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Kinetic Simulations of Particle Acceleration at Shocks

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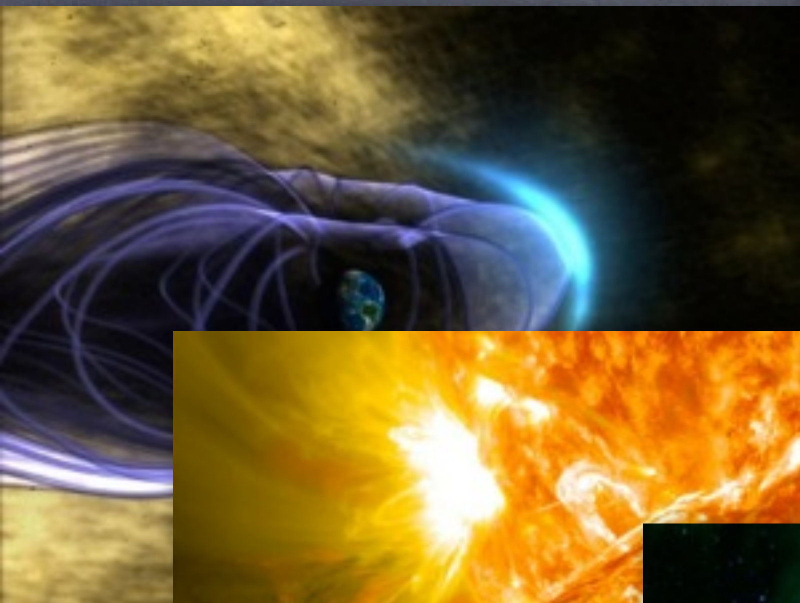
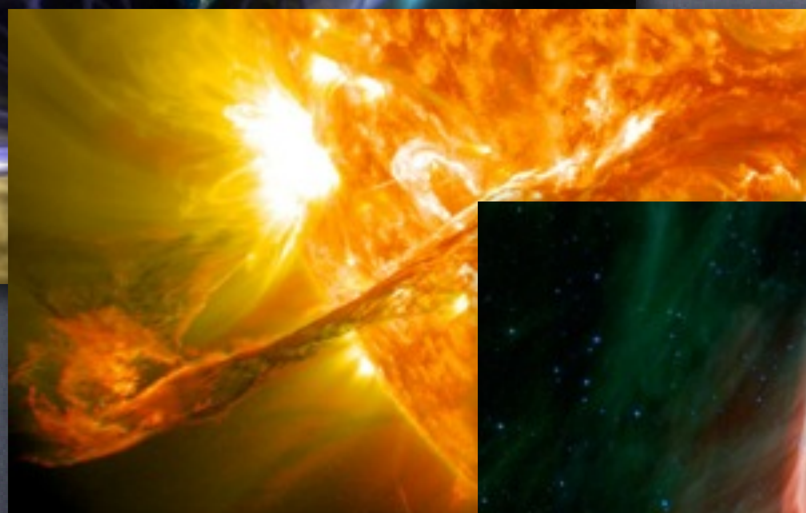
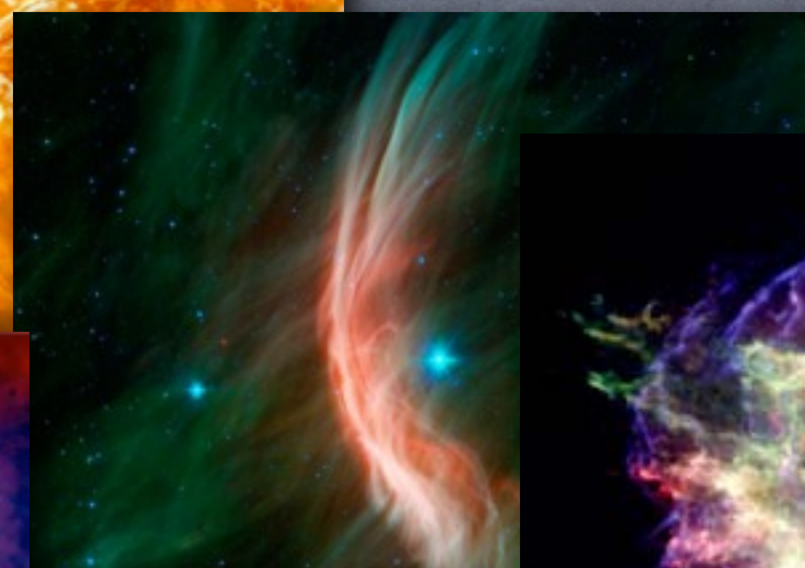
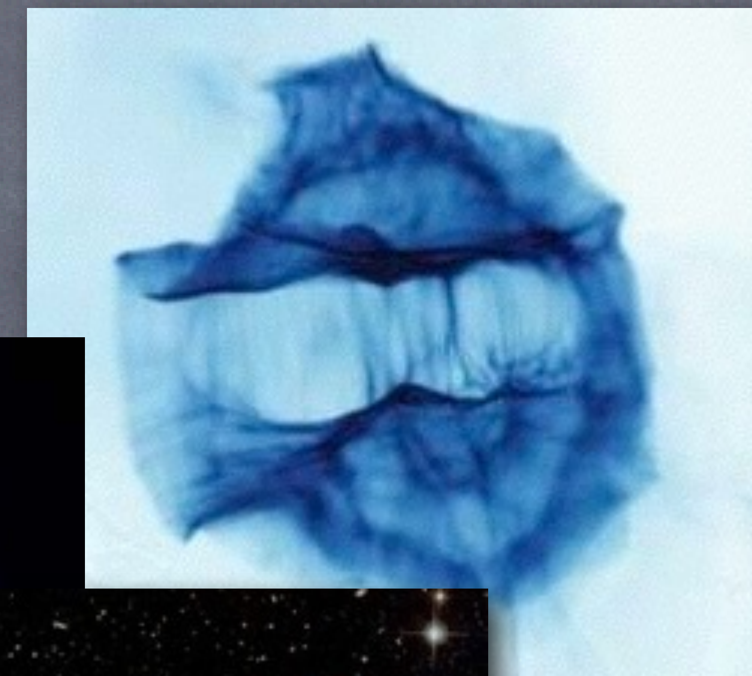
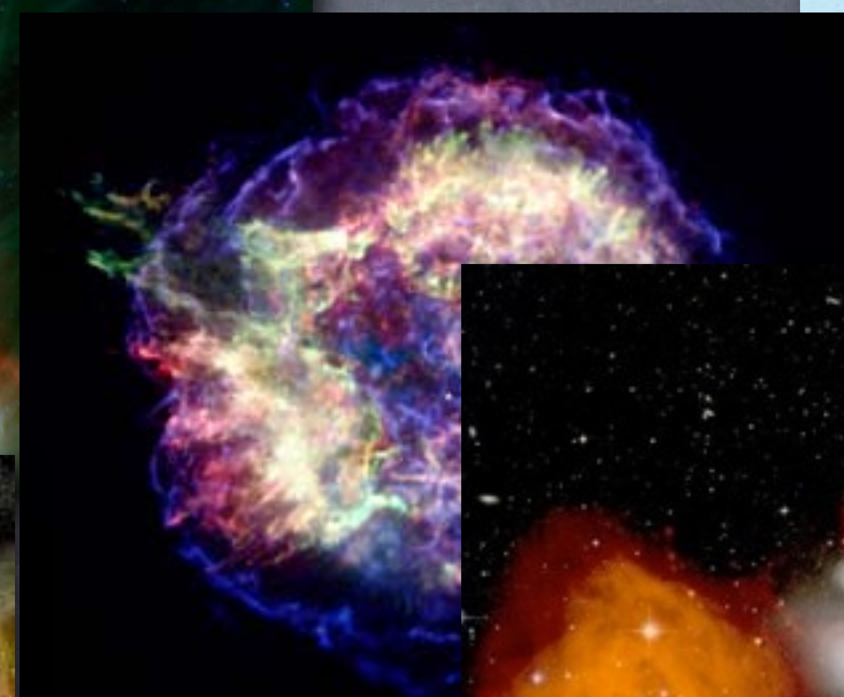
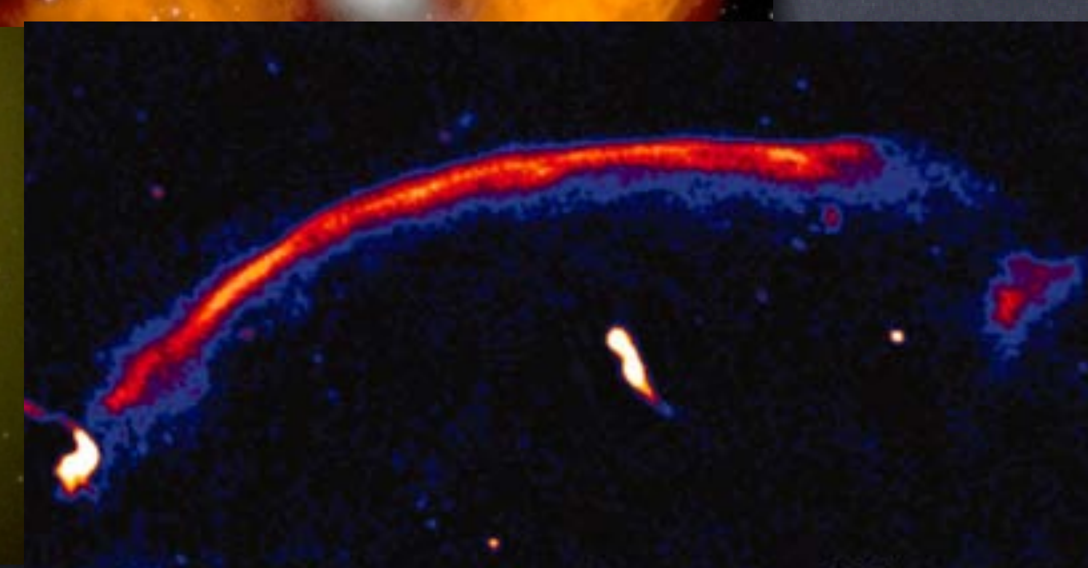
Princeton University

Collisionless shocks

- Mediated by collective electromagnetic interactions
- Sources of non-thermal particles and emission
- Reproducible in laboratory

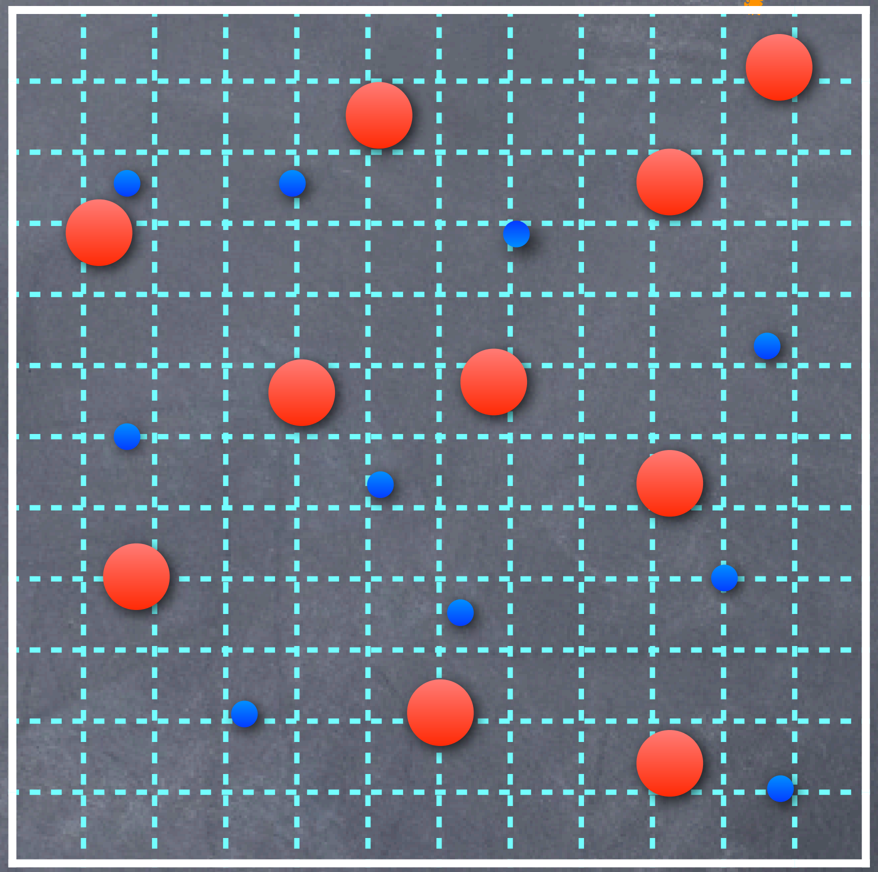






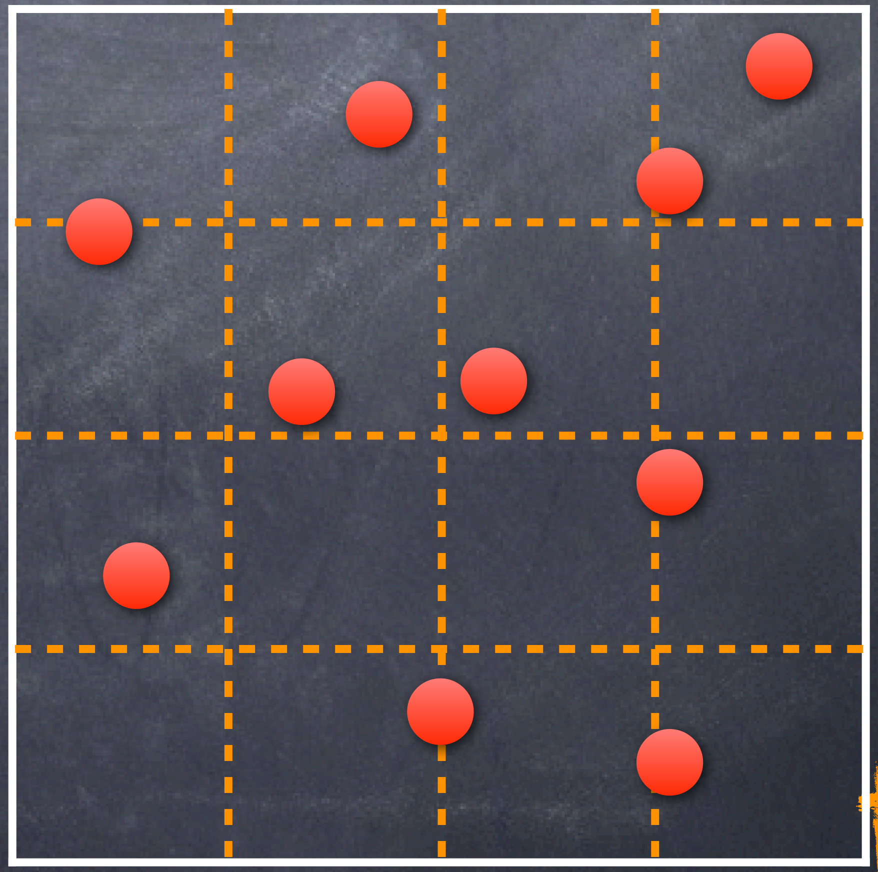


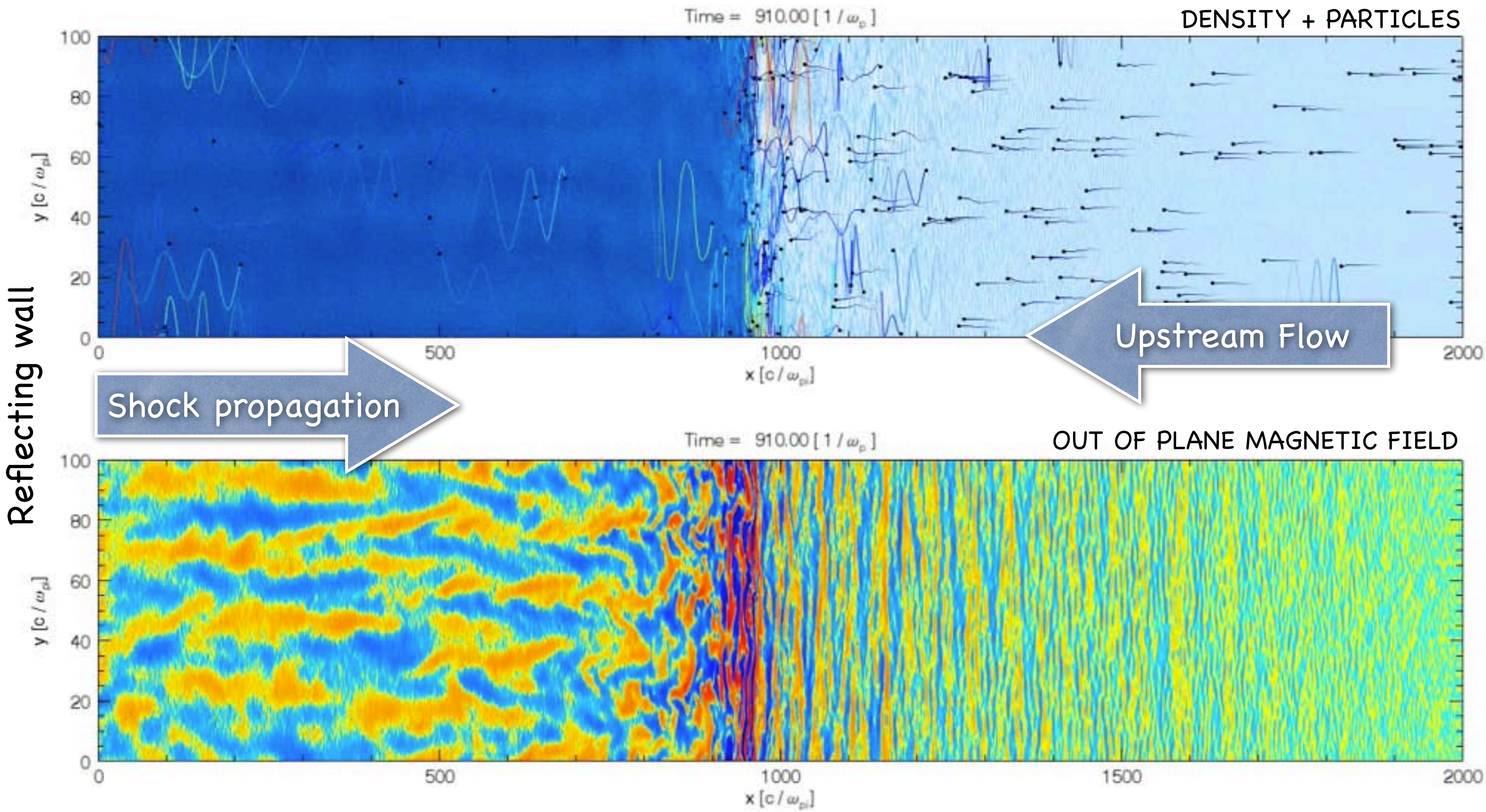
Acceleration from first principles

- Full particle in cell approach
  (..., Spitkovsky 2008, Niemiec+2008, Stroman+2009, Riquelme & Spitkovsky 2010, Sironi & Spitkovsky 2011, Park+2012,2015, Niemiec+2012, Guo+2014, DC+15...)
  - Define electromagnetic field on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!
- Hybrid approach:
  Fluid electrons - Kinetic protons
  (Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, DC & Spitkovsky 2013-2015,...)
  - massless electrons for more macroscopical time/length scales





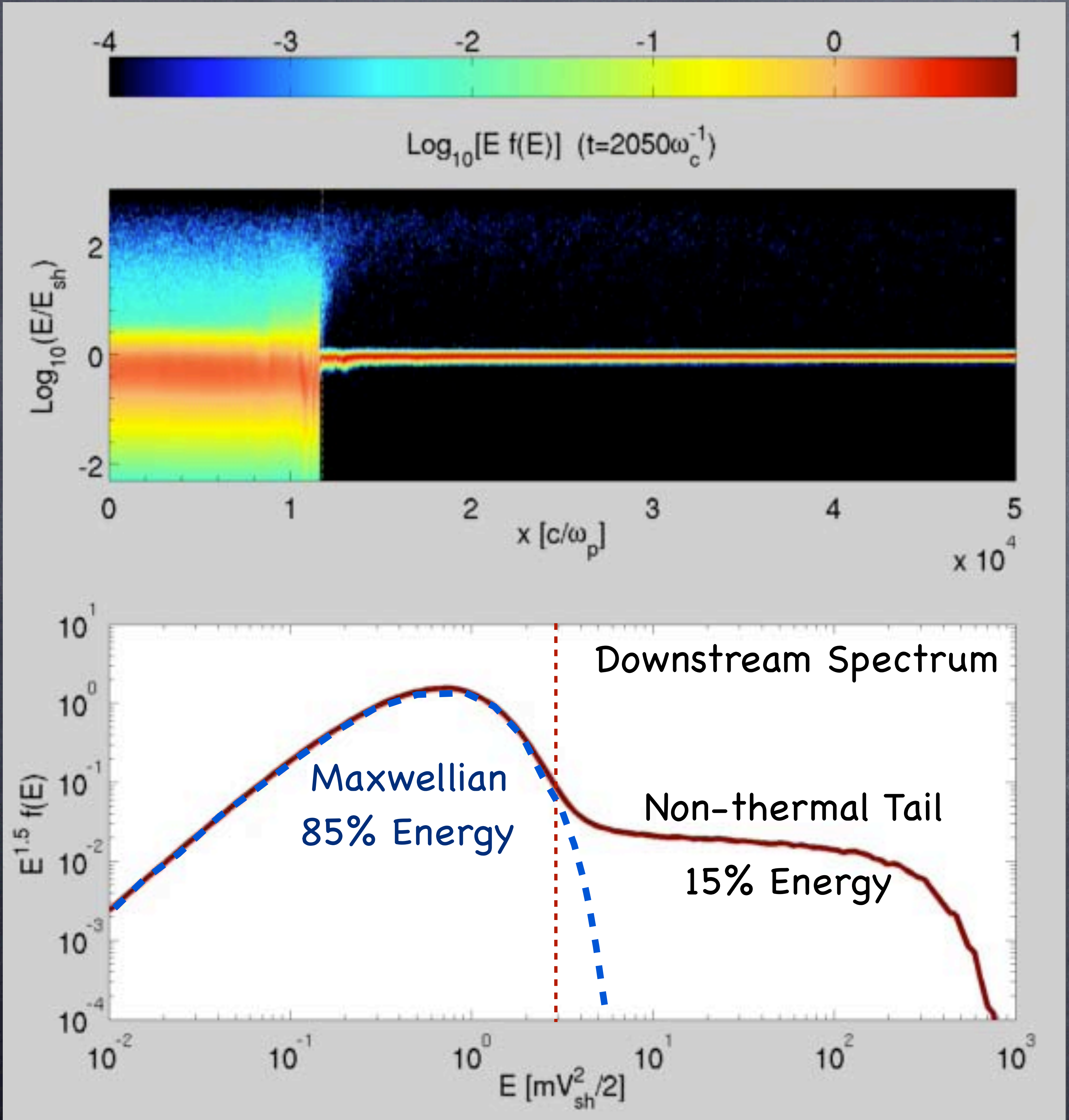
Hybrid simulations of collisionless shocks



- **dHybrid** code (Gargaté et al, 2007)

Initial B field

Spectrum evolution



First-order Fermi acceleration:

$f(p) \propto p^{-4}$

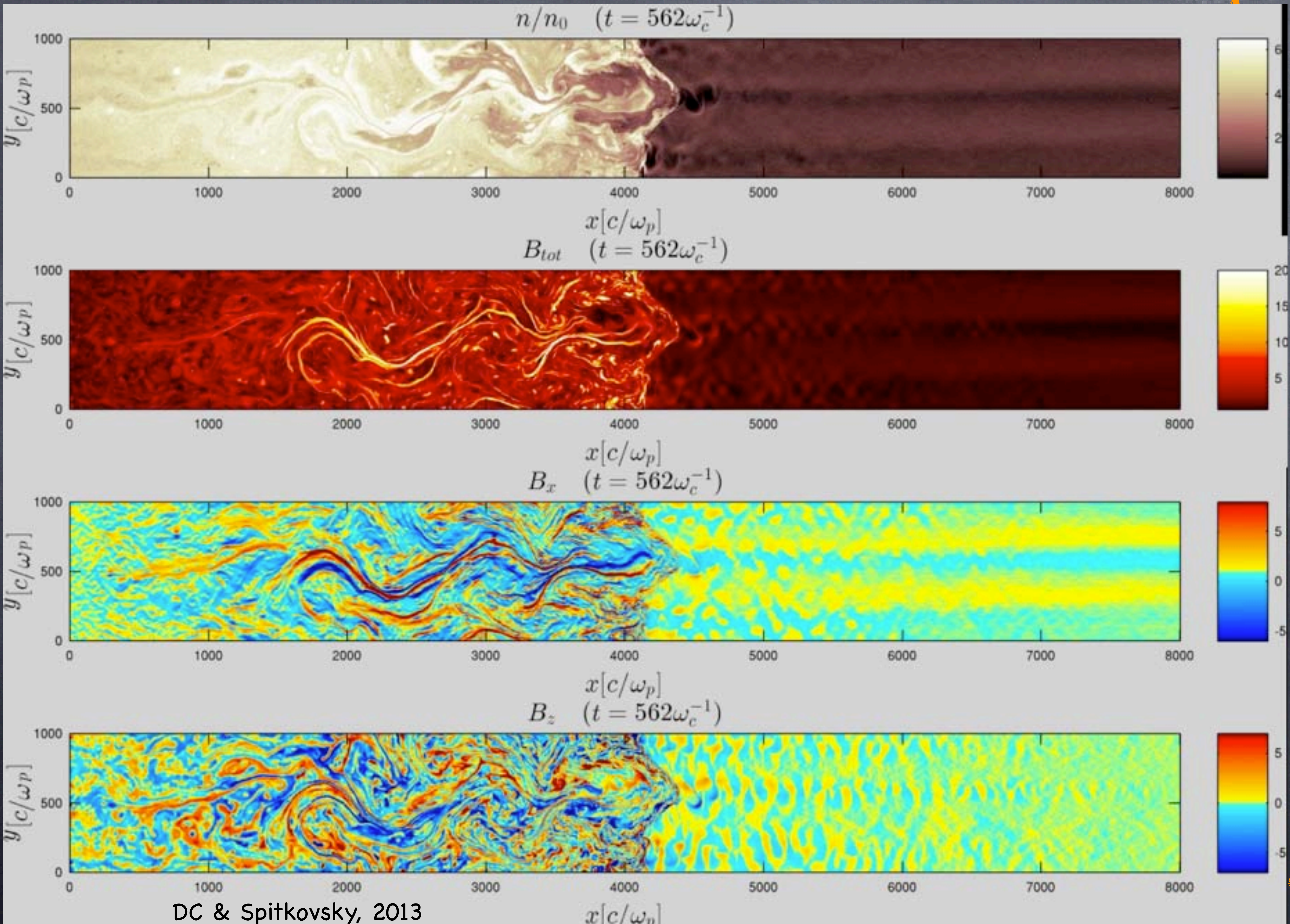
$4\pi p^2 f(p) dp = f(E) dE$

$f(E) \propto E^{-2}$ (relativ.)

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

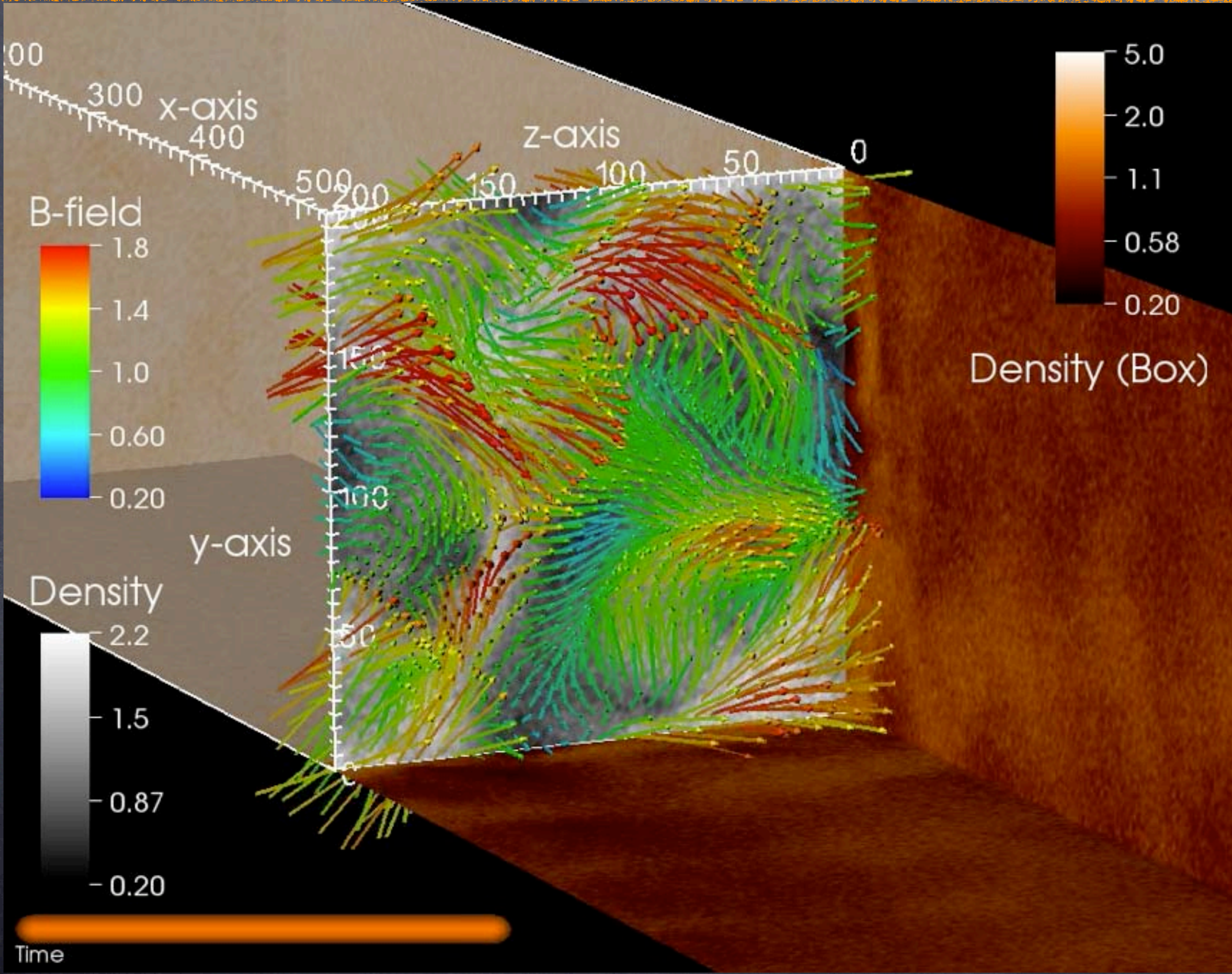
DC & Spitkovsky, 2014a

CR-driven instability



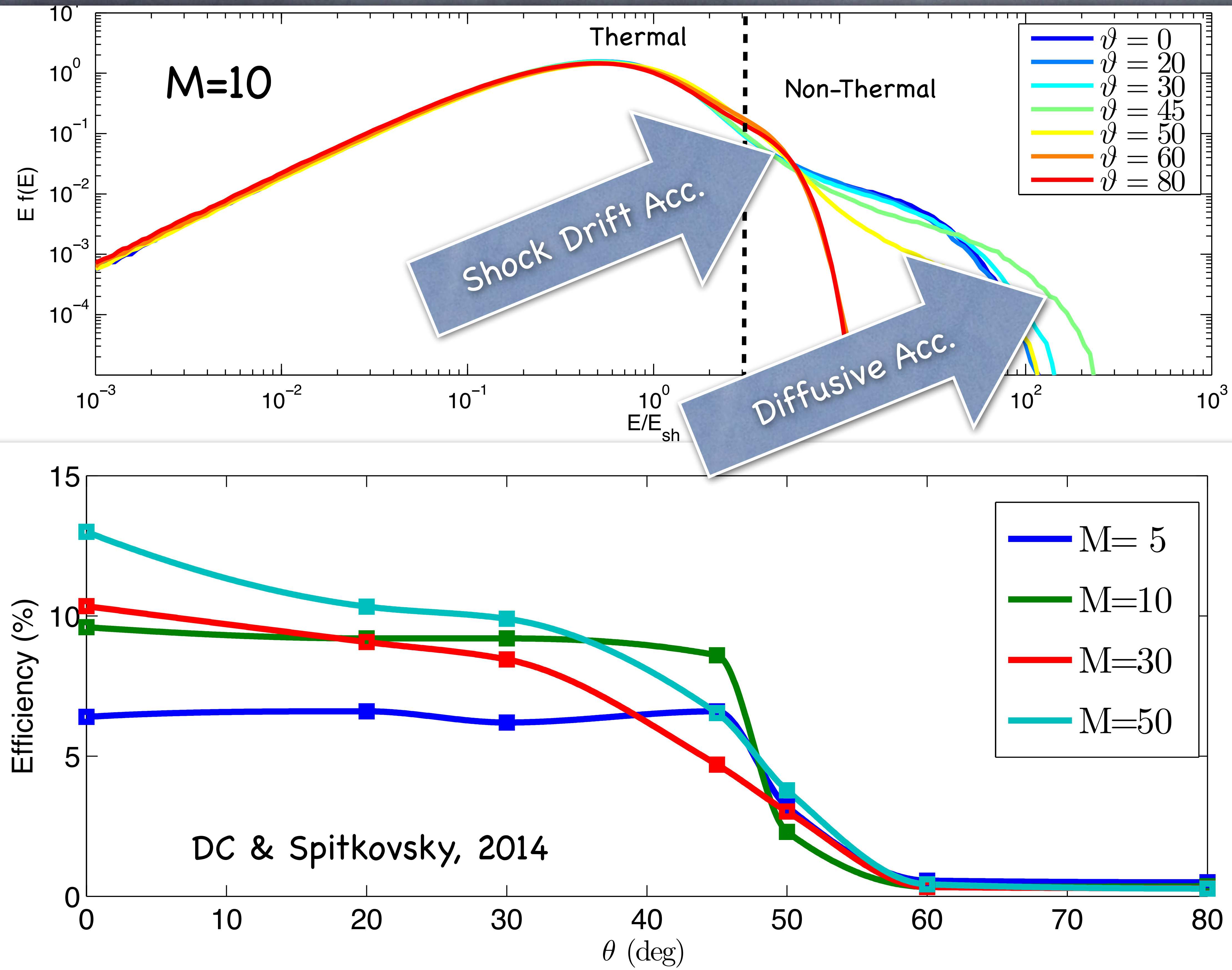
DC & Spitkovsky, 2013

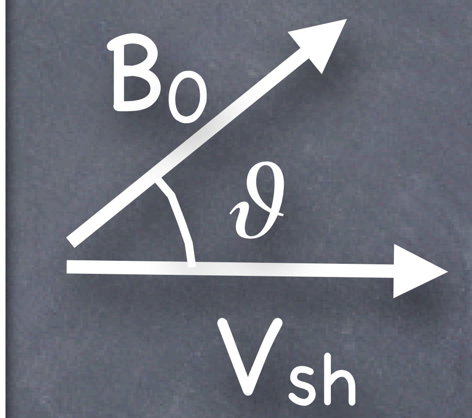
3D simulations of a parallel shock



DC & Spitkovsky, 2014a

Parallel vs Oblique shocks



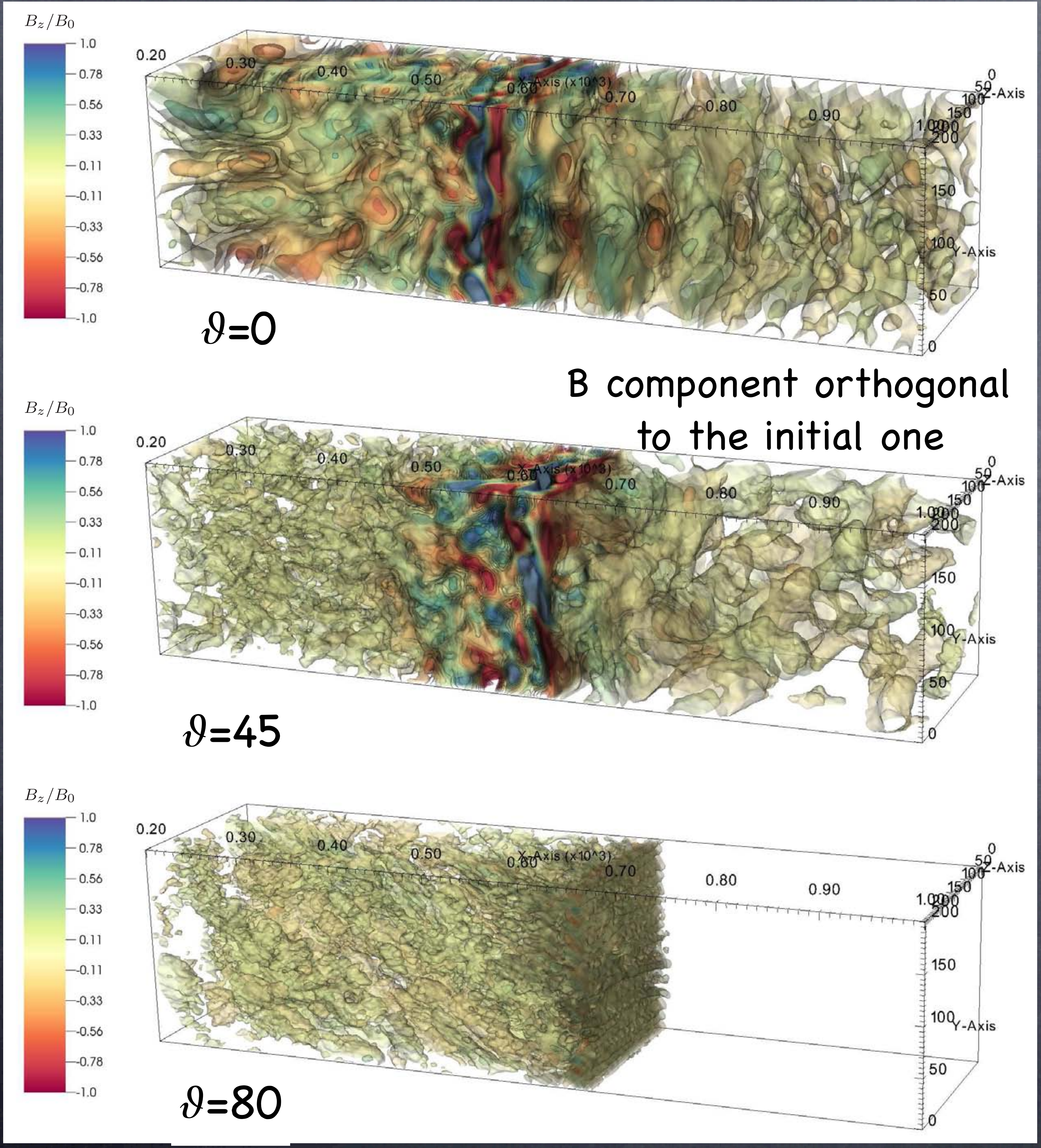


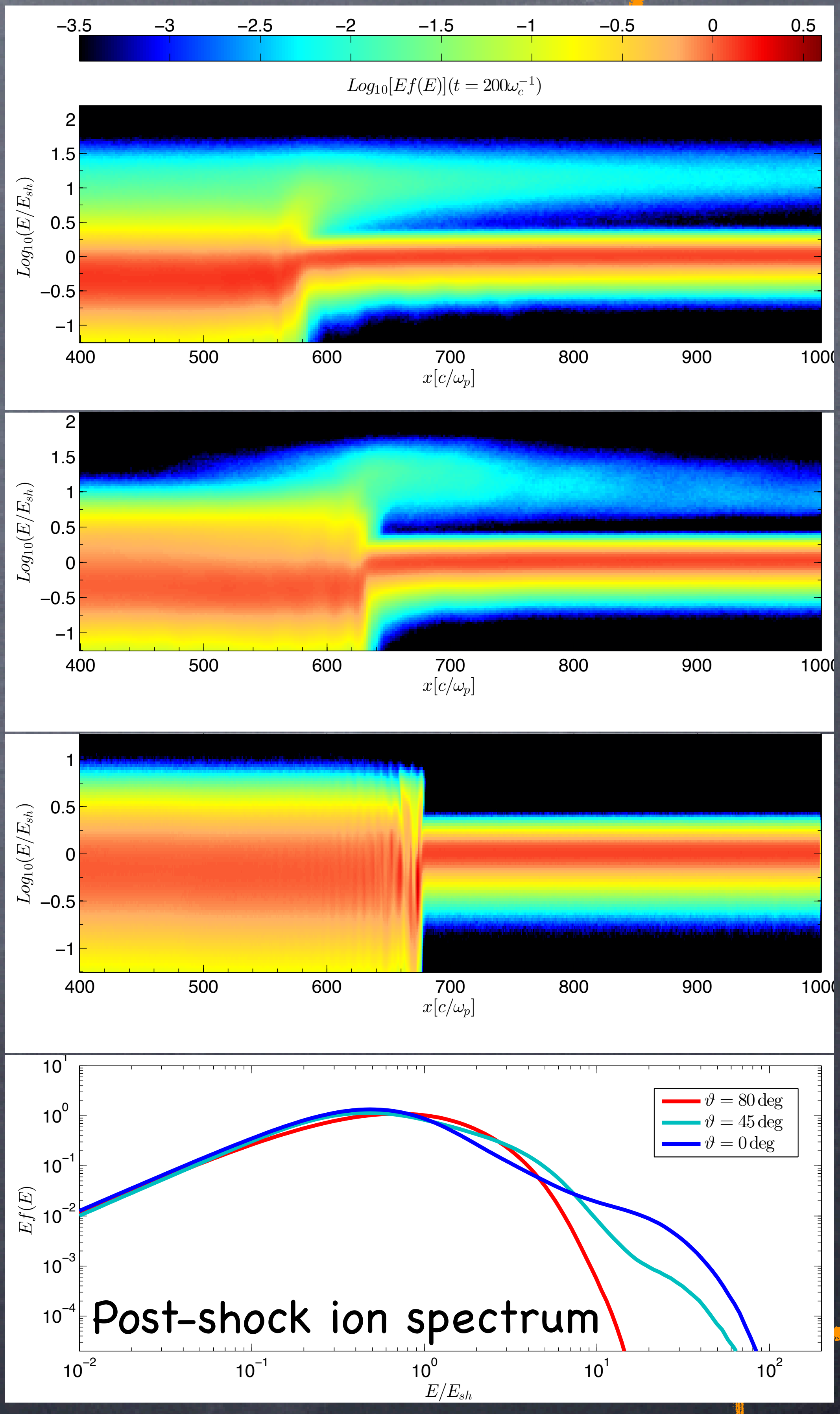
Each point corresponds to a simulation with about 10^9 particles

Computation time: almost

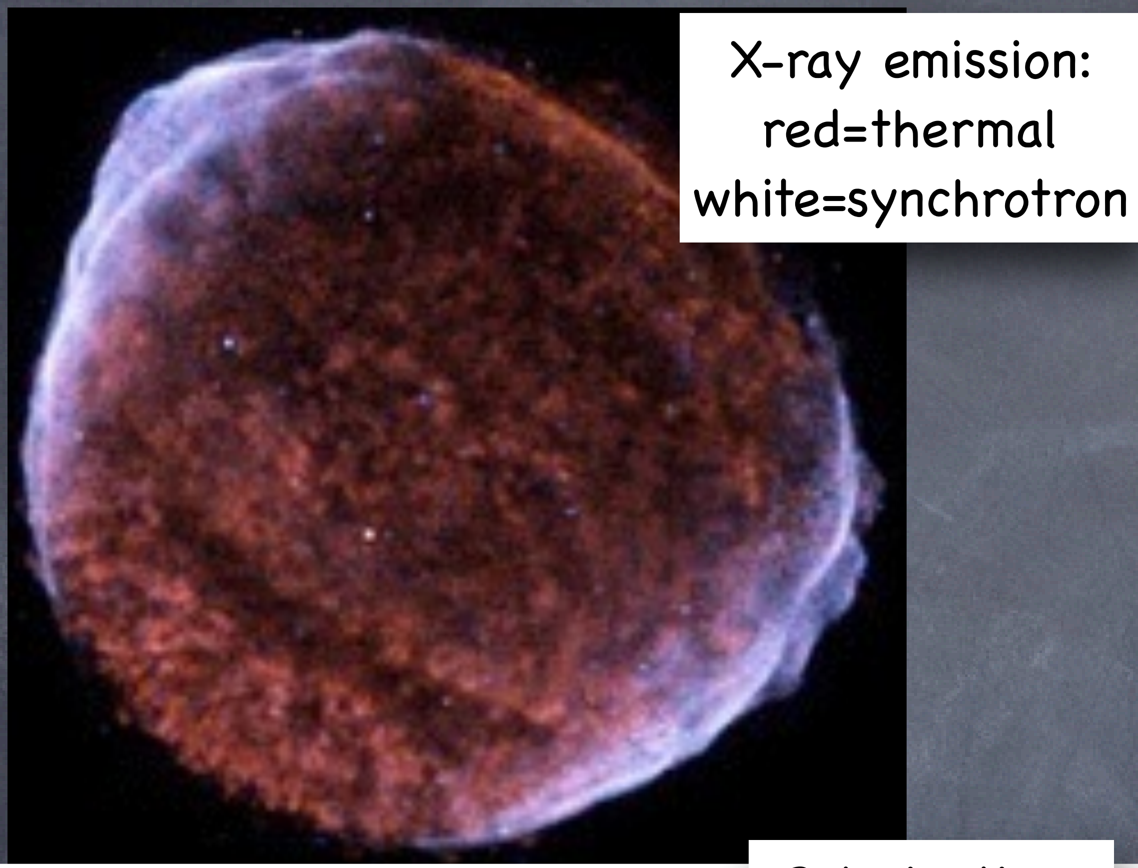
$2x10^6$ cpu h

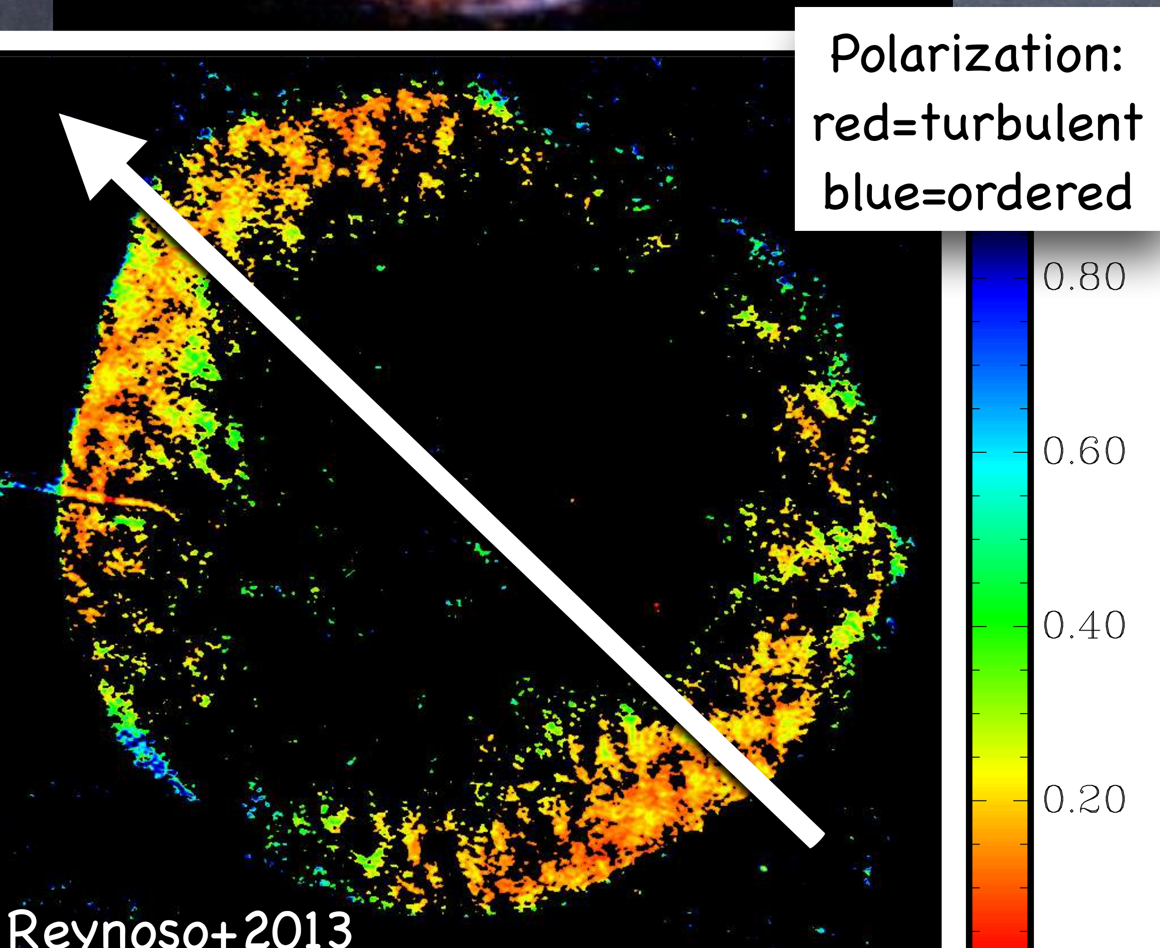
3D simulations

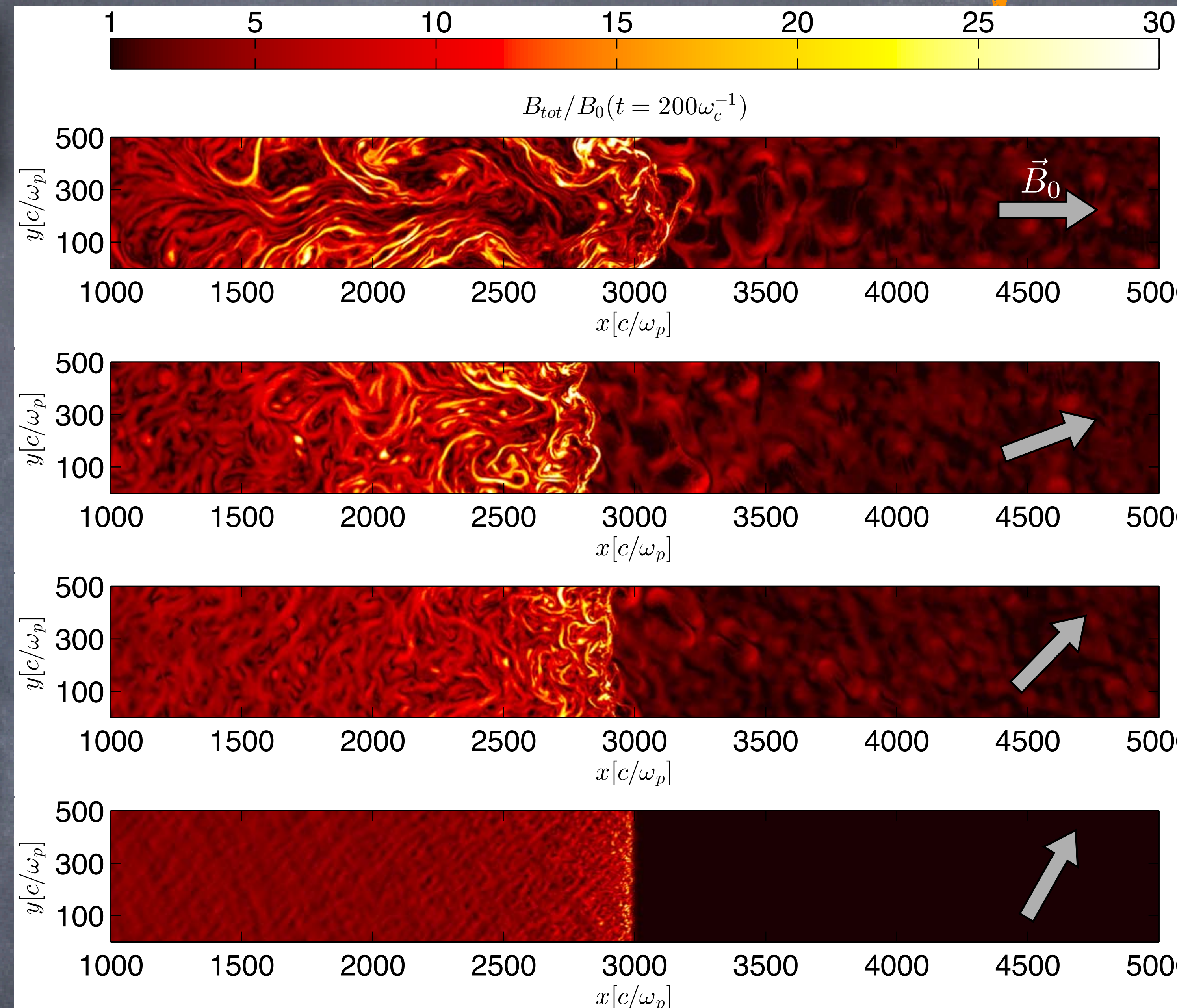




SN 1006: a parallel accelerator

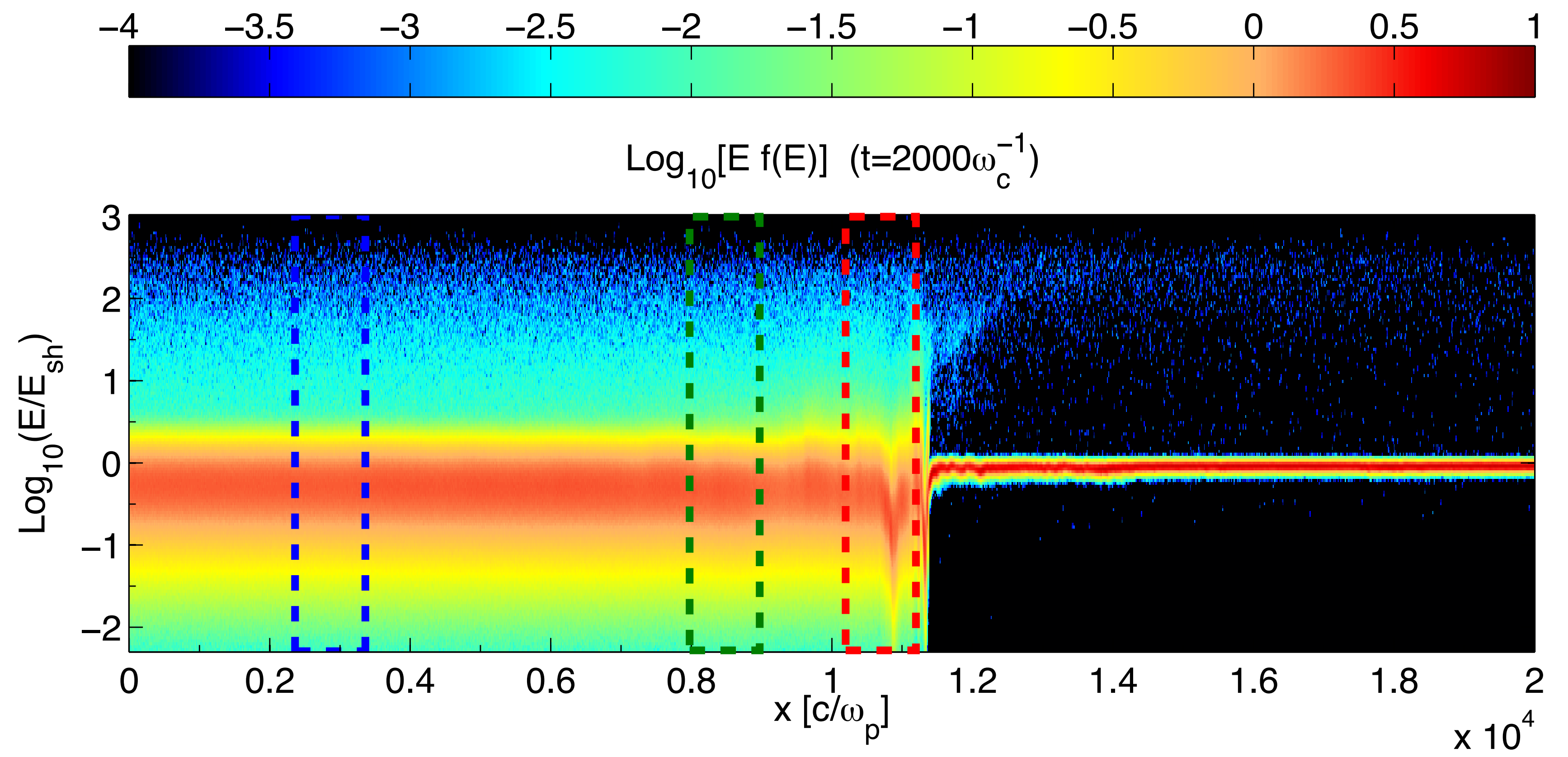


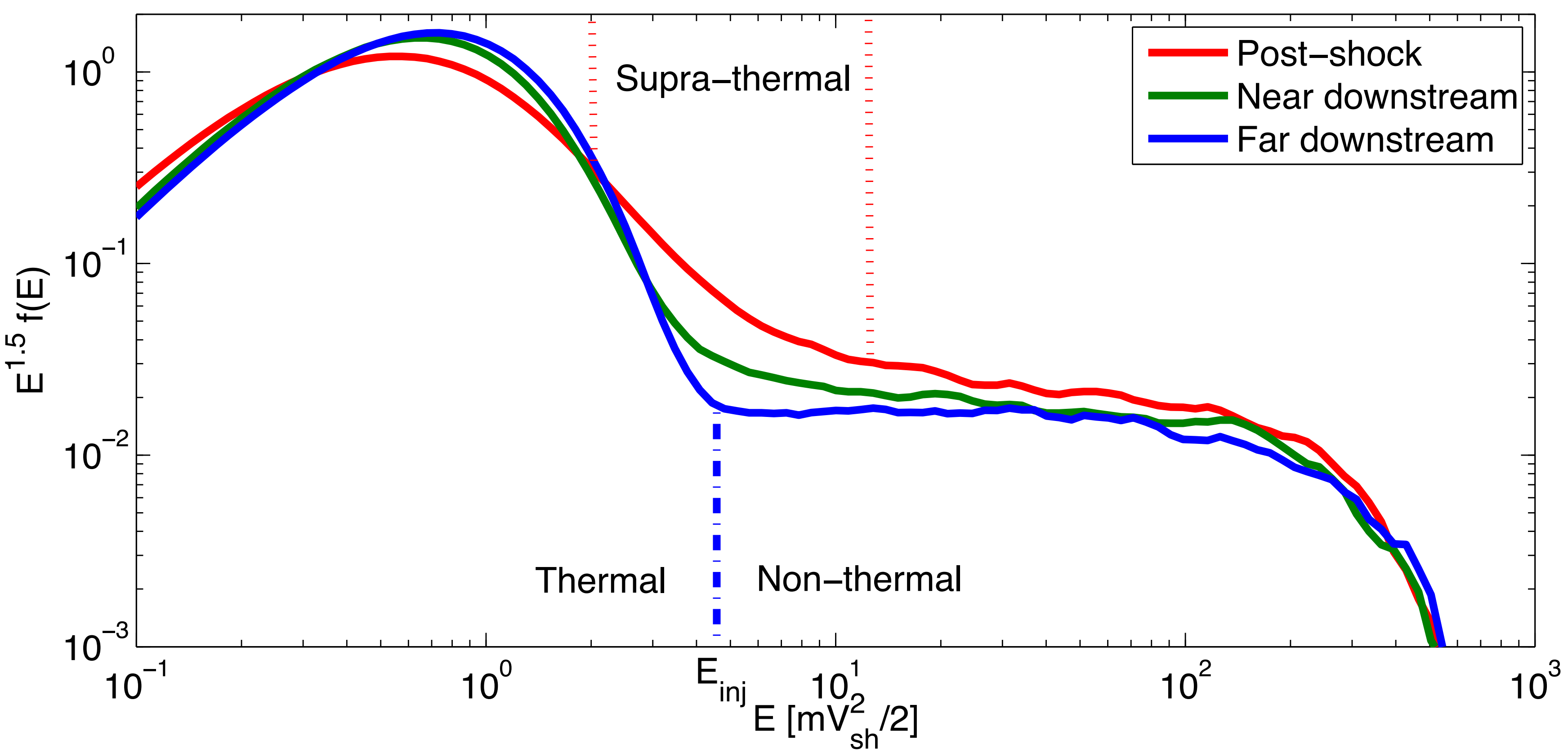




Ion acceleration and B field amplification where the shock is parallel

Supra-thermal ions

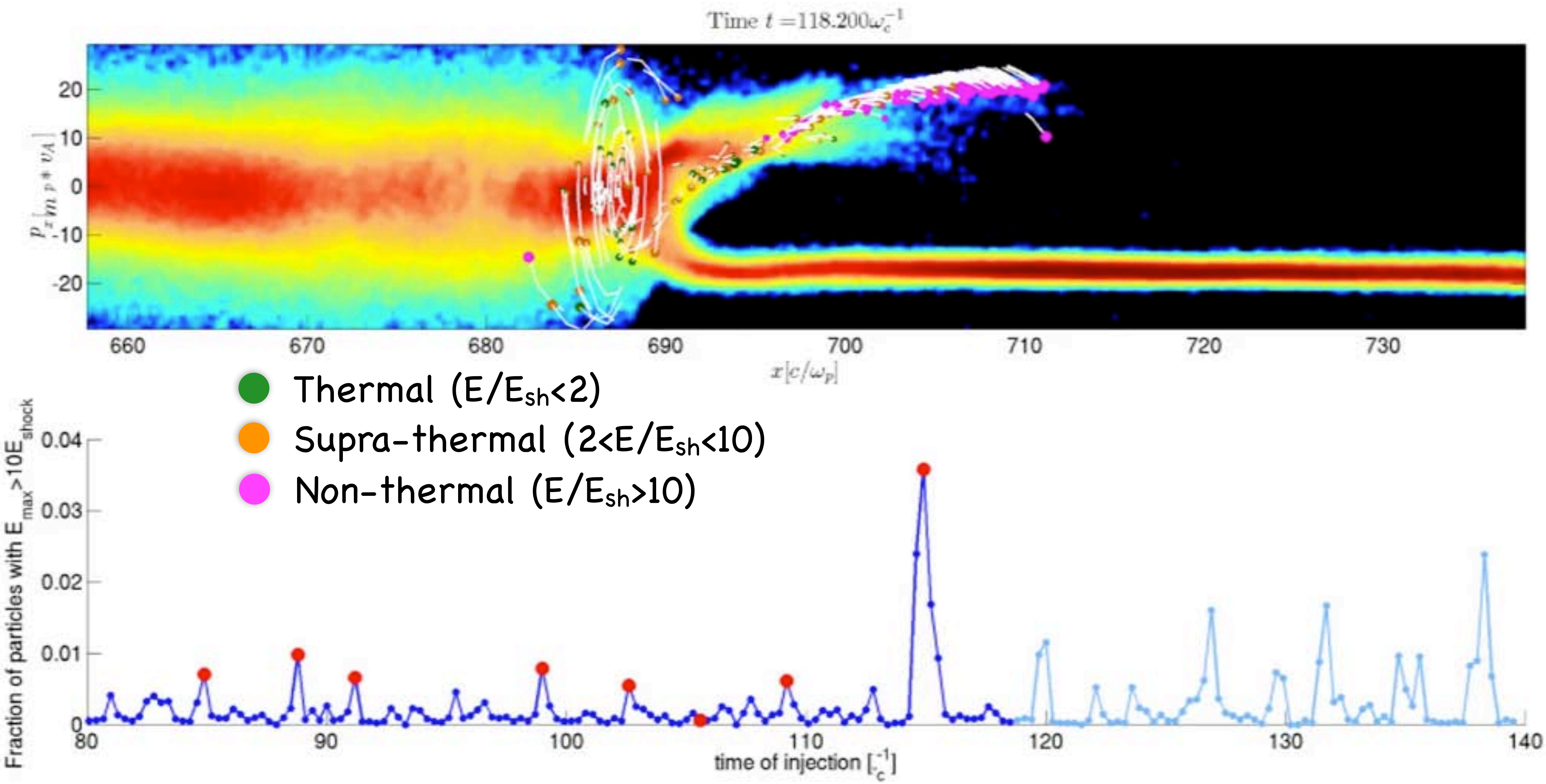




- Steep "bridge" immediately behind the shock
- Contains information on injection and thermalization
- The DSA power-law starts at $p_{inj} \sim 3\text{-}4\ p_{th,d}$

Particle Injection - Simulations

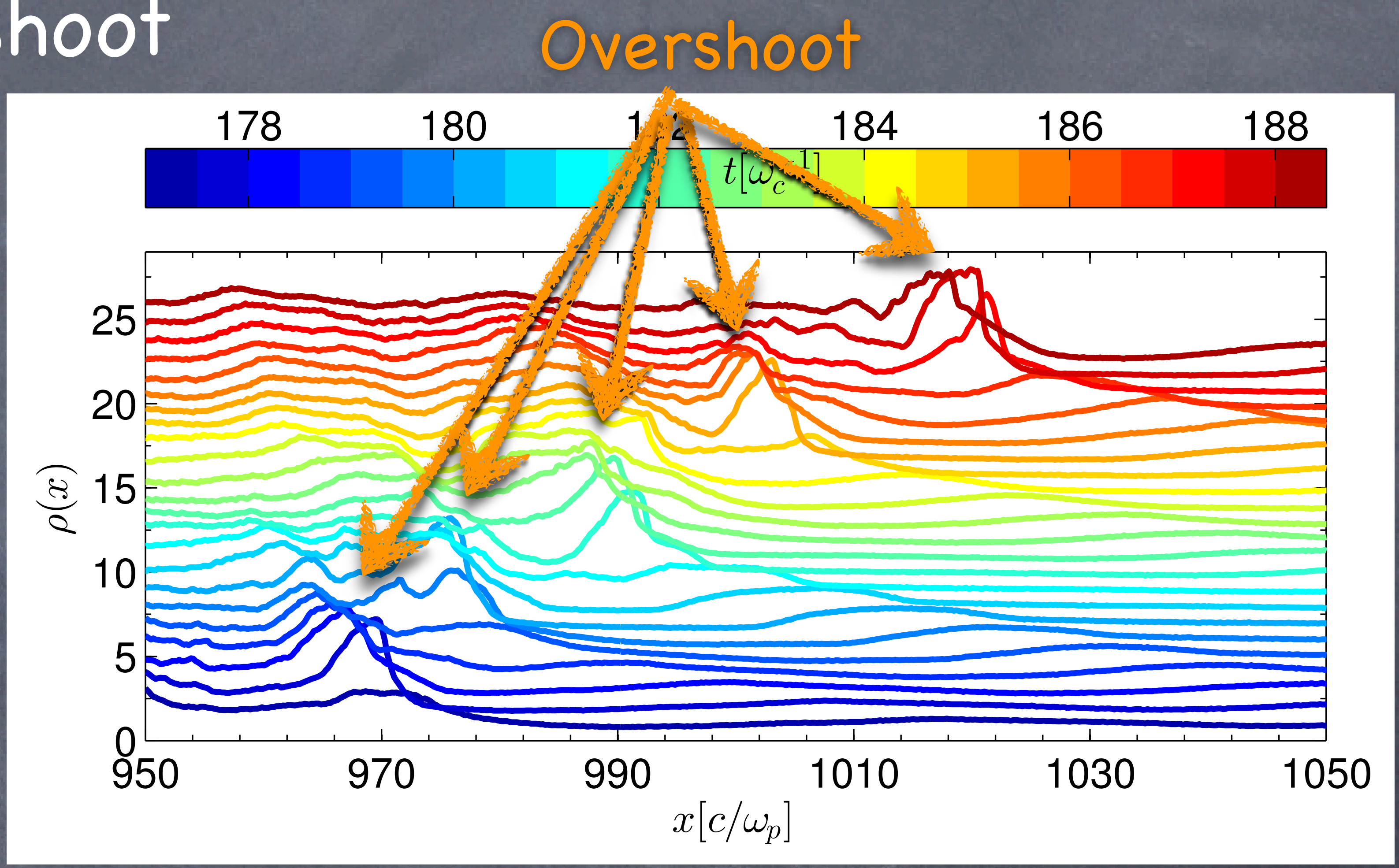
DC, Pop & Spitkovsky, 2015



The shock potential barrier

- Quasi-parallel shocks exhibit a time-varying potential barrier, with an overshoot
  - The jump in the electron pressure produces an electric field E_x directed upstream (microscopically due to the charge separation induced by different gyroradii of e and p)

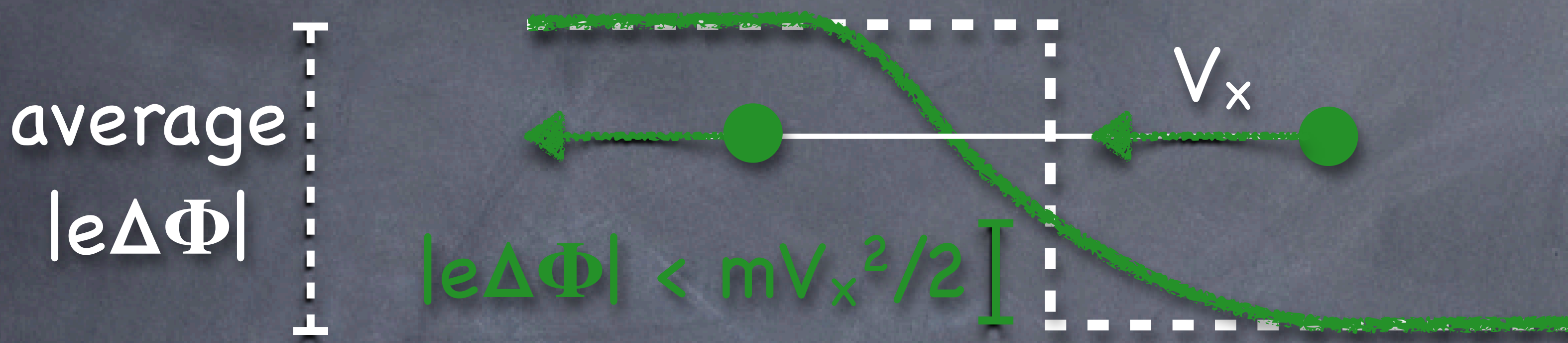
$$E_x \simeq -\frac{\Delta\Phi}{\Delta x} \simeq -\frac{1}{ne}\frac{\Delta P_e}{\Delta x}$$



- Ions impinging on the shock barrier can be reflected back because of such a E_x (also, because of the compressed B_{trans})
  - Barrier stationary in the downstream frame!

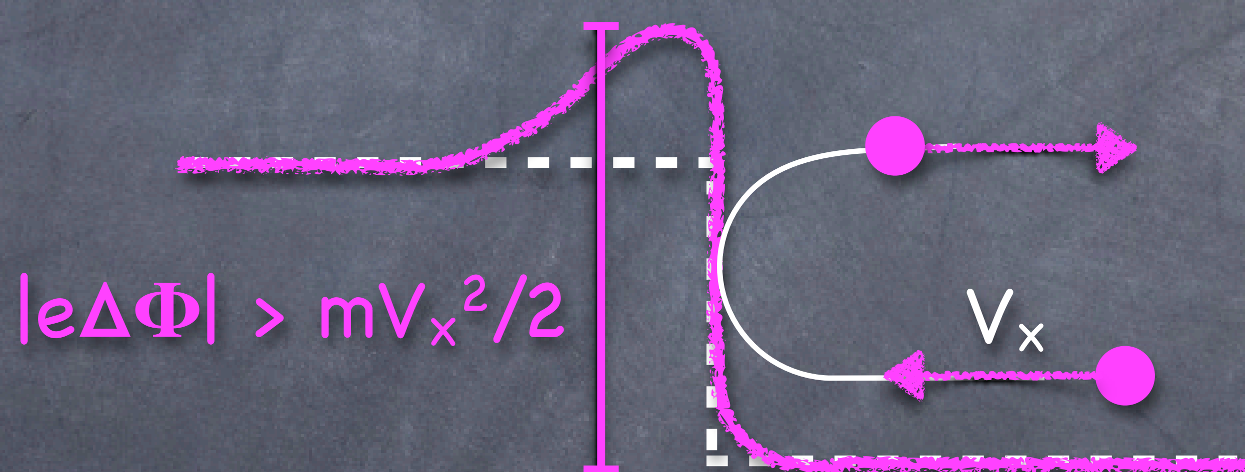
Encounter with the shock barrier

- Low barrier (shock reforming)



Particles are advected downstream, and thermalized

- High barrier (overshoot)



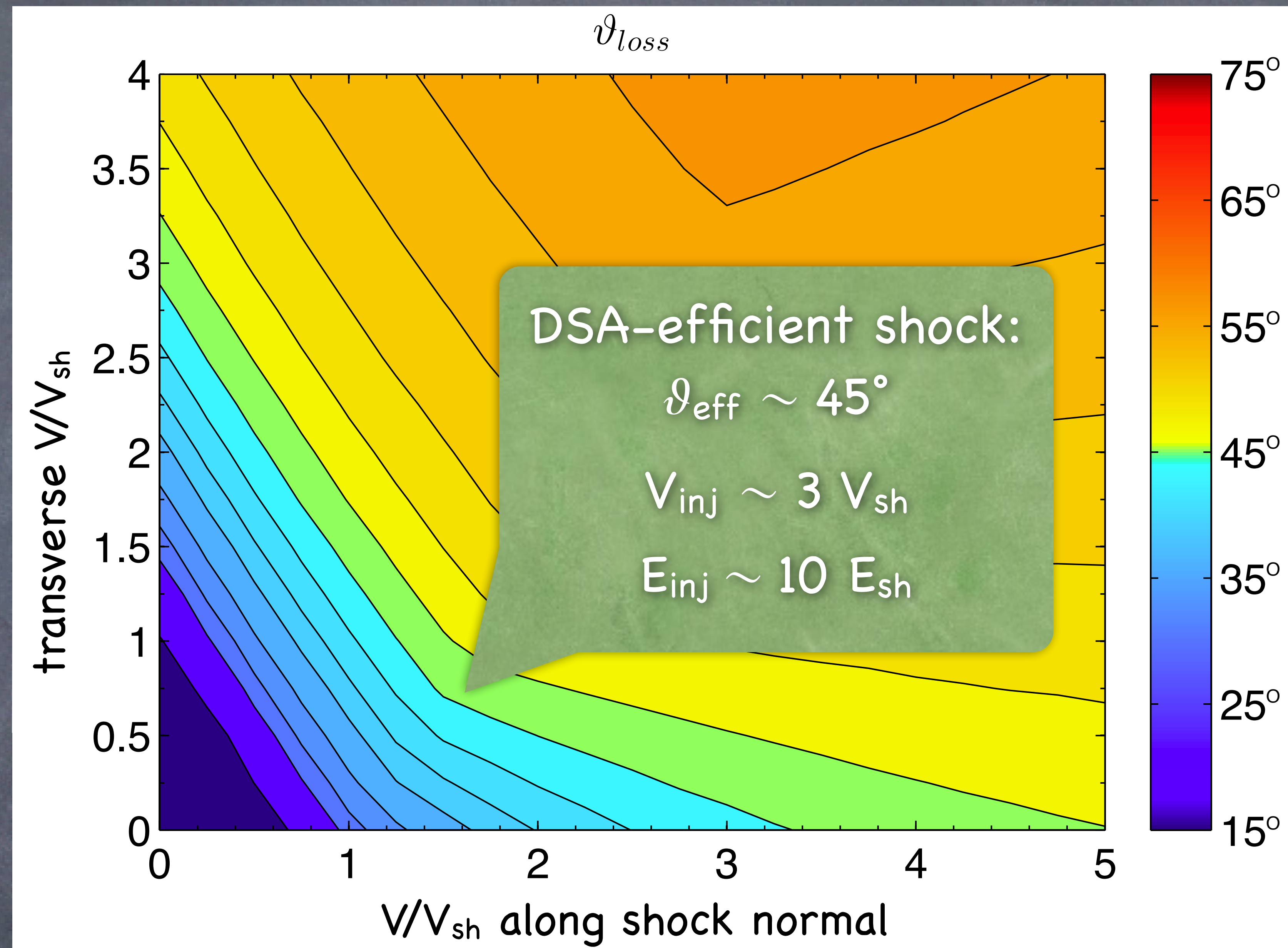
Particles are reflected upstream, and energized via Shock Drift Acc.

- Coherent reflection induces shock reformation
- Acceleration because of a transverse (motional) E field
- What is the particle fate after reflection?

Ion Injection - Theory

- Ion fate determined by
  - barrier duty-cycle (~25%)
  - pre-reflection V
  - shock inclination
- If $\vartheta < \vartheta_{loss}$, ions escape upstream, and are injected into DSA
- Otherwise, they experience SDA, return to the shock (with larger V), and may be either reflected or advected
  - After N SDA cycles, only a fraction $\eta \sim 0.25^N$ survives
  - For $\vartheta_{eff} \sim 45°$, N~3 -> $\eta \sim 1\%$

Max ϑ allowing reflection upstream



DC, Pop & Spitkovsky, 2015

E_{inj} is larger at oblique shocks: injection requires more SDA cycles, and fewer particles can achieve E_{inj}

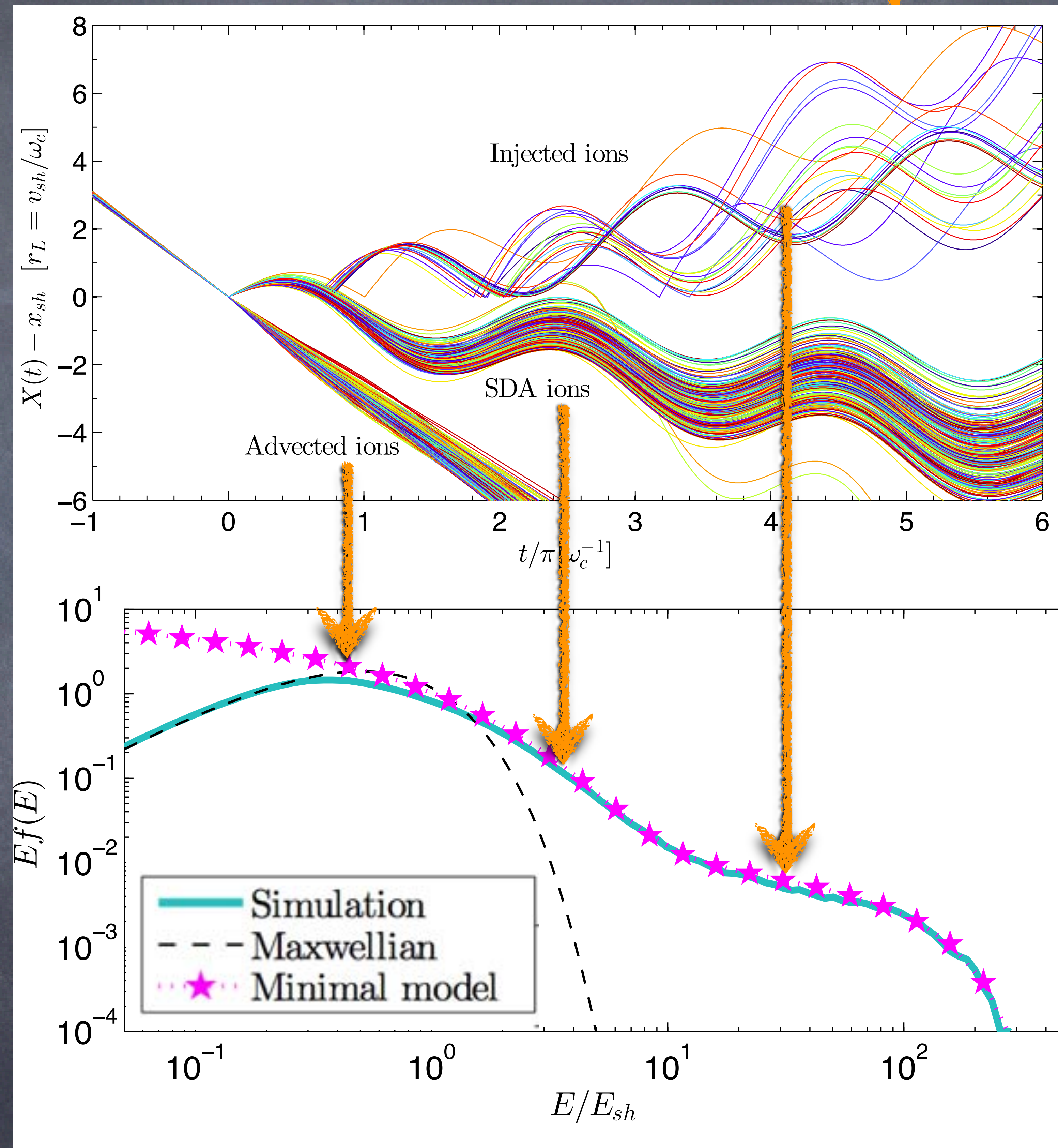
Minimal Model for Ion Injection

- Time-varying potential barrier
  - **High state** (duty cycle 25%)
    -> Reflection
    -> Shock Drift Acceleration
  - **Low-state** -> Thermalization

- Spectrum à la Bell (1978)

$$f(E) \propto E^{-1-\gamma}; \quad \gamma \equiv -\frac{\ln(1-\mathcal{P})}{\ln(1+\mathcal{E})}$$

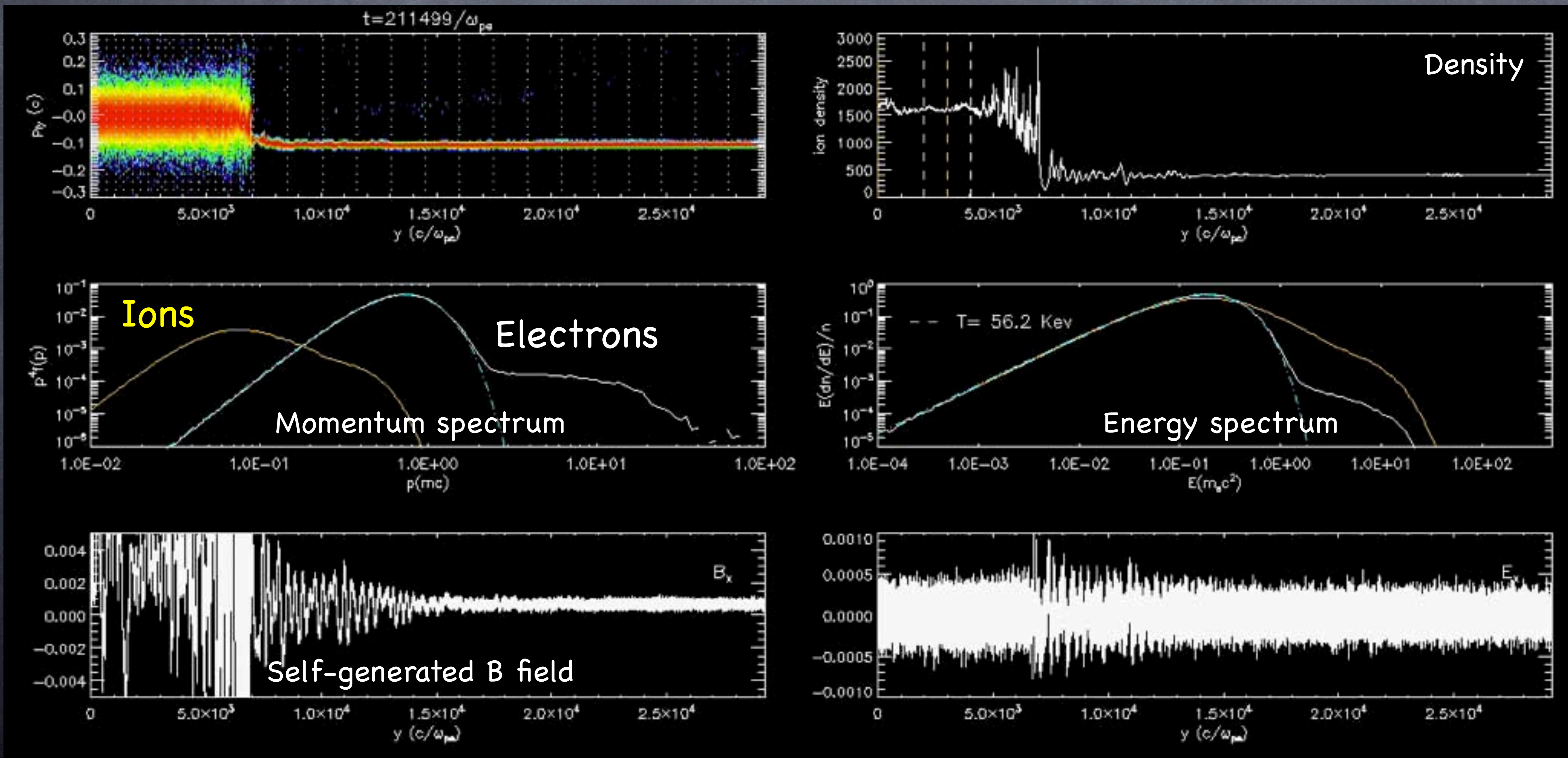
- P=probability of being advected
- ε =fractional energy gain/cycle



DC, Pop & Spitkovsky, 2015

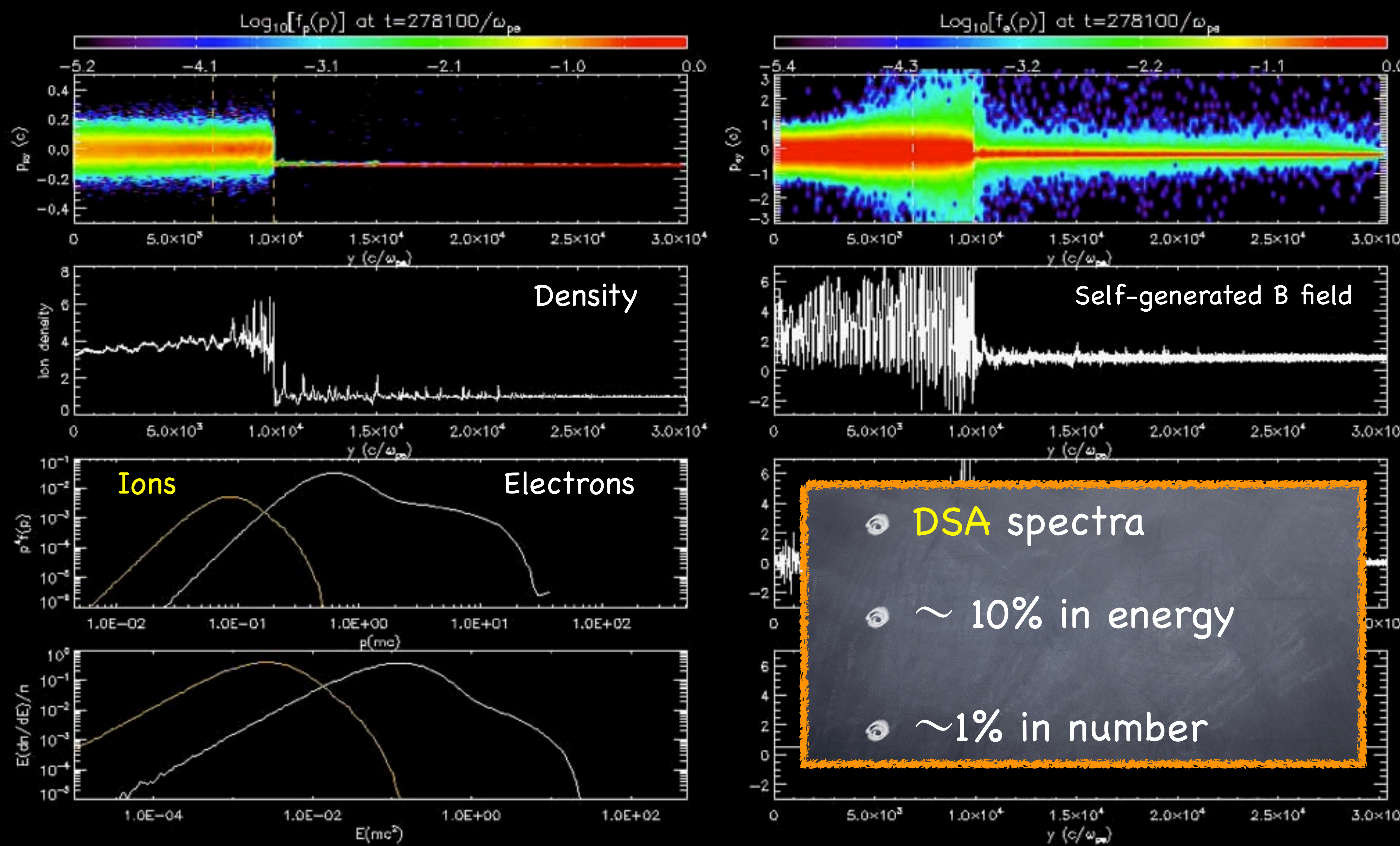
Electron/ion acceleration

- Full PIC simulations: Tristan-MP (Park, DC, Spitkovsky 2015, PRL)
  - M=20, v_{sh}=0.1c, quasi-parallel shock
  - Electrons are accelerated, but ele/proton ratio is a few %



Electron acceleration

- PIC simulations of oblique shocks (ϑ=60°): DC, Park, Spitkovsky, in prep.

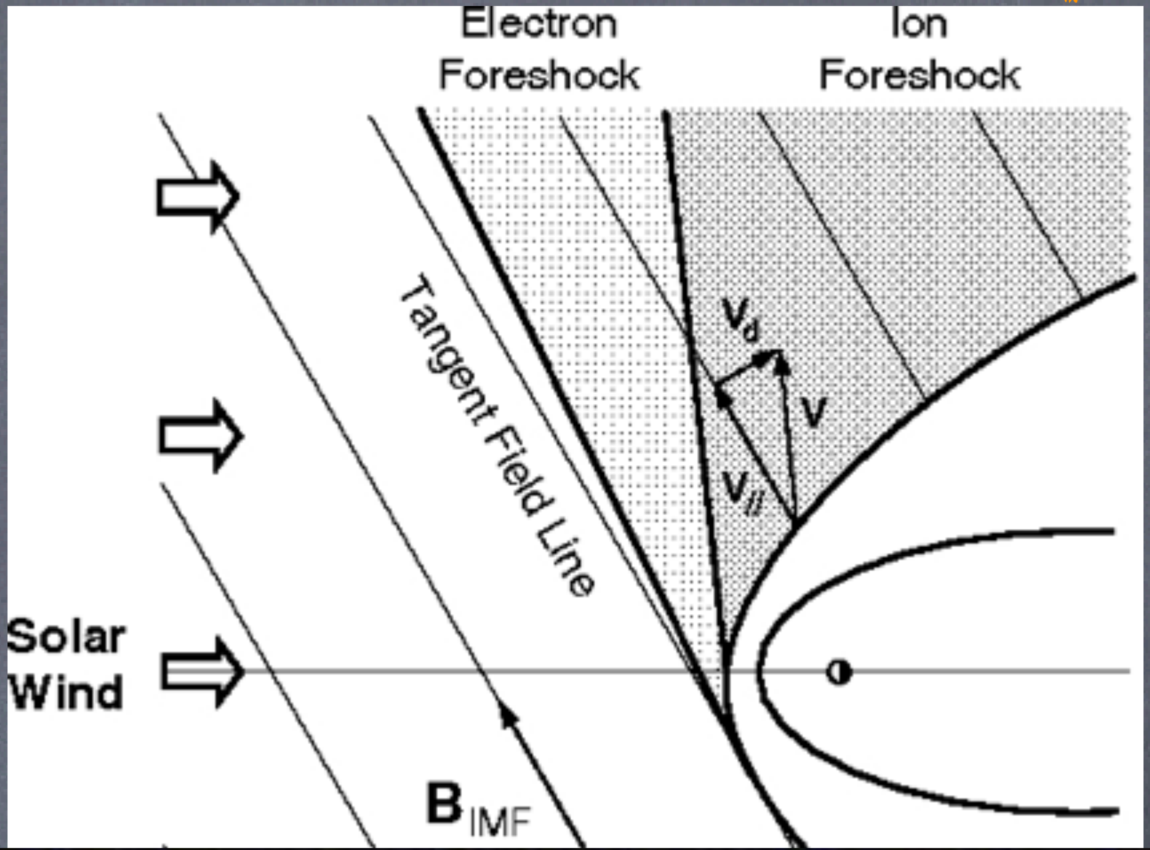


- DSA spectra
- ~ 10% in energy
- ~1% in number

Electron acceleration

- Planetary bow shocks
  (Earth, Venus, Saturn,...)

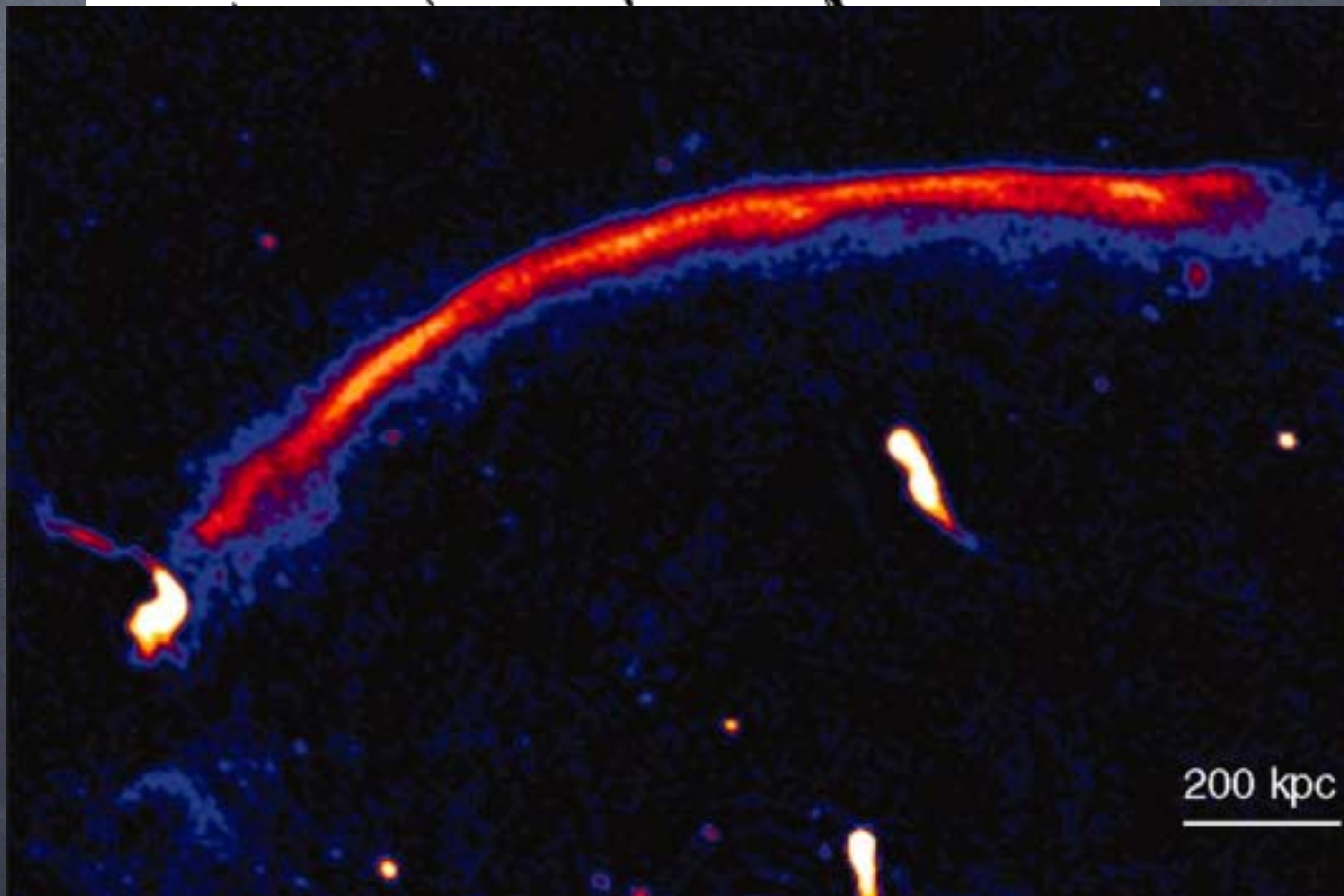
- In situ measurements:
  Geotail, Venus Orbiter, Polar, SoHO, WIND, Cluster, ...



- Radio relics in galaxy clusters
  (sausage, toothbrush,...)

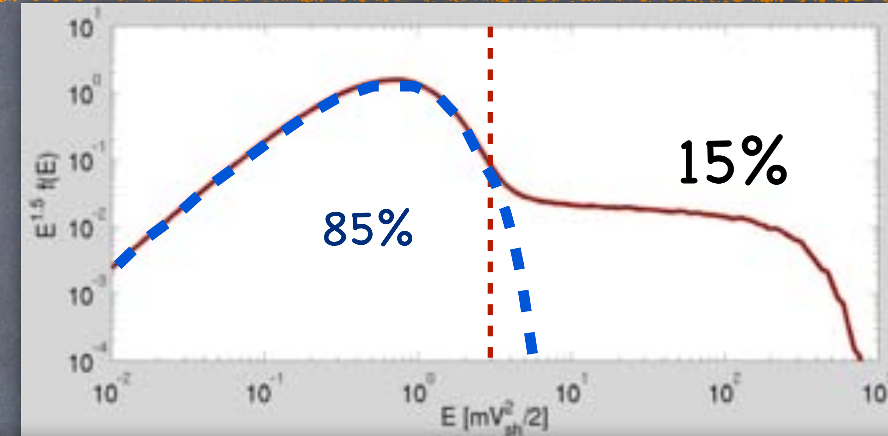
- Extended polarized structures

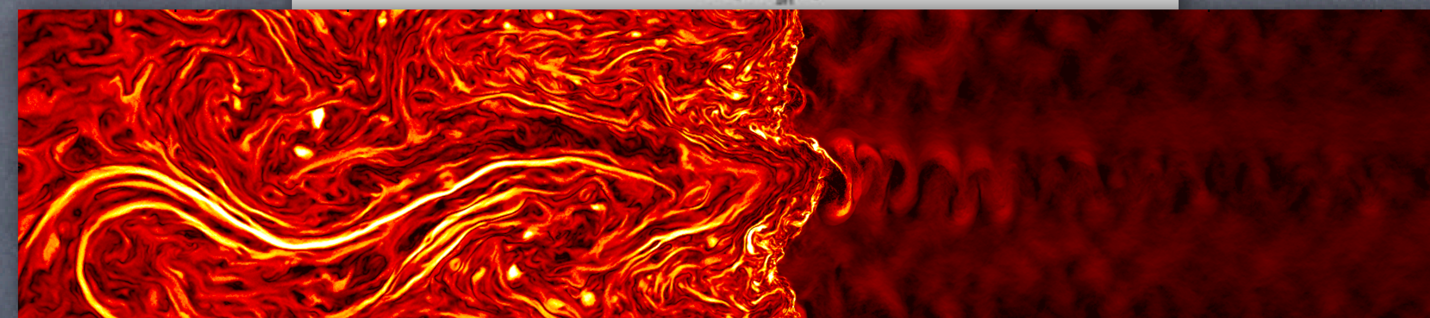
- Fermi-LAT limits on γ-ray emission: constrain e/p ratio!

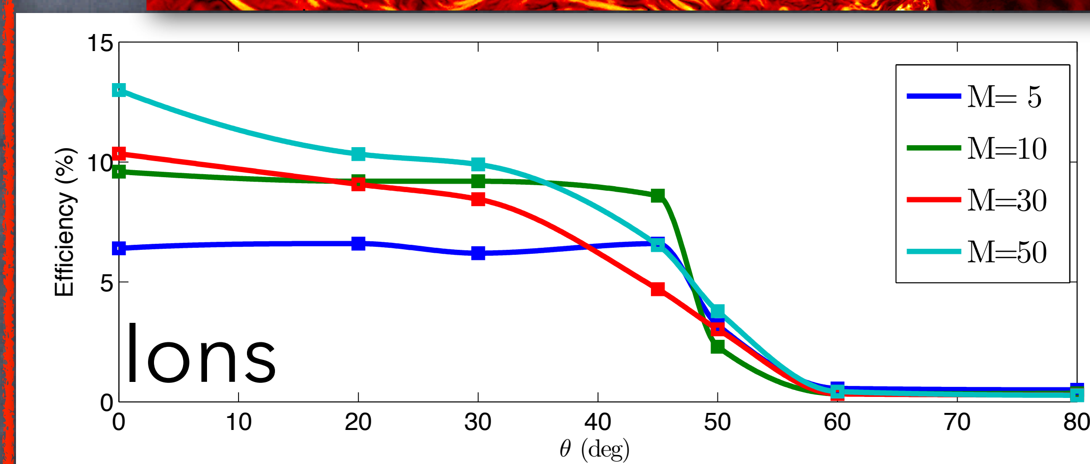


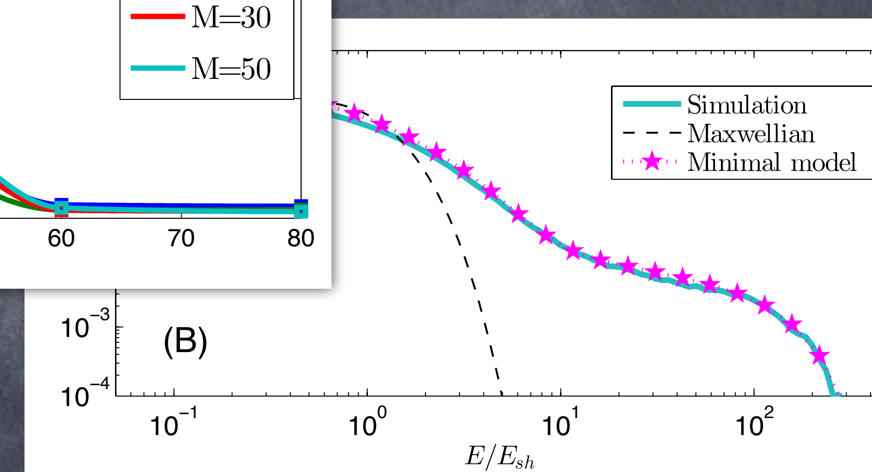
Conclusions

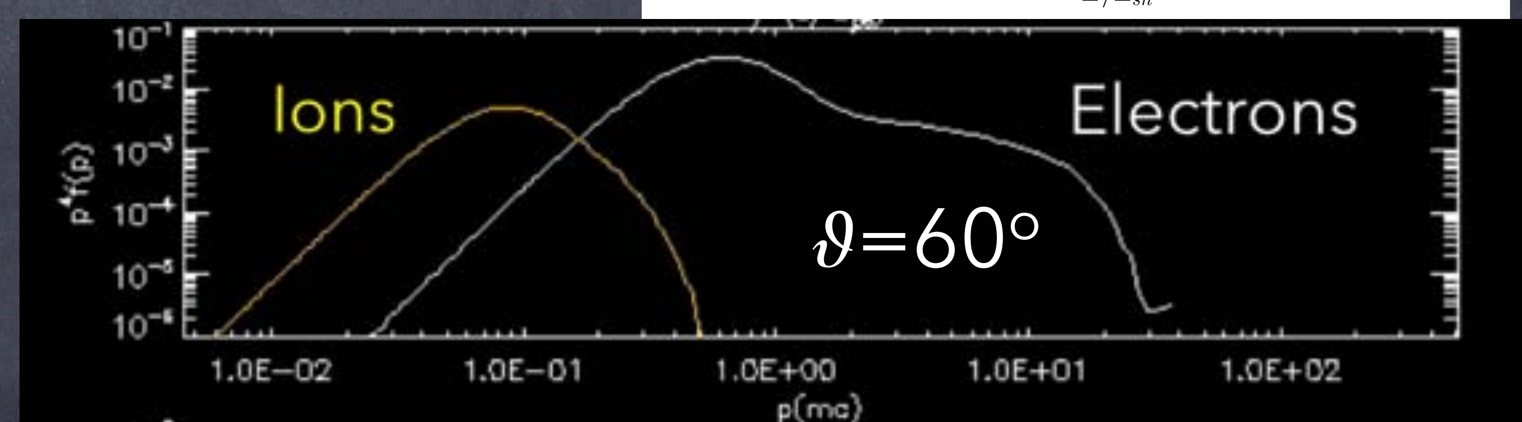
- Acceleration at shocks can be efficient: >15%
- CRs amplify B field via streaming instability
- Ion DSA efficient at parallel, strong shocks
- Ions are injected via reflection and shock drift acceleration
- Electron DSA efficient at oblique shocks







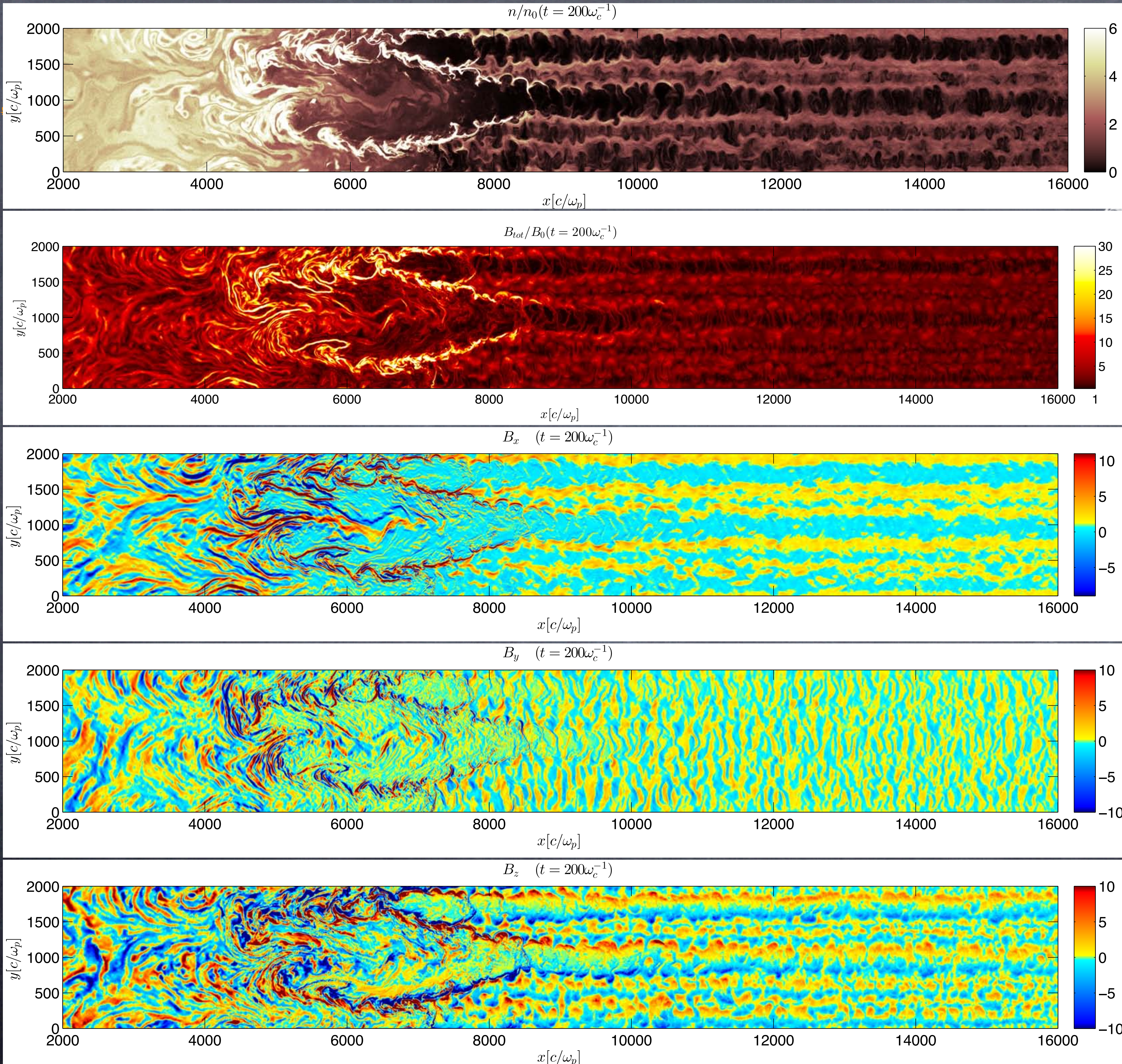




Exchanges between Fluid and Kinetic Scales

- Towards real shocks: going bigger and faster
  - Super-Hybrid (Bai, DC, Sironi, Spitkovsky 2014)
- Embedding microphysics in hydro/MHD simulations
  - CRAFT: CR Analytic Fast Tool (DC et al., in prep)

SN1006 rim - HST



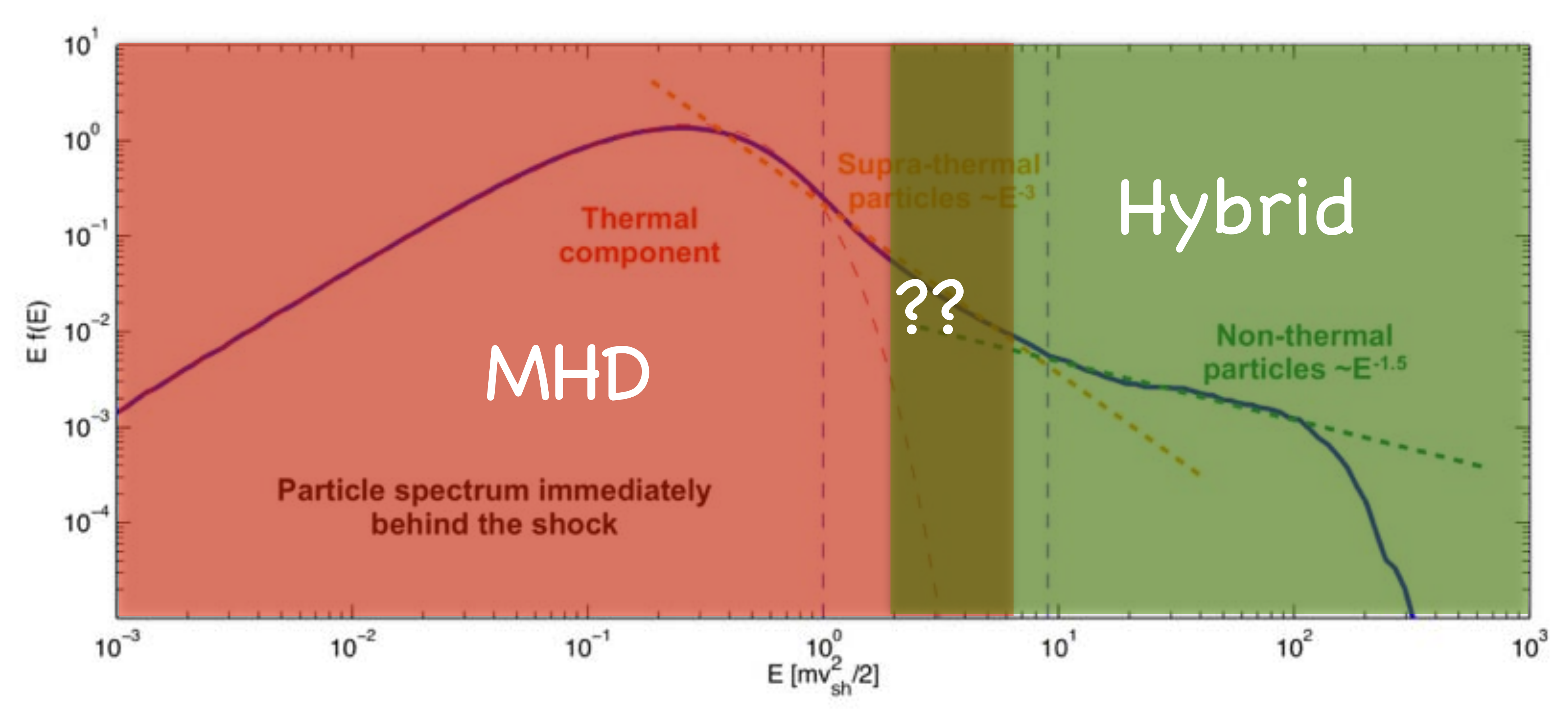
Hybrid simulations of a very strong shock: M=100

Total $\delta B/B$ larger than 10 in the precursor!

Very expensive to study in the hybrid limit

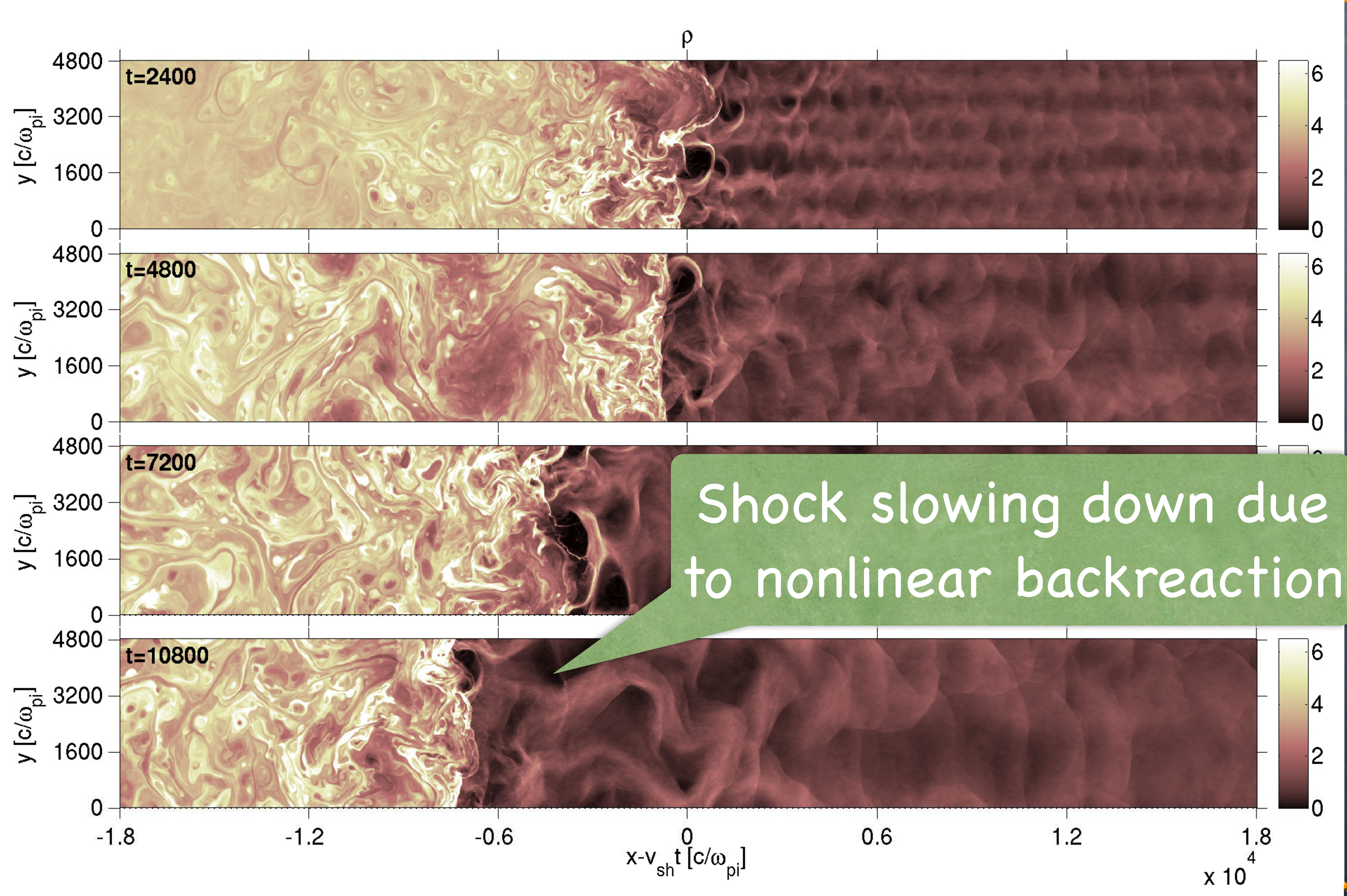
Going bigger: Super-Hybrid

- MHD (Athena) + kinetic ions (also relativistic)
- Needs injection (tuned form hybrid)
- Allows to go to higher Mach # and larger scales



Bai, DC, Sironi, Spitkovsky 1412.1087

Long-term evolution



Bai, DC, Sironi, Spitkovsky 1412.1087

CRAFT: a Cosmic-Ray Fast Analytic Tool

(Caprioli et al. 2009-2015, to be publicly released soon)

- Iterative solution of the CR transport equation:

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

$$Q(x,p) = \eta\frac{\rho_1 u_1}{4\pi m_p p_{inj}^2}\delta(p-p_{inj})\delta(x)$$

Injection

Mass+momentum conservation eqs.

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

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

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

u

$P_B + P_{cr}$

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

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

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

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

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

CR distribution function

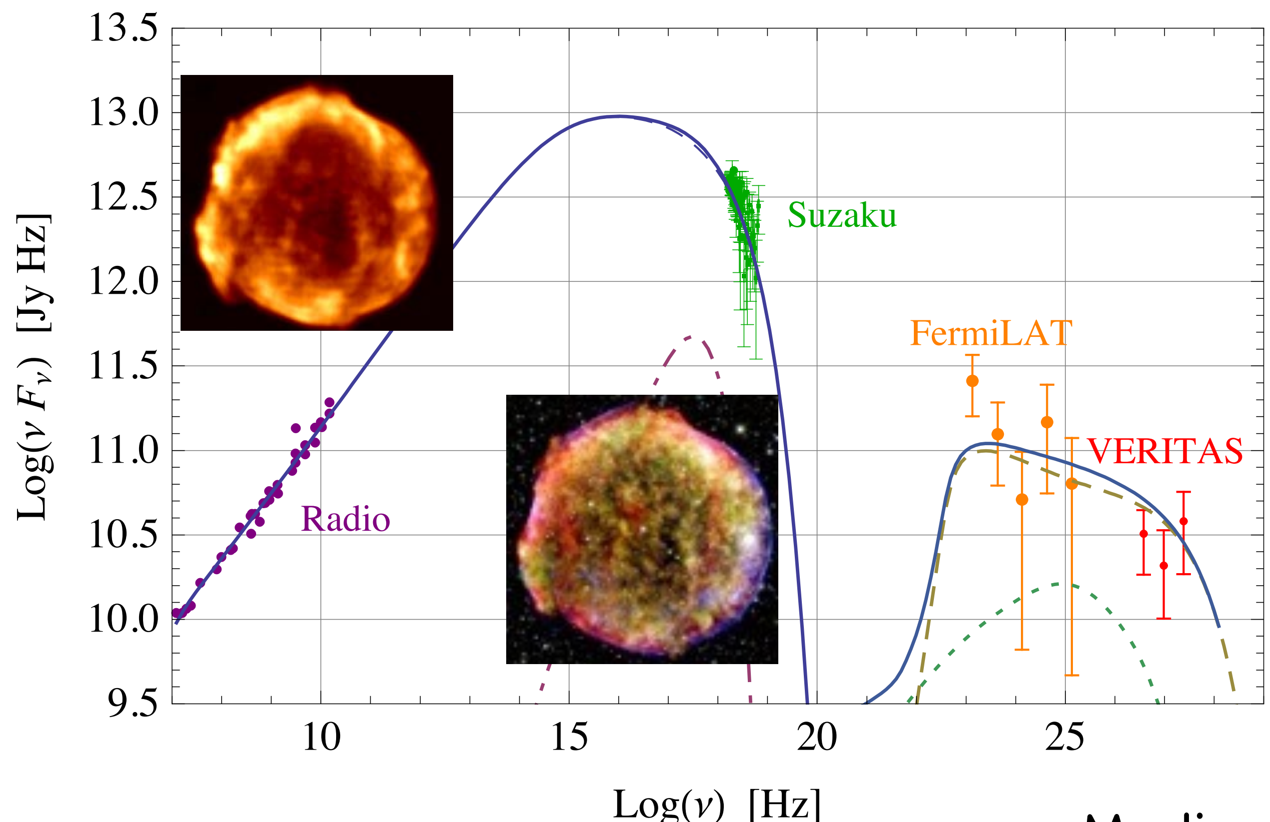
P_{cr}

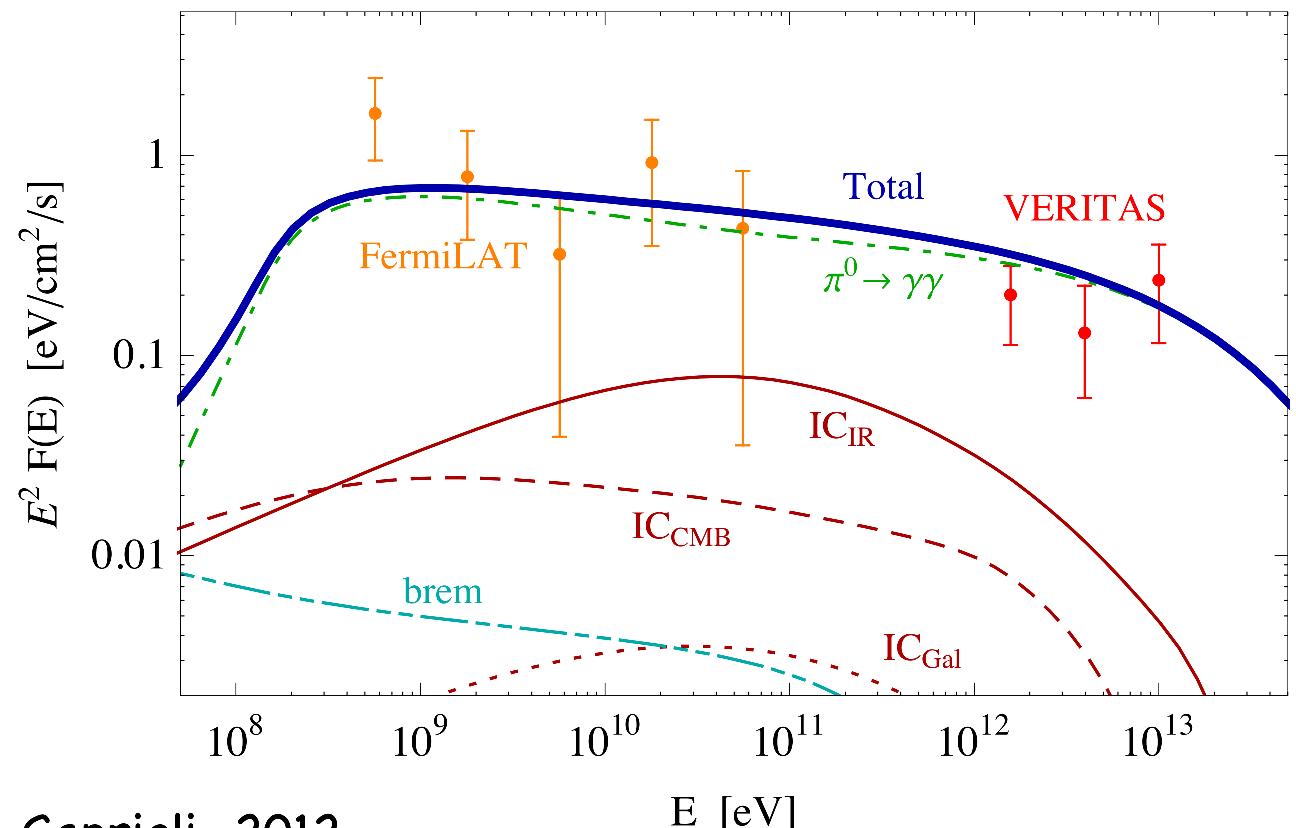
$$2\tilde{u}(x)\frac{dp_B(x)}{dx} = v_A(x)\frac{dp_{cr}(x)}{dx} - 3p_B(x)\frac{d\tilde{u}(x)}{dx}$$

Magnetic turbulence transport eq.

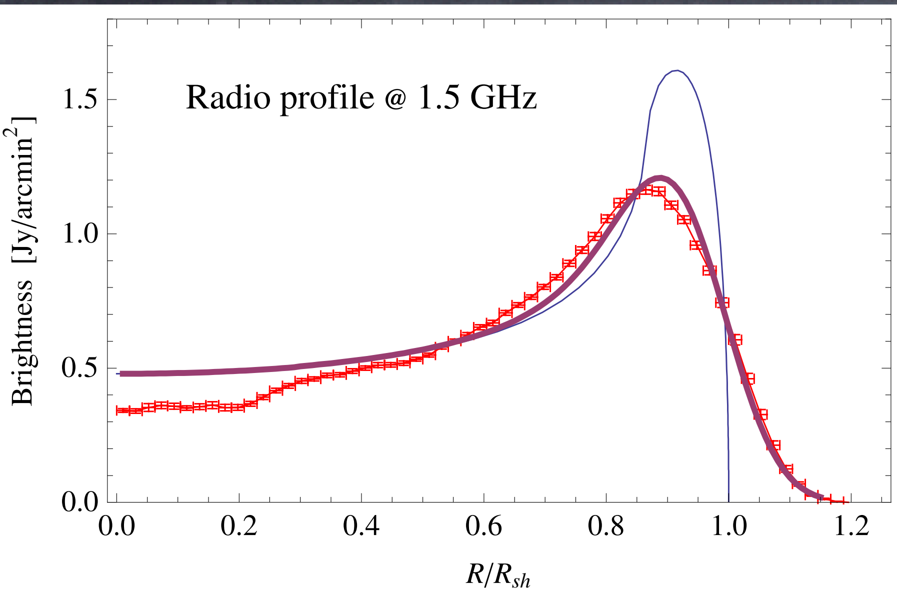
- Very fast: a few seconds on a laptop (vs days on clusters)
- Embeds microphysics from kinetic simulations into (M)HD

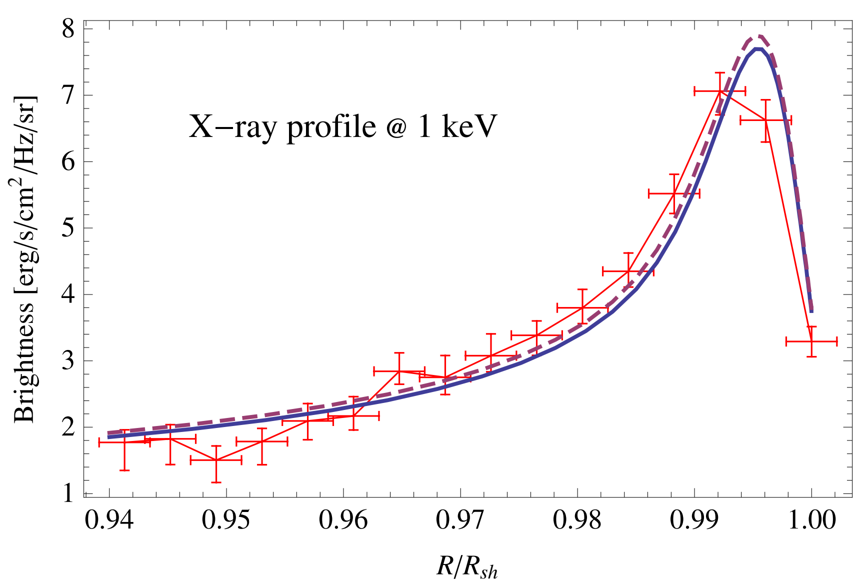
Tycho: a clear-cut hadronic accelerator





Morlino & Caprioli, 2012

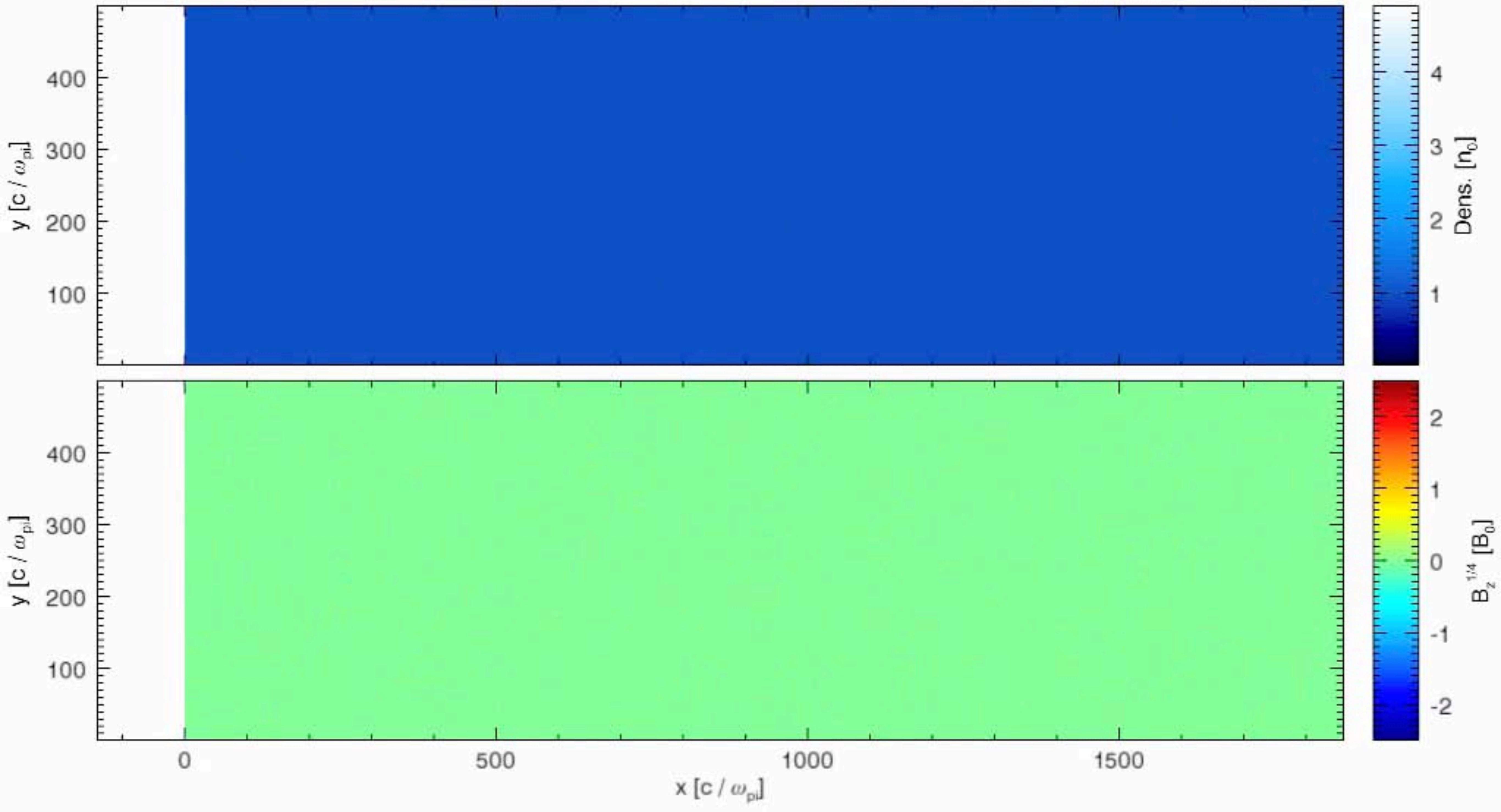




- Account for spectra, SNR hydrodynamics, and morphology
- Hadron acc. eff. ~10%
- Protons up to 0.5 PeV

- Only two free parameters: injection efficiency and electron/proton ratio

Thank you!



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