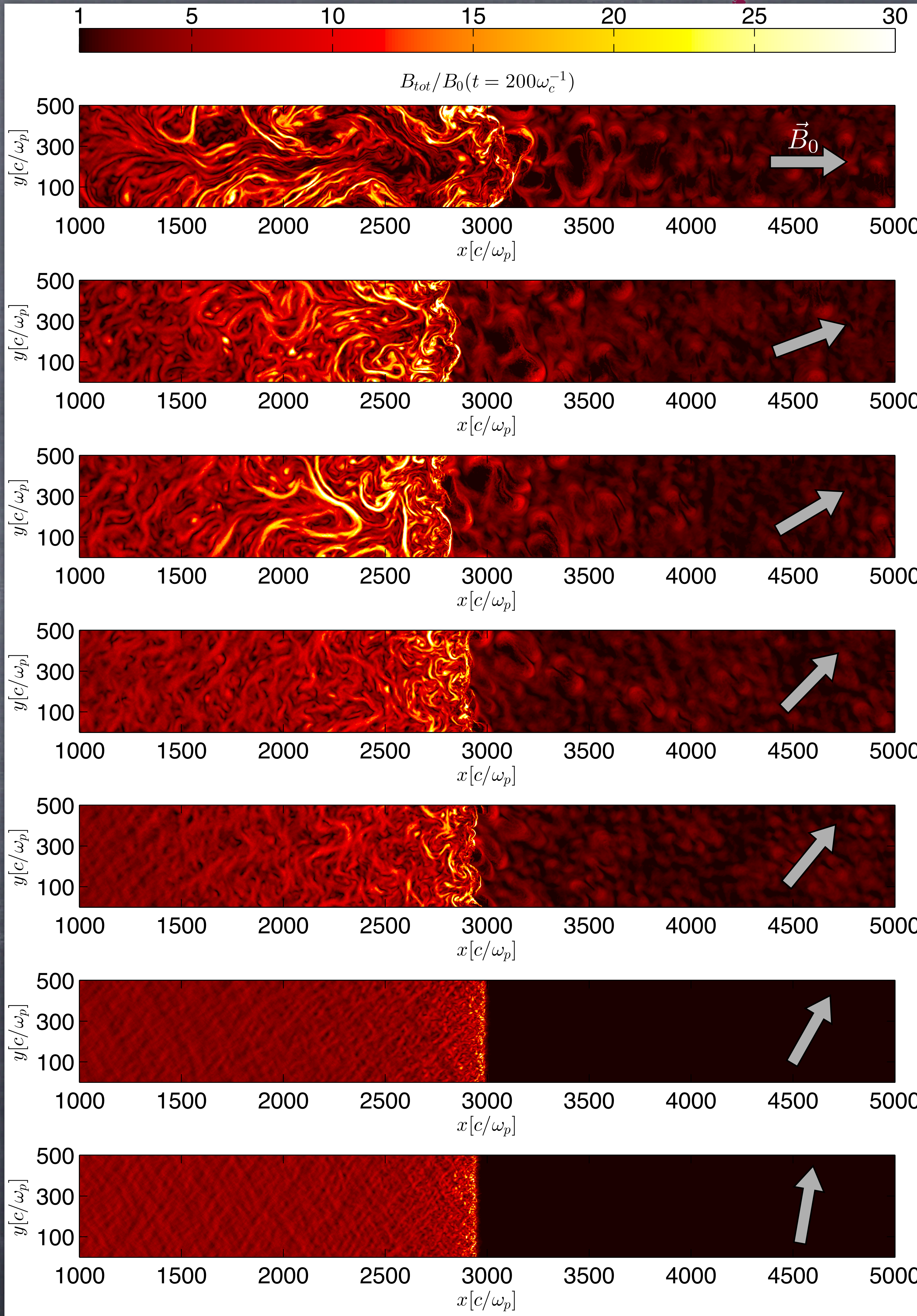
Caprioli, Haggerty & Blasi 2020

- 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…
  - Diesing-Caprioli21; See also R. Diesing's talk
- In a multi-wavelength fit B strength and particle slope are not independent!

Oblique Shocks

- Oblique shocks are good accelerators but bad ion injectors (Jokipii82, Giacalone+00, Giacalone05, Caprioli+15)
- Is there a critical magnetization ($\propto 1/M_A^2$) below which ϑ becomes *irrelevant*?
  - No evidence in 2D hybrid sims w/o CR or B seeds



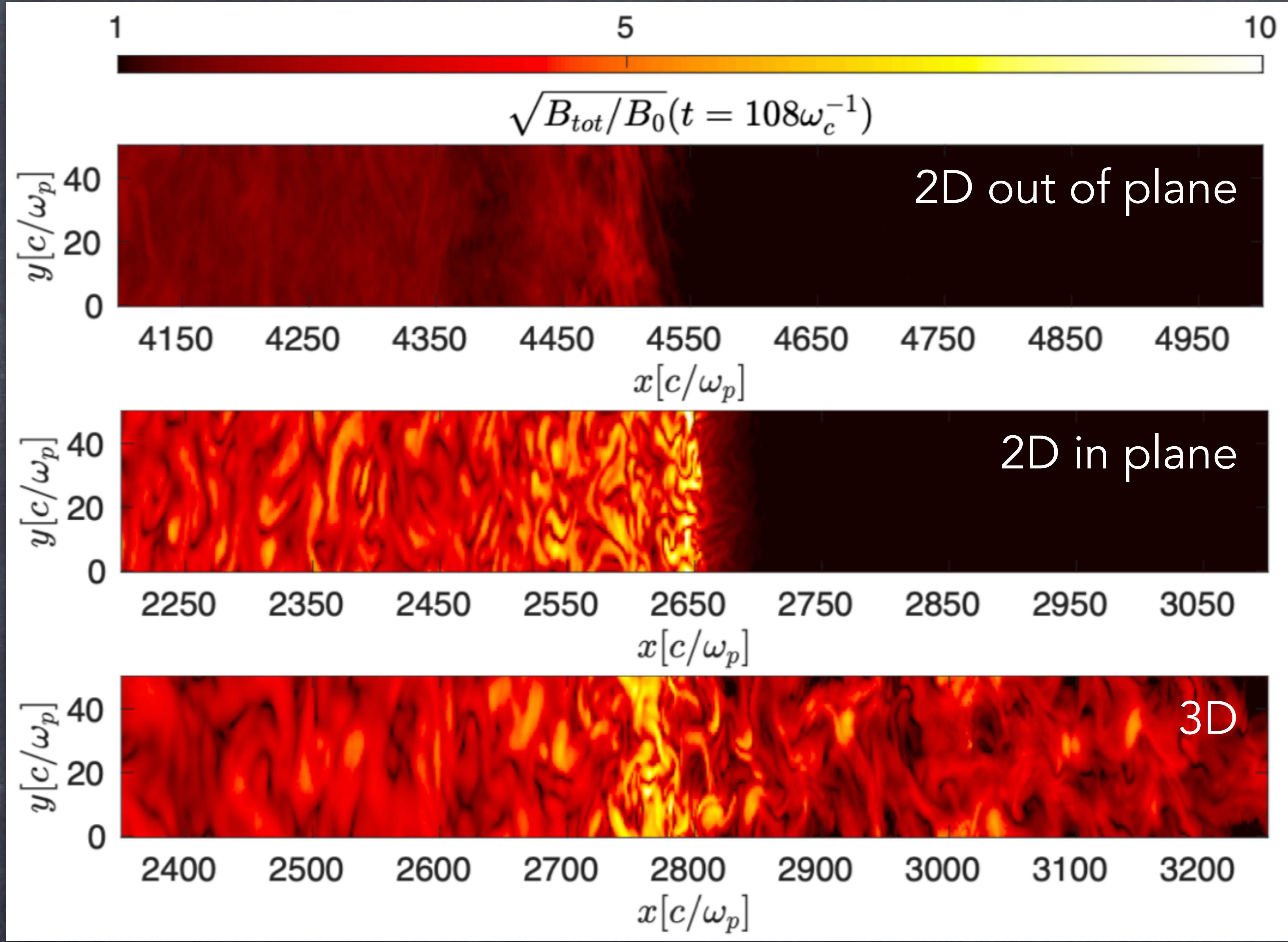


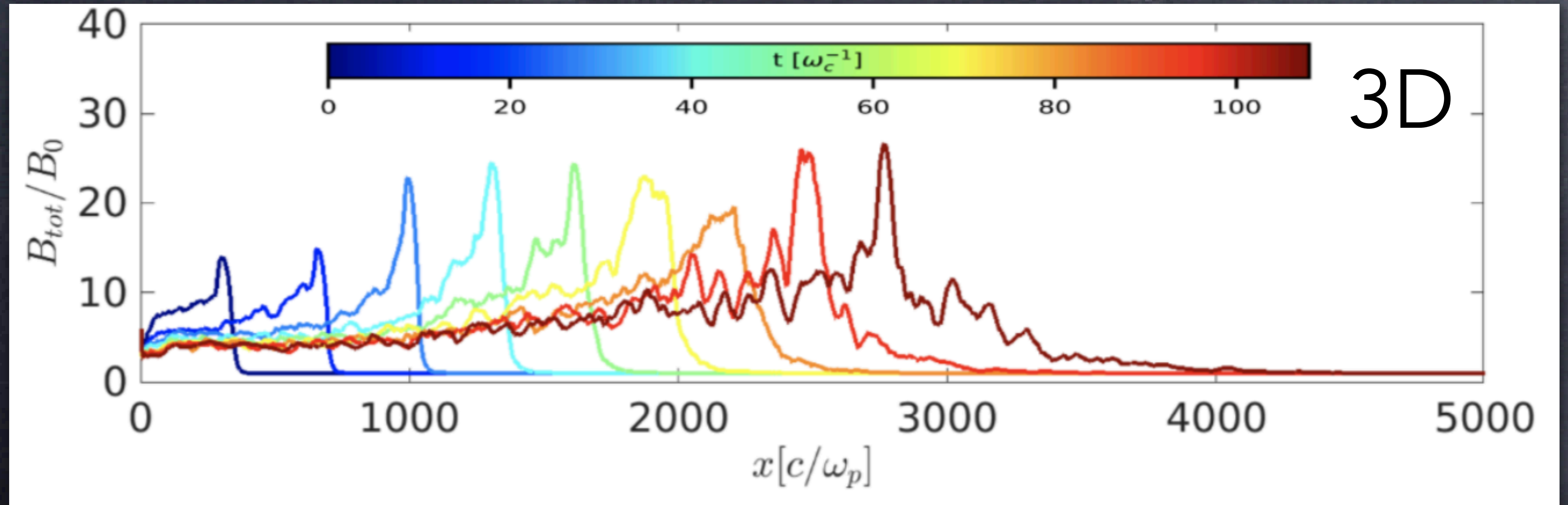
Caprioli & Spitkovsky14a,b

- Sironi+11 found $M_A^* \gtrsim 30$ for PIC relativistic shocks

Oblique Shocks: B-Field Amplification

- 2D/3D simulations of a shock with $M_A = 100,\ \theta_{Bn} = 80°$ (Orusa & Caprioli 2023)



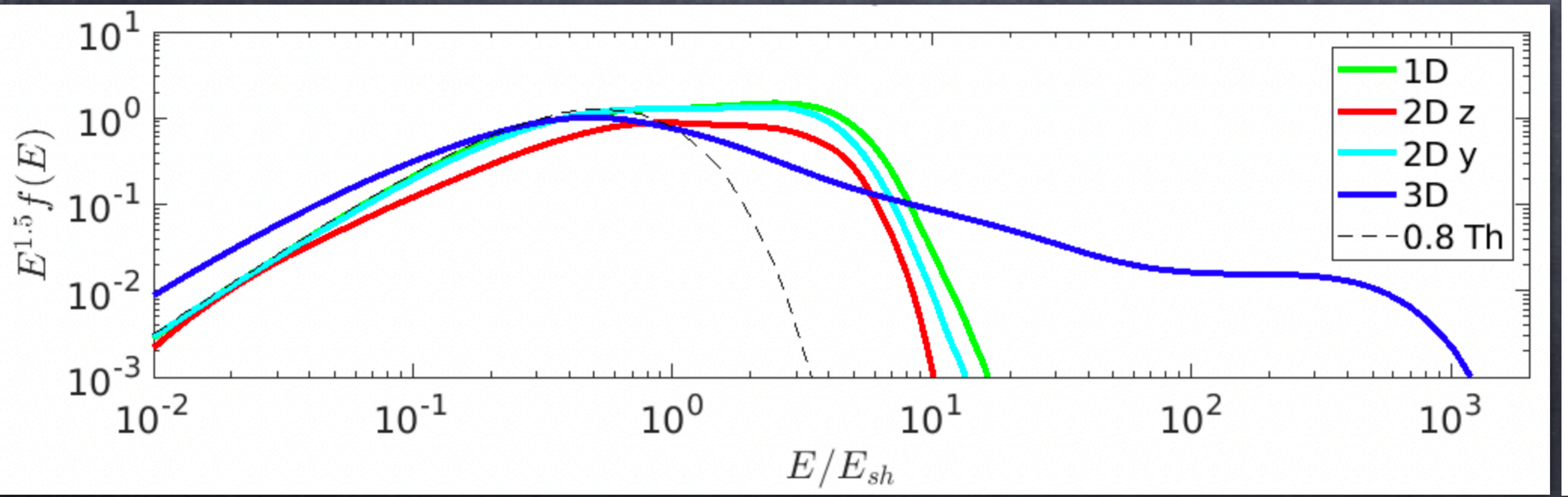


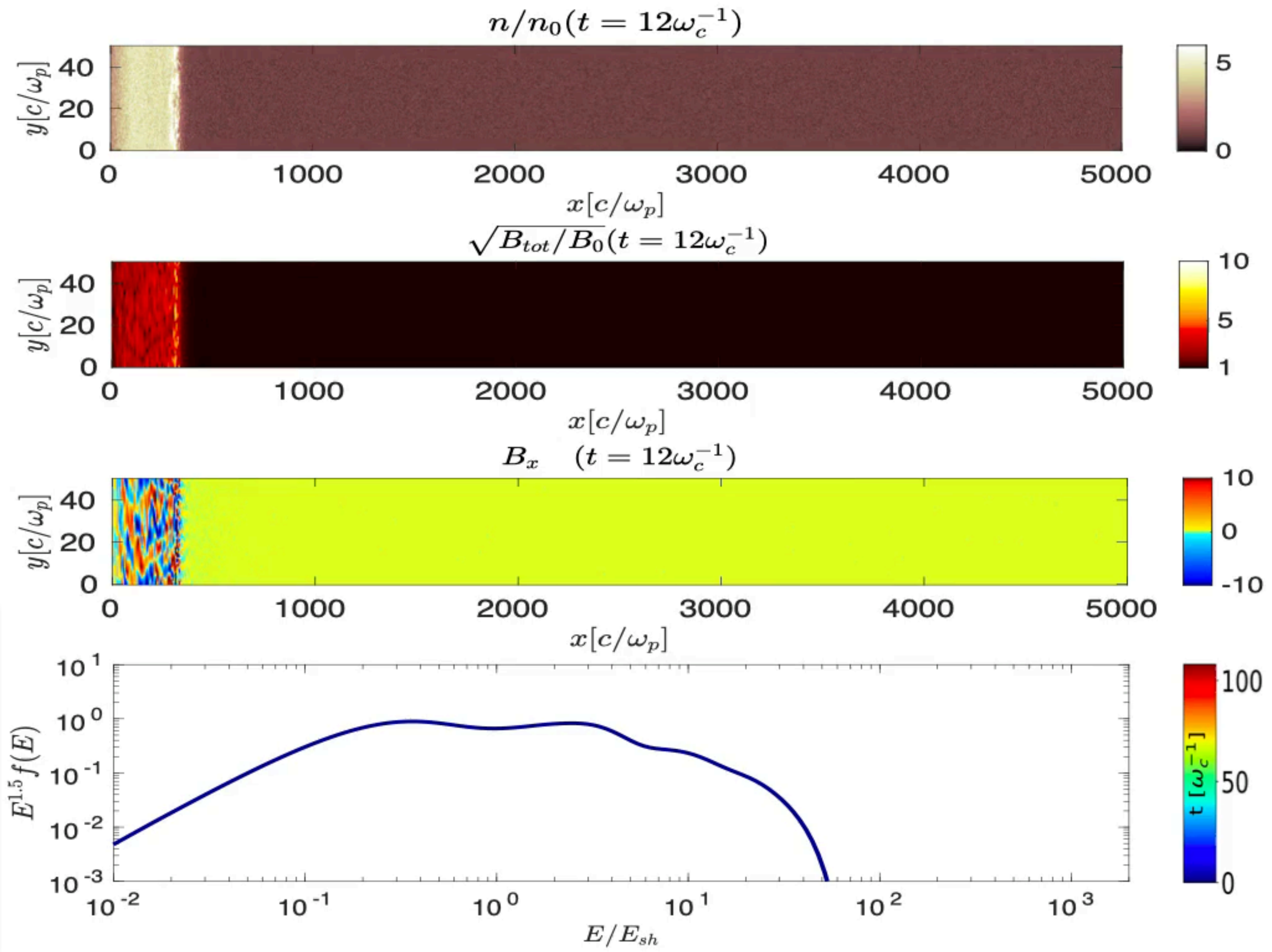
- Magnetic field generation:
  - 1D: simple compression (MHD)
  - 2D out-of-plane B_0: ~ compression
  - 2D in-plane B_0: $\delta B/B_0 \lesssim 40$ at the shock
  - 3D: $\delta B/B_0 \lesssim 40$ at the shock, but also $\delta B/B_0 \gg 1$ upstream
- Dimensionality matters! Why?
  - Turbulence is different in 3D…

Oblique Shocks: Ion Acceleration

- Self-generated turbulence *solves the injection problem*!

- 3D geometry unlocks cross-field diffusion / B-field line wandering
  - Supra-thermal Ions can diffuse back from downstream
  - and develop a non-thermal tail

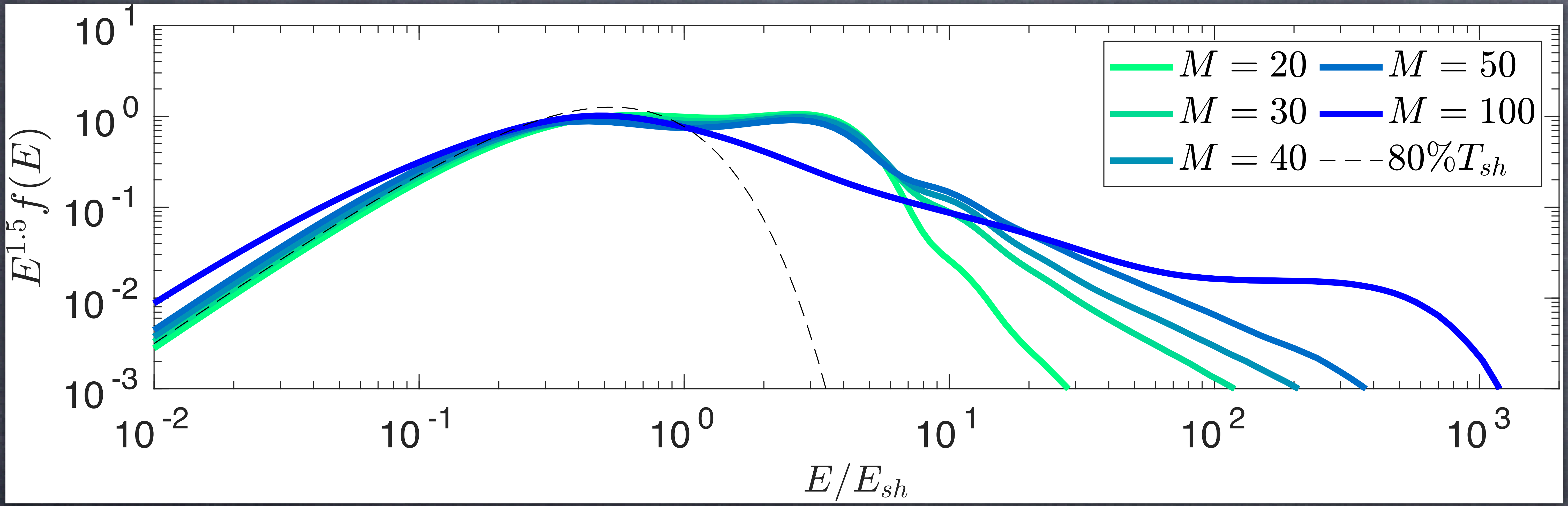


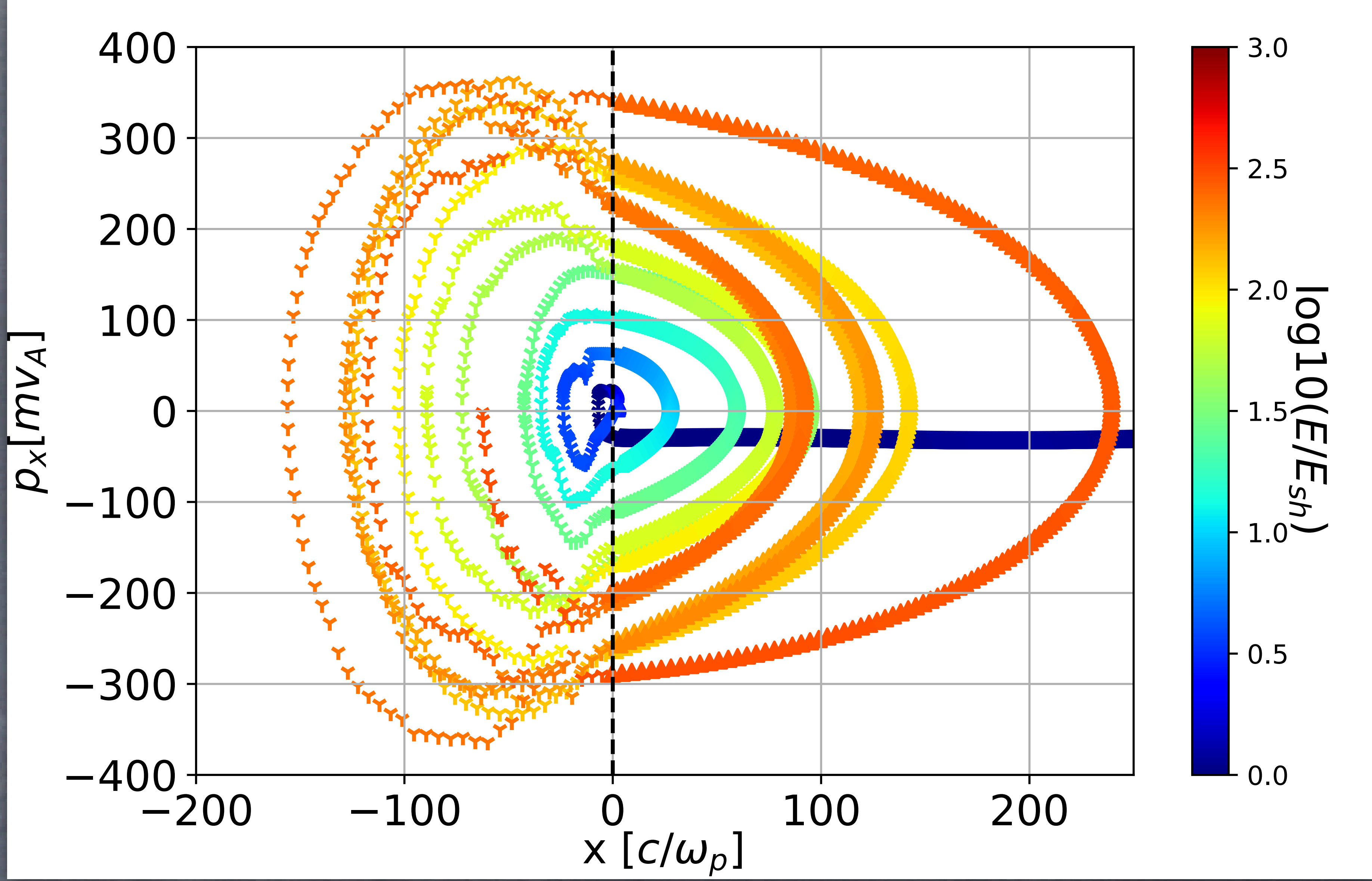


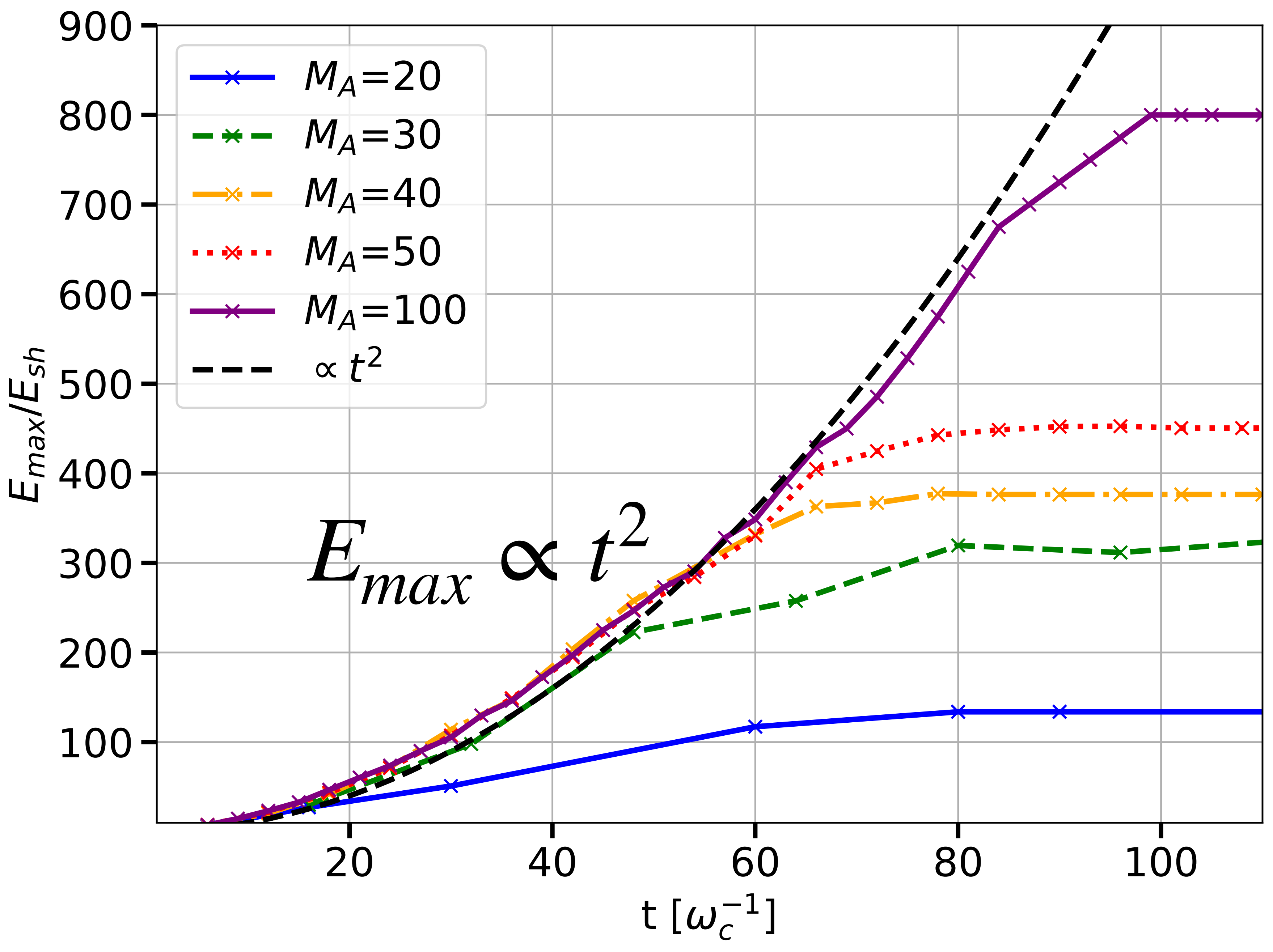
Orusa & Caprioli 2023

Oblique Shocks: Shock Drift Acceleration

- Particle tracking reveals that ions gain energy via shock drift acceleration
  - Acceleration efficient ($\gtrsim 15\,\%$) and very fast!







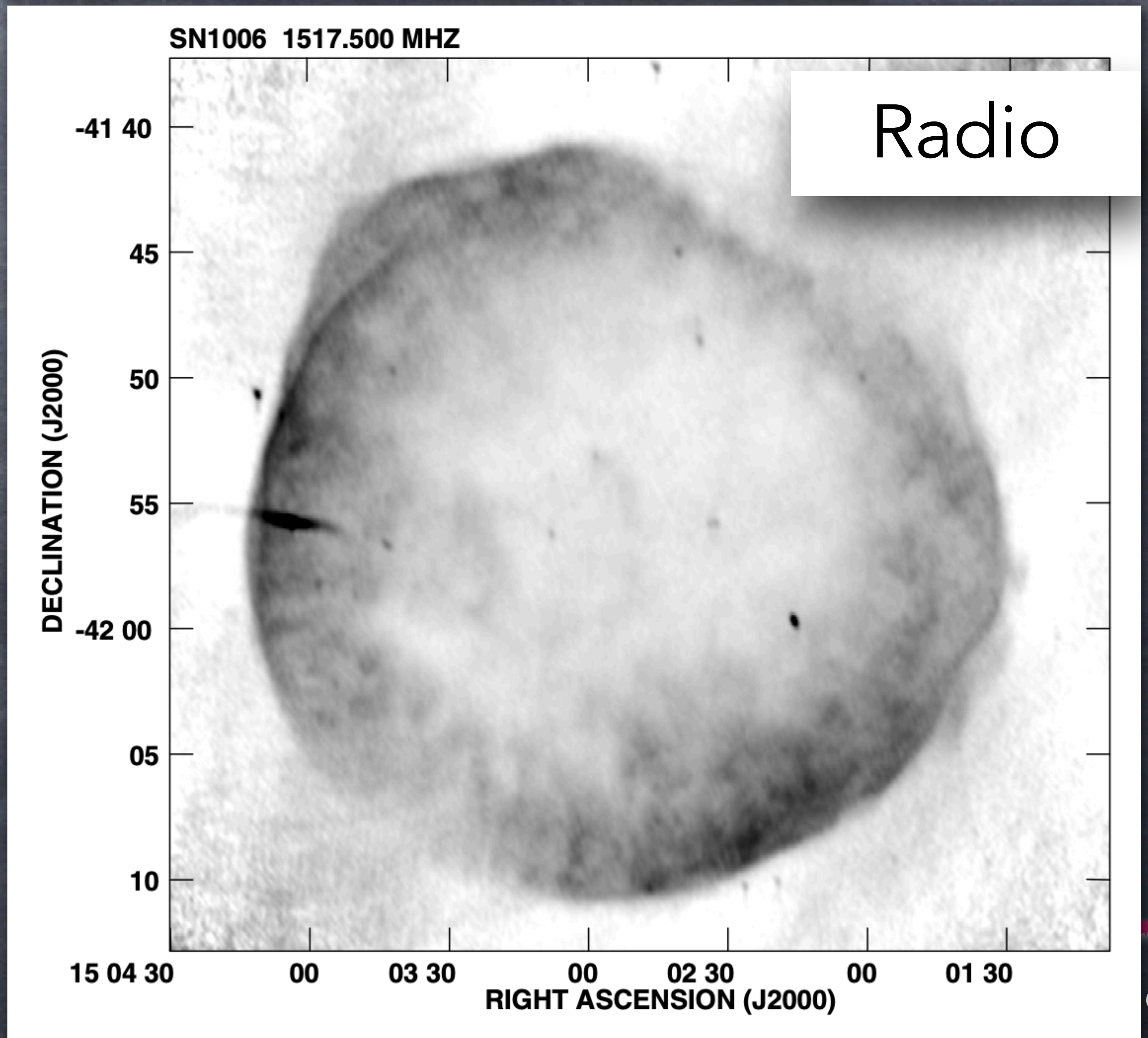
- There is maximum energy achievable via SDA
- Slope and maximum energy depend on M_A

Orusa & Caprioli 2023

Implications for SNRs (e.g., SN1006)

- Investigate dependence on θ_{Bn} and M_A (w. Orusa, Simon, in prog.)
- ***Preliminary***: allows injection also for oblique shocks with $45^\circ < \theta_{Bn} < 65^\circ$
  - consistent with the compressions inferred in SN1006 (Giuffrida+21)
- SDA energy gain is limited ($\propto M_A$), then ions escape upstream
- They have hard time driving Bell instability, so no DSA
  - See E. Simon's talk tomorrow

- SDA is very fast: $E_{max} \propto t^2$
  - A $v_{sh} \simeq 3{,}000$ km/s can make ~GeV particles in $\lesssim$ 1 day
  - Explains *azimuthally symmetric* radio emission from SN1006
- But is intrinsically limited to relatively small $E_{max}(\theta_{Bn})$
  - Explains *lack* of X-ray synch and TeV emission



Take-away Messages

- Particle acceleration is generally efficient in SNR shocks
- Q-parallel: DSA is efficient ($\gtrsim 10\,\%$)
  - Efficient *B* amplification via Bell's instability (Caprioli-Spitkovsky14a,b,c)
  - Slope *not* universal! Steeper than E^{-2}, depends on *B* (Caprioli+20, Diesing & Caprioli 21)
  - E_{max} determined by the time it takes to grow *B* (Simon's talk, in prog.)
- Q-perpendicular: SDA efficient if $M_A \gtrsim 30$; no injection problem (Orusa & Caprioli+20)
  - Slope not universal! Steep, but $\rightarrow E^{-2}$ for $M_A \gtrsim 100$
  - Generally limited to $E_{max} \lesssim 10$ GeV (Orusa & Caprioli, in prog.)
- Use shock acceleration theory to interpret SNR multi-wavelength emission!

y [c / ω_pi]
400
300
200
100
Dens. [n_0]
4
3
2
1
y [c / ω_pi]
400
300
200
100
B_z^1/4 [B_0]
2
1
0
-1
-2
0
500
1000
1500
x [c / ω_pi]