NBI, Copenhagen - August 2014

# Kinetic simulations of cosmic ray acceleration at shocks

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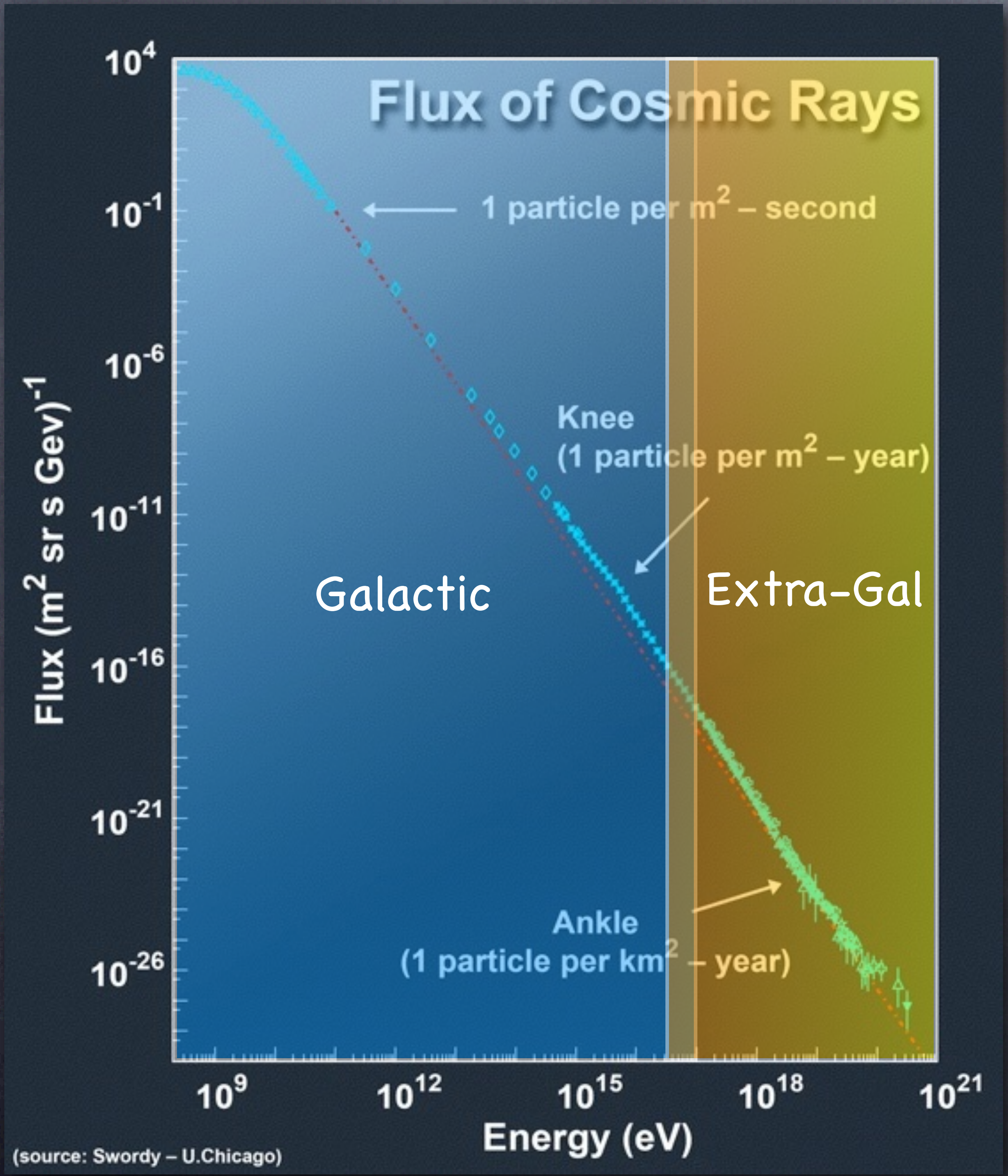
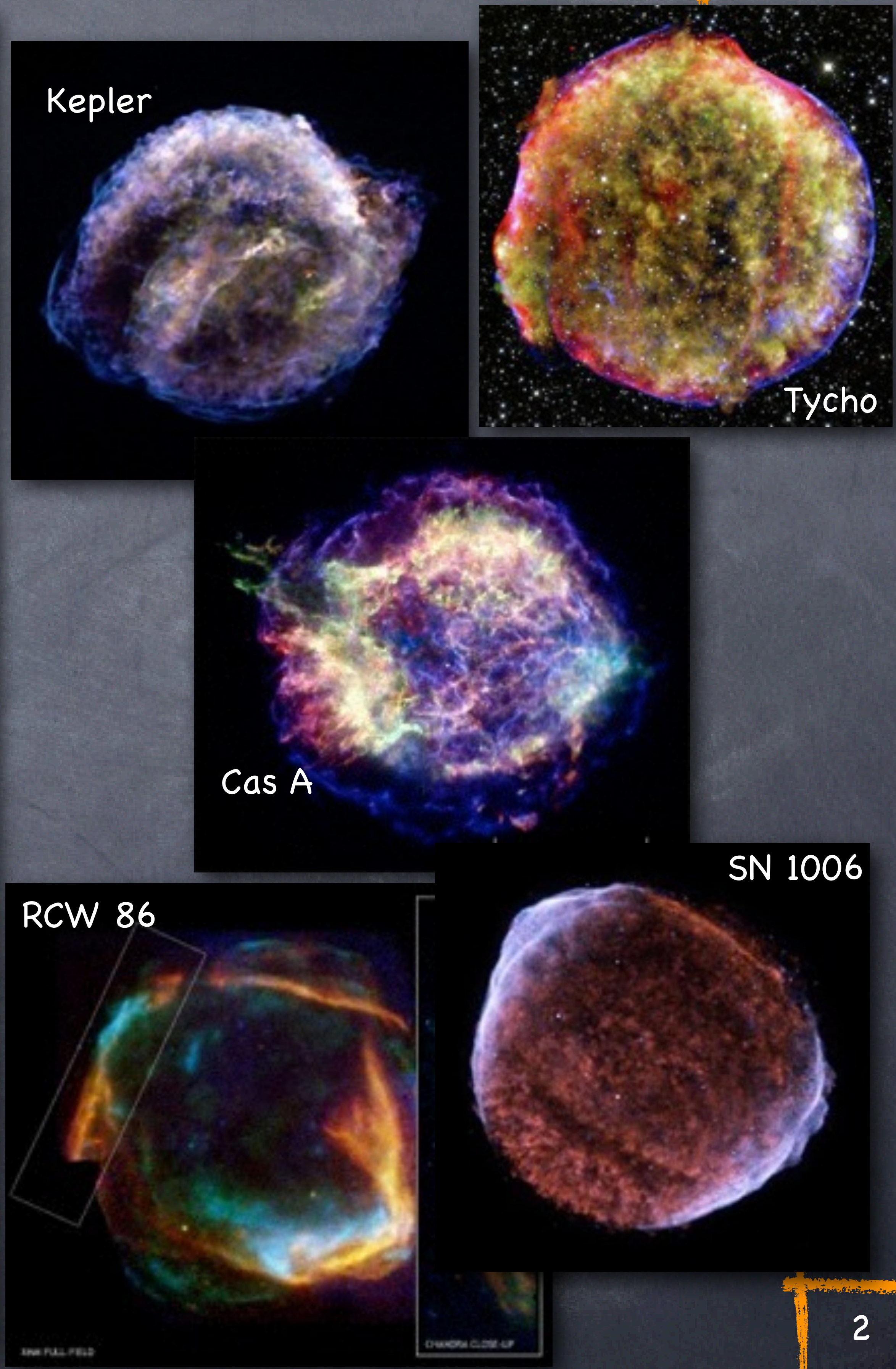
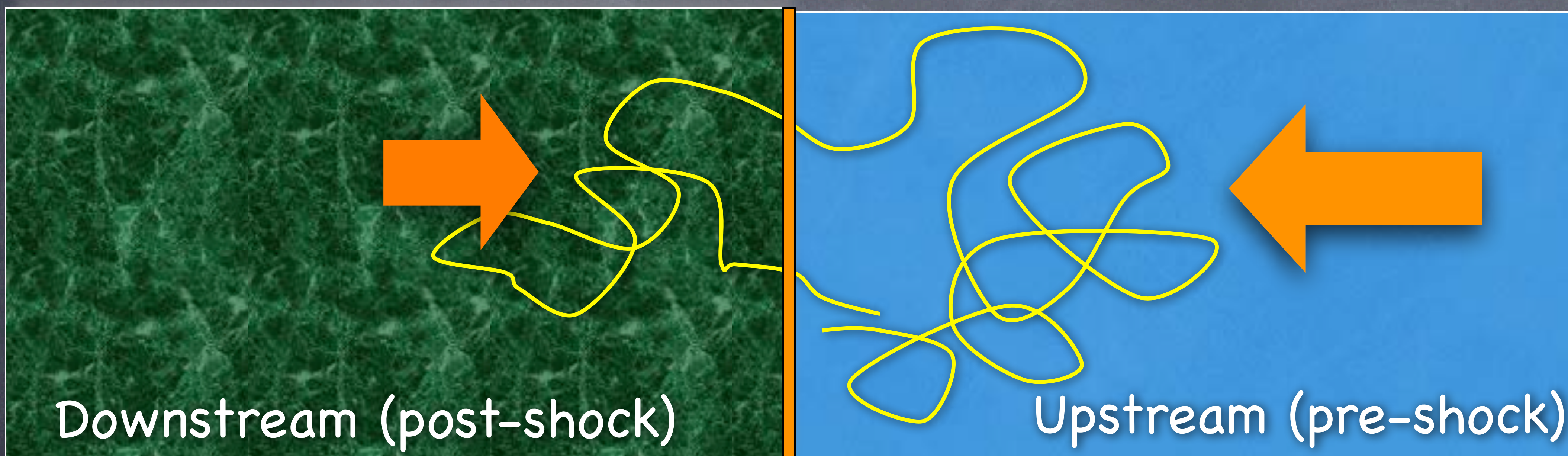
# The SNR paradigm for Galactic CRs



# 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



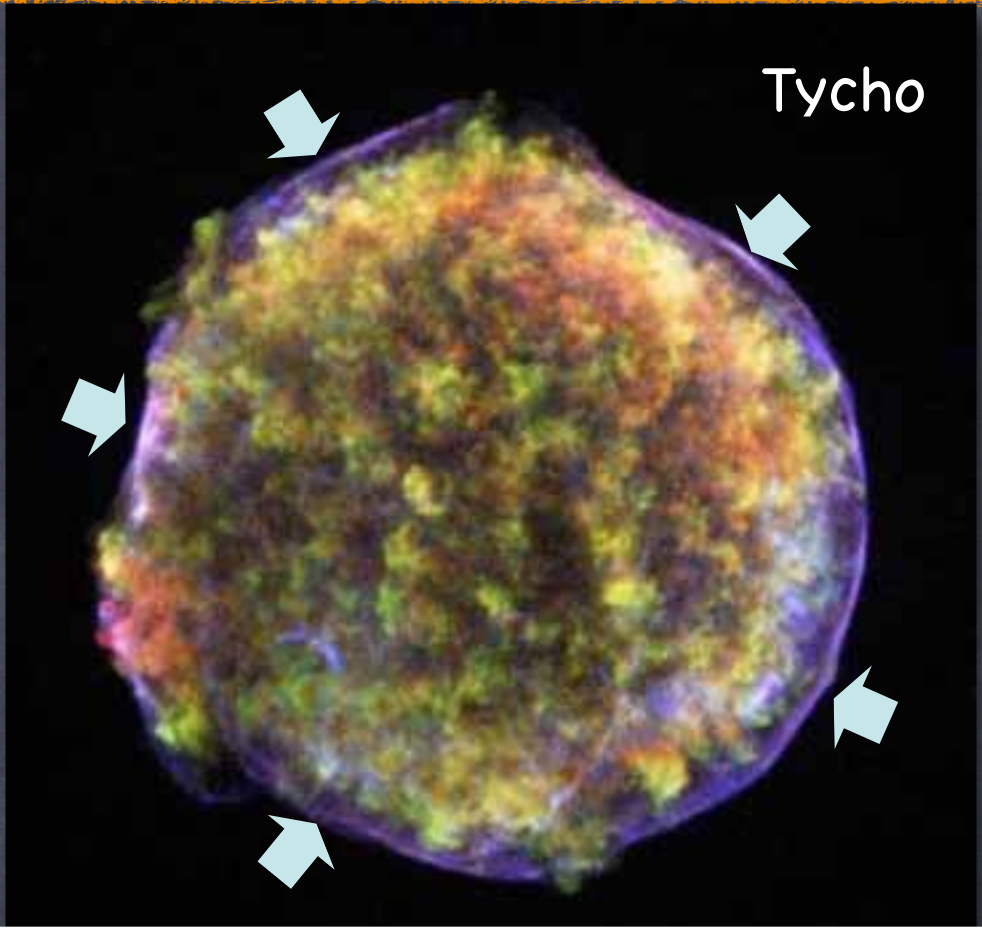

Test-particle squeezed between converging flows

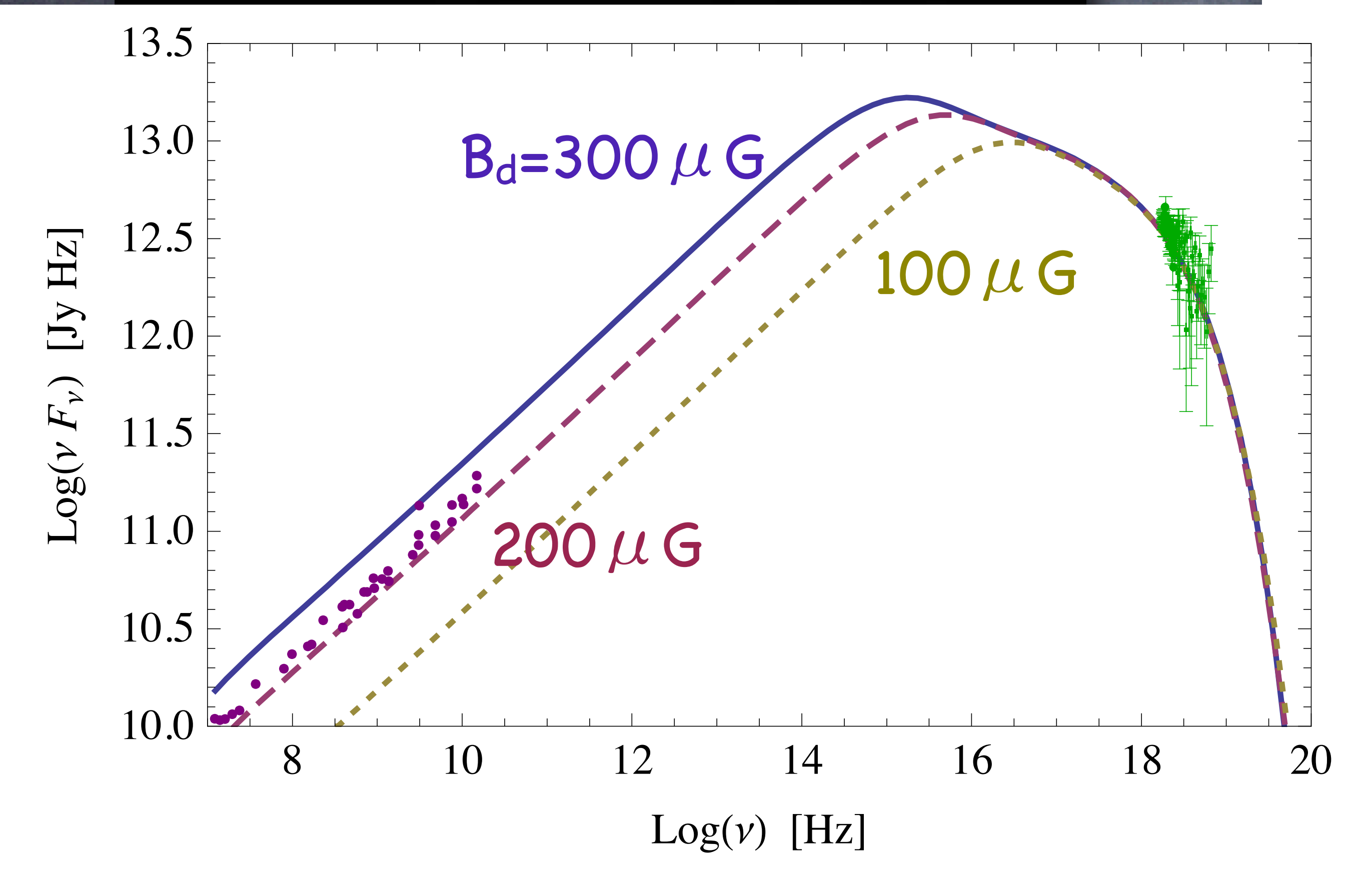
- DSA produces power-law $p^{-\alpha}$ in momentum, depending on the compression ratio $R=u_1/u_2$ only. For strong shocks: $\alpha=4$ (i.e., $\propto E^{-2}$)

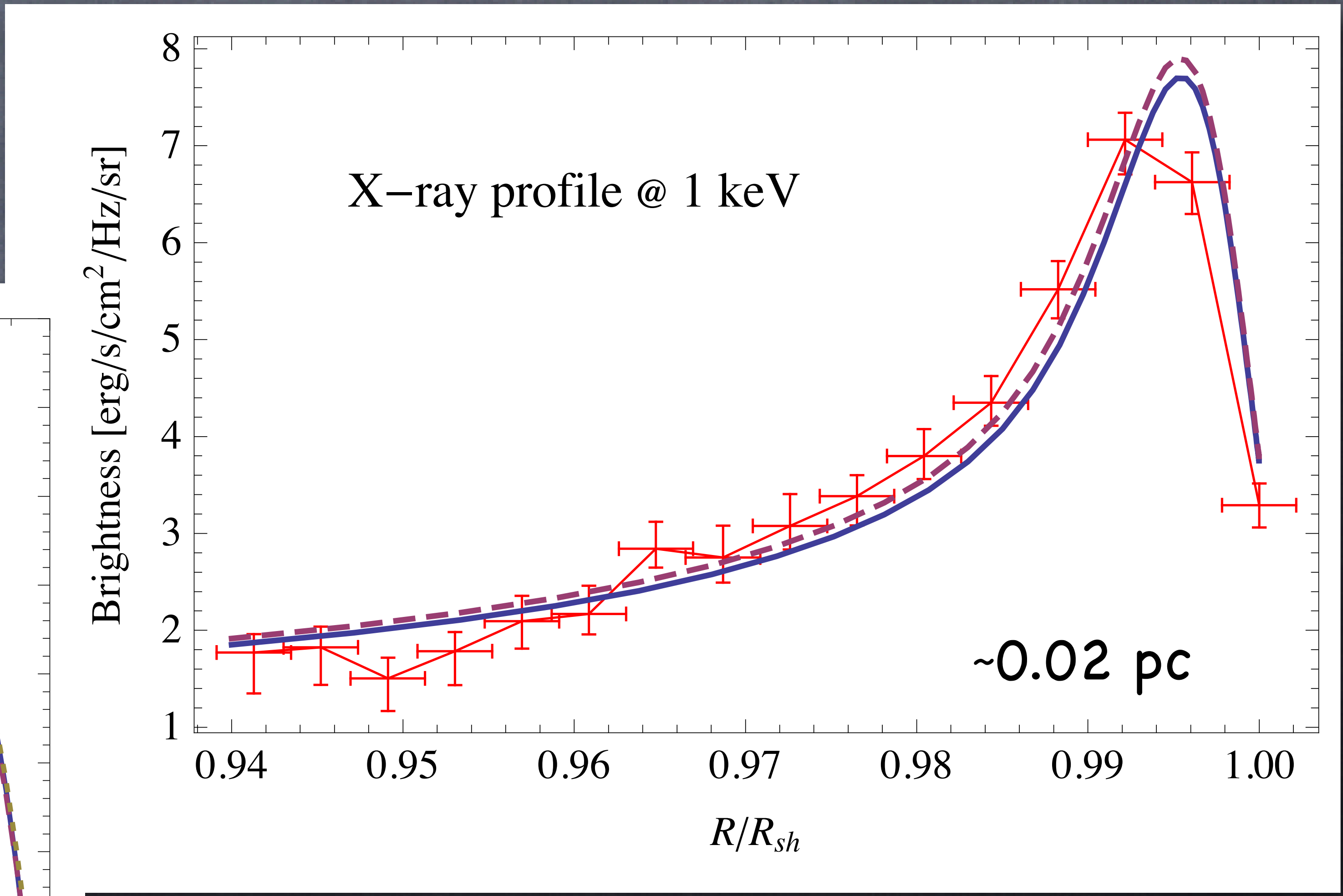
$$R = \frac{4M_s^2}{M_s^2+3} \qquad \alpha = \frac{3R}{R-1}$$

# 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 & Caprioli, 2012

# Conclusions?

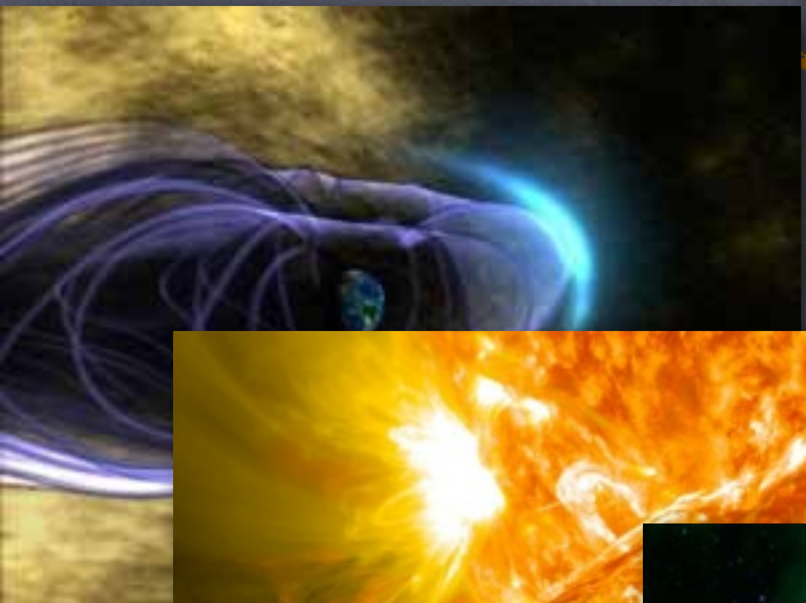
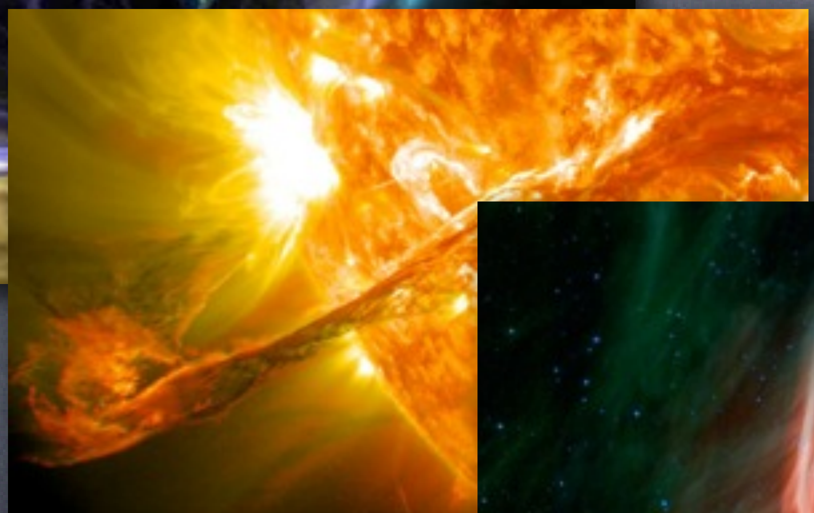
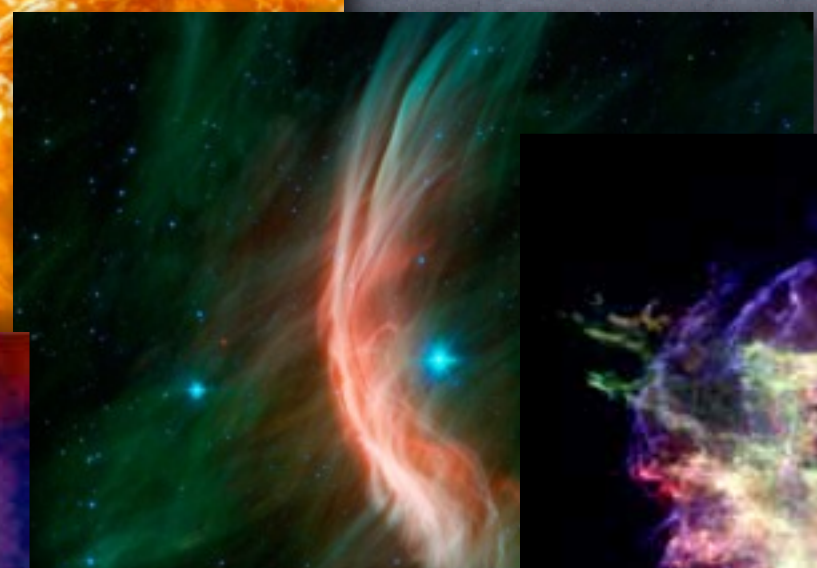
- Supernova Remnants
  - Have the right energetics
  - Diffusive shock acceleration produces power-laws
  - B amplification may help reaching the knee

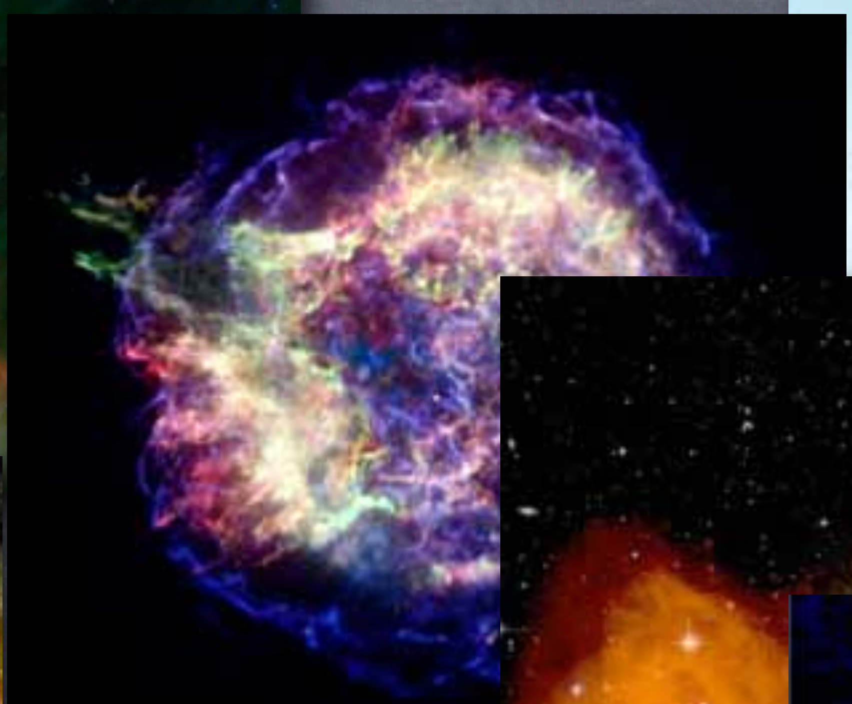
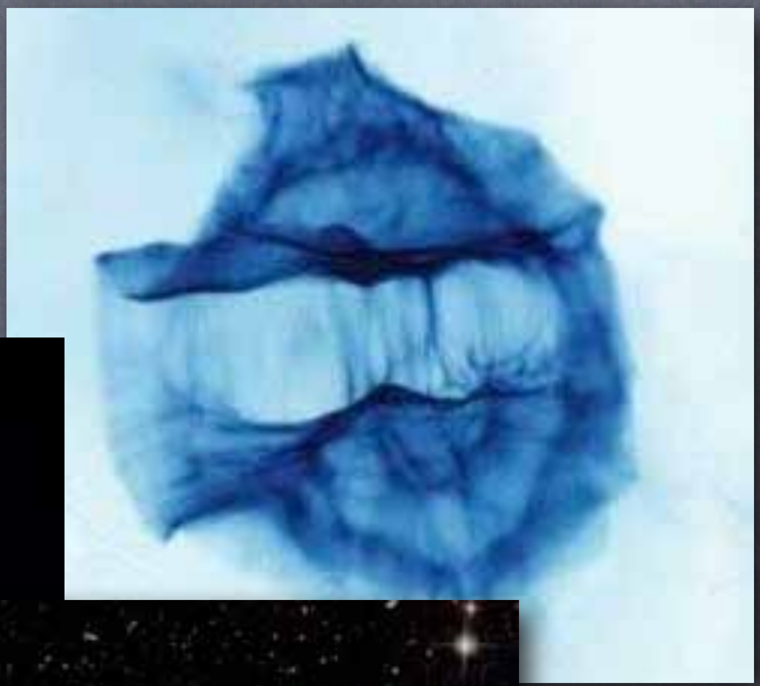
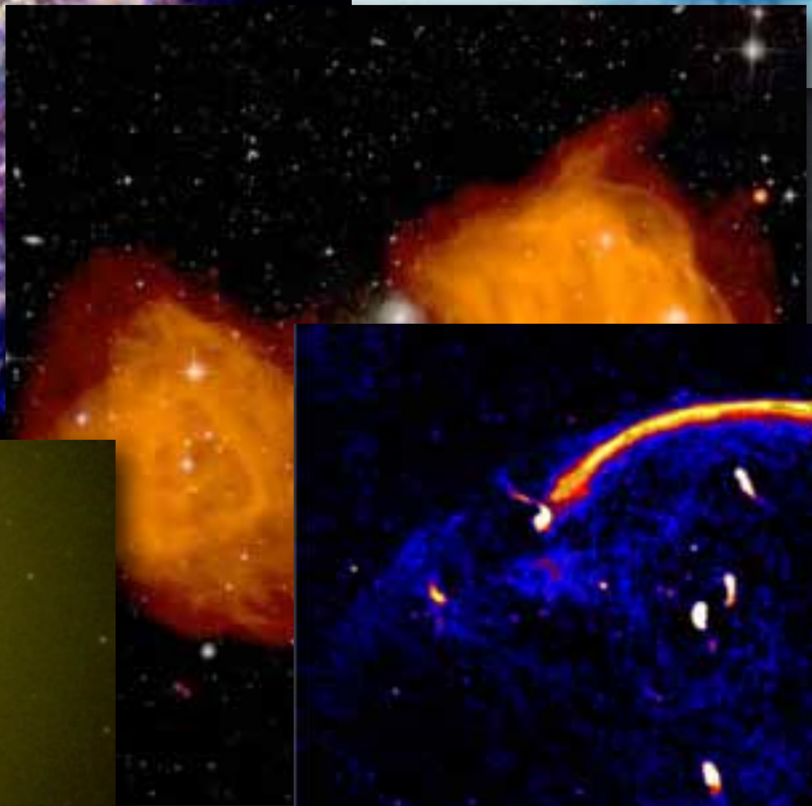

**BUT**

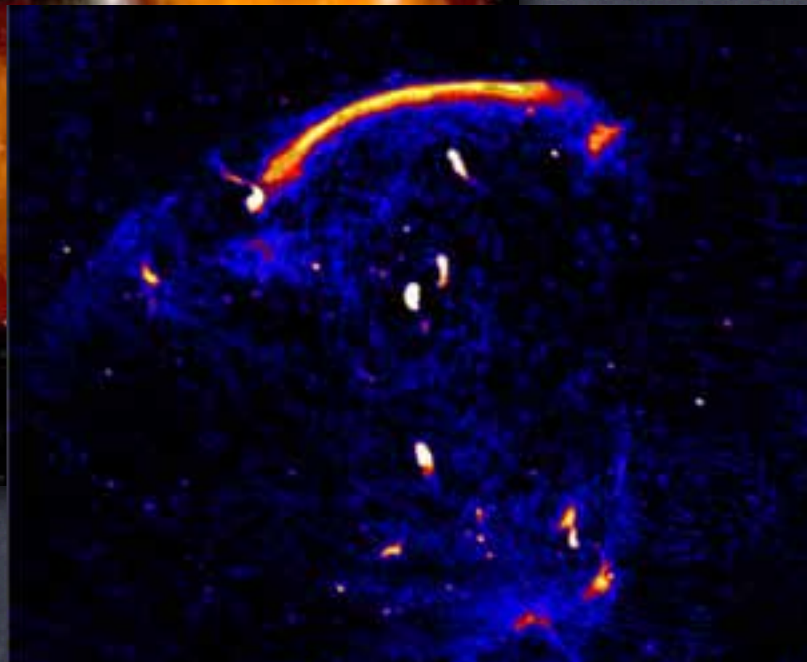
- Is acceleration at shocks efficient?
- How do CRs amplify the magnetic field?
- When is acceleration efficient?

# Collisionless shocks

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

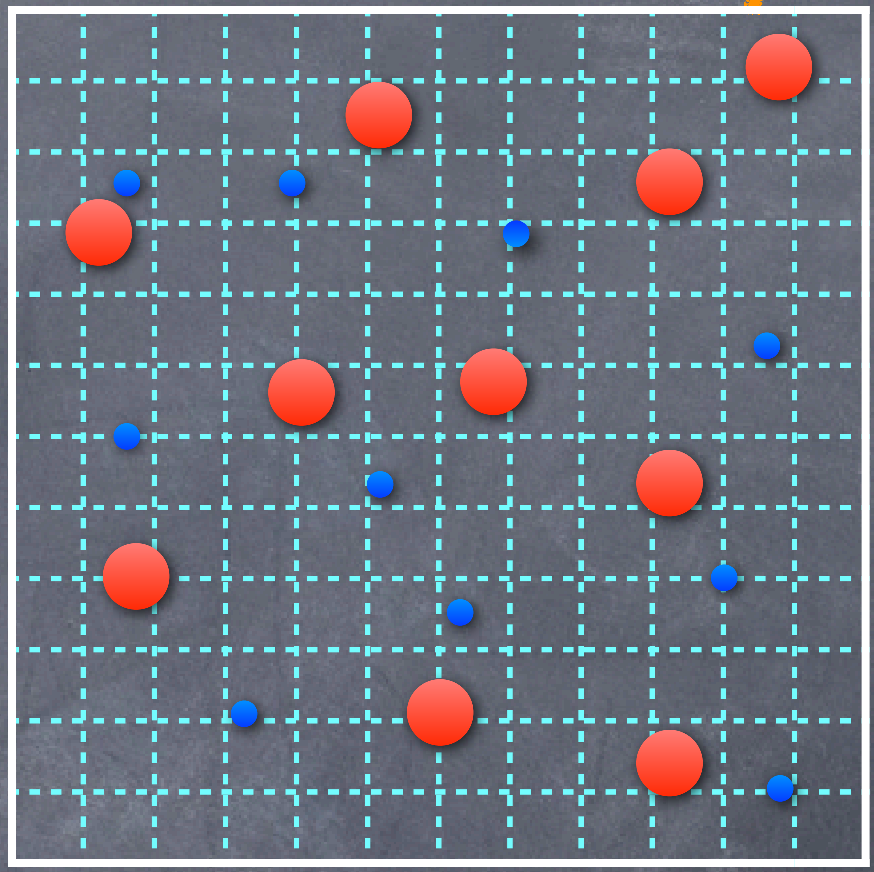




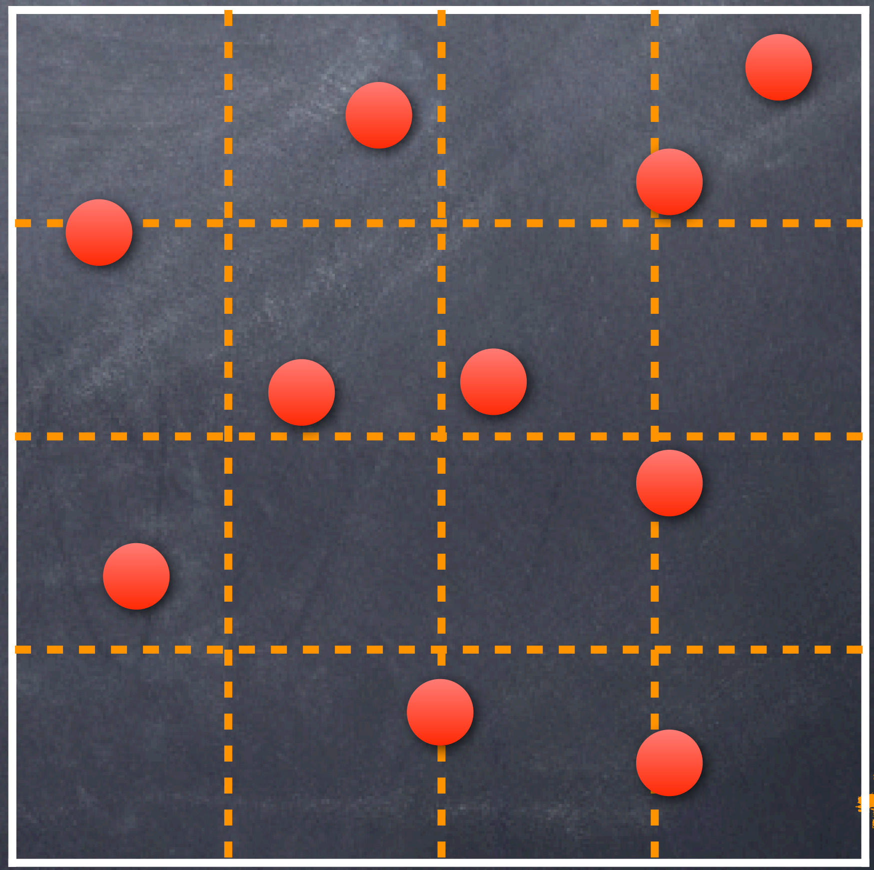


# Acceleration from first principles

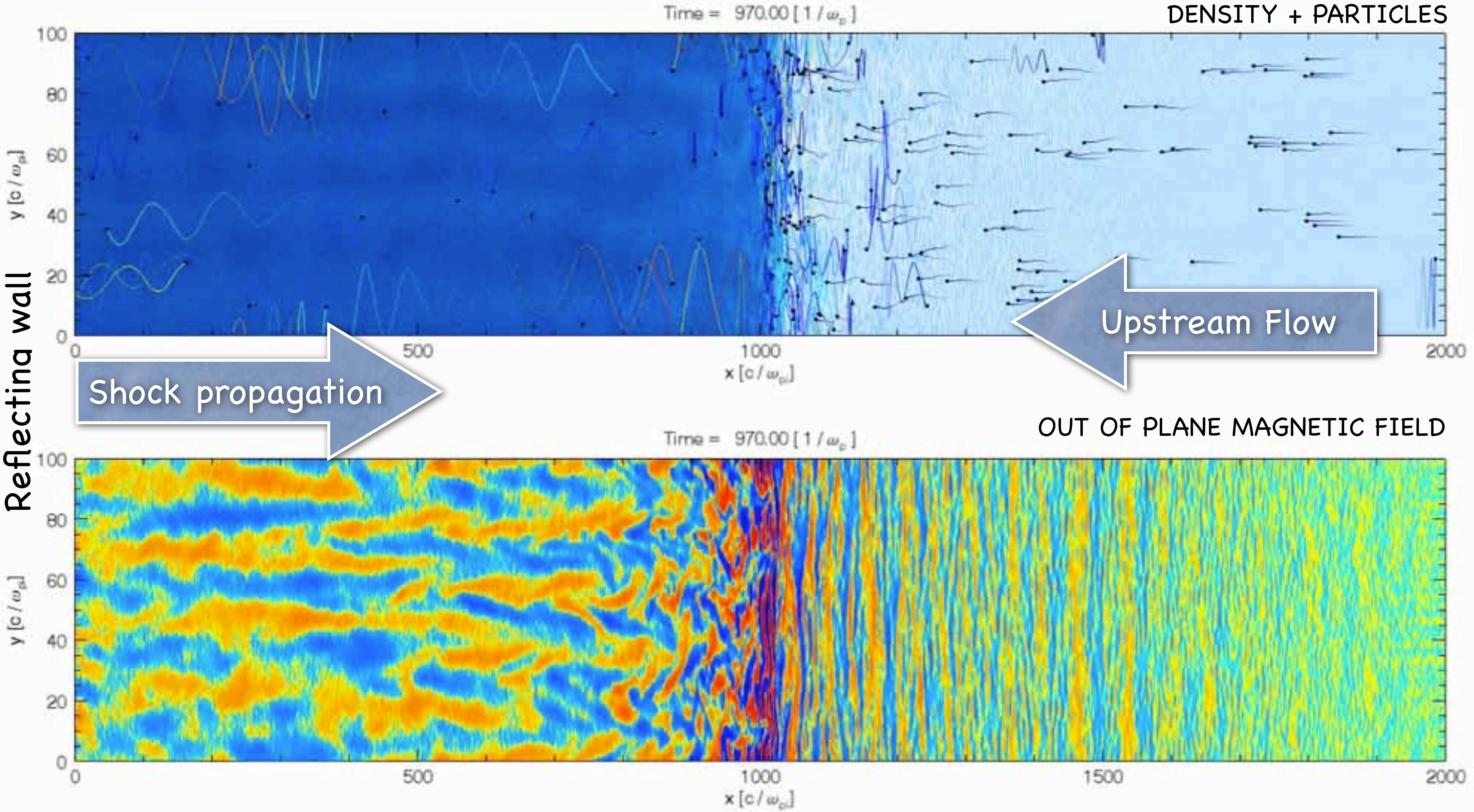
- Full particle in cell approach
  (Spitkovsky 2008, Niemiec et al. 2008, Stroman et al 2009, Riquelme & Spitkovsky 2010, Sironi & Spitkovsky 2011, Park et al 2012, Niemiec at al 2012,...)
  - Define electromagnetic field on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!



- Hybrid approach:
  Fluid electrons - Kinetic protons
  (Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, DC & Spitkovsky 2013, 2014)
  - massless electrons for more macroscopical time/length scales



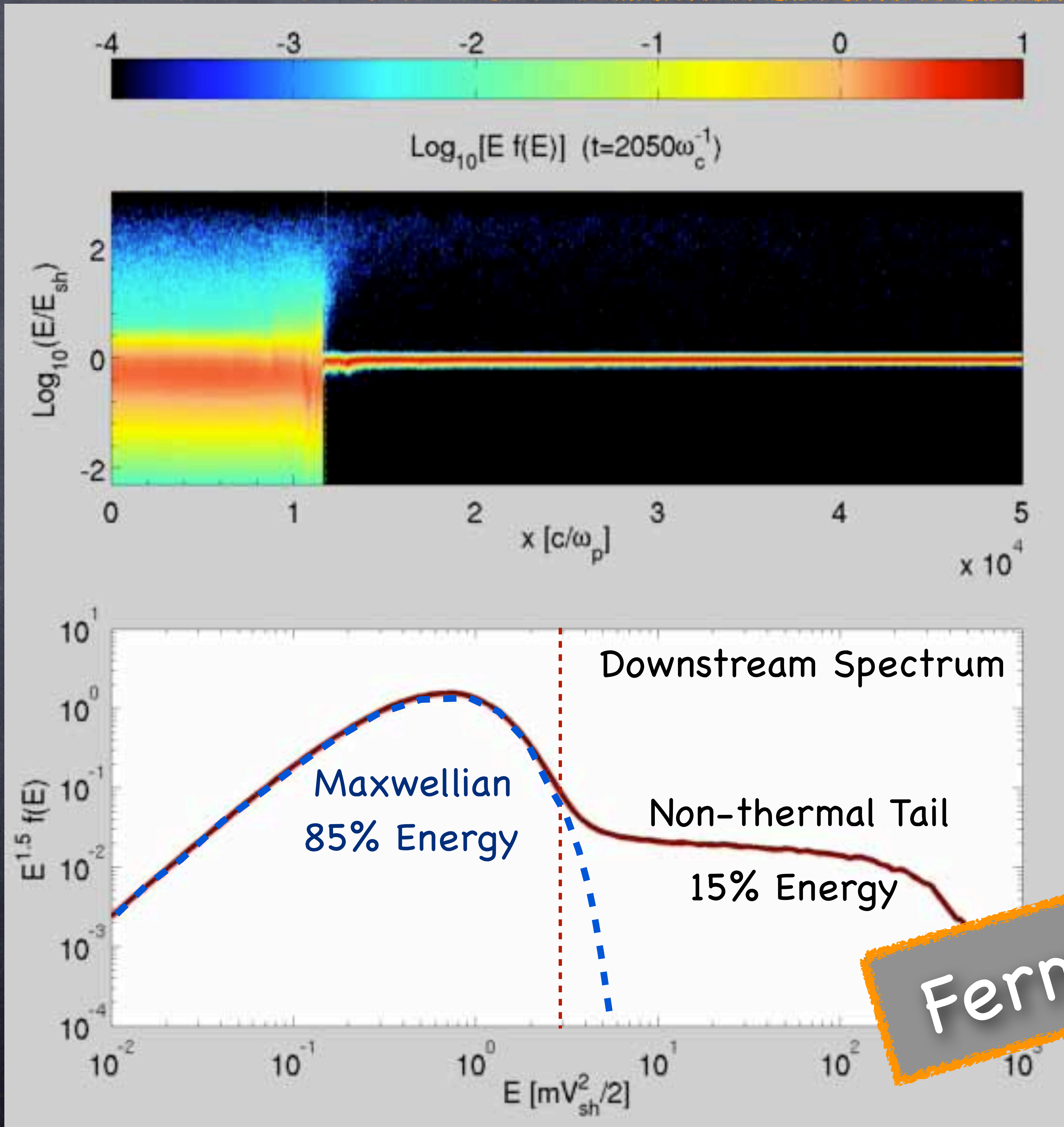
# Hybrid simulations of collisionless shocks




- **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.)

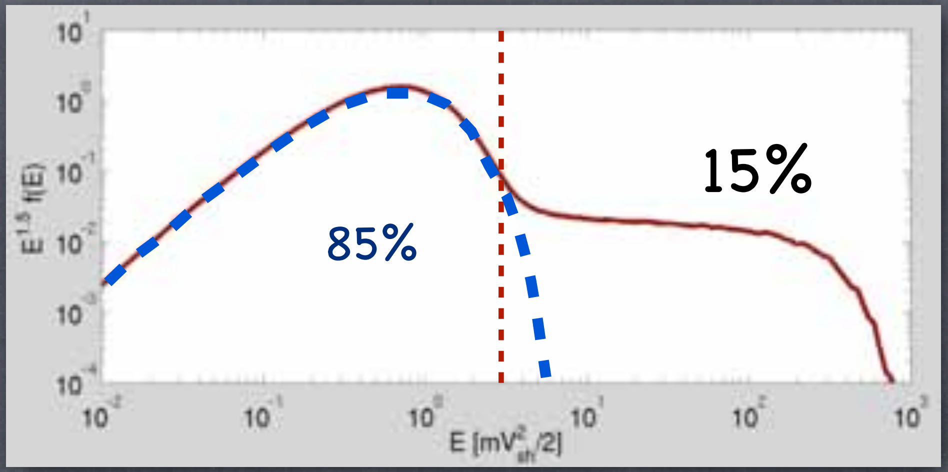
$f(E) \propto E^{-1.5}$ (non rel.)

Fermi acceleration

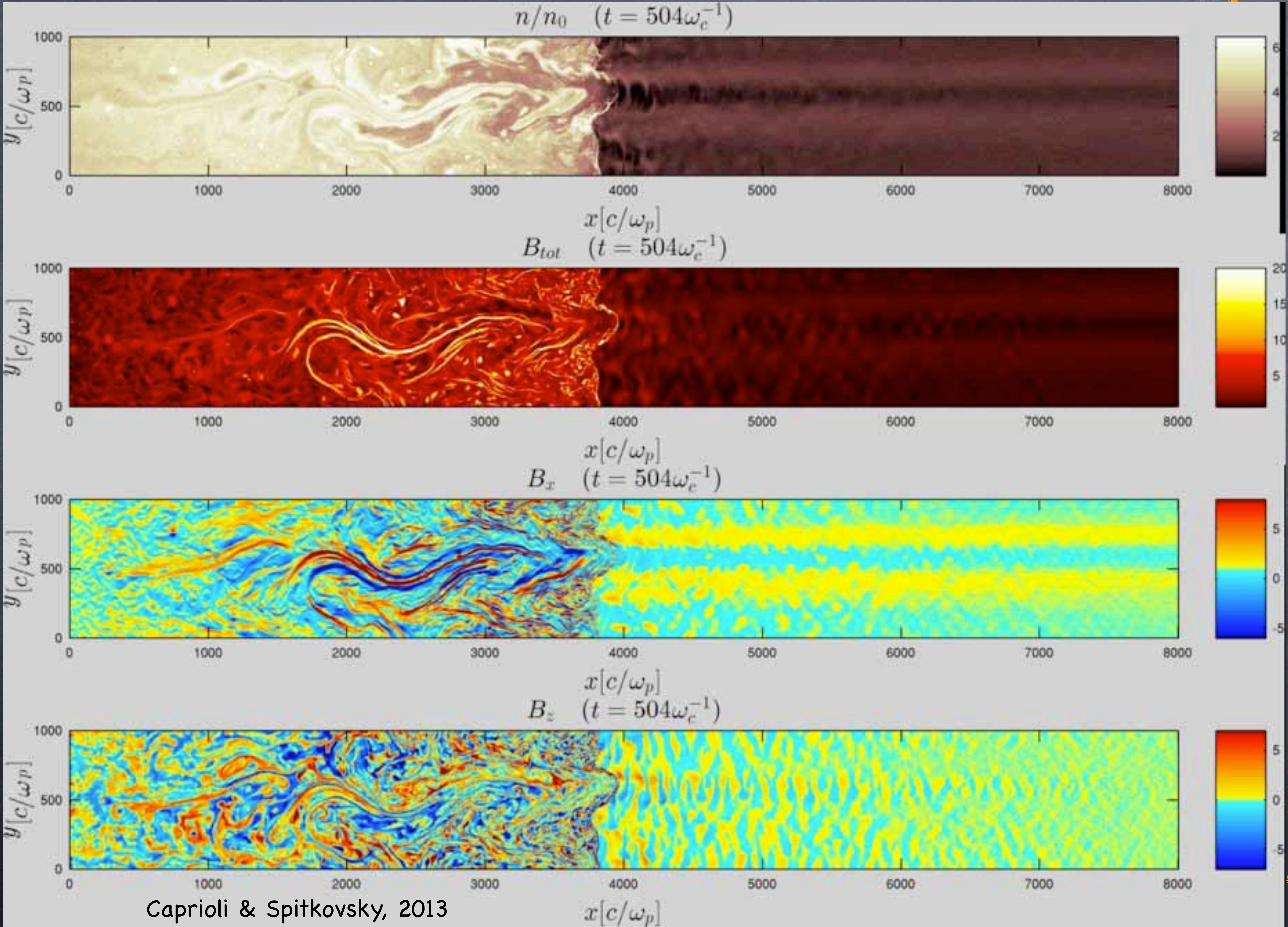
DC & Spitkovsky, 2014

# Outline

- Is acceleration at shocks efficient?
  - Hybrid simulations: >15%
- How do CRs amplify the magnetic field?

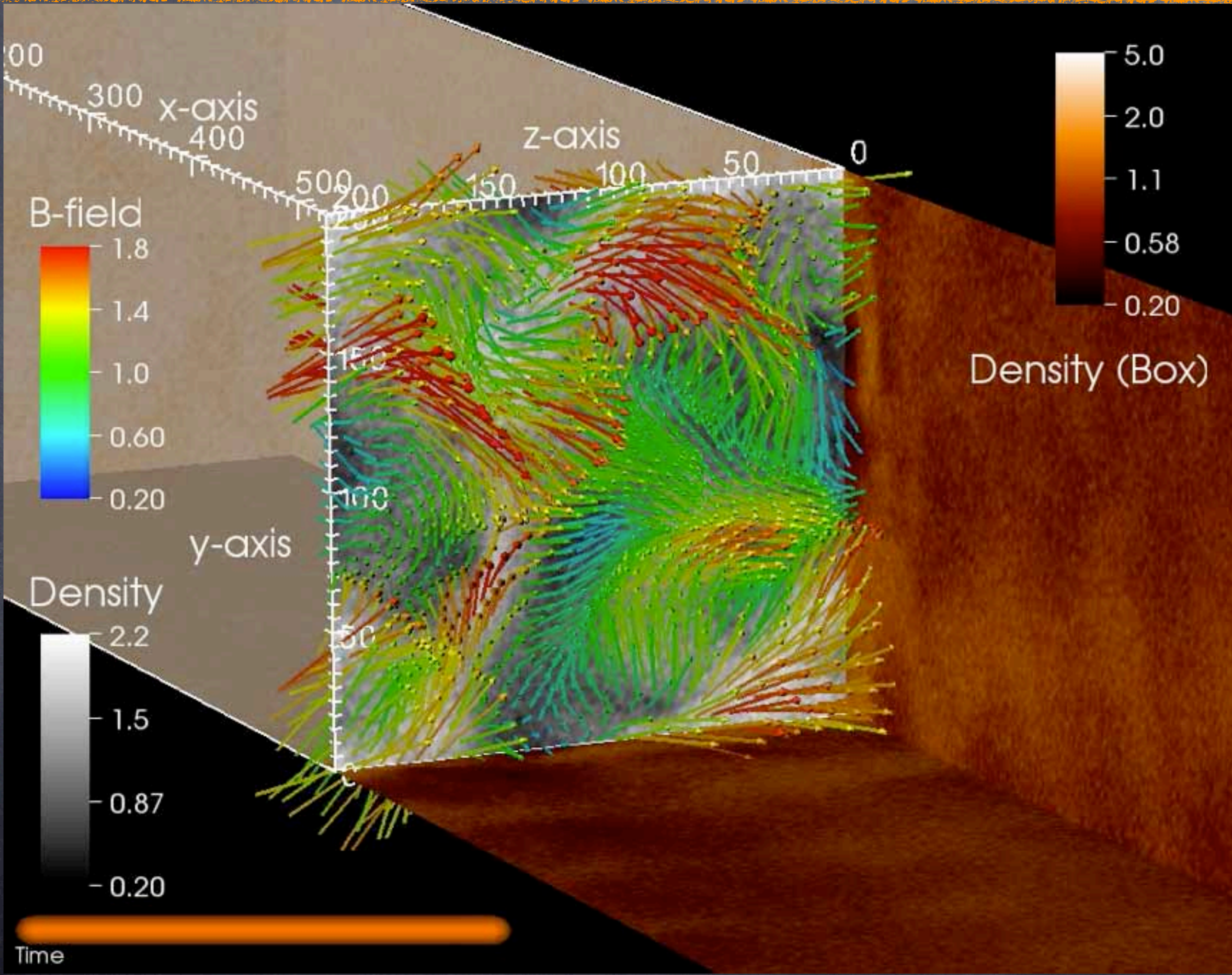


# Filamentation instability




Caprioli & Spitkovsky, 2013

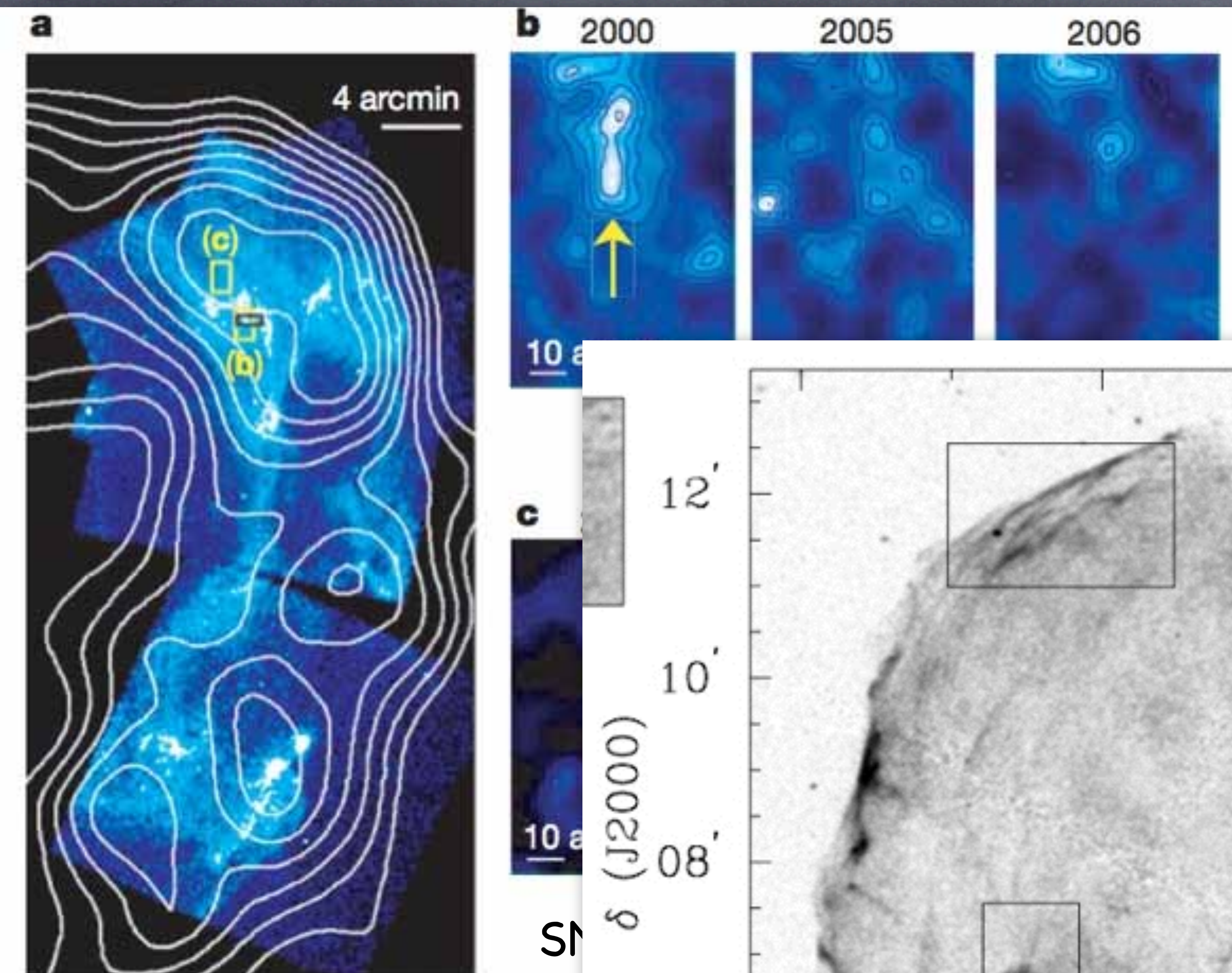
# 3D simulations of a parallel shock



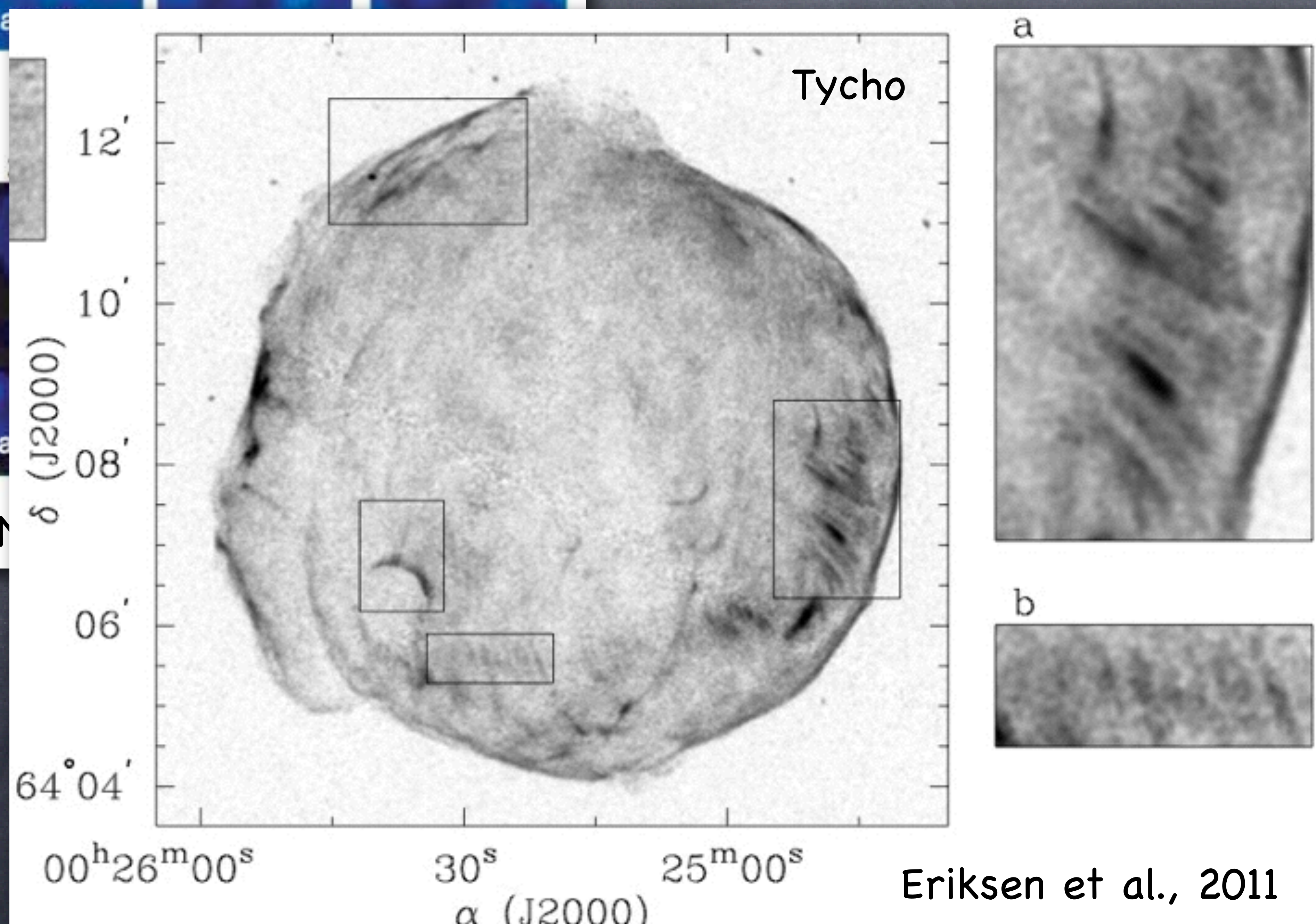

Caprioli & Spitkovsky, 2014

# Knots and filaments

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



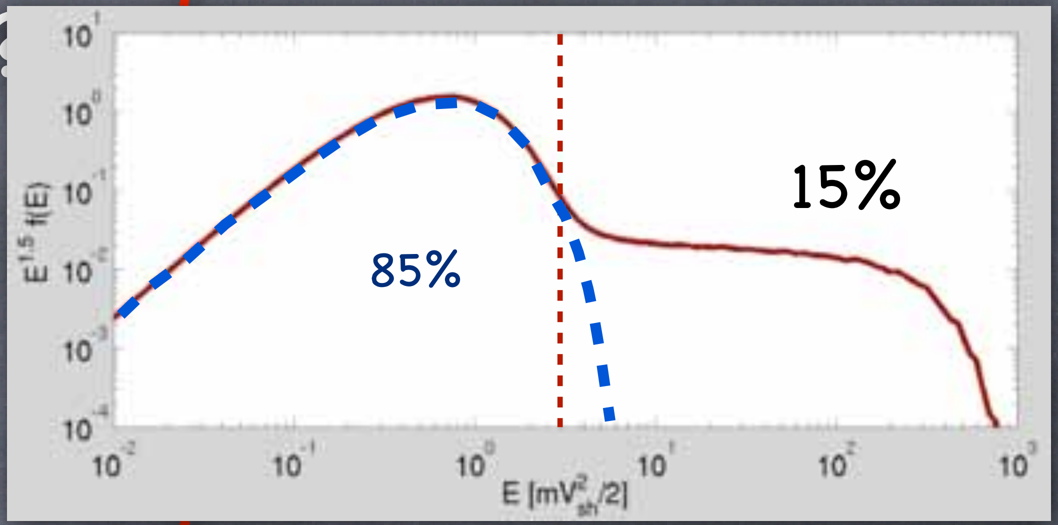

Uchiyama et al 2007

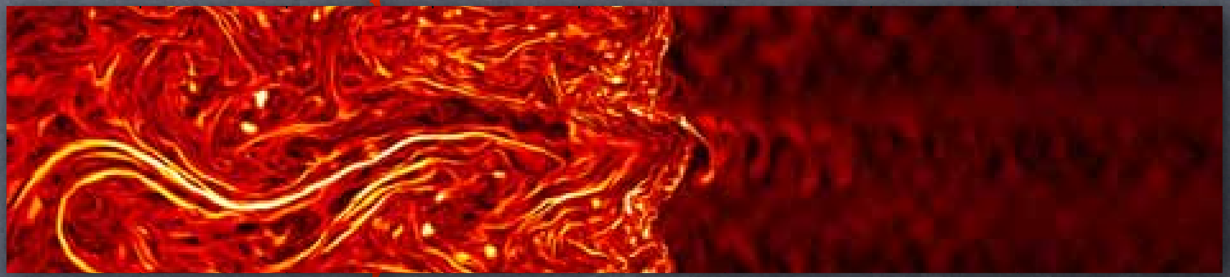



Eriksen et al., 2011

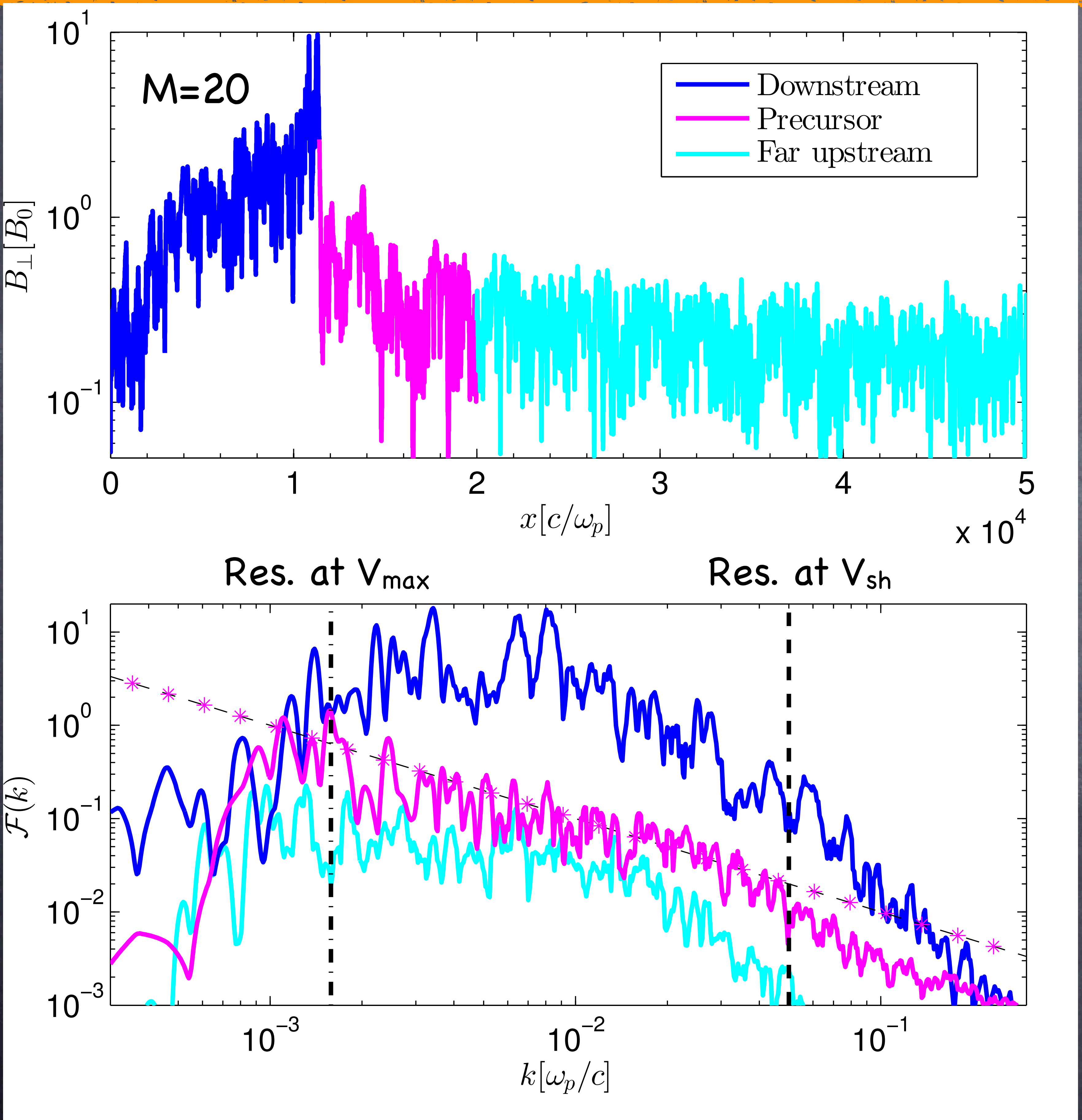
# Outline

- Is acceleration at shocks efficient?
  - Hybrid simulations: >15%
- How do CRs amplify the magnetic field?
  - Streaming instability
- How do magnetic fields scatter CRs?



# Magnetic field spectrum, low $M_A$




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 $\propto p^{-4}$

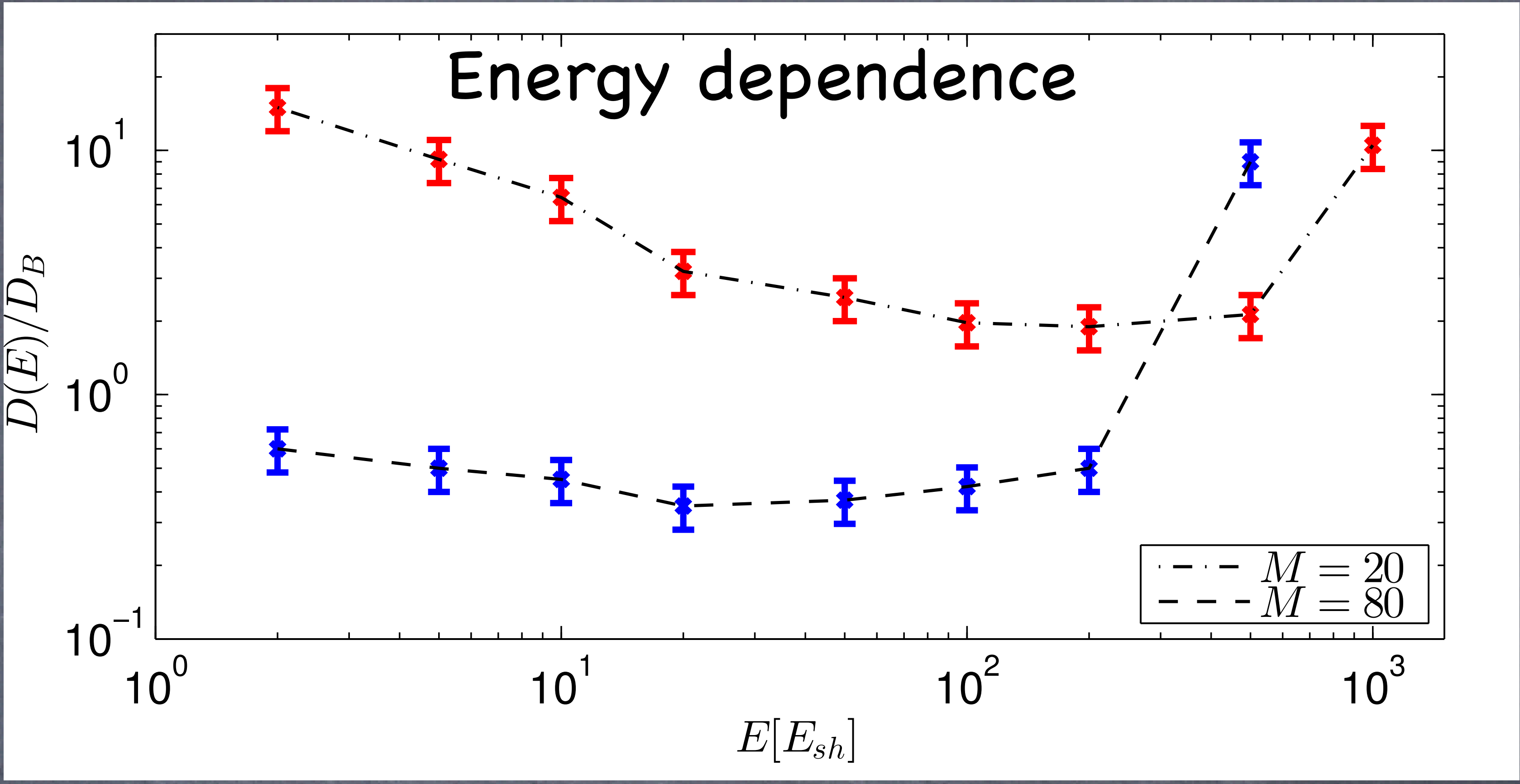
DC & Spitkovsky, 1401.7679

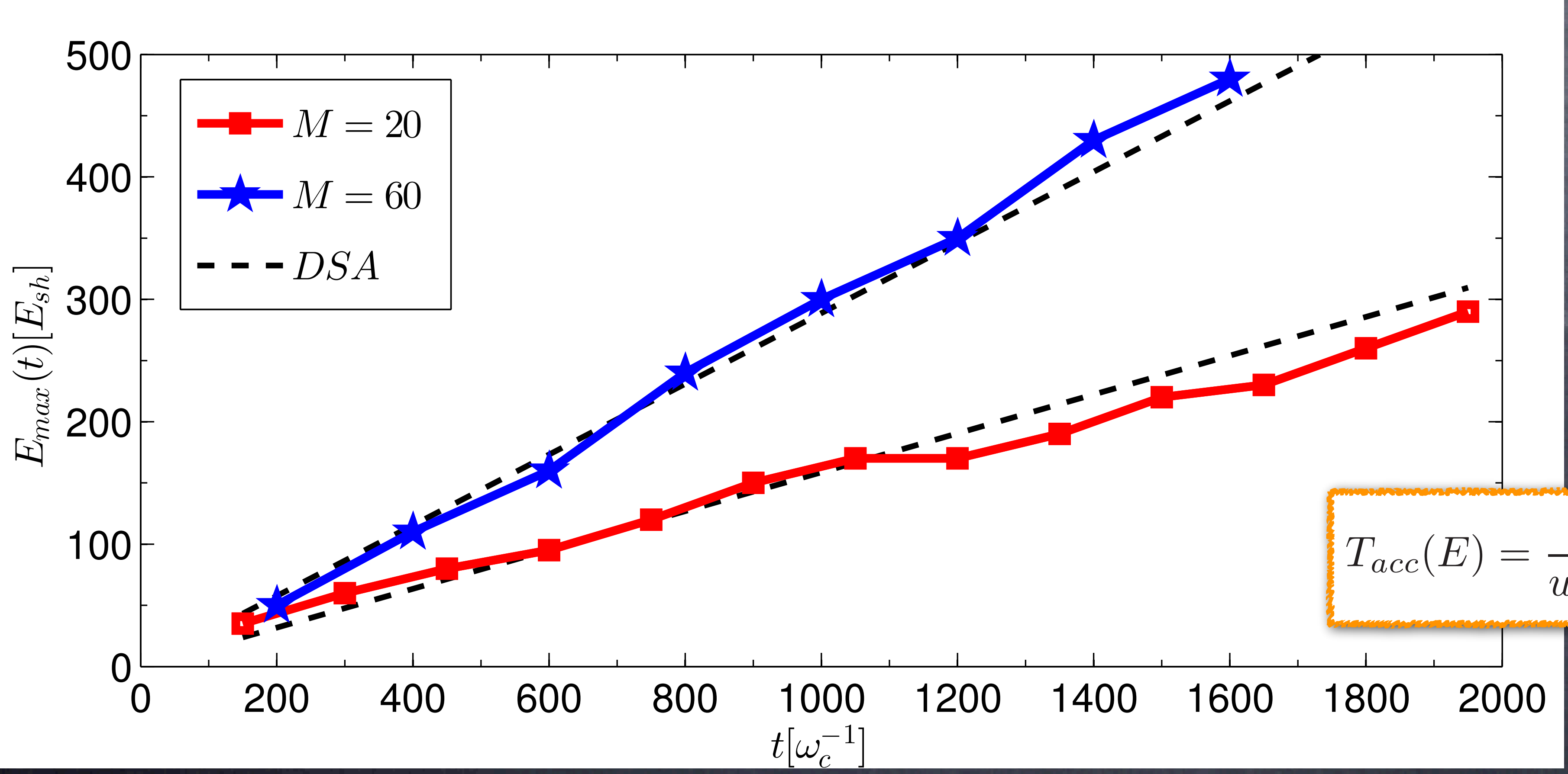
# Diffusion coefficient

- Directly measurable in simulations:

$$D(E) \equiv \lim_{t\to\infty} D(E,t) = \lim_{t\to\infty} \sum_{n=1}^{N} \frac{|x_n(t) - x_n(0)|^2}{2tN}.$$

**Bohm diffusion in the amplified B**




- Evolution of $E_{max}(t)$ according to DSA (Drury 83; Blasi+ 07)

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

# Outline

- Is acceleration at shocks efficient?
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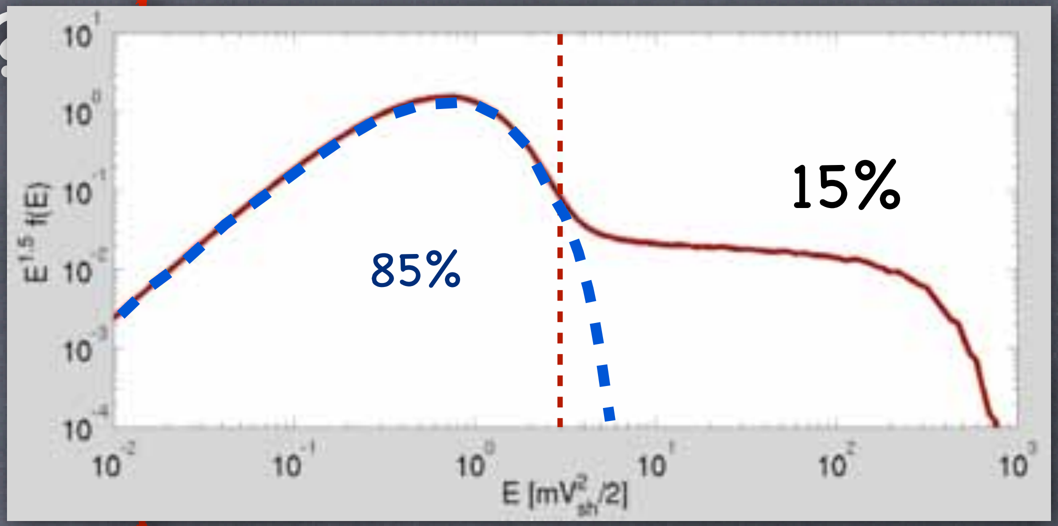
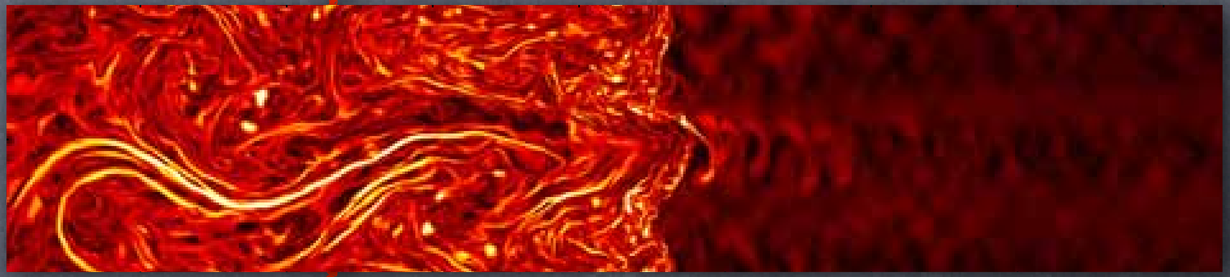
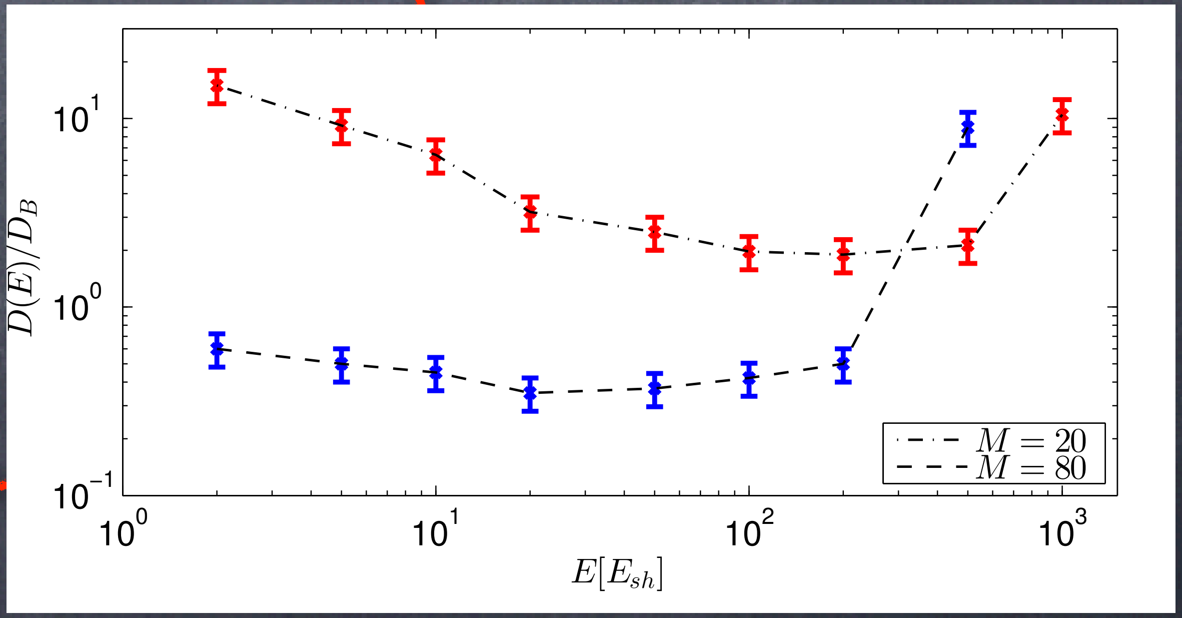
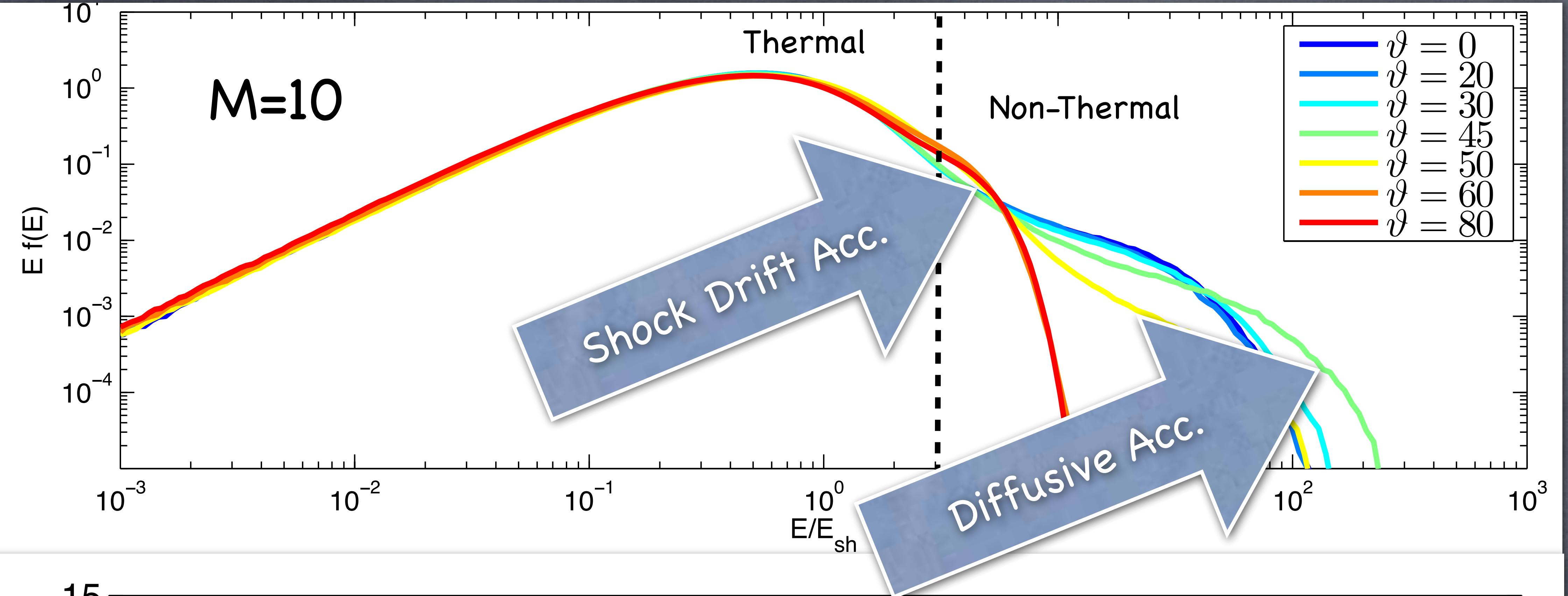
- How do CRs amplify the magnetic field?
  - Streaming instability
- How do magnetic fields scatter CRs?
  - Bohm diffusion in $\delta B$
- When is DSA efficient?

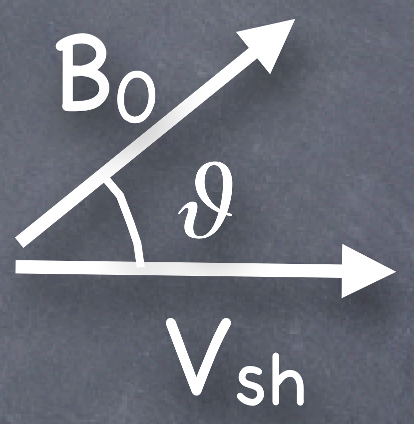


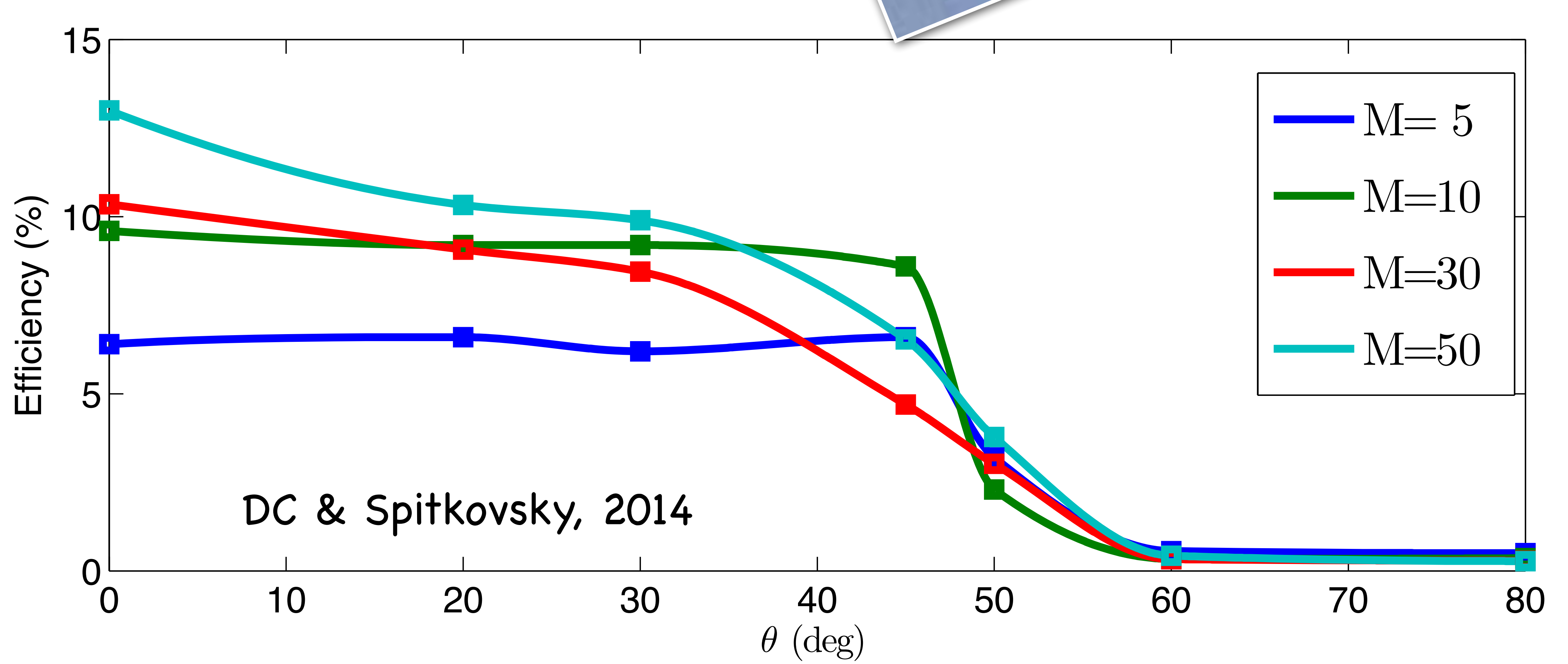





# Parallel vs Oblique shocks



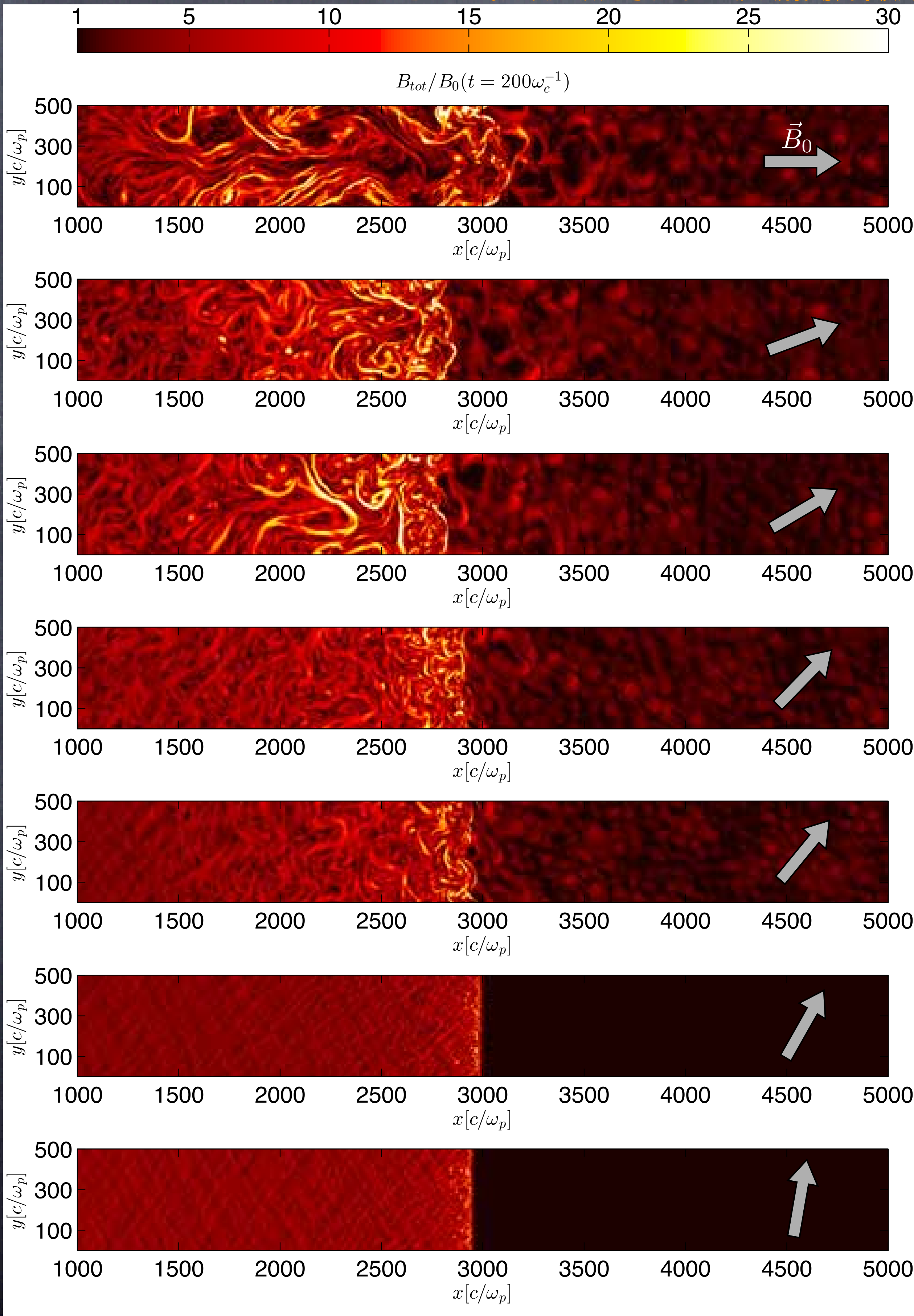



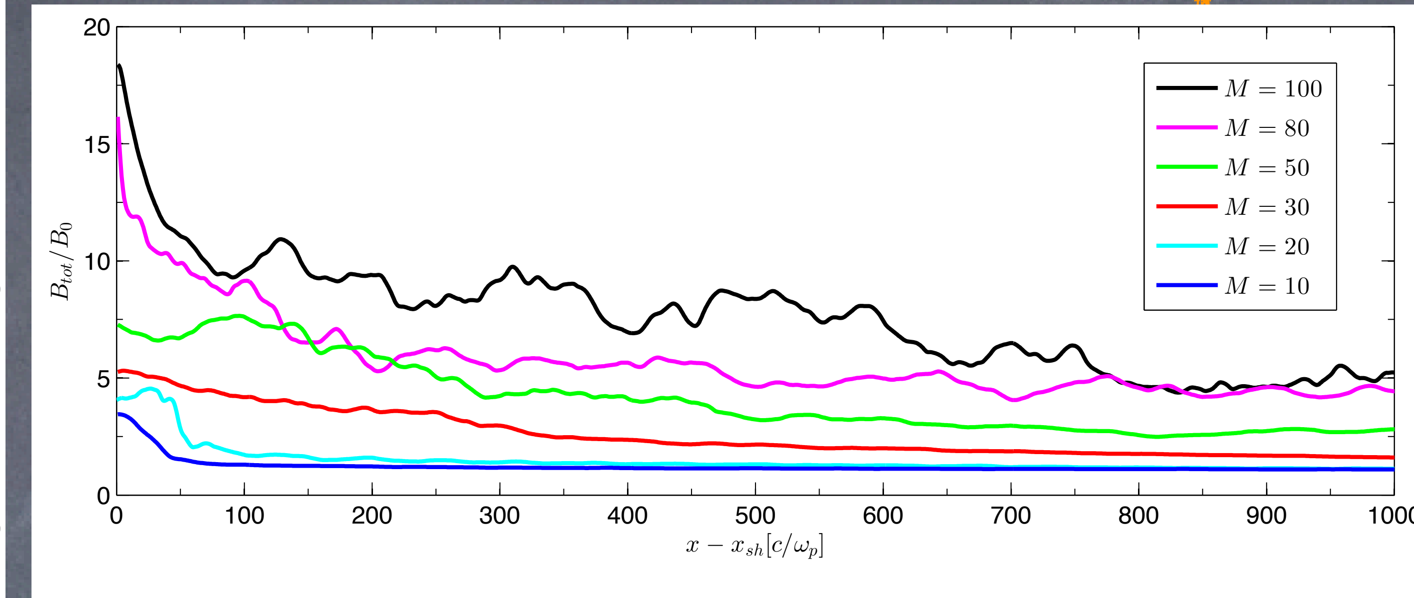

Each point is a state of the art simulation ($10^9$ particles)

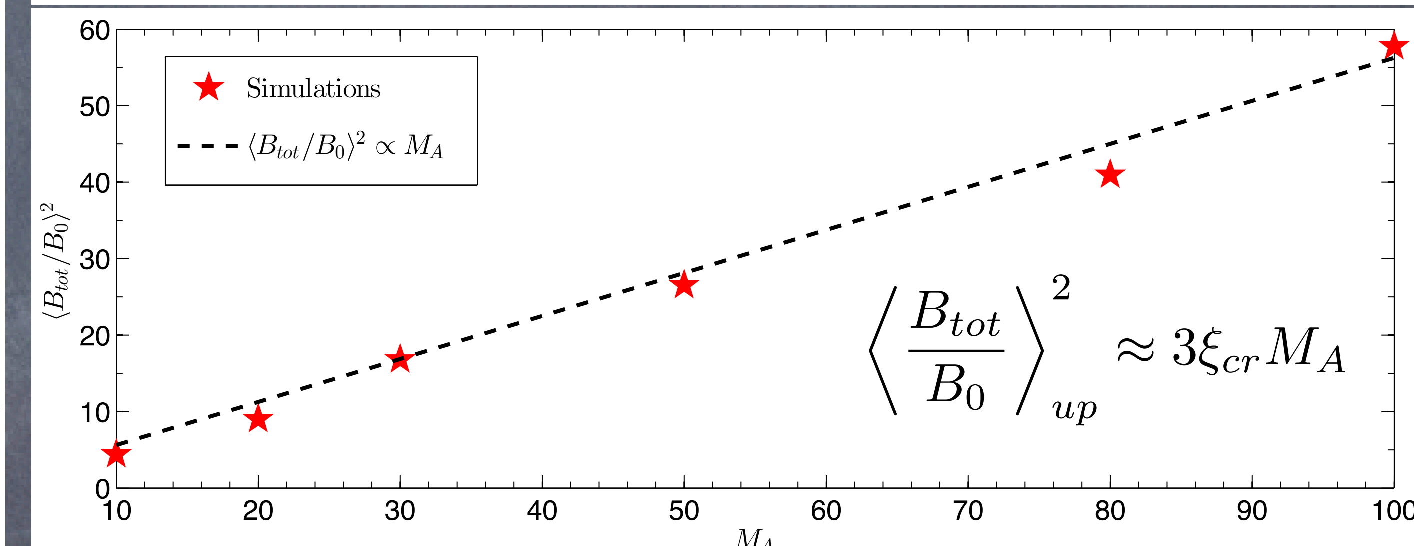
Computation time: almost

$2x10^6$ cpu h

# Dependence on inclination and M

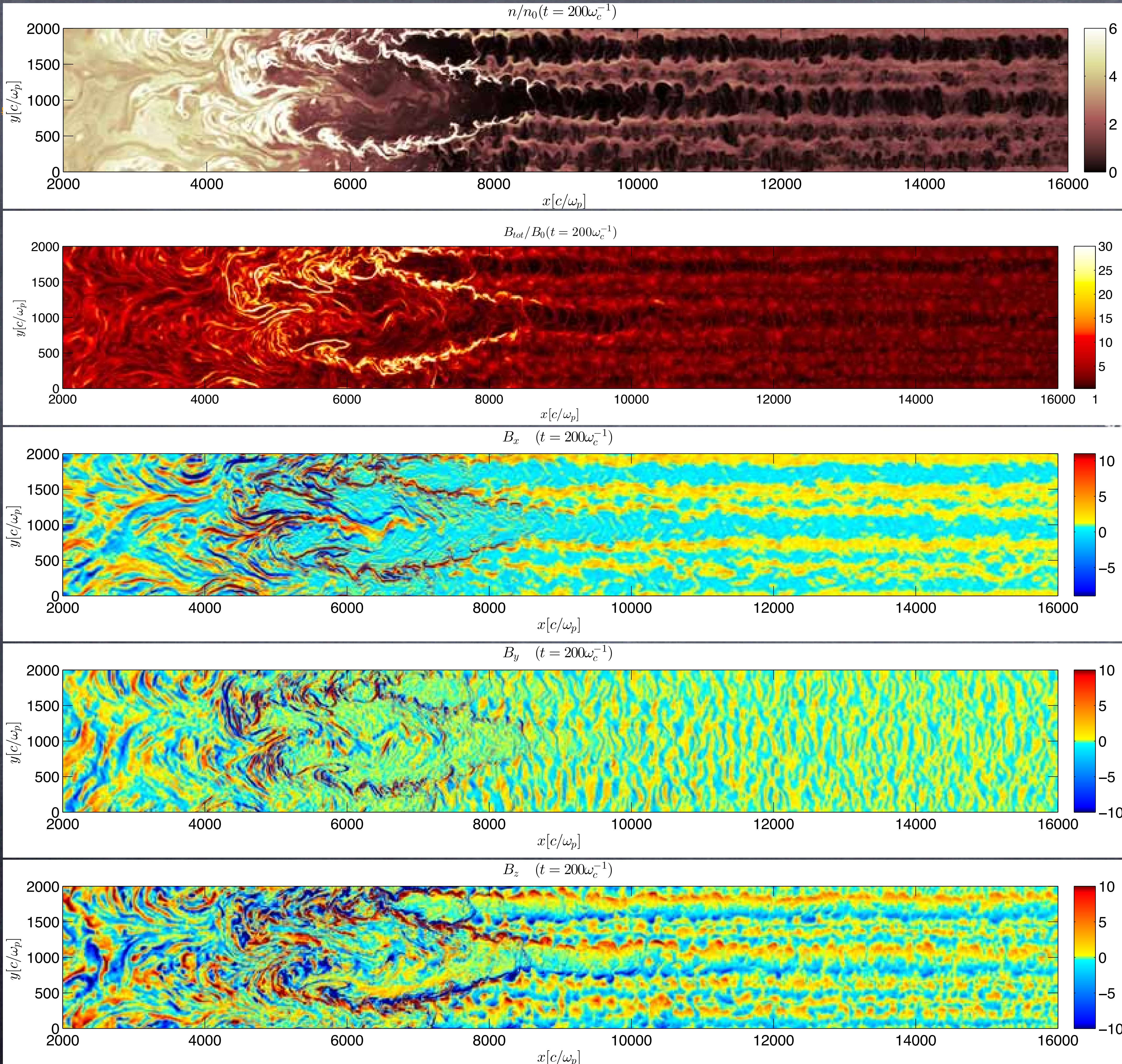



- In agreement with the prediction of resonant streaming instability

More B-field amplification for stronger shocks!

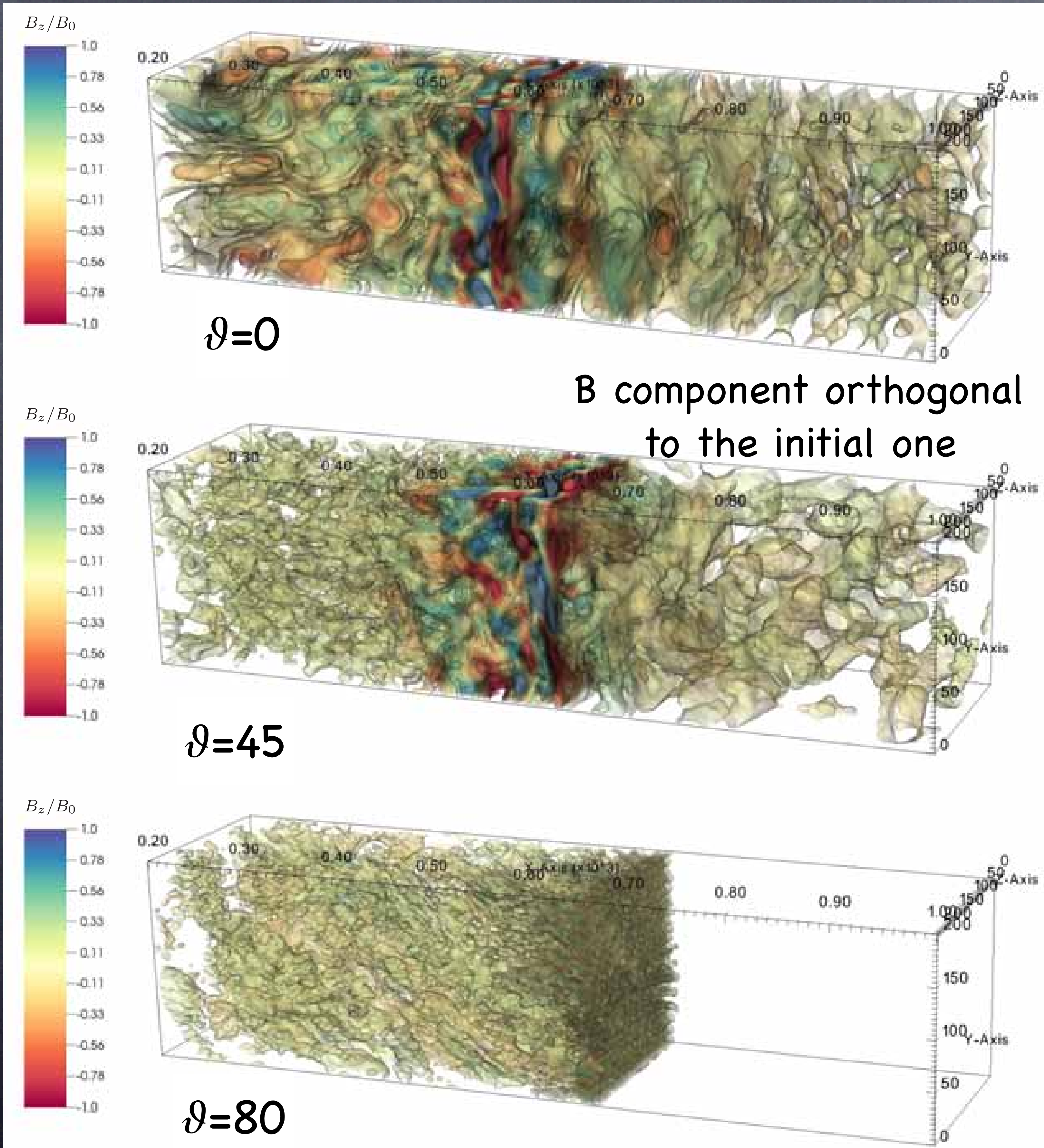


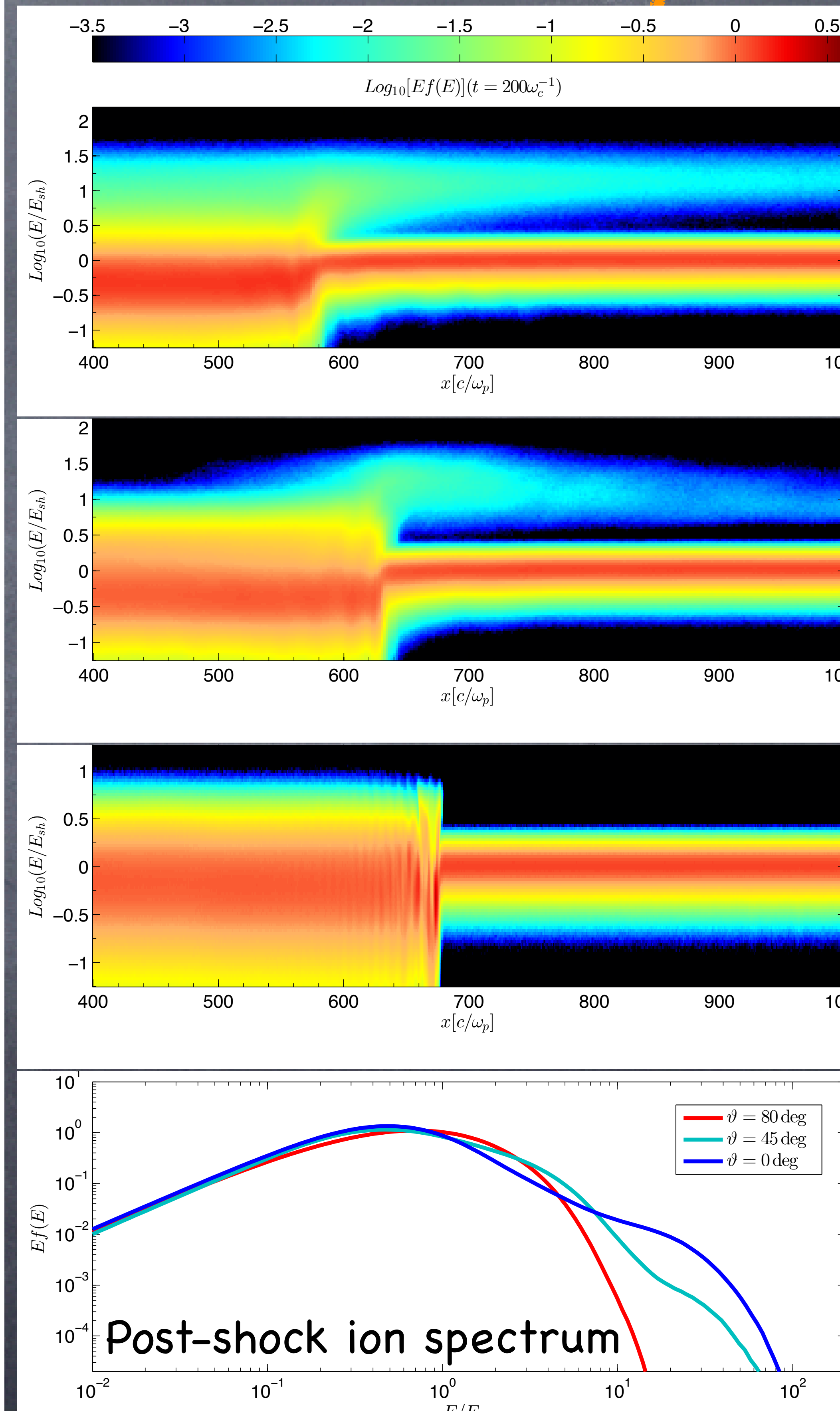

Preliminary
M=100 case

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

Very hard to study in the hybrid limit

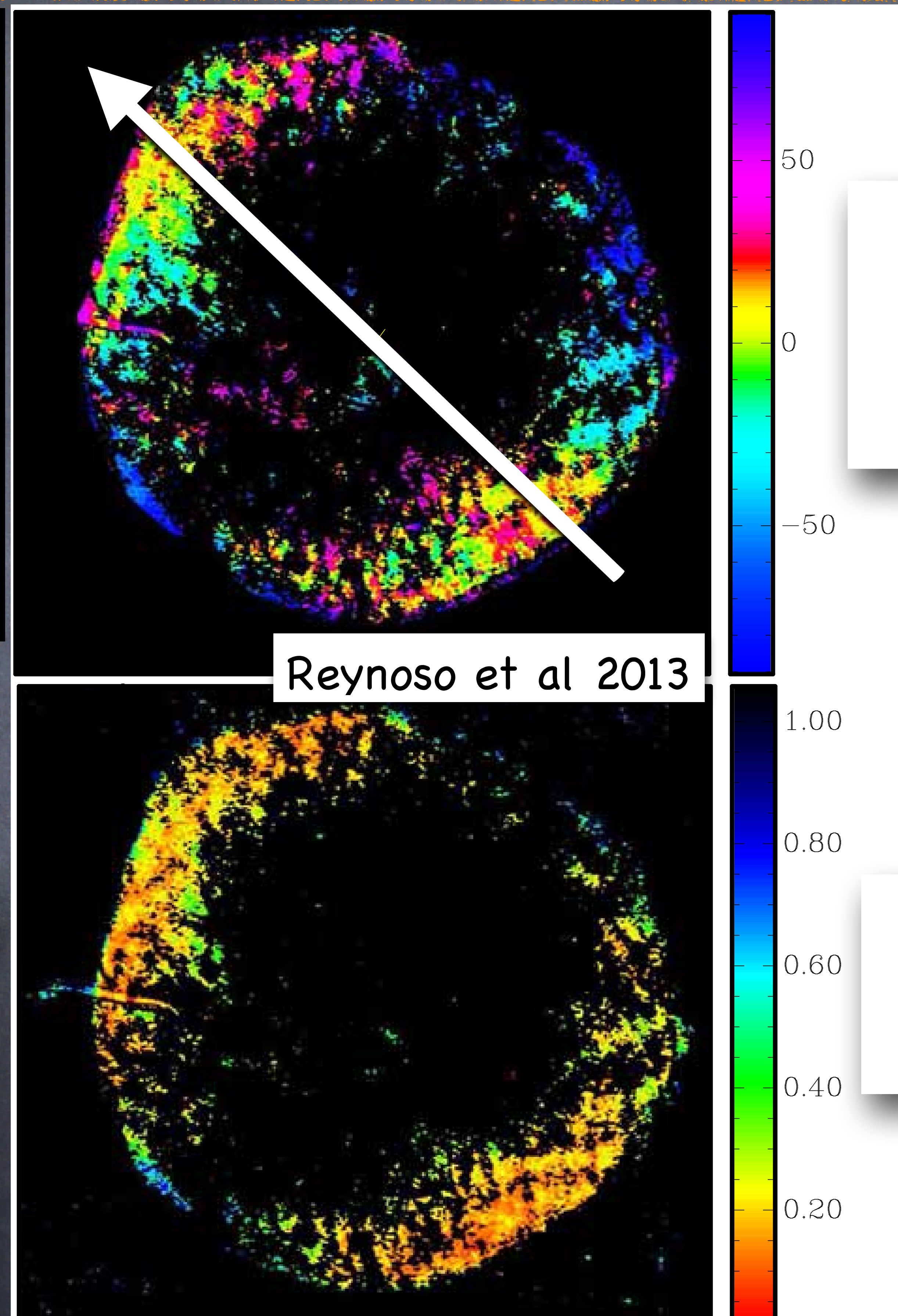
# 3D simulations



# SN 1006: a parallel accelerator

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




Inclination of the B field wrt to the shock normal

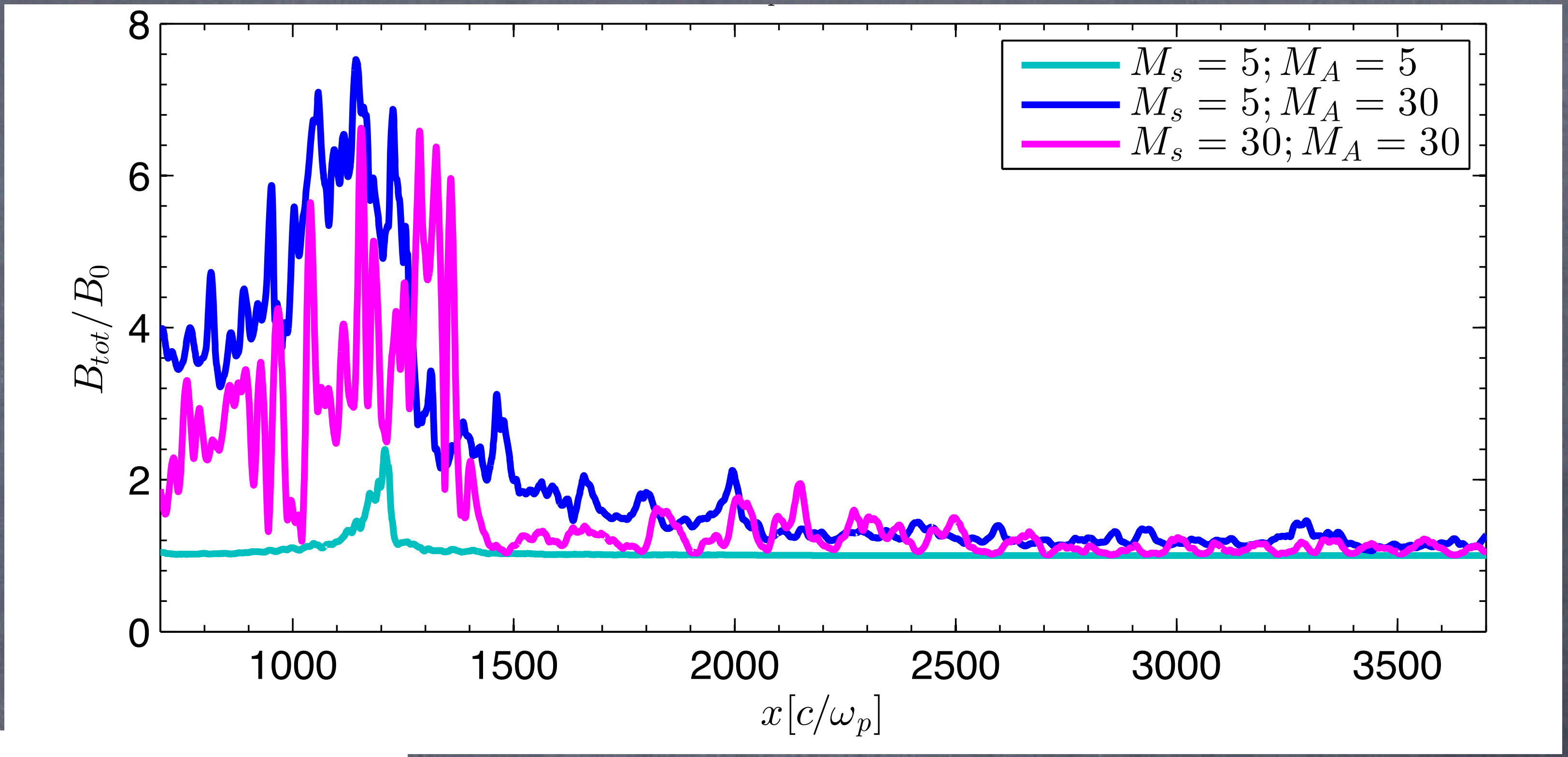
Polarization (low=turbulent high=ordered)

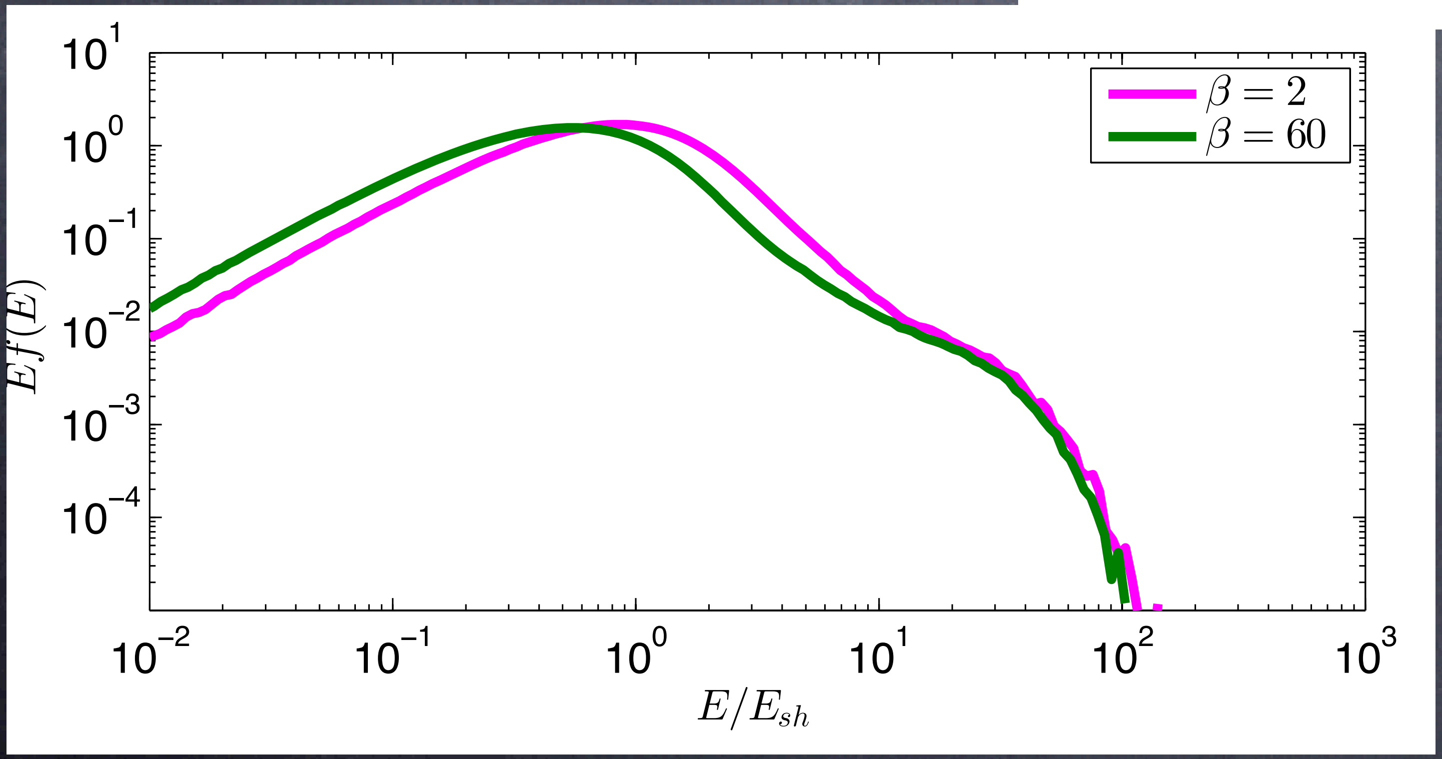
Magnetic field amplification and particle acceleration where the shock is parallel

# High-beta plasmas

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

Even for high $\beta$ magnetic fields are amplified!

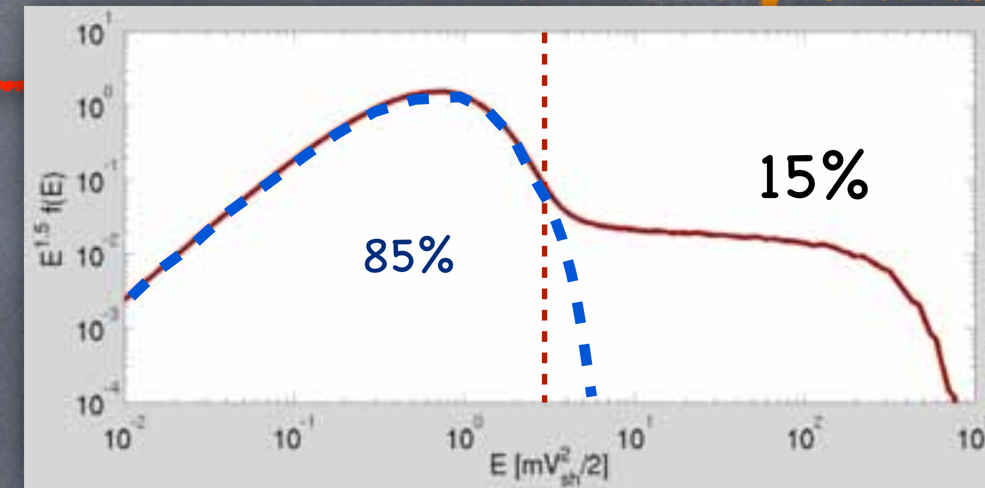


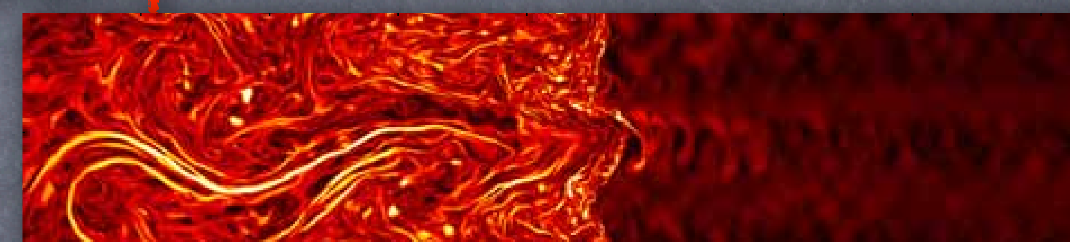

CR spectra agree with DSA prediction (steeper than $p^{-4}$ for r<4)

# Outline -> Conclusions

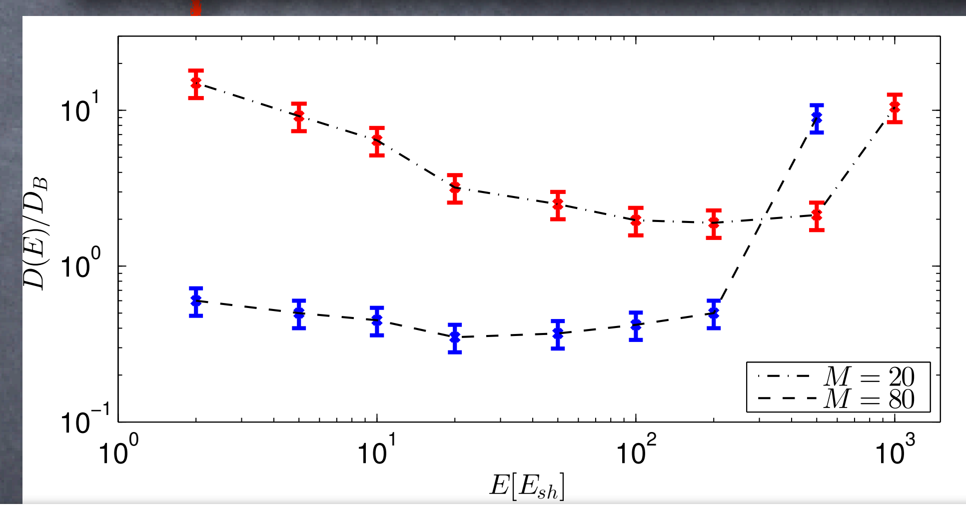
- Is acceleration at shocks efficient?
  - Hybrid simulations: >15%



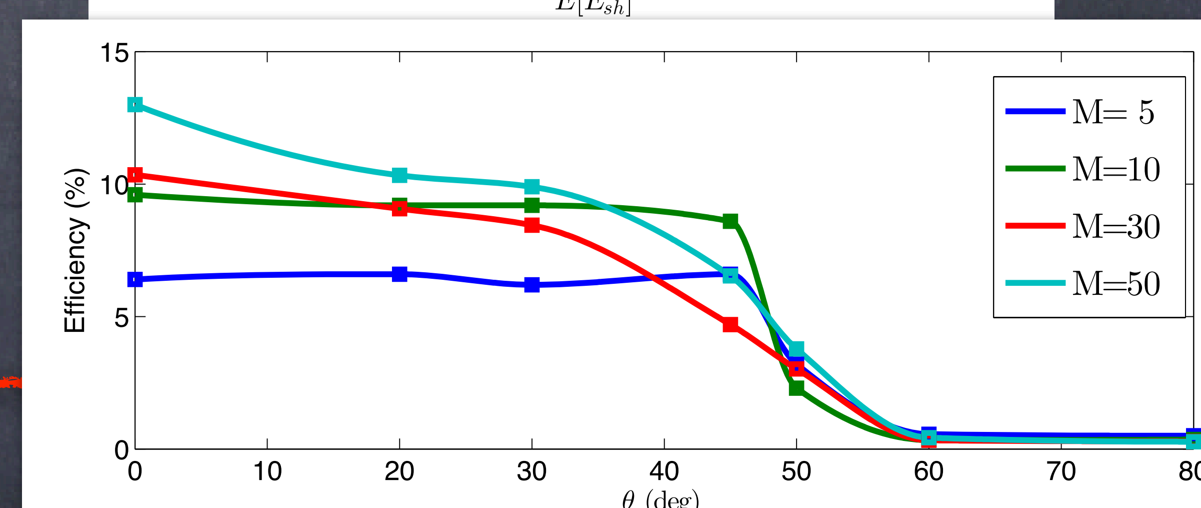

- How do CRs amplify the magnetic field?
  - Streaming & filamentation inst.



- How do fields scatter CRs?
  - Bohm diffusion in $\delta$B




- Where is DSA efficient?
  - At parallel, strong shocks

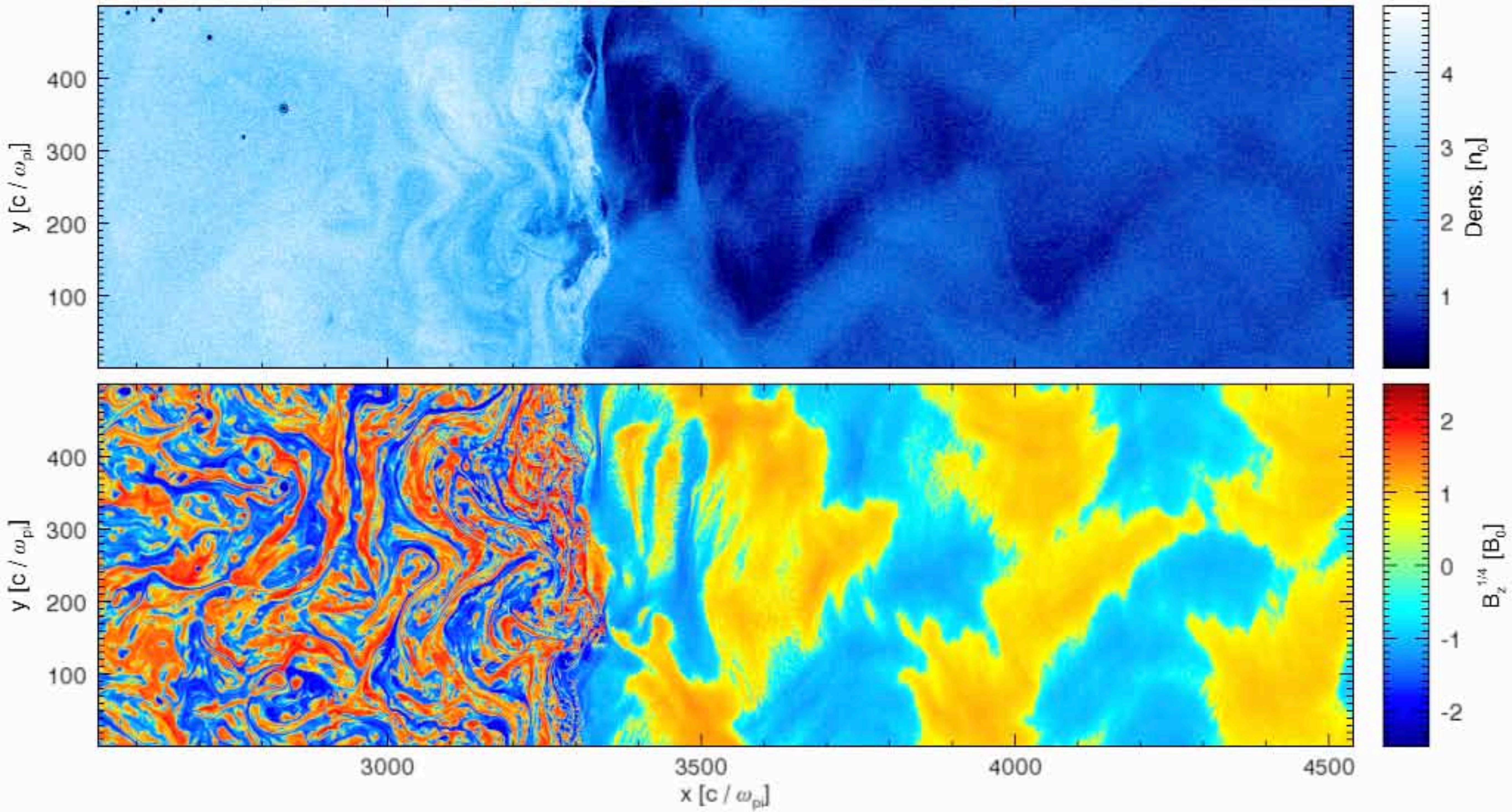


# (Near-)Future Perspectives

- Ion injection (DC, in prog.)
- Electrons with PIC (with J. Park, A. Spitkovsky) - PLEASE ASK!!
- Need to go relativistic, and to higher Mach numbers
  - Super-Hybrid, with A. Spitkovsky, X. Bai, L. Sironi (CfA)

- How to embed CR physics in large-scale simulations?
- CRAFT: Cosmic Ray Analytical Fast Tool (DC, in prog.)
  - Semi-analytical solution of CR transport equation
  - Very fast: few seconds on a laptop
  - Embeds microphysics from kinetic simulations

# Thank you!



400
300
200
100
y [c / ω_pi]
4
3
2
1
Dens. [n_0]
400
300
200
100
y [c / ω_pi]
2
1
0
-1
-2
B_z^1/4 [B_0]
3000
3500
4000
4500
x [c / ω_pi]