Numerical simulations of relativistic shocks

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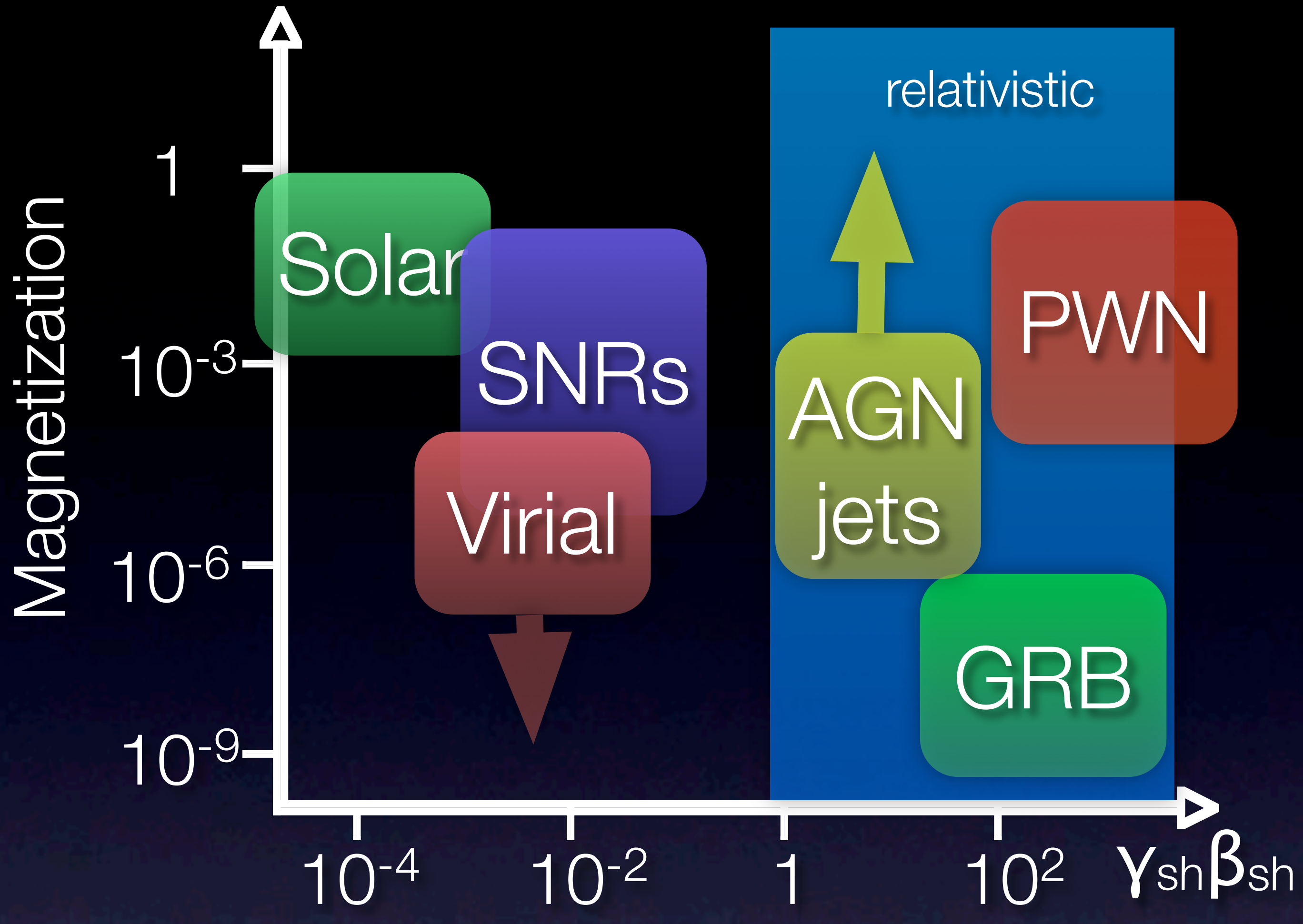
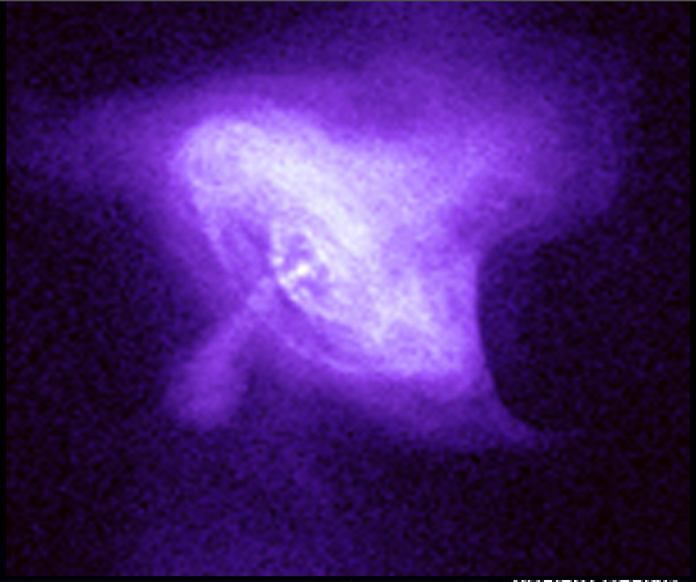
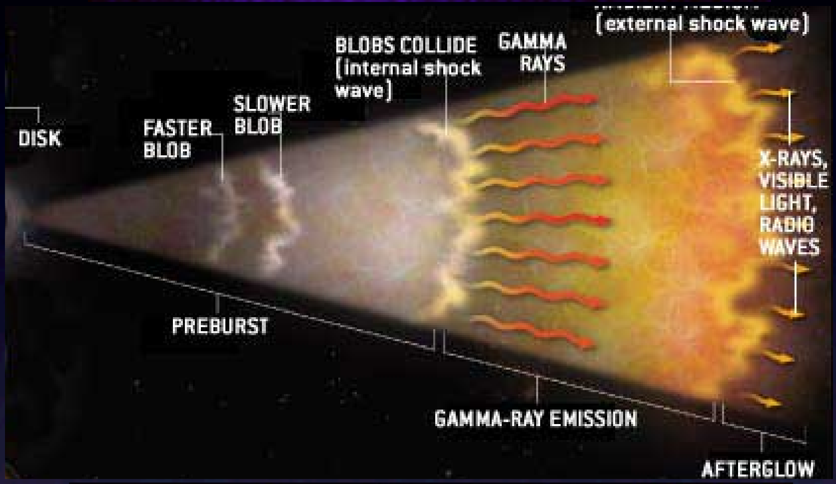
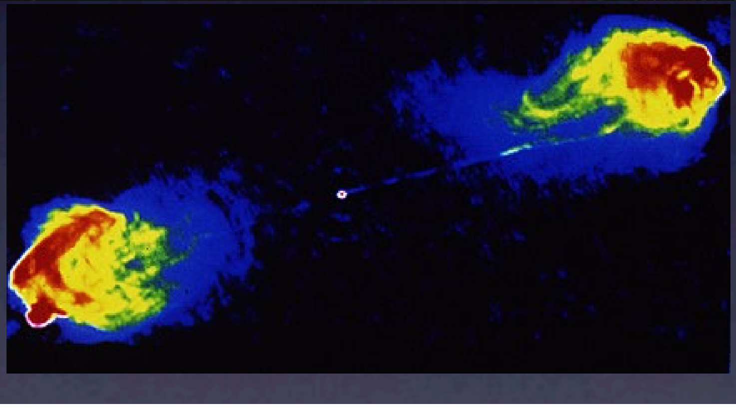
outline

- Relativistic vs Non-relativistic shocks
- Shock structure
- Particle acceleration
- CR back-reaction
- Opportunities/challenges

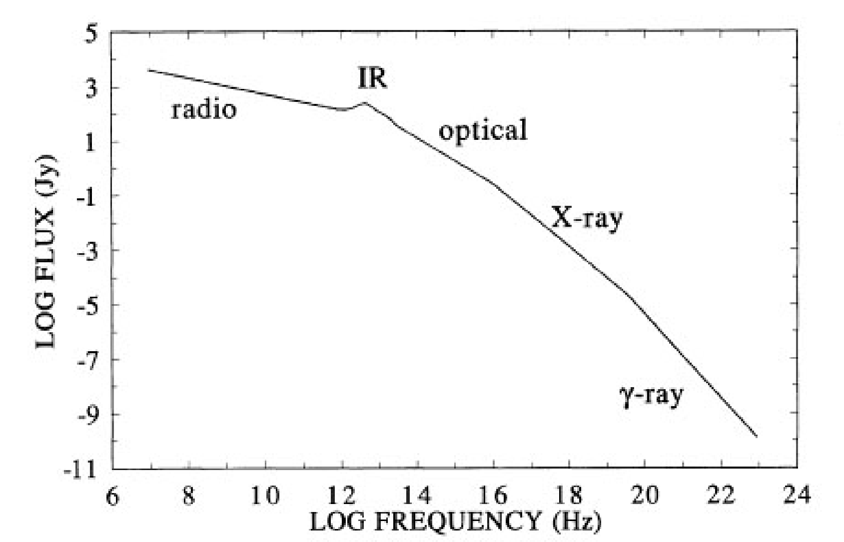








$$\sigma \equiv \frac{B^2/4\pi}{(\gamma-1)nmc^2} = \frac{1}{M_A^2} = \left(\frac{\omega_c}{\omega_p}\right)^2\left(\frac{c}{v}\right)^2 = \left[\frac{c/\omega_p}{R_L}\right]^2$$



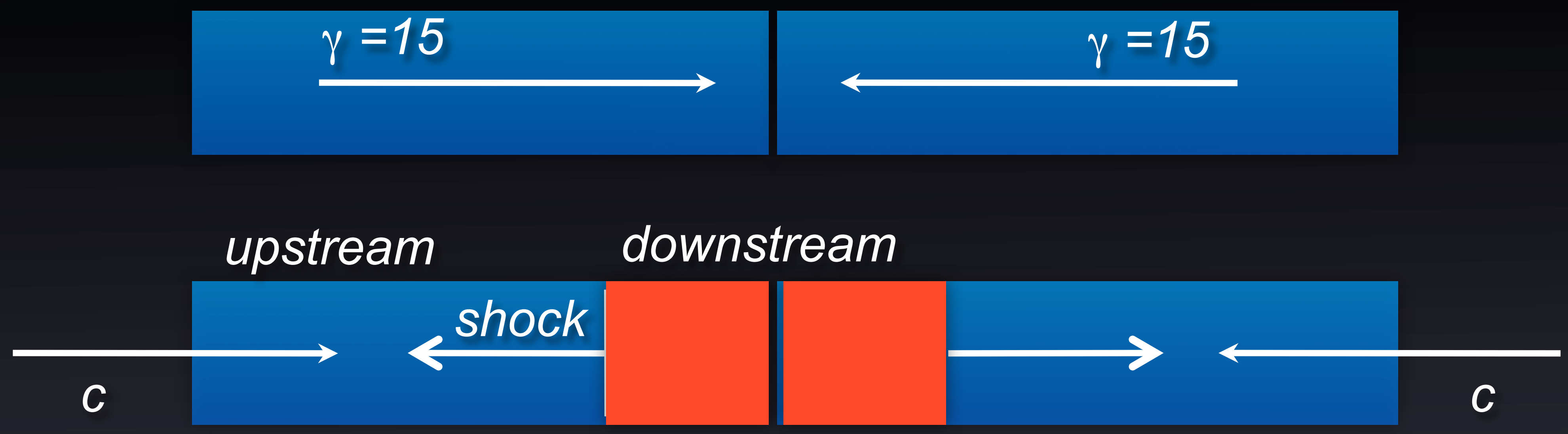
Relativistic shocks are easier!!!

$$\omega_c = \frac{qB}{\gamma mc}$$

$$\omega_p = \left(\frac{4\pi q^2 n}{\gamma m}\right)^{\frac{1}{2}}$$

acceleration is also faster

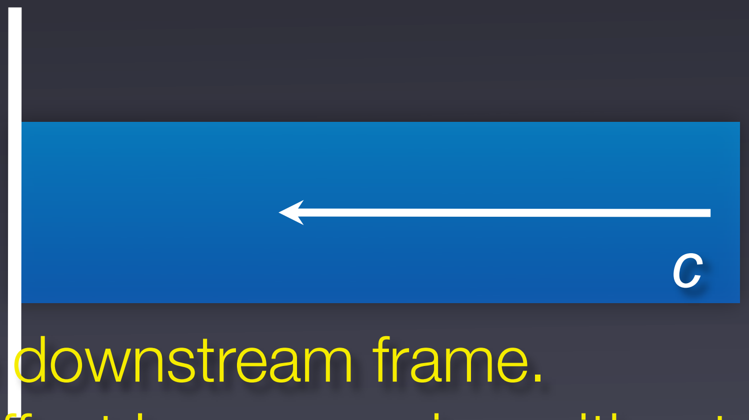
Problem setup



c/3 (3D) or c/2(2D)   c/3(3D) or c/2(2D)

"Shock" is a jump in density & velocity

Use reflecting wall to initialize a shock



Simulation is in the downstream frame.

We verified that the wall plays no adverse effect by comparing with a two-shell collision.

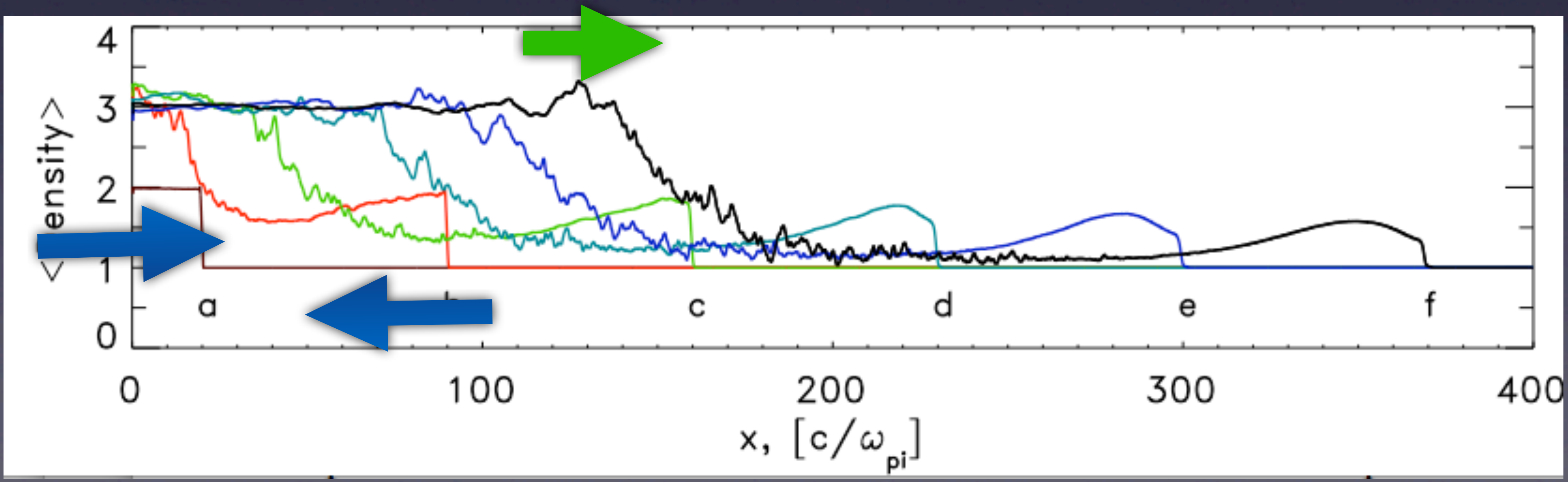
Many groups are working on PIC simultaions:
Silva et al, Hoshino et al, Nishikawa et al, Nordlund et al.
All groups agree on main points, though run times and simulation sizes differ.
Key is running simulations long enough to see "steady" shocks
Largest runs go for 10000 ω_p^{-1}; sizes up to 200^2x2000 skins; 4e10 particles

what is a shock?

- Jump in density, temperature and average velocity.
- NOT EVERY JUMP IS A SHOCK!

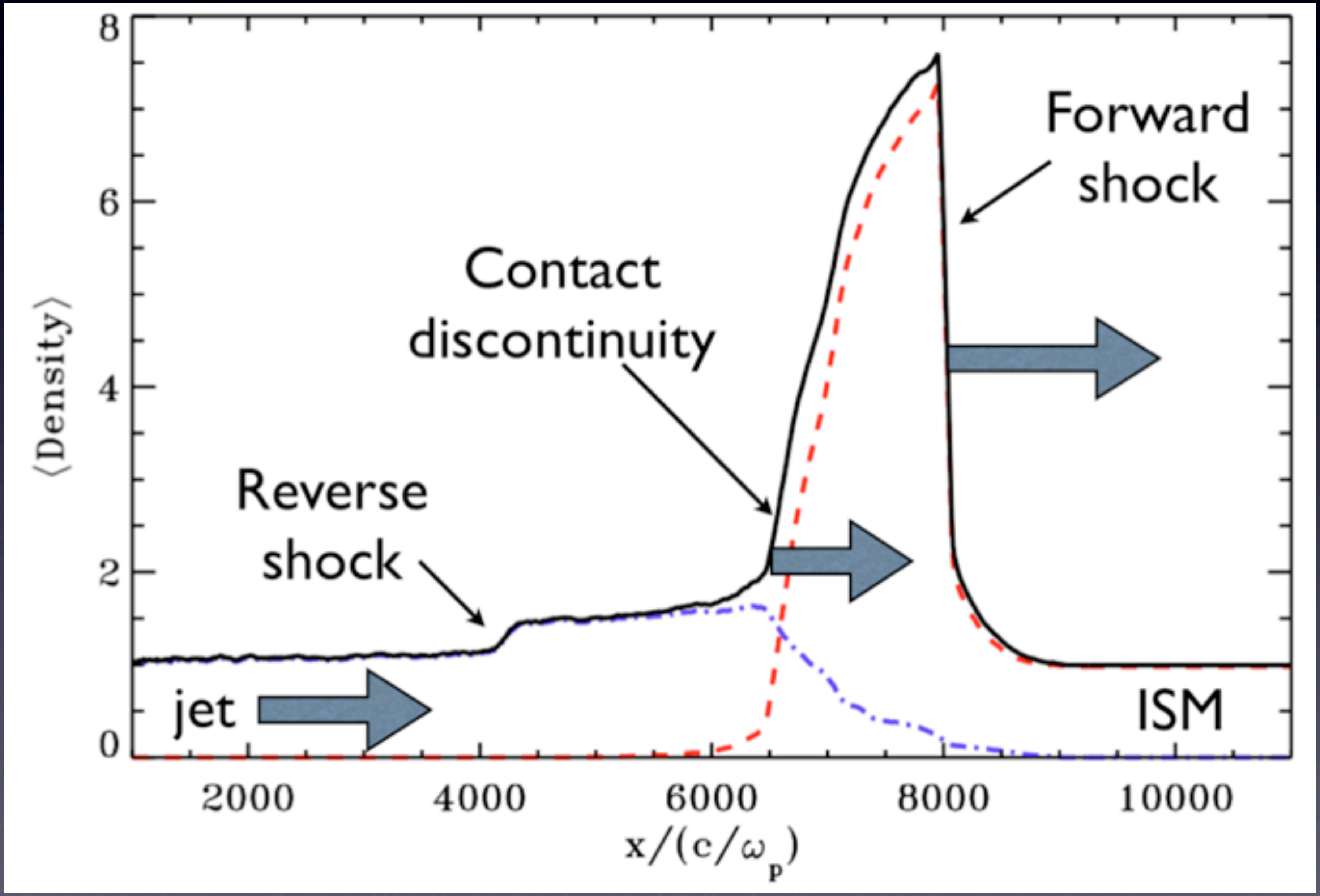
$v_{shock} < c$

~c



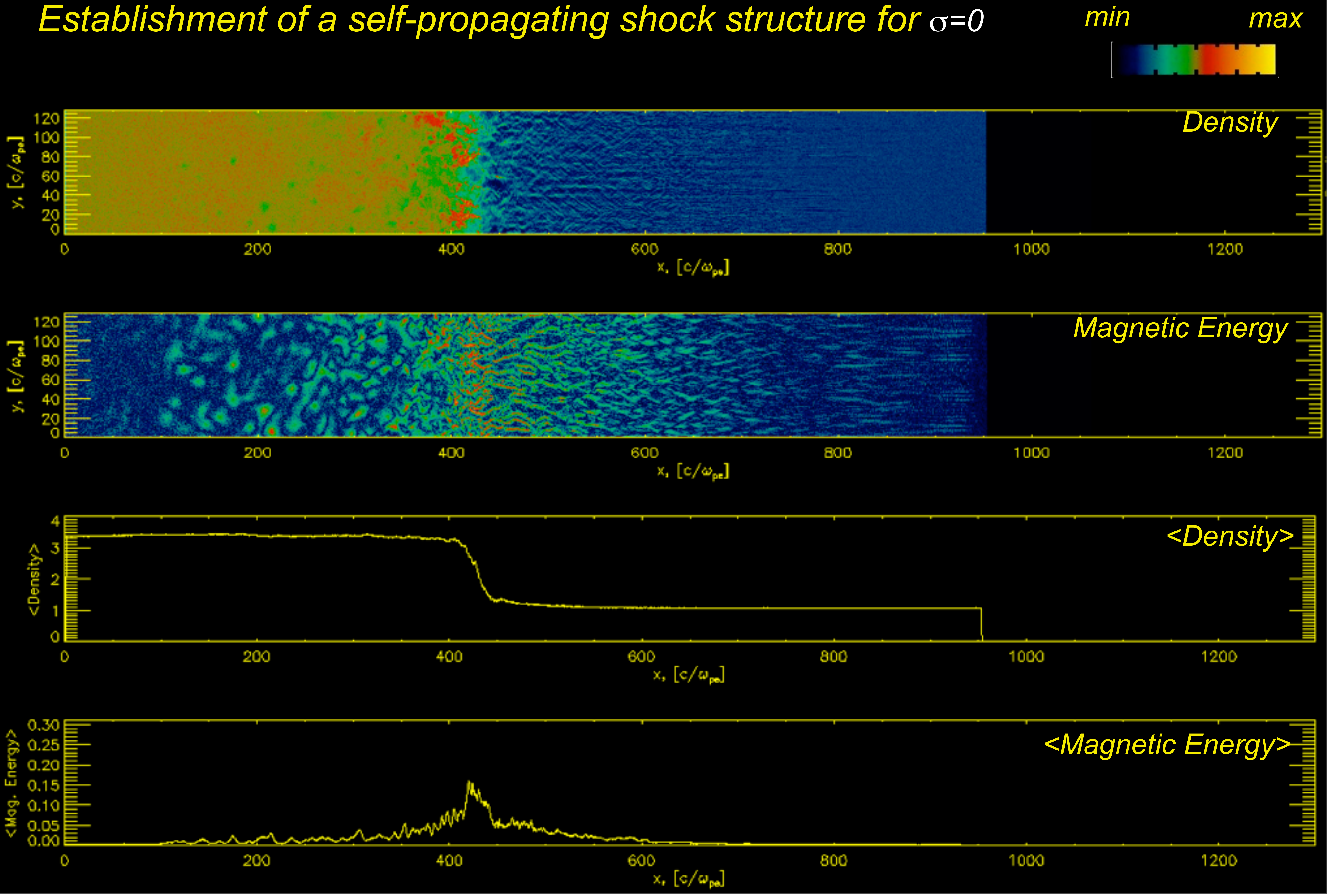
~50 skin depths of ions

what is a shock?



Relativistic pair shocks

Establishment of a self-propagating shock structure for $\sigma=0$



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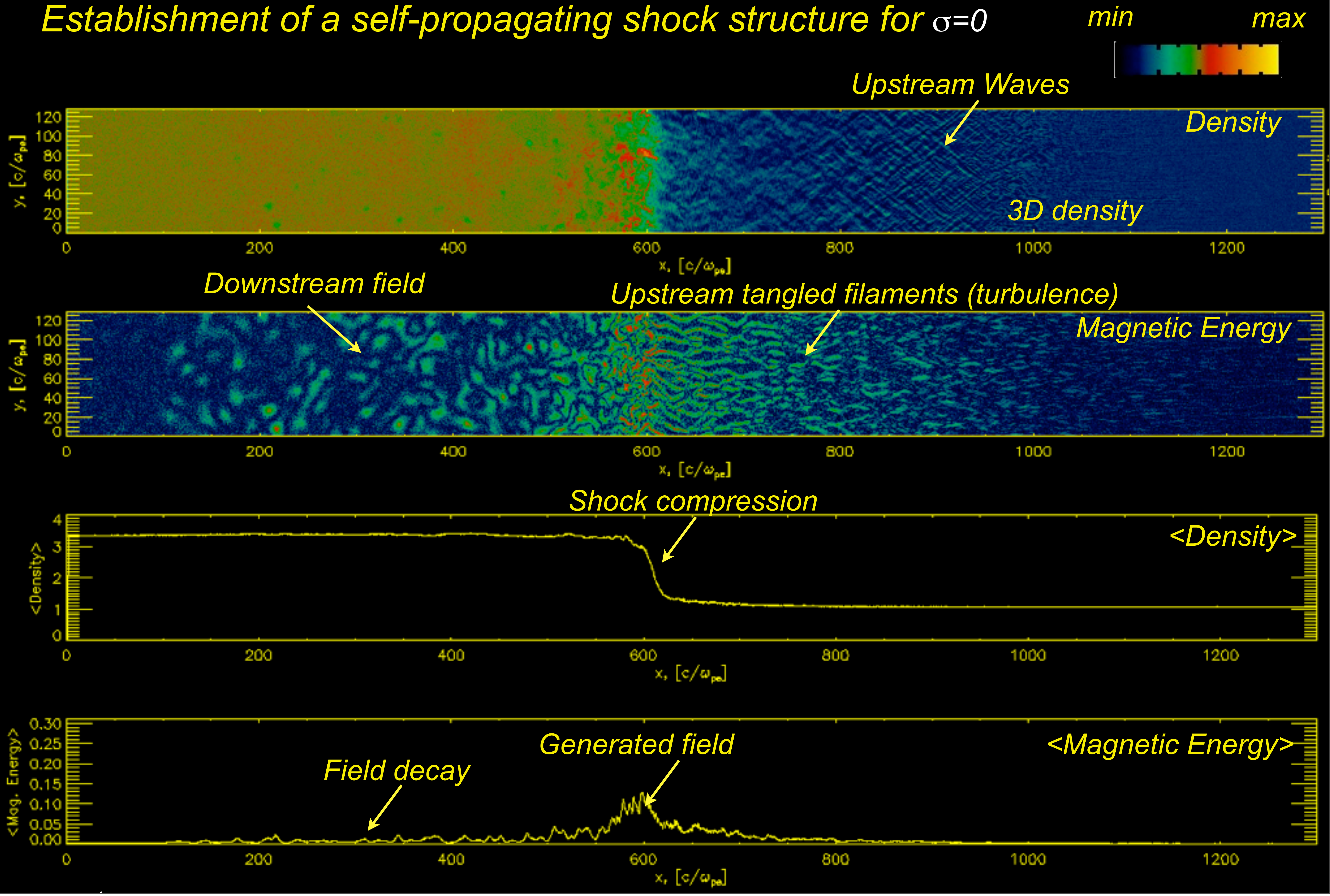


Upstream Waves

Density

3D density

Downstream field

Upstream tangled filaments (turbulence)

Magnetic Energy

Shock compression

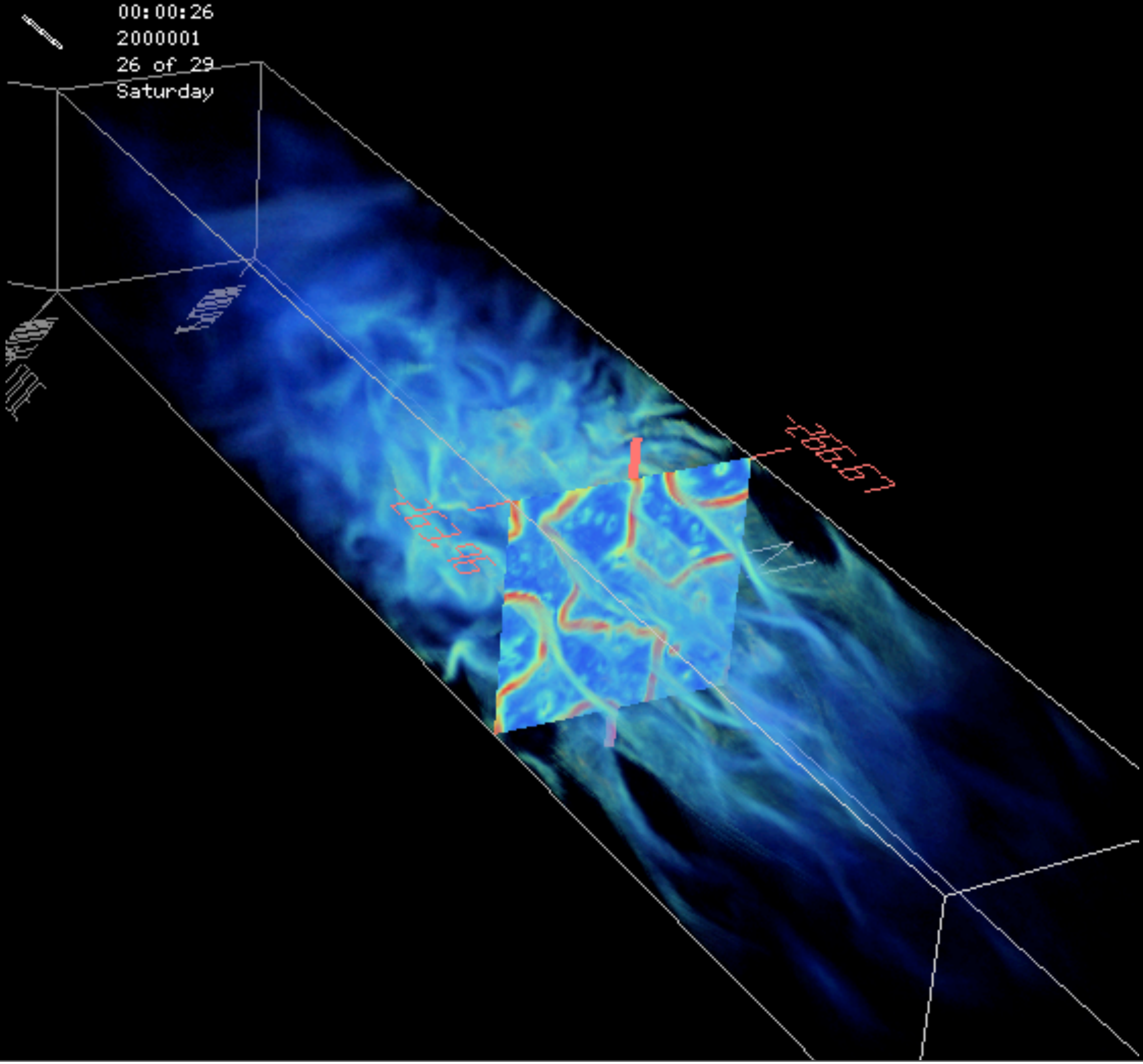
<Density>

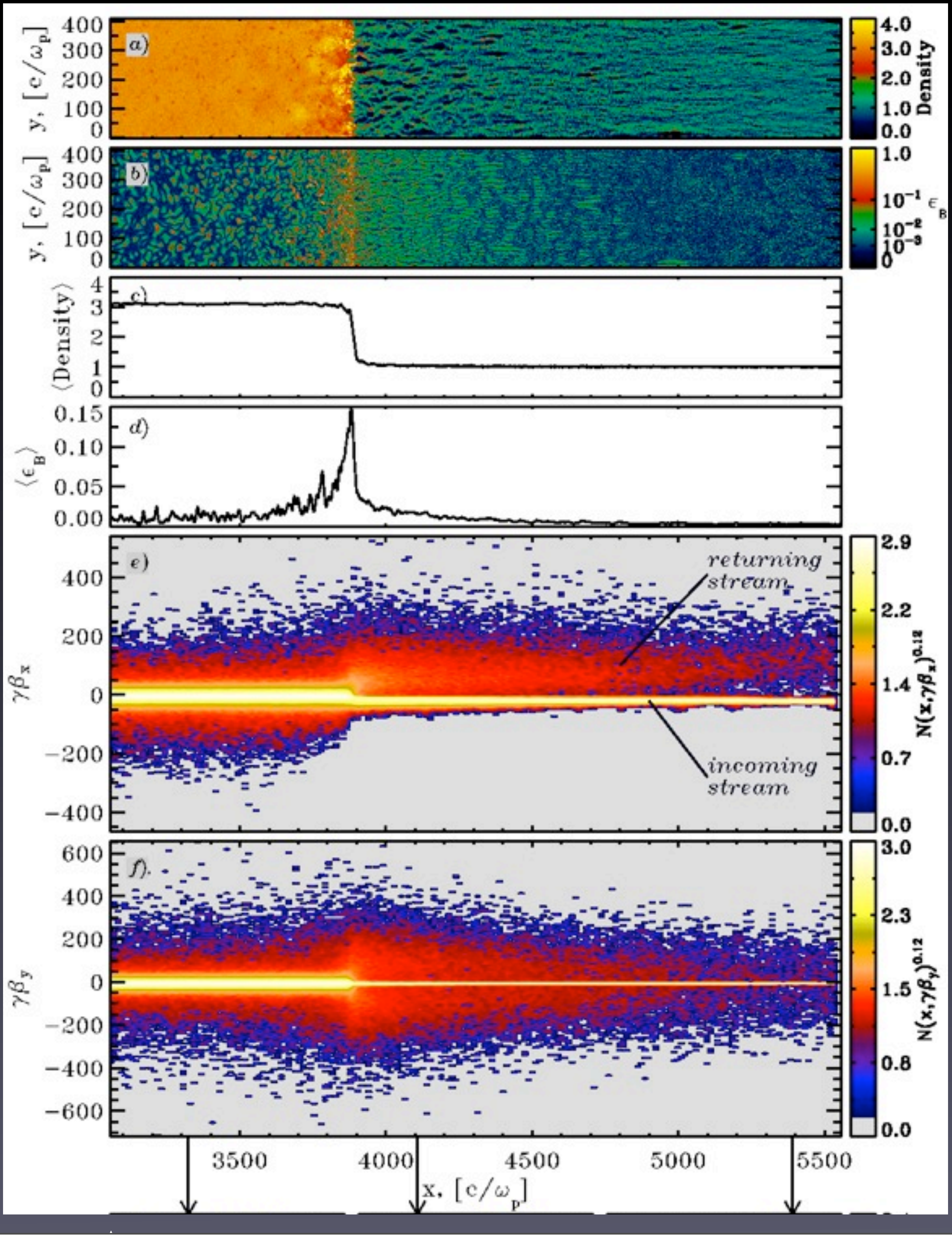
Generated field

Field decay

<Magnetic Energy>

3D unmagnetized pair shock: magnetic energy





Unmagnetized pair shock:

shock is driven by returning particle precursor (CR!)

Steady counterstreaming leads to self-replicating shock structure

x- px momentum space

Long term 2D simulation

x- py momentum space

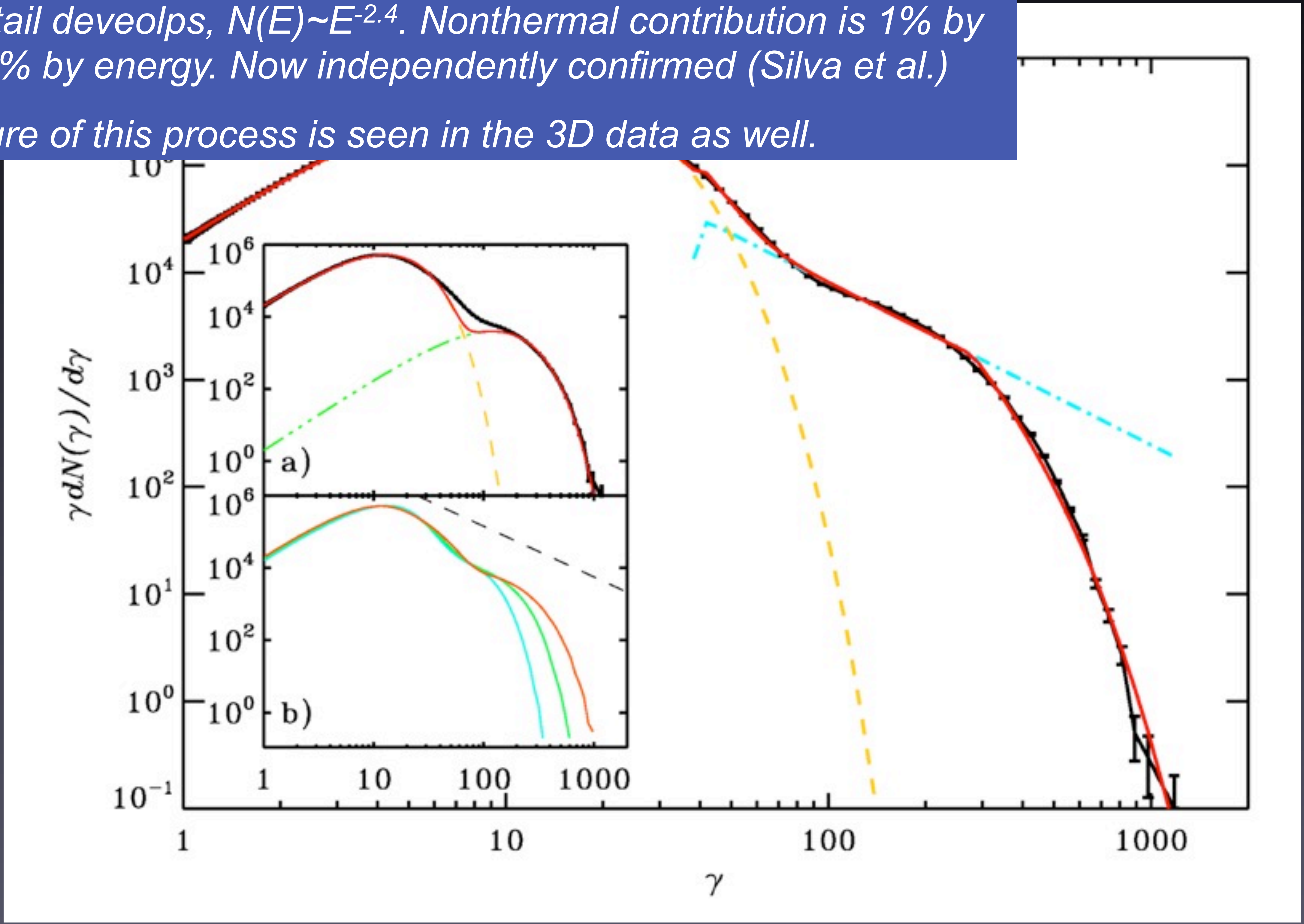
Shock structure for $\sigma=0$ (AS ’08)

Unmagnetized pair shock:

downstream spectrum: development of nonthermal tail!

Nonthermal tail deveolps, N(E)~E$^{-2.4}$. Nonthermal contribution is 1% by number, ~10% by energy. Now independently confirmed (Silva et al.)

Early signature of this process is seen in the 3D data as well.



A.S. 2008, ApJ, 682, L5

also seen by Martins et al 09

Unmagnetized pair shock: particle trajectories

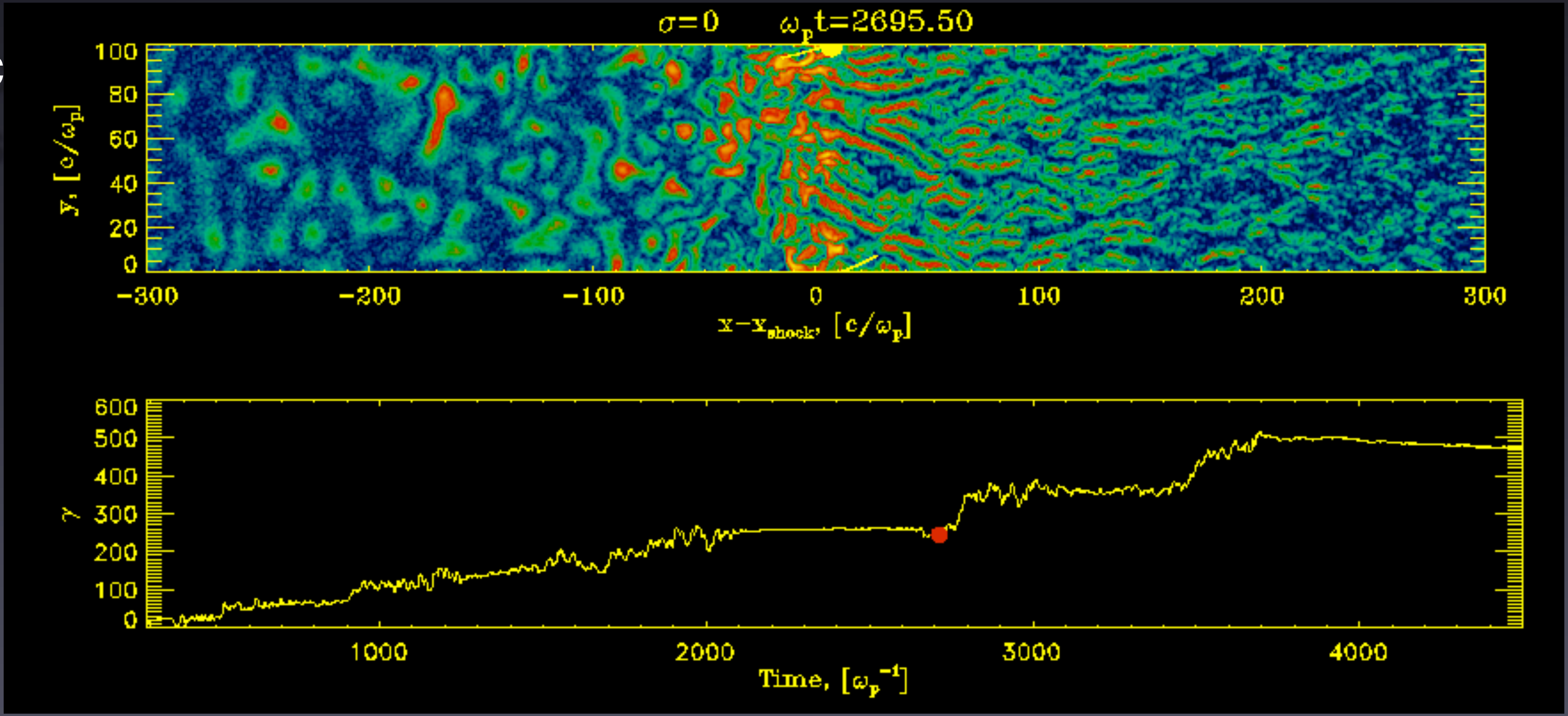
Nonthermal tail develops, N(E)~E$^{-2.4}$. Nonthermal contribution is 1% by number, ~10% by energy. Well fit by low energy Maxwellian + power law with cutoff.

Same process is seen in the 3D data as well. Easy to have ΔB/B>>1 when B=0!

Injection works self-consistently from the thermal distribution.

Magnetic filaments

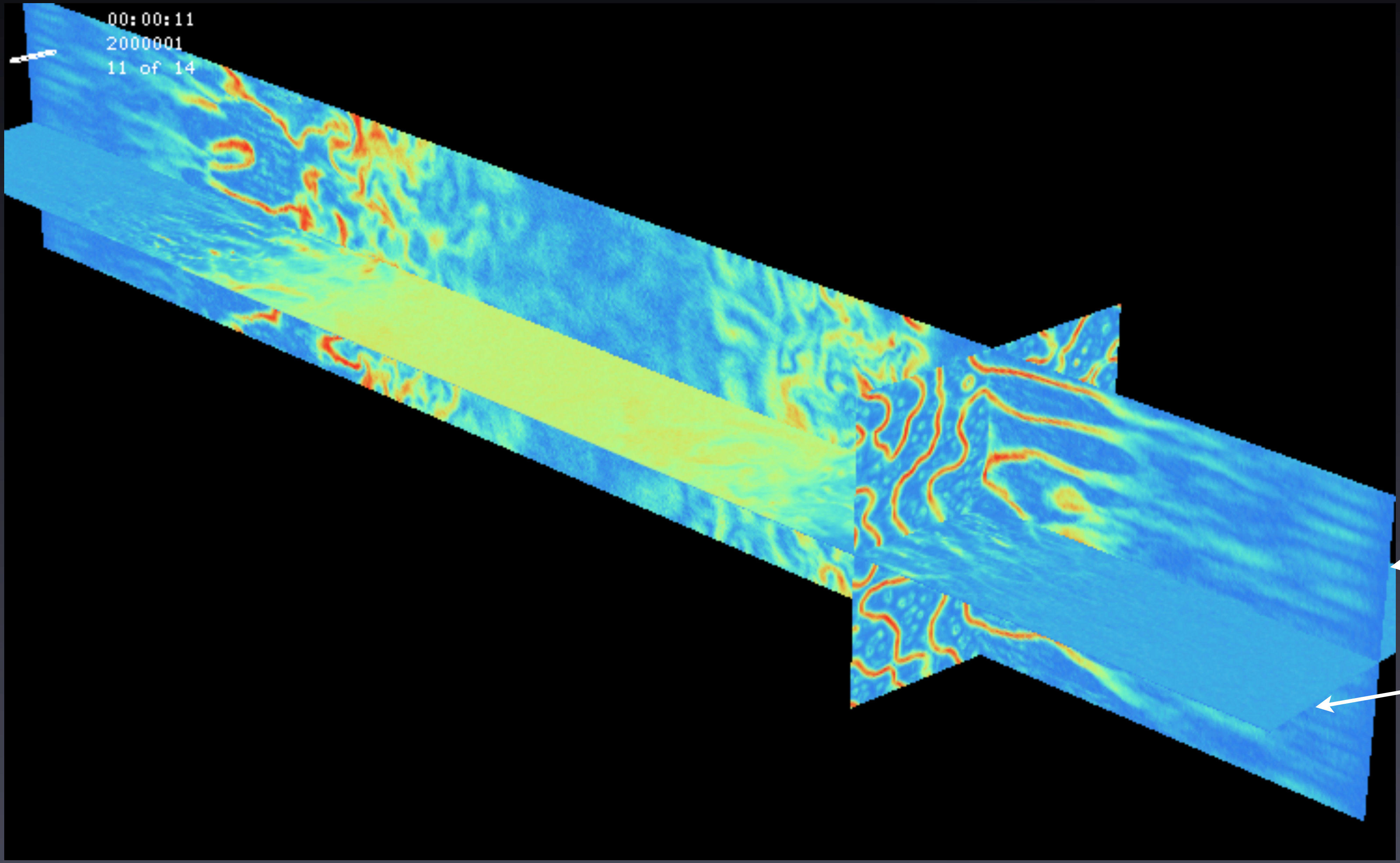
Particle energy



Particles that are accelerated the most, graze the shock surface

Transition between magnetized and unmagnetized shocks:

$\sigma=0$

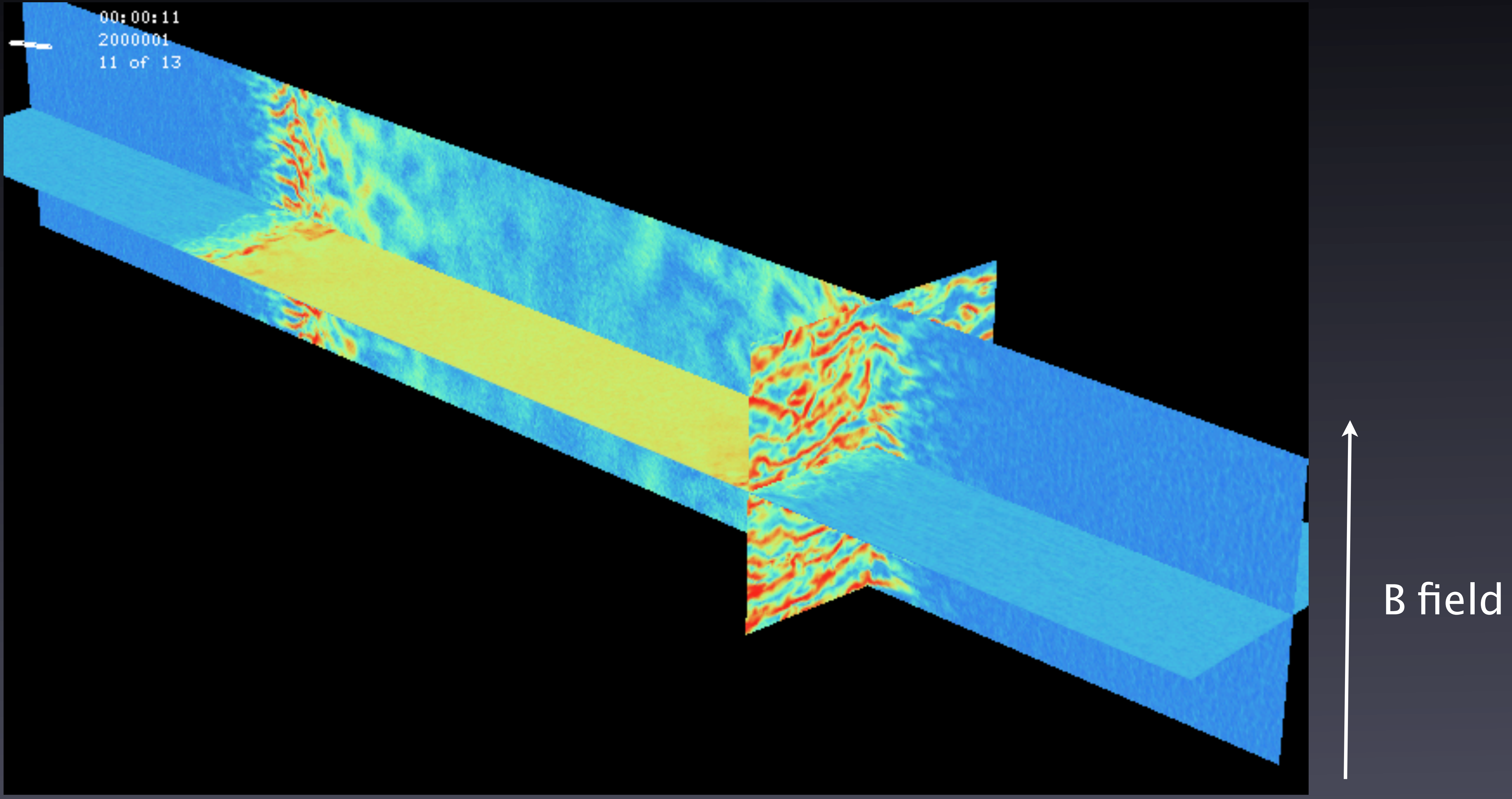


Magnetic energy

Density

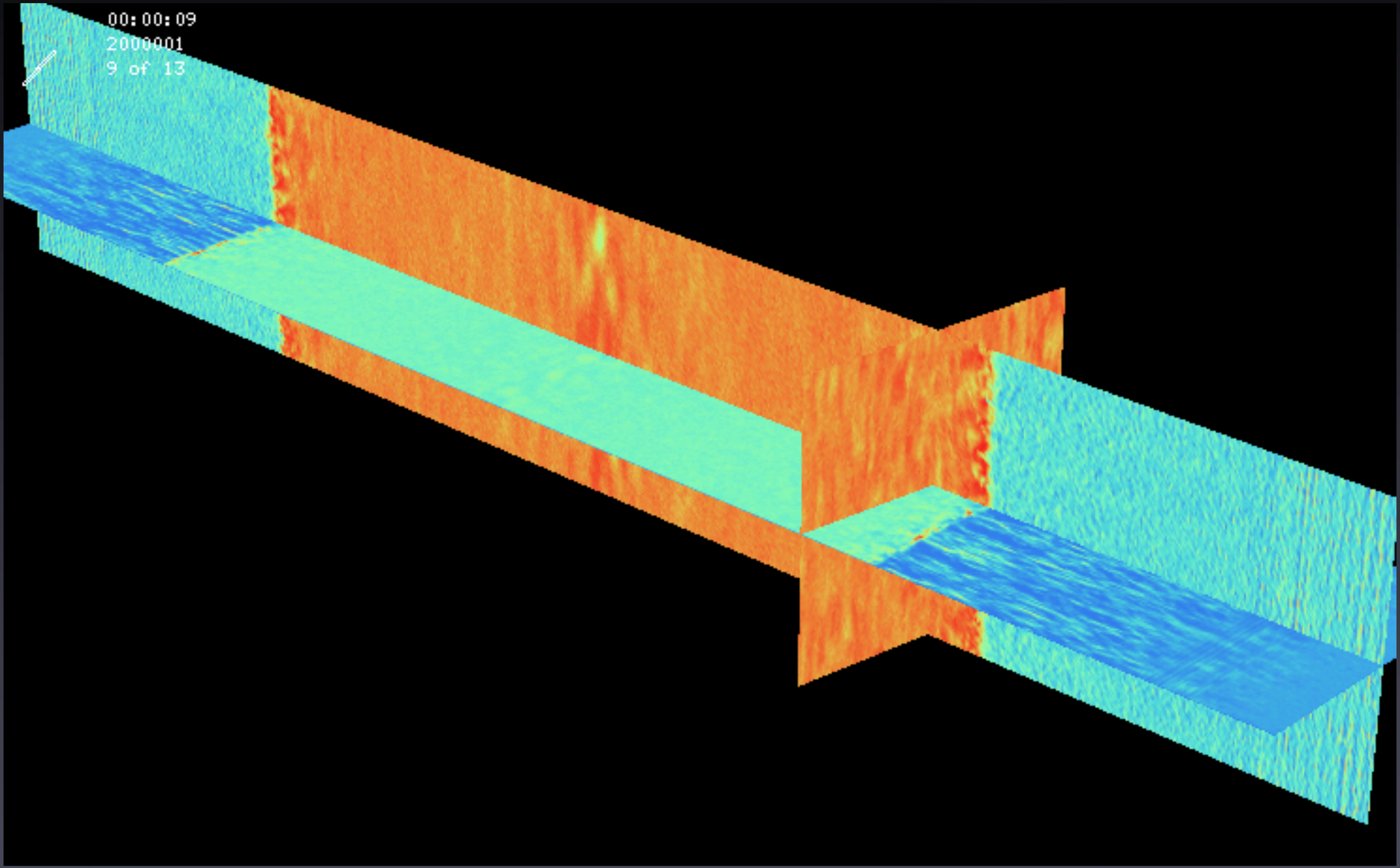
Transition between magnetized and unmagnetized shocks:

$\sigma = 10^{-3}$



Transition between magnetized and unmagnetized shocks:

$\sigma = 10^{-1}$

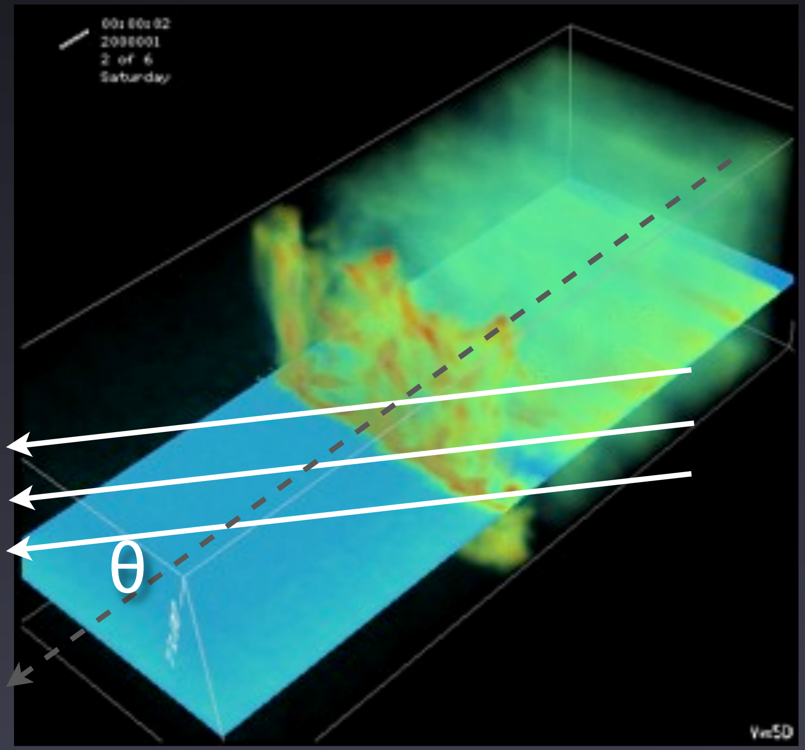


B field

Acceleration: $\sigma < 10^{-3}$ produce power laws, $\sigma > 10^{-3}$ just thermalize

Can magnetized pair shocks accelerate particles?

Investigate the dependence of acceleration on the angle between the background field and the shock normal (Sironi & AS 09): σ=0.1, γ=15; Find p-law index near -2.3



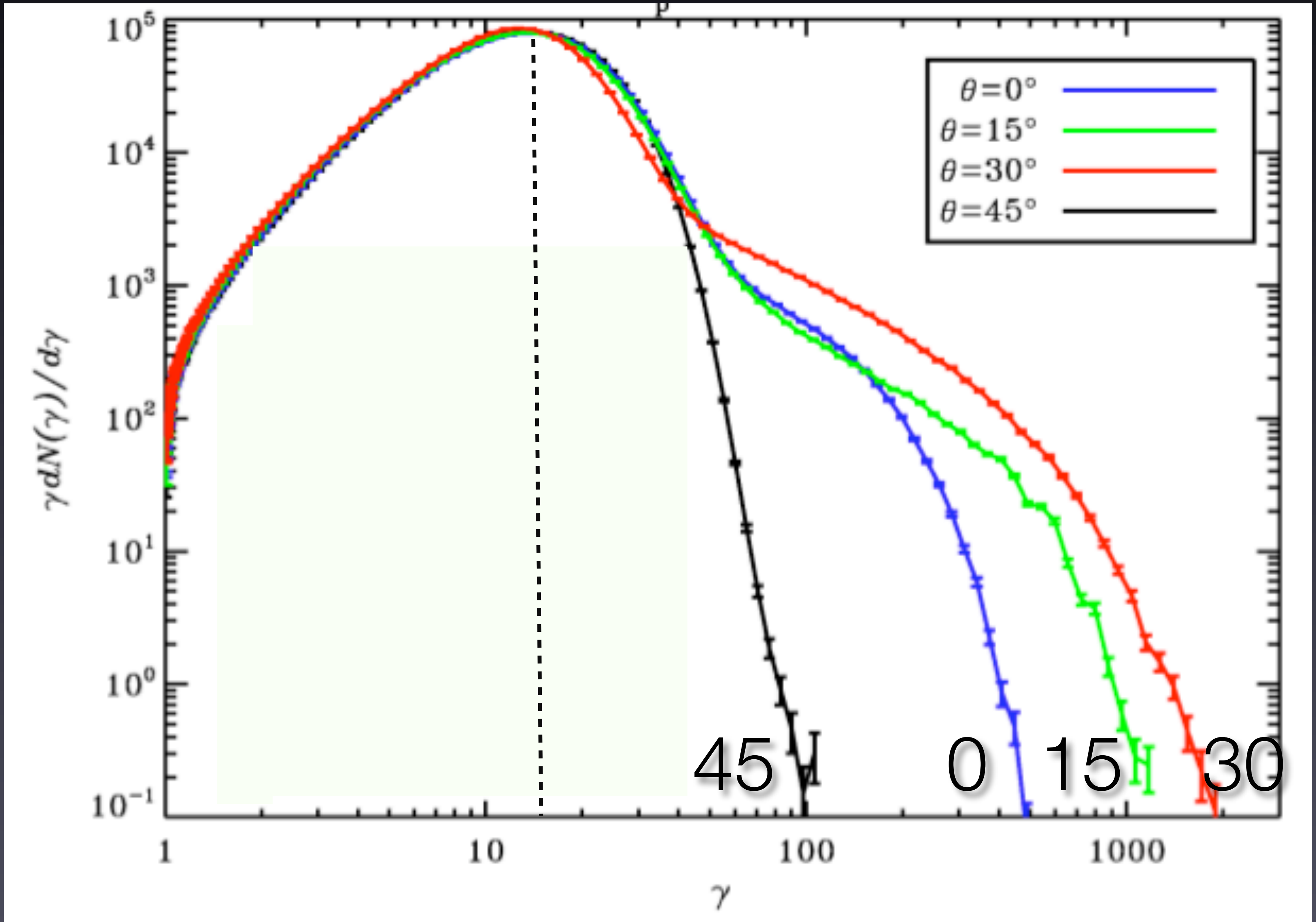
$\beta_{sh}/\cos\theta < 1$ -- subluminal

Self-turbulence is not enough to exceed superluminal constraint

In upstream frame need:

$$\theta_{upstream} < 32^\circ/\gamma$$

for acceleration

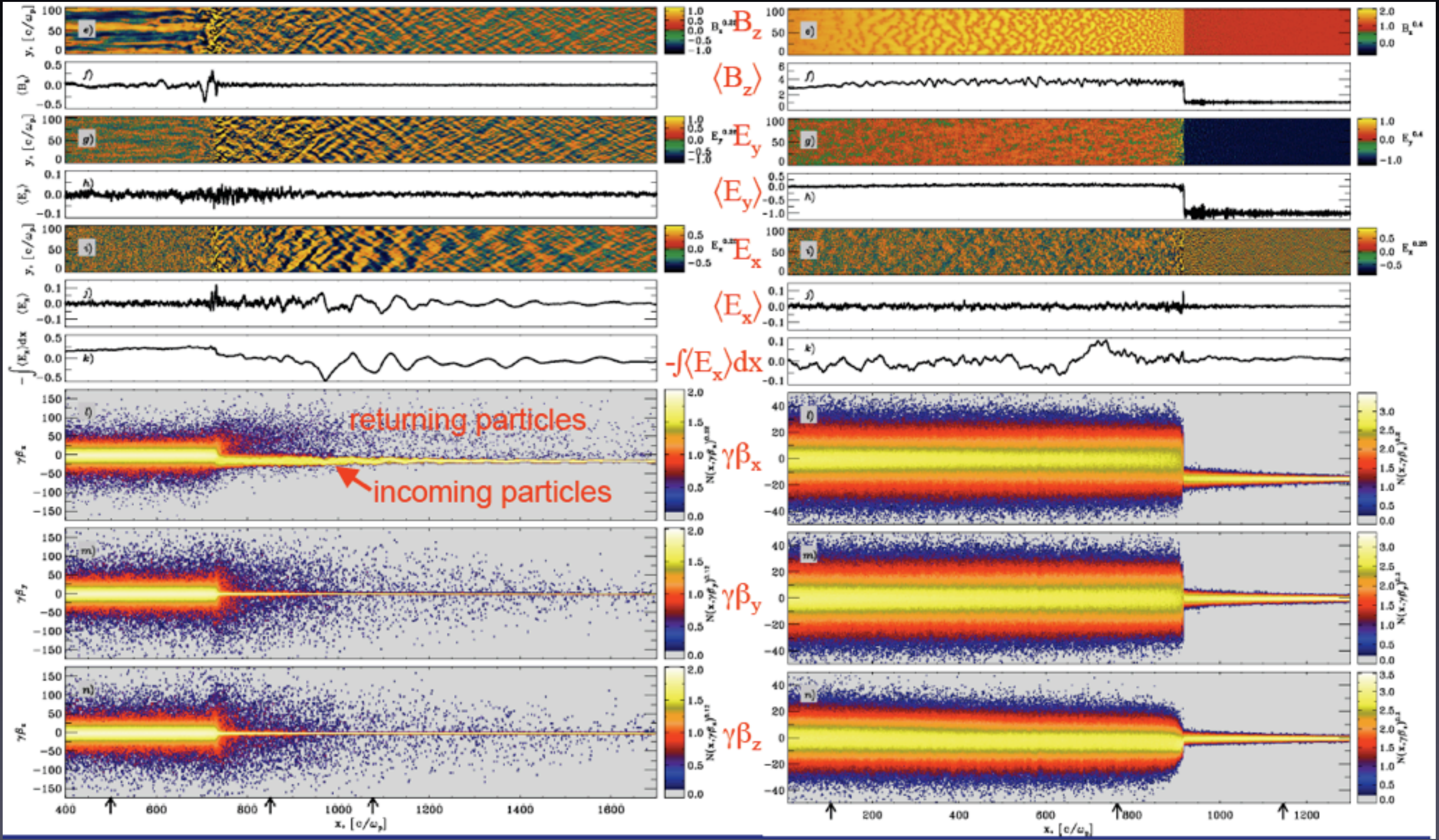


Observe transition between subluminal and superluminal shocks. Shock drift acceleration is important near transition.

Perpendicular shocks are poor accelerators.

Returning particles and upstream waves

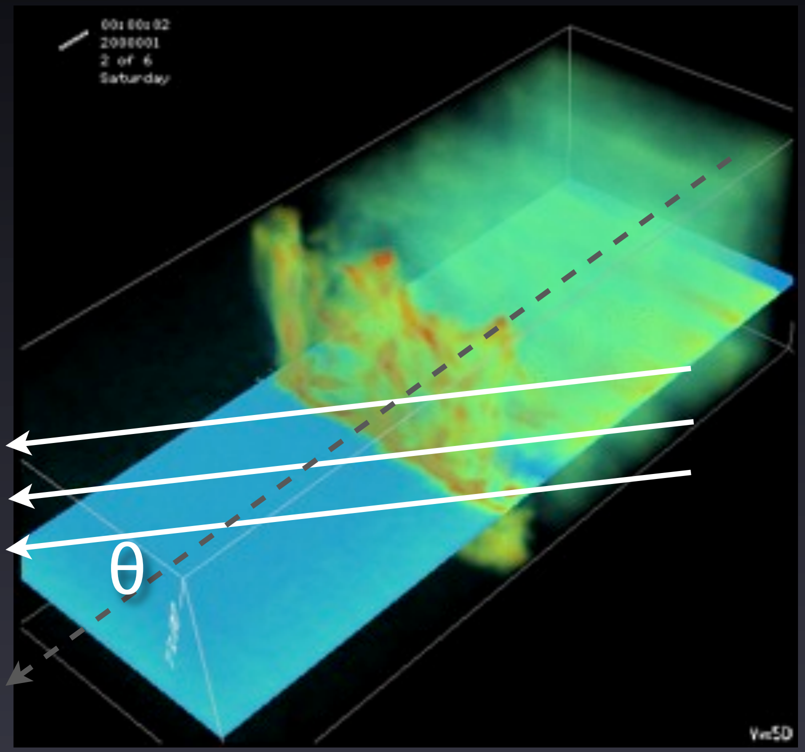
0 degrees, subluminal *45 degrees, superluminal*

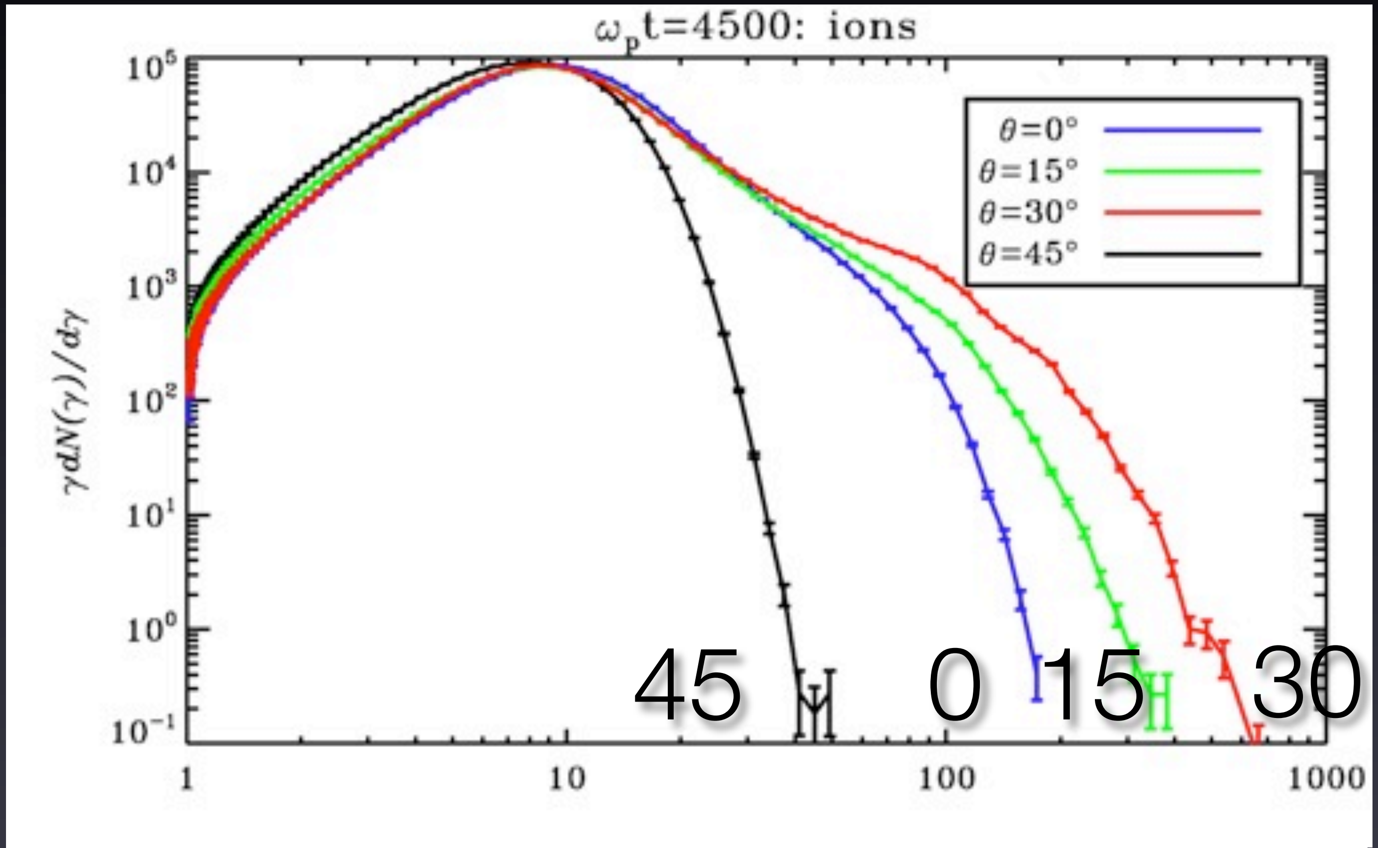


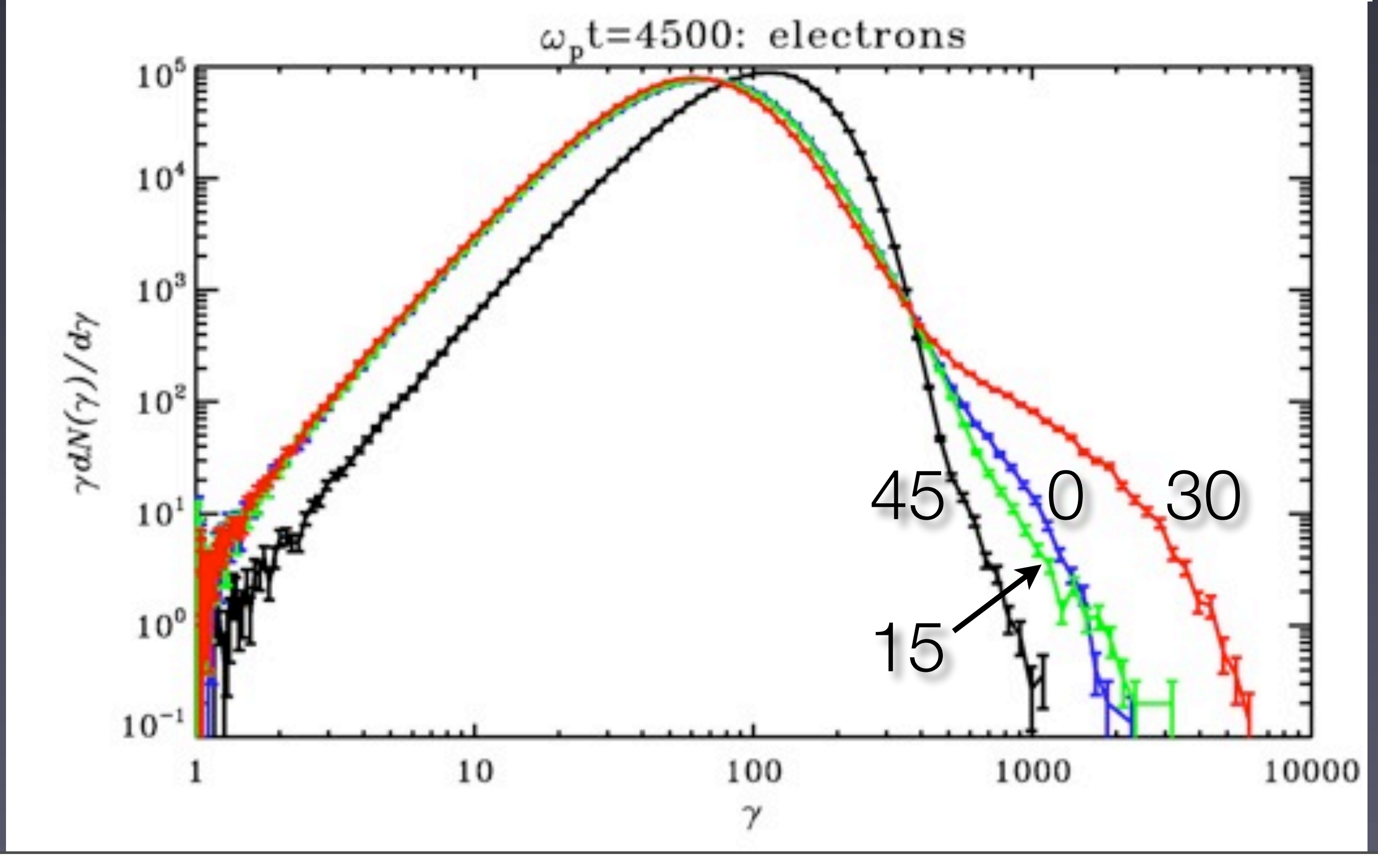
Upstream oblique waves are caused by returning particles which are scattered by these waves

Can magnetized e-ion shocks accelerate particles?

Investigate the dependence of acceleration on the angle between the background field and the shock normal (Sironi & AS in prep): σ=0.1, γ=15, mass ratio 16.







$\beta_{sh}/\cos\theta < 1$ -- subluminal

Self-turbulence is not enough to exceed superluminal constraint

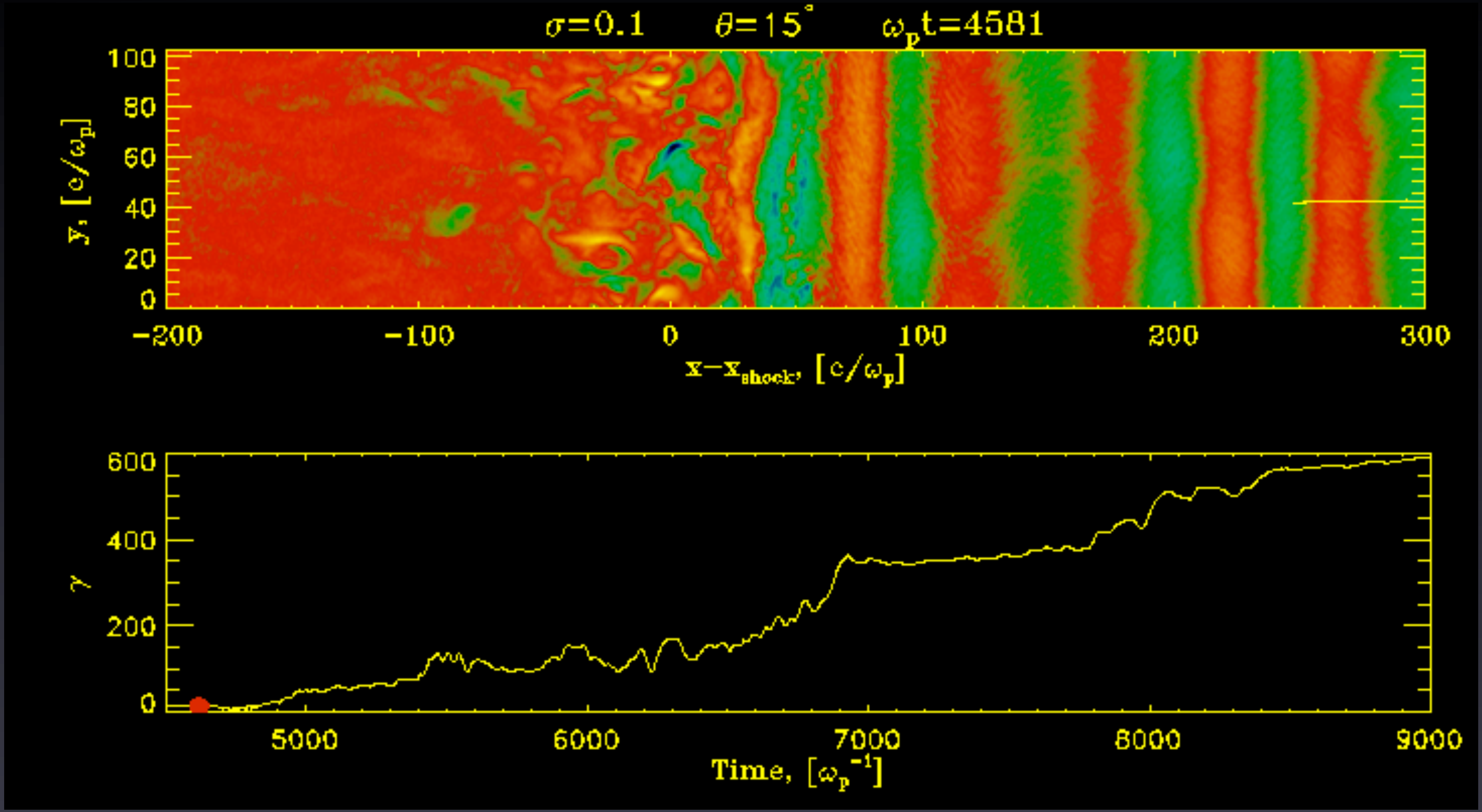
Superluminal constraint works even for electron-ion plasmas (relativistic)

Perpendicular shocks are poor accelerators.

Electron heating -- 10-50% of ion energy; up to 25% of flow energy in ion tail

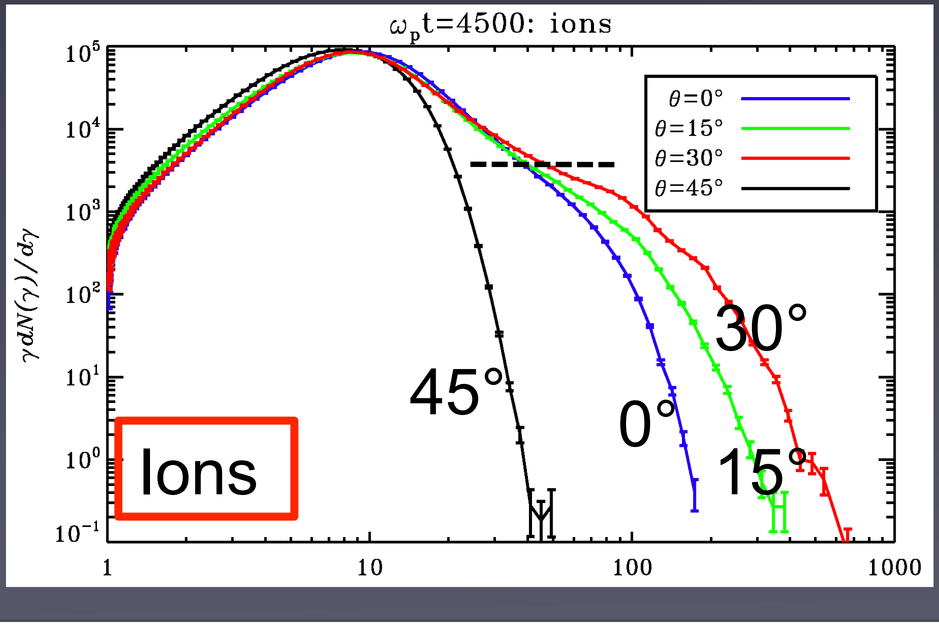
Electrons -- 2-10%

Electron-ion shocks: growth of upstream waves



Sironi & AS, in prep

Growth of upstream waves leads to more efficient scattering and acceleration of ions. Feedback of acceleration on the shock structure.



B field amplification

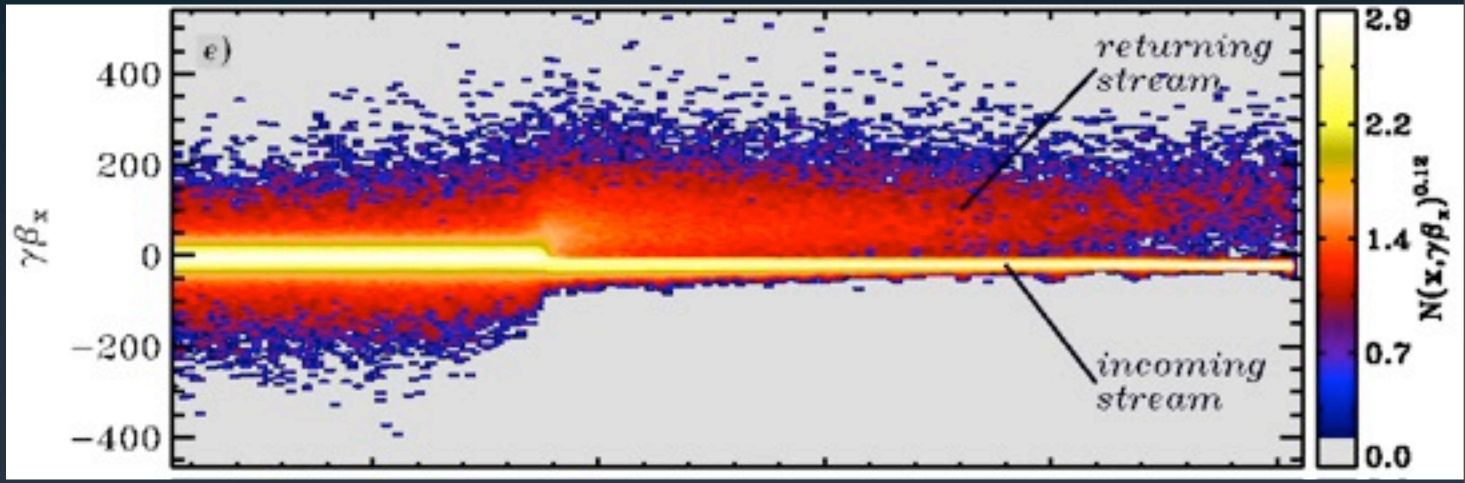
CR accelerating shocks can cause a current of protons to propagate through the upstream. Bell (04, 05) found an MHD instability of CRs flying through magnetized plasma.

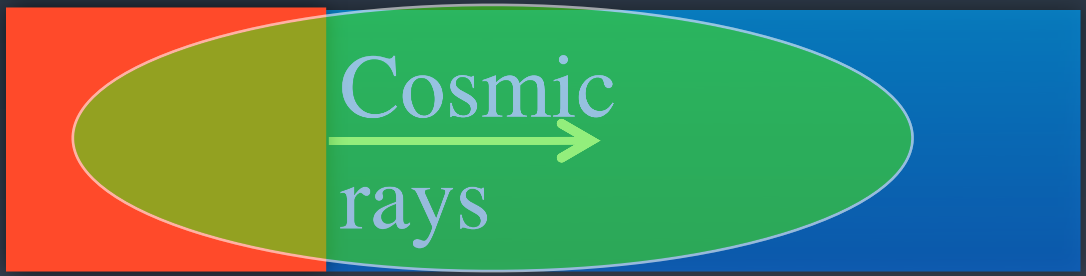
The interaction is nonresonant at wavelength << Larmor radius of CRs.

We simulated this instability with PIC in 2D and 3D (Riquelme and A.S. 09)

Saturation is due to plasma motion ($v_A \sim v_{d,CR}$), or CR deflection; for SNR conditions expect ~10 field increase.

Bell's nonresonant CR instability





Cosmic ray current $J_{cr}=en_{cr}v_{sh}$

B field amplification

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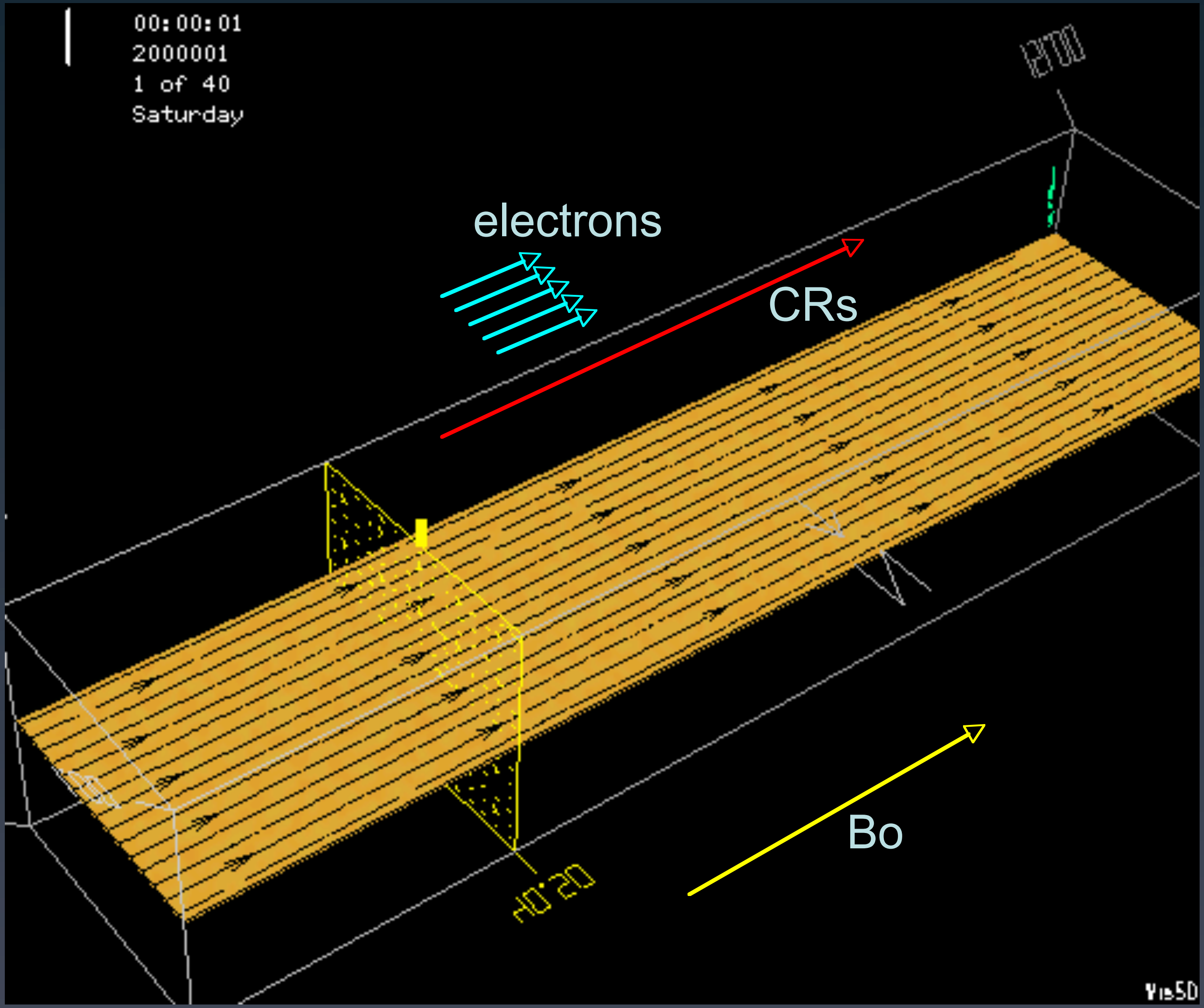
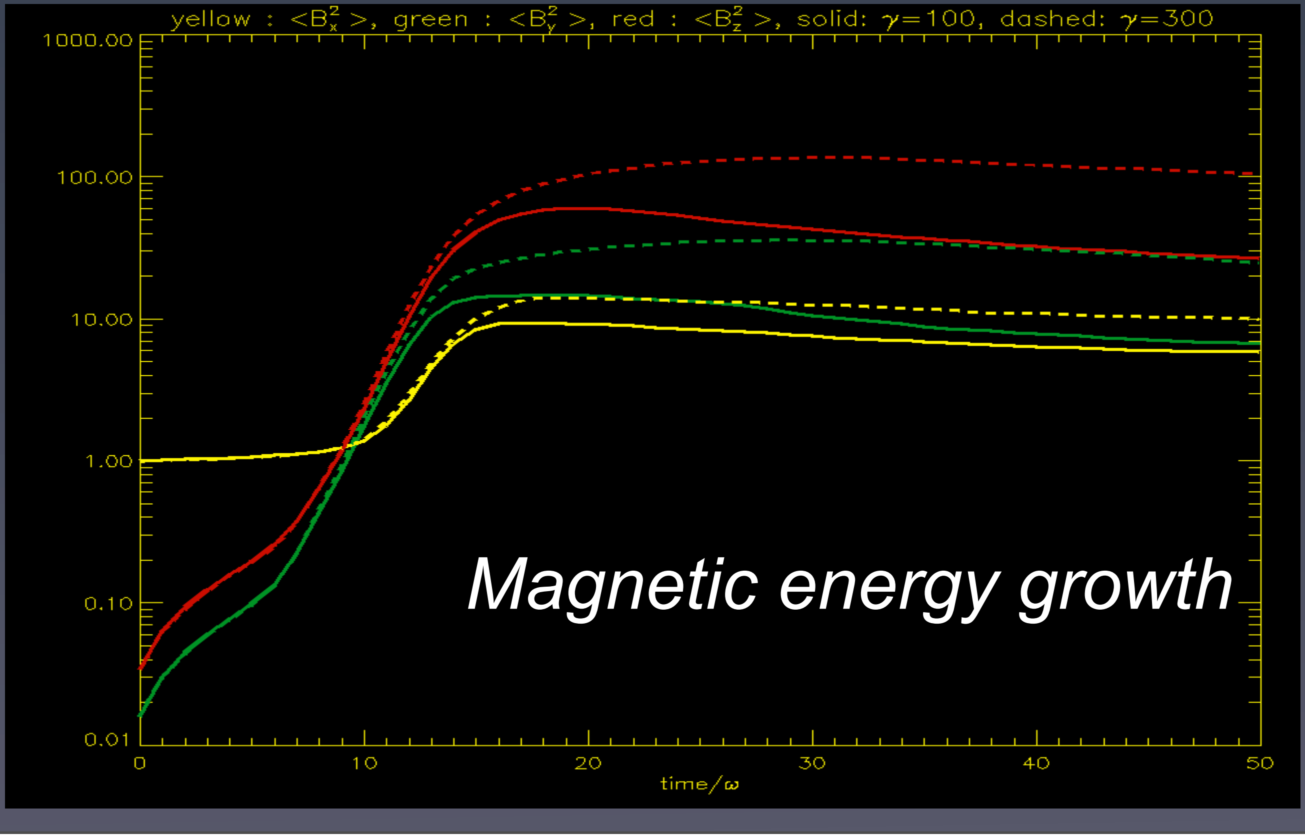




Magnetic energy growth

$$k_{max}\, c = 2\pi J_{cr}/B_0$$

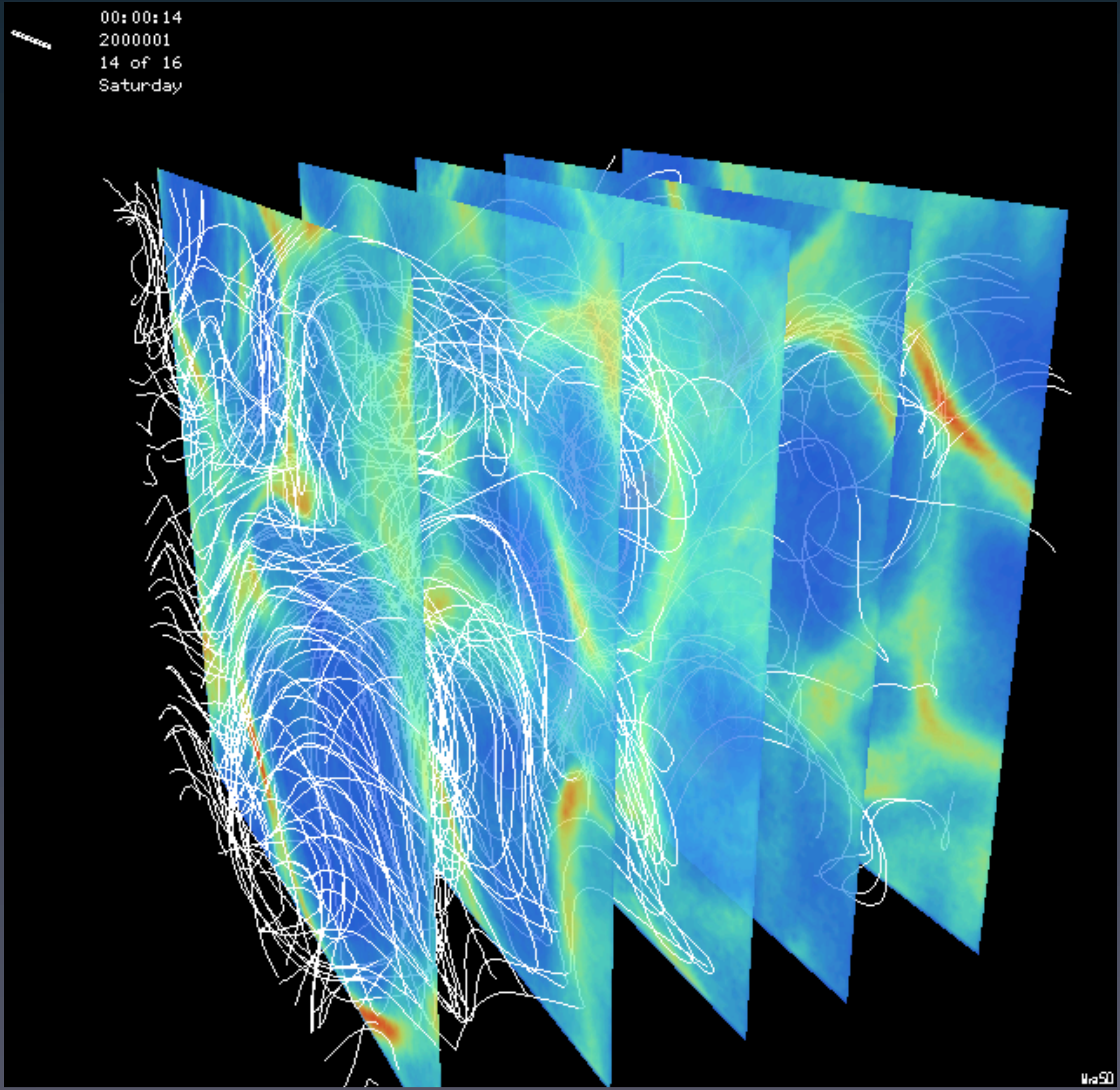
$$\gamma_{max} = k_{max} V_{Alfven,0}$$

Need magnetized plasma: $\omega_{ci} \gg \gamma_{max}$

B field amplification: 3D runs

Bell's nonresonant CR instability

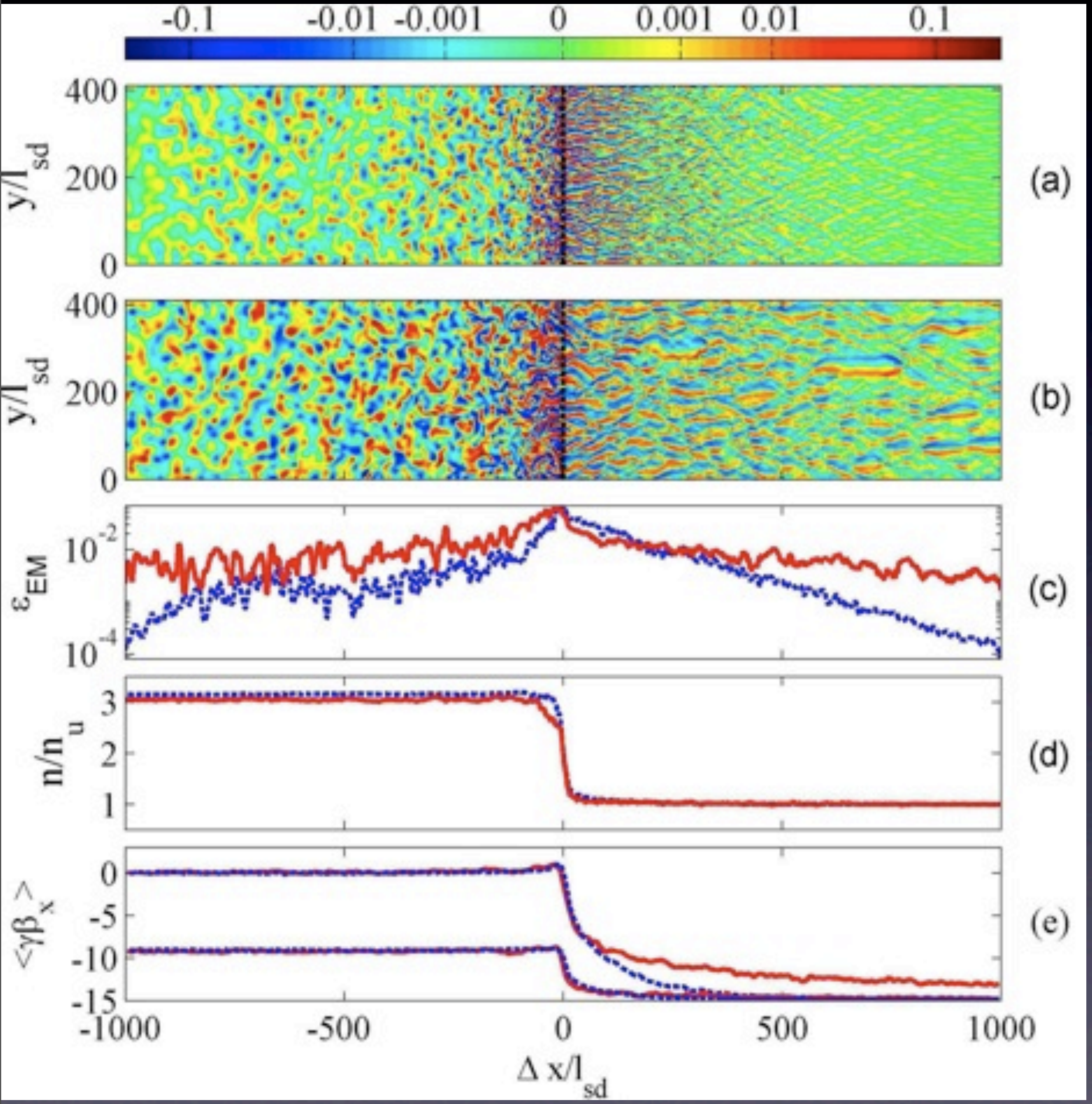
(Riquelme and A.S. 2009 ApJ)



Field amplification of ~10 in SNRs can be due to Bell's instability

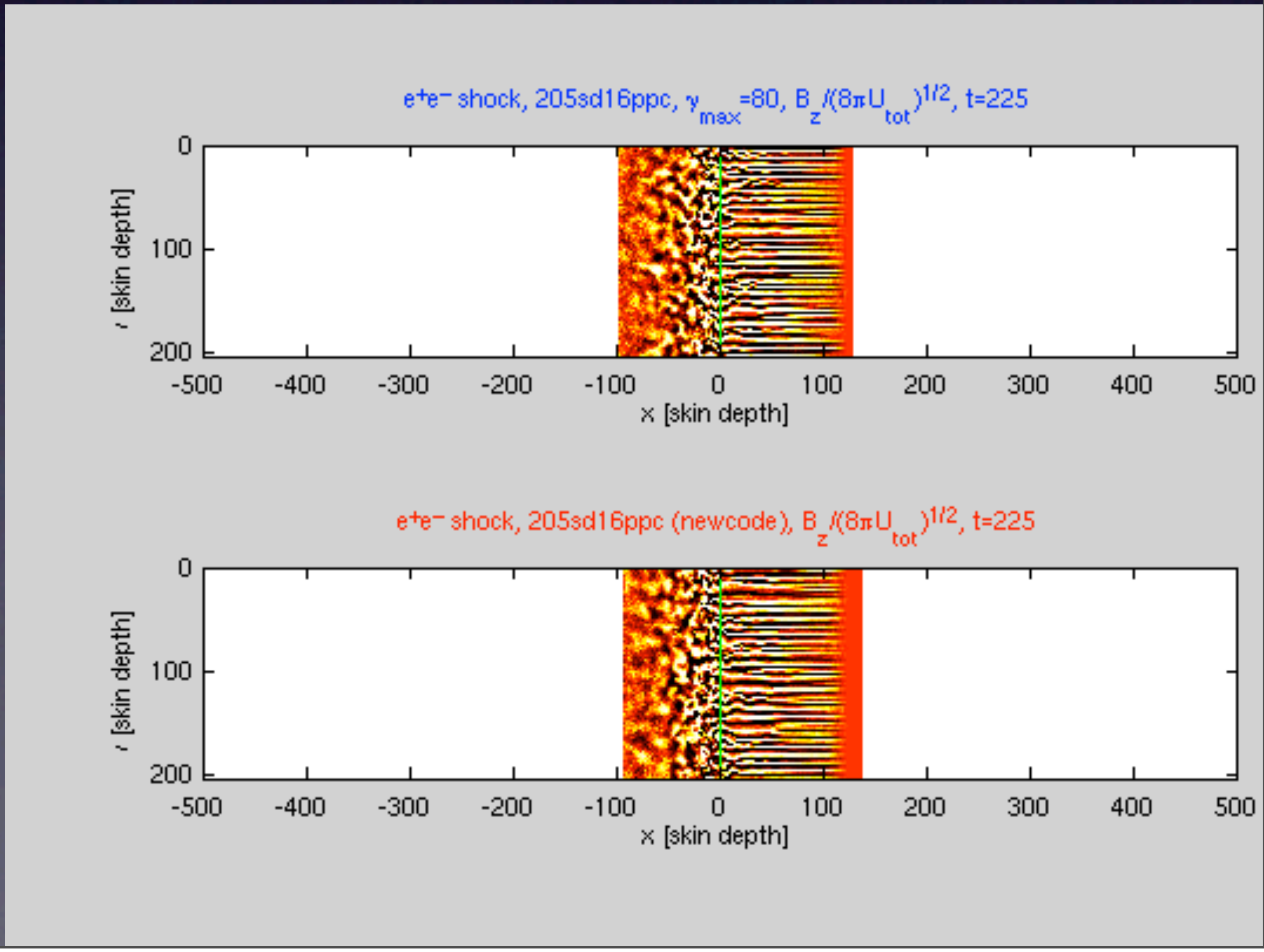
Field growth

we see growth of field energy and scale with time near shock, and slower decay downstream at 10^4 skindepths



Keshet et al 09

Accelerated particles backreact on the flow



Opportunities/challenges

Large scale simulations produce collisionless shocks and particle acceleration from first principles.

Dependence on field orientation and strength is now more understood -- strong constraints on astrophysical scenarios

New observations are driving this field: Fermi, HESS, CRs are constraining the shock physics and back-reaction on ISM.

Experiments: if scales of experiment >> c/ω_p , R_L interesting shocks can be produced.

Simulations of experimental conditions necessary for interpretation

Challenge (both experiment and simulations) to have large enough scales to probe both the shock formation + subsequent back-reaction beyond transients.

Simulation issues:

Coupling of small and large scales, perhaps PIC + hybrid

More physics: radiation effects

Effects of upstream turbulence

Effects of self-generated turbulence

Stability and robustness at long time evolution

Numerical heating vs physical heating

Better interpretation tools: visualization and test-particle