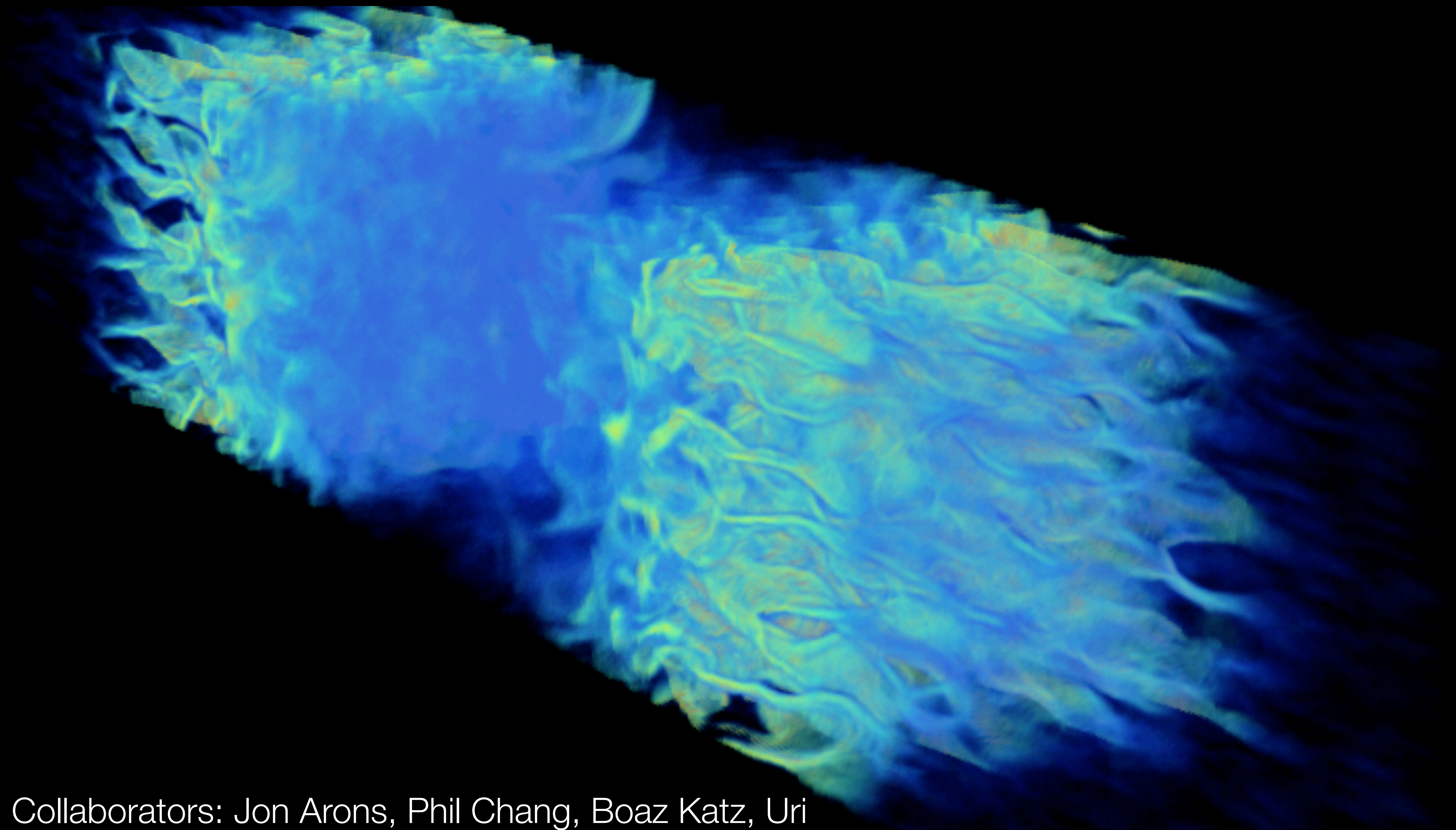
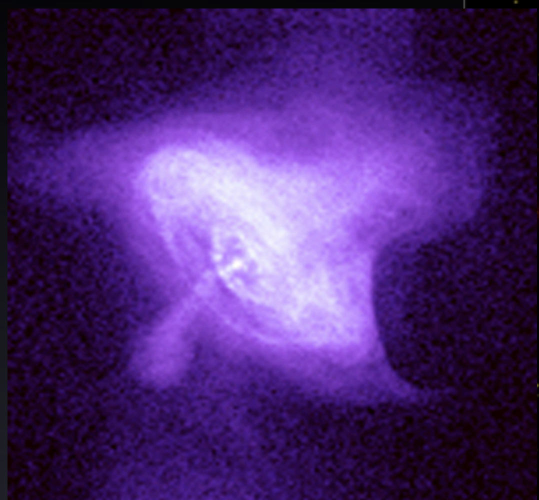
Relativistic Collisionless Shocks

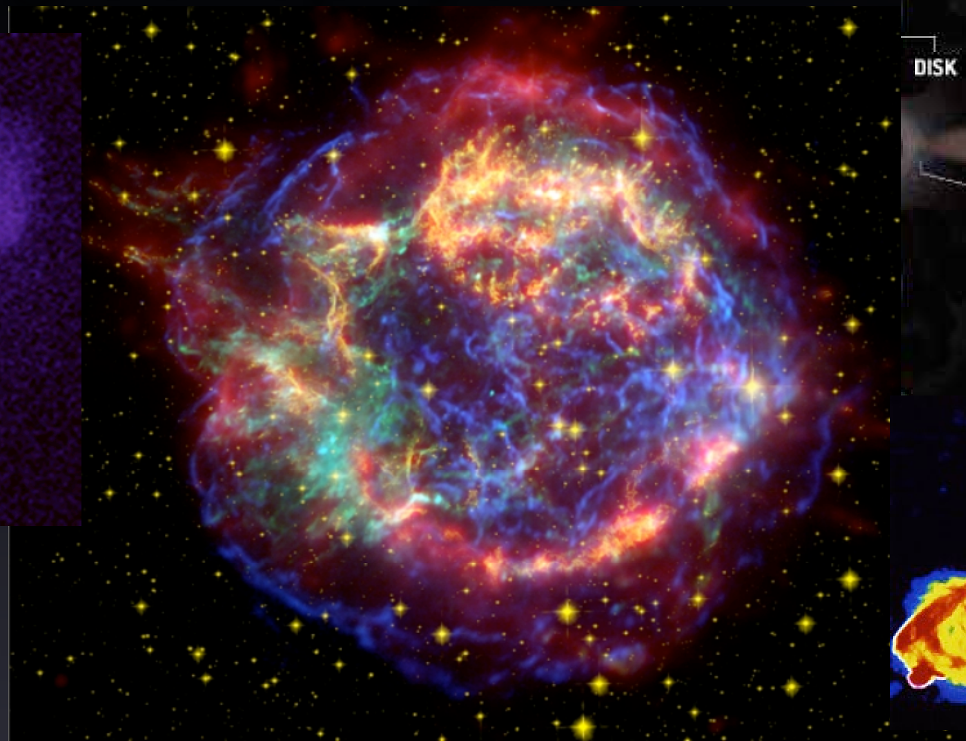
Anatoly Spitkovsky (Princeton)

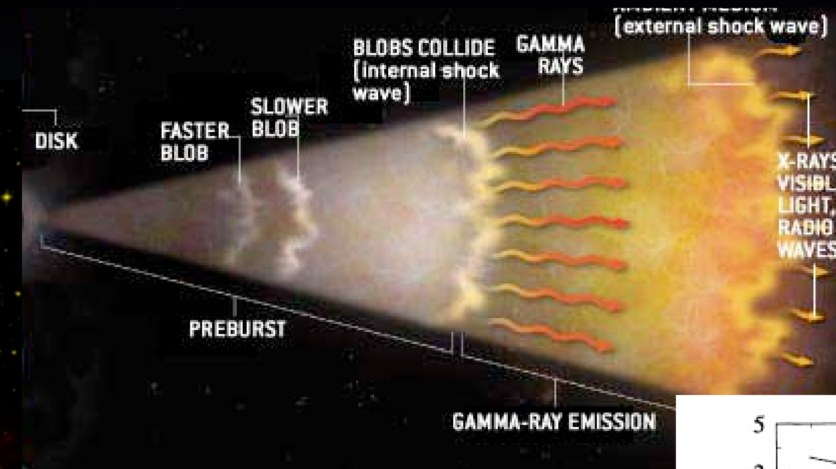


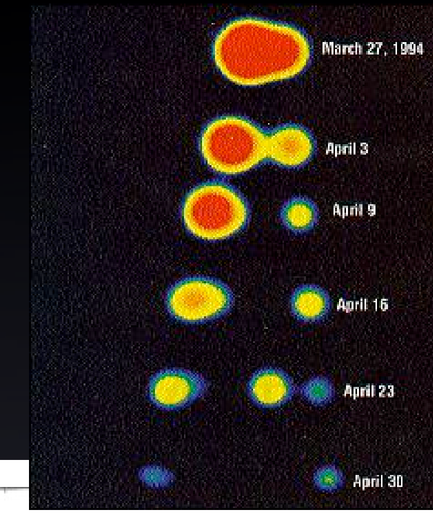
Collaborators: Jon Arons, Phil Chang, Boaz Katz, Uri Keshet, Mario Riquelme, Lorenzo Sironi, Eli Waxman

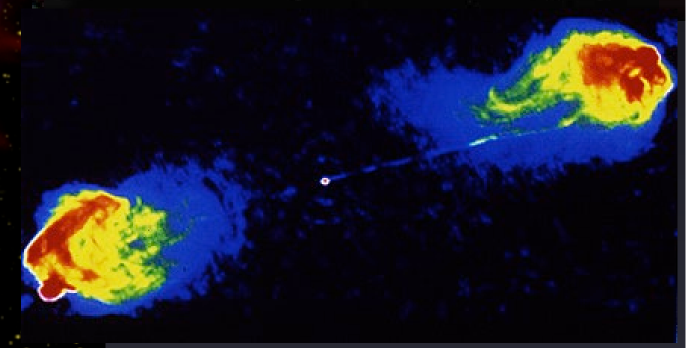
Shocking astrophysics

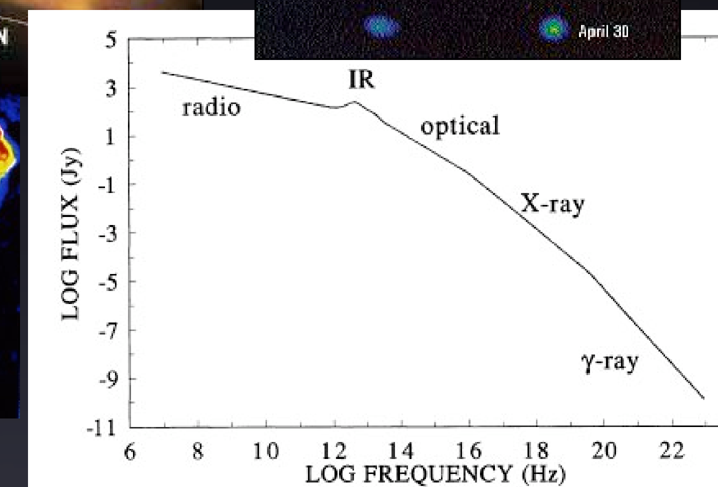










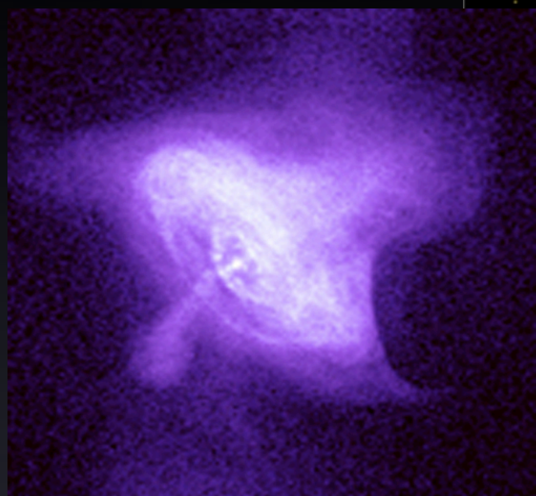


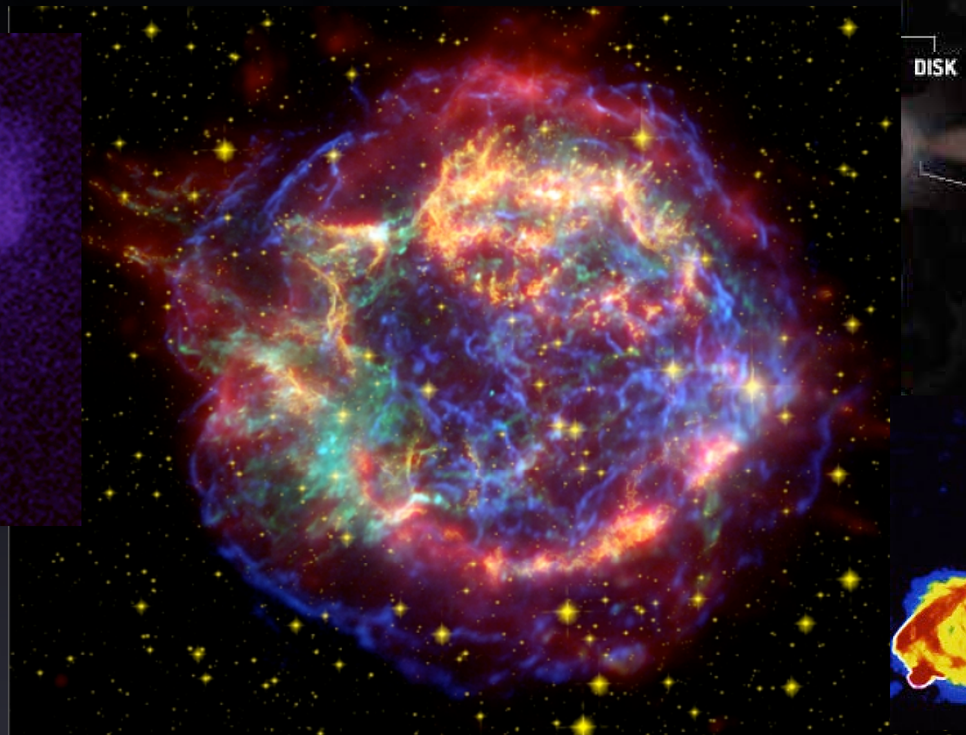
Astrophysical shocks are collisionless (mean free path >> system size).
Shocks span a range of parameters:
nonrelativistic to relativistic flows (Solar Wind < SNR < jets < GRB < PWN)
magnetization (magnetic/kinetic energy ratio: GRB?< jets?< SNR < Solar Wind)
composition (pairs/e-ions/pairs + ions)

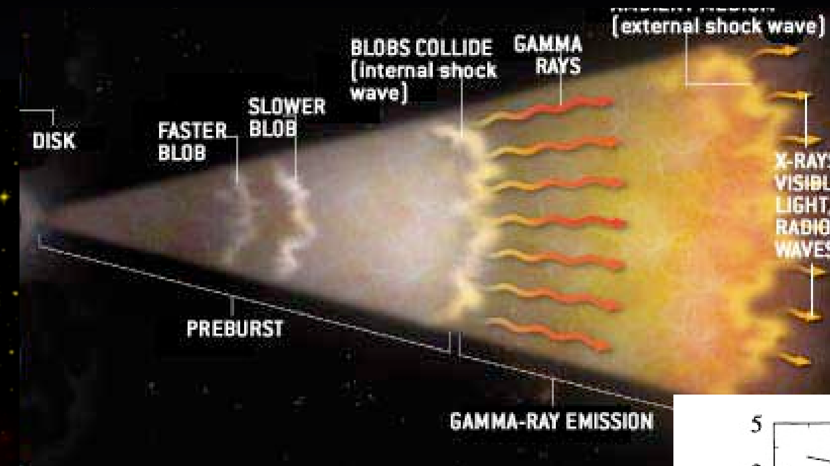
Astrophysical collisonless shocks can:

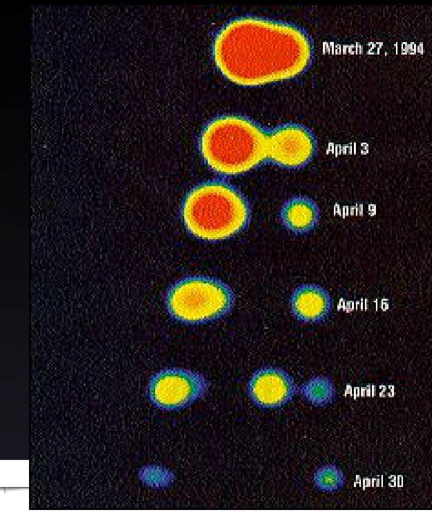
1. accelerate particles
2. amplify magnetic fields (or generate them from scratch)
3. exchange energy between electrons and ions

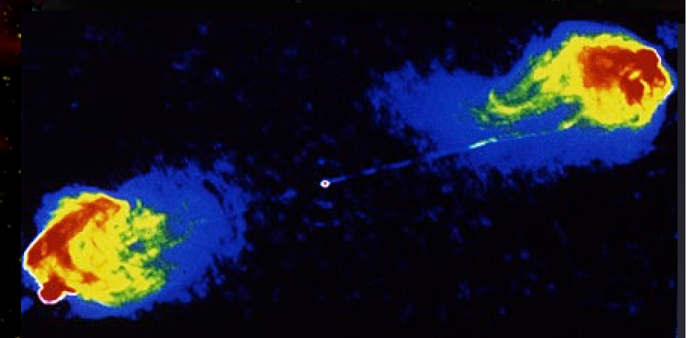
Shocking astrophysics

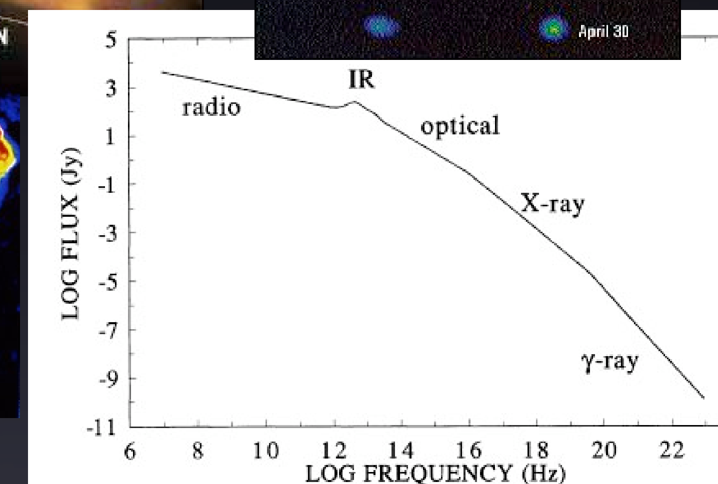












Open issues:

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

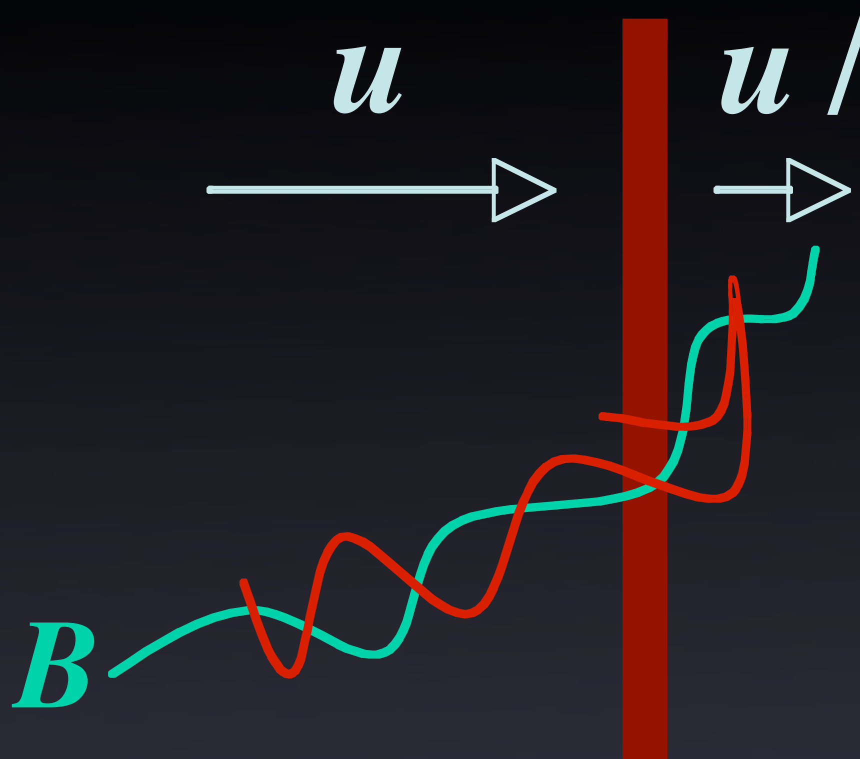
Particle acceleration -- Fermi mechanism? Other? Efficiency?

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

Equilibration between ions and electrons?

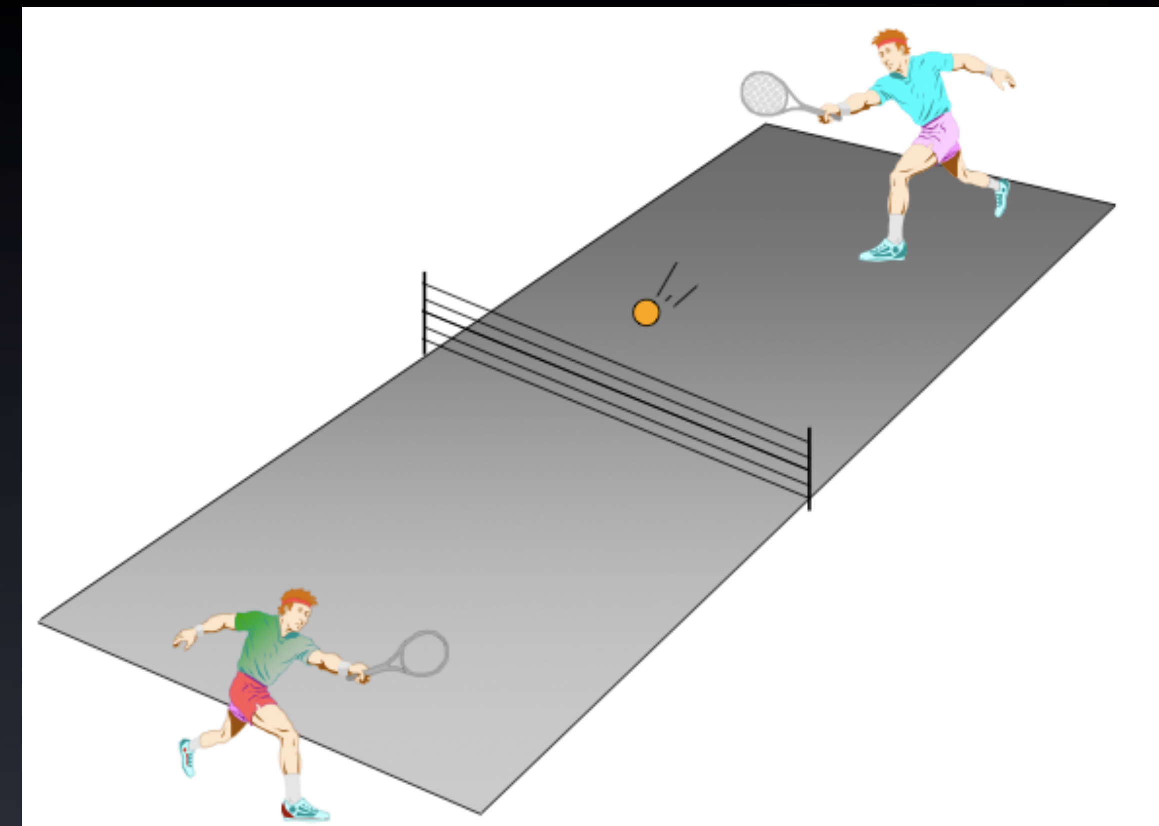
Turns out that all questions are related, and particle acceleration is the crucial link

Particle acceleration:



$\Delta E/E \sim v_{shock}/c$

$N(E) \sim N_0\, E^{-K(r)}$



- Original idea -- Fermi (1949) -- scattering off moving clouds. Too slow (second order in v/c) to explain CR spectrum, because clouds both approach *and* recede.

- In shocks, acceleration is first order in v/c, because flows are always converging (Bell 78, Krymsky 77, Blandford & Ostriker 78)

- Efficient scattering of particles is required. Particles diffuse around the shock. Monte Carlo simulations show that this implies very high level of turbulence. Is this realistic? Are there specific conditions?

Need to understand the microphysics of collisionless shocks

For this need either kinetic theory or plasma simulations

Superficial, incomplete overview of relativistic shock research

(semi-)Analytical

Calculate CR spectrum by solving transport equation assuming diffusion function near relativistic shocks.

Kirk, Drury, Gallant, Achterberg, Pelletier, Blasi, Keshet, Reville

Monte Carlo

Trace test-particles assuming pitch-angle scattering, or in prescribed fields. Feedback on shock-compression ratio can be included.

Ellison, Niemiec, Duffy, Ostrowski, Baring, Gallant, Pelletier

Power-law spectra obtained

Complication: most relativistic shocks are superluminal, so large amount of scattering is needed to have particles cross the shock, $\Delta B/B \gg 1$

Ab-initio

Plasma simulations with PIC method from 1D to (recently) 3D. Importance of streaming instabilitiies (Medvedev & Loeb)

Hoshino, Arons, Gallant, Nishikawa, Silva, Frederiksen, Hededal, Kato, Amato, Spitkovsky

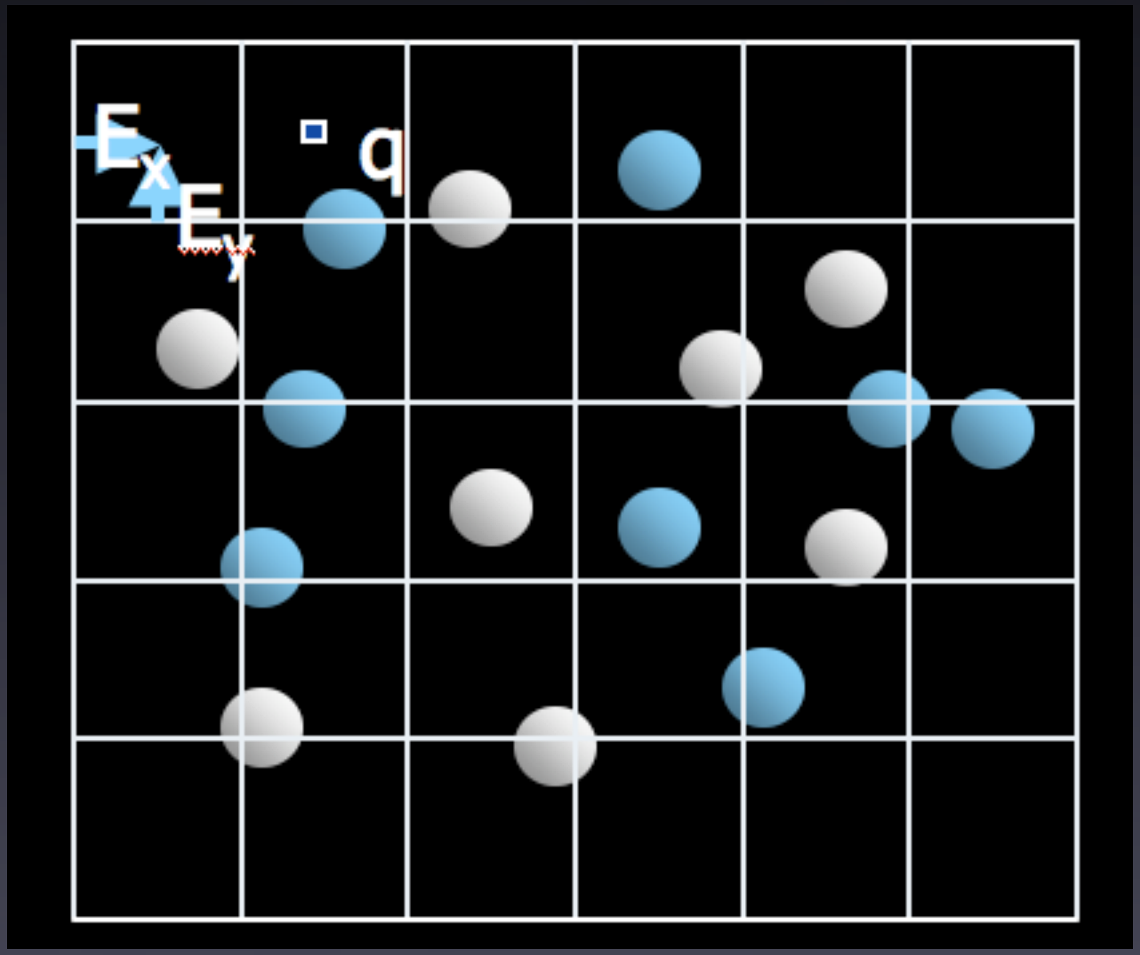
Until recently, no DSA

Now -- self-consistent acceleration in many cases.

What changed?

Advances in computer hardware and better algorithms have enabled running large enough simulations to resolve shock formation, particle acceleration, and back-reaction of particles on the shock.

Particle-in-Cell (PIC) method



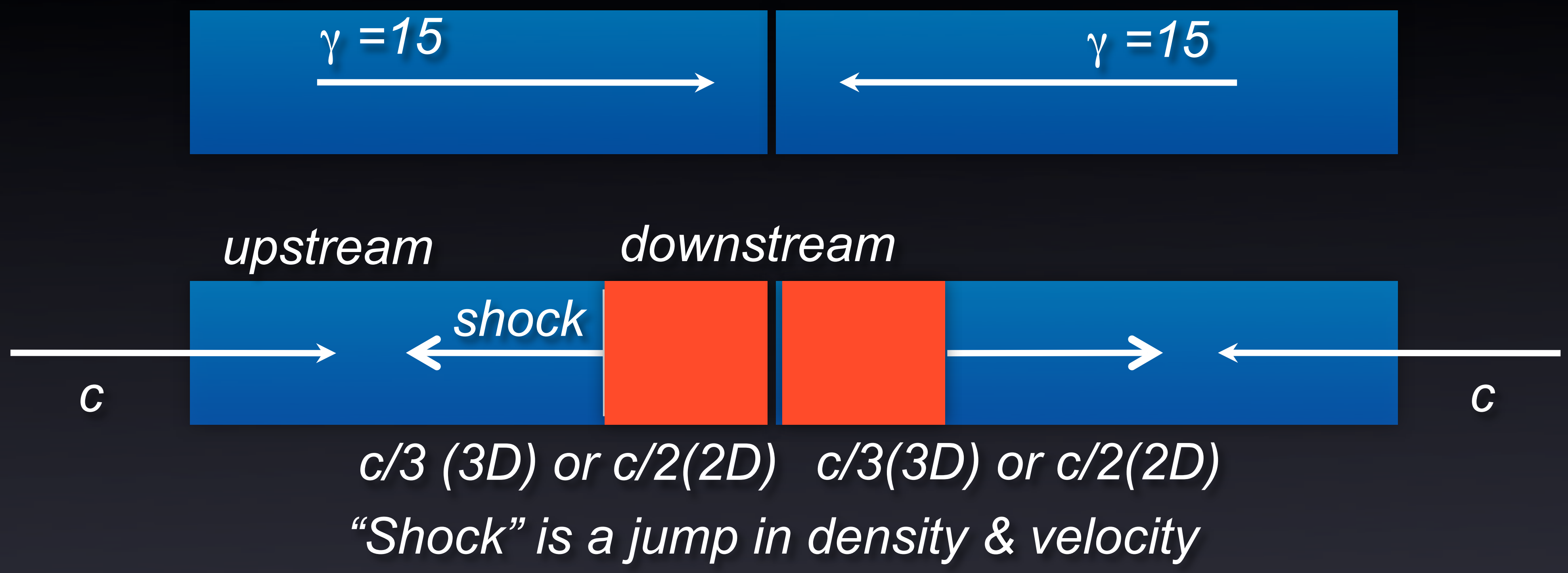
PIC method (aka PM method):

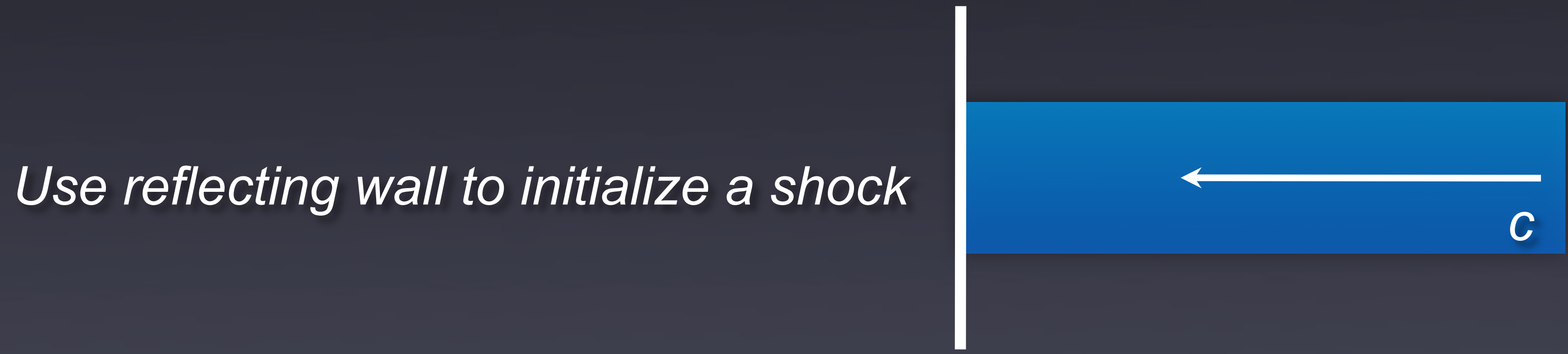
- Collect currents at cell edges
- Solve fields on the mesh (Maxwell's eqs)
- Interpolate fields to particle positions
- Move particles under Lorentz force

Commonly used in accelerator/plasma physics, and now starting to be accepted in astrophysics (!!!)

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





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

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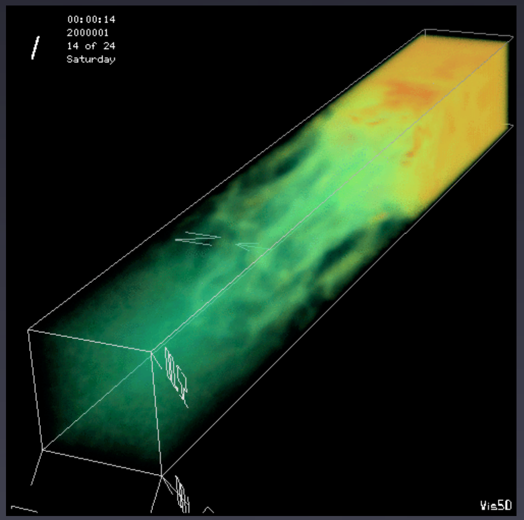
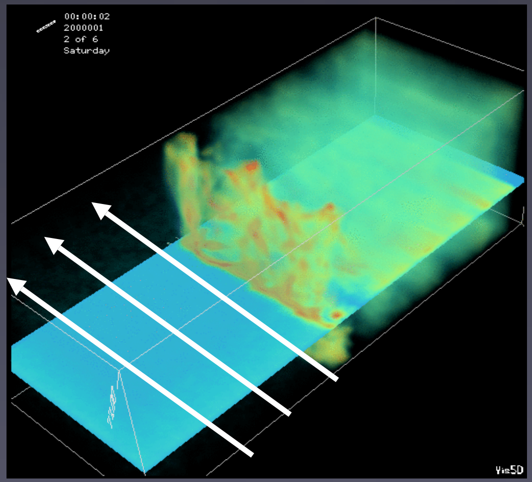
We explored the parameter space for pair and e-ion plasmas in 2D and 3D.



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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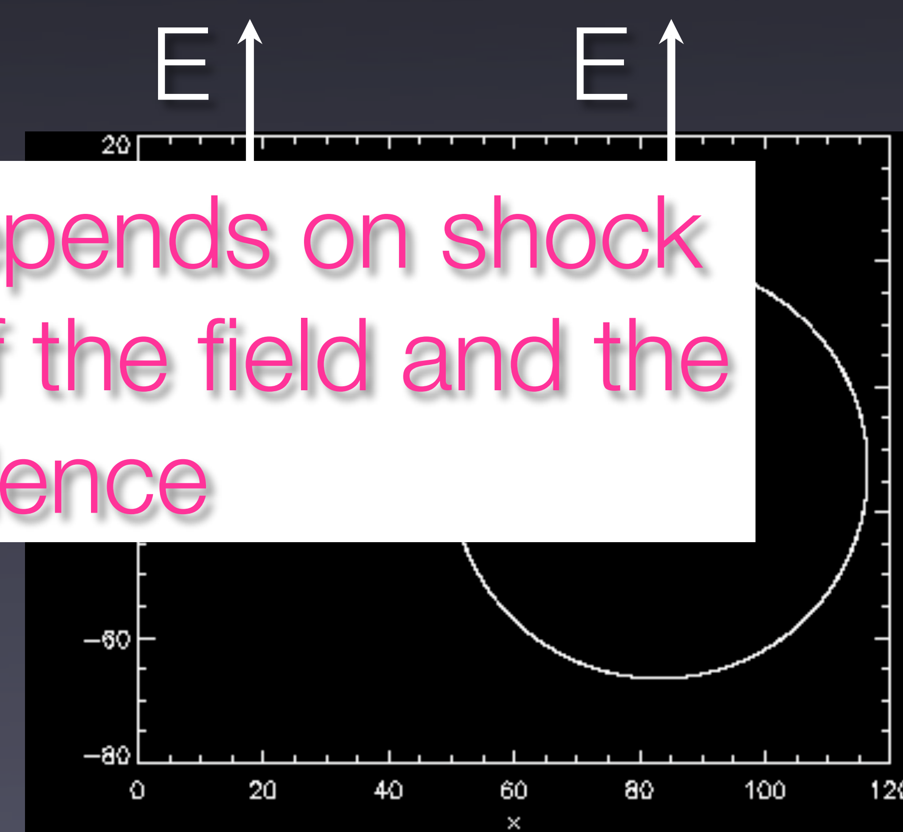
Lo
ins

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

Hi
magnetic reflection, compressing background



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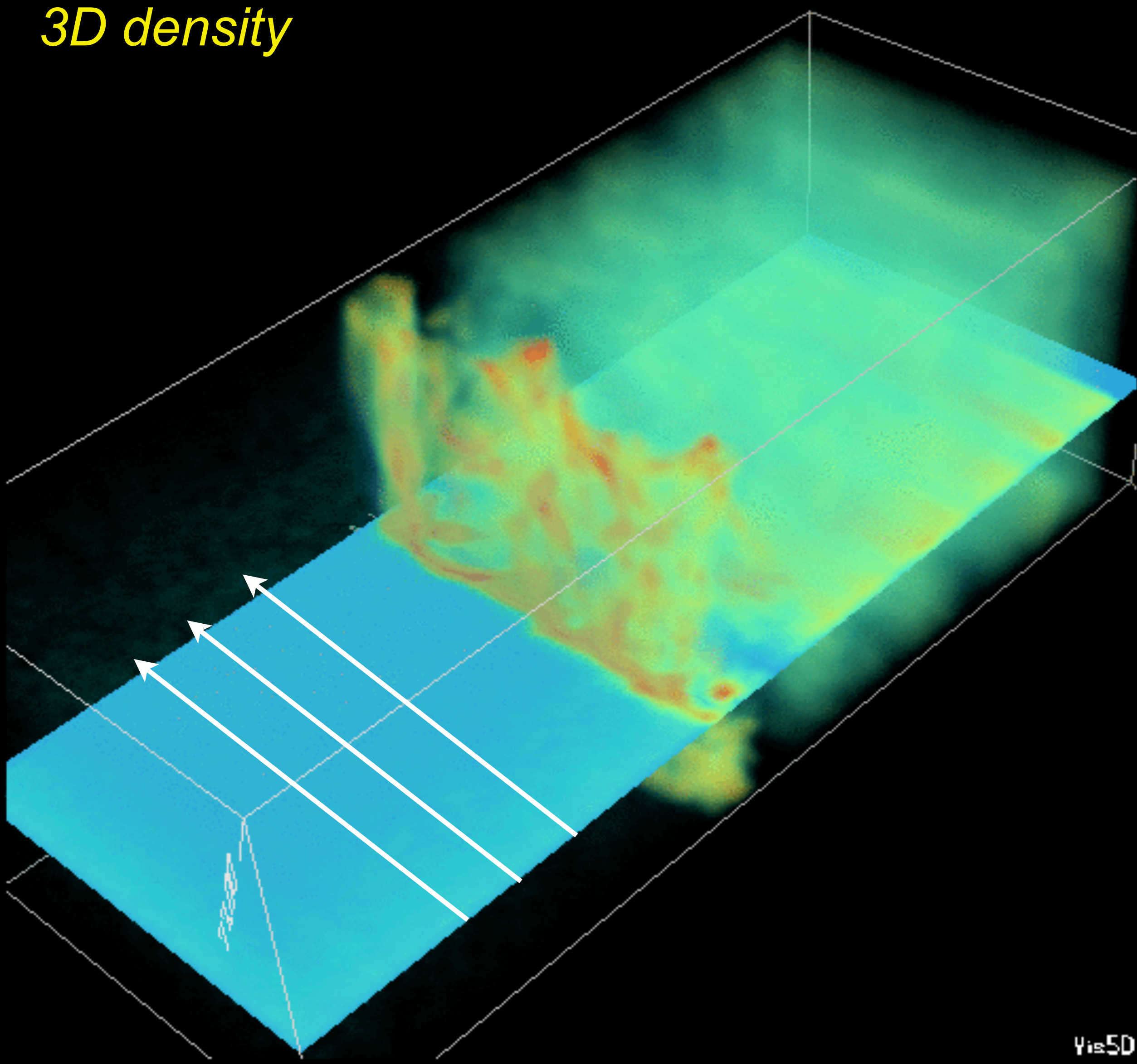
Relativistic pair shocks

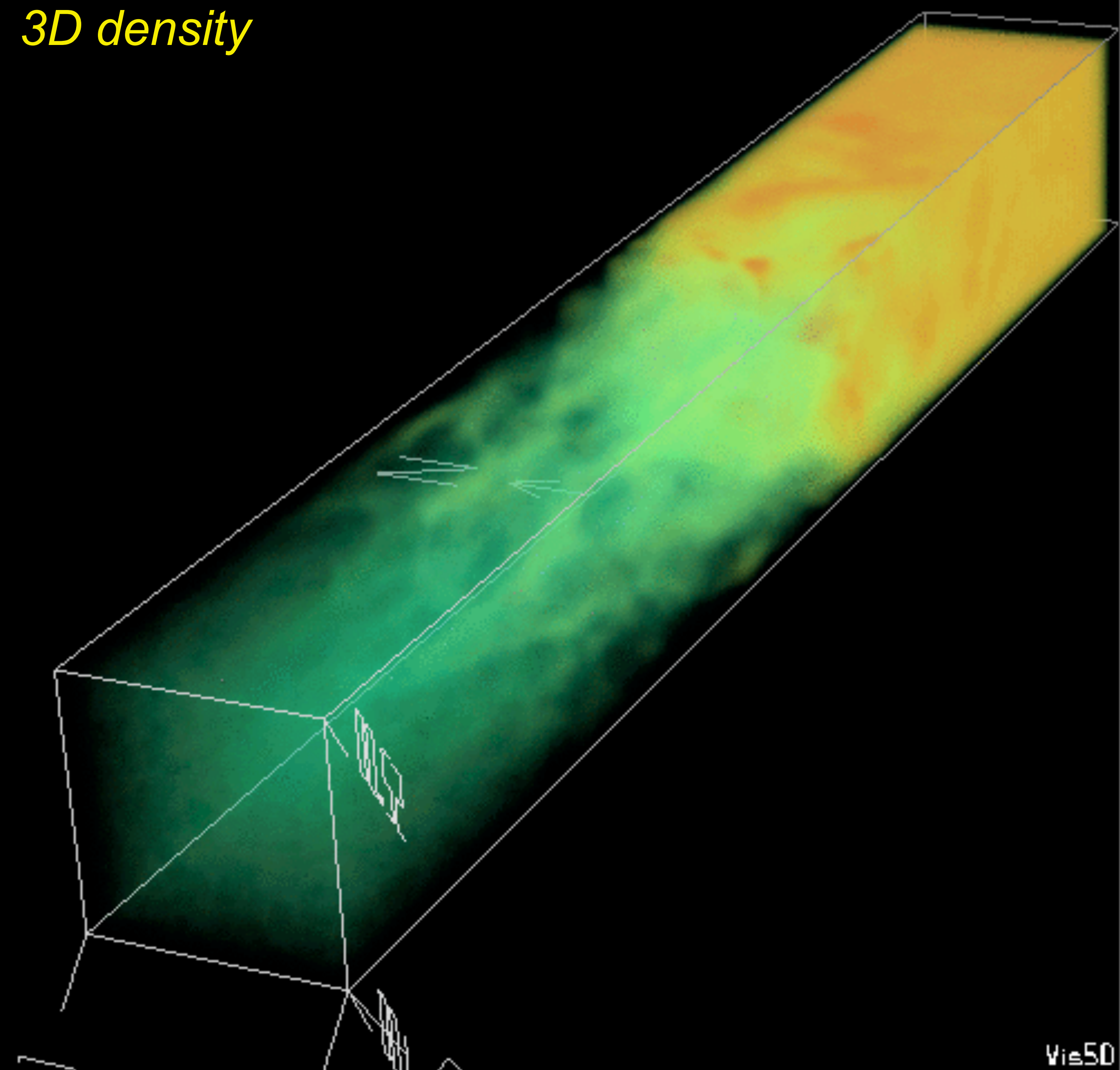
Shock structure for σ*=0.1*

3D density



Shock structure for σ*=0*

3D density

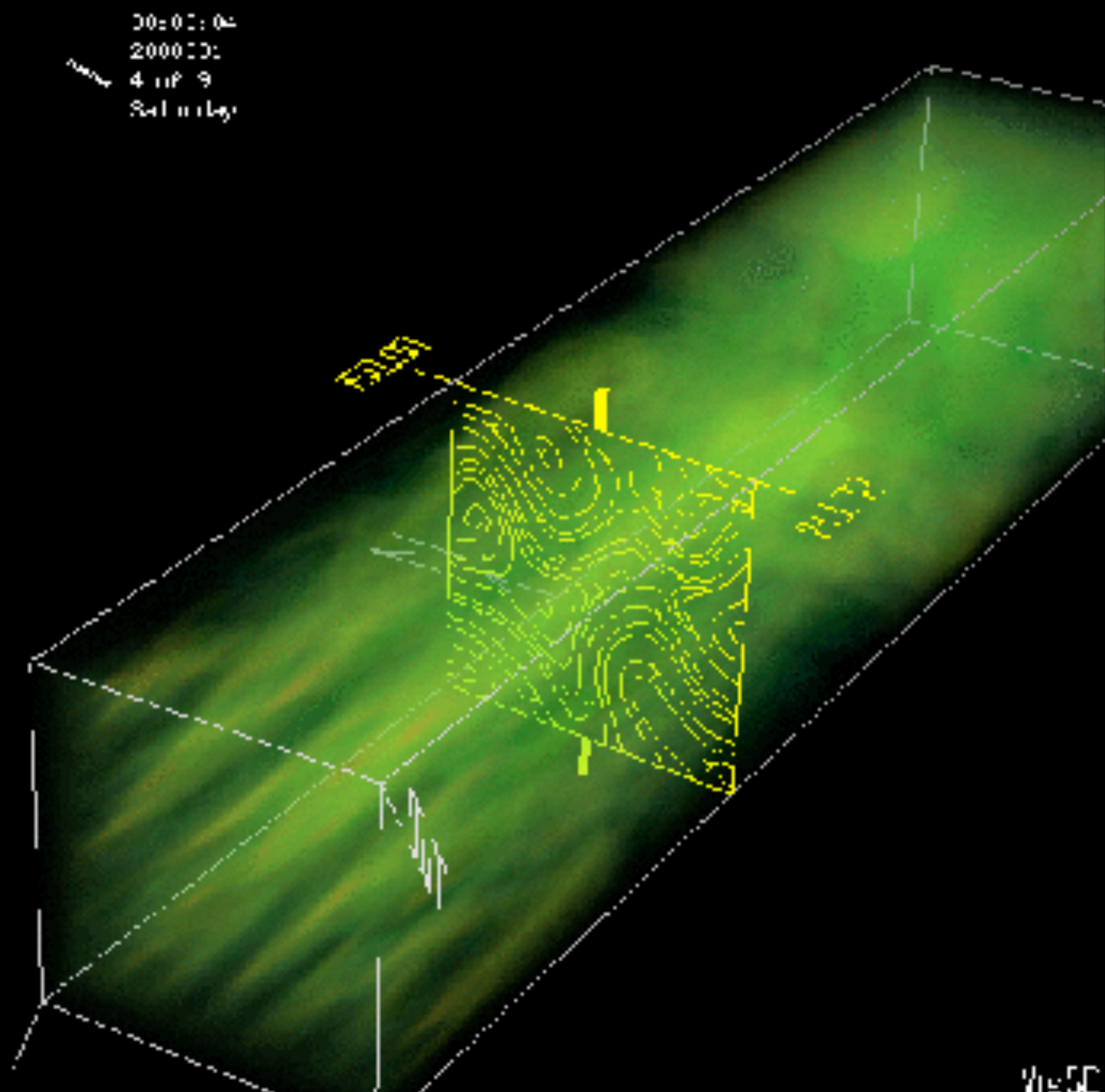


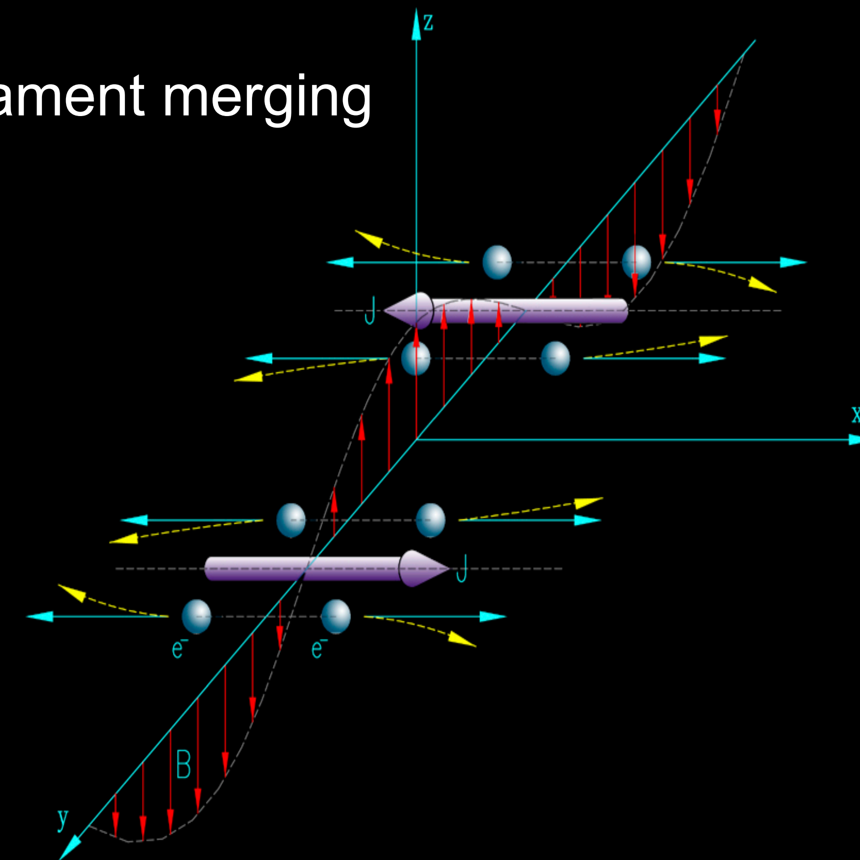
Magnetized shock is mediated by magnetic reflection, while the unmagnetized shock -- by field generation from filamentation instability. Transition is near σ*=1e-3* *(A.S. 2005)*

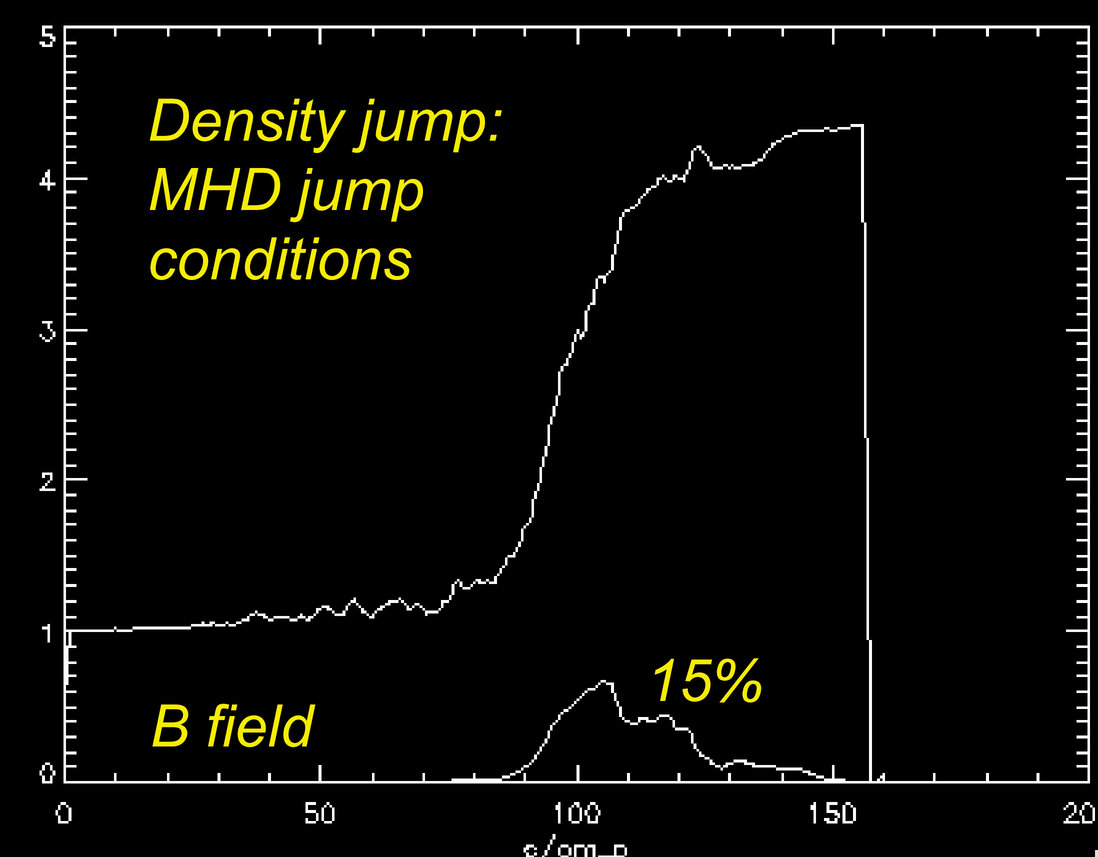
Unmagnetized pair shock

Magnetic field generation: Weibel instability

Field cascades from c/ω_p scale to larger scale due to current filament merging

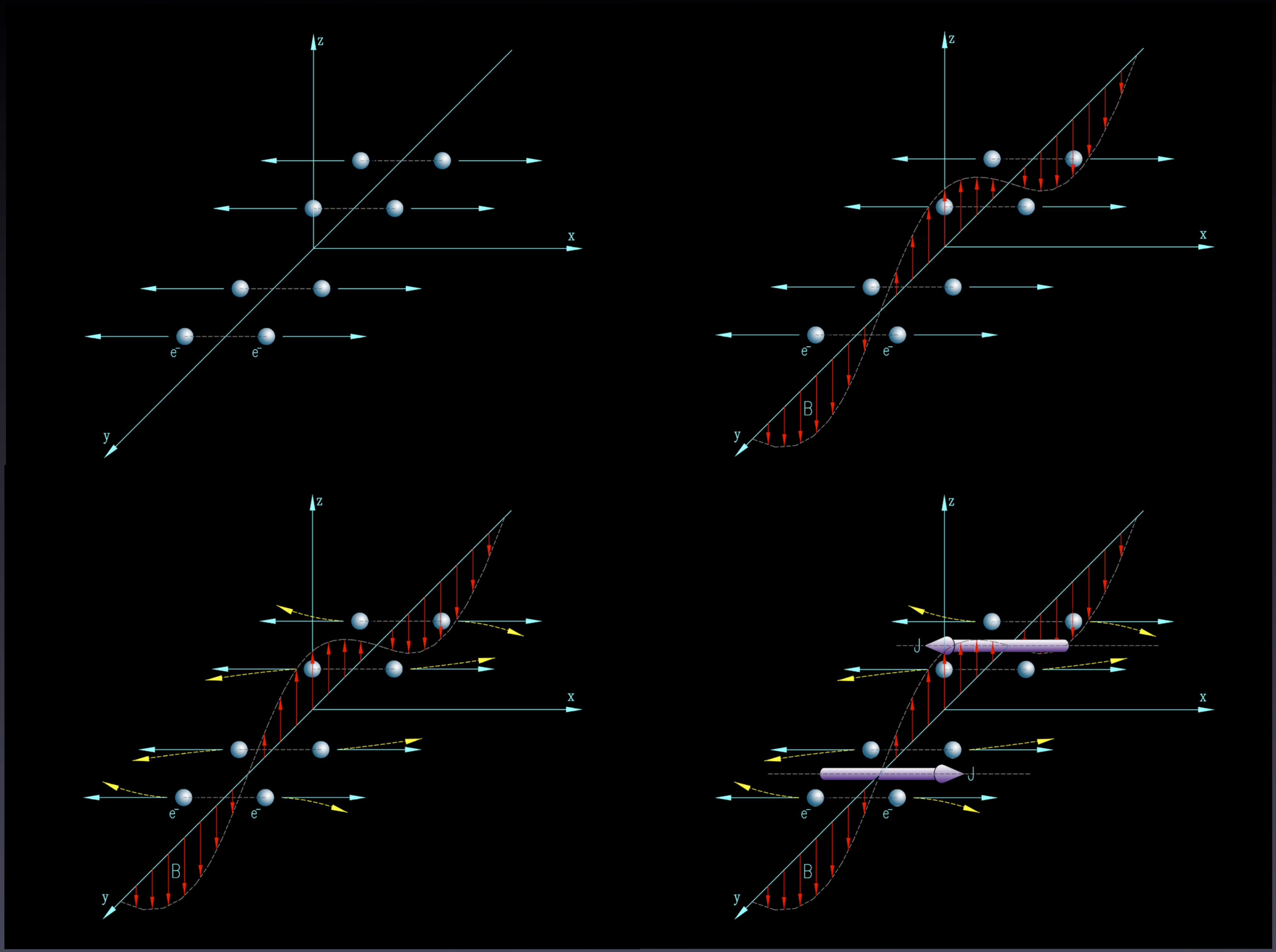






Weibel instability generates subequipartition B fields that decay. Is asymptotic value nonzero? Competition between decay and inverse cascade (Chang, AS, Arons 08).

Weibel instability



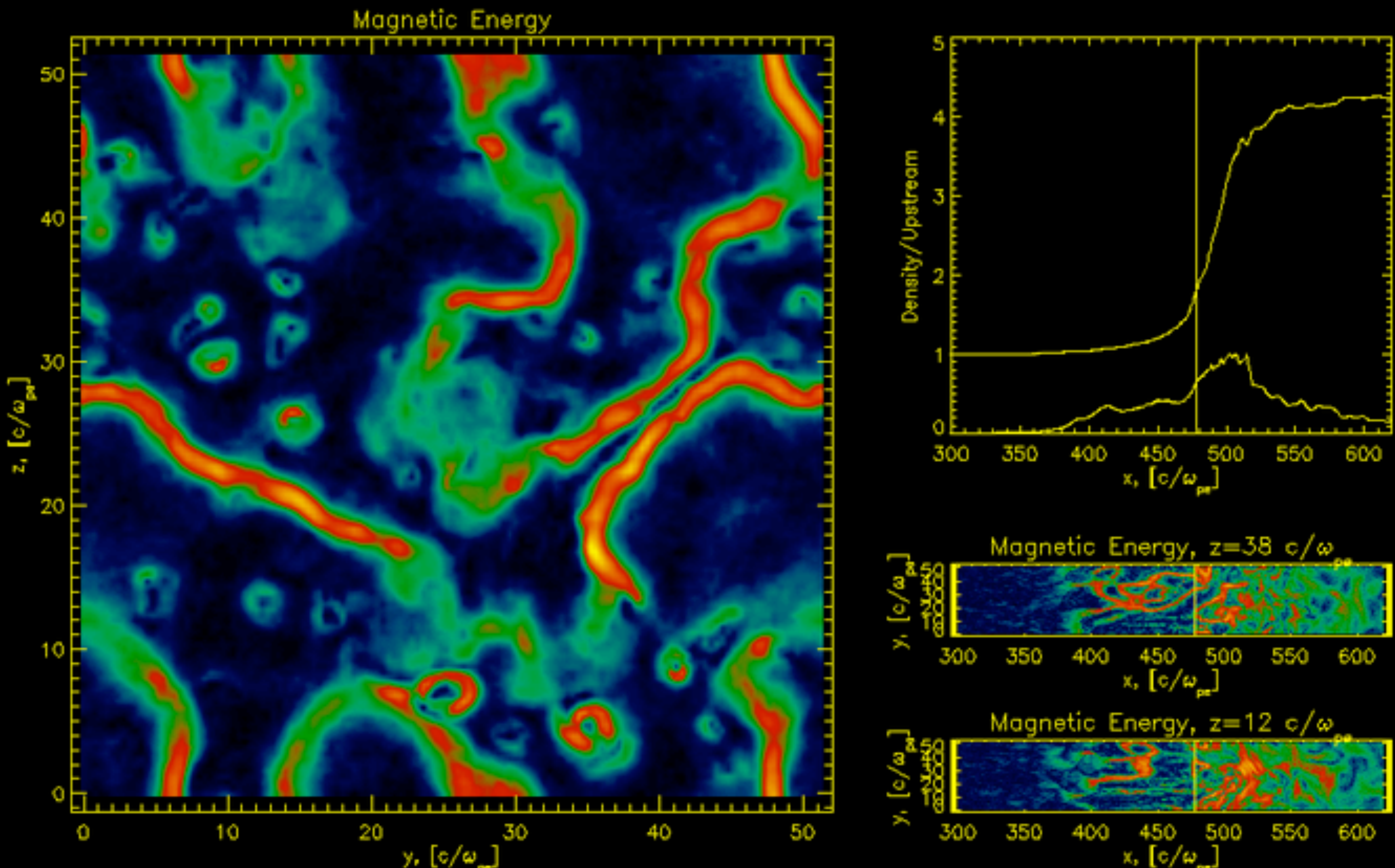
Weibel (1959)
Moiseev & Sagdeev (1963)
Medvedev & Loeb (1999)

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

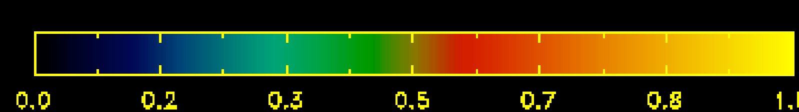
$$L \approx c/\omega_{pe} = 10 \text{ km} \sqrt{\gamma/\mathrm{n}_0[\mathrm{cm}^{-3}]}$$

$$T \approx 1/\omega_p = 30\ \mu\mathrm{s} \sqrt{\gamma/\mathrm{n}_0[\mathrm{cm}^{-3}]}$$

3D shock structure: long term

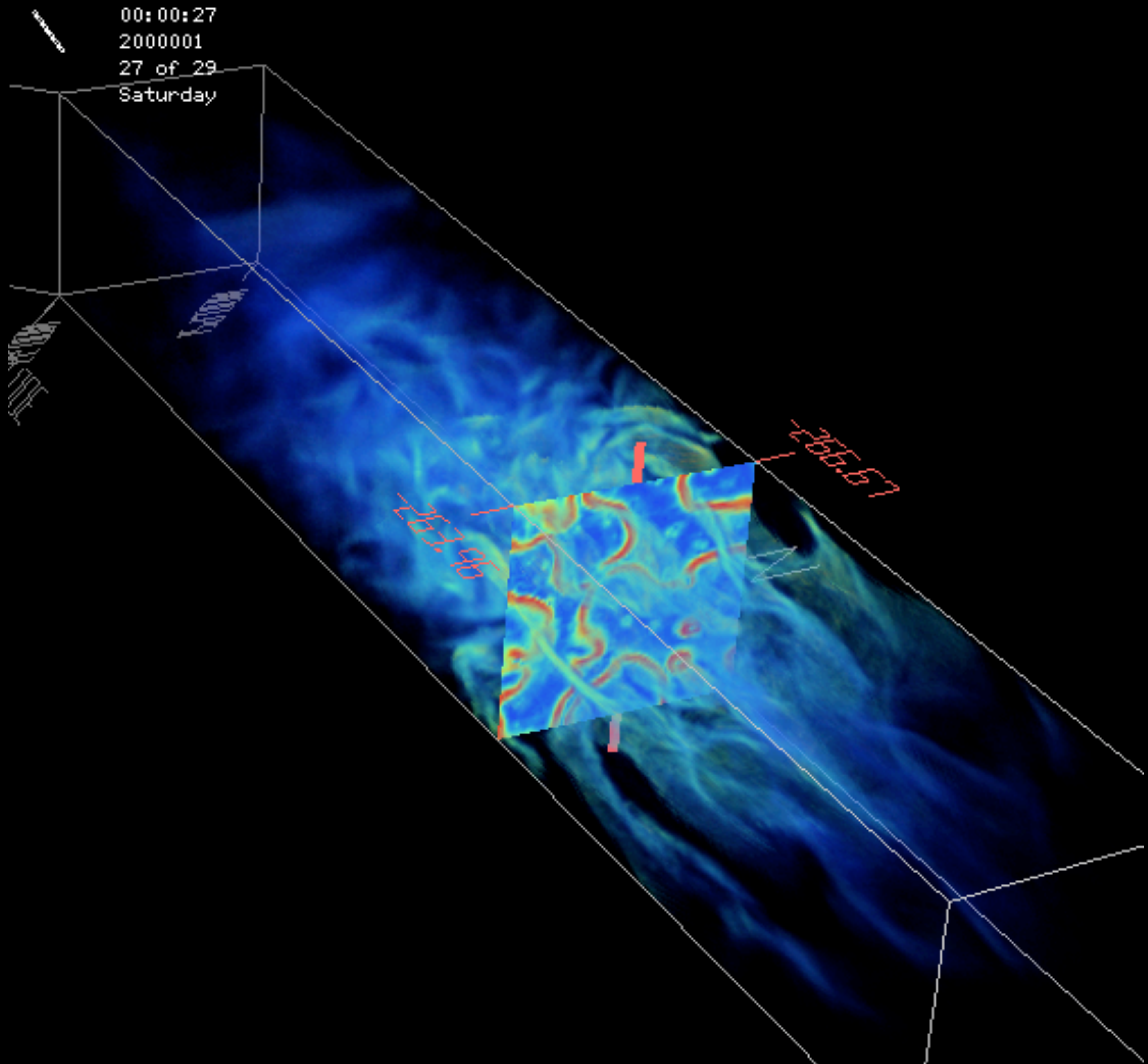


50x50x1500 skindepths. Current merging (like currents attract).

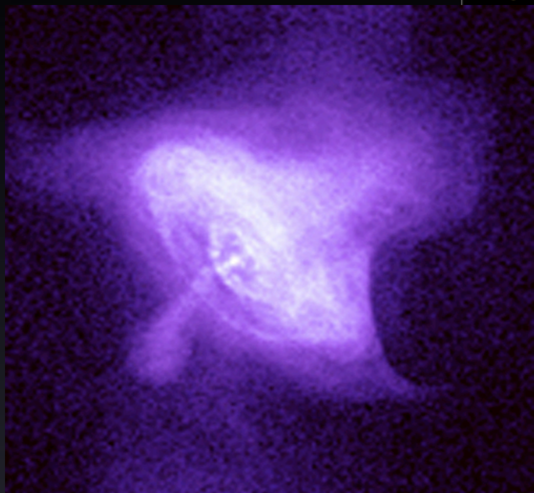


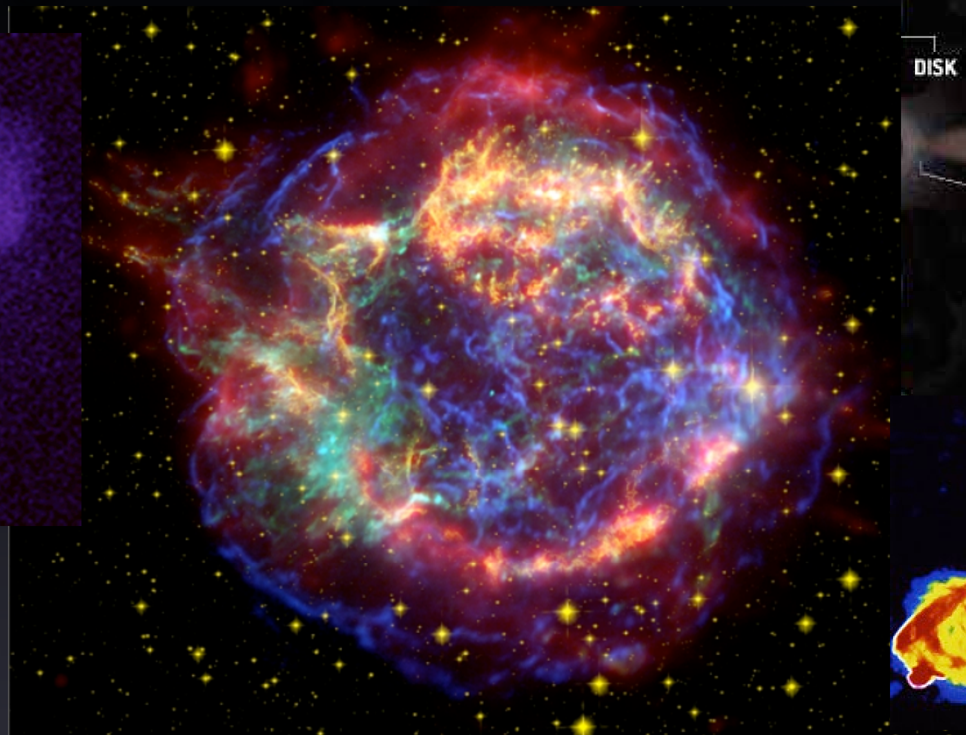
Secondary Weibel instability stops the bulk of the plasma. Pinching leads to randomization.

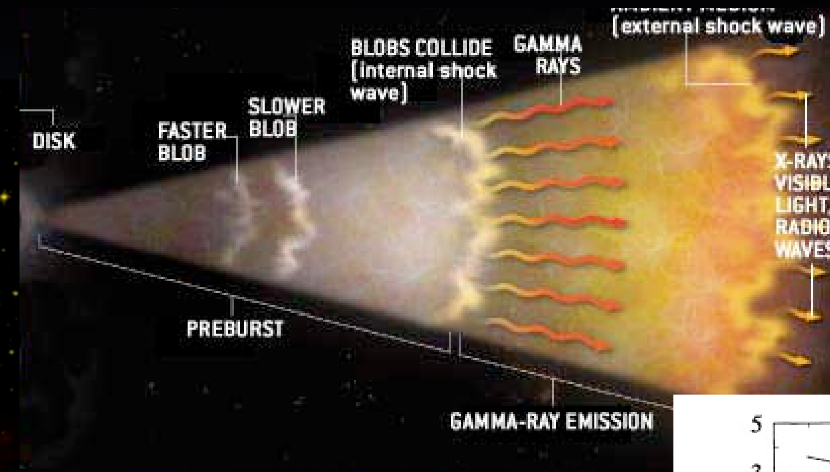
3D unmagnetized pair shock: magnetic energy

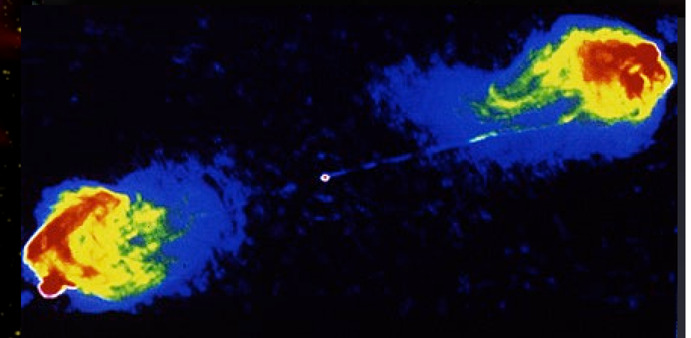


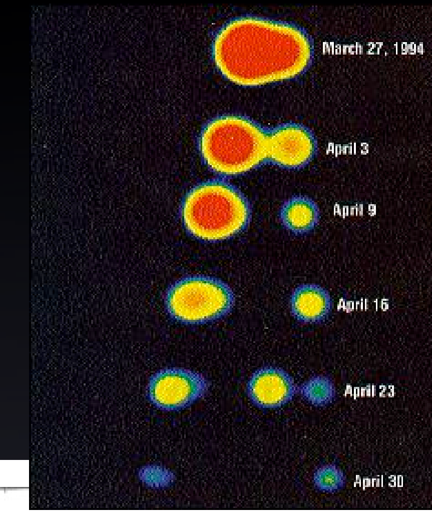
Shocking astrophysics

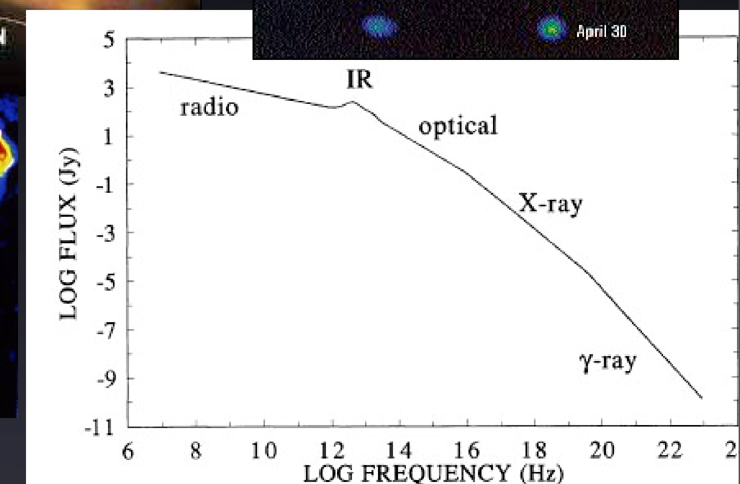












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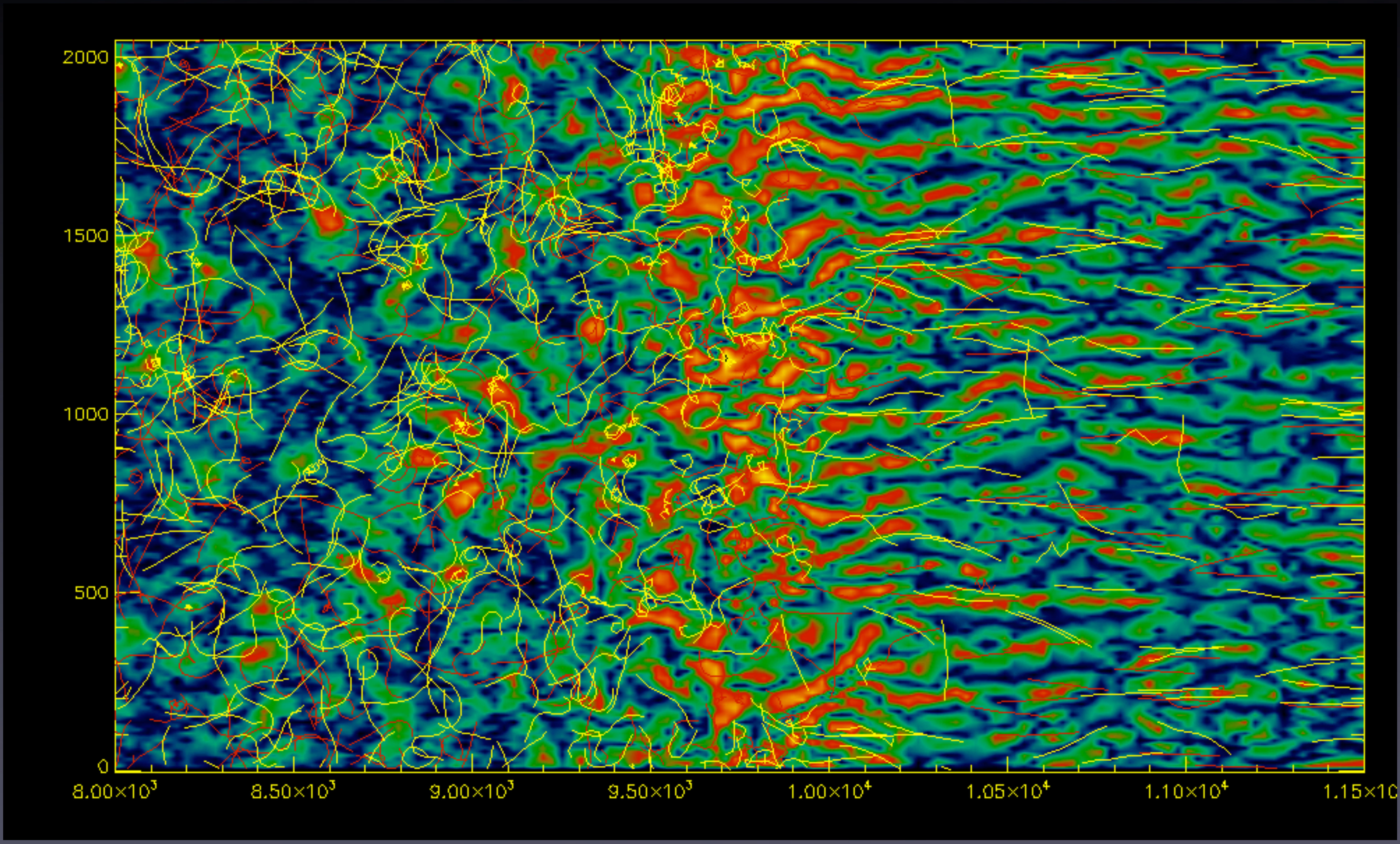
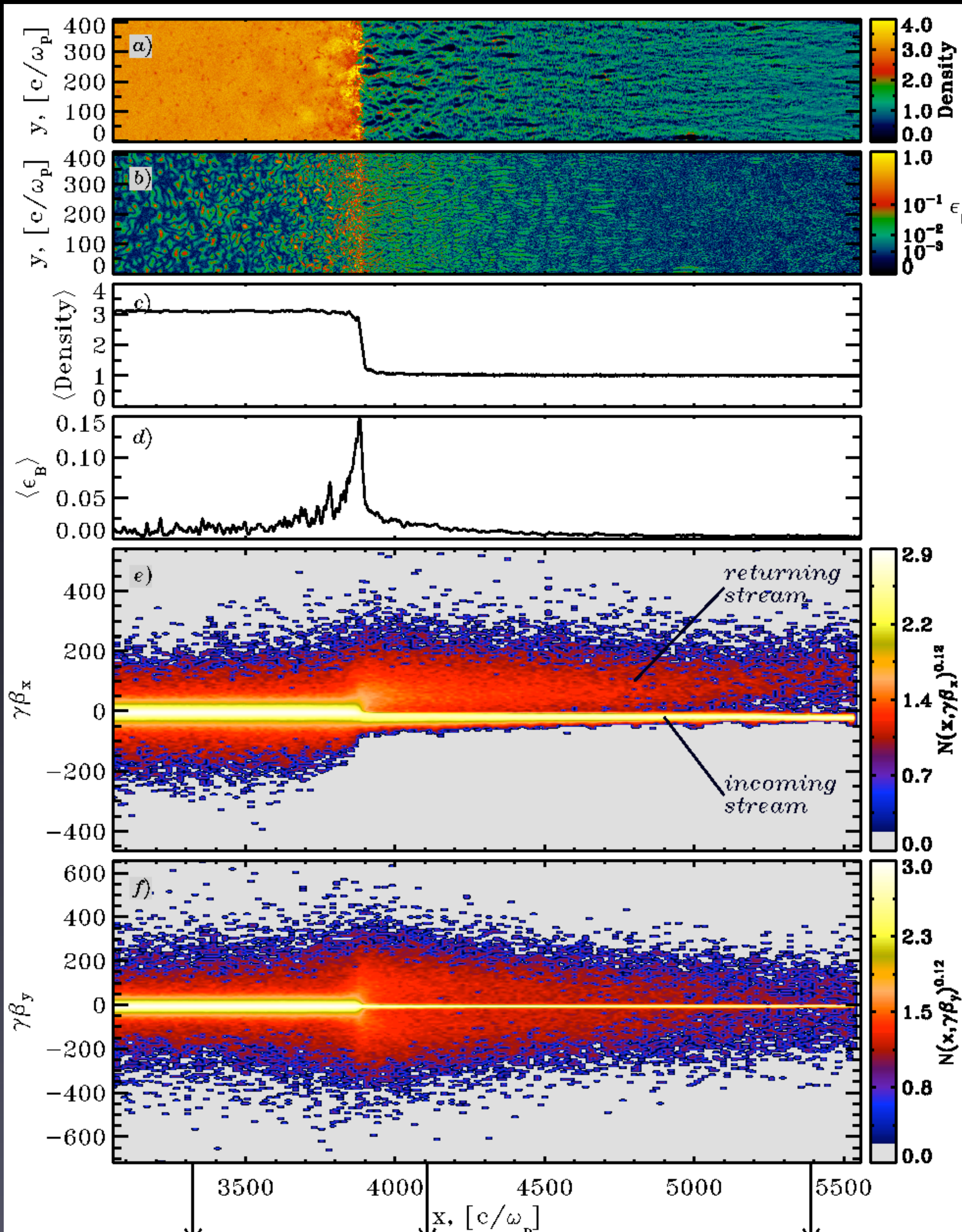
Unmagnetized pair shock: particle trajectories





Unmagnetized pair shock:

shock is driven by returning particle precursor (CR!)

Steady counterstreaming leads to self-replicating shock structure

x- px momentum space

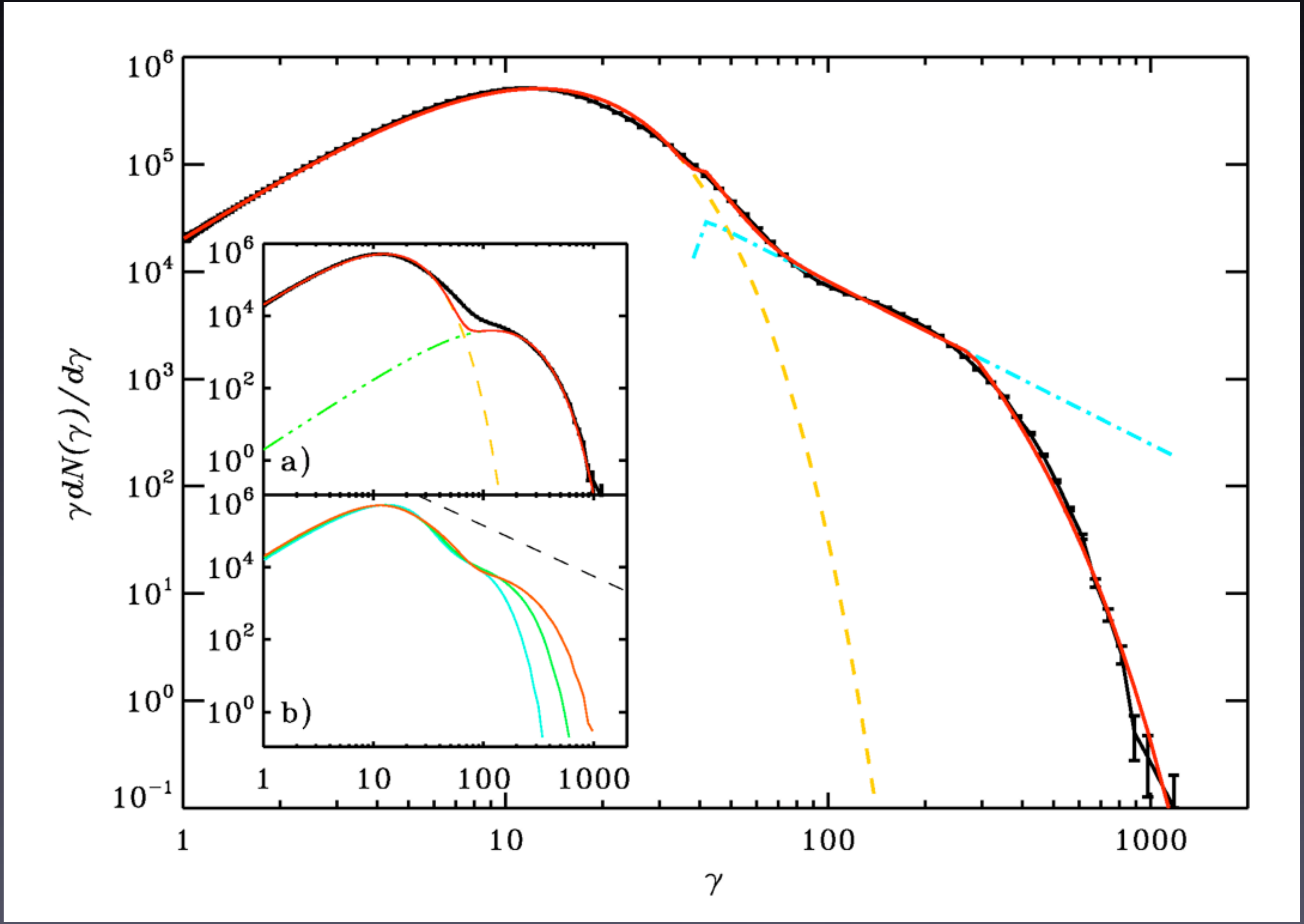
Long term 2D simulation

x- py momentum space

Shock structure for σ=0 (AS '08)

Unmagnetized pair shock:

downstream spectrum: development of nonthermal tail!



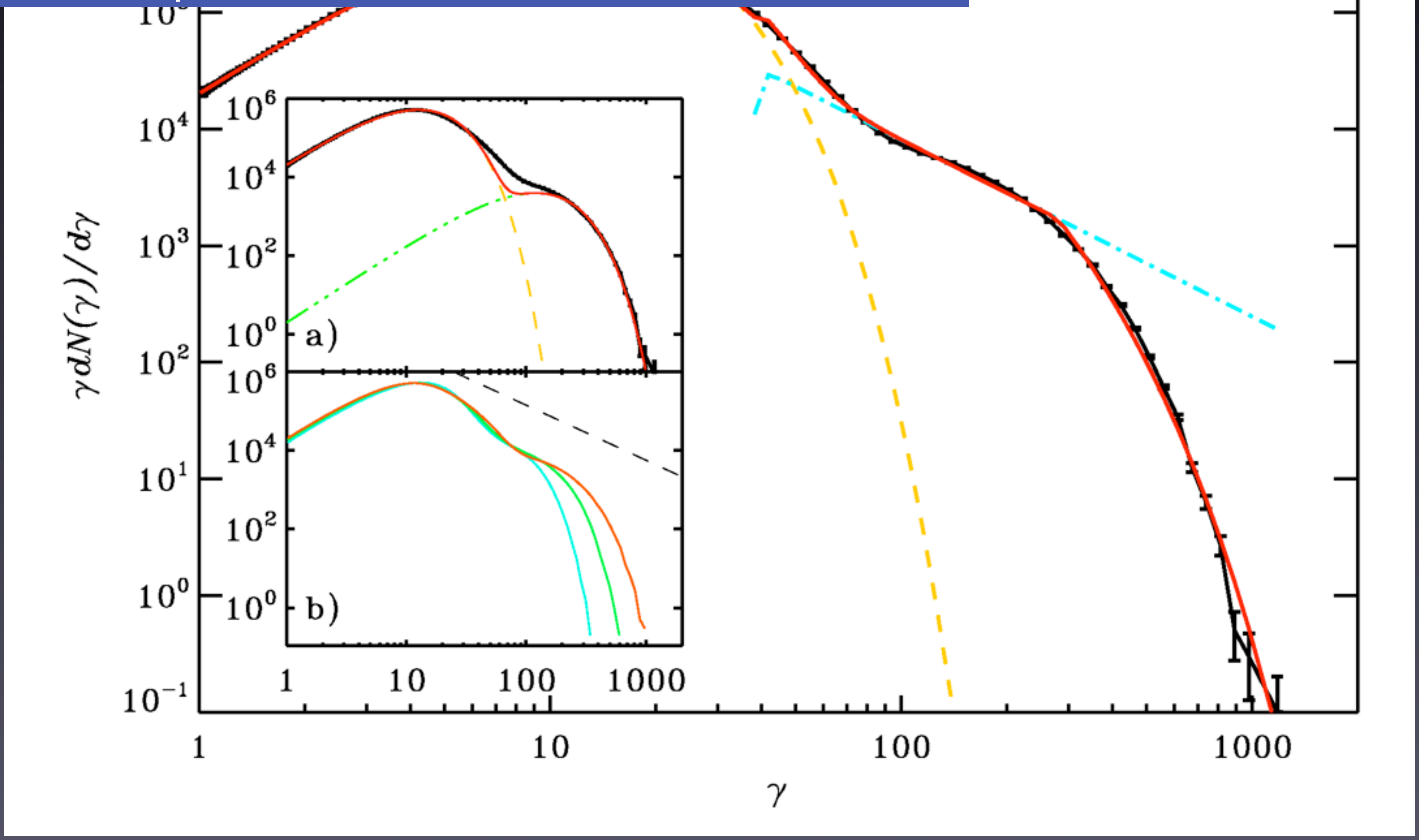
A.S. 2008, ApJ, 682, L5

Unmagnetized pair shock:

downstream spectrum: development of nonthermal tail!

Nonthermal tail deveolps, N(E)~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.



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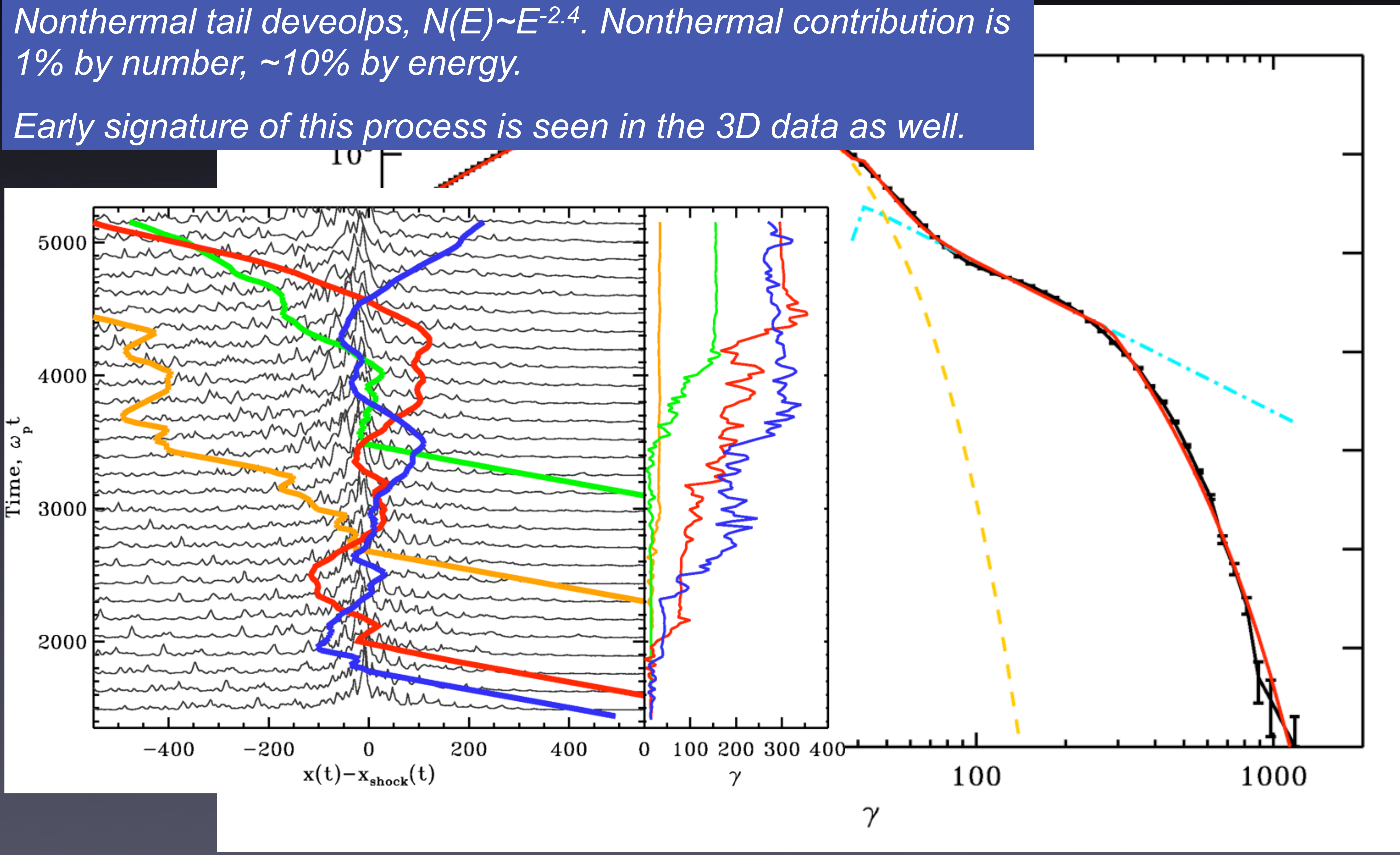

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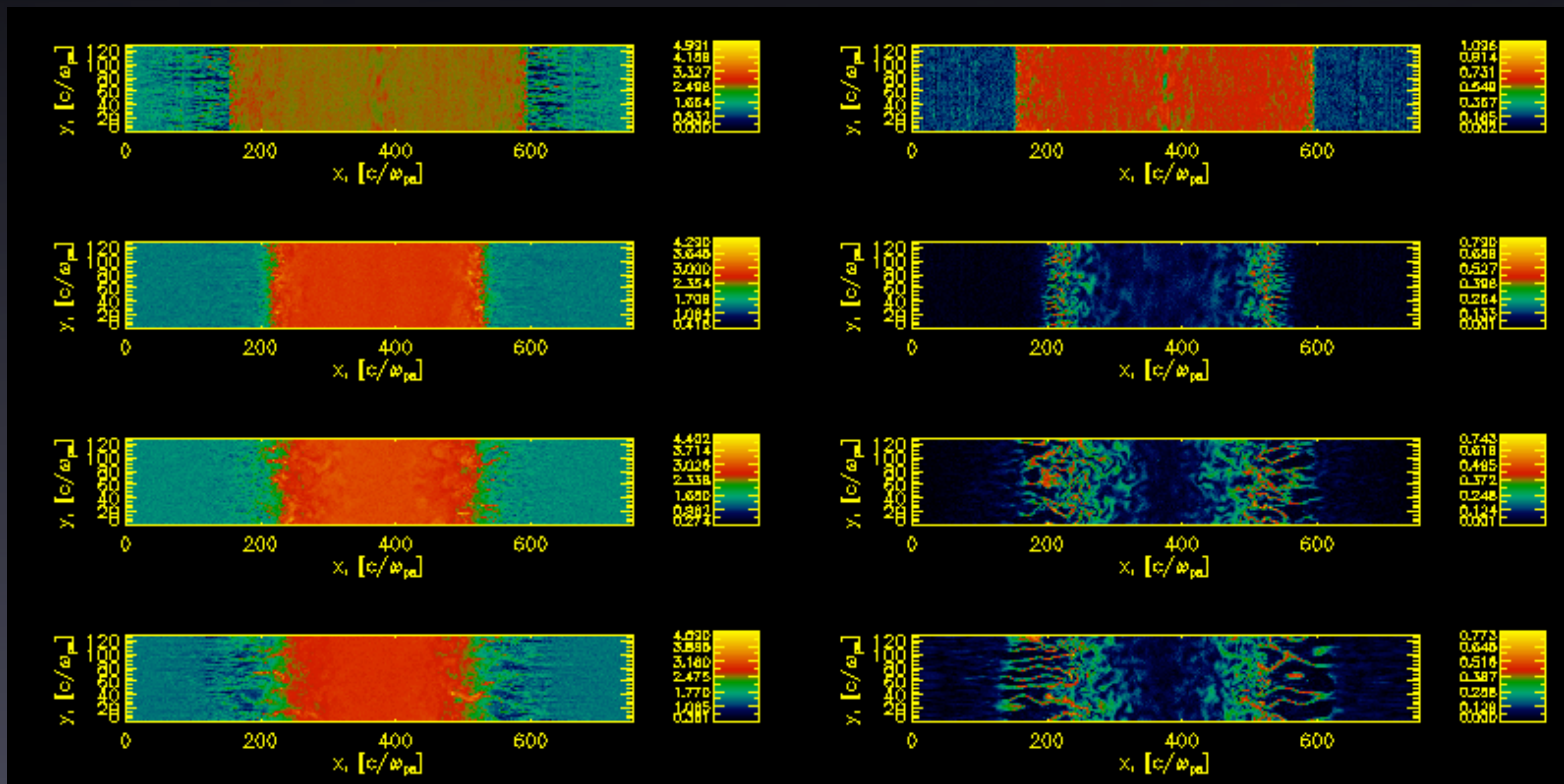
Transition between magnetized and unmagnetized shocks:

$\sigma=0.1$

$\sigma=10^{-3}$

$\sigma=10^{-5}$

$\sigma=0$

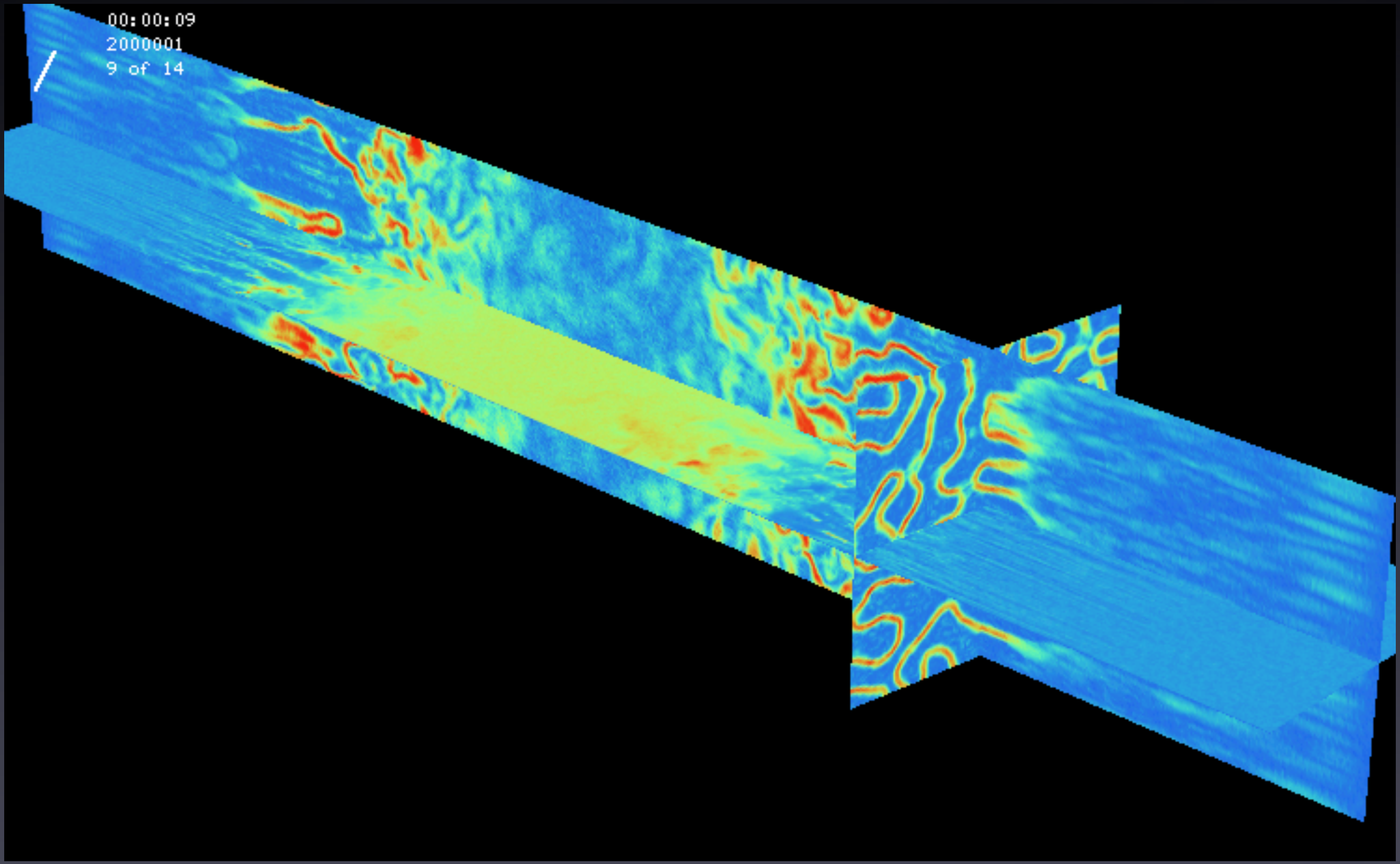


Density

Magnetic Energy

Transition between magnetized and unmagnetized shocks:

$\sigma=0$



Density

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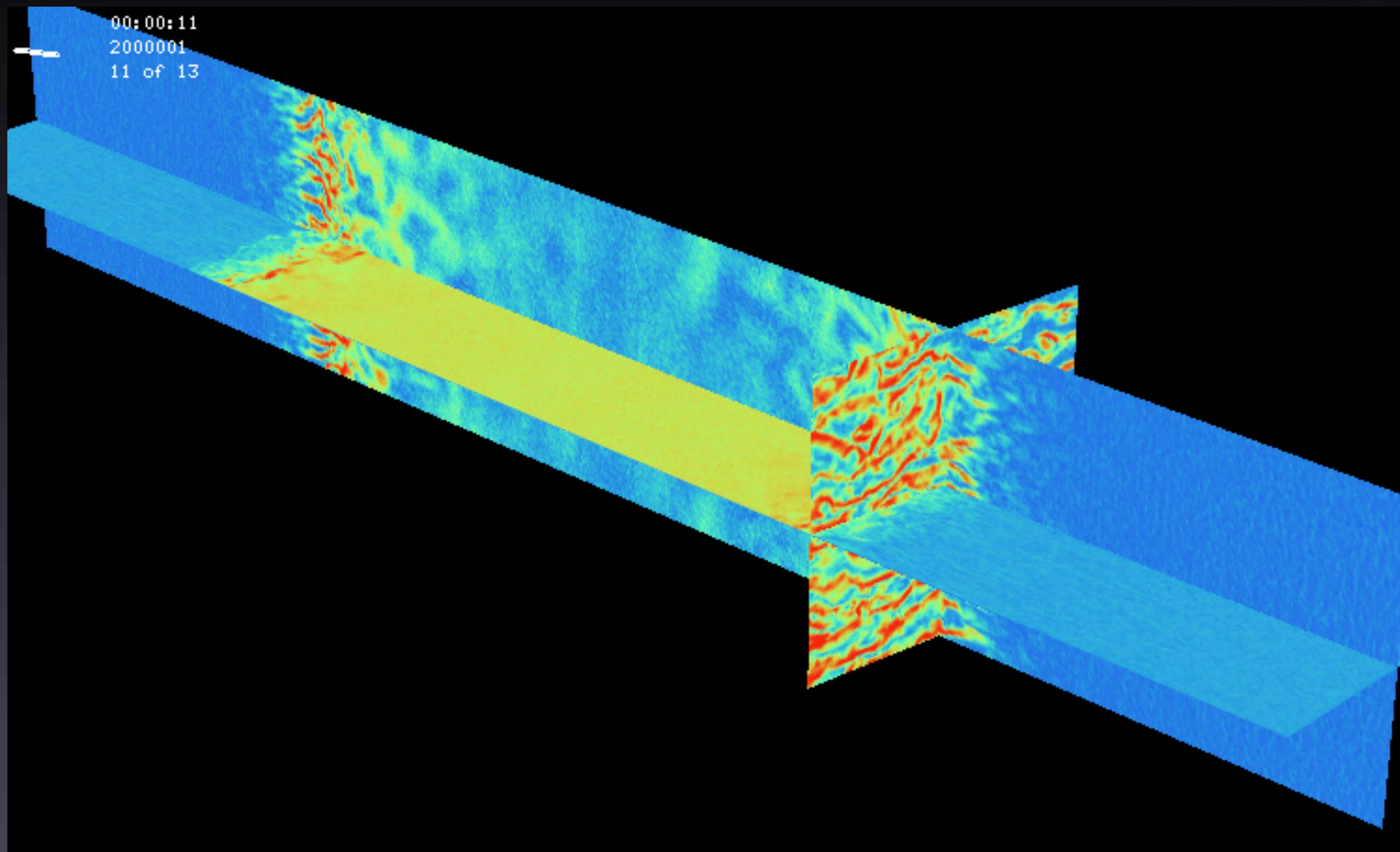
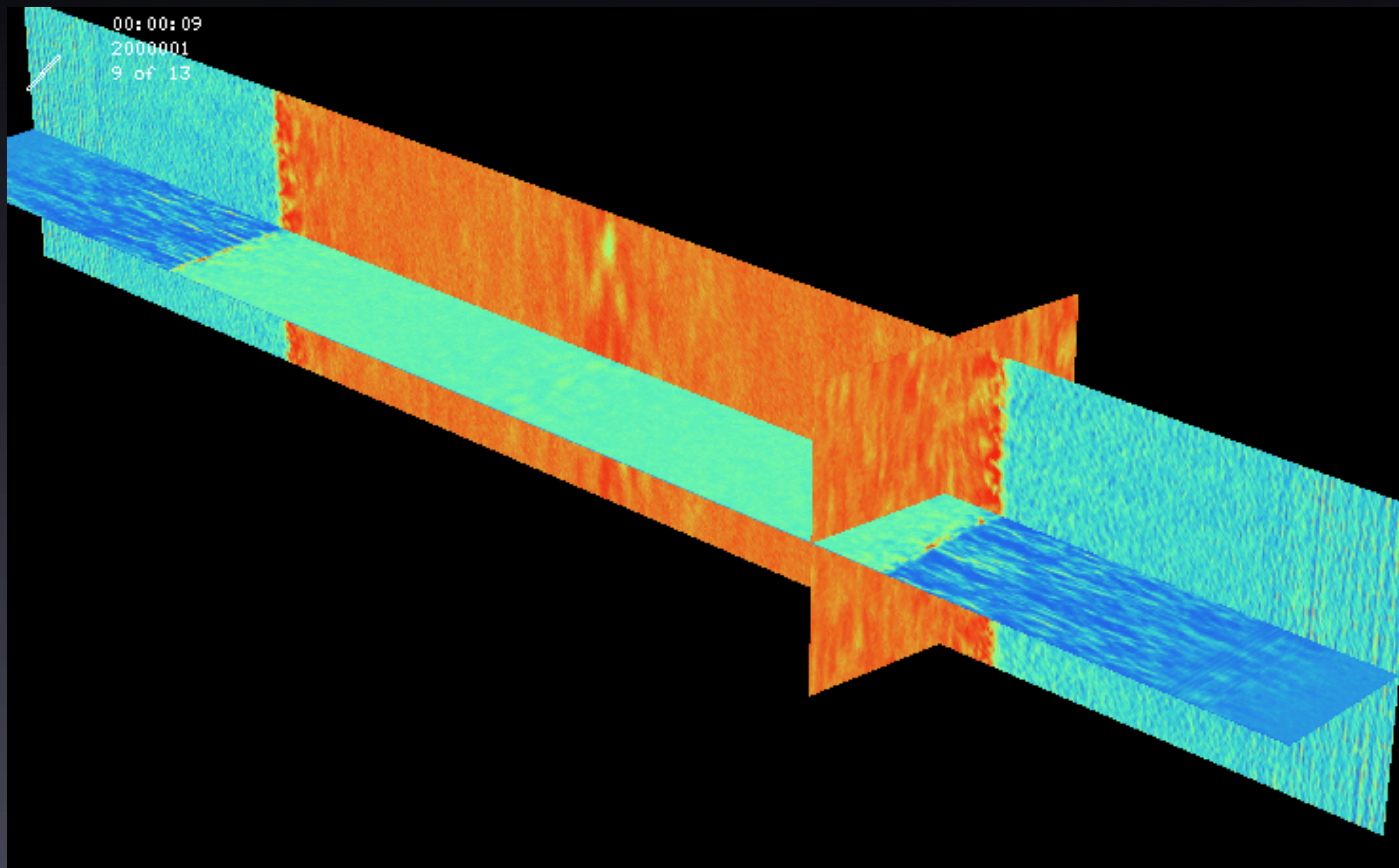


$\sigma = 10^{-3}$

B field

Transition between magnetized and unmagnetized shocks:

$\sigma = 10^{-1}$

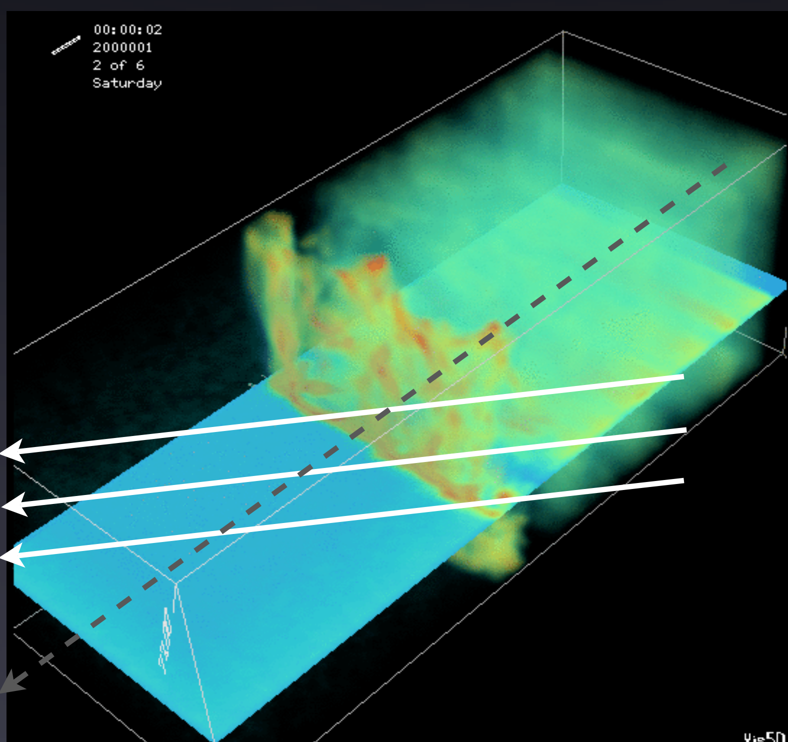


B field

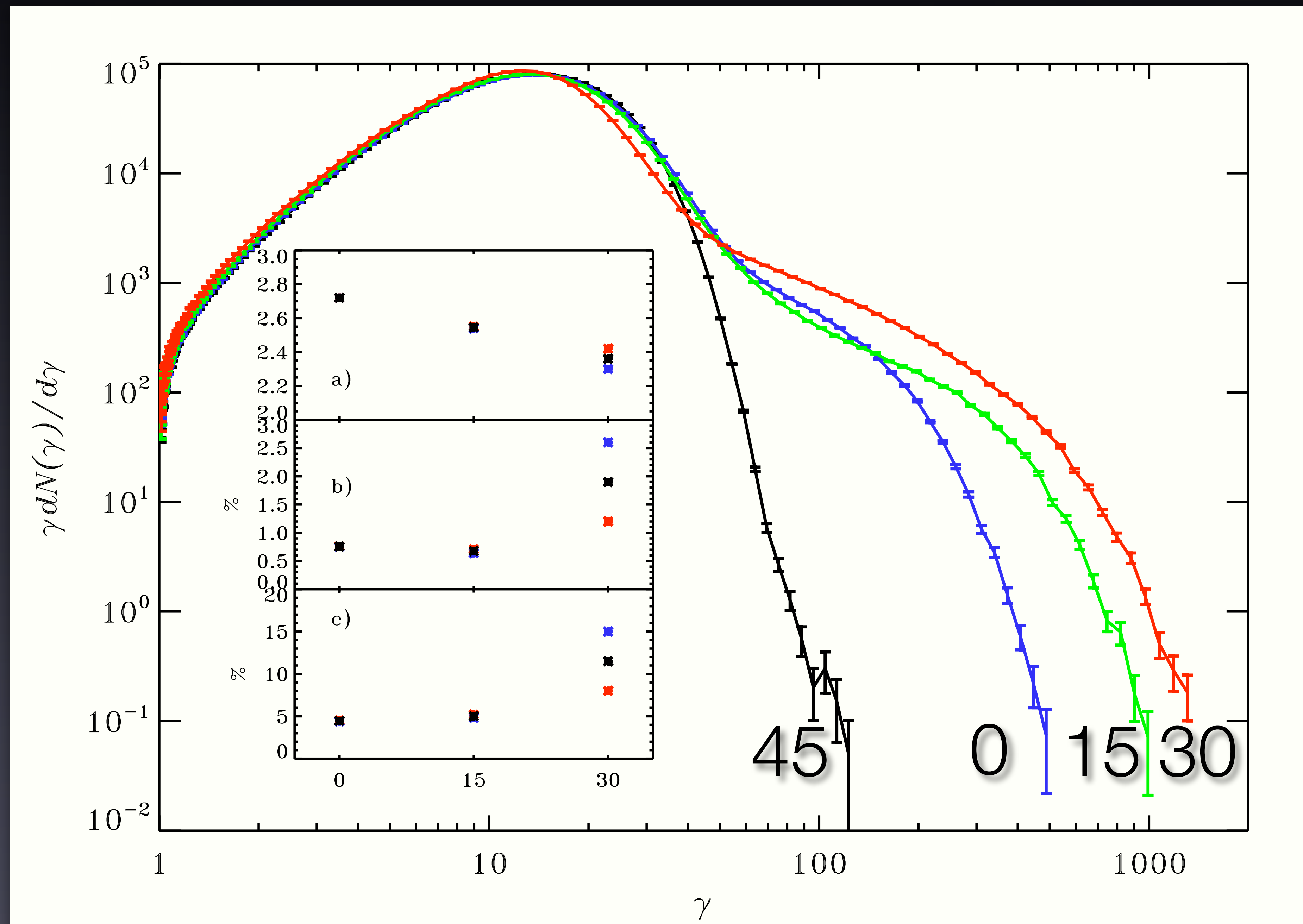
Acceleration: $\sigma < 10^{-3}$ produce power laws, $\sigma > 10^{-3}$ just thermalize

Can magnetized pair shocks accelerate particles?

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



See poster by Lorenzo Sironi

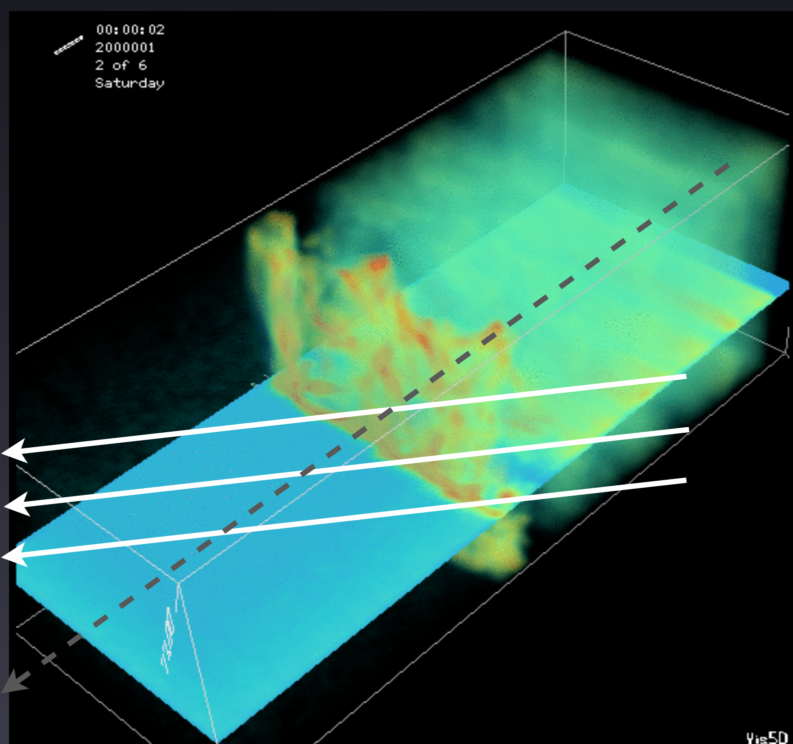


Observe transition between subluminal and superluminal shocks. Shock drift acceleration is important near transition.

Perpendicular shocks are poor accelerators.

Can magnetized pair shocks accelerate particles?

Accelerated particles generate upstream turbulence in magnetized shocks.



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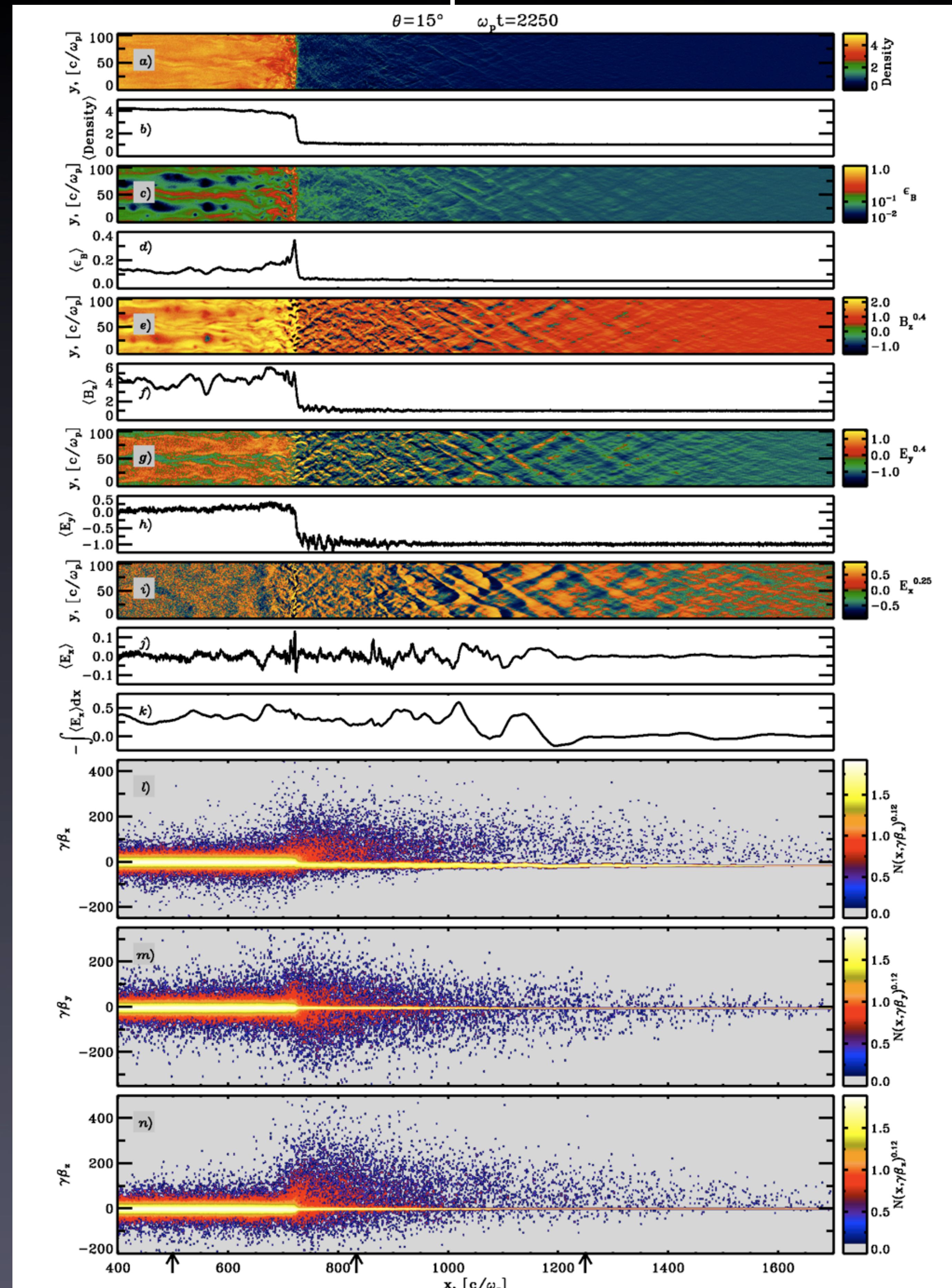

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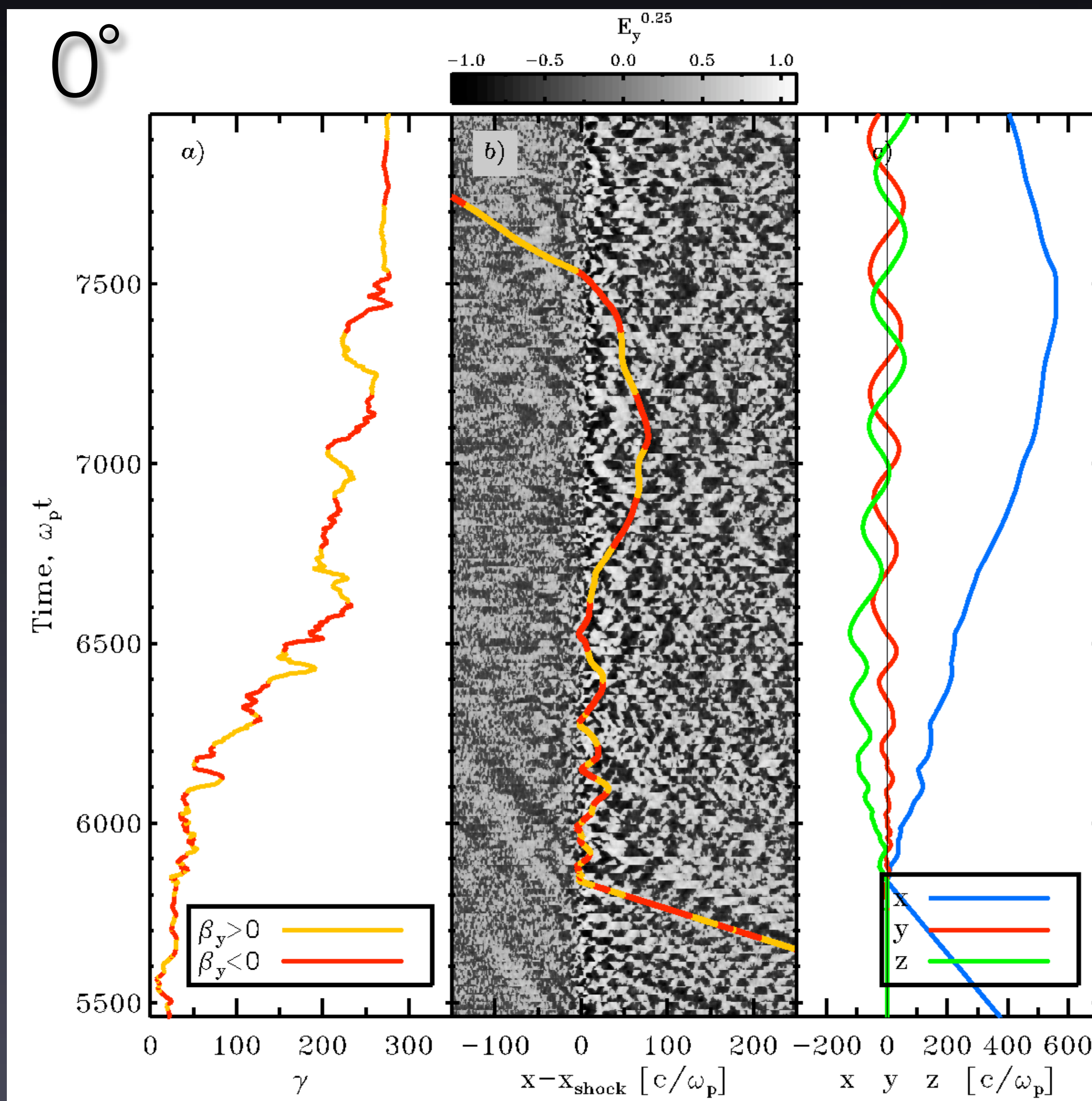

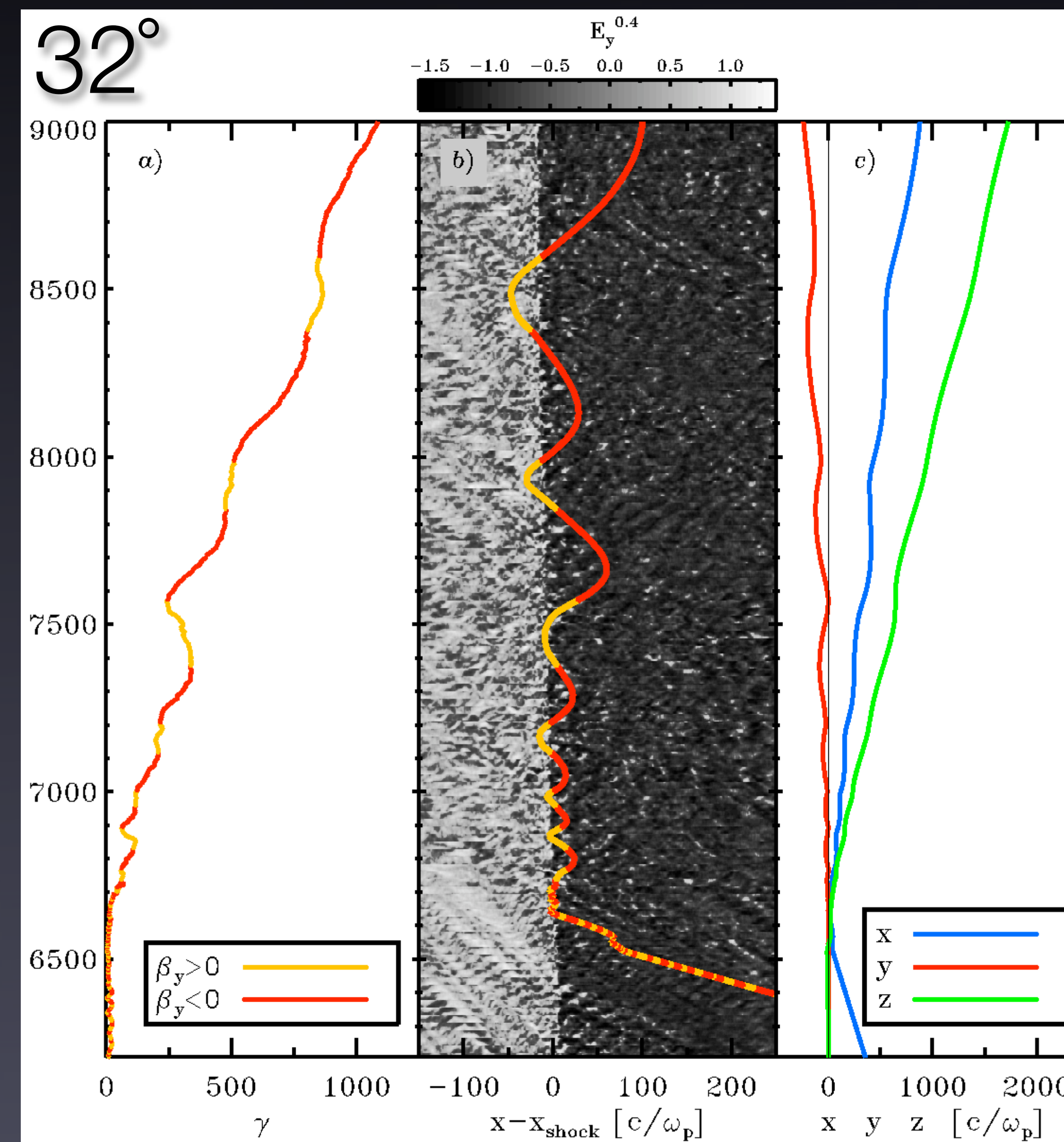

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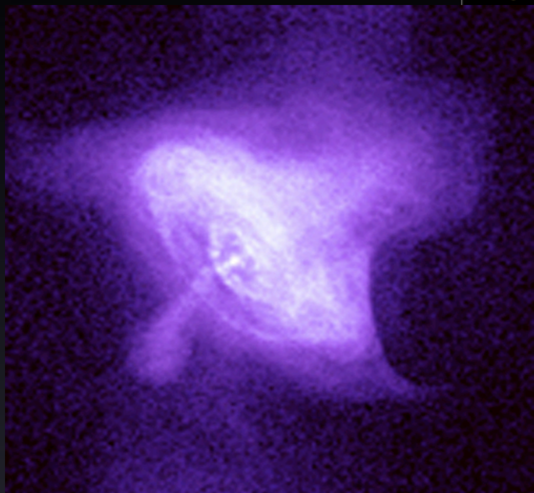
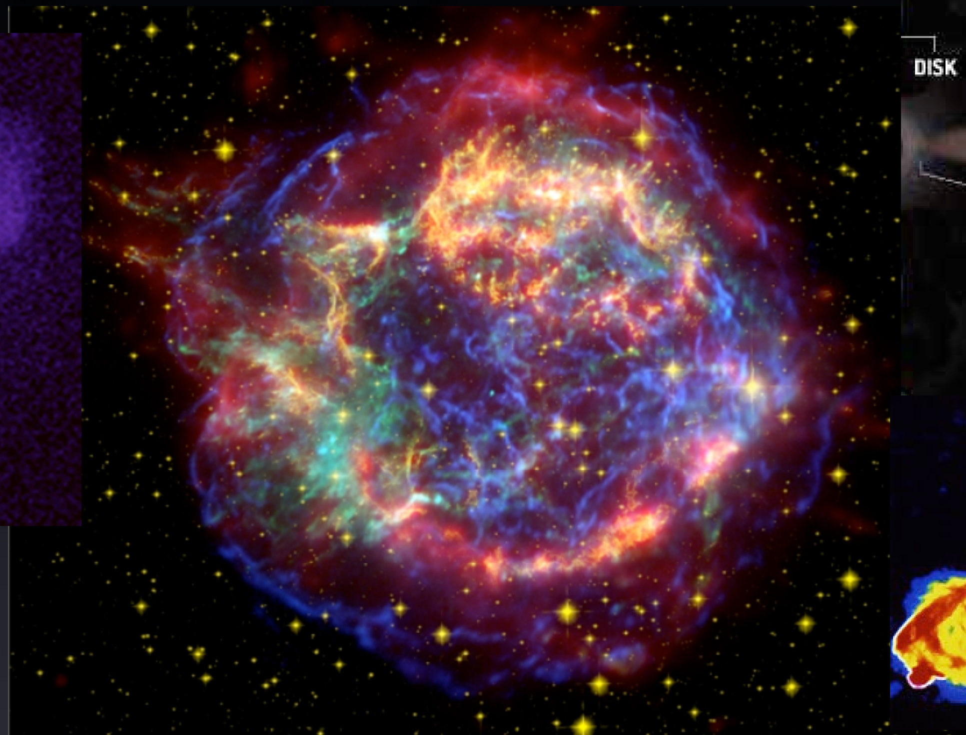
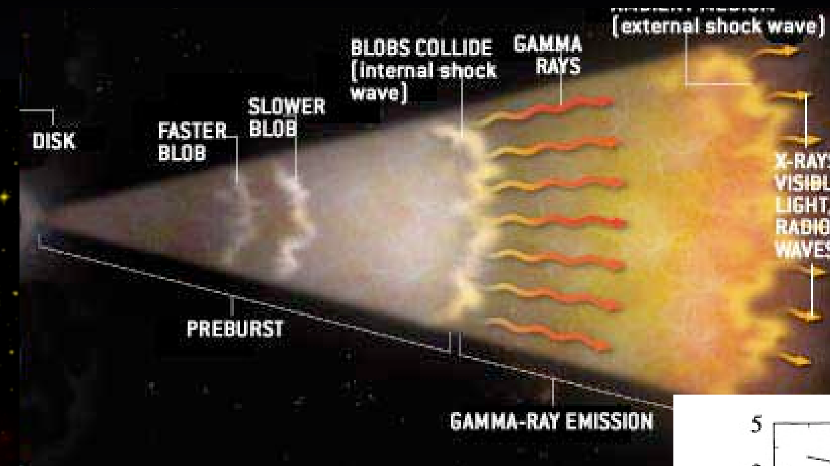
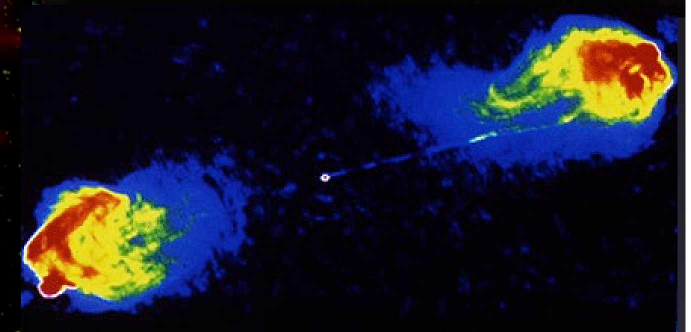
Perpendicular shocks are poor accelerators.

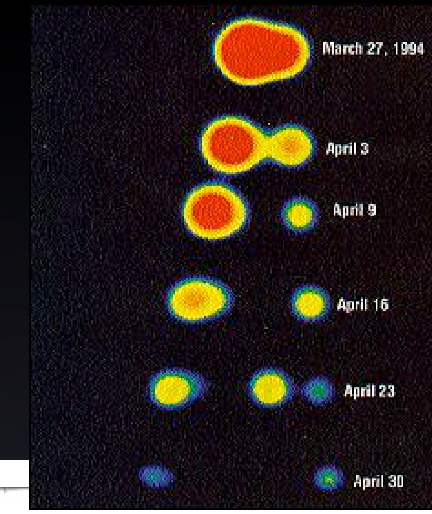
Shocking astrophysics

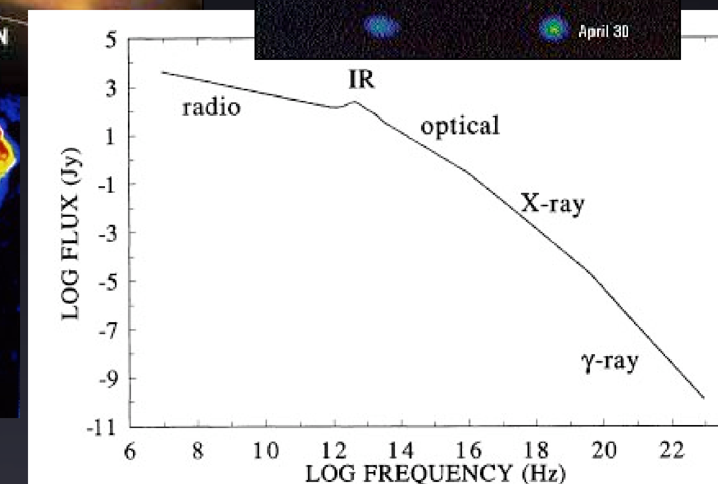












Open issues:

✓ 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?

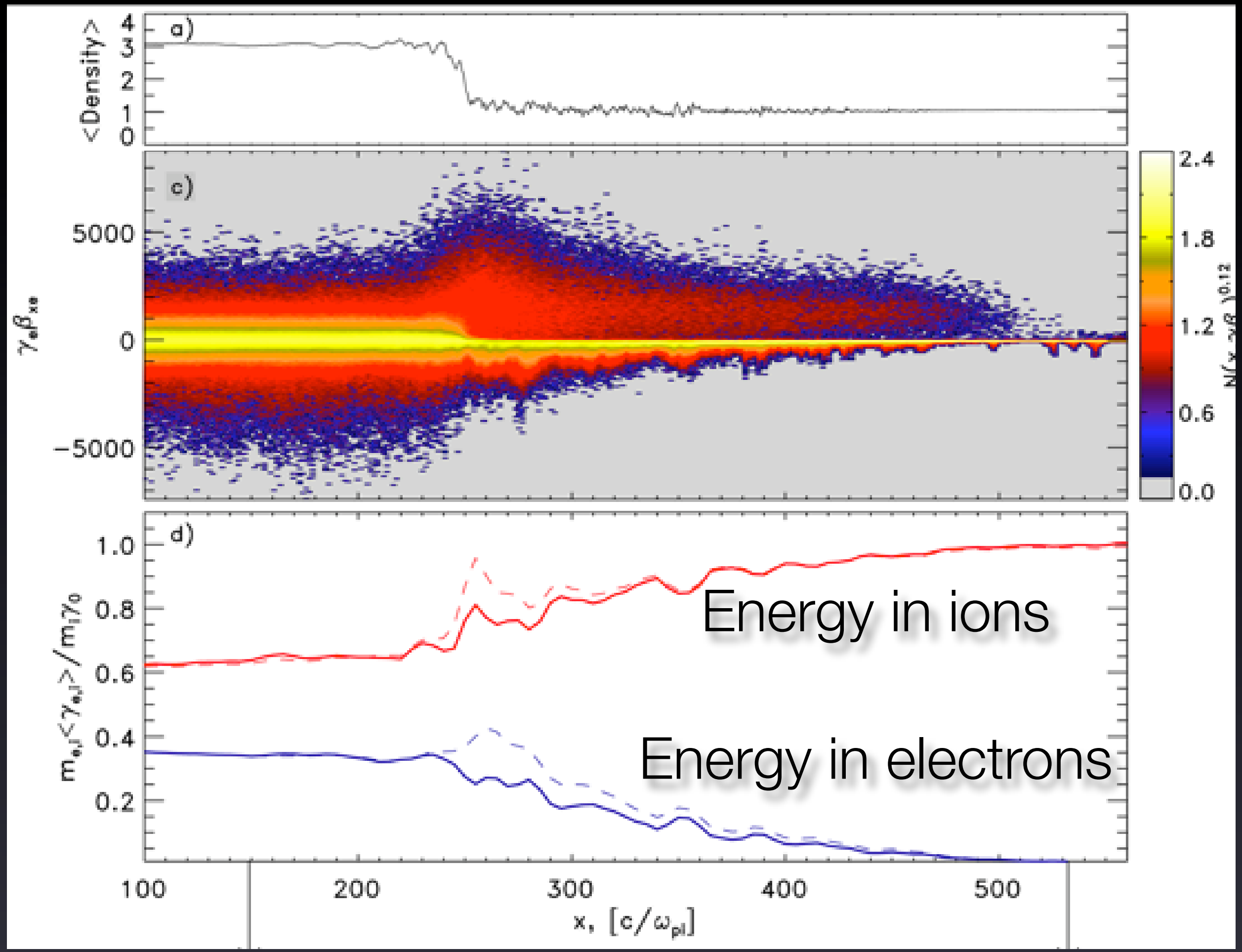
A.S. 2008, ApJ, 673, L39

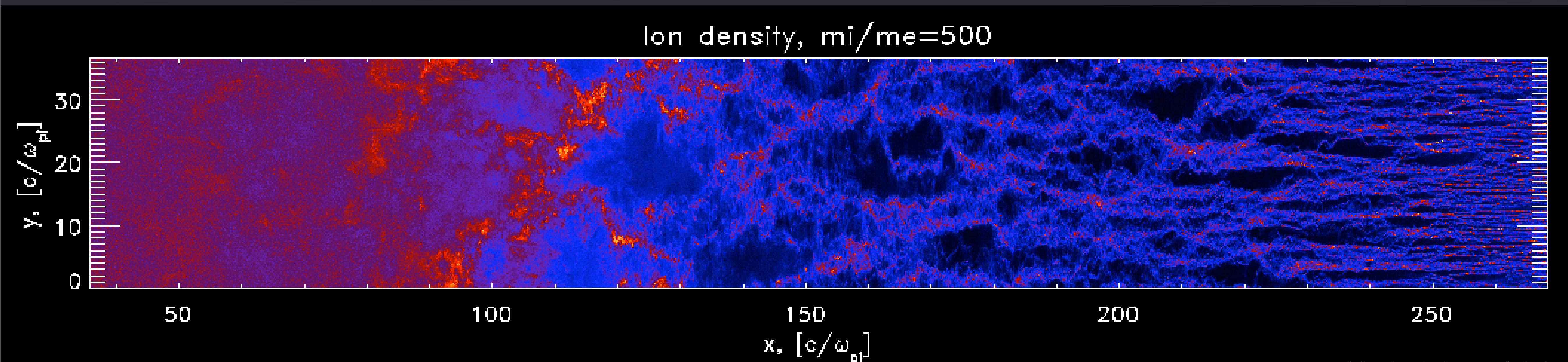
Relativistic Electron-ion shocks

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.

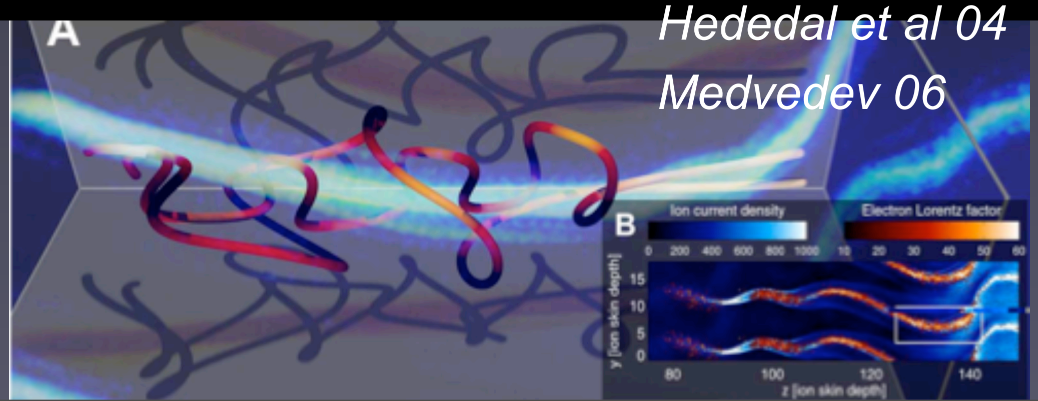
Fermi acceleration proceeds very similarly in unmagnetized e-ion shocks

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





Electron heating is related to electron oscillation in ion filameents, and the longitudinal instability of the filaments.

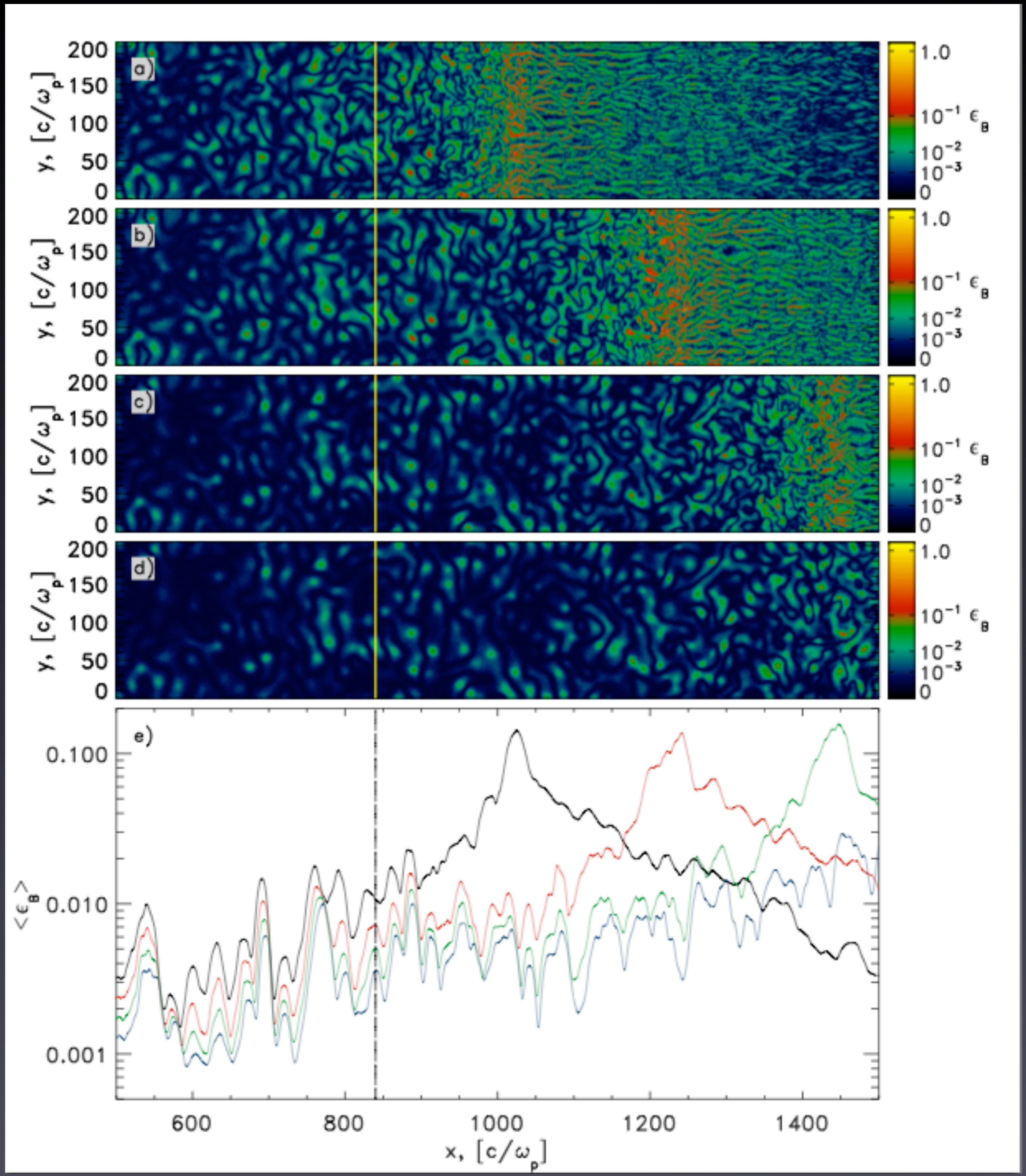


Hededal et al 04

Medvedev 06

Pair shocks: magnetic field evolution

Can Weibel shocks generate enough field for downstream synchrotron emission?



Chang, AS, Arons (08) see decay below $\epsilon_B < 10^{-4}$

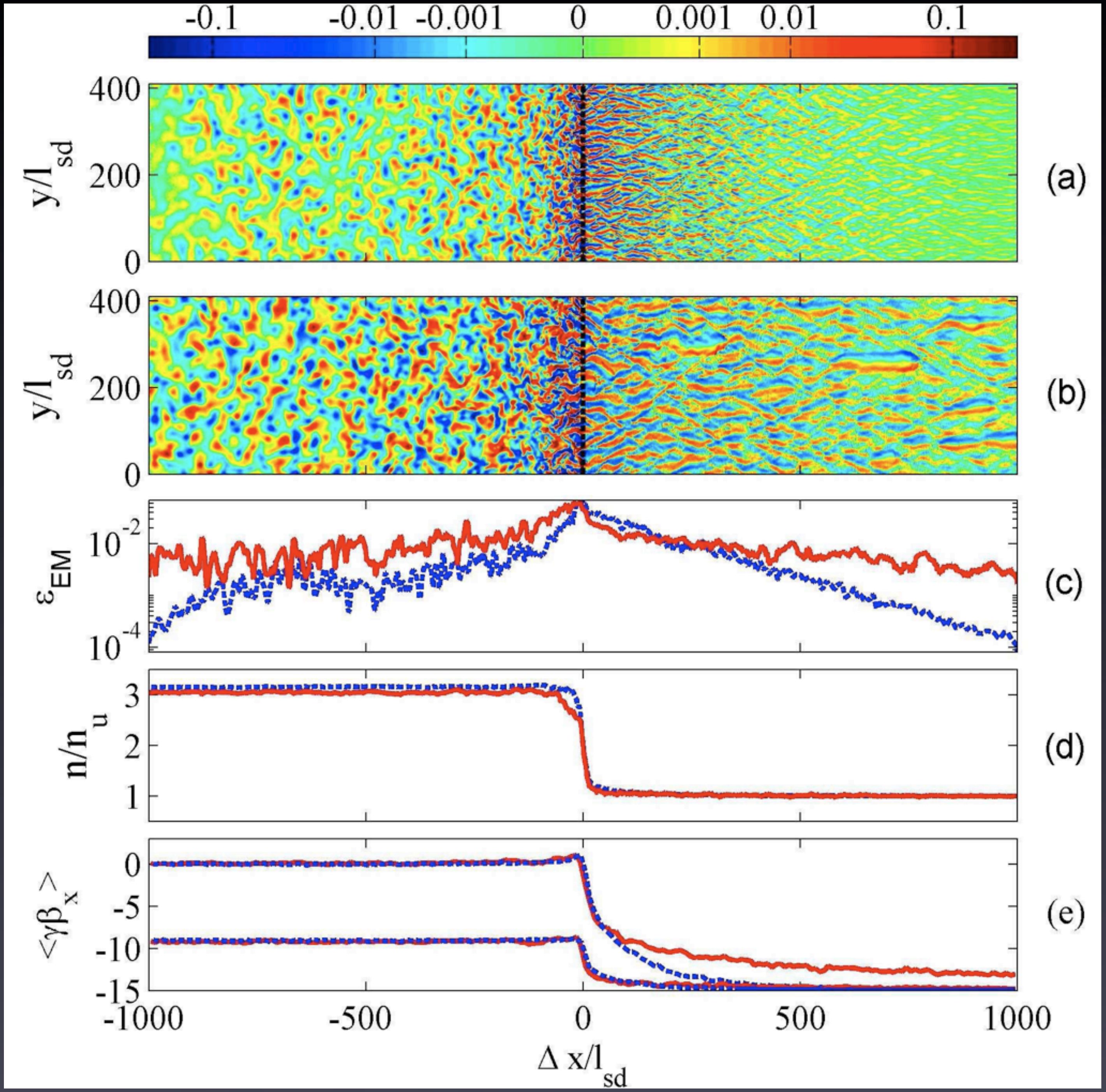
Pair shocks: magnetic field evolution

Can Weibel shocks generate enough field for downstream synchrotron emission?

Returning particles cause filamentation far in the upstream region and cause growth of the scale and amplitude of the upstream field.

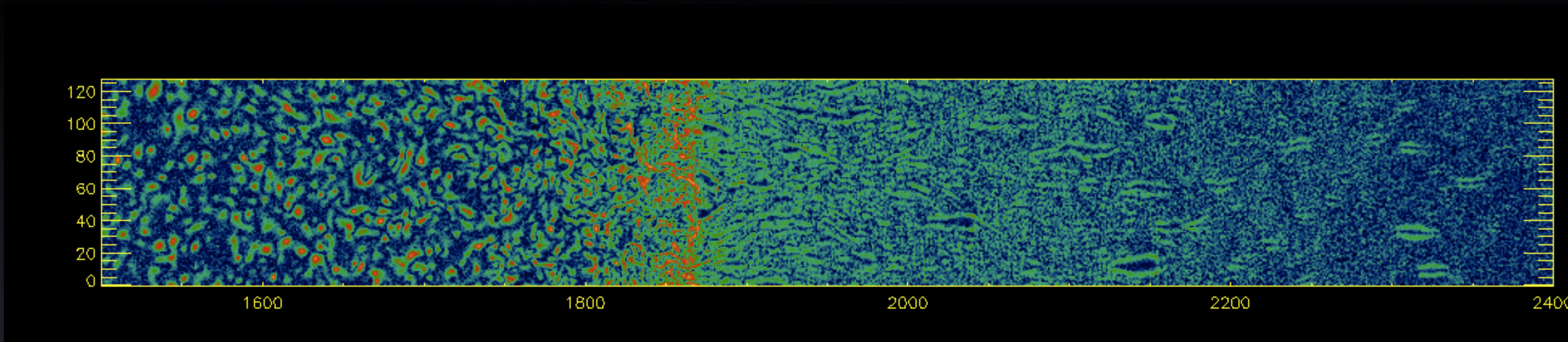
This affects the rate of decay of the field in the downsream (longer wavelengths decay slower).

1% magnetization is not unreasonable (Keshet, Katz, A.S, Waxman 2008).



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

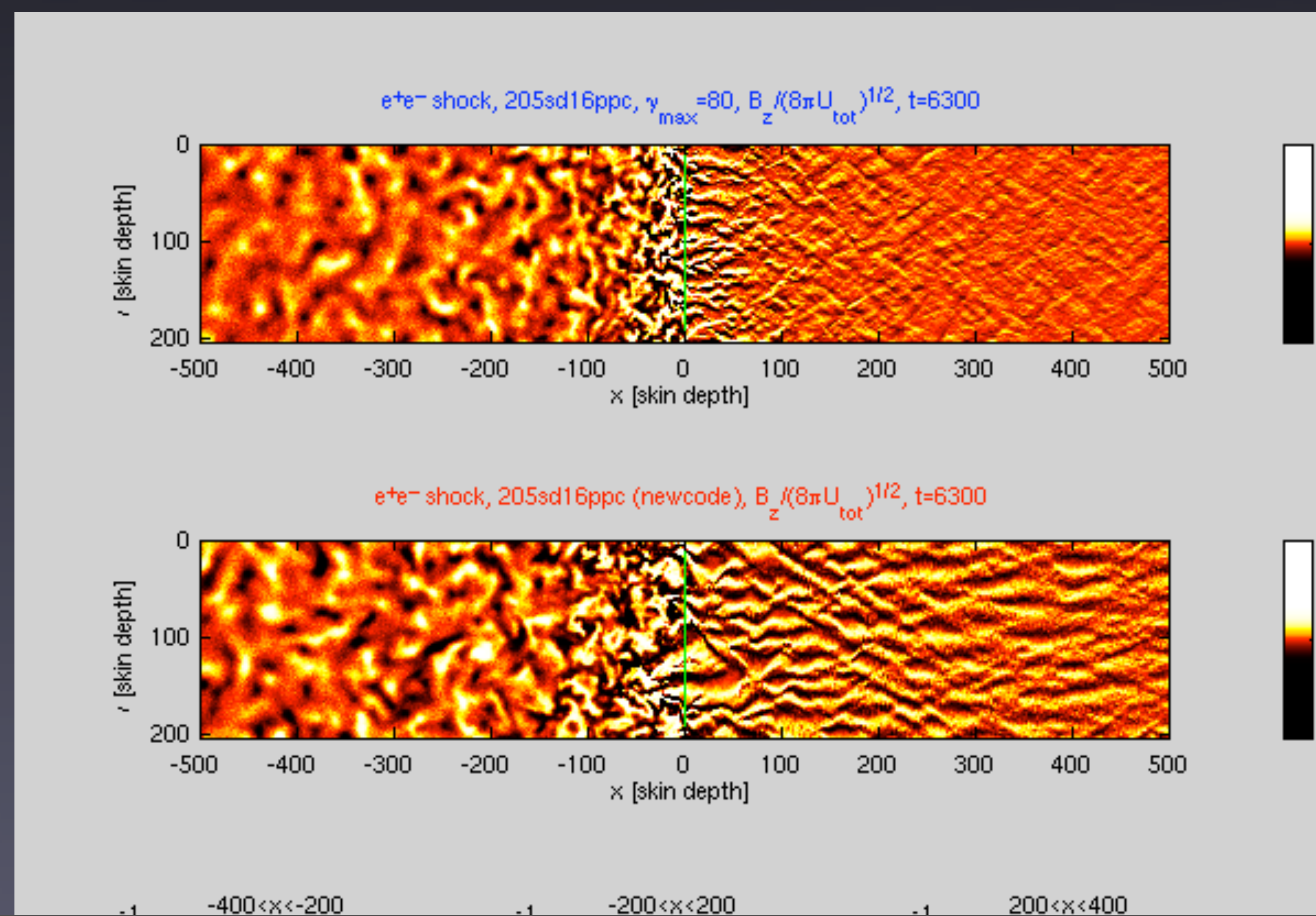
Pair shocks: magnetic field evolution



Field evolution:

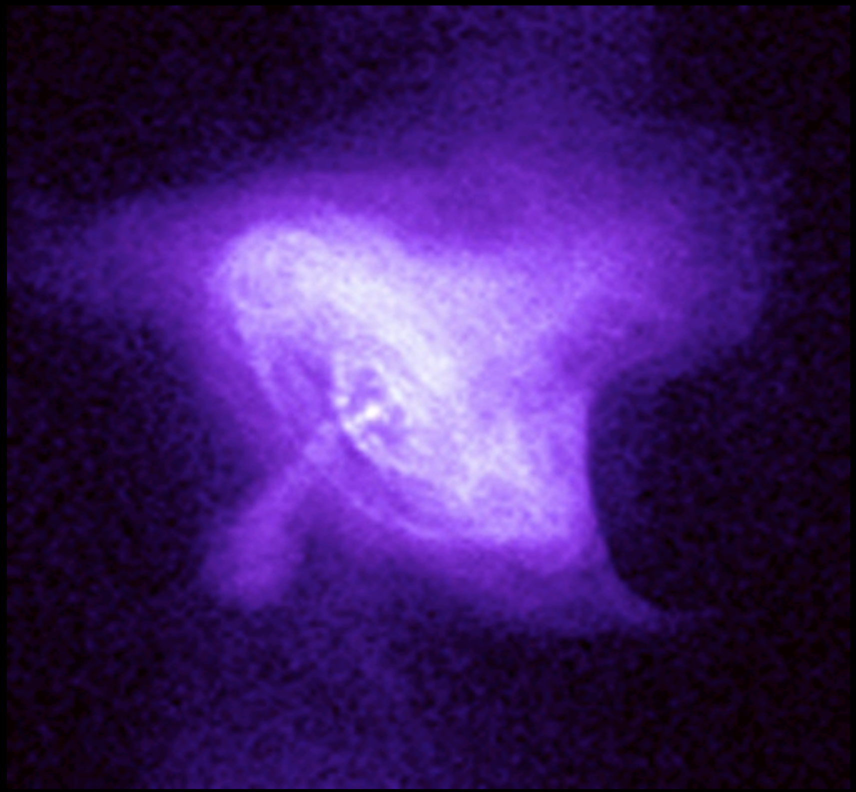
Without high energy particles:

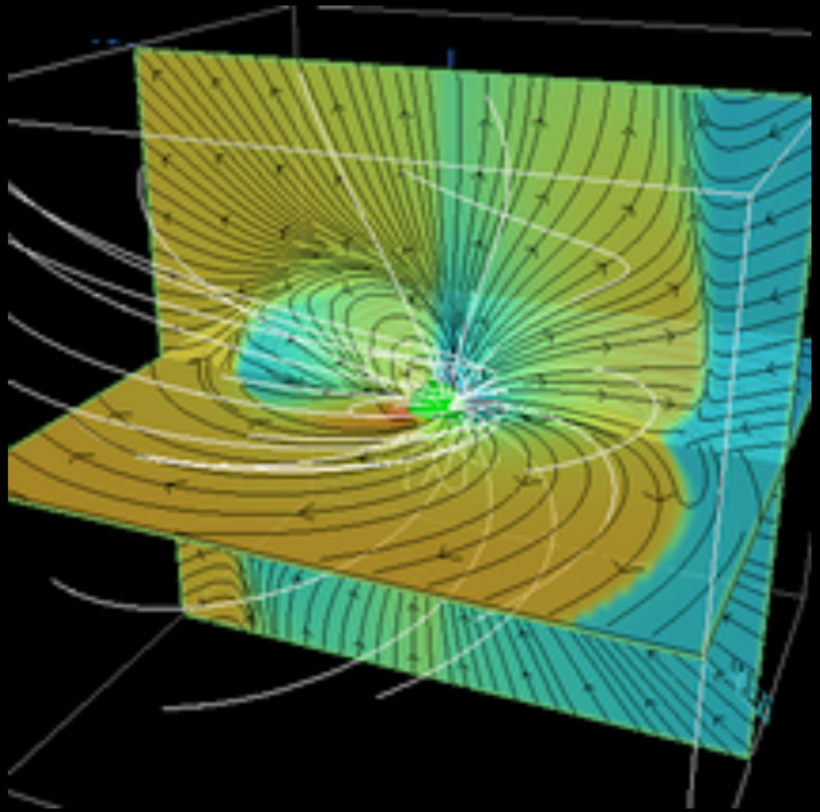
With high energy particles:

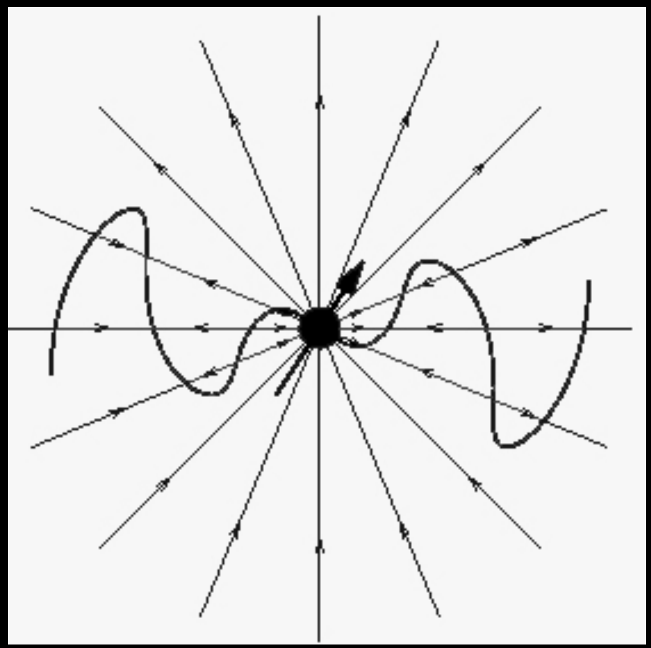


Scale growth is caused by accelerated particles. Larger field accelerates more particles -- bootstrapping!

Astrophysical implications: Pulsar Wind Nebulae (PWNe)







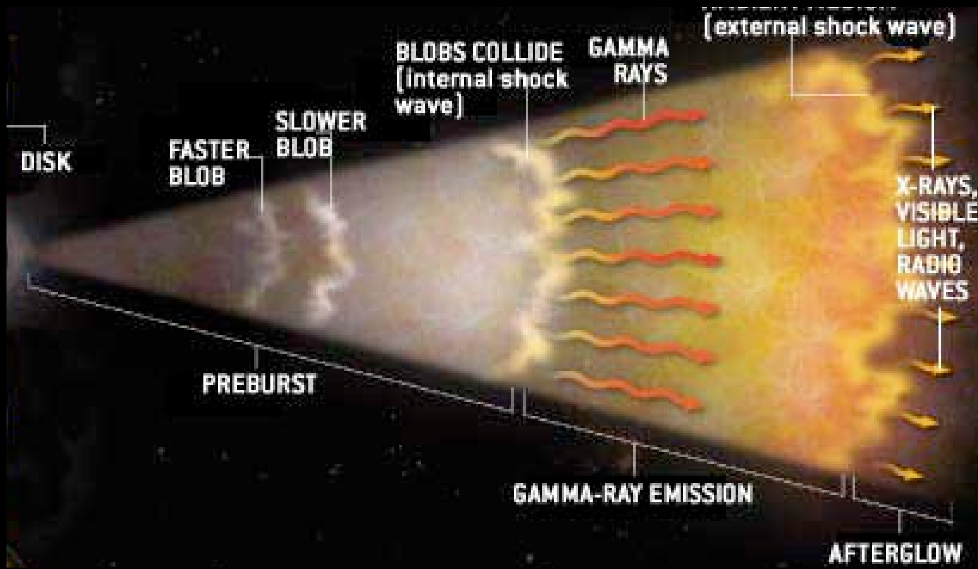
Shock acceleration in PWN implies low magnetization shock. σ=0.001 is inferred from modeling of the nebulae. This is a "transition" regime between magnetized and unmagnetized shocks -- expect Weibel instability to dominate the shock.

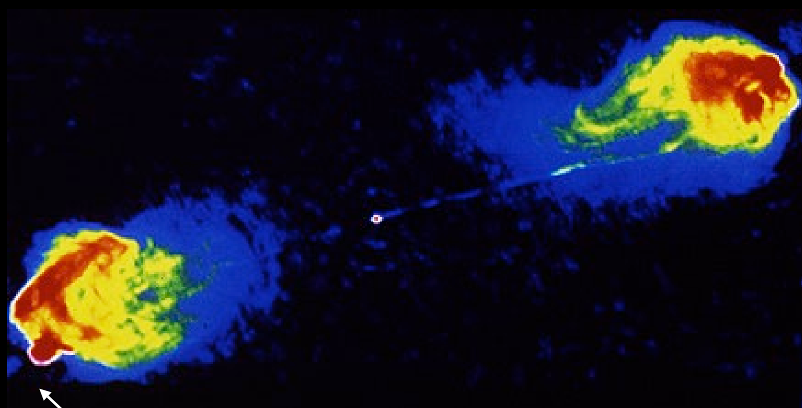
Equatorial shock occurs where the current sheet lies -- hence expect a weakly magnetized "equatorial wedge" -- consistent with shock physics.

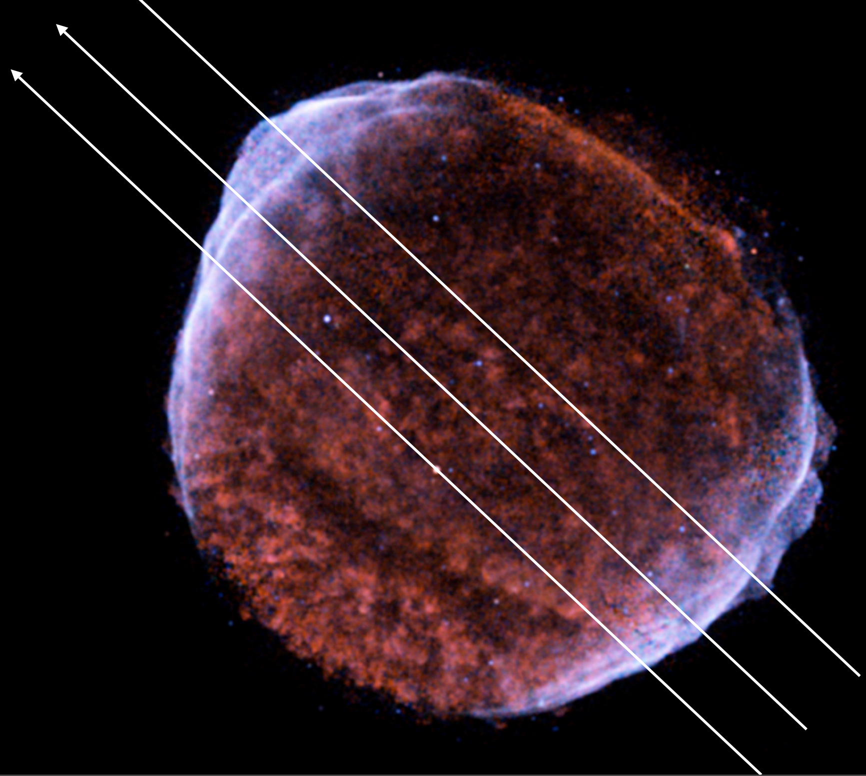
At the moment pair composition could be ok, although other arguments suggest the presence of pair-ion plasma (A.S. & Arons 04).

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

Astrophysical Implications







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

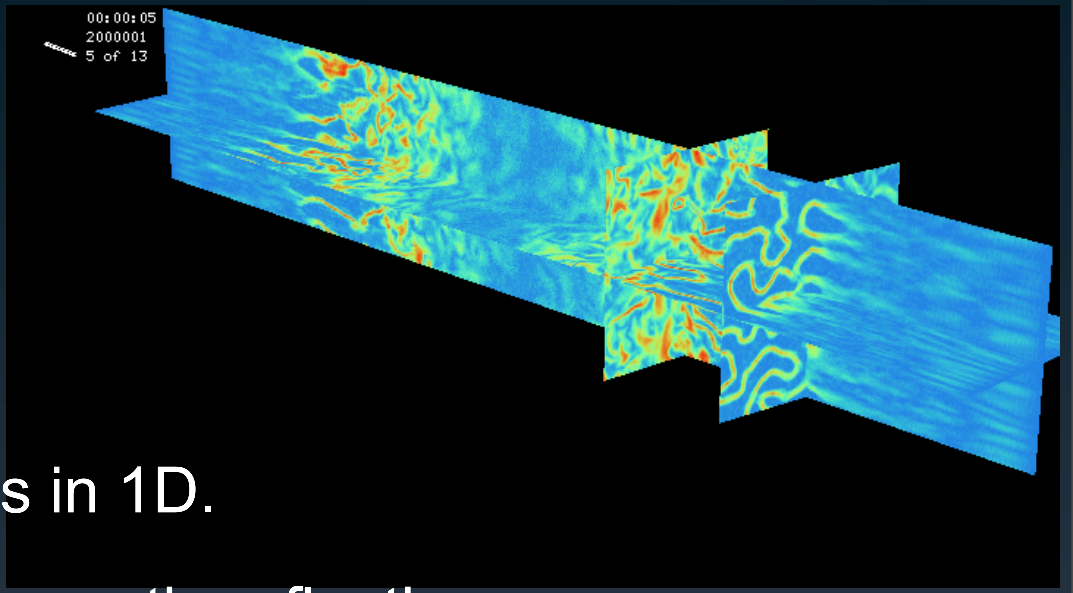
High magnetization perpendicular pair flows are unlikely to generate nonthermal particles through Fermi acceleration. Other physics needed? Not pure pair flows? Sheath flow?

Supernova Remnants

Parallel shocks are more likely to accelerate particles than perpendicular shocks (e.g. SN1006?).

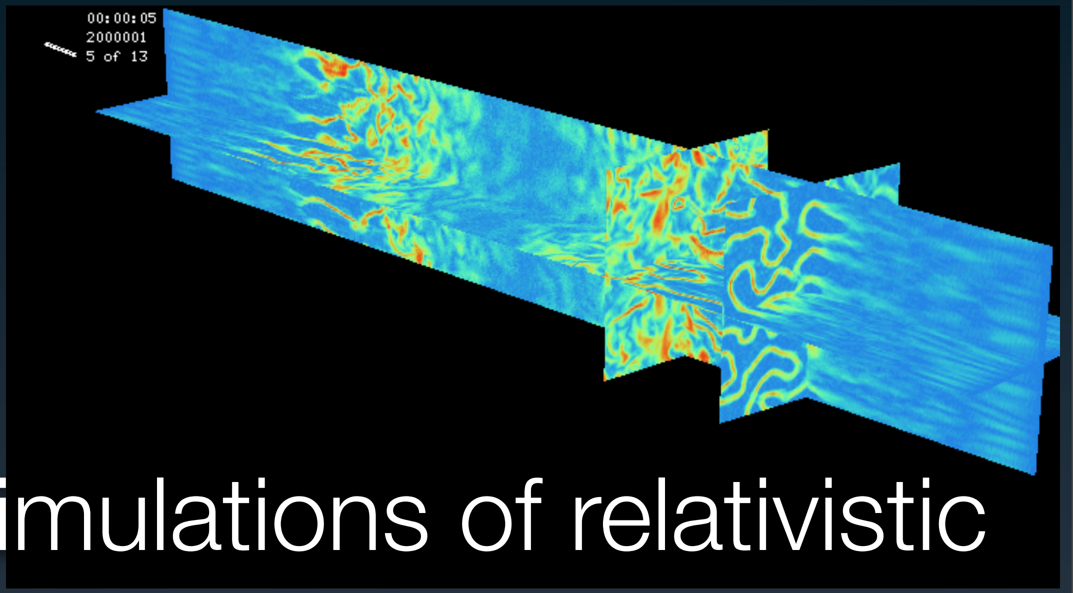
Also, we see field amplification due to streaming CRs (see Mario Riquelme's talk)

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: σ~0.001 is the transition region for pairs.
- 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 σ to be working as unmagnetized shocks.
- First signatures of backreaction of self-consistently accelerated particles on the shock: generation of upstream turbulence and growth of field scale with time. The nature of these waves is still uncertain.

Conclusions



Future progress in large-scale PIC simulations of relativistic flows hinges on the control and elimination of grid-Cerenkov instabilities that prevent longer runtimes.

Also, we need to develop a consistent test suite of simulations that can be used to test and compare codes.

Announcement
Postdoctoral opportunity in PIC work at Princeton:
https://www.astro.princeton.edu/postapp09.php