E. Fermi School - Varenna (LC)
June 26, 2022

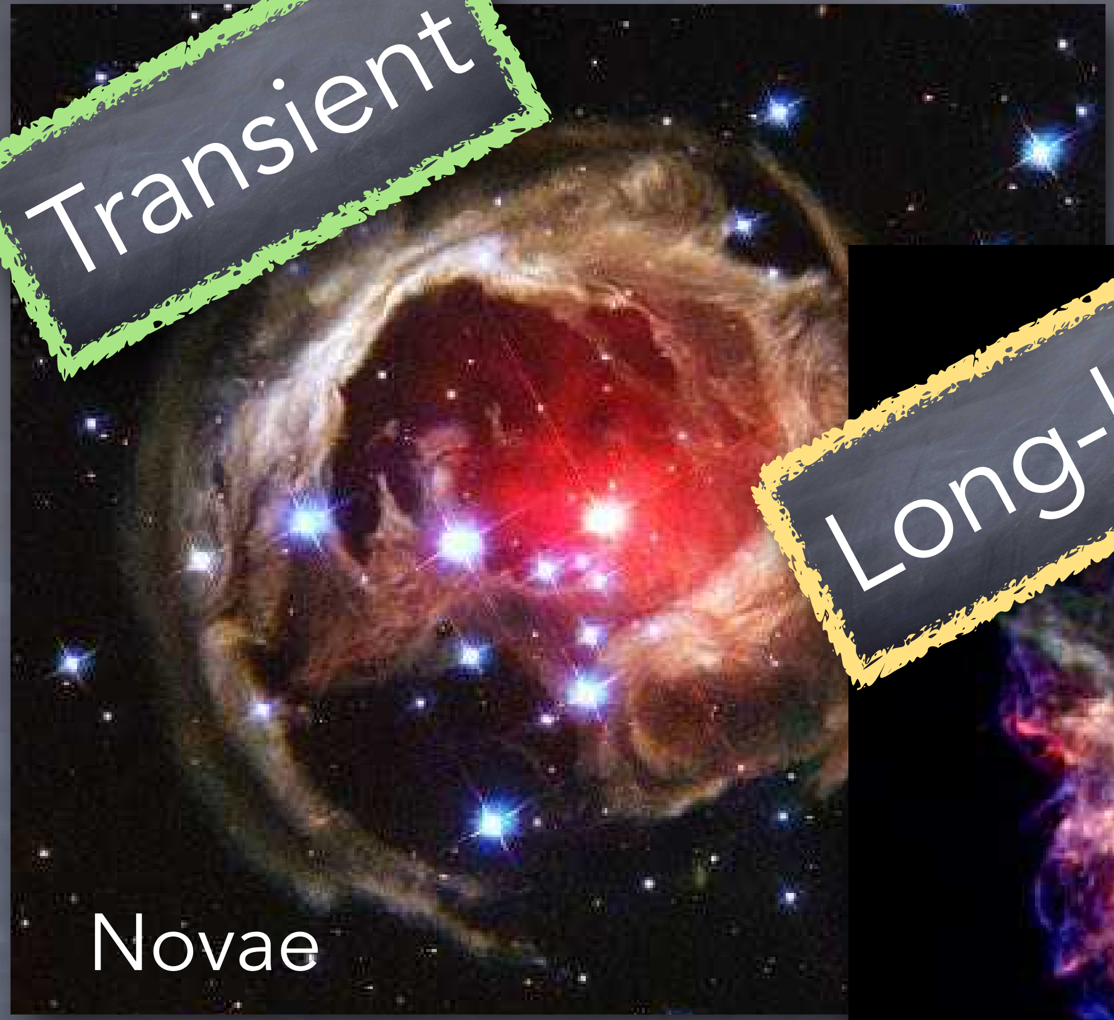
Particle Acceleration at Shocks and in Turbulence

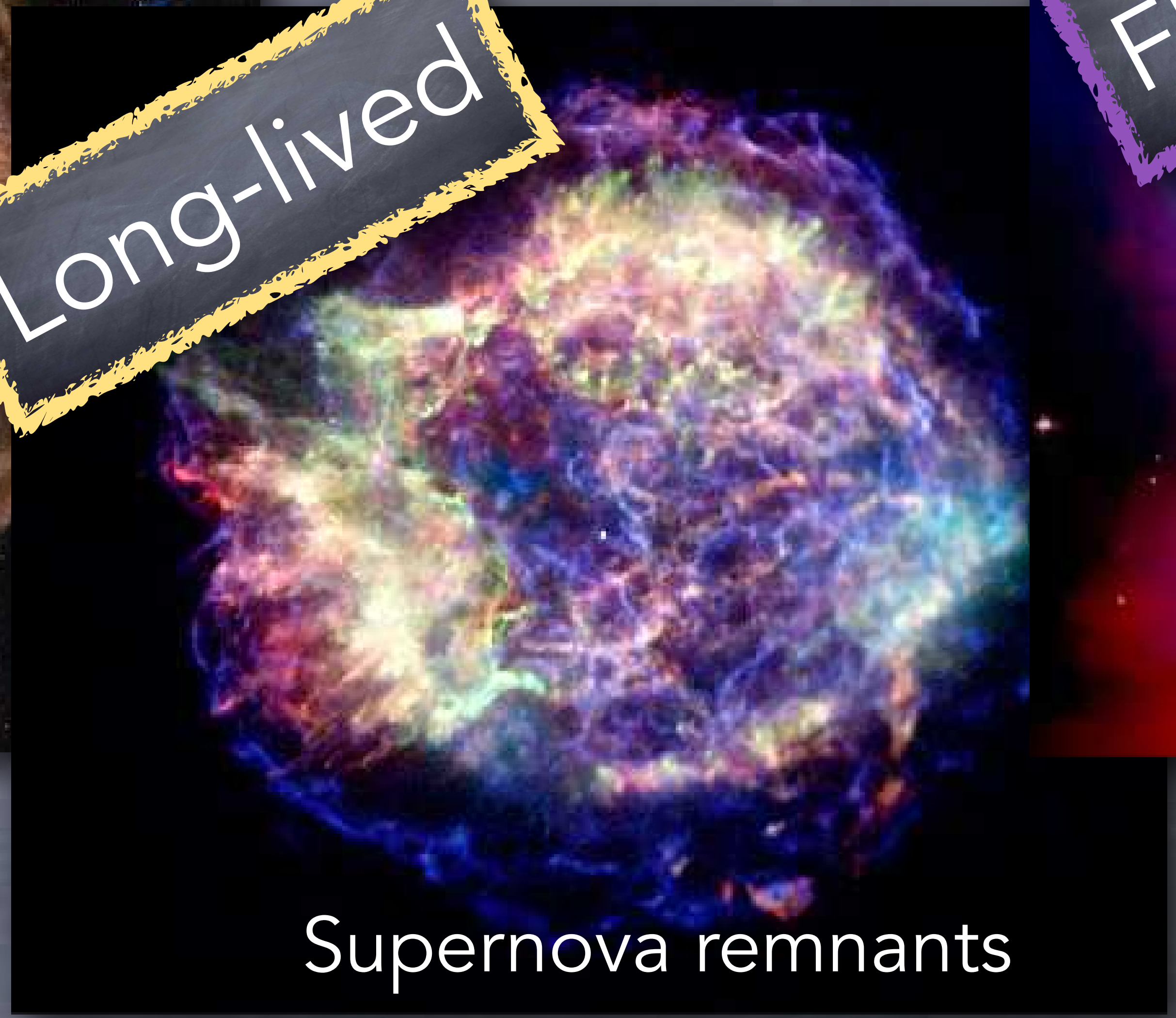
Damiano Caprioli
University of Chicago

WHERE: From Helio to Cosmological Scales

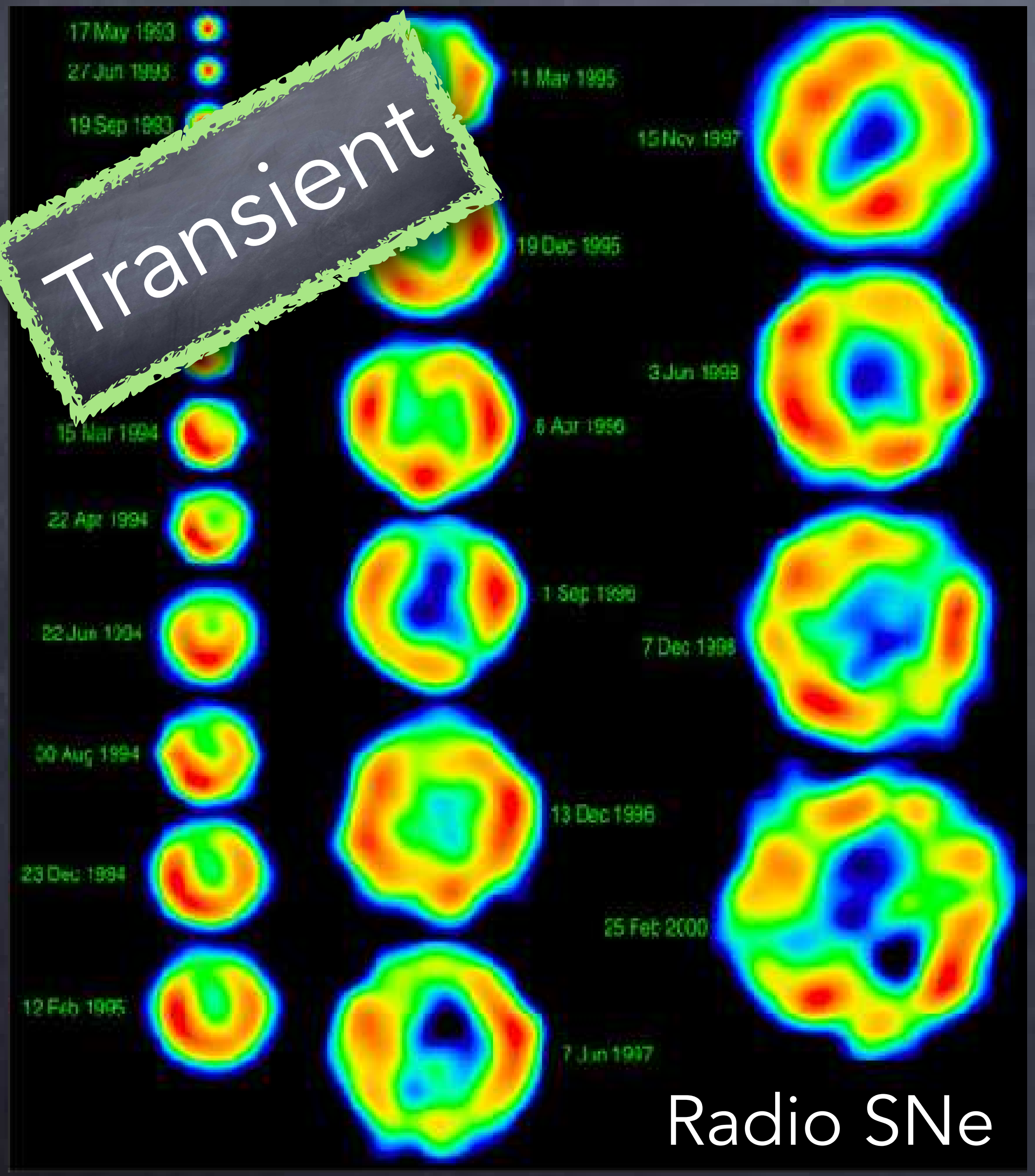
HELIOSPHERIC

GALACTIC





EXTRA-GALACTIC



A universal acceleration mechanism

- Fermi mechanism (Fermi, 1949): random elastic collisions lead to energy gain

PHYSICAL REVIEW VOLUME 75, NUMBER 8 APRIL 15, 1949

On the Origin of the Cosmic Radiation

ENRICO FERMI
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(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.

rd+78)

- 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 $M_s = V_{sh}/c_s \gg 1$): $R = 4$ and $\alpha = 4$

DSA: Like playing ping pong (*without friction!*)

Simulating Shock Acceleration

HOW: A Multi-scale Approach

Micro

Meso

Macro

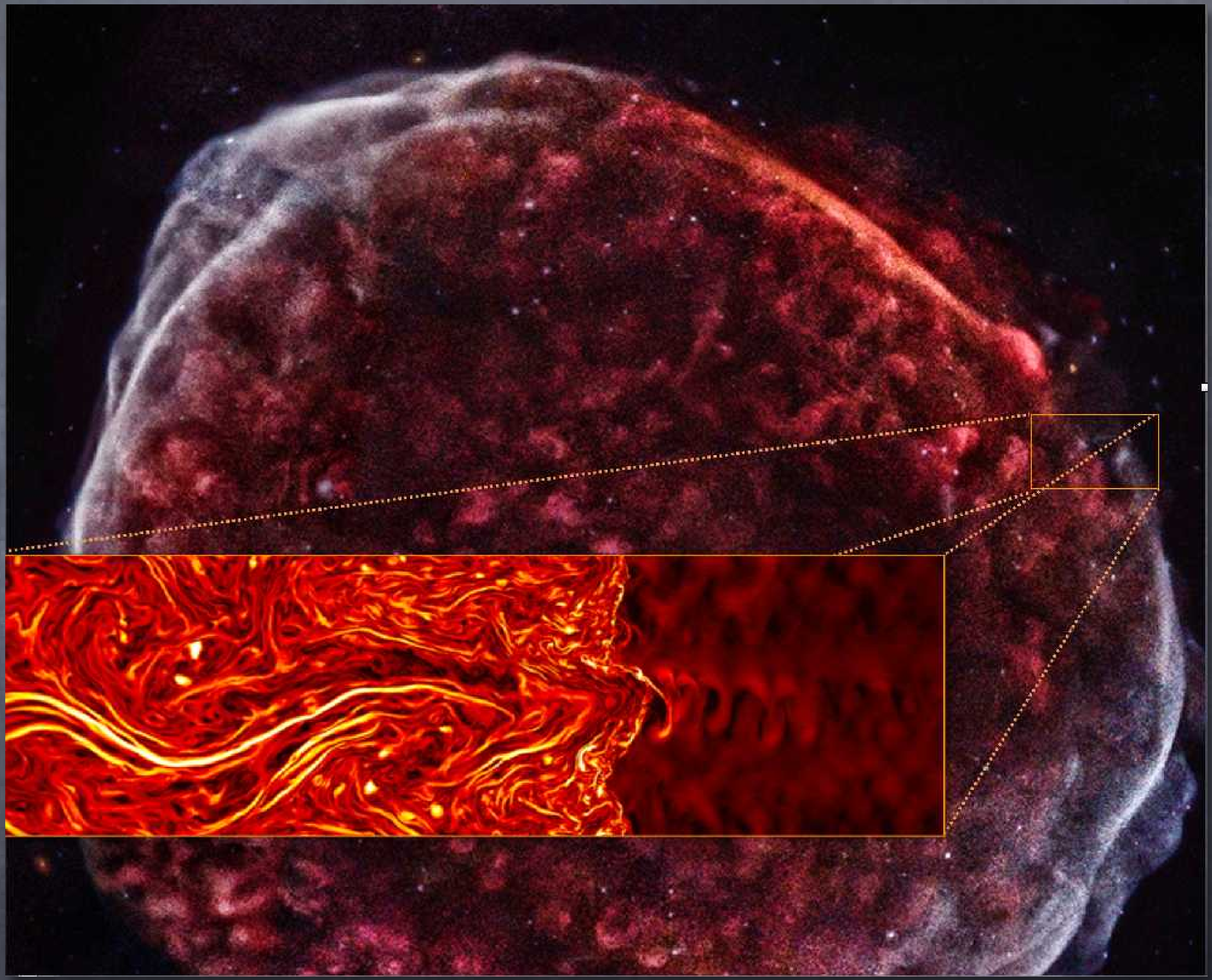
Astro

PIC Plasma Simulations
electron + ion dynamics

Hybrid: ion dynamics,
magnetic field amplification

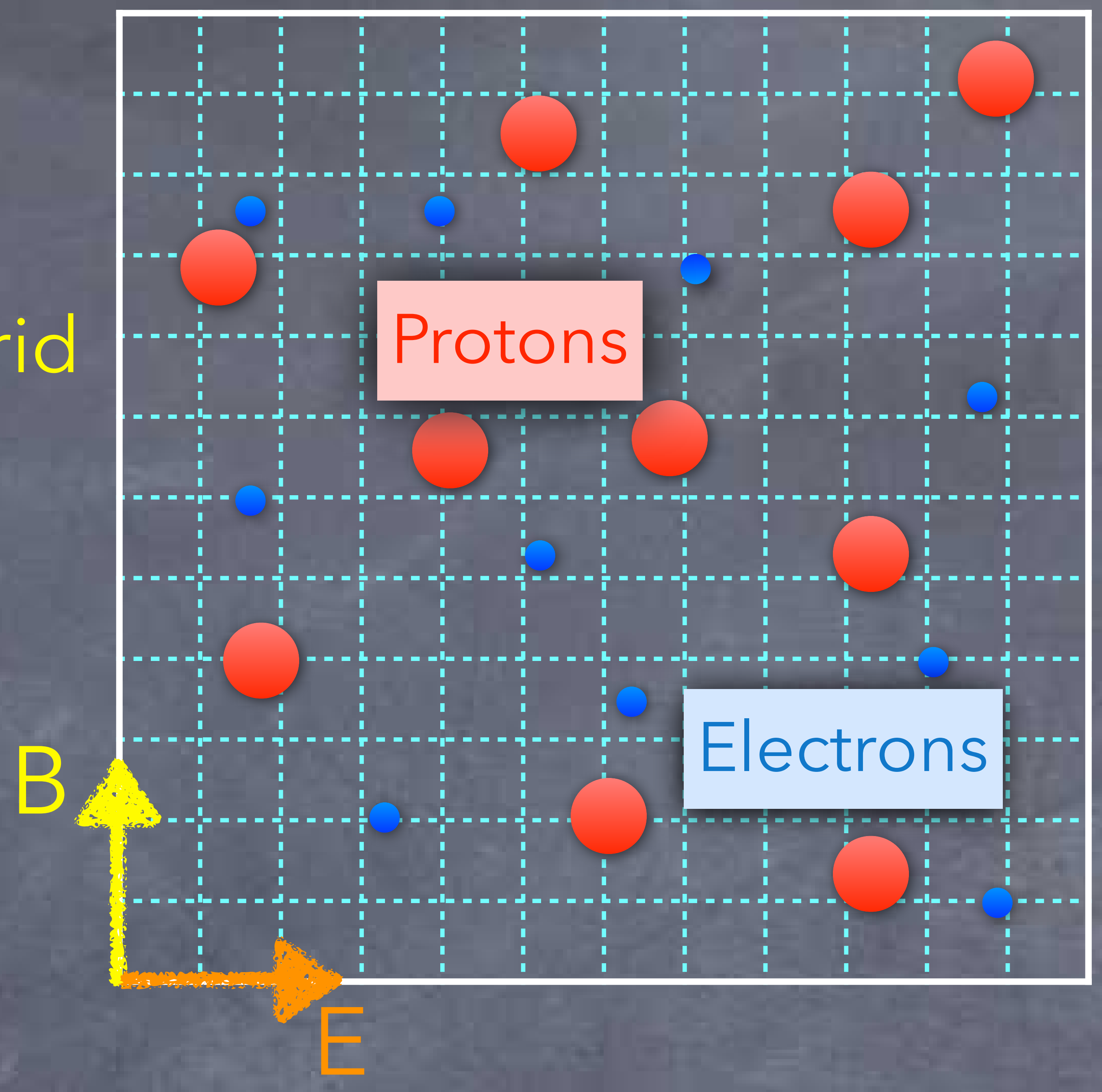
Super-Hybrid (MHD+hybrid)
Large/long scales
High-Mach numbers

Semi-Analytical
CRAFT = *Cosmic Ray Analytical Fast Tool*



Astroplasmas from first principles

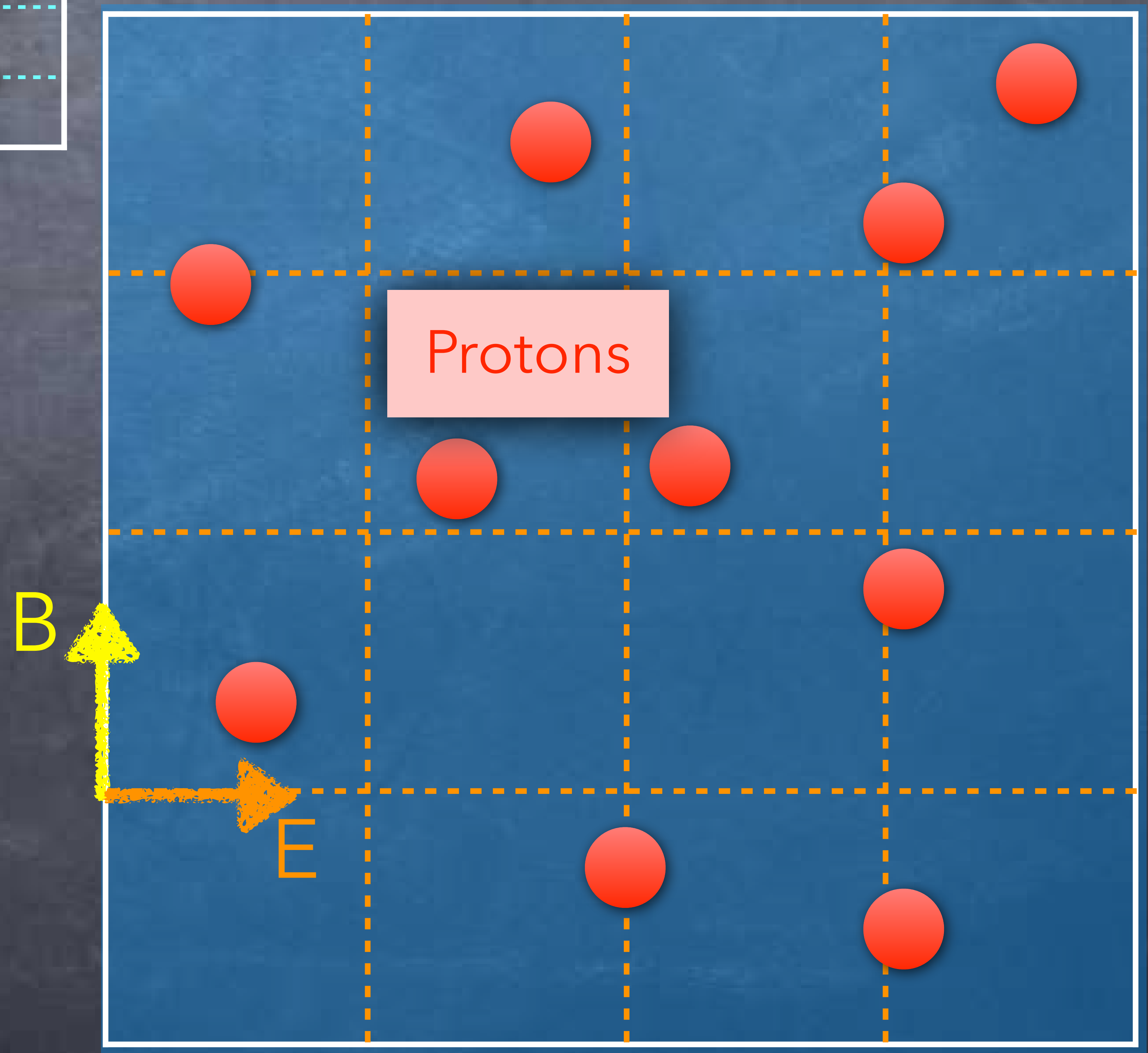
- Full-PIC approach
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



- 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 2019-2022)

  - massless electrons for more macroscopical time/length scales



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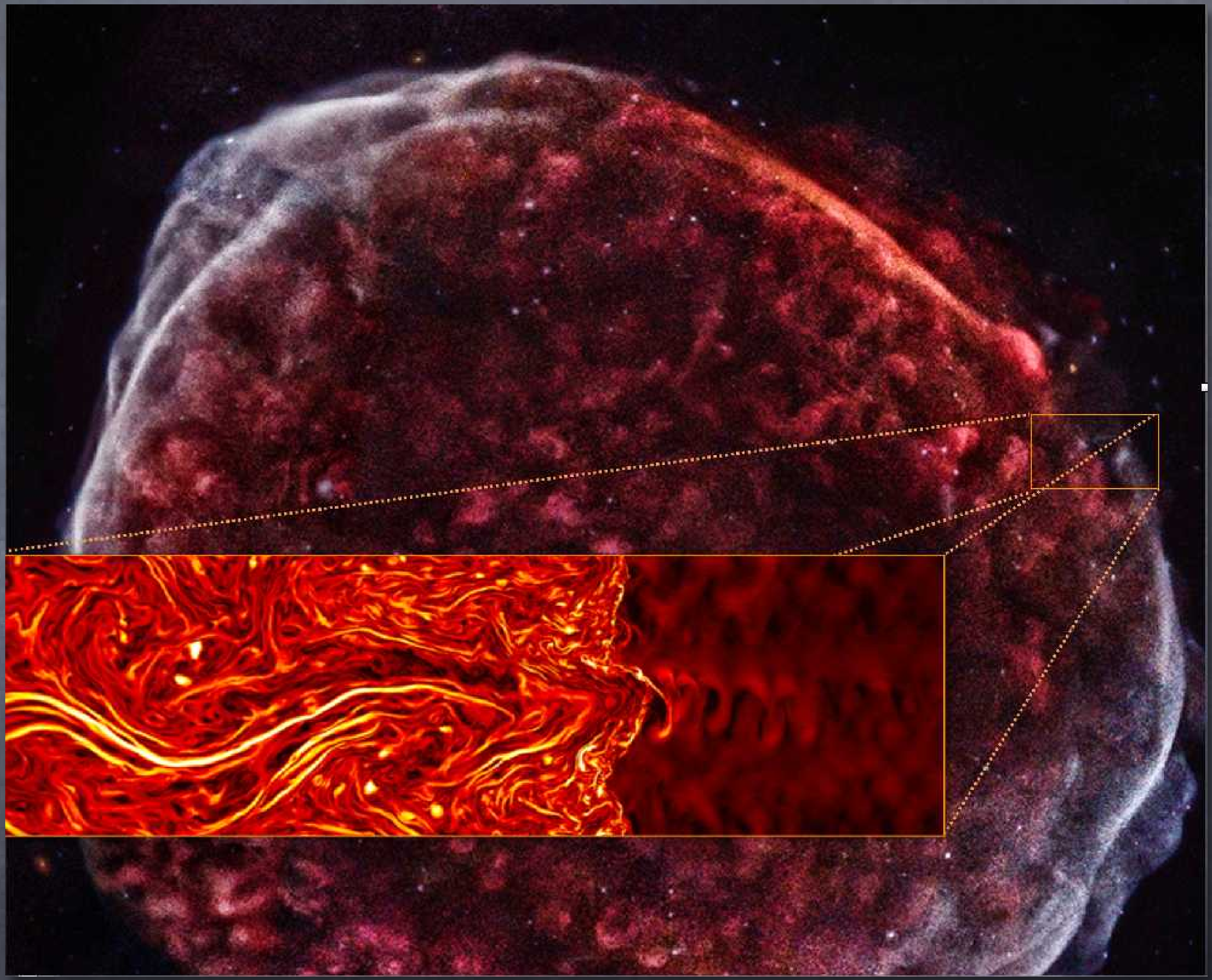
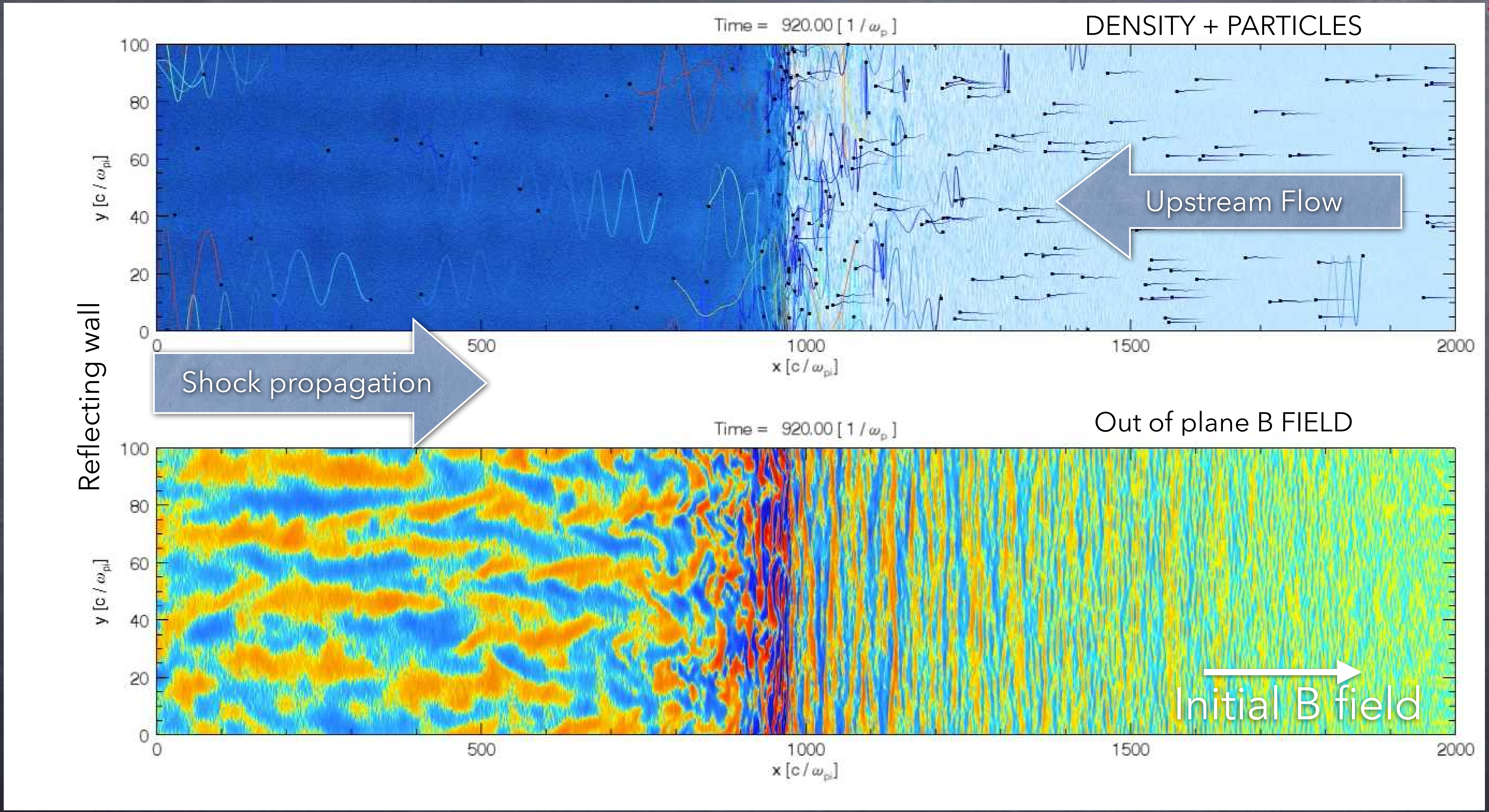
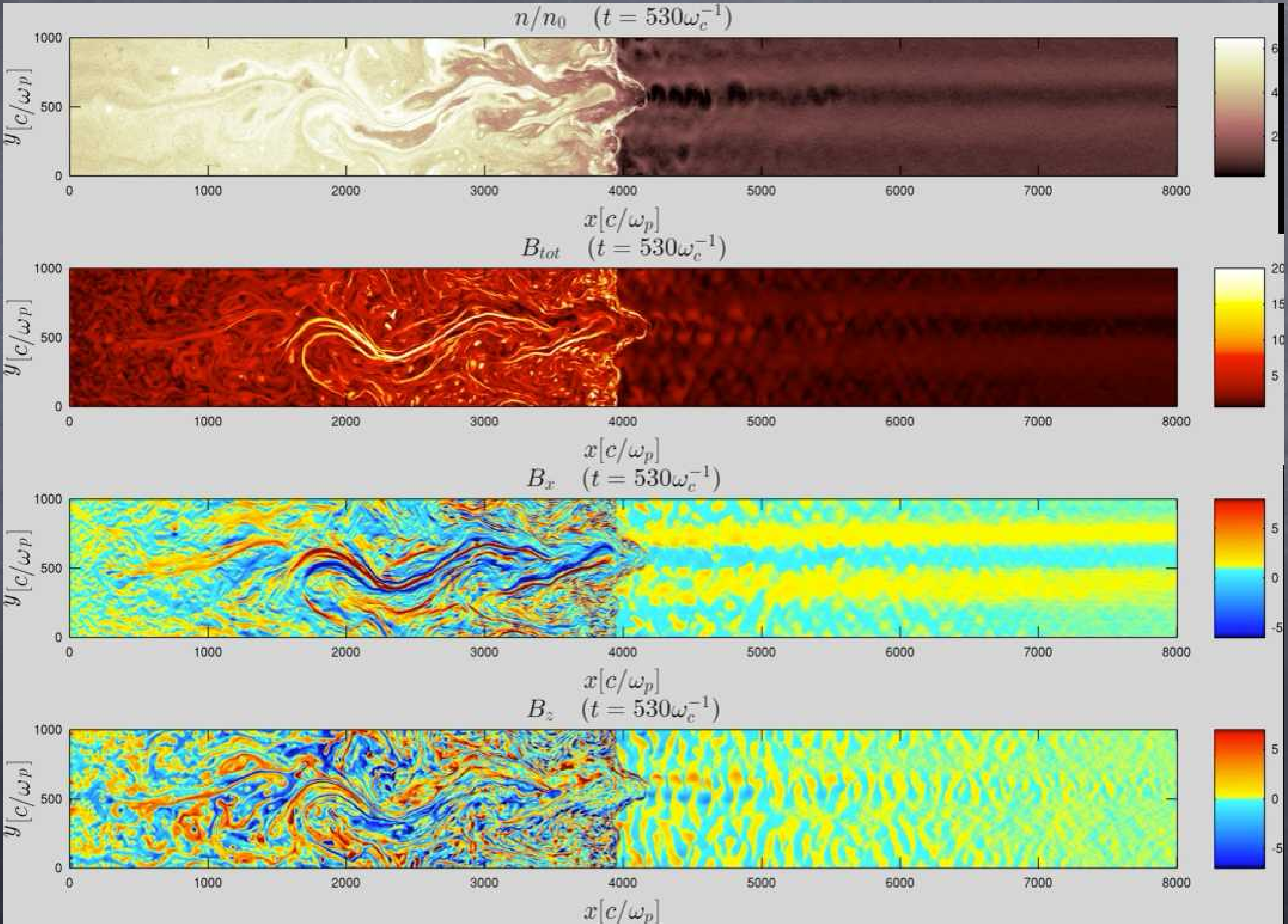


Hybrid Simulations of Collisionless Shocks



dHybrid code (Gargaté+07; Caprioli-Spitkovsky13-18), now ***dHybridR*** (+relativity; Haggerty & Caprioli 2019)

CR-driven Magnetic Field Amplification



Initial B field

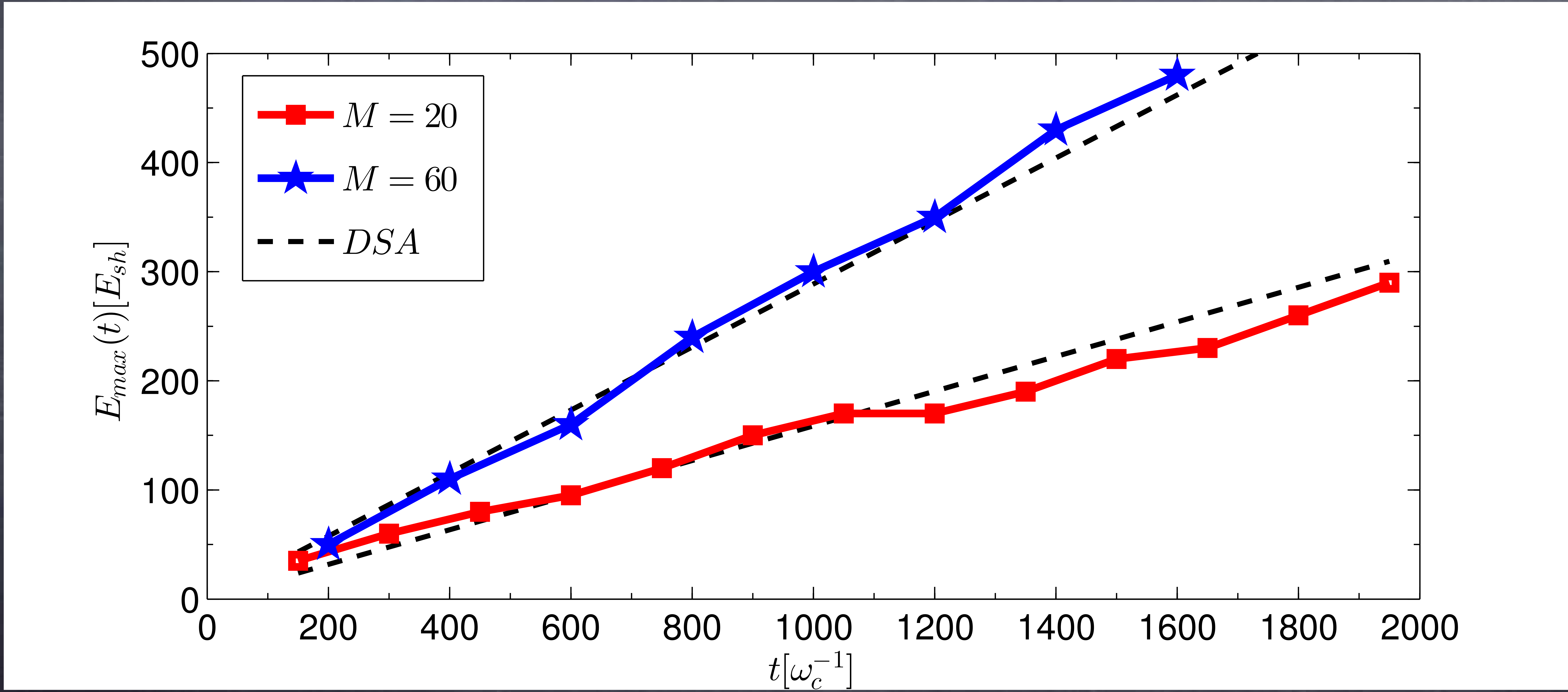
$M_s = M_A = 30$

DC & Spitkovsky, 2013

Time evolution of E_{max}

- Evolution of $E_{max}(t)$ according to DSA (Drury 1983, Blasi+2007)
- Consistent with Bohm diffusion in the amplified B field

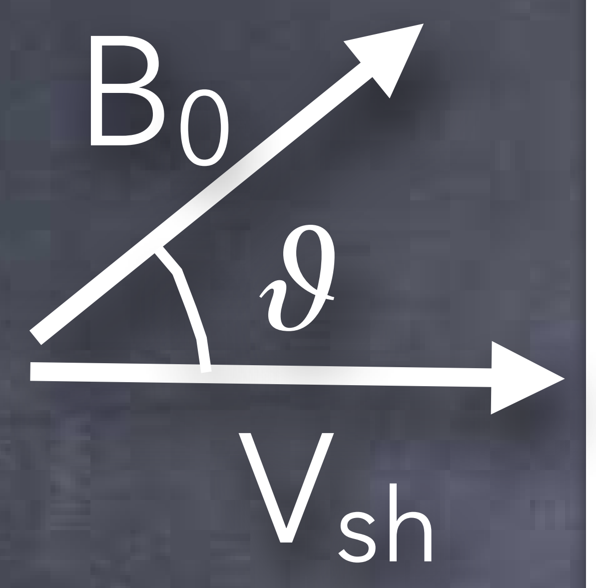
$$T_{acc}(E) = \frac{3}{u_1 - u_2}\left[\frac{D_1(E)}{u_1} + \frac{D_2(E)}{u_2}\right] \simeq \frac{3r^3}{r^2-1}\frac{D(E)}{v_{sh}^2}.$$

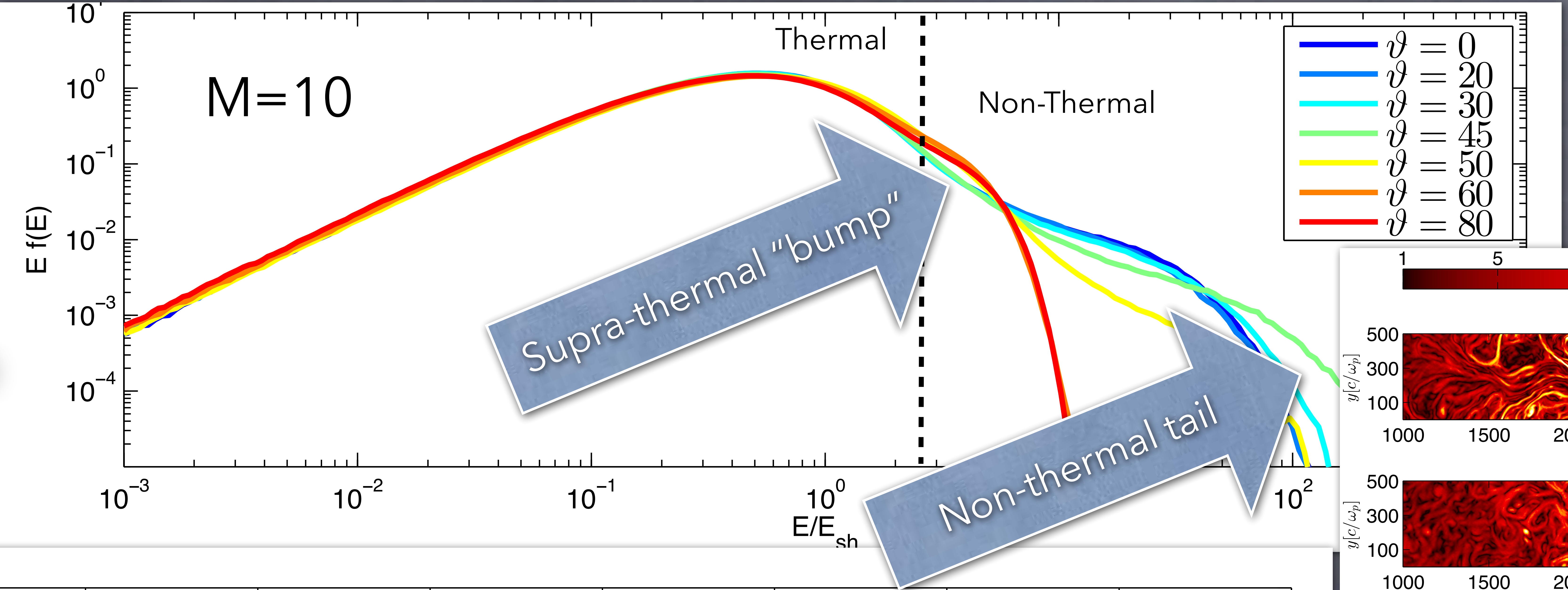


Caprioli & Spitkovsky, 2014c

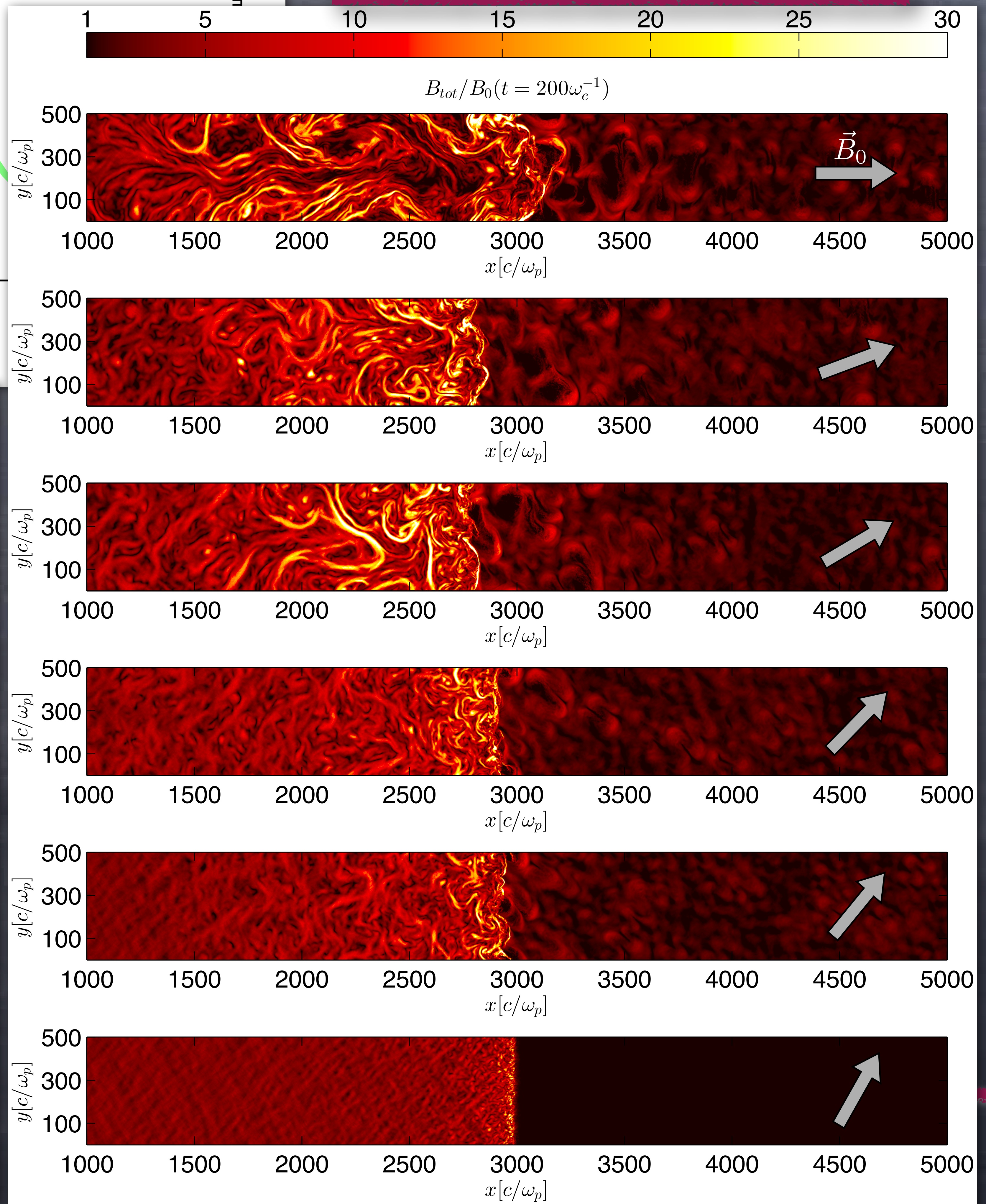
Parallel vs Oblique shocks

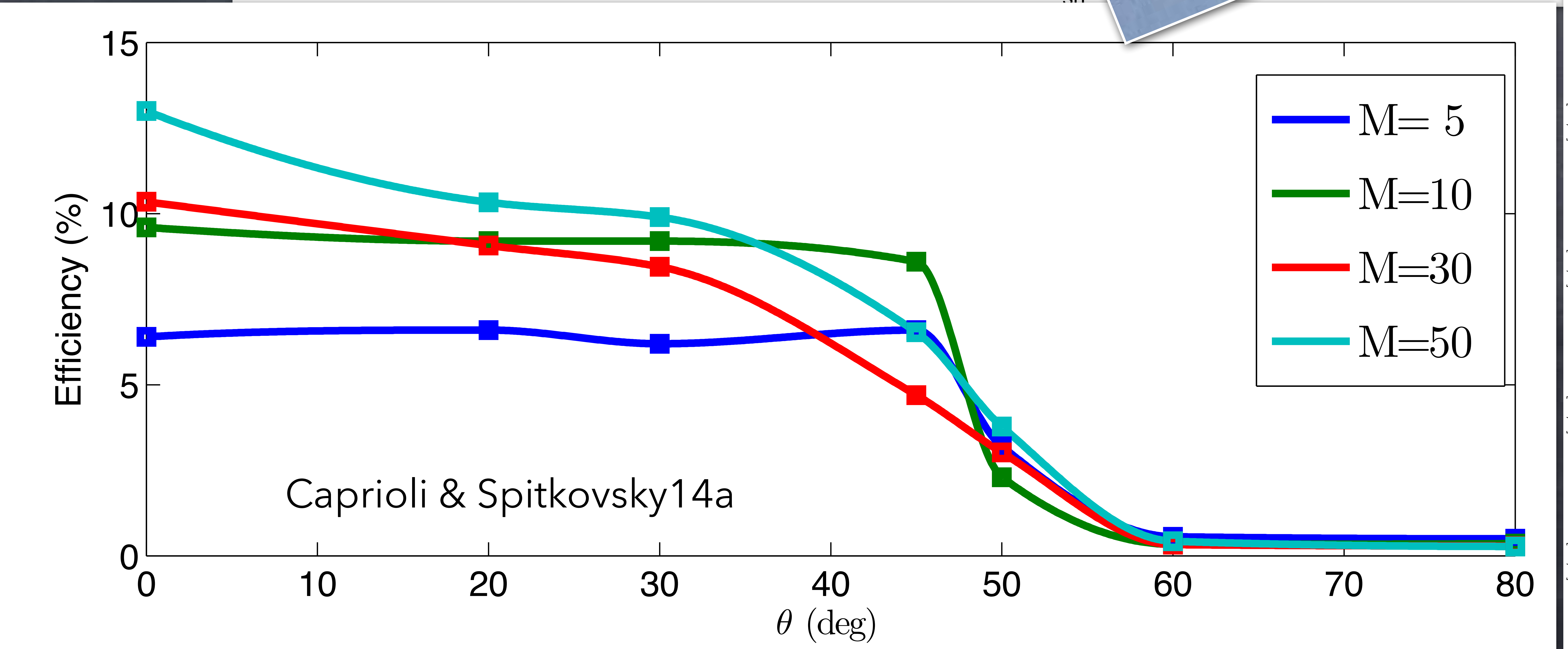
Shock
inclination





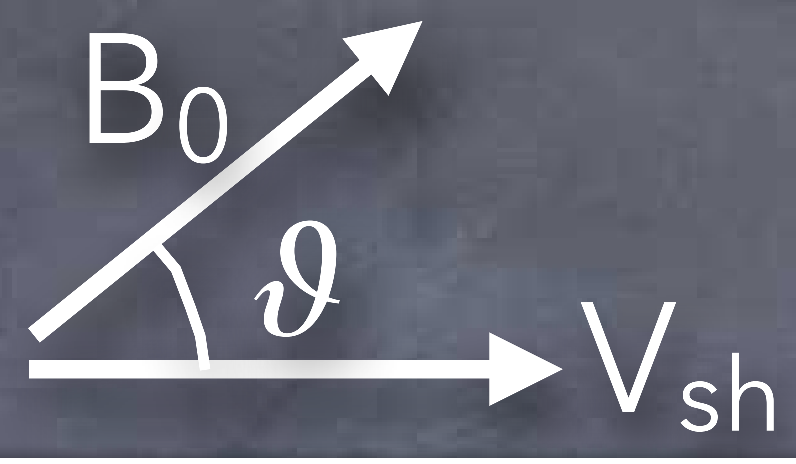
Ion acceleration
correlates with
B-field amplification

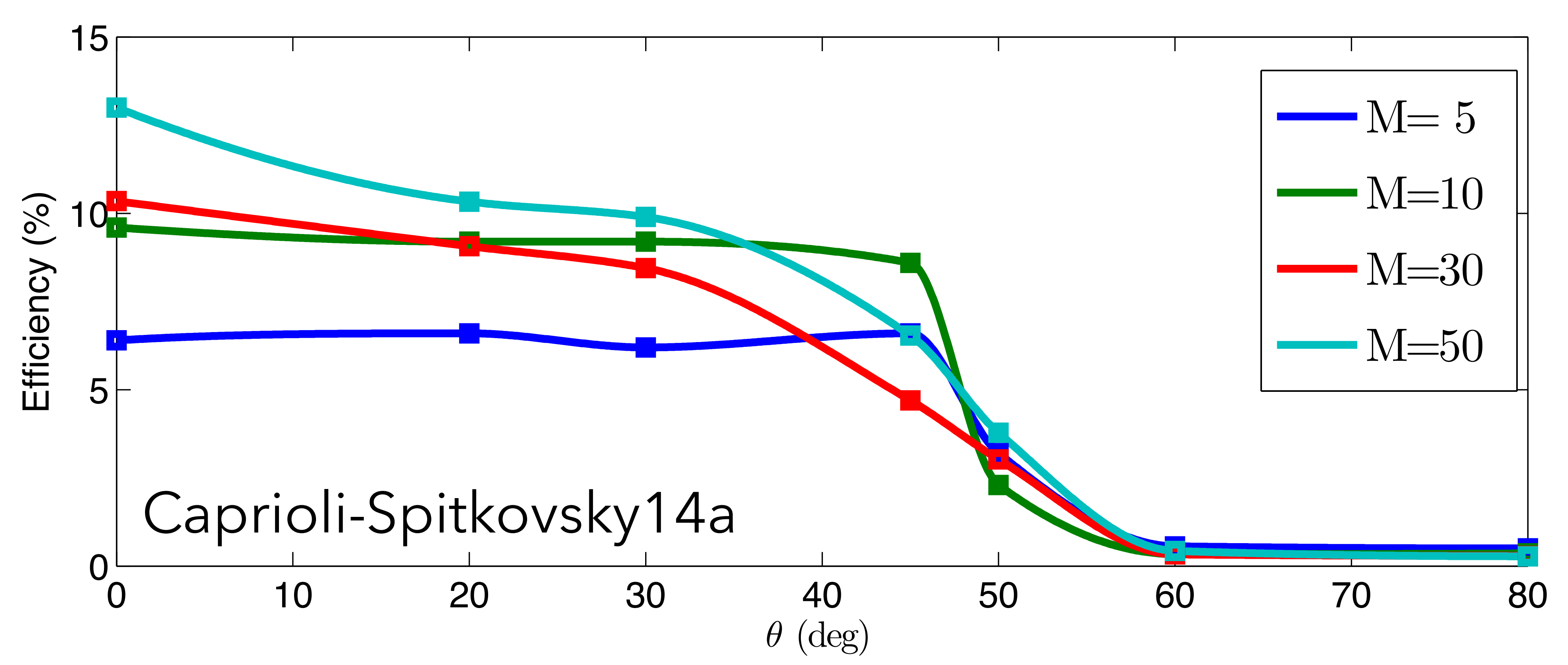


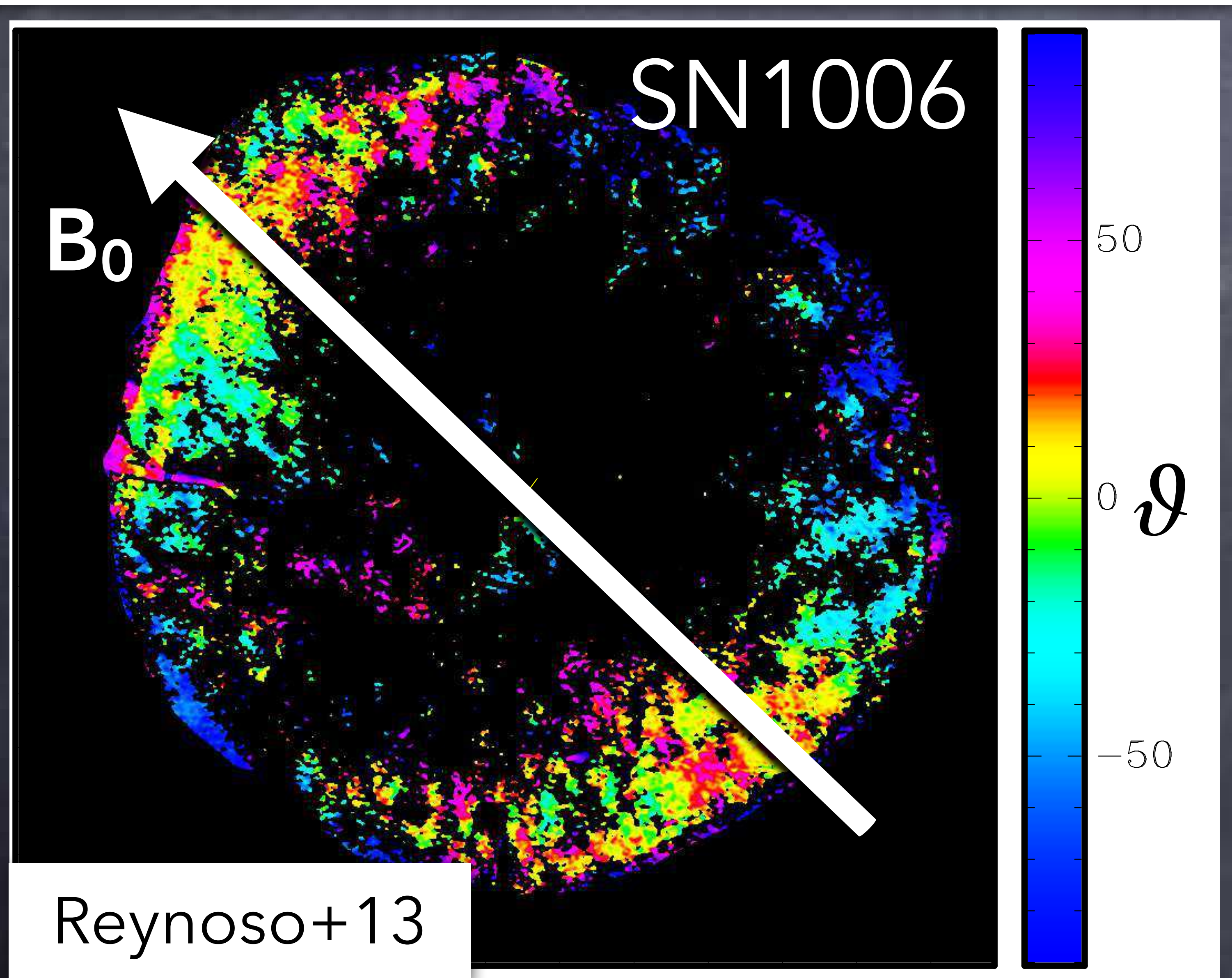


DSA Efficiency

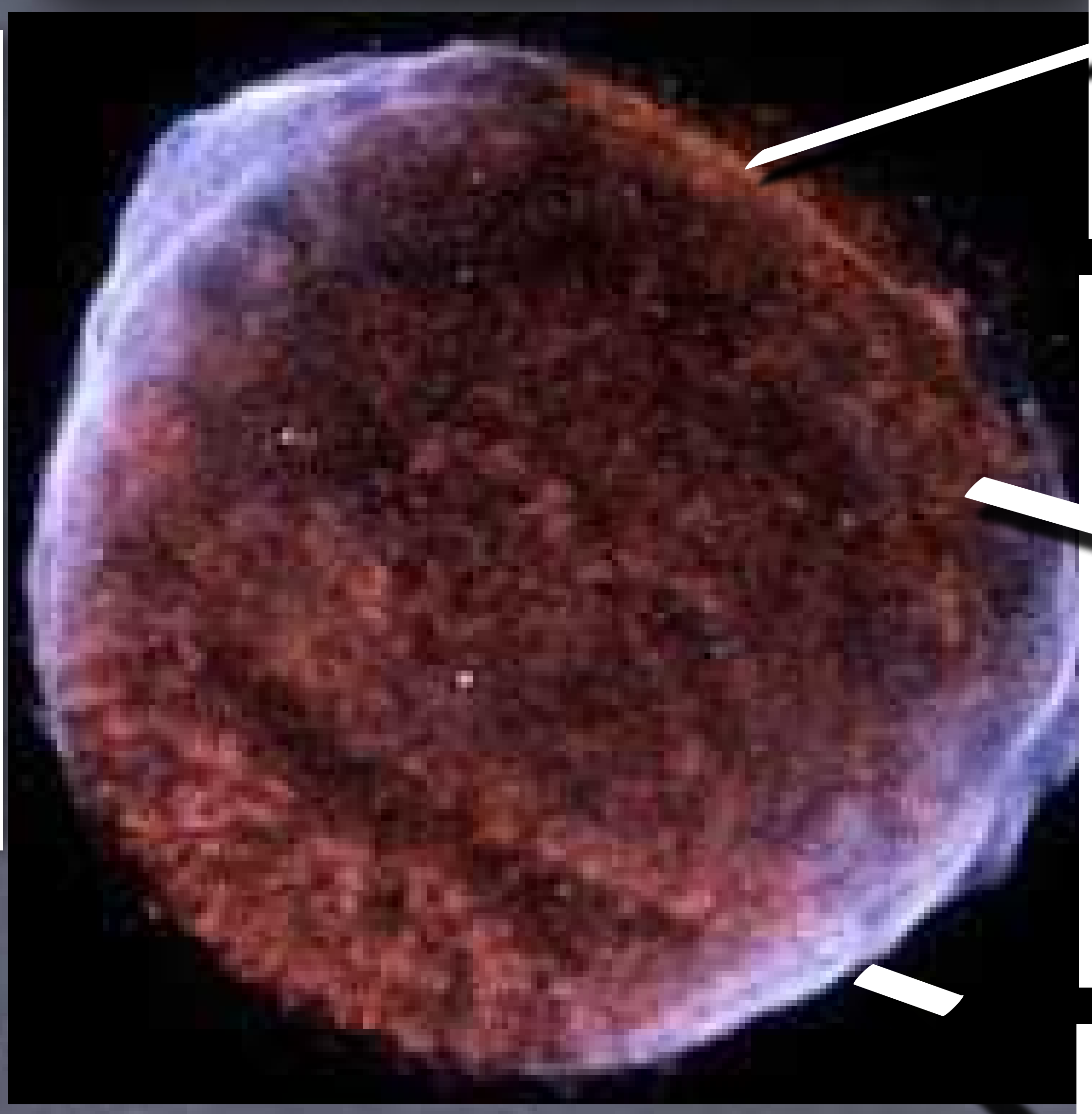
Acceleration depends on the shock inclination



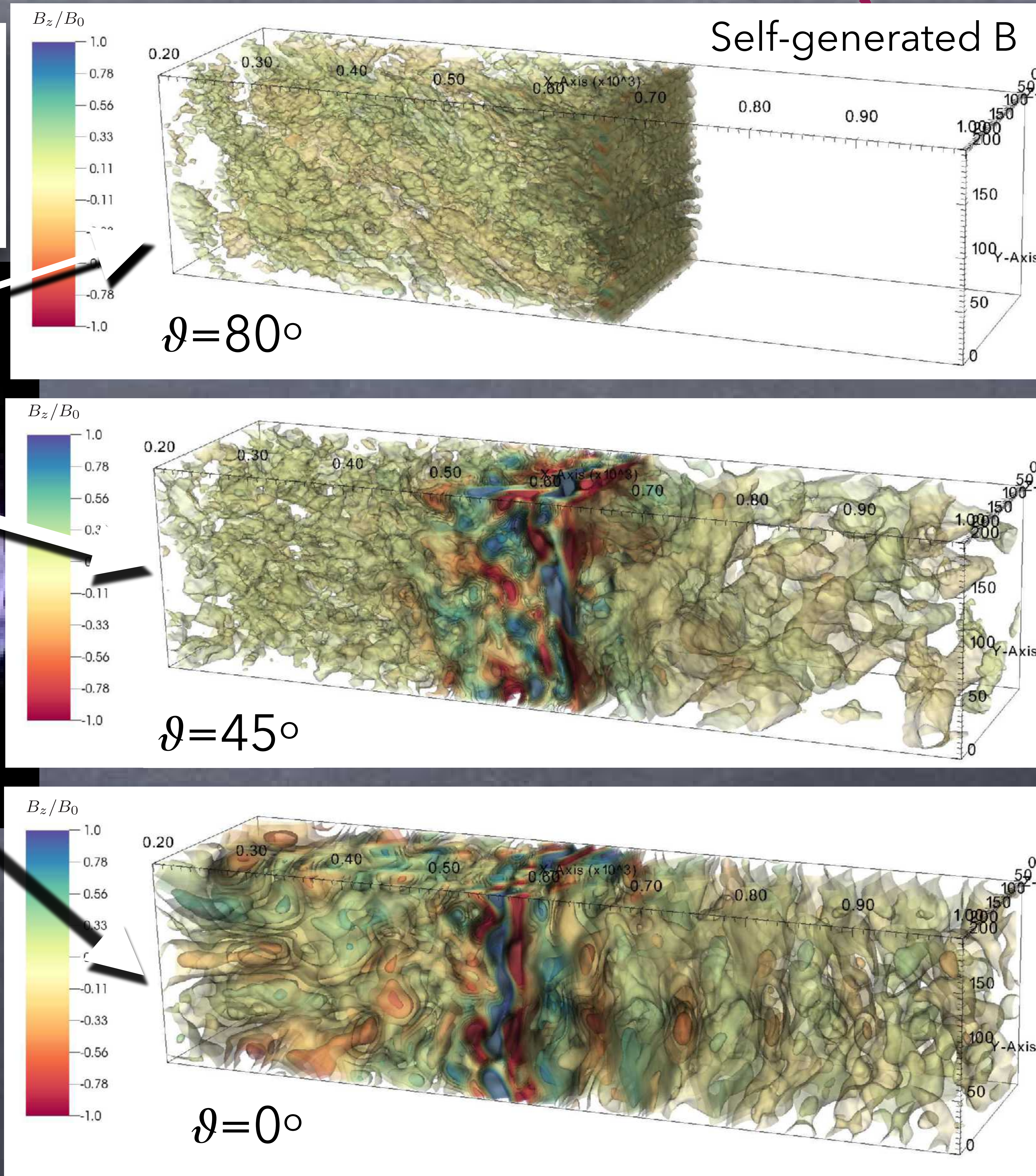




X-ray emission:
red=thermal
white=synchrotron



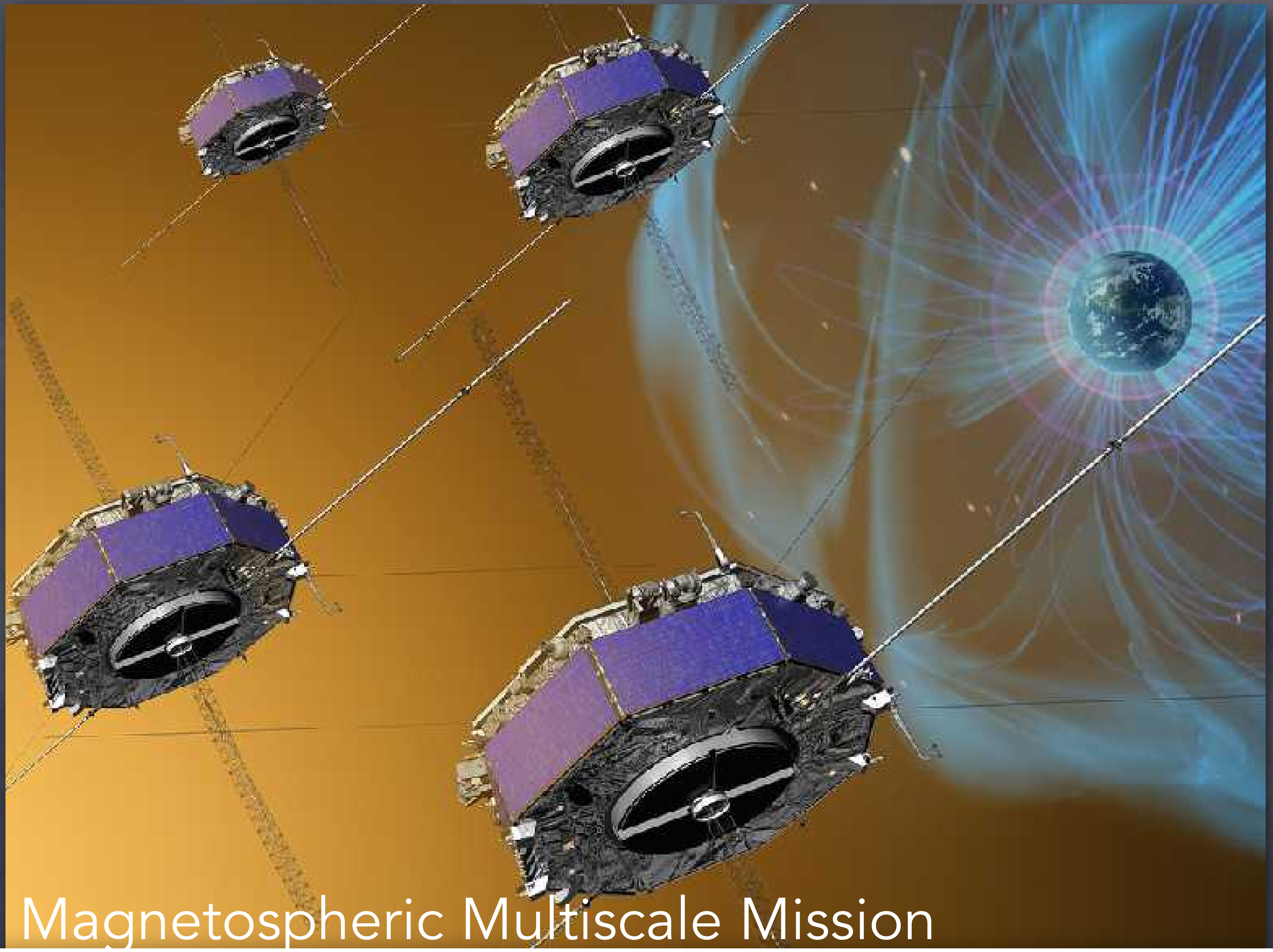
B amplification and ion acceleration where the shock is parallel

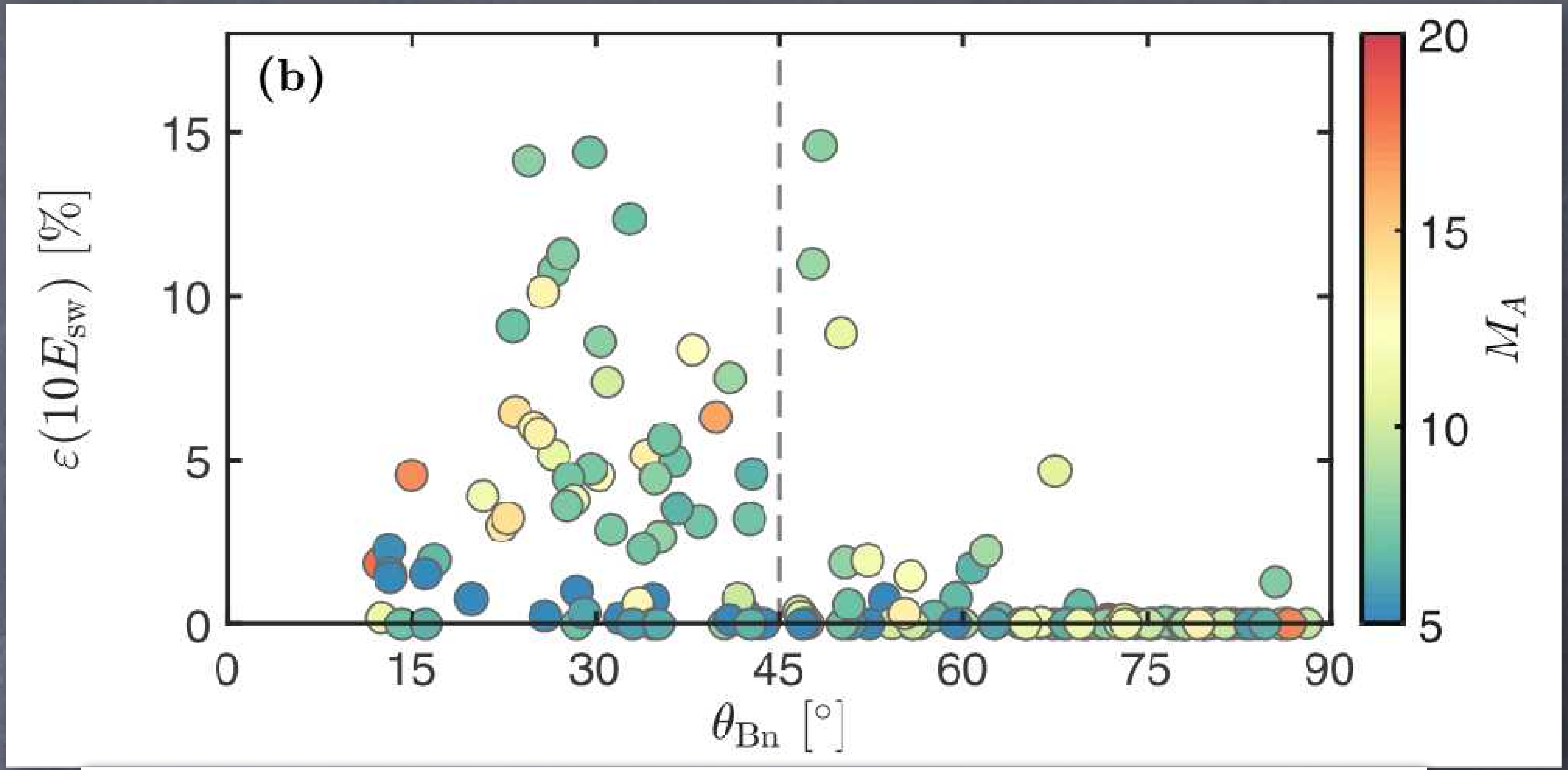


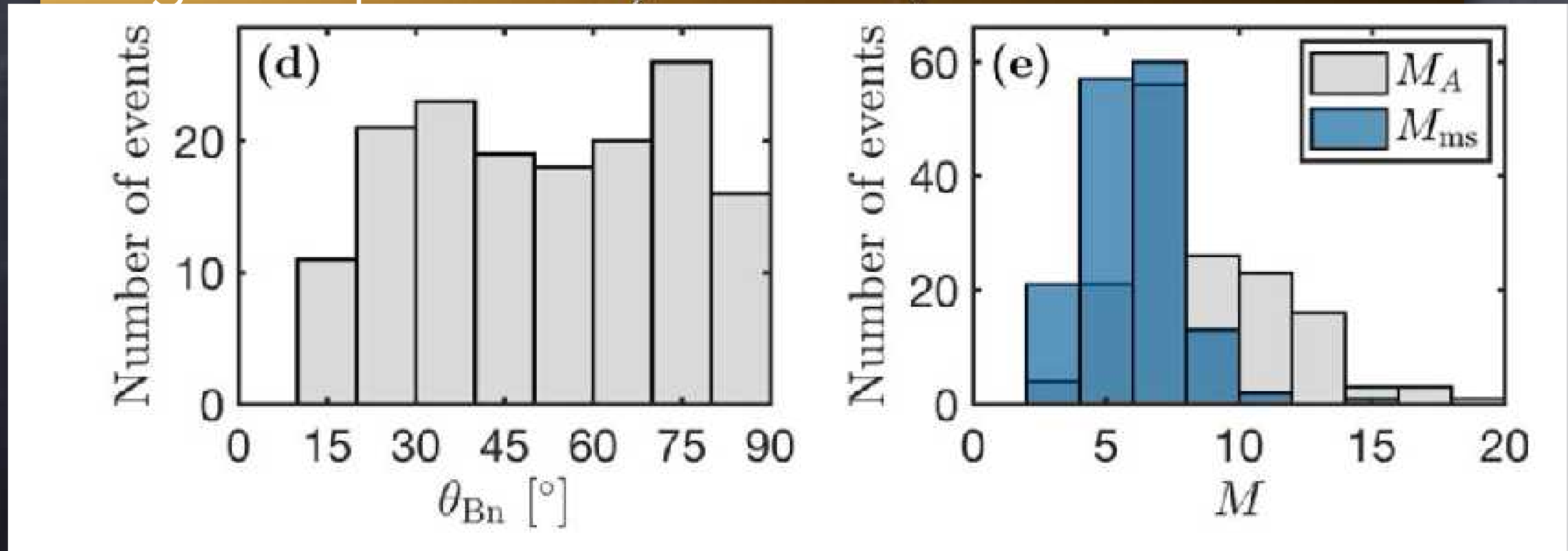
Caprioli-Spitkovsky14a,b,c

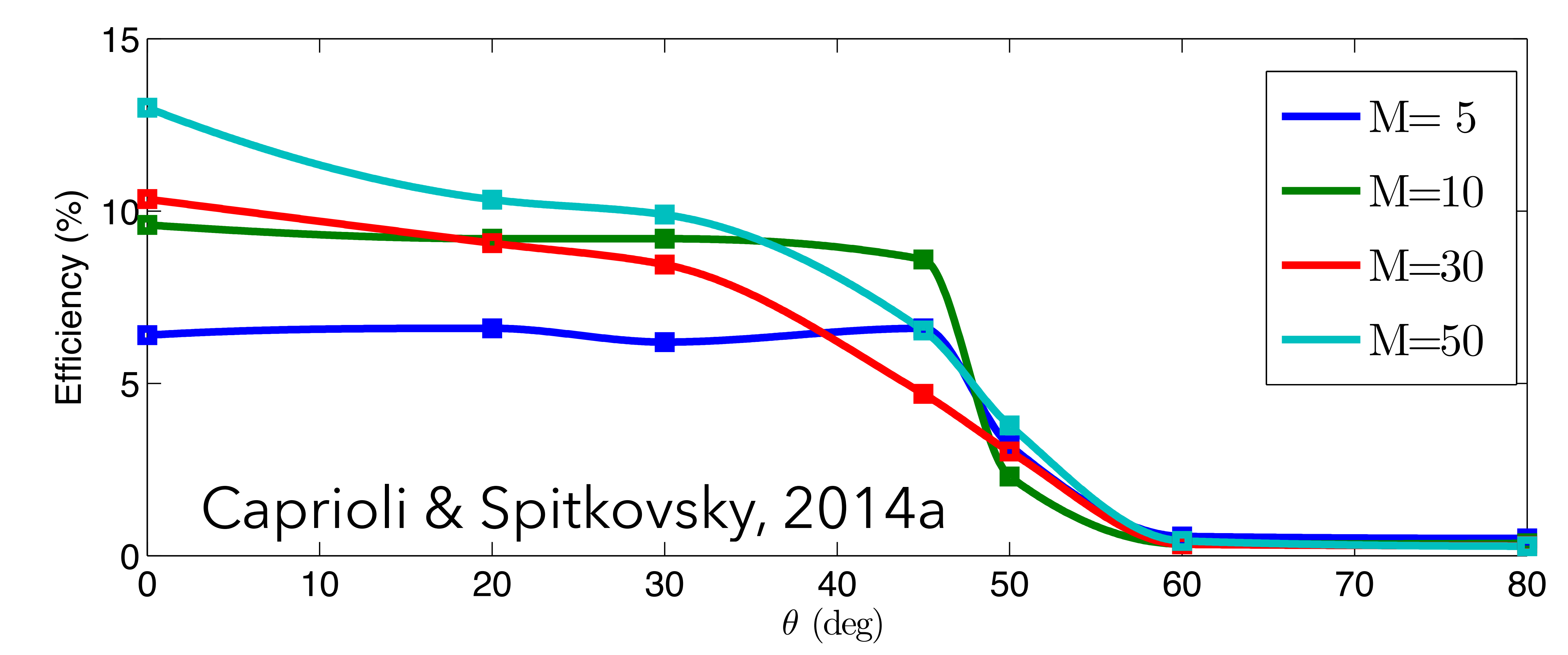
Ion DSA at the Earth Bow Shock

- MMS confirms that DSA is efficient at quasi-parallel shocks (Johlander, Caprioli+21)



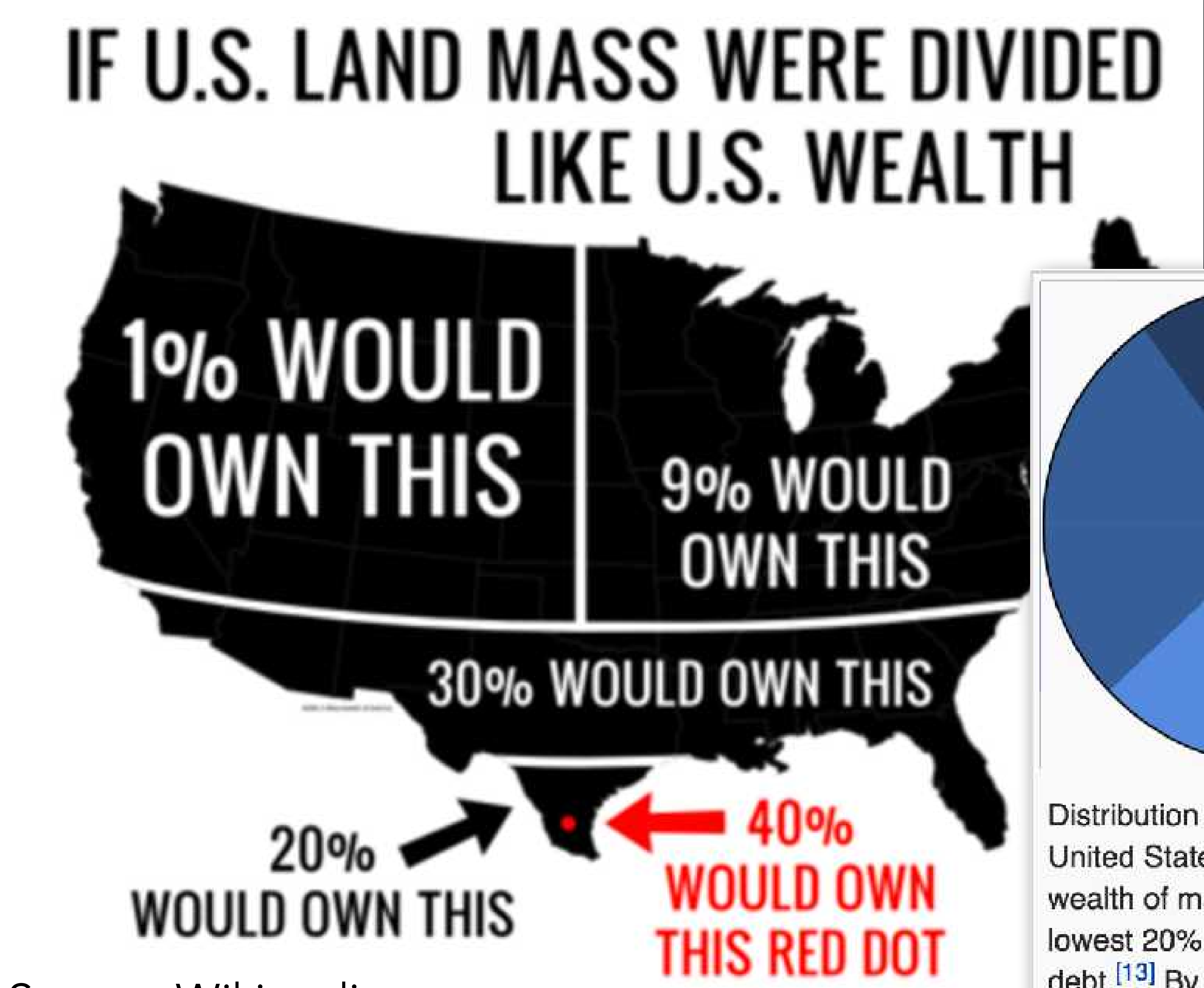




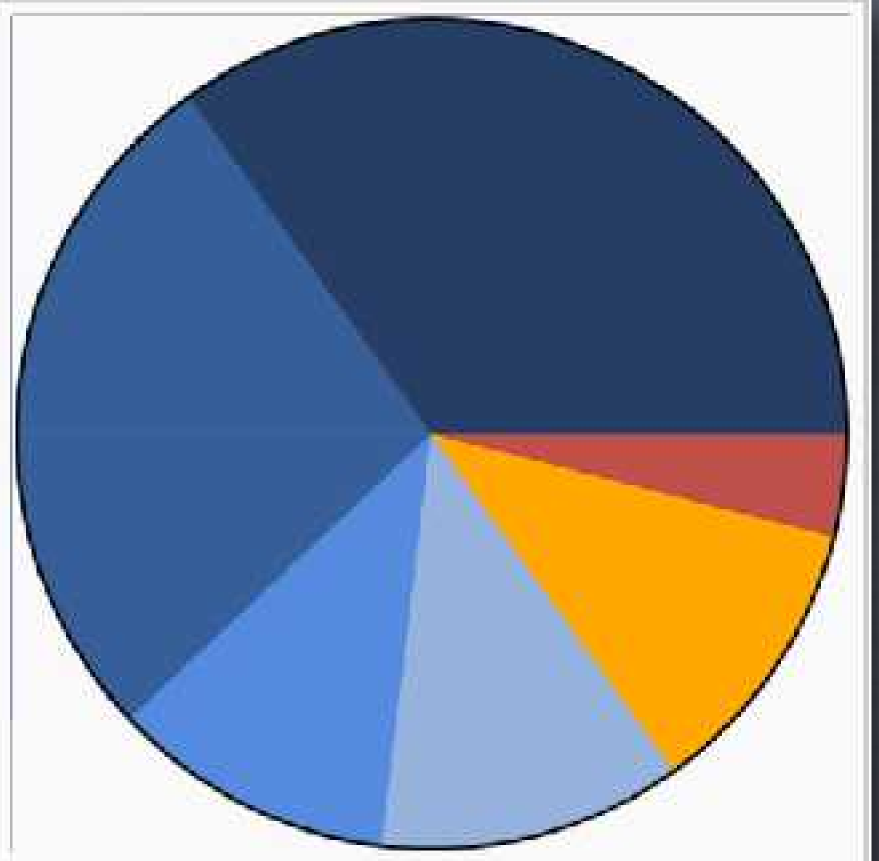


The Injection *"Problem"*

Cosmic Wealth

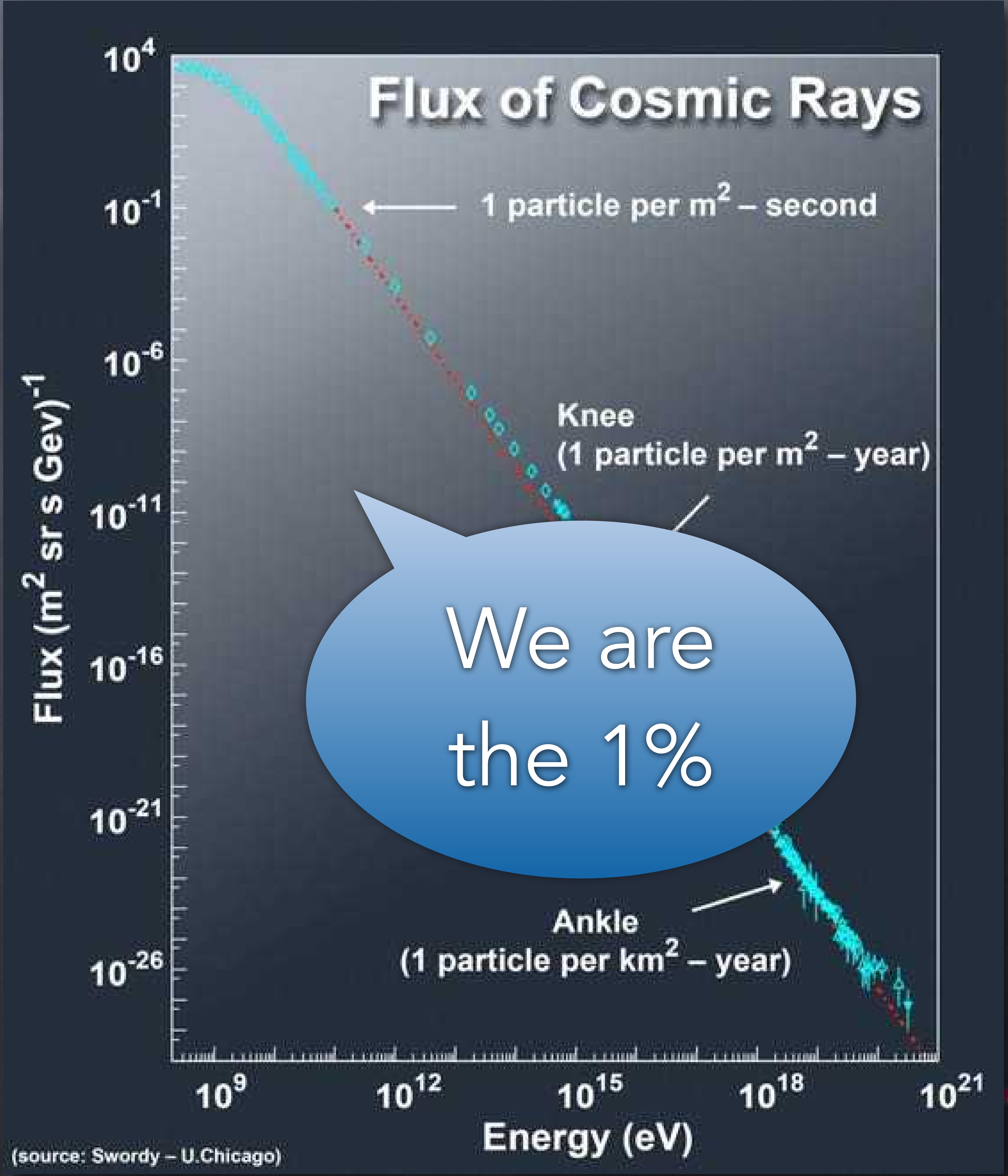


Source: Wikipedia



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

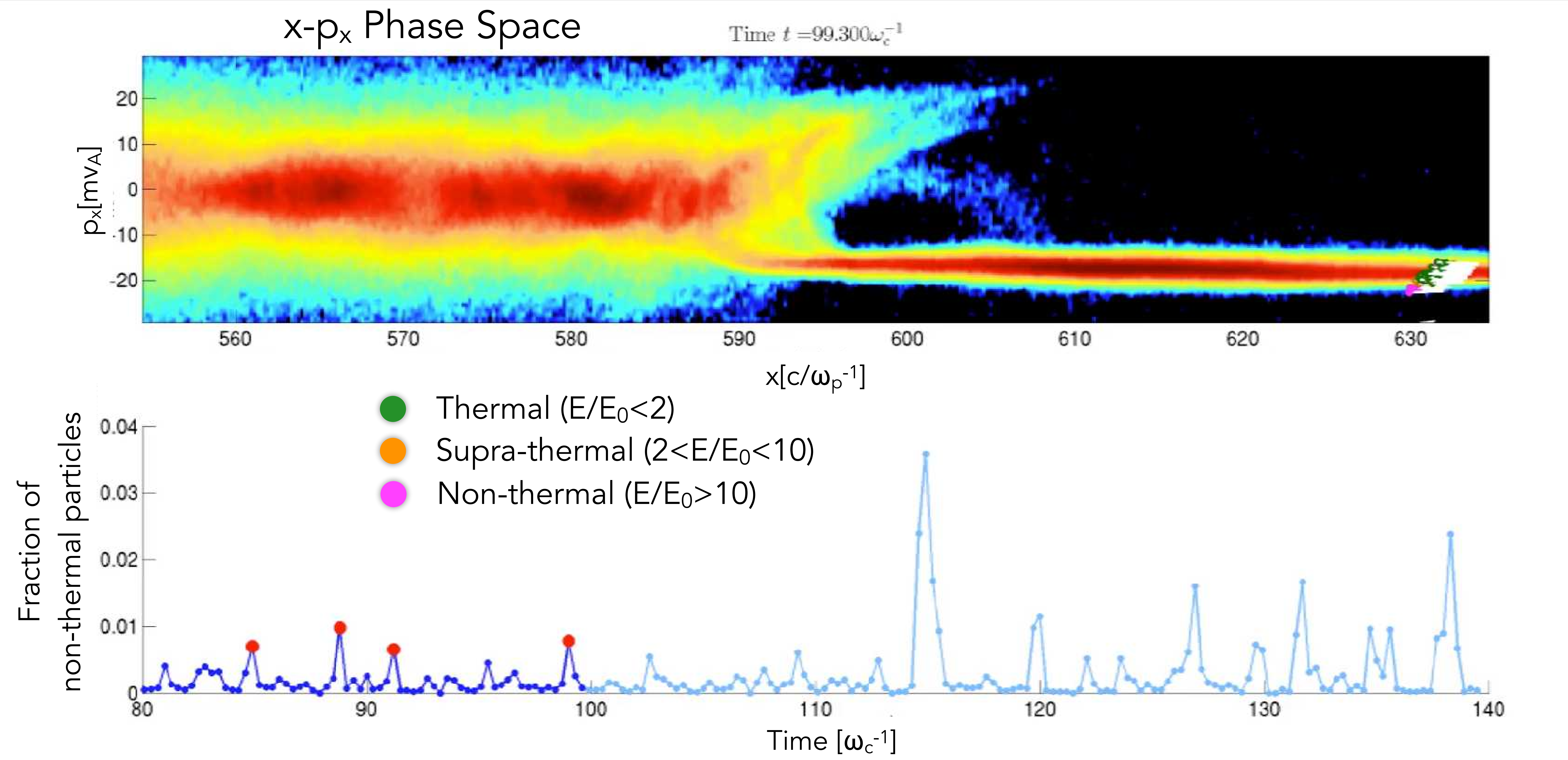
What determines the fraction of particles that become CRs?

3 golden rules of Real Estate:

LOCATION,
LOCATION,
LOCATION!

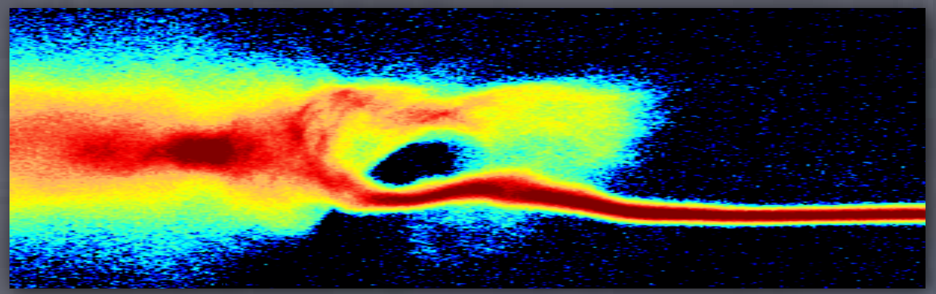
Particle Injection - Simulations

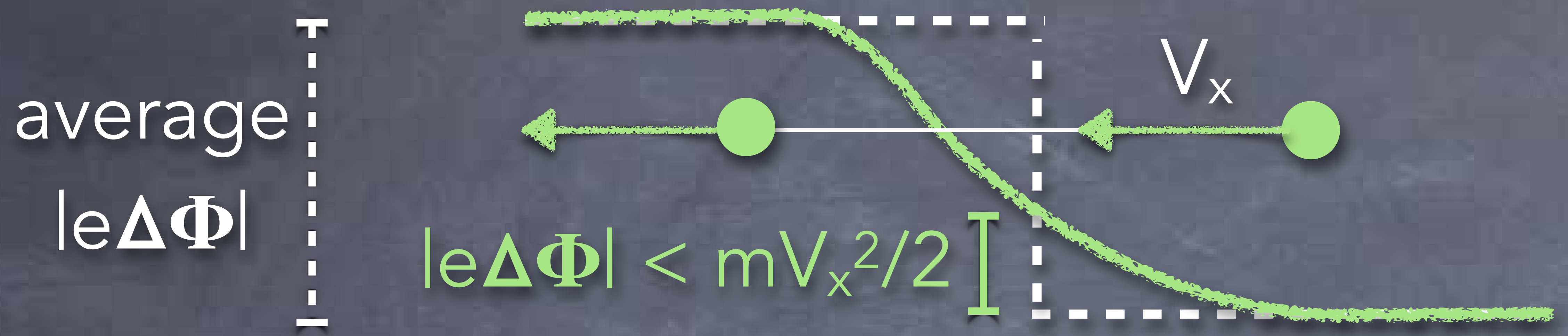
DC, Pop & Spitkovsky, 2015



Encounter with the shock barrier

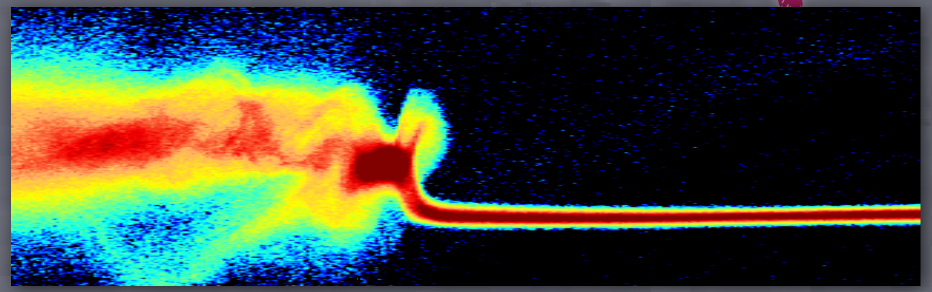
- Low barrier (reformation)

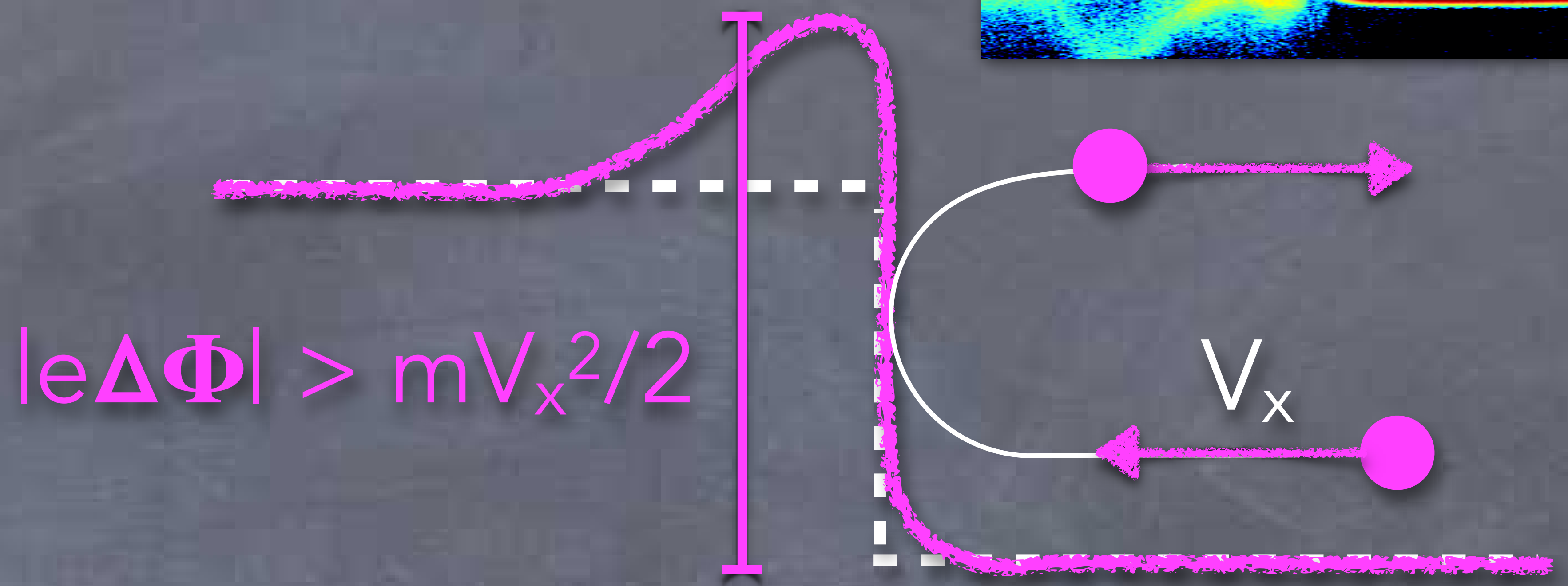




Ions advected downstream, and thermalized

- High barrier (overshoot)





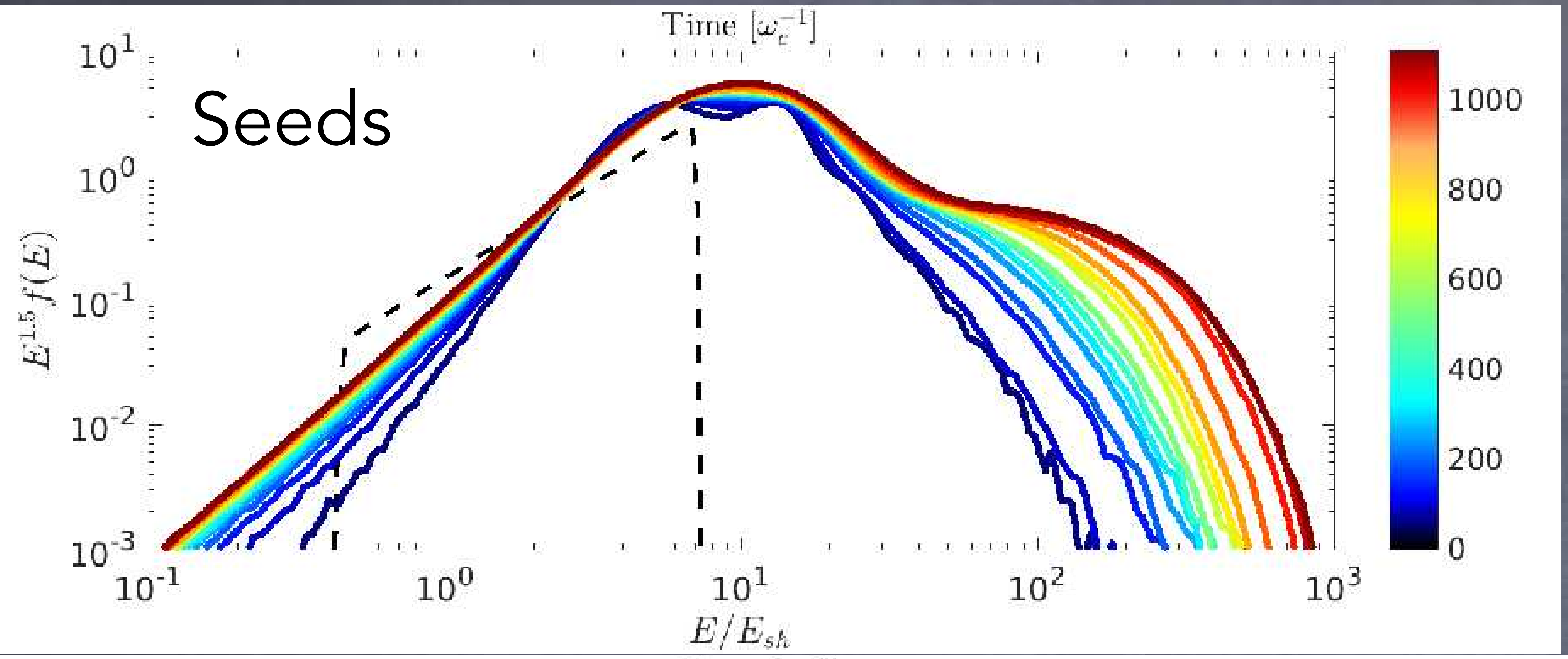
Ions reflected upstream, and energized via Shock Drift Acceleration

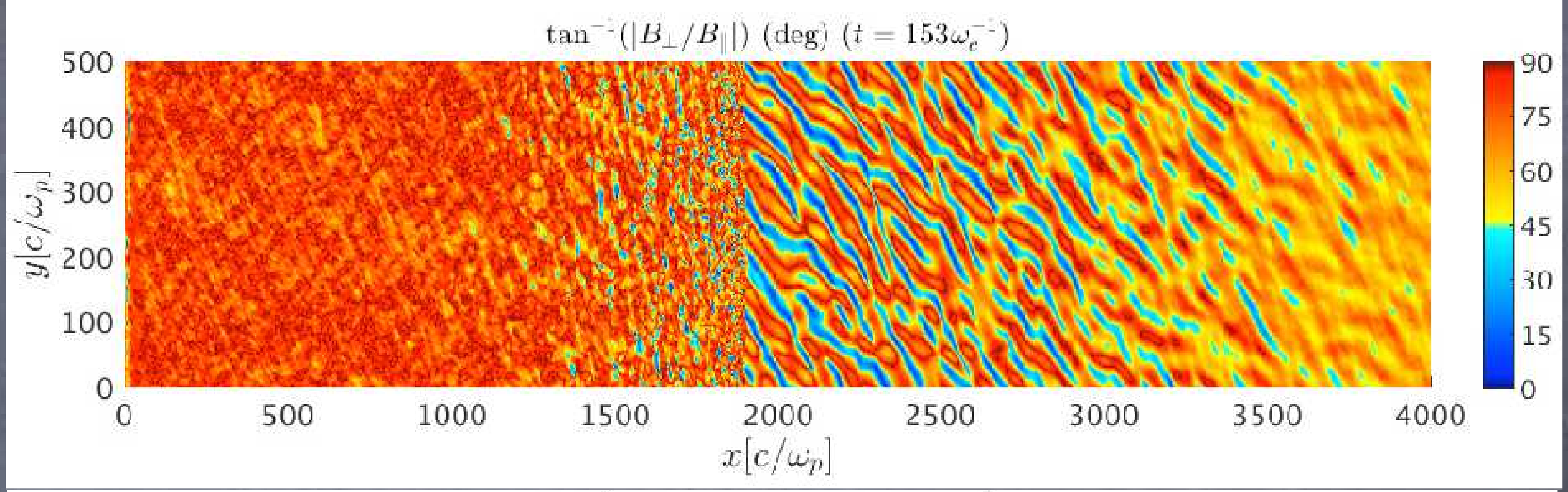
- To overrun the shock, ions need a minimum E_{inj}, increasing with ϑ (DC, Pop & Spitkovsky 15)
  - Ion fate determined by barrier duty cycle (~25%) and shock inclination
- After N SDA cycles, only a fraction $\eta \sim 0.25^N$ has not been advected
  - For $\vartheta=45^\circ$, $E_{inj} \sim 10E_0$,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

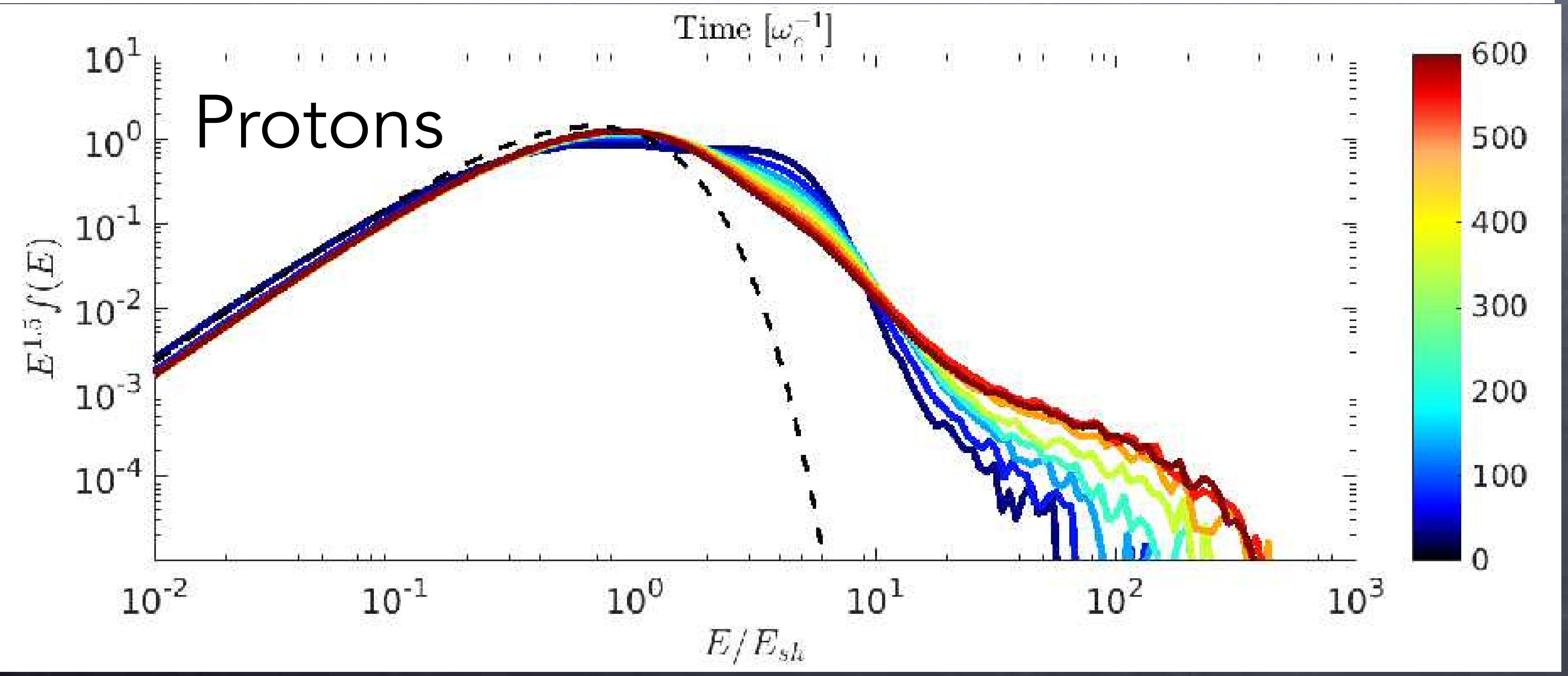
What if there are already energetic particles (seeds)?

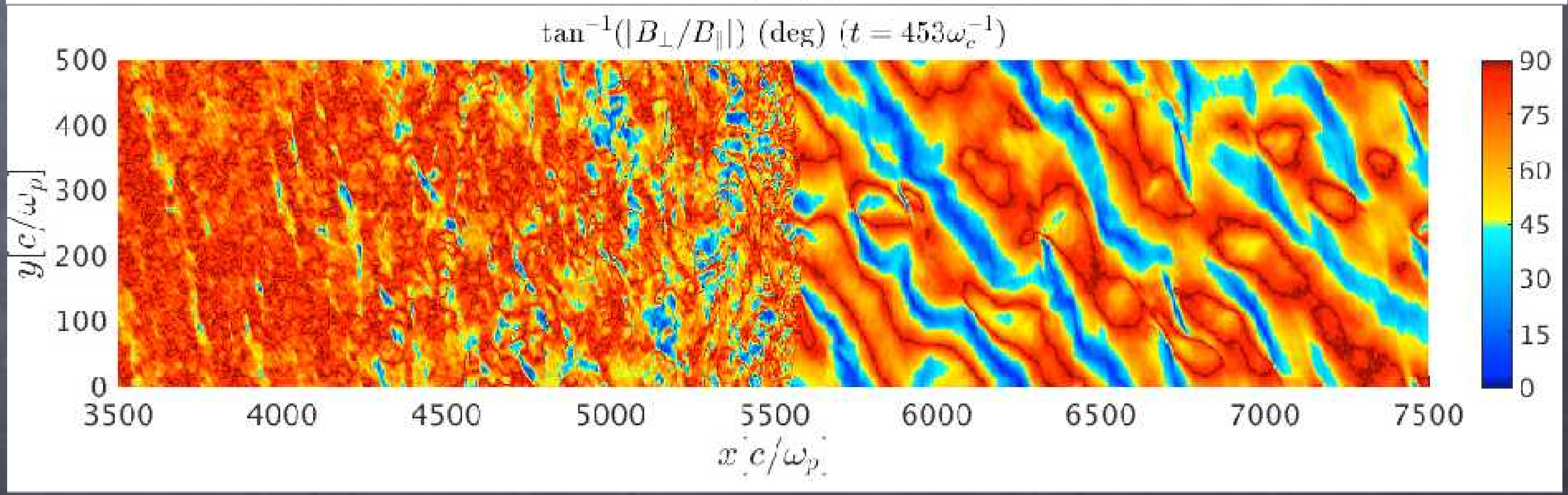
Diffusive Shock Re-Acceleration

- 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!



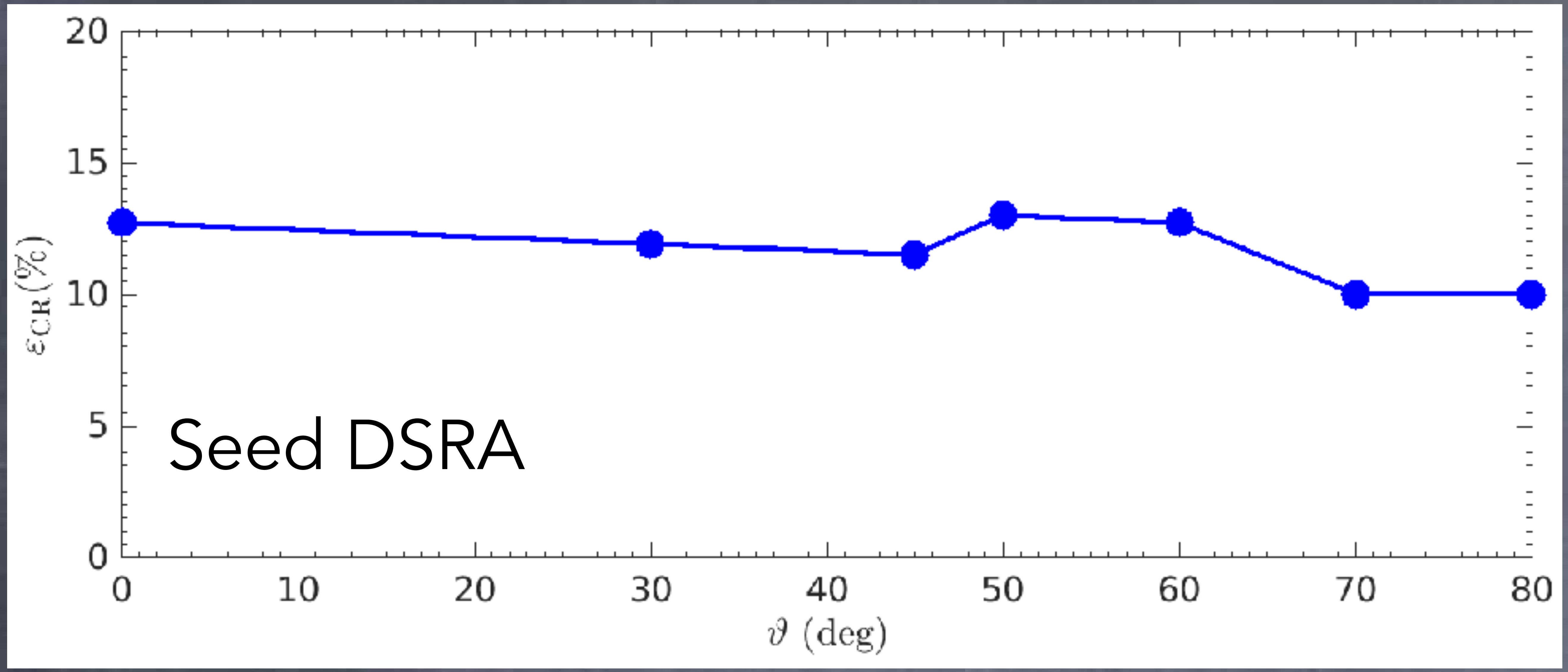


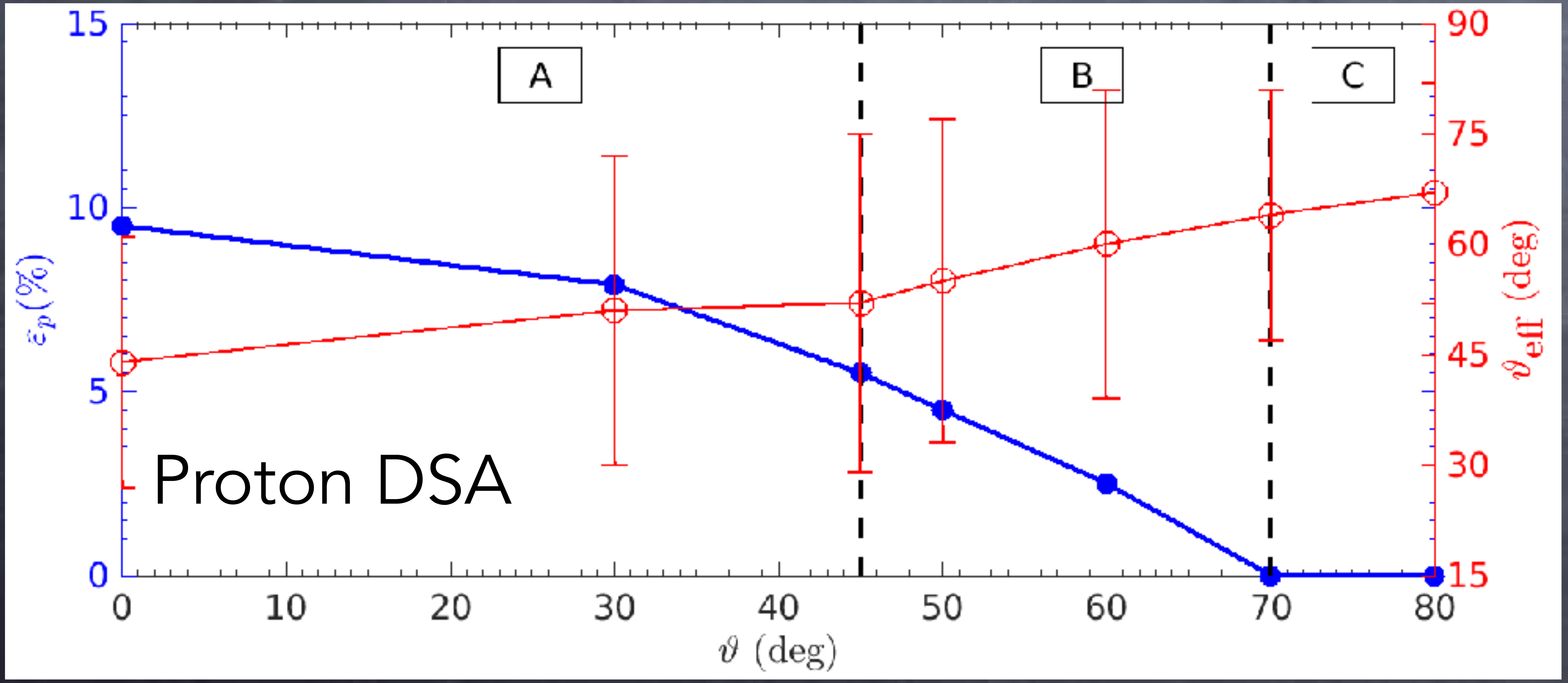




B-amplification opens up quasi-parallel patches at the shock where protons can be injected

Efficiency



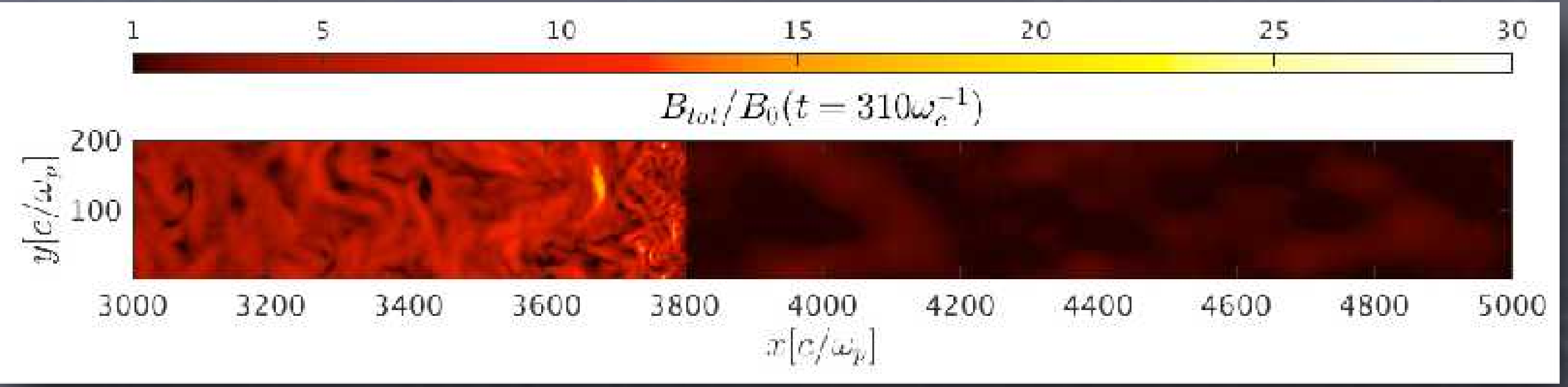


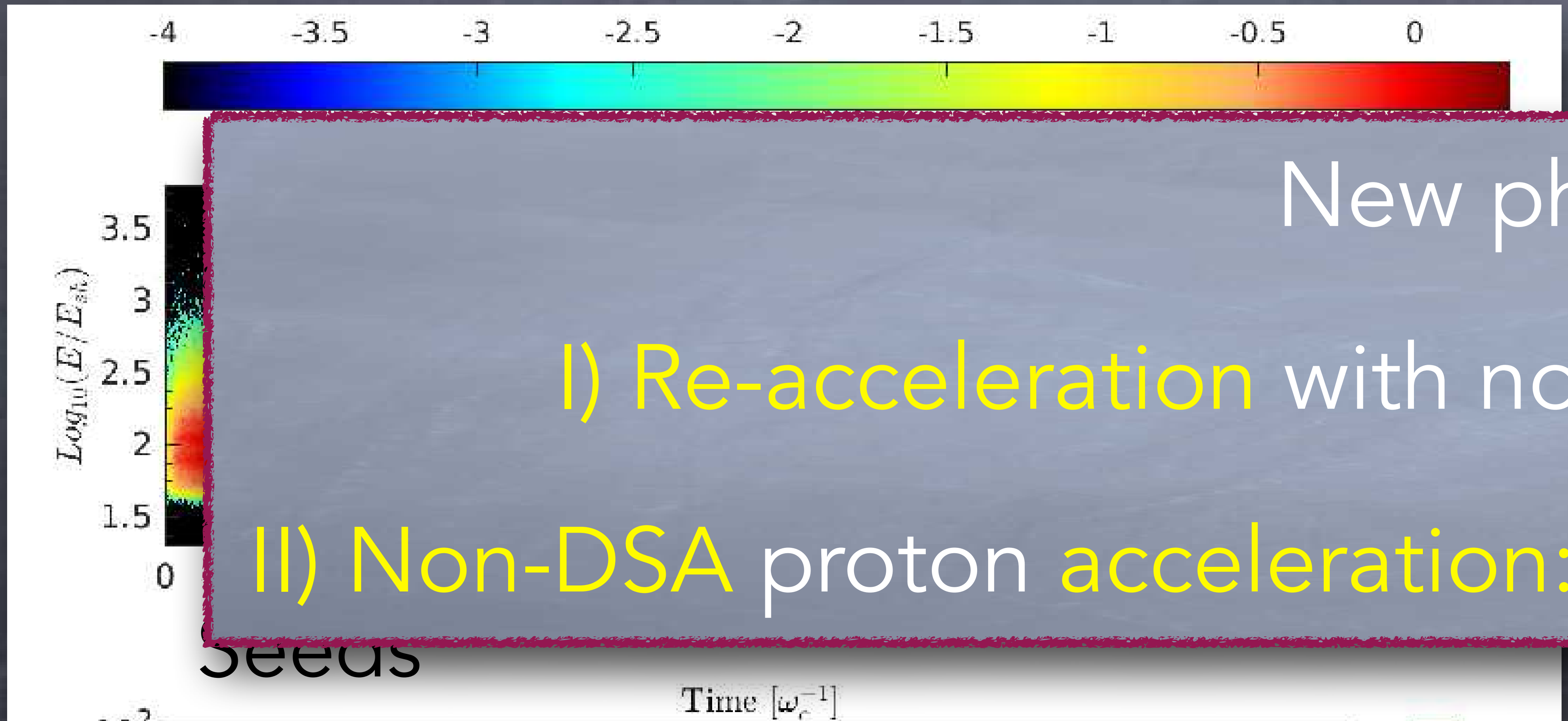
- Seed DSRA independent of ϑ, about 4x the initial CR energy density
  - *Absolute* efficiency depends on seed energy density
- Also electrons can be reaccelerated!

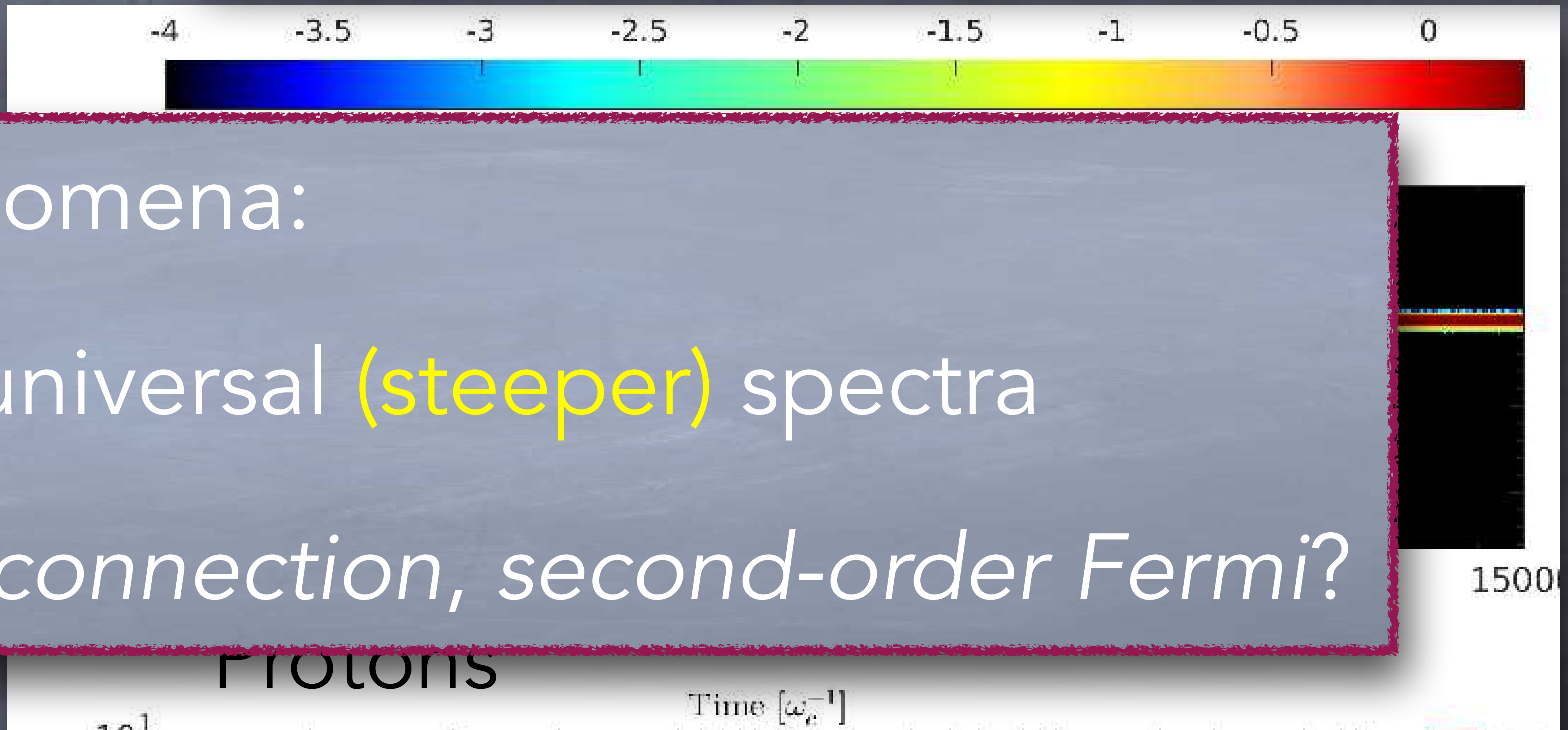
- A (ϑ<45°): Same proton efficiency
- (45°<ϑ<70°): Boosted to few %
- C (ϑ>70°): No proton DSA

Quasi-Perpendicular SEEDED Shocks

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



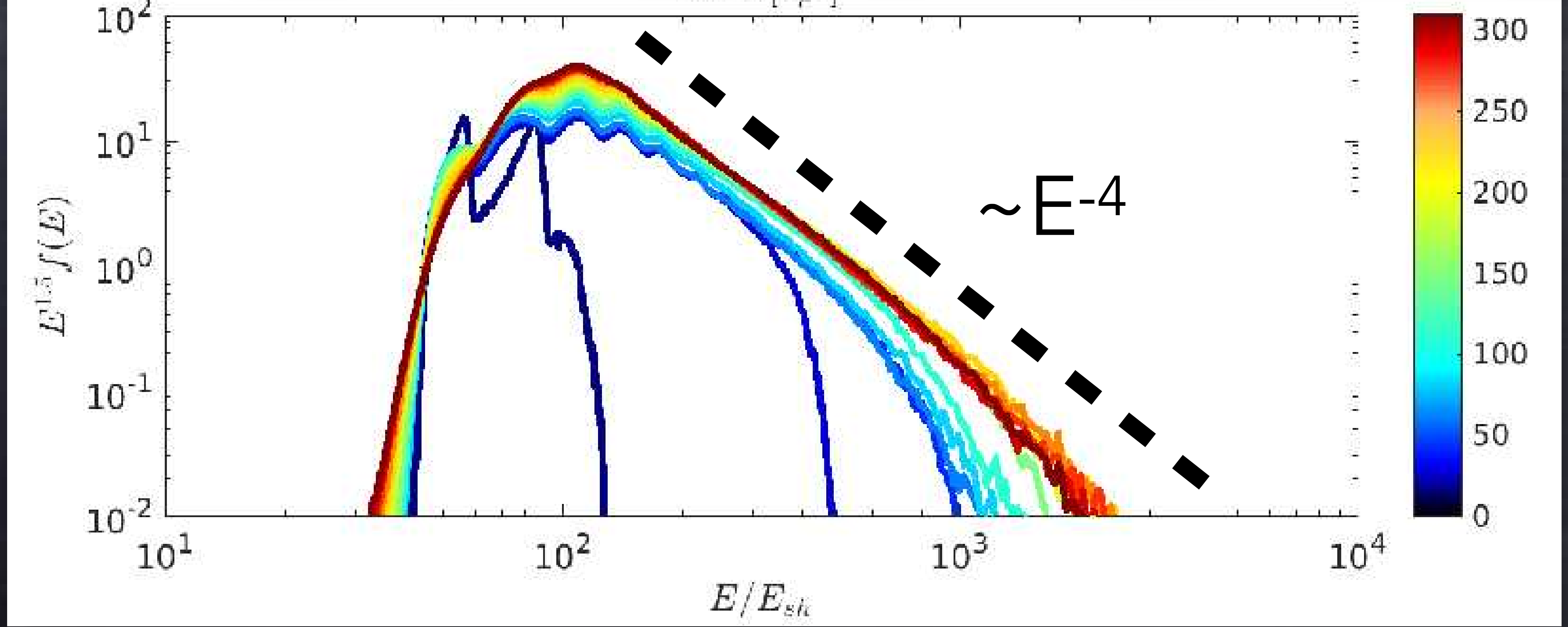


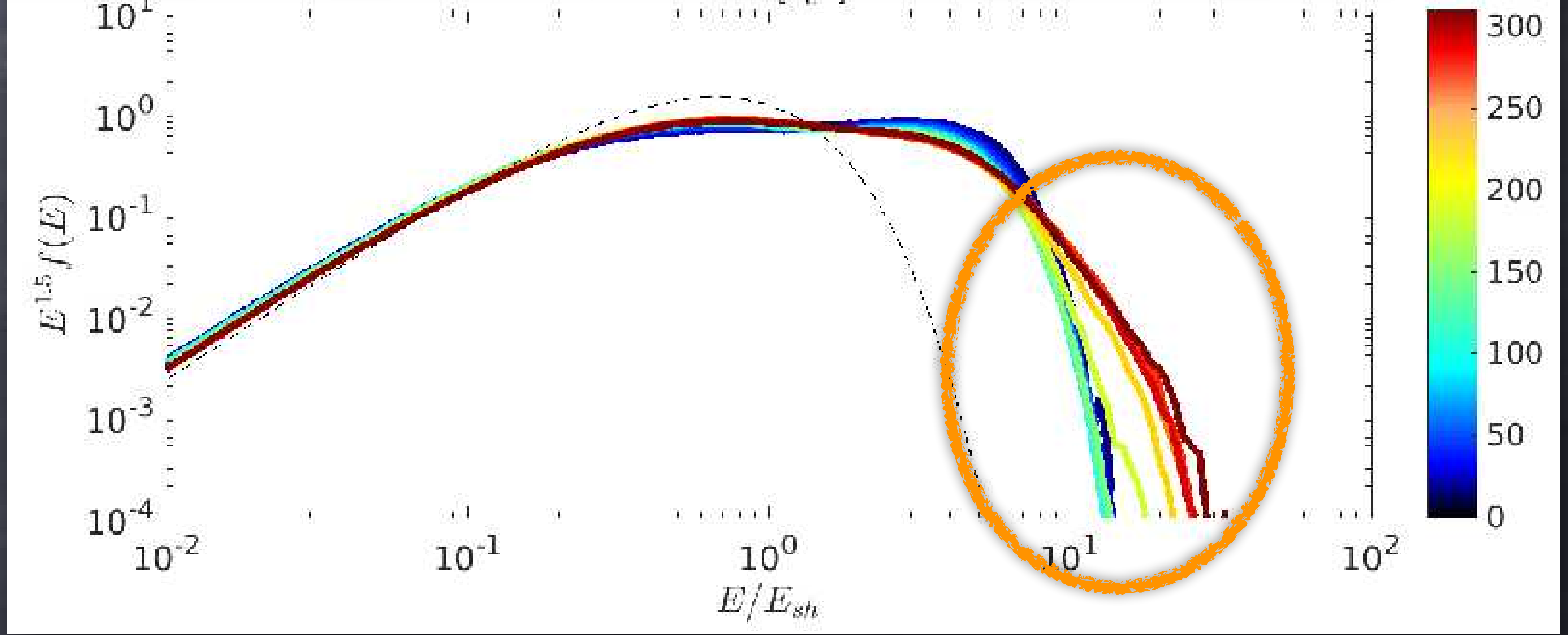


New phenomena:

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

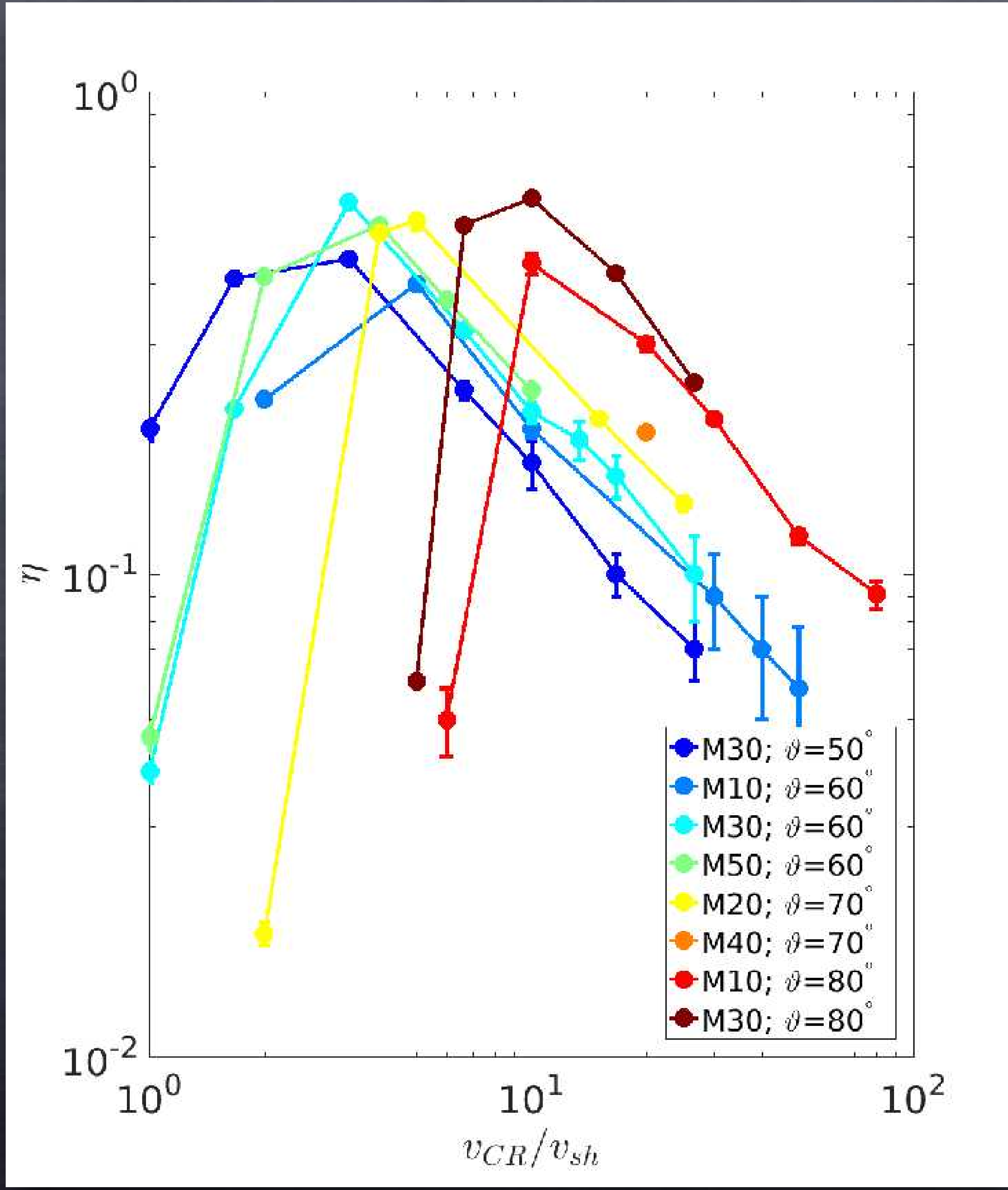
II) Non-DSA proton acceleration: *reconnection, second-order Fermi*?

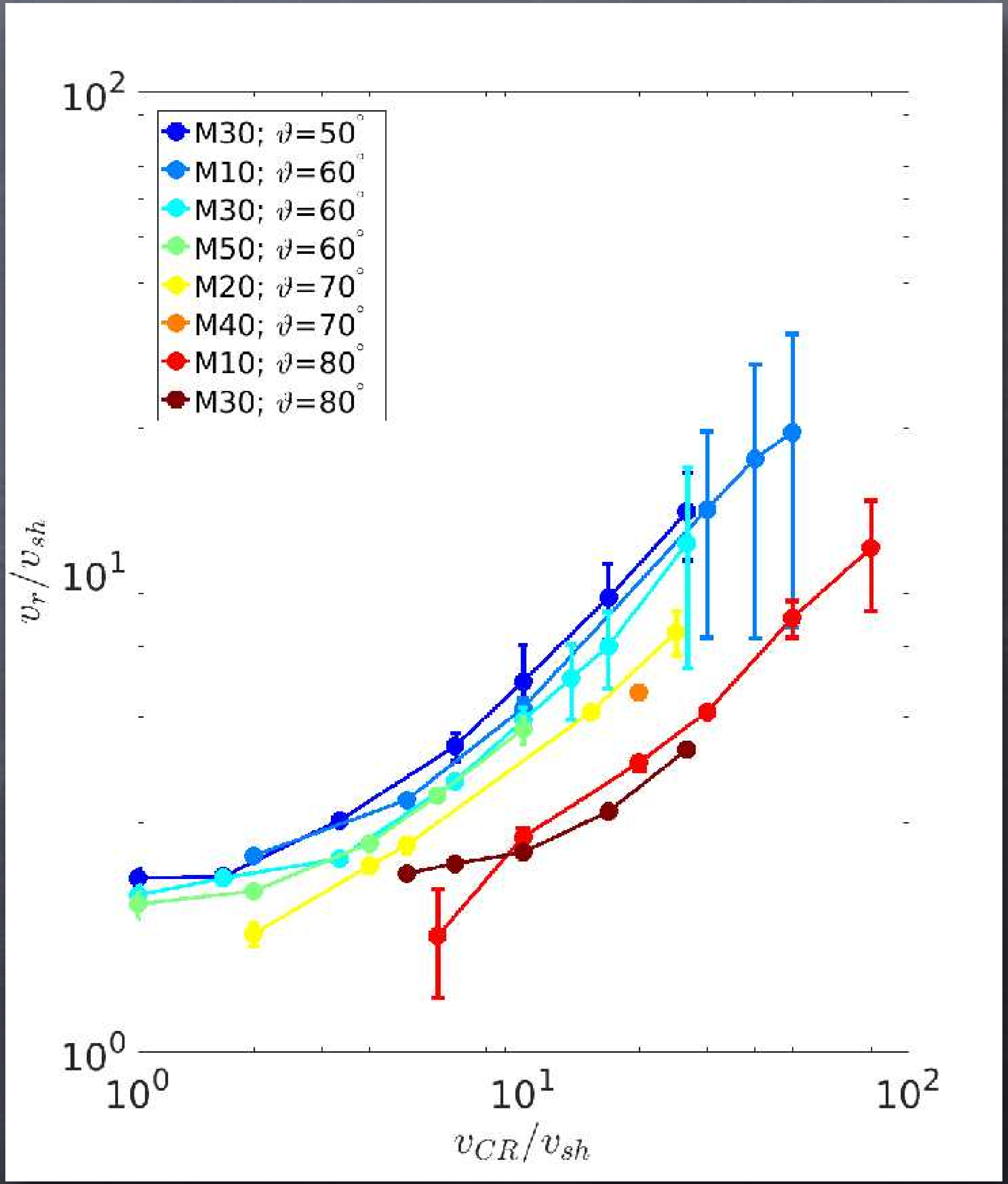




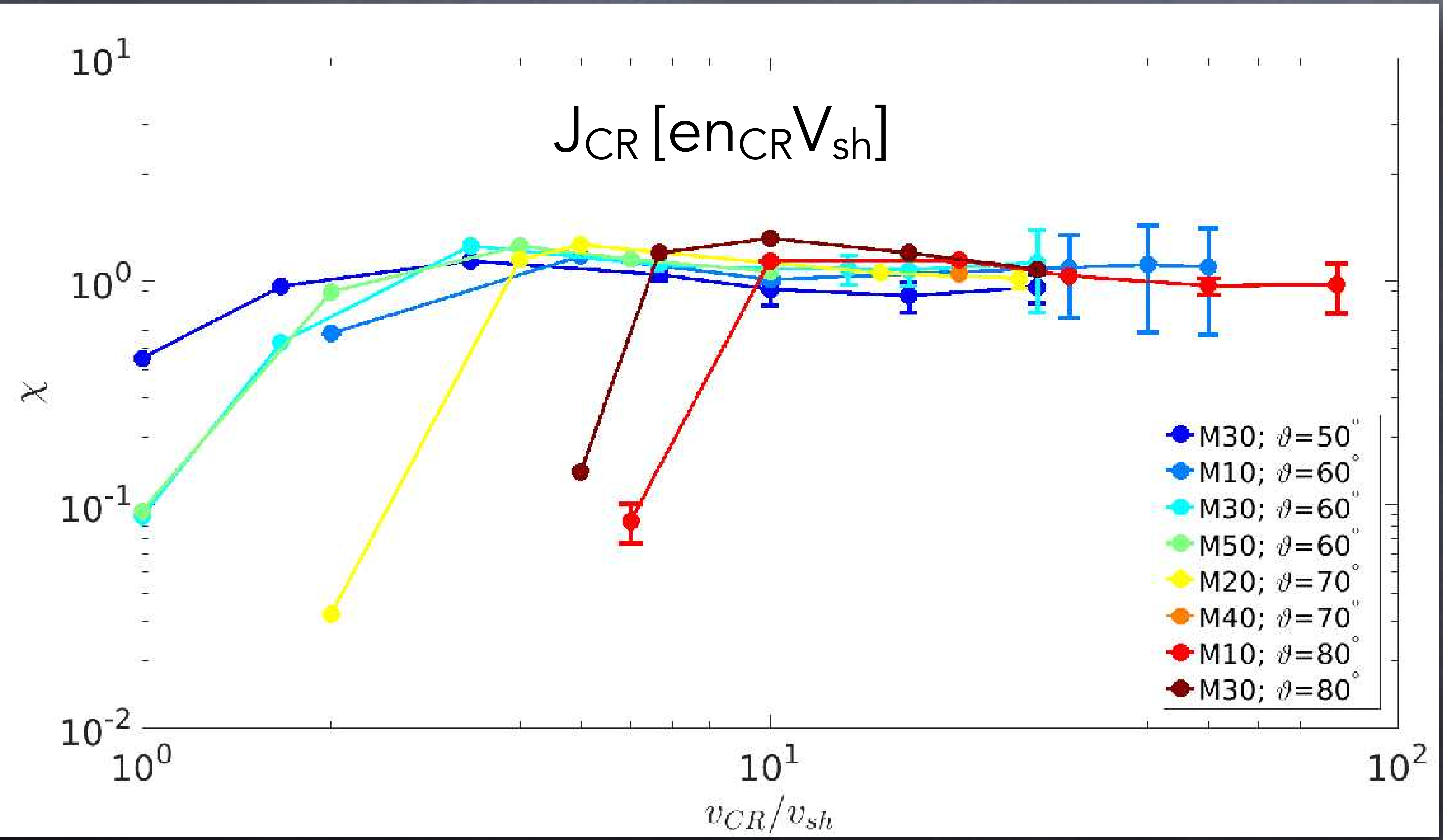
The Current in Reflected CRs

- 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:

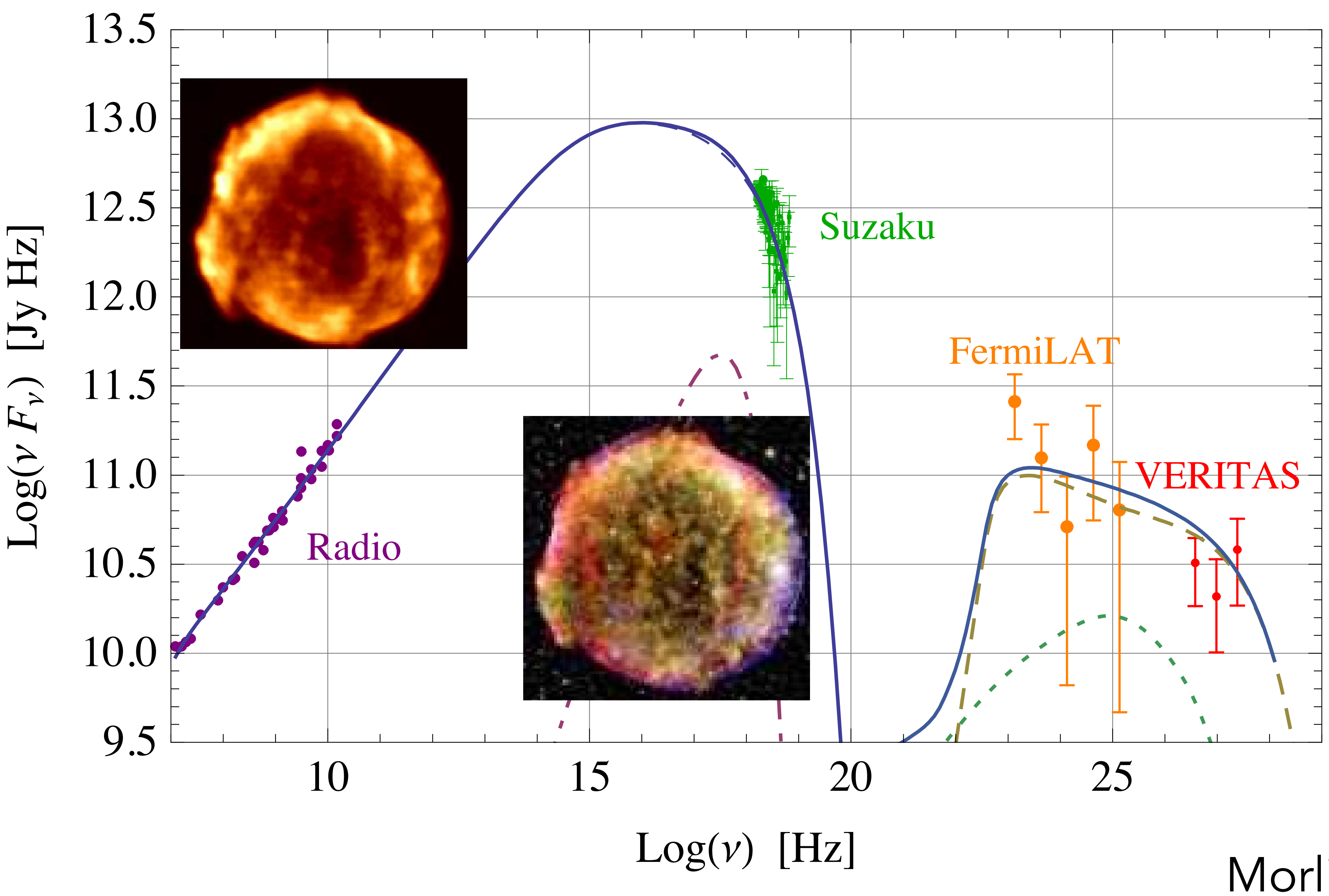
$$T_{\text{stream inst}} \sim 10\text{yr}$$

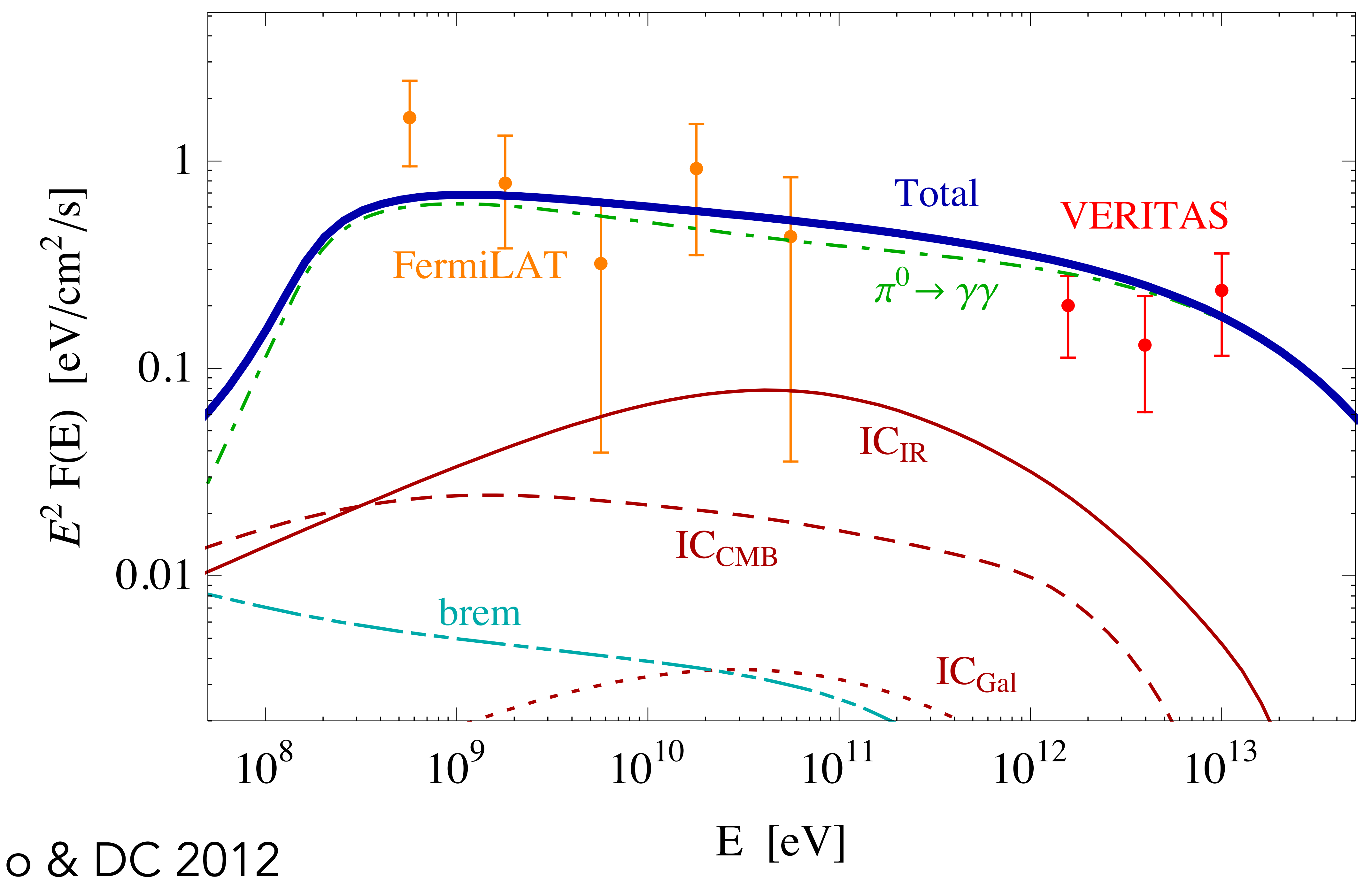
Minimum level of B-amplification for shocks in the ISM

Ion DSA can be *Efficient*!

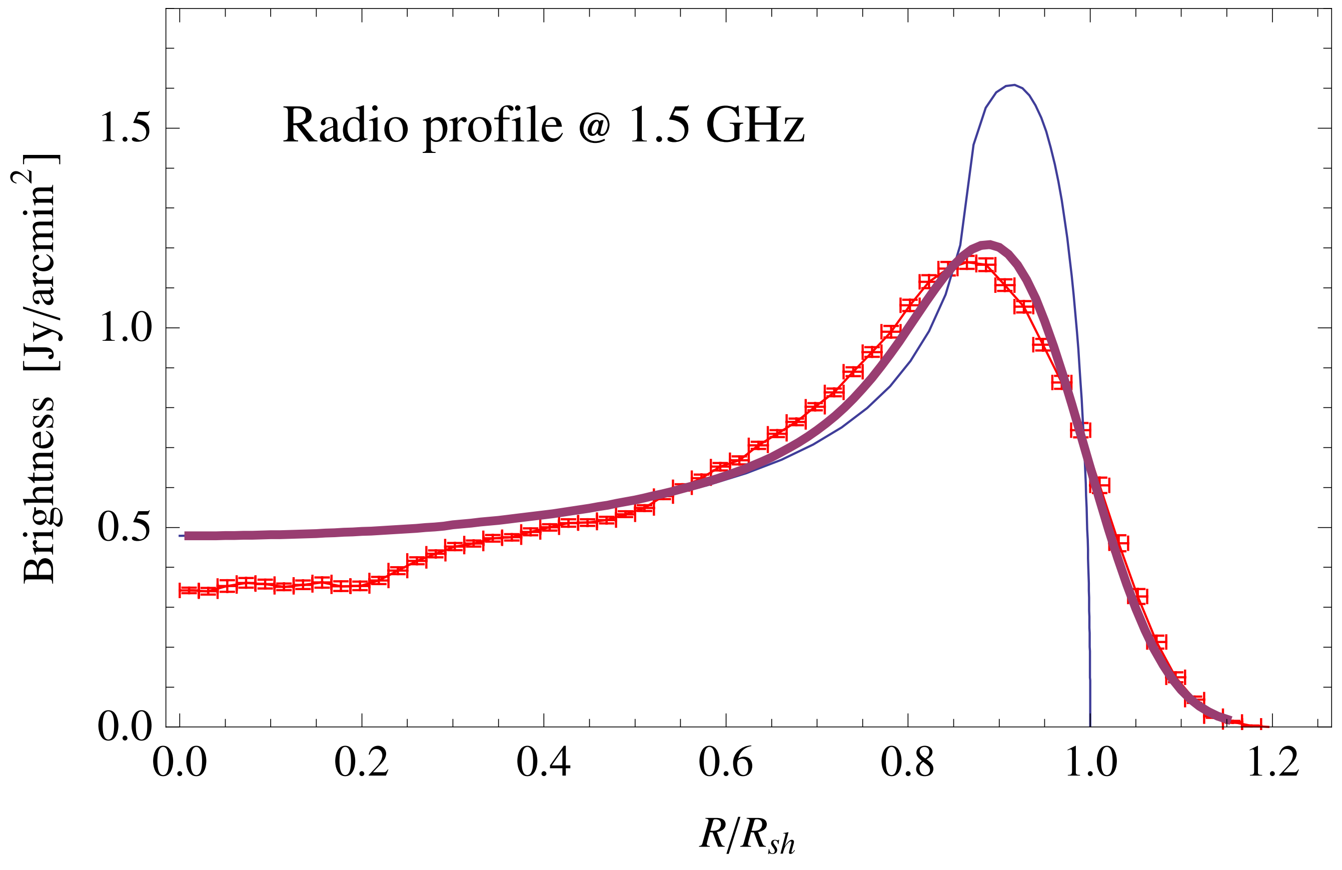
Tycho: the smoking gun for hadron acceleration

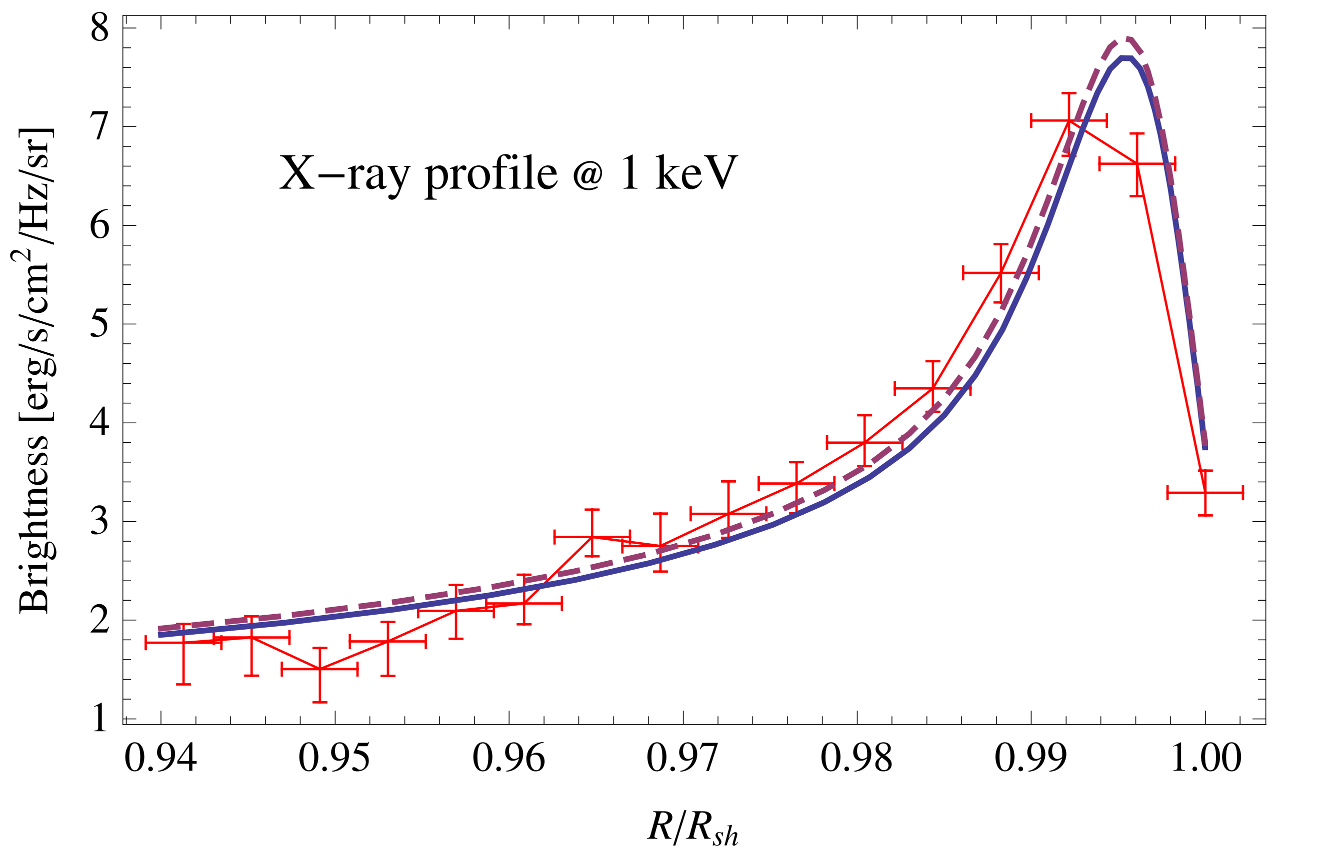
Type Ia SN
Age=446yr
Distance~3kpc





Morlino & DC 2012



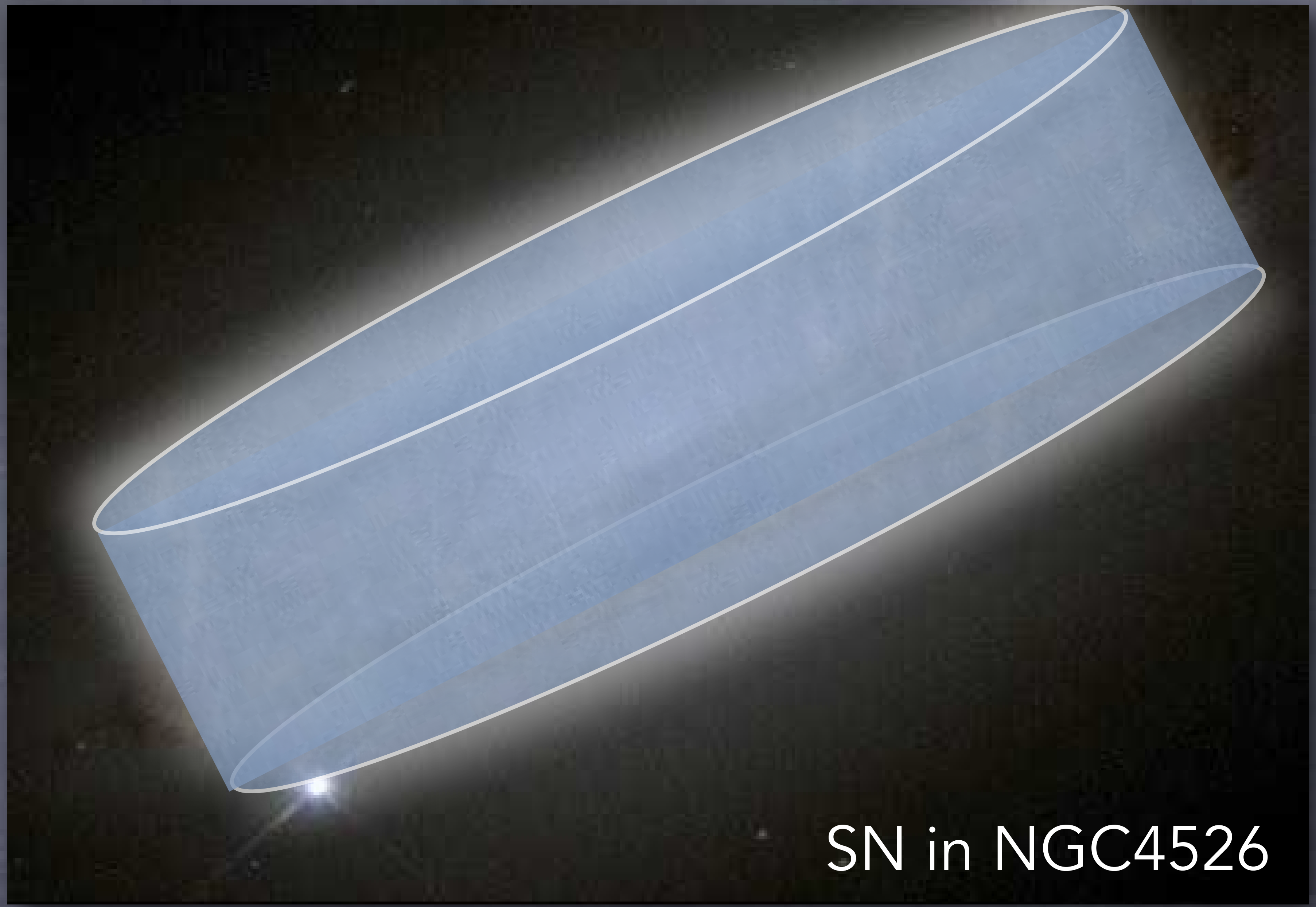


- Semi-analytical spectra from CRAFT
- Acceleration efficiency. ~15%
- Protons up to ~0.5 PeV

- Only two free parameters: electron/proton ratio and injection (now constrained with PIC!)

CR 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

The Issue with DSA

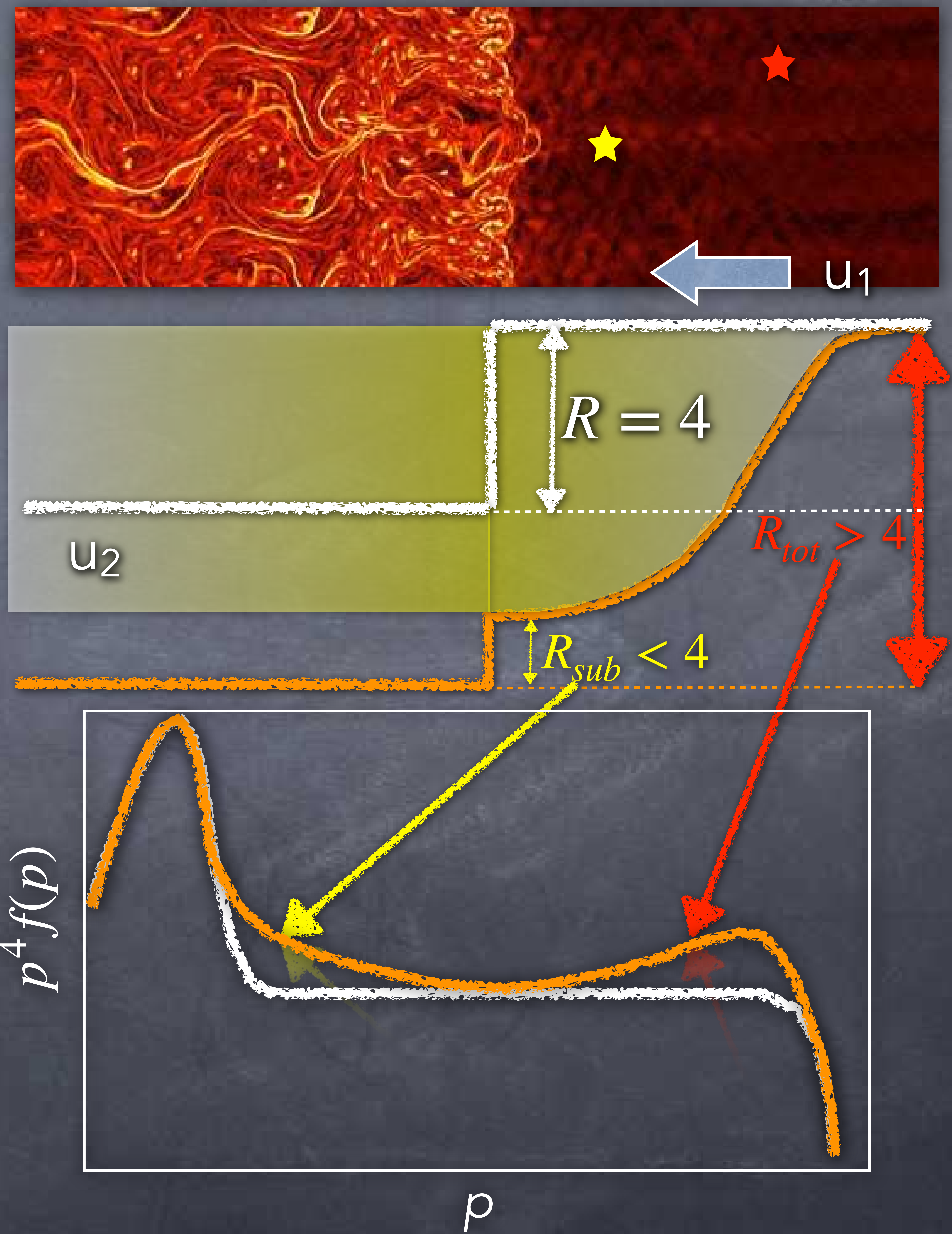
Non-Linear Diffusive Shock Acceleration

- The momentum spectral index depends only on the compression ratio

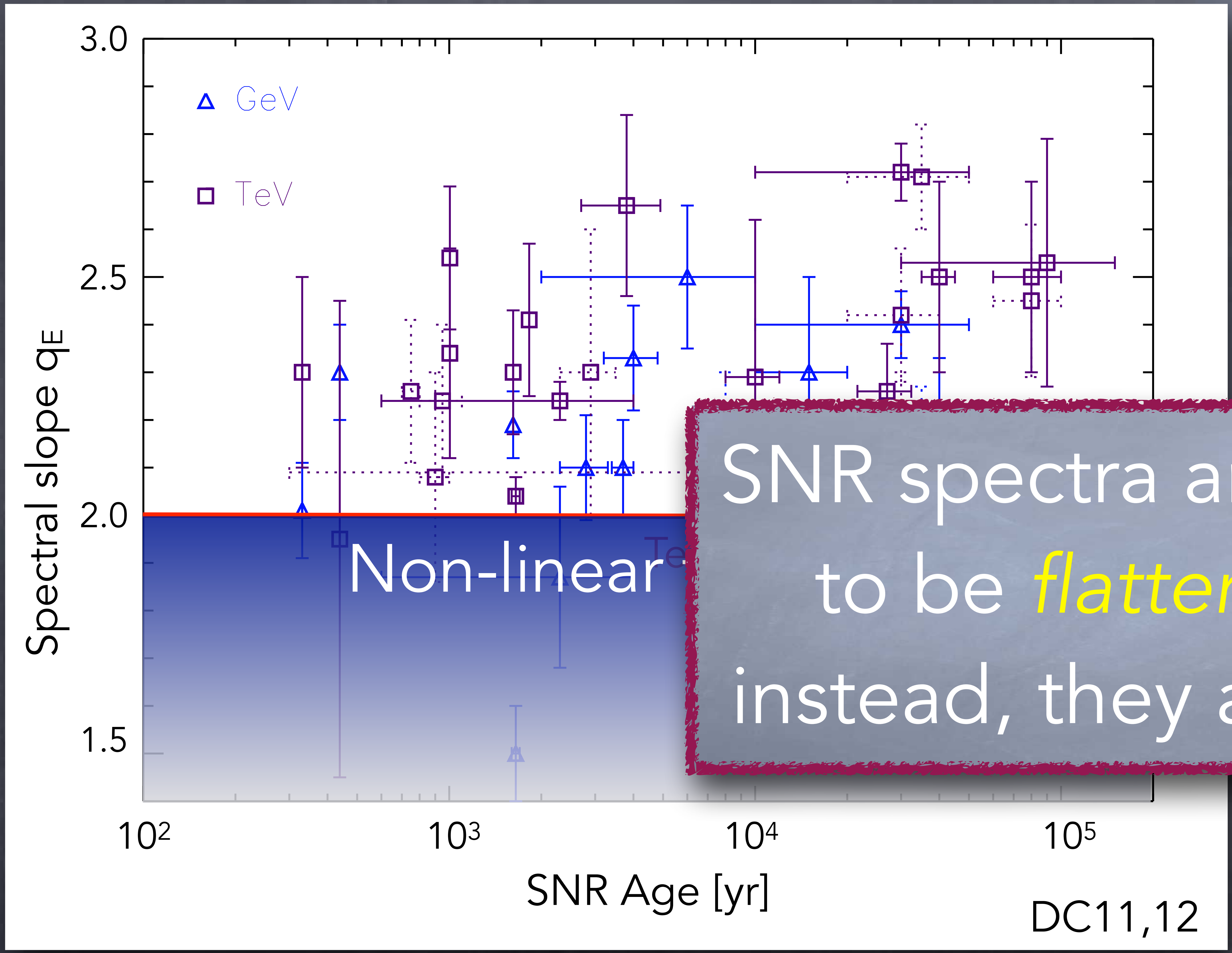
$$q = \frac{3R}{R-1}; \qquad R = \frac{\gamma+1}{\gamma-1}$$

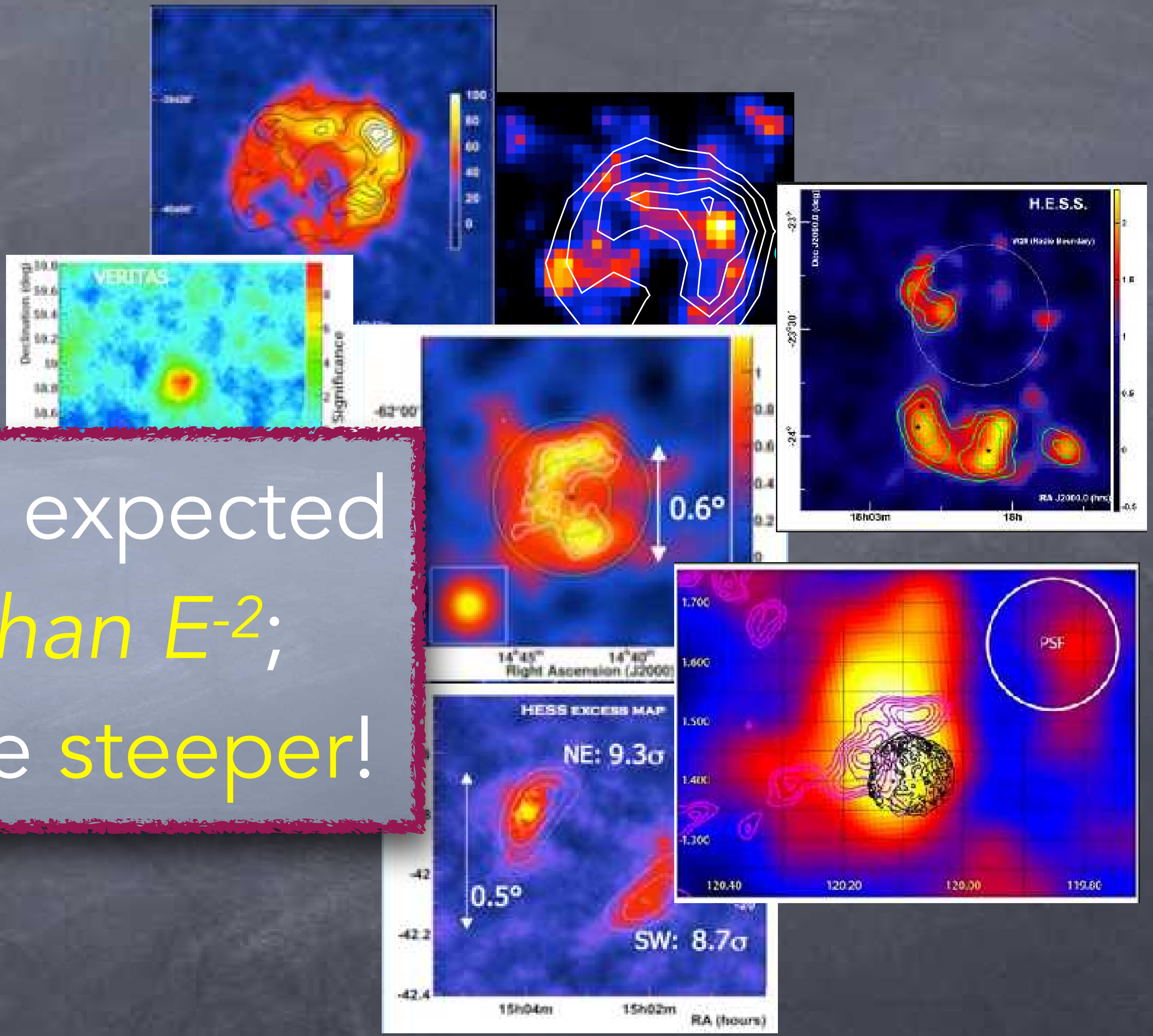
- The CR pressure makes the adiabatic index smaller and induce a shock precursor
- Particles "feel" different compression ratios: spectra should become concave
- If acceleration is efficient, at energies >1 GeV: $q < 4$ (flat spectra!)

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



I) Gamma-Rays from SNRs





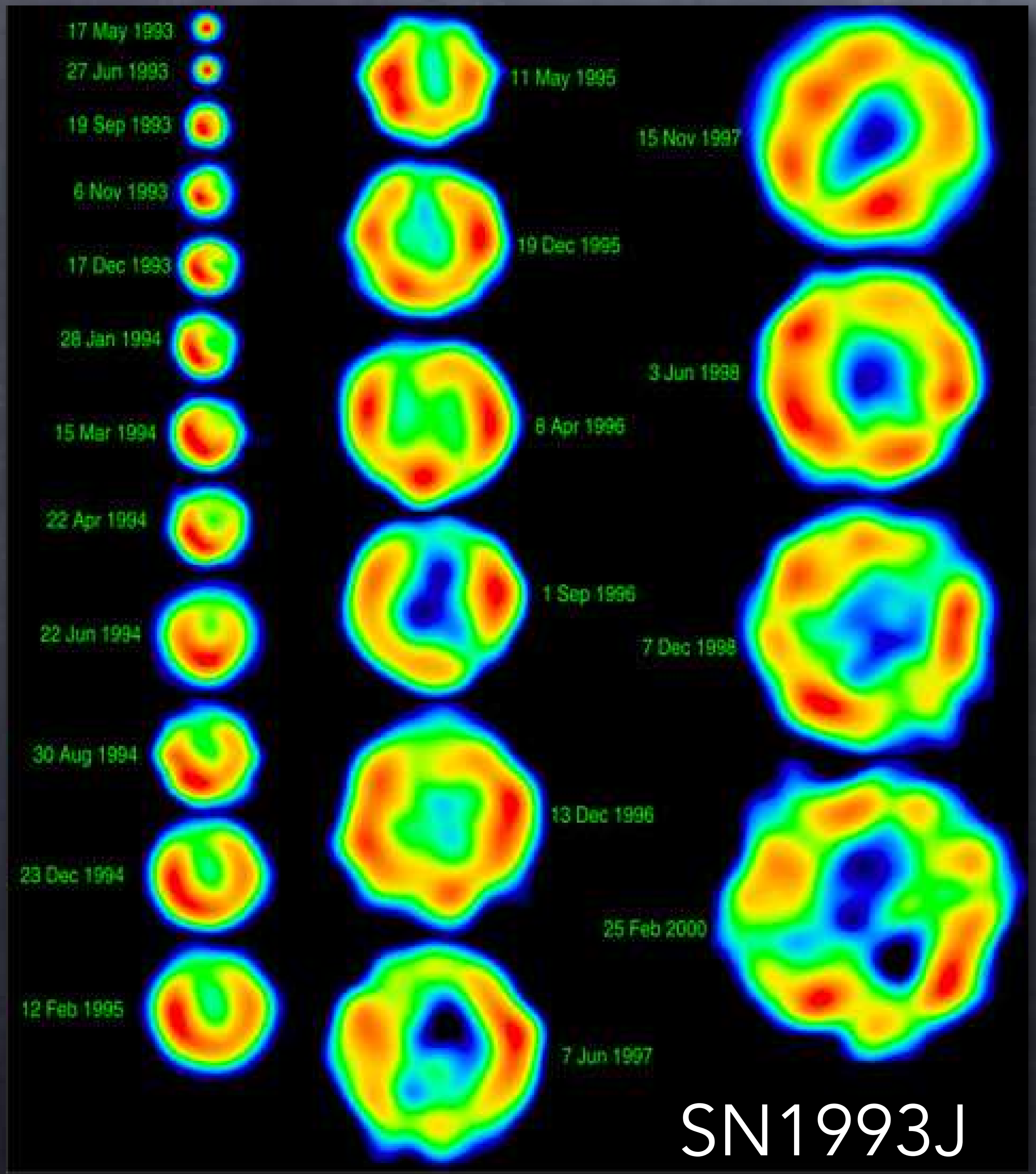
SNR spectra are expected to be *flatter than E^{-2}*; instead, they are steeper!

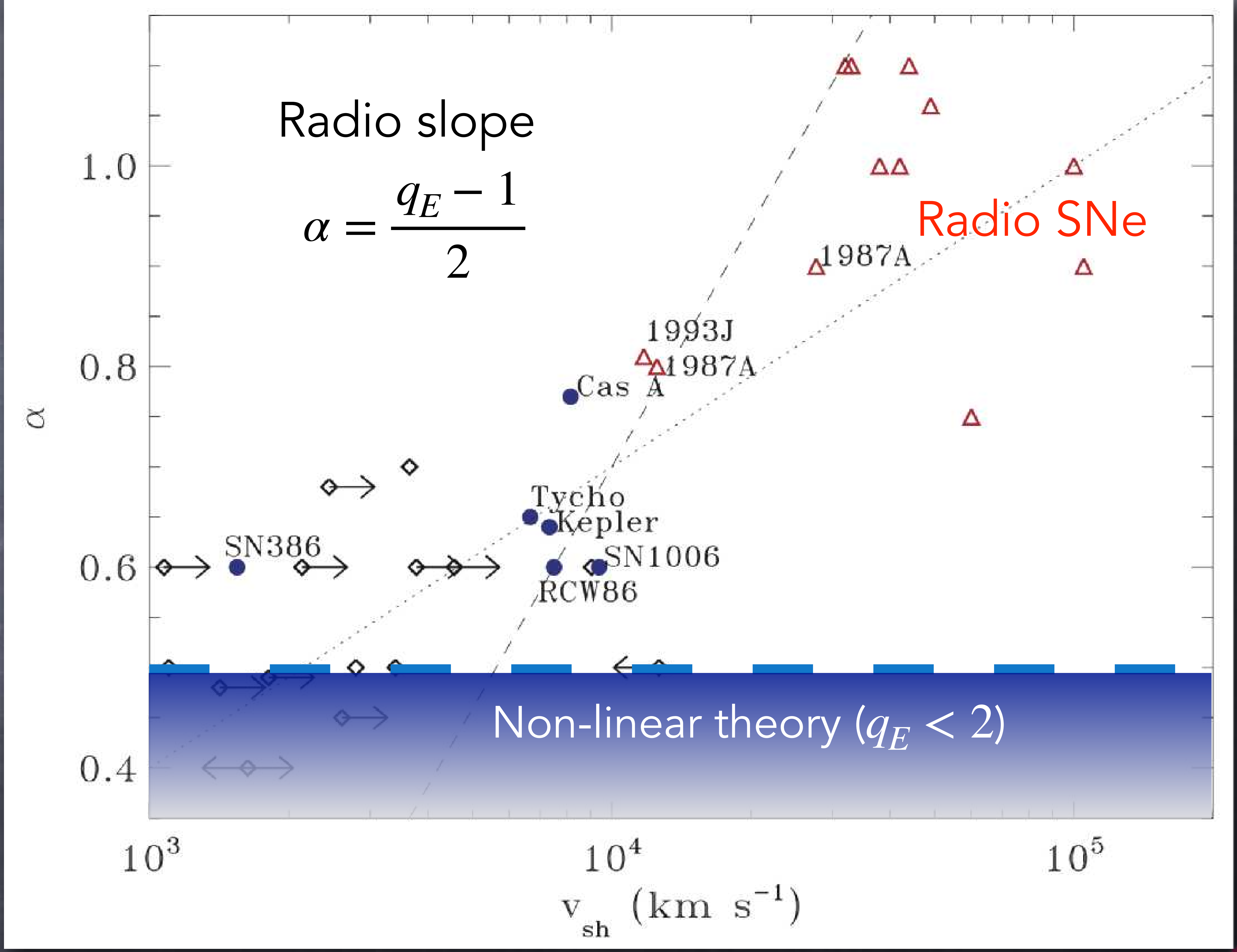
- Too steep to be leptonic: hadronic emission
- Not consistent with non-linear DSA theory!

II) Extra-galactic SNe

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

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

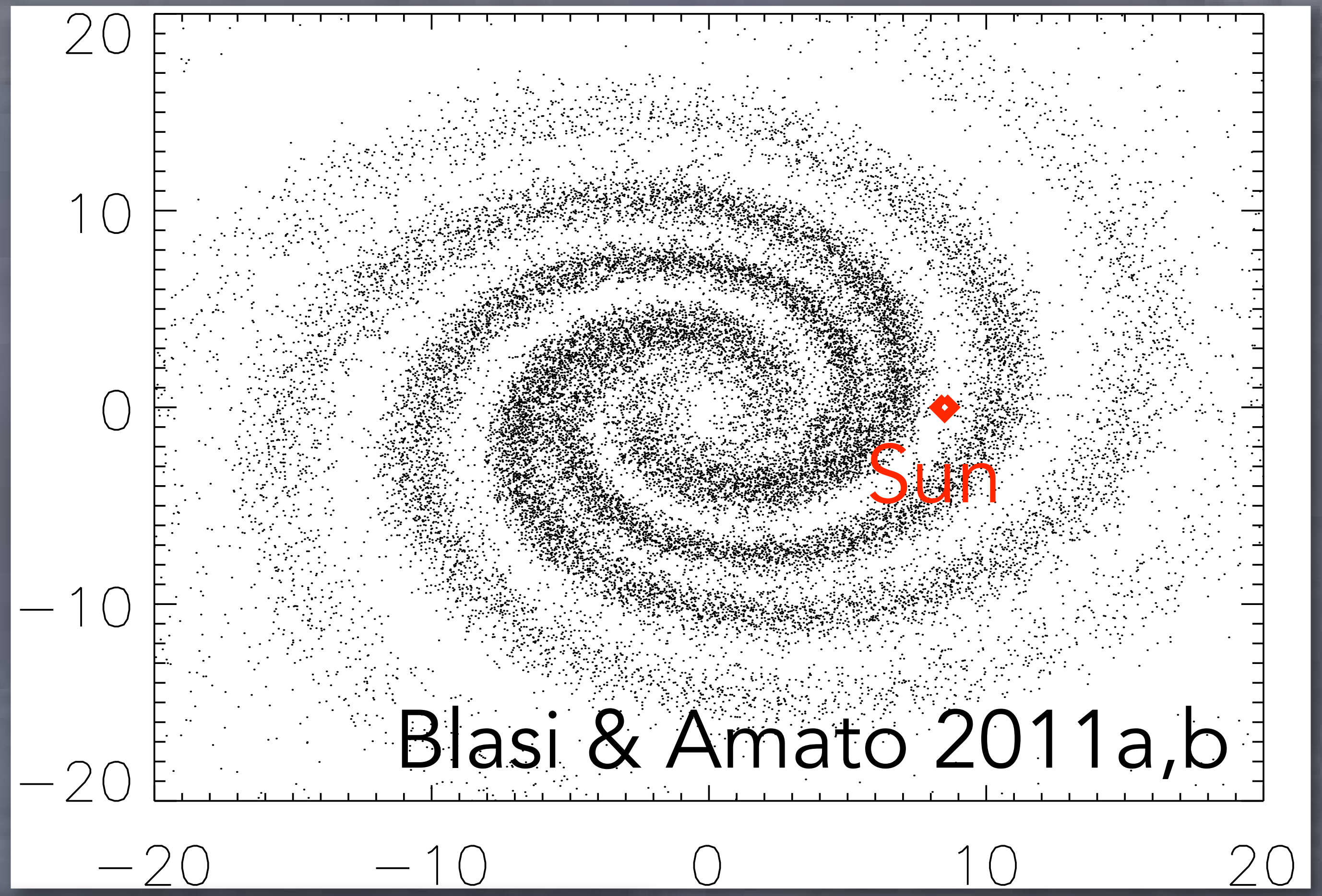


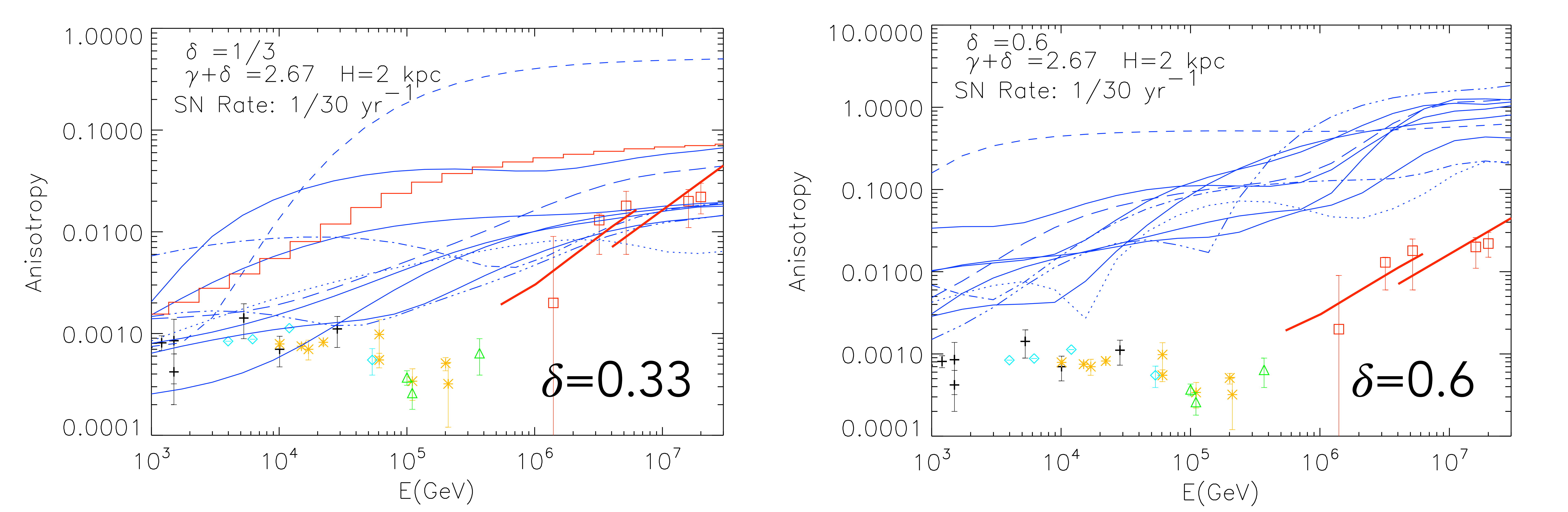


Adapted from Bell+11

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

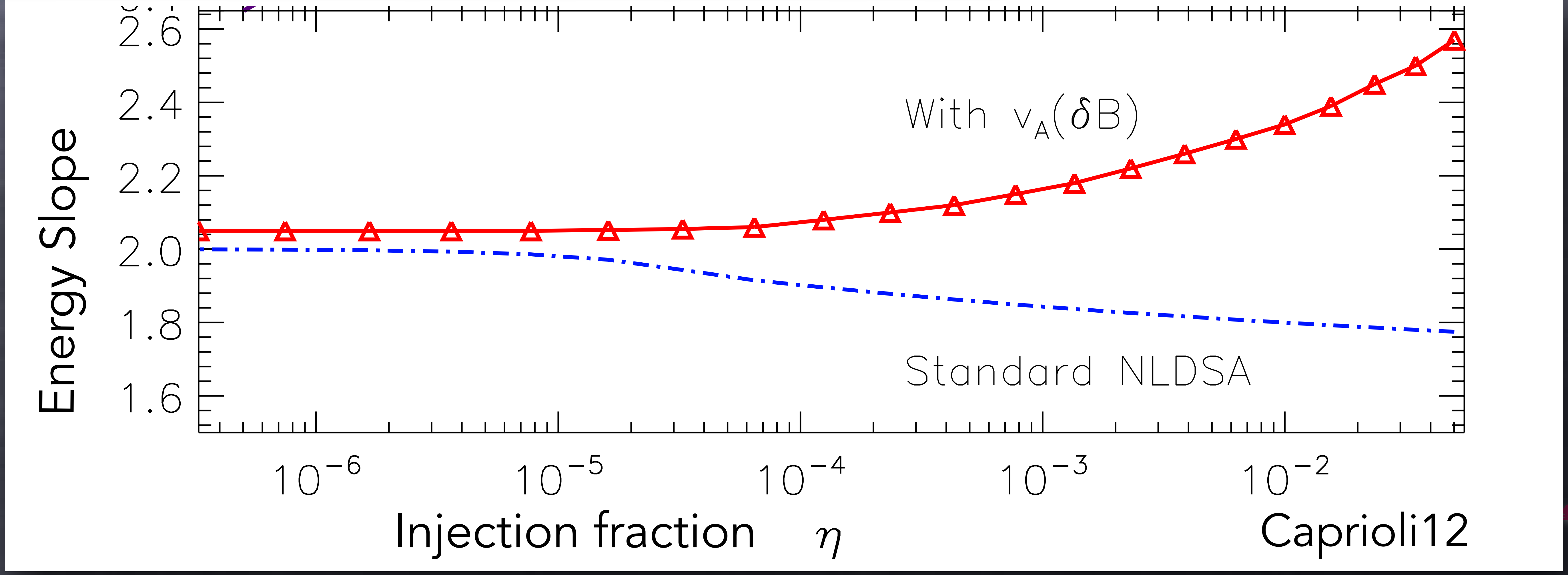
A Theoretical Challenge

- 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:

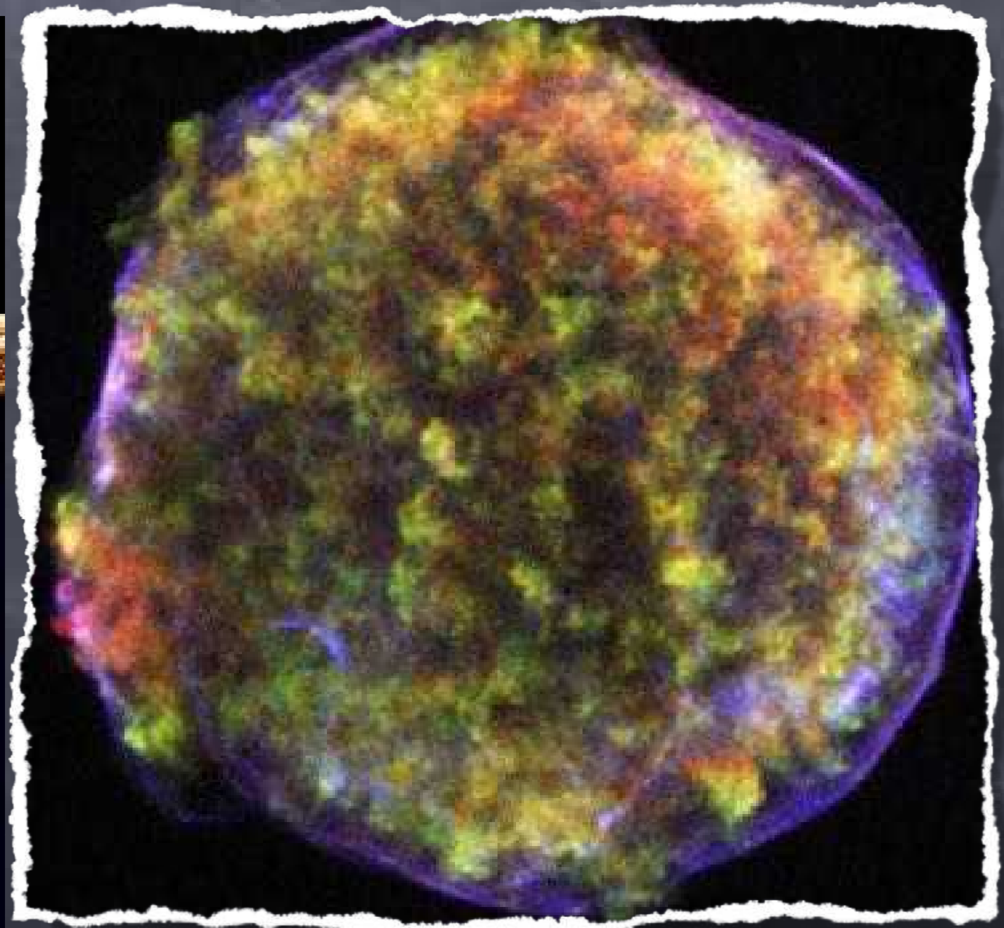
$$R_{cr} \simeq \frac{u_1 \pm v_{A,1}}{u_2 \pm v_{A,2}} \lesssim R_{gas}$$



Theory vs Observations

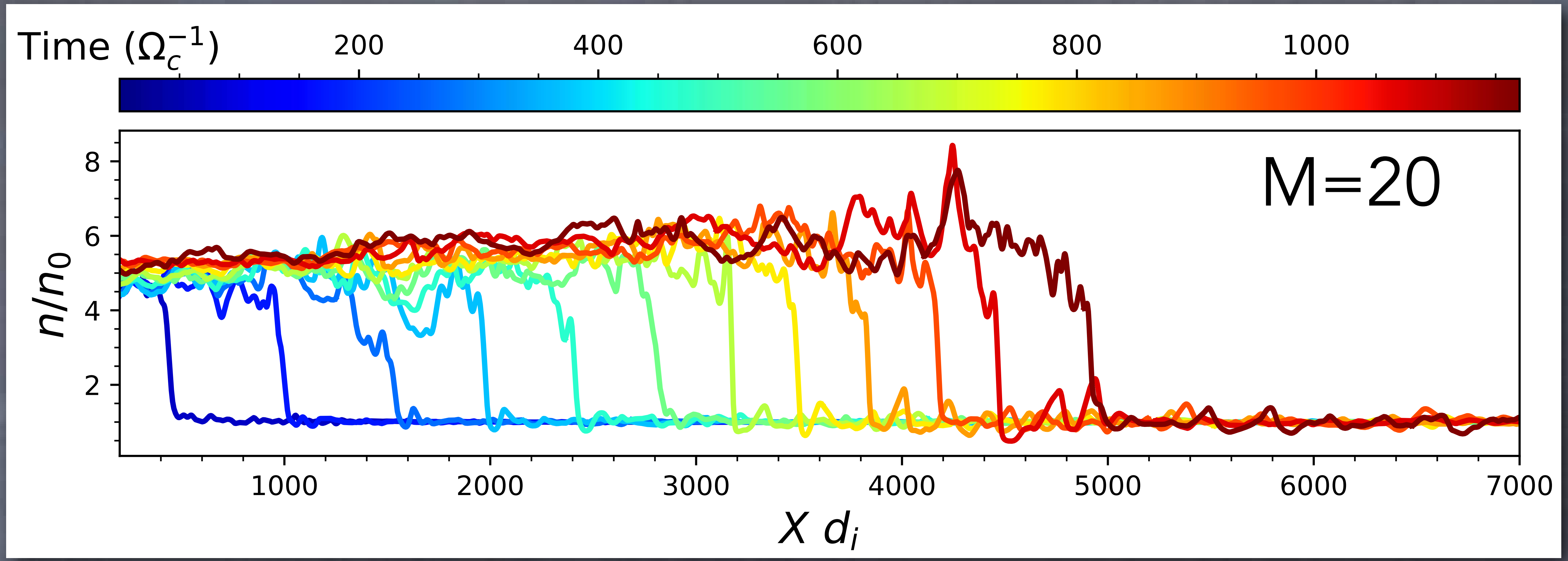
- ***Efficient DSA*** (Drury 1983, Jones & Ellison 1991, Malkov & Drury 2001,...) should return:
  - Compression ratios $R > 4$;
  - CR spectra flatter than p^{-4} (flatter than E^{-2} for relativistic particles)
- **Observations**, instead, point to significantly steeper spectra:
  - Hadronic γ-rays 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, Margutti+18, …);
  - Propagation of Galactic CRs suggests source spectra with $q \sim 4.3 - 4.4$ (e.g., Blasi-Amato11a,b; Evoli+19).





CR-modified Shocks: Enhanced compression!

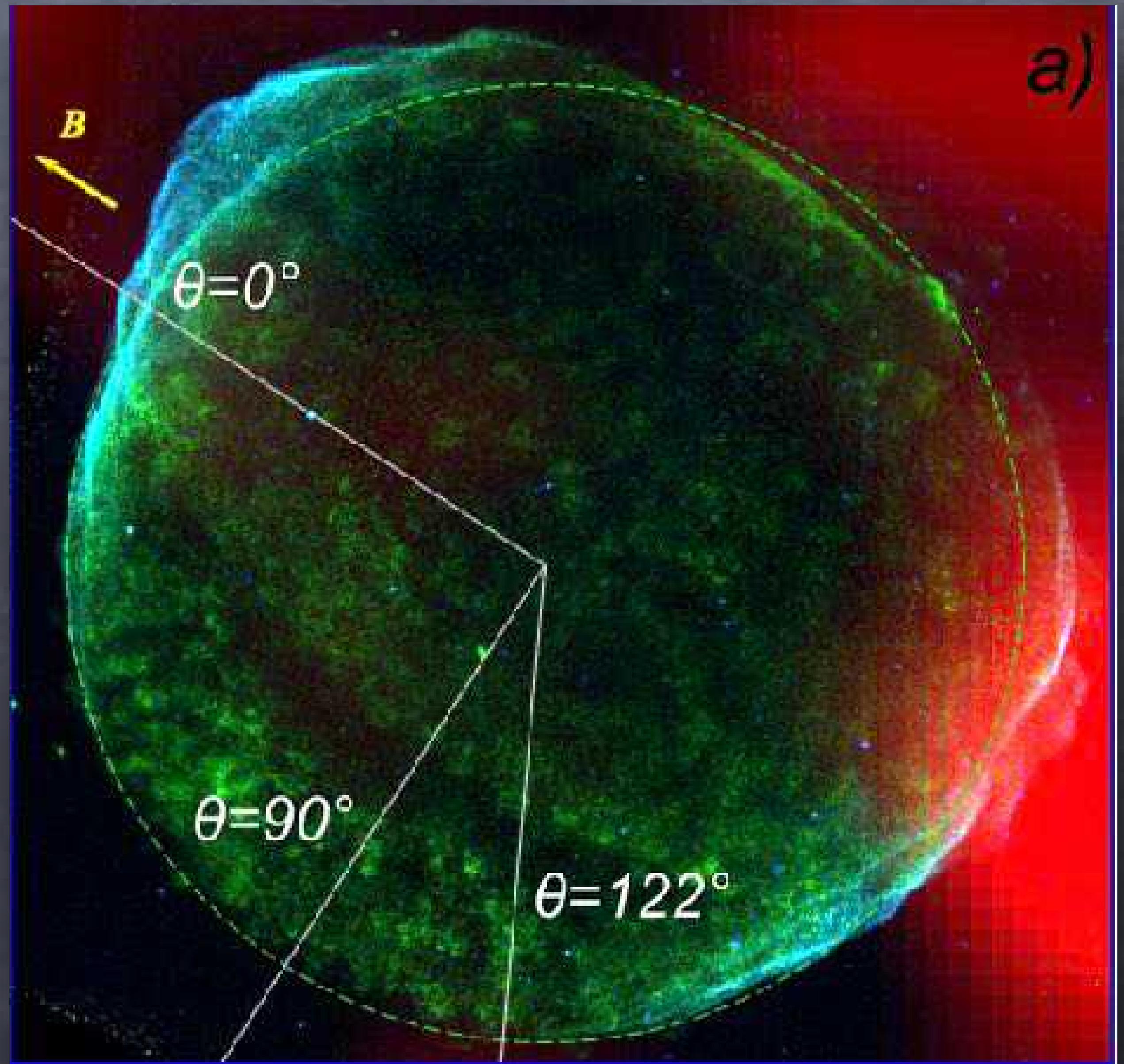
- Hybrid simulations (Haggerty & Caprioli20)
  - Efficiency $\lesssim 15\,\%$ at parallel shocks
  - Formation of upstream precursor
  - R increases with time, up to ~ 6

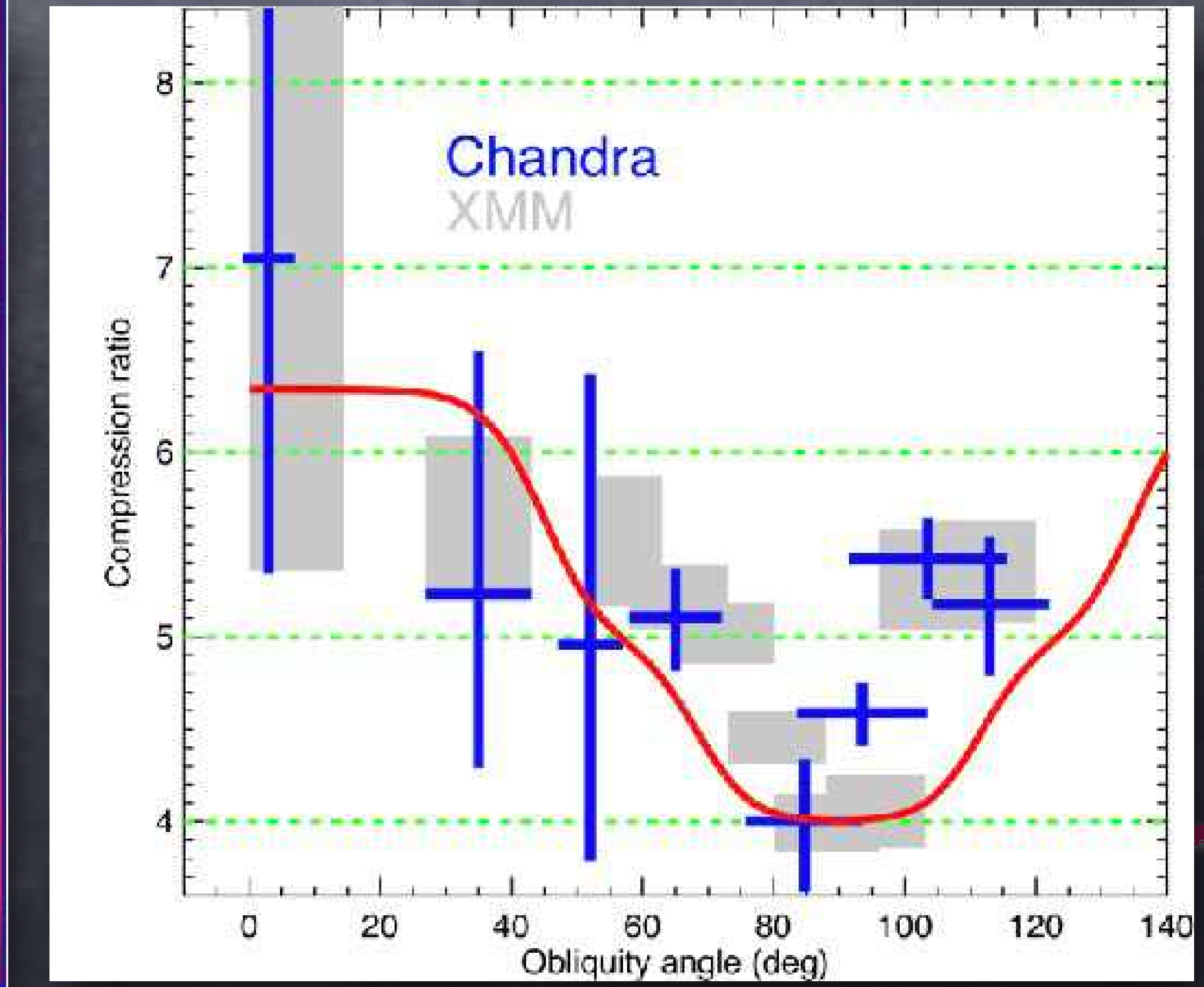


- $R \sim 6-7$ inferred in Tycho (Warren+05). In SN1006: $R \sim 4-7$, modulated with the azimuth/shock inclination (Giuffrida, Miceli, Caprioli+21, Nature Comm, in press)
  - If $R \simeq 7 \rightarrow q_{\rm expected} \simeq 3.5$
  - SNRs: radio to γ-ray observations:

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

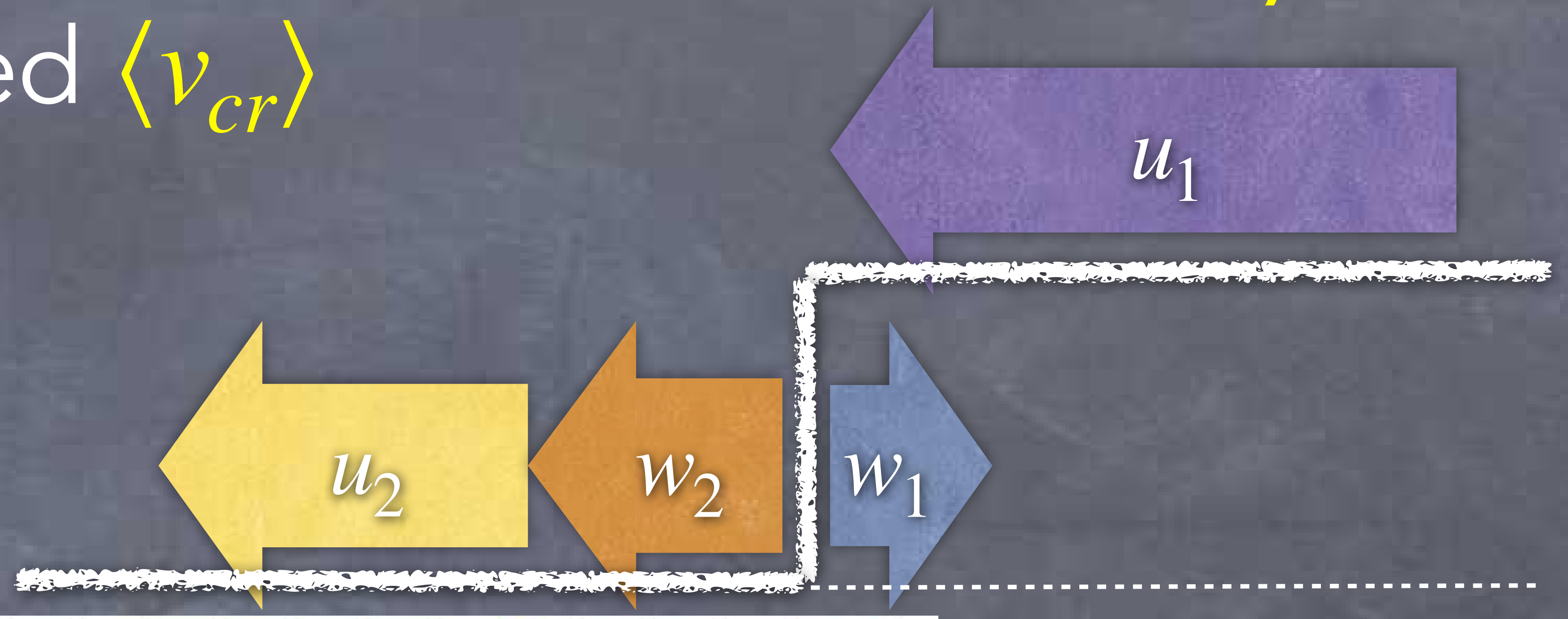
A challenge to DSA theory!

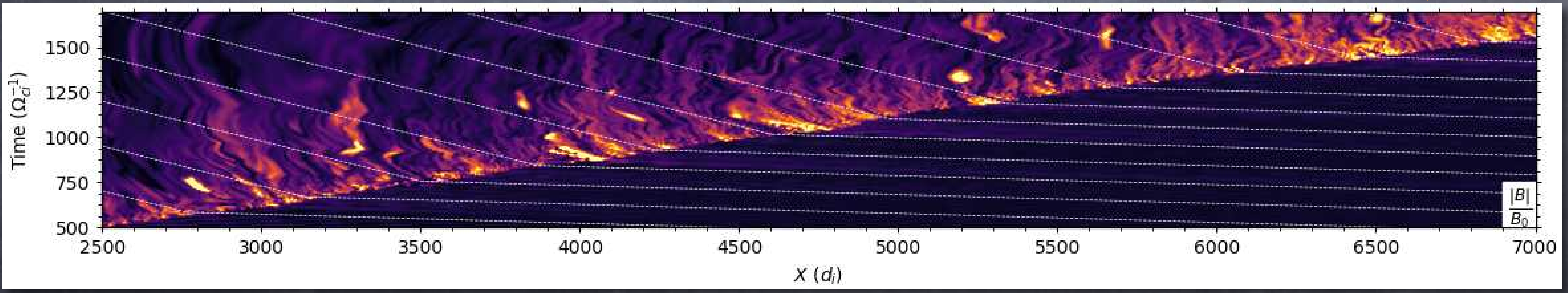




The Role of Amplified Magnetic Fields

- CRs feel an effective compression $R_{cr} = \dfrac{u_1 + w_1}{u_2 + w_2}$; 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: $\langle v_{cr} \rangle \simeq w_2 \simeq +v_{A,2}(\delta B_2) \equiv \alpha\ u_2$



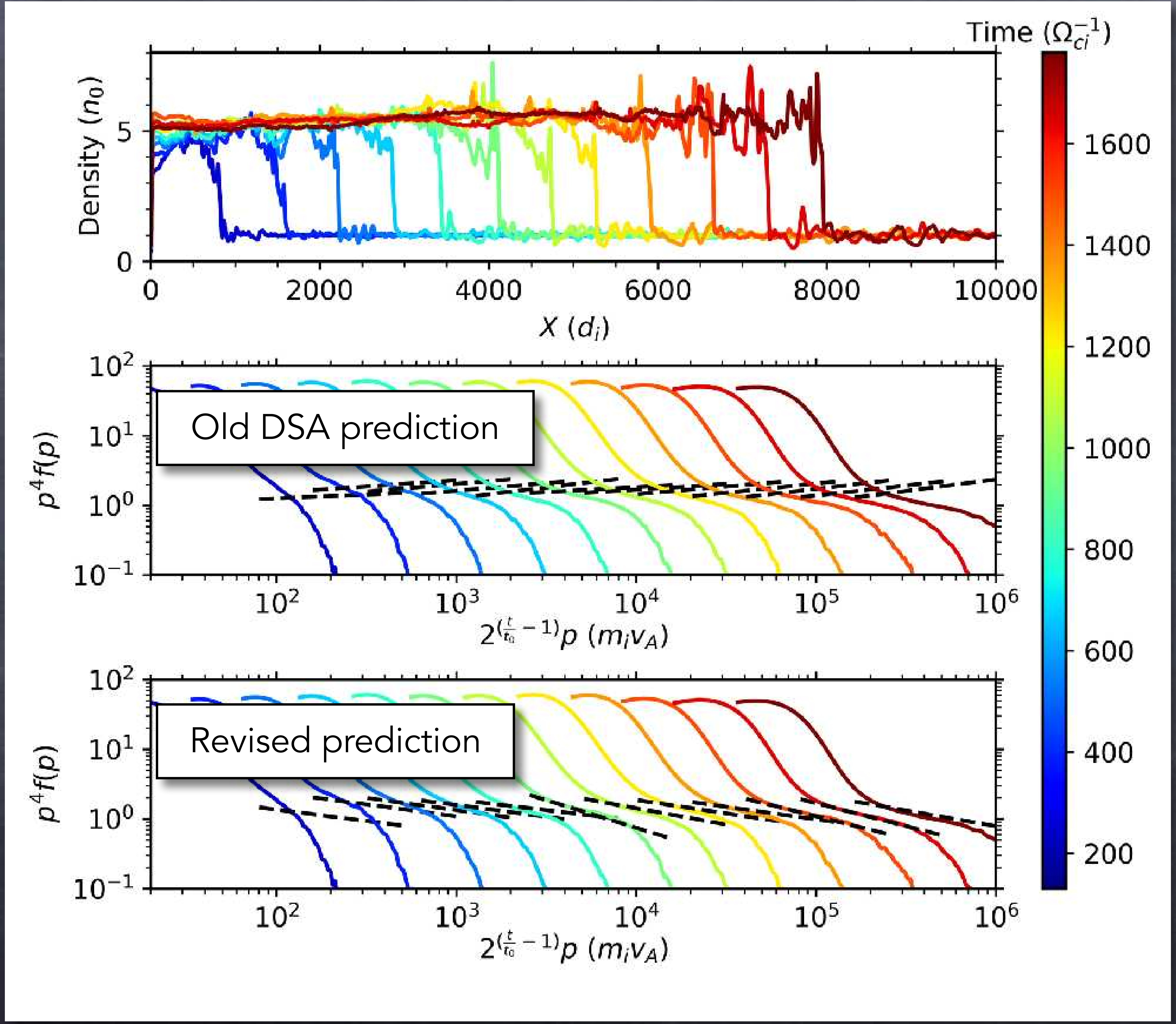


Haggerty-Caprioli20

- 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 the (CR-produced) B field*
- *Ab-initio* explanation for the steep spectra observed?

From Theory to Observations

HOW: A Multi-scale Approach

Micro

Meso

Macro

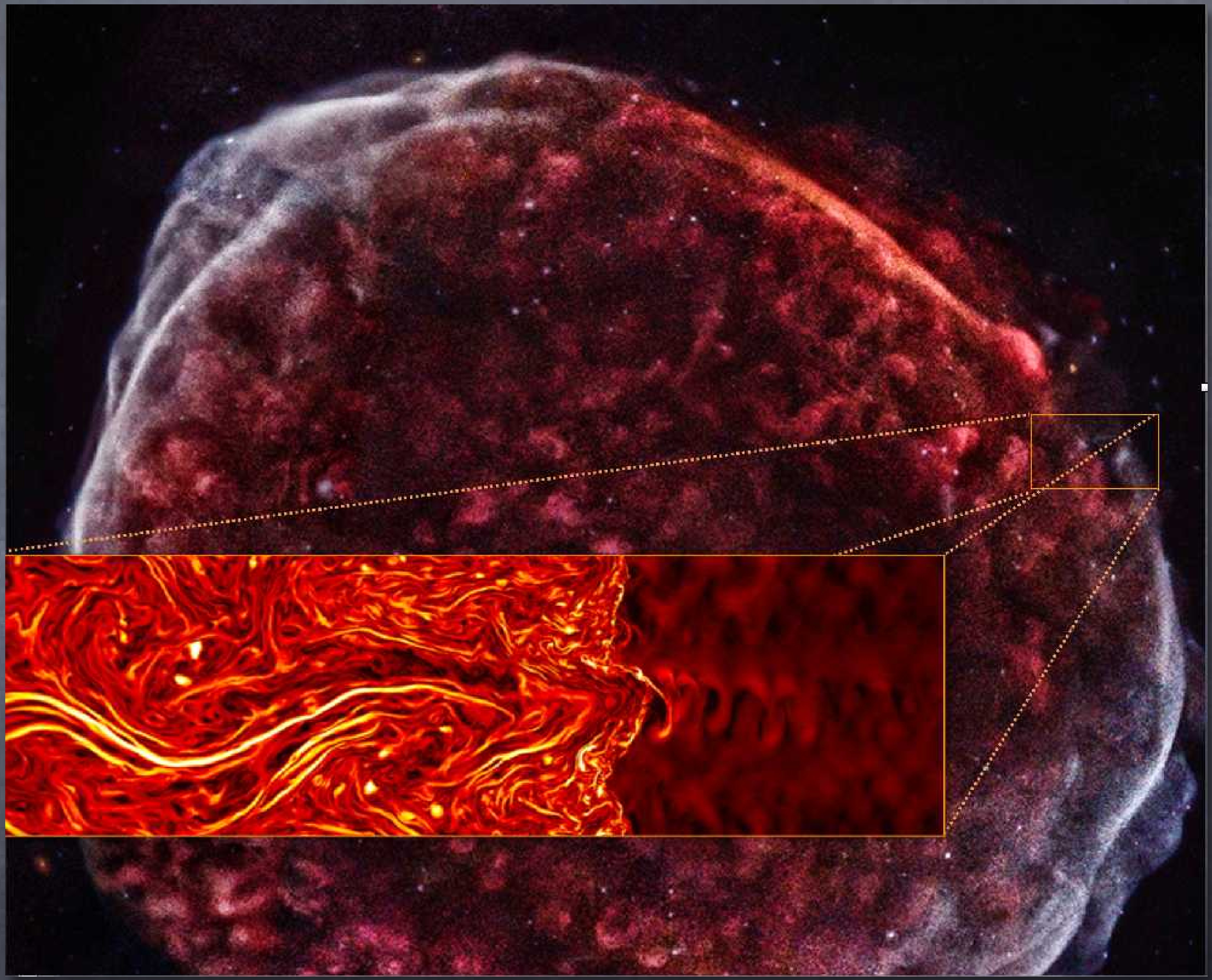
Astro

PIC Plasma Simulations
electron + ion dynamics

Hybrid: ion dynamics,
magnetic field amplification

Super-Hybrid (MHD+hybrid)
Large/long scales
High-Mach numbers

Semi-Analytical
CRAFT = *Cosmic Ray Analytical Fast Tool*



CRAFT: a Cosmic-Ray Fast Analytic Tool

(Amato & Blasi05-, Caprioli+09-12-,… Diesing & Caprioli21, + in prep.)

- Iterative analytical solution of the CR transport (Parker) equation:

$$\tilde{u}(x)\frac{\partial f(x,p)}{\partial x} = \frac{\partial}{\partial x}\left[D(x,p)\frac{\partial f(x,p)}{\partial x}\right] + \frac{p}{3}\frac{d\tilde{u}(x)}{dx}\frac{\partial f(x,p)}{\partial p} + Q(x,p)$$

Advection Diffusion Energy change Injection

- Very fast: a few seconds on a laptop (vs days on clusters: Caprioli+2010)
- Can embed microphysics from kinetic simulations into (M)HD

$$\boxed{f(x,p)} = f_2(p)\exp\left[-\int_x^0 dx'\frac{\tilde{u}(x')}{D(x',p)}\right]\left[1-\frac{W(x,p)}{W_0(p)}\right];$$

$$\boxed{\Phi_{esc}(p)} = -D(x_0,p)\left.\frac{\partial f}{\partial x}\right|_{x_0} = -\frac{u_0 f_2(p)}{W_0(p)};$$

$$W(x,p) = \int_x^0 dx'\frac{u_0}{D(x',p)}\exp\left[\int_{x'}^0 dx''\frac{\tilde{u}(x'')}{D(x'',p)}\right].$$

$$f_2(p) = \frac{\eta n_0 q_p(p)}{4\pi p_{inj}^3}\exp\left\{-\int_{p_{inj}}^p \frac{dp'}{p'}q_p(p')\left[U_p(p')+\frac{1}{W_0(p')}\right]\right\}$$

$$U_p(p) = \frac{\tilde{u}_1}{u_0} - \int_{x_0}^0 \frac{dx}{u_0}\left\{\frac{\partial\tilde{u}(x)}{\partial x}\exp\left[-\int_x^0 dx'\frac{\tilde{u}(x')}{D(x',p)}\right]\left[1-\frac{W(x,p)}{W_0(p)}\right]\right\}$$

CR distribution function

u

P_{cr}

Mass+momentum conservation eqs.

$$\frac{p(x)}{\rho(x)^\gamma} = \frac{p_0}{\rho_0^\gamma};$$

$$\rho(x)u(x) = \rho_0 u_0$$

$$\rho(x)u(x)^2 + p(x) + p_{cr}(x) + p_B(x) = \rho_0 u_0^2 + p_{g,0} + p_{B,0}$$

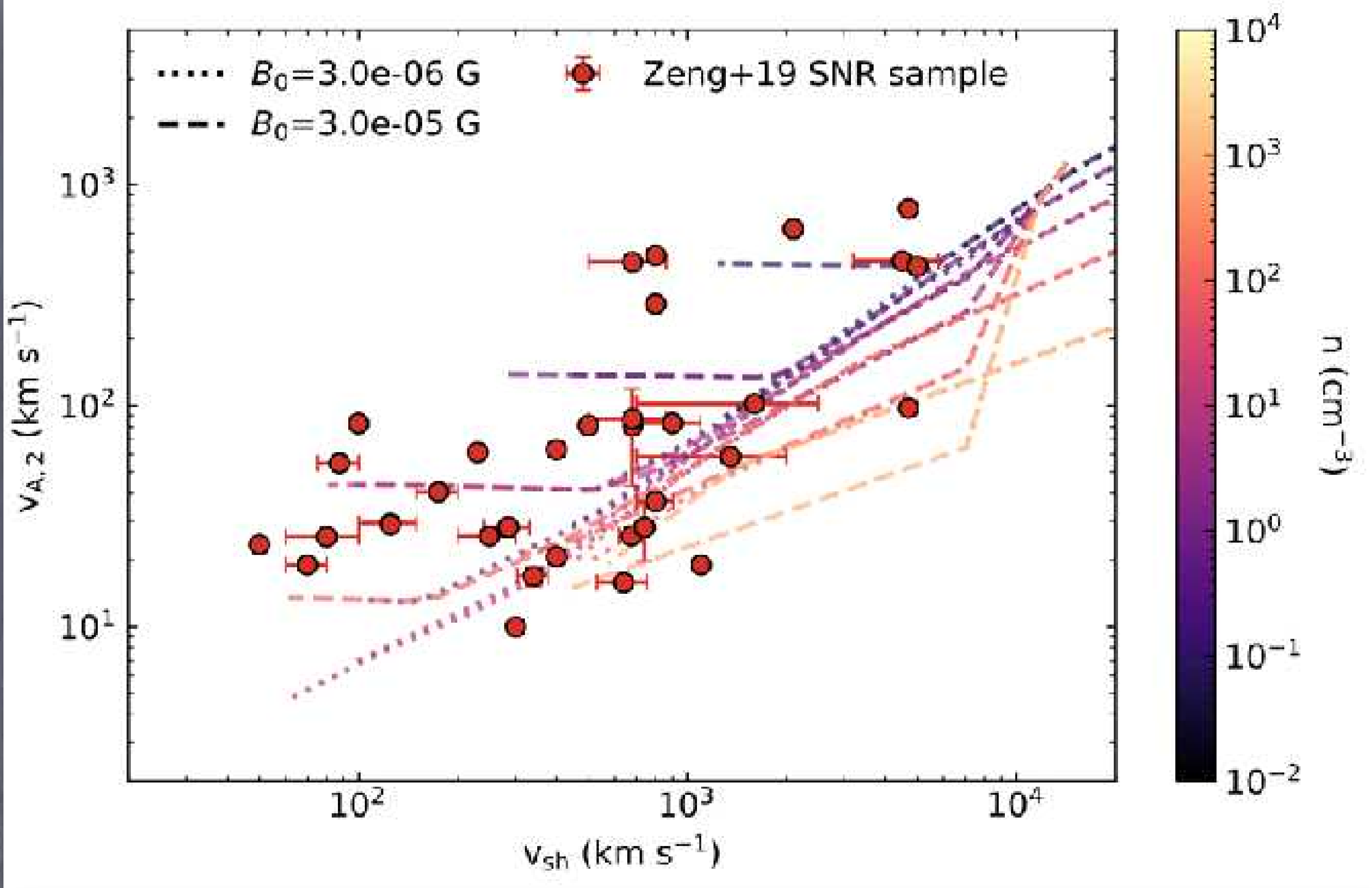
$P_B + P_{cr}$

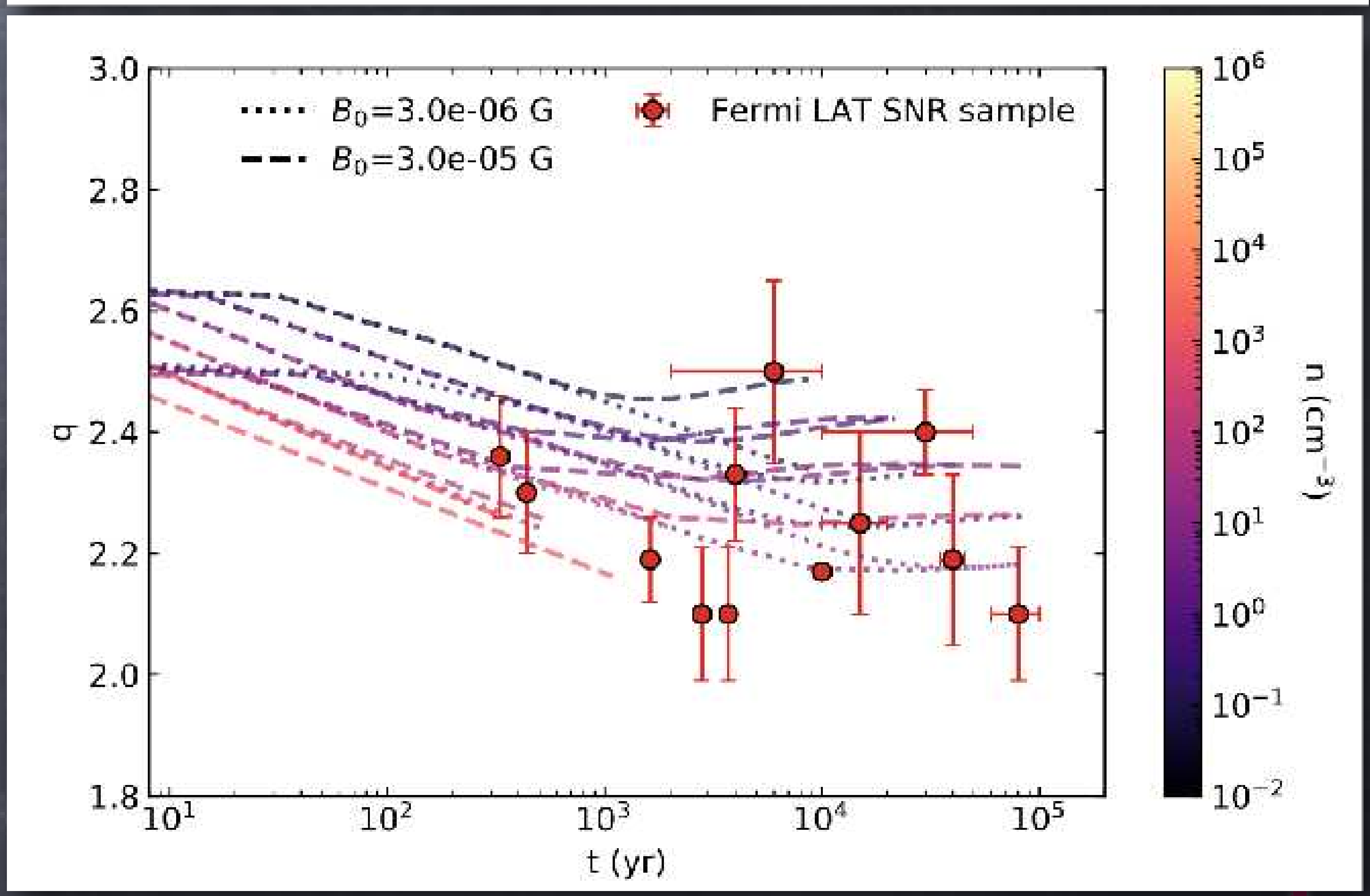
$$2\tilde{u}(x)\frac{dp_B(x)}{dx} = v_A(x)\frac{dp_{cr}(x)}{dx} - 3p_B(x)\frac{d\tilde{u}(x)}{dx}$$

Magnetic turbulence transport equation

CRAFT: radio SNe and SNRs

- Postcursor effects included in CRAFT
  - Young SNe ($v_{sh} \sim 10^4$ km/s): $f(E) \propto E^{-3}$
  - SNRs ($v_{sh} \sim 10^3$ km/s): $f(E) \propto E^{-2.3} - E^{-2.7}$
- The saturation of the Bell instability *naturally* explains both regimes!
  - see also Cristofari, Blasi & Caprioli 2022
- Modeling of shock-powered transients, including synchrotron absorption (Diesing, Margutti, Caprioli, in prep)
  - Radio SNe, kilonovae, COWs/FBOTs, …





Diesing & Caprioli 2021

Acceleration of Electrons

HOW: A Multi-scale Approach

Micro

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electron + ion dynamics

Hybrid: ion dynamics,
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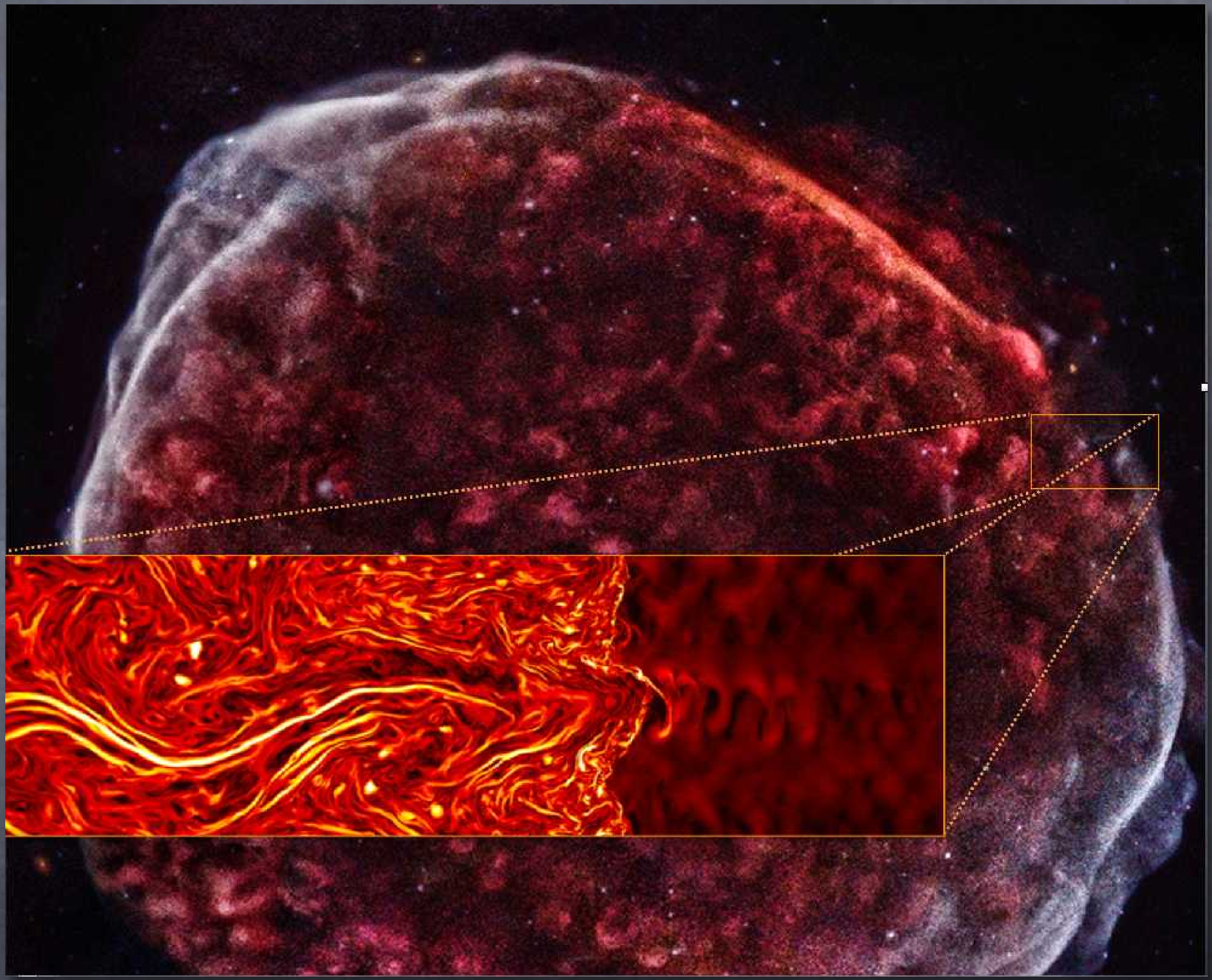
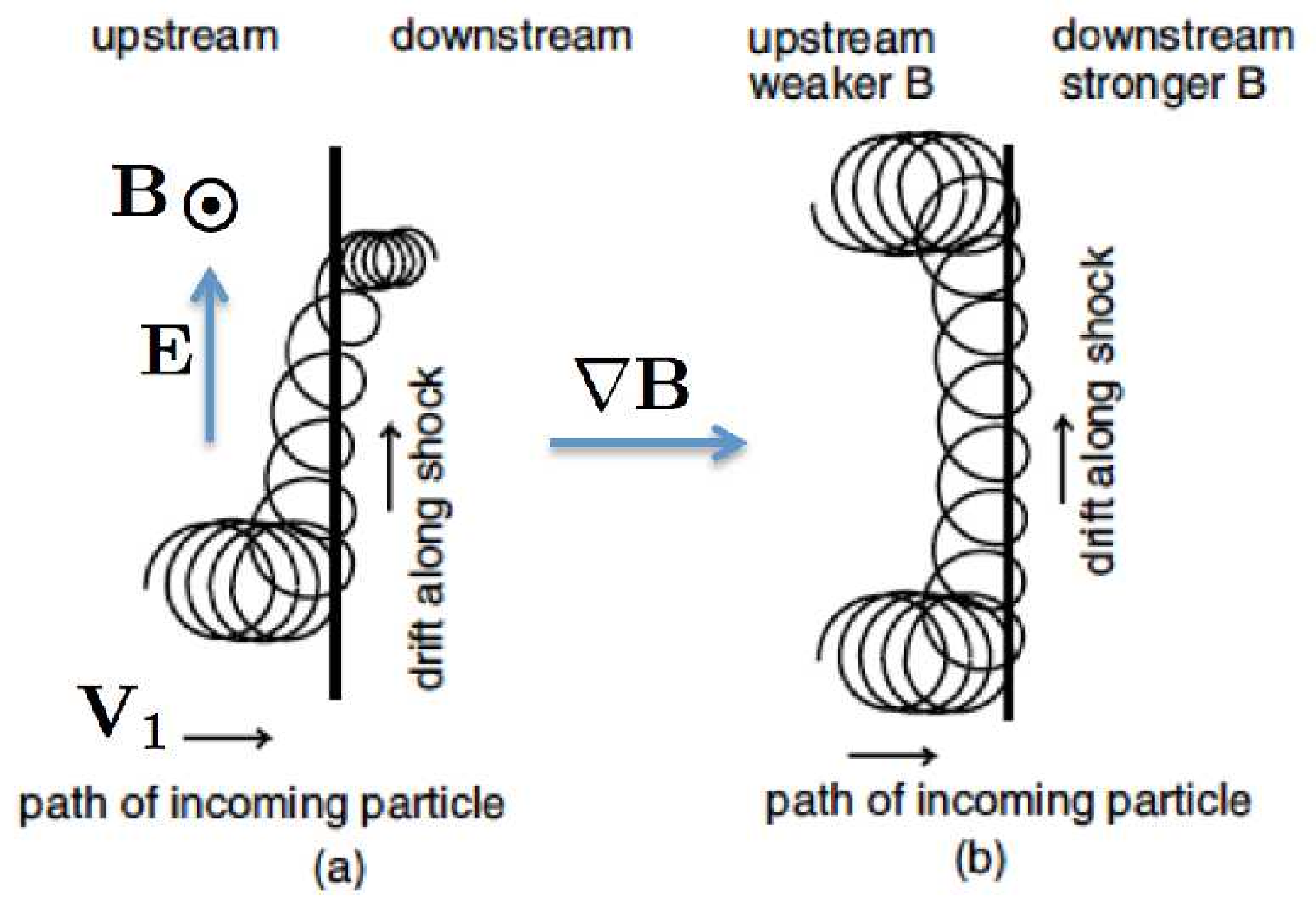


Ion vs Electron Injection

- 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

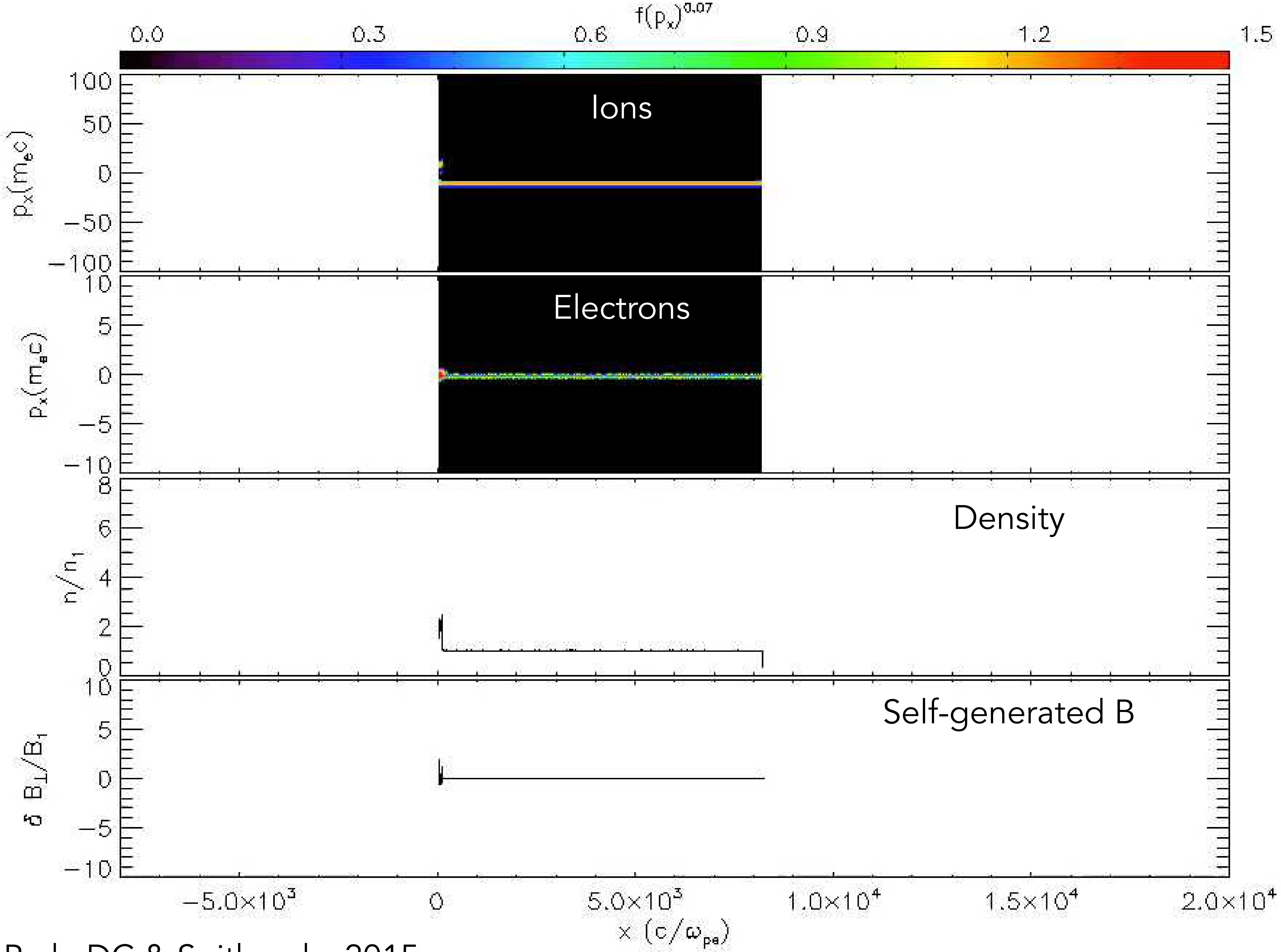
Reflection condition: $\theta_p > \theta_{\rm crit}$

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

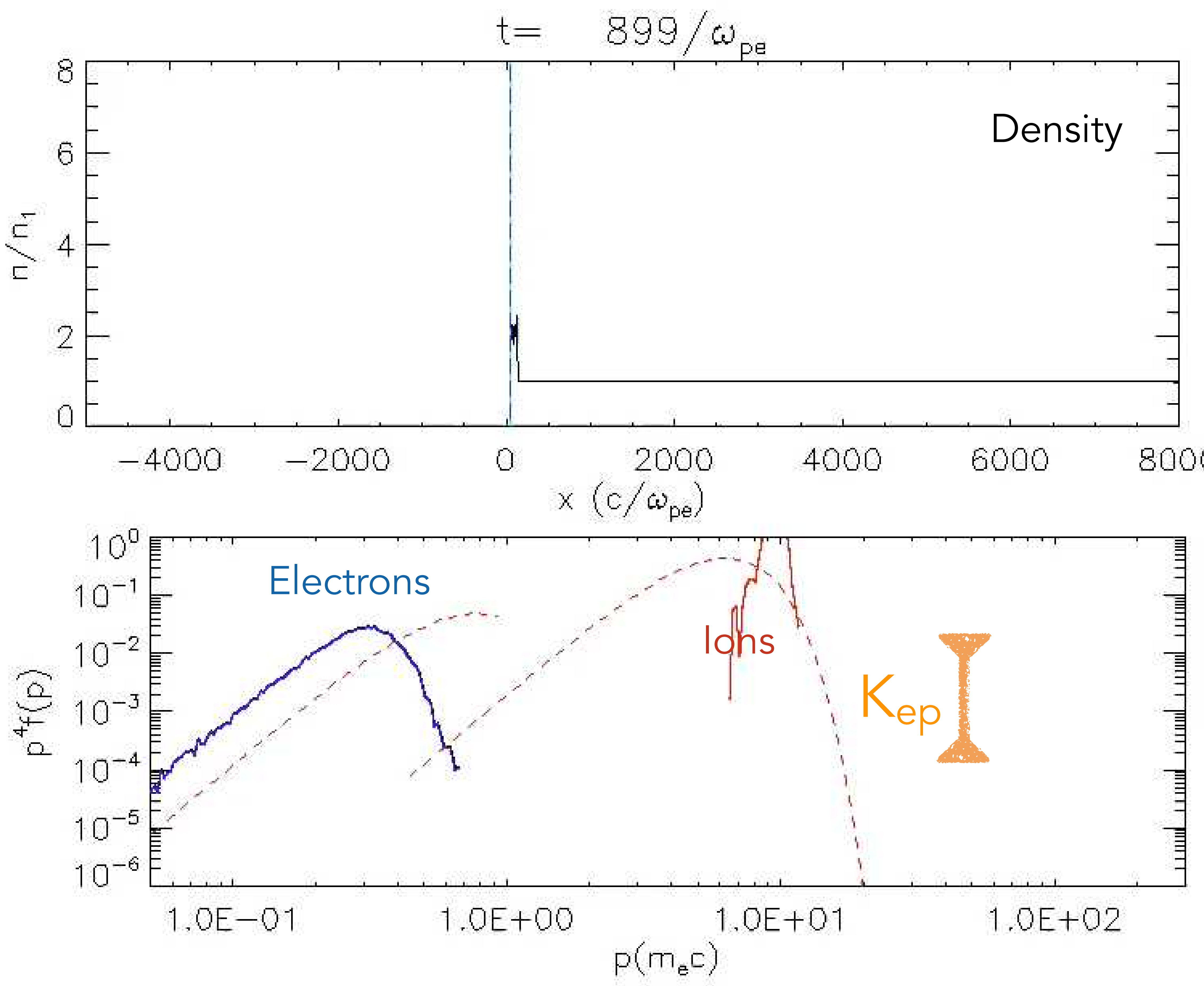
$$\theta_{\rm crit} = \sin^{-1}\sqrt{B_1/B_2}$$

Electron Acceleration

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



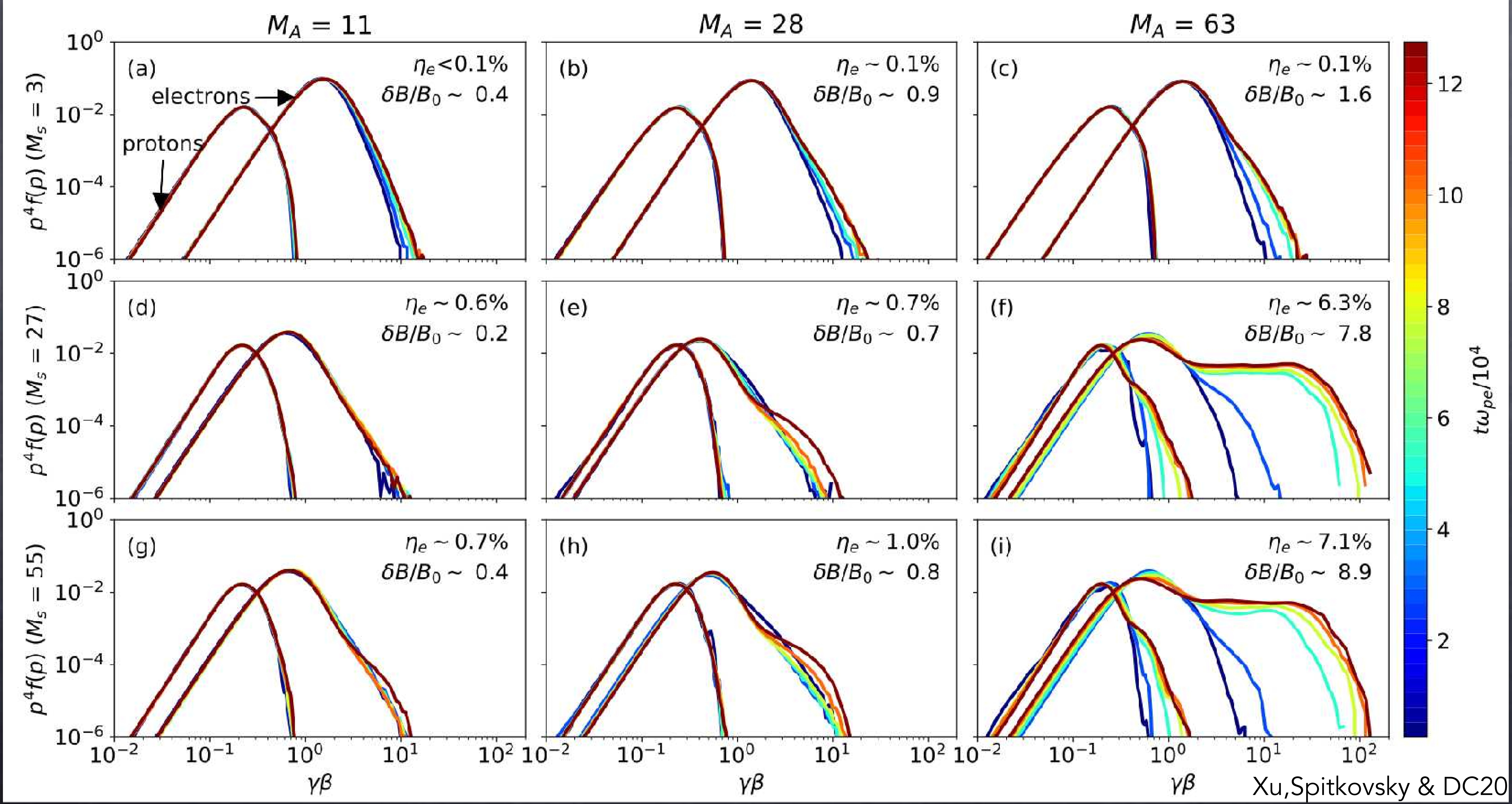
Park, DC & Spitkovsky 2015



Electron/proton ratio K_{ep}~0.01

Electron acceleration at oblique shocks

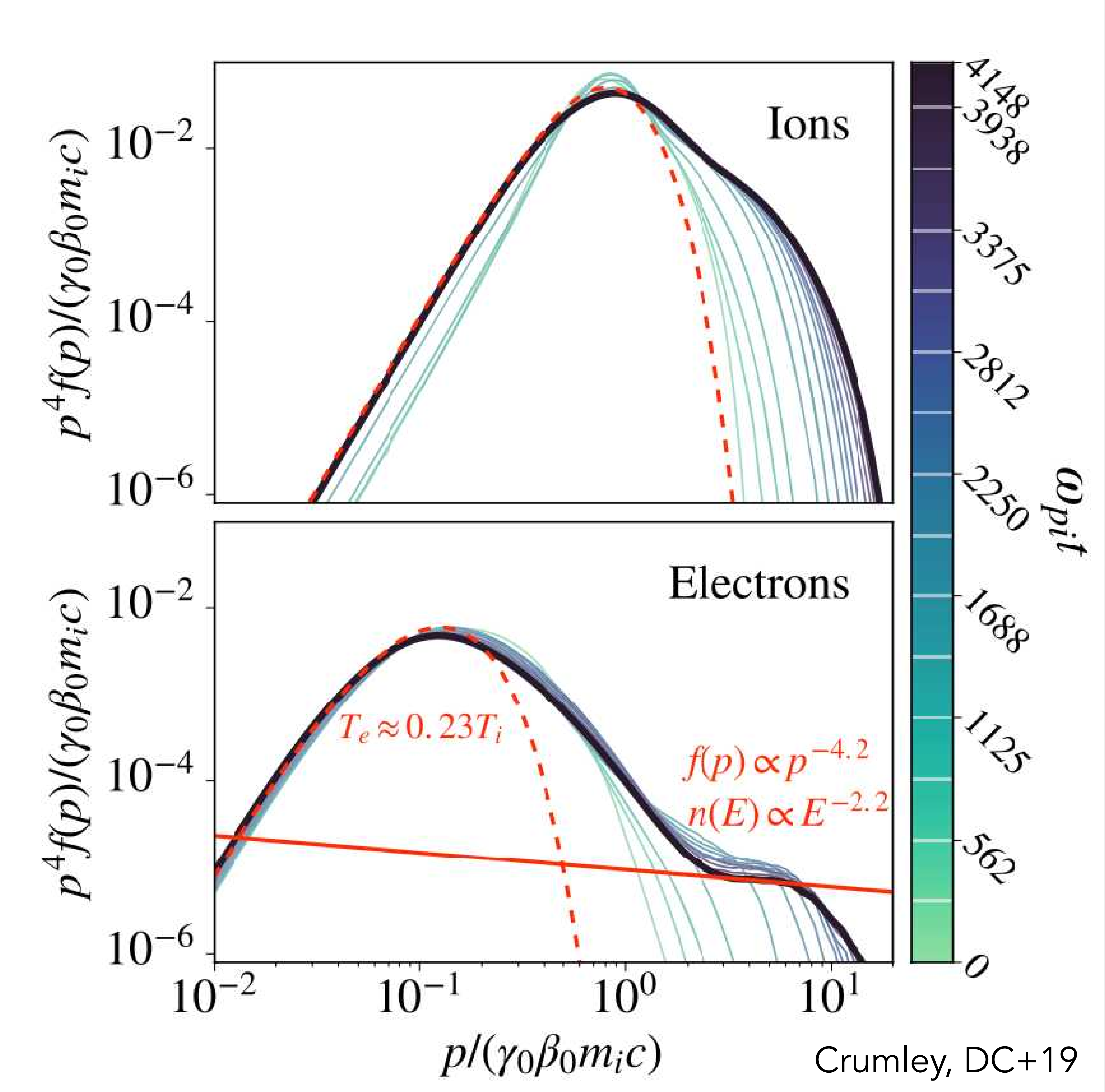
- PIC sim of $\theta = 63°$ shocks with different Mach numbers (e.g., Guo+14ab, Xu+20, Morris+22)



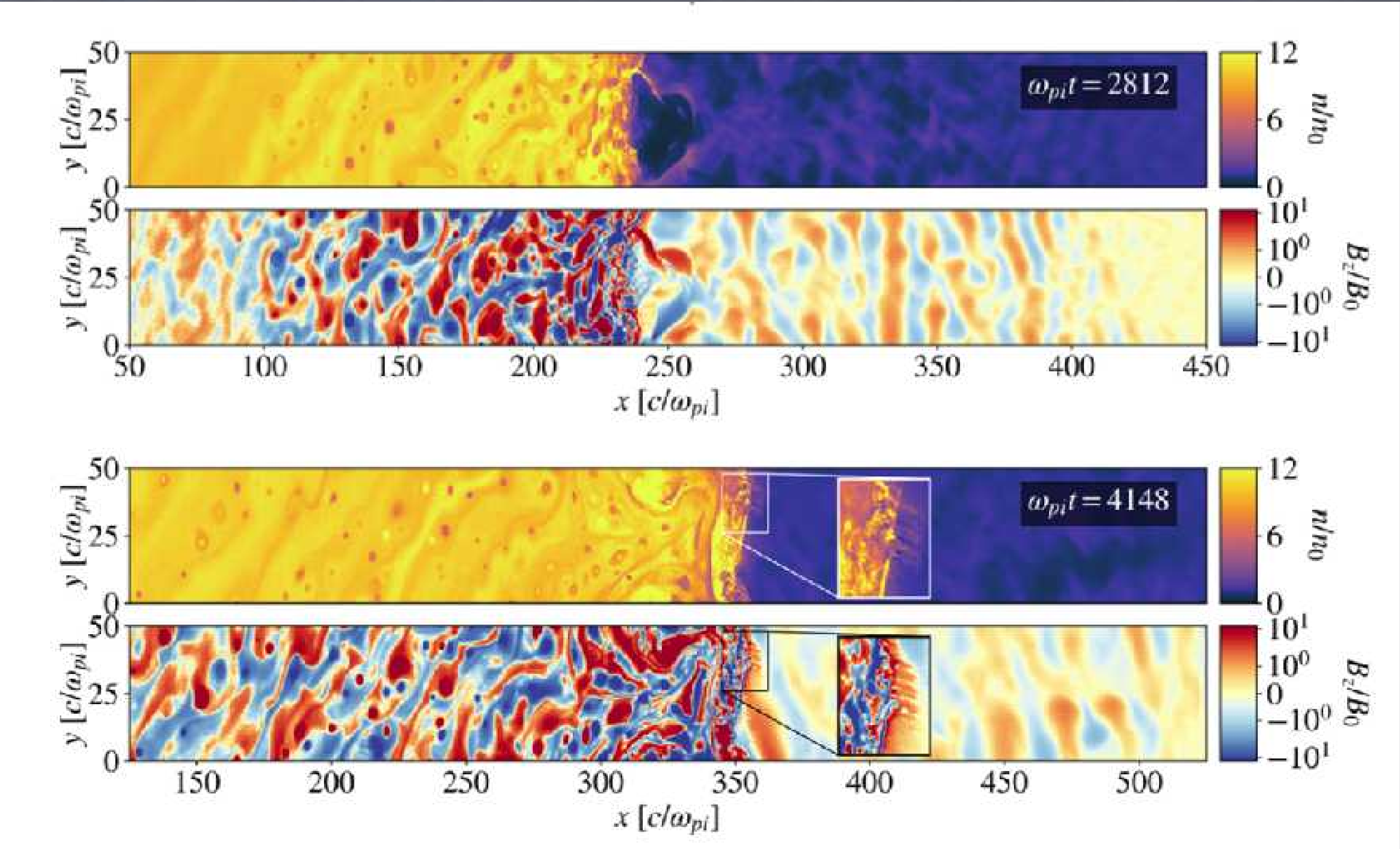
Xu,Spitkovsky & DC20

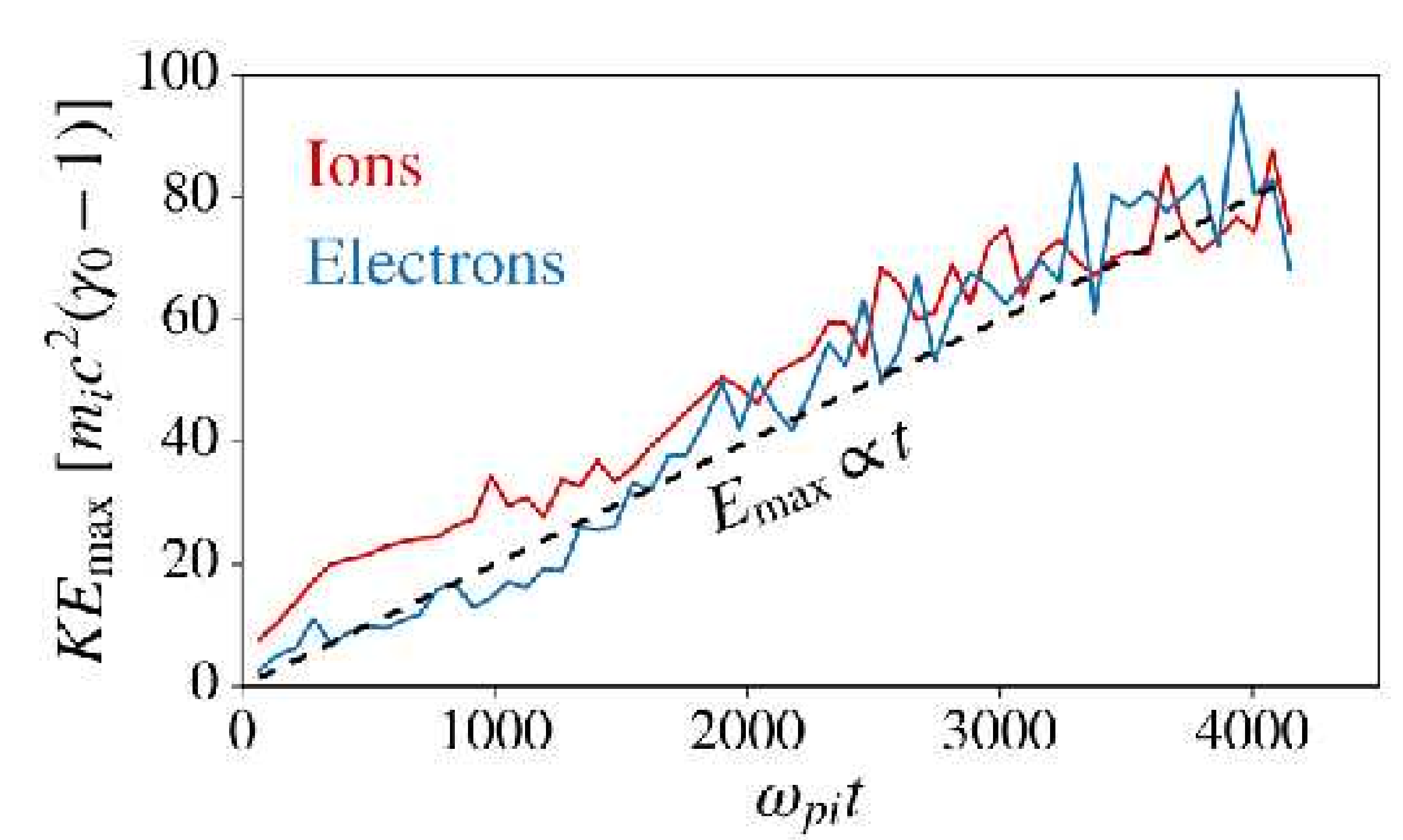
Trans-relativistic shocks

- Q-parallel shocks with $v_{sh} \lesssim 0.8c$: both electron and ion DSA (Crumley+19)



Crumley, DC+19

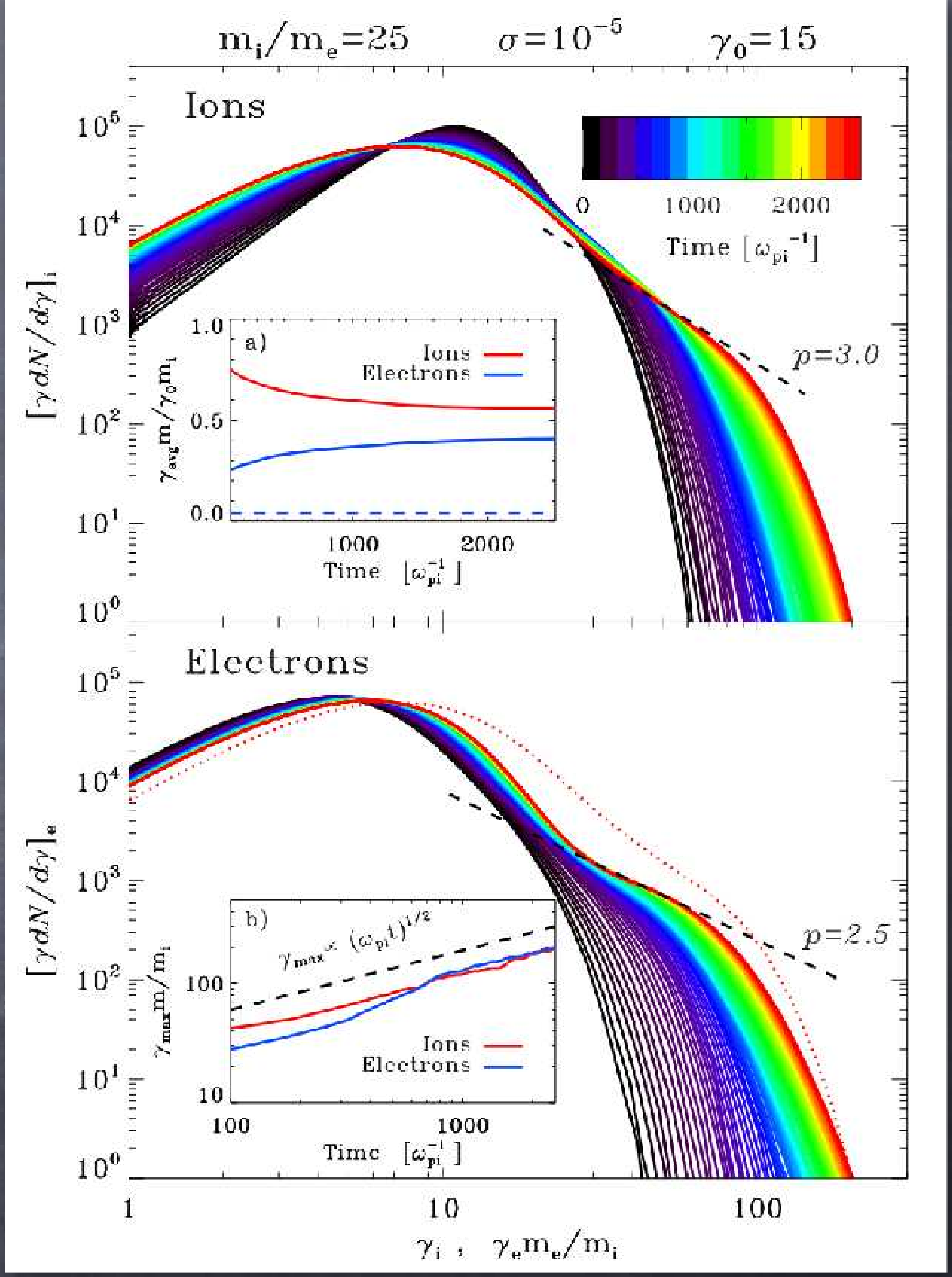




Acceleration still fast as in non-rel shocks

Relativistic Shocks

- Comprehensive PIC campaign by Sironi & Spitkovsky09-11) as a function of shock speed (γ_0), angle (θ), B field (σ)
- DSA only at *subluminal* shocks with $\theta < 34°/\gamma_0$
- In *superluminal* shocks, synchrotron maser instability (Hoshino & Arons 1991) may produce EM waves that heat upstream electrons. This is *not* DSA!
- Magnetization! $\sigma \equiv \dfrac{B^2/4\pi}{(\gamma-1)nmc^2} = \dfrac{1}{M_A^2} = \left(\dfrac{\omega_c}{\omega_p}\right)^2\left(\dfrac{c}{v}\right)^2 = \left[\dfrac{c/\omega_p}{R_L}\right]^2$
- For low $\sigma \lesssim 10^{-3}$, the shock is Weibel-mediated and inclination does not matter (Spitkovsky08)
- DSA is slower, since in small-scale B fields diffusion is $D \propto E^2$ and then $E_{max} \propto \sqrt{t}$ (instead of $\propto t$ for Bohm). For more details, also see Sironi+2013



Sironi & Spitkovsky 2011

A critical assessment on DSA

- Ion and electron DSA depend on shock inclination and magnetization
- When proton DSA, also ion and electron DSA (e.g., parallel shocks)
- Rel shocks: electron DSA as ion/positron, but not ubiquitous and generally slow

- We have no theory of electron DSA, yet
  - Simulations are hard (small/short electron scales, especially for non-rel shocks)
  - Exact conditions for electron reflection/heating/(pre-)acceleration unknown
  - Electron/ion relative efficiency still to unravel
  - See also PIC simulations by Riquelme-Spitkovsky11; Sironi-Spitkovsky09-13, Guo+14; Amano-Hoshino07-10; Matsumoto+15, Crumley+19, Bohdan+19-22, Shalaby+22, Morris+22