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Hybrid simulations of cosmic ray acceleration at shocks

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In collaboration with: Anatoly Spitkovsky (Princeton)

Conclusions?

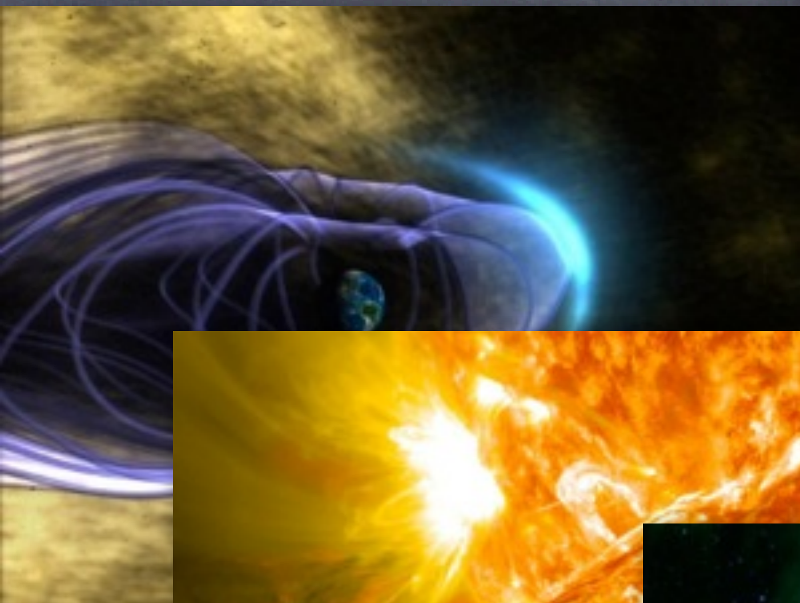
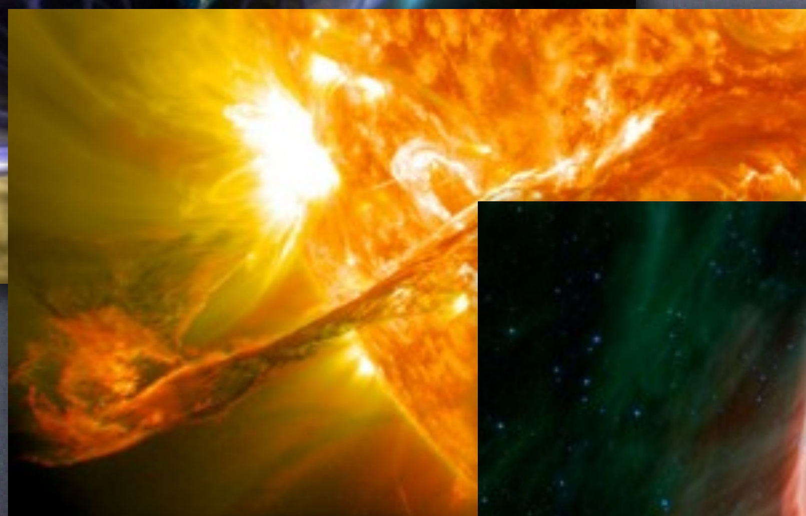
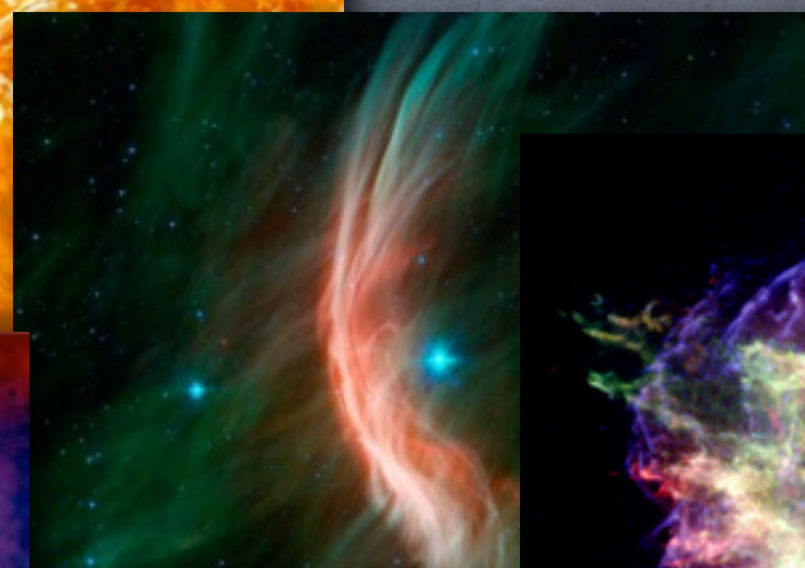
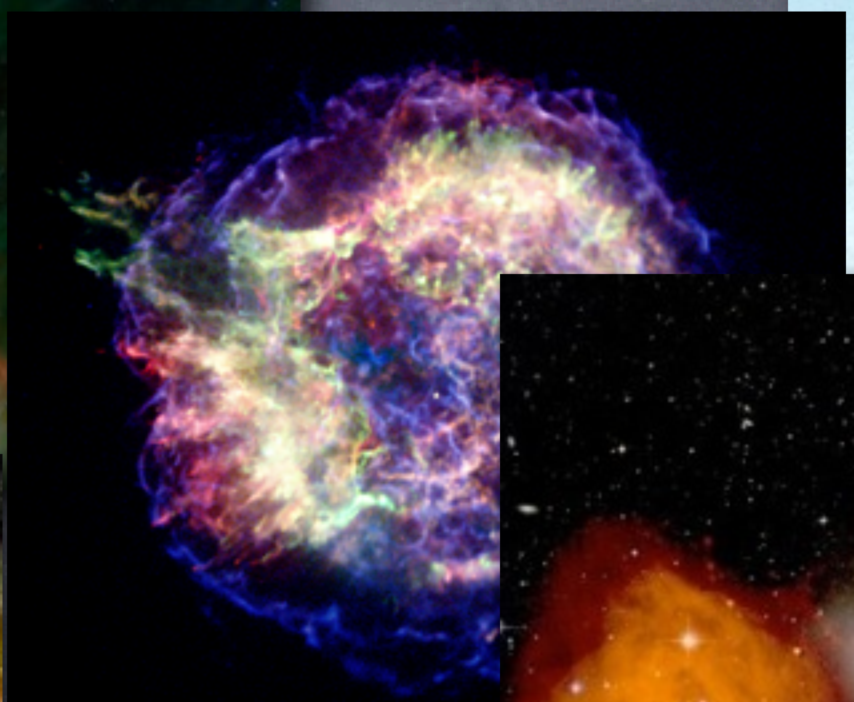
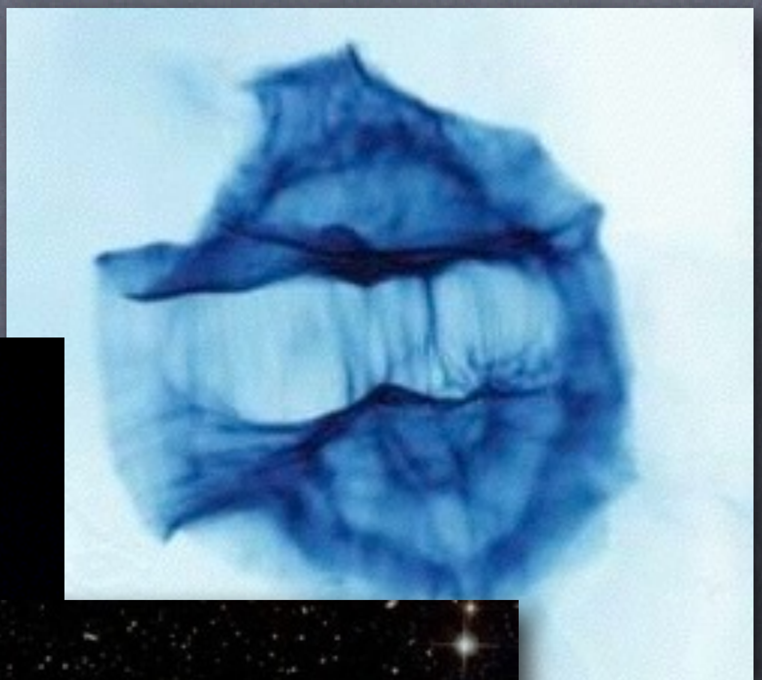
- Supernova Remnants
  - Have the right energetics
  - Diffusive shock acceleration produces power-laws
  - B amplification may help reaching the knee

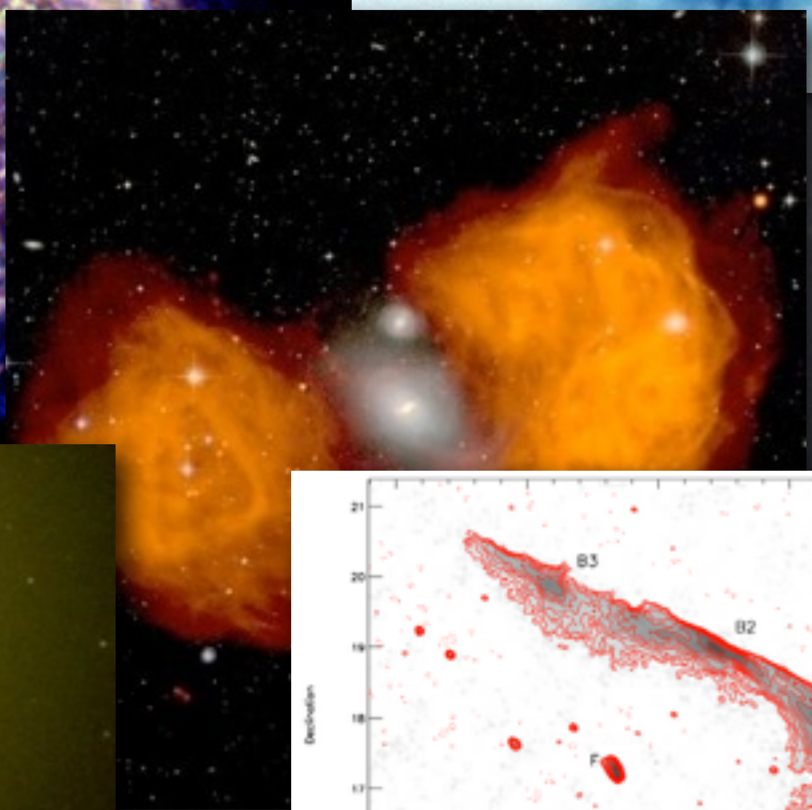
BUT

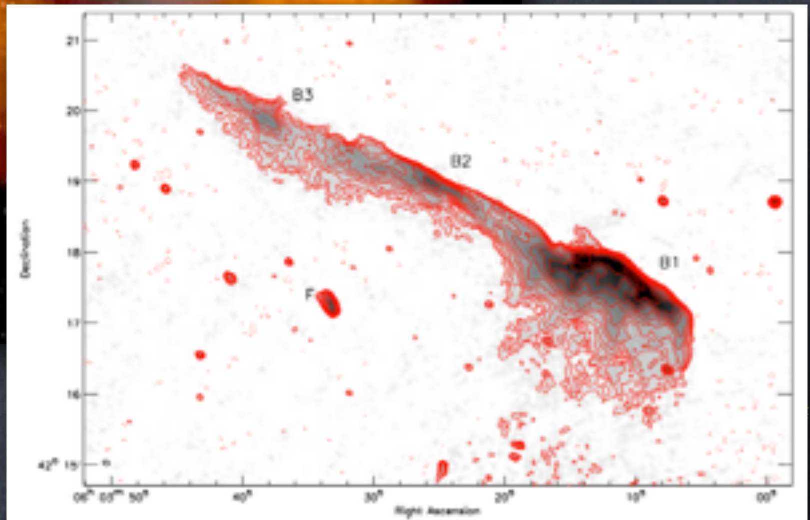
- Is acceleration at shocks efficient?
- How do CRs amplify the magnetic field?
- When is acceleration efficient?

Collisionless shocks

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

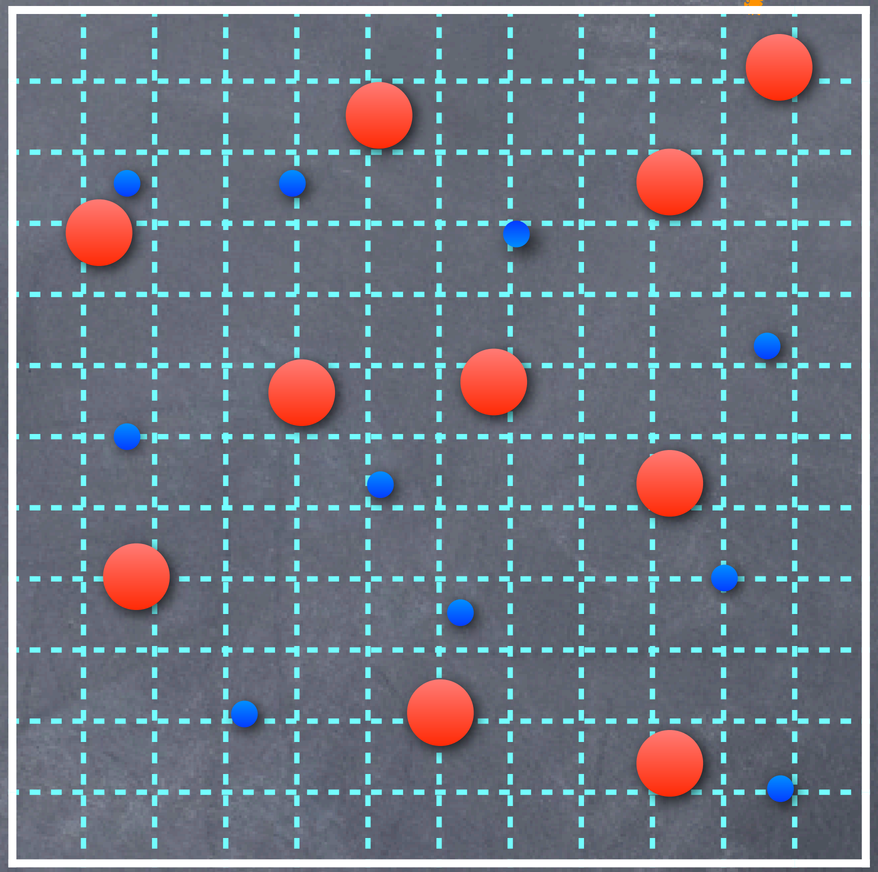






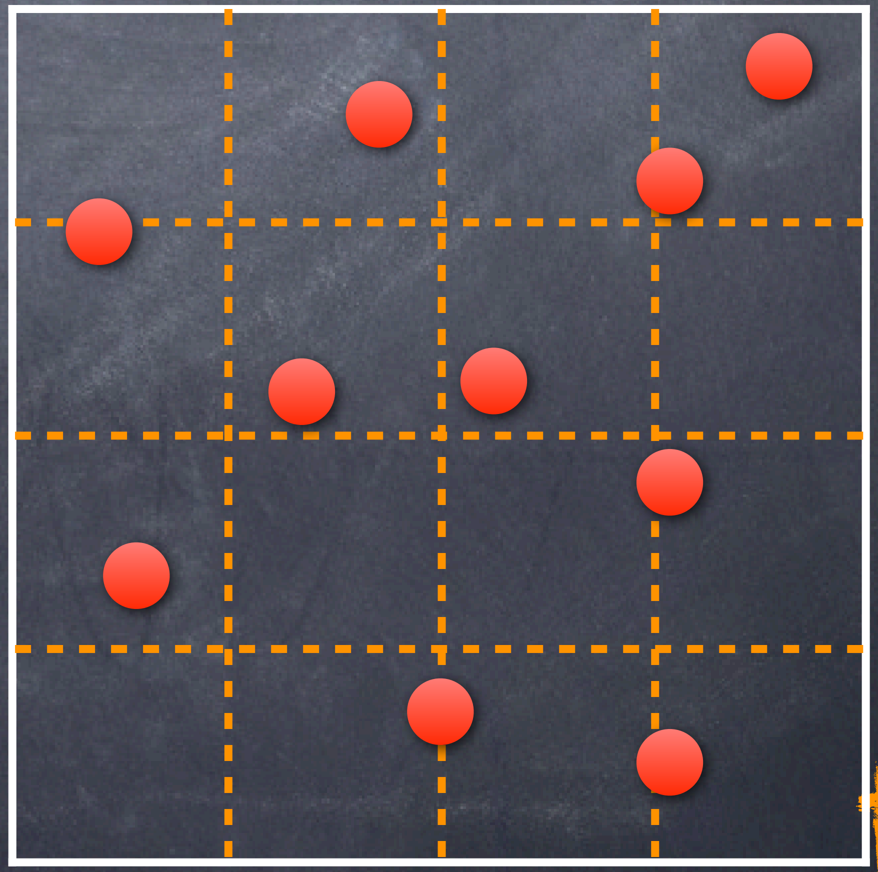


Acceleration from first principles

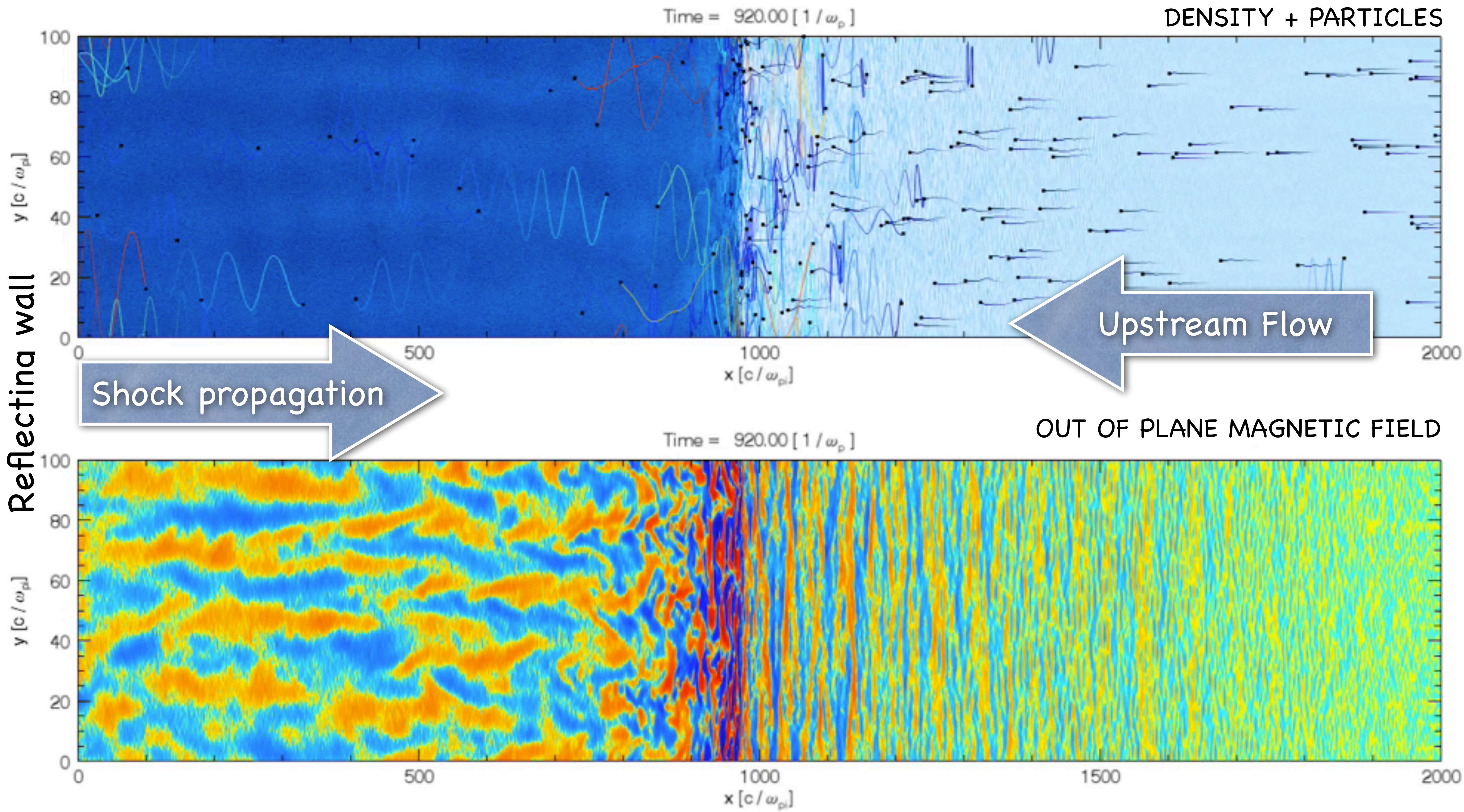
- Full particle in cell approach
  (Spitkovsky 2008, Niemiec et al. 2008, Stroman et al 2009, Riquelme & Spitkovsky 2010, Sironi & Spitkovsky 2011, Park et al 2012, Niemiec at al 2012,...)
  - Define electromagnetic field on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations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



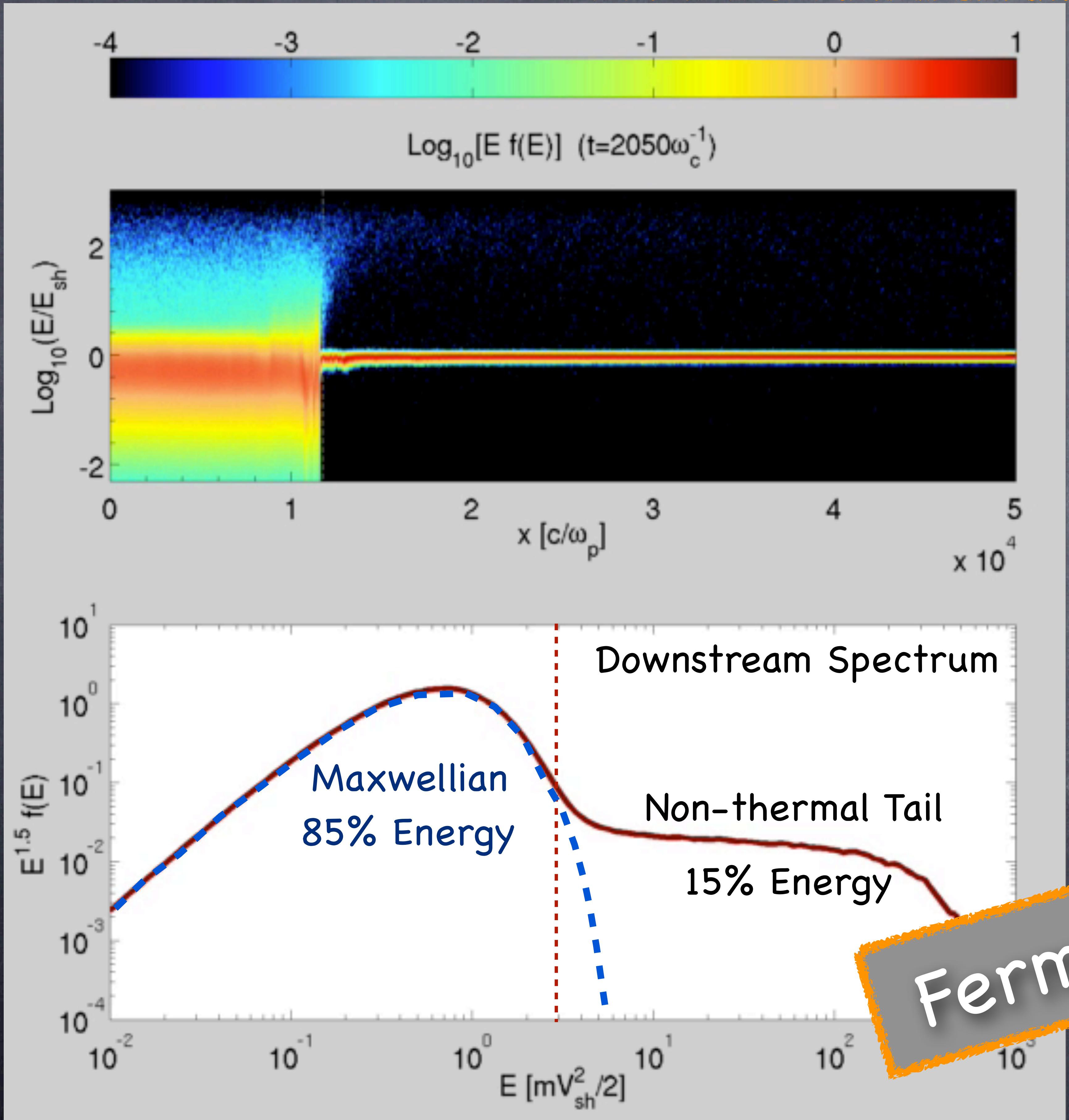
Hybrid simulations of collisionless shocks



- **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.)

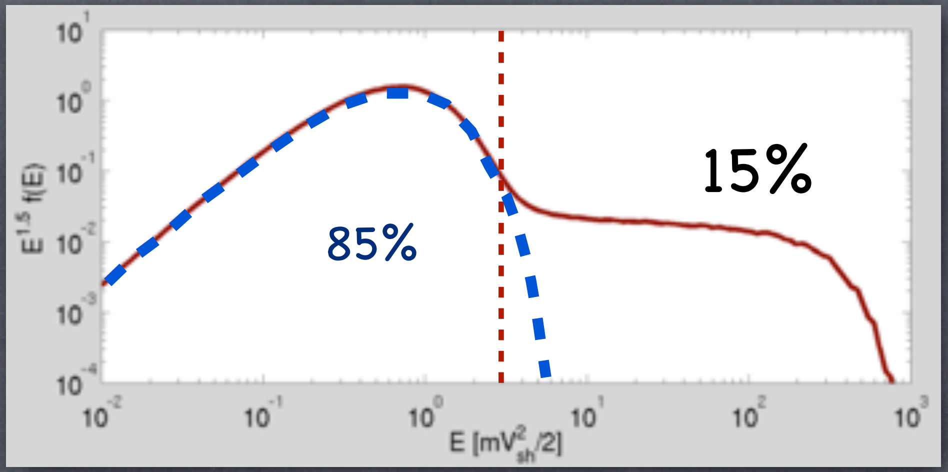
$f(E) \propto E^{-1.5}$ (non rel.)

Fermi acceleration

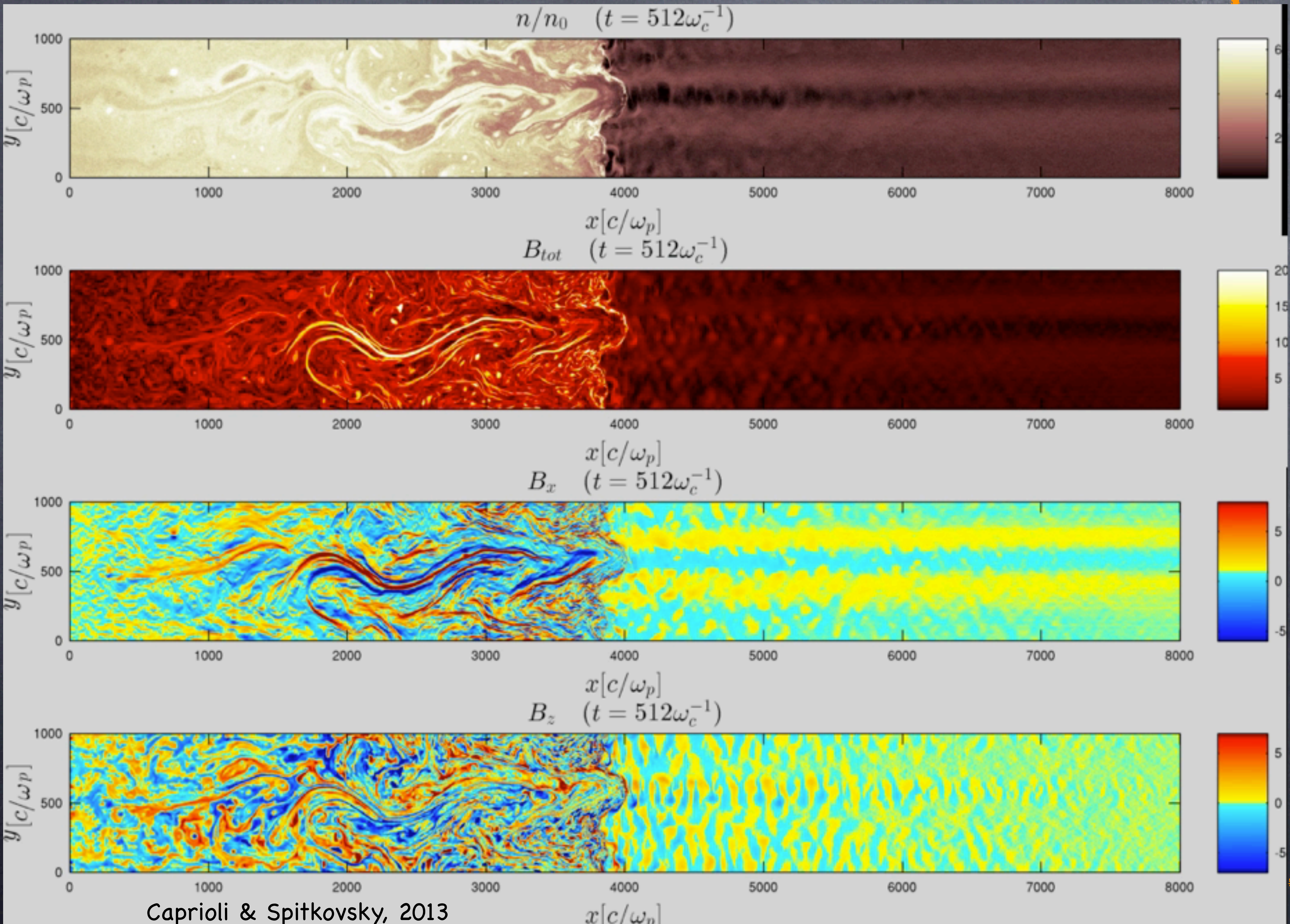
DC & Spitkovsky, 2014

Outline

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

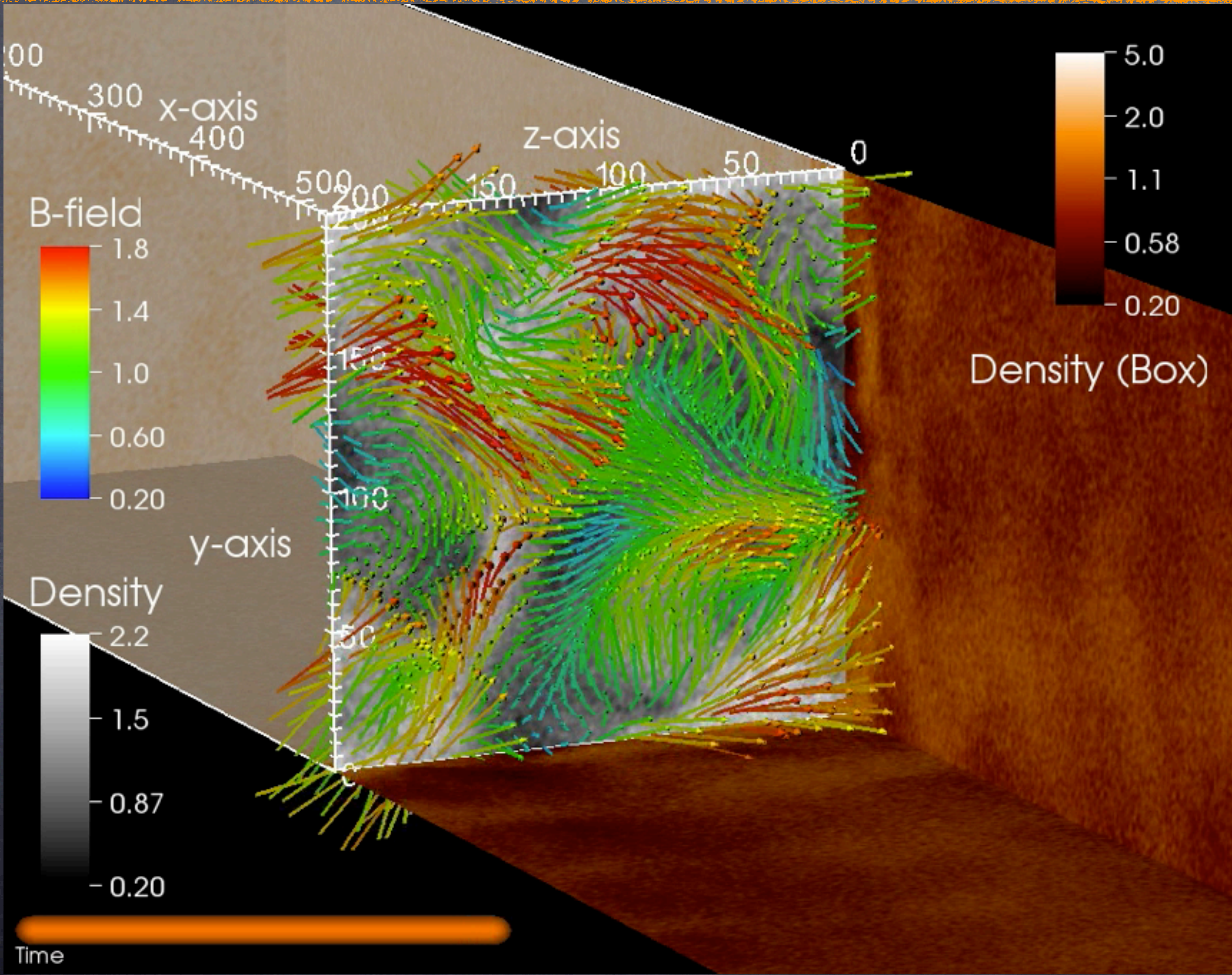


Filamentation instability



Caprioli & Spitkovsky, 2013

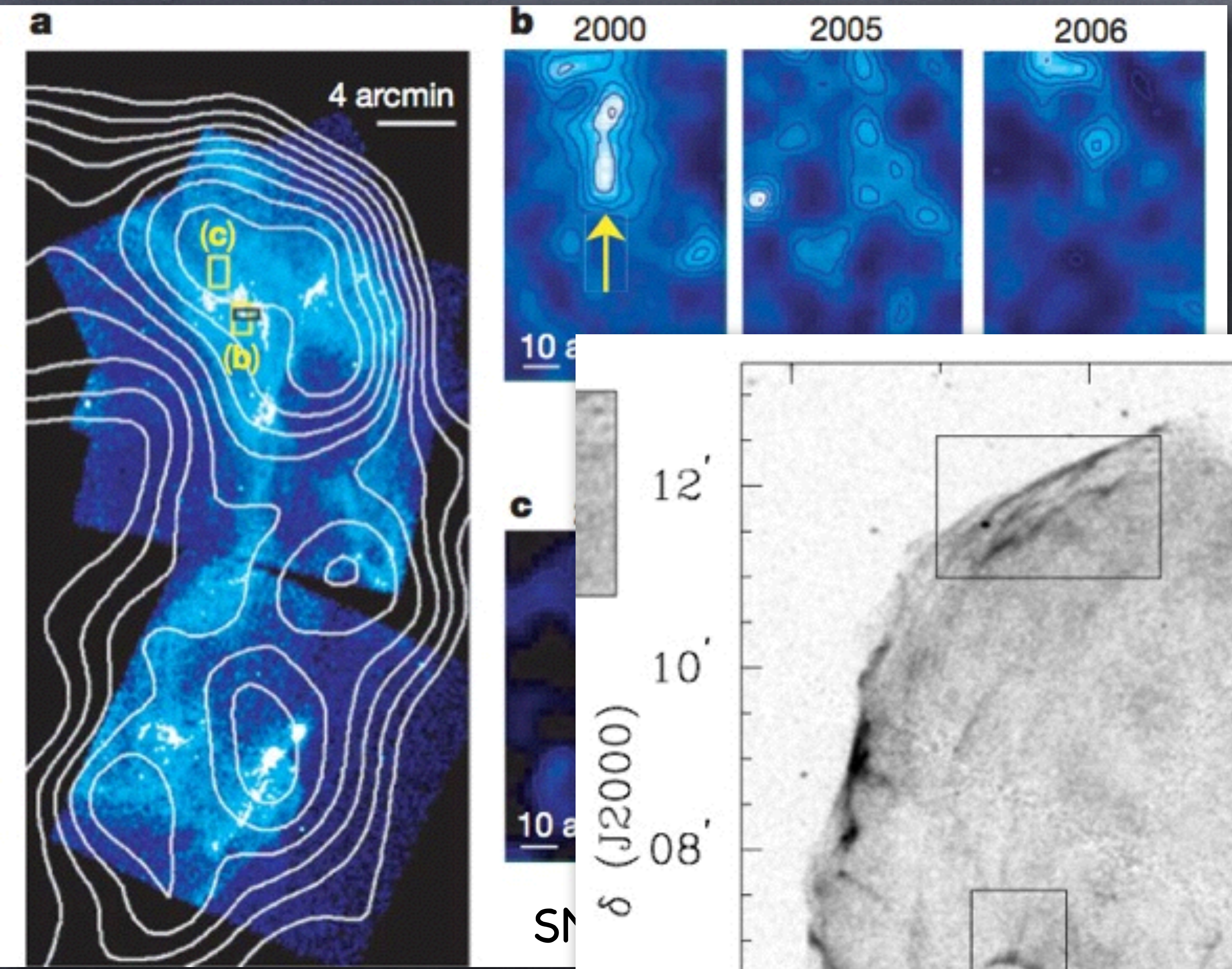
3D simulations of a parallel shock



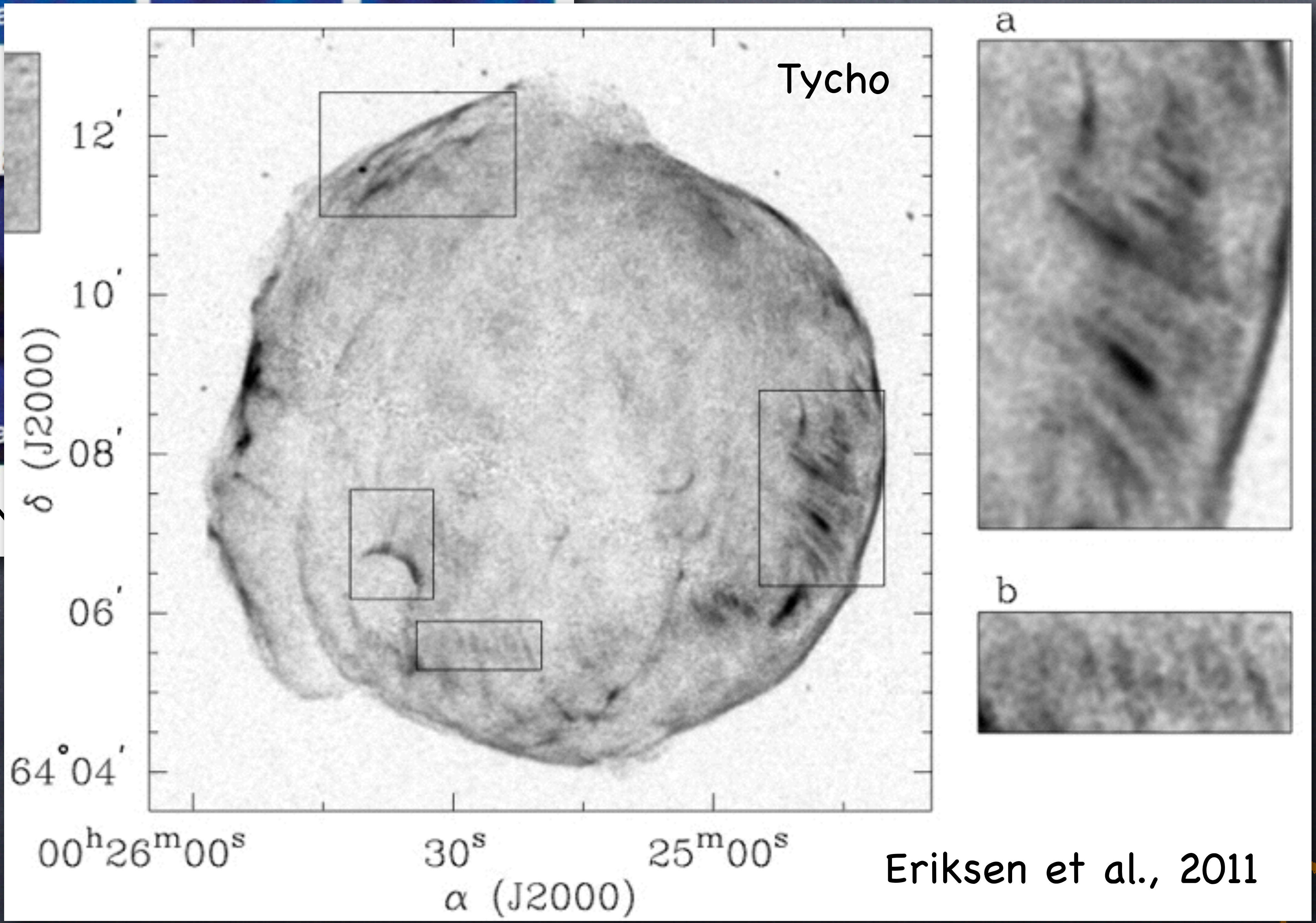
Caprioli & Spitkovsky, 2014

Knots and filaments

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



Uchiyama et al 2007



Eriksen et al., 2011

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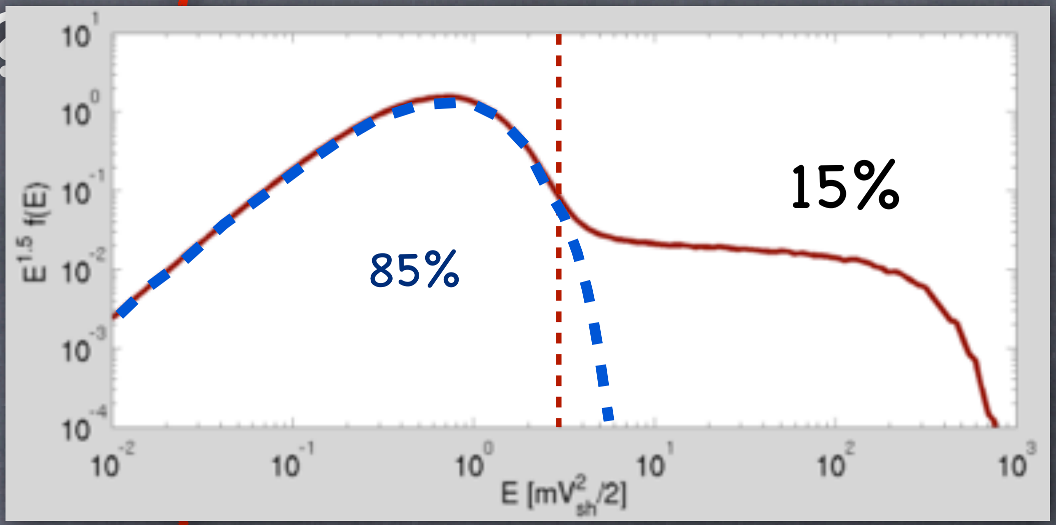
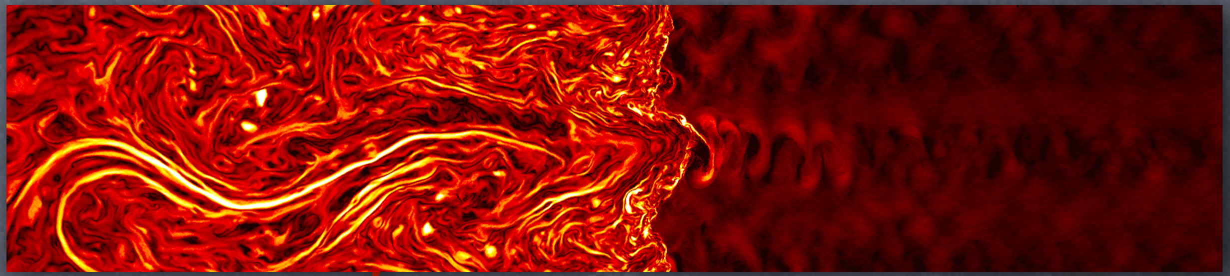
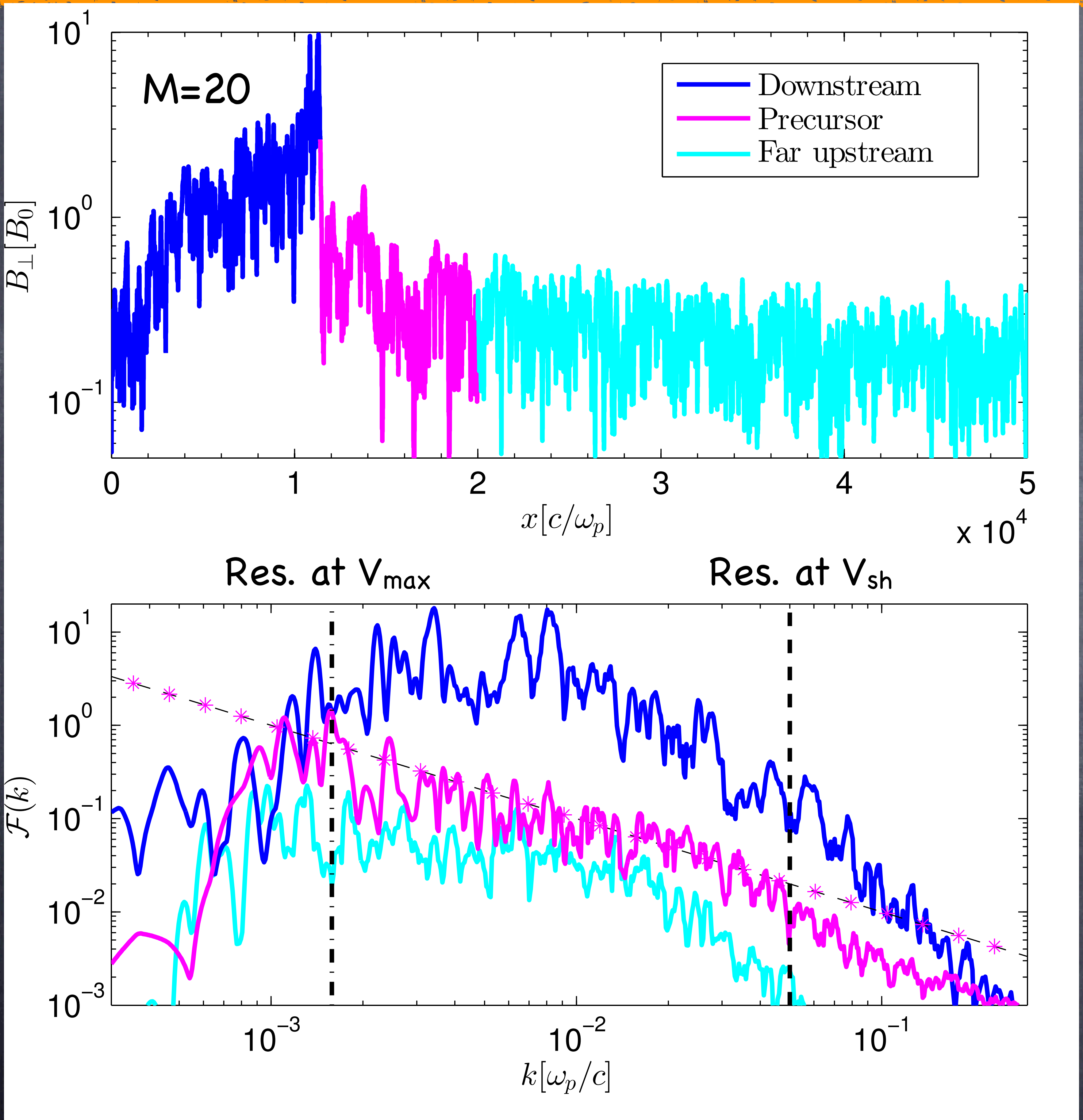
- How do CRs amplify the magnetic field?
  - Streaming instability
- How do magnetic fields scatter CRs?





Magnetic field spectrum, low M_A



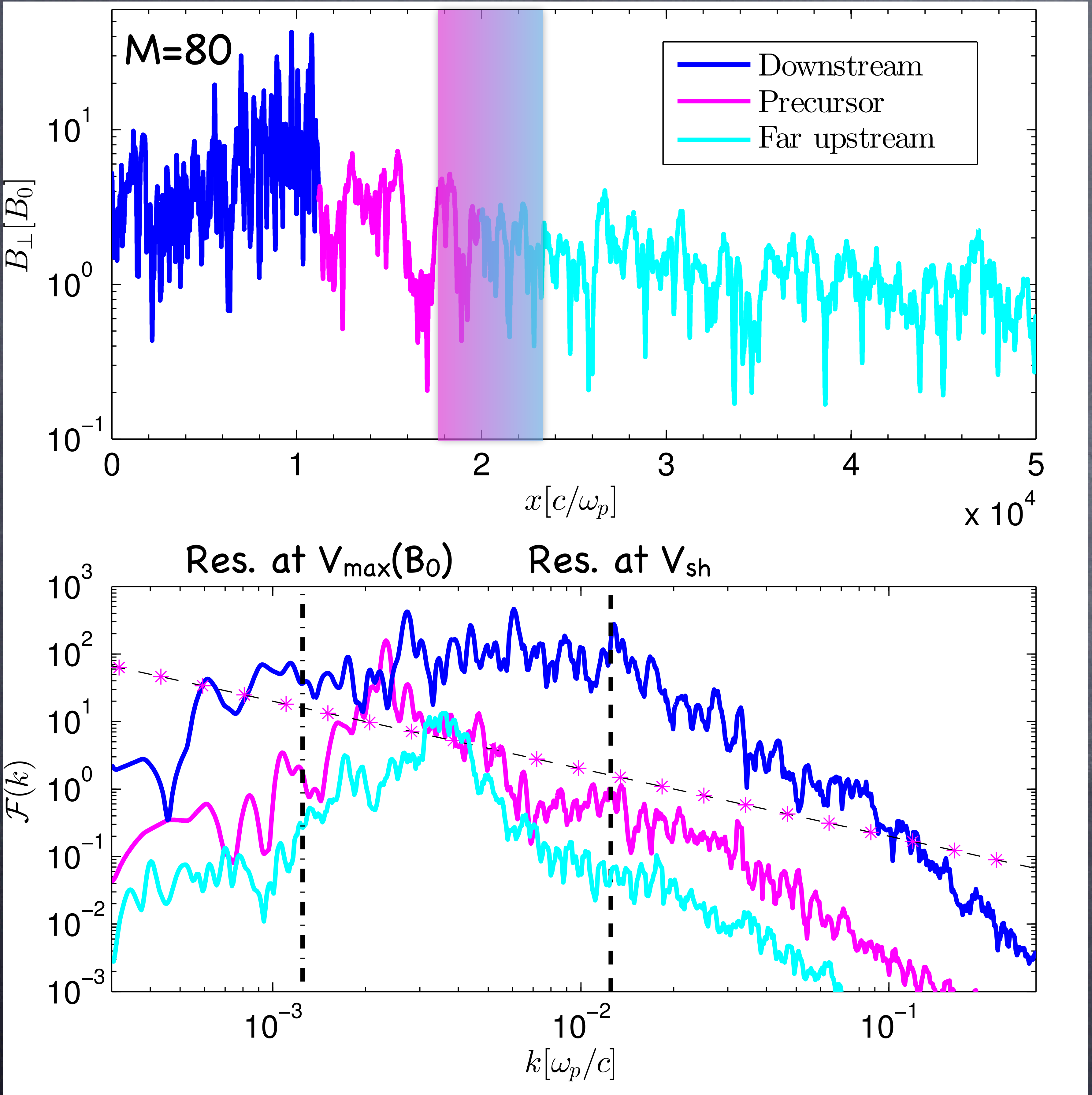
Magnetic energy density per unit logarithmic band-width, F(k)

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

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

DC & Spitkovsky, 1401.7679

Magnetic field spectrum, high M_A



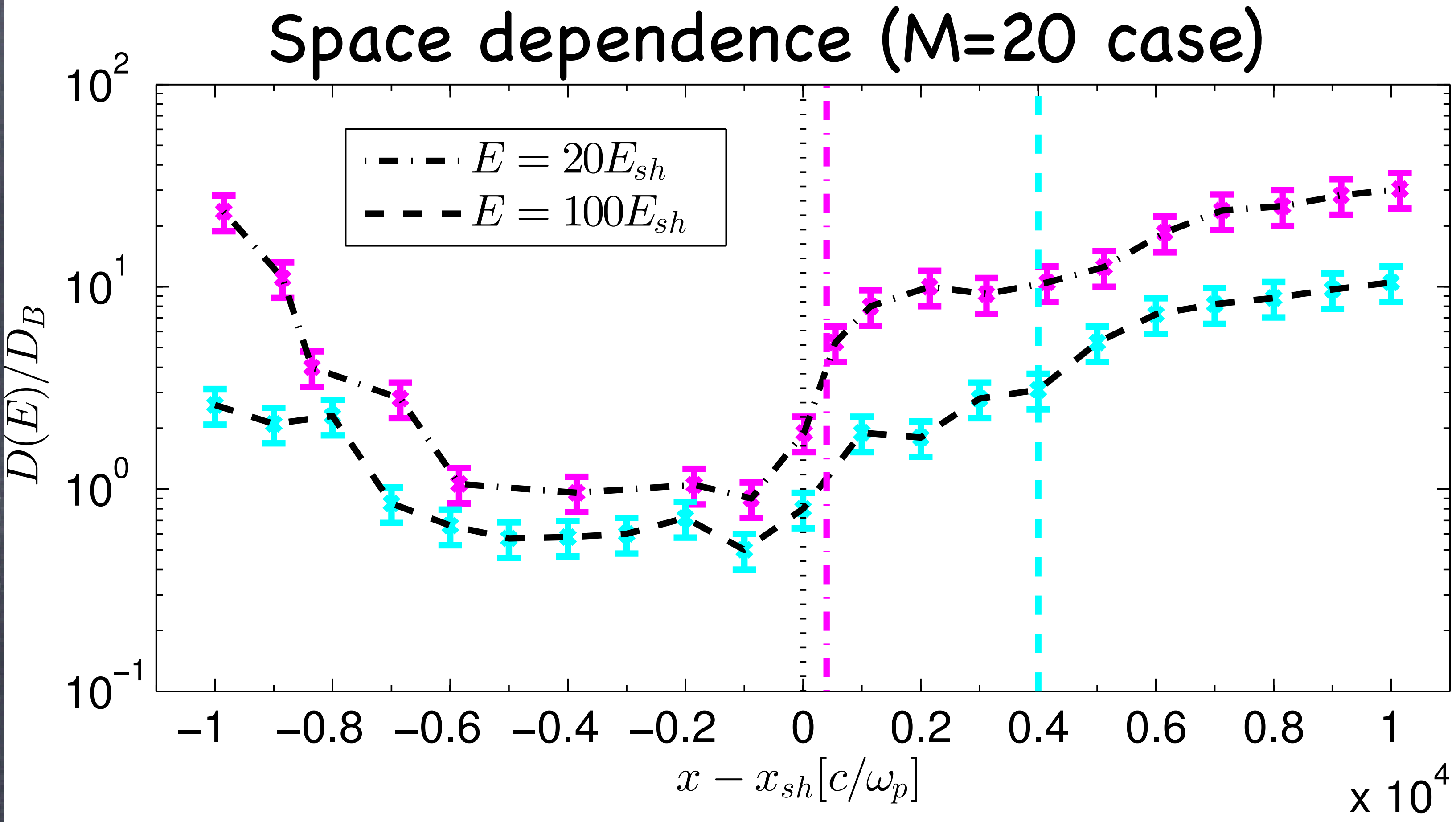
- Bell modes (short-wavelength, right-handed) grow faster than resonant
- Far upstream: escaping CRs at $\sim p_{max}$ (Bell)
- For large $b=\delta B/B_0$ $k_{max}(b) \sim k_{max,0}/b^2$
- There exist a b^* such that $k_{max}(b^*) r_L(p_{esc}) \sim 1$

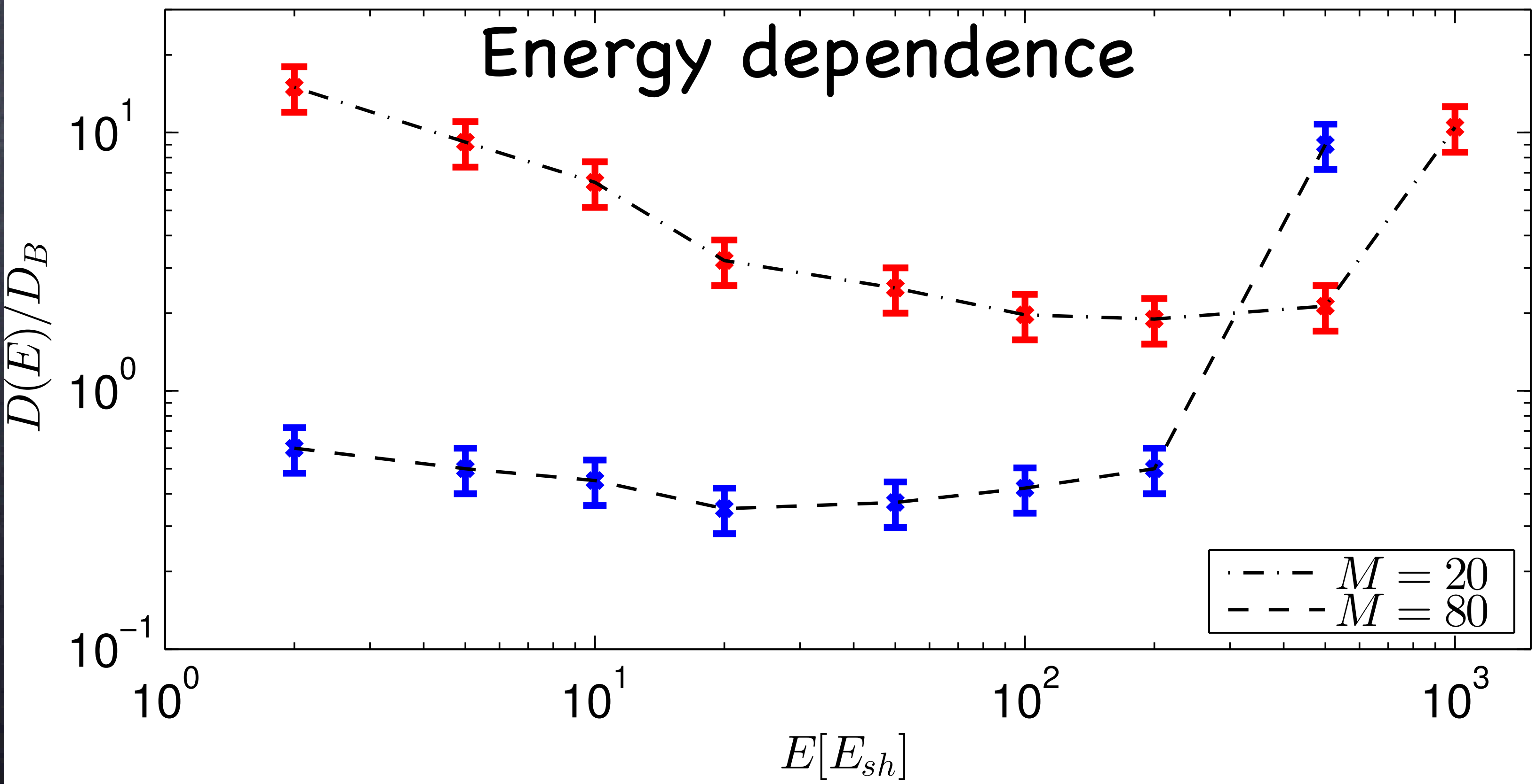
Free escape boundary

- Precursor: diffusion + resonant

DC & Spitkovsky, 1401.7679

Diffusion coefficient





- Directly measured in simulations

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

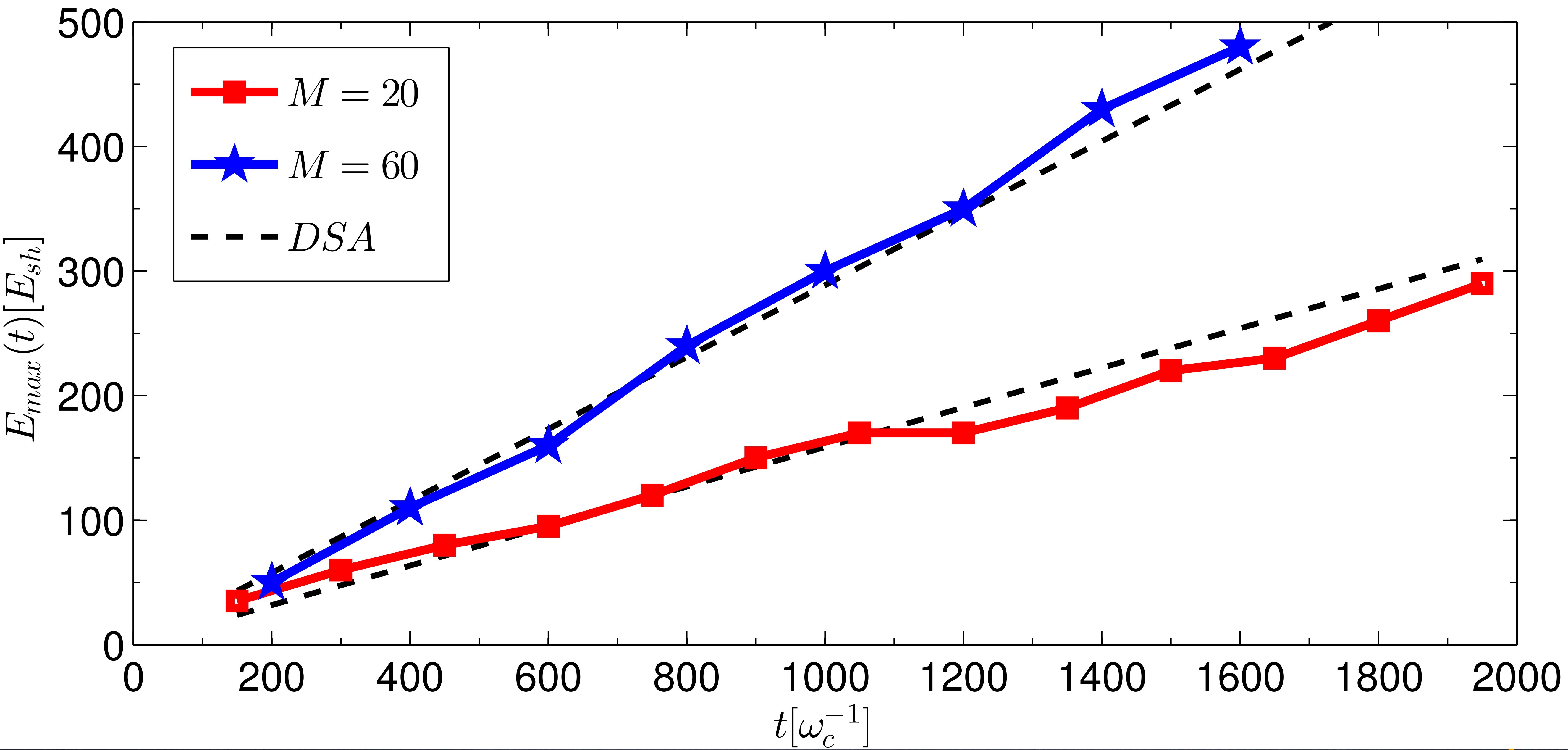
Bohm diffusion in the amplified B

- D enhancement larger
  - near the shock
  - below E_{max}
- Suppression depends on M (B amplification)

Time evolution of E_{max}

- Evolution of $E_{max}(t)$ according to DSA (Drury 1983, Blasi et al. 2007)

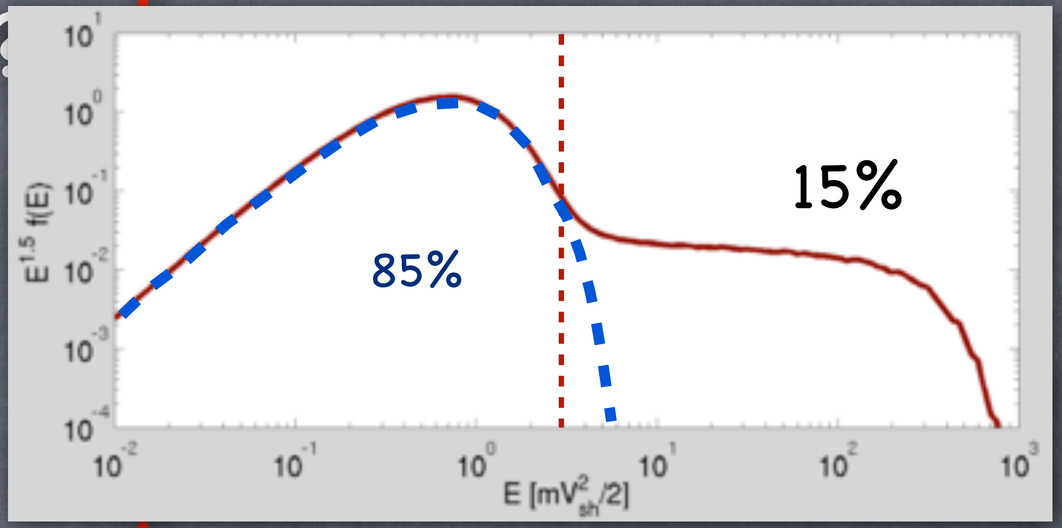
$$T_{acc}(E) = \frac{3}{u_1 - u_2}\left[\frac{D_1(E)}{u_1} + \frac{D_2(E)}{u_2}\right] \simeq \frac{3r^3}{r^2-1}\frac{D(E)}{v_{sh}^2}.$$

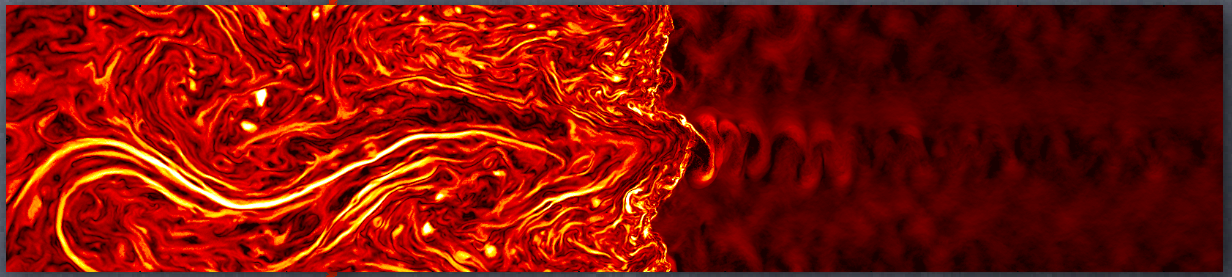


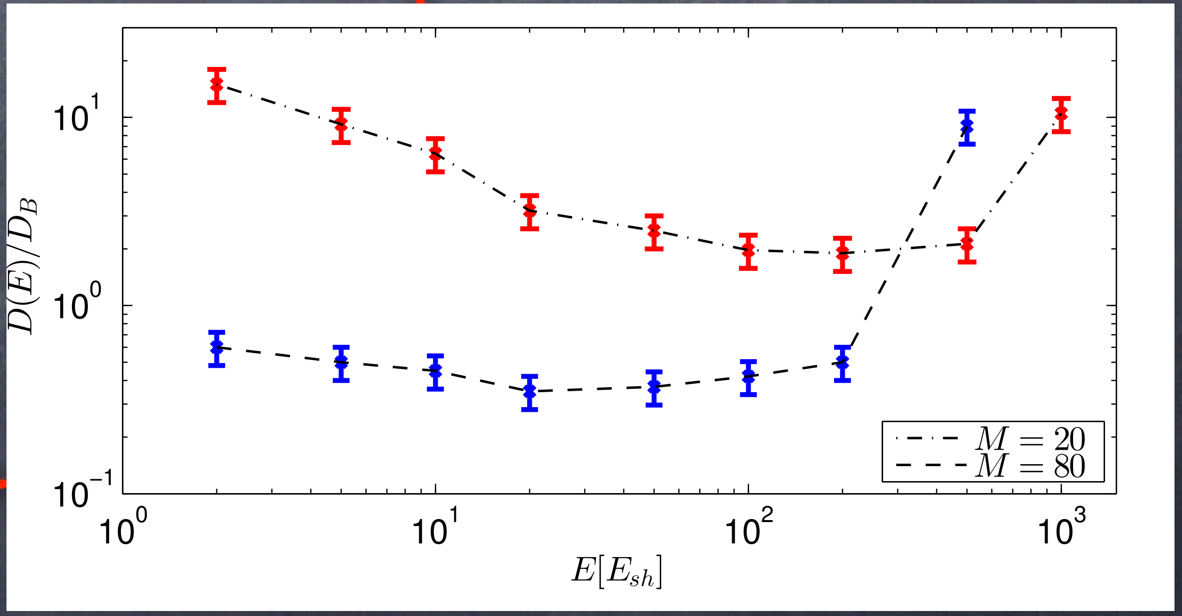
DC & Spitkovsky, 1401.7679

Outline

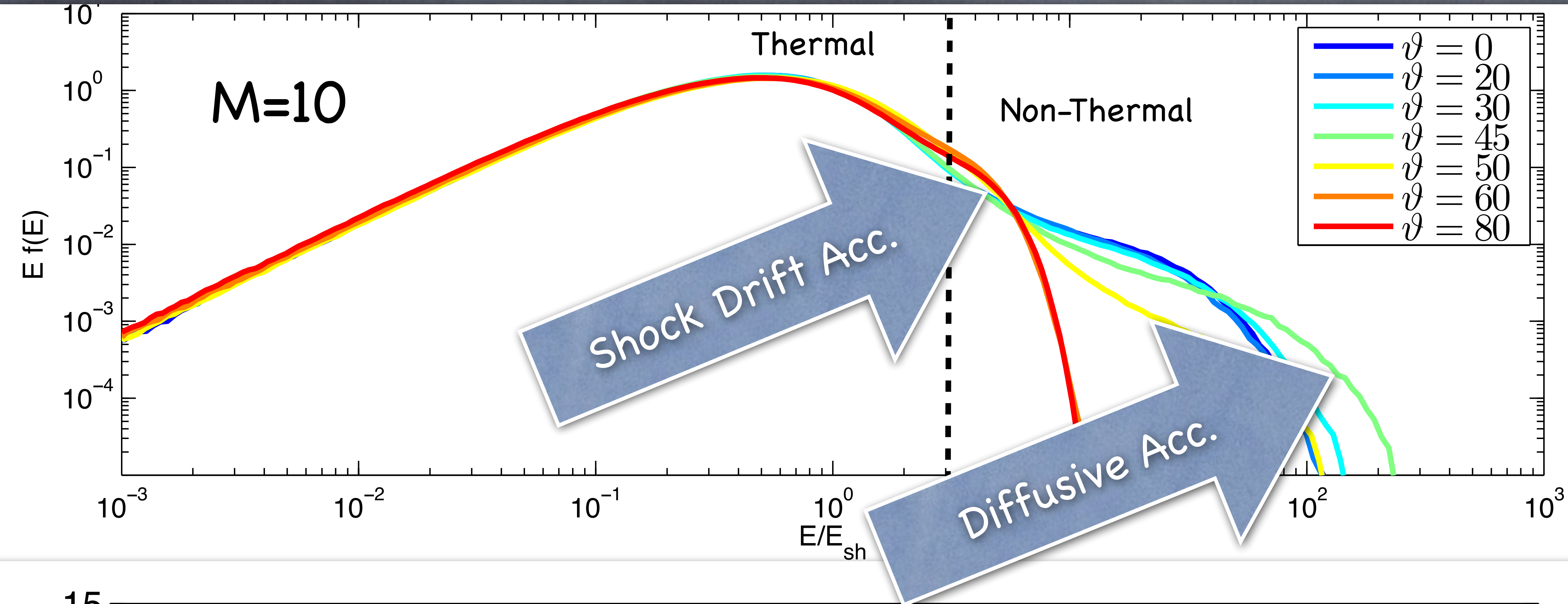
- Is acceleration at shocks efficient?
  - Hybrid simulations: >15%
- How do CRs amplify the magnetic field?
  - Streaming instability
- How do magnetic fields scatter CRs?
  - Bohm diffusion in δB
- When is DSA efficient?

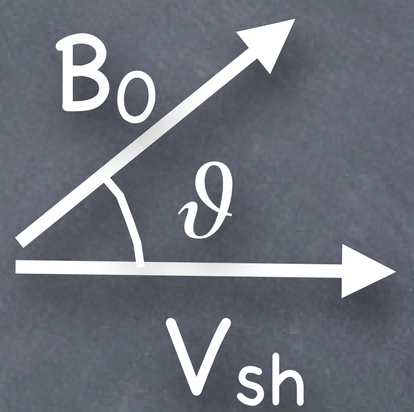


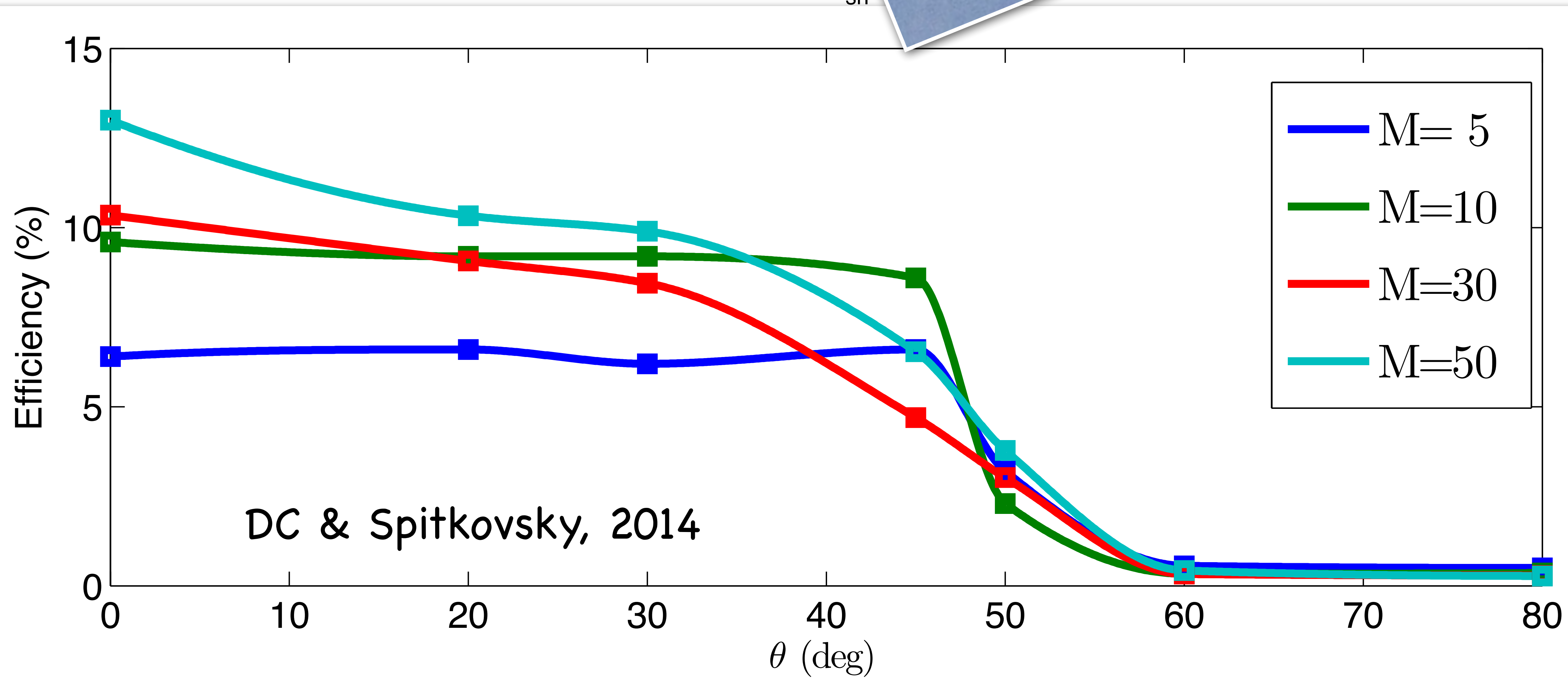




Parallel vs Oblique shocks





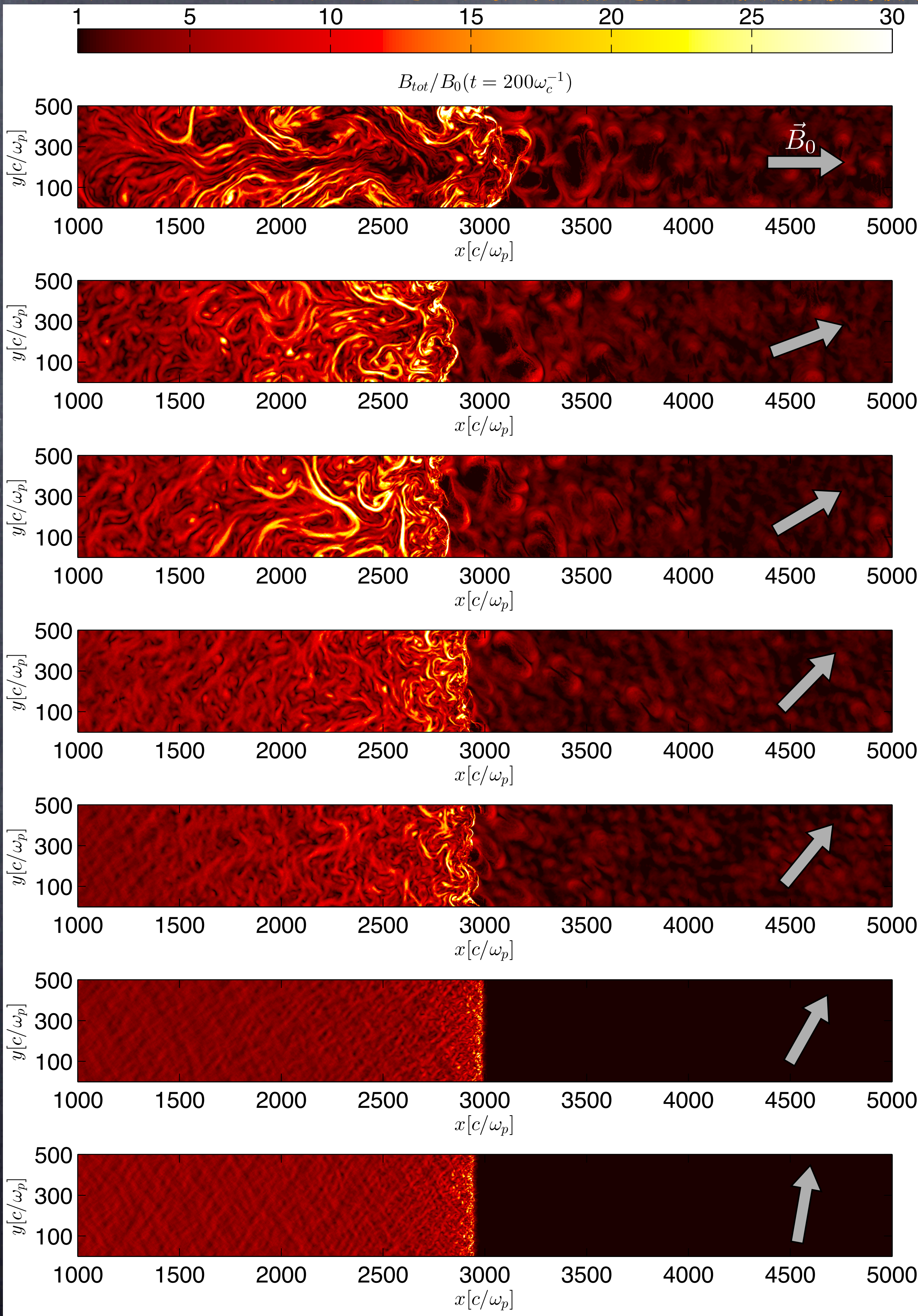


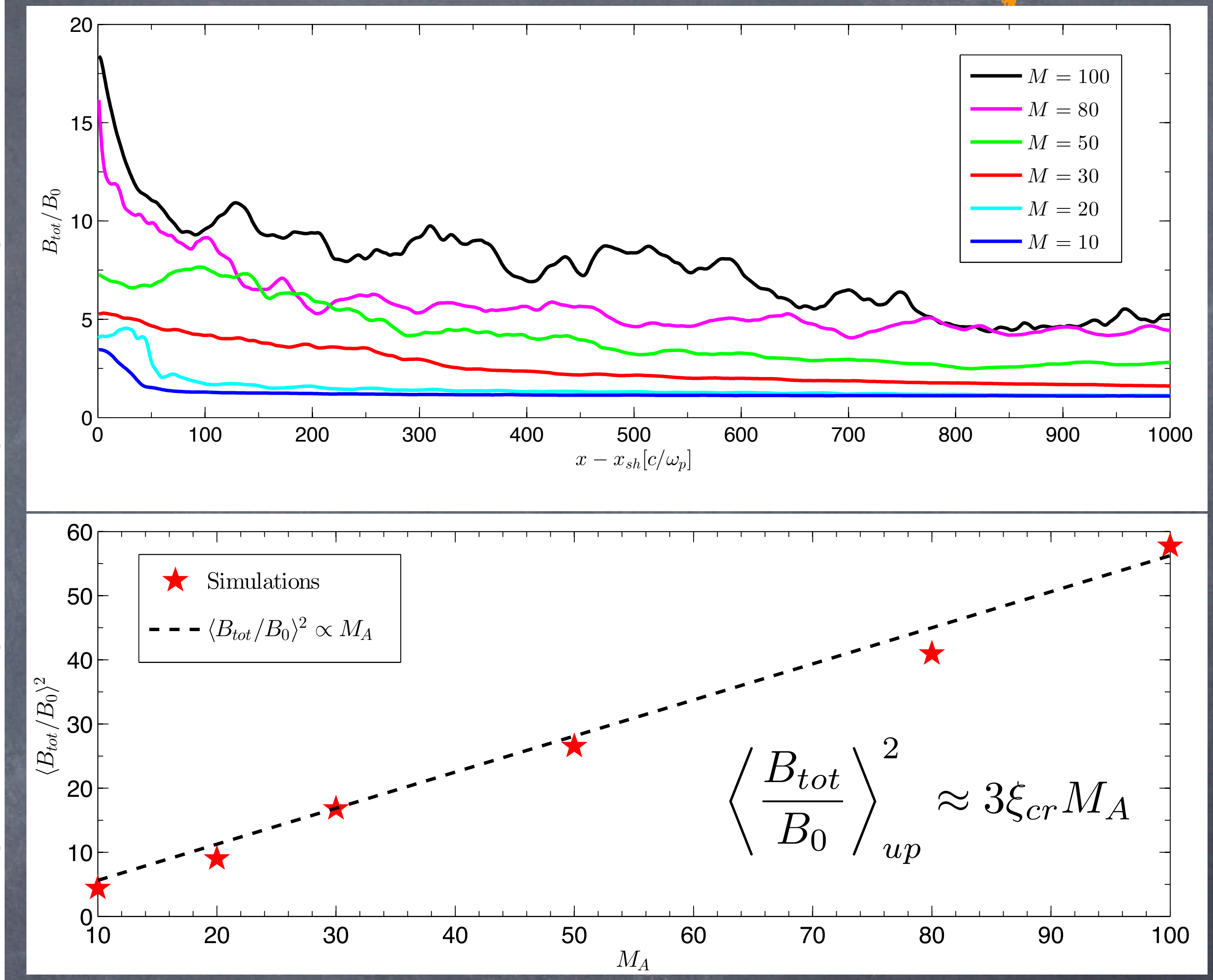
Each point is a state of the art simulation (10^9 particles)

Computation time: almost

$2x10^6$ cpu h!

Dependence on inclination and M

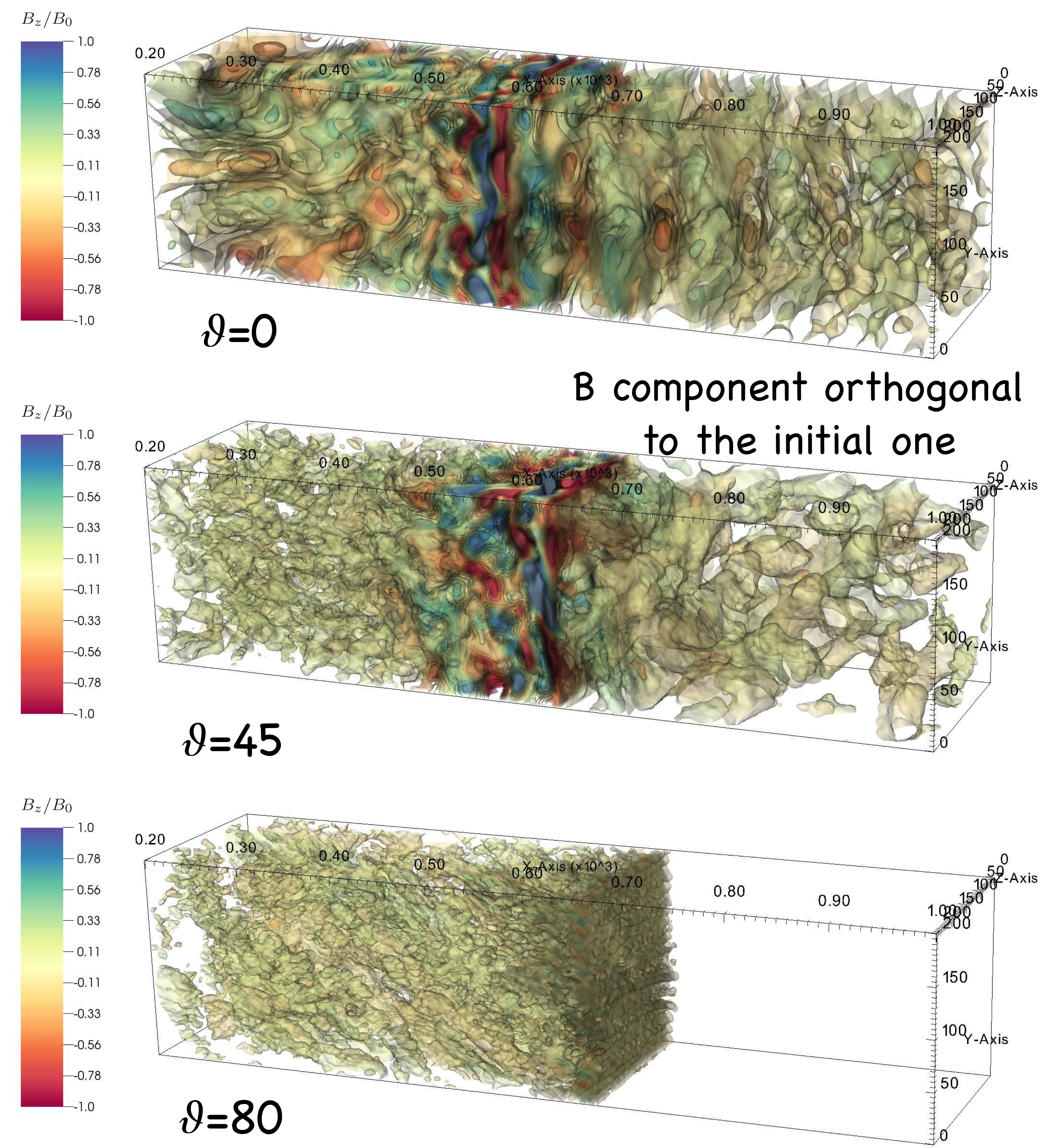


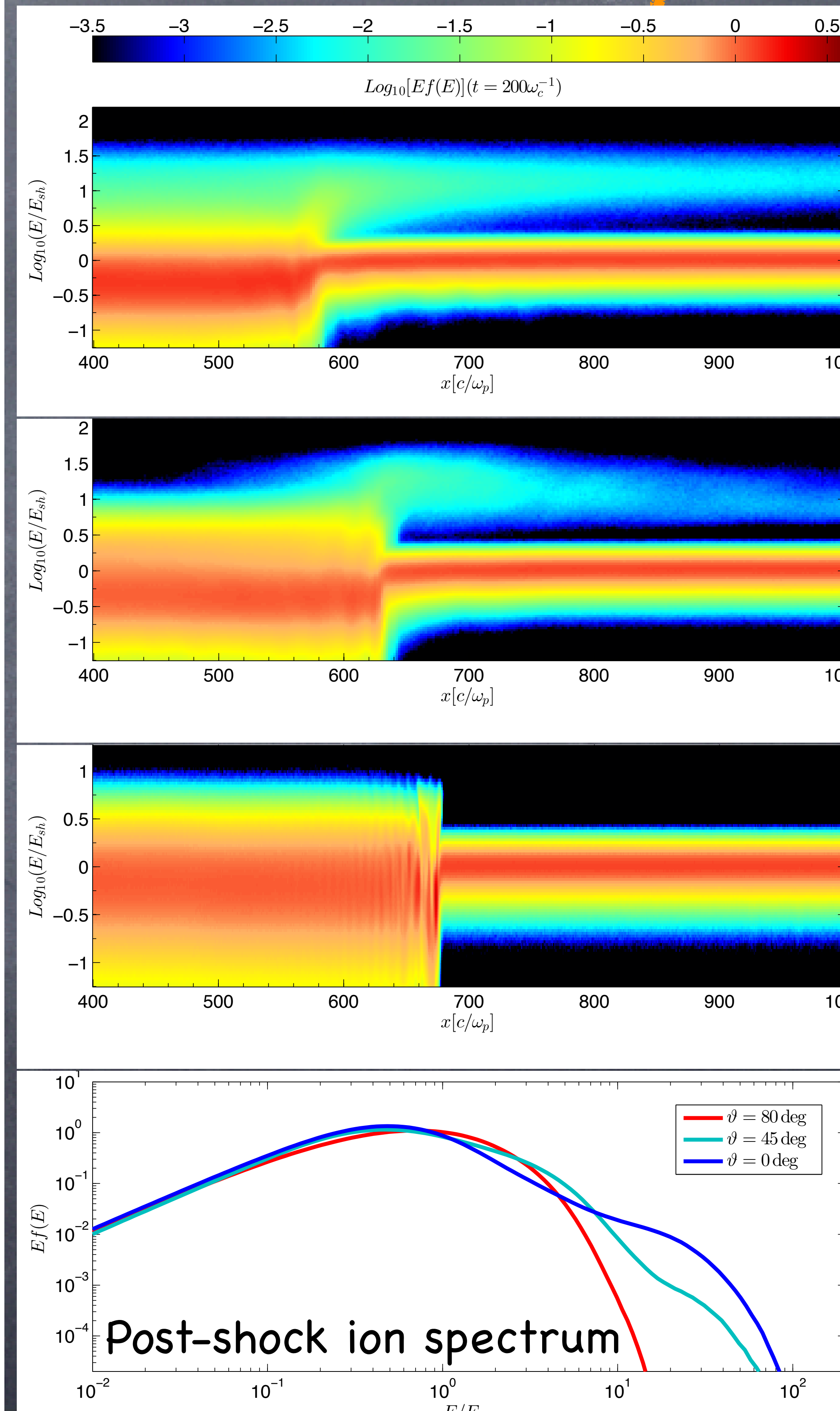


- In agreement with the prediction of resonant streaming instability

More B-field amplification for stronger shocks!

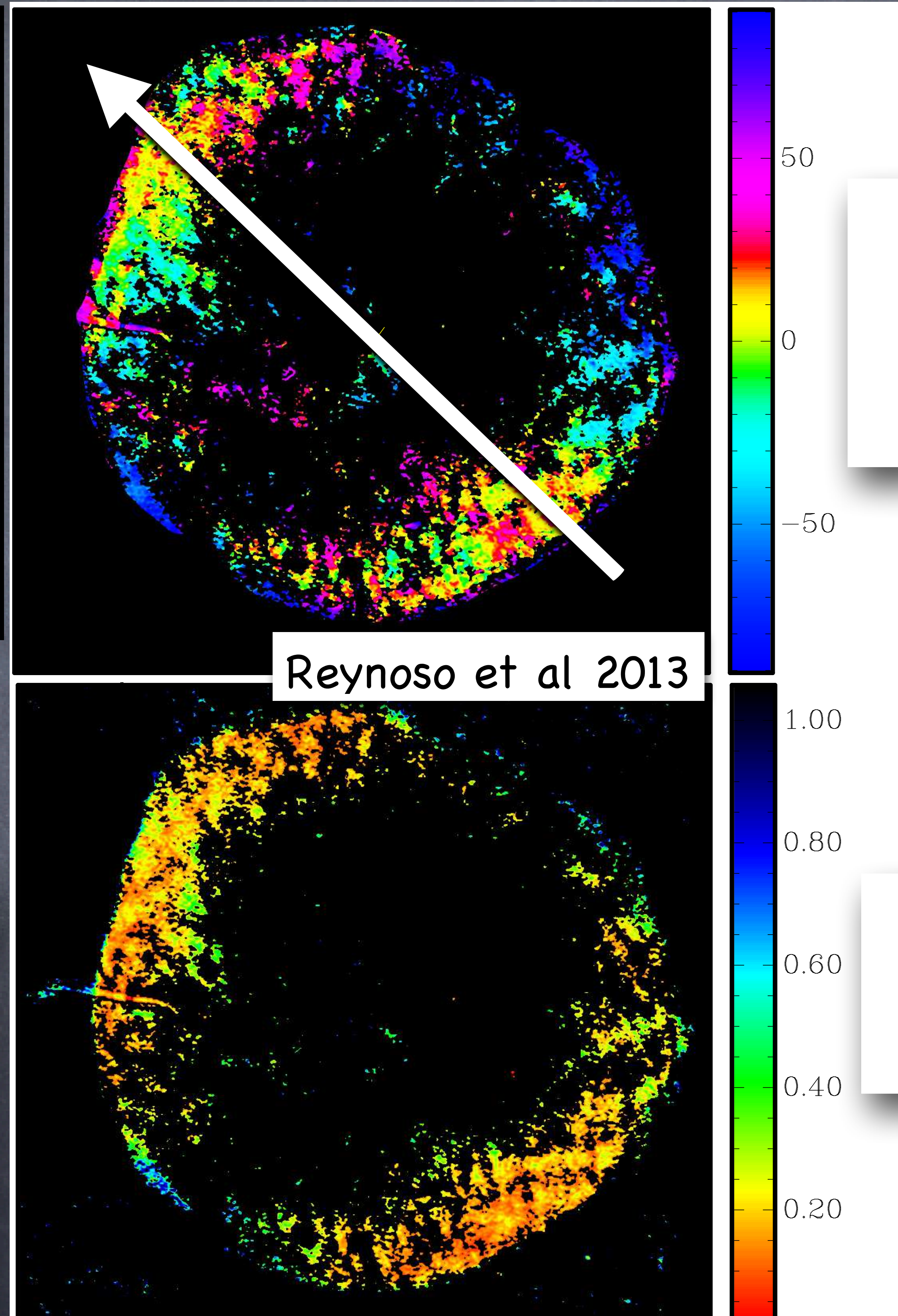
3D simulations





SN 1006: a parallel accelerator

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



Reynoso et al 2013

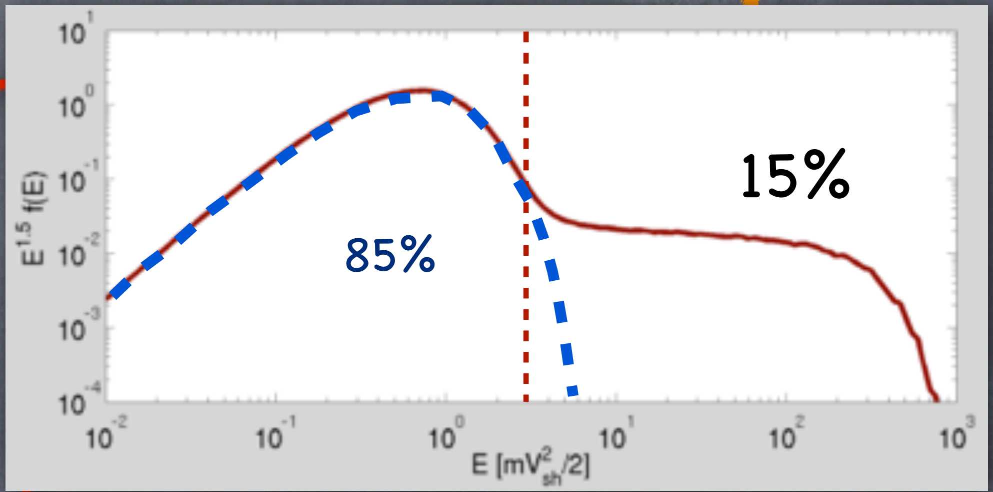
Inclination of
the B field
wrt to the
shock normal

Polarization
(low=turbulent
high=ordered)

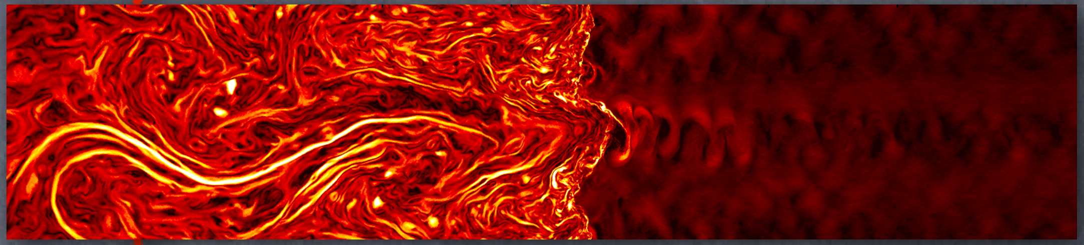
Magnetic field
amplification and
particle acceleration
where the shock is
parallel

Outline -> Conclusions

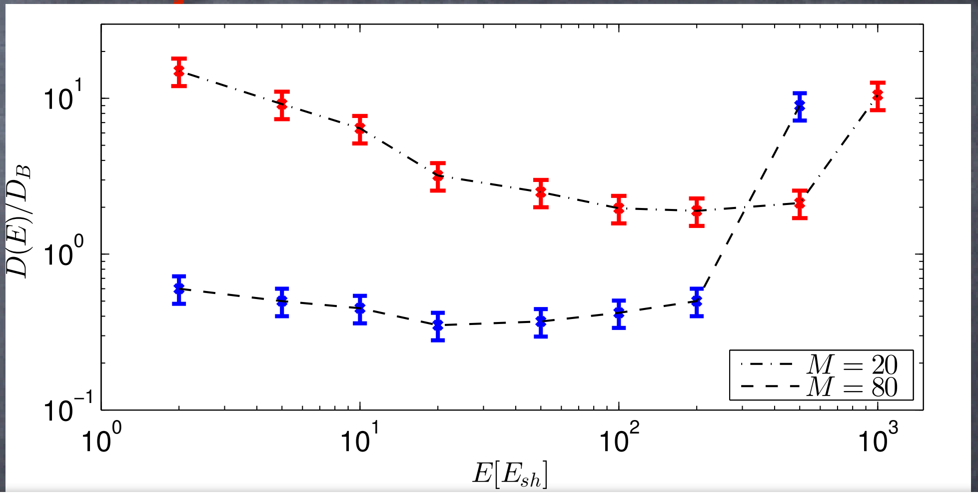
- Is acceleration at shocks efficient?
  - Hybrid simulations: >15%



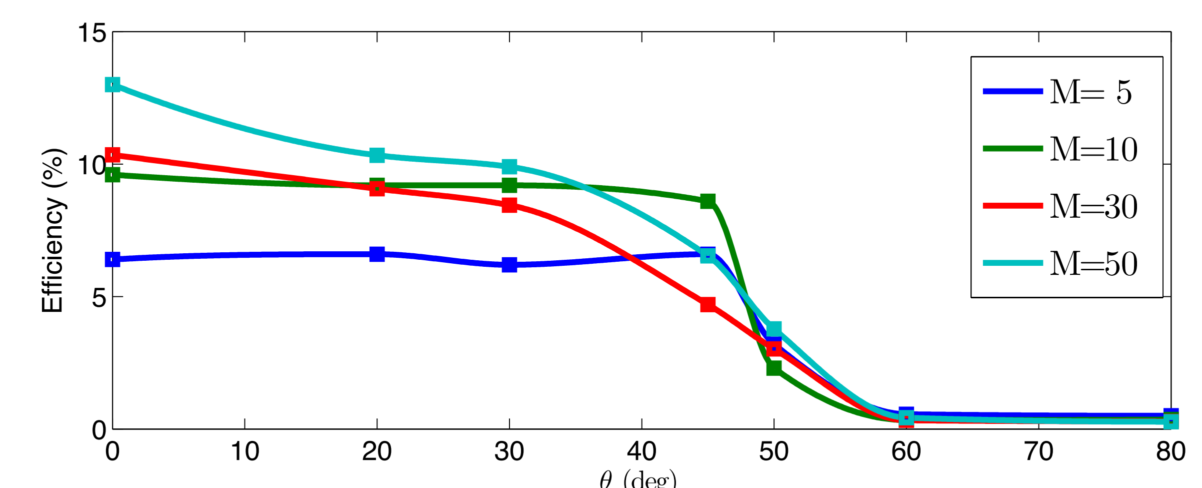
- How do CRs amplify the magnetic field?
  - Streaming & filamentation inst.



- How do fields scatter CRs?
  - Bohm diffusion in δB



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

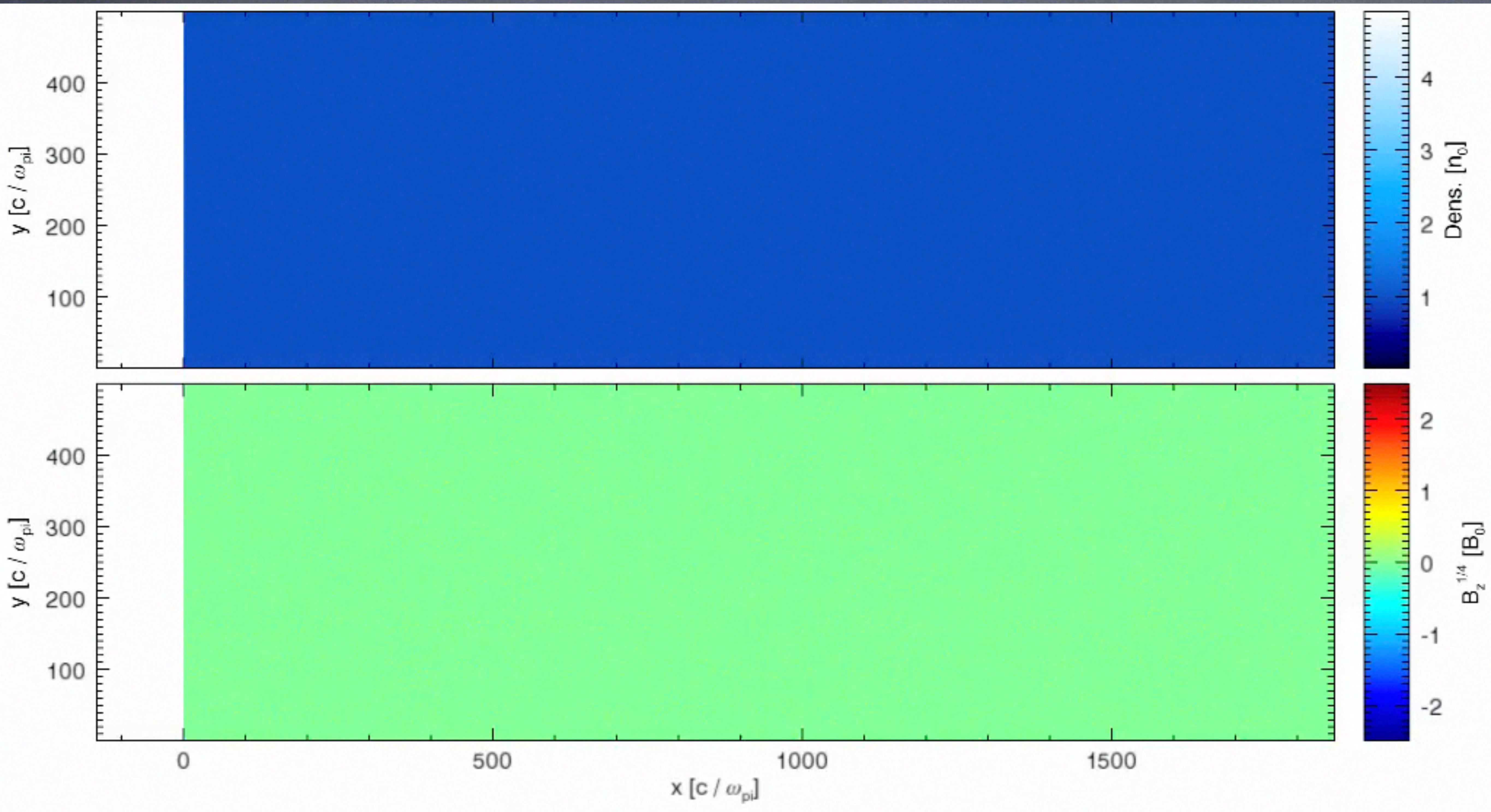


(Near-)Future Perspectives

- 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!



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]
0
500
1000
1500
x [c / ω_{pi}]