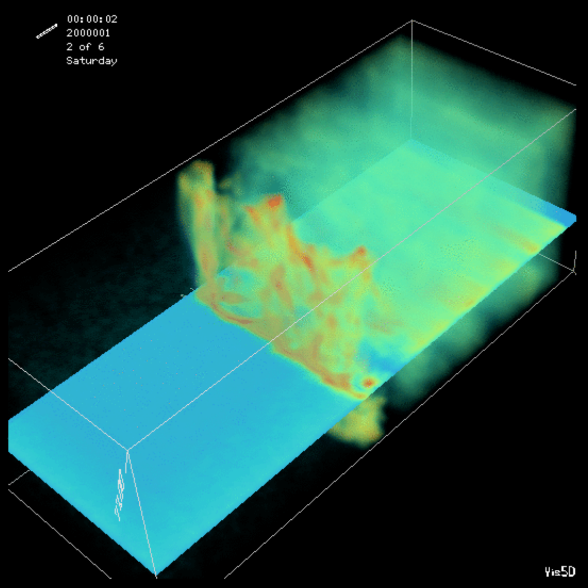
Relativistic Collisionless Shocks: Shock Structure and Particle Acceleration

Anatoly Spitkovsky (KIPAC, Stanford)

Outline:

1. *Shocks in astrophysics: expectations of composition, structure and shock properties*
2. *3D shock modeling -- simulation setup*
3. *Unmagnetized shocks in pair plasma*
4. *Magnetized shocks in pair plasma*
   a) *Perpendicular*
   b) *Oblique*
5. *Shocks in electron-ion plasma*
   a) *Magnetized*
   b) *Unmagnetized*
6. *Conclusions*



3D PIC results are generally consistent with work by

Silva, Mori et al
Nishikawa et al
Hededal, Frederiksen, Nordlund et al

Shocking astrophysics

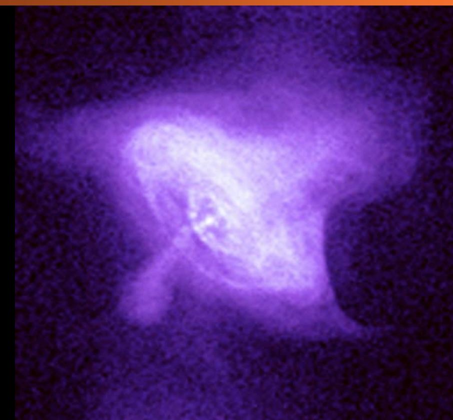
Relativistic collisionless shocks in astrophysics

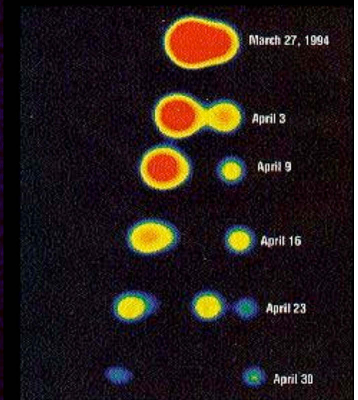
- *Pulsars + winds (plerions, J0737)* $\gamma \sim 10^6$
- *Extragalactic radio sources* $\gamma \sim 10$
- *Gamma ray bursts* $\gamma > 100$
- *Galactic superluminal sources* $\gamma \sim$ few
- *Sources for UHE CR?*

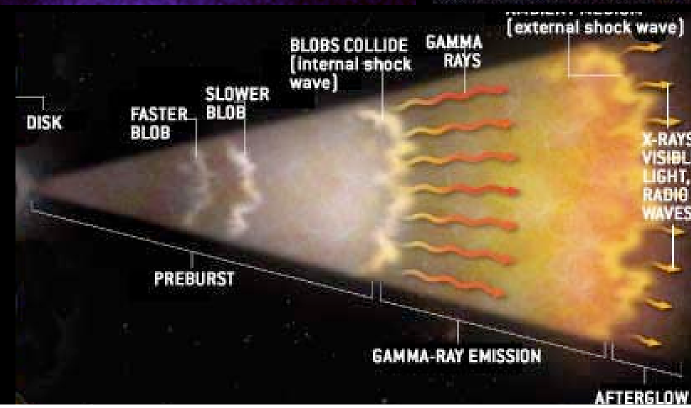
Open issues:

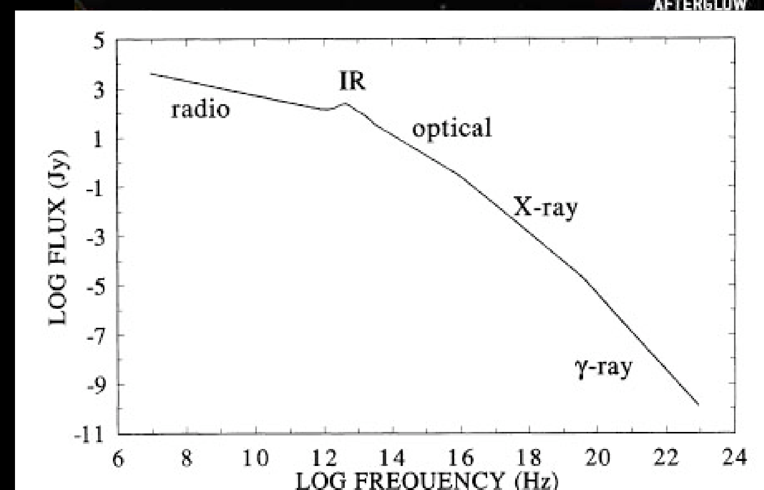
- *What is the structure of collisionless shock waves?*
- *Particle acceleration -- Fermi mechanism? Something else?*
- *Generation of magnetic fields (GRB shocks, primordial fields?)*

By using direct ab-initio numerical simulations of collisionless shocks we can place constraints on astrophysical models of composition and structure of relativistic outflows in nature.

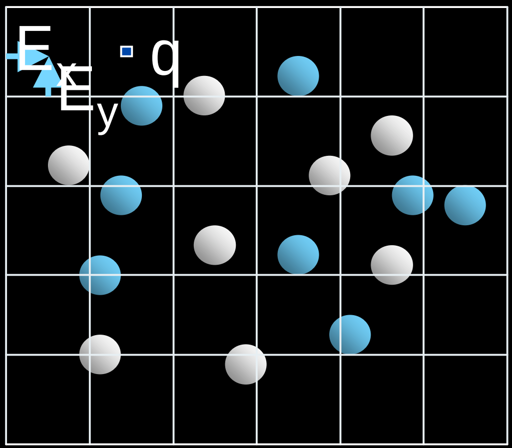








Numerical simulation of collisionless shocks

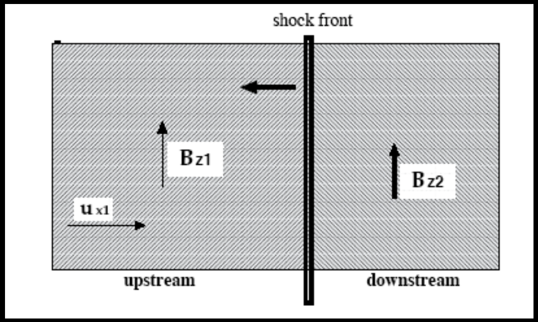


Particle-in-cell method:

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

Modified code "TRISTAN":

- *3D cartesian electromagnetic particle-in-cell code*
- *Radiation BCs*
- *Charge-conservative current deposition (no Poisson eq)*
- *Filtering of current data*
- *Fully parallelized (128proc+) domain decomposition*
- *3 billion+ particles*



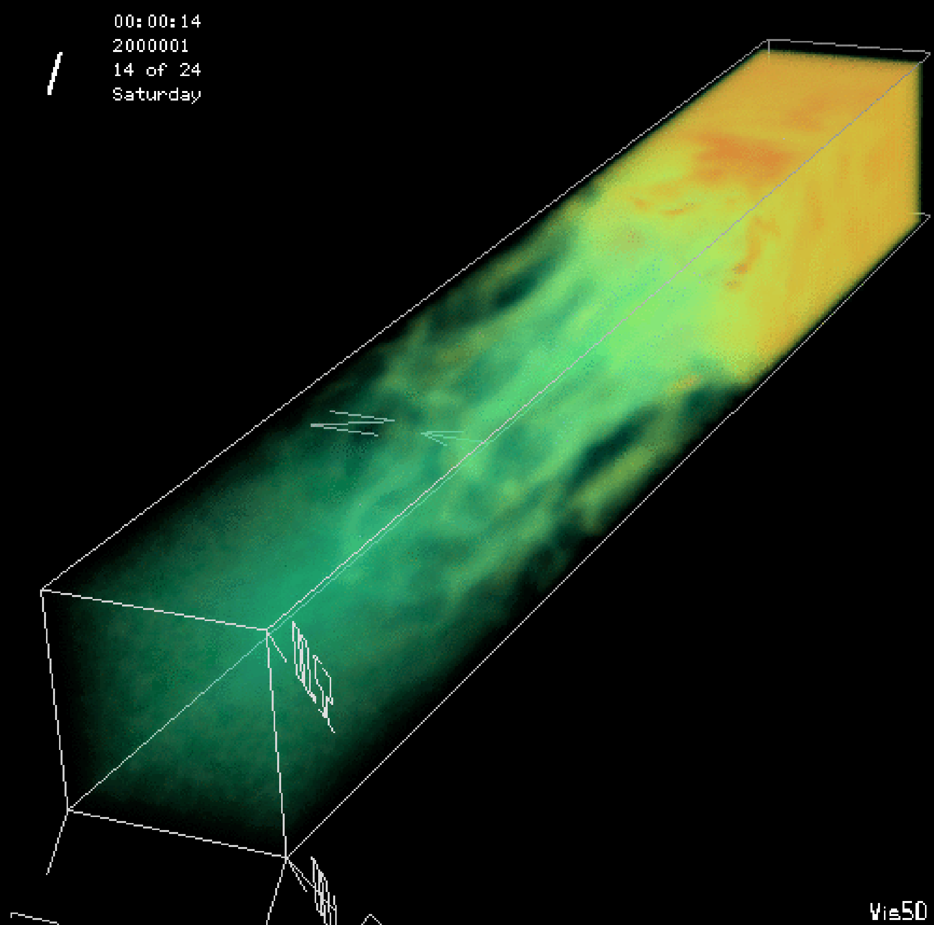
Simulation setup:

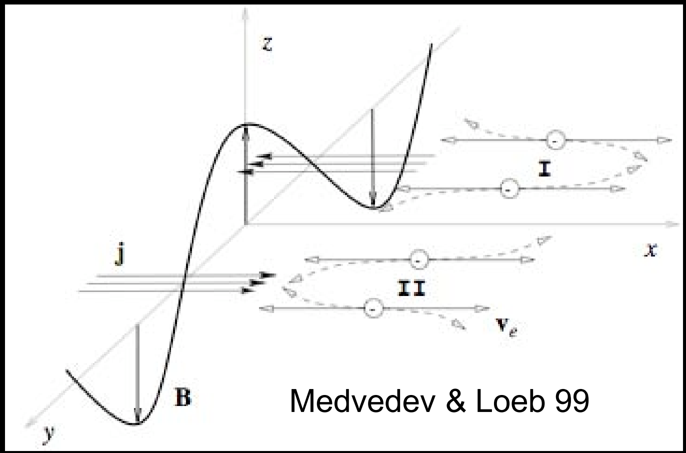
Relativistic $e^{\pm}$ or e^{-}- ion wind (γ =15) with B field ($\sigma = \omega_c^2 / \omega_p^2 = B^2/(4\pi n \gamma m c^2)$ = 0-10)
Reflecting wall (particles and fields)
Upstream c/ω_p=15 cells, c/ω_c>5 cells; 800x150x150 grid, 60x10x10 c/ω_p

Unmagnetized pair shock

Why does a shock exist?

Particles are slowed down either by instability (two-stream-like) or by magnetic reflection. Electrostatic reflection is important for nonrelativistic shocks and when ions are present.

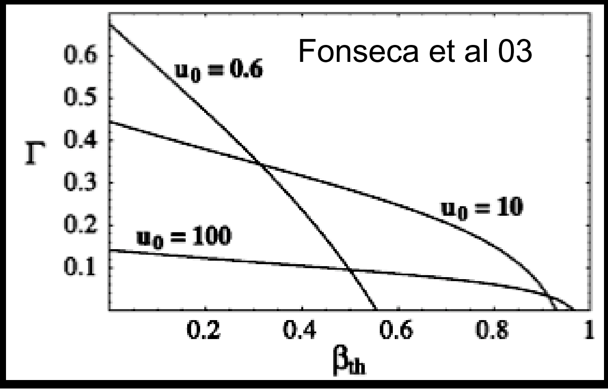




Medvedev & Loeb 99

Weibel instability

Spatial growth scale c/ω_p; timescale $10/\omega_p$

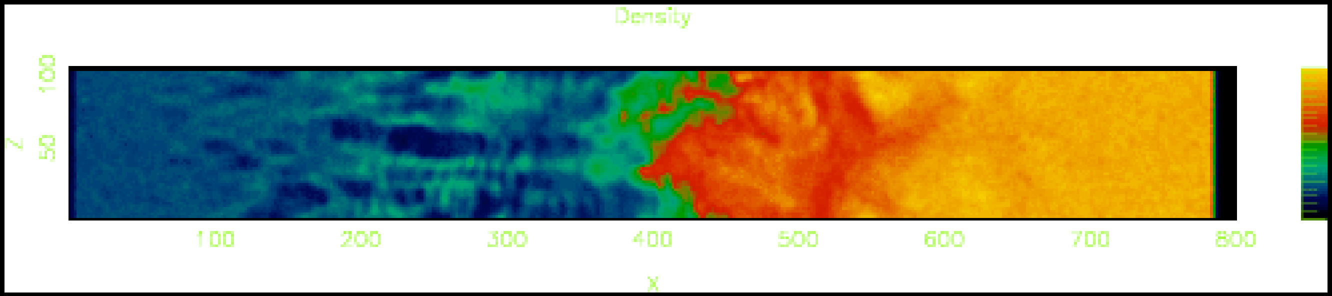


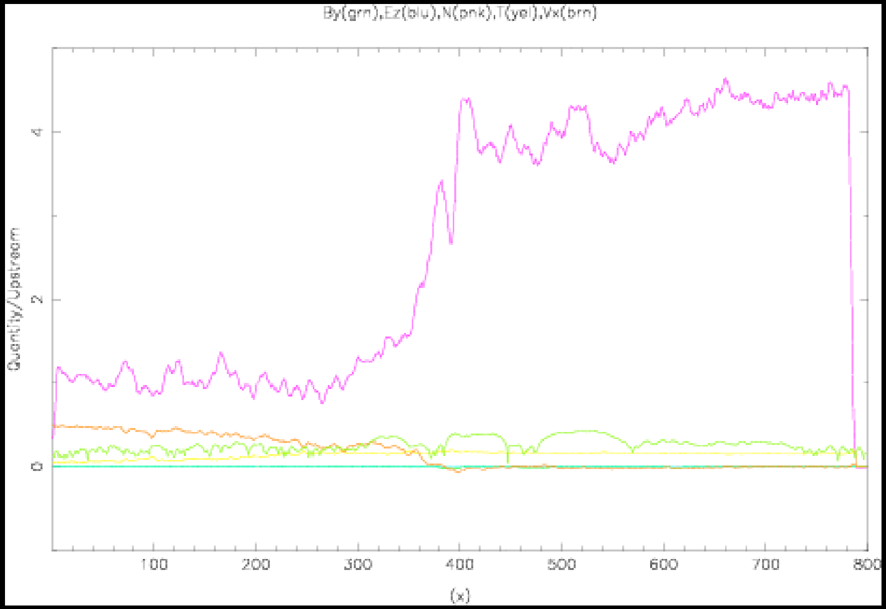
Fonseca et al 03

Unmagnetized pair shock

Shock structure: Density evolution

Shock transitioin is accomplished in roughly 20-50 c/ω_p





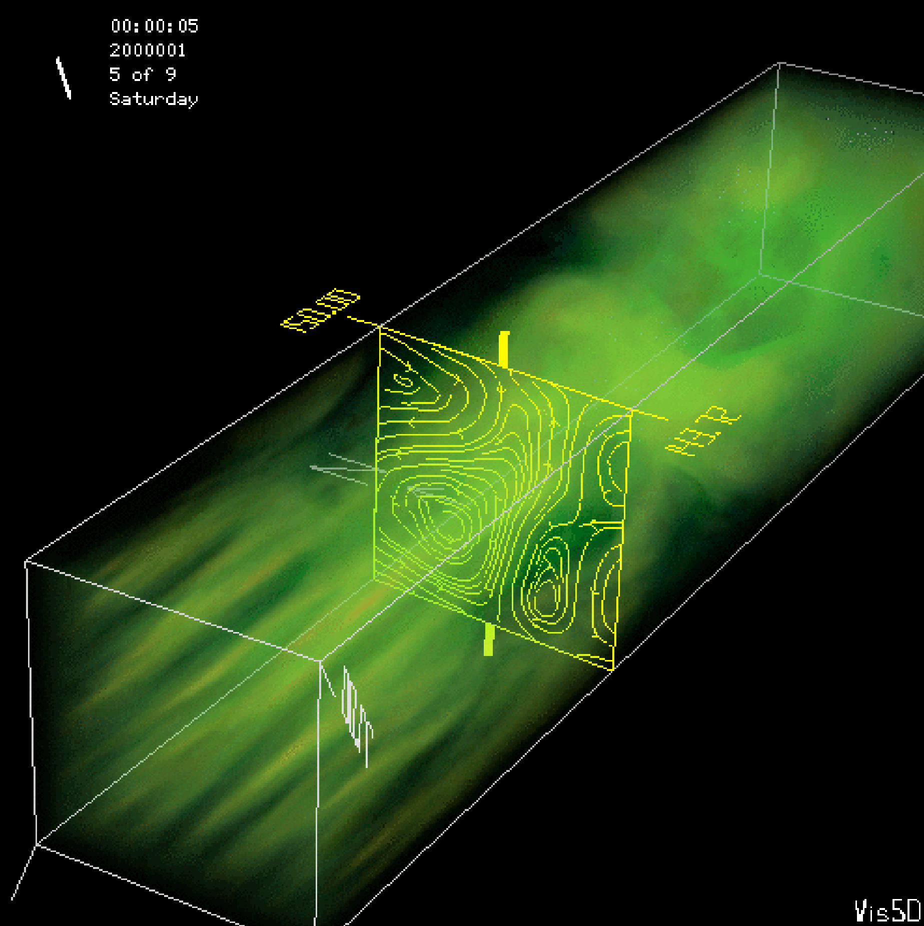
MHD jump conditions satisfied

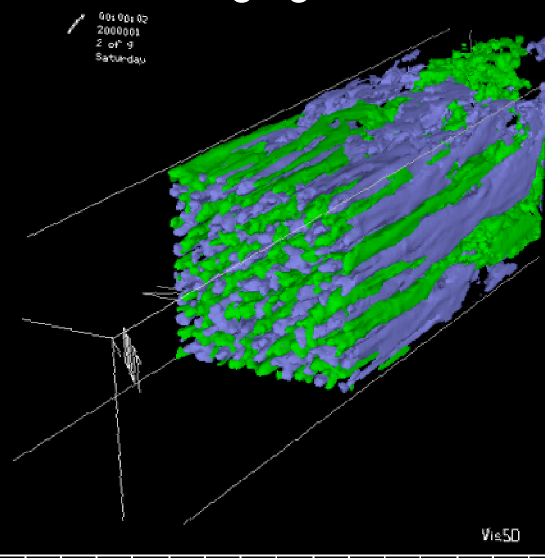
$$\frac{N_2}{N_1} = \frac{\Gamma}{\Gamma - 1} - \frac{(2-\Gamma)\Gamma}{2(\Gamma-1)^3}\sigma\ldots$$

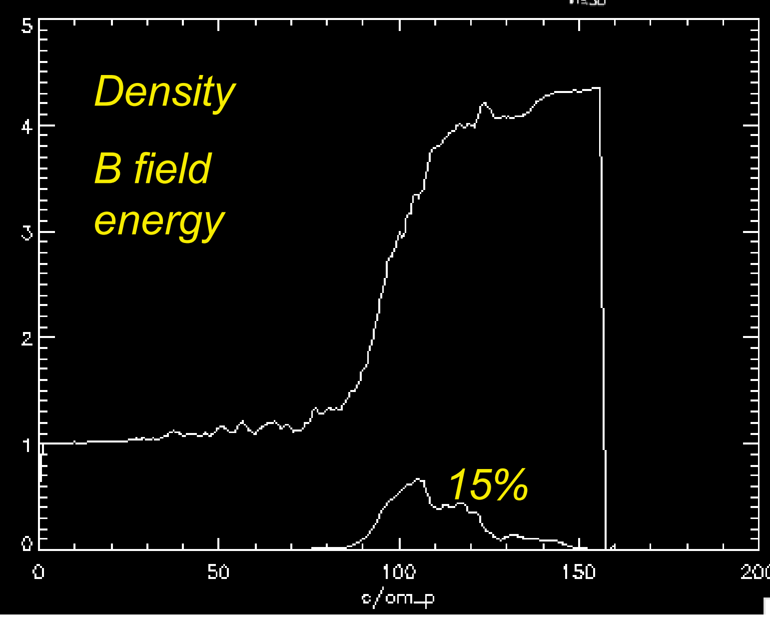
Unmagnetized pair shock

Magnetic field generation

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



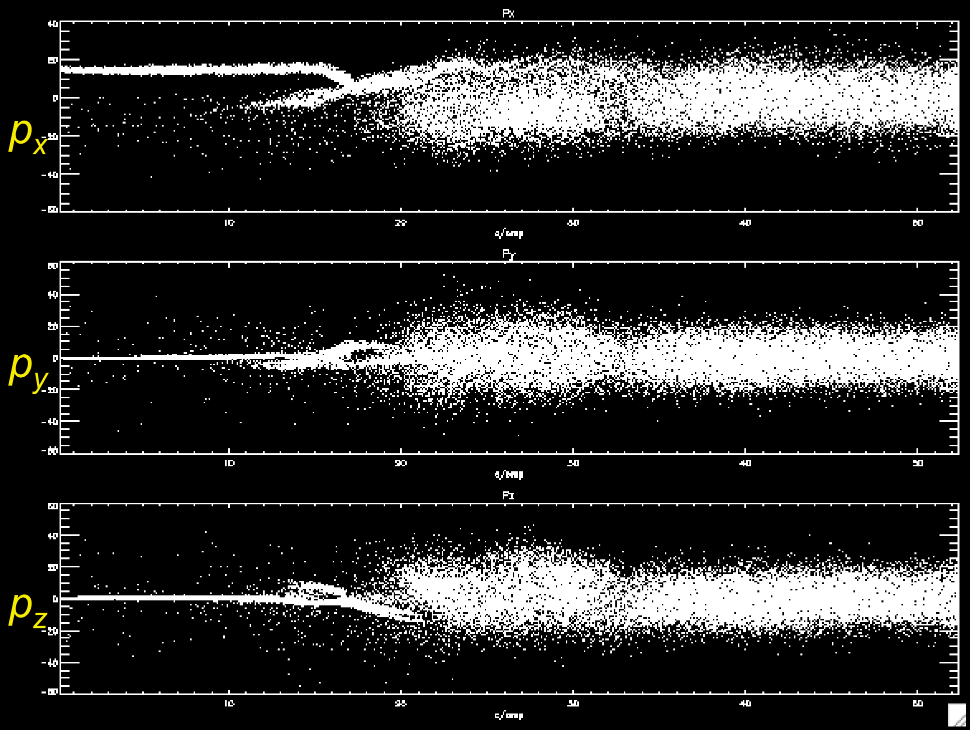




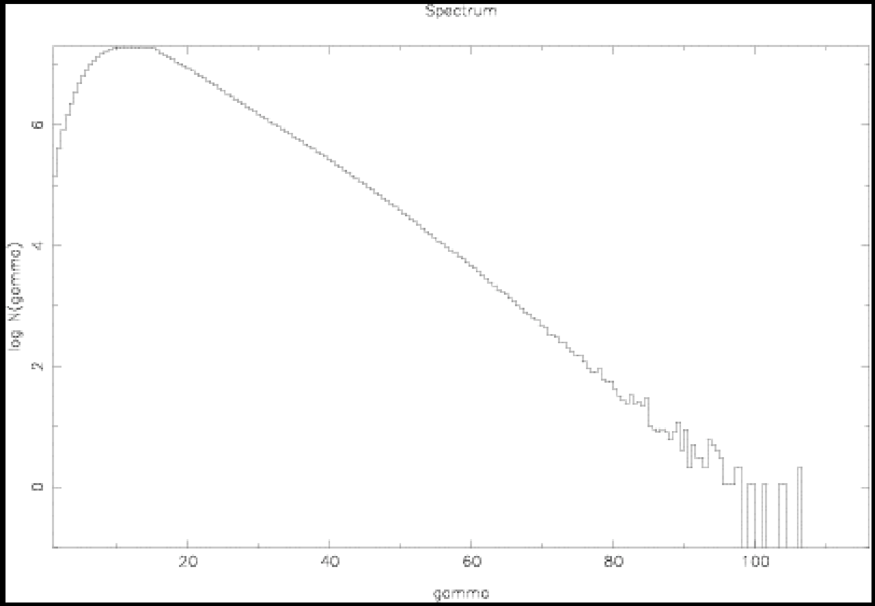
Weibel instability generates subequipartition B fields that decay. Asymptotic value is nonzero (see Medvedev et al 04): competition between diffusion and inverse cascade.

Unmagnetized pair shock

Particle acceleration



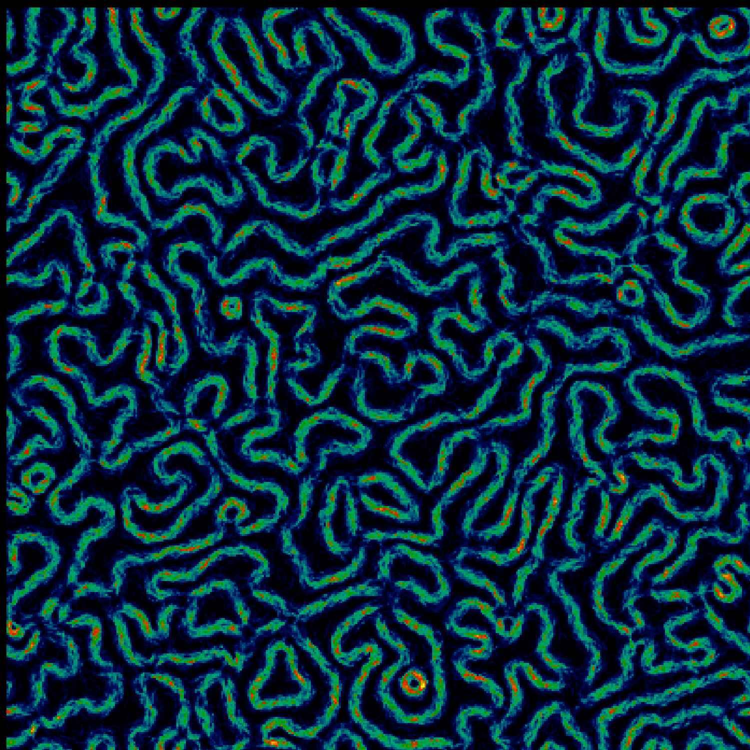
Particle spectrum

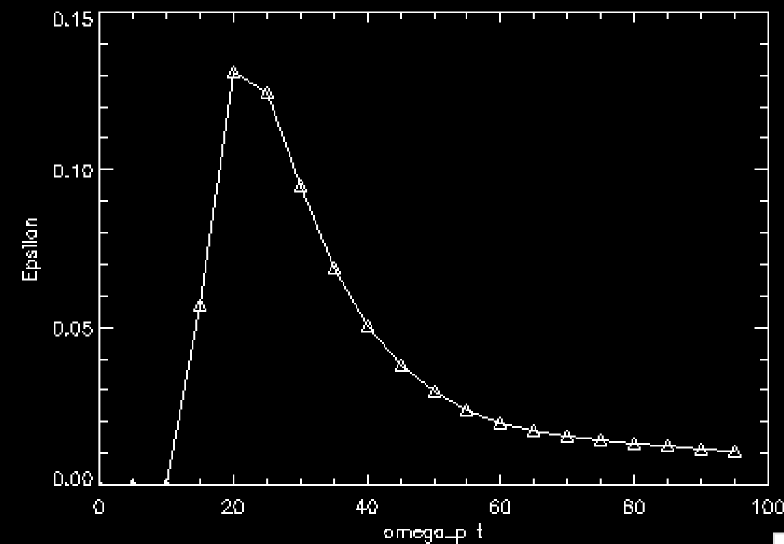


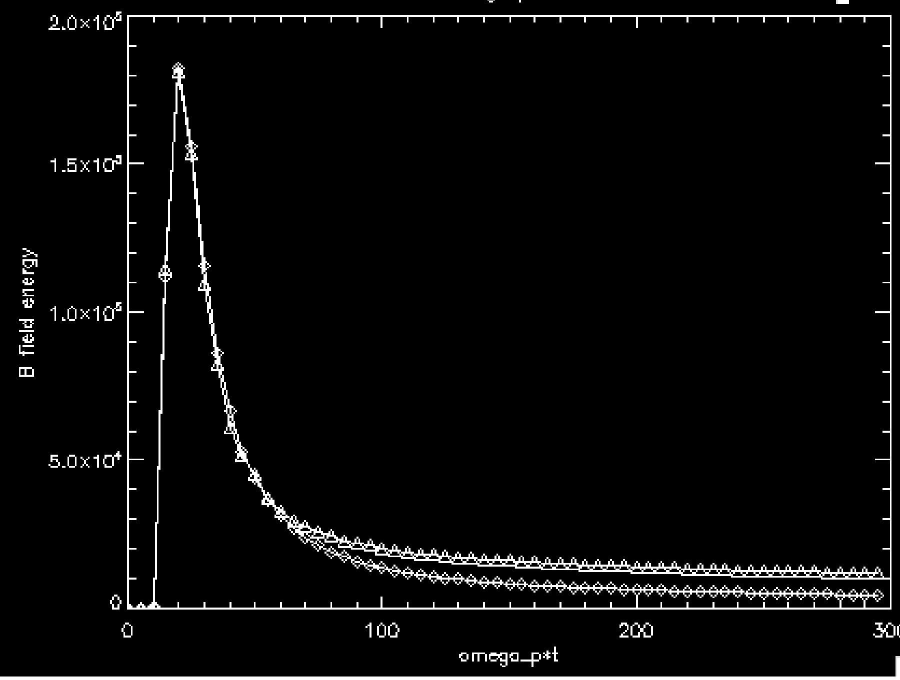
No nonthermal tail is created, particles are efficiently thermalized by interacting with the Weibel magnetic field. Thermalization leads to particle with energies upto 4kT

Evolution of magnetic field

Field cascades from c/ω_p scale to larger scale due to current filament merging. Decay of field energy $\langle B^2 \rangle \propto t^{-0.8}$. 2D simulation 240x240$c/\omega_p$:



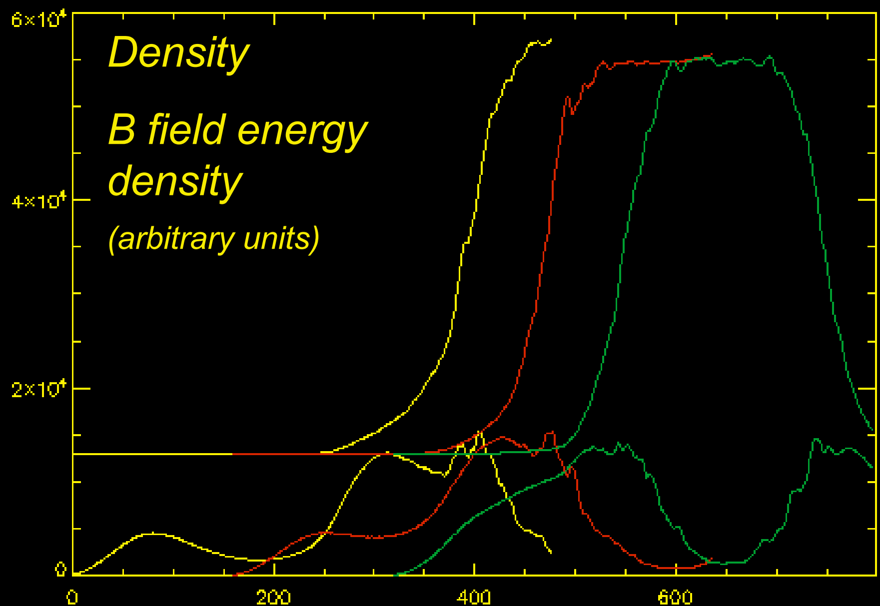


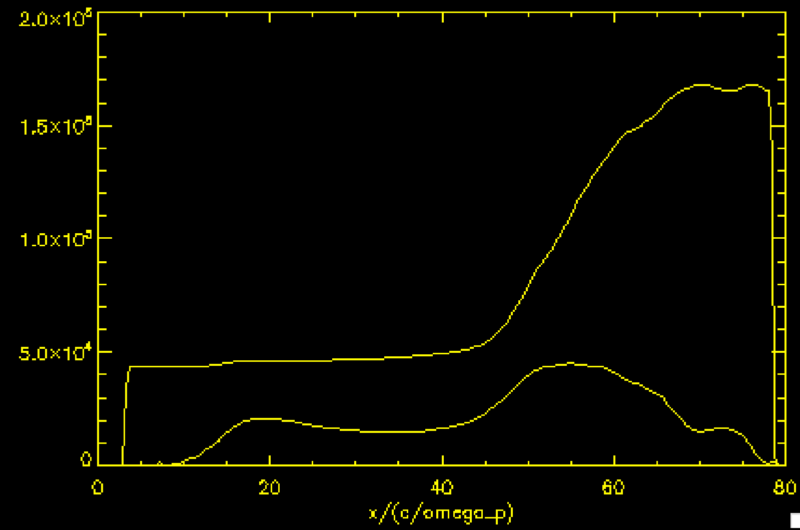


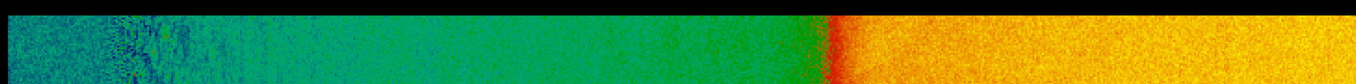
At late times field energy continues to decay below 0.5% equipartition, albeit slowly. It is not clear whether asymptotic value exists in simulations.

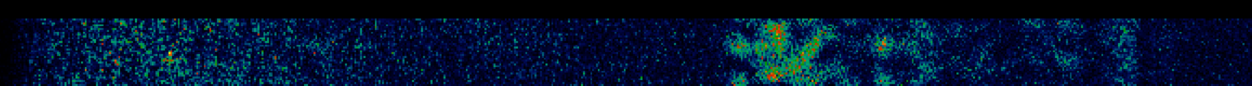
Shock structure: precursor

Streaming particles from the initial shell plow through the upstream medium, creating turbulence. This modifies shock jump conditions. These particles always outrun the shock.



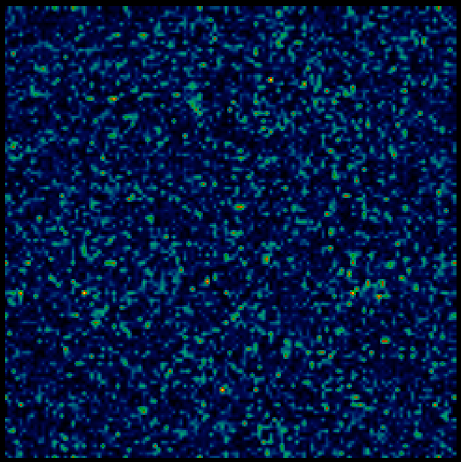


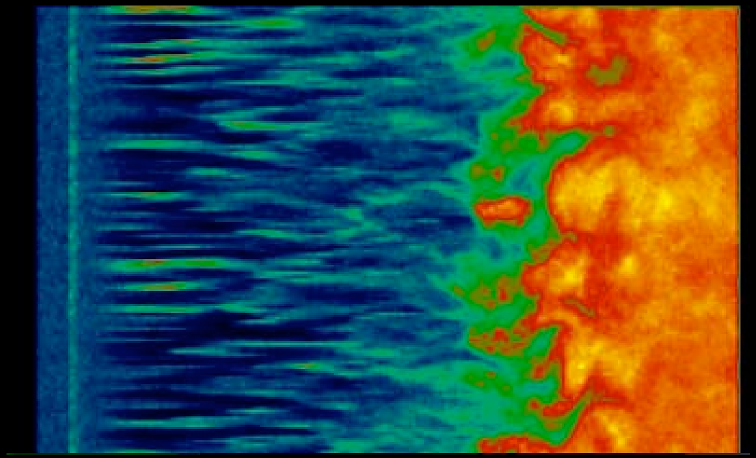


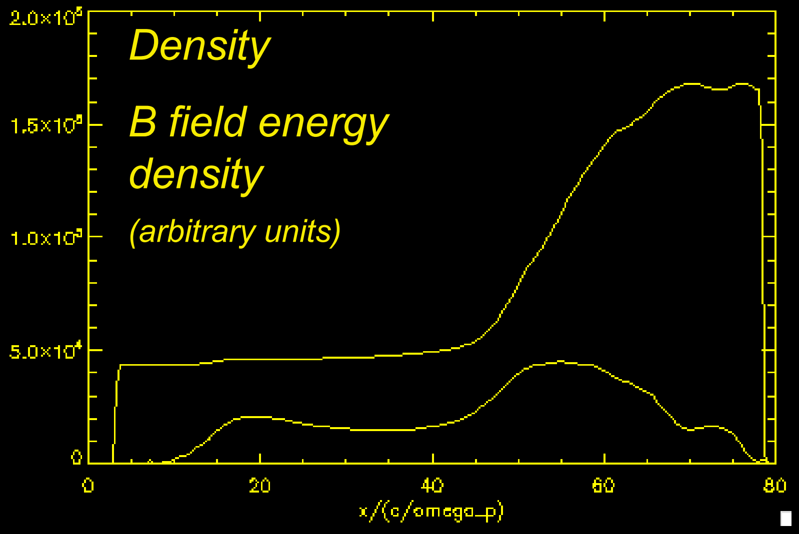


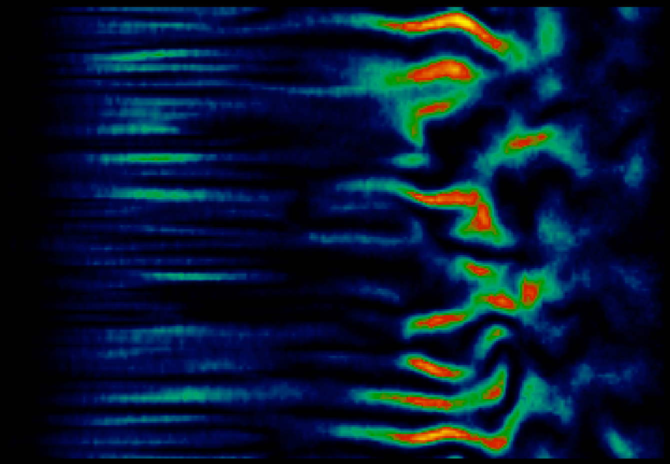
3D shock structure

Evolution of field energy through the 3D shock structure, including the precursor.







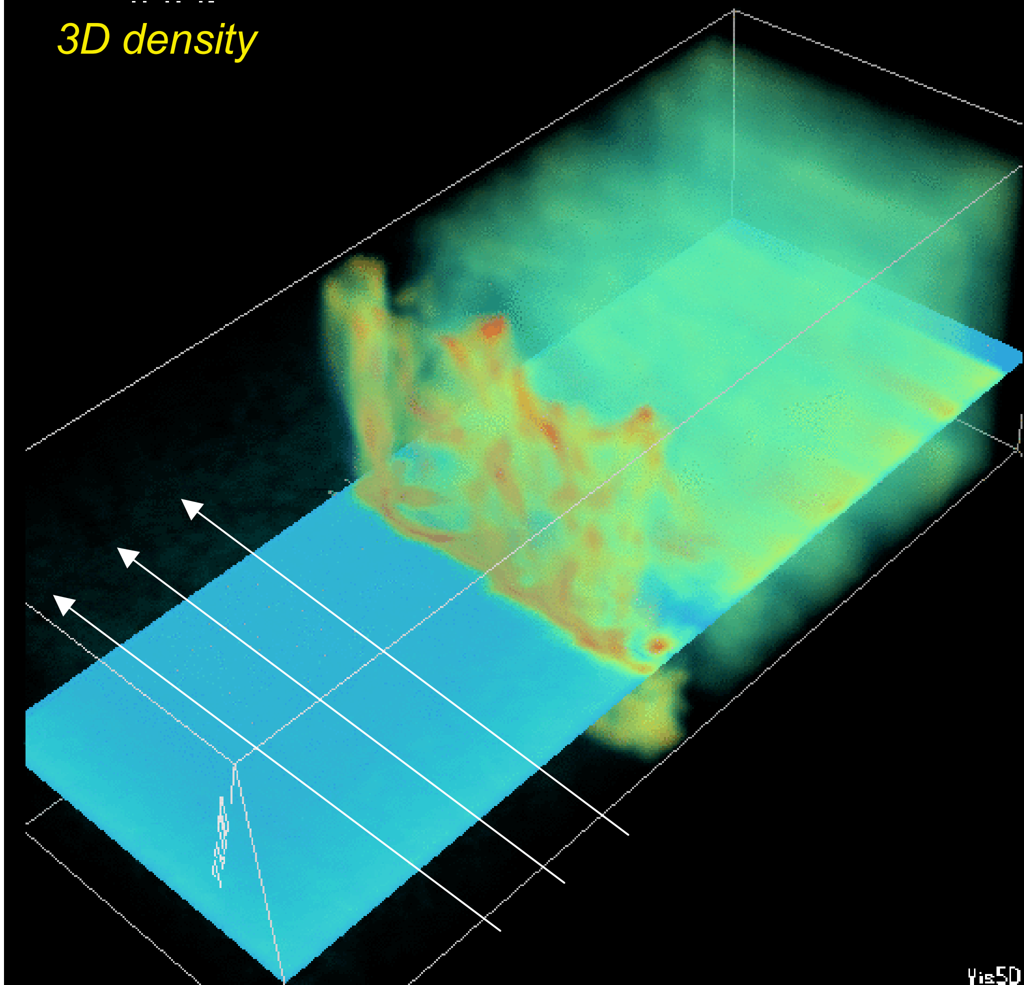


Upstream turbulence created by the precursor may be important for particle acceleration.

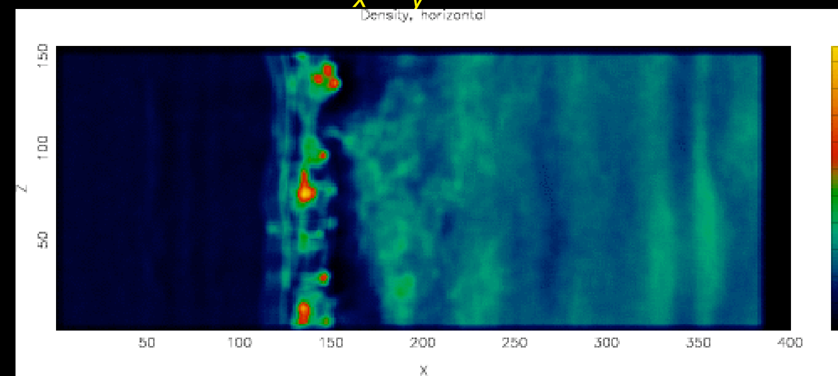
Magnetized perpendicular pair shock

Shock structure σ=0.1

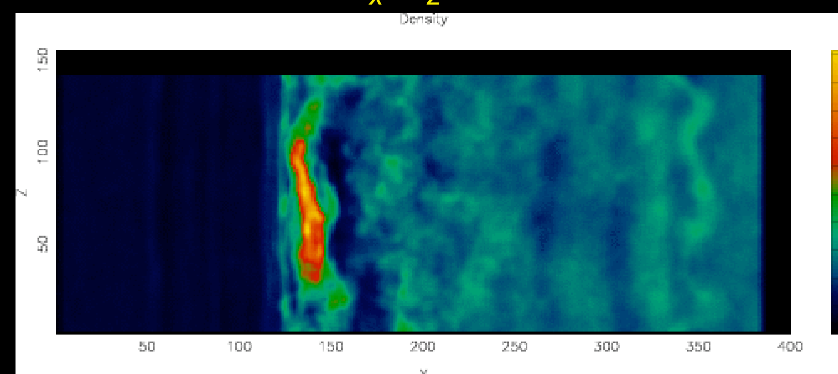
3D density



Plane of v_x-B_y



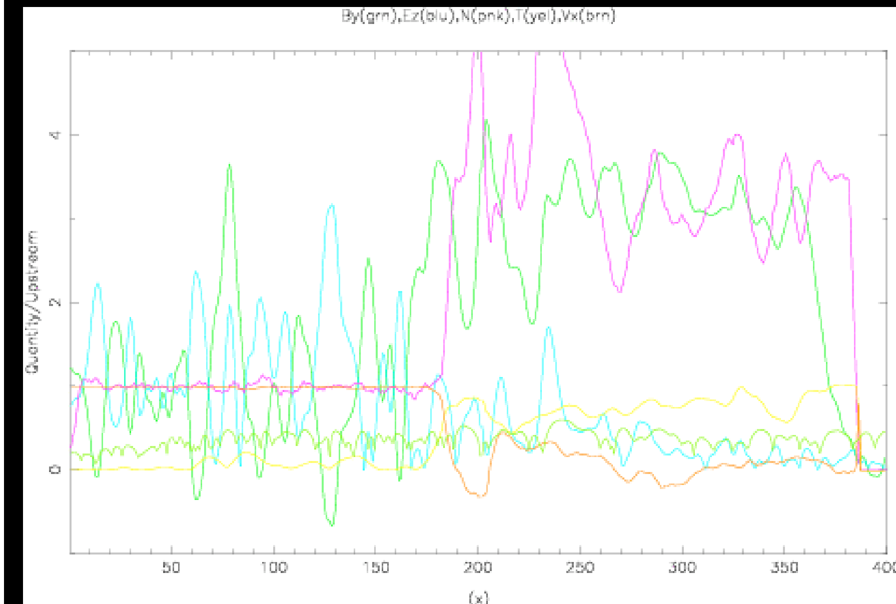
Plane of v_x-E_z

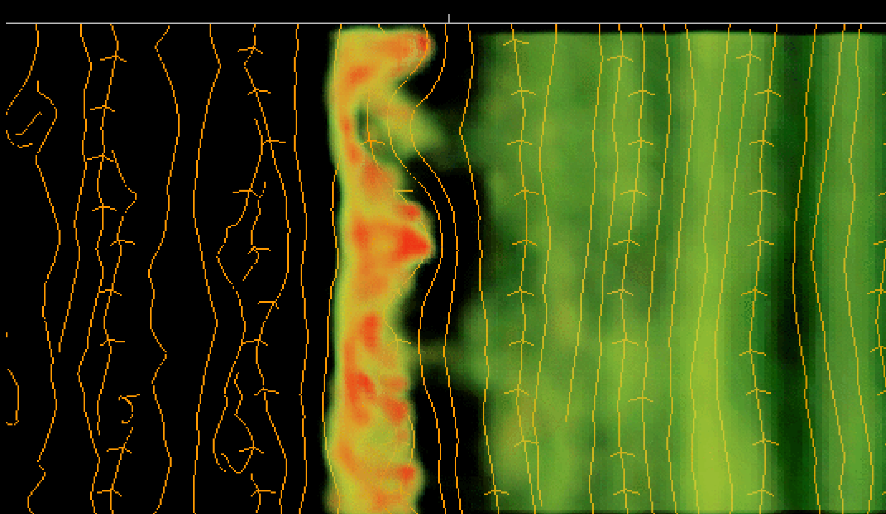


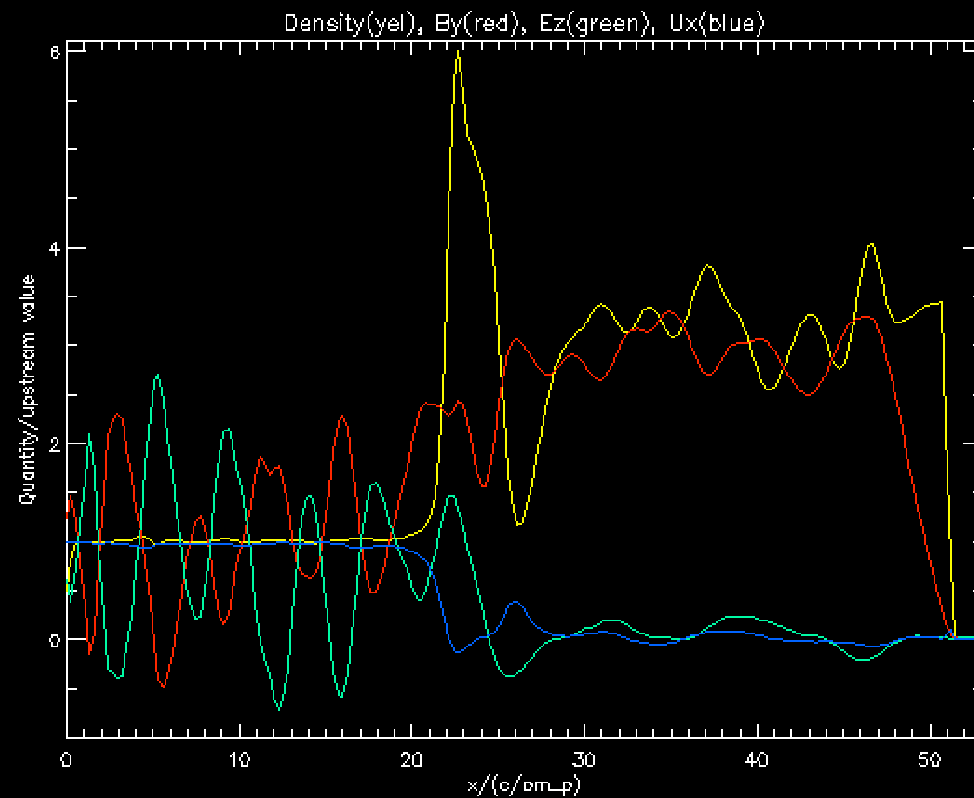
Shock is clearly magnetized -- anisotropy with respect to B.

Magnetized perpendicular pair shock

Shock structure σ=0.1 -- electromagnetic precursor



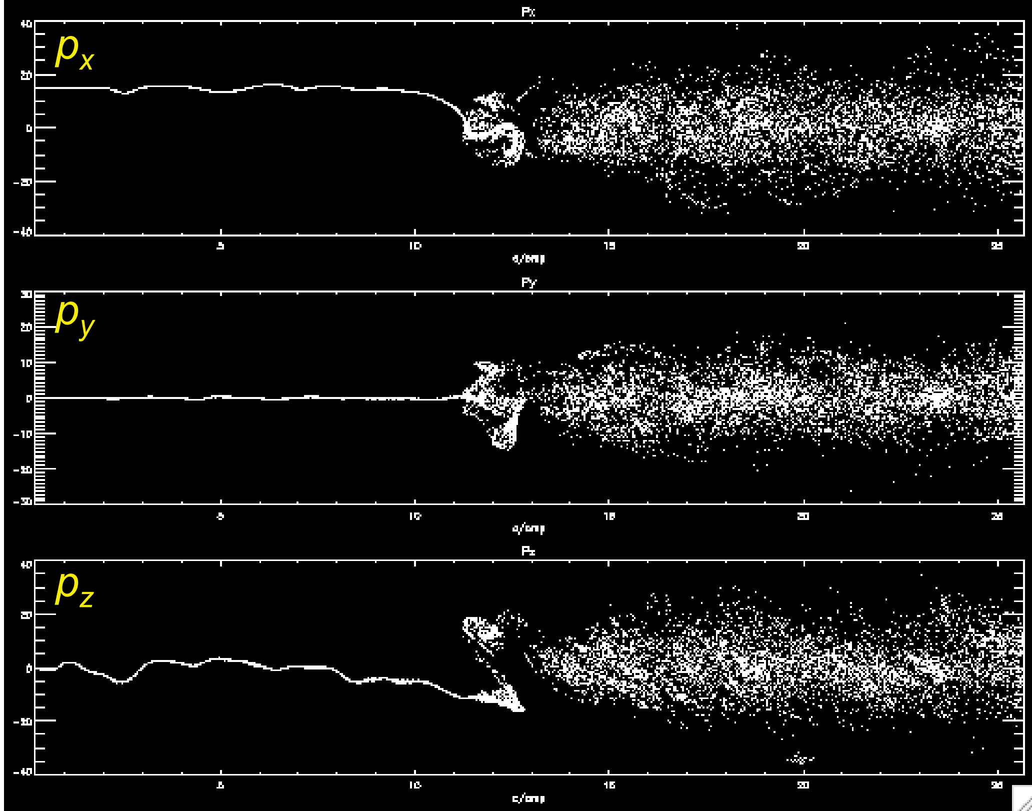


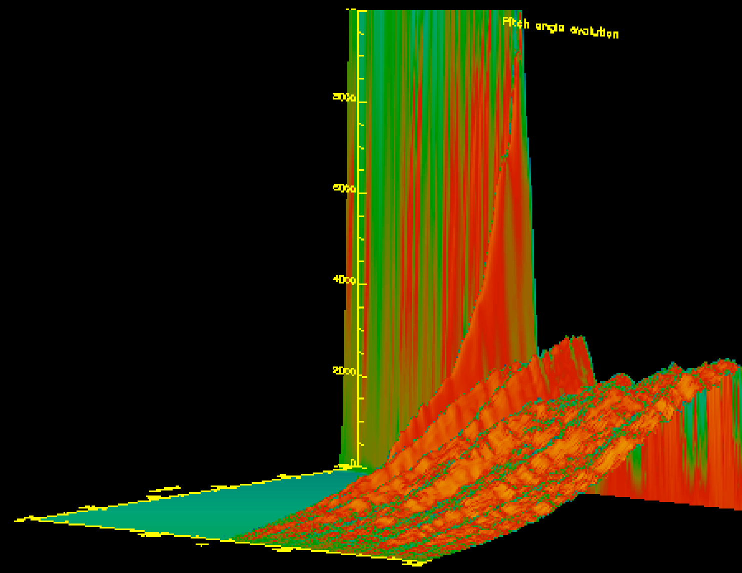


Shock compression is ~3. Plasma is quasi-2D with Γ=3/2

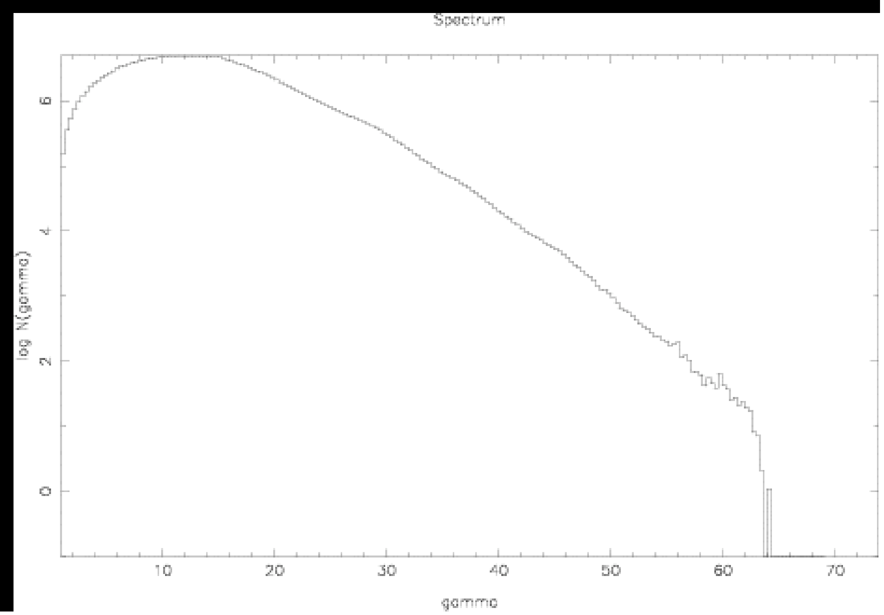
Magnetized perpendicular pair shock

Shock structure σ=0.1 -- particle phase space



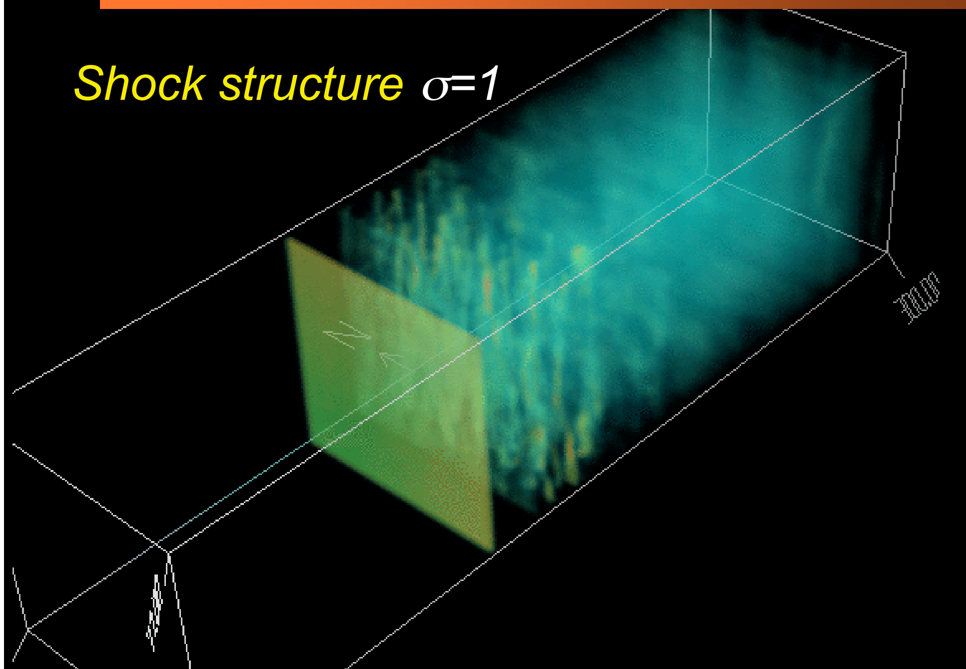


Shock structure dominated by magnetic reflections as in 1D. No nonthermal acceleration even in 3D.

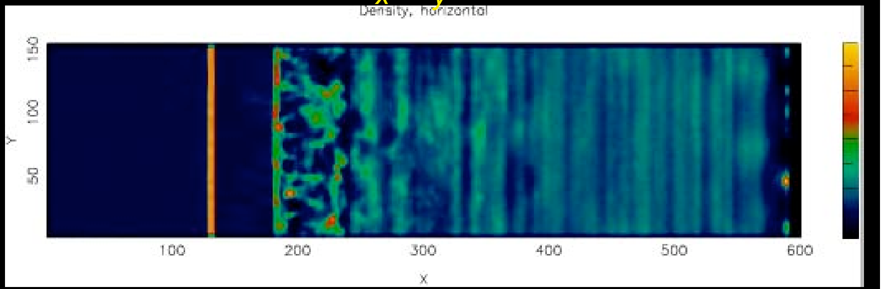


Magnetized perpendicular pair shock

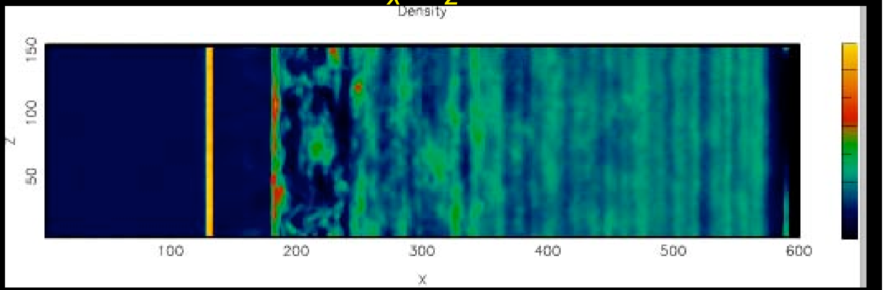
Shock structure σ=1

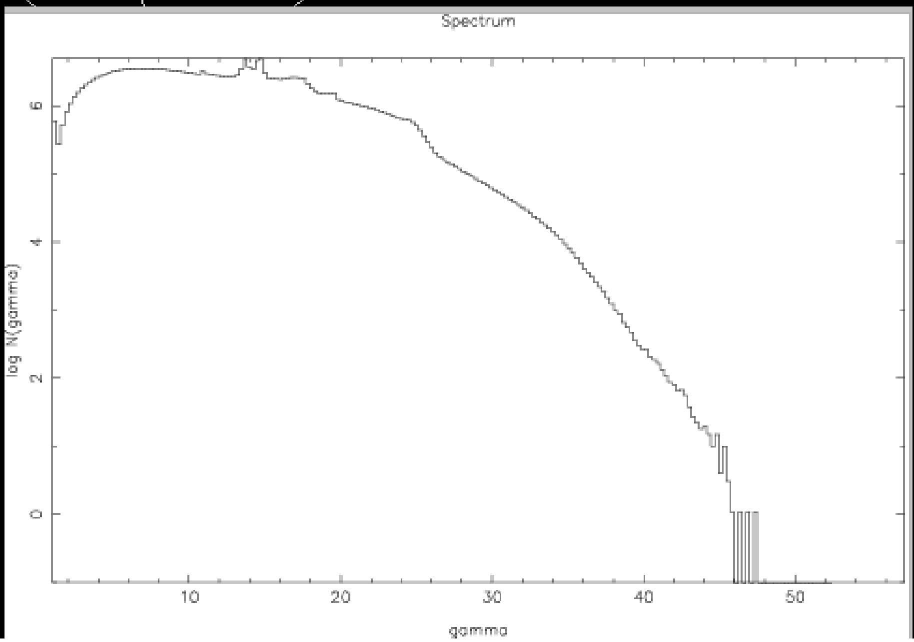


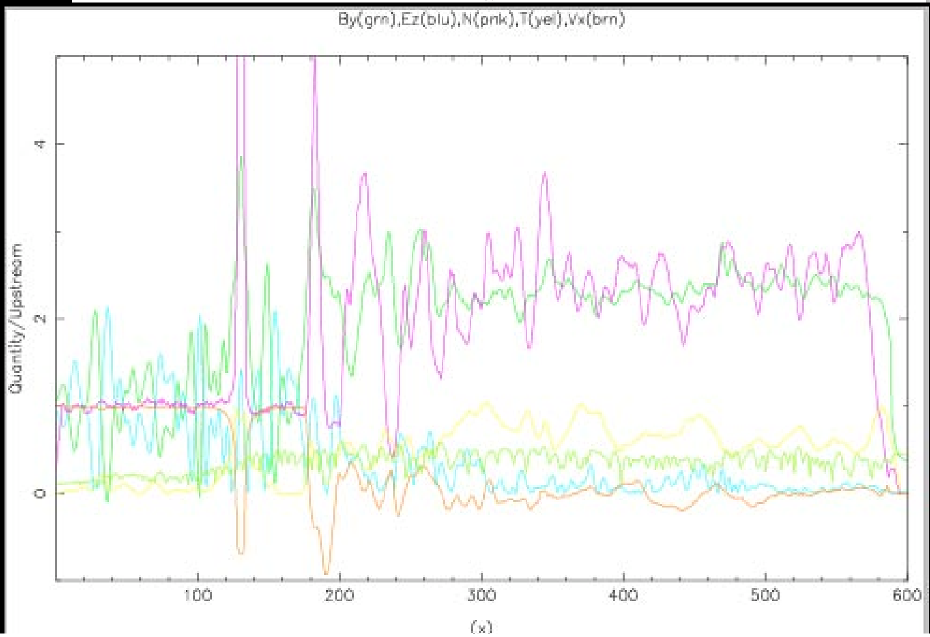
Plane of v_x-B_y



Plane of v_x-E_z

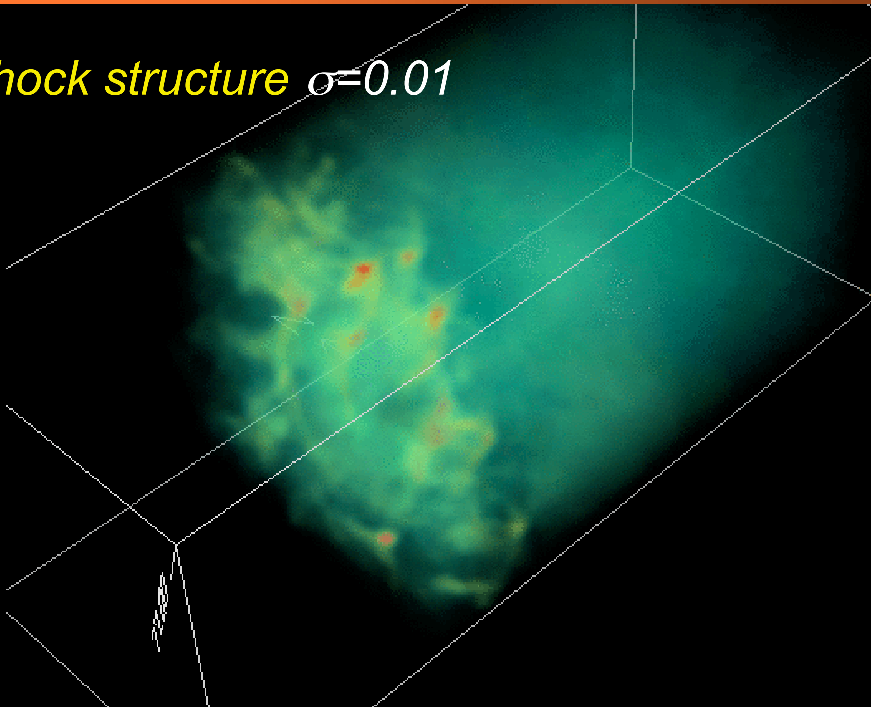




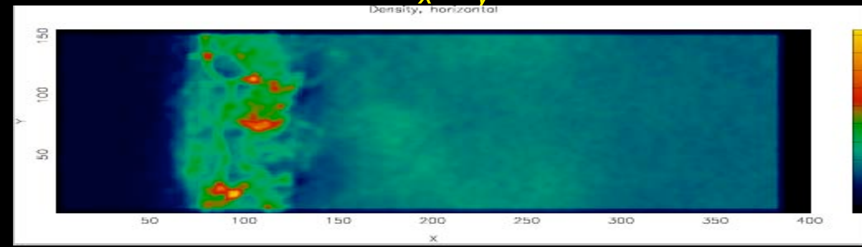


Magnetized perpendicular pair shock

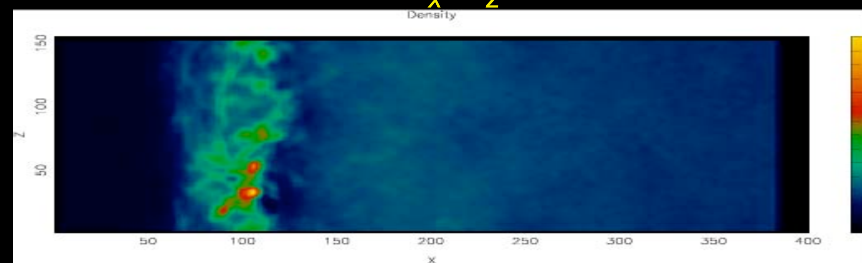
Shock structure σ=0.01

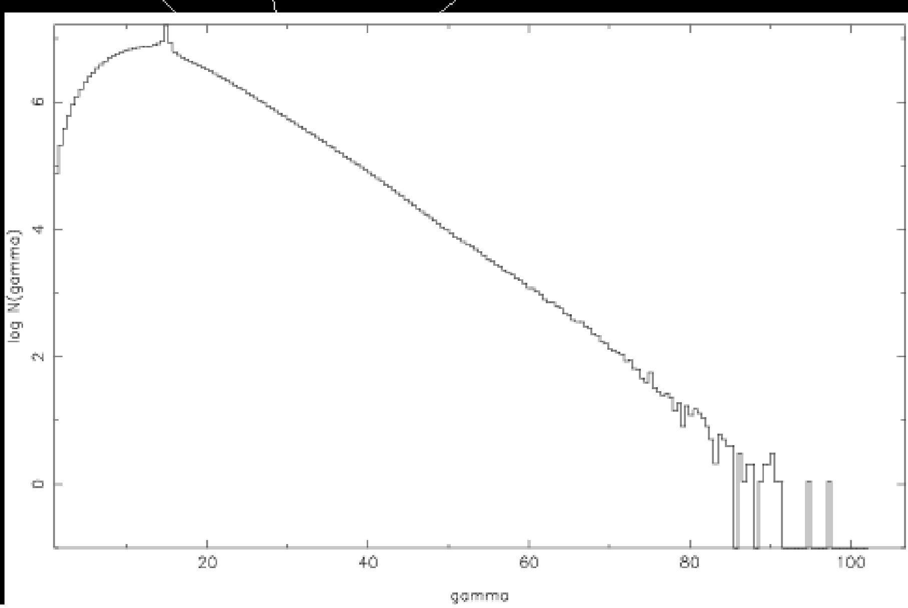


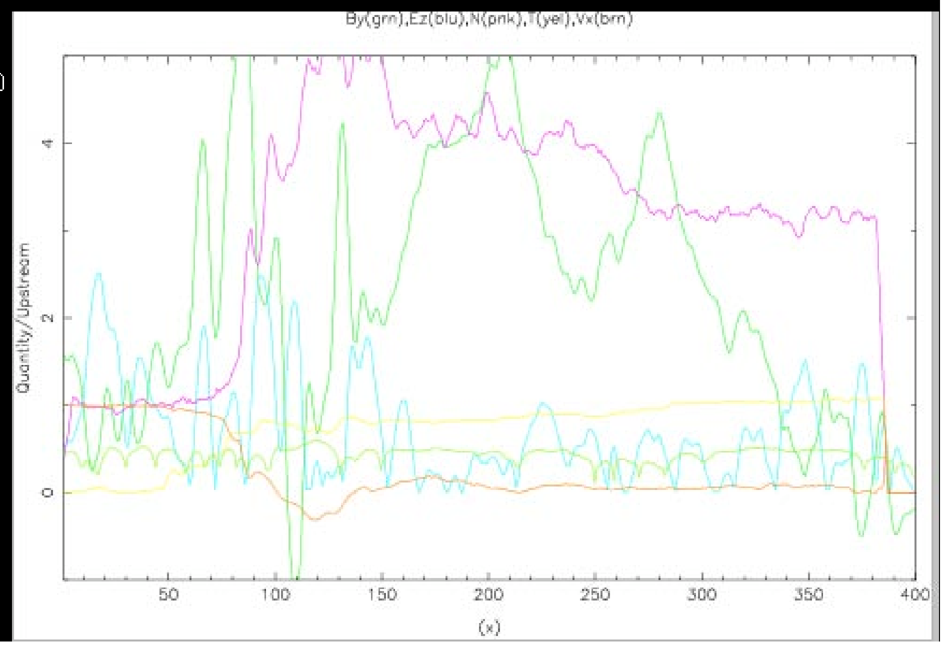
Plane of v_x-B_y



Plane of v_x-E_z

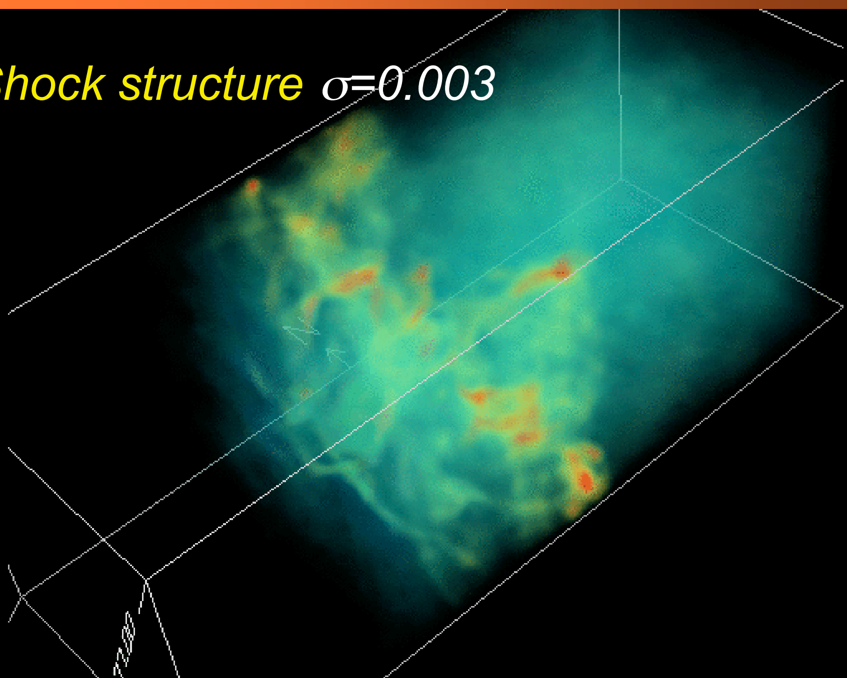




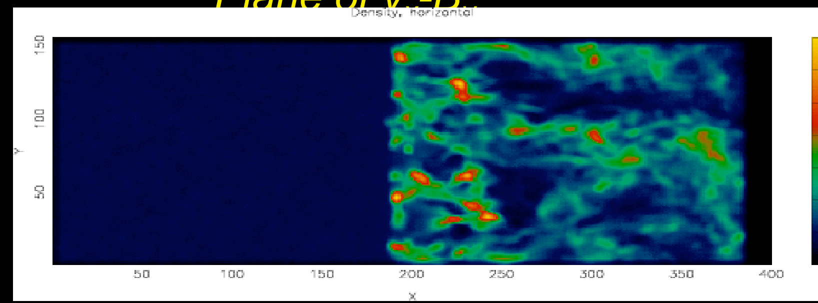


Magnetized perpendicular pair shock

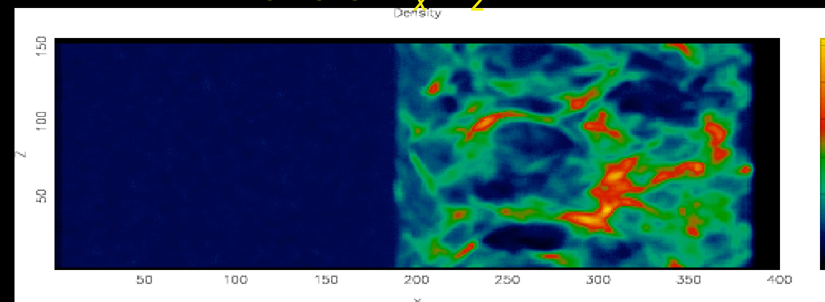
Shock structure σ*=0.003*

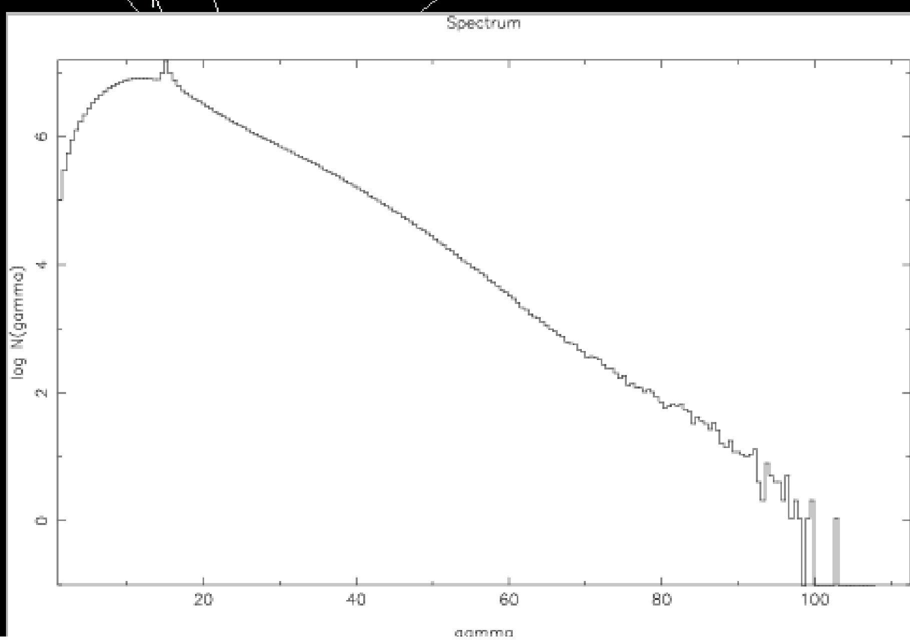


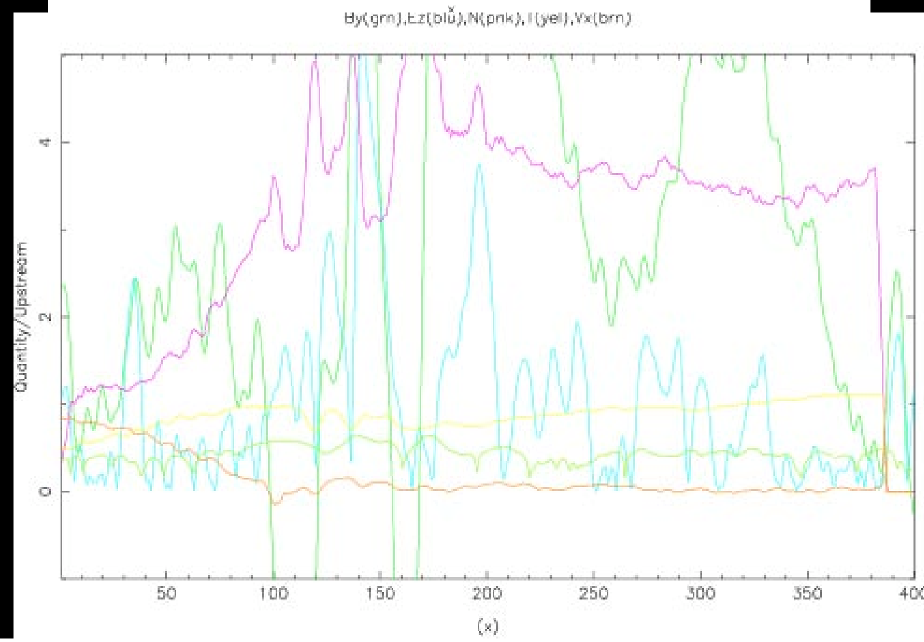
Plane of v_x*-*B_y



Plane of v_x*-*E_z







Perpendicular pair shocks: conclusions

Shock structure is controlled by magnetization parameter $\sigma = \omega_c^2 / \omega_p^2 = B^2/(4\pi n \gamma m c^2)$

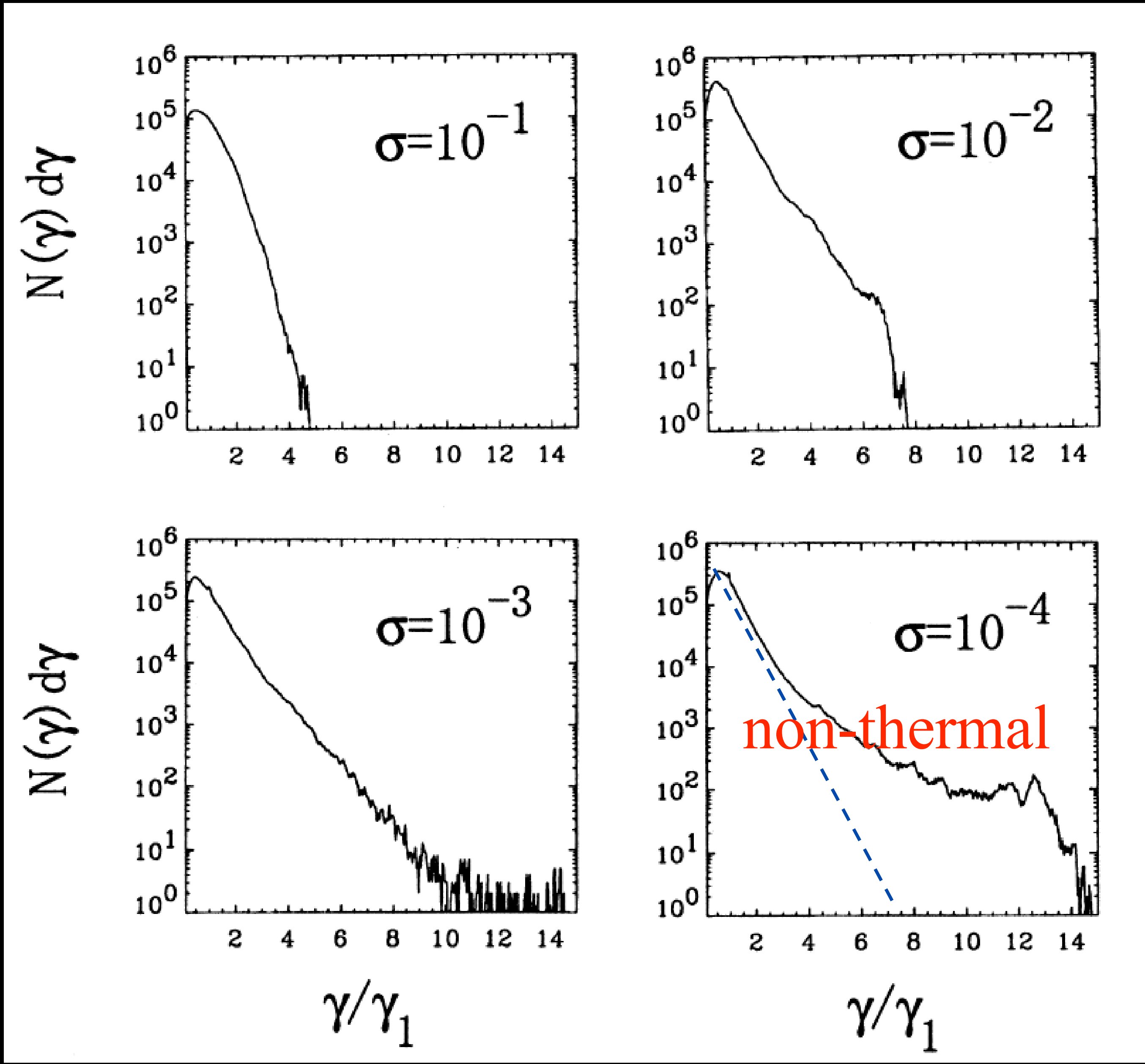
$\sigma < 0.005$ *pair shocks are effectively unmagnetized. Such shocks don't have coherent magnetic overshoots characteristic of higher magnetization shocks (cf also Hededal & Nishikawa 05)*

Roughly, if the Larmor radius is comparable to the Weibel shock lengthscale ($>20c/\omega_p$*) Weibel instability dominates.*

Interestingly, even though in 1D coherent low magnetization shocks are possible, in 3D they cannot exist -- Weibel instability dominates and significantly perturbs the field.

1D studies of shock-drifting acceleration in low-sigma shocks are suspect because of this

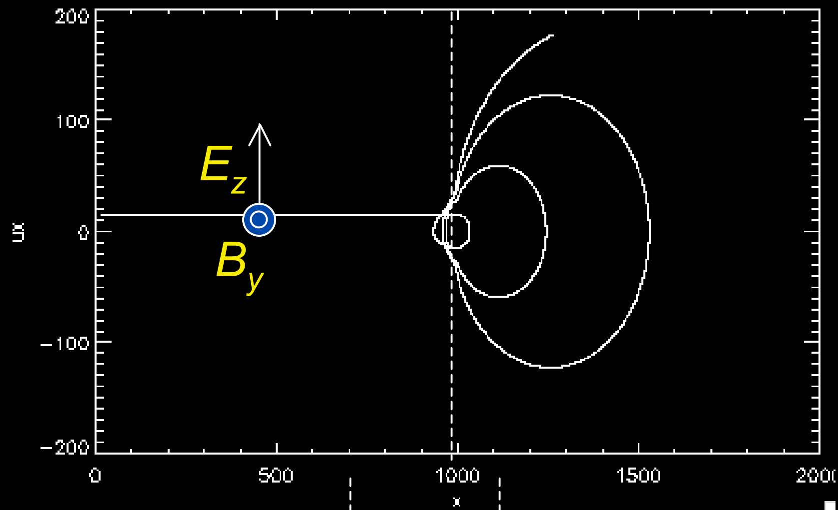
Perpendicular pair shocks: conclusions

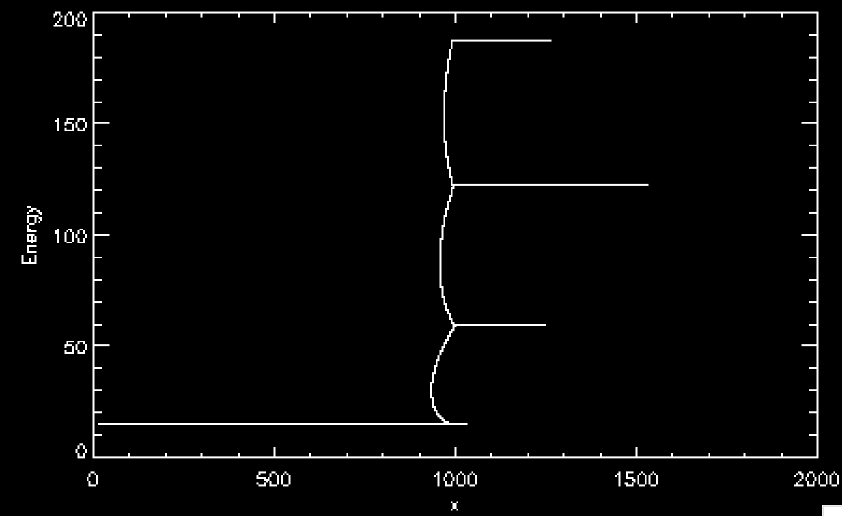


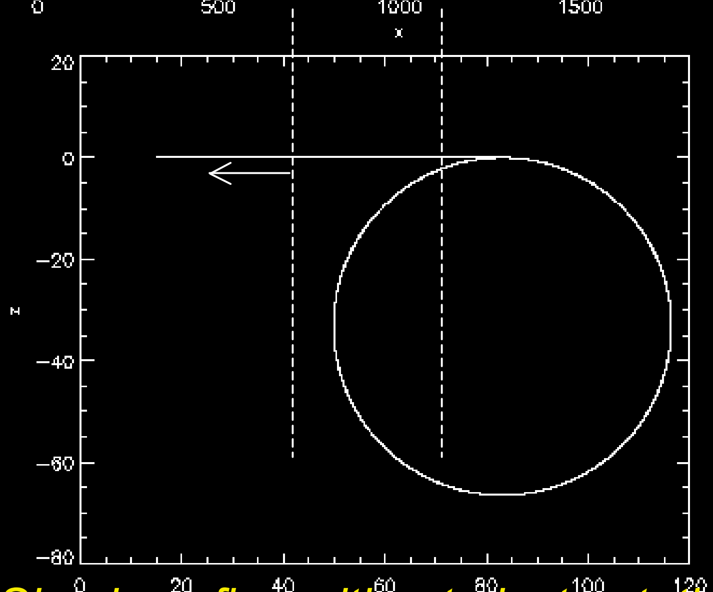
Hoshino 2002

Shock acceleration failure

Is it the injection problem? Perhaps high-energy preaccelerated particles will have easier time crossing the shock?







In order to outrun a moving shock, need

$$v_{sh} T < r_L = c/\omega_c$$

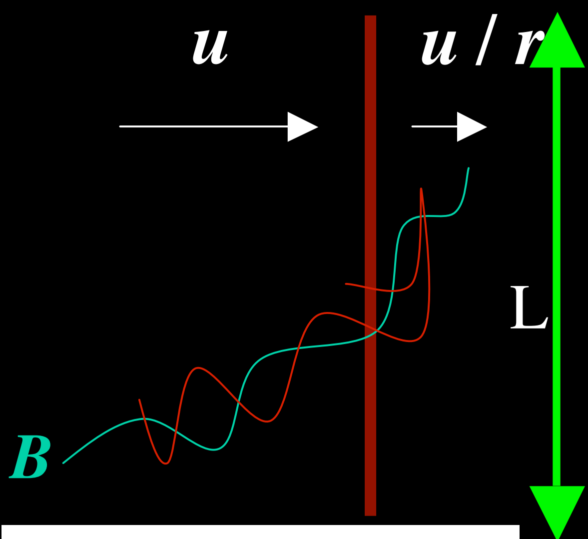
$$\frac{T_L}{2} < T < \frac{3T_L}{4} \qquad T_L = \frac{2\pi}{\omega_c}$$

$$v_{sh} < \frac{c/\omega_c}{\pi/\omega_c} = \frac{c}{\pi}$$

Shock surfing without electrostatic trap will only work in nonrelativistic shocks!

First-order Fermi acceleration

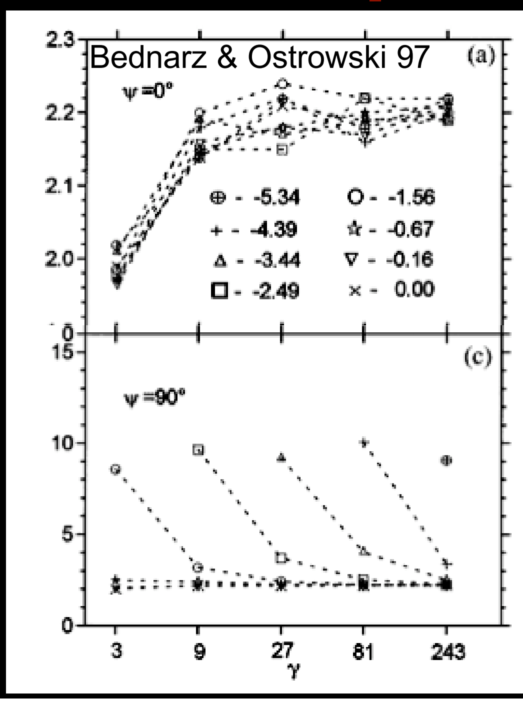
Fermi acceleration in converging flows produces power-laws with universal index



$$t_{cyc}\frac{dF}{dt} = -\langle \Delta p \rangle \frac{\partial F}{\partial p} - P_{esc}F = 0 \qquad F(p) = \int_p^{\infty} f(p_1)dp_1$$

$$f(p) \propto p^{-n}, \qquad n = 1 + \frac{pP_{esc}}{\langle \Delta p \rangle} = \frac{r+2}{r-1}, \qquad r = \frac{u_1}{u_2}$$

Classic mechanism assumes isotropic distribution in the rest frame of the flow -- not true for relativistic shocks



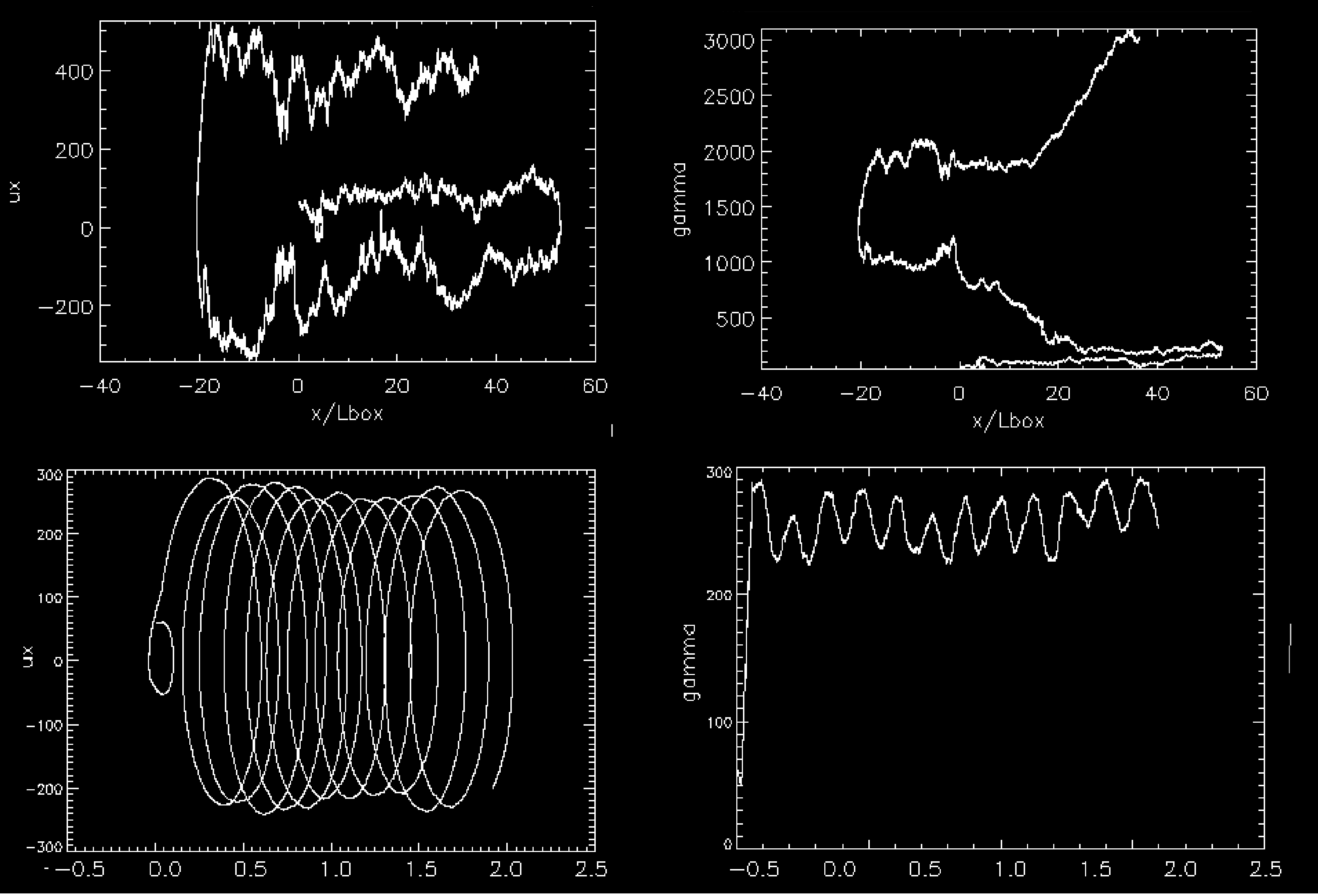
Monte-Carlo simulations have been used to study test-particle acceleration in shocks with assumed turbulence sturcture (Ostrowski et al 1990+, Heavens & Drury 1988). Index 2.2 is recovered in asymptotic limit (Bednarz & Ostrowski 1997). Sensitivity to turbulence level (Niemiec & Ostrowski 2004)

Recently, Keshet & Waxman 04 got the same index analytically:

$$n = (3\beta_u - 2\beta_u\beta_d^2 + \beta_d^3)/(\beta_u - \beta_d) - 2 \rightarrow \frac{20}{9} = 2.22$$

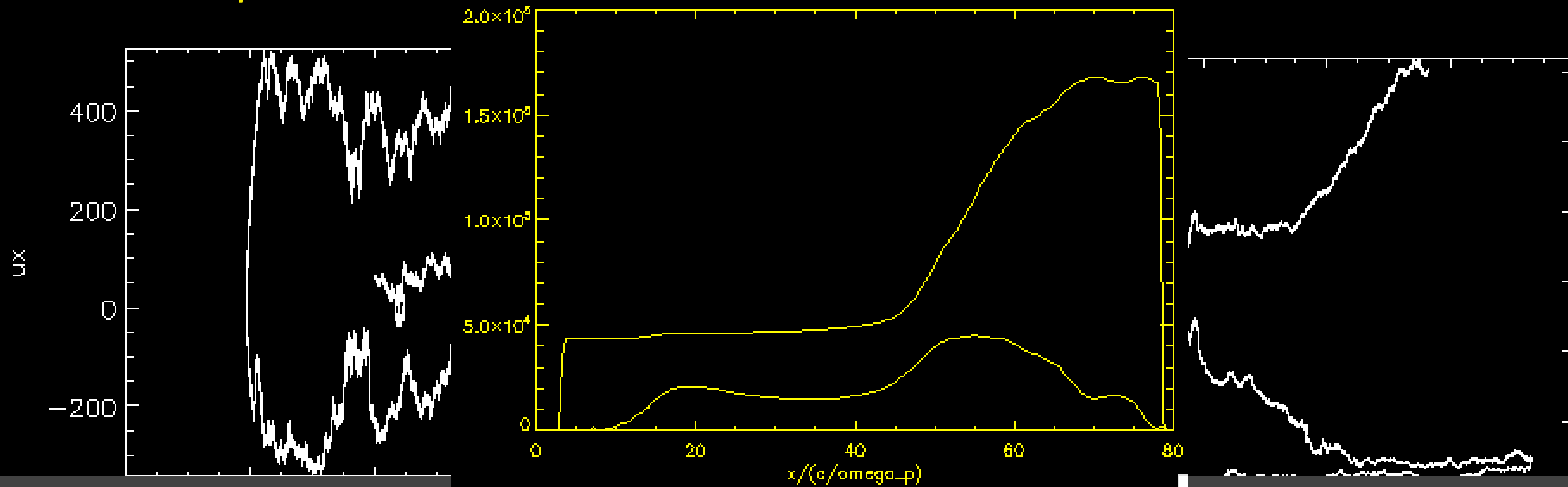
Diffusive shock acceleration

Both test-particle and analytic analysis assumes efficient diffusion and scattering



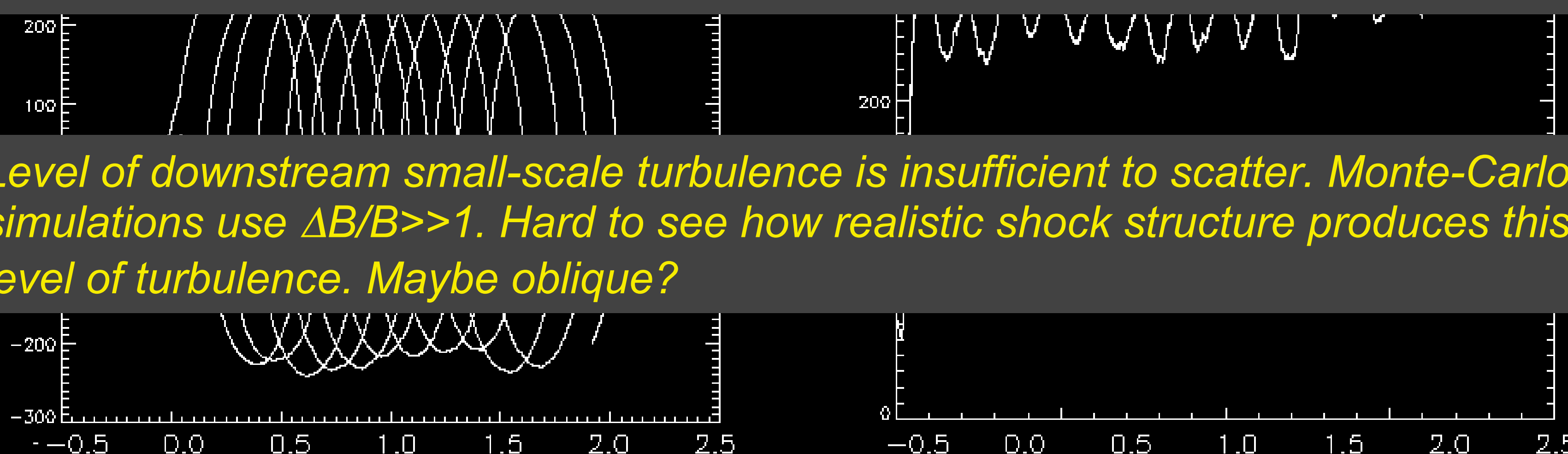
Diffusive shock acceleration

Both test-particle and analytic analysis assumes efficient diffusion and scattering



Assume upstream turbulence from precursor to cause scattering of particles

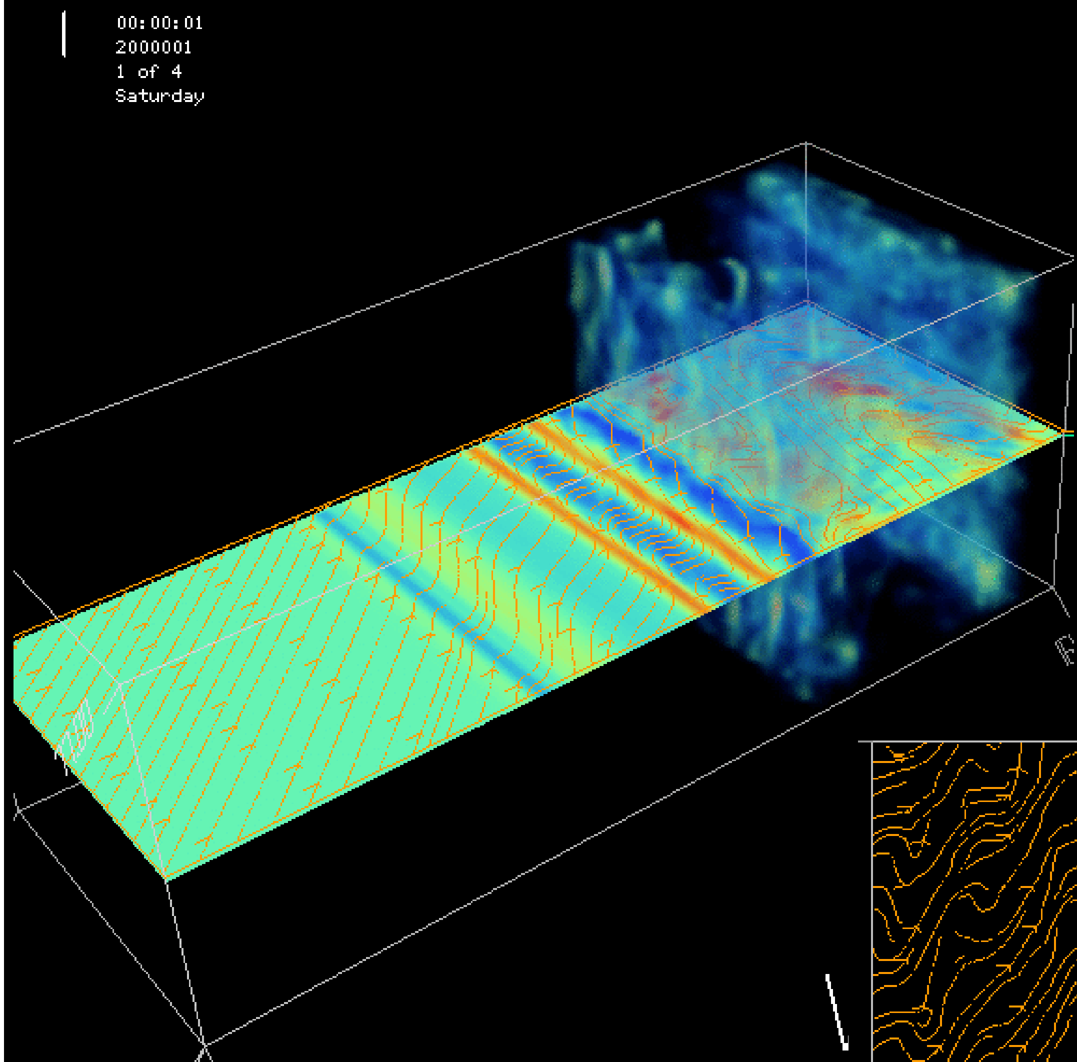
Fermi acceleration may work for unmagnetized (or oblique) shocks. Much larger box and simulation time needed!

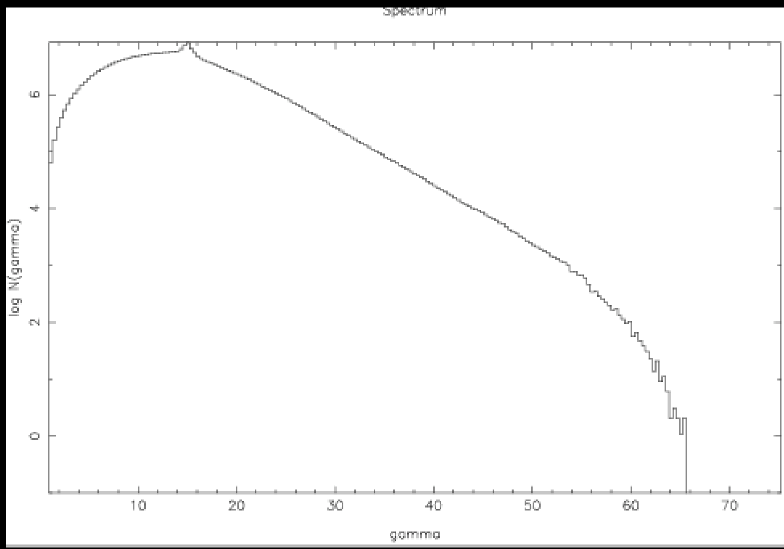


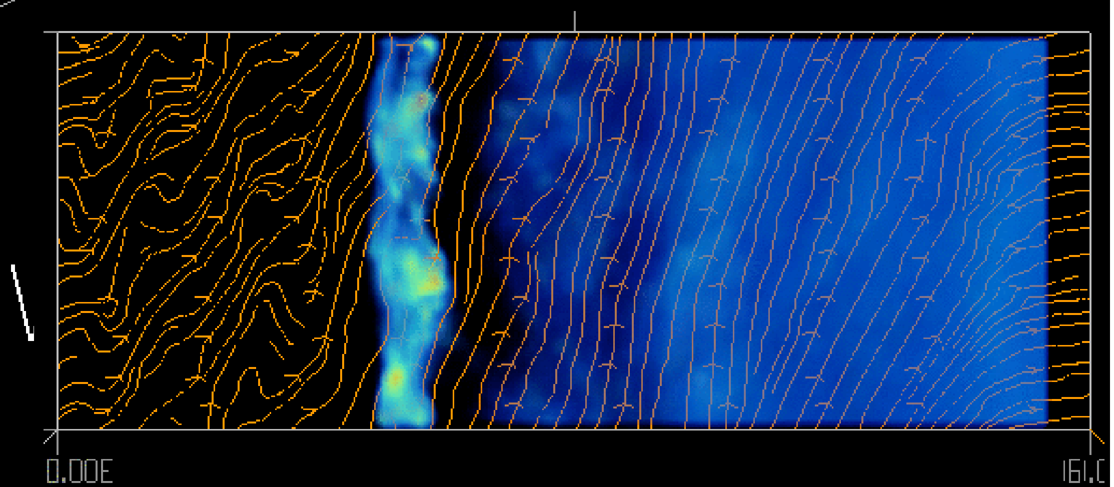
Level of downstream small-scale turbulence is insufficient to scatter. Monte-Carlo simulations use $\Delta B/B >> 1$. Hard to see how realistic shock structure produces this level of turbulence. Maybe oblique?

Oblique pair shocks

B field 45 degrees to the shock -- behaves like an orthogonal shock

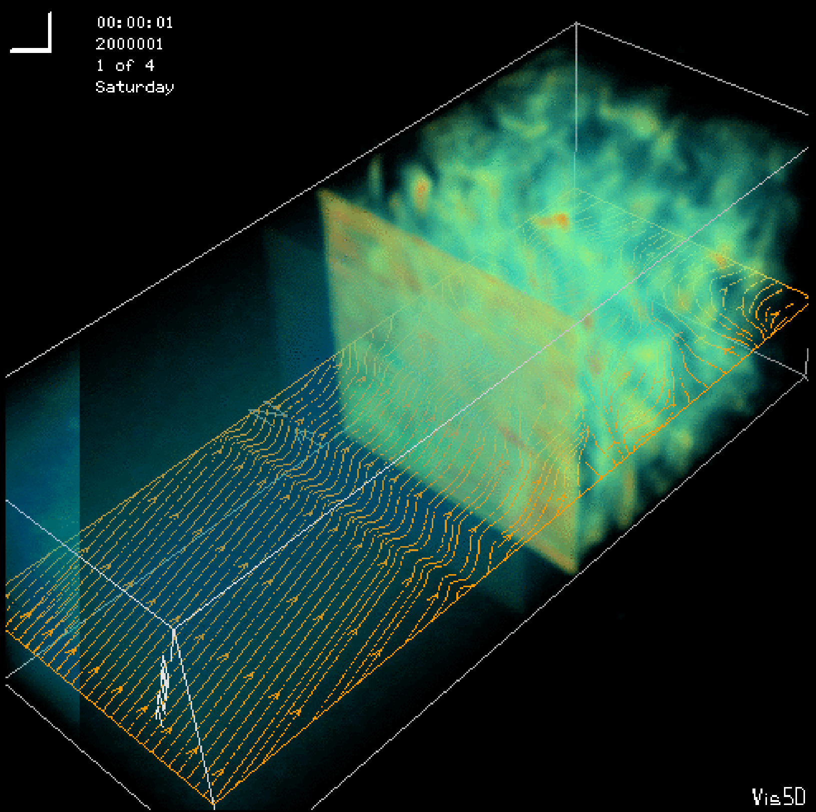


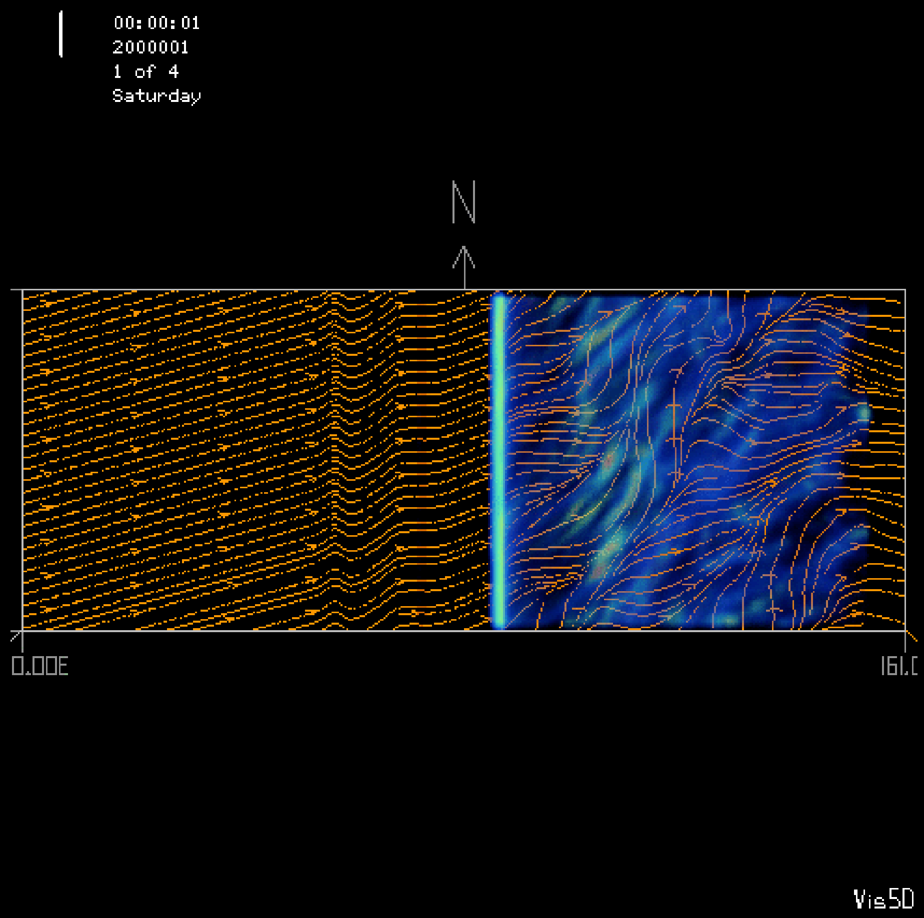




Oblique pair shocks

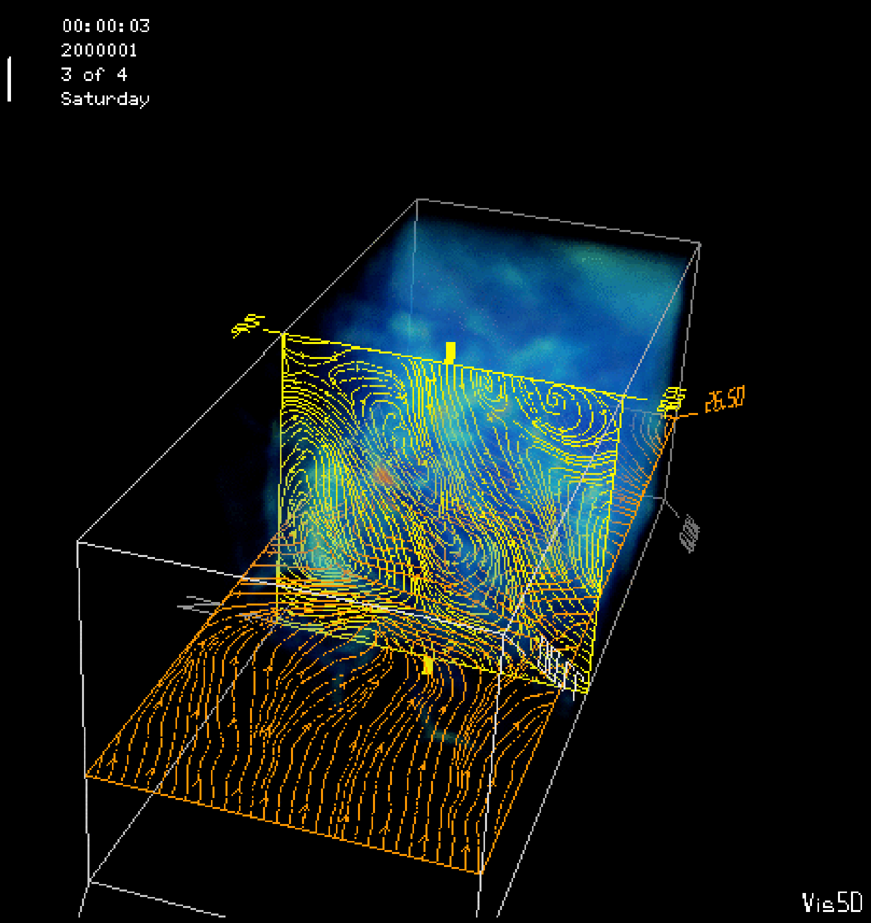
B field 15 degrees to the shock normal -- behaves like unmagnetized shock

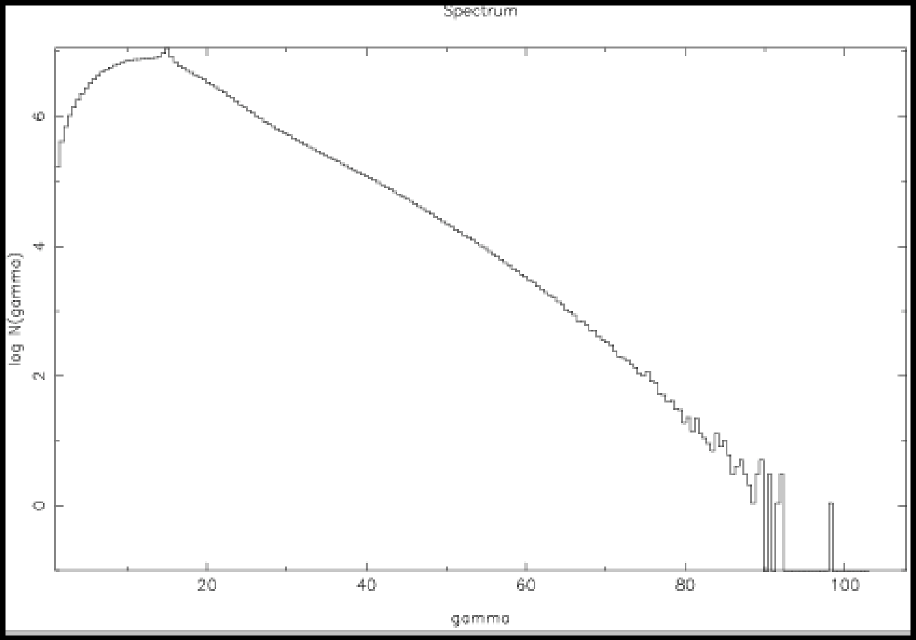




Oblique pair shocks

B field 15 degrees to the shock normal -- behaves like unmagnetized shock



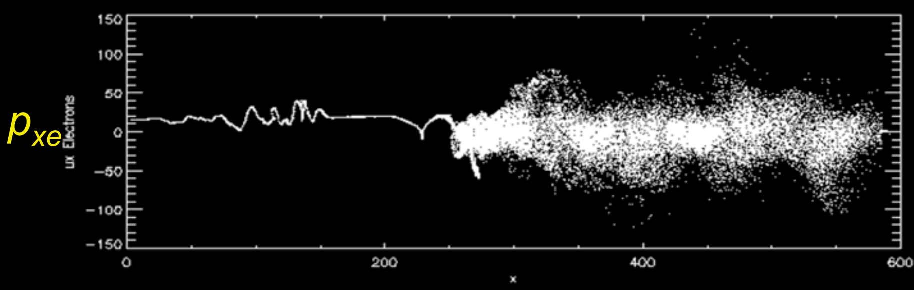


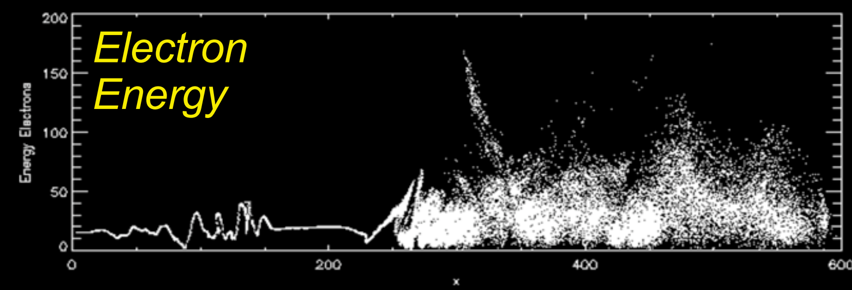
Shock structure is probably determined by the effective transverse σ

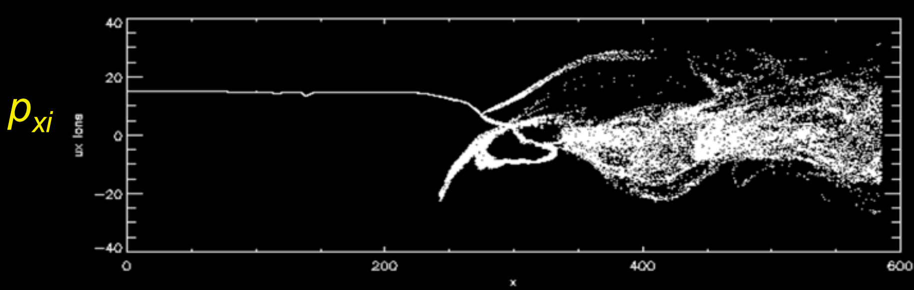
Electron-ion shocks

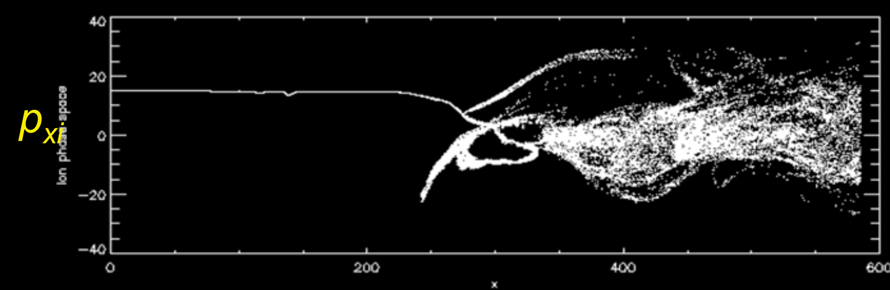
Magnetization is mainly determined by ion energy density $\sigma = B^2/(4\pi n\gamma(m_i+m_e)c^2)$

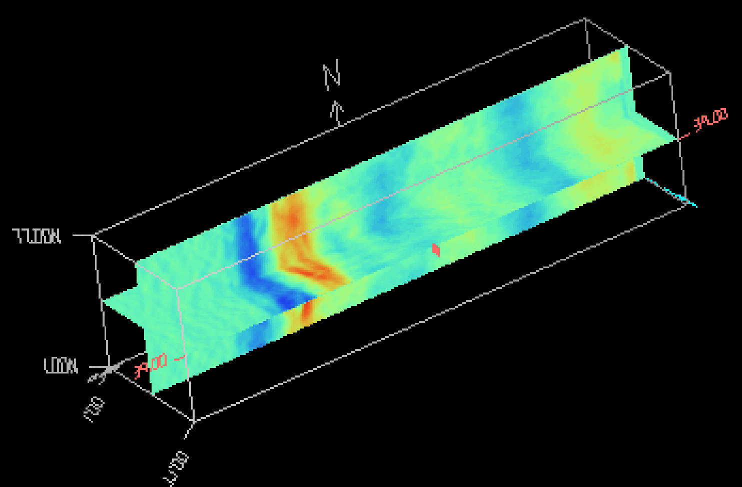
Electrons are magnetized much stronger than ions. $\sigma=0.1$

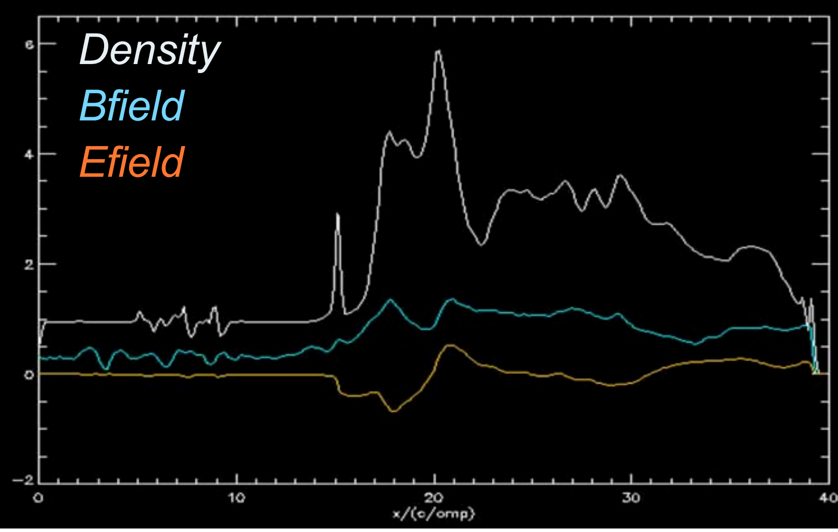








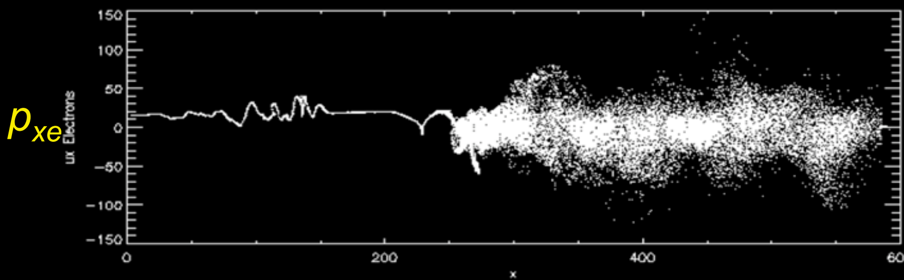


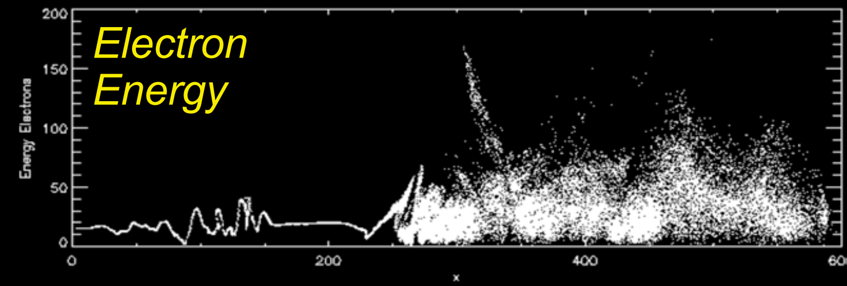


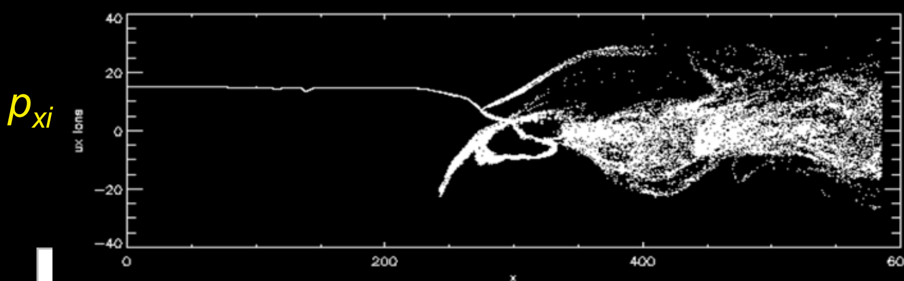
Electron-ion shocks

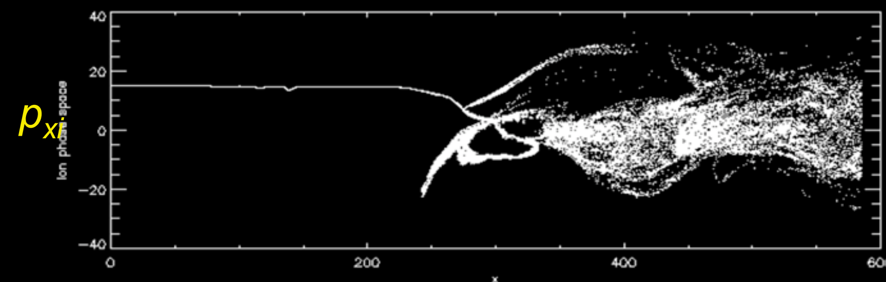
Magnetization is mainly determined by ion energy density $\sigma = B^2/(4\pi n\gamma(m_i+m_e)c^2)$

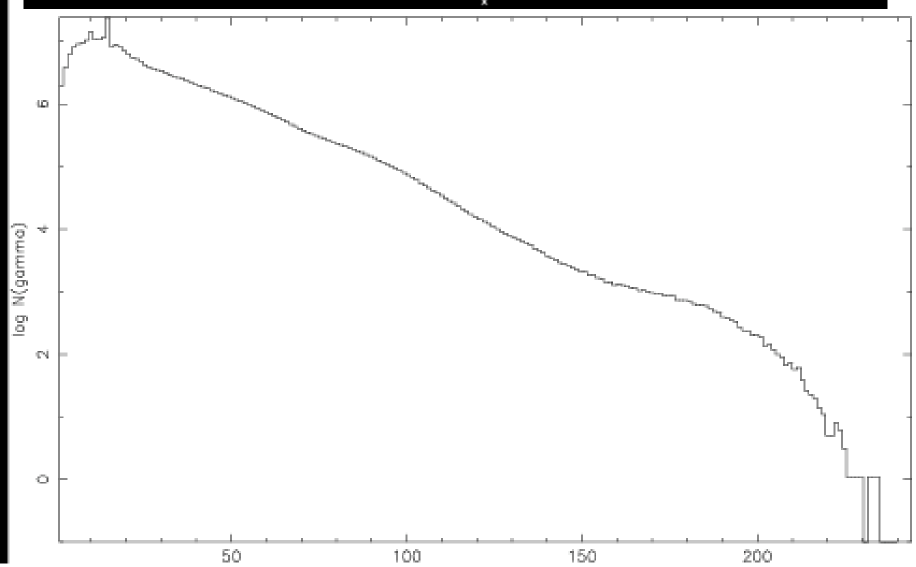
Electrons are magnetized much stronger than ions. $\sigma = 0.1$

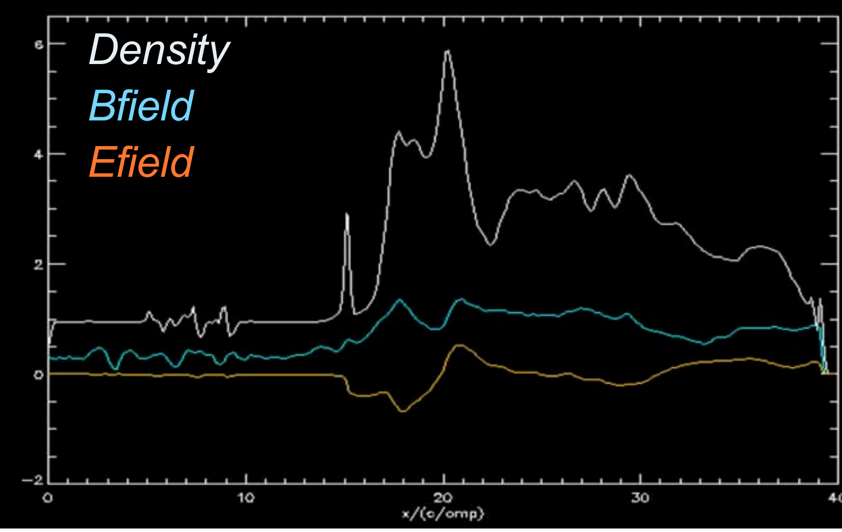






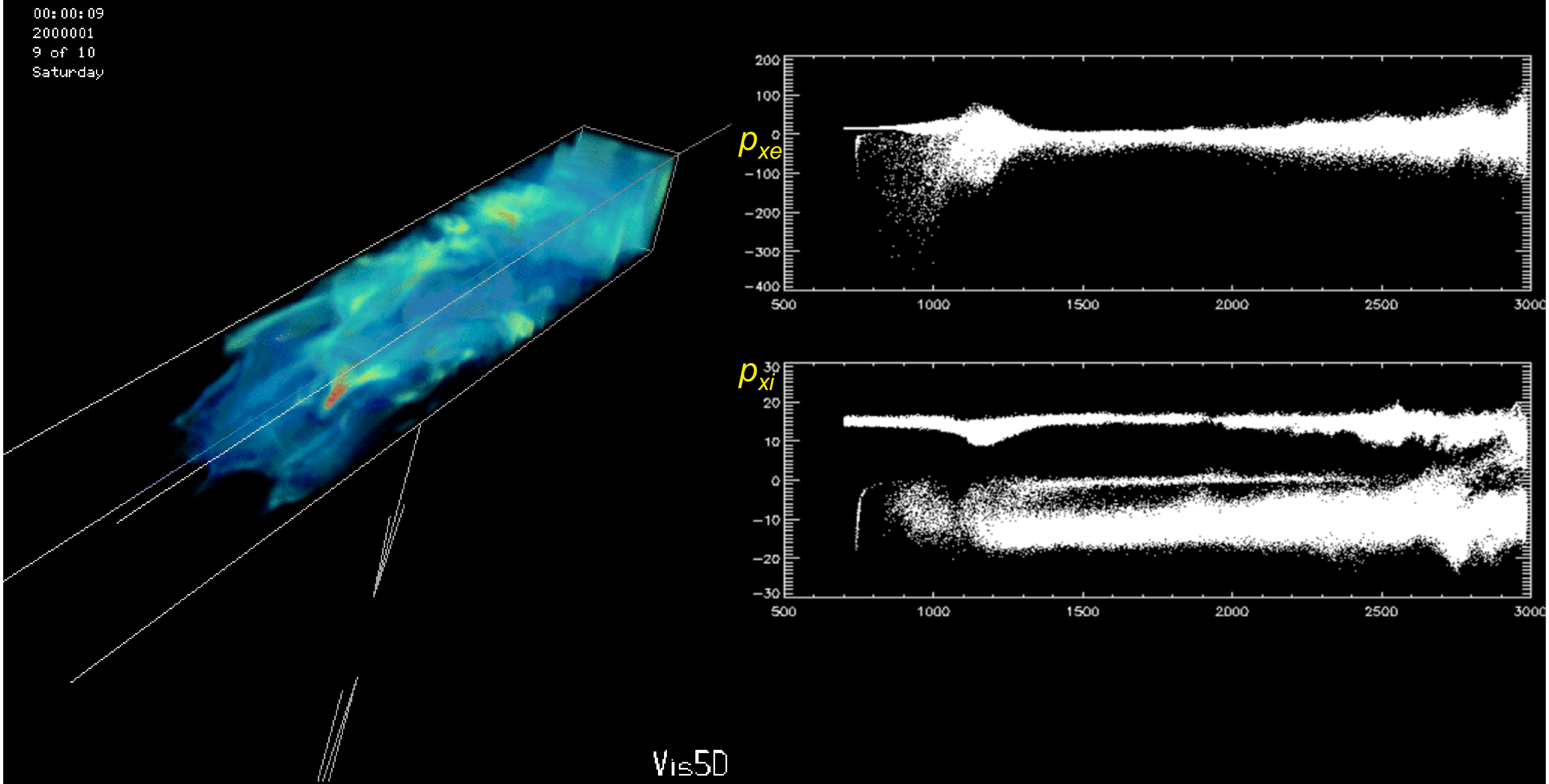






Electron-ion shocks

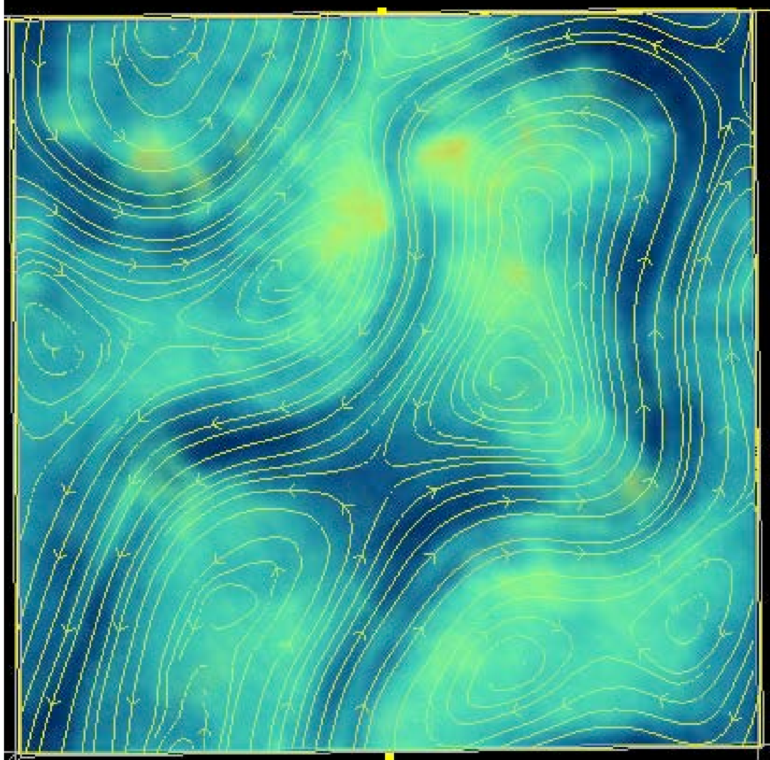
Unmagnetized ion-electron shock: $\sigma=0$, $m_i/m_e=16$



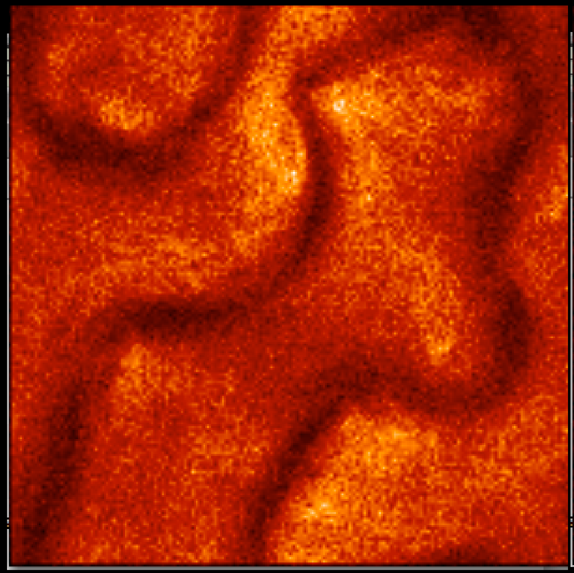
Acceleration is by non-Fermi process, most likely in the ion current channels (as in Hededal et al 04)

Electron-ion shocks: shielding

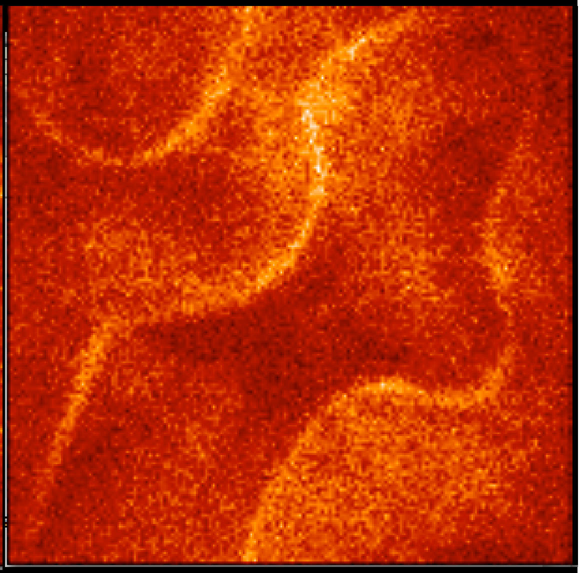
Unmagnetized ion-electron shock: σ=0, m_i/m_e=16



Ion density



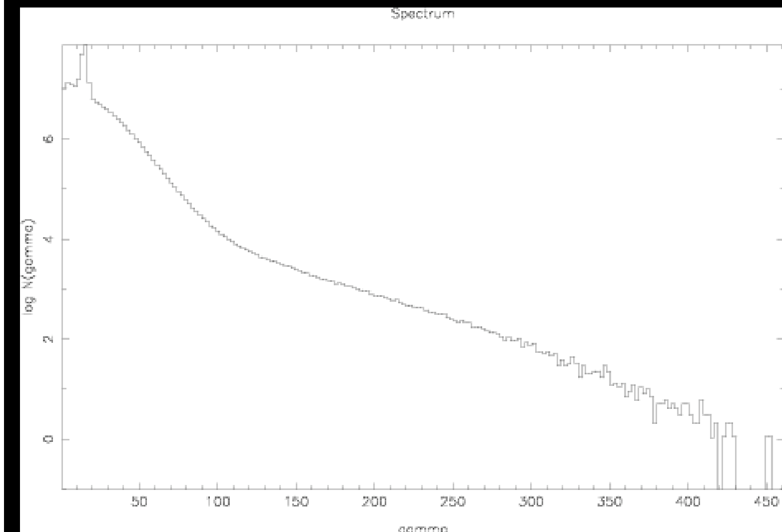
Electron density

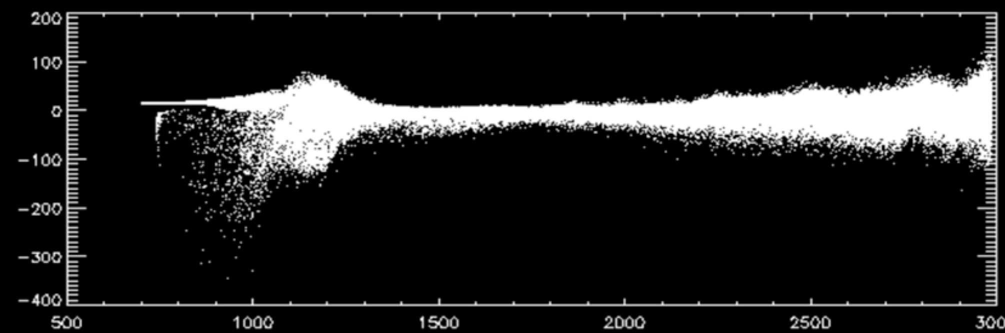


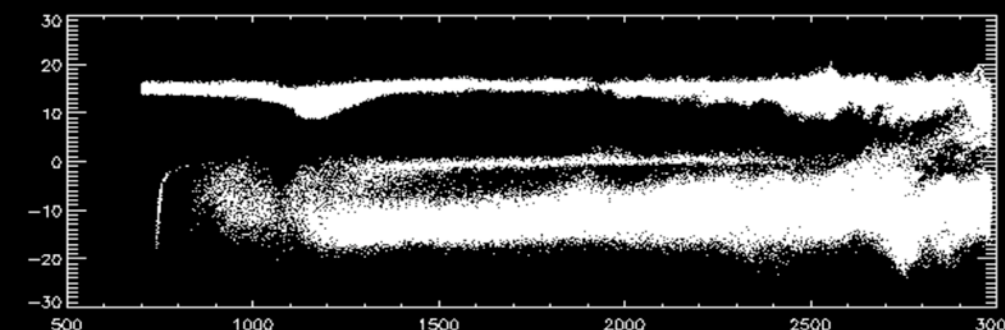
Electrons shield ion current fillaments, slowing down the recombination of filaments.

Electron-ion shocks

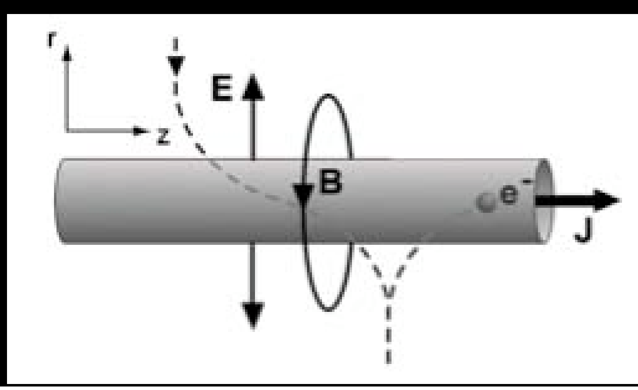
Unmagnetized ion-electron shock: $\sigma=0,\ m_i/m_e=16$

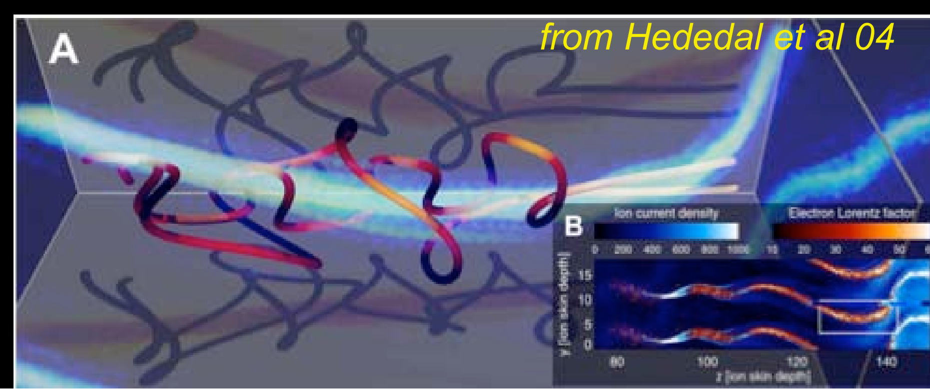






Ion channel acceleration?

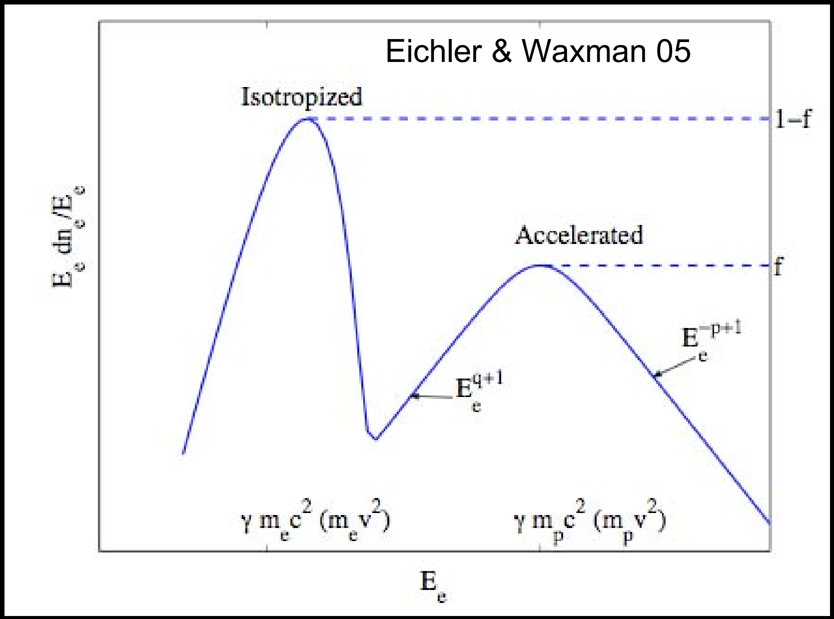




from Hededal et al 04

Acceleration efficiency

We do not know from observations what fraction of electrons gets accelerated



If the acceleration mechanism is intrinsically low efficiency, we expect to see a thermal component in the GRB afterlglow (require radio observations within an hour of GRB).

(Eichler & Waxman 05)

Such component is not seen in the pulsar wind sources.

Furrther simulations will allow to address the efficiency of the acceleration process and its dependence on composition

Conclusions

- Collisionless shocks exist in 3D
- Shocks are mediated by Weibel instability or magnetic reflection
- Shock structure is controlled mainly by the magnetization parameter, σ~0.005 is the transition region. Composition also important.
- Magnetized pair shocks do not efficiently produce nonthermal particles, unmagnetized shocks and oblique shocks show more promise.
- Very low-sigma shocks do not exist as magnetic shocks in more than 1D
- Electron-ion shocks produce nonthermal particles only in the low magnetization limit -- not by Fermi process thus far.
- Simulations predict a thermal component of the spectrum -- efficiency?
- Do pure pair plasmas really exist in astrophysics?