Potsdam, Germany
March 6, 2018

New Insights on Particle Acceleration at Non-relativistic Shocks

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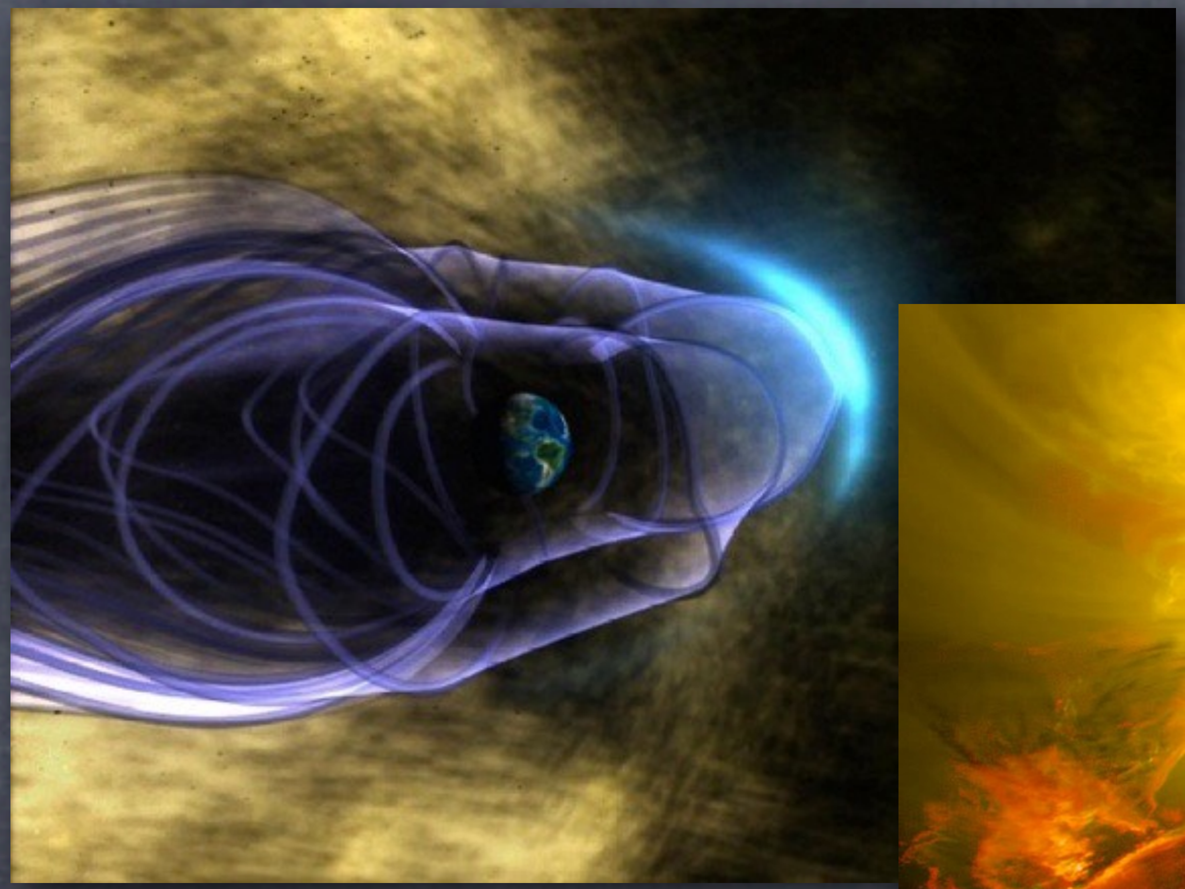
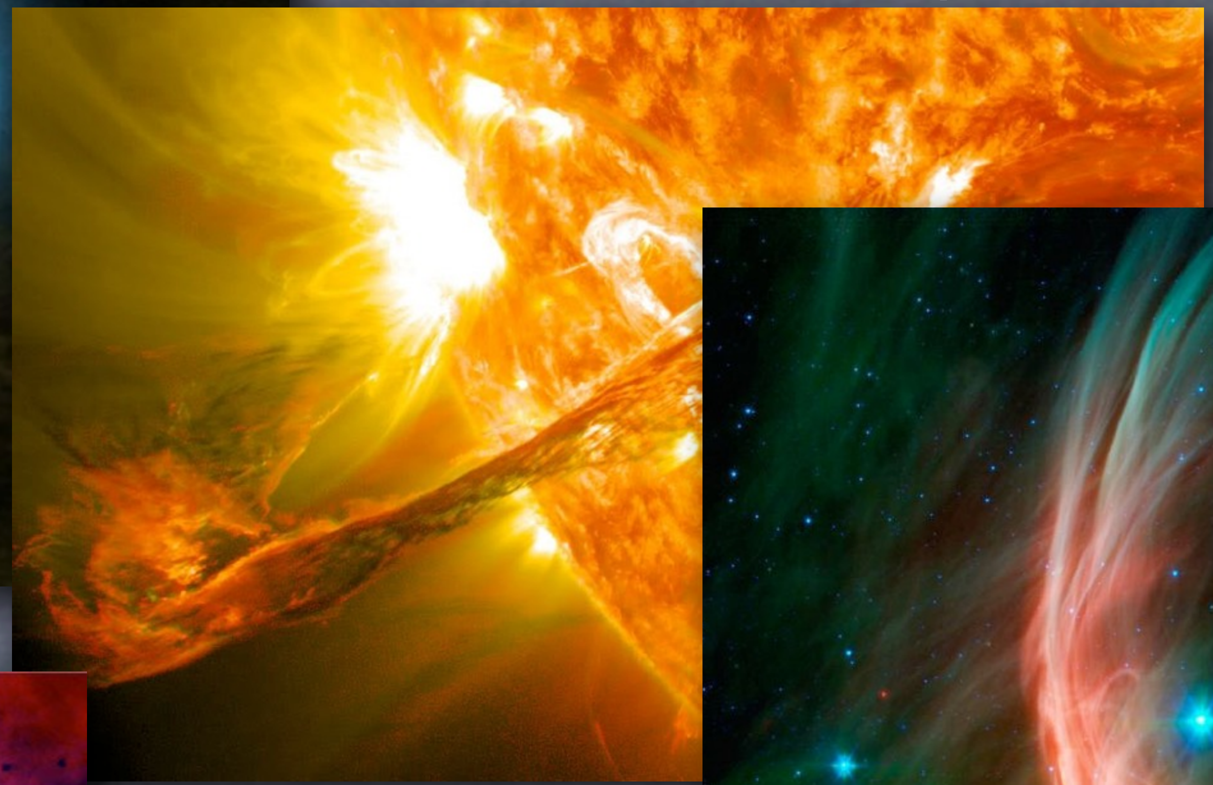
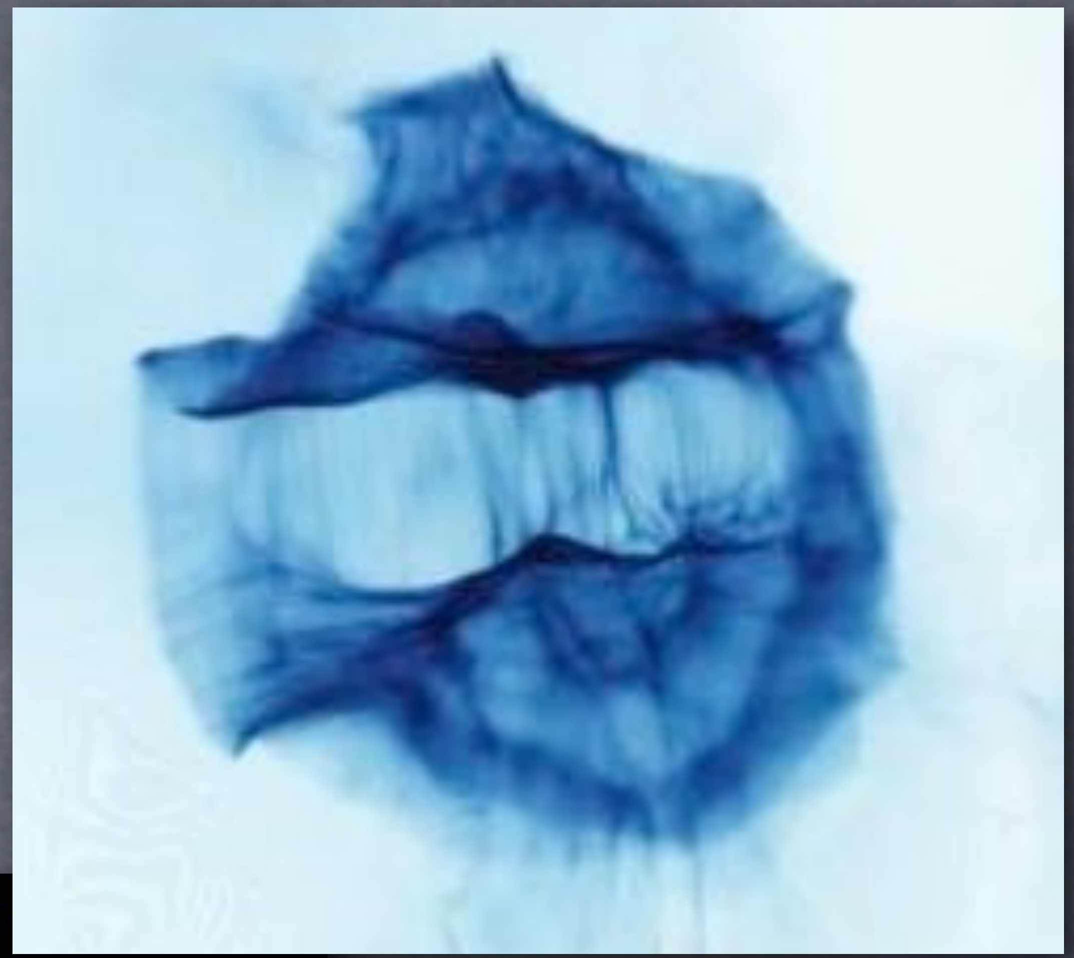
University of Chicago

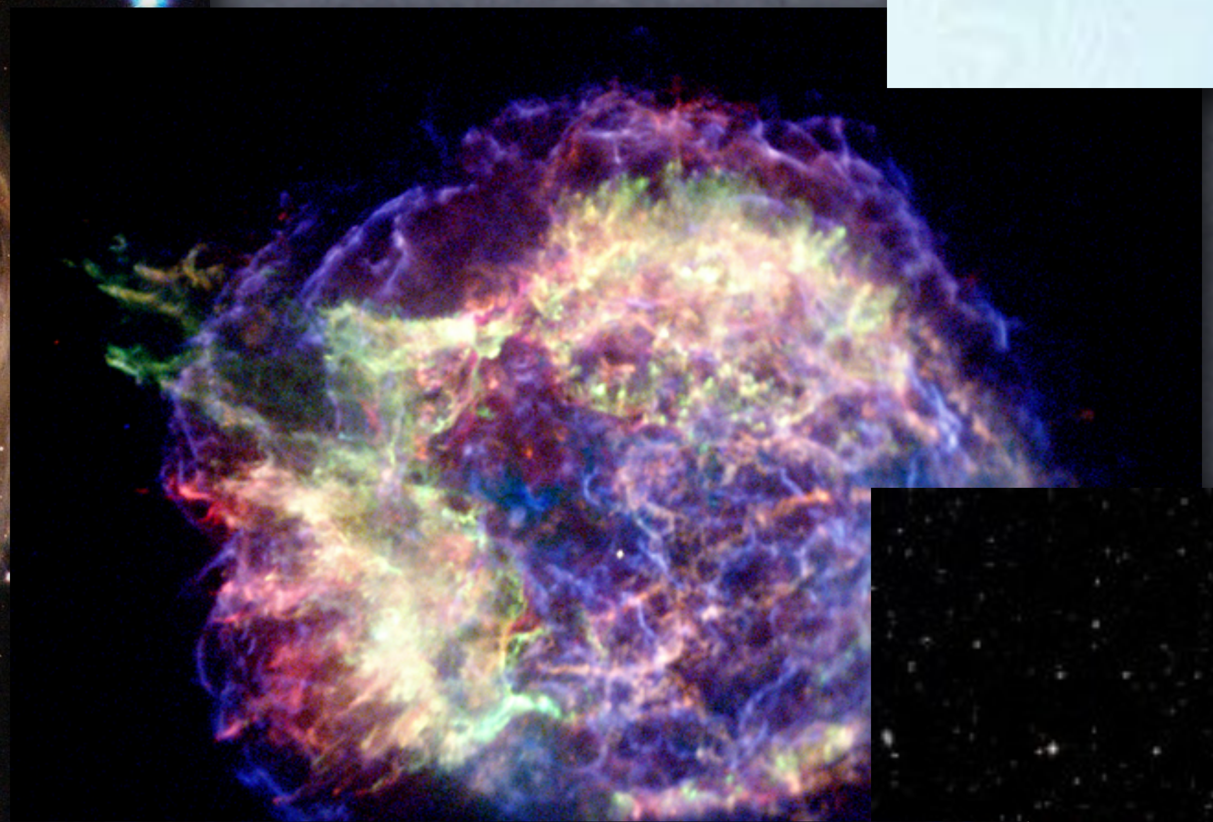
Collisionless Shocks

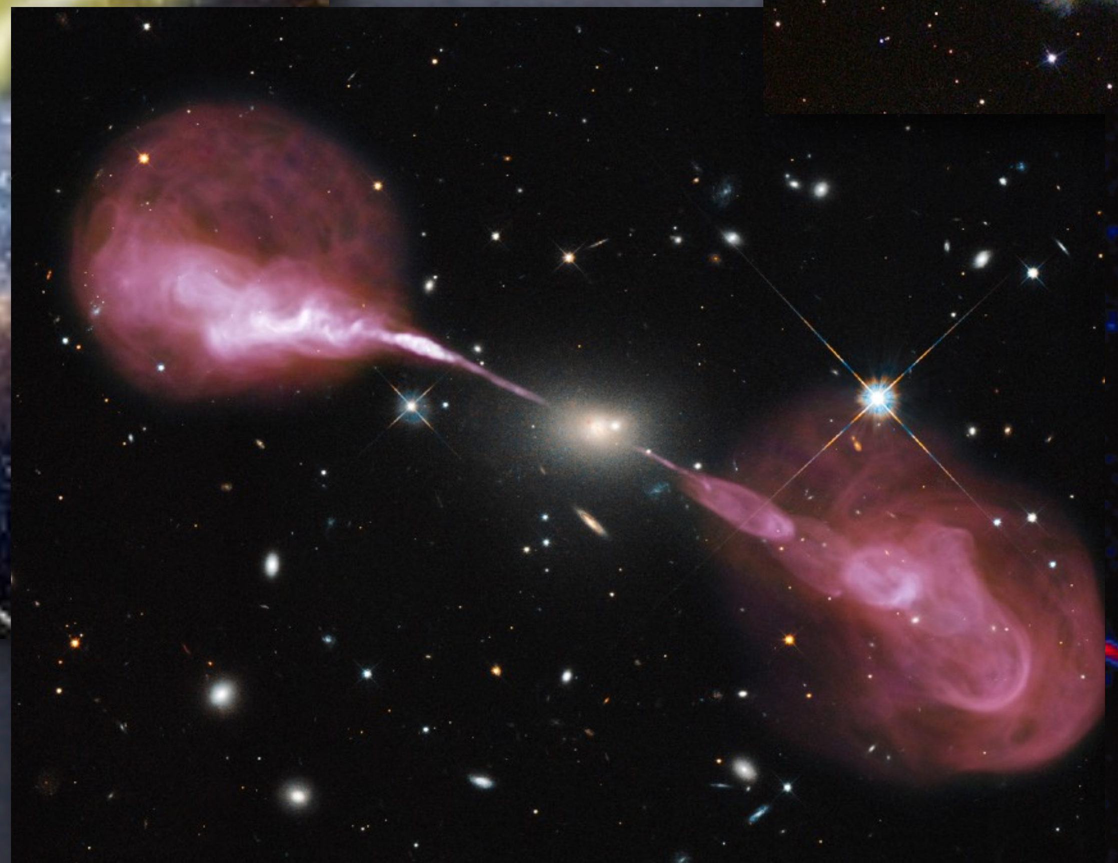
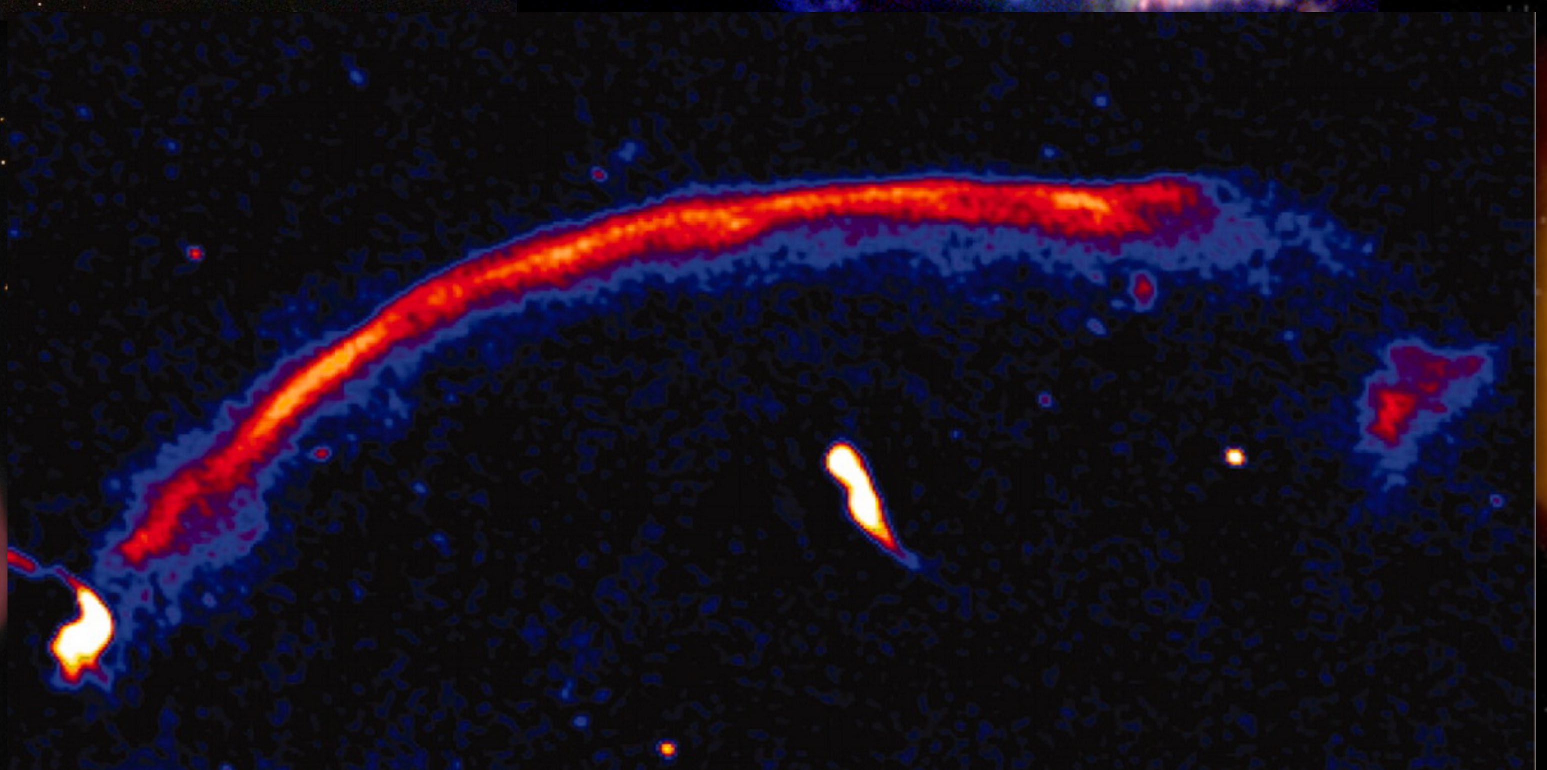
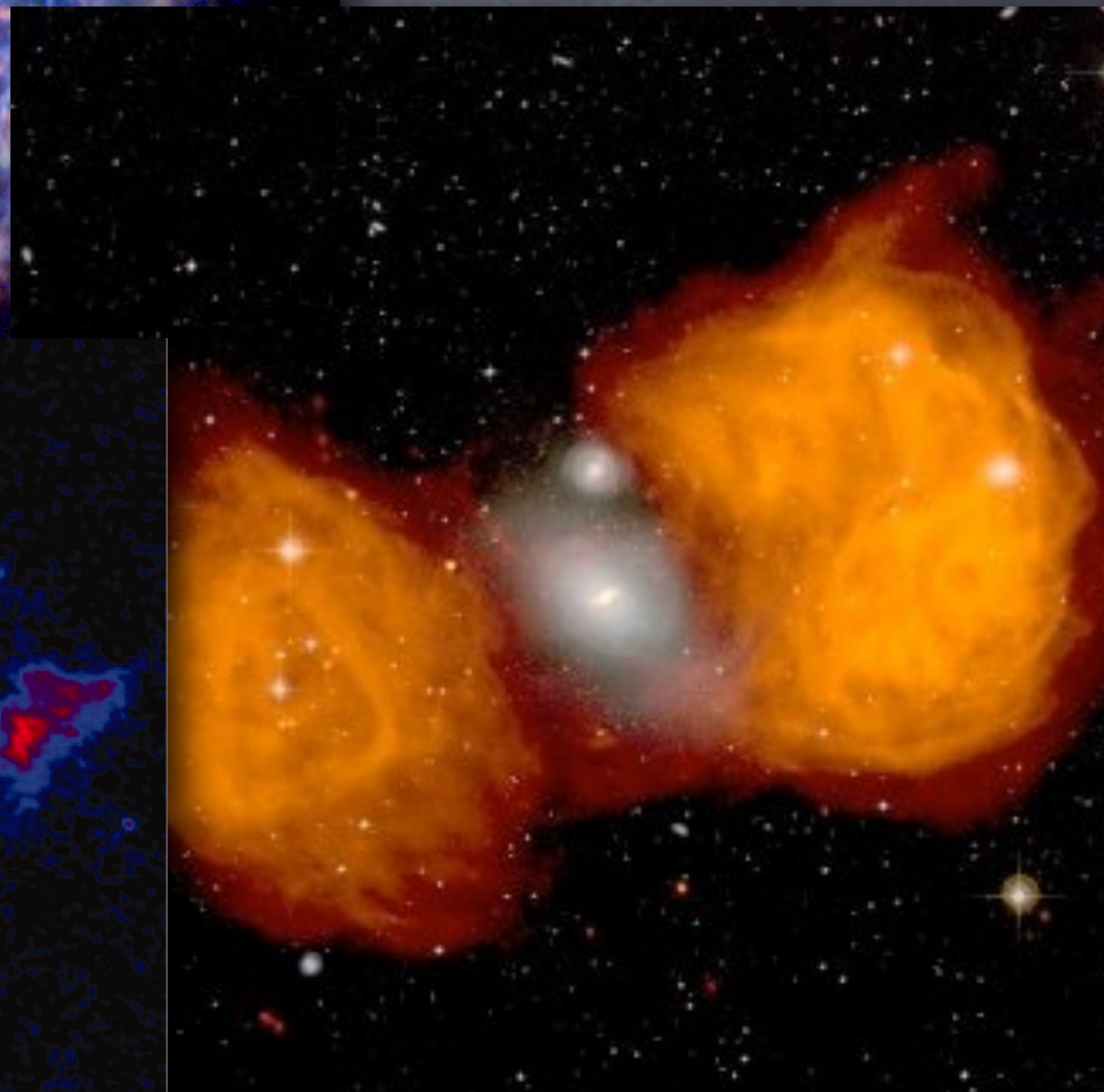
- Mediated by collective electromagnetic interactions
- Show prominent non-thermal activity


- Now studied in laboratory with laser experiments!





A universal acceleration mechanism

- Fermi mechanism (Fermi, 1949): random elastic collisions lead to energy gain
- ...rd et al.; 1978)

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.

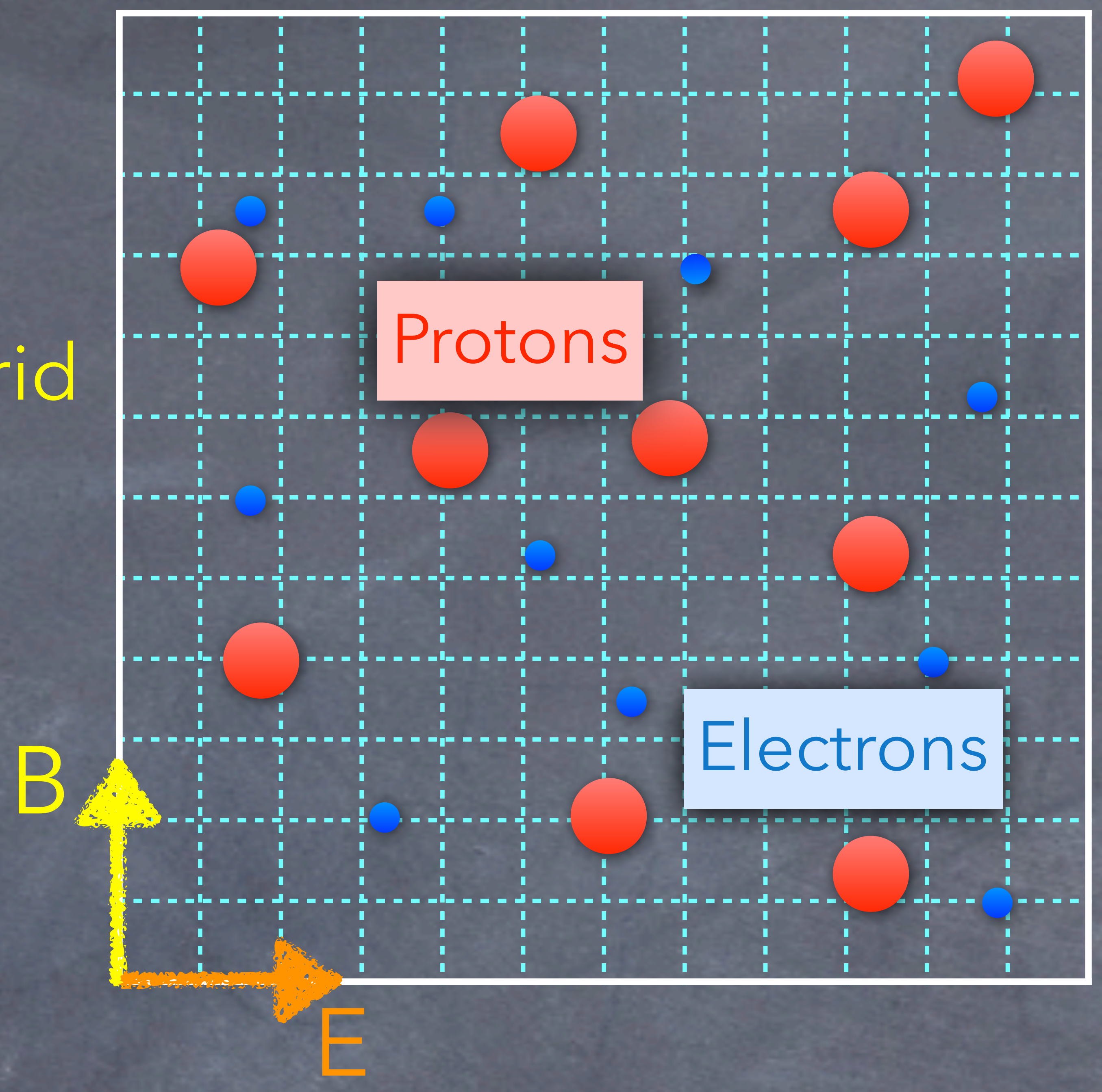
- DSA produces power-laws $N(p) \propto 4\pi p^2 p^{-\alpha}$, depending on the compression ratio $R=\rho_d/\rho_u$ only.

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

  - 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!

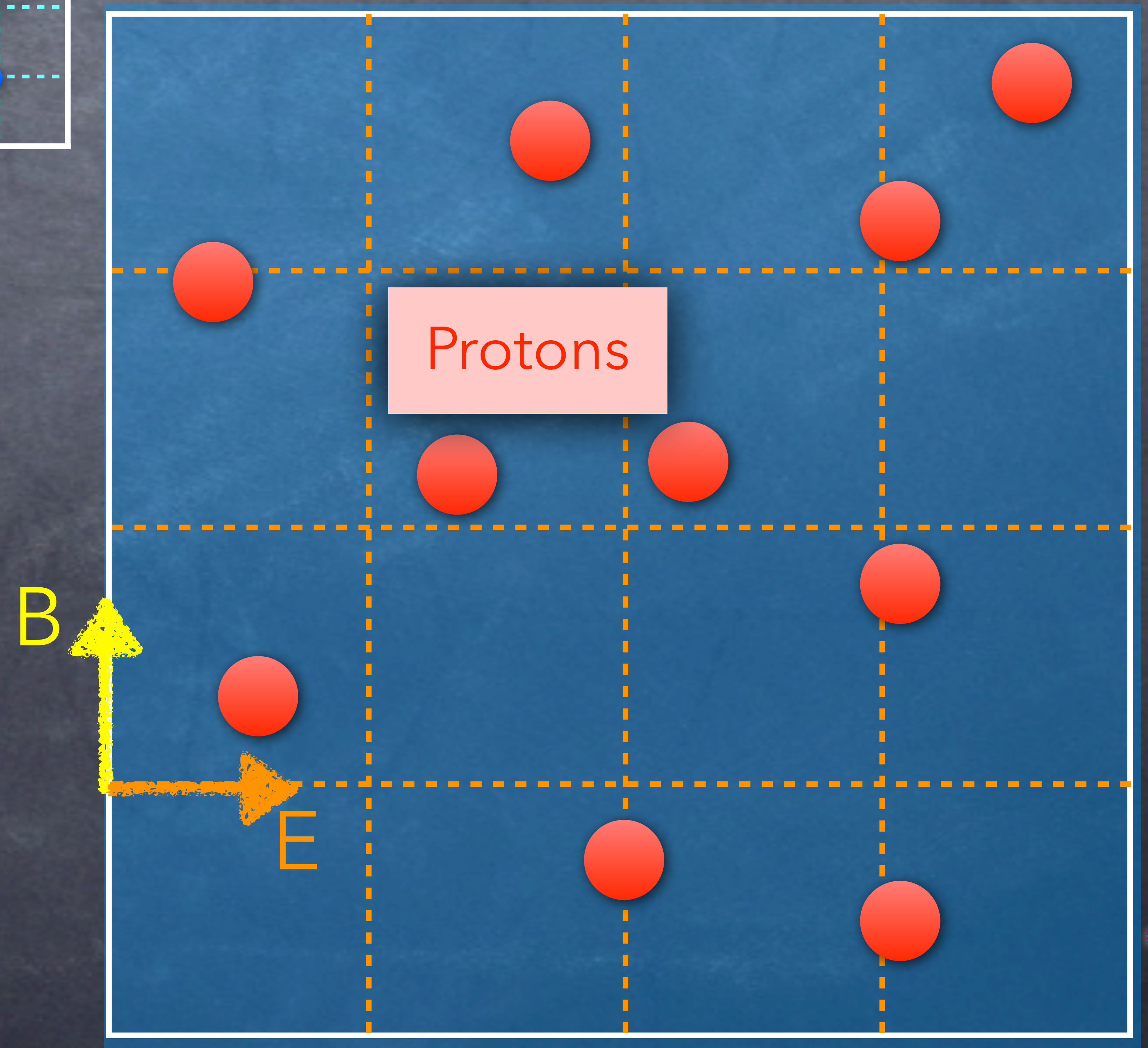


- Hybrid approach: Fluid electrons - Kinetic protons

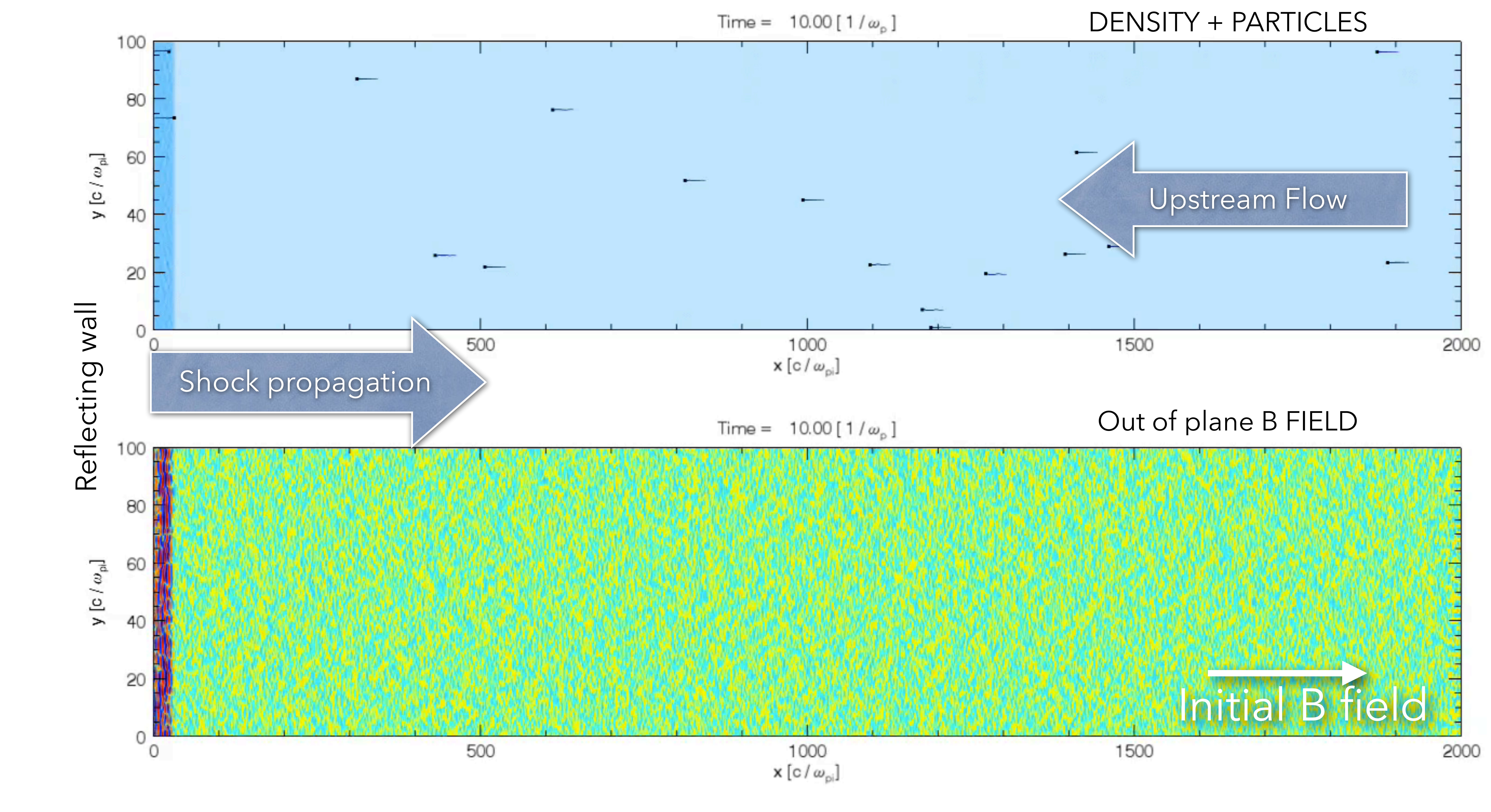
  (Winske & Omidi; Burgess et al., Lipatov 2002; Giacalone et al. 1993,1997,2004-2013; DC & Spitkovsky 2013-2015,…)

  - massless electrons for more macroscopical time/length scales

$$\mathbf{E} = -\frac{\mathbf{V}_i}{c} \times \mathbf{B} + \frac{1}{4\pi n\, e}(\nabla \times \mathbf{B}) \times \mathbf{B} - \frac{T_e}{n}\nabla n^{\gamma_e}$$



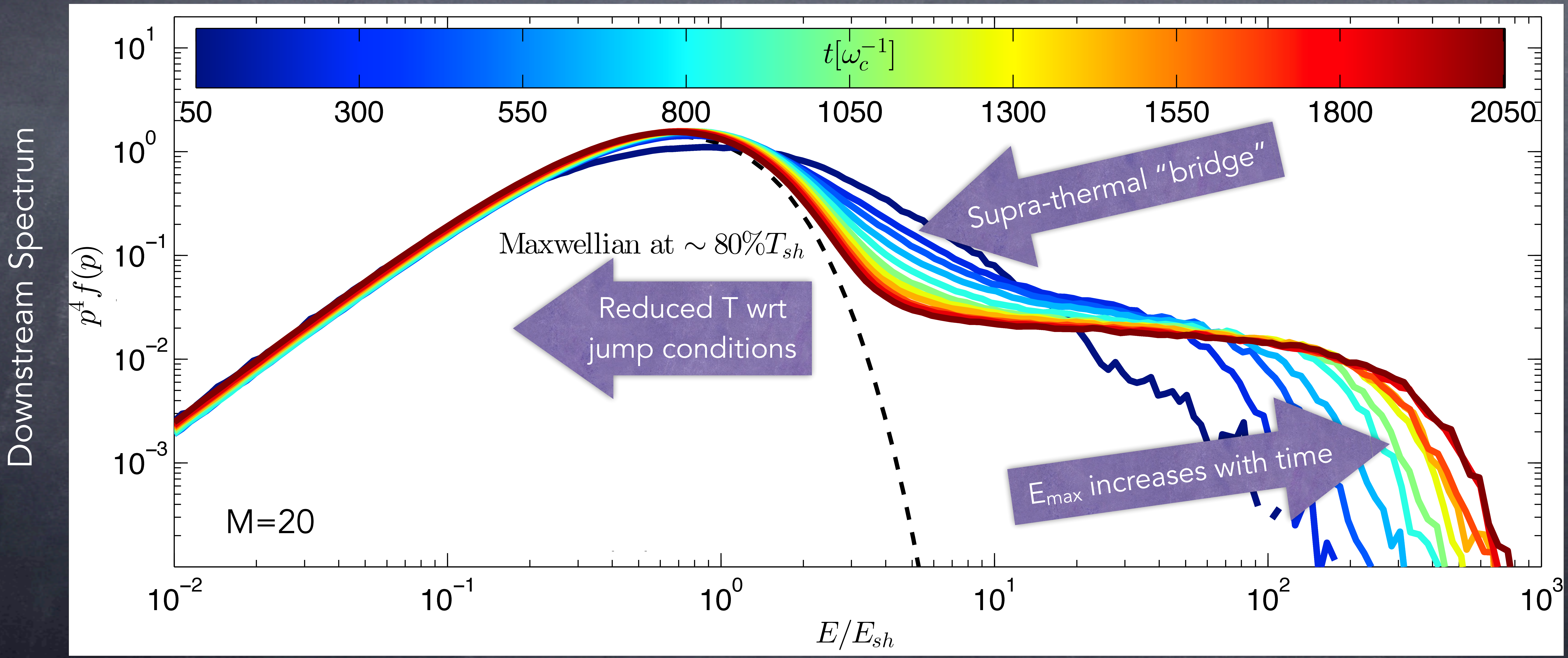
Hybrid simulations of collisionless shocks



dHybrid code (Gargaté et al, 2007; DC & Spitkovsky 2014, Haggerty & DC, 2018)

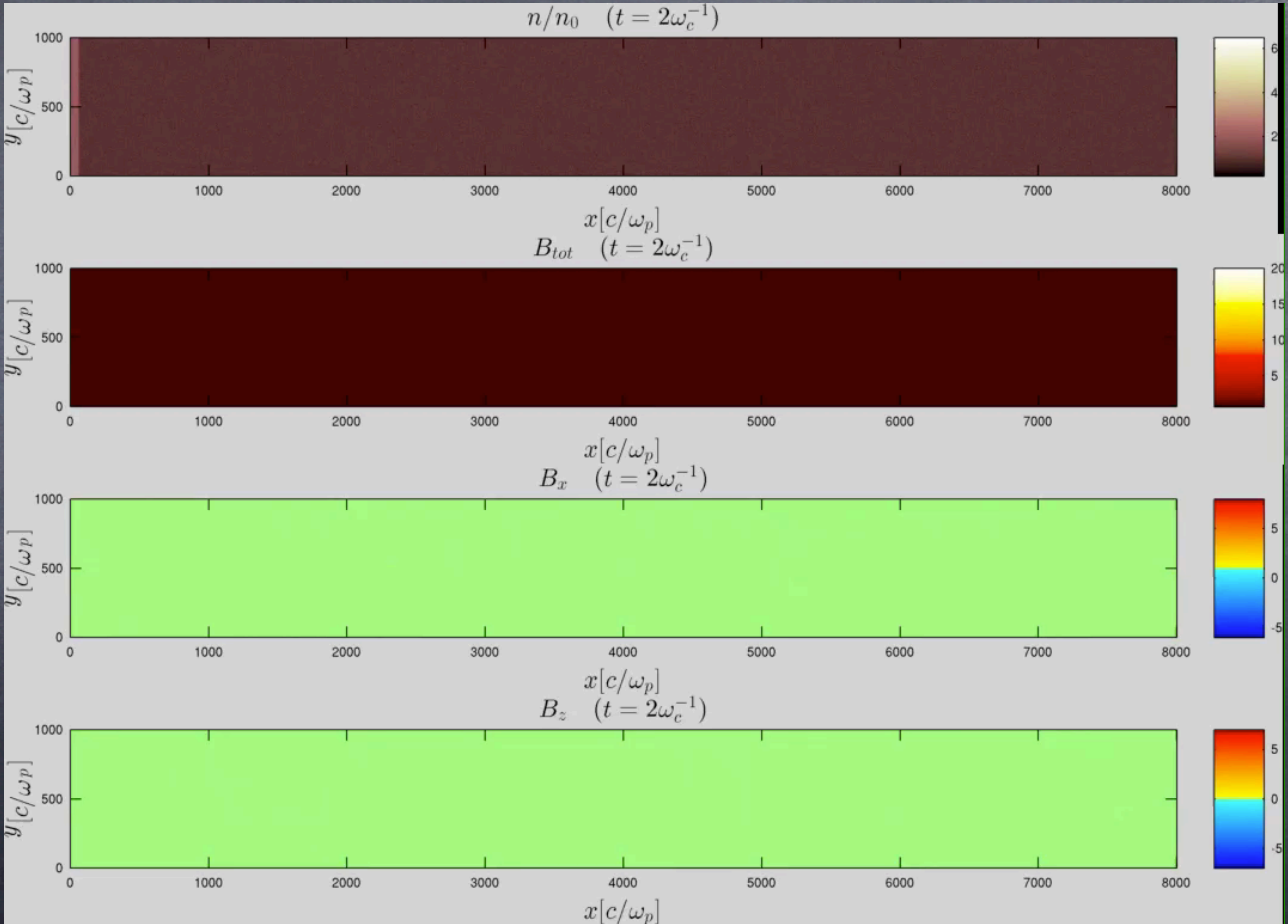
Spectrum evolution

- Diffusive Shock Acceleration: non-thermal tail with universal spectrum $f(p) \propto p^{-4}$
- Acceleration efficiency: ~15% of the shock bulk energy!



DC & Spitkovsky, 2014a

CR-driven Magnetic-Field Amplification

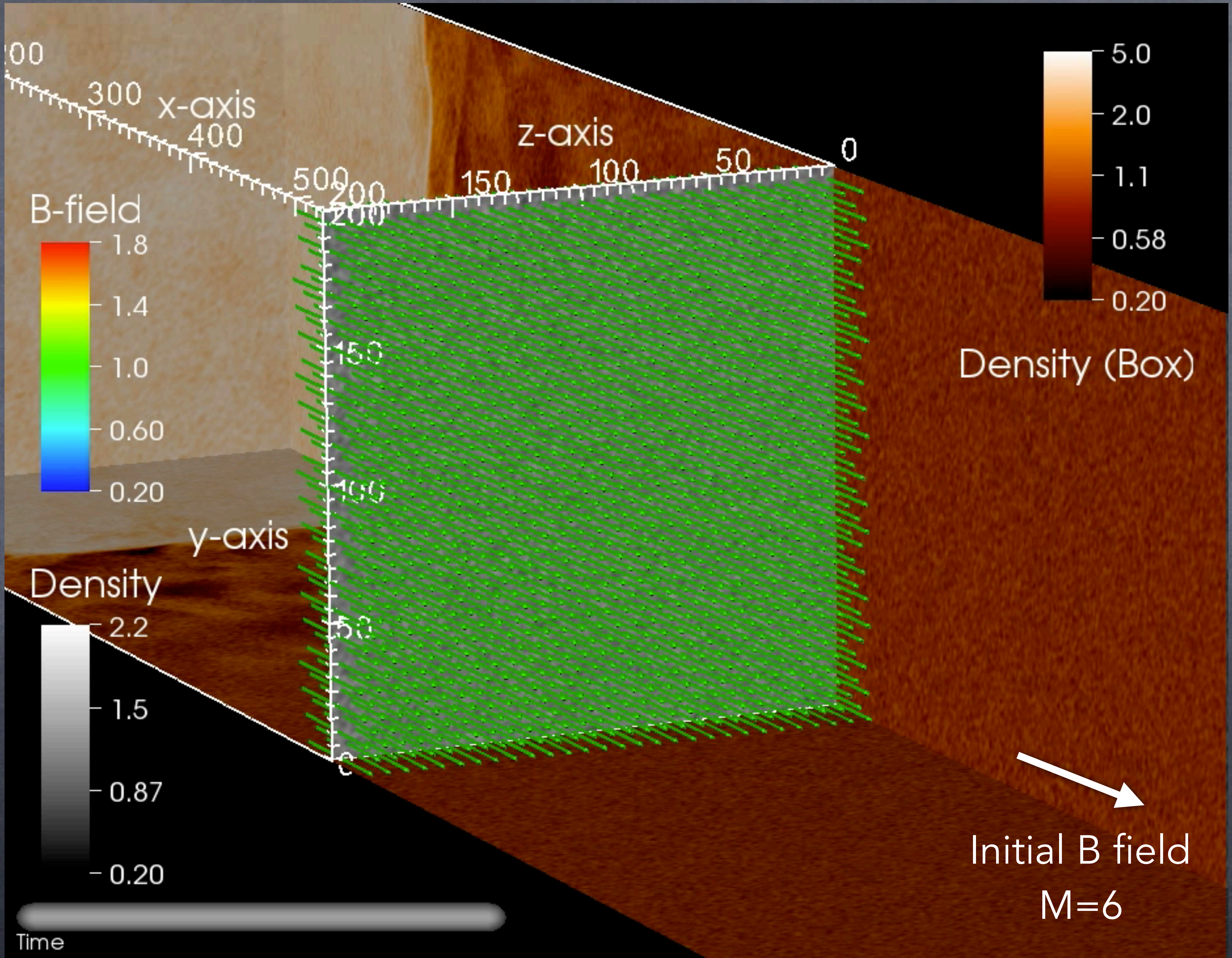


Initial B field

$M_s = M_A = 30$

DC & Spitkovsky, 2013

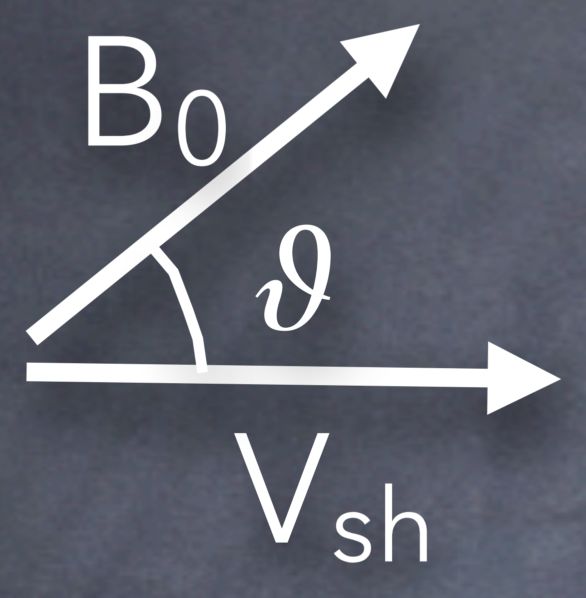
3D simulations of a parallel shock

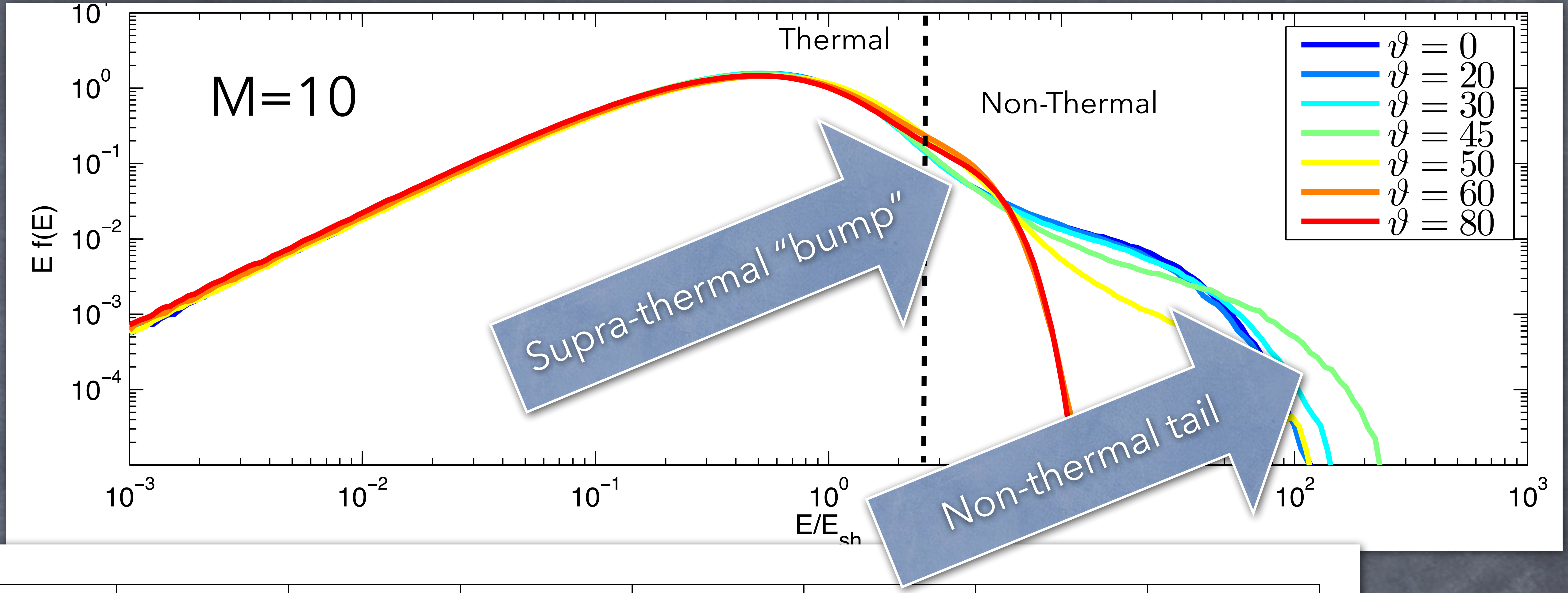


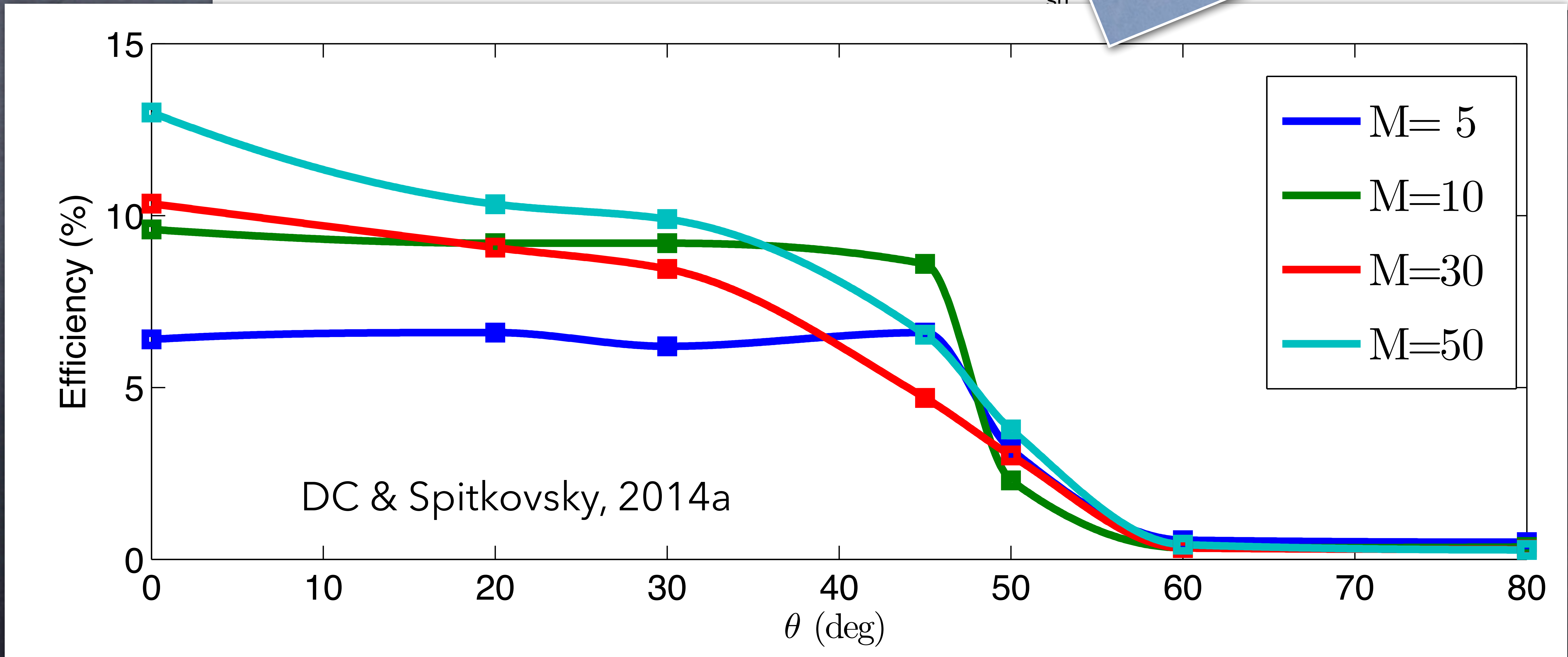
DC & Spitkovsky, 2014a

Parallel vs Oblique shocks

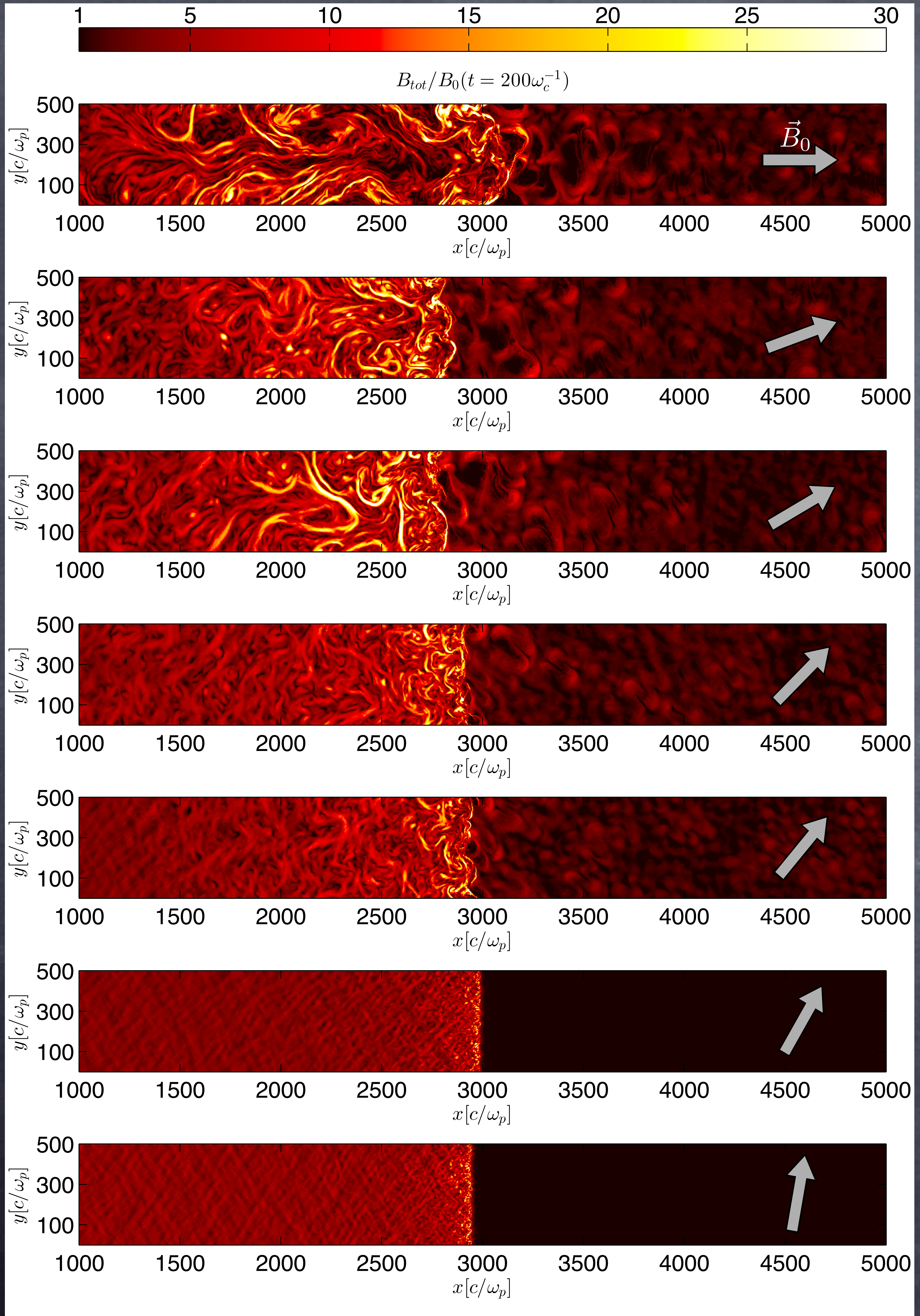
Shock inclination

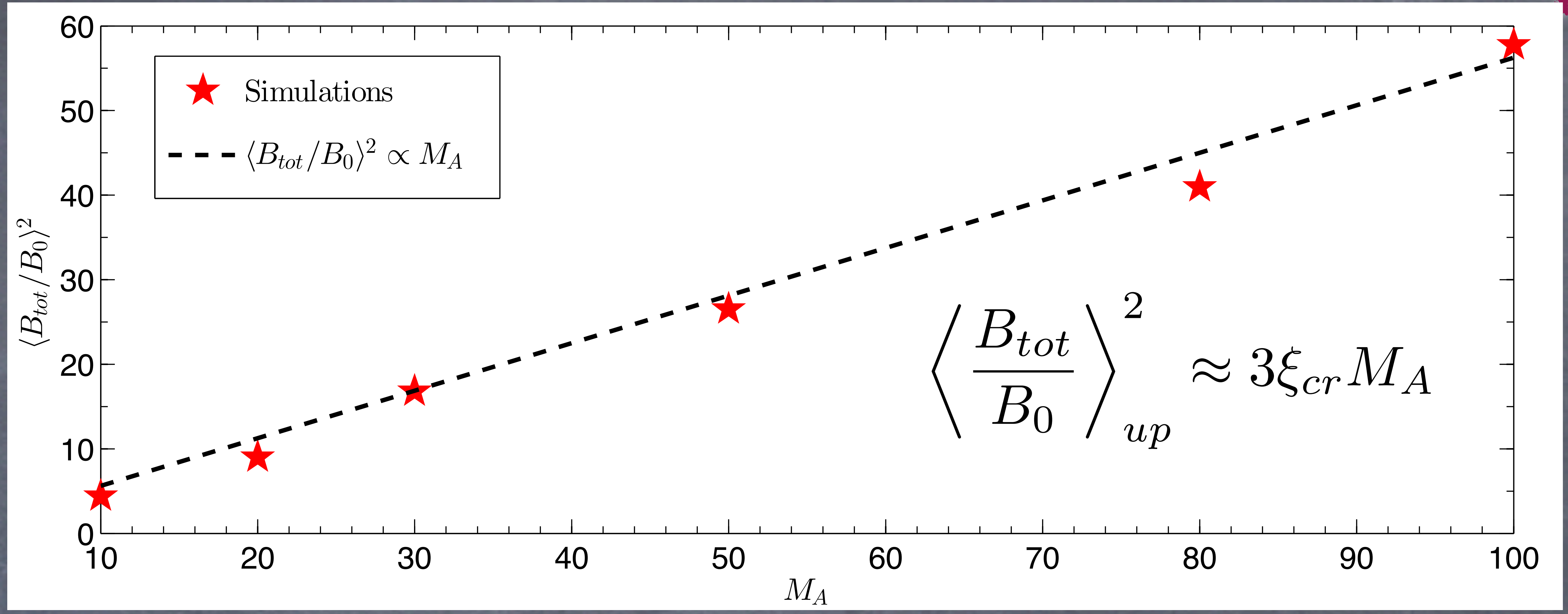






Dependence on shock strength (M_A) and inclination

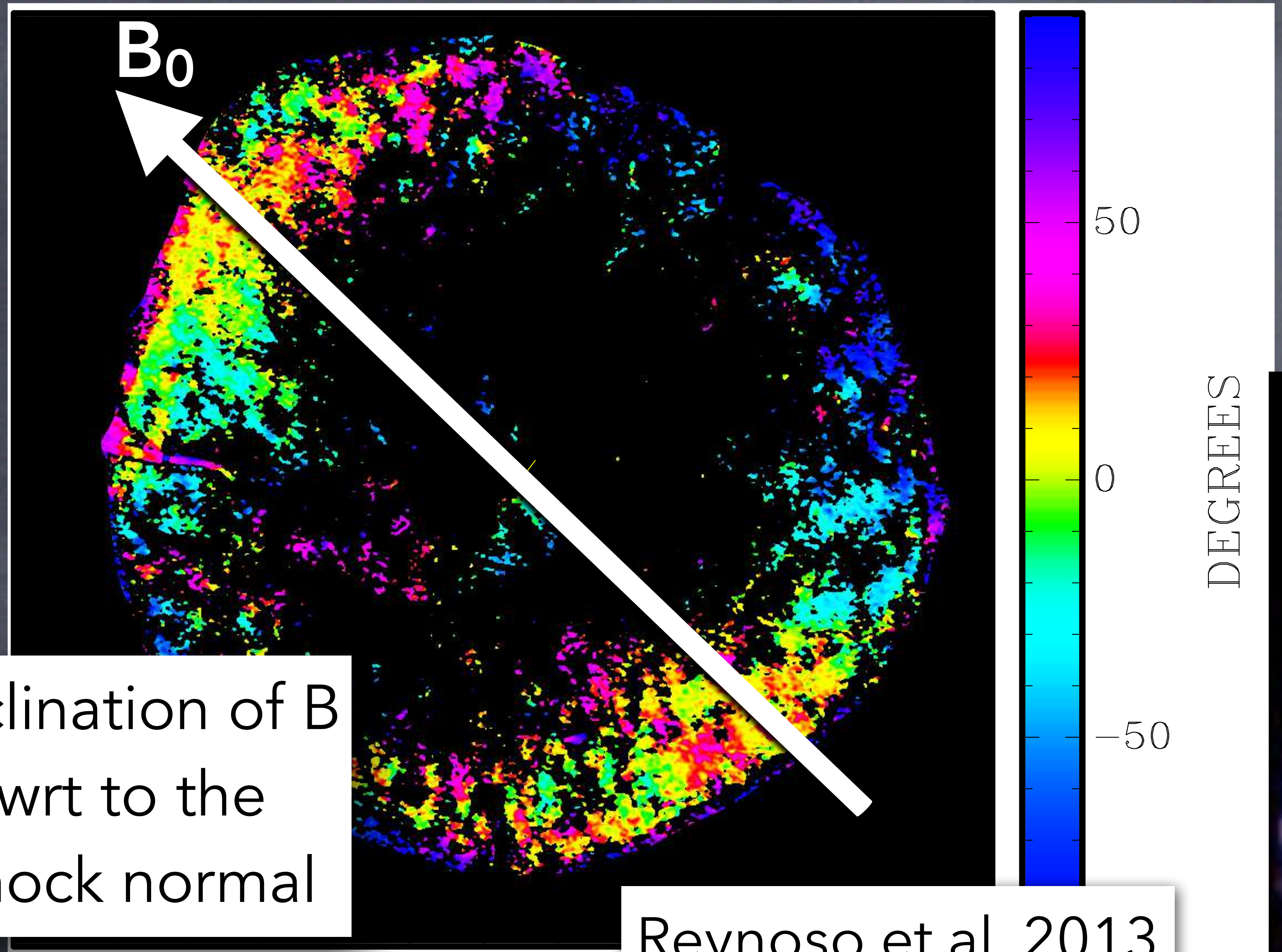




More B amplification for stronger (higher M_A) shocks

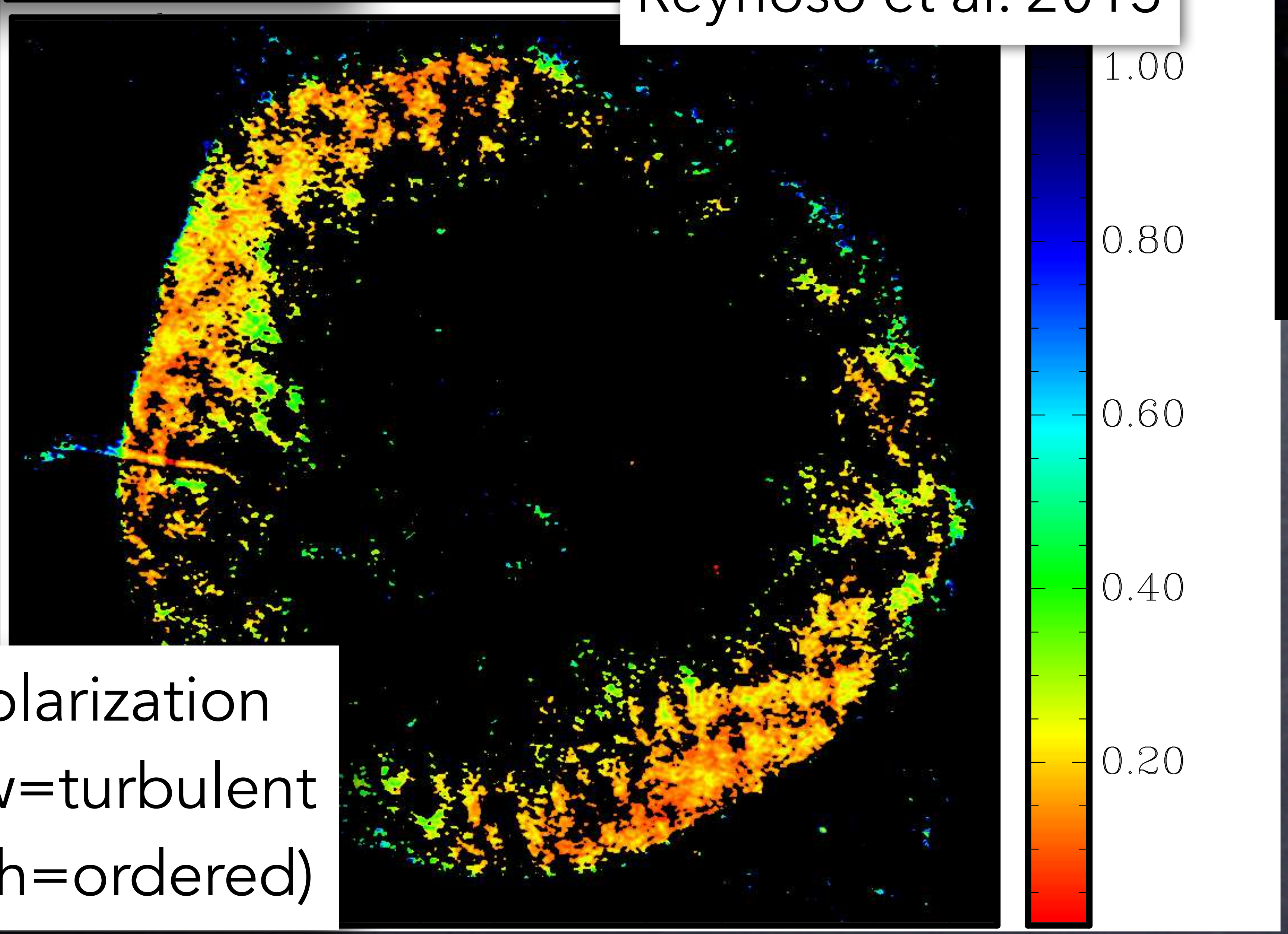
- Different flavors of CR-driven streaming instabilities (Amato & Blasi 2009; DC & Spitkovsky 2014b)
- Study how CRs diffuse in the self-generated turbulence Bohm-like diffusion (DC & Spitkovsky 2014c)

SN 1006: a parallel accelerator



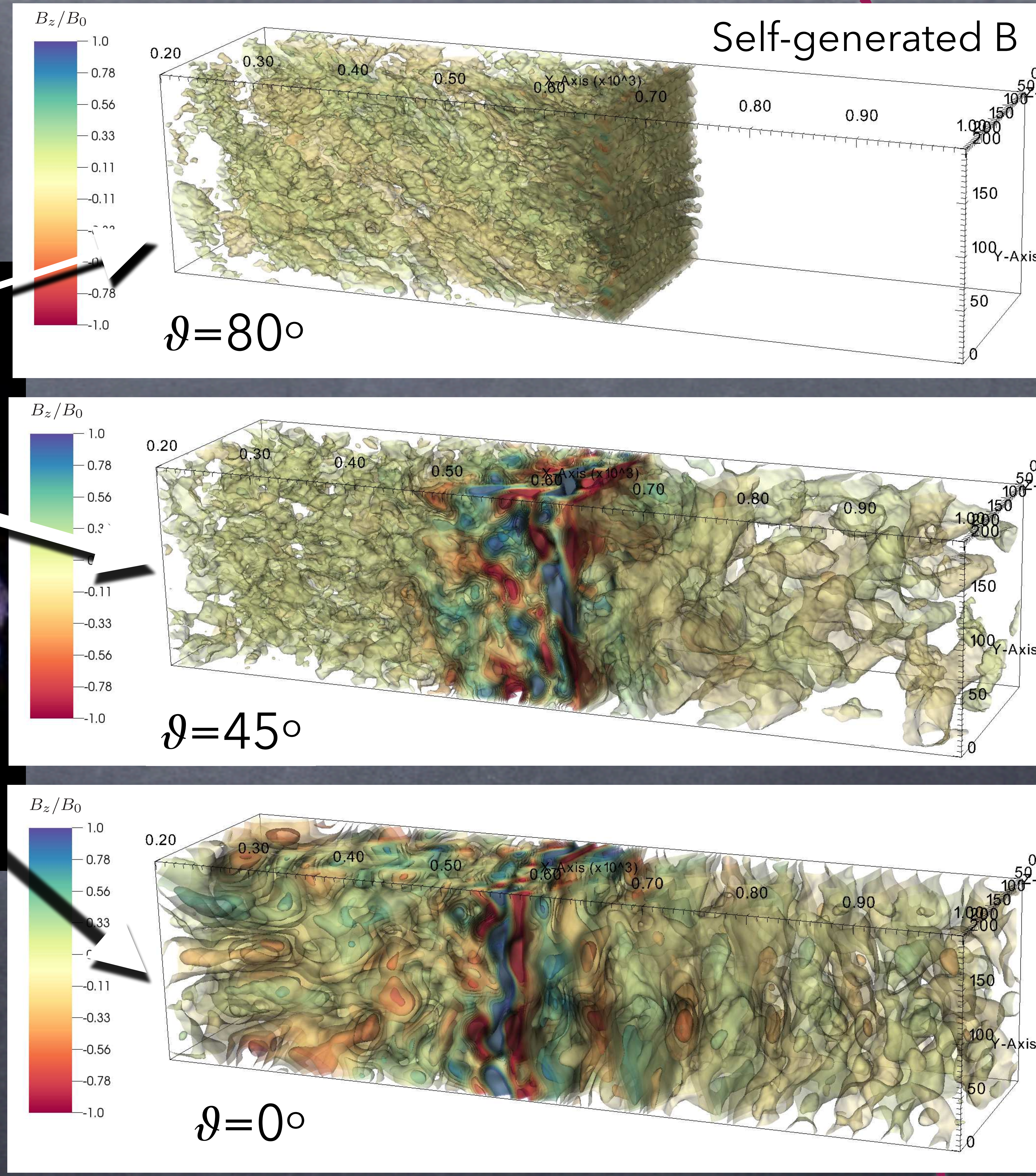
Inclination of B wrt to the shock normal

Reynoso et al. 2013



Polarization (low=turbulent high=ordered)

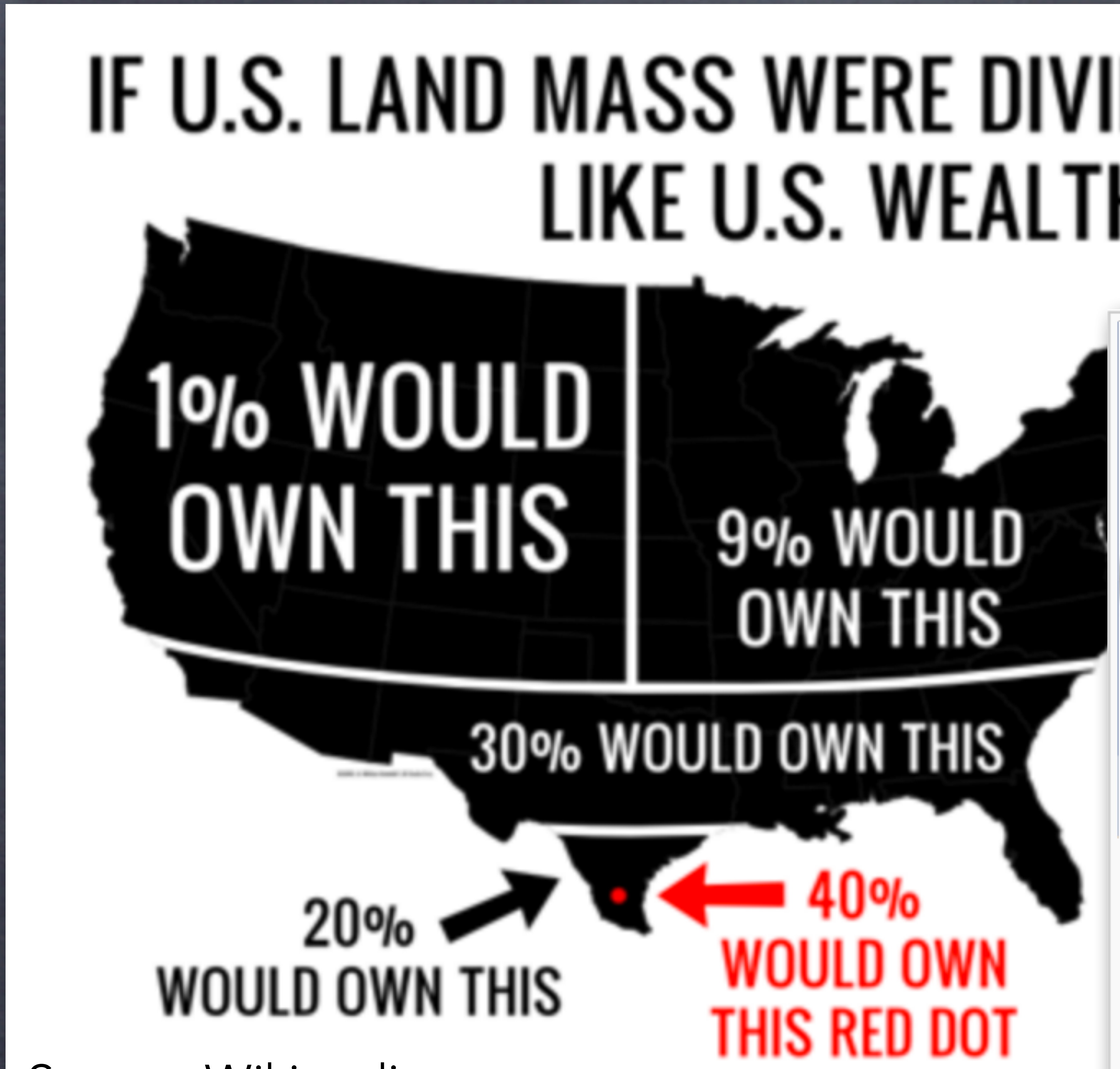
X-ray emission:
red=thermal
white=synchrotron



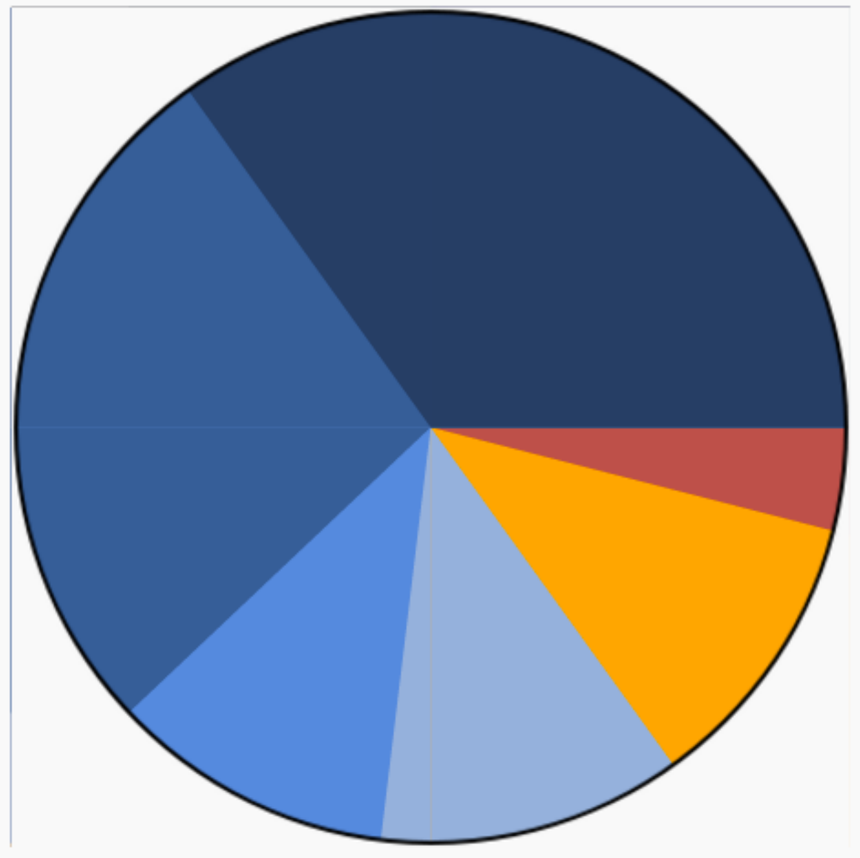
B amplification and ion acceleration where the shock is parallel

DC & Spitkovsky, 2014a

Cosmic Wealth

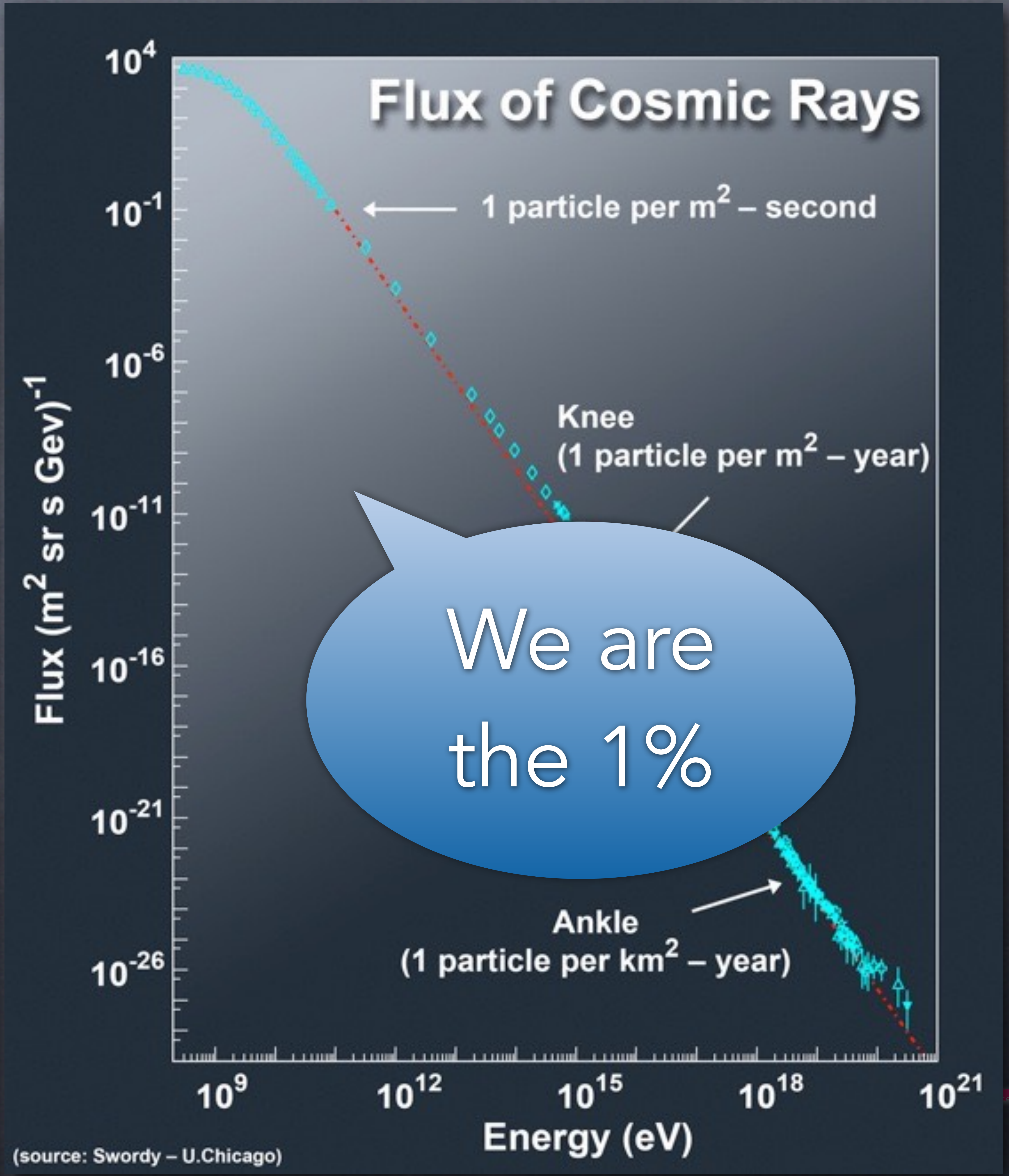


Source: Wikipedia



Distribution of net worth in the United States (2007).[13] The net wealth of many people in the lowest 20% is negative because of debt.[13] By 2014 the wealth gap deepened.

- Top 1% (35%)
- Next 4% (27%)
- Next 5% (11%)
- Next 10% (12%)
- **Upper Middle 20%** (11%)
- **Middle 20%** (4%)
- **Bottom 40%** (<1%)



The top 1% carries ~one third of the total US wealth

How to Become Non-Thermal: the Injection Problem

What determines the fraction of particles that become CRs?

3 golden rules of Real Estate:

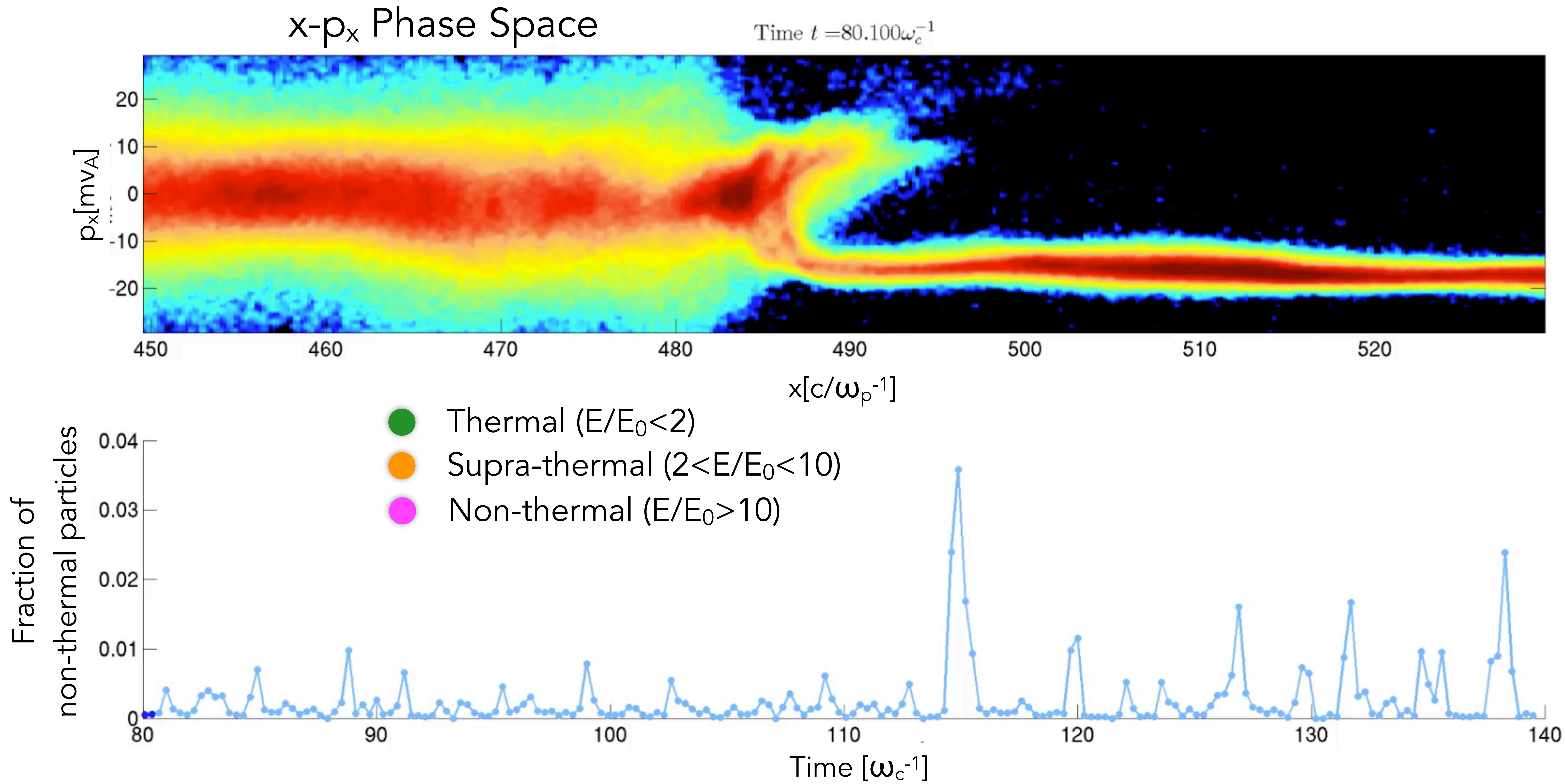
LOCATION,

LOCATION,

LOCATION!

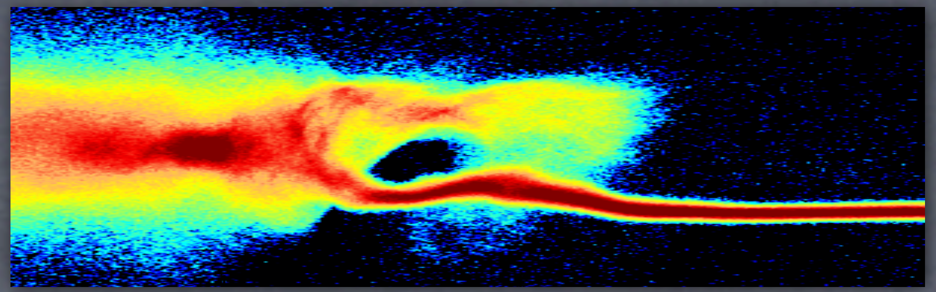
Particle Injection - Simulations

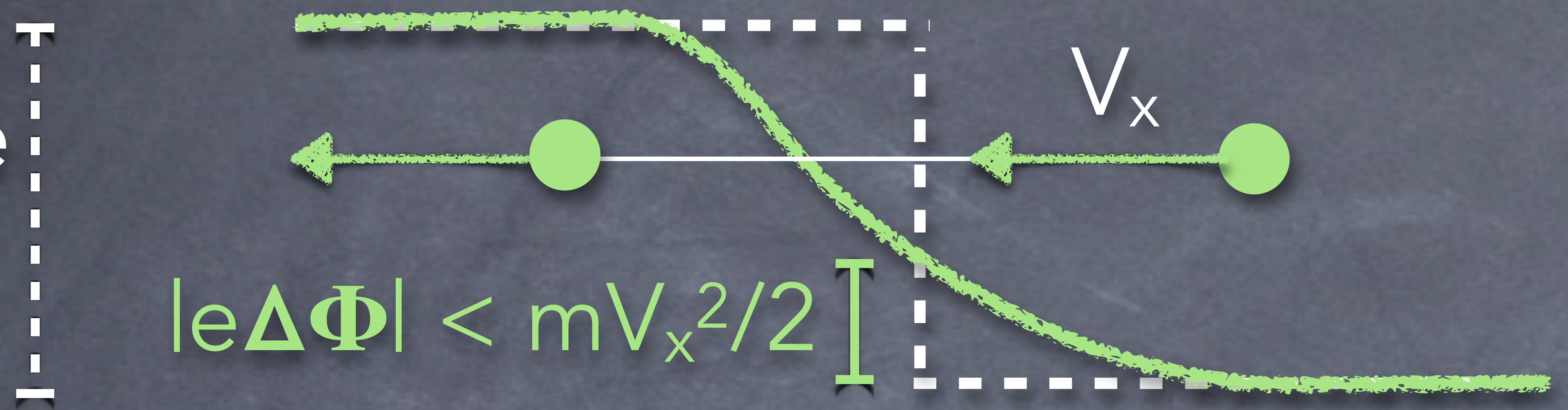
DC, Pop & Spitkovsky, 2015



Encounter with the shock barrier

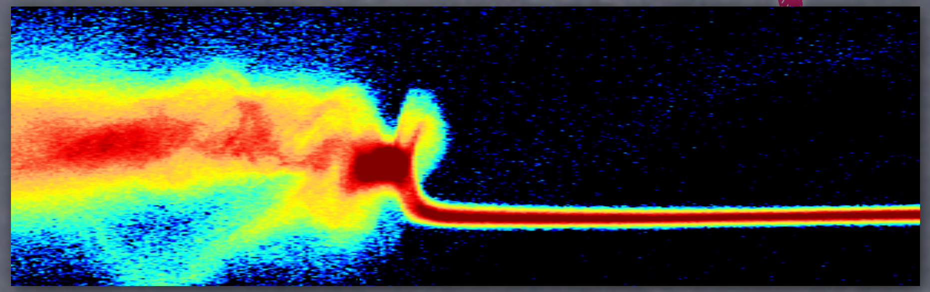
- Low barrier (reformation)

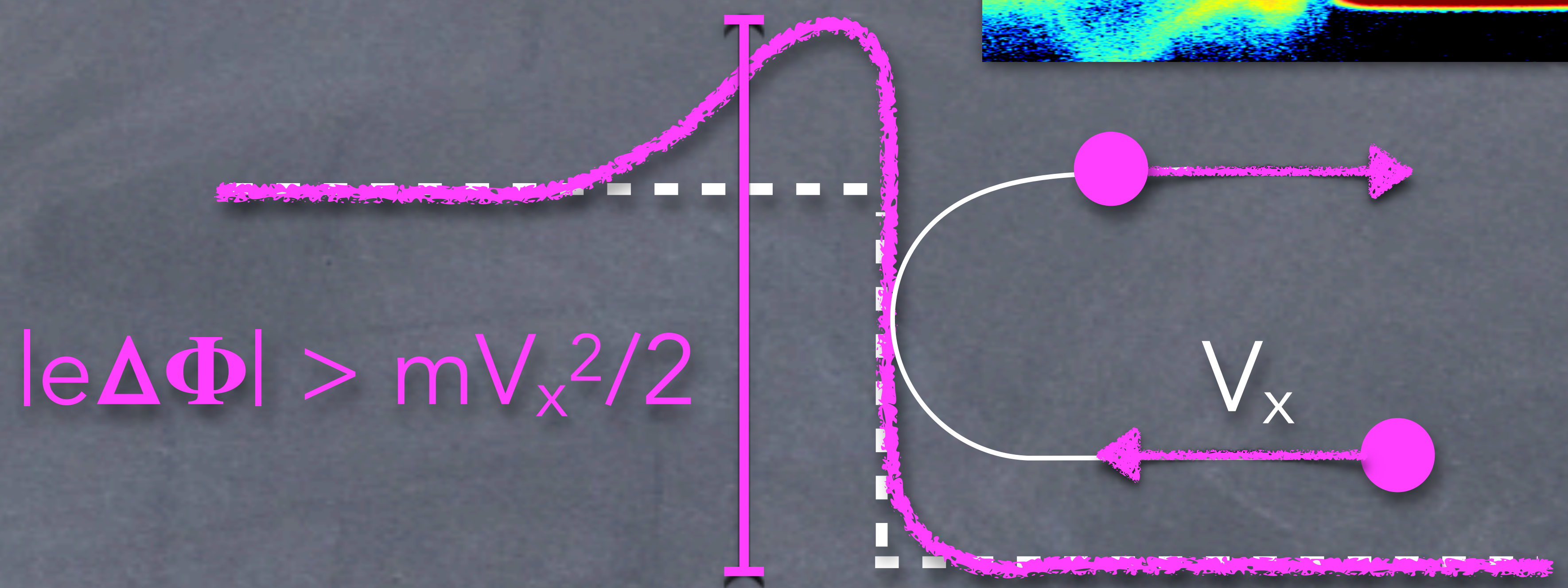




Ions advected downstream, and thermalized

- High barrier (overshoot)





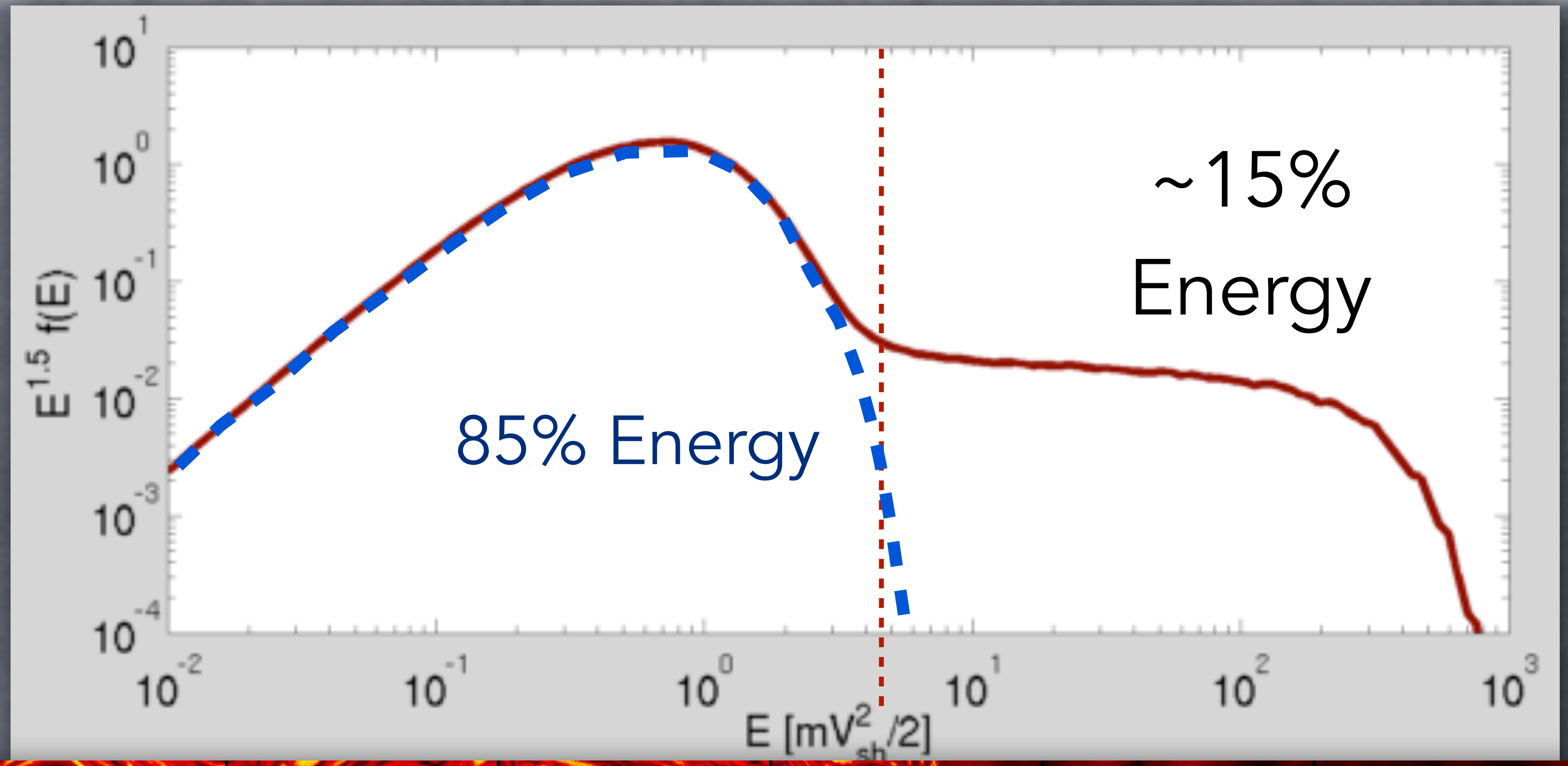
Ions reflected upstream, and energized via Shock Drift Acceleration

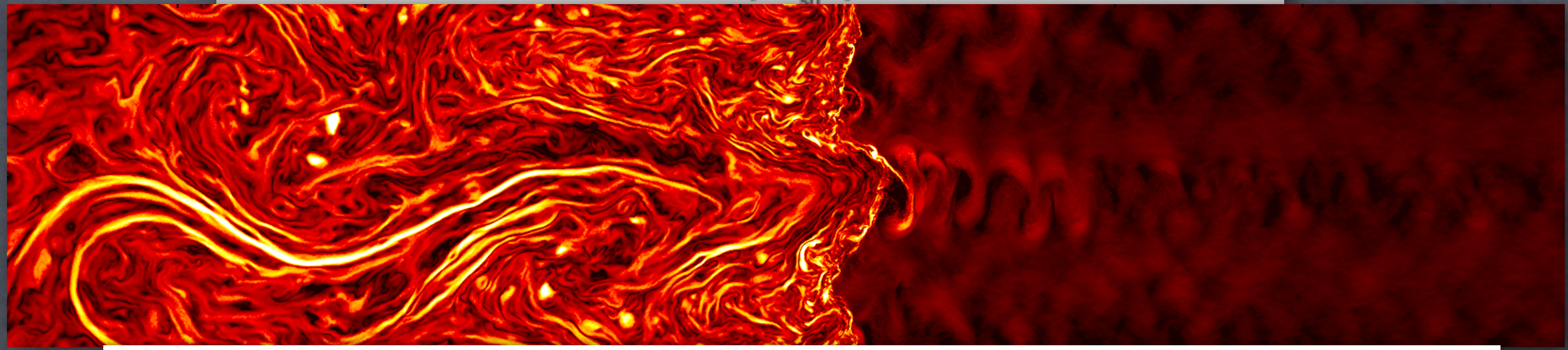
- To overrun the shock, ions need a minimum E_{inj}, increasing with ϑ (DC, Pop & Spitkovsky 15)
  - Ion fate determined by barrier duty cycle (~25%) and shock inclination
- After N SDA cycles, only a fraction $\eta \sim 0.25^N$ has not been advected
  - For $\vartheta=45^\circ$, $E_{inj}\sim 10E_0$, which requires N~3 -> $\eta\sim 1\%$
  - For $\vartheta>45^\circ$, $E_{inj}>10E_0$, hence N>3 and $\eta<<1\%$

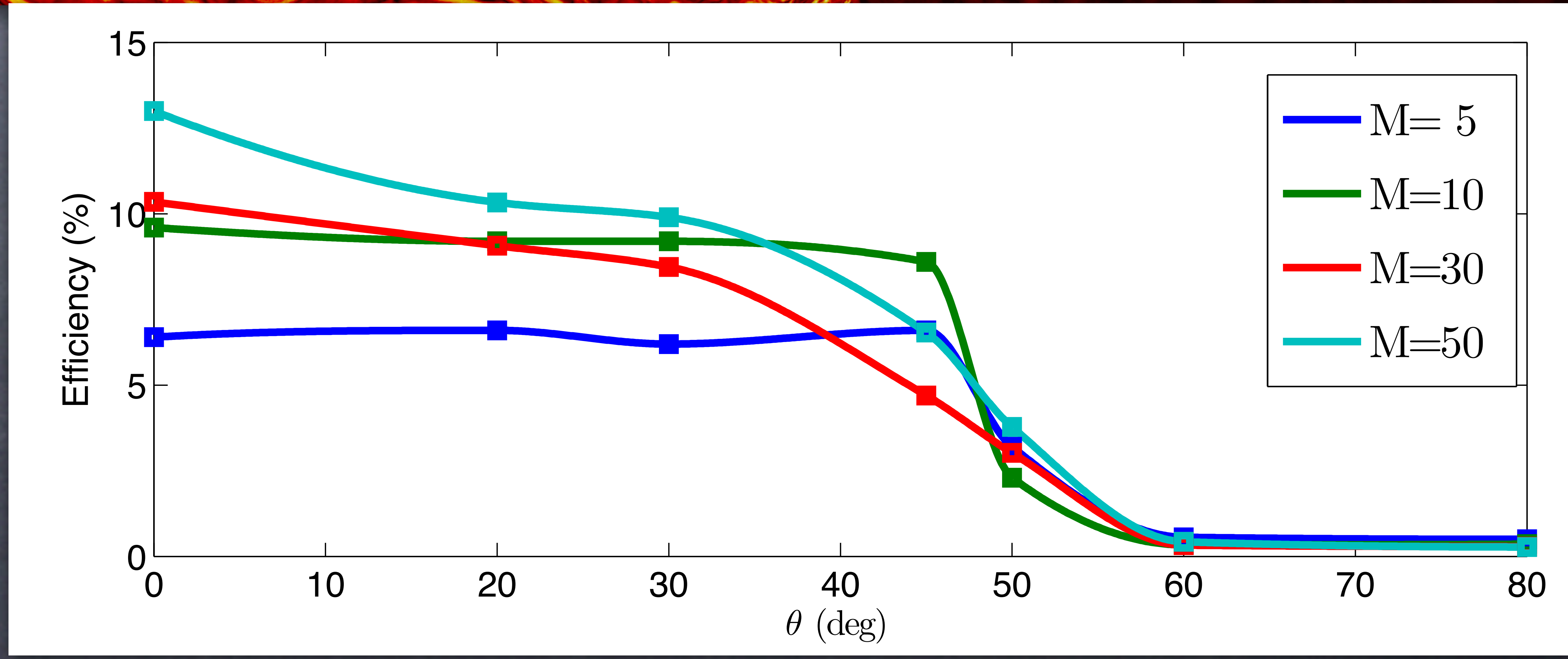
Proton DSA: Summary

- Shock Acceleration can be efficient
- CRs amplify B via streaming instability
- DSA efficient at parallel, strong shocks
- Injection via specular reflection and shock-drift acceleration

- What about other ions?



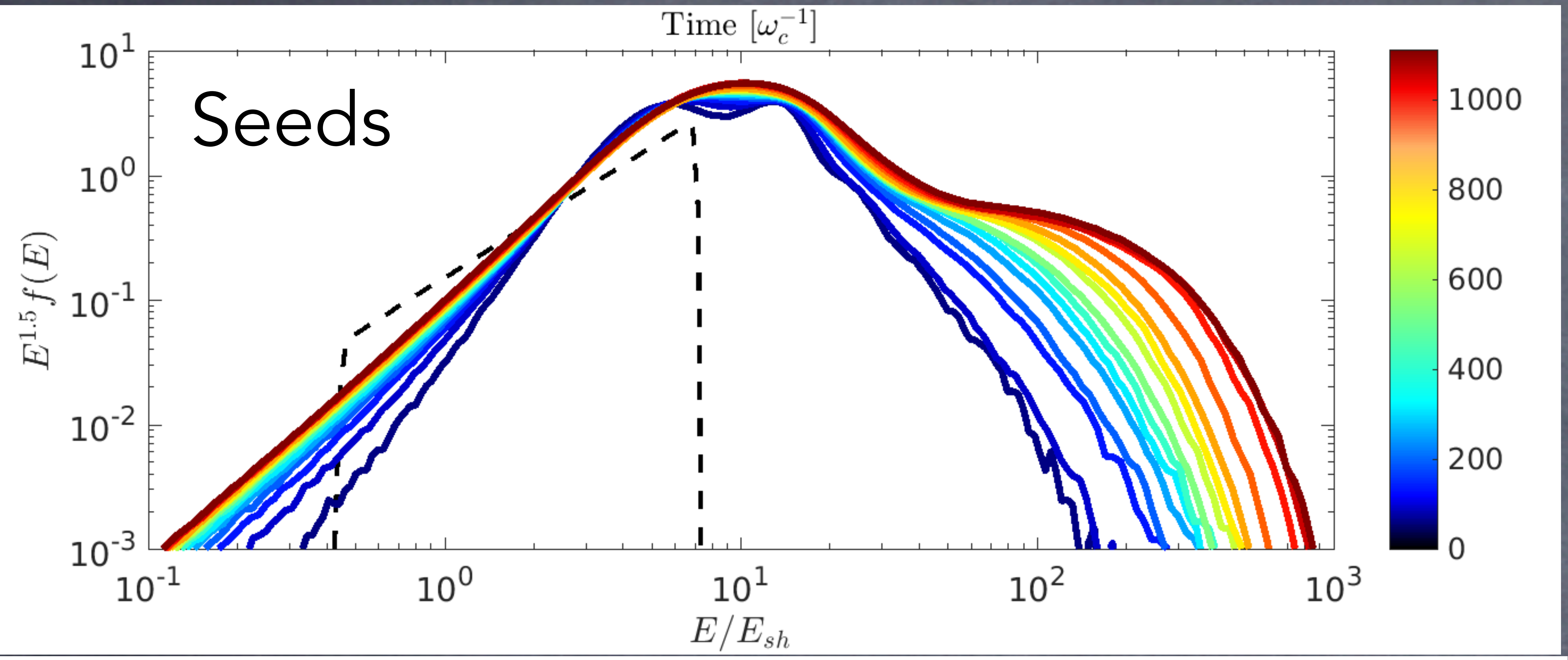


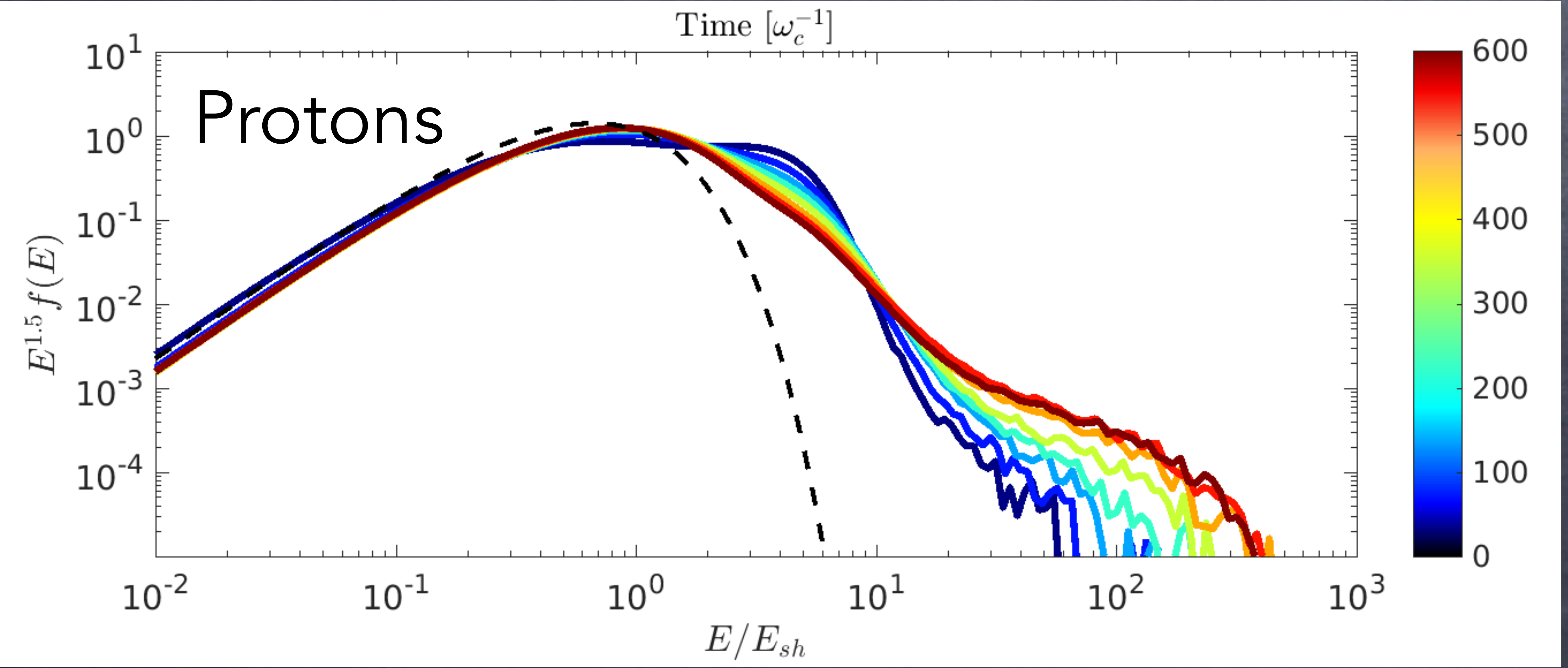


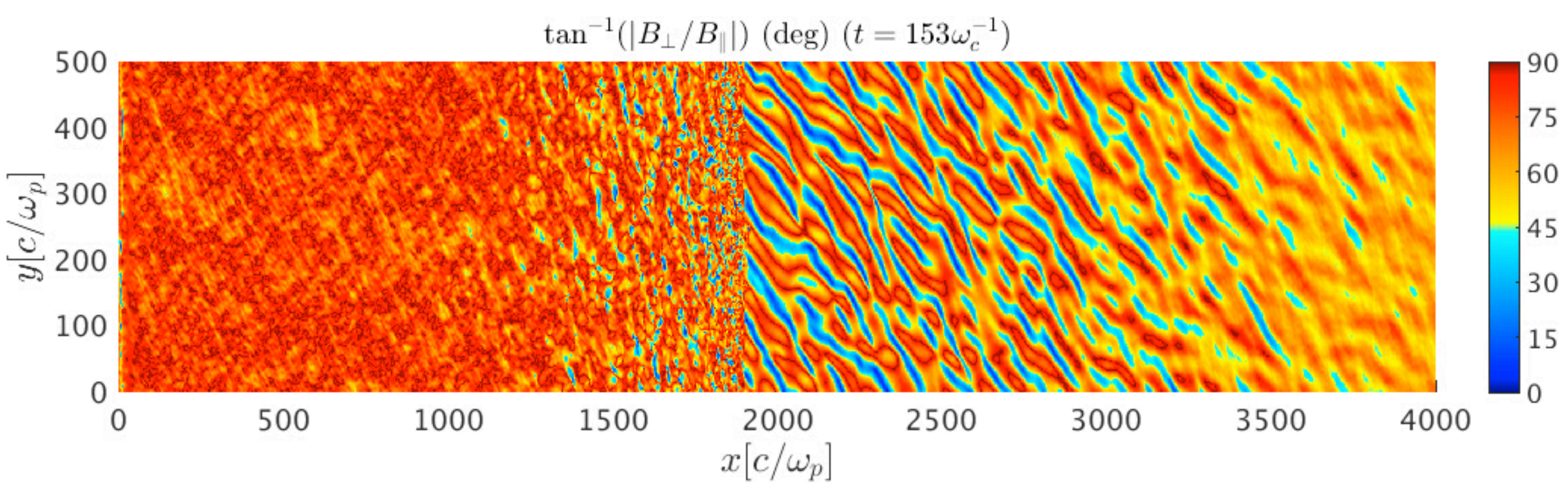
What if there are already energetic particles (seeds)?

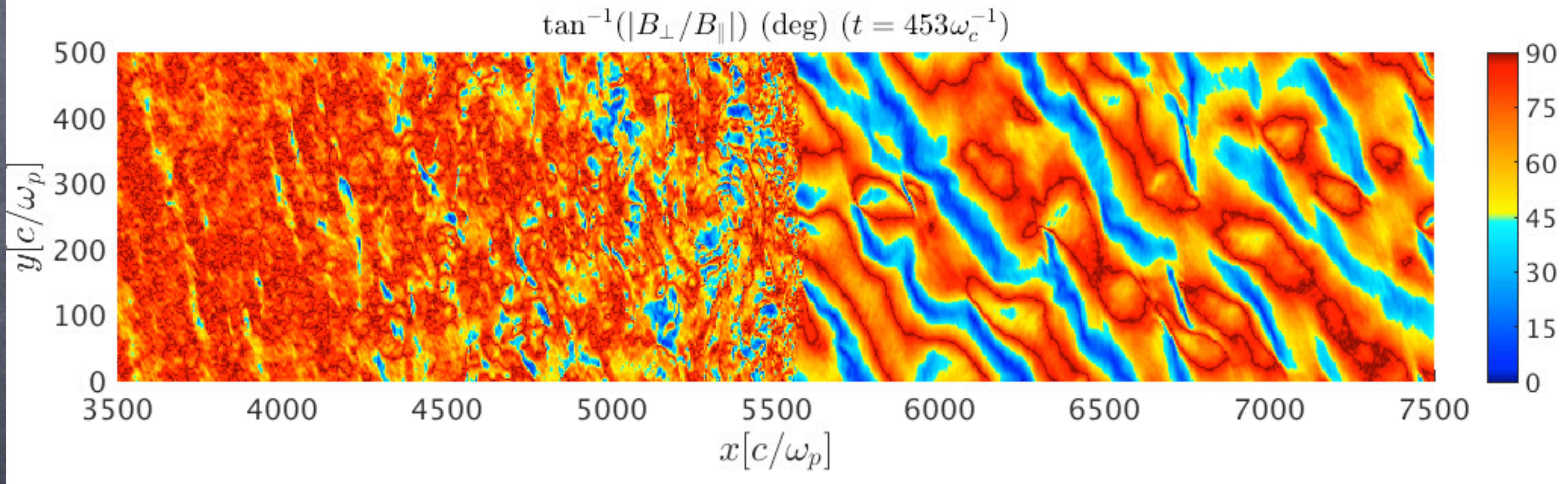
Diffusive Shock Re-Acceleration

- ϑ=60° shock with *isotropic* seeds with $E_{CR}=3E_{sh}$; n_{CR}=0.01 (DC, Zhang, Spitkovsky, 2018)
  - Seeds are effectively reflected at the shock, amplify the upstream B, and undergo DSA: DSRA!



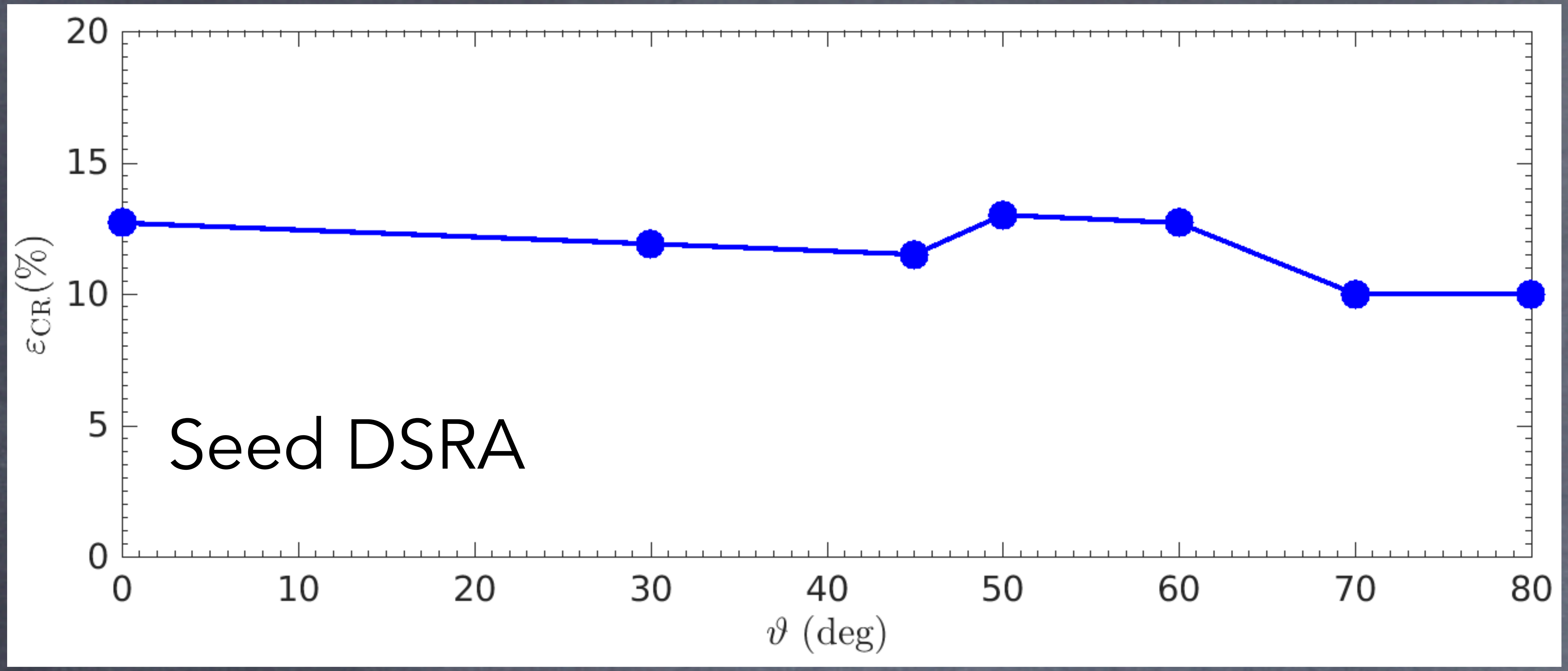


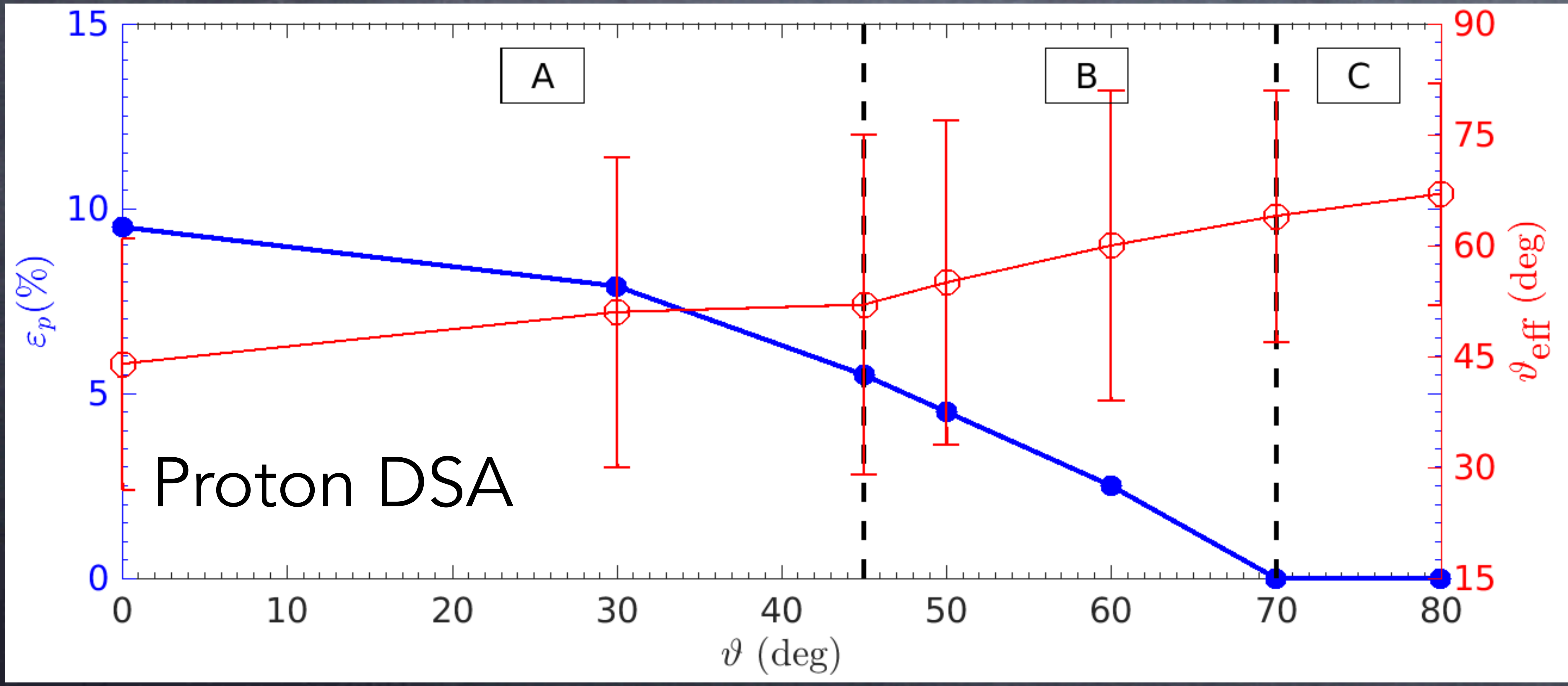




B-amplification opens up quasi-parallel patches at the shock where protons can be injected

Efficiency

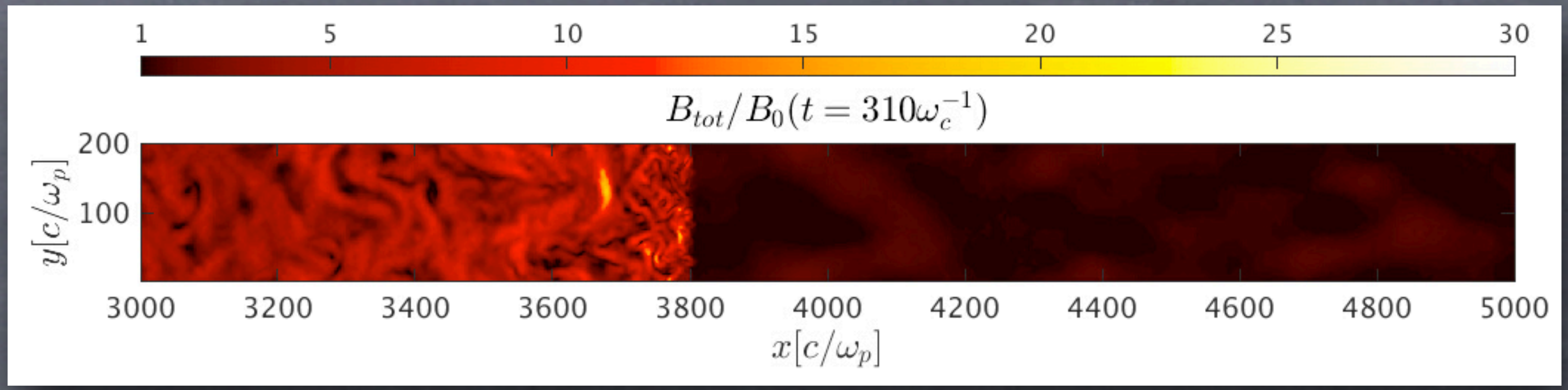


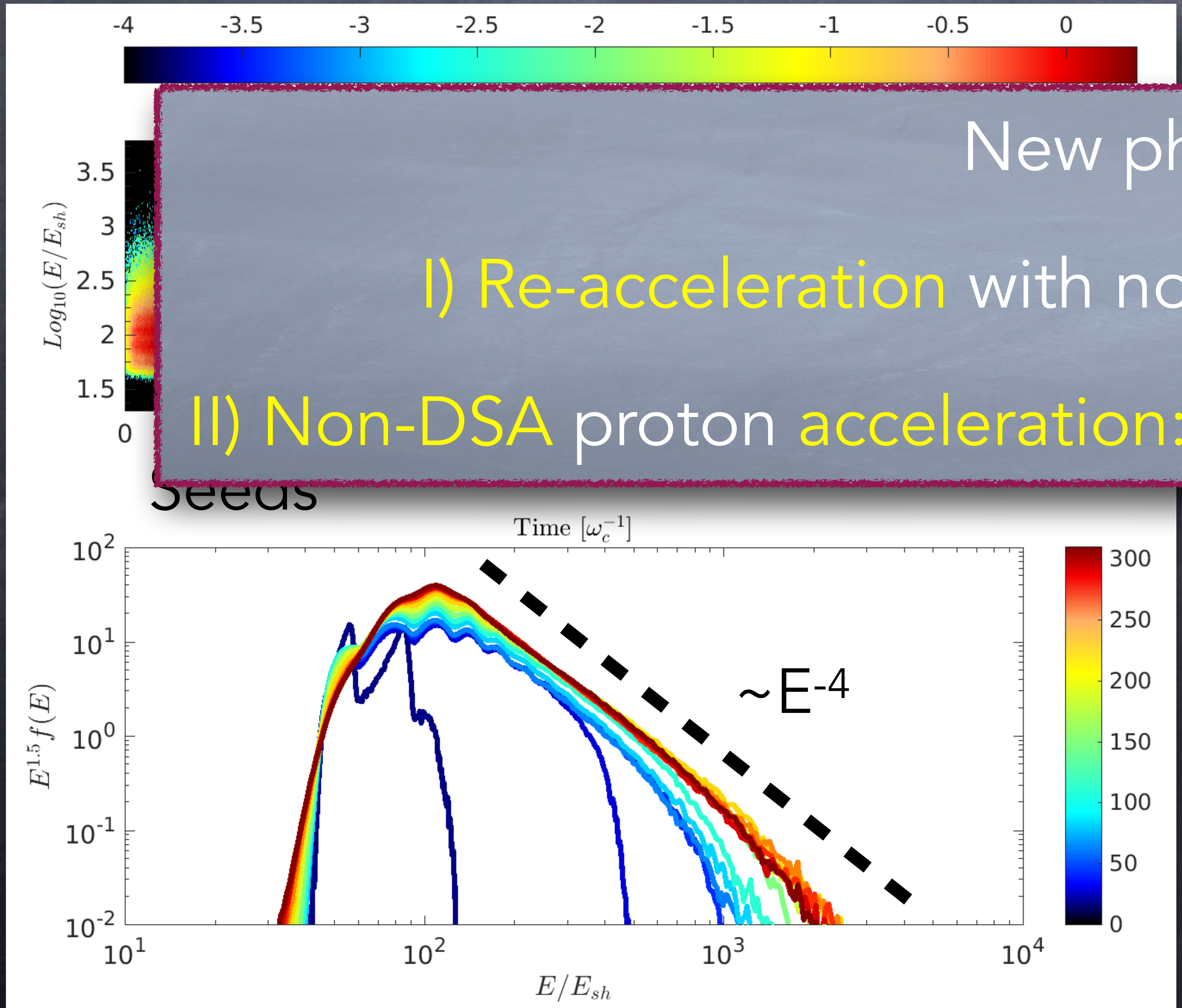


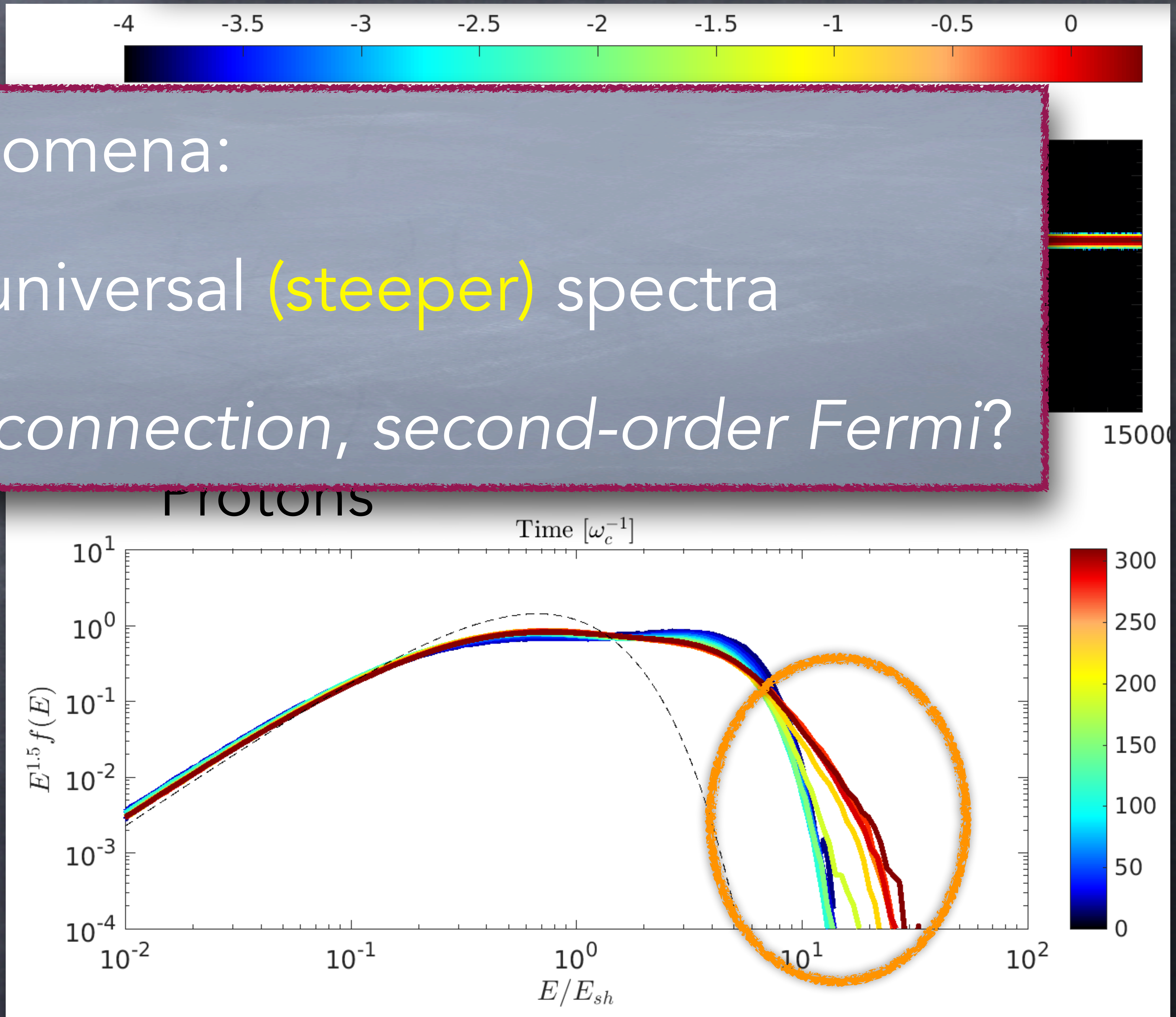
- Seed DSRA independent of ϑ, about 4x the initial CR energy density
  - *Absolute* efficiency depends on seed energy density
- Also electrons can be reaccelerated!
- A (ϑ<45°): Same proton efficiency
- (45°<ϑ<70°): Boosted to few %
- C (ϑ>70°): No proton DSA

Quasi-Perpendicular SEEDED Shocks

- ϑ=80° quasi-perp shock with seeds $E_{CR}=3E_{sh}$
  - Seeds diffuse but their spectrum is steeper than DSA
  - Non-thermal protons only downstream







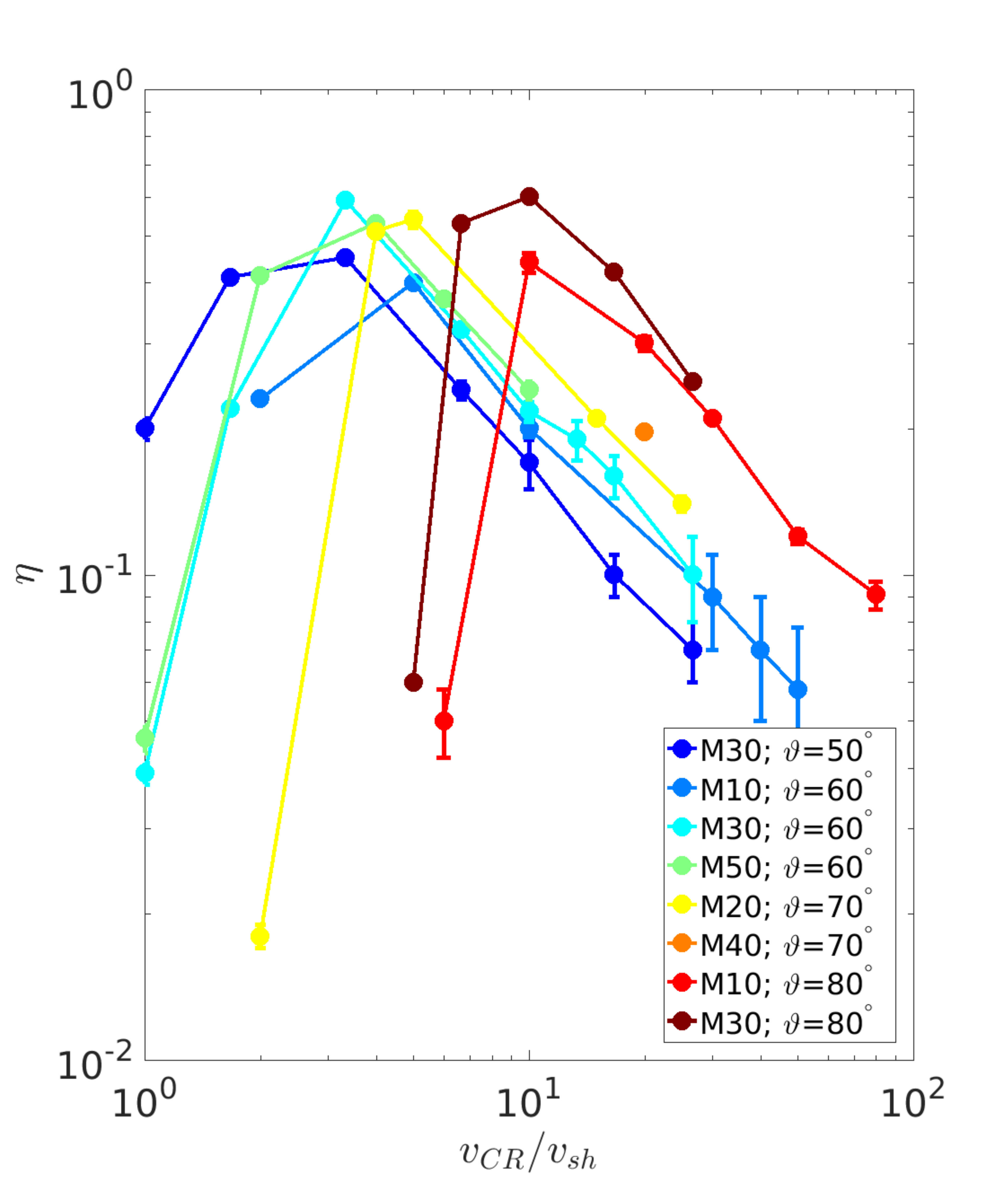
New phenomena:

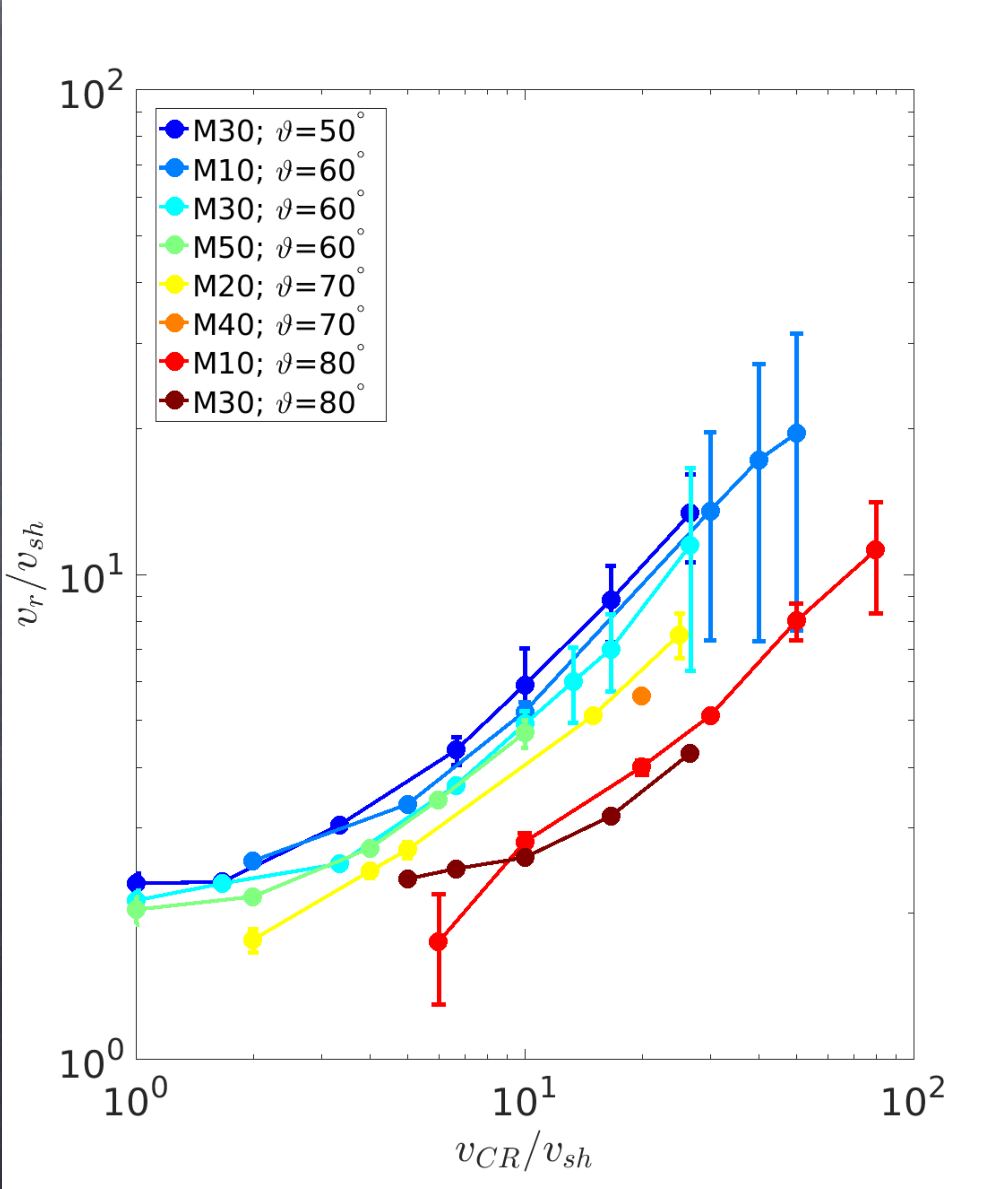
I) Re-acceleration with non-universal (steeper) spectra

II) Non-DSA proton acceleration: *reconnection, second-order Fermi*?

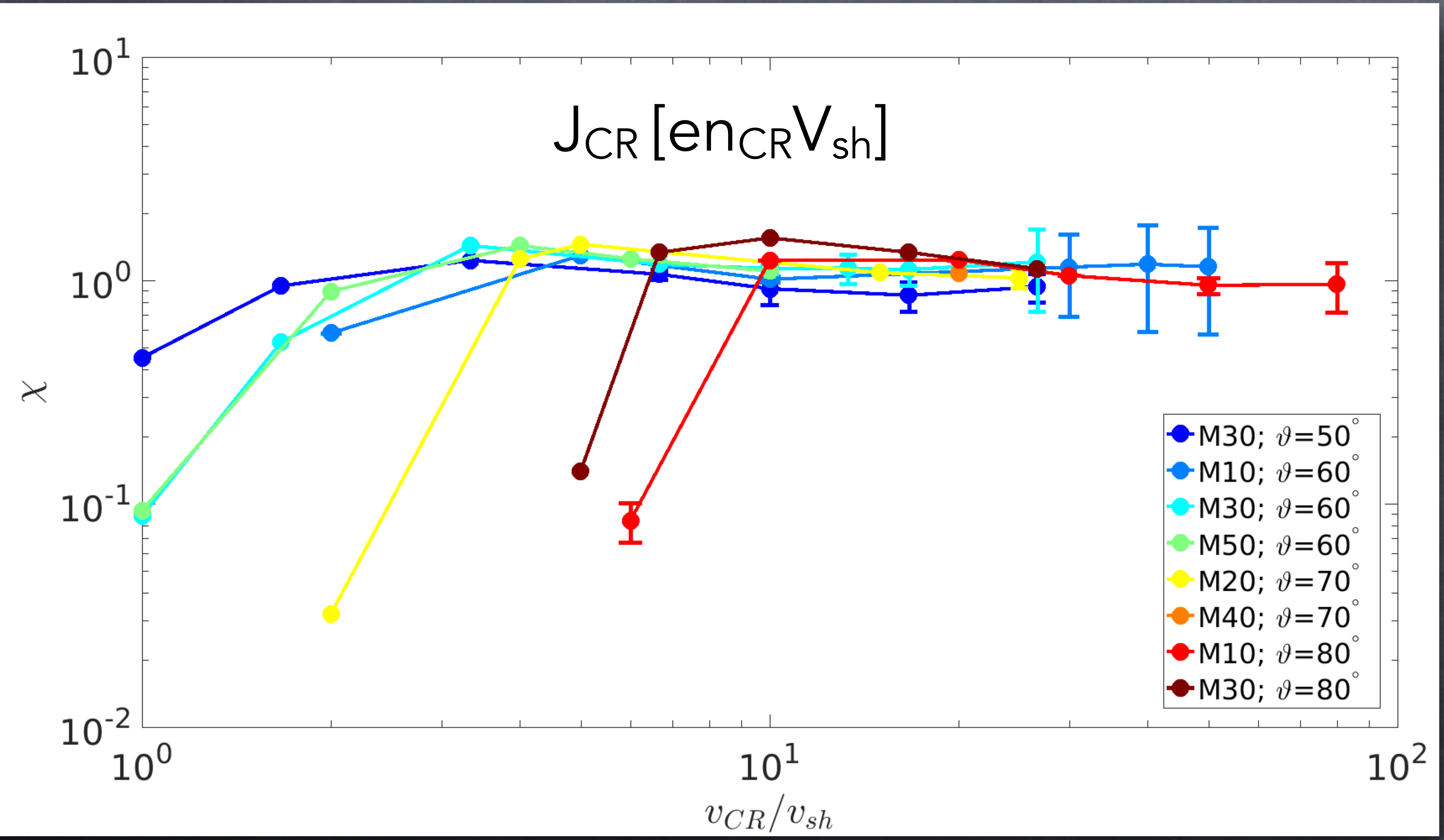
The Current in Reflected CRs

- Depends on the fraction of reflected seeds, η, and their speed, v_r





A *Universal* Current in Reflected CRs



- η and v_r "magically" balance their dependence on ϑ and M exactly:

$$J_{CR} = e n_{CR} V_{sh}$$

- Easy explanation: CRs tend to become isotropic at the shock, *in the shock frame*: they become anisotropic *in the upstream frame*
- For SNRs and Galactic CRs:

$$T_{\text{stream inst}} \sim 10\,\text{yr}$$

Minimum level of B-amplification for shocks in the ISM

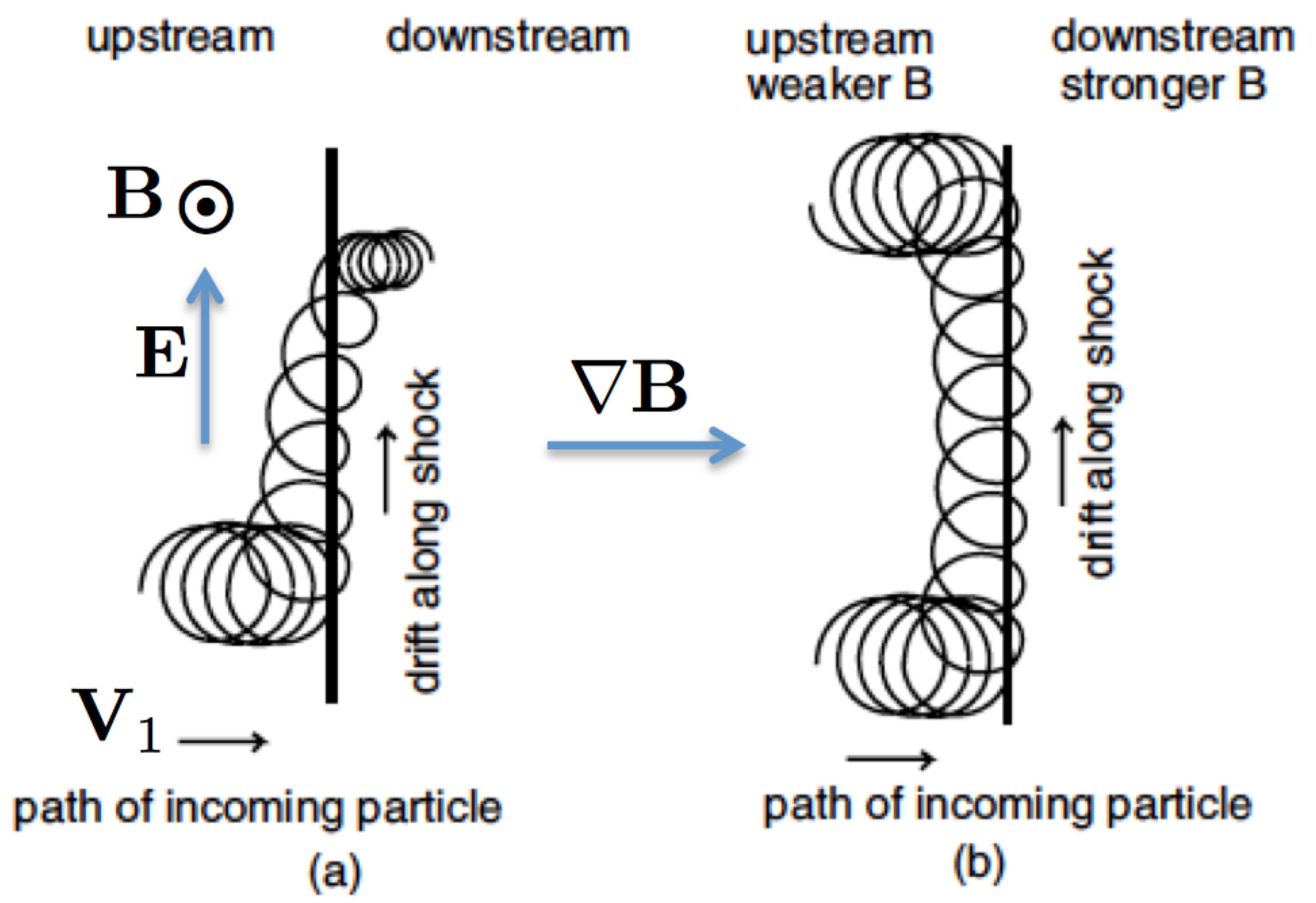
What about electrons?

Ion vs Electron Injection

- Ions injected by specular reflection
  - Their magnetic moment $W_\perp = p_\perp^2/B$ is not conserved: the shock is evolving on their gyro-time!
- Electrons cannot be reflected by the shock potential barrier, but conserve their $W_\perp$
  - ∇B-drift + shock drift acceleration

$$\mathbf{v}_{\nabla B} = \frac{W_\perp}{qB}\frac{\mathbf{B}\times\nabla B}{B^2} \qquad \mathbf{E} = -\mathbf{V}_1/c\times\mathbf{B}$$

  - Electron injection requires oblique shocks!
    - How can we have simultaneous acceleration of ions and electrons?



cartoon: Ball & Melrose 2001

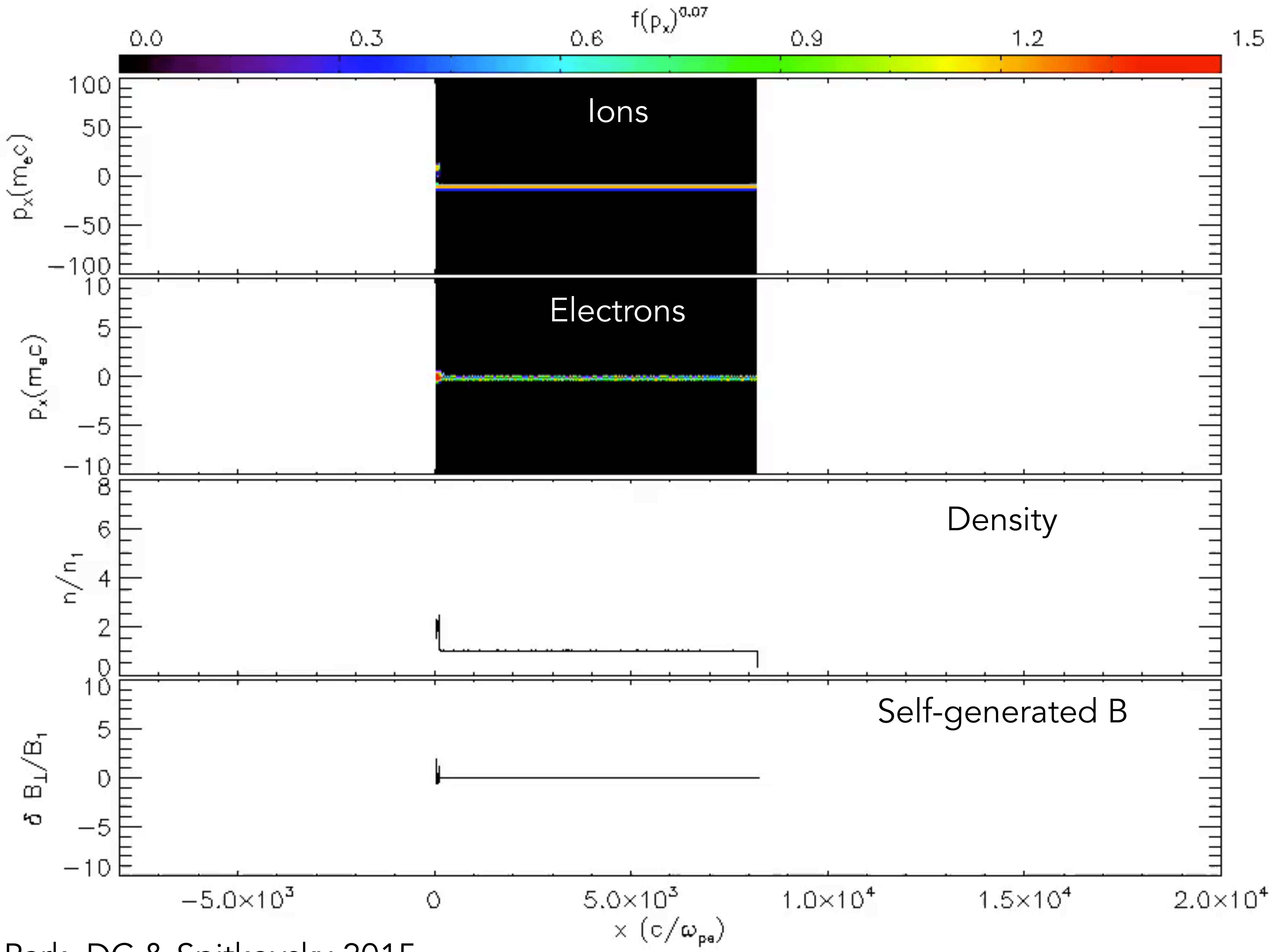
Reflection condition: $\theta_p > \theta_{\mathrm{crit}}$

$$\theta_p = \angle(\mathbf{v}, \mathbf{B_1})$$

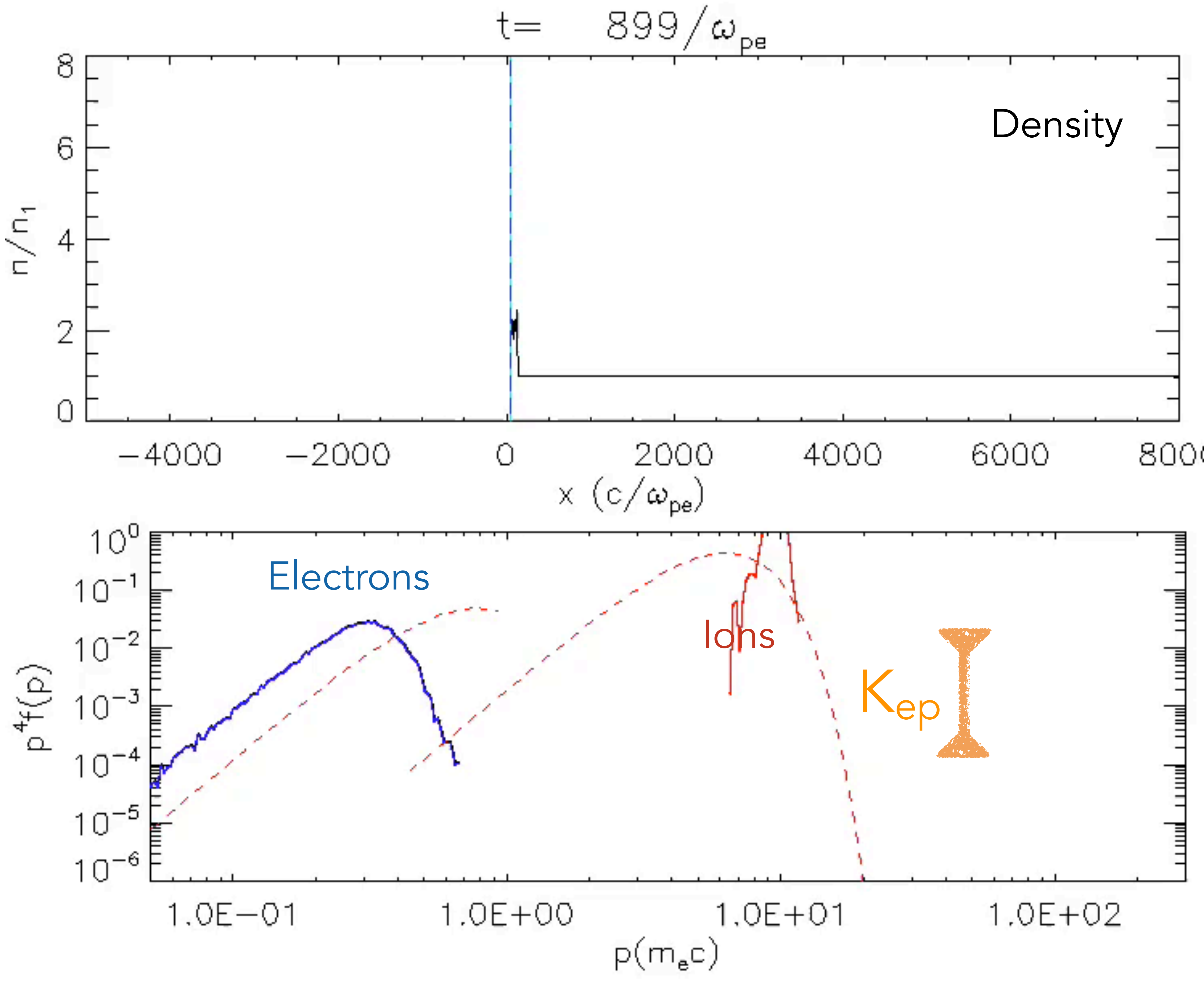
$$\theta_{\mathrm{crit}} = \sin^{-1}\sqrt{B_1/B_2}$$

Electron Acceleration

- Full PIC simulations (Tristan-MP code) M=20, V_{sh}=0.1c, quasi-parallel (ϑ=30°) 1D shock



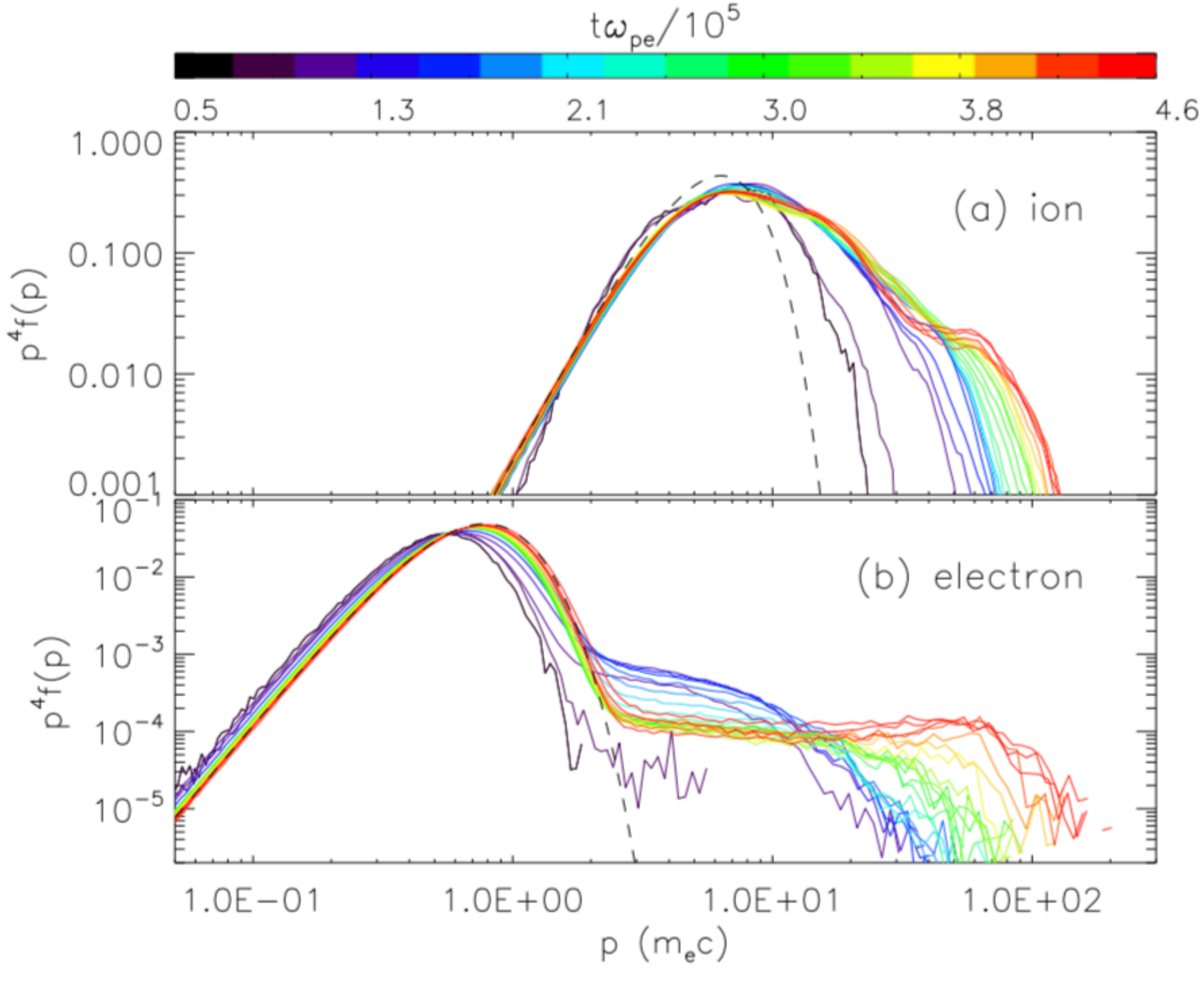
Park, DC & Spitkovsky 2015

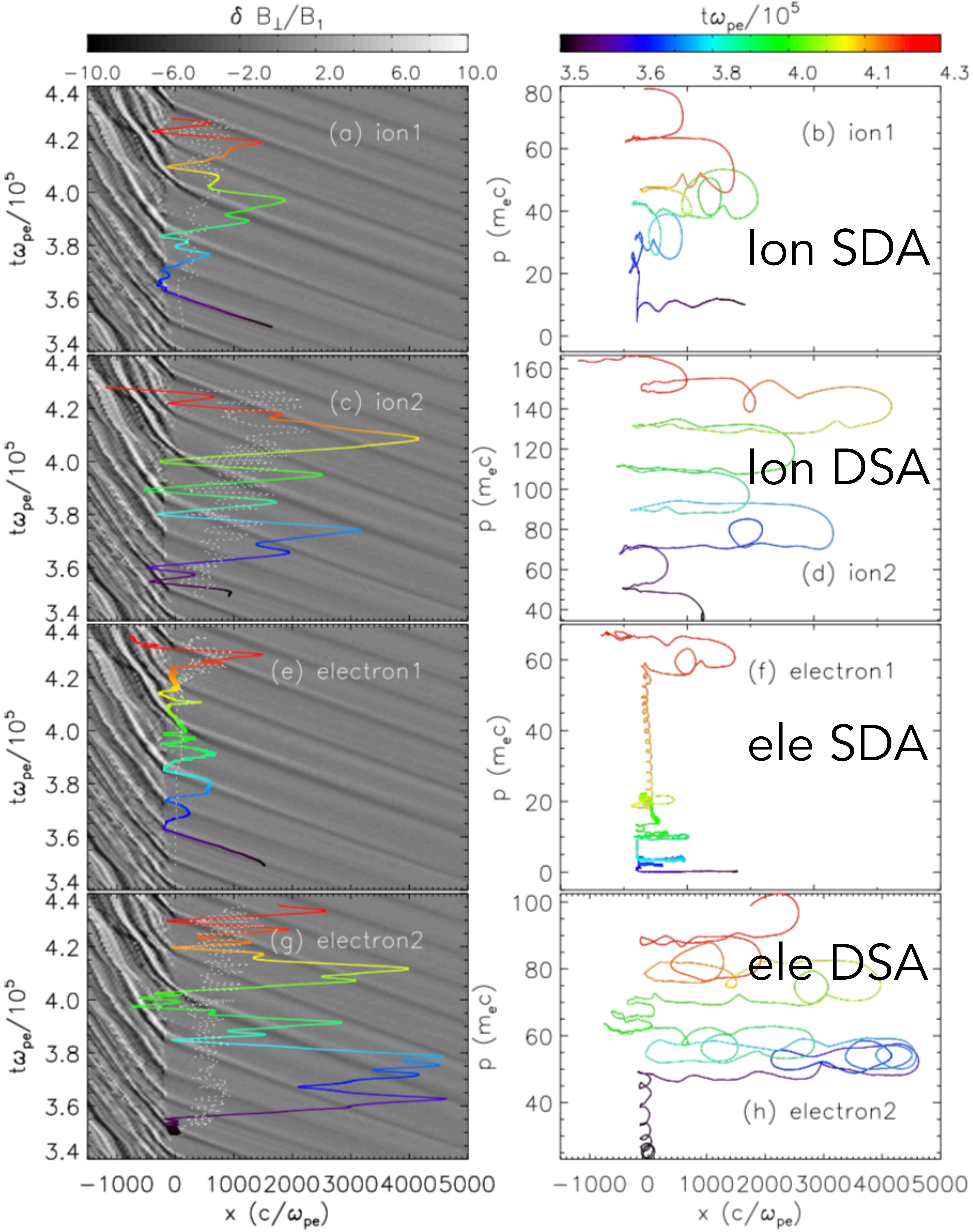


Electron/proton ratio K_{ep}~0.01

Electron injection

- Electron pre-heating via SDA
- DSA starts at the same p_{inj} as for ions



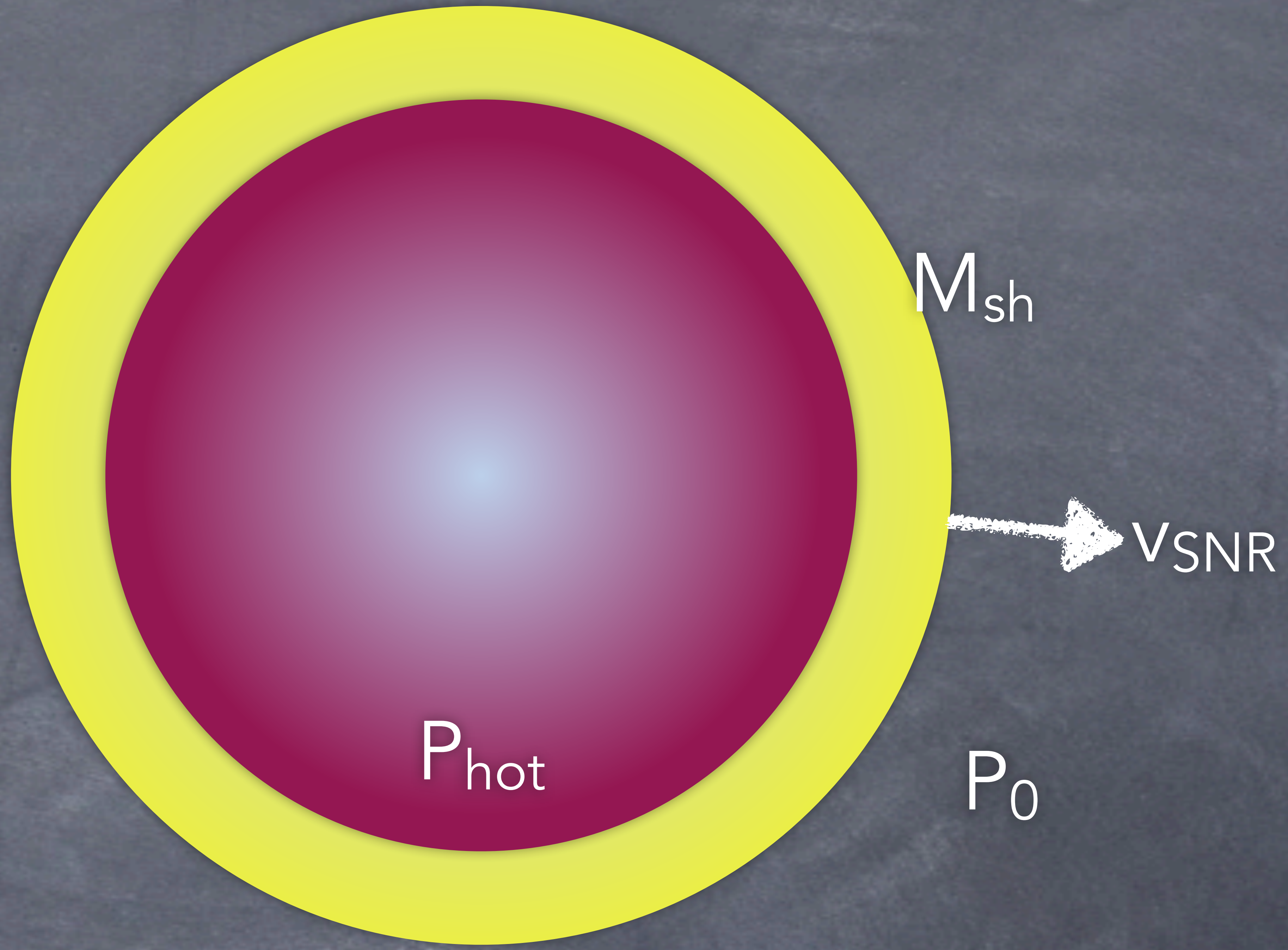


What is the feedback of

CRs on SNR evolution?

SNR Evolution in a Thin-Shell

- **Ejecta-dominated** stage: $R_{sh} \sim V_{sh}\, t$
- **Sedov-Taylor** (adiabatic) stage: $R_{sh} \sim t^{2/5}$
- **Radiative stage** ($T_{sh} <\sim 10^6$K)
  - Pressure-driven snowplow ($P_{hot} > P_0$)
  - Momentum-driven snowplow ($P_{hot} \sim P_0$)



$$\frac{d\left(M_{\rm sh} v_{\rm SNR}\right)}{dt} = 4\pi r_{\rm SNR}^2 \left(P_{\rm hot} - P_0\right),$$

SNRs deposit energy and momentum in the interstellar medium
Crucial for feedback that can suppress star formation!