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Hybrid simulations of particle acceleration at non-relativistic shocks

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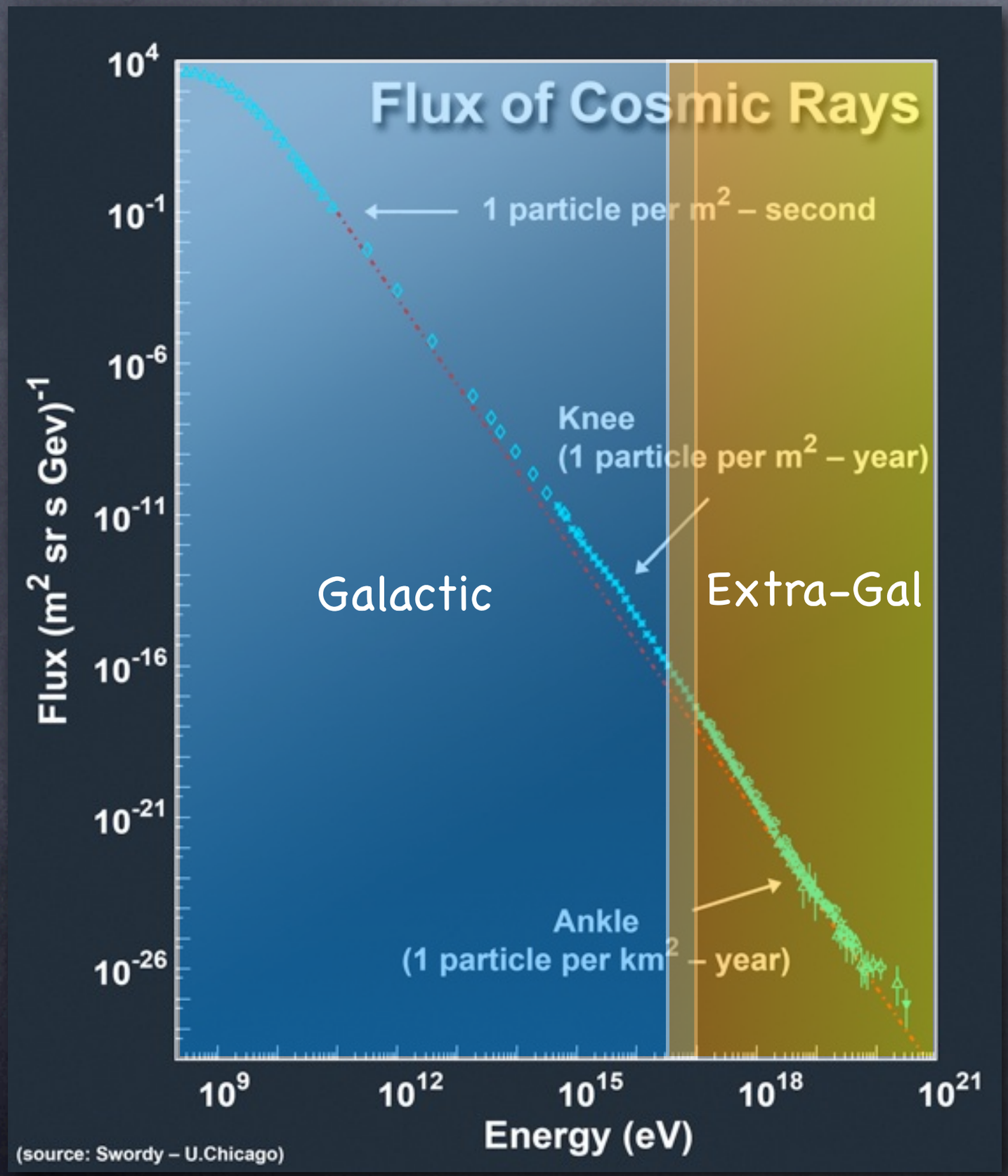
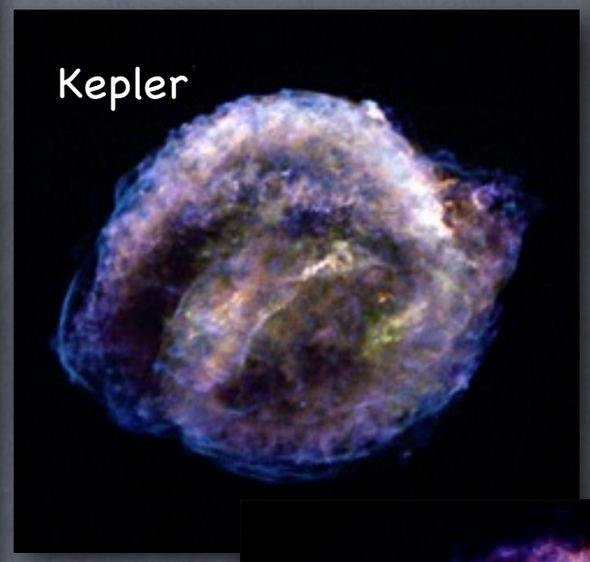
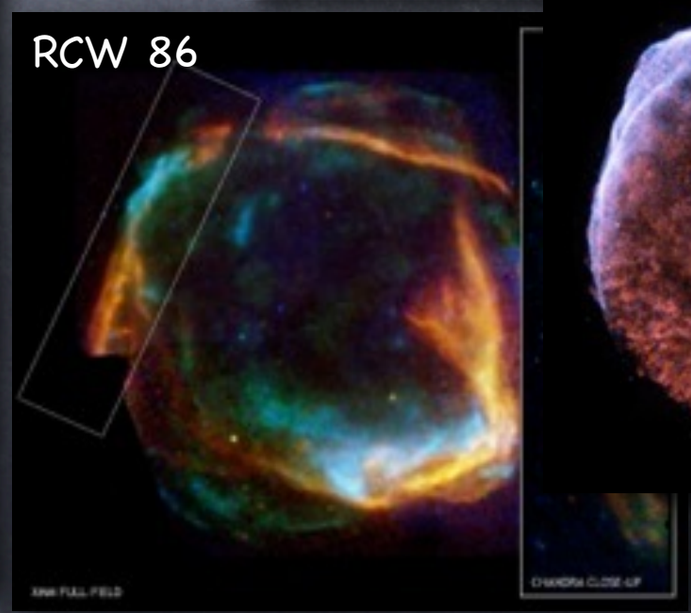
In collaboration with: Anatoly Spitkovsky (Princeton)

The SNR paradigm for Galactic CRs







Conclusions?

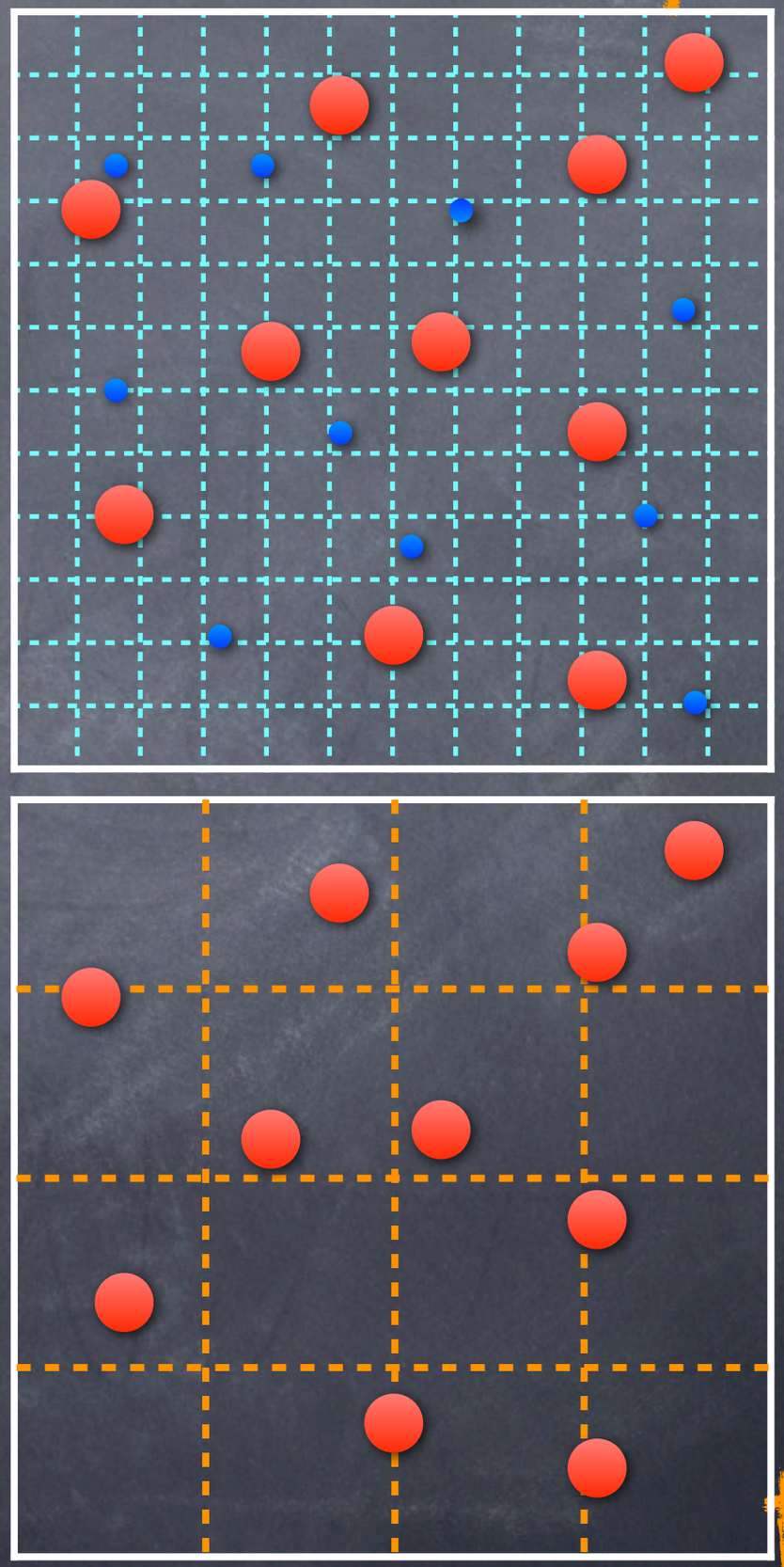
- **Supernova Remnants**
  - Have the right energetics
  - Diffusive shock acceleration produces power-laws
  - B amplification helps reaching the knee

BUT

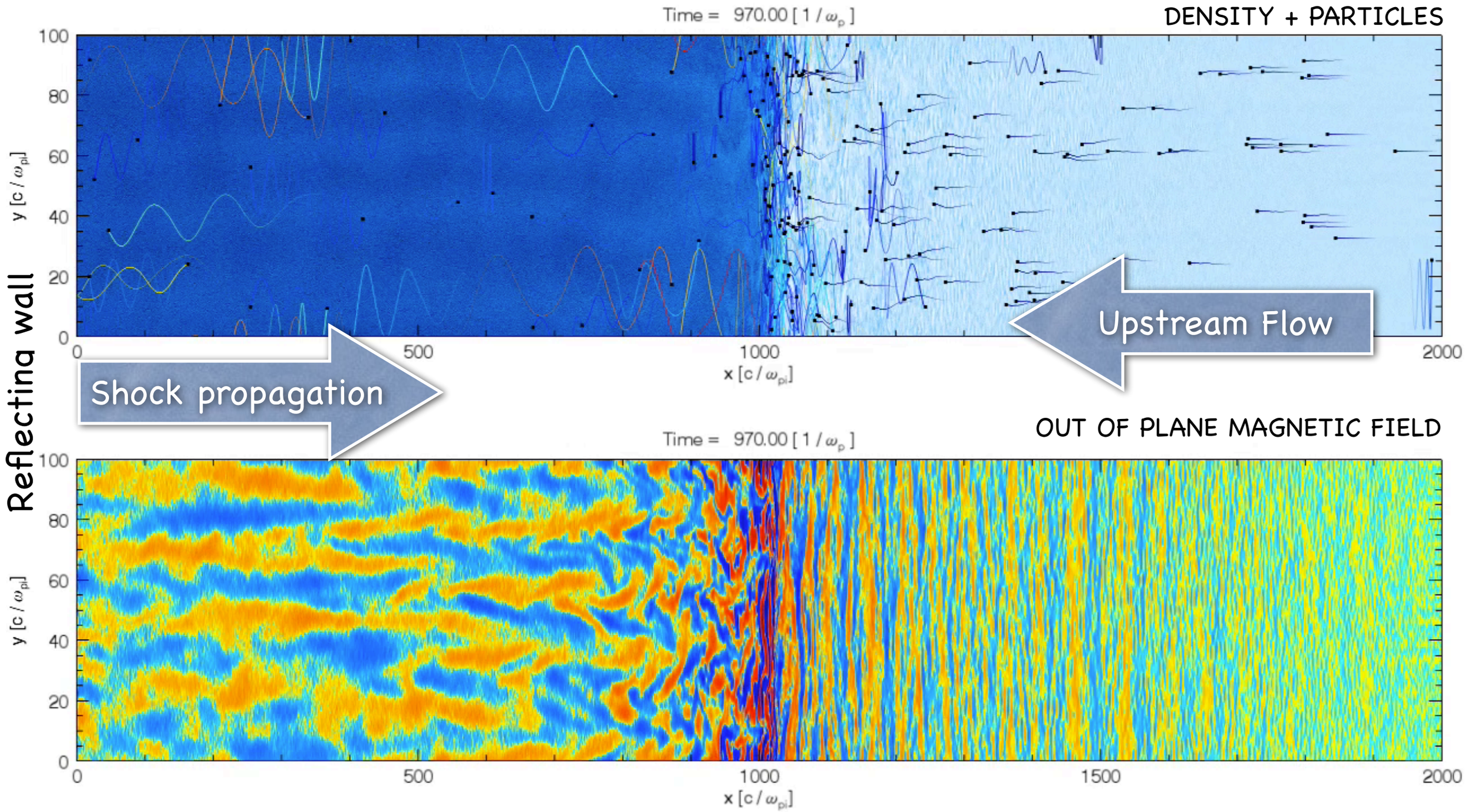
- Is acceleration at shocks efficient?
- How do CRs amplify the magnetic field?
- When is acceleration efficient?

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



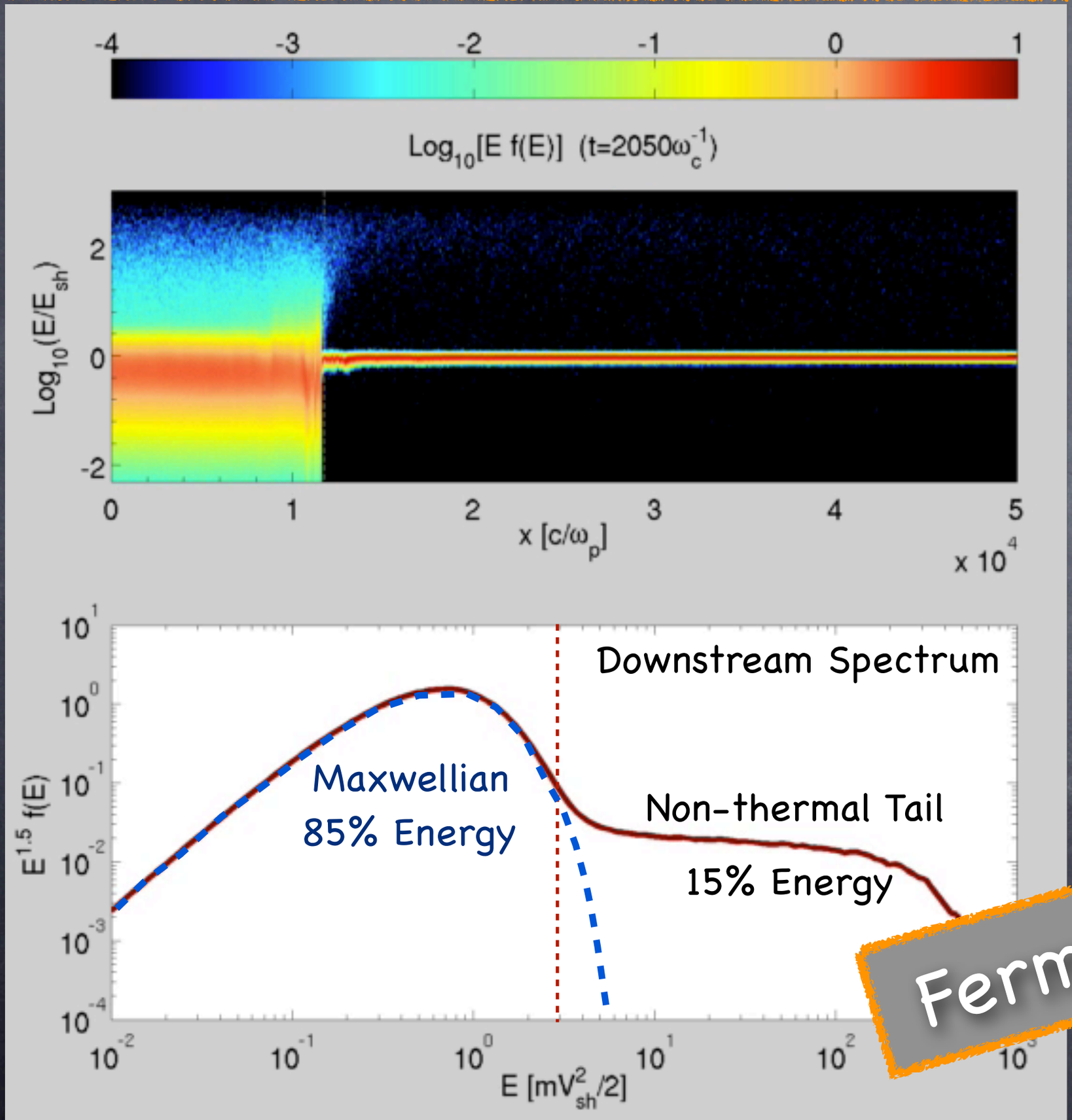
Hybrid simulations of collisionless shocks



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

Initial B field

Spectrum evolution



First-order Fermi acceleration:

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

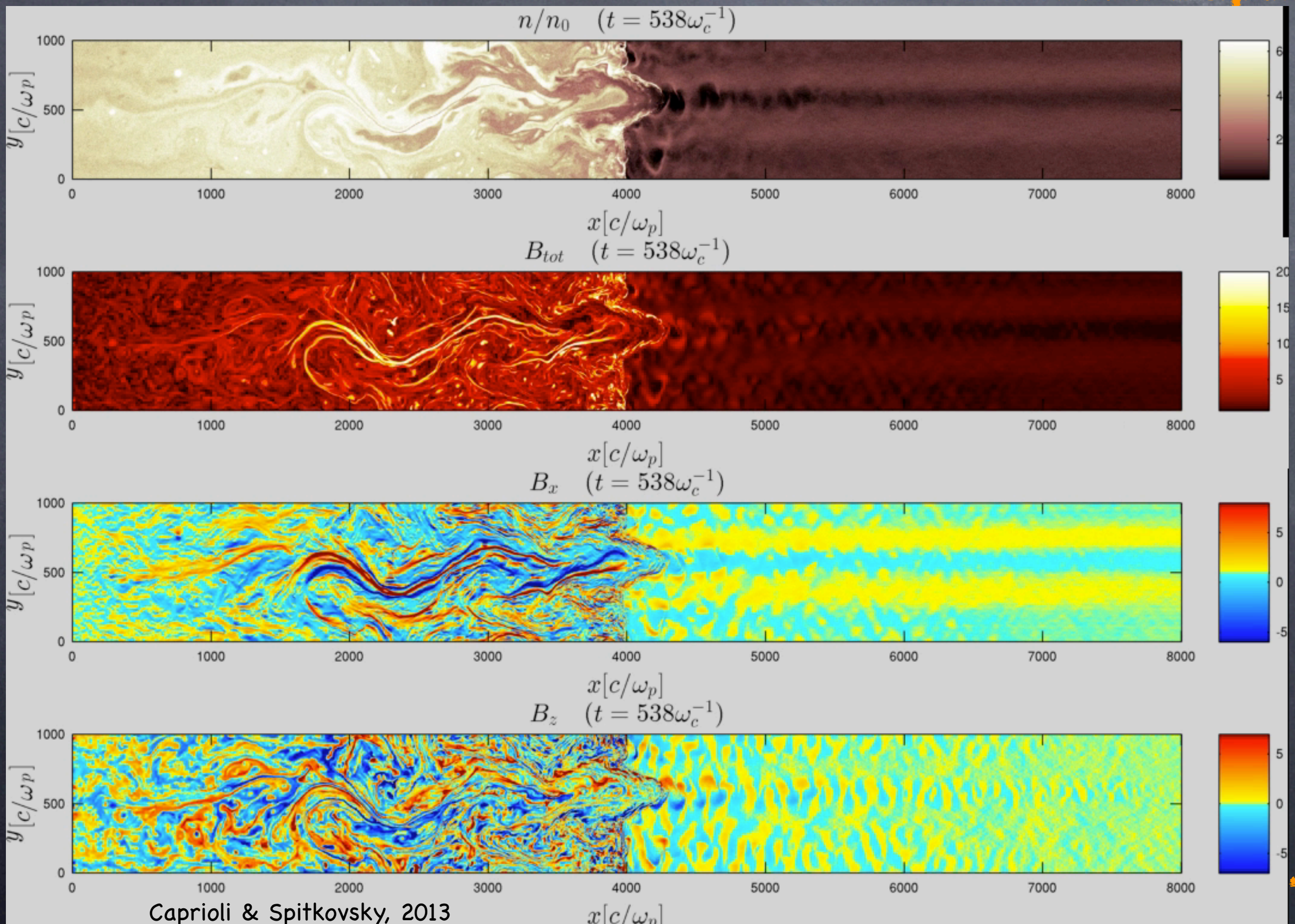
$4\pi p^2 f(p) dp = f(E) dE$

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

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

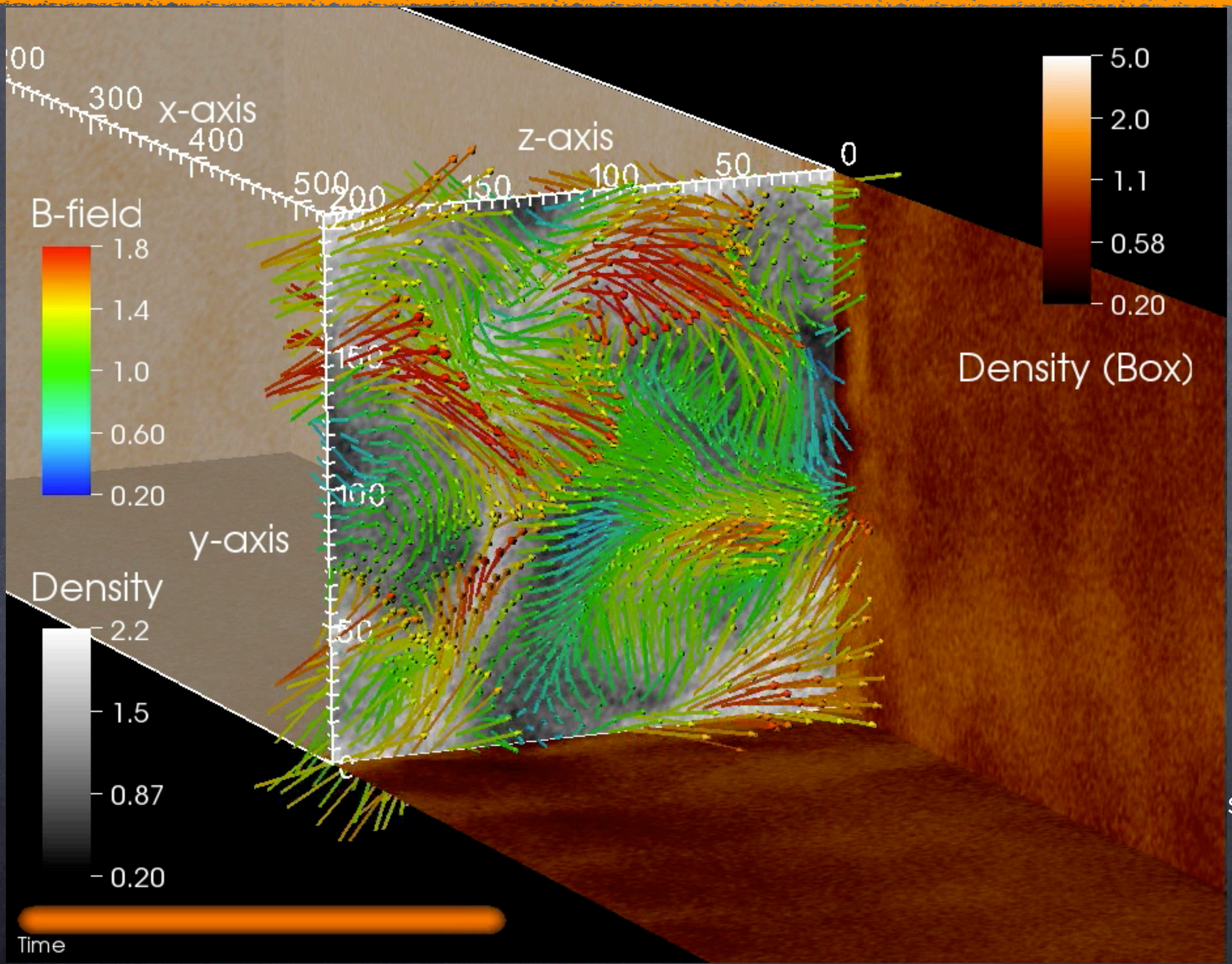
Fermi acceleration

Filamentation instability



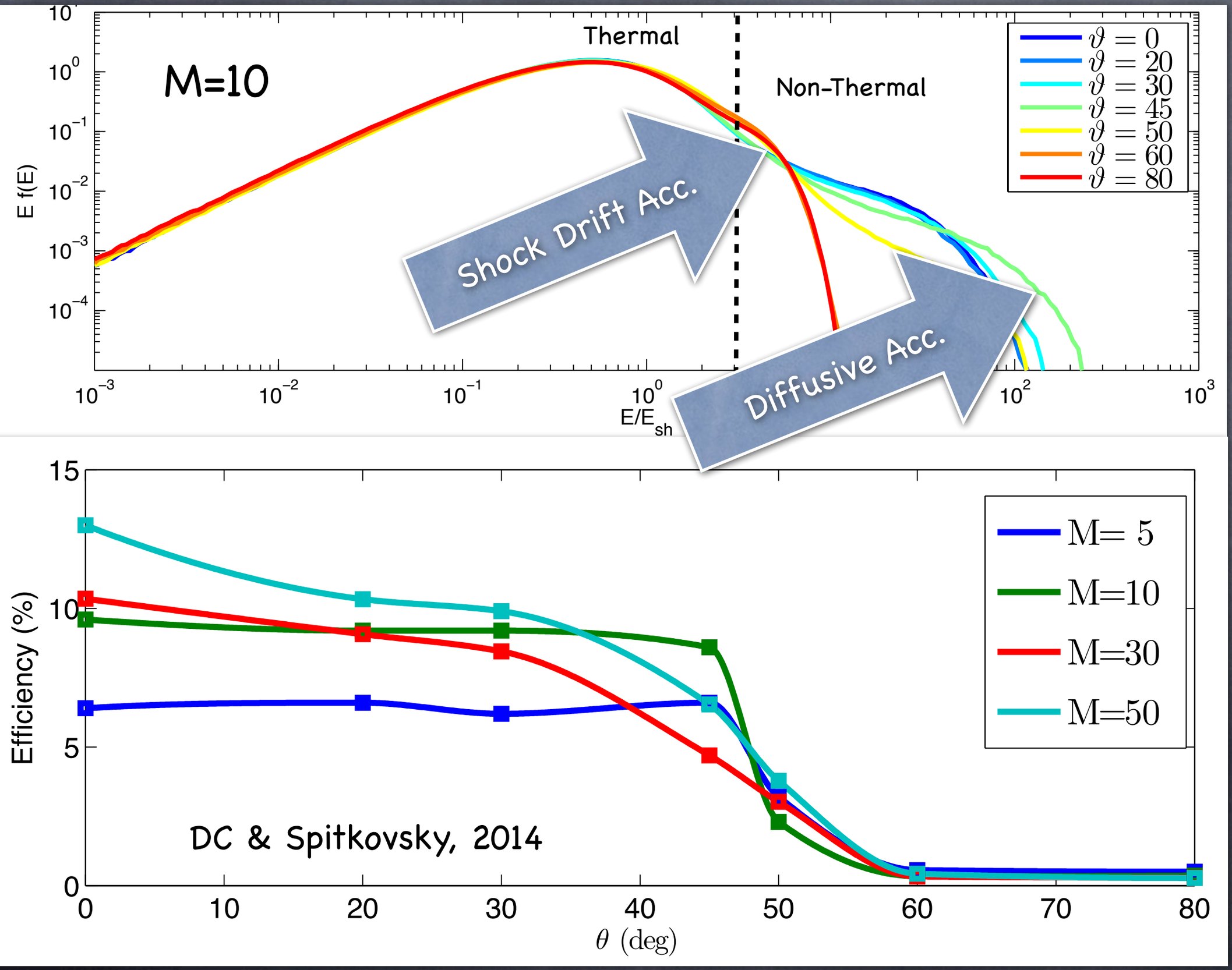
Caprioli & Spitkovsky, 2013

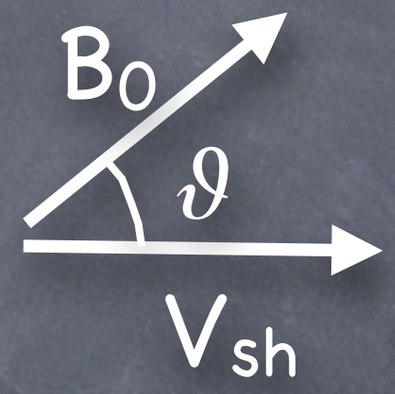
3D simulations of a parallel shock



Caprioli & Spitkovsky, 2014

Parallel vs Oblique shocks



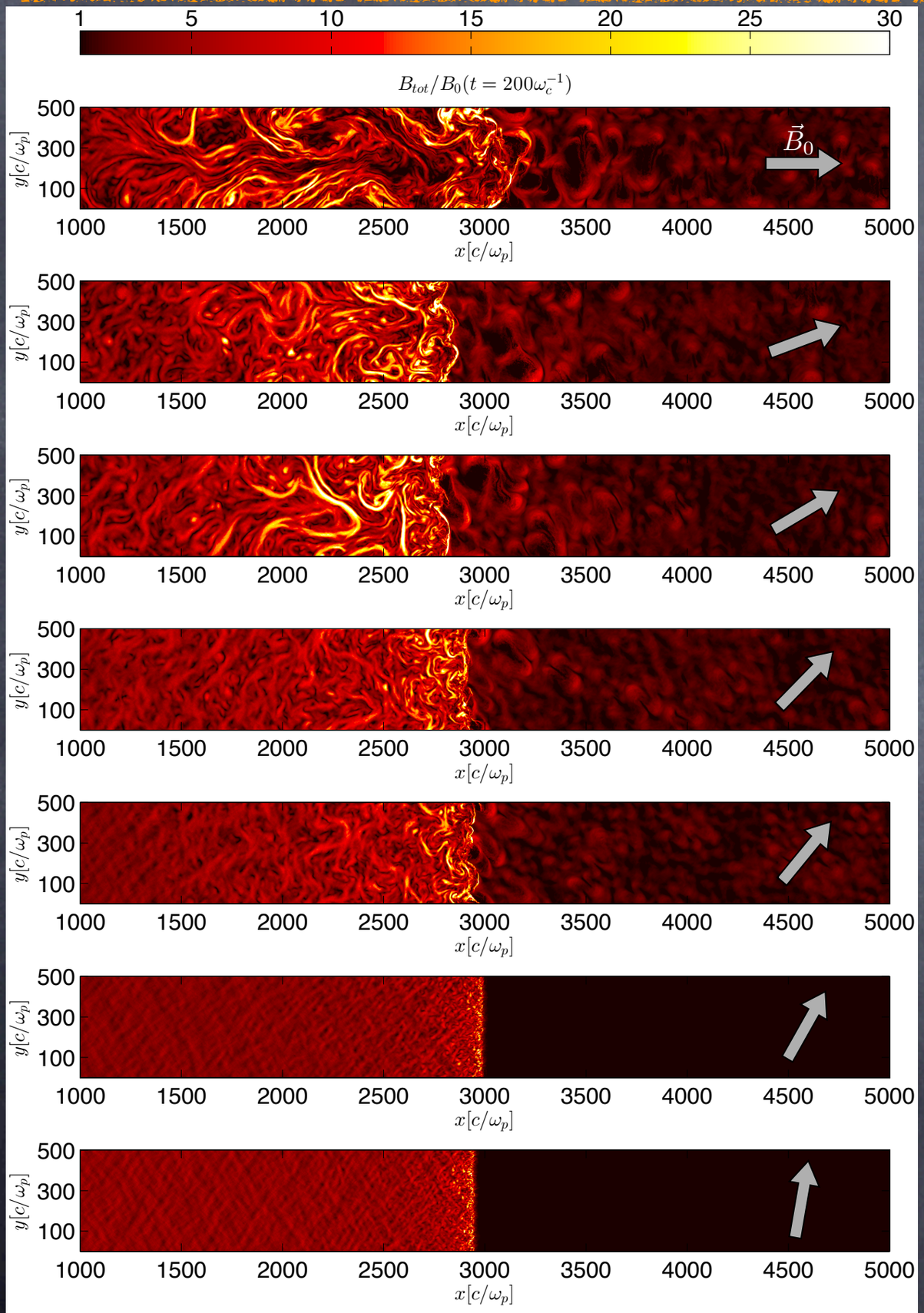


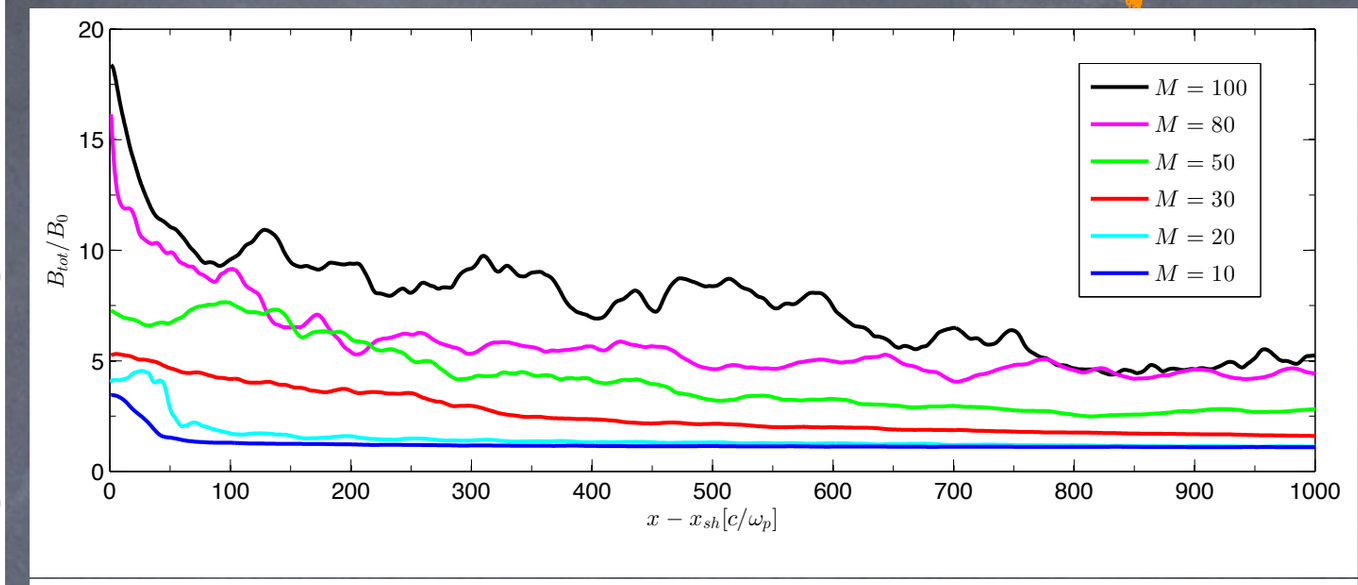
Each point is a state of the art simulation (10^9 particles)

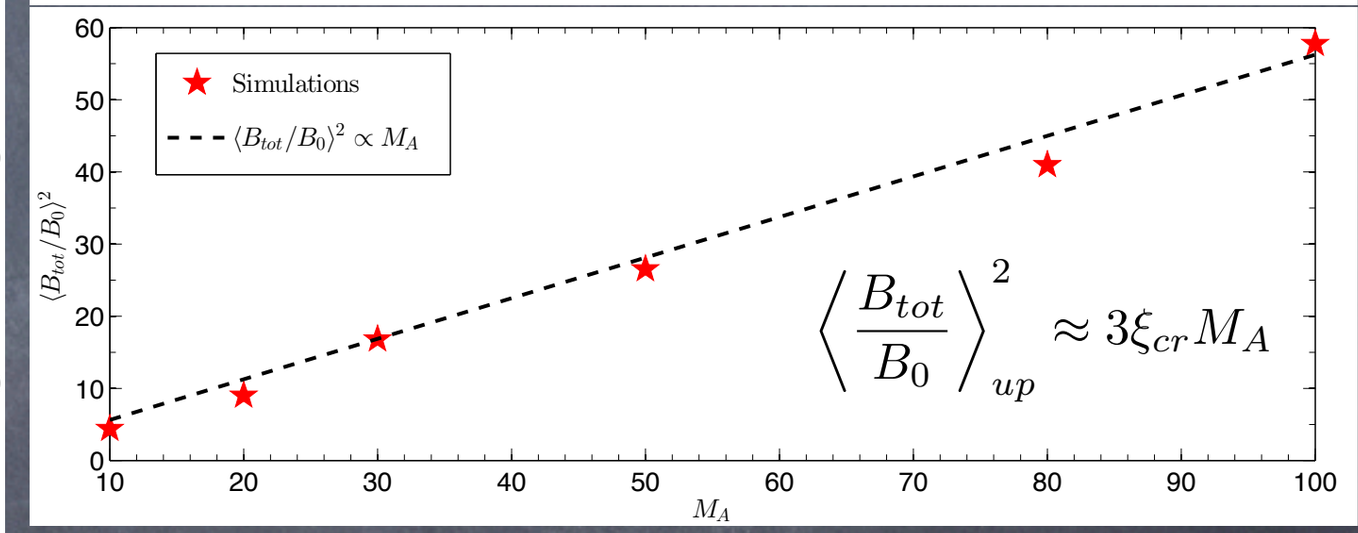
Computation time: almost

2×10^6 cpu h!

Dependence on inclination and M



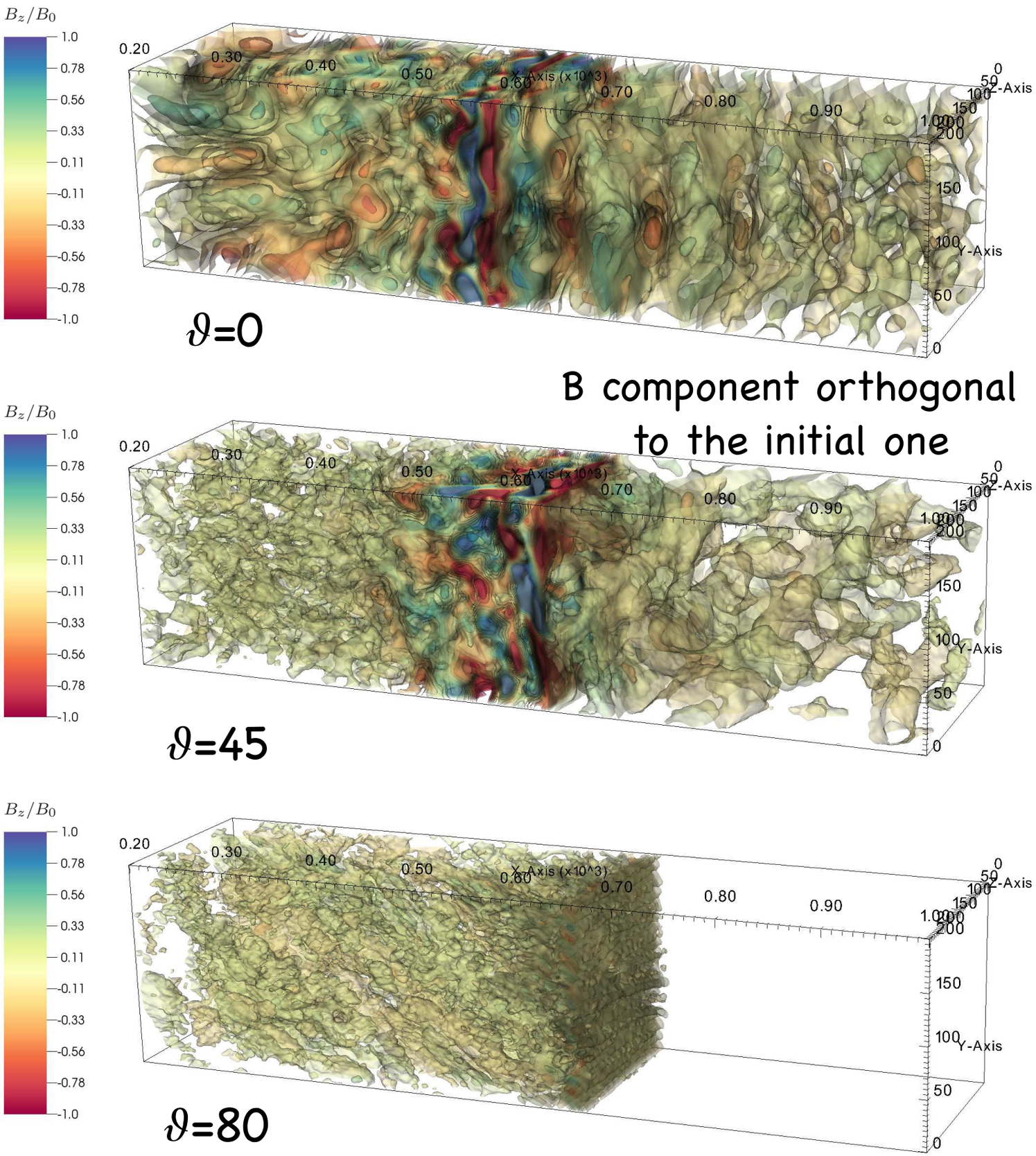




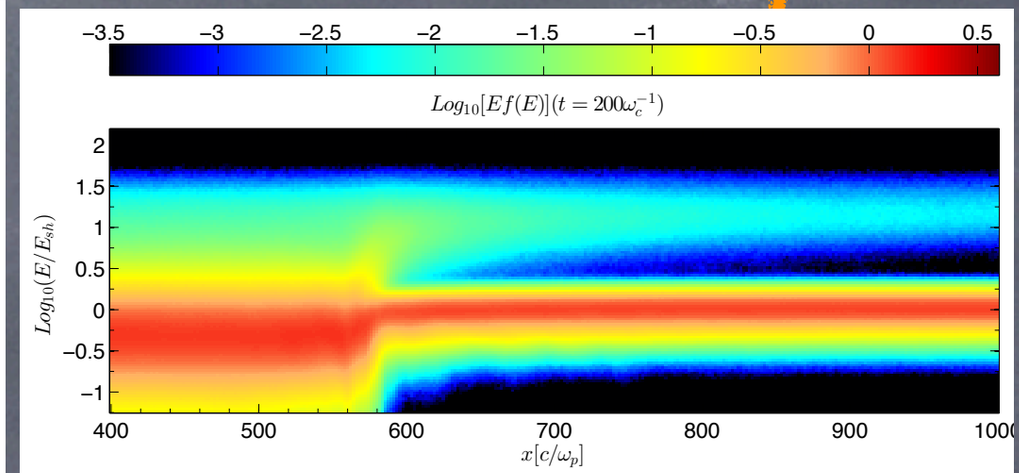
- In agreement with the prediction of resonant streaming instability

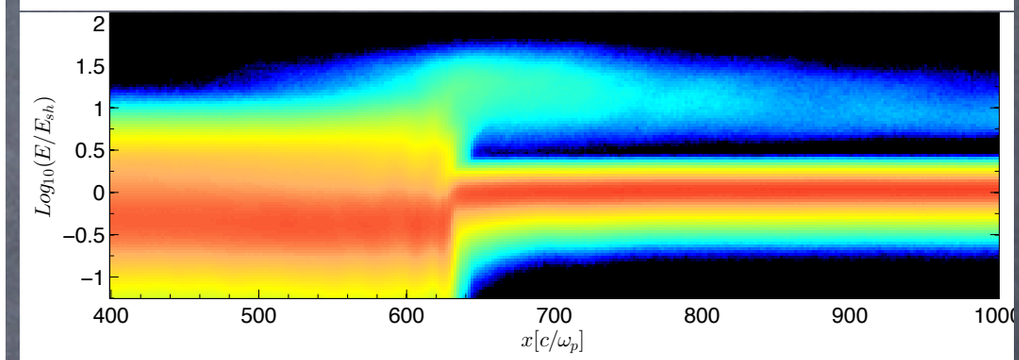
More B-field amplification for stronger shocks!

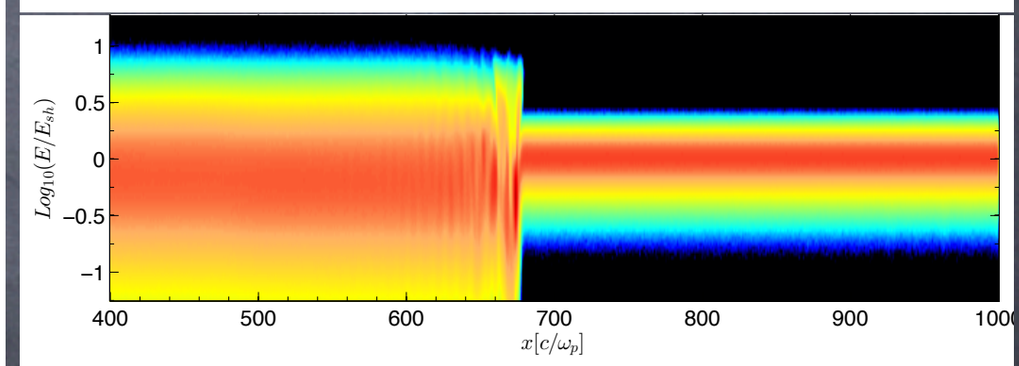
3D simulations

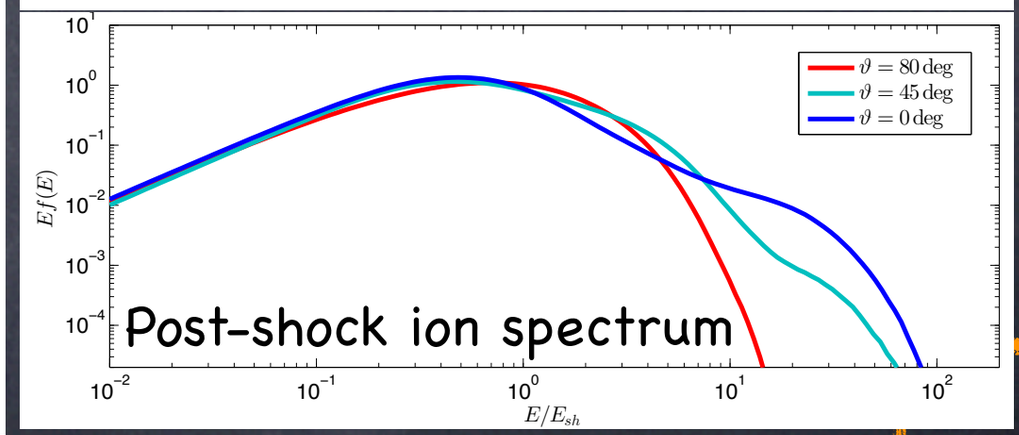


B component orthogonal to the initial one



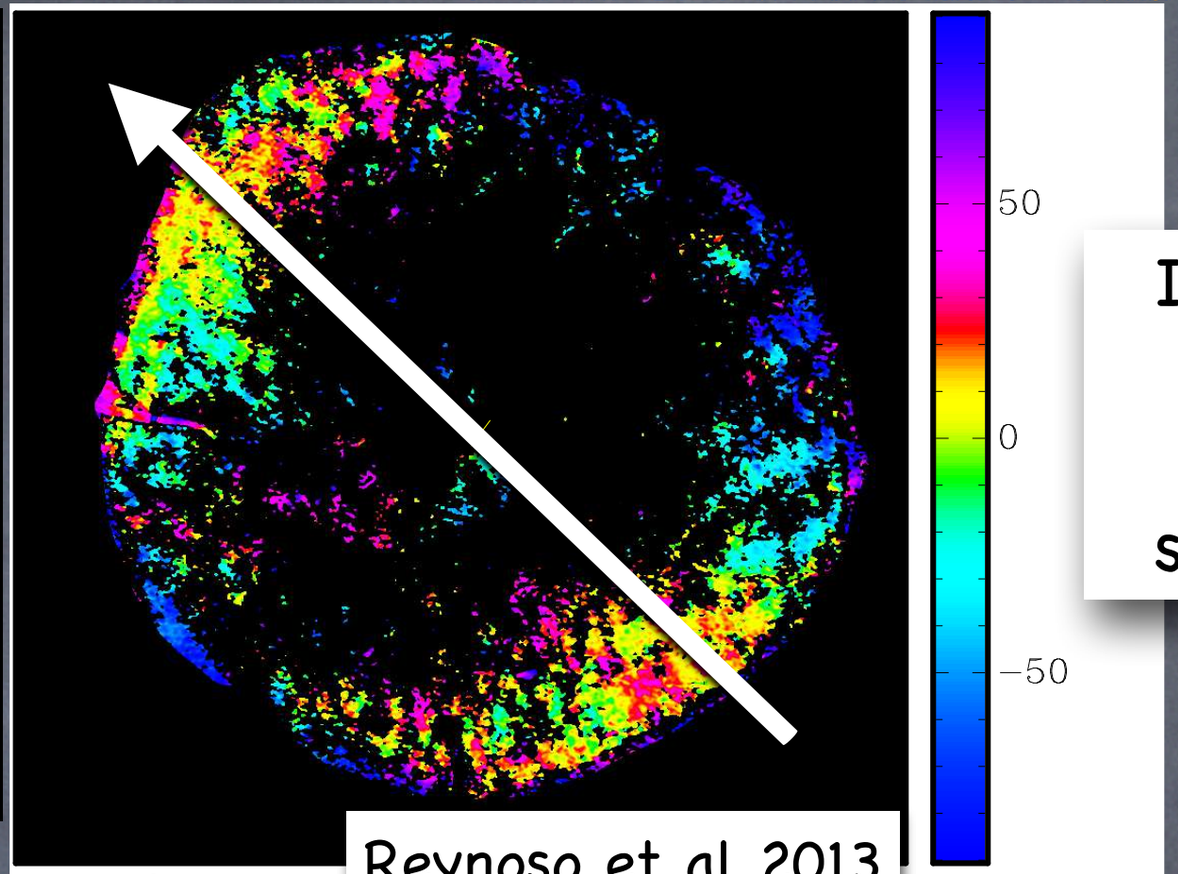






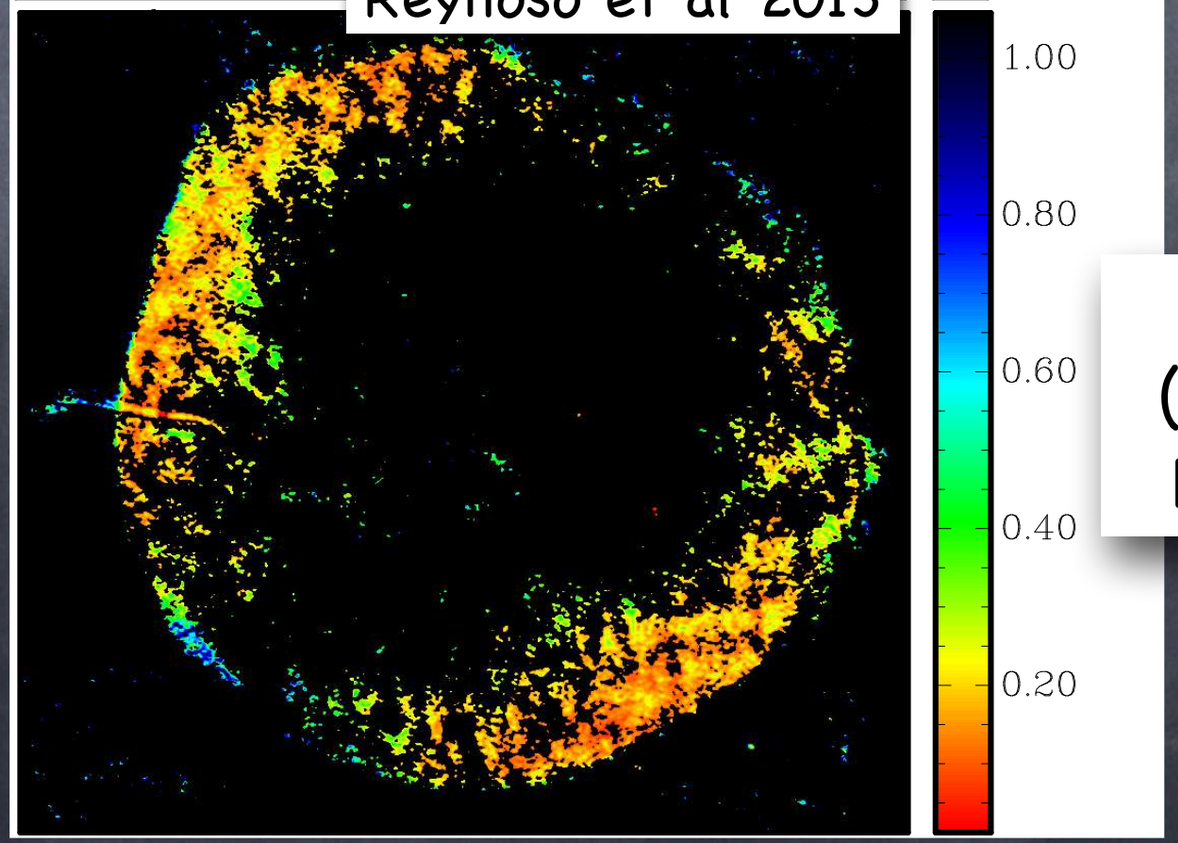
SN 1006: a parallel accelerator

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



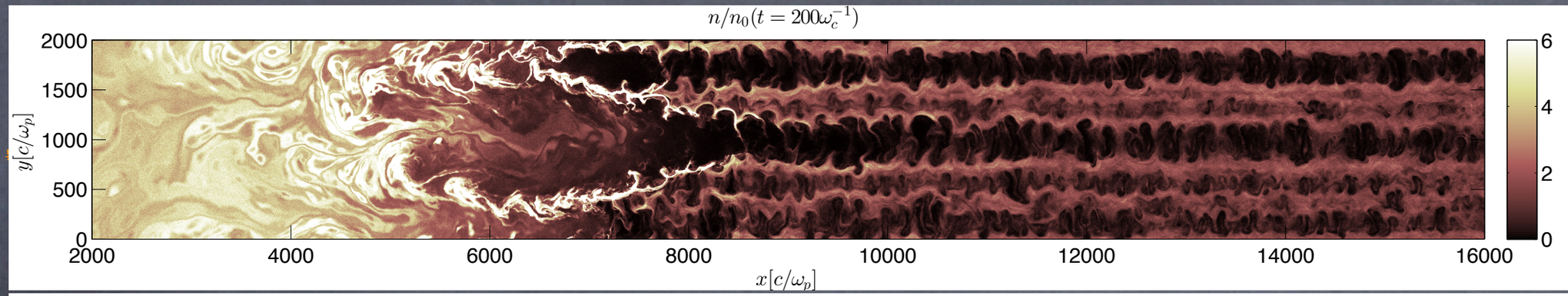
Inclination of the B field wrt to the shock normal

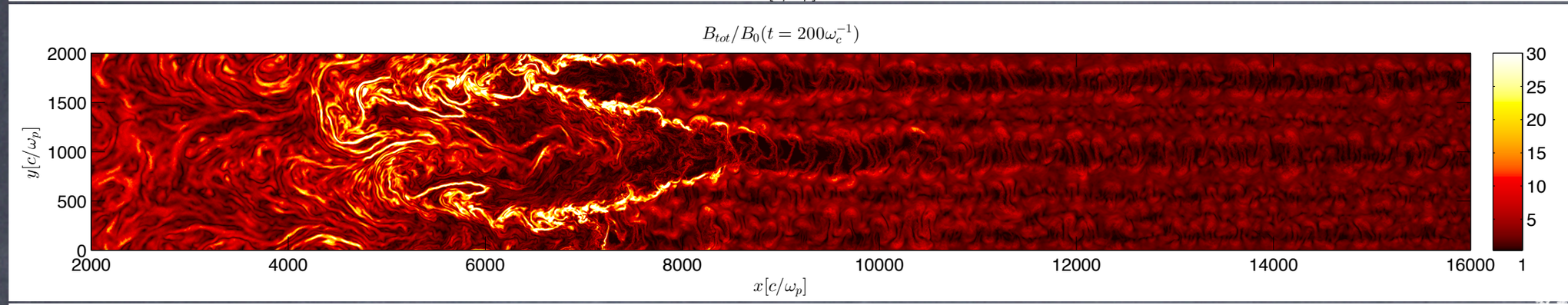
Reynoso et al 2013

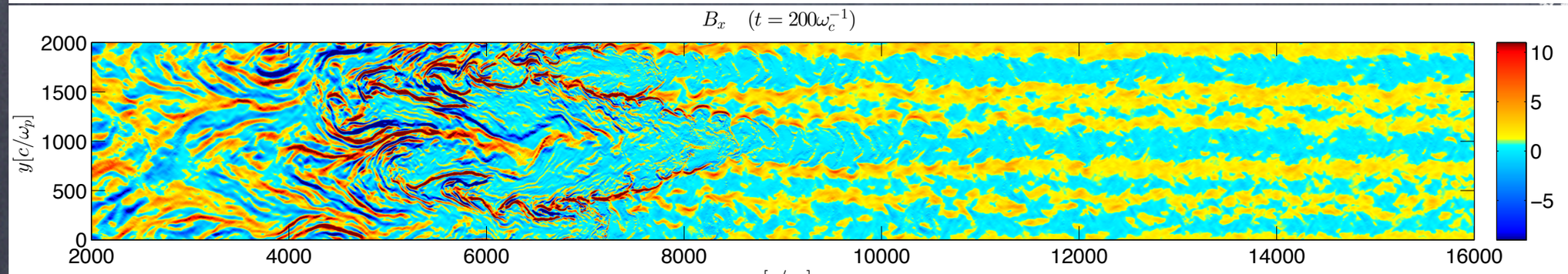


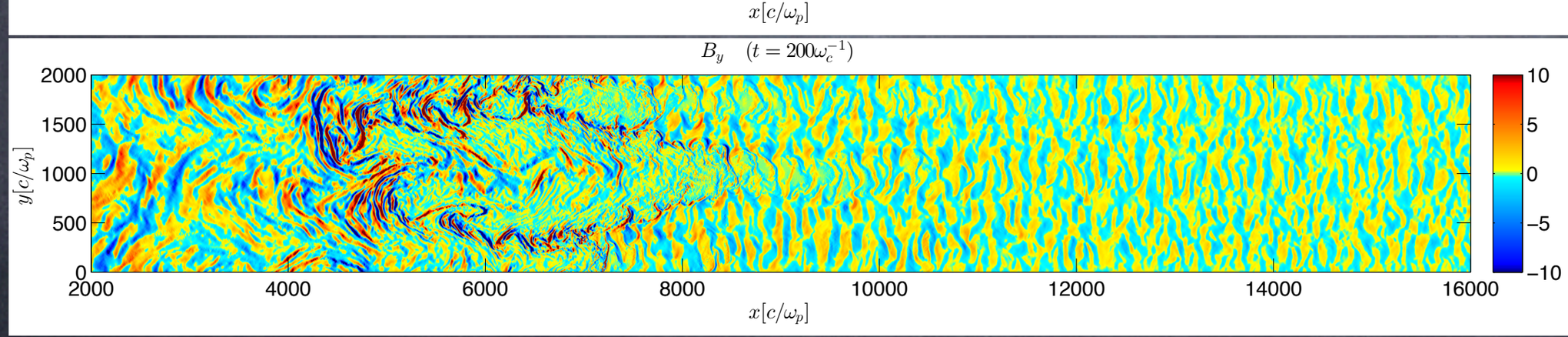
Polarization (low=turbulent high=ordered)

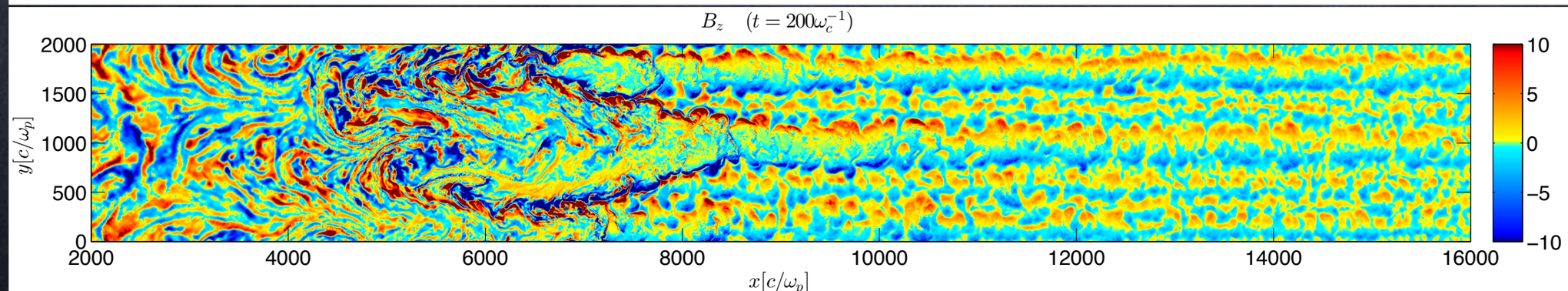
Magnetic field amplification and particle acceleration where the shock is parallel











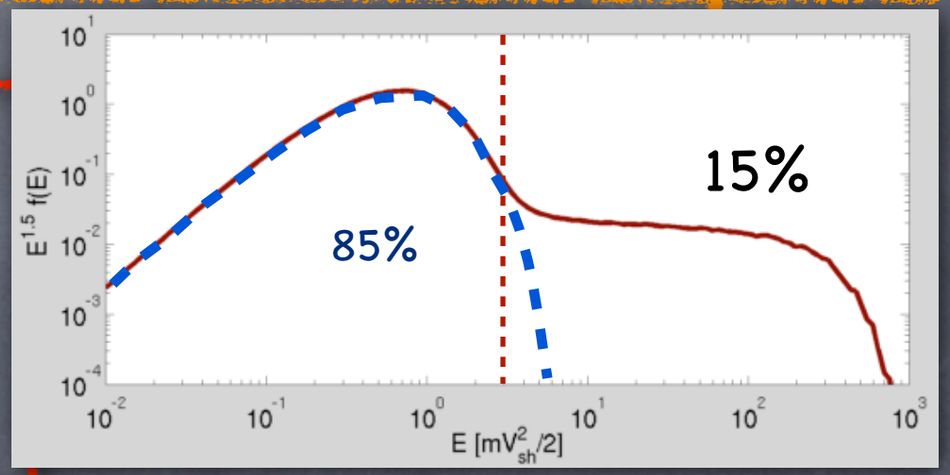
Preliminary M=100 case

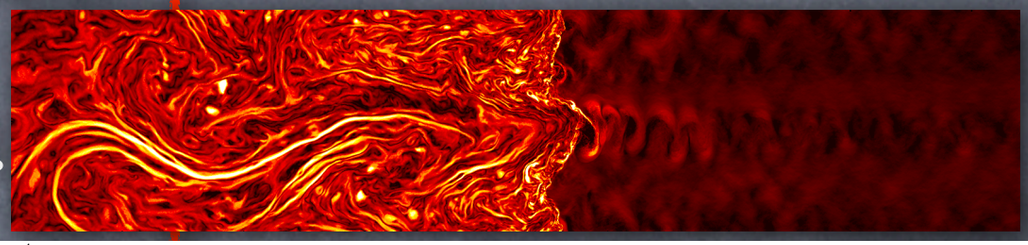
Total $\delta B/B$ larger than 10 in the precursor!

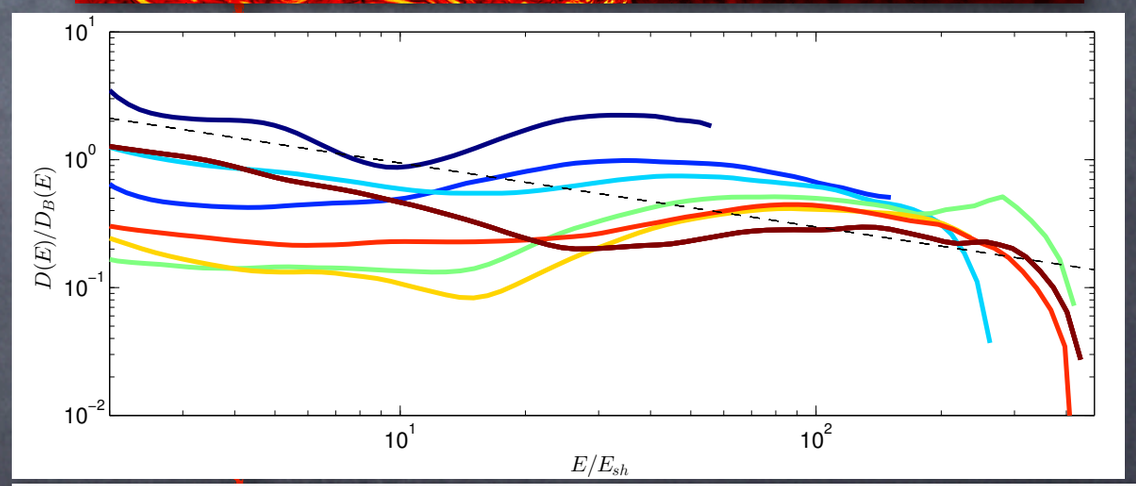
Very hard to study in the hybrid limit

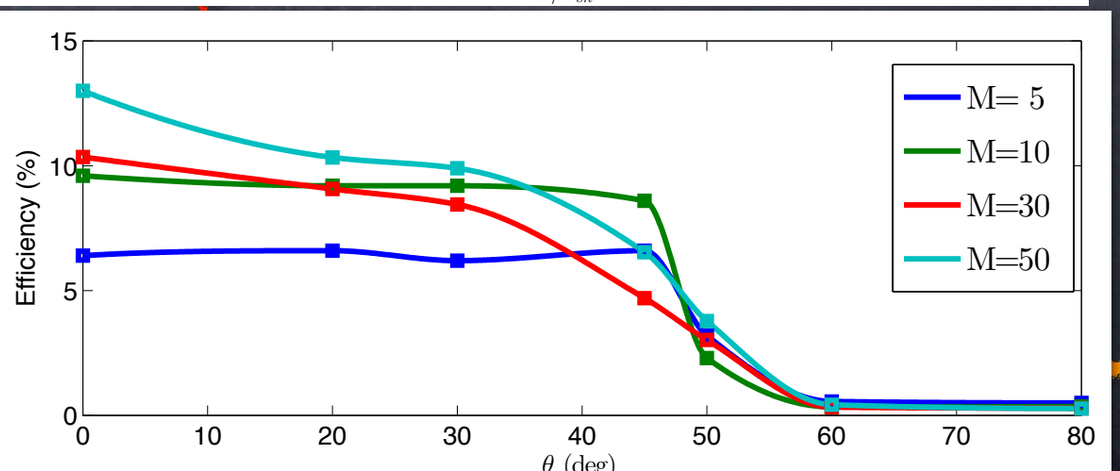
Outline

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







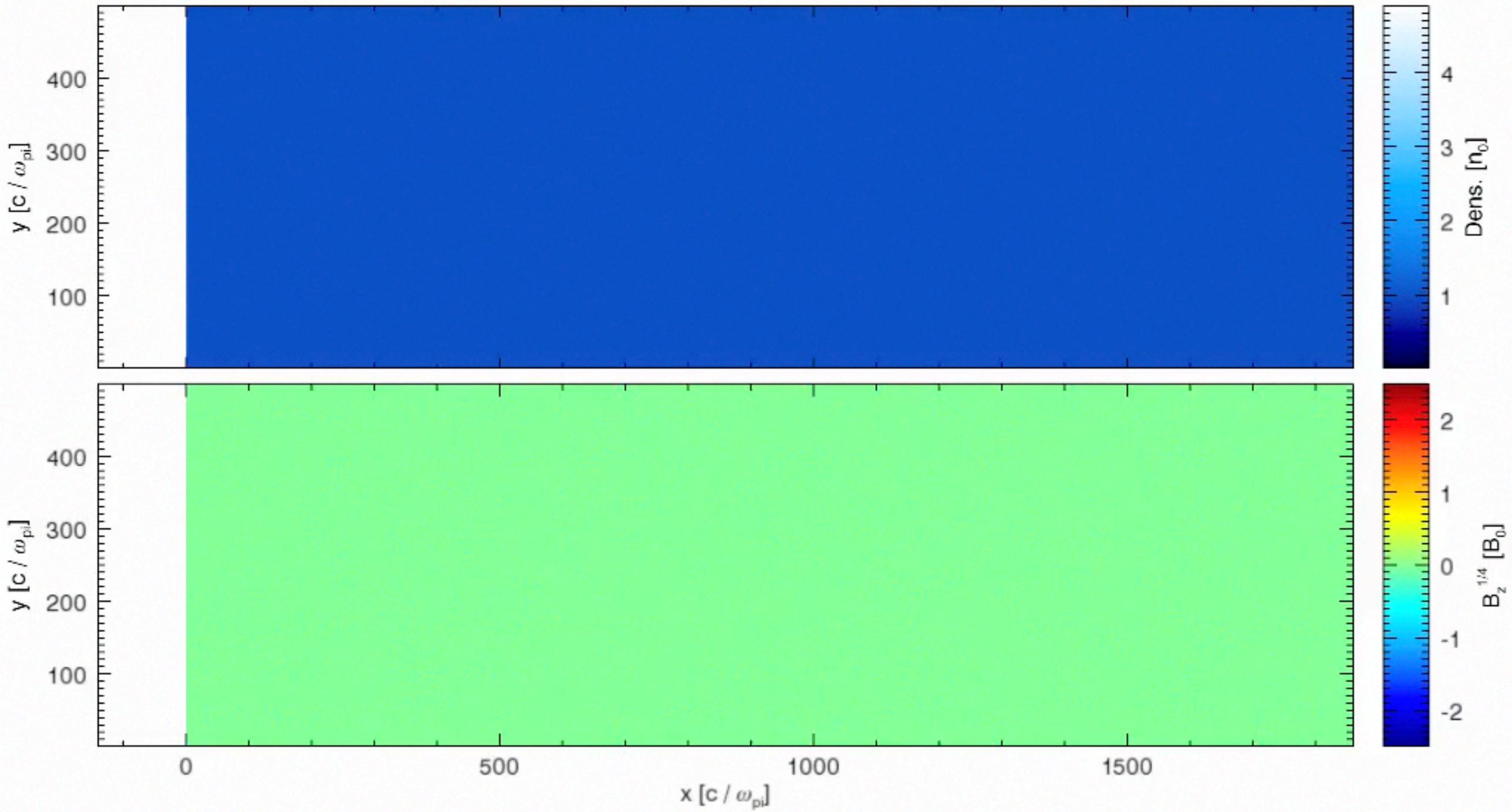


(Near-)Future Perspectives

- Ion injection
- Electron injection (with J. Park, A. Spitkovsky)
- Shocks in partially-neutral media (Blasi+2012, Morlino+13...)
- Need to go relativistic, and to higher Mach numbers
  - Super-Hybrid, with A. Spitkovsky, X. Bai, L. Sironi (CfA)

SN1006 rim - HST

Thank you!


y [c / ω_{pi}]
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300
200
100
Dens. [n_0]
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3
2
1
y [c / ω_{pi}]
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300
200
100
$B_z^{1/4}$ [B_0]
2
1
0
-1
-2
0
500
1000
1500
x [c / ω_{pi}]