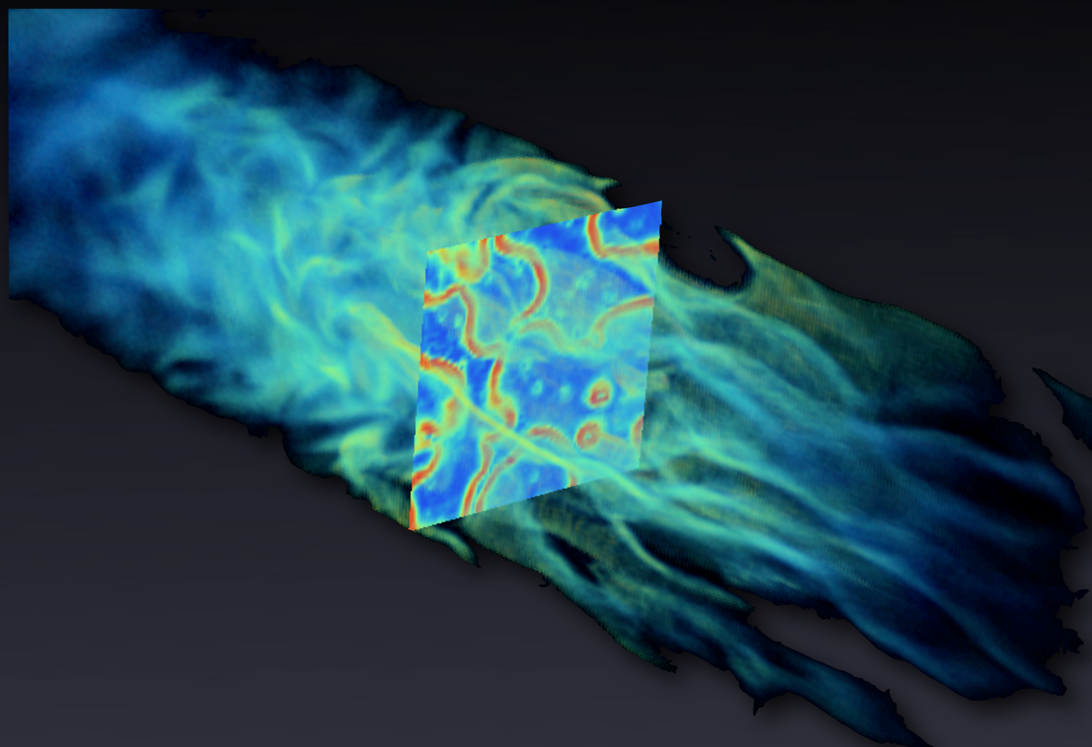
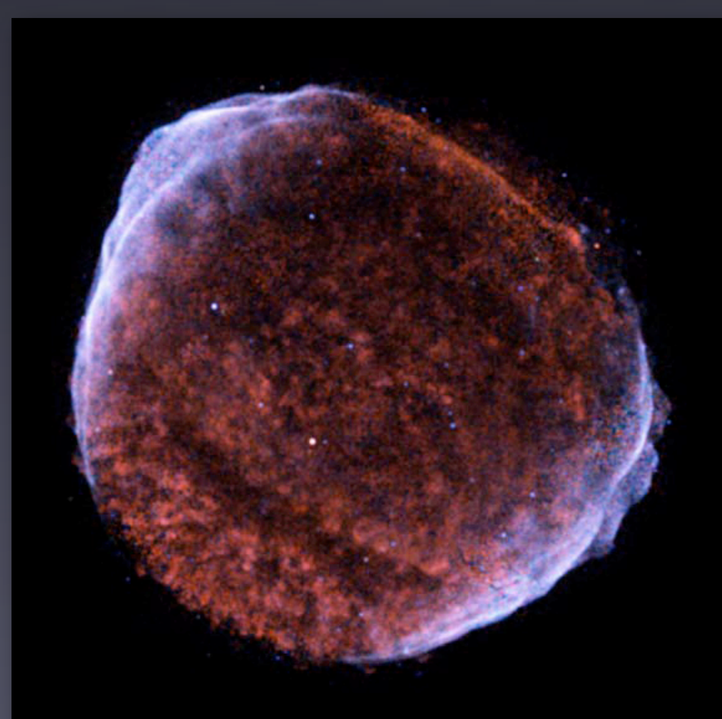
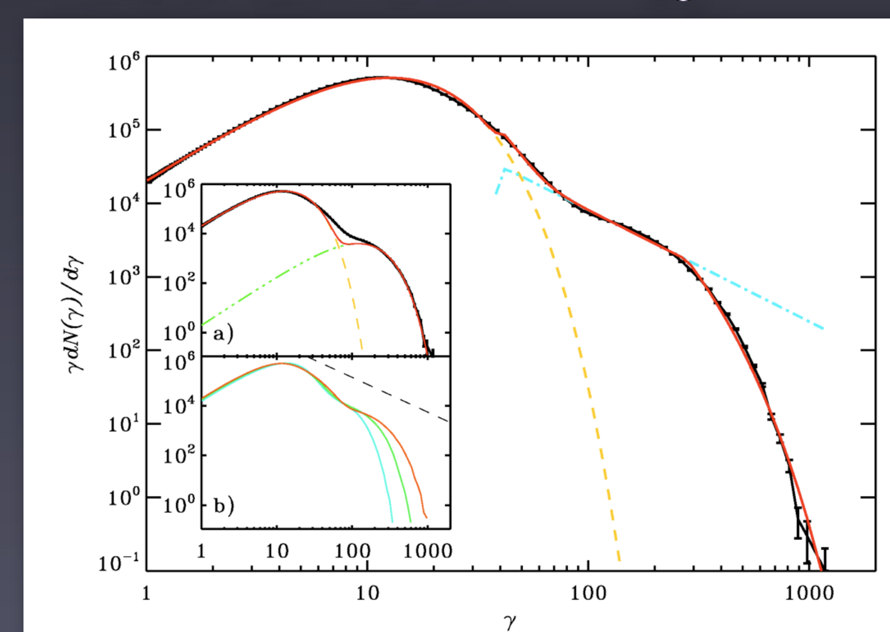
# Numerical simulations of relativistic collisionless shocks

Anatoly Spitkovsky (Princeton)







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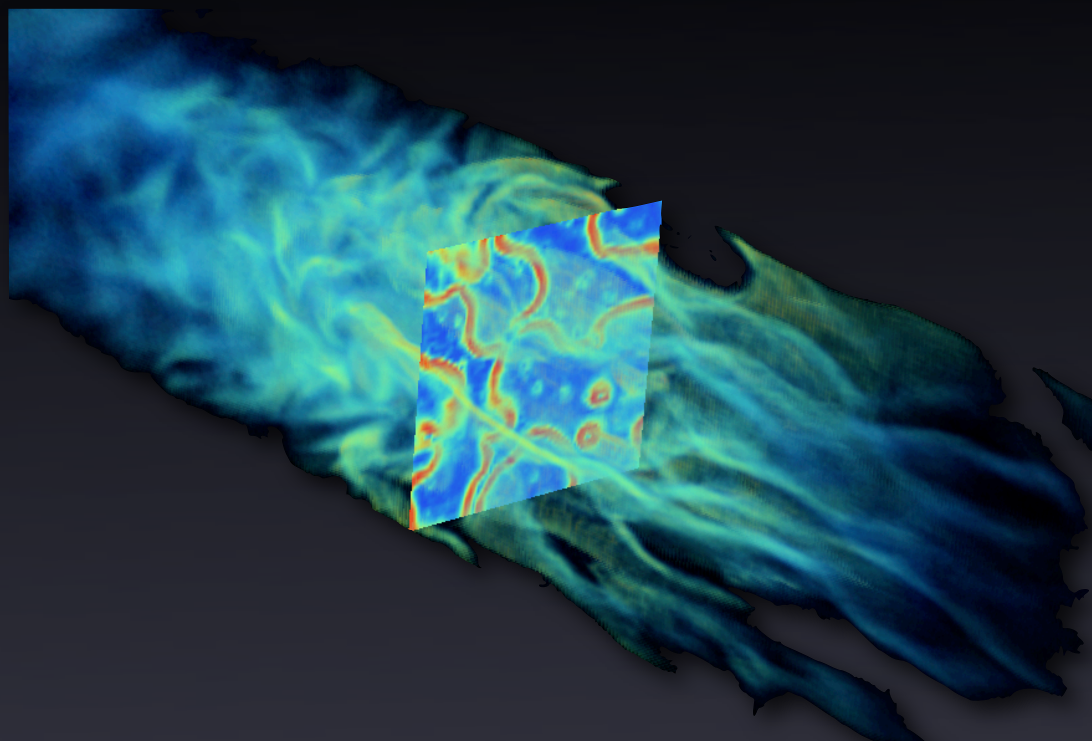
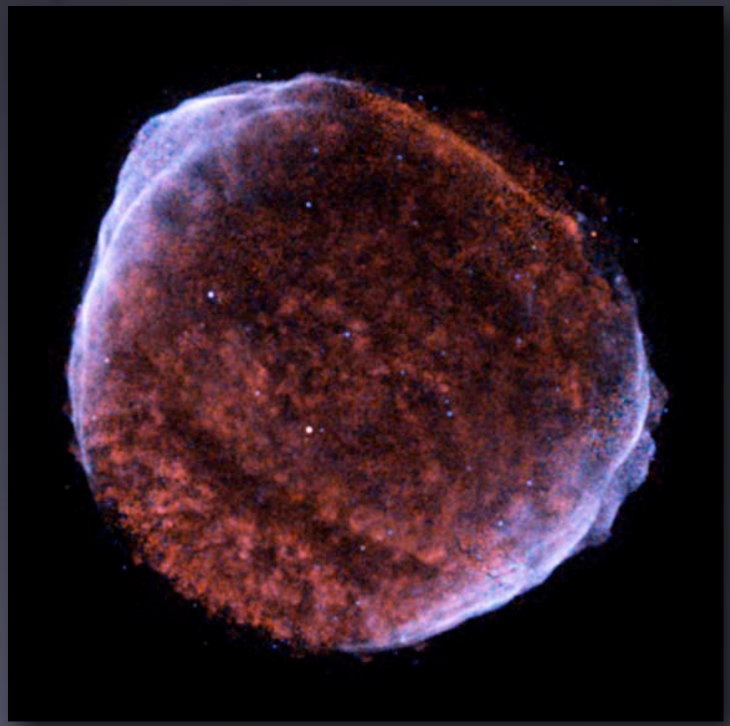
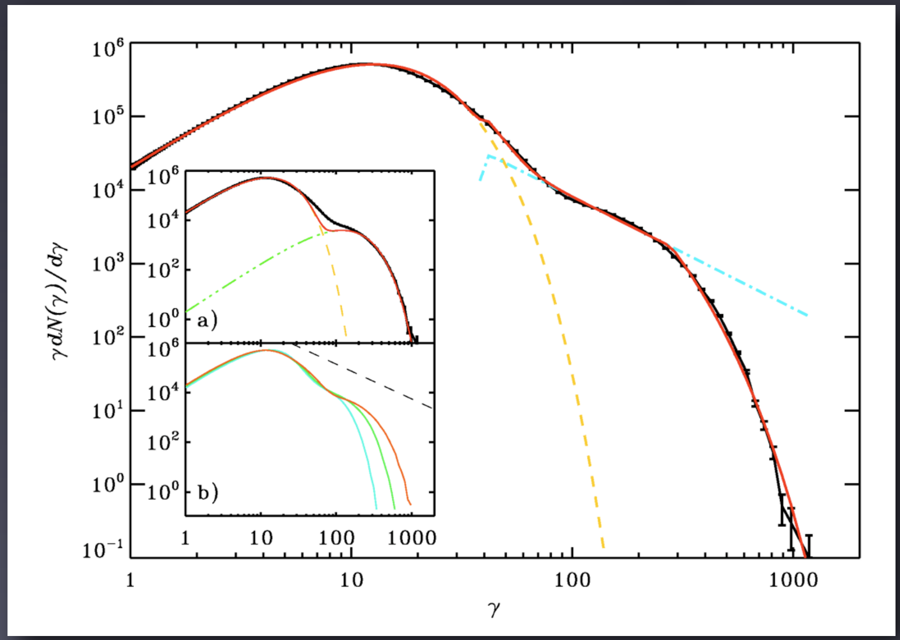
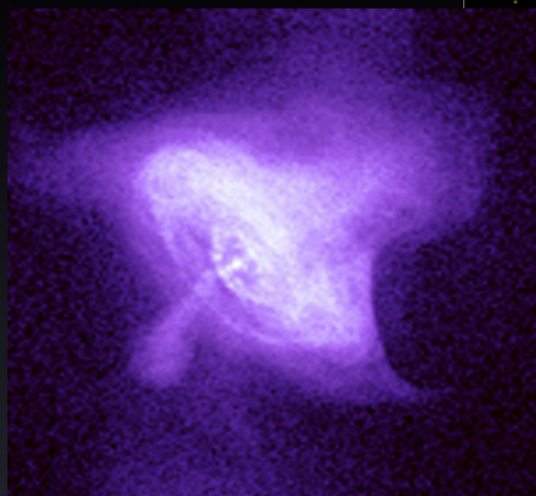


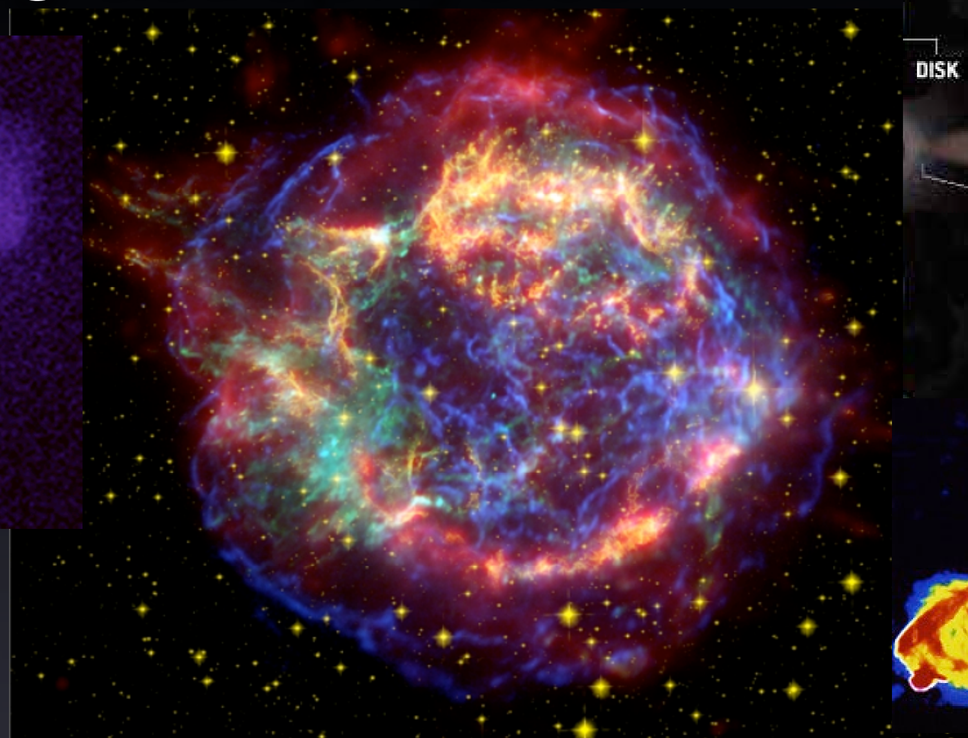
Collaborators: Jon Arons, Phil Chang, Boaz Katz, Uri Keshet, Mario Riquelme, Lorenzo Sironi, Eli Waxman

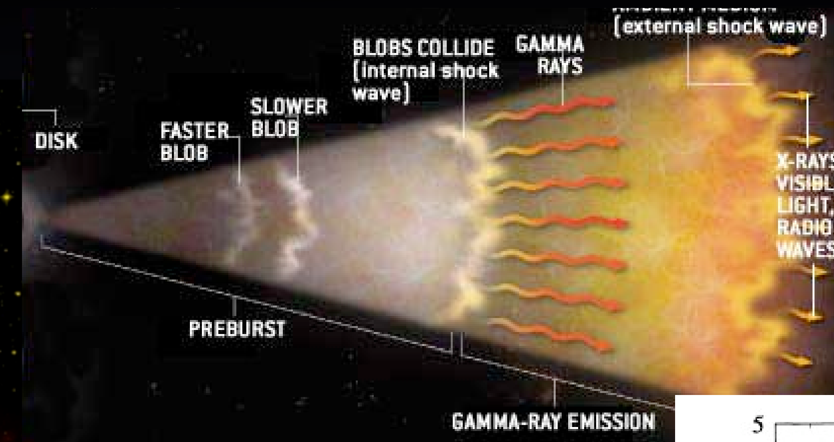


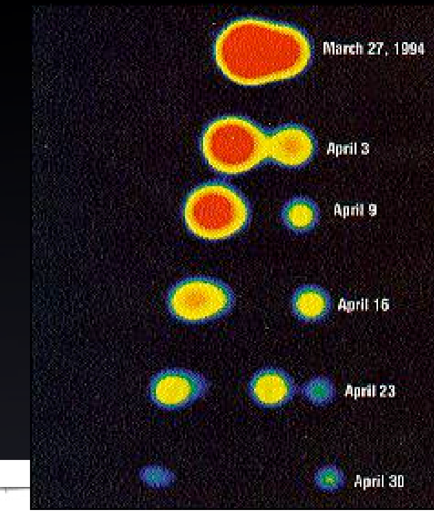


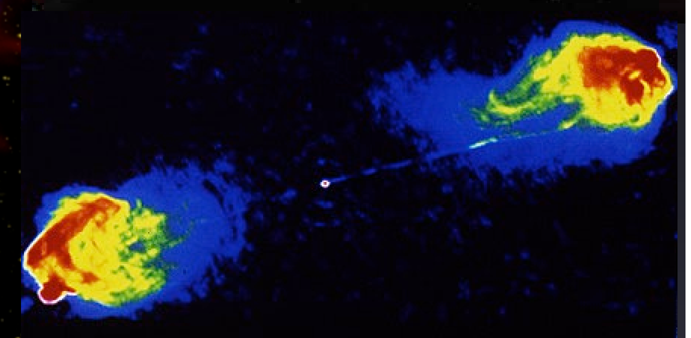
# Shocking astrophysics

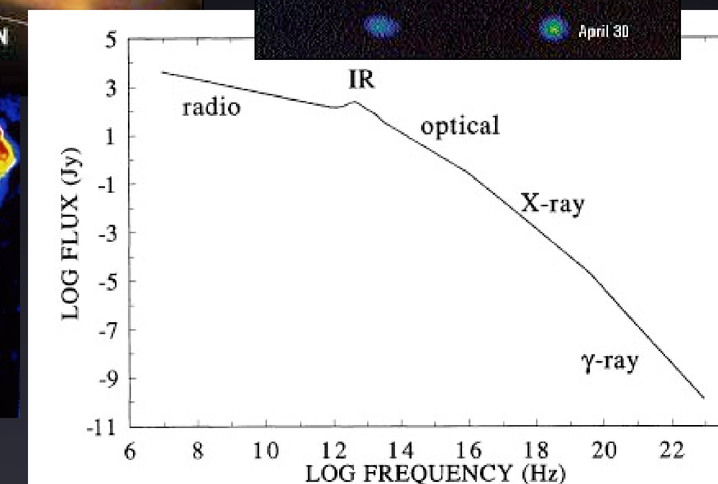






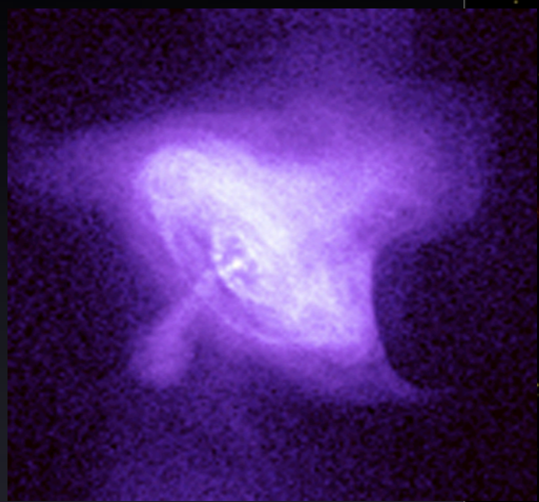



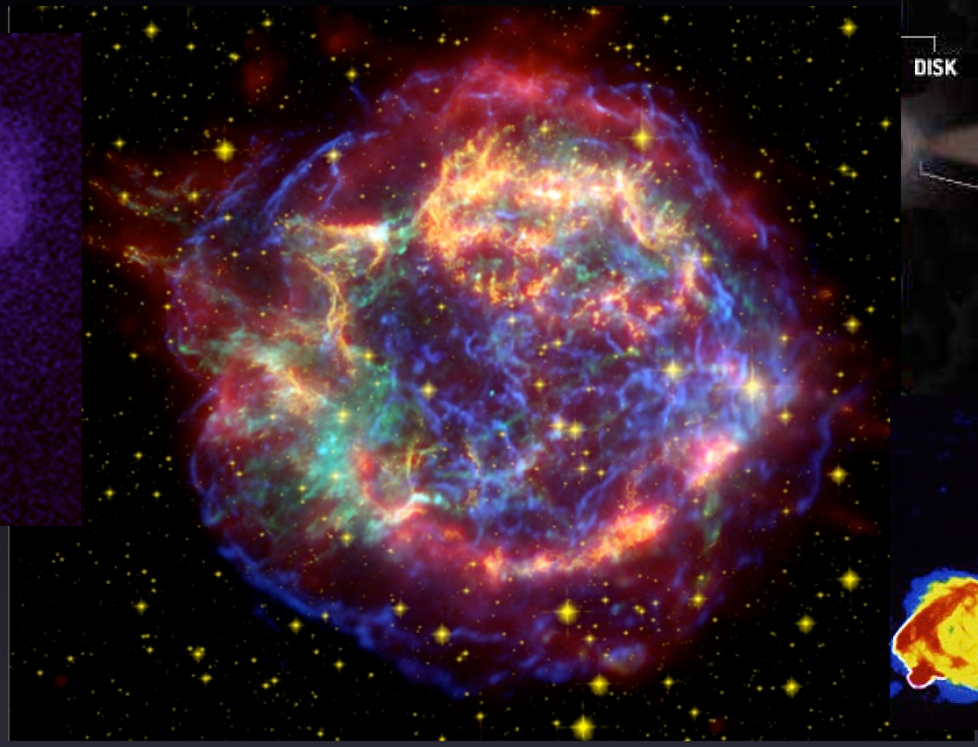



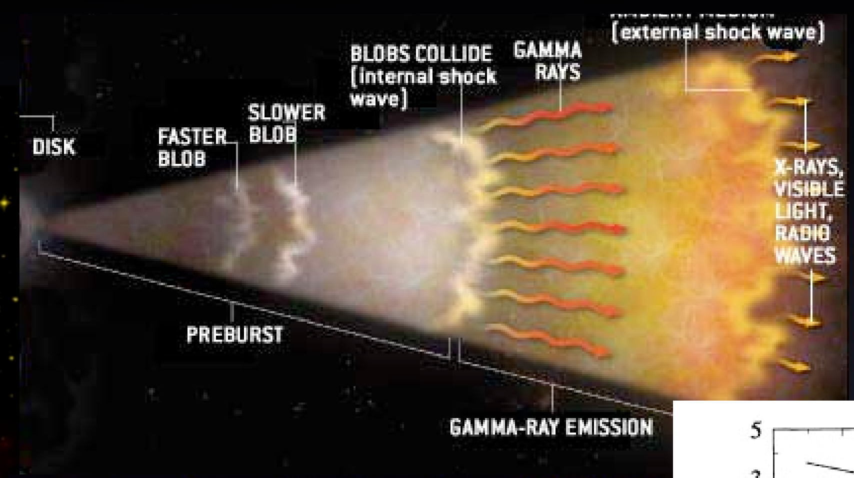


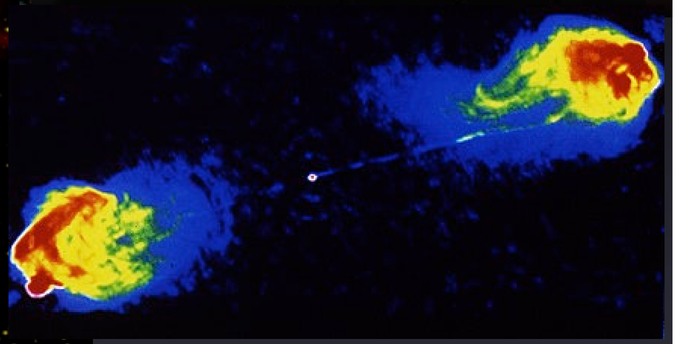

Astrophysical shocks are collisionless (mean free path >> system size).
Shocks span a range of parameters:
nonrelativistic to relativistic flows
magnetization (magnetic/kinetic energy ratio)
composition (pairs/e-ions/pairs with ions)

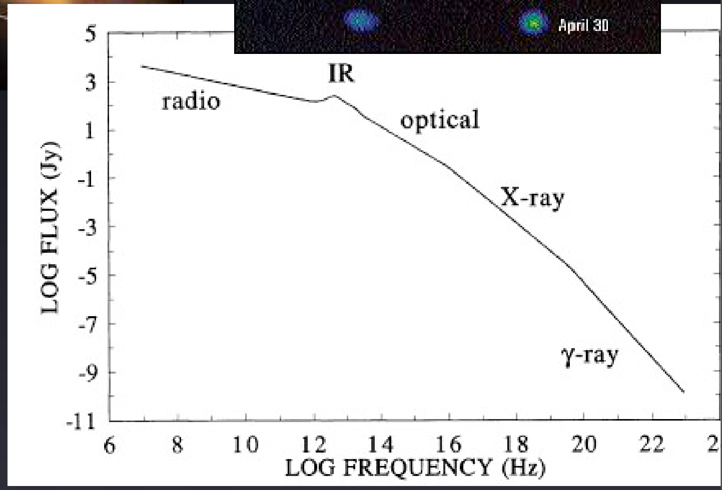
# Shocking astrophysics

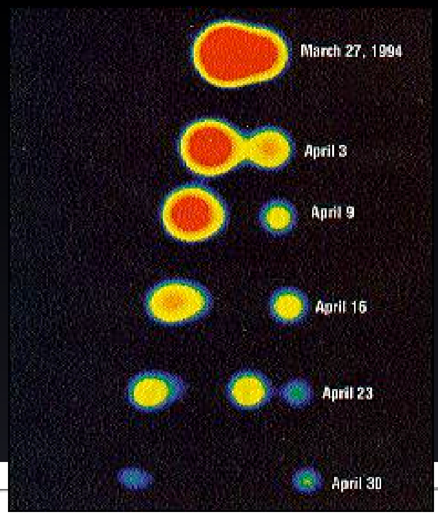






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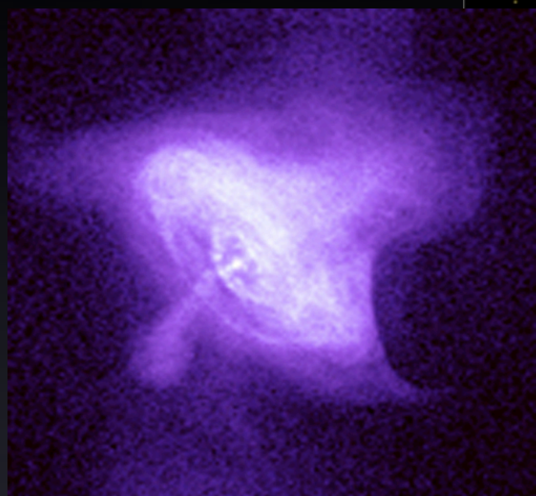
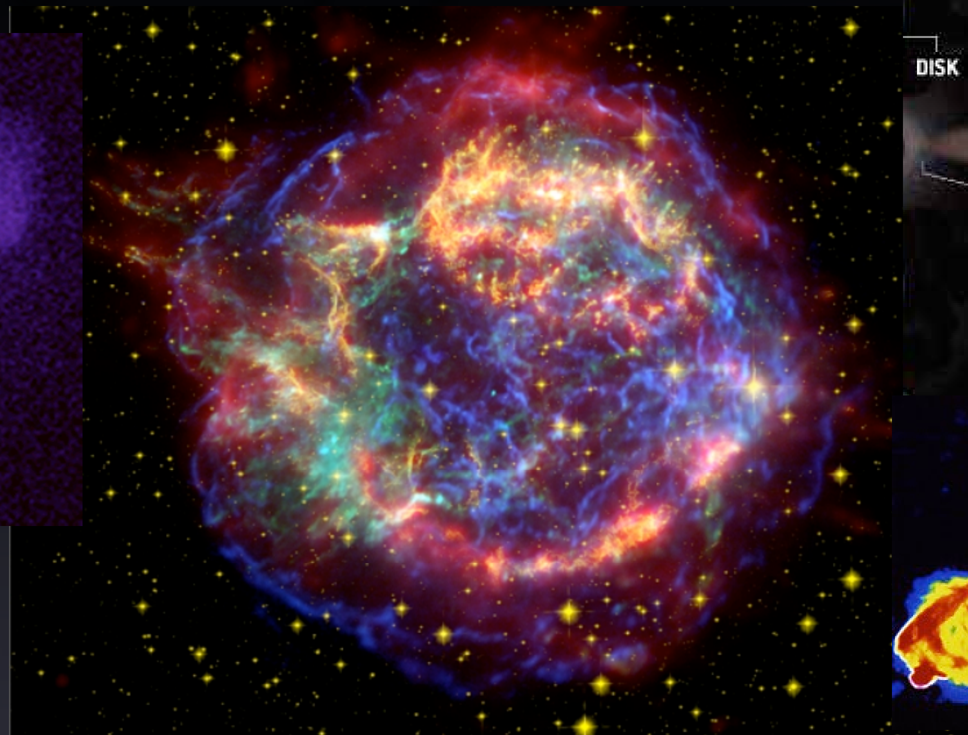
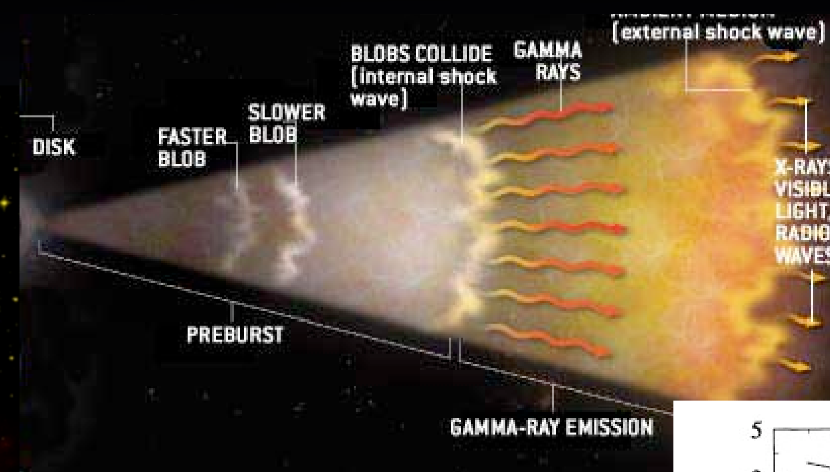
## Astrophysical collisonless shocks can:

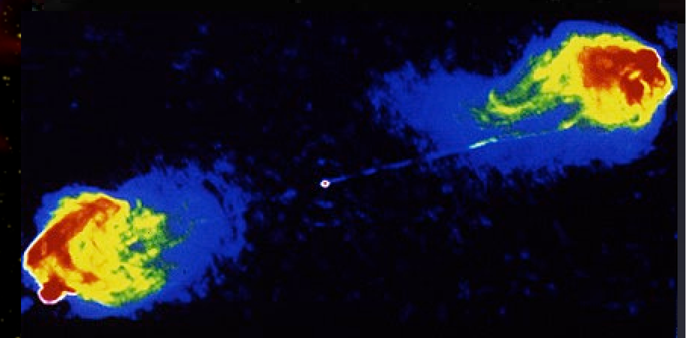
1. accelerate particles
2. amplify magnetic fields (or generate them from scratch)
3. exchange energy between electrons and ions

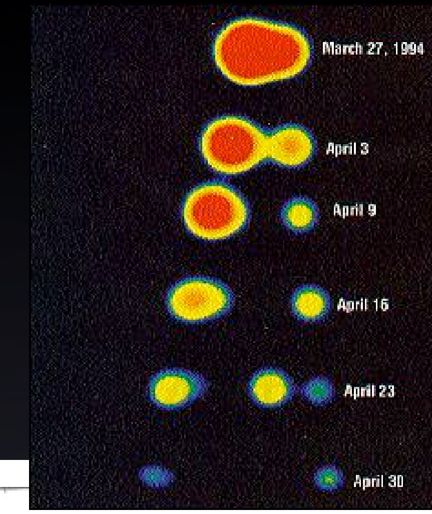
# Shocking astrophysics

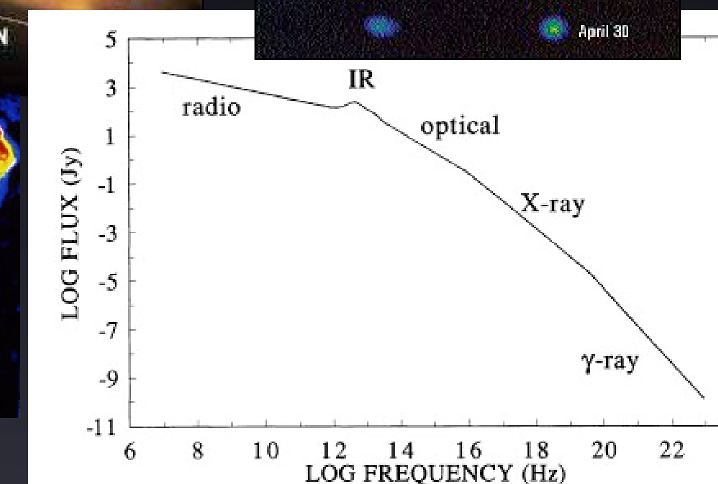









Open issues:

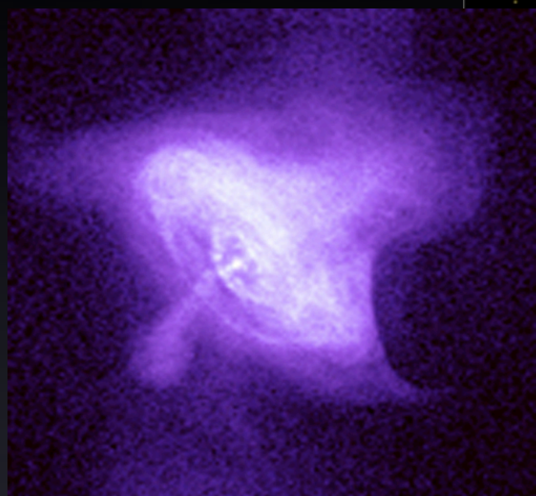
What is the structure of collisionless shocks? Do they exist? How do you collide without collisions?

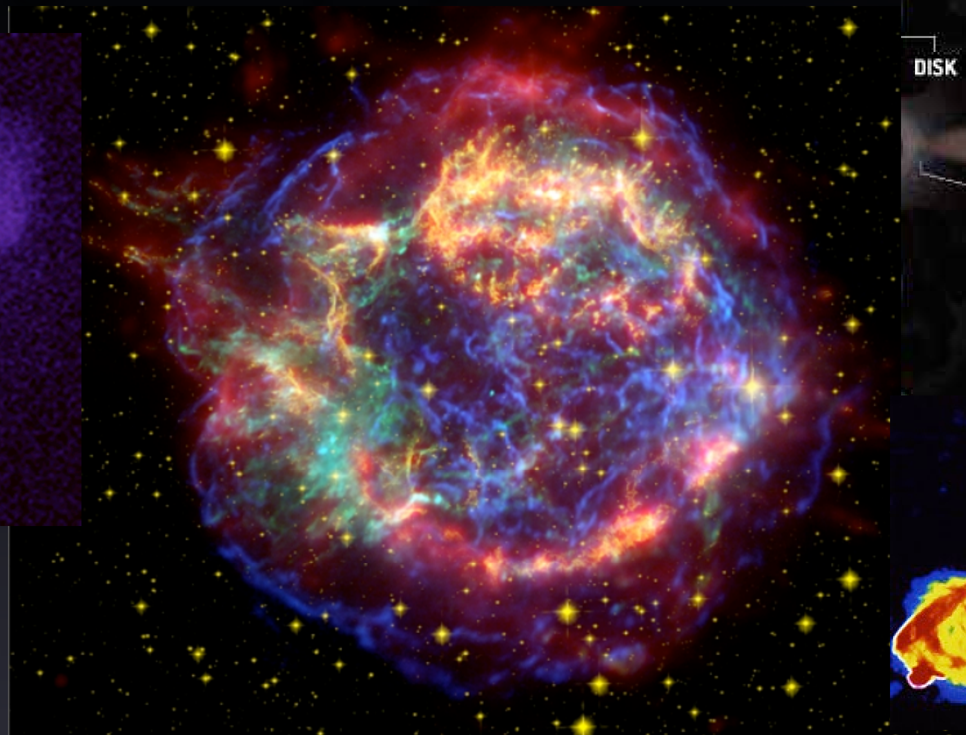
Particle acceleration -- Fermi mechanism? Other? Efficiency?

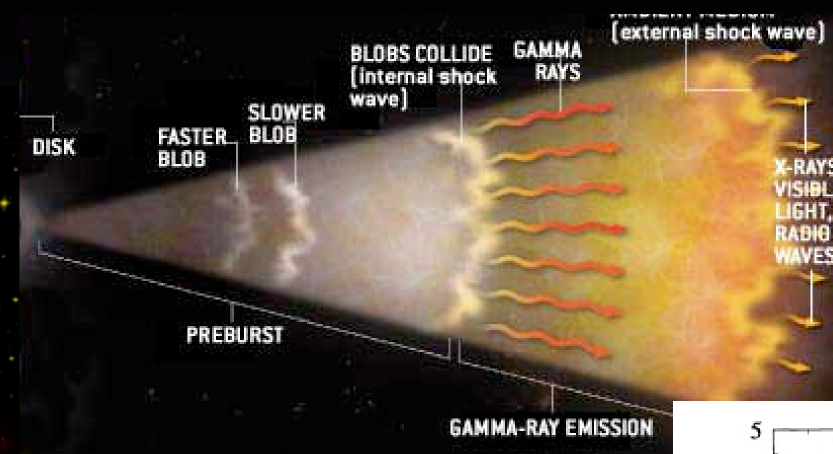
Generation of magnetic fields? GRB/SNR shocks, primordial fields?

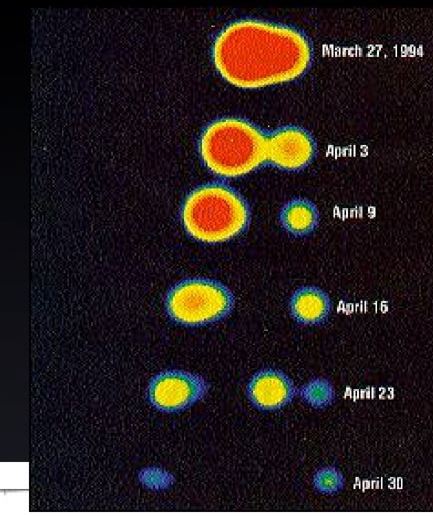
Equilibration between ions and electrons?

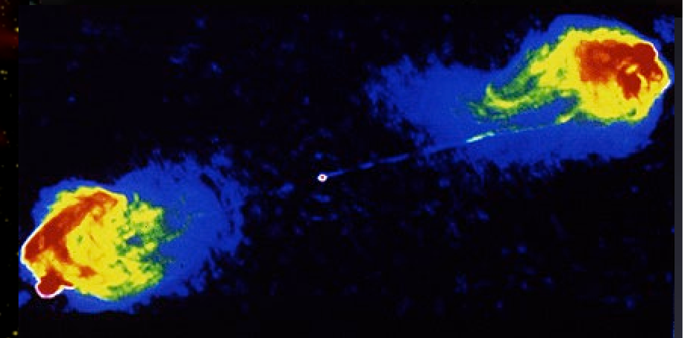
# Shocking astrophysics

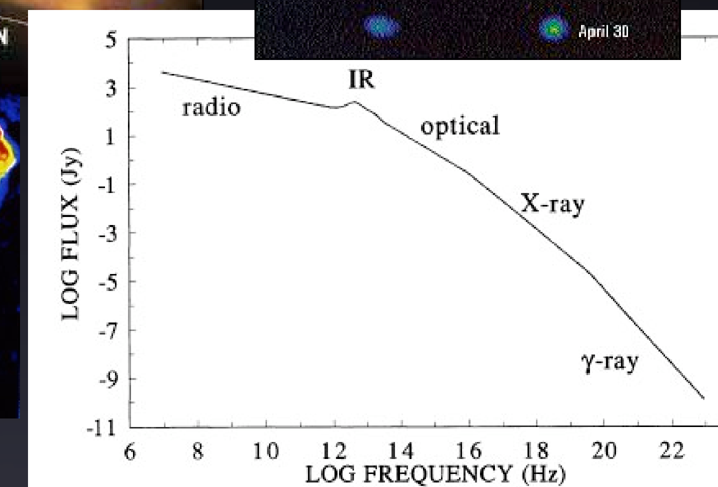






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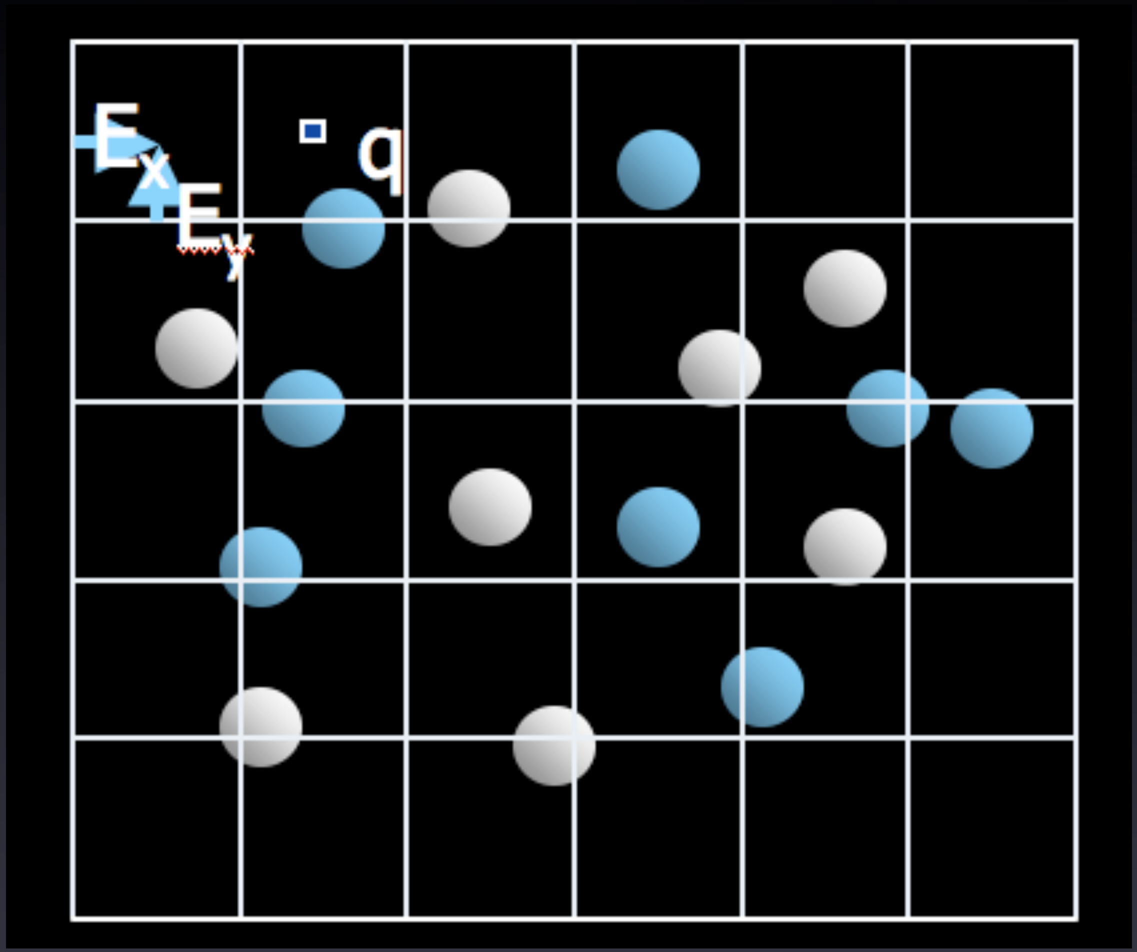
All questions are sensitive to nonlinear plasma physics...

Investigate this using ab-initio Particle-In-Cell simulations

# Particle-in-Cell (PIC) method




PIC method (aka PM method):

- Collect currents at cell edges
- Solve fields on the mesh (Maxwell's eqs)
- Interpolate fields to particle positions
- Move particles under Lorentz force

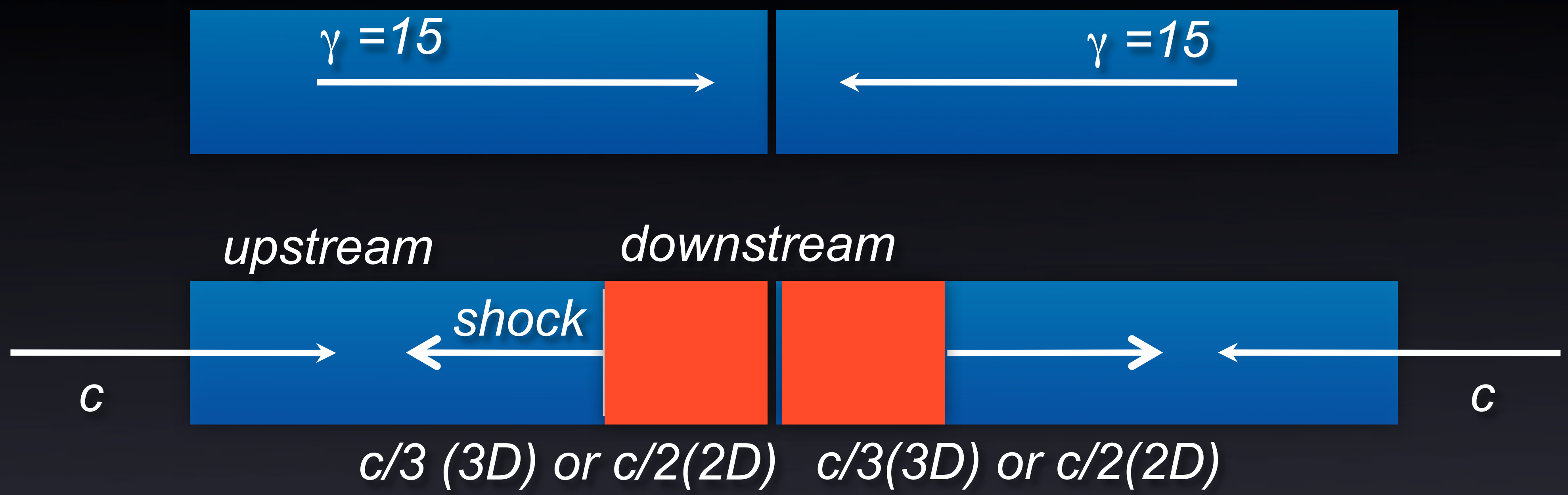
Commonly used in accelerator physics.

Other examples of PIC work in astro shocks: Hoshino, Hededal, Nishikawa, Silva

*Most fundamental way to treat plasma physics without (m)any approximations*
*price: have to resolve tiny and fast scales (plasma skin depth and plasma freq.)*
*to be interesting, simulations have to HUGE (small simulations don't shock)*

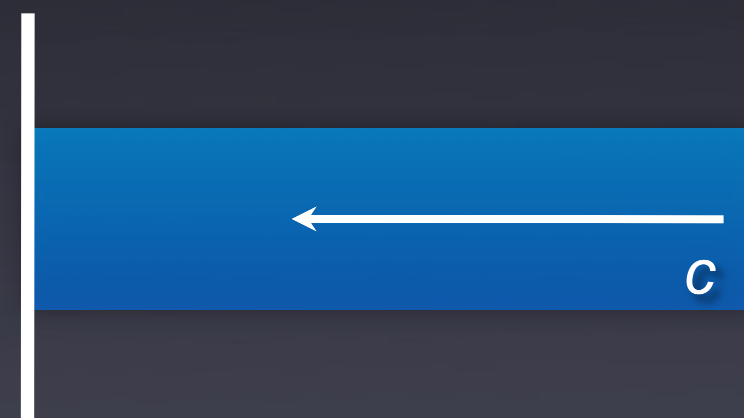
*The code*: relativistic 3D EM PIC code *TRISTAN-MP*
Optimized for large-scale simulations with more than 20e9 particles.
Noise reduction, improved treatment of ultra-relativistic flows.
Works in both 3D and 2D configurations. Most of the physics is captured in 2D
*Most of our results are now starting to be reproduced by independent groups*

# Problem setup




*"Shock" is a jump in density & velocity*

*Use reflecting wall to initialize a shock*




Simulation is in the downstream frame. If we understand how shocks work in this simple frame, we can boost the result to any frame to construct astrophysically interesting models. (in these simulations we do not model the formation of contact discontinuity)

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

# Parameter space of collisionless shocks

Properties of shocks can be grossly characterized by several dimensionless parameters:

*Alfven Mach number* $M_A = \frac{v}{v_A}$ *Composition* $r = \frac{m_i}{m_e}$ *Sonic Mach number* $M_s = \frac{v}{c_s}$

*Magnetization*

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

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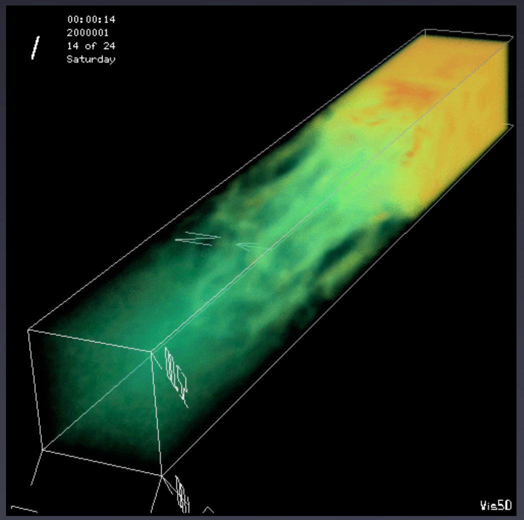
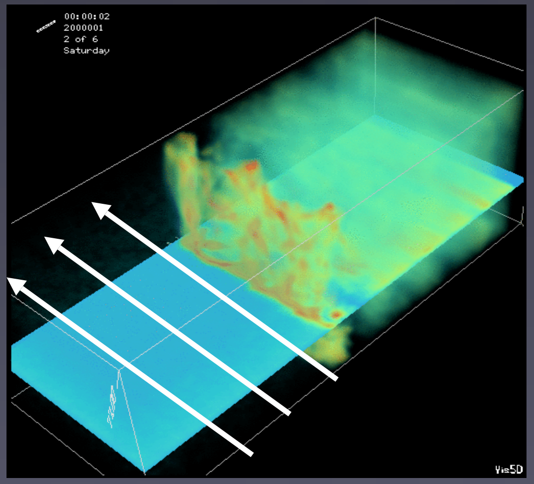
We explored the parameter space for pair and e-ion plasmas in 2D and 3D.

Low magnetization: shock mediated by Weibel instability, which generates field > background

High magnetization: shock mediated by magnetic reflection, compressing background

True for both pairs and e-ions, relativistic and ... nonrelativistic (+electrostatics)



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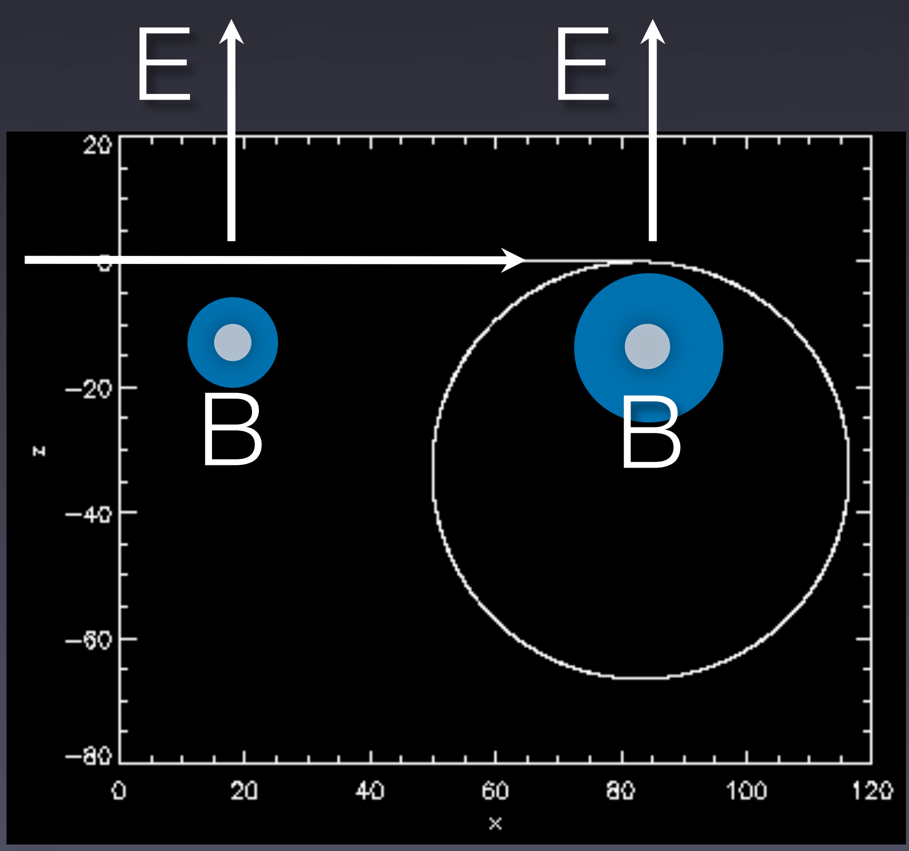

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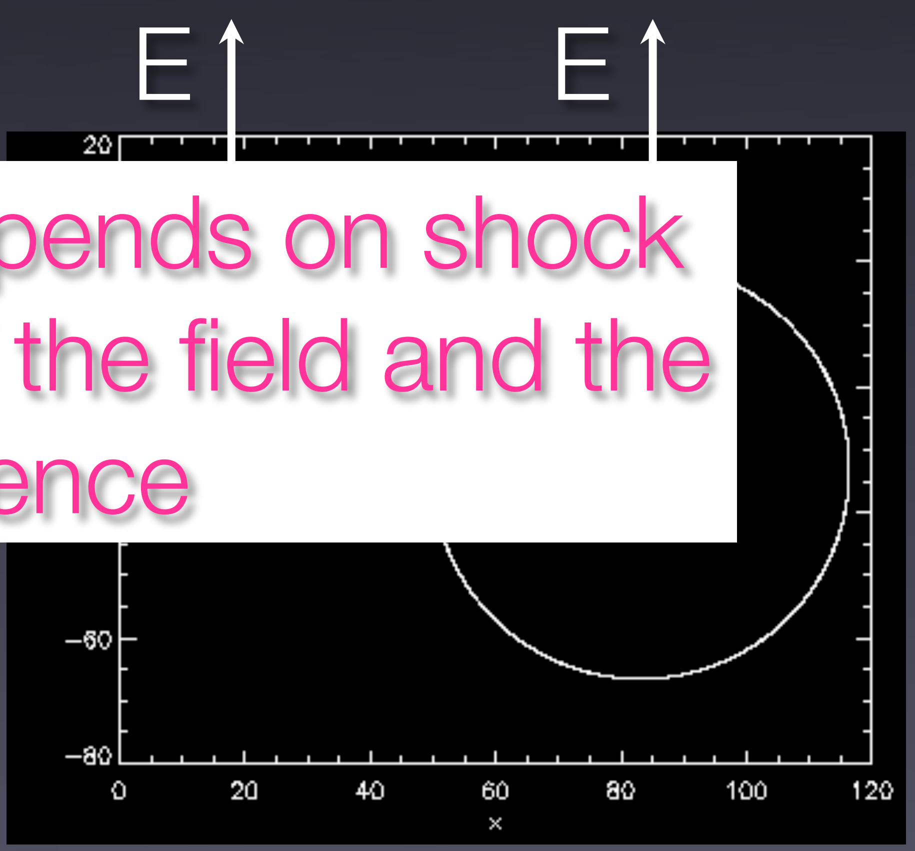
Lo
ins

Efficiency of shock acceleration depends on shock mediation mechanism, geometry of the field and the level of magnetic turbulence

Hi
magnetic reflection, compressing background

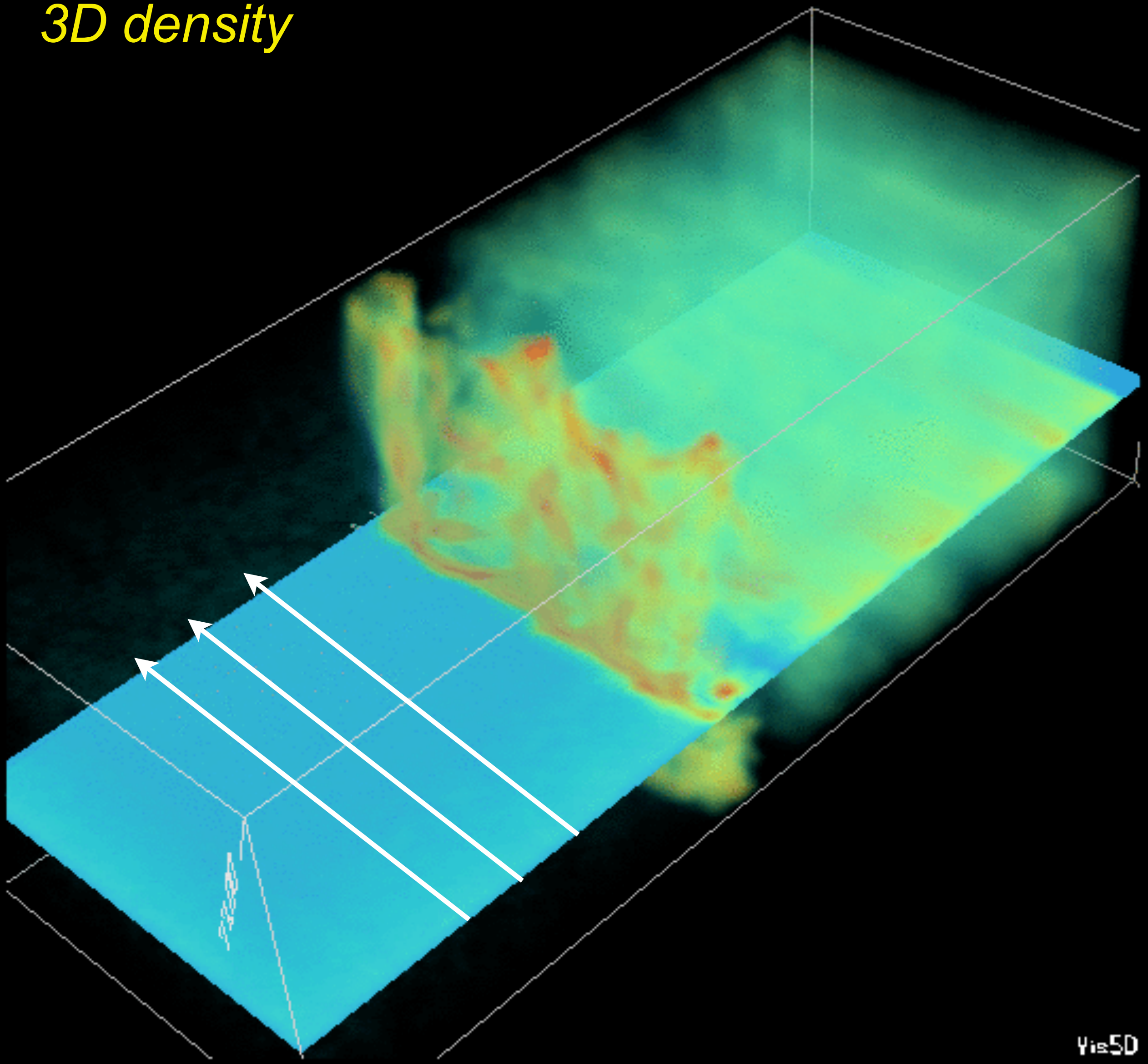
True for both pairs and e-ions, relativistic and ... nonrelativistic (+electrostatics)



# Relativistic pair shocks

*Shock structure for* $\sigma$*=0.1*

*3D density*




*Shock structure for* $\sigma$*=0*

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Magnetized shock is mediated by magnetic reflection, while the unmagnetized shock -- by field generation from filamentation instability. Transition is near $\sigma$*=1e-4* *(A.S. 2005)*

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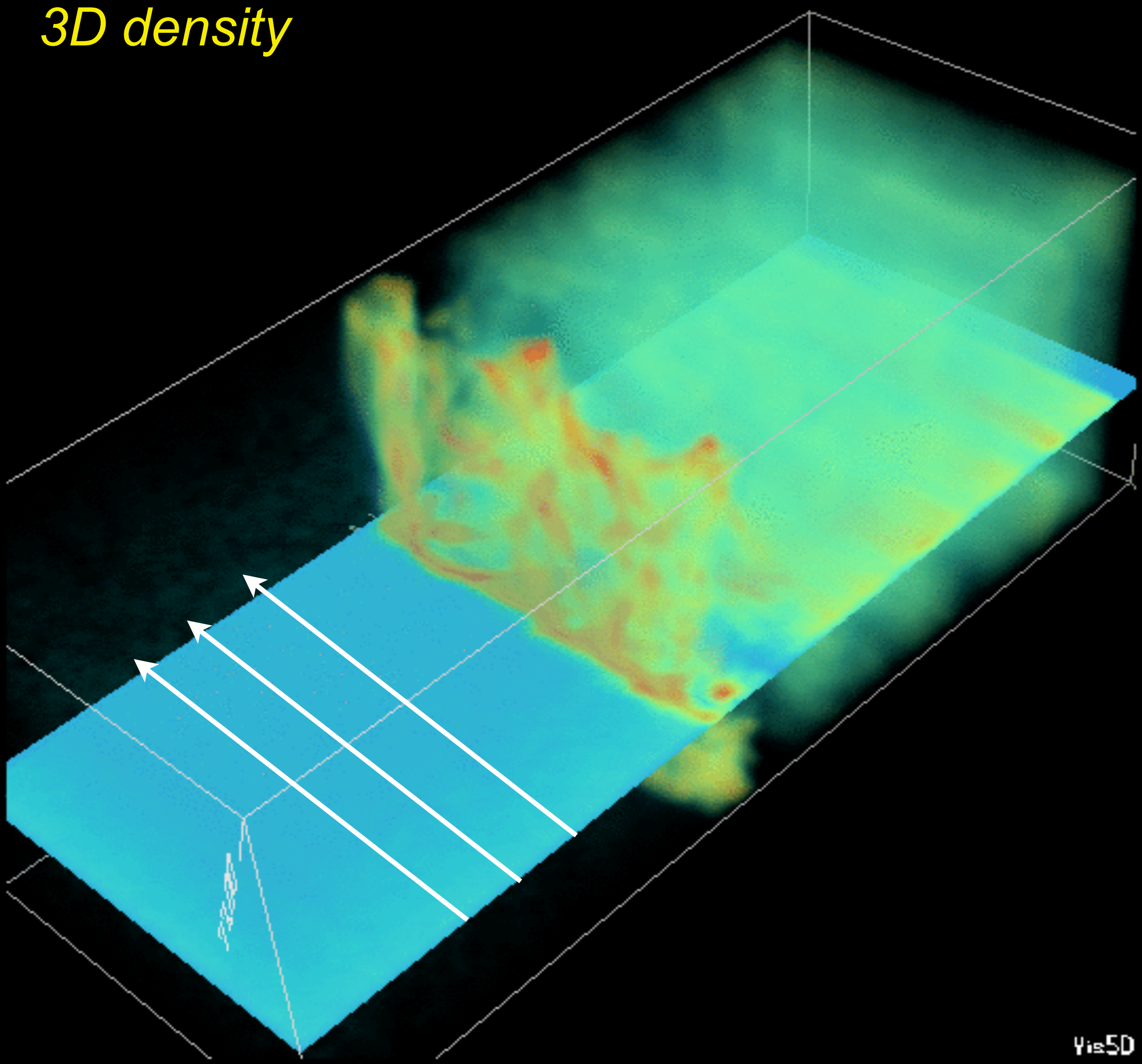


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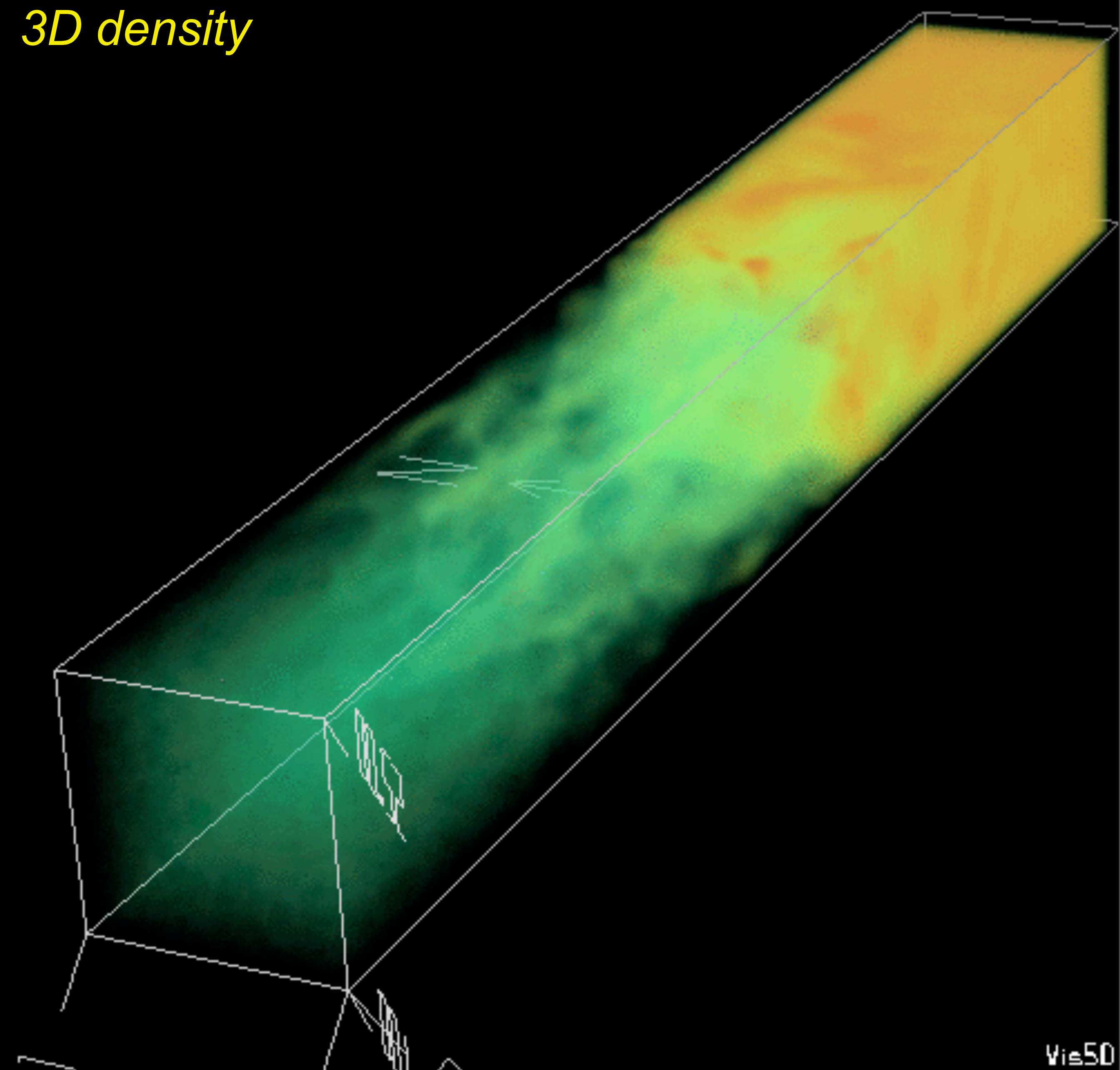


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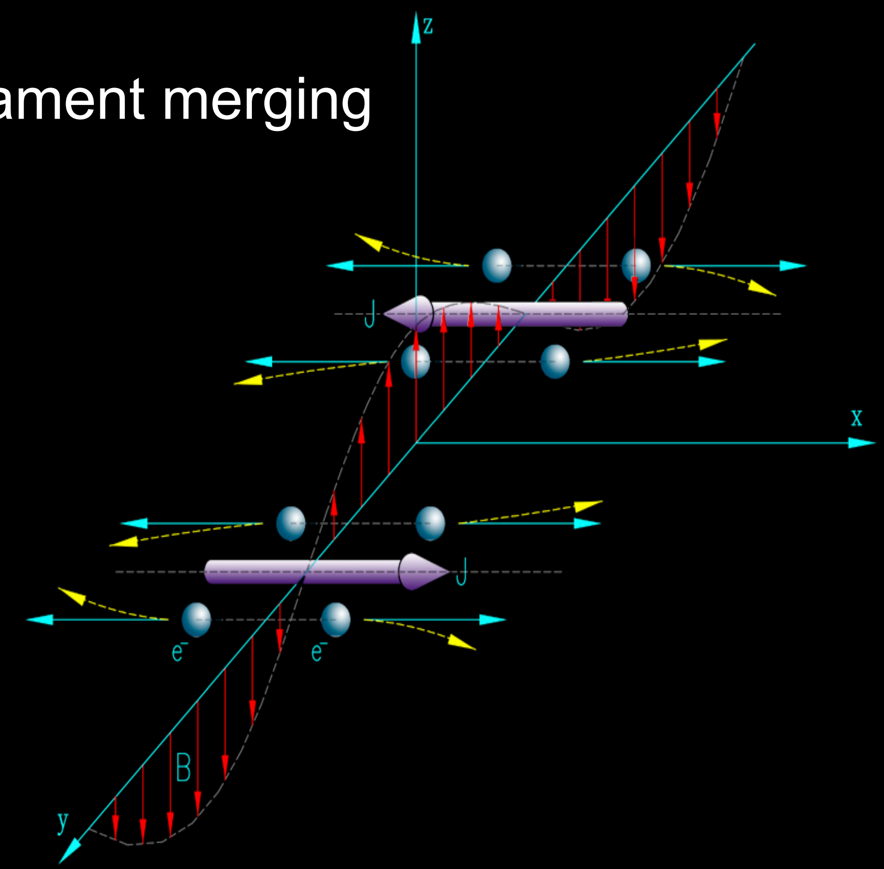
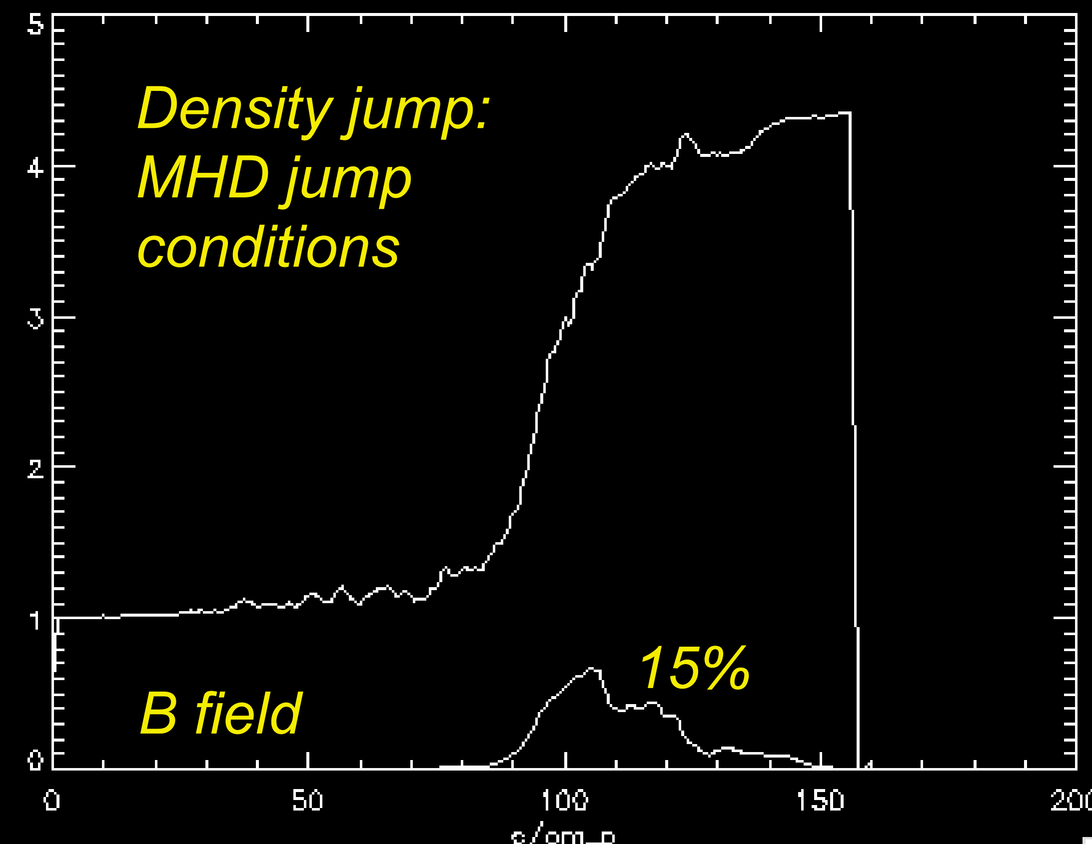
# *Unmagnetized pair shock*

## *Magnetic field generation: Weibel instability*

Field cascades from $c/\omega_p$ scale to larger scale due to current filament merging




*Weibel instability generates subequipartition B fields that decay. Is asymptotic value nonzero? Competition between decay and inverse cascade (Chang, AS, Arons 08).*

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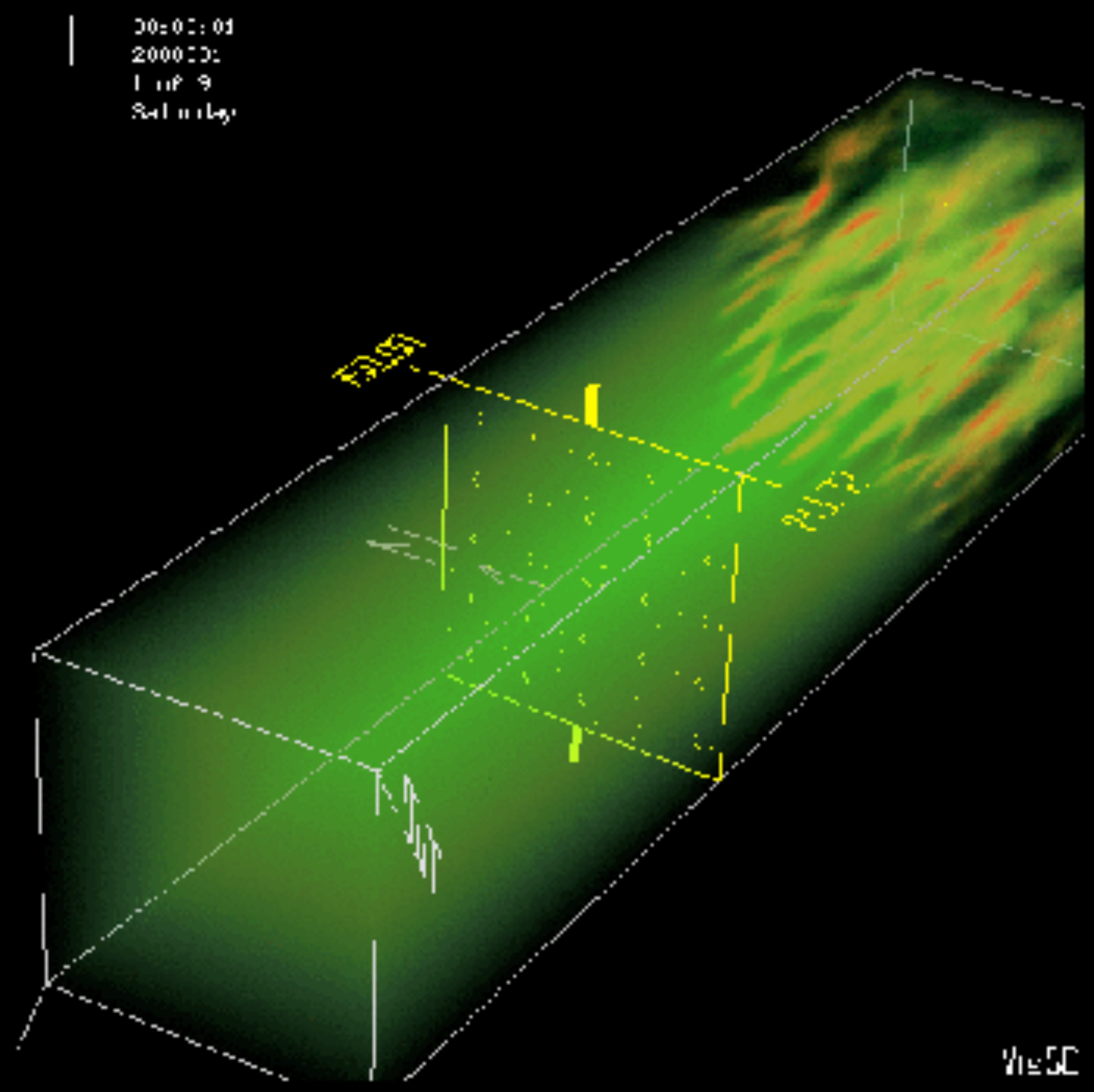

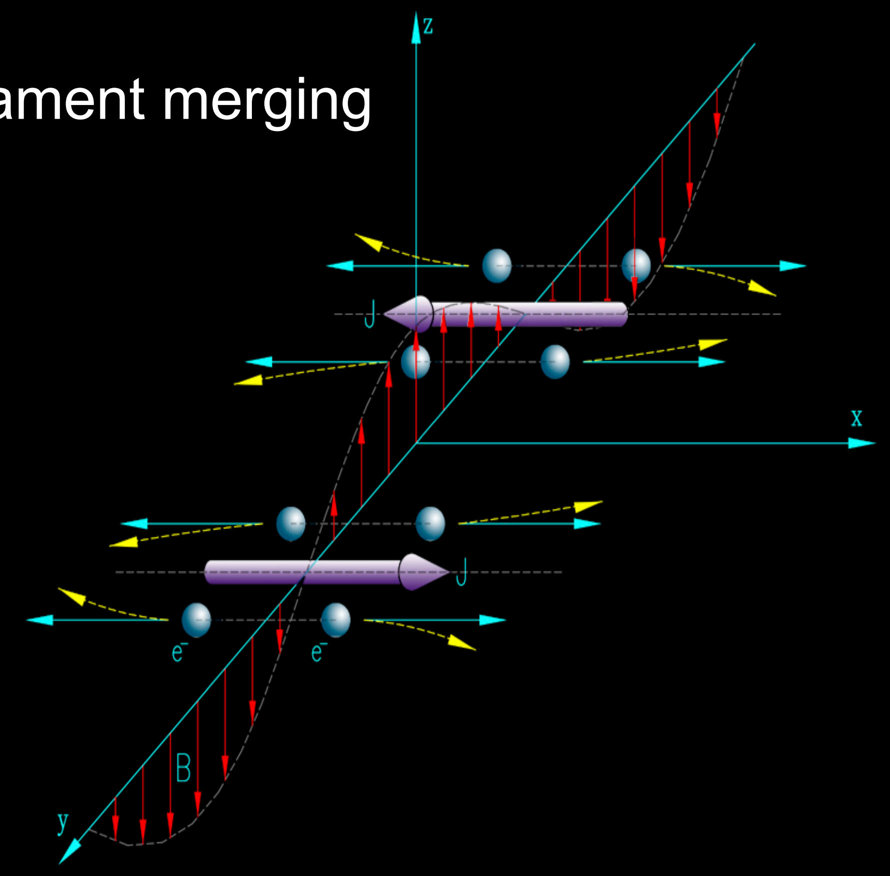


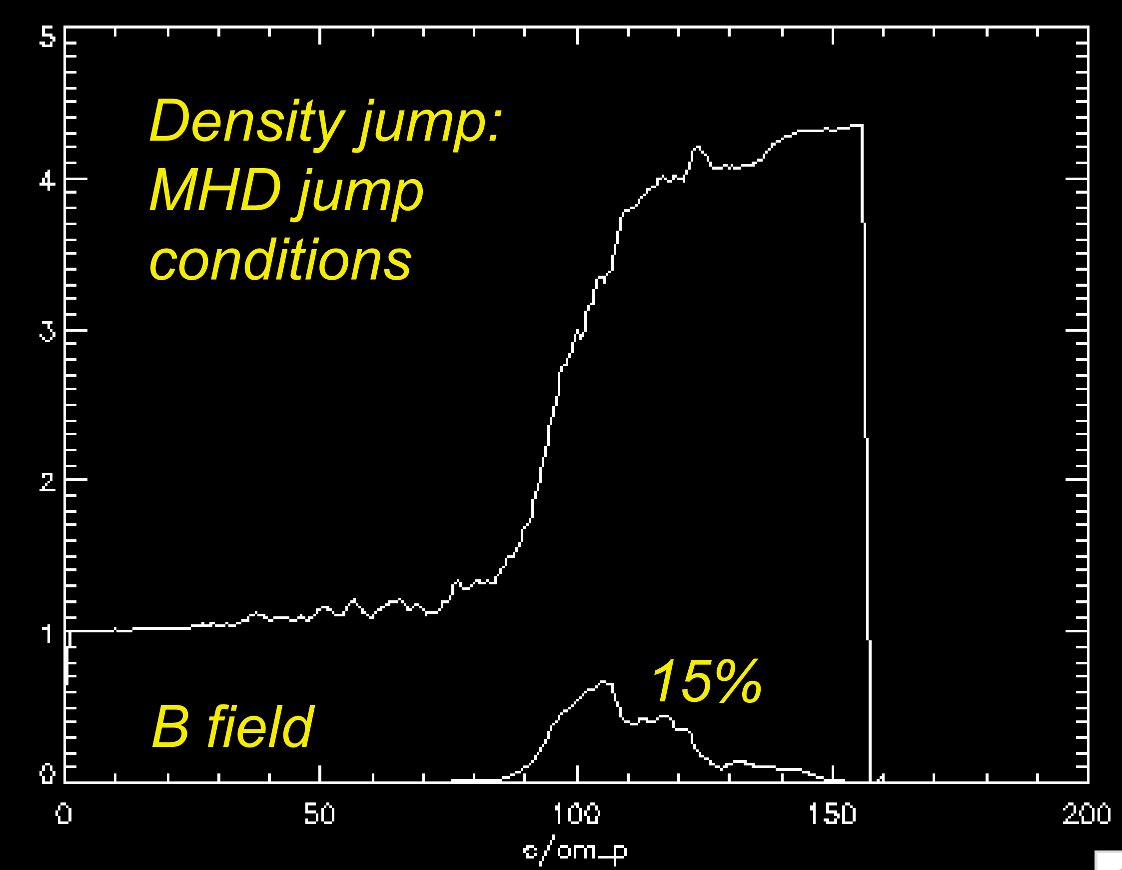


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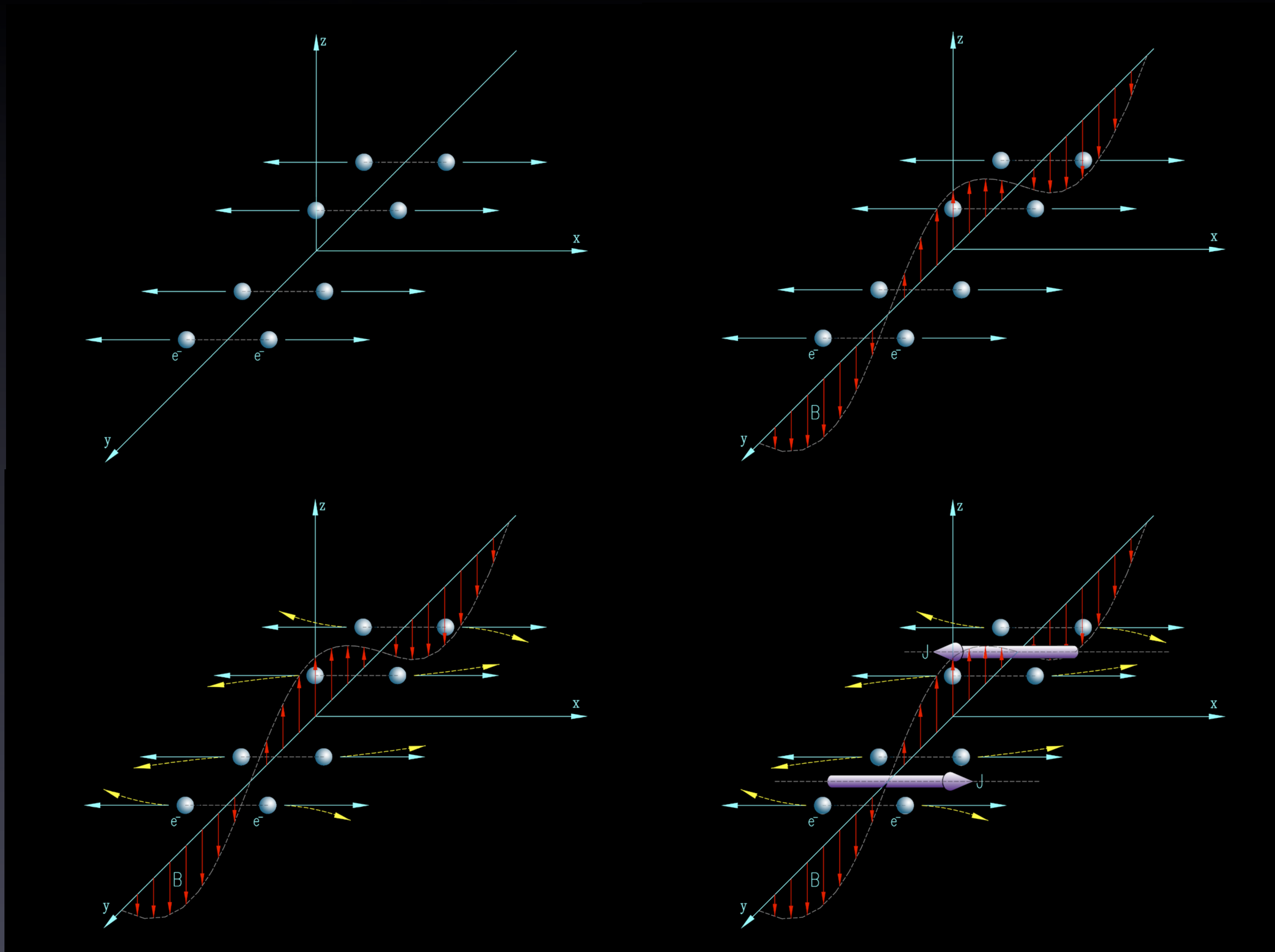
# Weibel instability



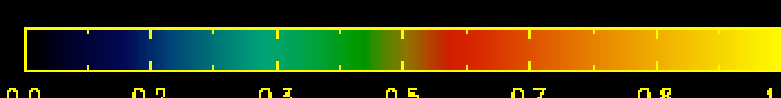

Weibel (1959)
Moiseev & Sagdeev (1963)
Medvedev & Loeb (1999)
Gruzinov & Waxman (1999)

Electromagnetic streaming instability.
Works by filamentation of plasma
Spatial growth scale -- skin depth,
time scale -- plasma frequency

$$L \approx c/\omega_{pe} = 10\ \mathrm{km}\ \sqrt{\gamma/\mathrm{n_0[cm^{-3}]}}$$

$$T \approx 1/\omega_p = 30\ \mu s\ \sqrt{\gamma/\mathrm{n_0[cm^{-3}]}}$$

# *3D shock structure: long term*




50x50x1500 skindepths. Current merging (like currents attract).

Secondary Weibel instability stops the bulk of the plasma. Pinching leads to randomization.

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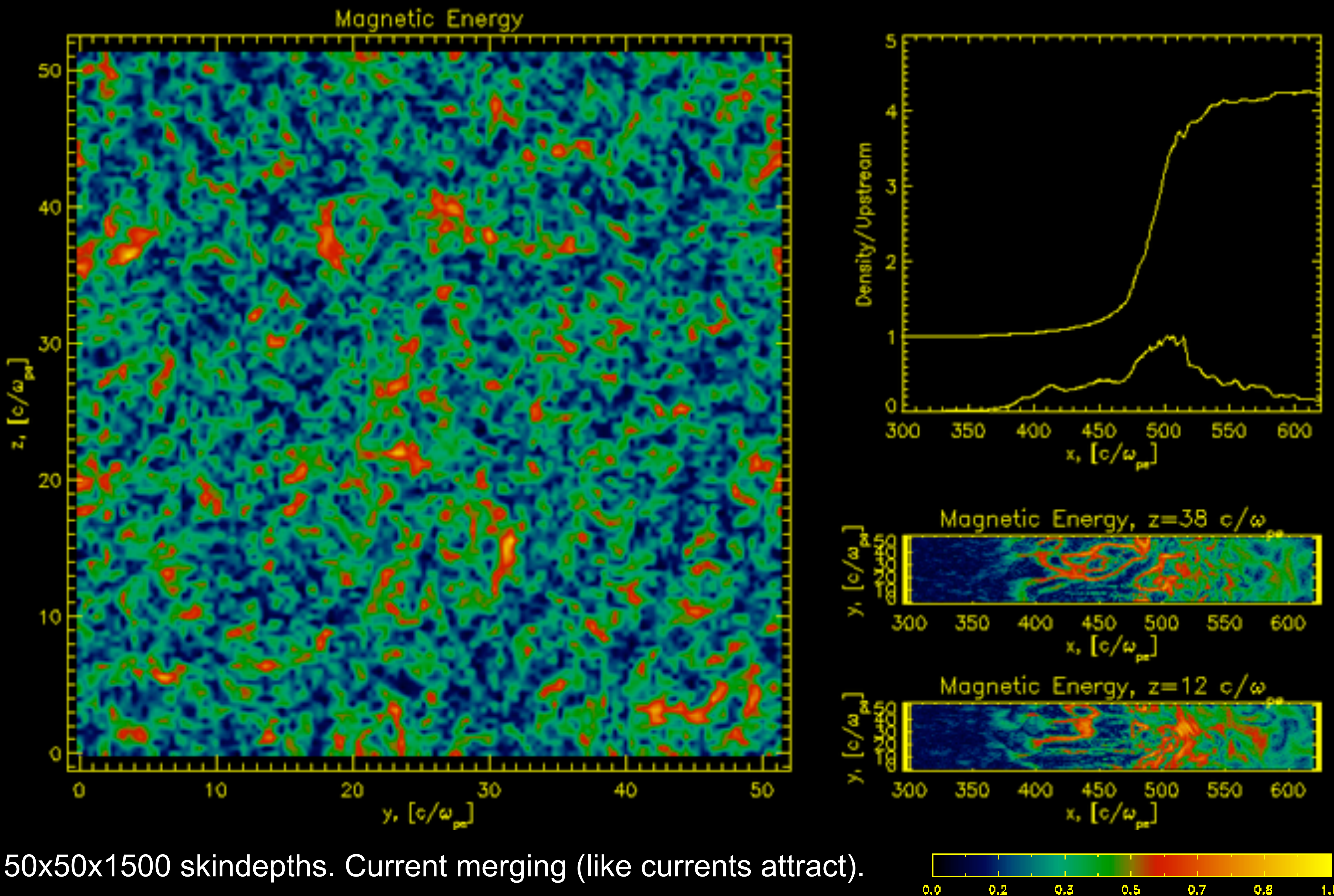


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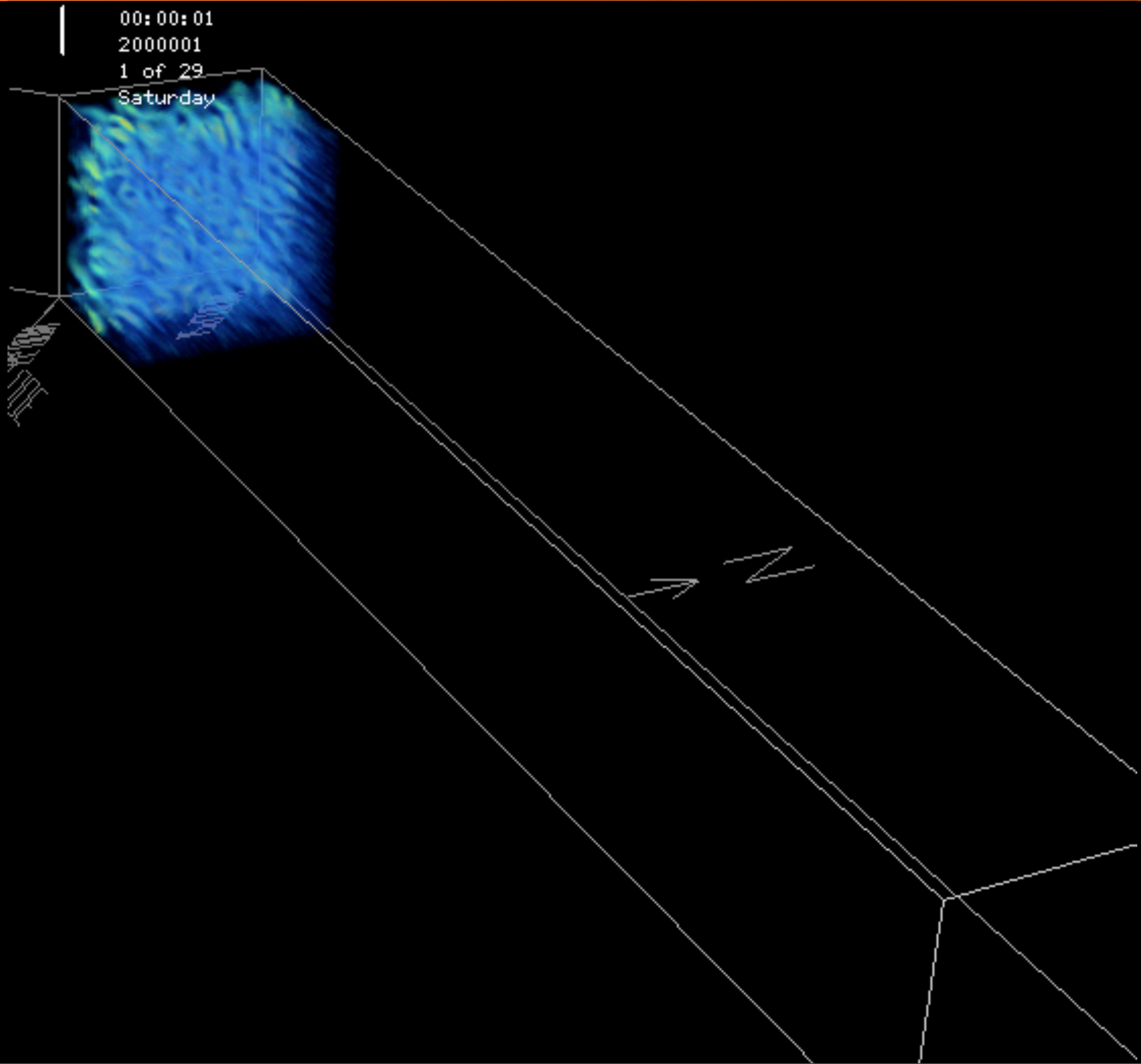
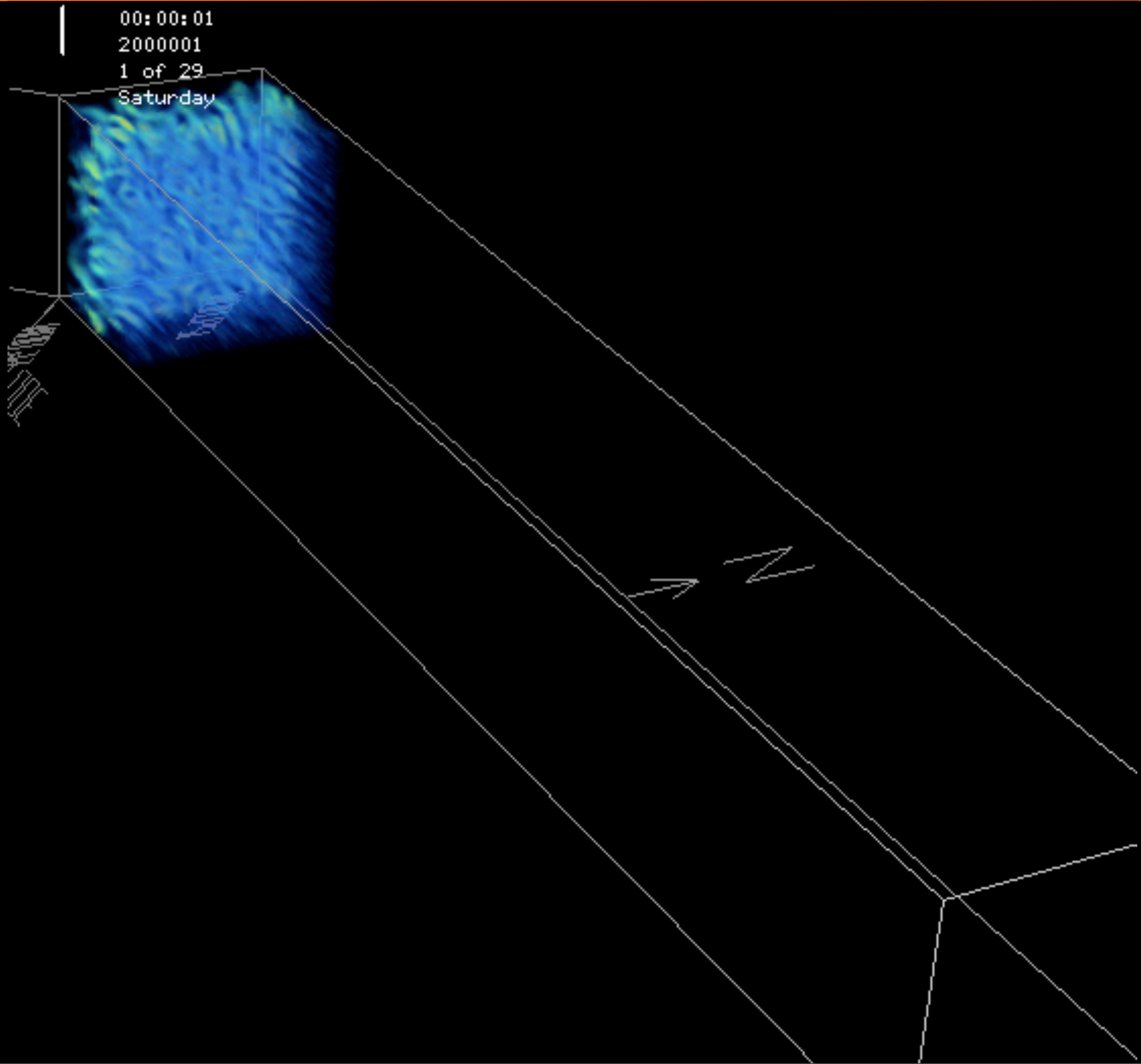


# 3D unmagnetized pair shock: magnetic energy



# Unmagnetized pair shock: particle trajectories

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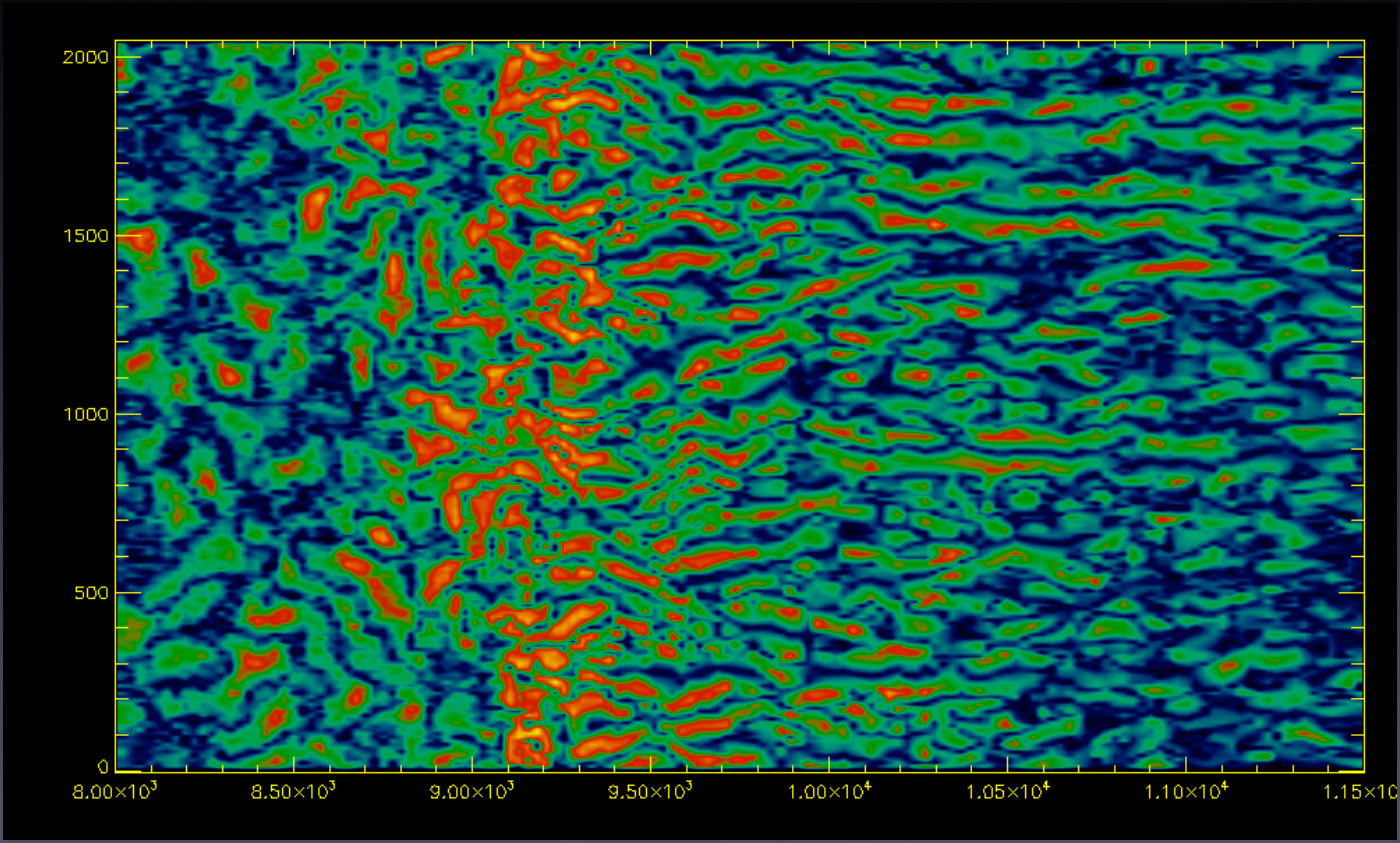
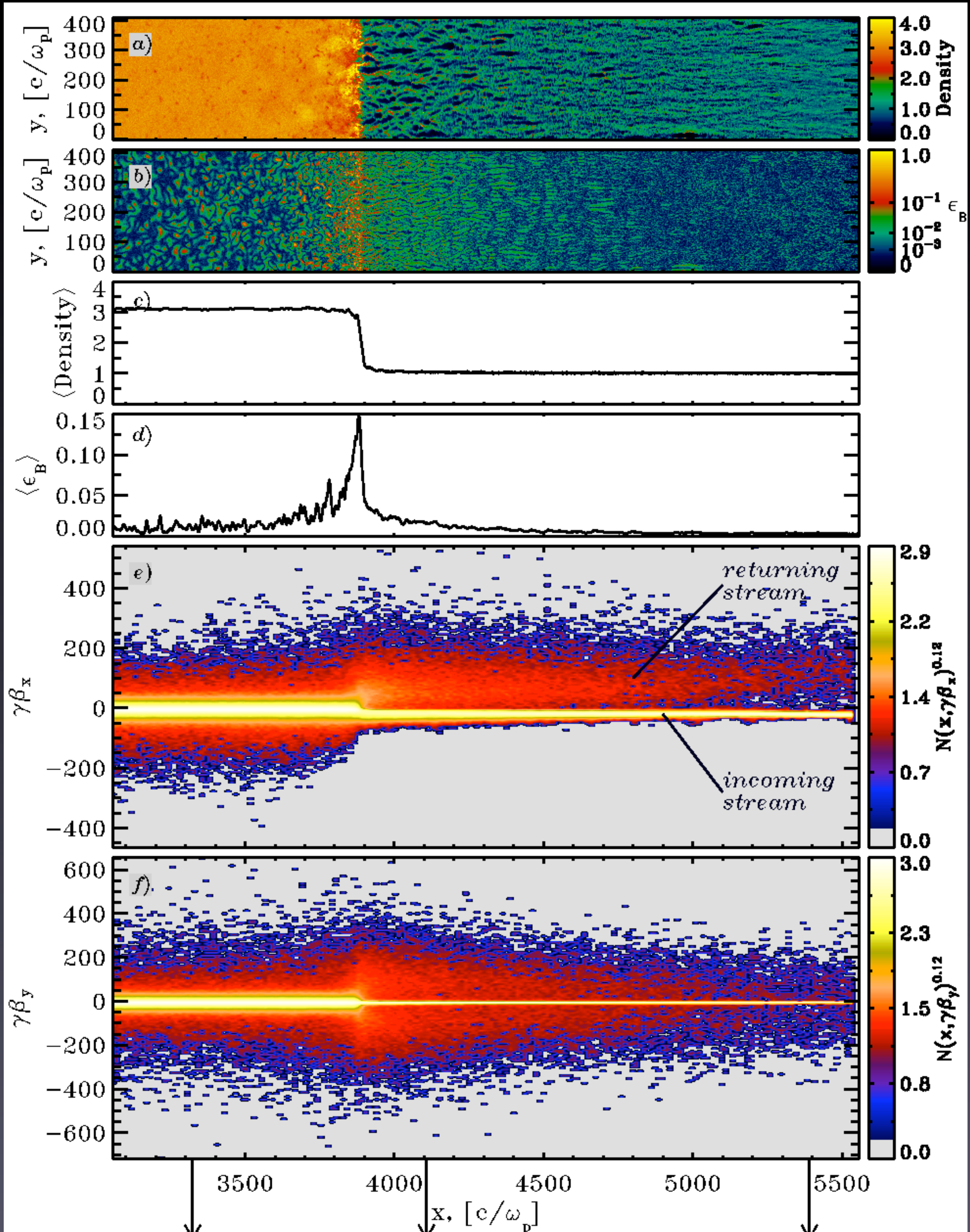





# Unmagnetized pair shock:

shock is driven by returning particle precursor (CR!)

*Steady counterstreaming leads to self-replicating shock structure*

*x- px momentum space*

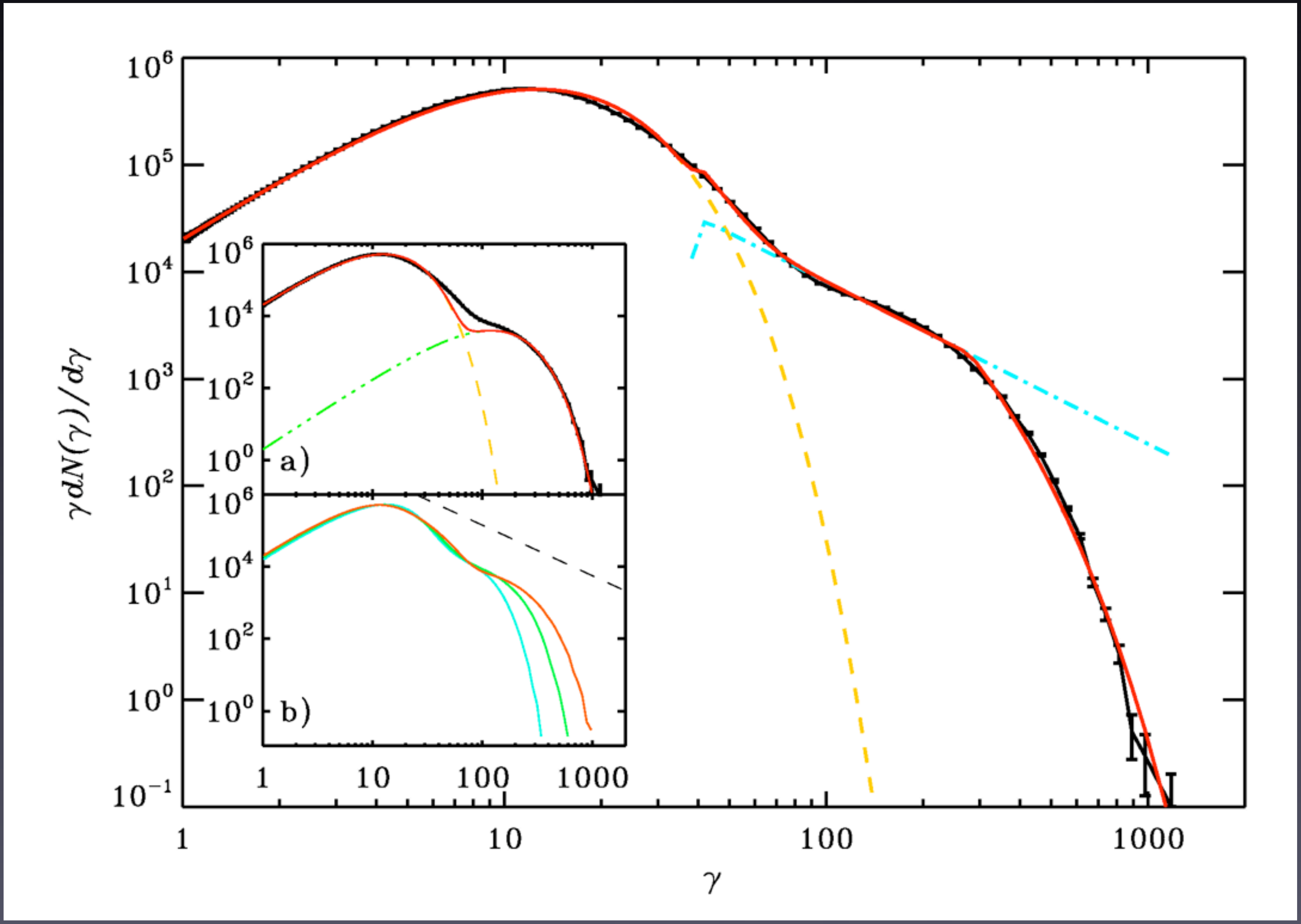
## Long term 2D simulation

*x- py momentum space*

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

# Unmagnetized pair shock:

downstream spectrum: development of nonthermal tail!



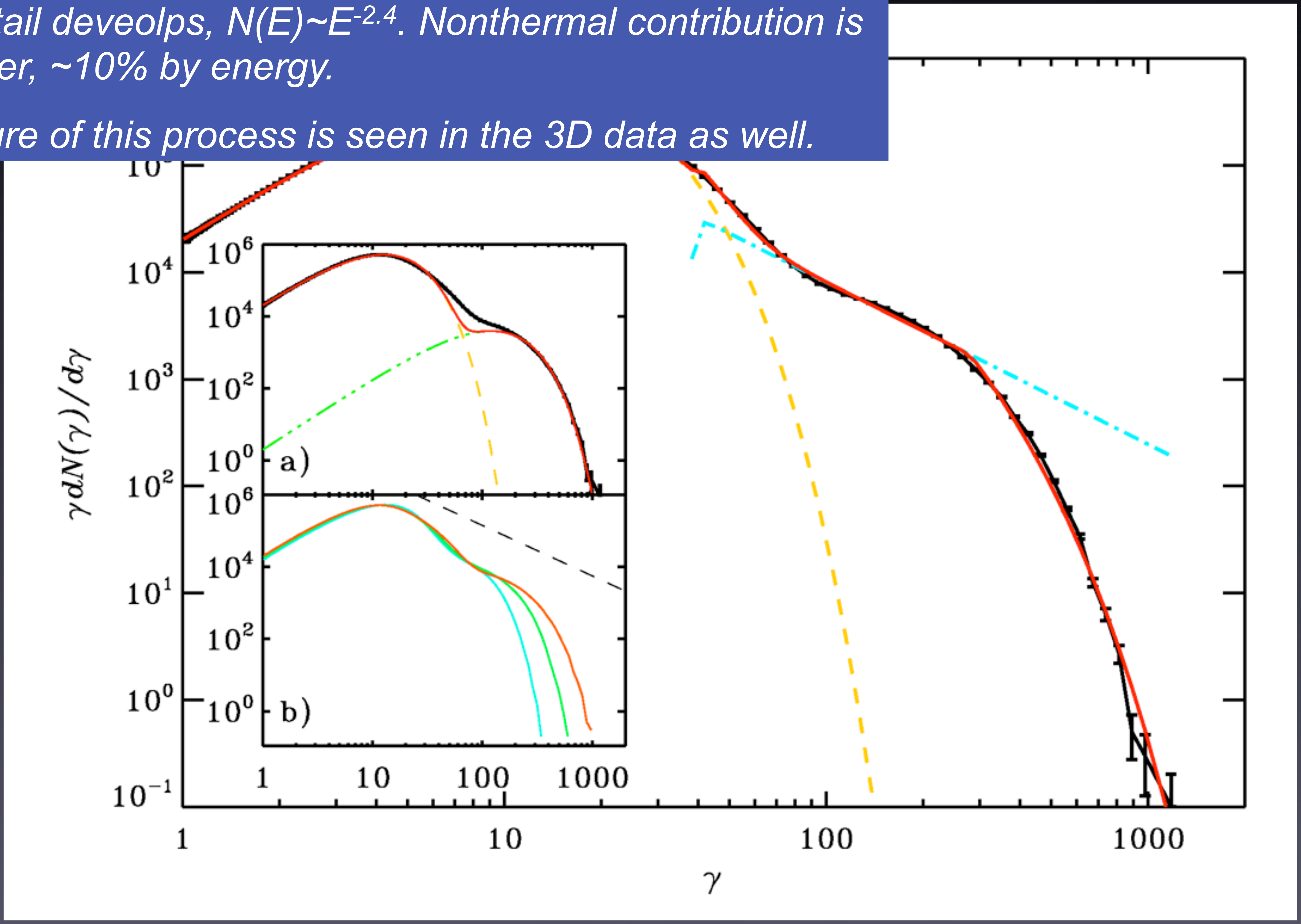

A.S. 2008, ApJ, 682, L5

# Unmagnetized pair shock:

downstream spectrum: development of nonthermal tail!

*Nonthermal tail deveolps, $N(E) \sim E^{-2.4}$. Nonthermal contribution is 1% by number, ~10% by energy.*

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




A.S. 2008, ApJ, 682, L5

# Unmagnetized pair shock:

downstream spectrum: development of nonthermal tail!

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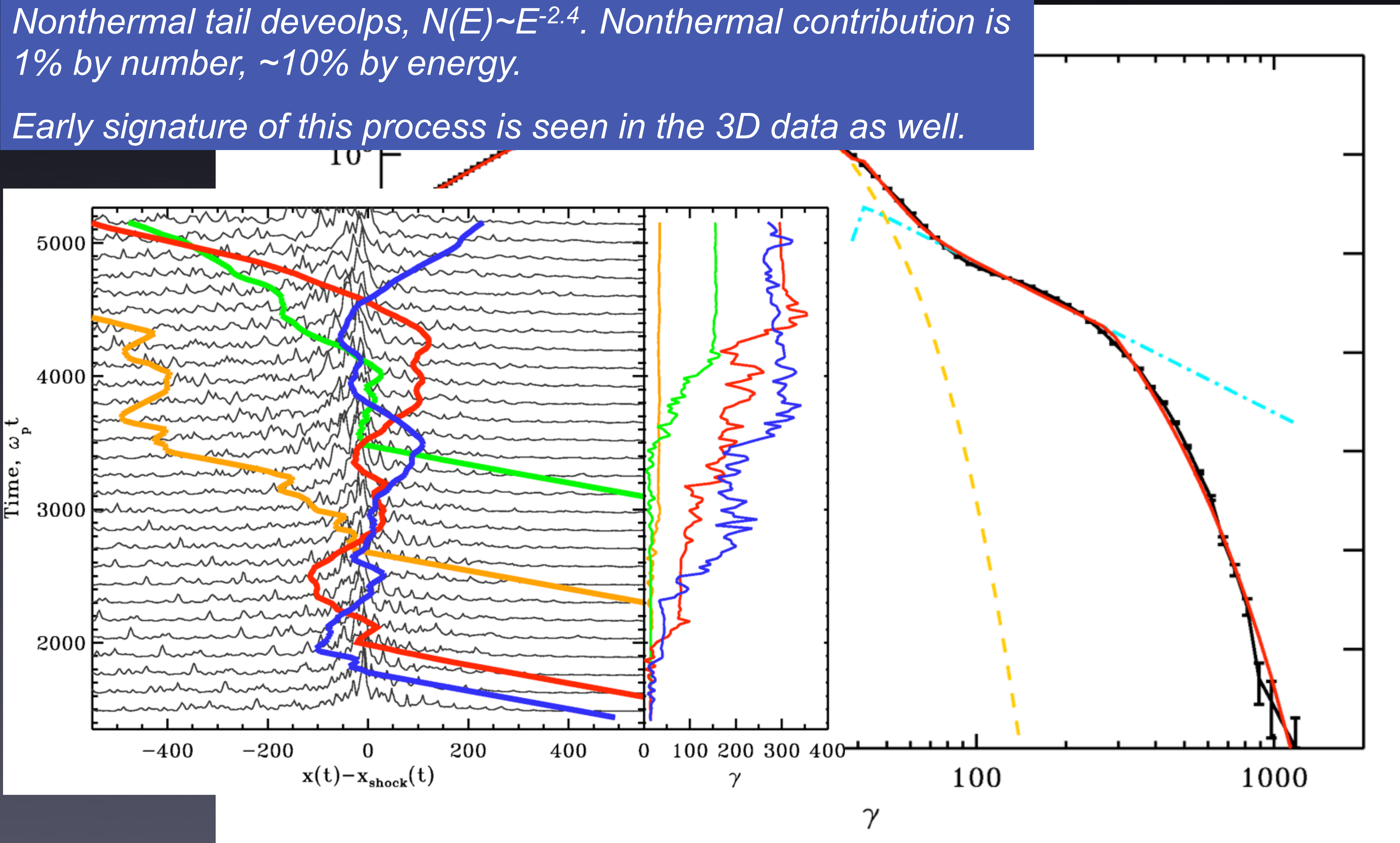


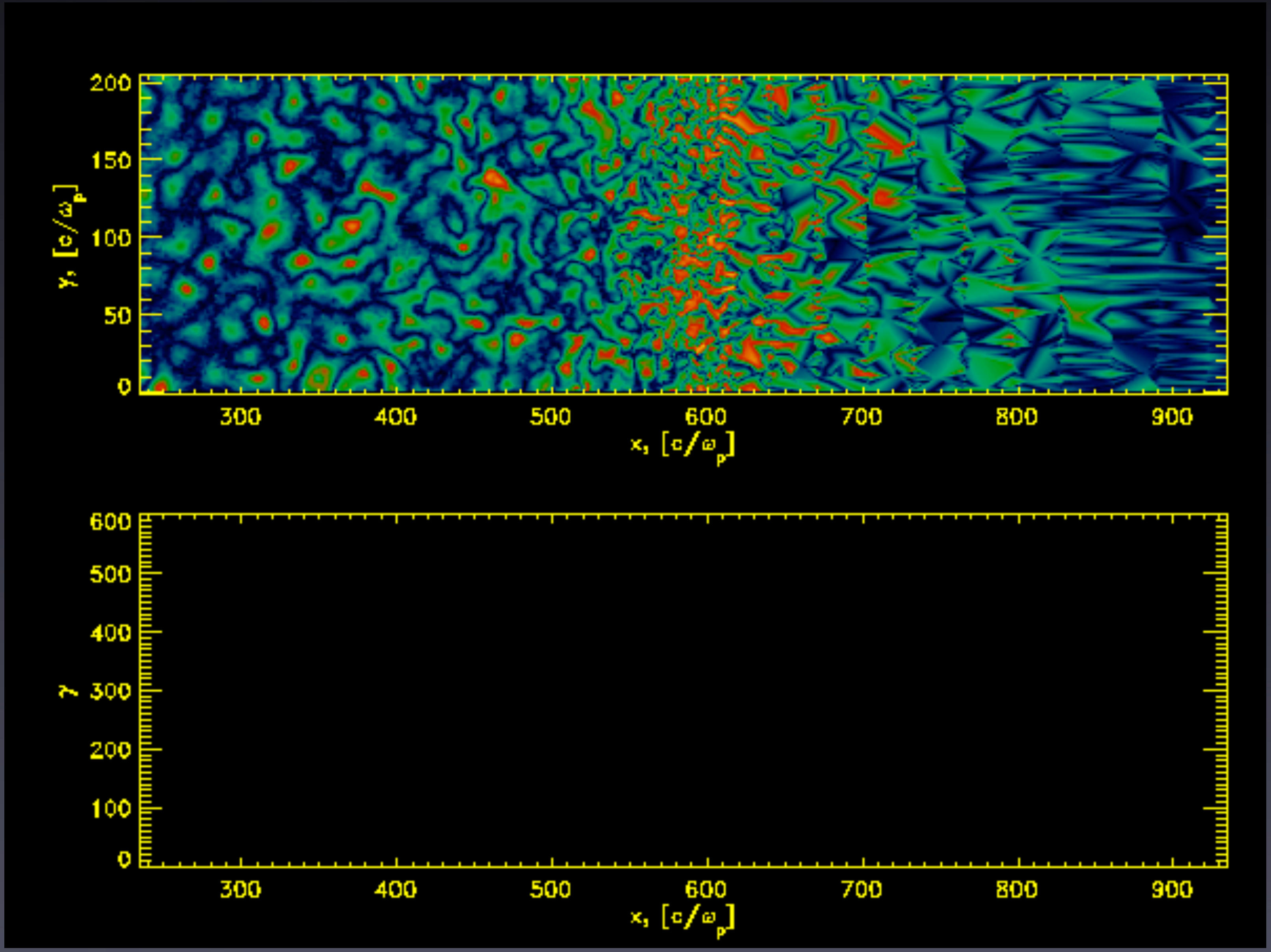

A.S. 2008, ApJ, 682, L5

# Unmagnetized pair shock: particle trajectories

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

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

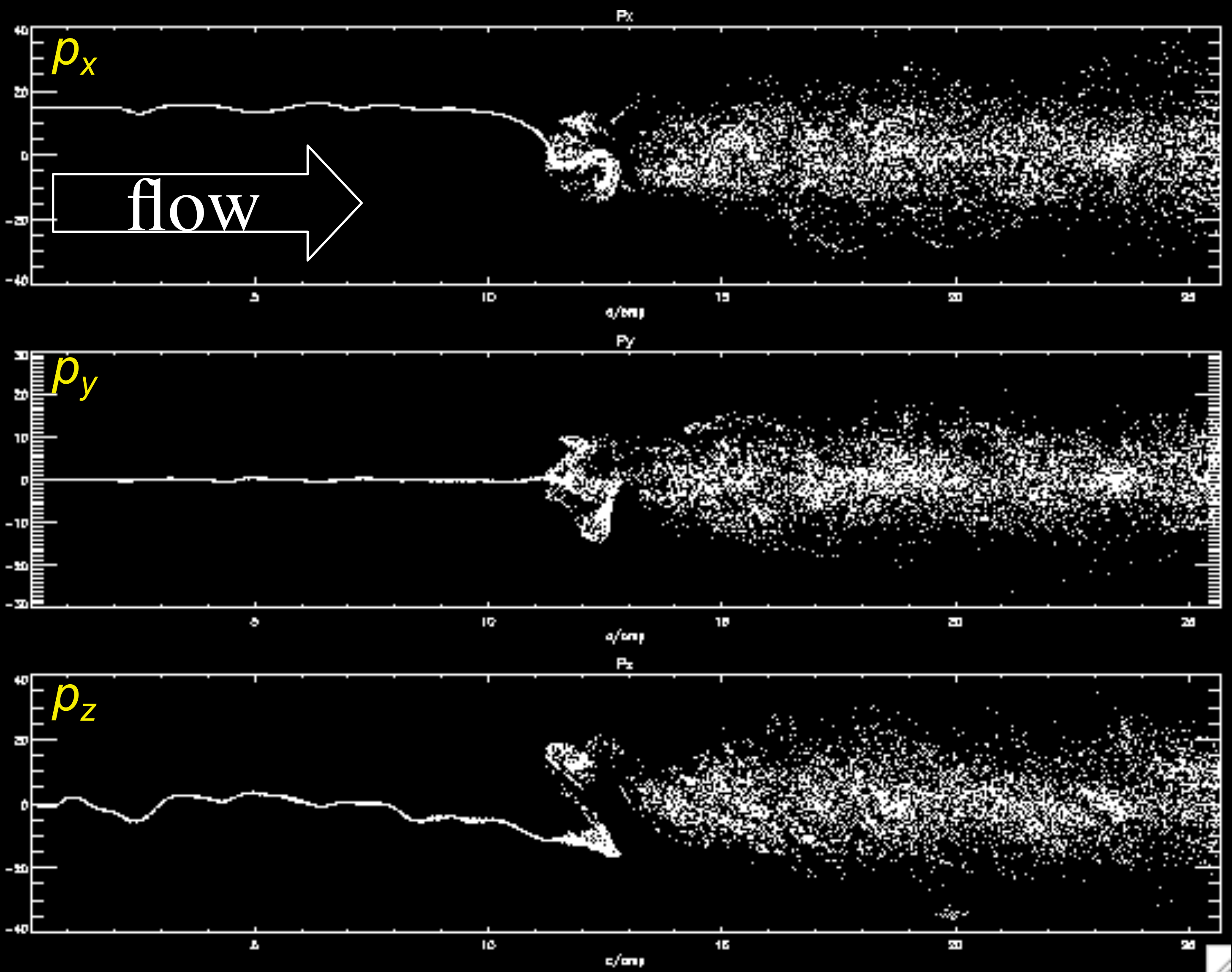
*Injection works self-consistently from the thermal distribution.*



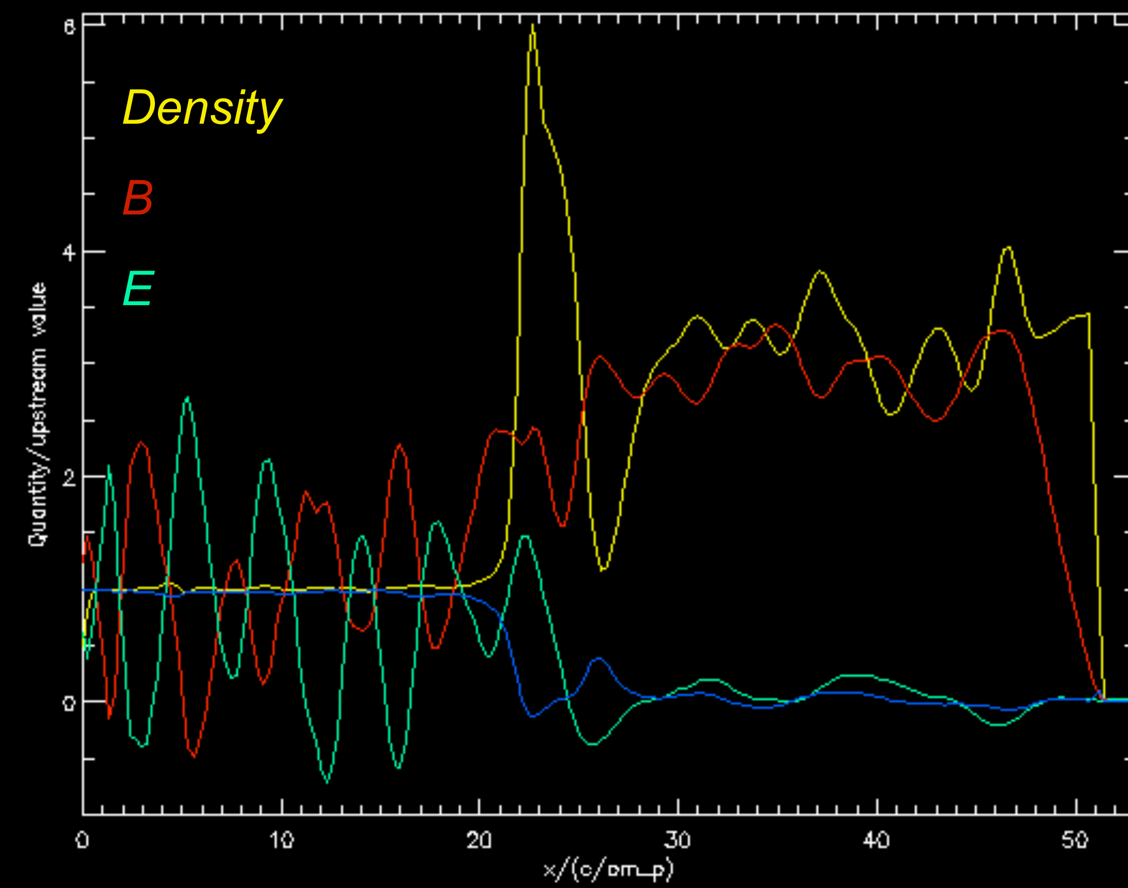

Particles that are accelerated the most graze the shock surface

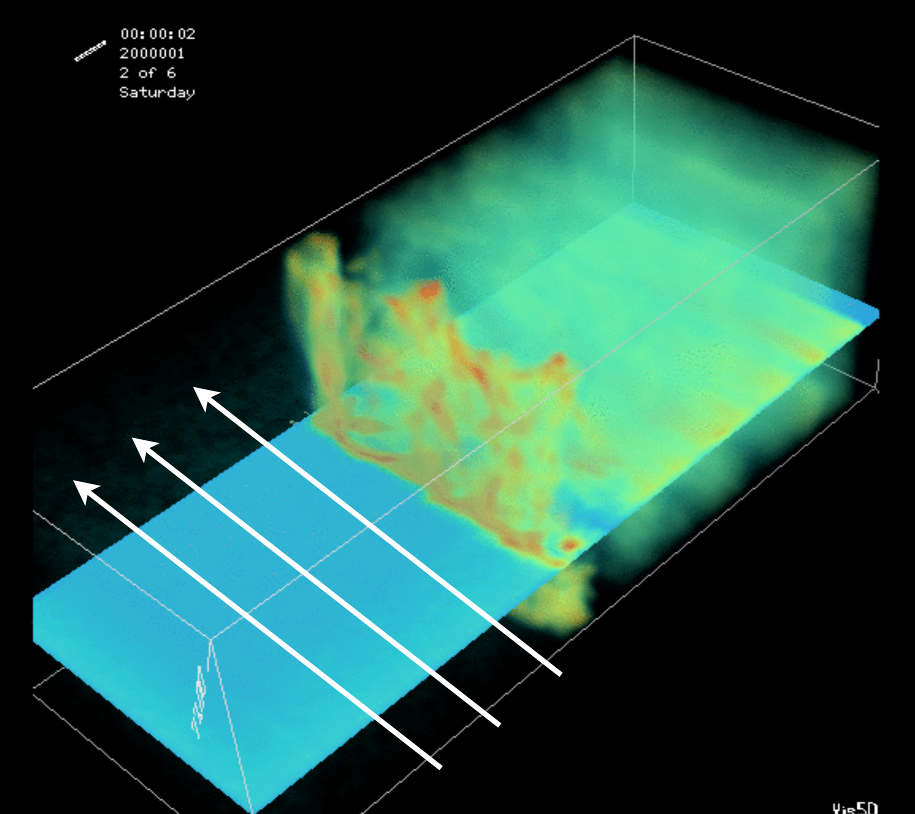
# Magnetized perpendicular relativistic pair shock:

*Shock structure $\sigma$=0.1 -- particle phase space*




*Shock structure*

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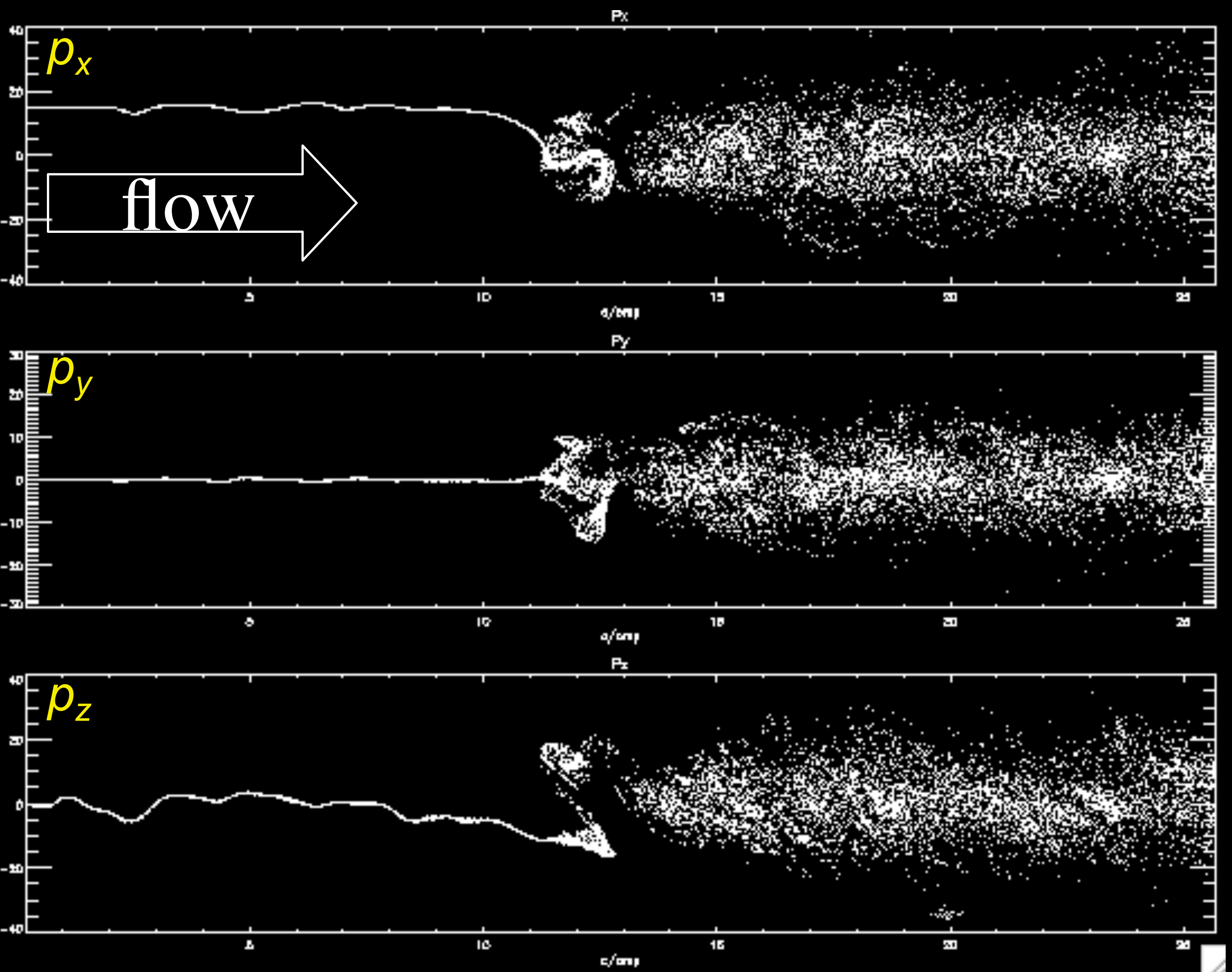


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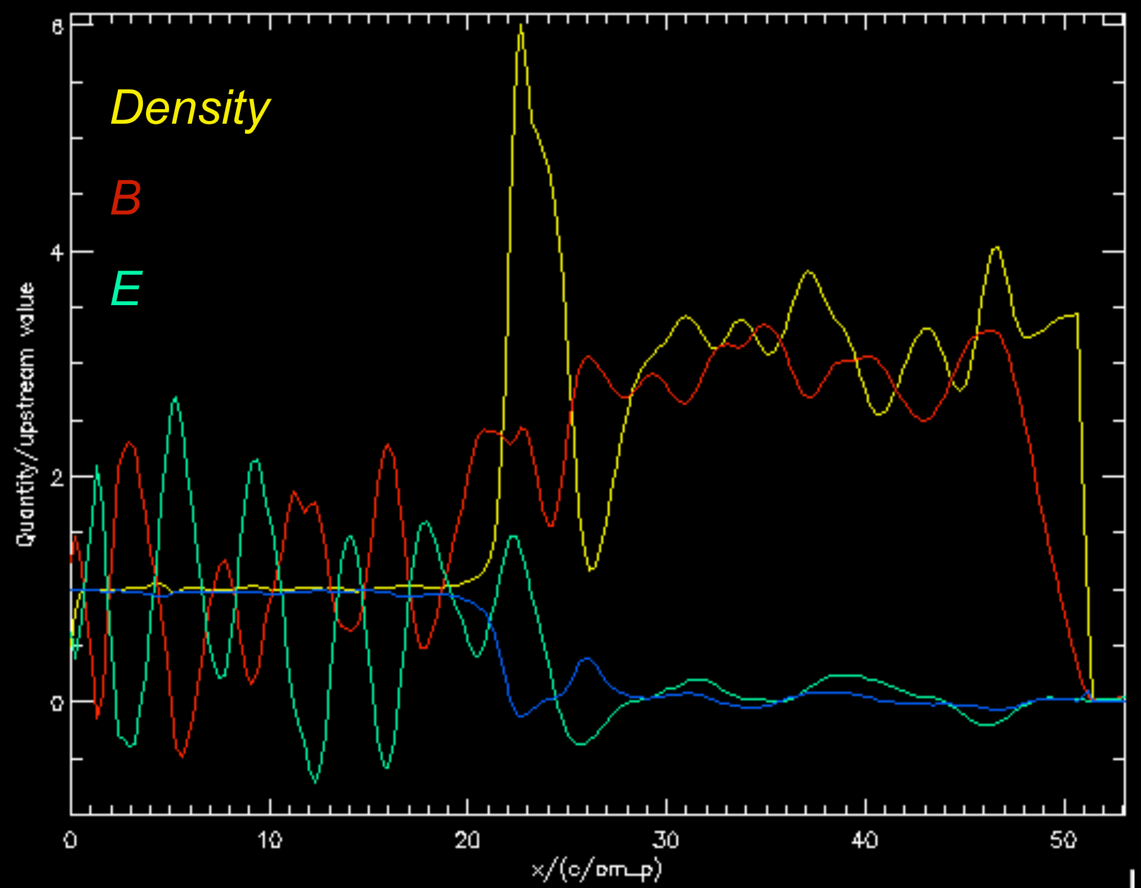
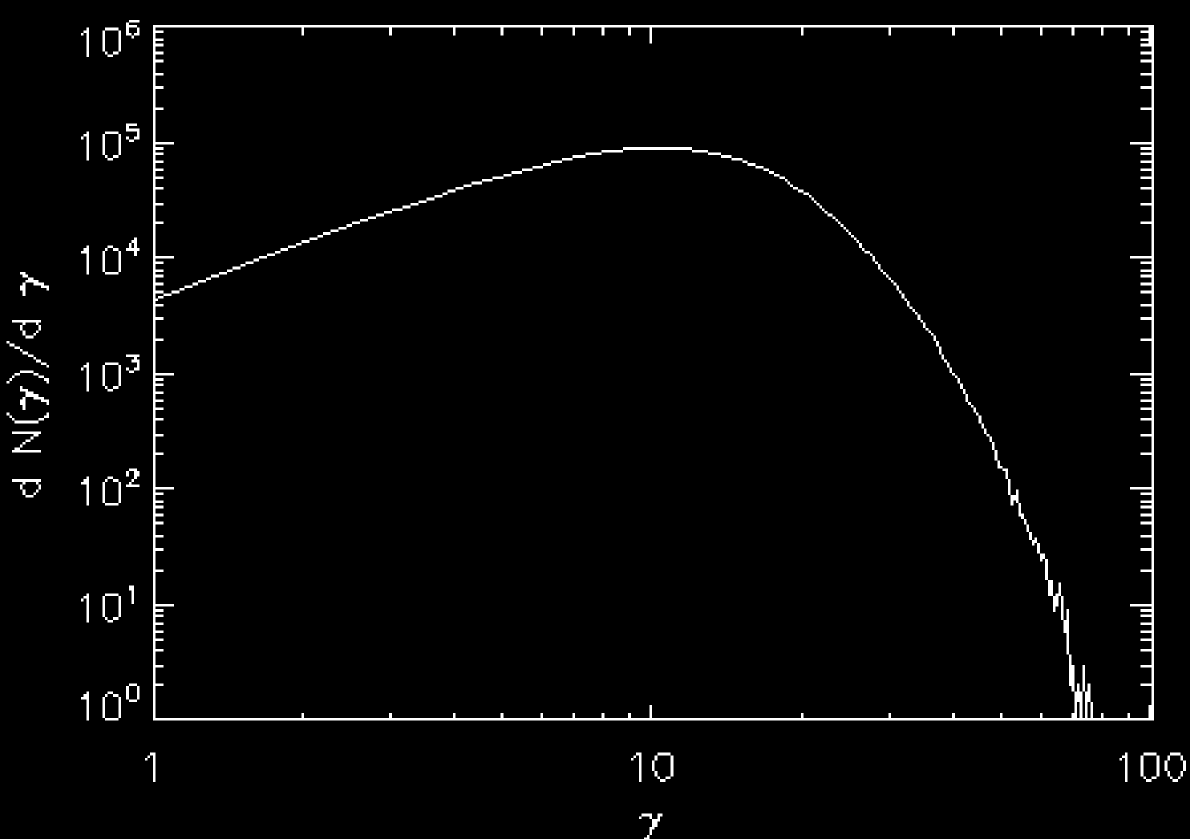


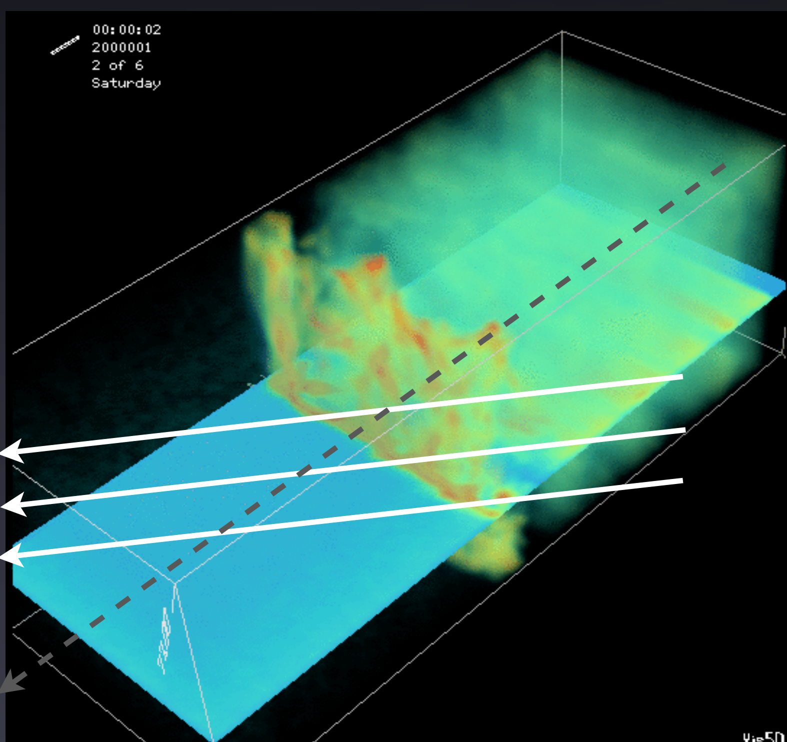



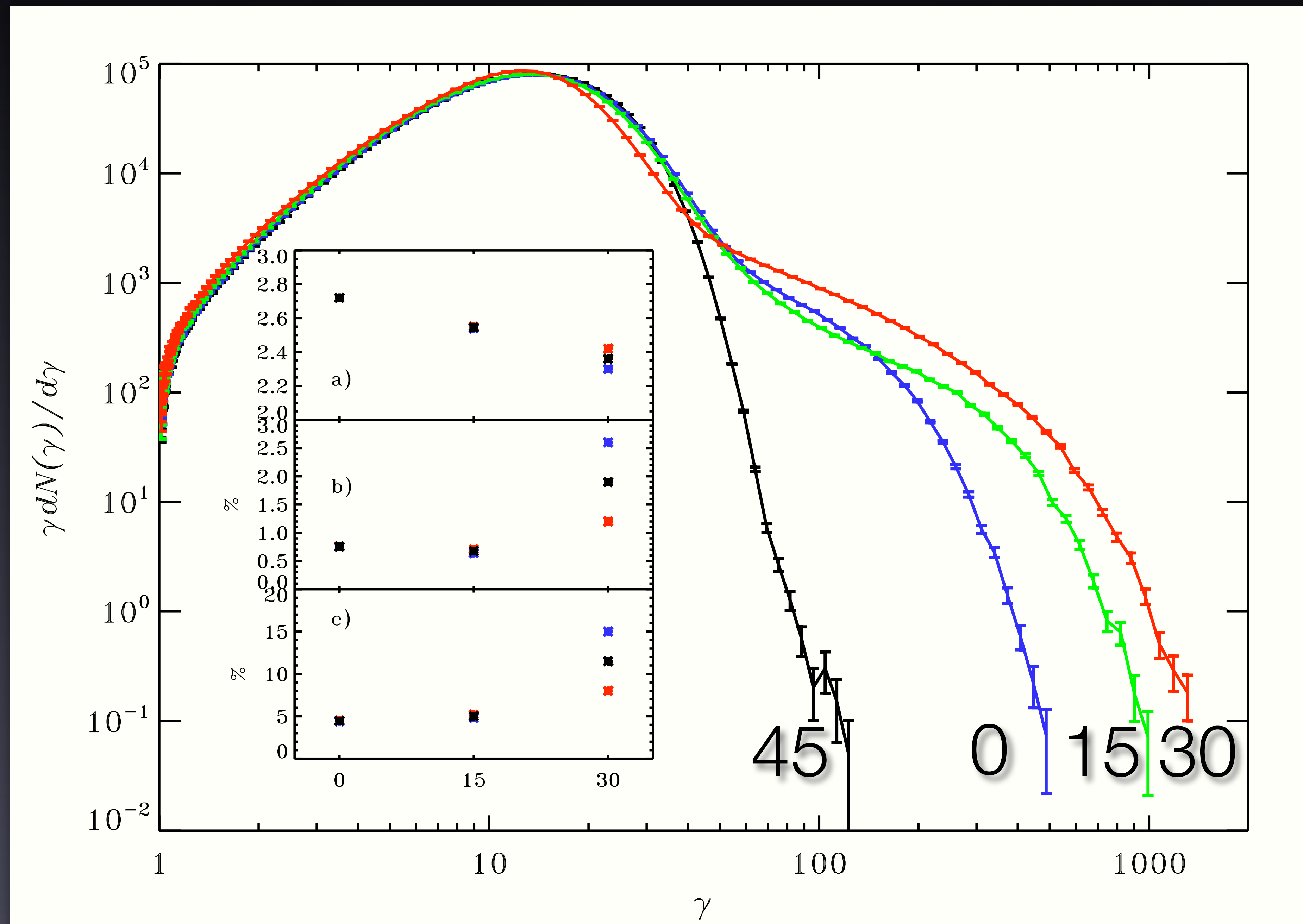

*Shock structure is dominated by magnetic reflections as in 1D (Hoshino & Arons,92).*

***No nonthermal acceleration even in 3D.***

# Can magnetized pair 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; Find p-law index near -2.3*




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

*Perpendicular shocks are poor accelerators.*

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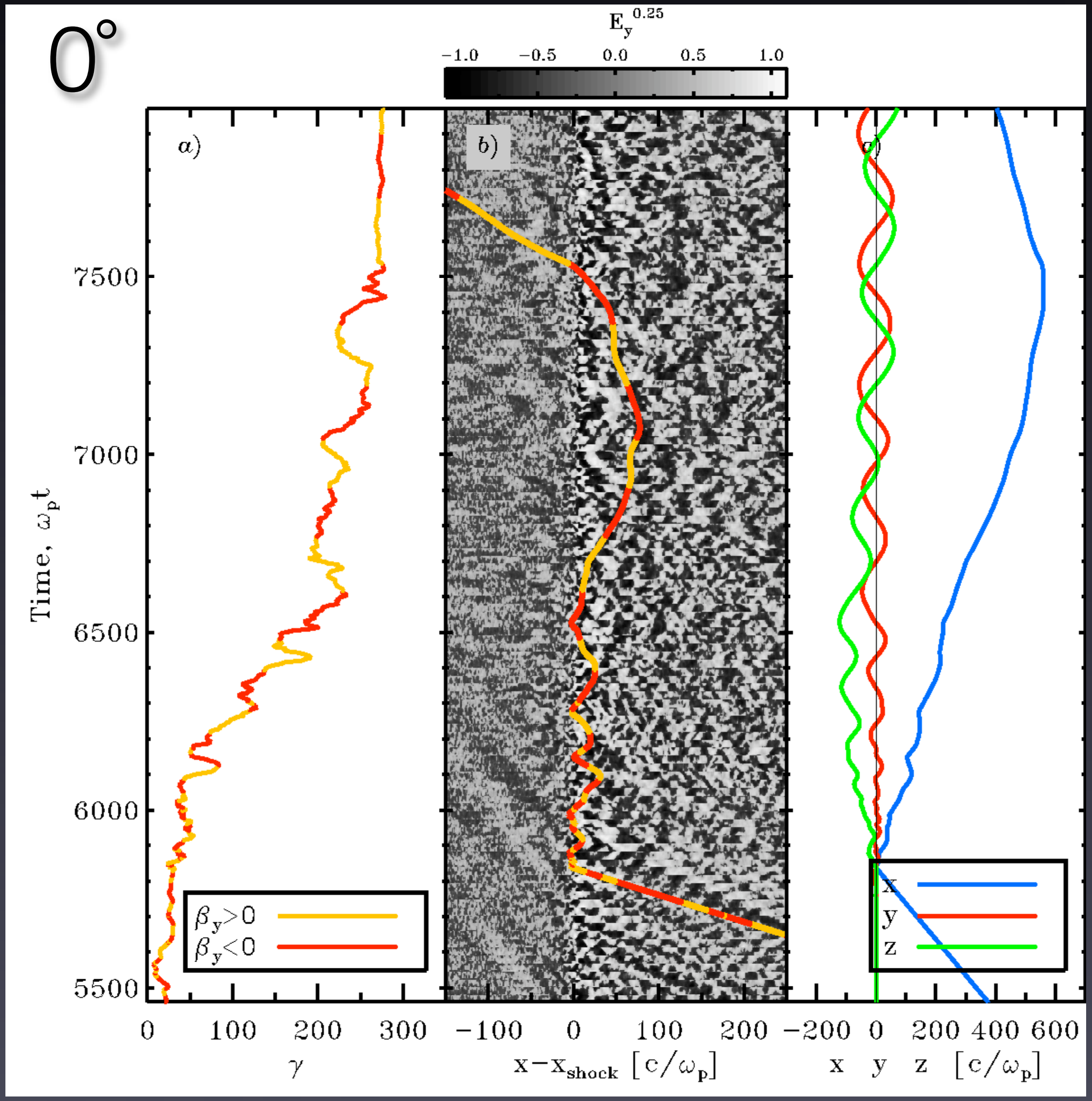


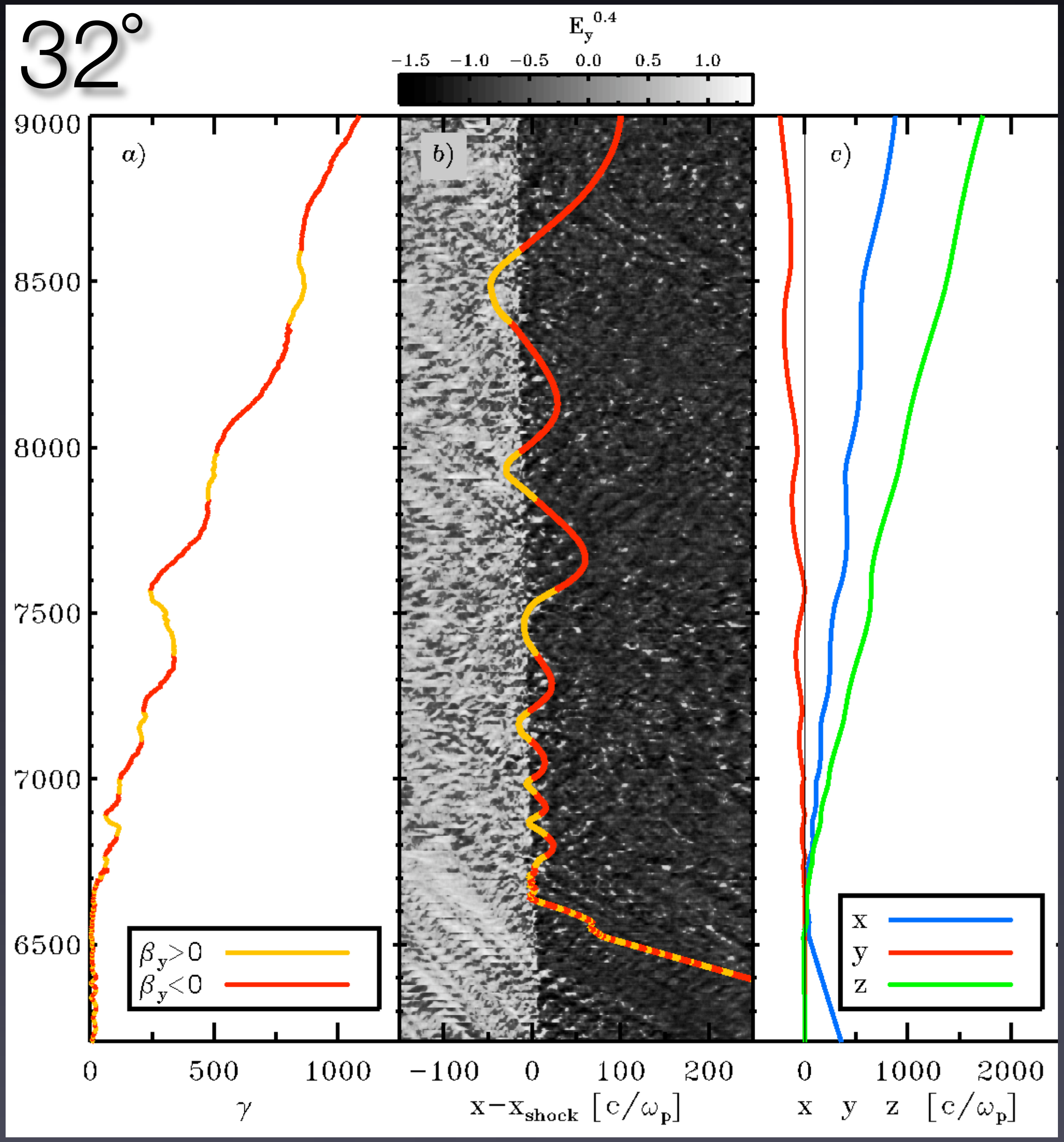


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*Shock drift acceleration is important near transition.*

*Perpendicular shocks are poor accelerators.*

A.S. 2008, ApJ, 673, L39

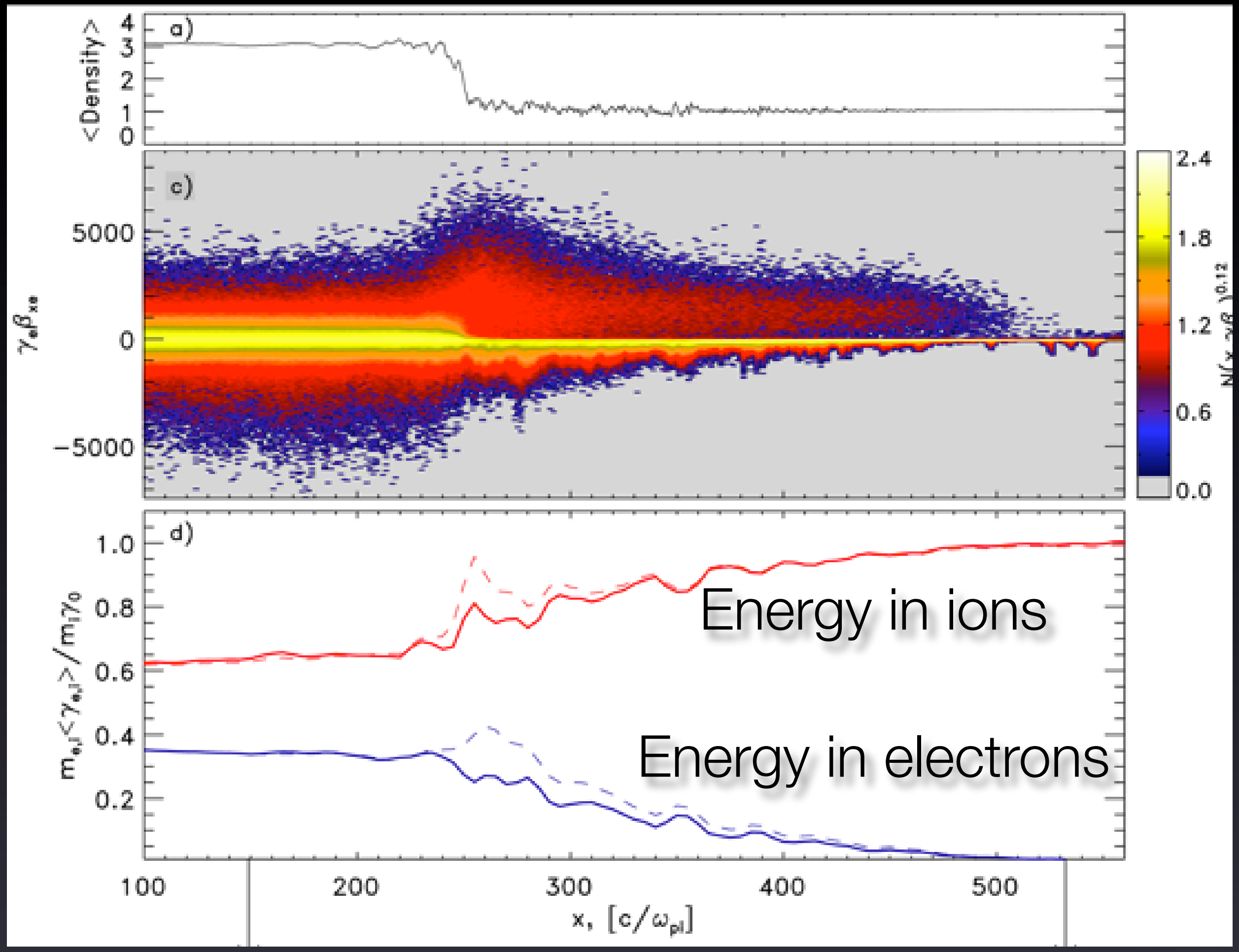
# Other results:

*Relativistic Electron-ion shocks*

*We observe electron-ion energy exchange in the shock. Electrons come close to equipartition with the ions. Behaves like pair shock! This helps to explain the high electron energy fraction inferred in GRB afterglows.*

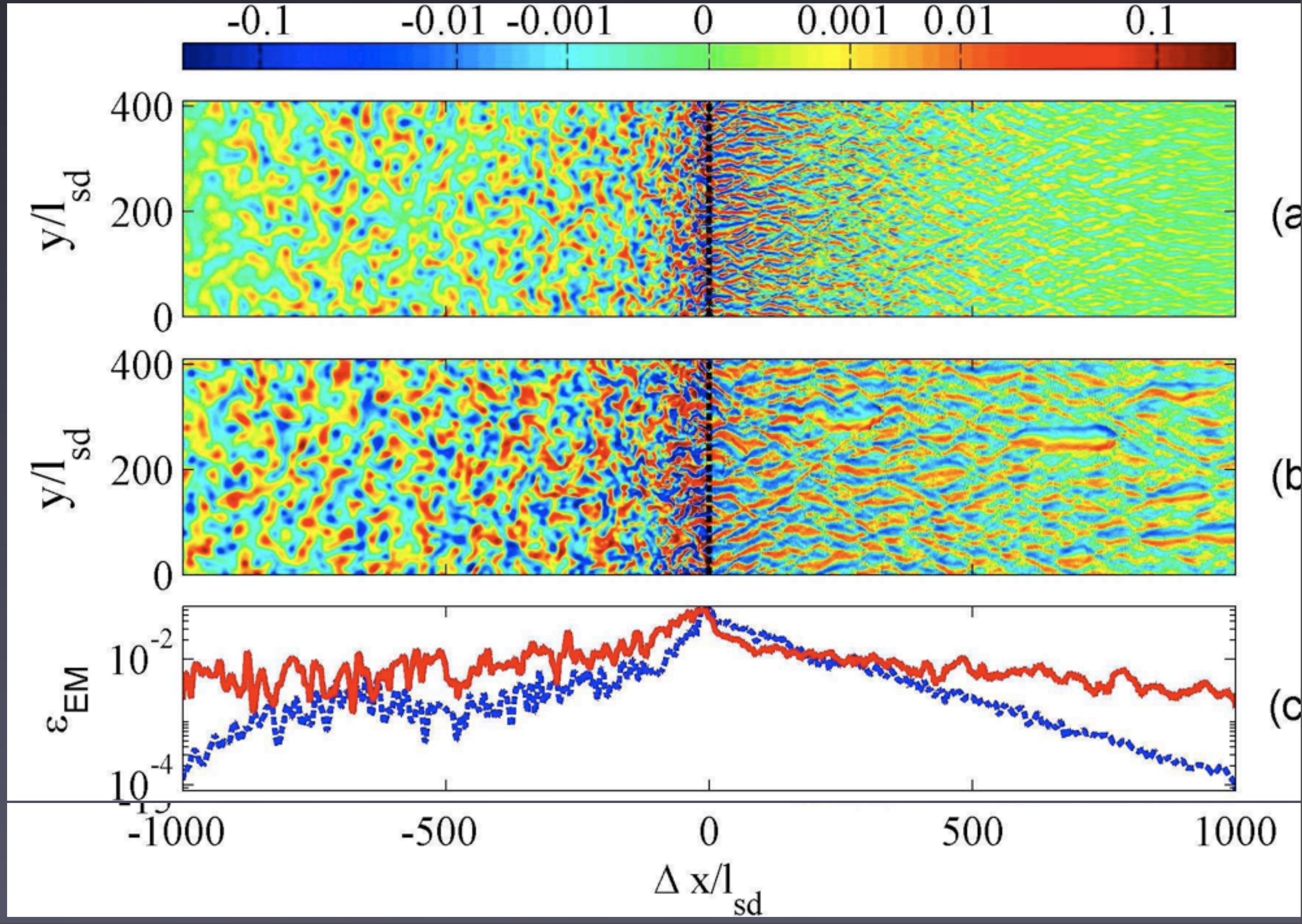
*Fermi acceleration proceeds very similarly in unmagnetized e-ion shocks*

*Perpendicular e-ion shocks do heating, but not significant acceleration.*

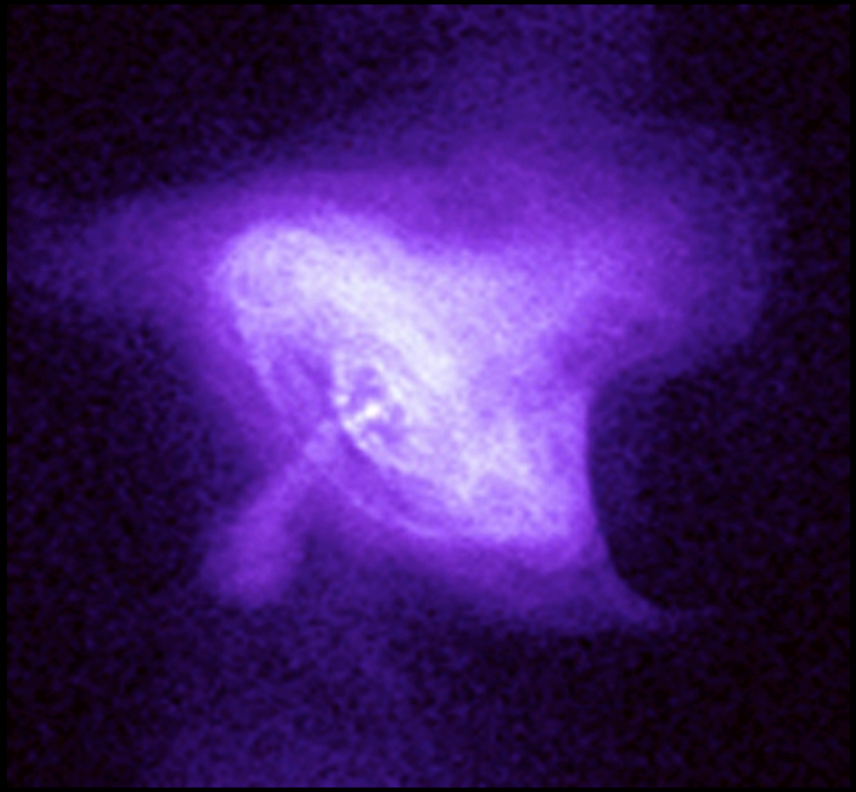


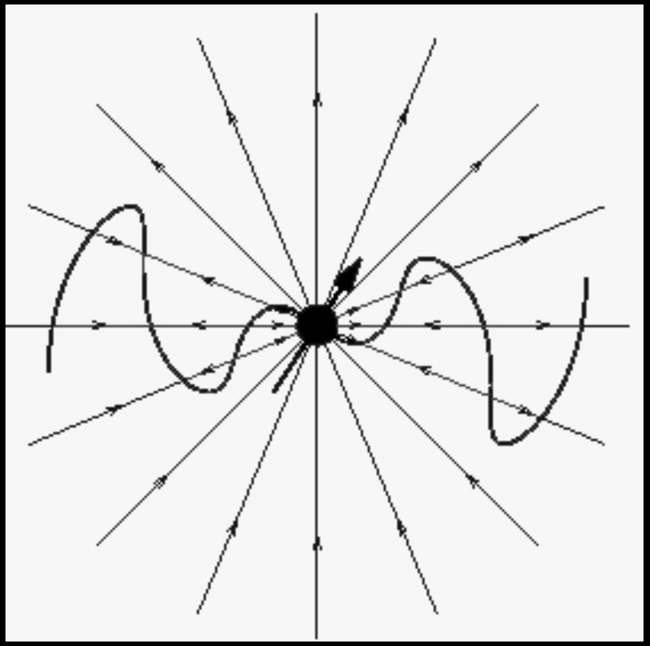

*Magnetic field growth and evolution*

*Returning particles cause filamentation far in the upstream region and cause growth of the scale and amplitude of the upstream field. This affects the rate of decay of the field in the downsream (longer wavelengths decay slower). 1% magnetization is not unreasobable (Keshet, Katz, A.S, Waxman 2008).*



# Astrophysical implications: Pulsar Wind Nebulae (PWNe)





*Shock acceleration in PWN implies low magnetization shock. $\sigma$=0.001 is inferred from modeling of the nebulae. This is a “transition” regime between magnetized and unmagnetized shocks -- expect Weibel instability to dominate the shock.*

*Equatorial shock occurs where the current sheet lies -- hence expect a weakly magnetized “equatorial wedge” -- consistent with shock physics.*

*At the moment pair composition could be ok, although other arguments suggest the presence of pair-ion plasma (A.S. & Arons 04).*

*Alternative -- reconnecting flow at the termination shock (Lyubarsky & Petri 07)*

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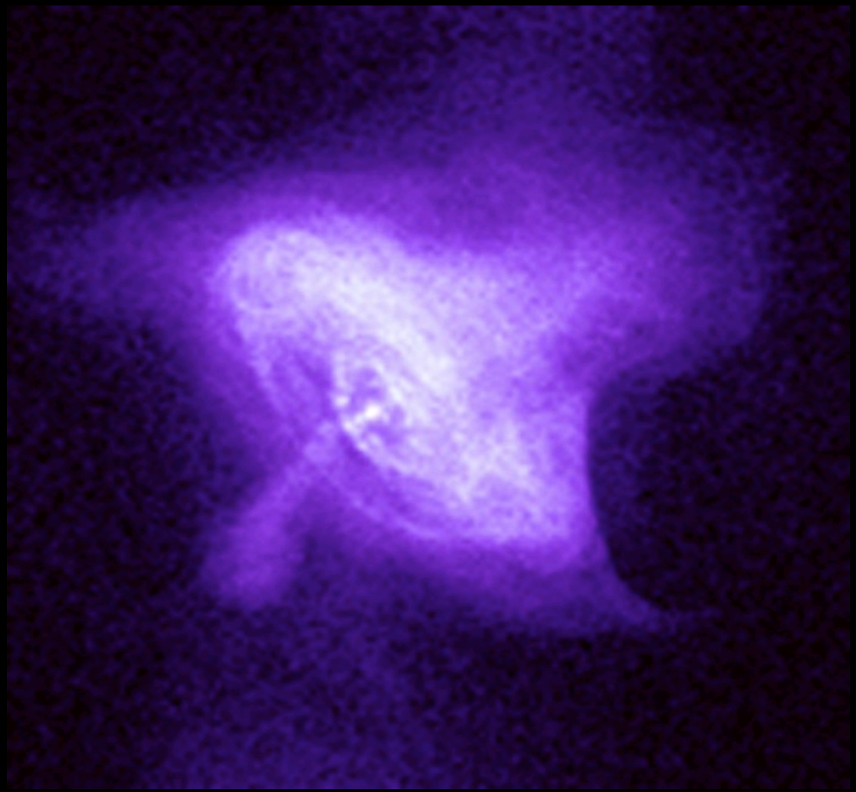

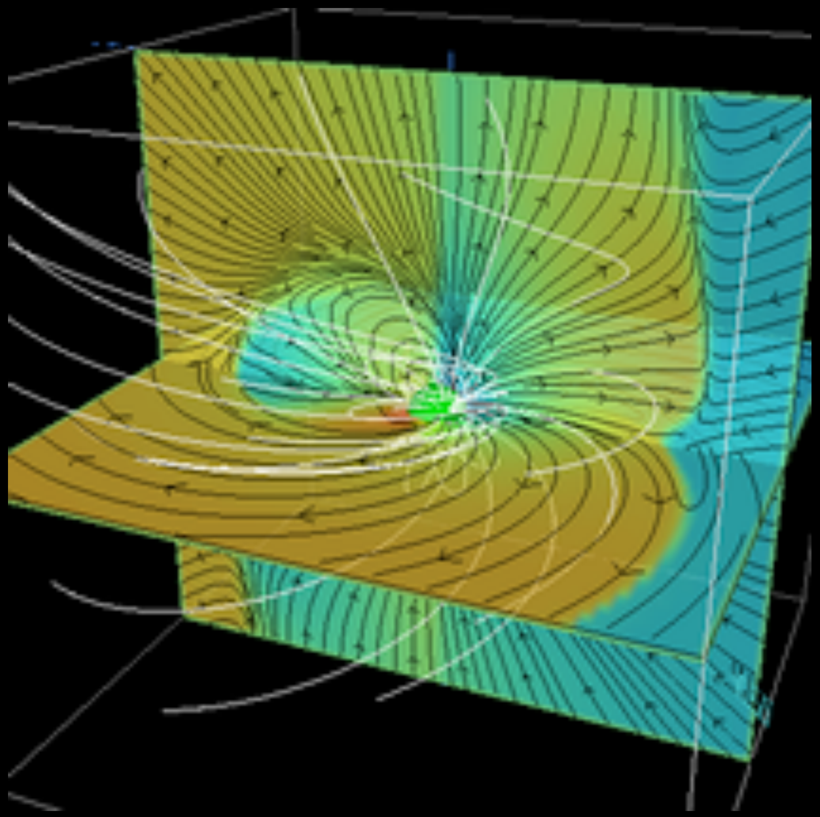

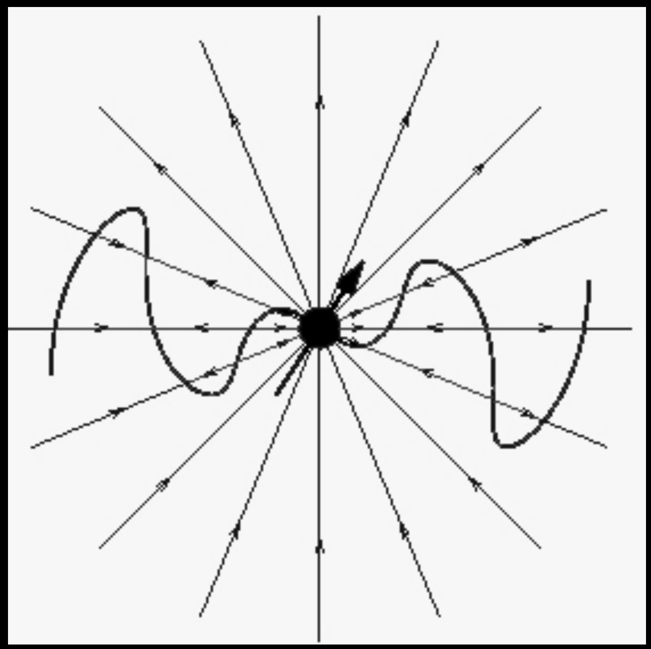

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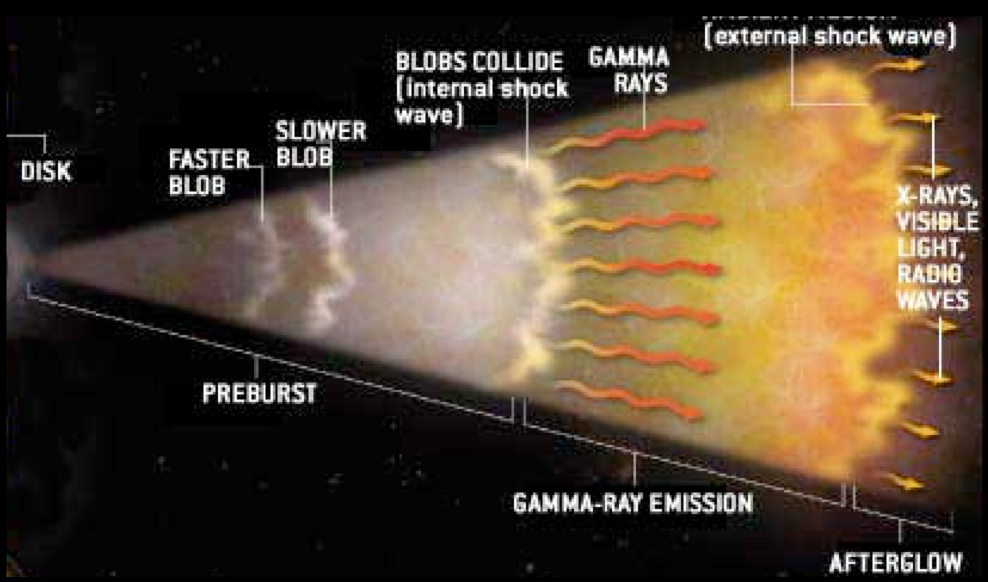
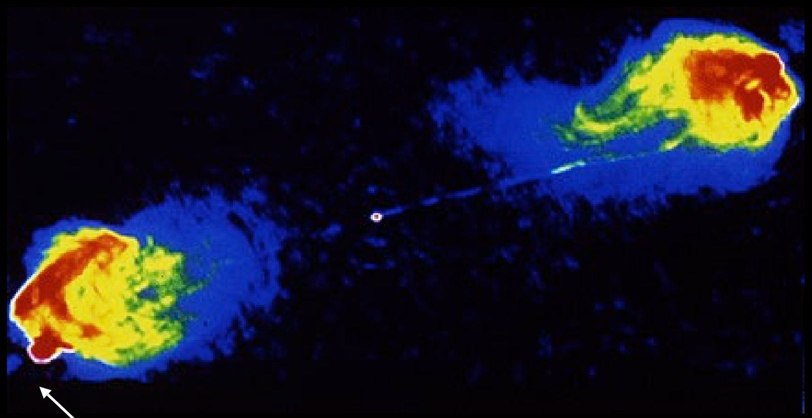
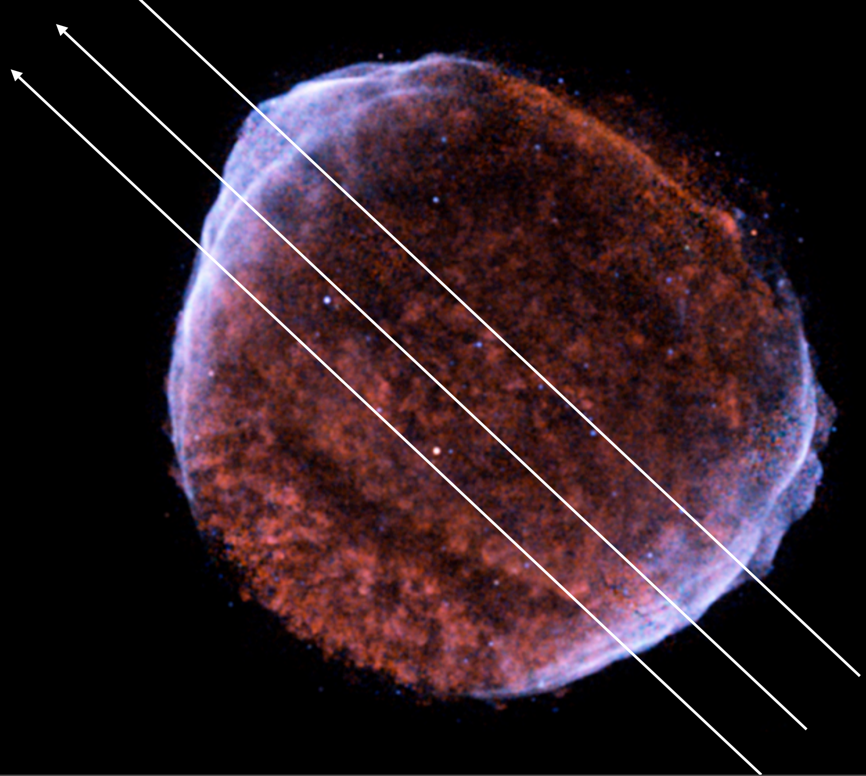




## *Gamma Ray Bursts*

*Very low magnetization $\sigma=10^{-8}$ shocks can operate even in electron-ion plasma.*

*Electron heating to near equipartition with the ions implies that high electron energy fraction ($\varepsilon_e=0.1$) is not unreasonable. Magnetic fields near ($\varepsilon_B=0.01$) could also be generated. Can we see thermal component?*

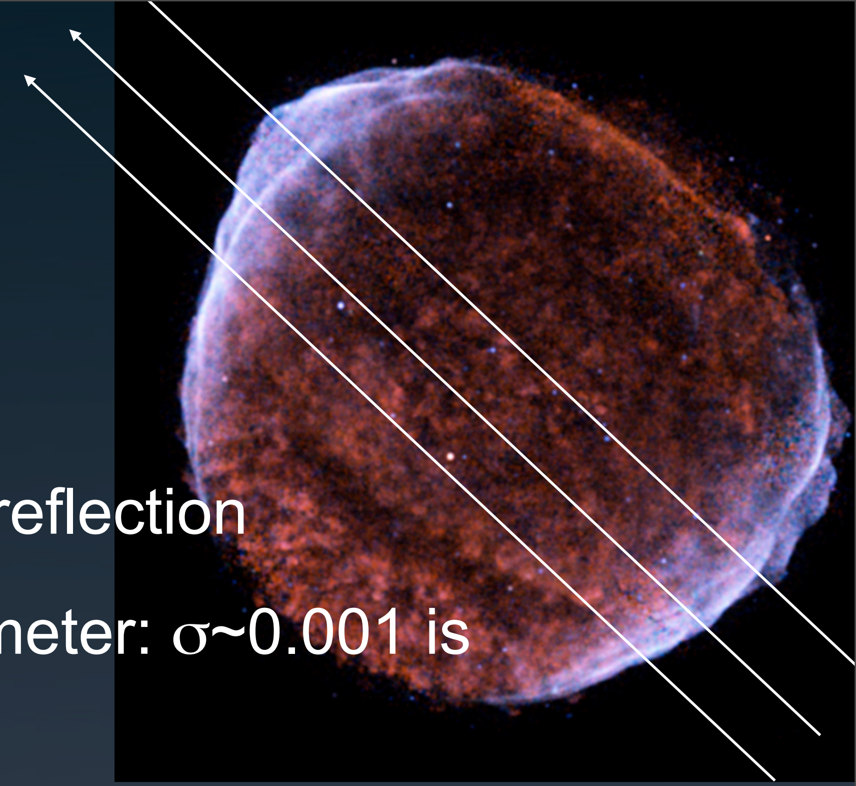
## *AGN and other jets*

*High magnetization perpendicular pair flows are unlikely to generate nonthermal particles through Fermi acceleration. Other physics needed? Not pure pair flows? Sheath flow?*

## *Supernova Remnants*

*Parallel shocks are more likely to accelerate particles than perpendicular shocks. SN1006 shows caps of nonthermal emission, thought to correspond to the region permeated by parallel magnetic field. e-ion temperature equilibration depends on background field.*

# Conclusions



- Collisionless shocks exist in 3D, 2D, and sometimes in 1D.
- Rel. shocks are mediated by Weibel instability or magnetic reflection
- Shock structure is controlled mainly by magnetization parameter: $\sigma$~0.001 is the transition region for pairs. Composition also important.
- First evidence of self-consistent Fermi-type process operating near the unmagnetized shocks and nearly-parallel shocks. Efficiency ~ 1%, Energetics ~ 10%.
- Magnetized perpendicular pair shocks do not efficiently produce nonthermal particles, weakly magnetized shocks and oblique shocks show more promise. Implications for geometry of PWN current layers and AGN jet fields.
- Do all accelerating relativistic shocks have to be weakly magnetized or parallel? Pulsar wind nebulae may have interestingly small $\sigma$ to be working as unmagnetized shocks.
- Magnetic field amplification with CRs works in PIC. Amplification by factors of 25 can be achieved with the Bell's instability. Do shocks produce significant CR currents?

# B field amplification

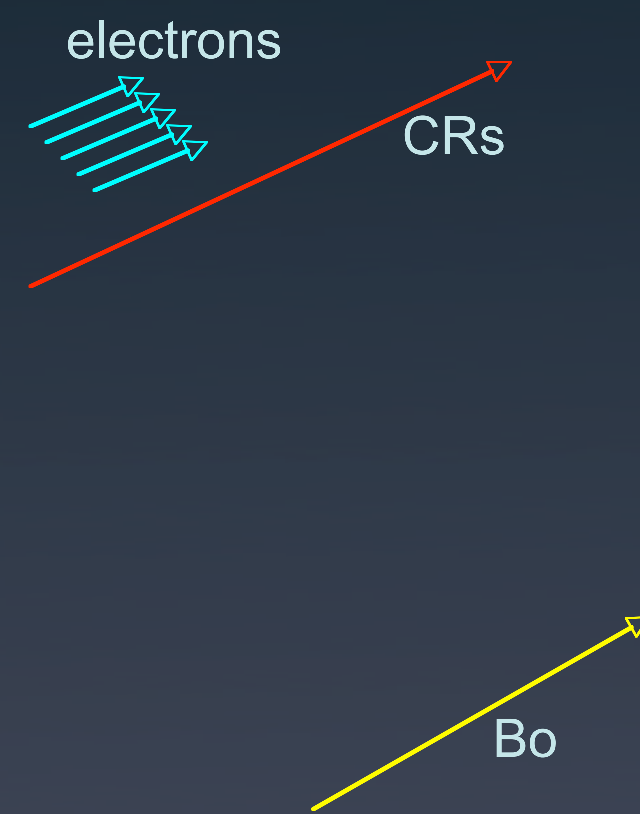
*Bell's nonresonant CR instability*

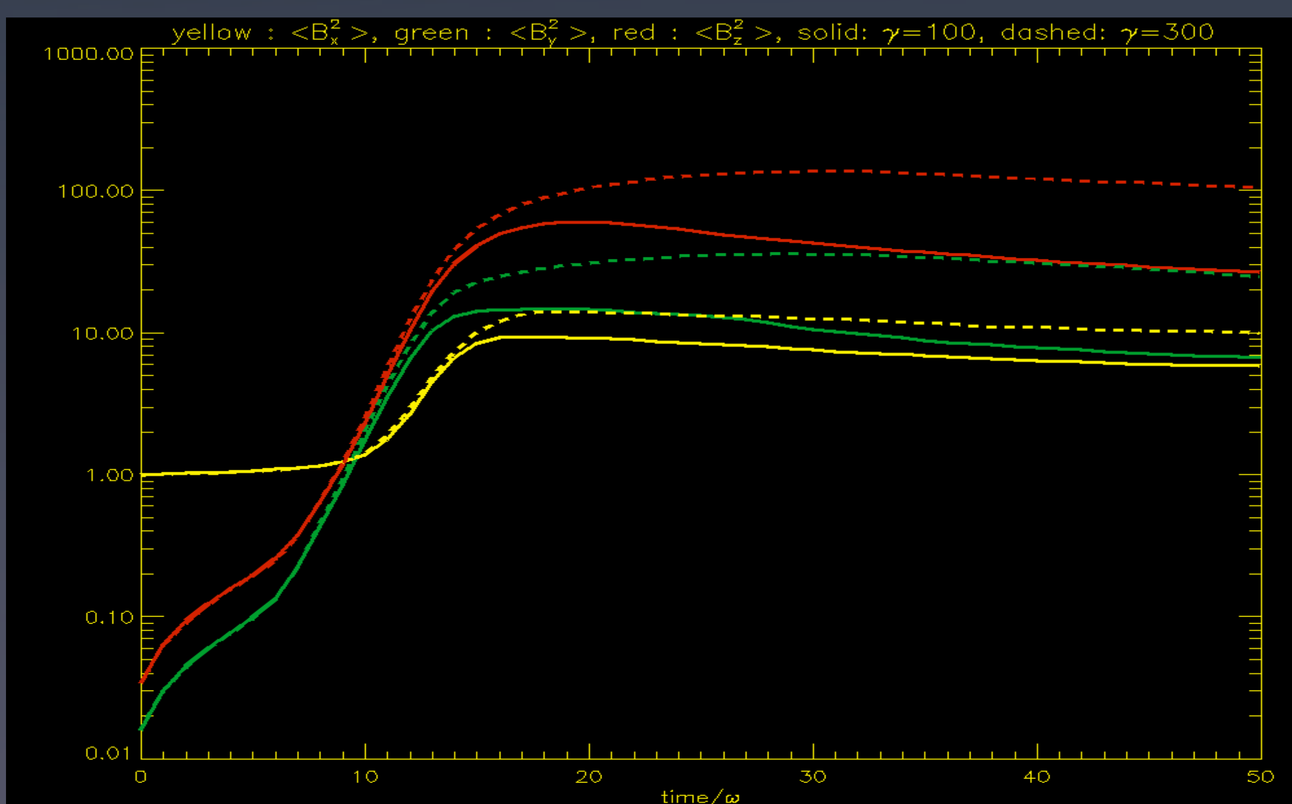
*CR accelerating shocks can cause a current of protons to propagate through the upstream. Bell (04, 05) found an MHD instability of CRs flying through magnetized plasma.*

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

*We simulated this instability with PIC in 2D and 3D*

*Saturation is due to plasma filametnation and motion ($v_A \sim v_{d,CR}$), or CR deflection; for SNR conditions 10-100 field increase.*




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

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

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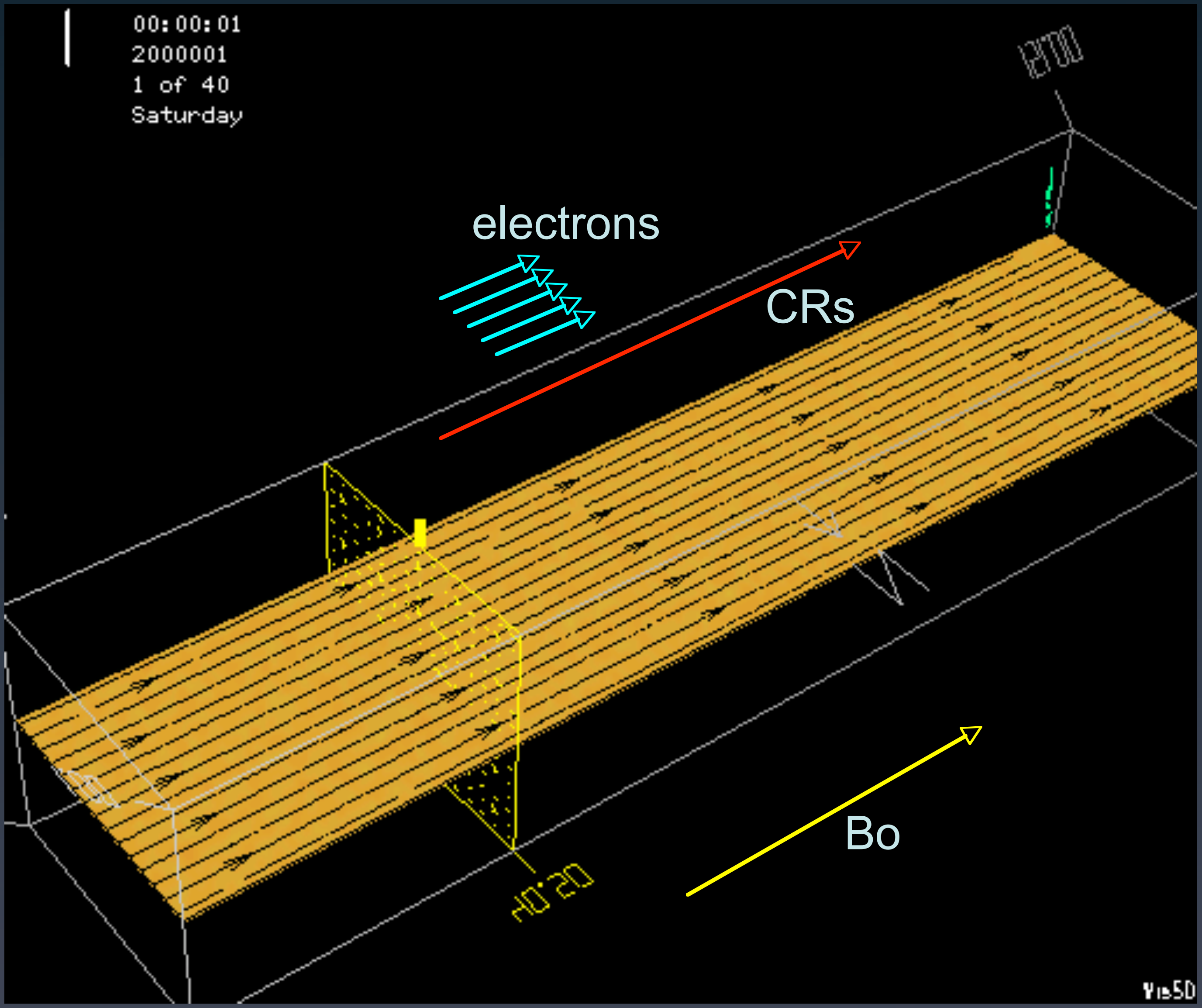


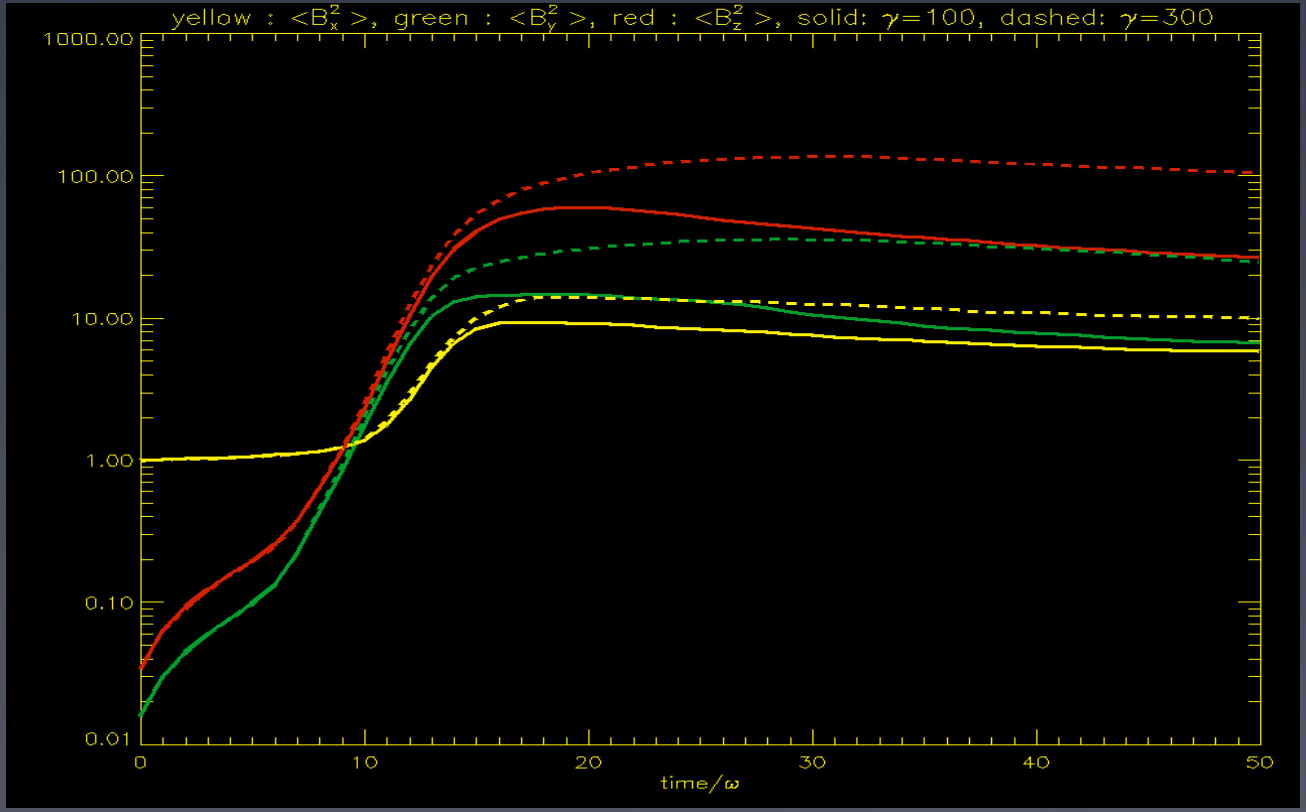


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*Cut in x-z plane*

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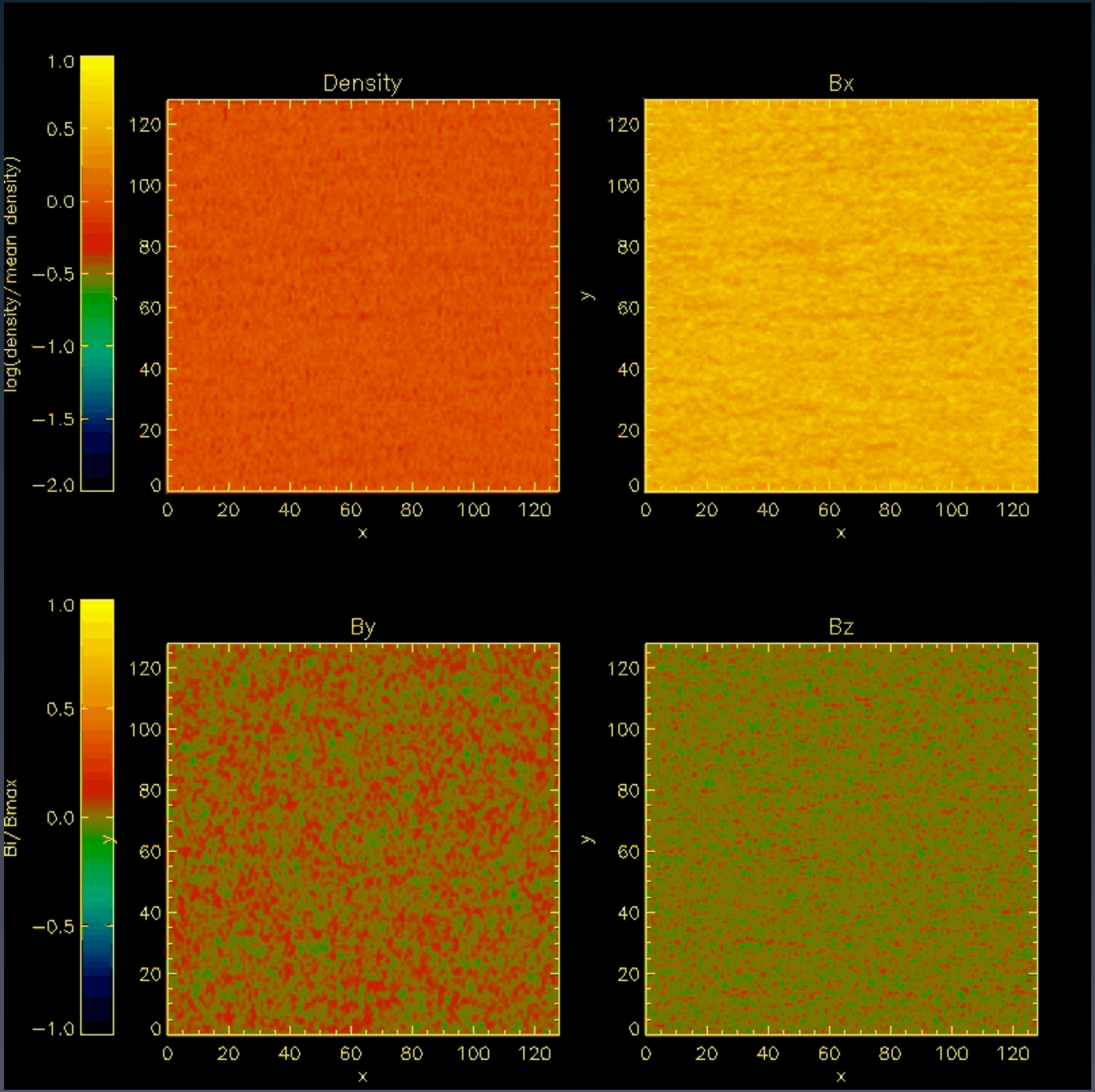

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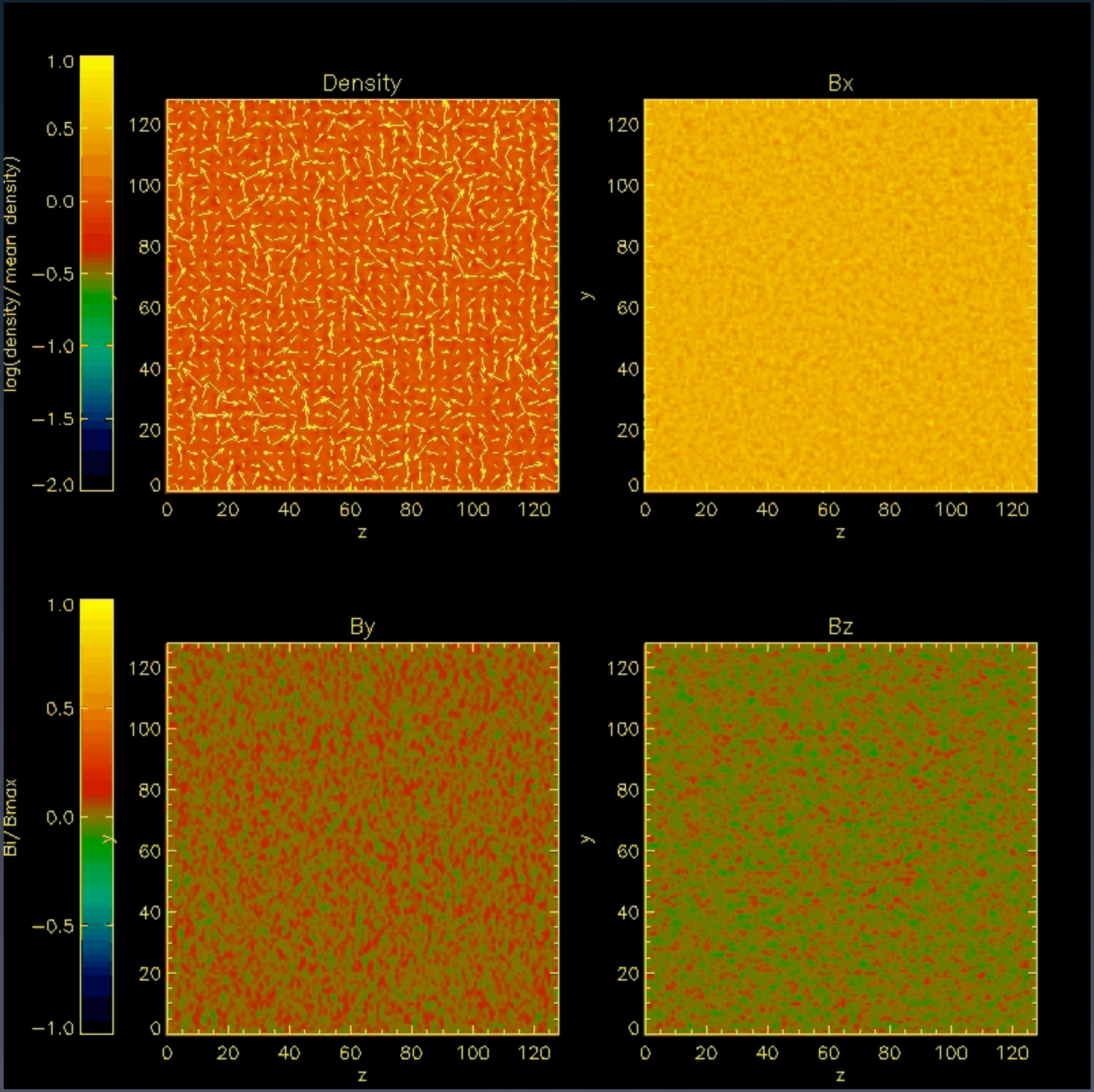

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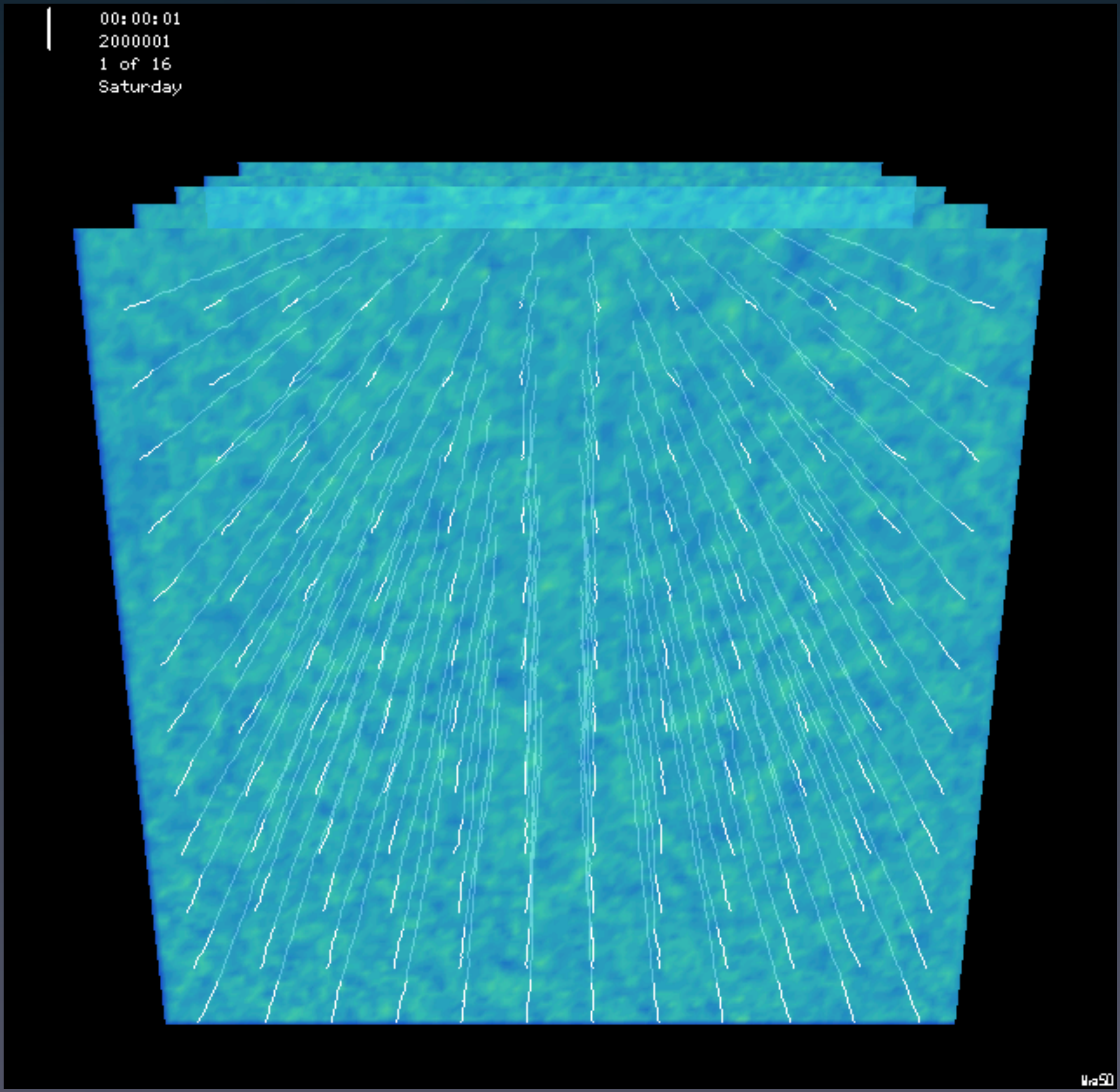

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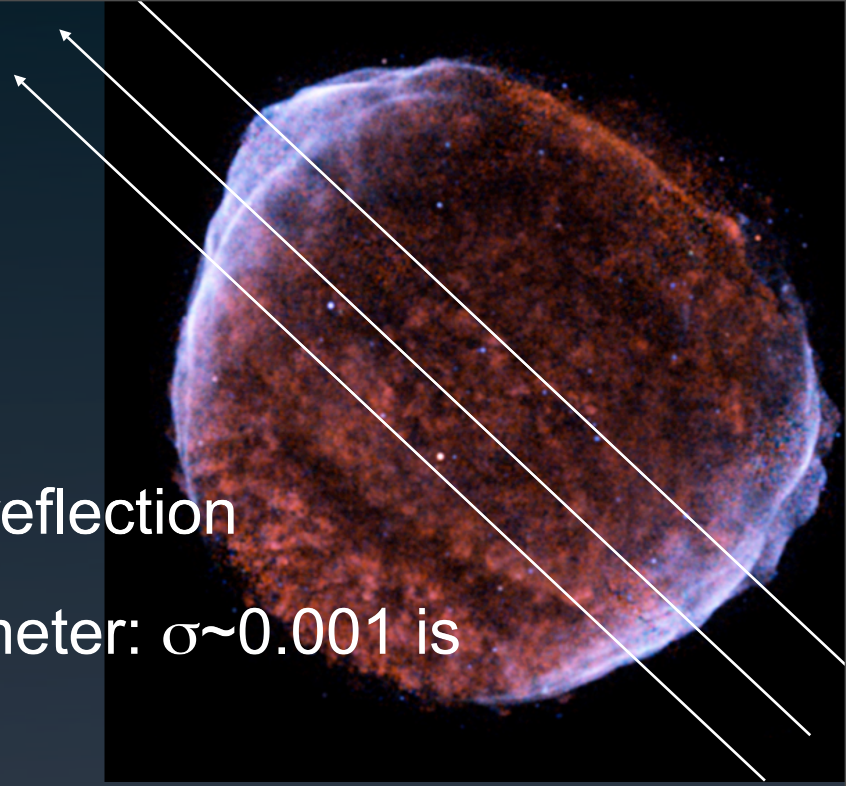

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