Ann Arbor, Jan 2015

# Simulations of Particle Acceleration at Astrophysical Shocks

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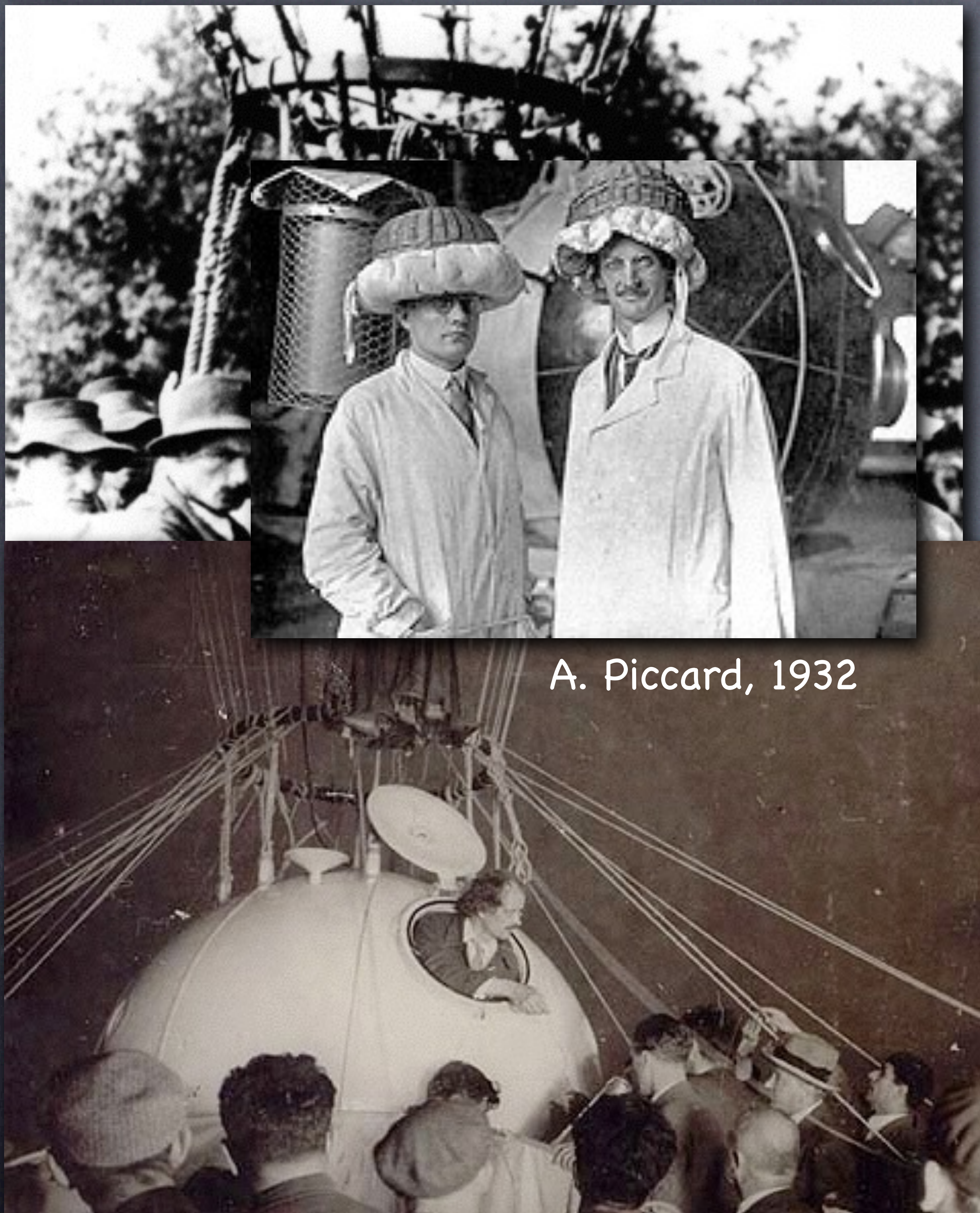
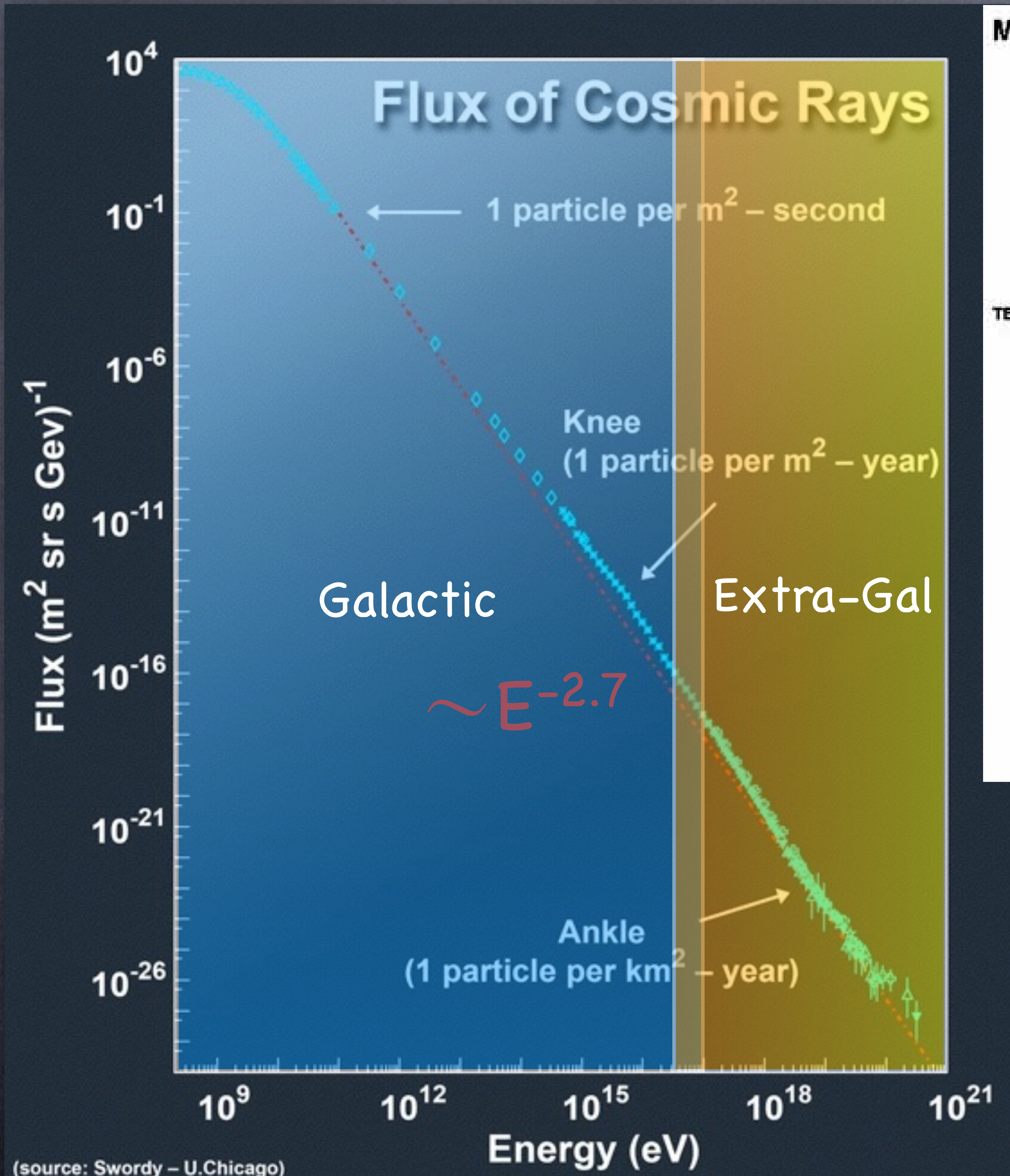
# An extraterrestrial radiation!

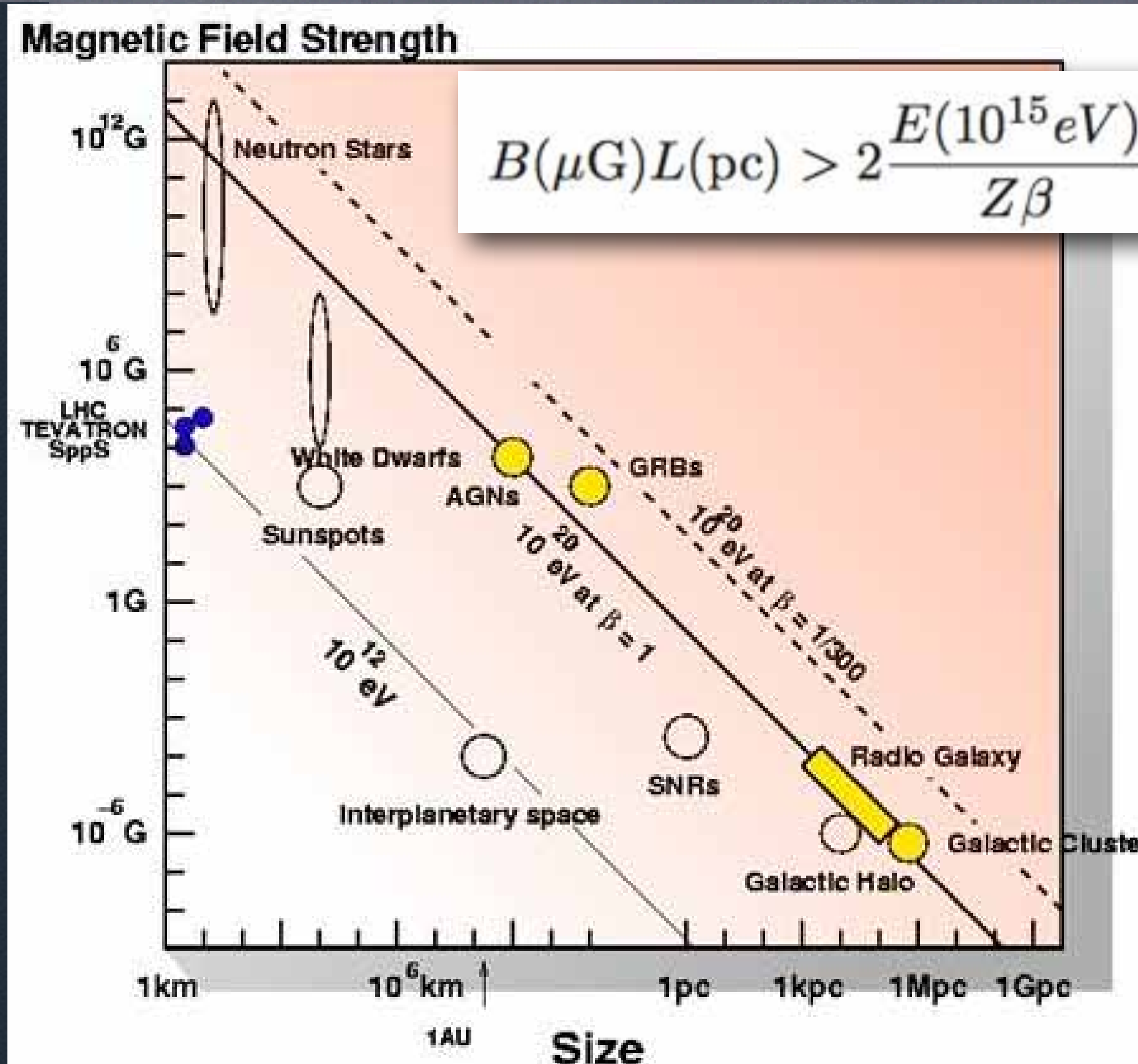


A. Piccard, 1932

- 1912: V. Hess discovers an extraterrestrial source of ionization: Cosmic Rays
- 1930-1932: A. Piccard reaches the stratosphere with a pressurized aluminum gondola attached to a ballon to measure CRs
- 1940: B. Rossi and P. Auger measure Extensive Air Showers:
  - CRs up to $10^4$-$10^5$ GeV

# The CR spectrum at Earth



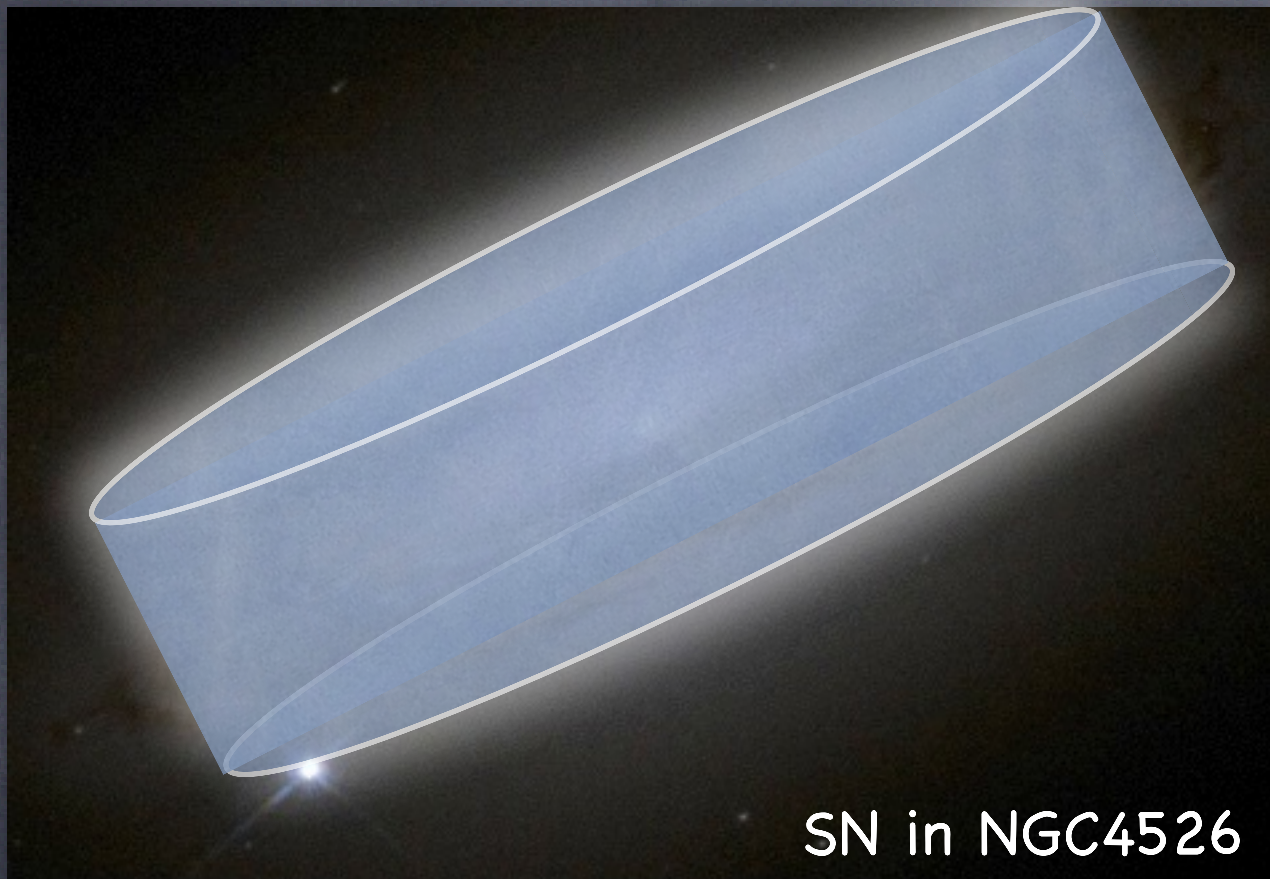




$$B(\mu G)L(pc) > 2\frac{E(10^{15}eV)}{Z\beta}$$

- Hillas criterion: size of the system larger than the particle gyroradius

# SNR paradigm: energetics

- Baade-Zwicky (1934) energetic argument, updated




$$\varepsilon_{CR} = 0.5 eV cm^{-3}$$

$$V_{conf} = \pi R^2 h = 2 \times 10^{67}\ cm^3$$

$$W_{CR} = \varepsilon_{CR} V_{conf} \approx 2 \times 10^{55}\ erg$$

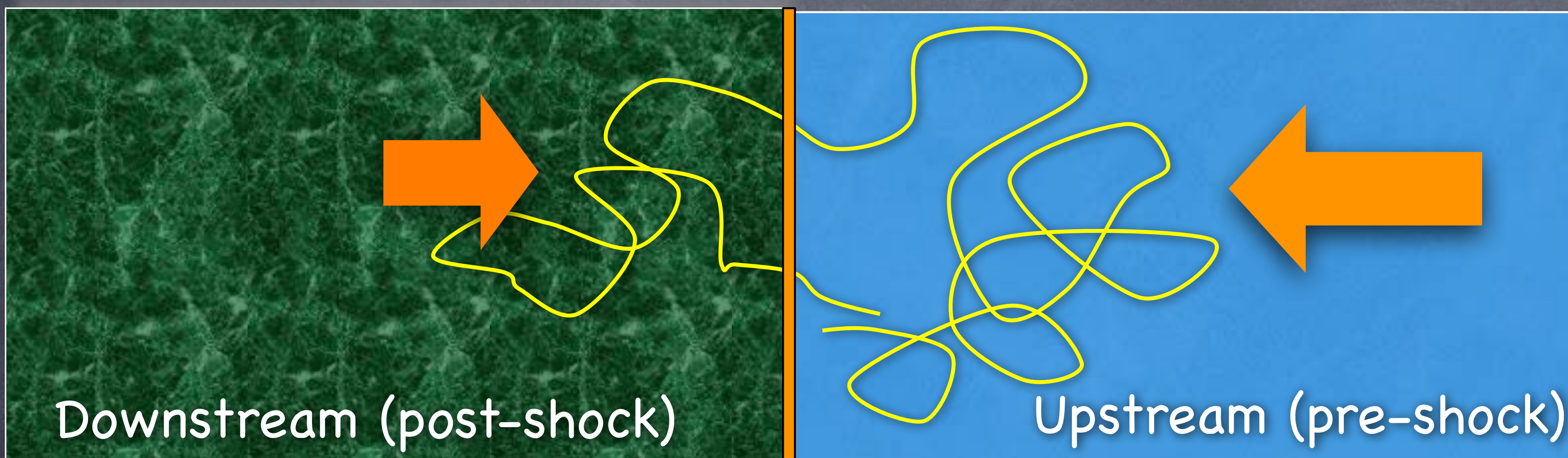
$$L_{CR} \approx \frac{W_{CR}}{\tau_{conf}} \approx 5 \times 10^{40}\ erg\ s^{-1}$$

$$L_{SN} = R_{SN} E_{kin} \approx 3 \times 10^{41}\ erg\ s^{-1}$$

**10-20% of SN ejecta kinetic energy converted into CRs can account for the energetics**

# SNR paradigm: acceleration mechanism

- Fermi mechanism (Fermi, 1954): random scattering leads to energy gain
- In a shock a particle gains energy at any reflection (Blandford & Ostriker; Bell; Axford et al.; 1978): Diffusive Shock Acceleration (DSA)

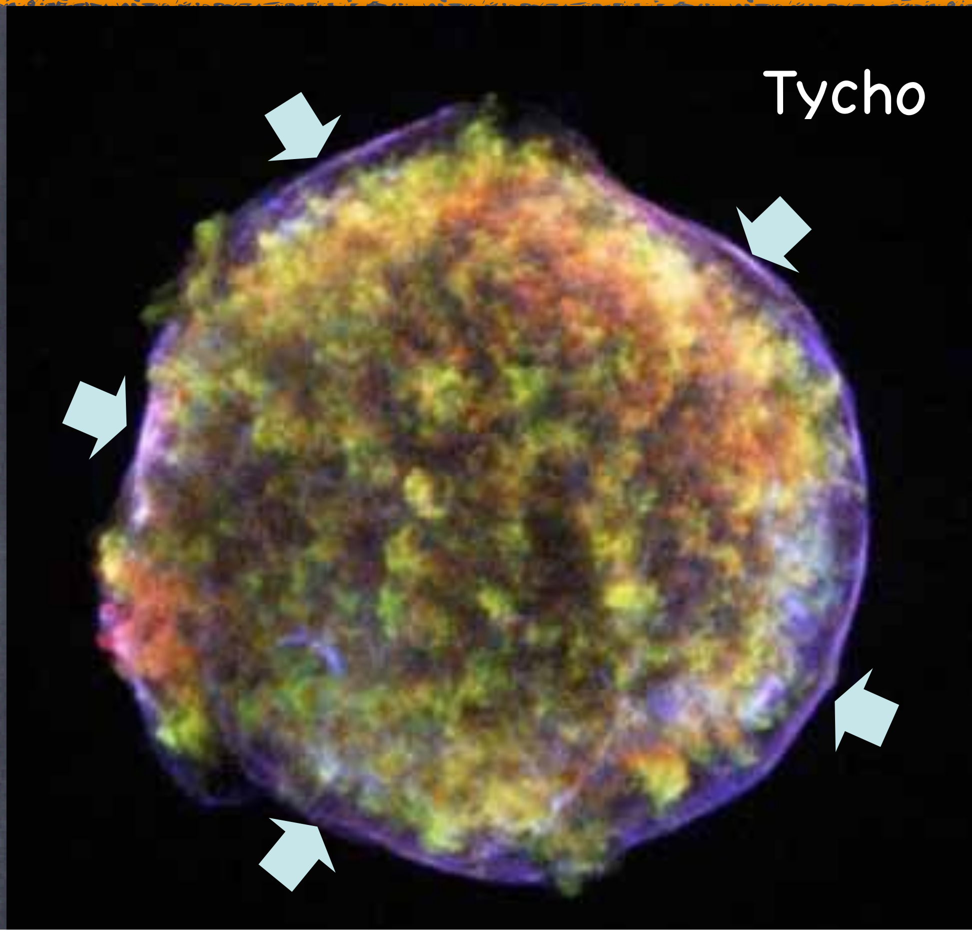



Test-particle squeezed between converging flows

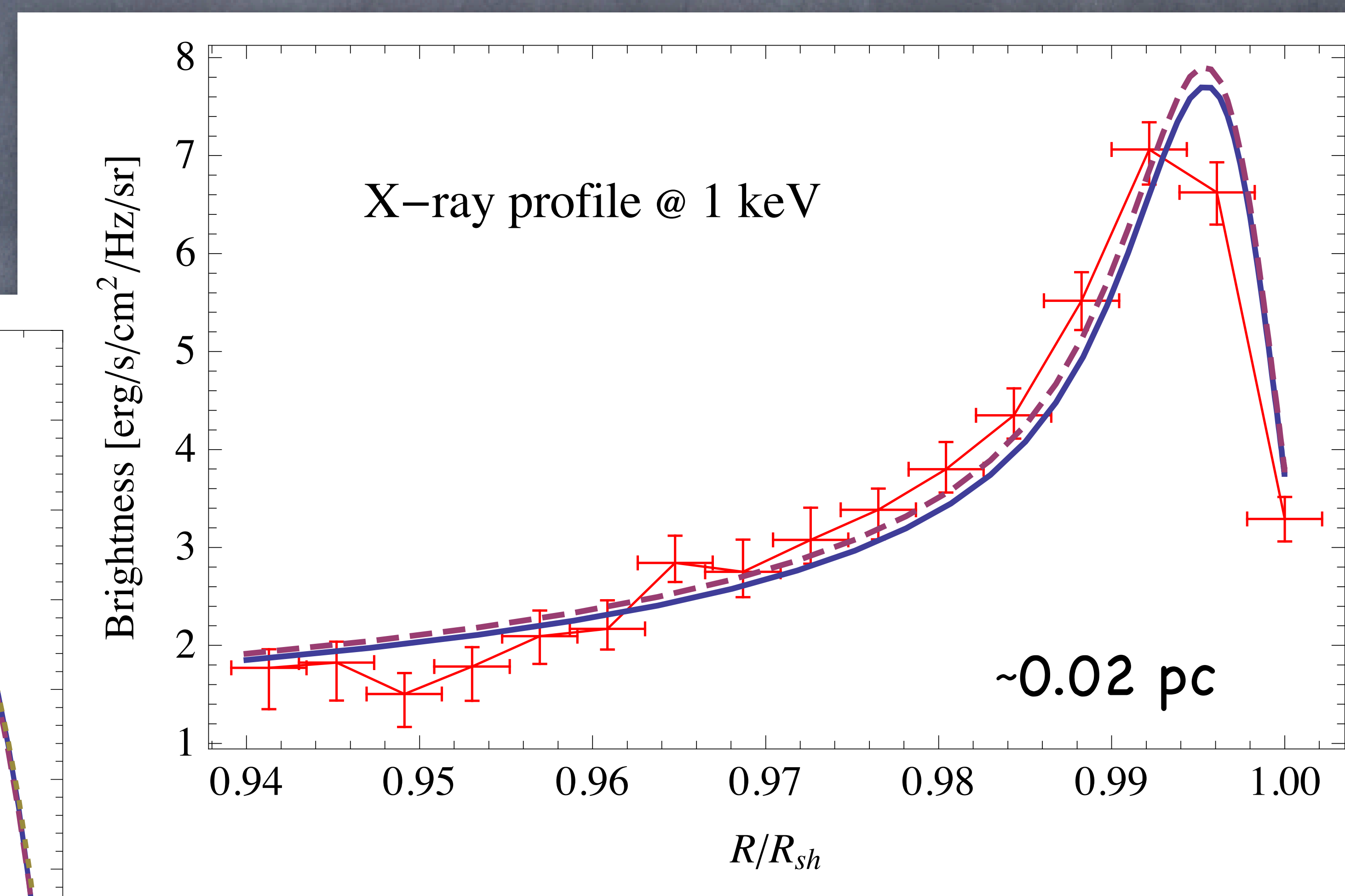
- DSA produces power-law $p^{-\alpha}$ in momentum, depending on the compression ratio $R=\rho_d/\rho_u$ only. For strong shocks: $\alpha=4$

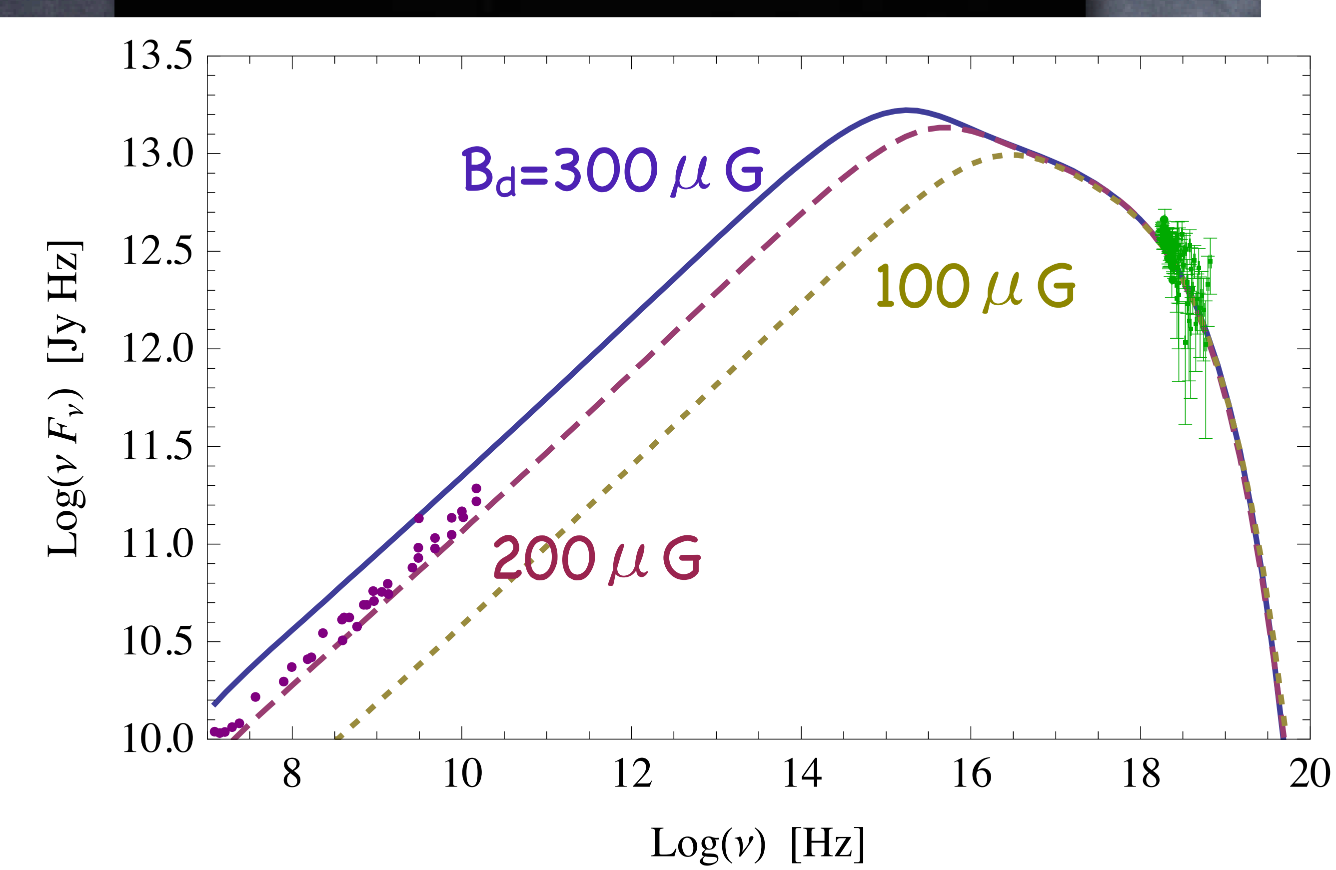
$$R = \frac{4M_s^2}{M_s^2+3} \qquad \alpha = \frac{3R}{R-1}$$

# Evidence of magnetic field amplification




- Narrow (non-thermal) X-ray rims due to synchrotron losses of 10-100 TeV electrons...
- ...in fields as large as B~100-500 μG

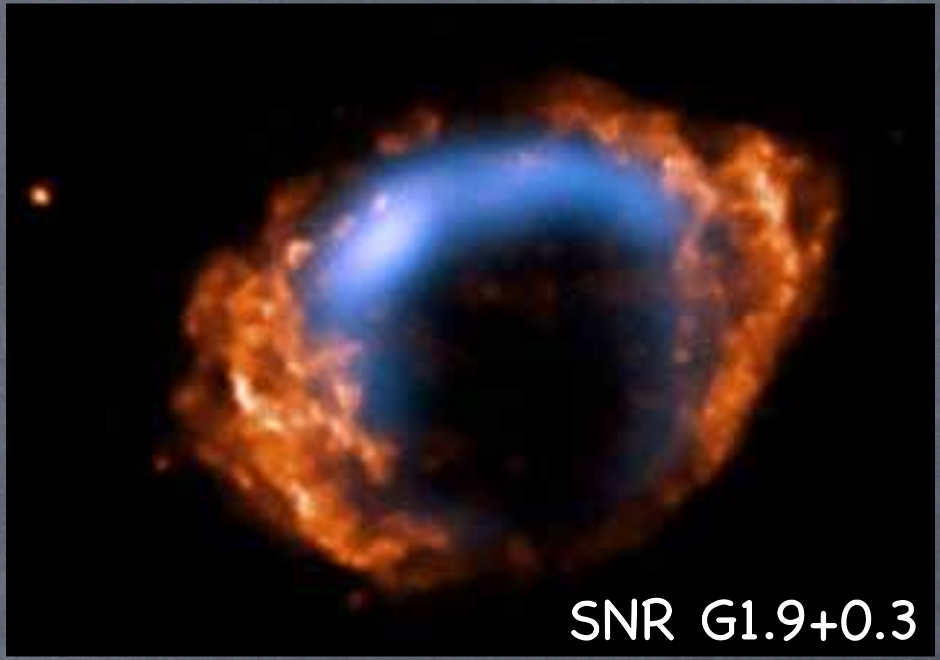



Morlino & DC, 2012

# Conclusions?

- Supernova Remnants
  - Have the right energetics
  - Diffusive shock acceleration produces power-laws
  - B amplification may help reaching the knee

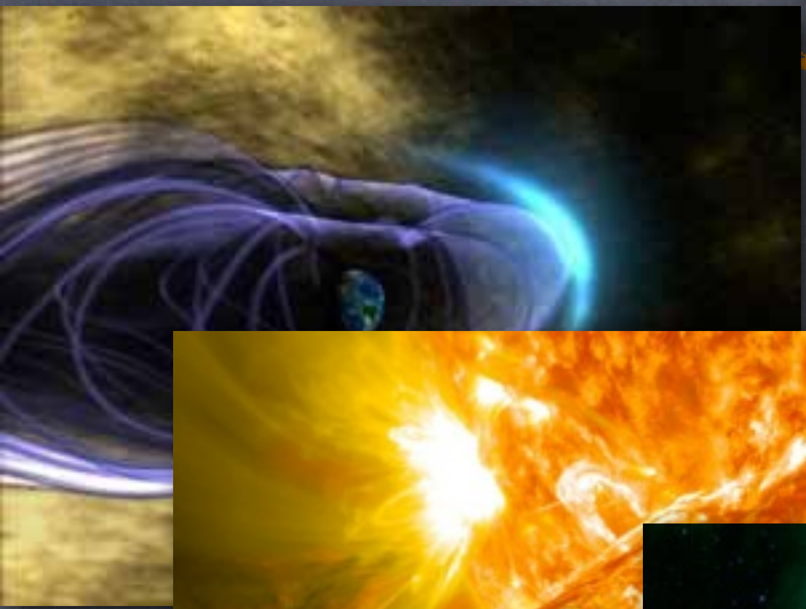
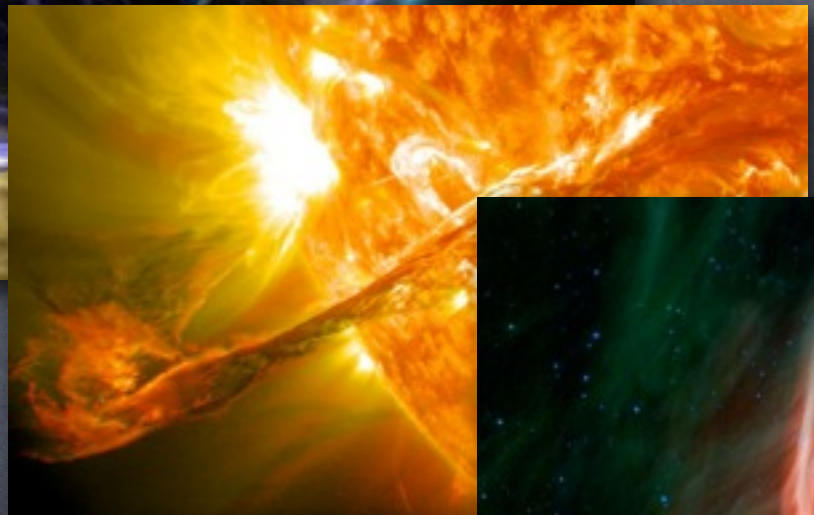


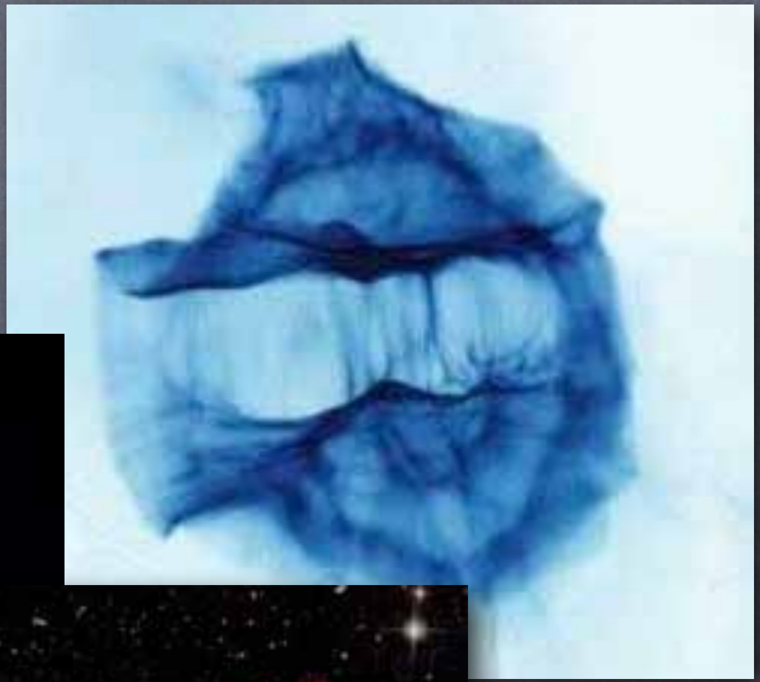
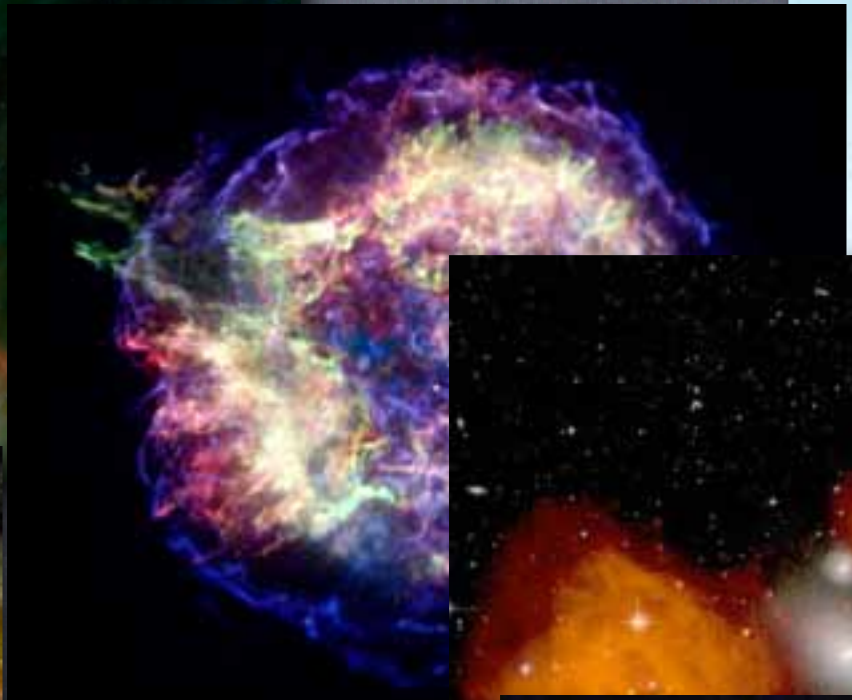

**BUT**

- Is acceleration at shocks efficient?
- How do CRs amplify the magnetic field?
- When is acceleration efficient?
- How are ions and electrons injected?

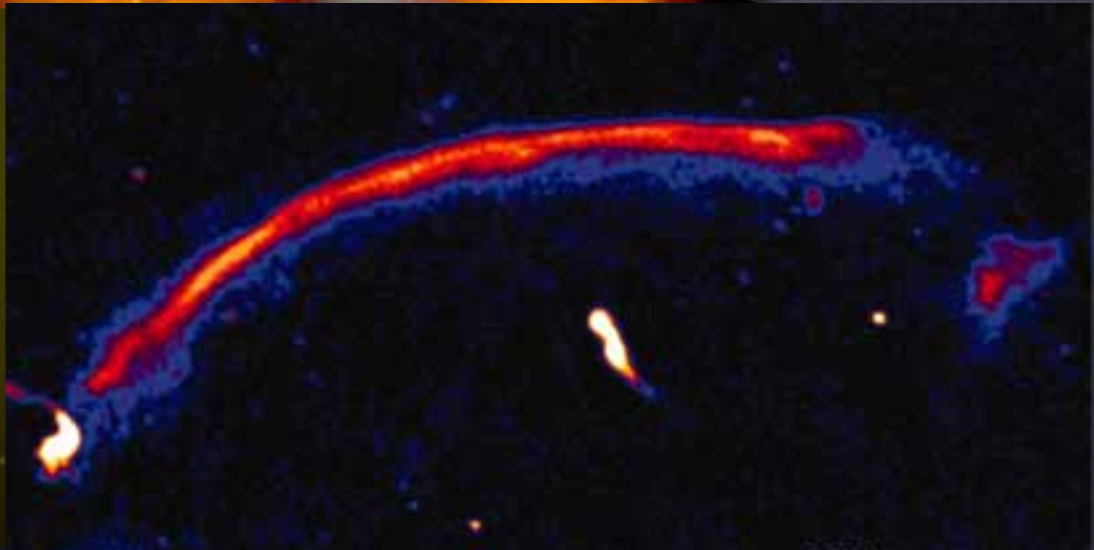
# Collisionless shocks

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

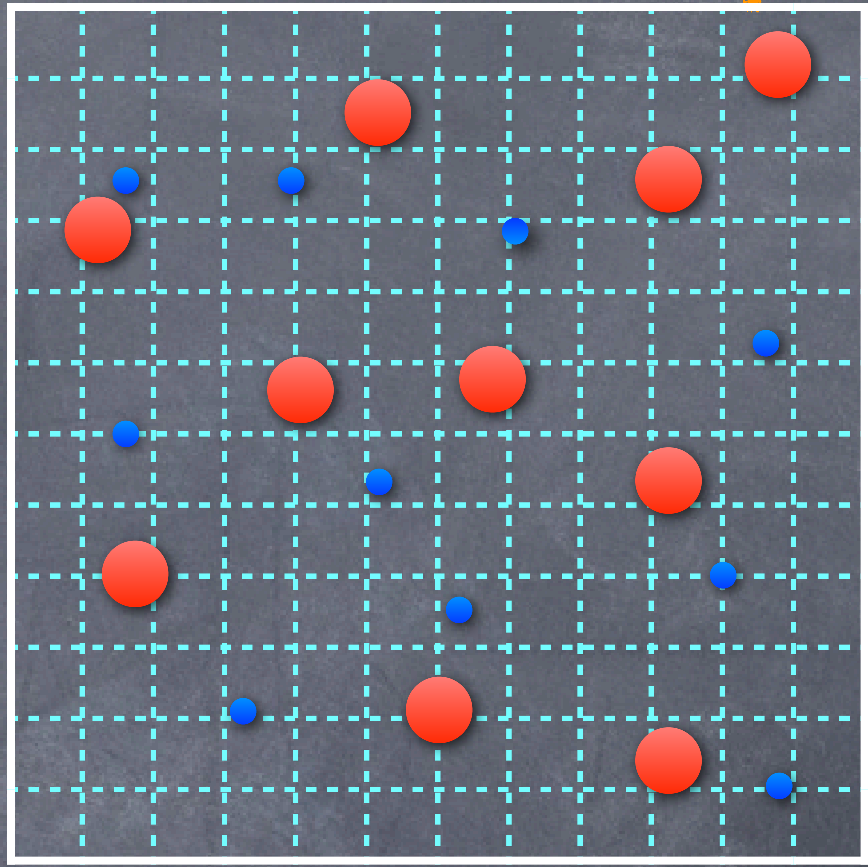





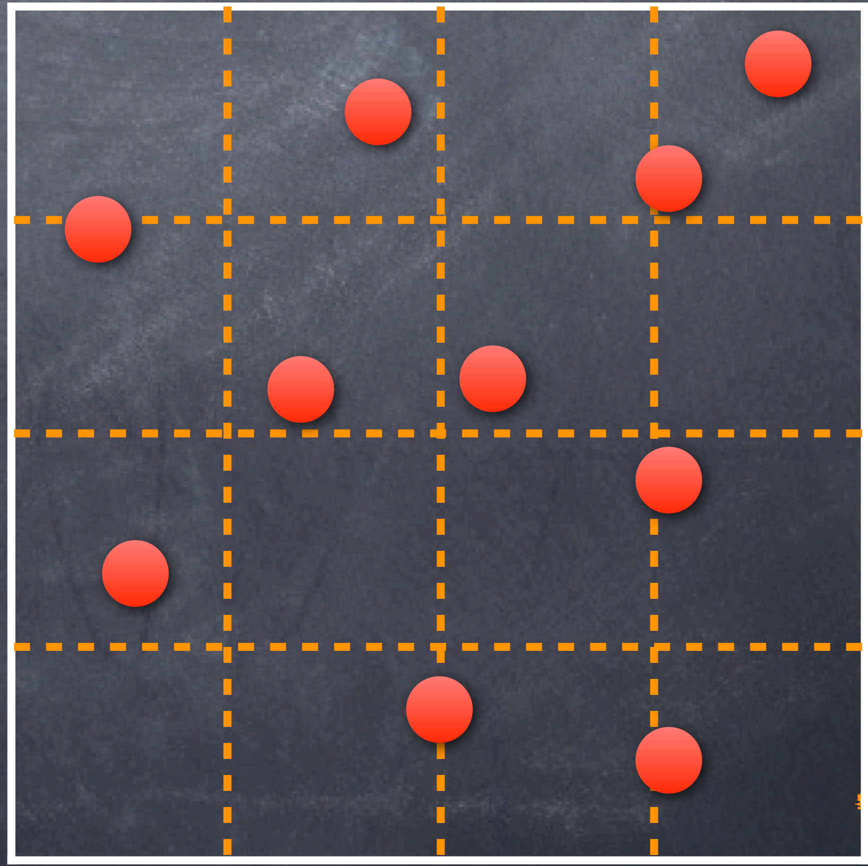



# Acceleration from first principles

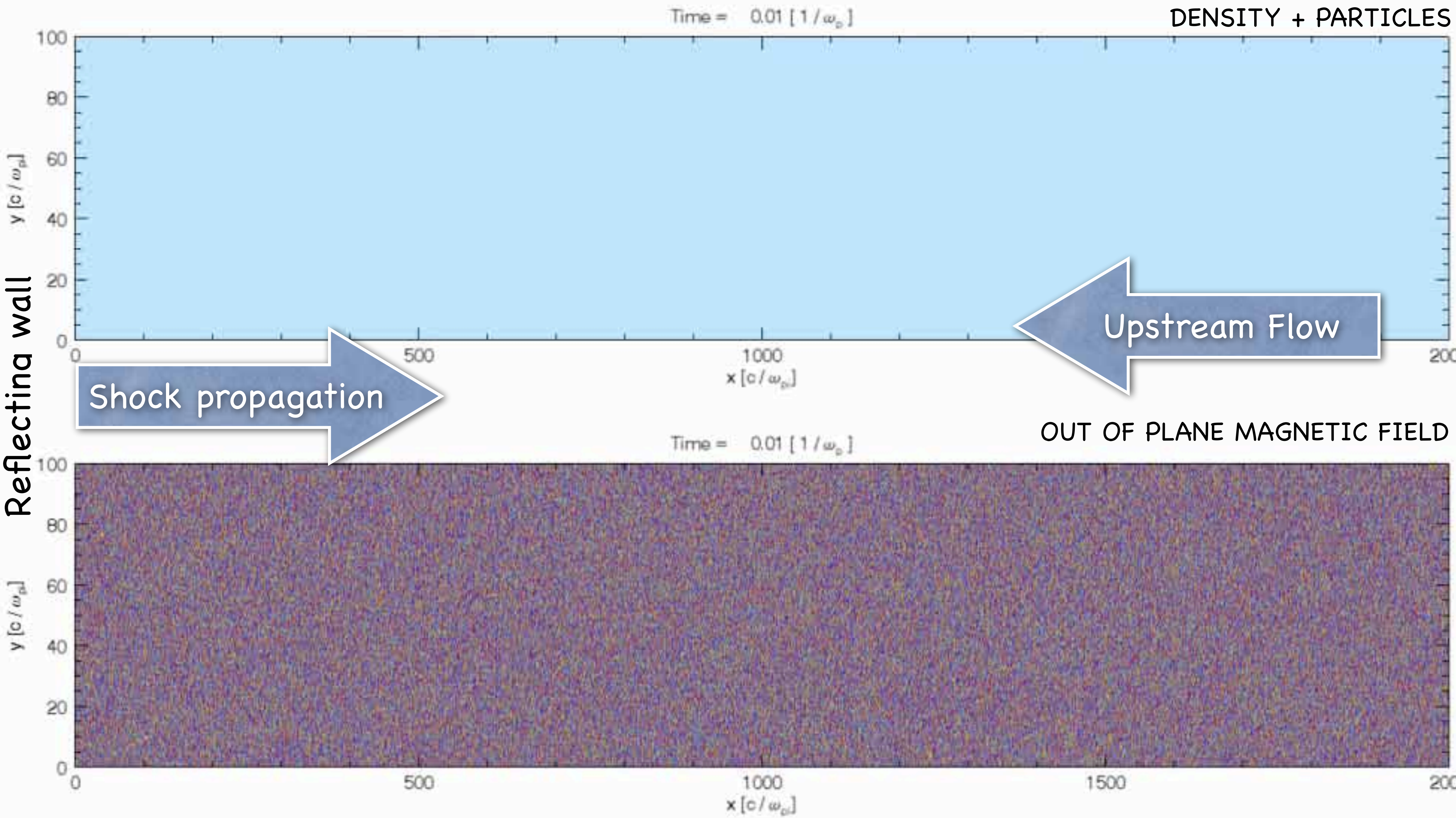
- Full particle in cell approach
  (..., Spitkovsky 2008, Niemiec+2008, Stroman+2009, Riquelme & Spitkovsky 2010, Sironi & Spitkovsky 2011, Park+2012,2015, Niemiec+2012, Guo+2014, DC+15...)
  - Define electromagnetic field on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - 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



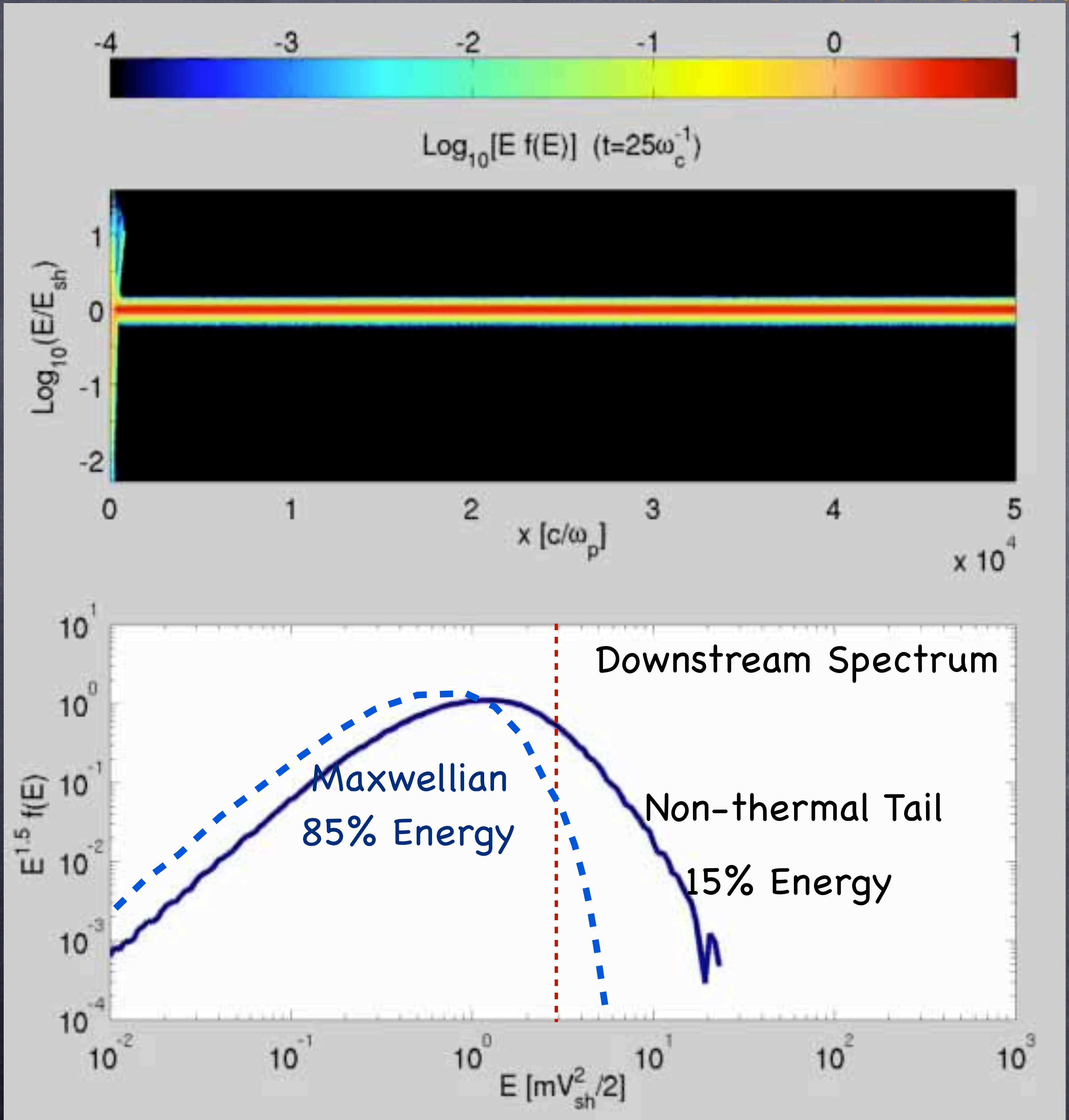
# Hybrid simulations of collisionless shocks




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

Initial B field

# Spectrum evolution




First-order Fermi acceleration:

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

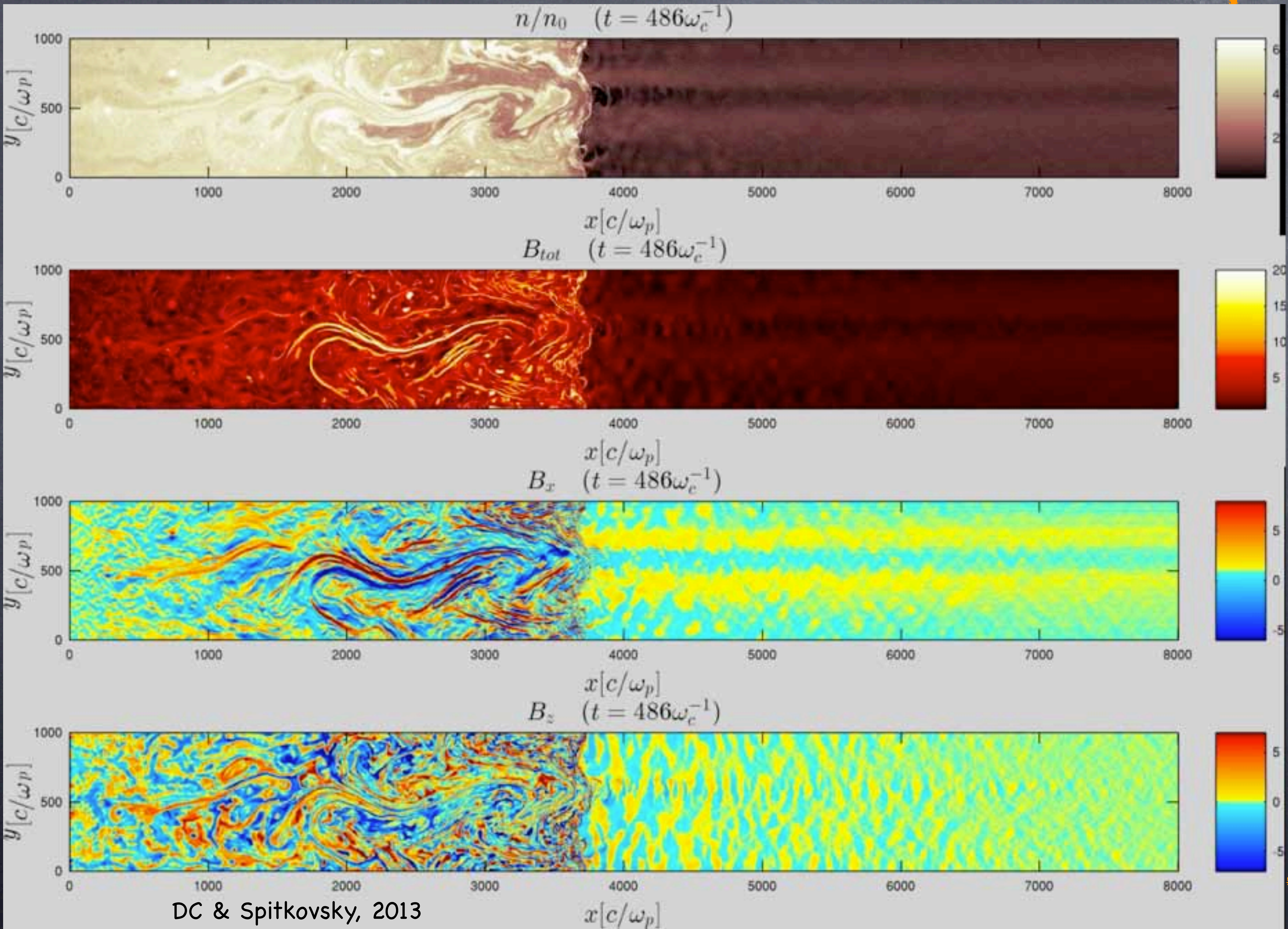
$4\pi p^2 f(p)dp = f(E)dE$

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

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

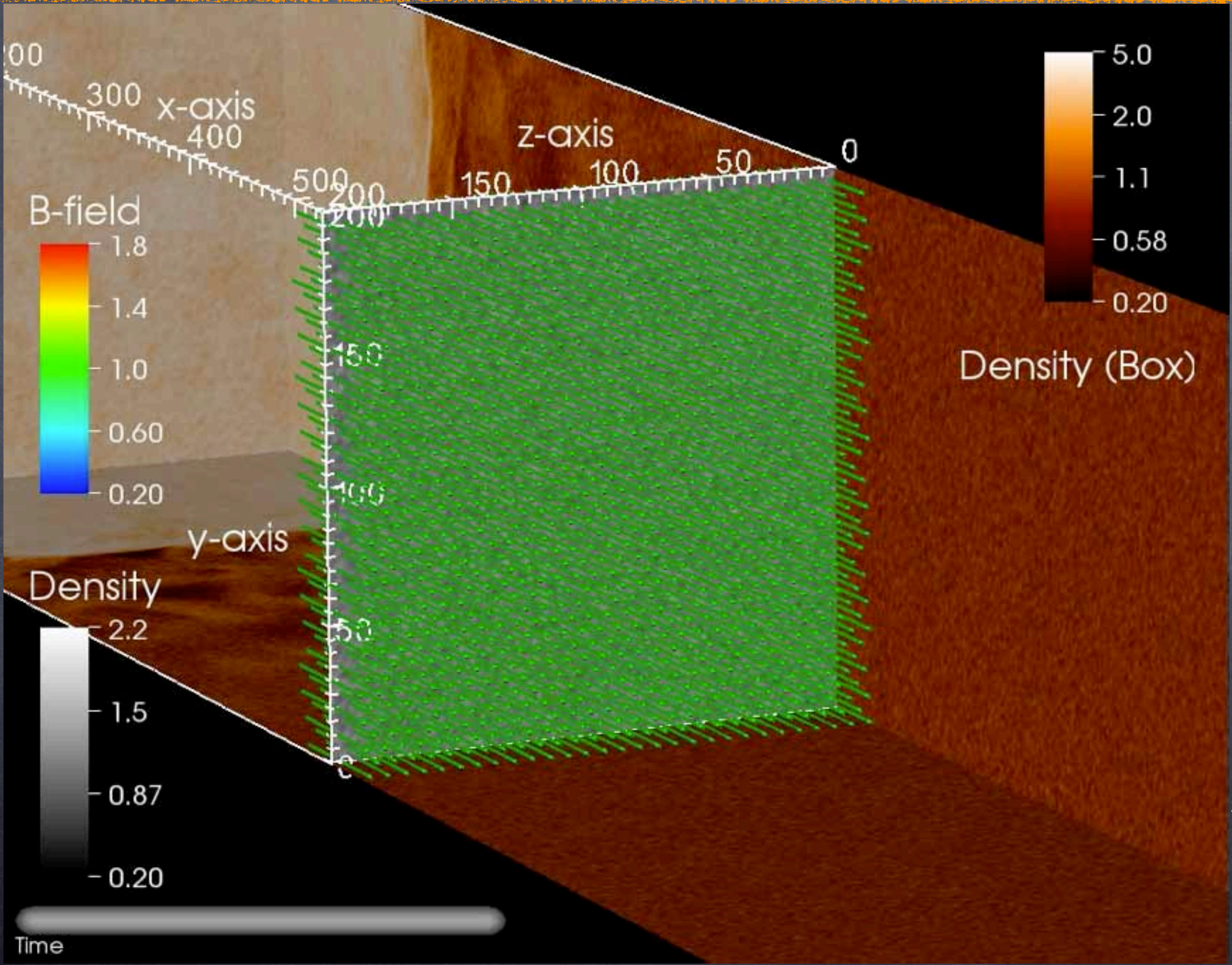
DC & Spitkovsky, 2014a

# Filamentation instability




DC & Spitkovsky, 2013

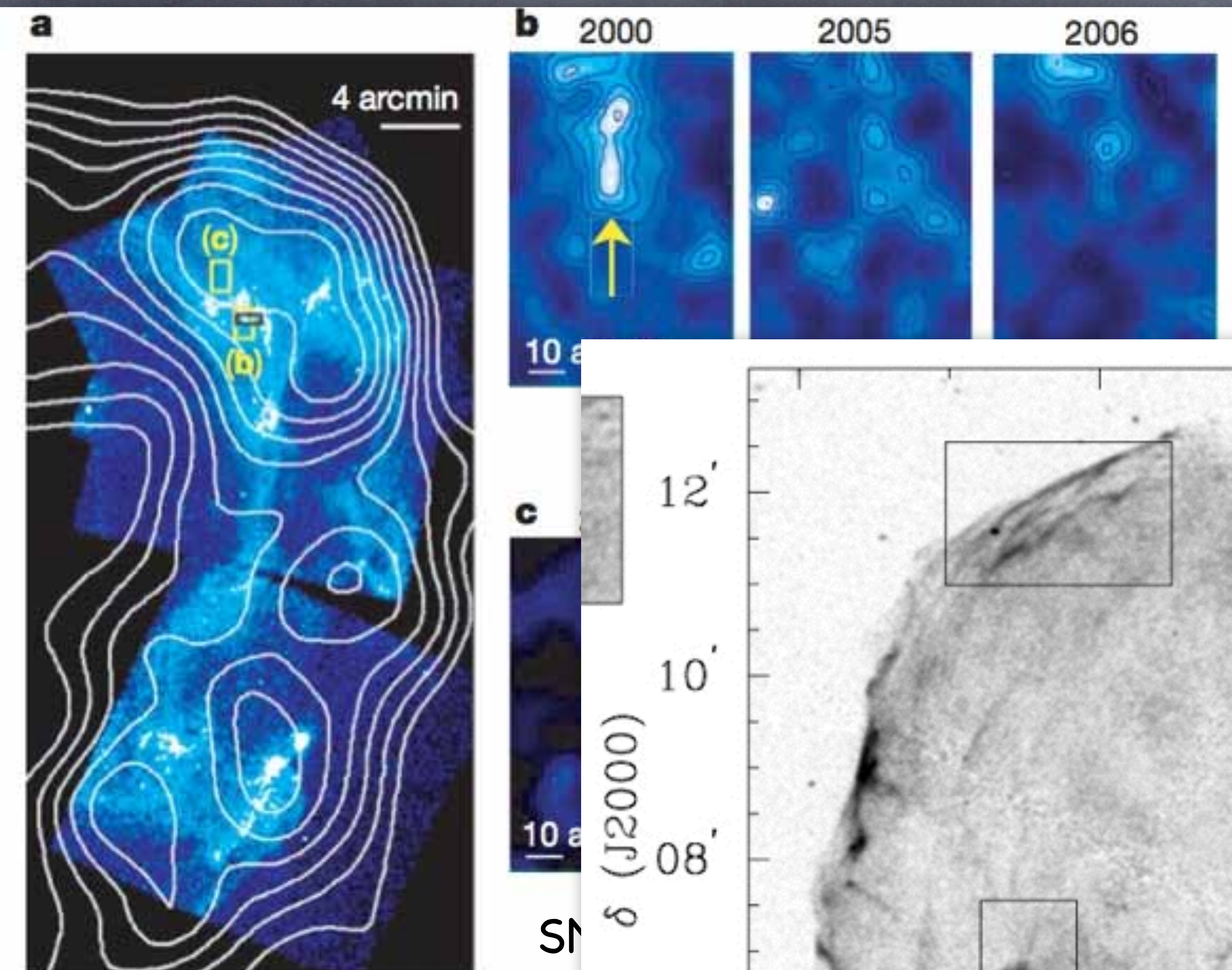
# 3D simulations of a parallel shock



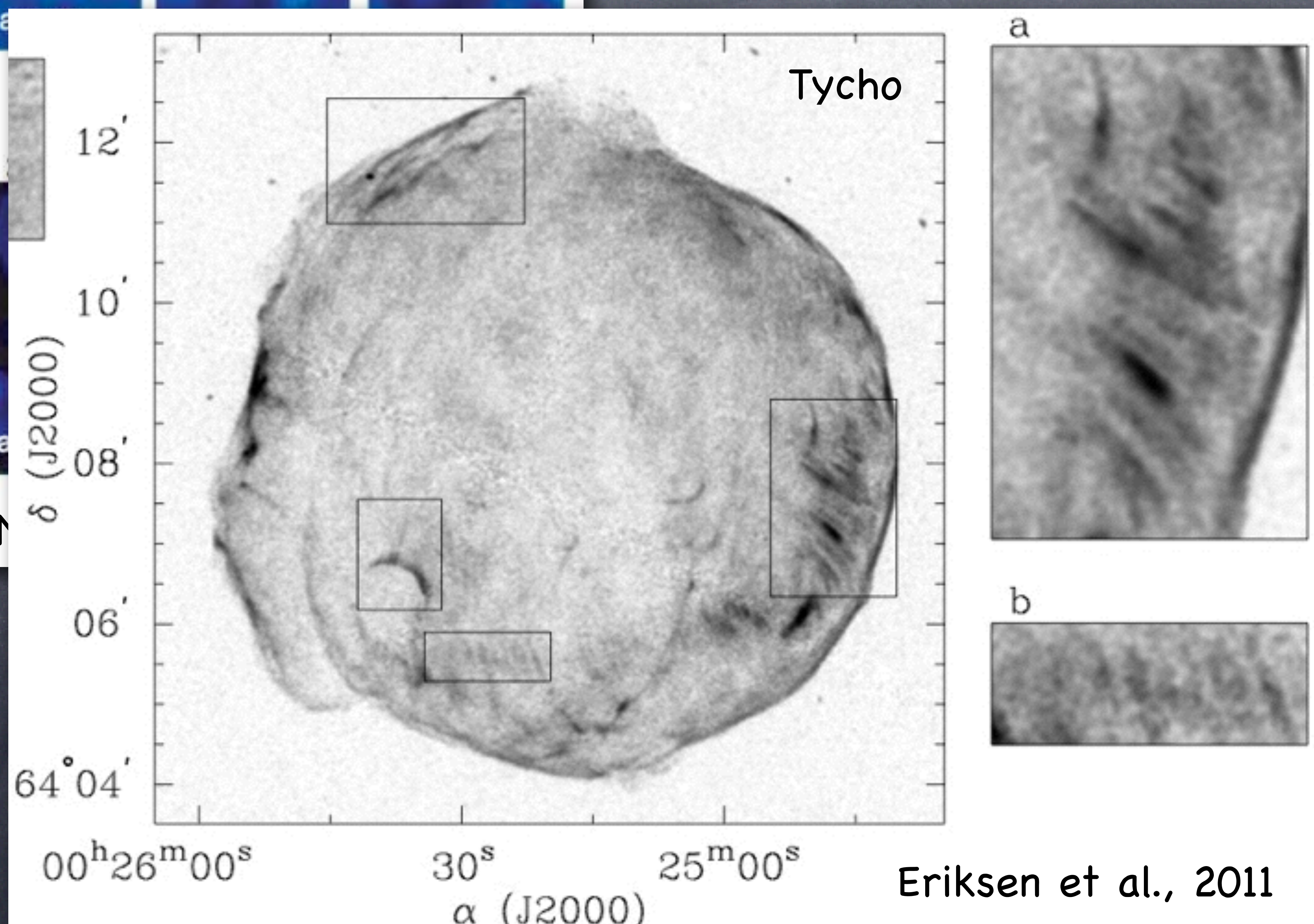

DC & Spitkovsky, 2014

# Knots and filaments

- Knots $\delta B/B \sim 100$
- Radial filaments

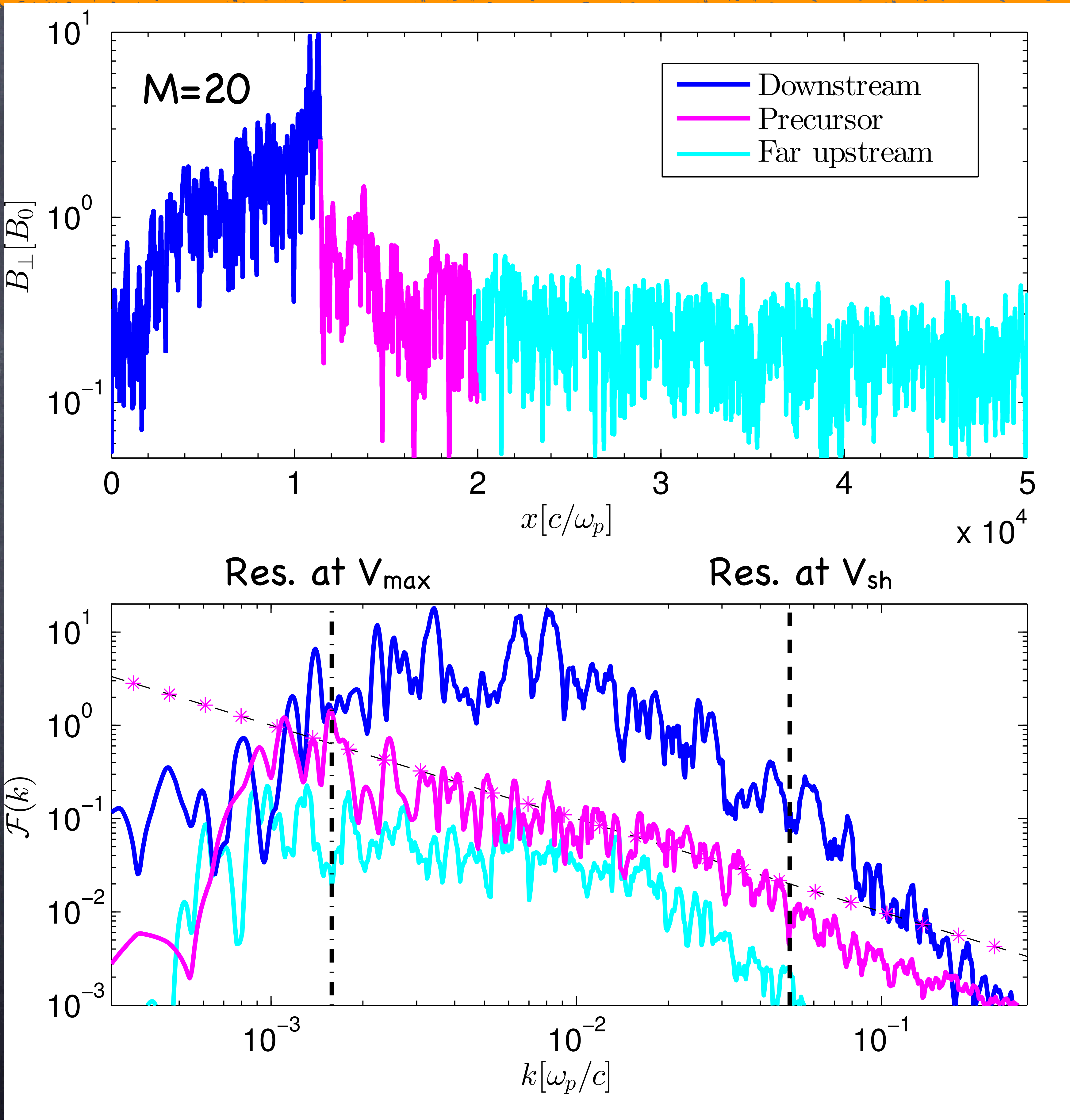



Uchiyama et al 2007




Eriksen et al., 2011

# Magnetic field spectrum



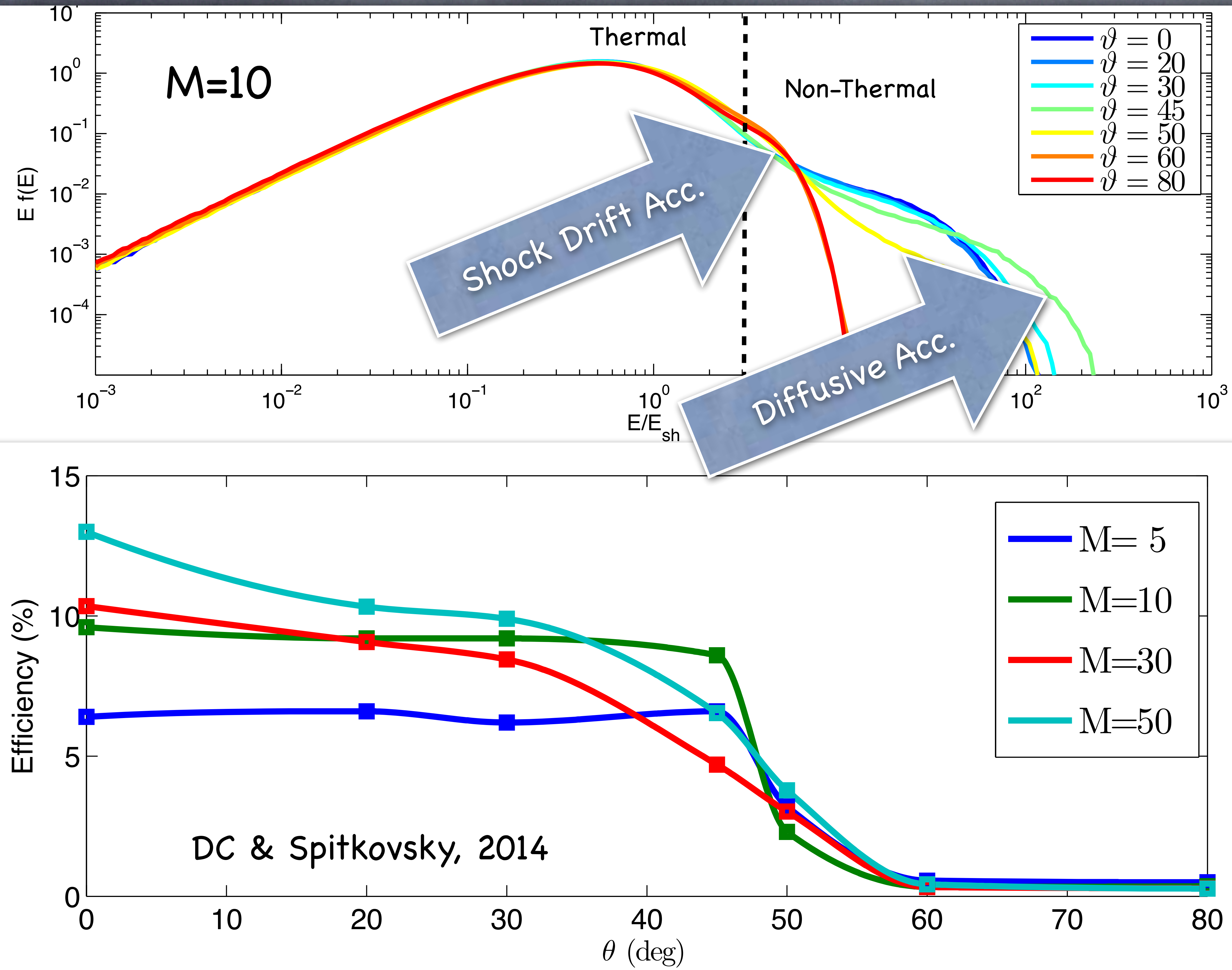

Magnetic energy density per unit logarithmic band-width, F(k)

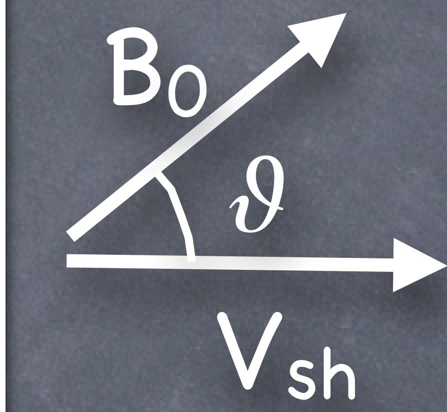
$$\frac{B_\perp^2}{8\pi} = \frac{B_0^2}{8\pi}\int_{k_{min}}^{k_{max}} \frac{dk}{k}\mathcal{F}(k)$$

- $F(k) \propto k^{-1}$ for $\omega_c/V_{max} < k < \omega_c/V_{sh}$
- Turbulence self-generated by a spectrum $\propto p^{-4}$

DC & Spitkovsky, 2014b

# Parallel vs Oblique shocks



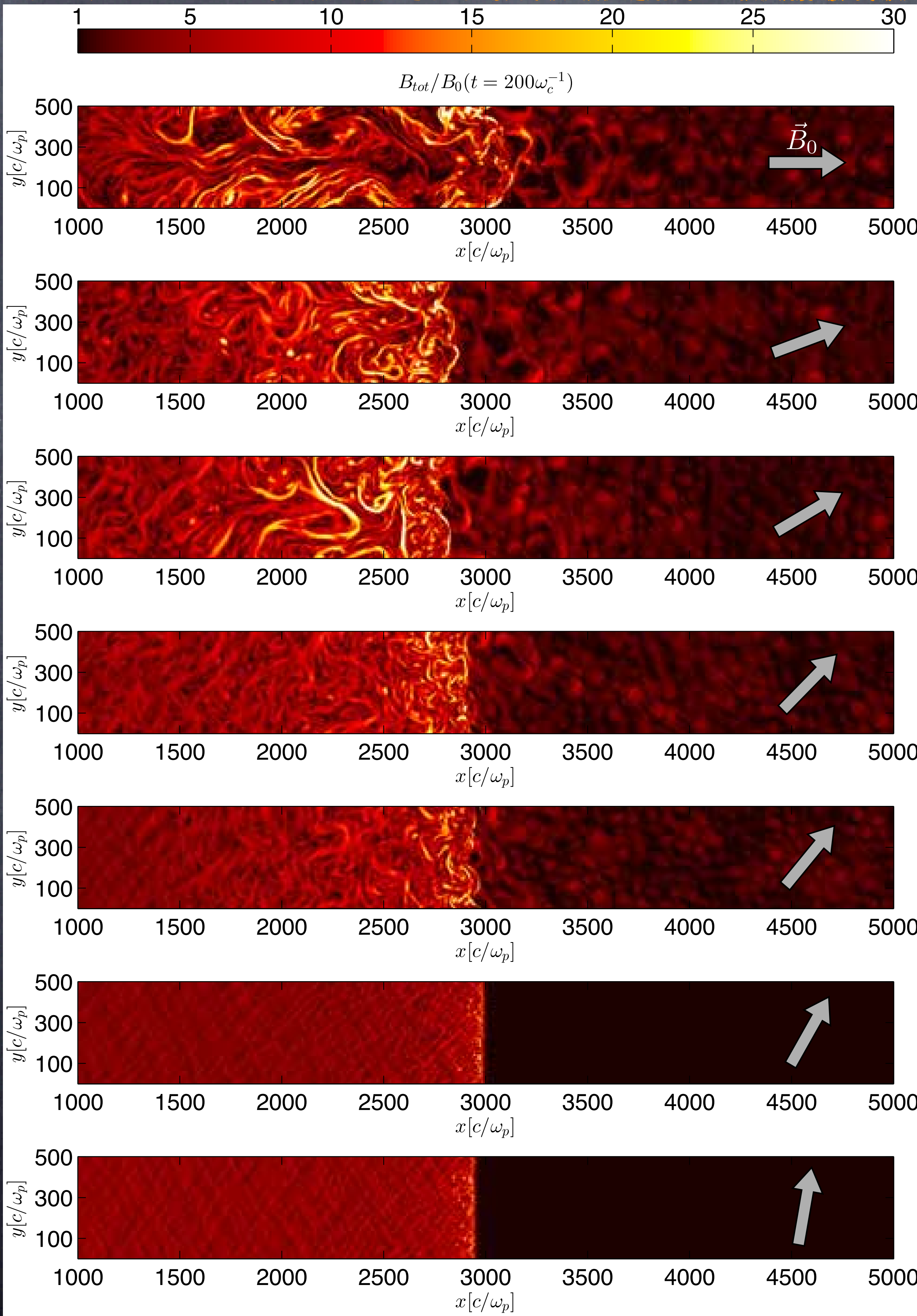



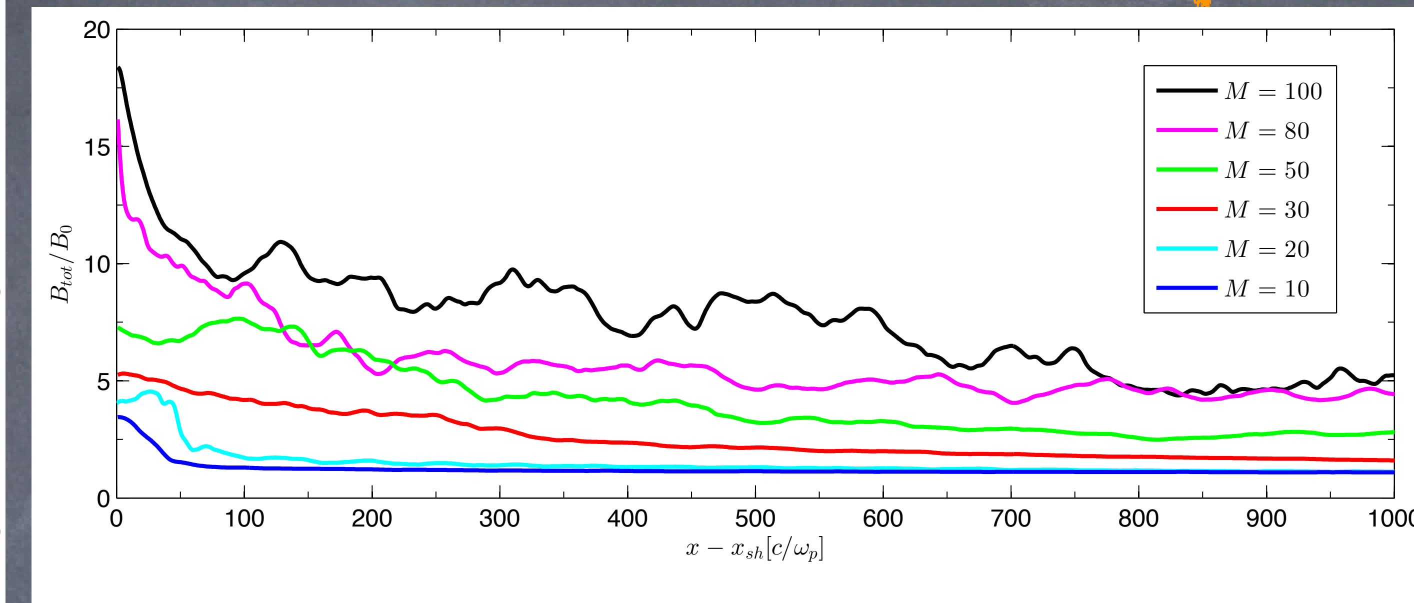

Each point corresponds to a simulation with about $10^9$ particles

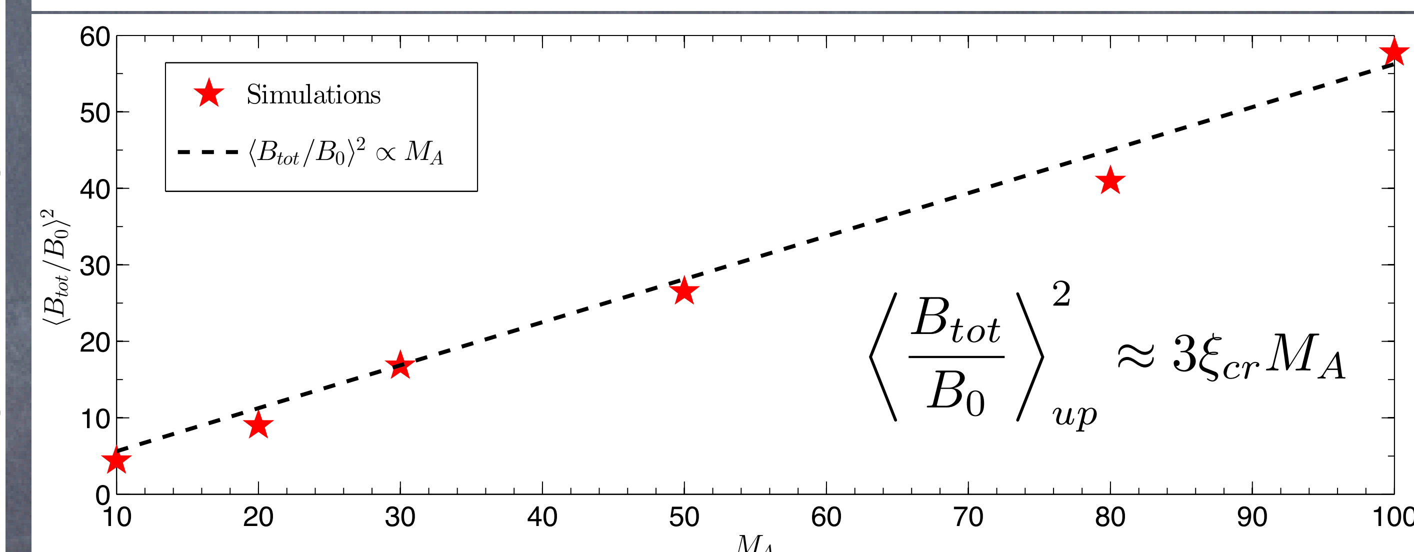
Computation time: almost

$2x10^6$ cpu h

# Dependence on inclination and M



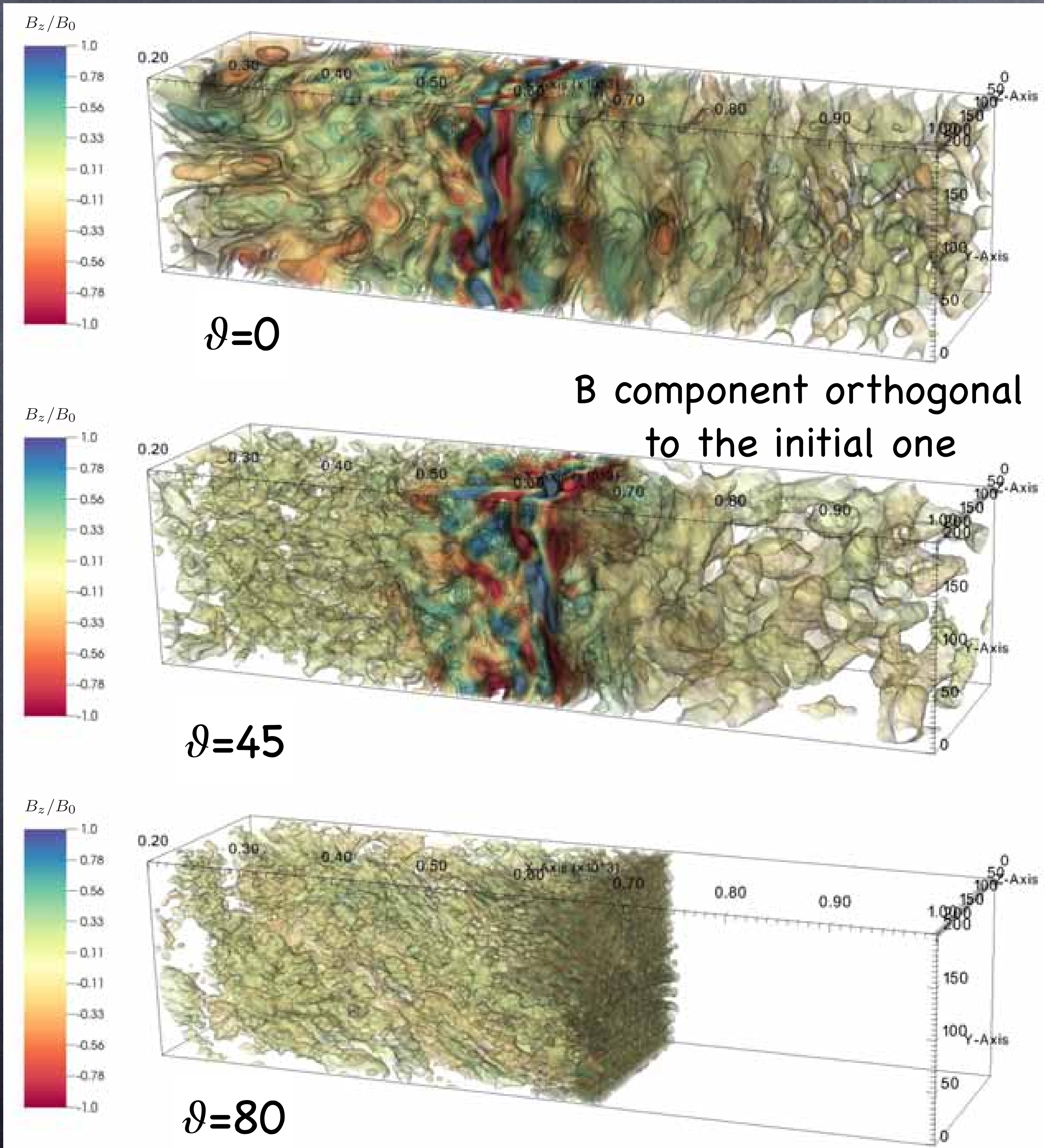



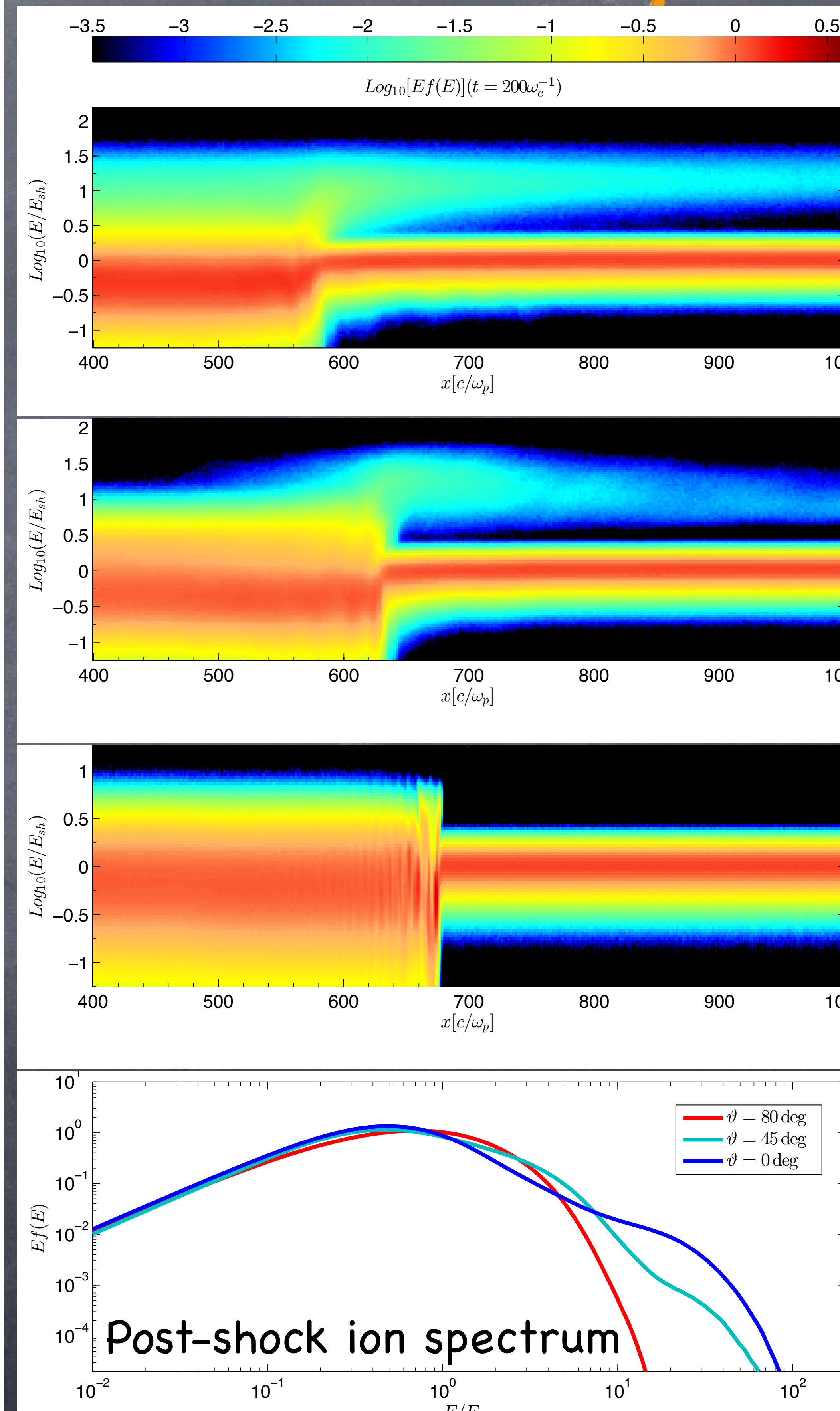




- In agreement with the prediction of resonant streaming instability

More B-field amplification for stronger shocks!

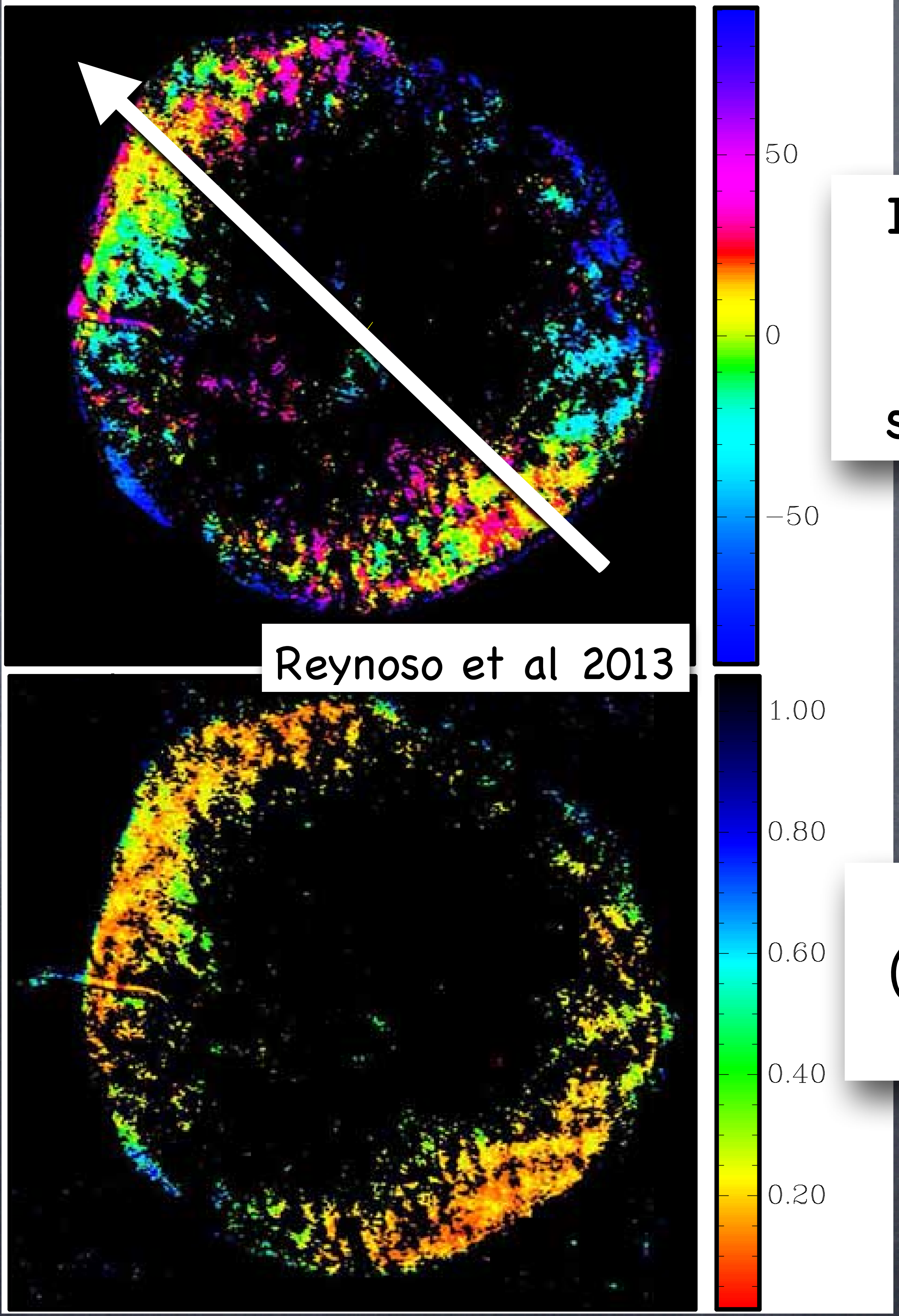
# 3D simulations



# SN 1006: a parallel accelerator

X-ray emission (red=thermal white=synchrotron)




Reynoso et al 2013

Inclination of the B field wrt to the shock normal

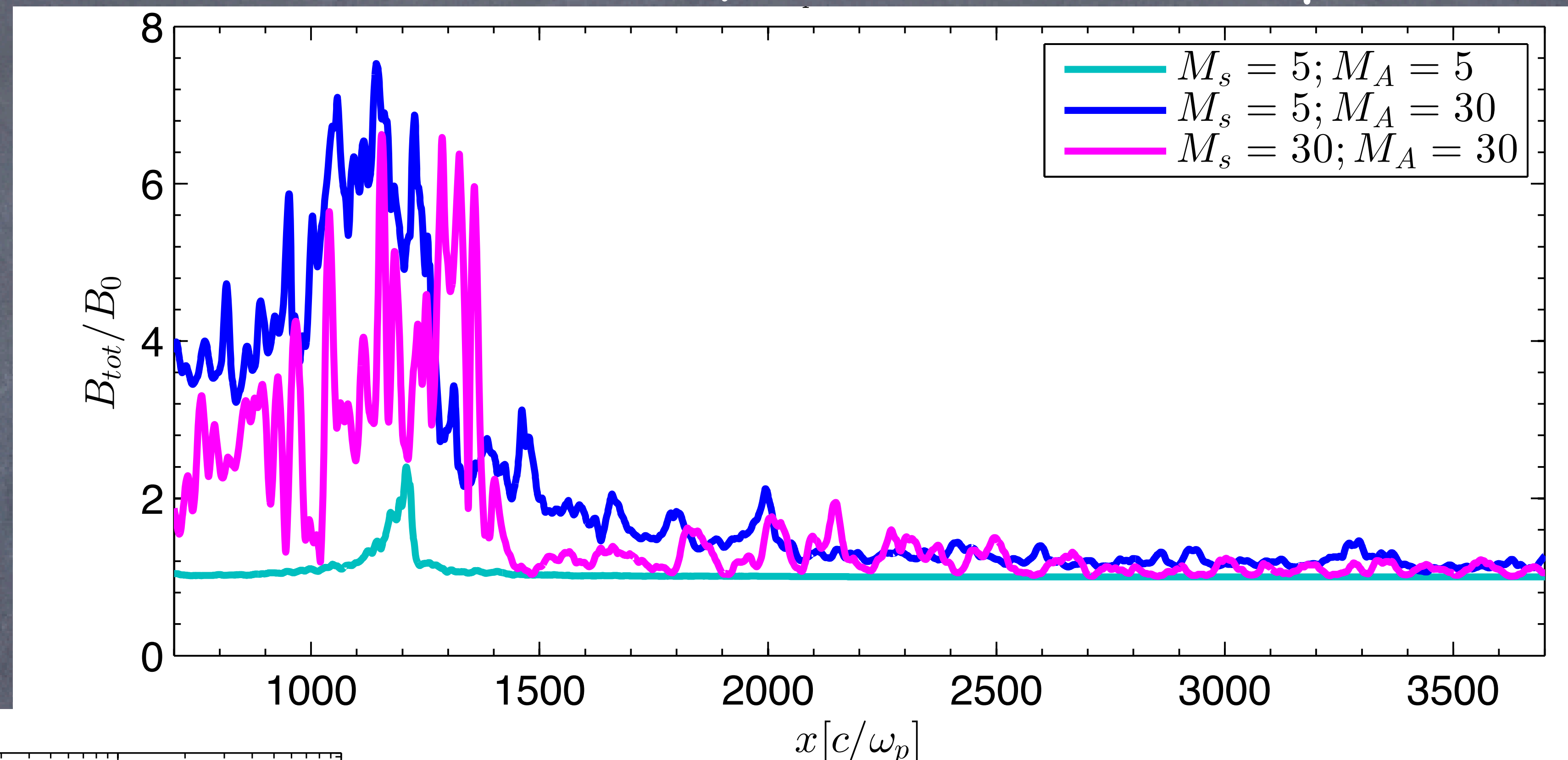
Polarization (low=turbulent high=ordered)

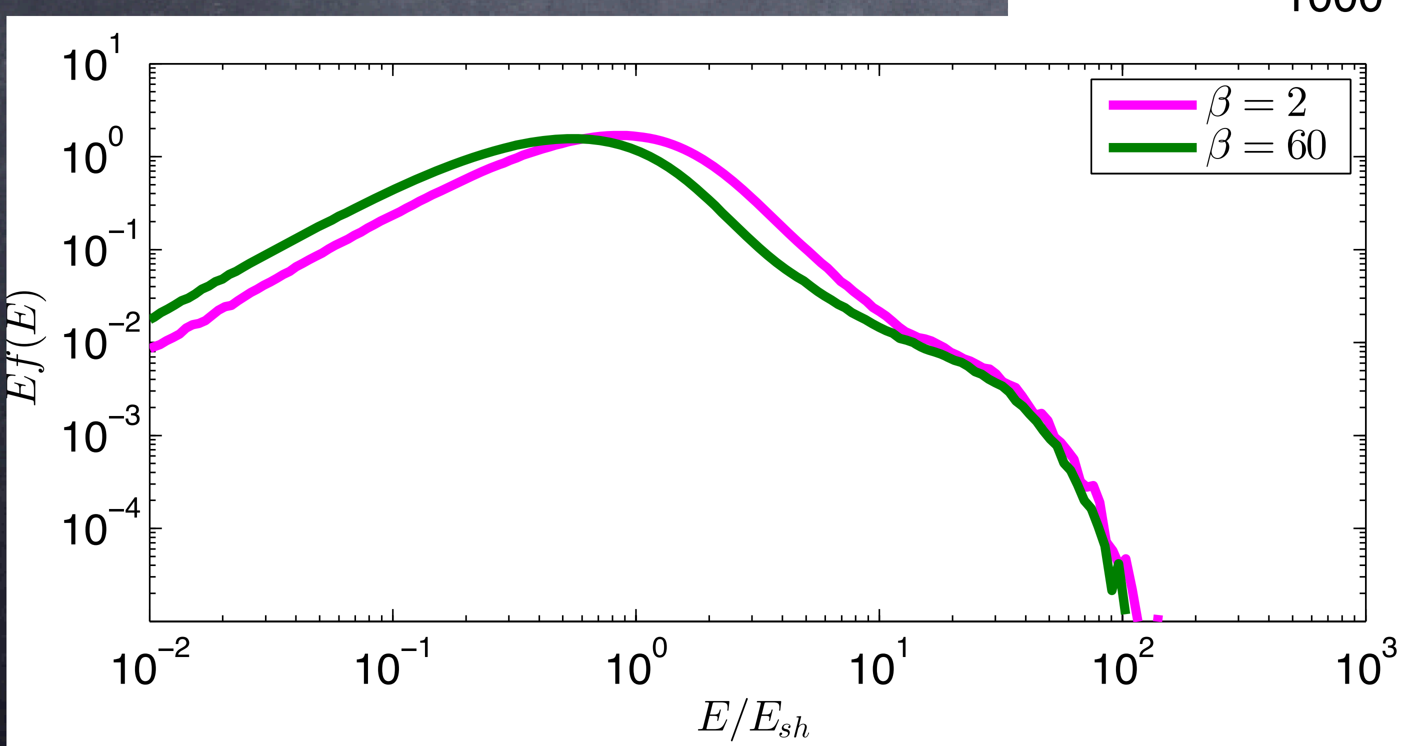
Magnetic field amplification and particle acceleration where the shock is parallel

# High-beta plasmas

- The Alfvènic Mach # controls magnetic field amplification
- The (magneto-)sonic Mach # controls shock dynamics and CR spectrum

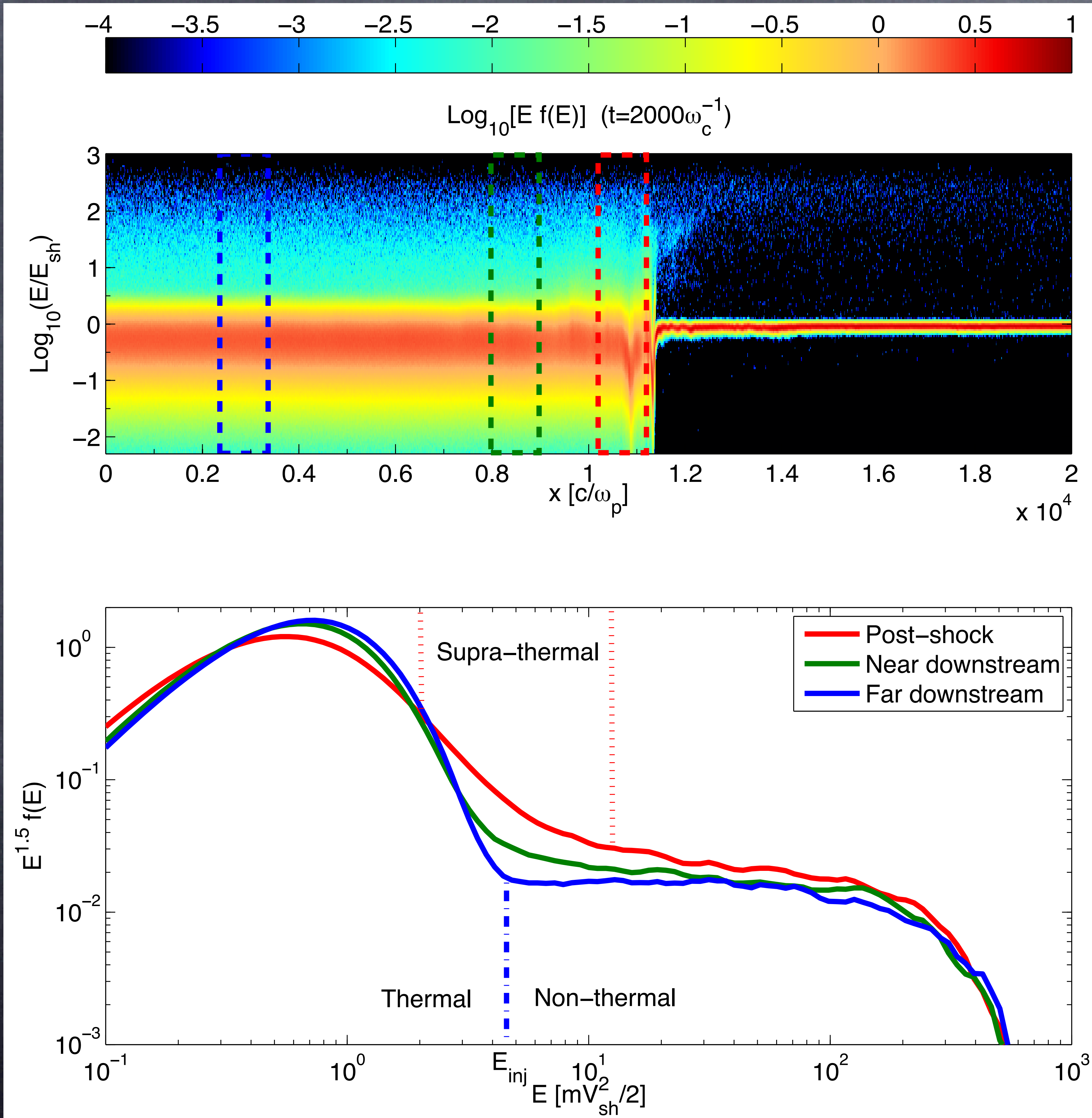
Magnetic fields are amplified also in high $\beta$ plasmas!




CR spectra agree with DSA prediction (steeper than $p^{-4}$ for r<4)

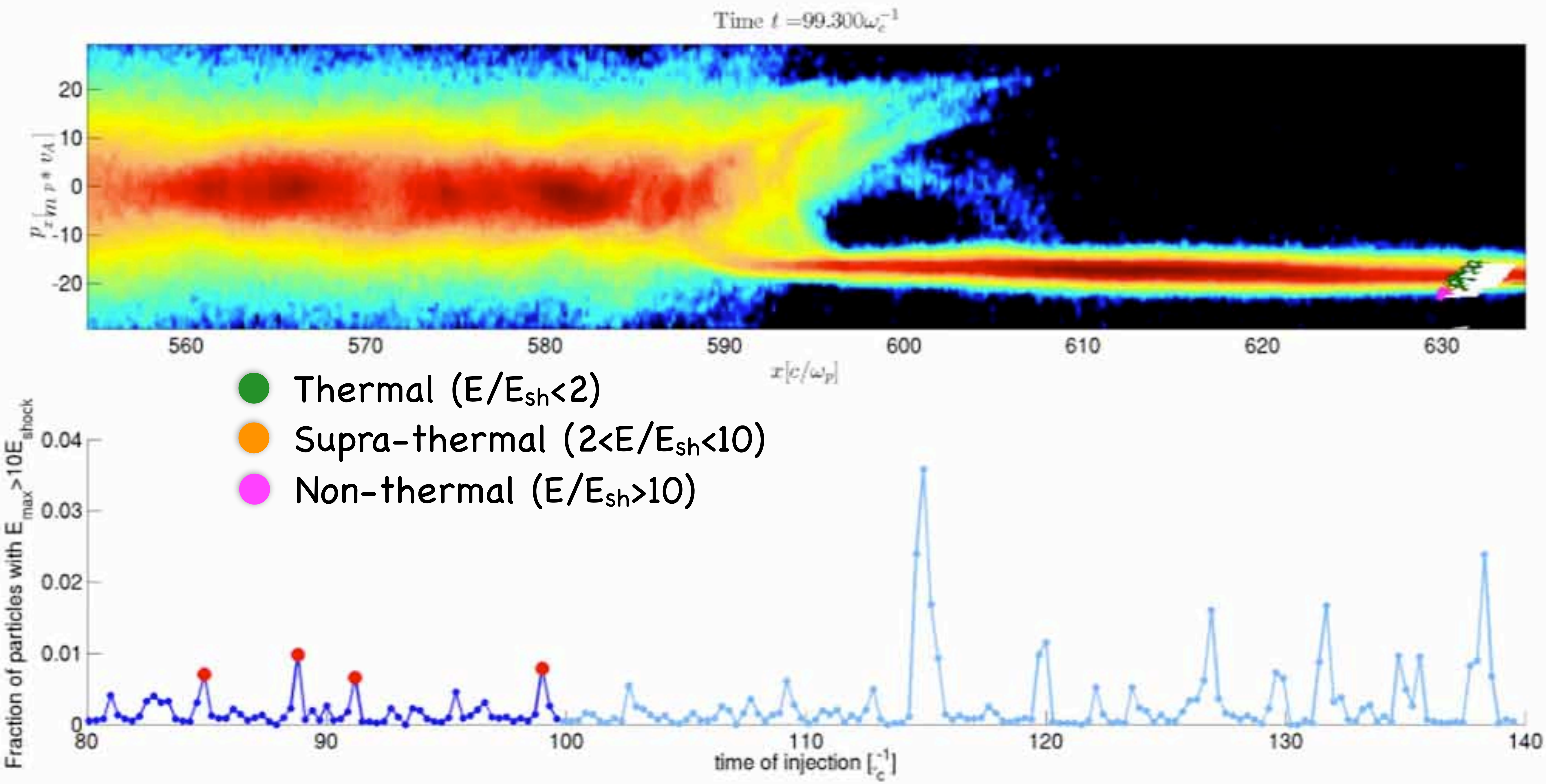
# Supra-thermal ions




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

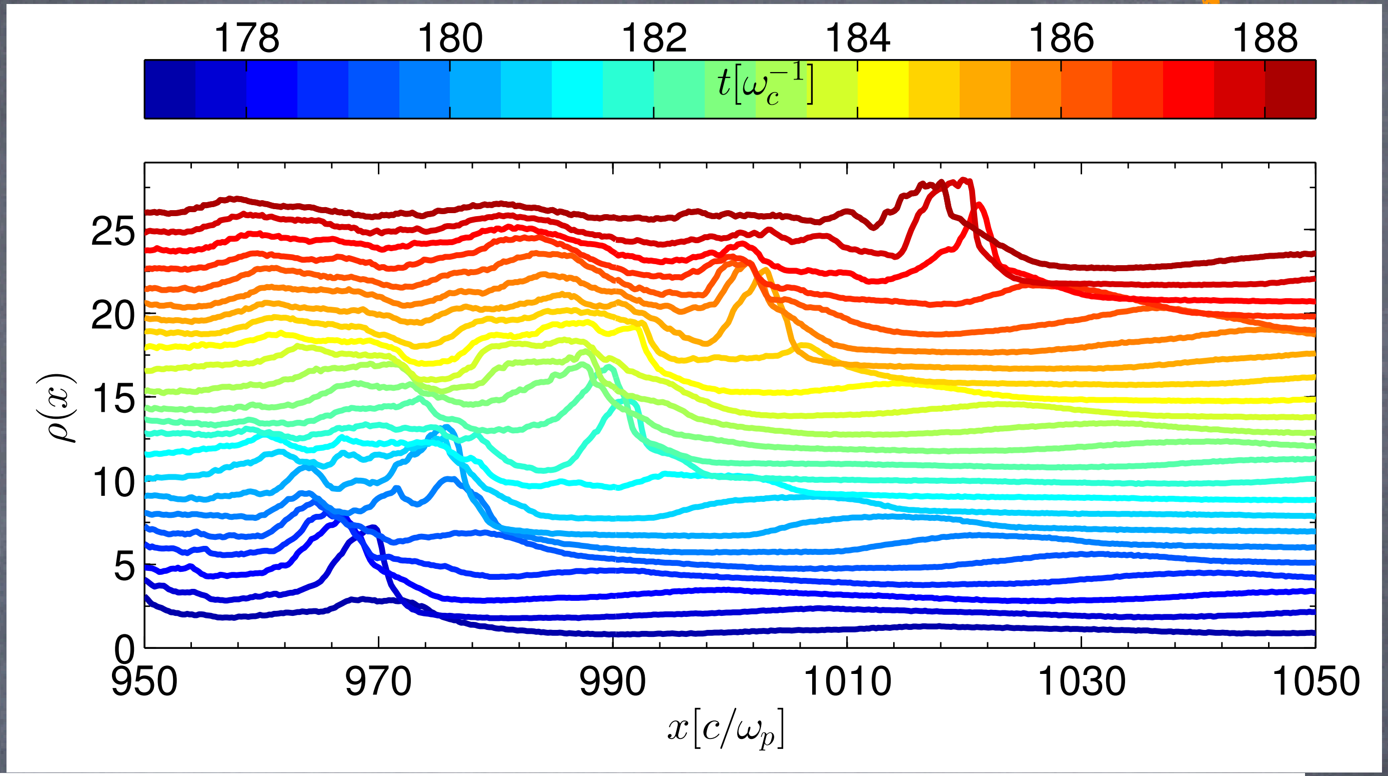
# Particle Injection - Simulations

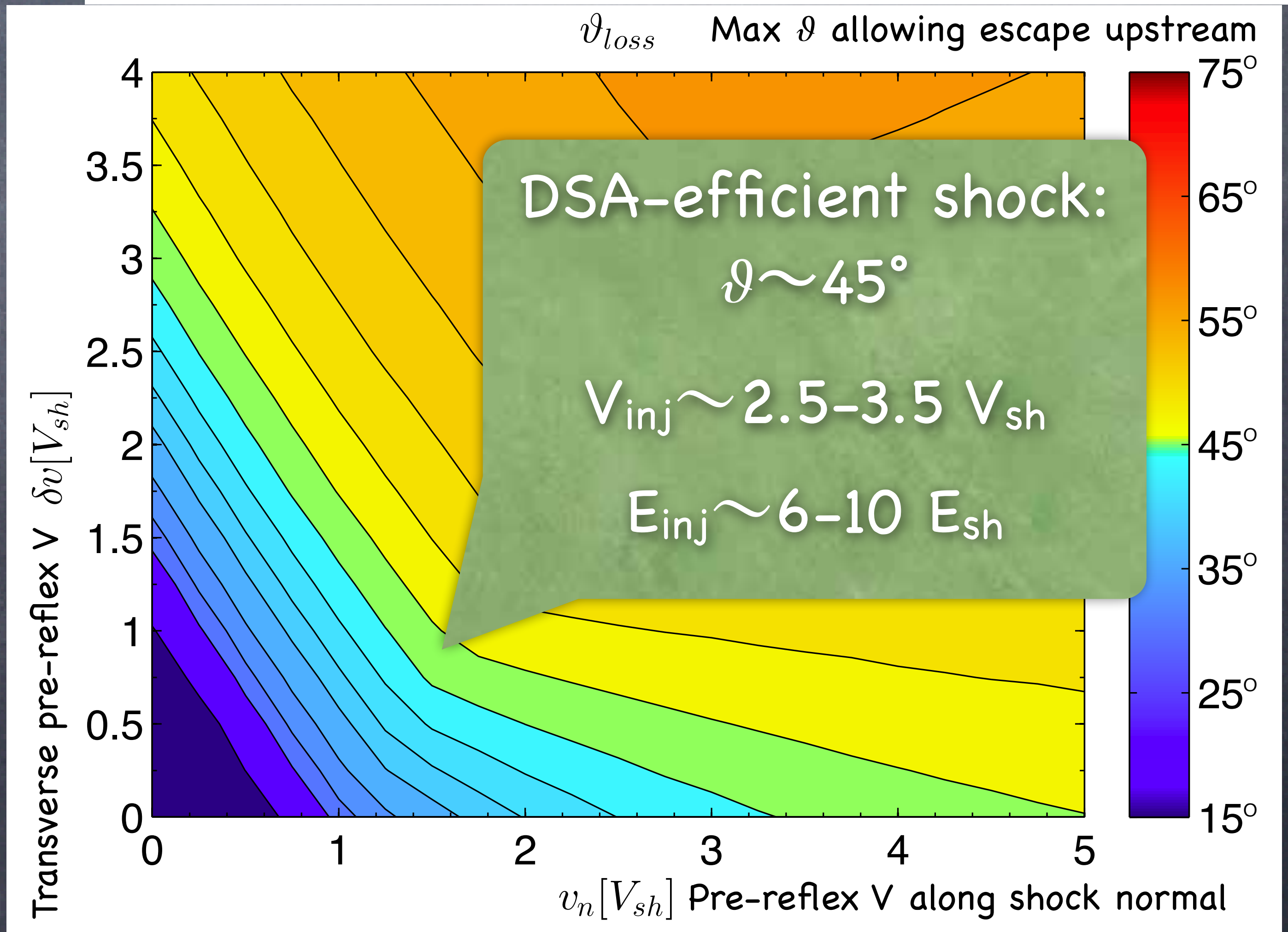
DC, Pop & Spitkovsky, 2015



# Ion Injection - Theory

- Reflection off a reforming shock potential barrier (stationary in the downstream frame)
- Calculate ion trajectories (de Hoffmann-Teller frame)
  - Ion fate determined by pre-reflection velocity and shock inclination
  - At given velocity, ion escape upstream of shocks with $\vartheta<\vartheta_{loss}$



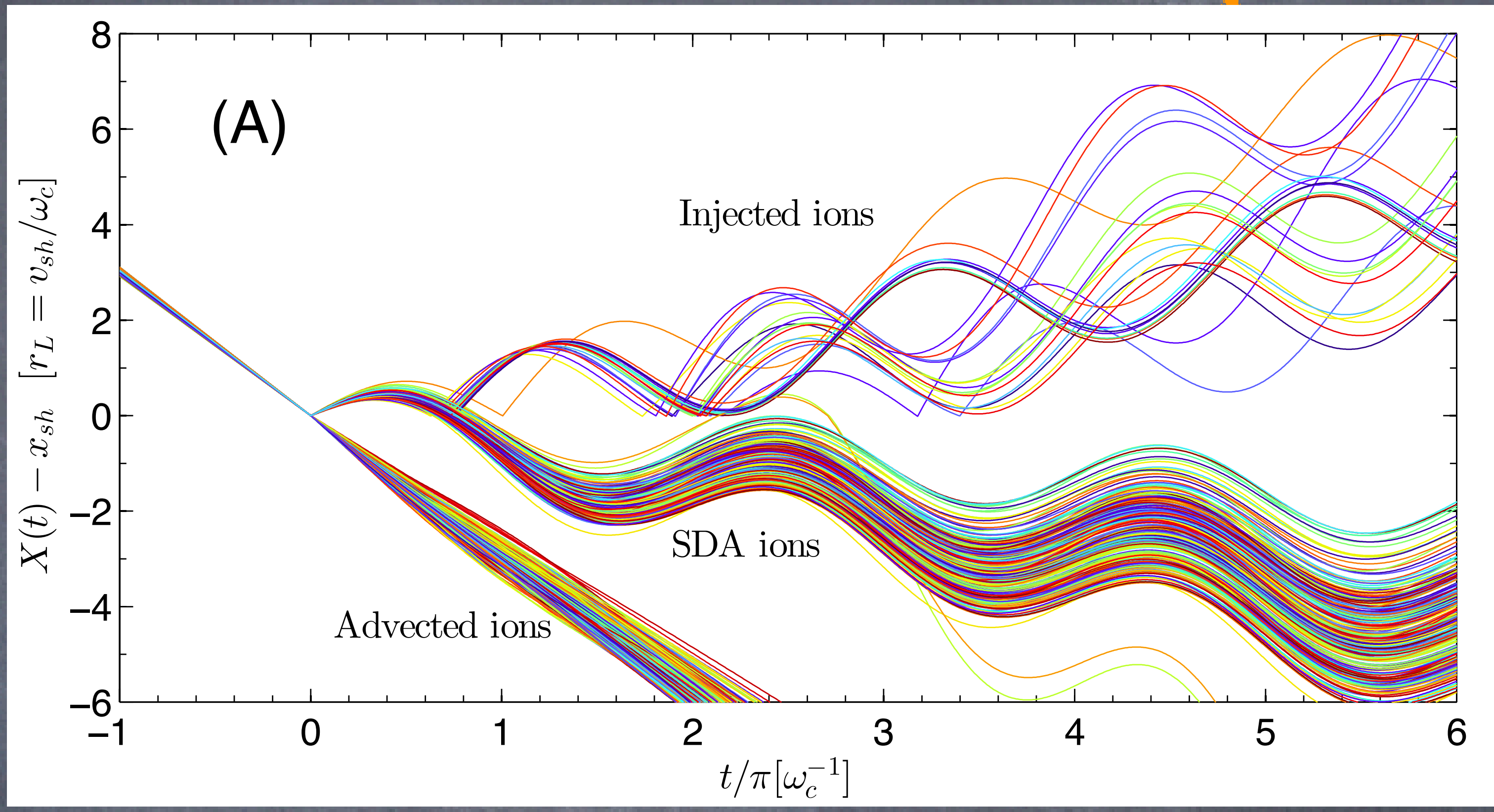



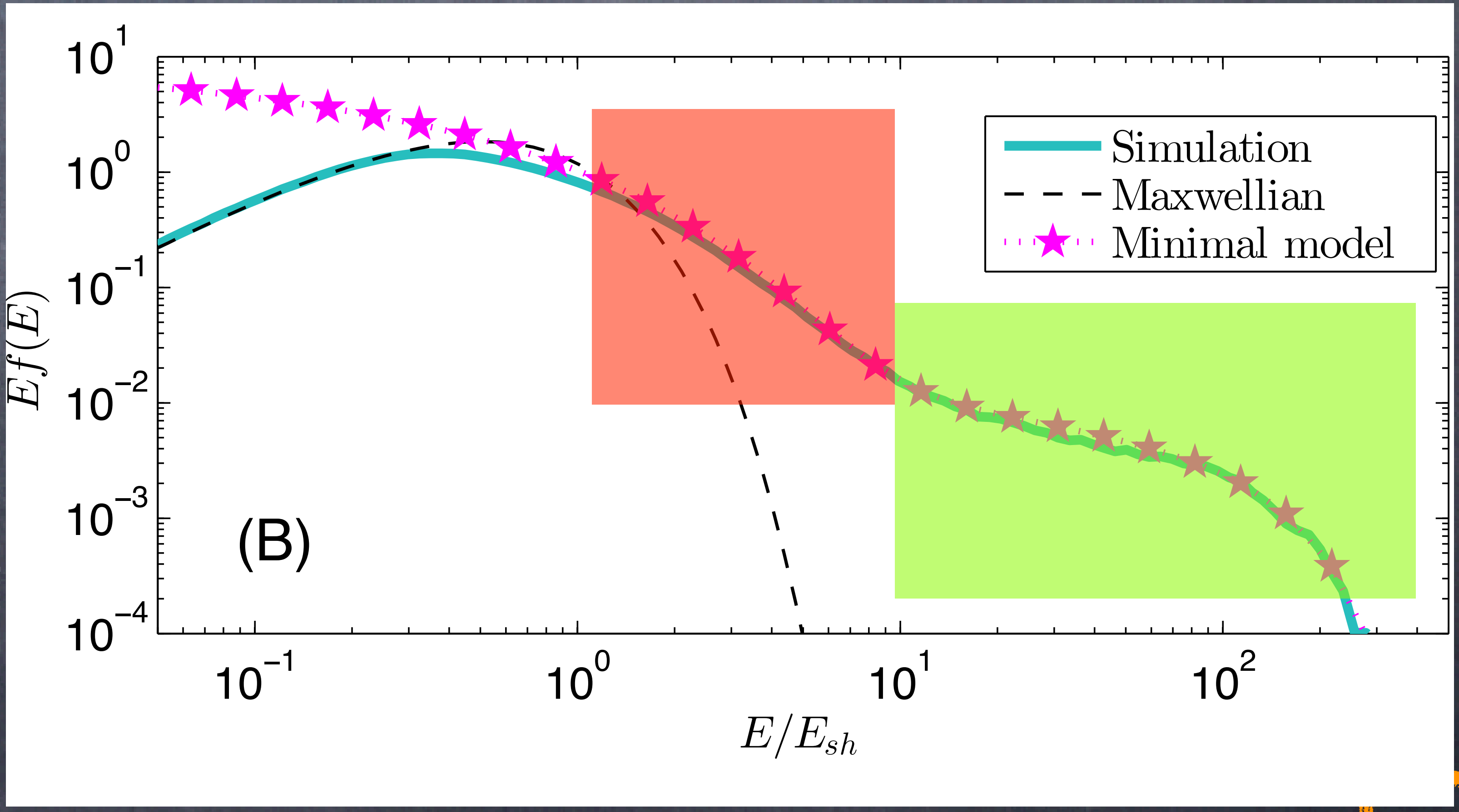
# Minimal Model for Ion Injection

- Time-varying potential barrier
  - **High state** (25% of the time)
    -> Reflection
    -> Shock Drift Acceleration
  - **Low-state** -> Thermalization
- Multiple cycles of SDA
- Spectrum à la Bell 1978

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

  - Supra-thermal
    - $P=0.75$; $\mathcal{E} = 2V_{sh}/v$
  - Non-thermal
    - $P=V_{sh}/v$; $\mathcal{E} = 2V_{sh}/v$

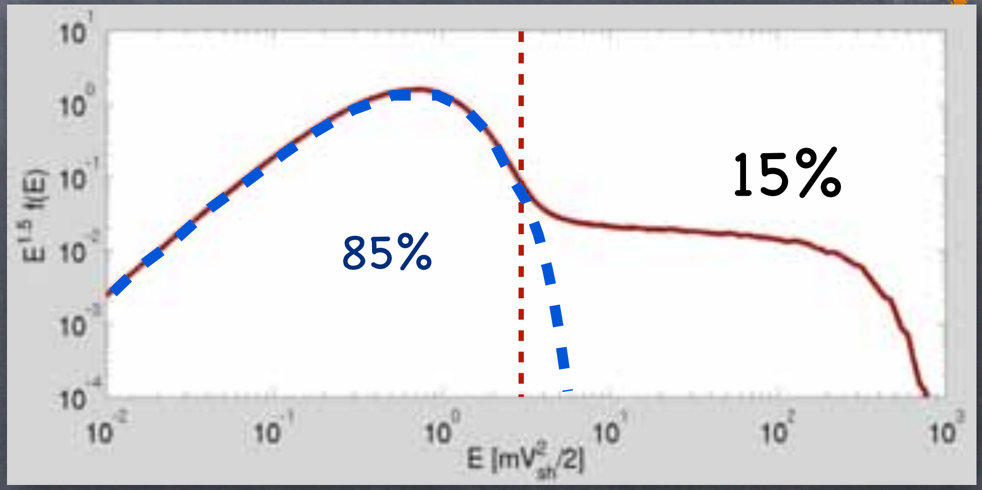


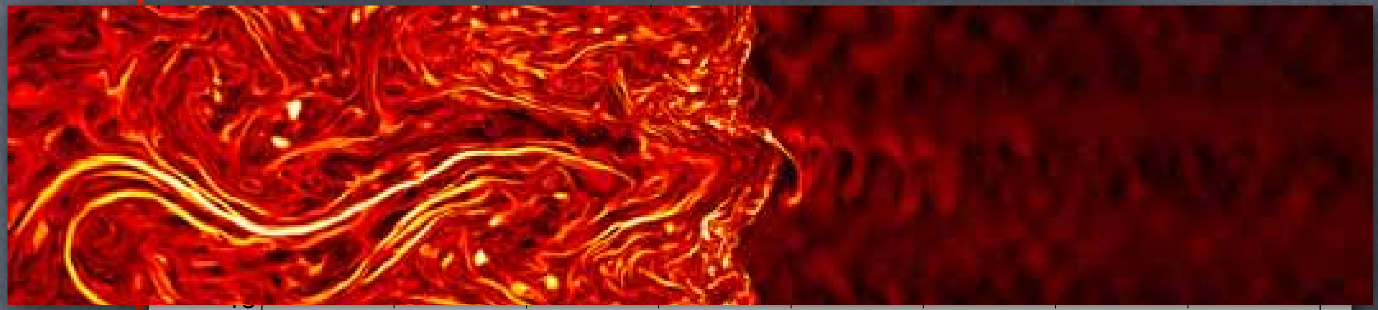



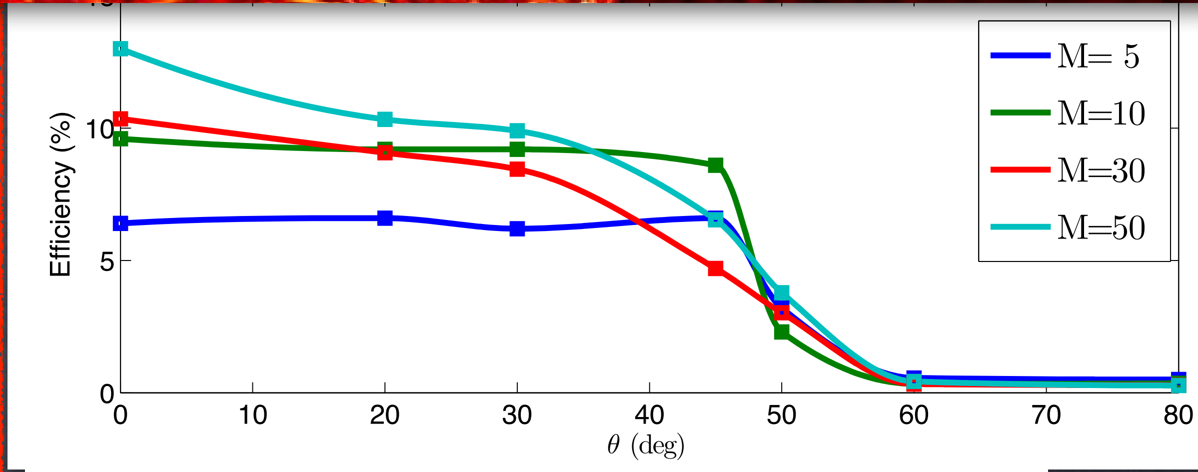

DC, Pop & Spitkovsky, 2015

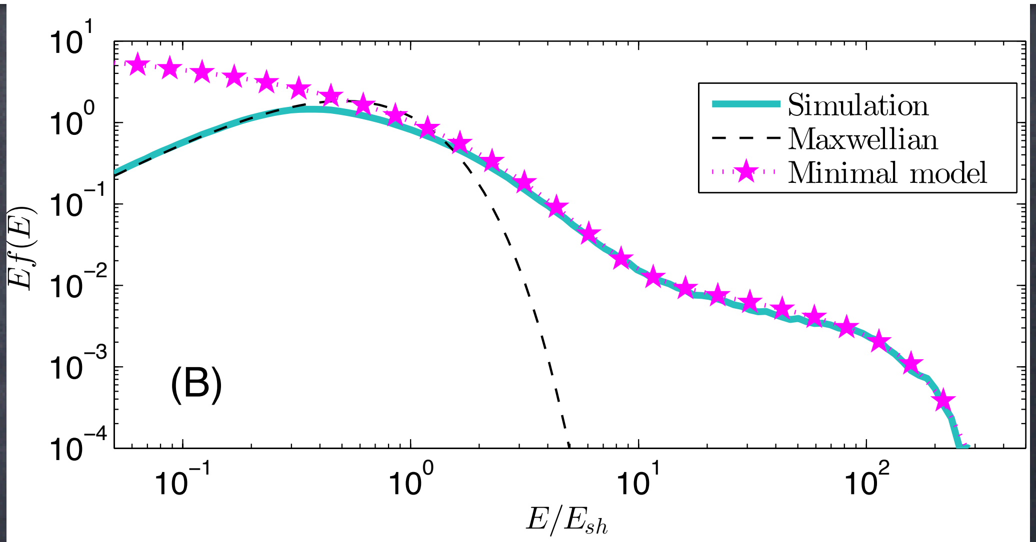
# Conclusions!

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



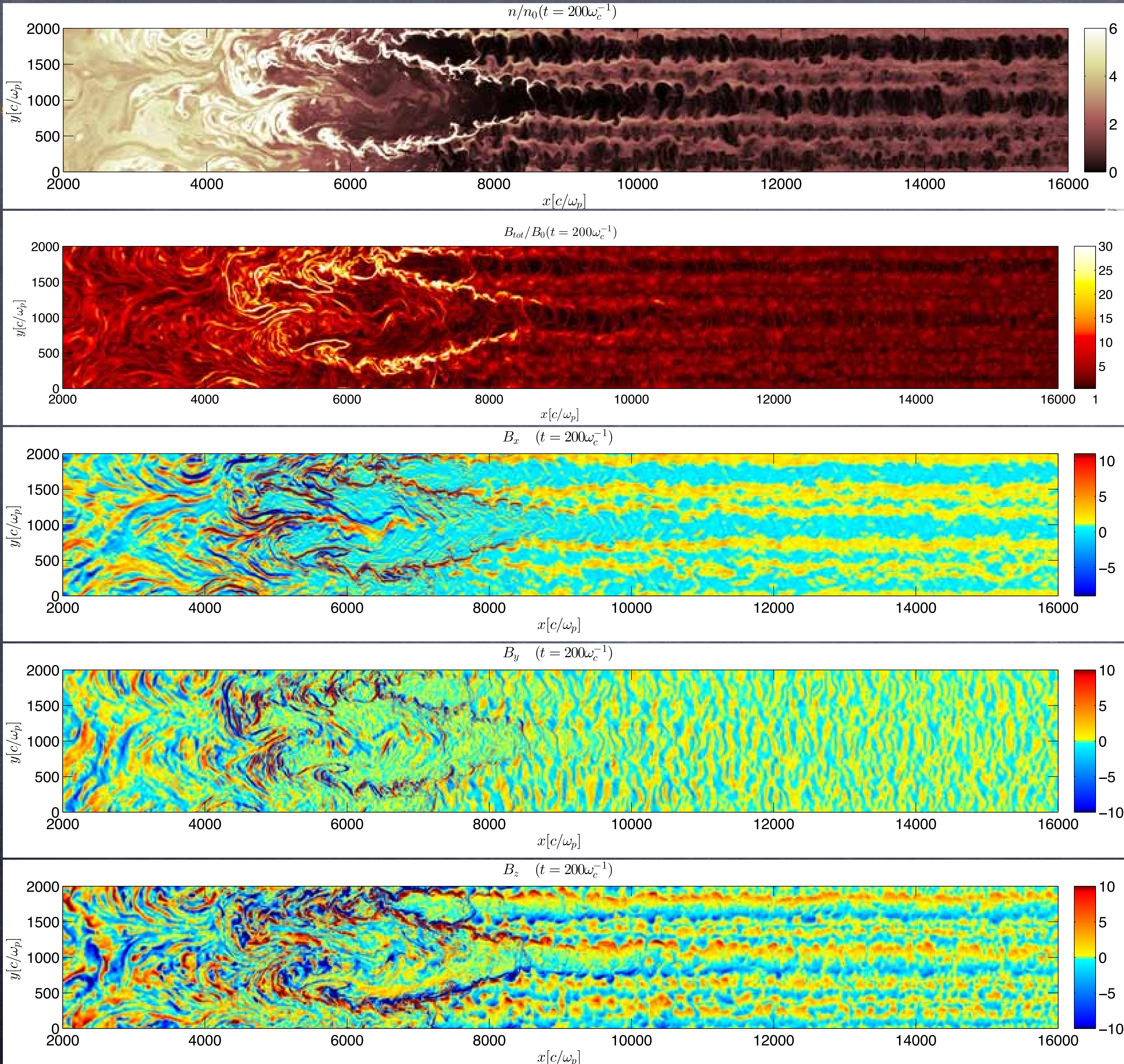


# Perspectives

- Towards real shocks: going bigger and faster
  - Super-Hybrid (Bai, DC, Sironi, Spitkovsky 2014)
- Electron physics with full PIC (Park, DC, Spitkovsky 2015)
- Embedding microphysics in hydro/MHD simulations
  - CRAFT: CR Analytic Fast Tool (DC et al., in prep)
- Relativistic shocks (GRB, AGN jets, pulsars, radio-SNe,...)
  - Partitioning energy into ions, electrons, and magnetic fields
- Almost any problem in collisionless astro and lab plasmas!

SN1006 rim – HST



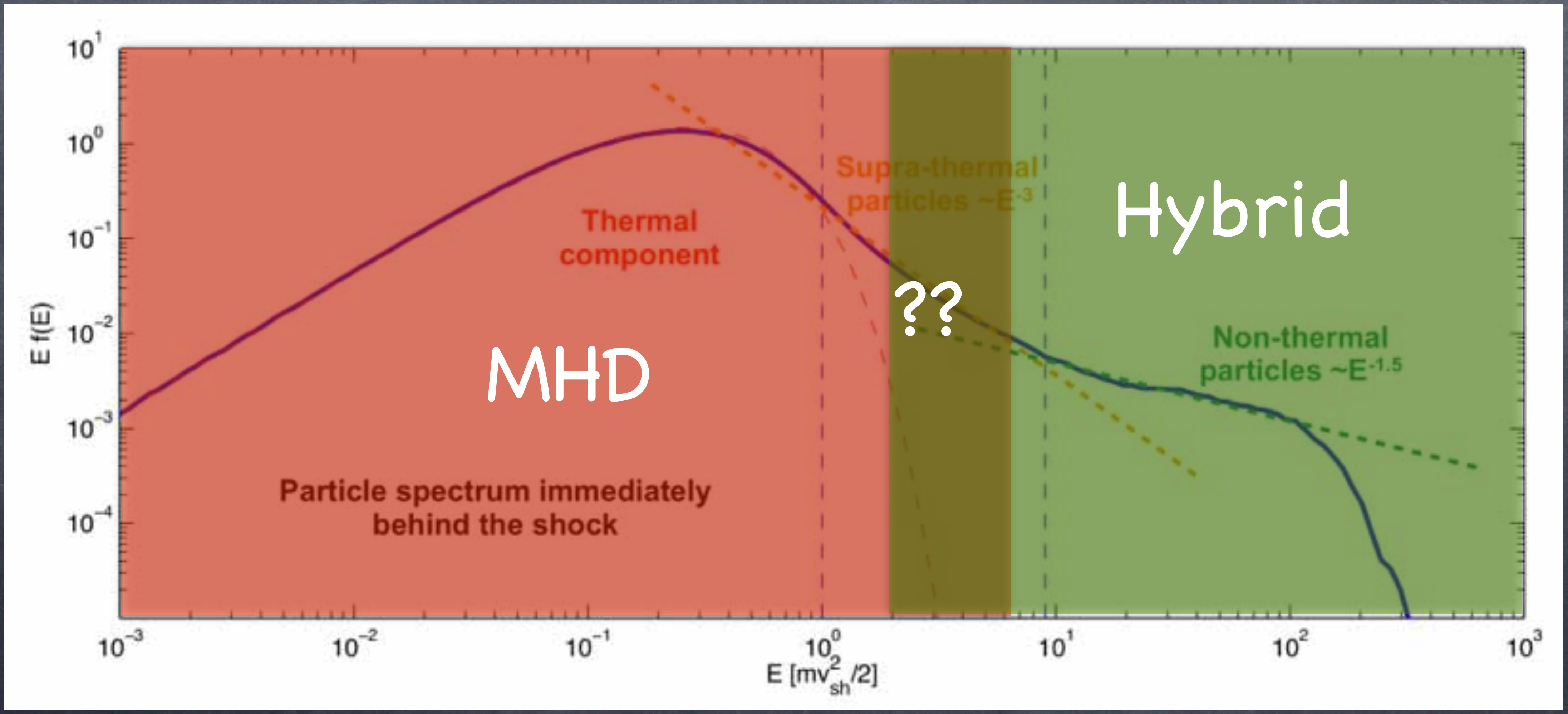

Hybrid simulations of a very strong shock: M=100

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

Very expensive to study in the hybrid limit (about $10^6$ cpu h)

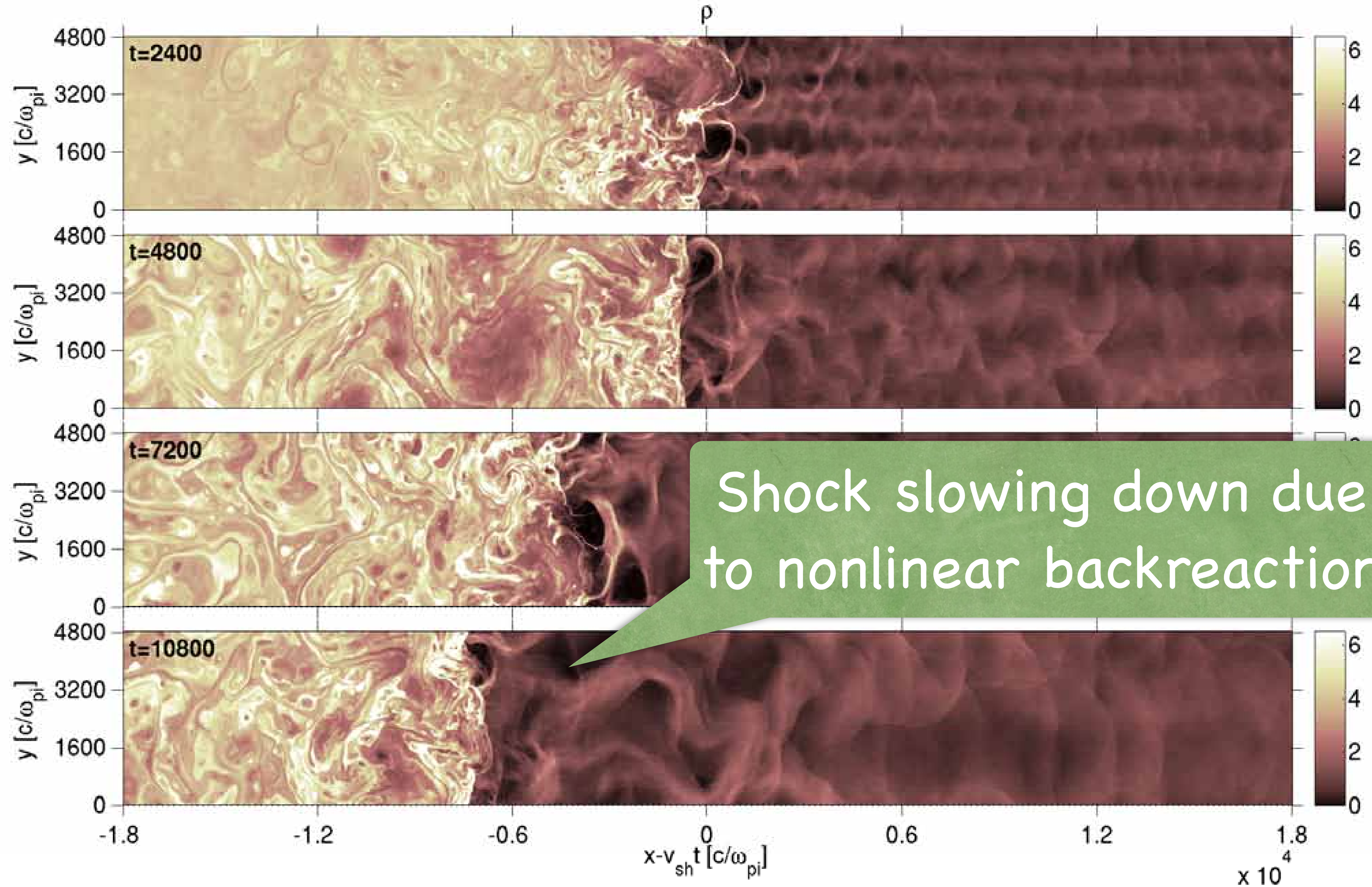
# Going bigger: Super-Hybrid

- 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

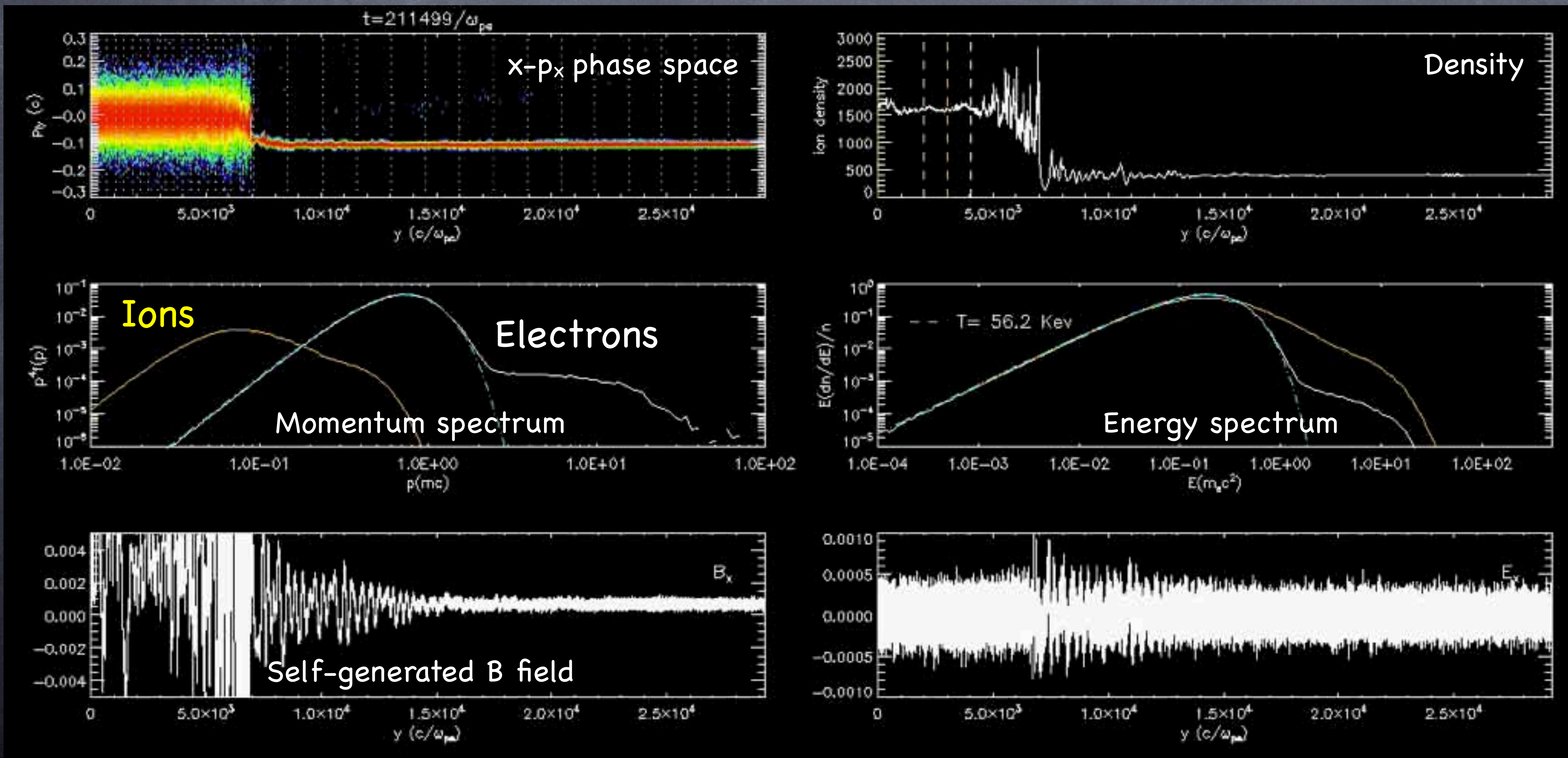



Shock slowing down due to nonlinear backreaction

Bai, DC, Sironi, Spitkovsky 1412.1087

# Electron/ion acceleration

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



# CRAFT: a Cosmic-Ray Fast Analytic Tool

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

- Iterative solution of the CR transport equation:

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

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

Injection

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

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

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

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

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

CR distribution function

u

Mass+momentum conservation eqs.

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

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

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

$P_B + P_{cr}$

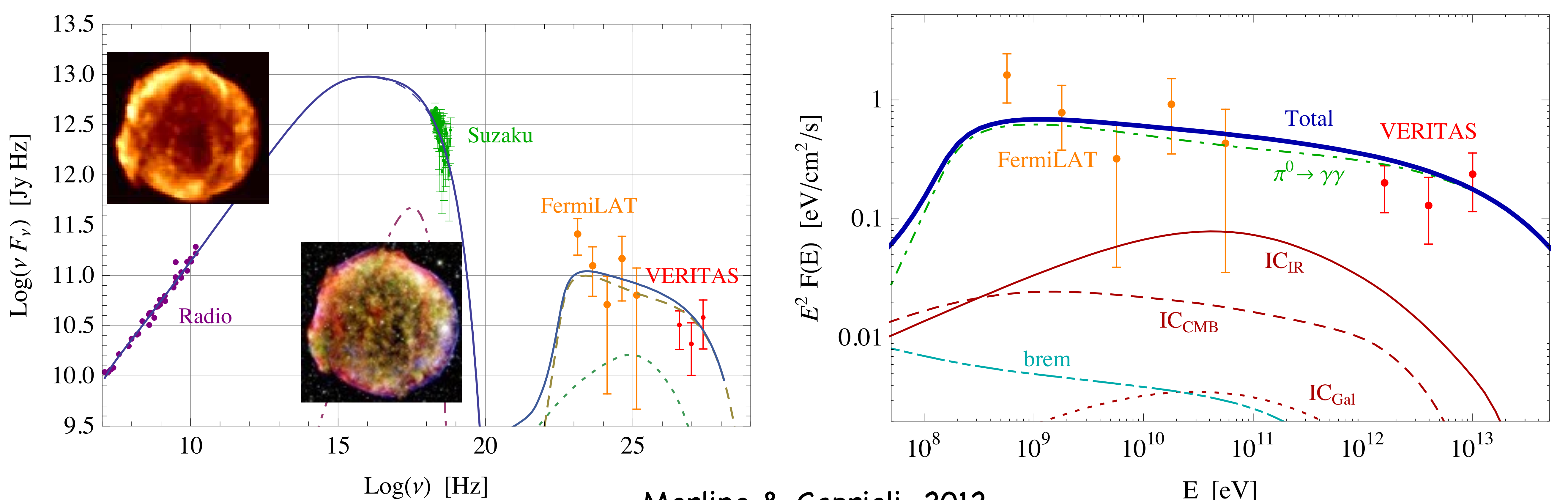
$P_{cr}$

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

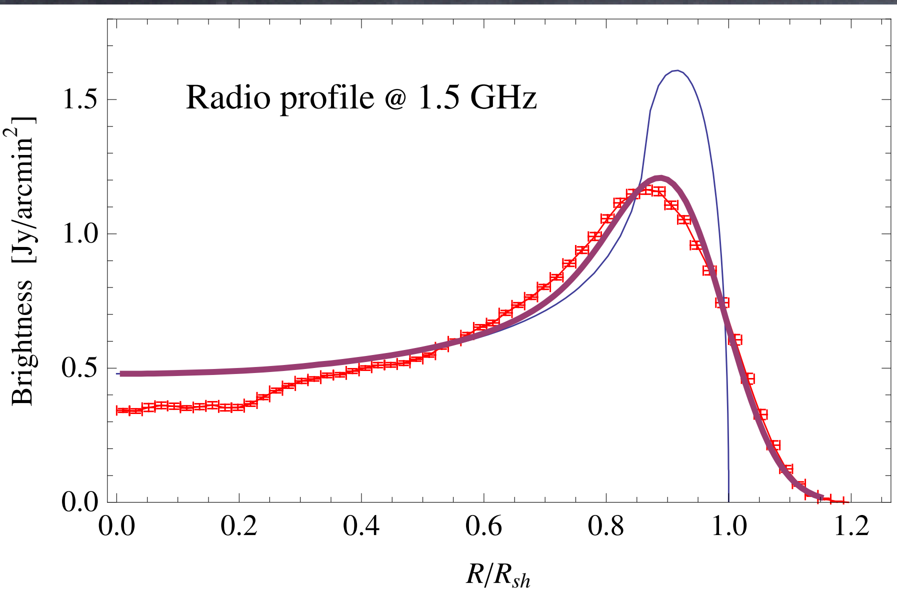
Magnetic turbulence transport eq.

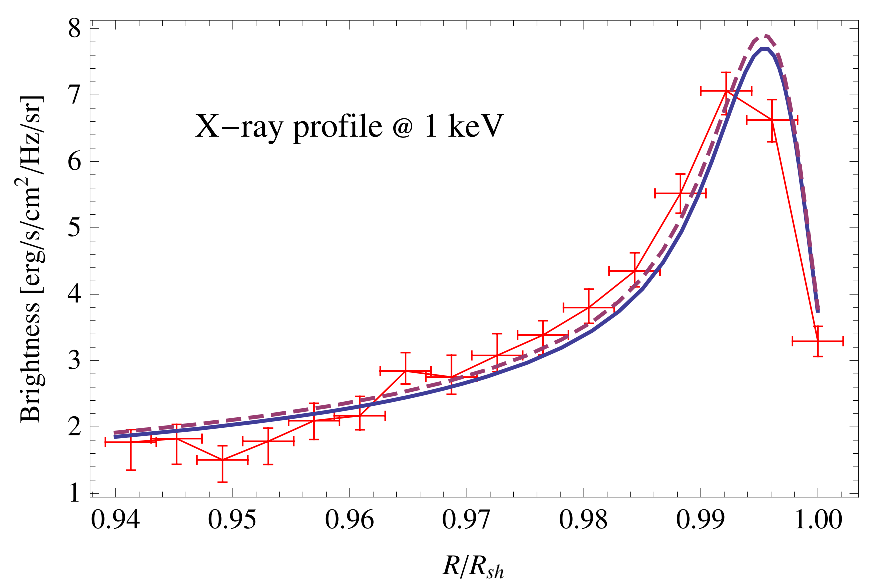
- Very fast: a few seconds on a laptop (vs days on clusters)
- Embeds microphysics from kinetic simulations into (M)HD

# Tycho: a clear-cut hadronic accelerator




Morlino & Caprioli, 2012

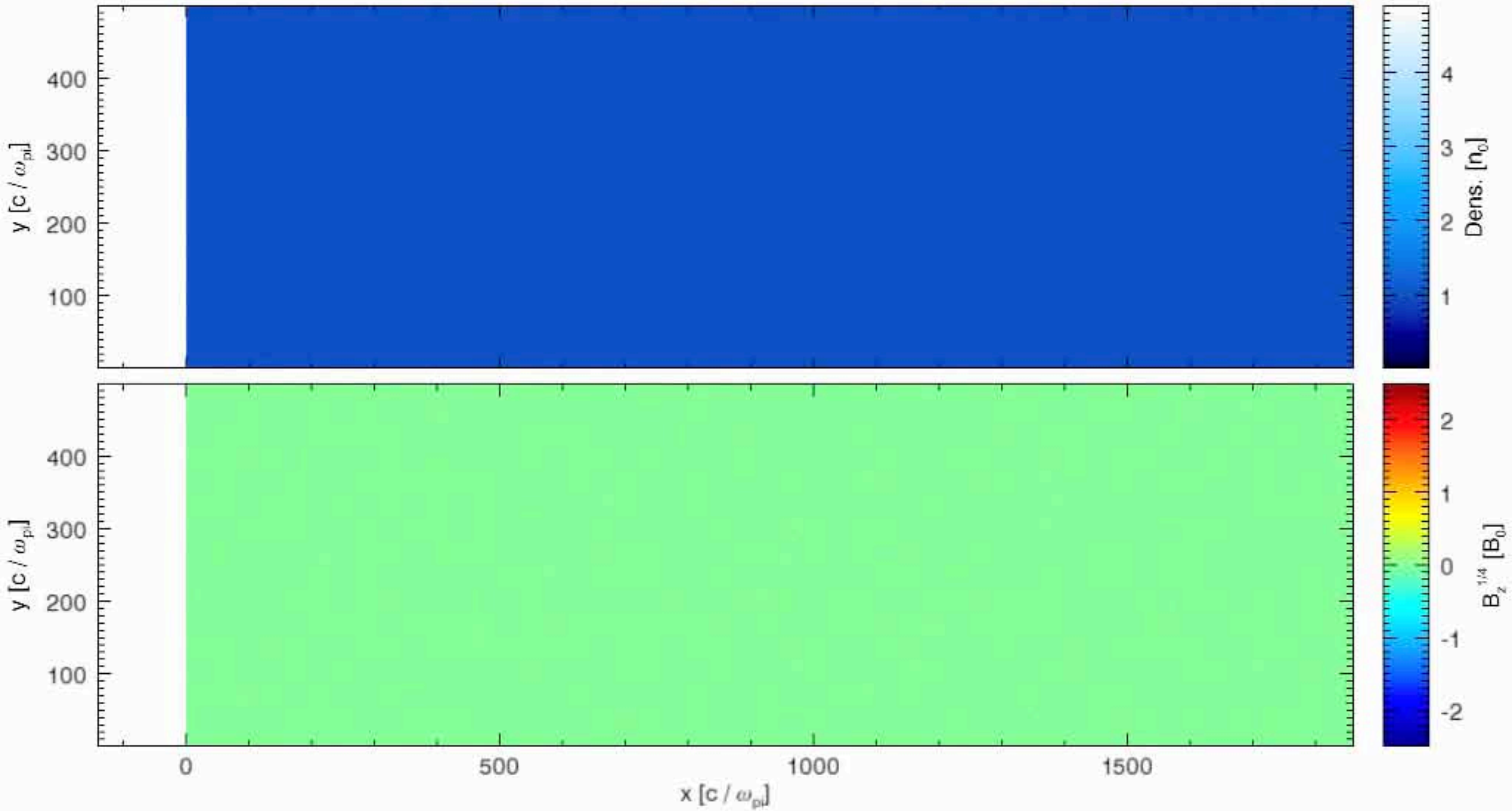



- Account for spectra, SNR hydrodynamics, and morphology
- Hadron acc. eff. ~10%
- Protons up to 0.5 PeV

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

# Thank you!



y [c / ωpi]
400
300
200
100
Dens. [n0]
4
3
2
1
y [c / ωpi]
400
300
200
100
B_z^1/4 [B0]
2
1
0
-1
-2
0
500
1000
1500
x [c / ωpi]