Relativistic Collisionless Shocks and Particle Acceleration: an Inconvenient Truth

Anatoly Spitkovsky (KIPAC, Stanford)

Collaborator: Jonathan Arons (Berkeley)

Outline:

1. *Shocks in astrophysics: expectations of composition, structure and shock properties*

2. *3D shock modeling -- simulation setup*

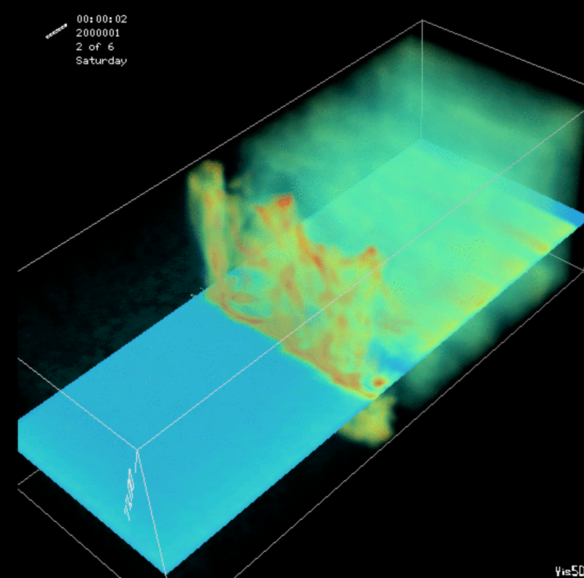
3. *Unmagnetized shocks in pair plasma*

4. *Magnetized shocks in pair plasma*
   a) *Perpendicular*
   b) *Oblique*

5. *Acceleration properties: Where is Fermi?*

6. *Shocks in electron-ion plasma: varying mass ratio*

7. *Conclusions*



3D PIC results are generally consistent with work by

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Composition

6. *Shocks in electron-ion plasma: varying mass ratio*

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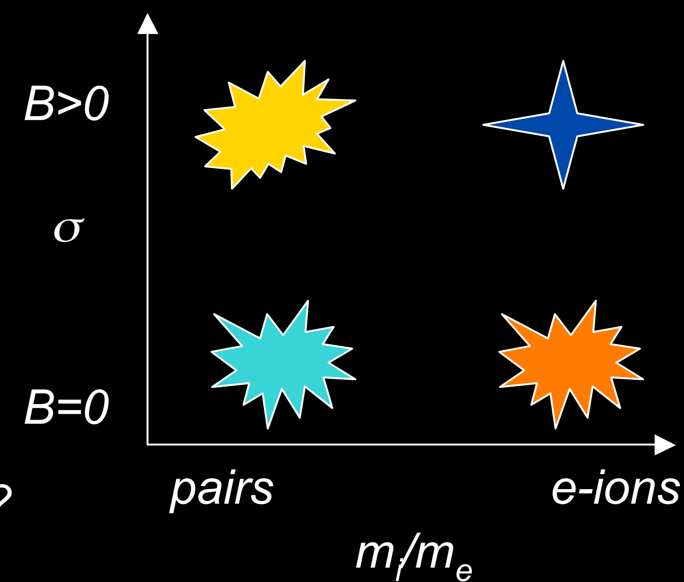

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Shocking astrophysics

Relativistic collisionless shocks in astrophysics

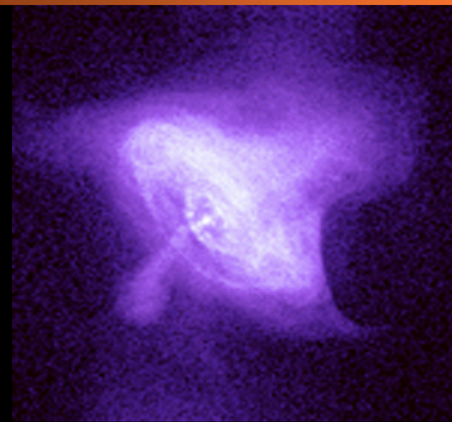
- *Pulsars + winds (plerions, J0737)* $\gamma \sim 10^6$, $\sigma \sim 10^{-3}$-1, composition: pairs (+ions?)
- *Extragalactic radio sources* $\gamma \sim 10$, σ*-?, composition -- pairs? baryons? both?*
- *Gamma ray bursts* $\gamma > 100$, σ -- ?, *composition: ?*
- *Galactic superluminal sources* $\gamma \sim$ few
- *Sources for UHE CR?*

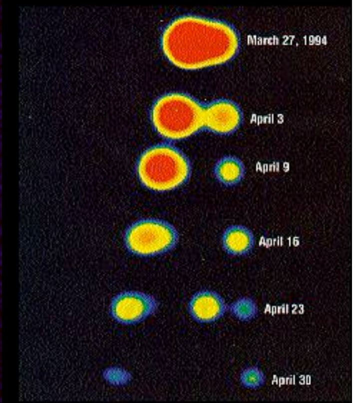
$$\sigma \equiv \frac{\text{Magnetic Energy}}{\text{Kinetic Energy}}$$

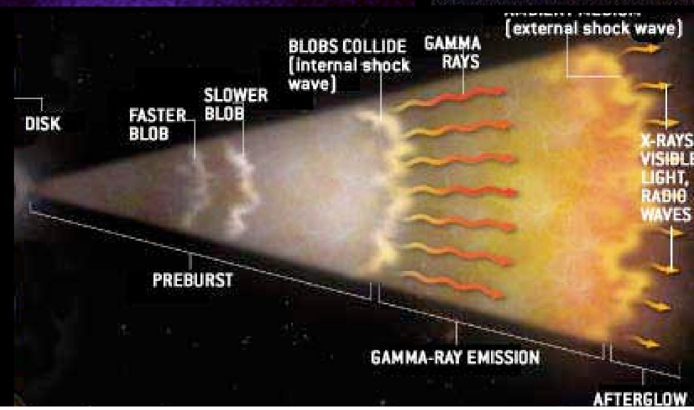
Open issues:

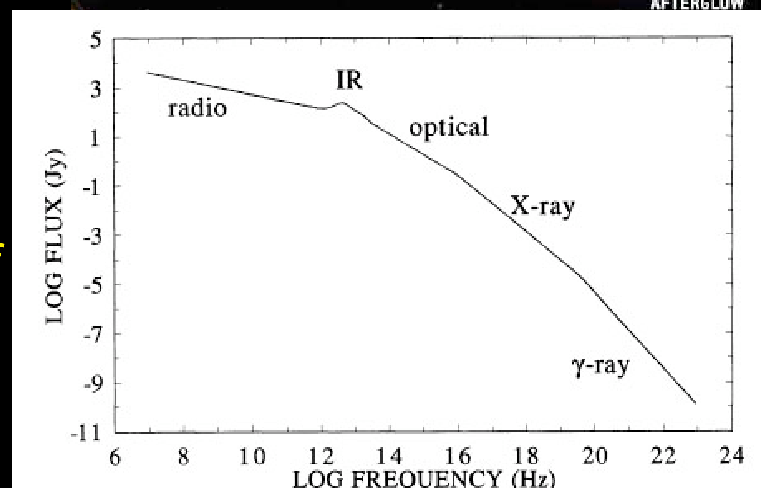
- *What is the structure of collisionless shock waves?*
- *Particle acceleration -- Fermi mechanism? Something else?*
- *Generation of magnetic fields (GRB shocks, primordial fields?)*

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.

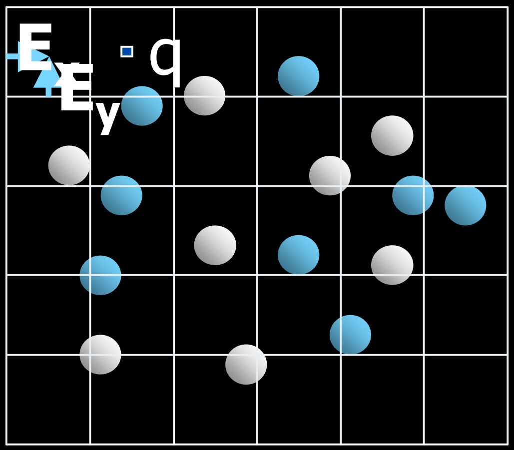








Numerical simulation of collisionless shocks

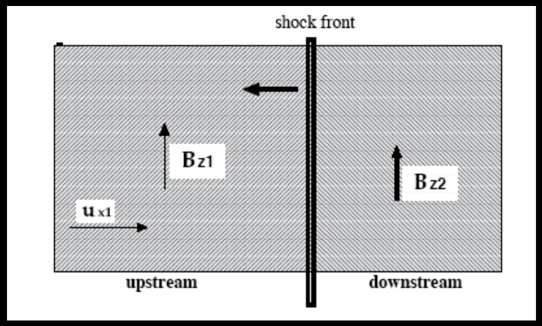


Particle-in-cell method:

- *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":

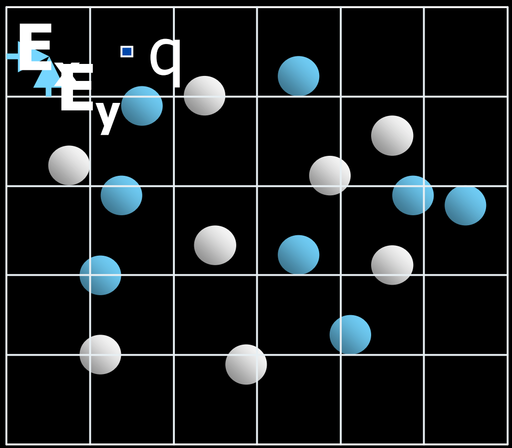
- *3D cartesian electromagnetic particle-in-cell code*
- *Radiation BCs; moving window*
- *Charge-conservative current deposition (no Poisson eq)*
- *Filtering of current data*
- *Fully parallelized (128proc+) domain decomposition*
- *Tried upto 3 billion+ particles*



Simulation setup:

Relativistic $e^{\pm}$ or e^{-}- ion wind (γ =15) with B field ($\sigma = \omega_c^2 / \omega_p^2 = B^2/(4\pi n\gamma mc^2)$ = 0-10)
Reflecting wall (particles and fields)
Upstream c/ω_p=10 cells, c/ω_c>5 cells; upto 2500x320x320 grid, 250x32x32 c/ω_{pe}

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*

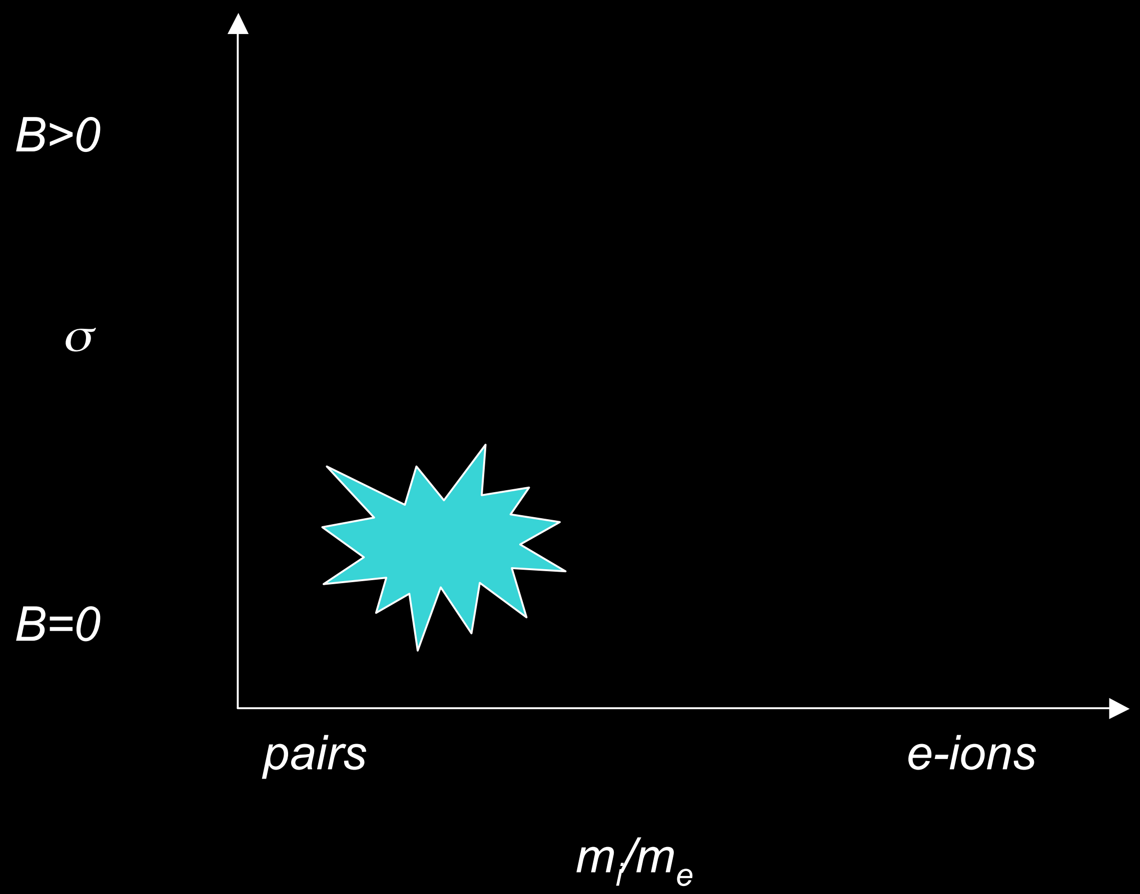
Lessons learned:

Short and small simulations are dangerous

Reduced dimensionality is dangerous

Doing what you can rather than what you should is really dangerous

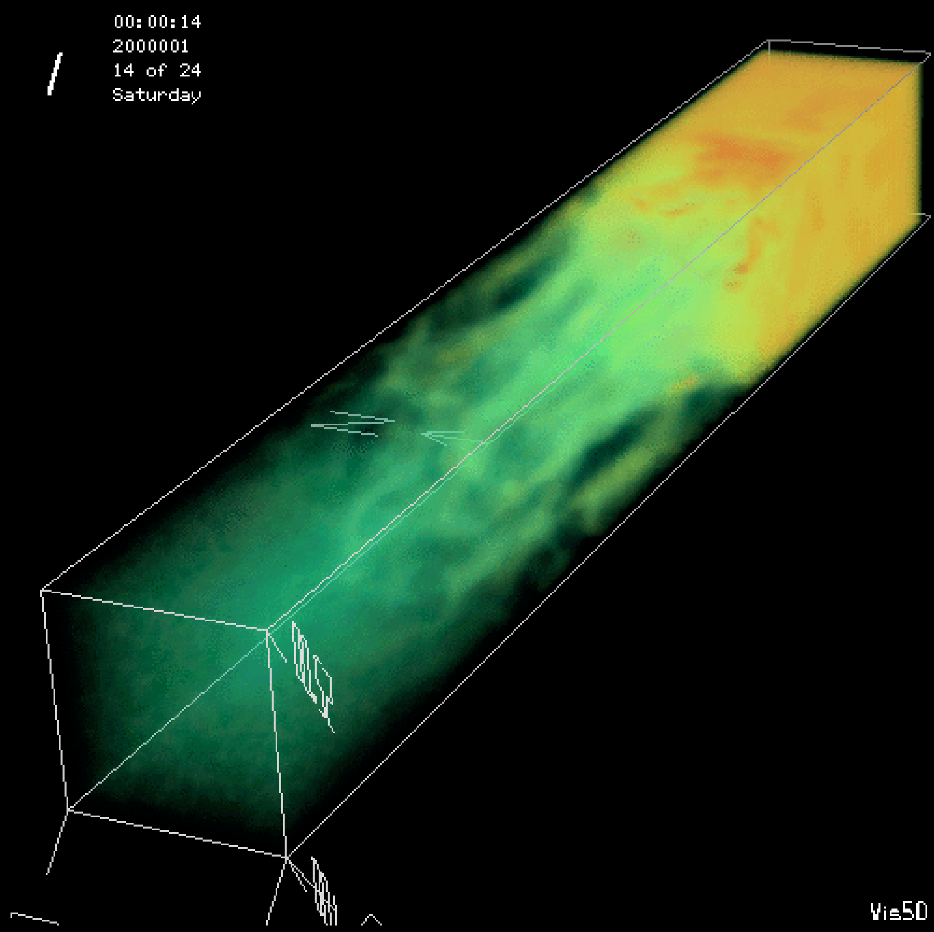
Chapter I: Unmagnetized pair shocks

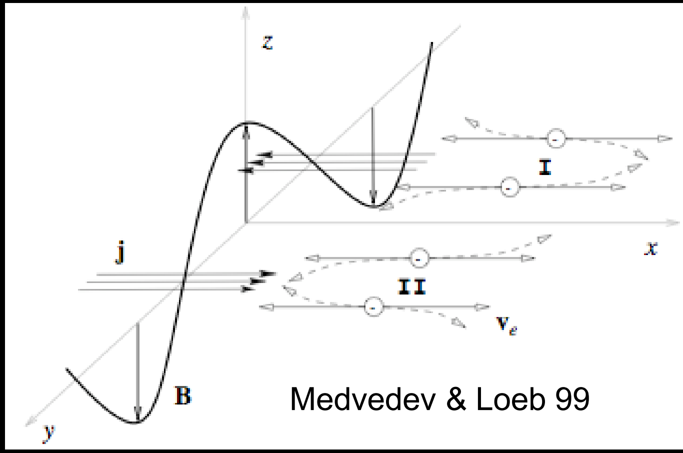


Unmagnetized pair shock

Why does a shock exist?

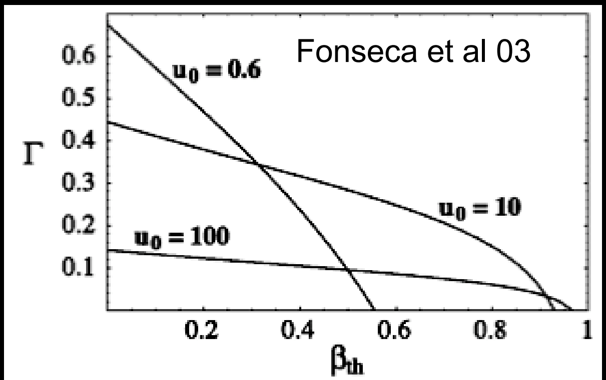
Particles are slowed down either by instability (two-stream-like) or by magnetic reflection. Electrostatic reflection is important for nonrelativistic shocks and when ions are present.





Weibel instability *(Weibel 1959)*

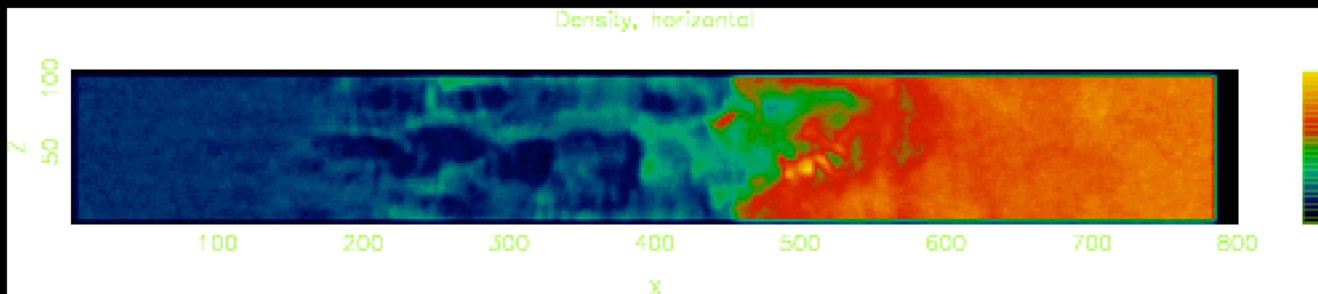
Spatial growth scale c/ω_p; timescale $10/\omega_p$



Unmagnetized pair shock

Shock structure: Density evolution

Shock transitioin is accomplished in roughly 20-50 c/ω_p. *Shocks have to provide density jump!!!*



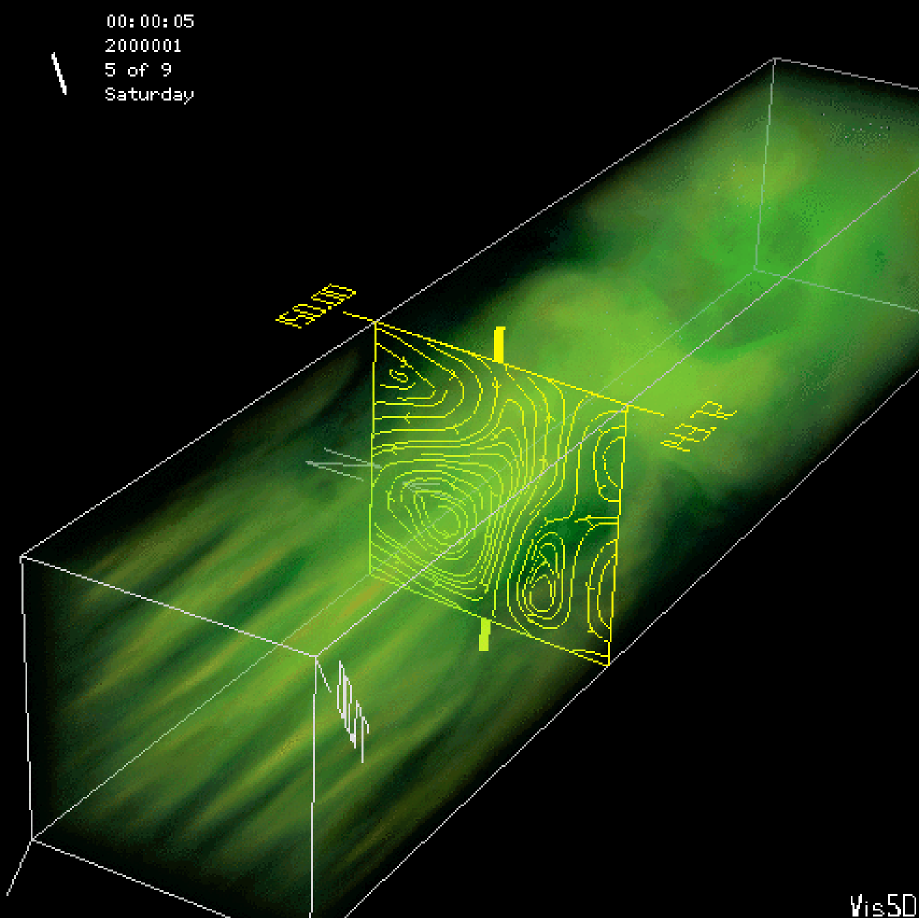
MHD jump conditions satisfied

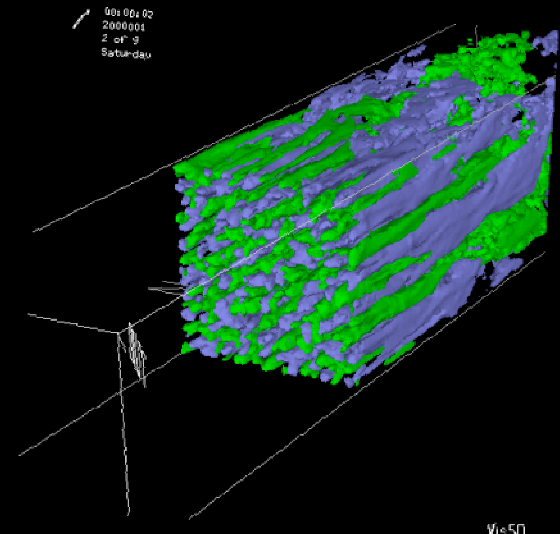
$$\frac{N_2}{N_1} = \frac{\Gamma}{\Gamma - 1} - \frac{(2-\Gamma)\Gamma}{2(\Gamma-1)^3}\sigma \ldots$$

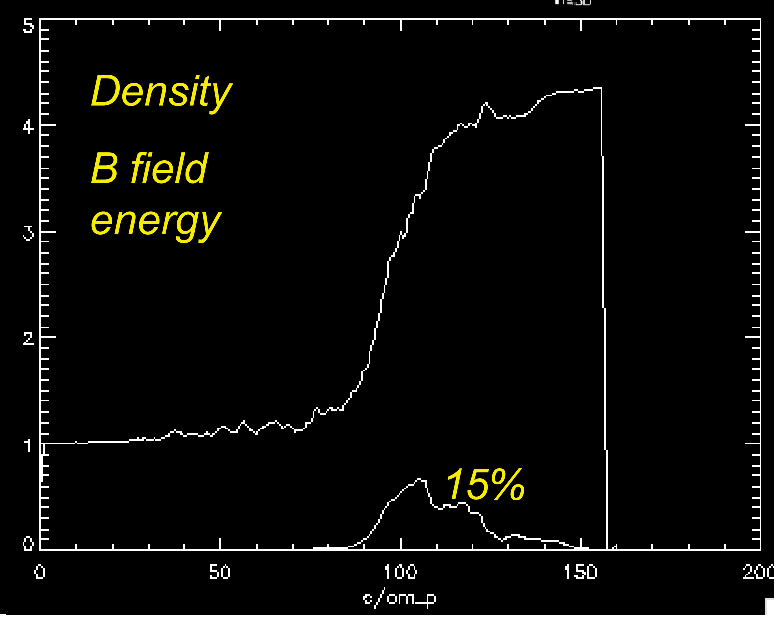
Unmagnetized pair shock

Magnetic field generation

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



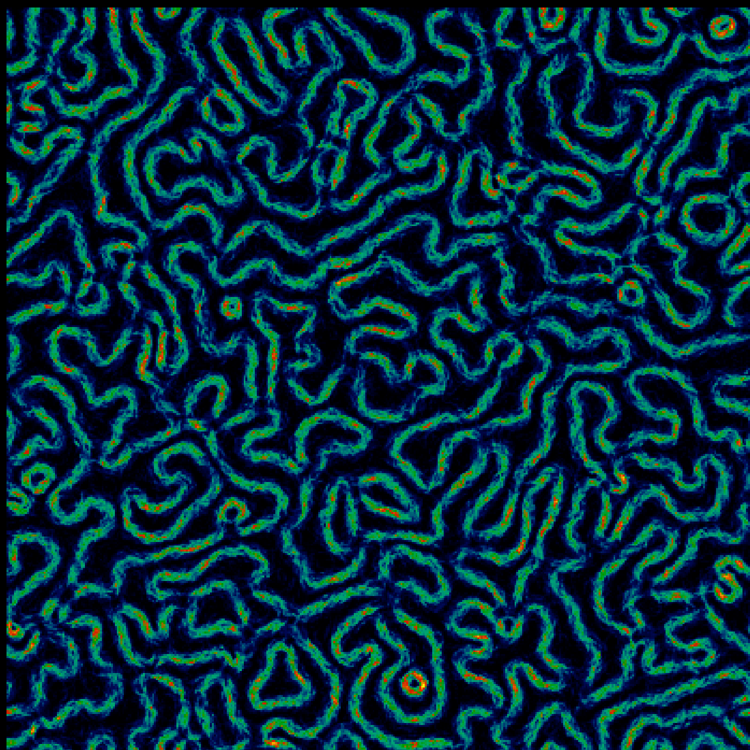


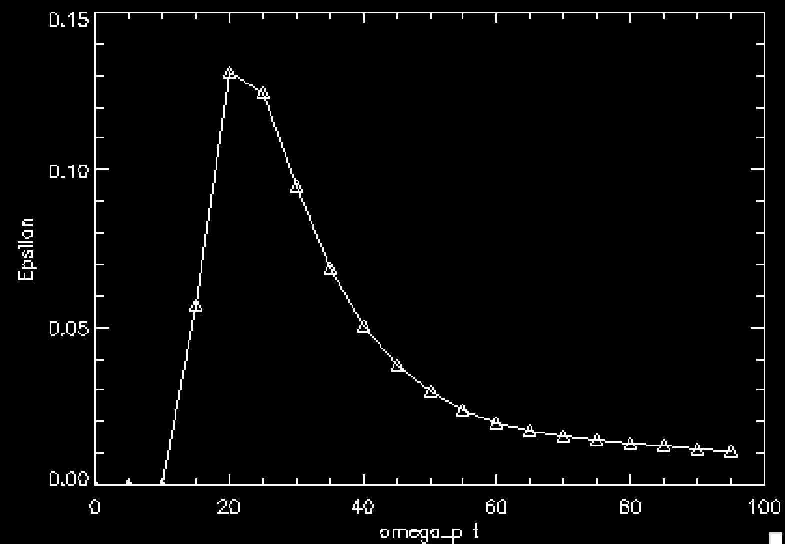


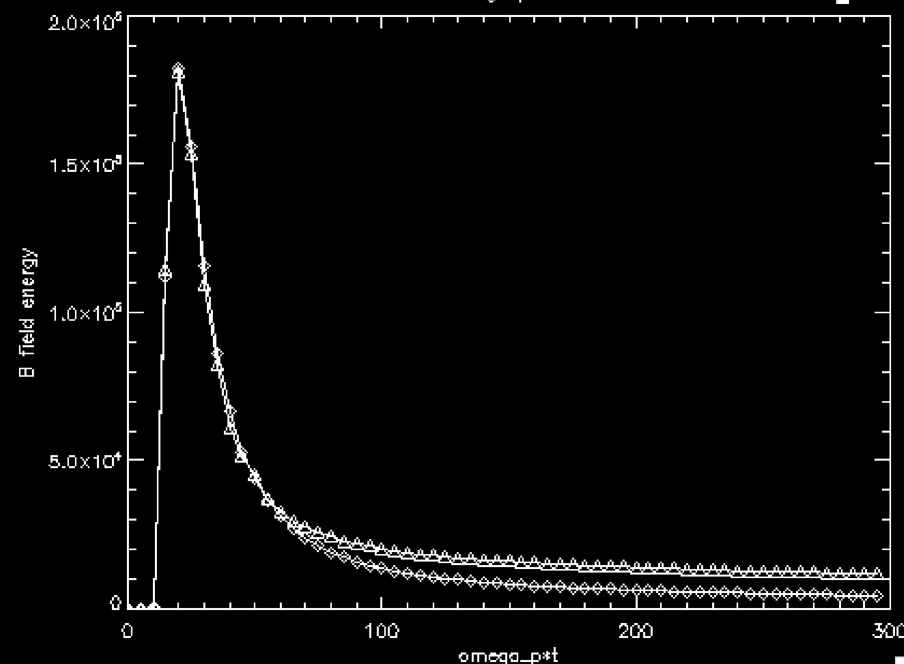
Weibel instability generates subequipartition B fields that decay. Is asymptotic value nonzero? (see Medvedev et al 04): competition between diffusion and inverse cascade.

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$c/\omega_p$:





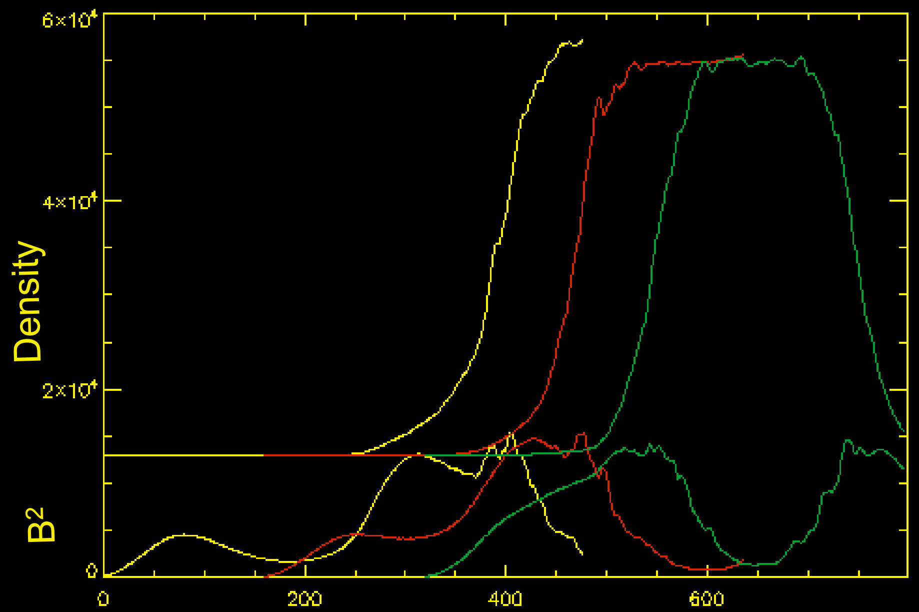


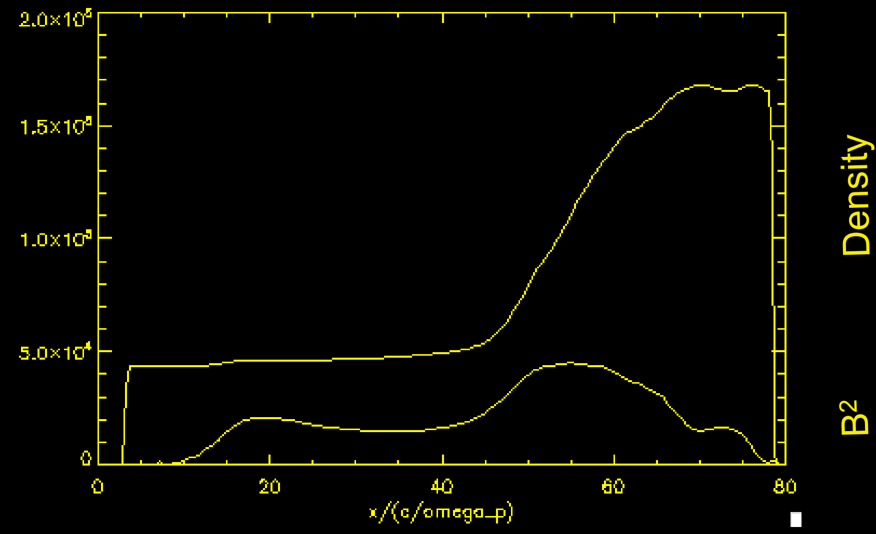
At late times field energy continues to decay below 0.5% equipartition, albeit slowly. It is not clear whether asymptotic value exists in simulations. Alfven critical current at peak.

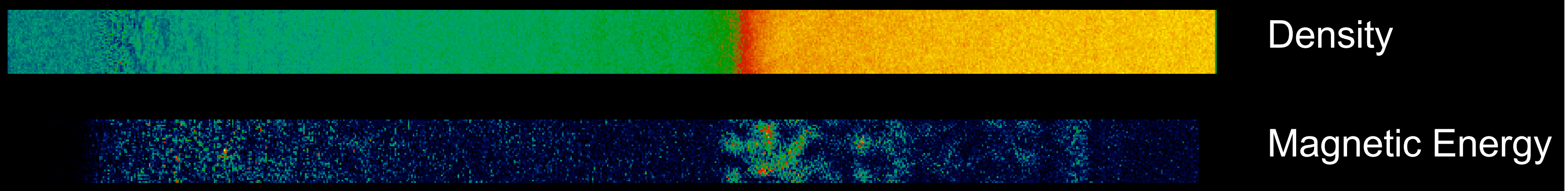
Transverse size of the simulation matters!!!

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.







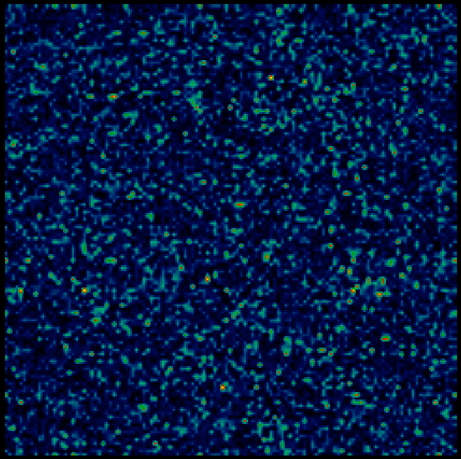
Precursor physics is similar to fast ignitor! Instability growth rate depends on density ratio.

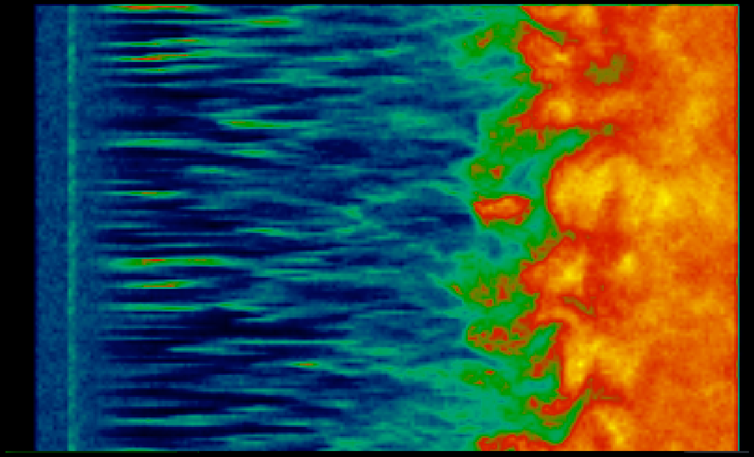
Precursor complicates simulations, requiring larger domains or moving window

3D shock structure

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

B^2

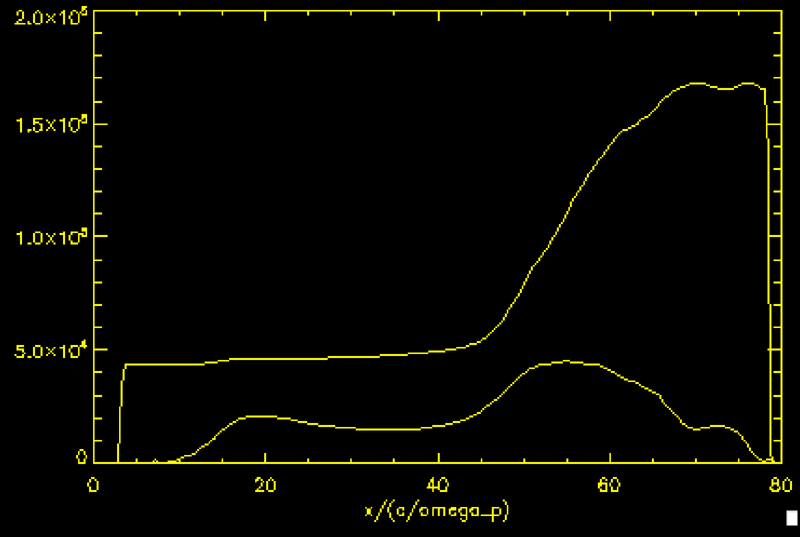


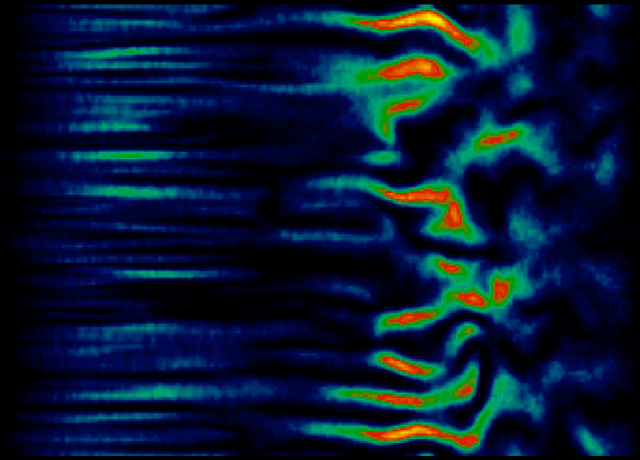


Density

Density

B^2





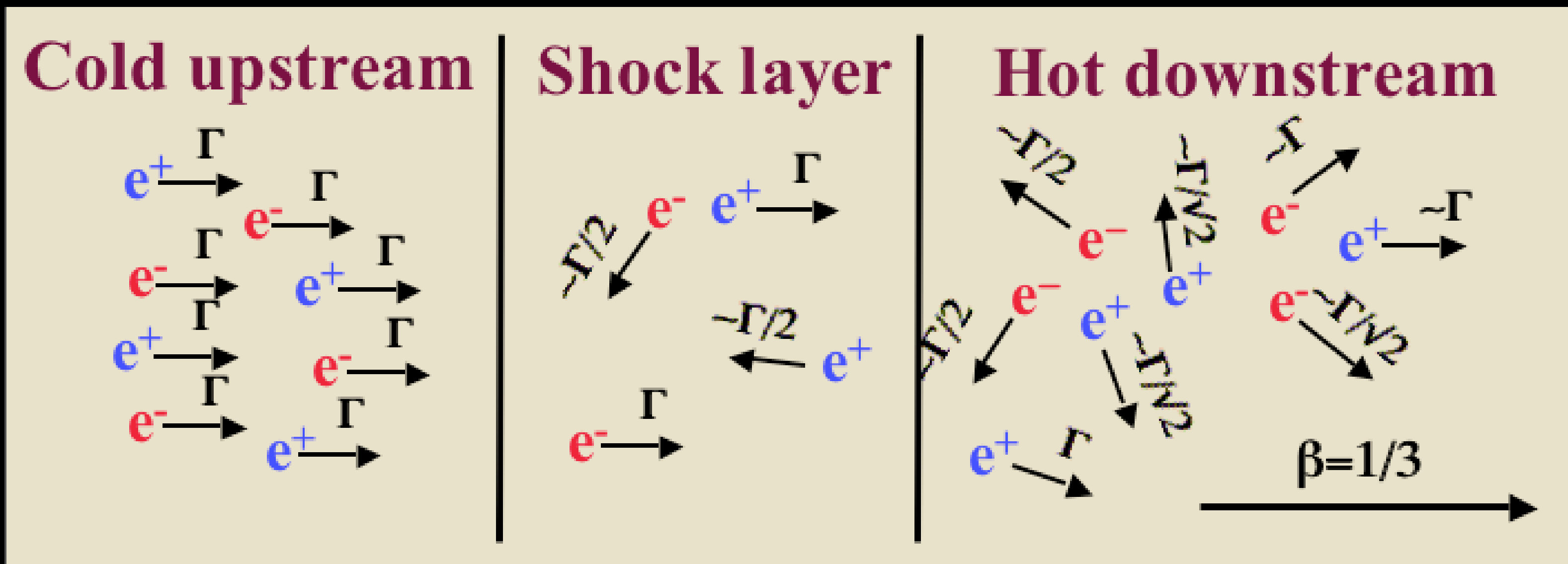
B^2

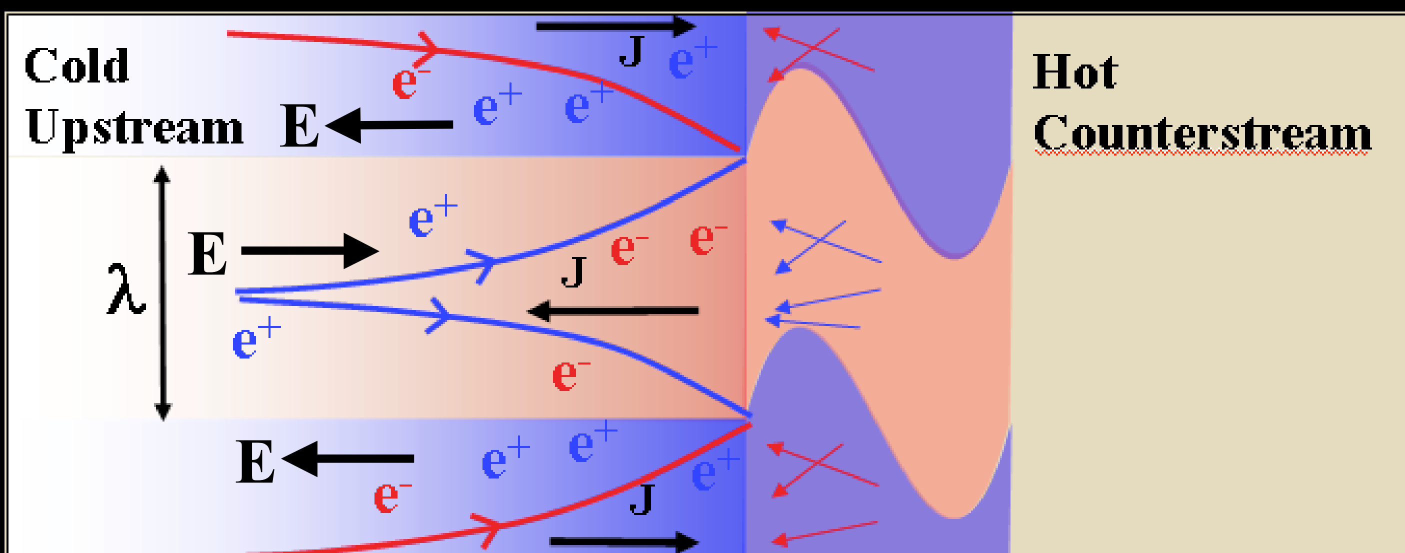
Upstream turbulence created by the precursor may be important for particle acceleration.

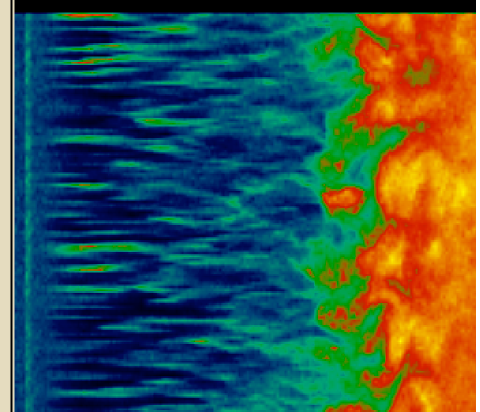
Electrostatics is important for segregating downstream from upstream (Miloslavlevic, Nakar, AS 05)

3D shock structure

How does it work? Electrostatic diode *(Miloslavlevic, Nakar, A.S. 06) due to charge separation in the filaments.*

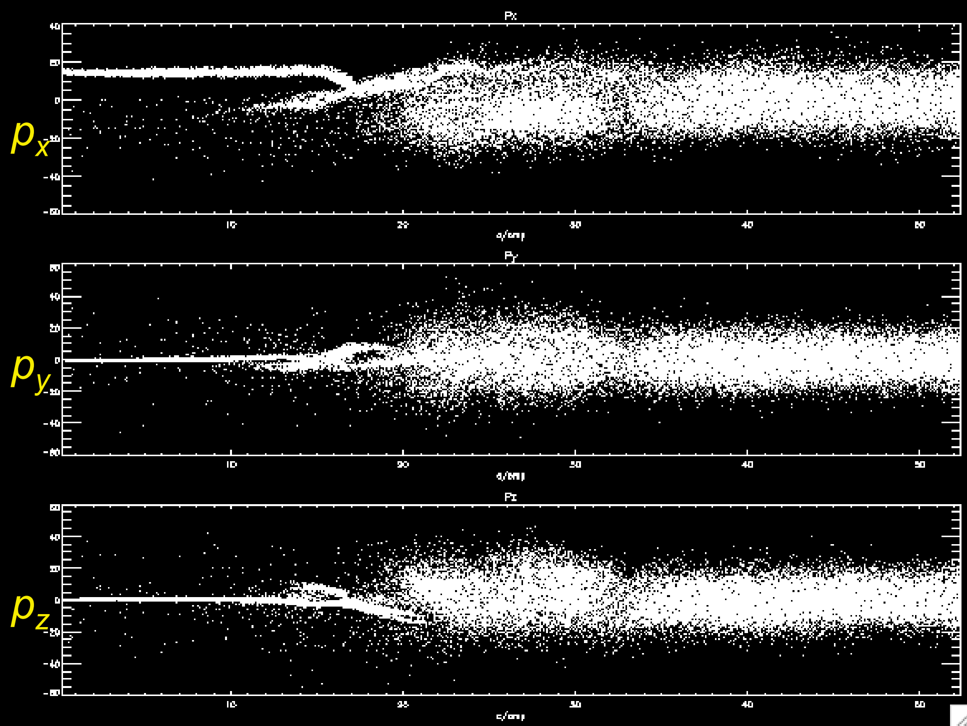




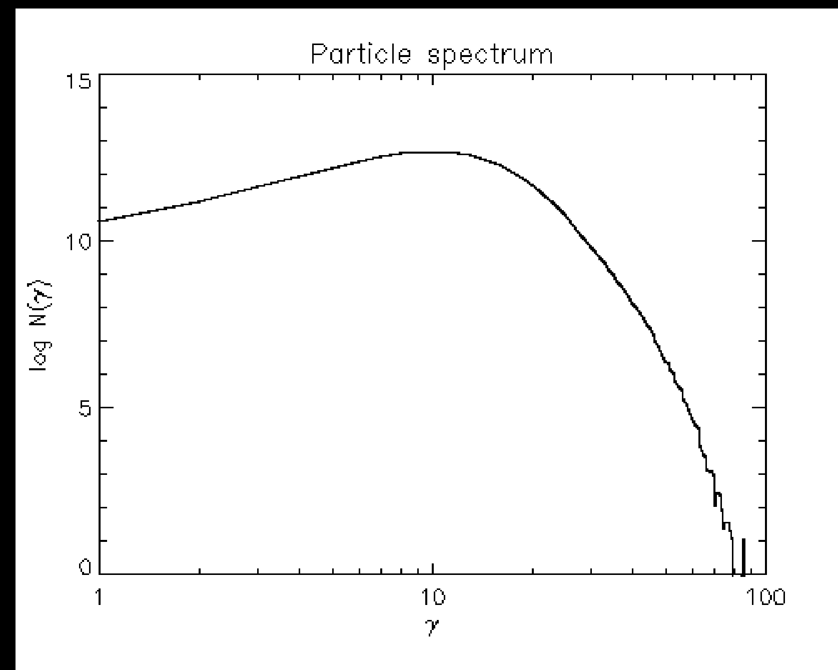


Unmagnetized pair shock

Particle heating/acceleration



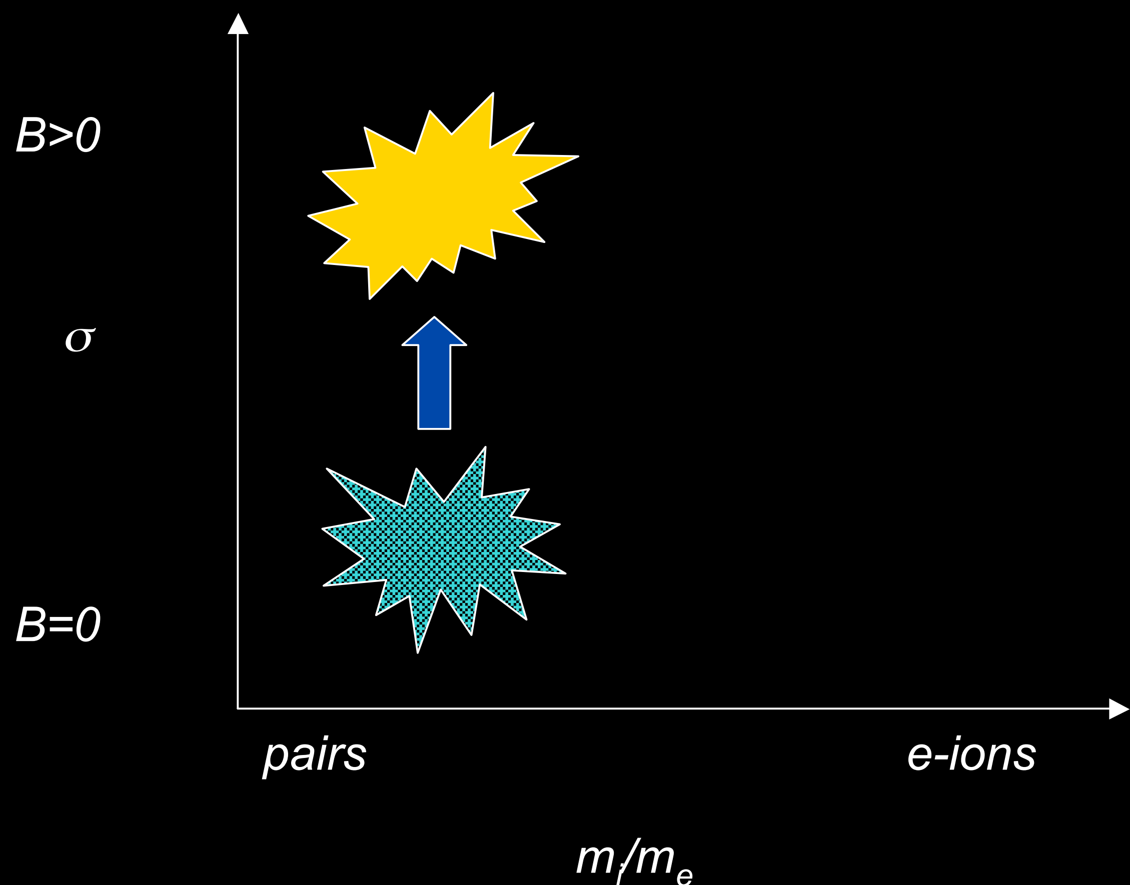
Downstream particle spectrum



In relatively short 3D simulations no obvious nonthermal tail appears in the downstream; particles are efficiently thermalized by interacting with the Weibel magnetic field. Thermalization leads to particle with energies upto 7kT.

More on this in a few slides.

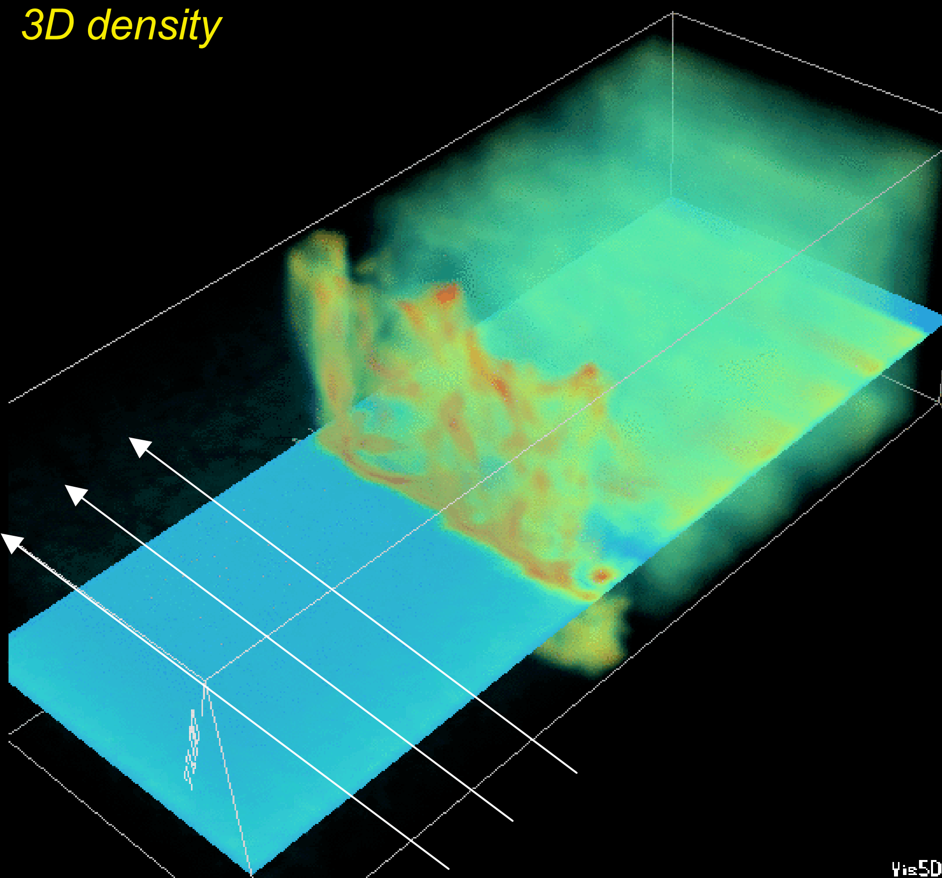
Chapter II: Magnetized pair shocks



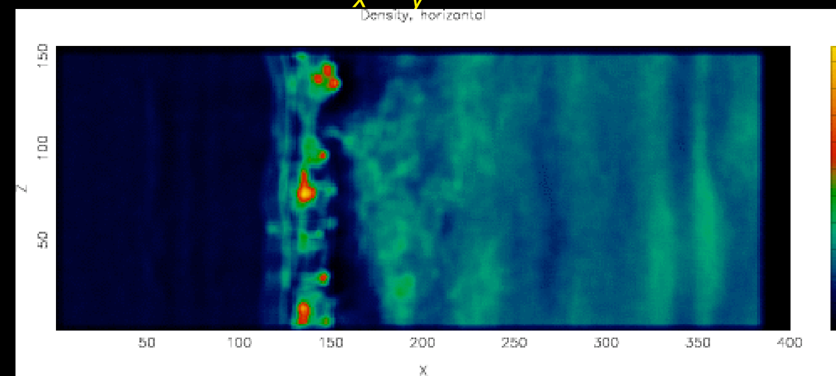
Magnetized perpendicular pair shock

Shock structure for σ=0.1

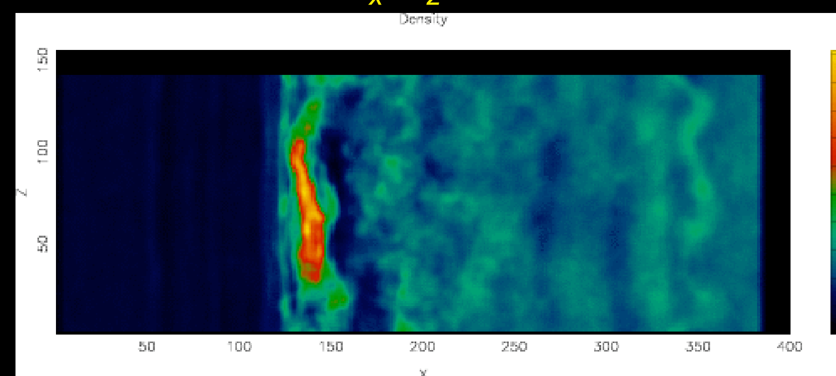
3D density



Plane of v_x-B_y



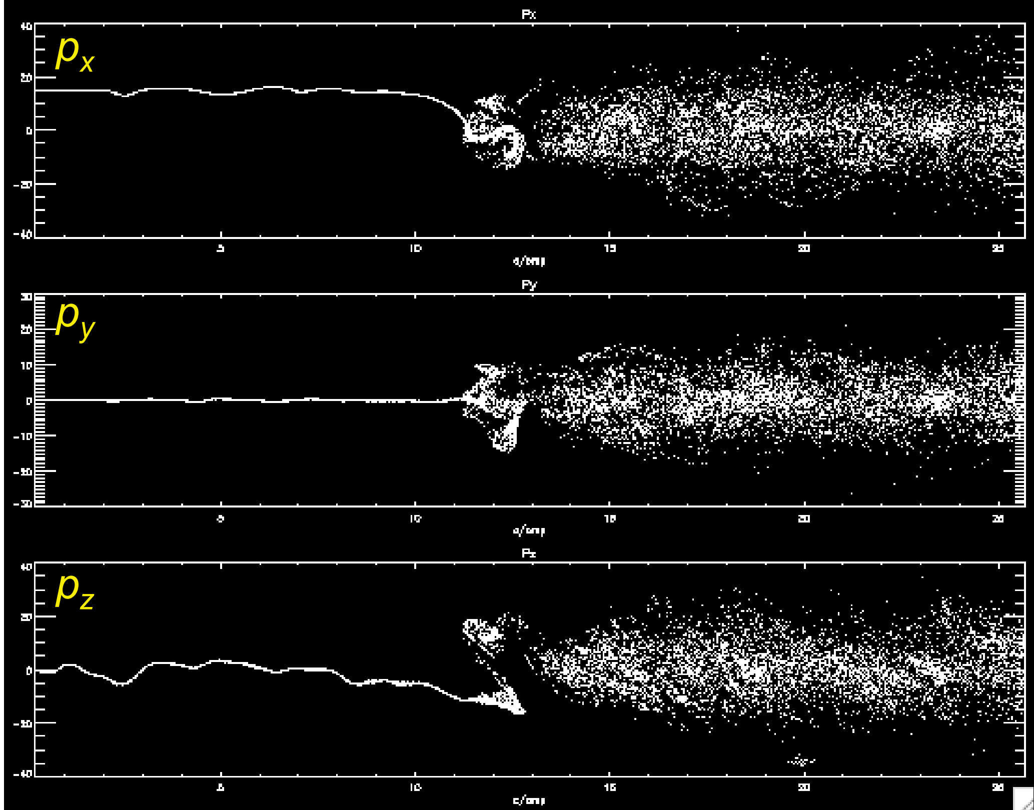
Plane of v_x-E_z



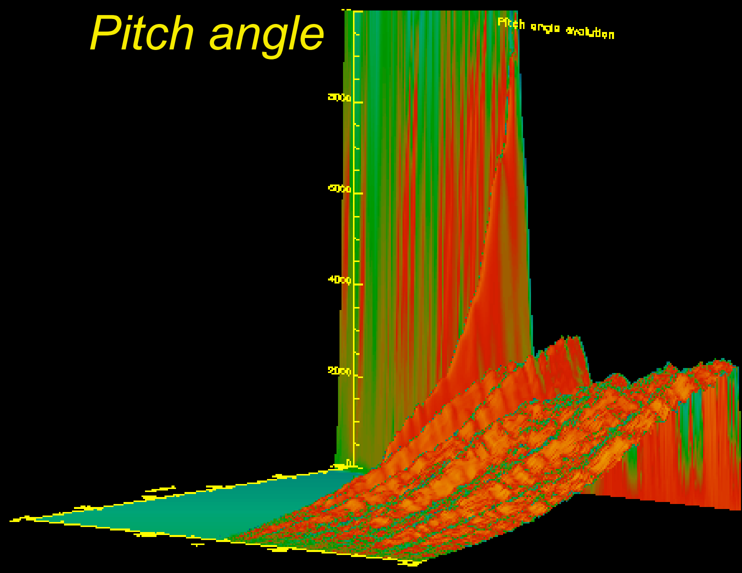
Shock is clearly magnetized -- anisotropy with respect to B. Shock thickness -- several Larmor radii.

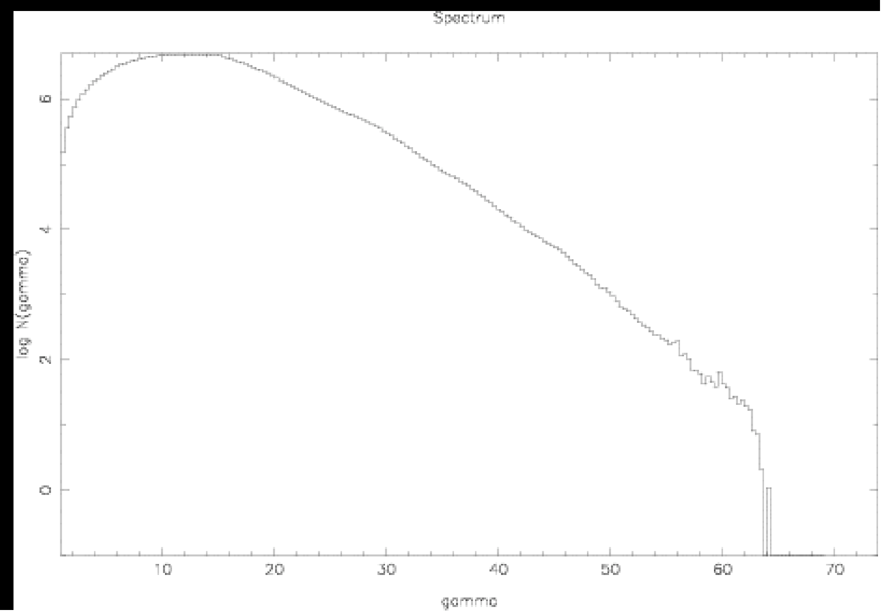
Magnetized perpendicular pair shock

Shock structure σ=0.1 -- particle phase space



Pitch angle

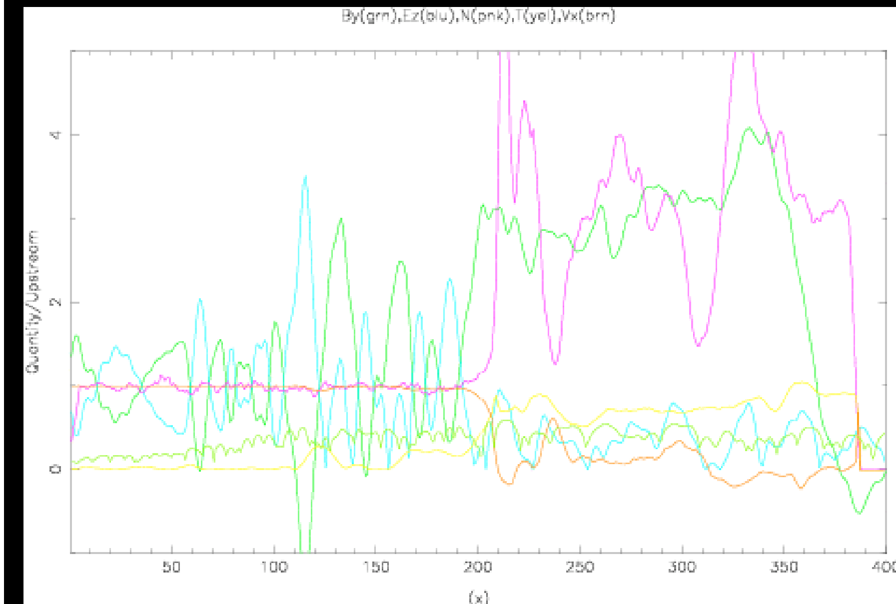


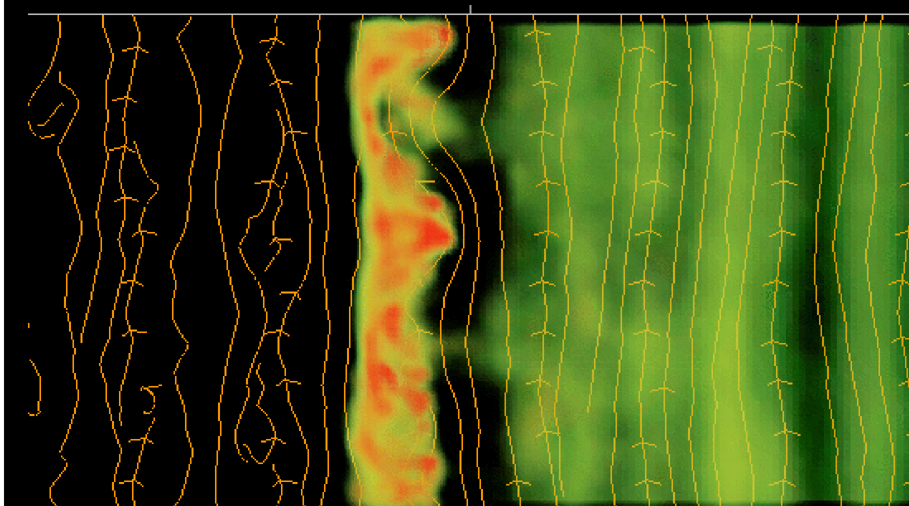


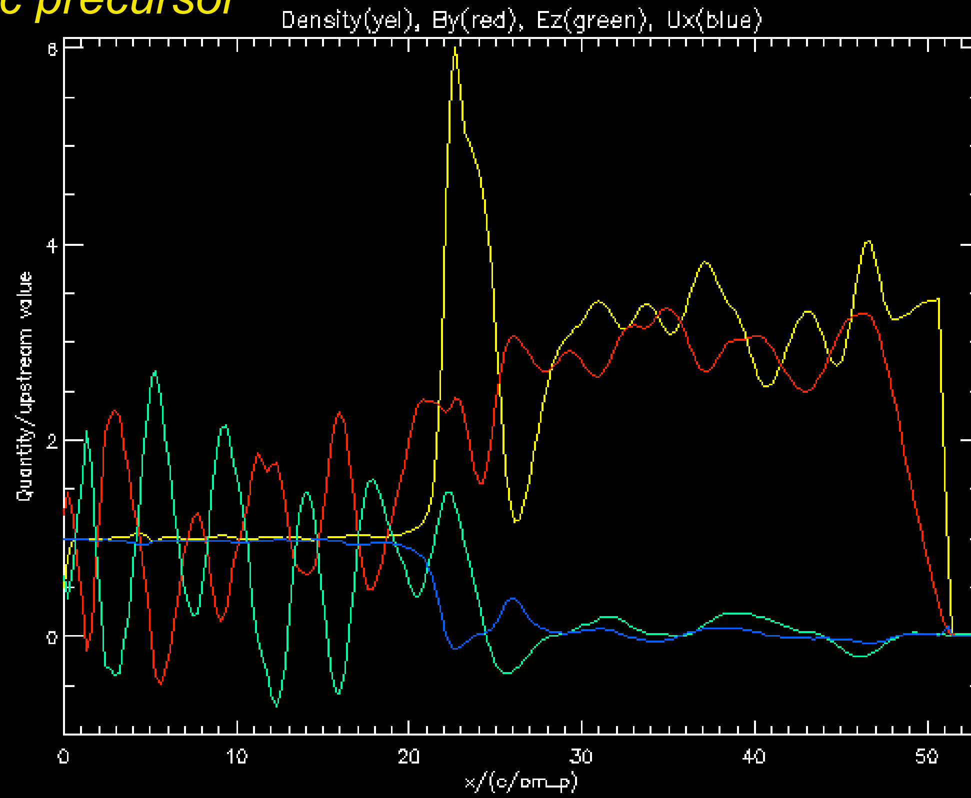
Shock structure dominated by magnetic reflections as in 1D (Hoshino & Arons,92). No nonthermal acceleration even in 3D.

Magnetized perpendicular pair shock

Shock structure σ=0.1 -- electromagnetic precursor



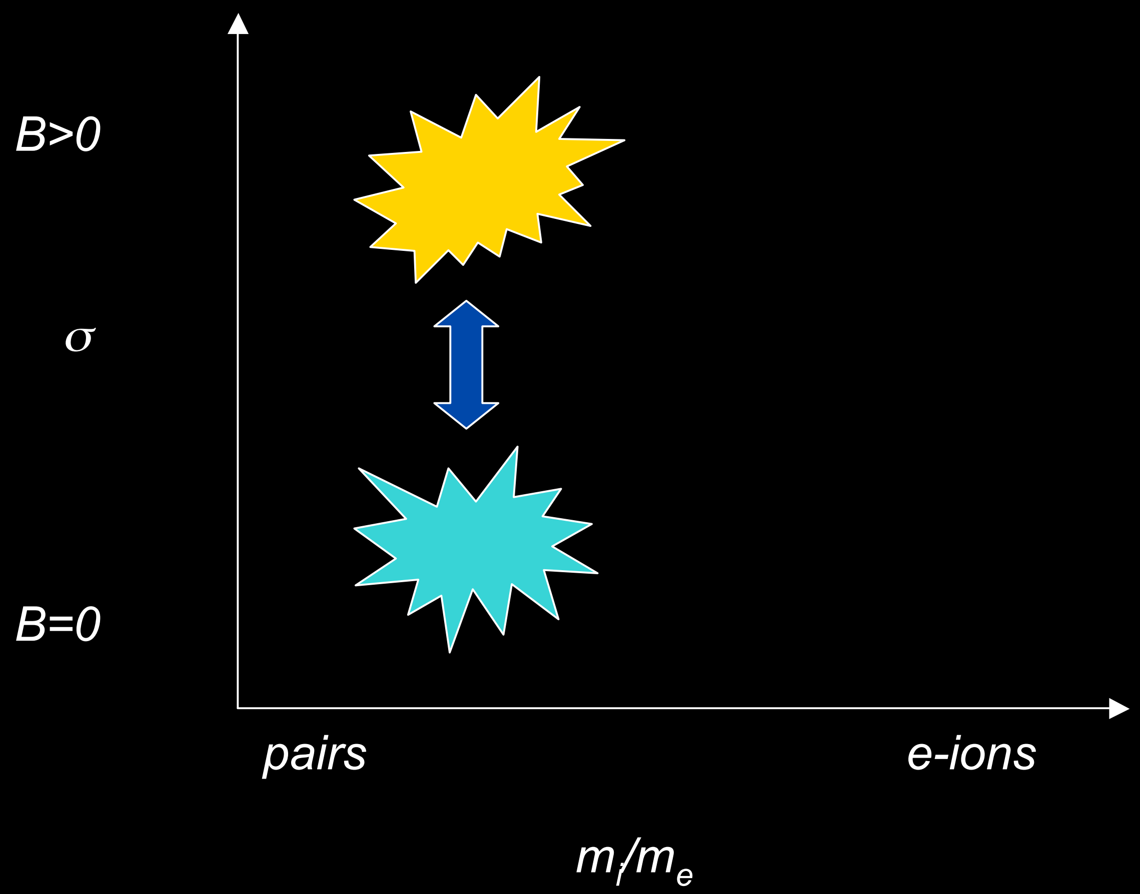




Shock compression is ~3. Plasma is quasi-2D with Γ=3/2

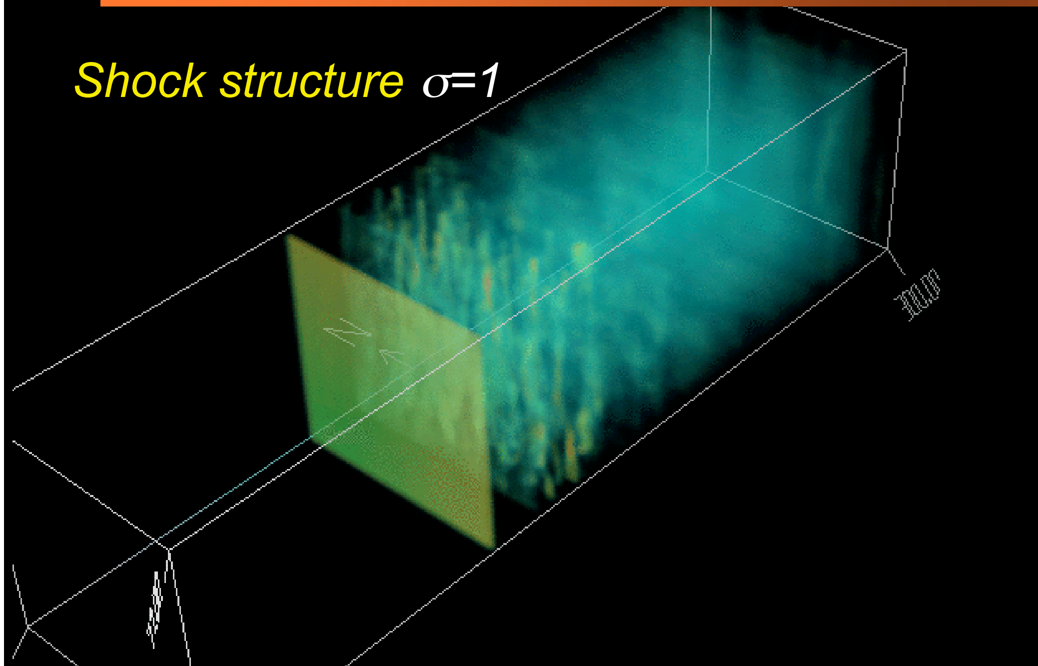
Efficient thermalization, no Fermi. Injection doesn't help.

Chapter III: Pair shocks at intermediate magnetization

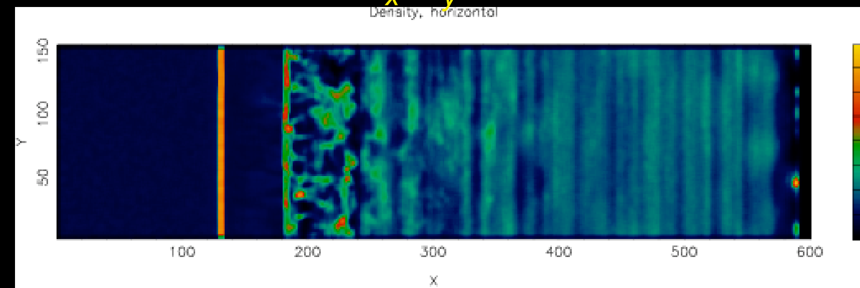


Magnetized perpendicular pair shock

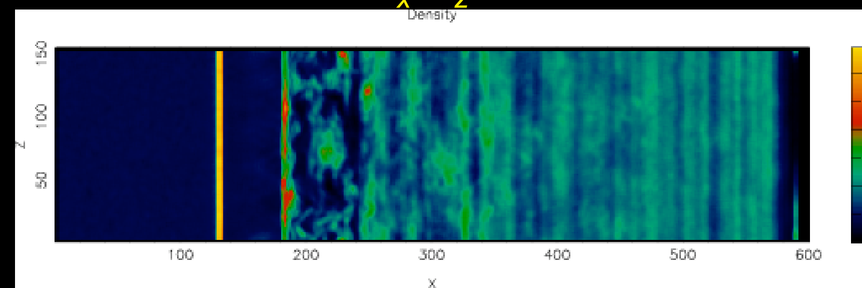
Shock structure σ=1

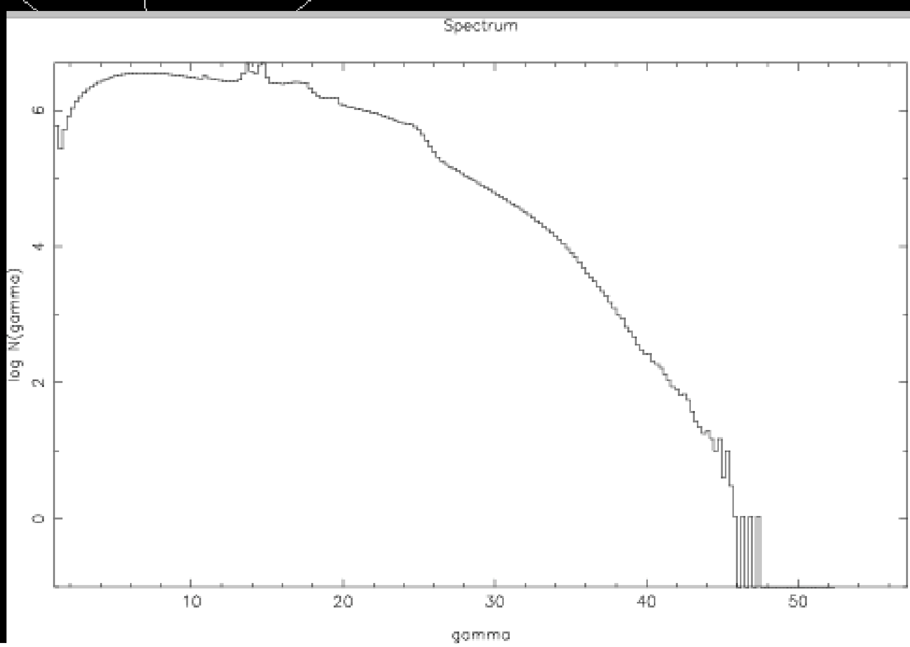


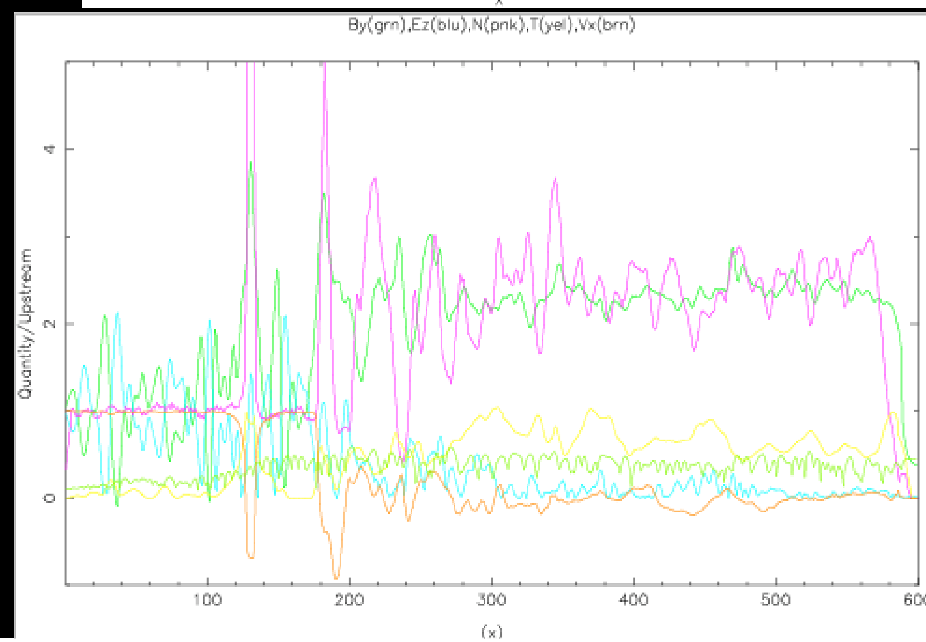
Plane of v_x-B_y



Plane of v_x-E_z







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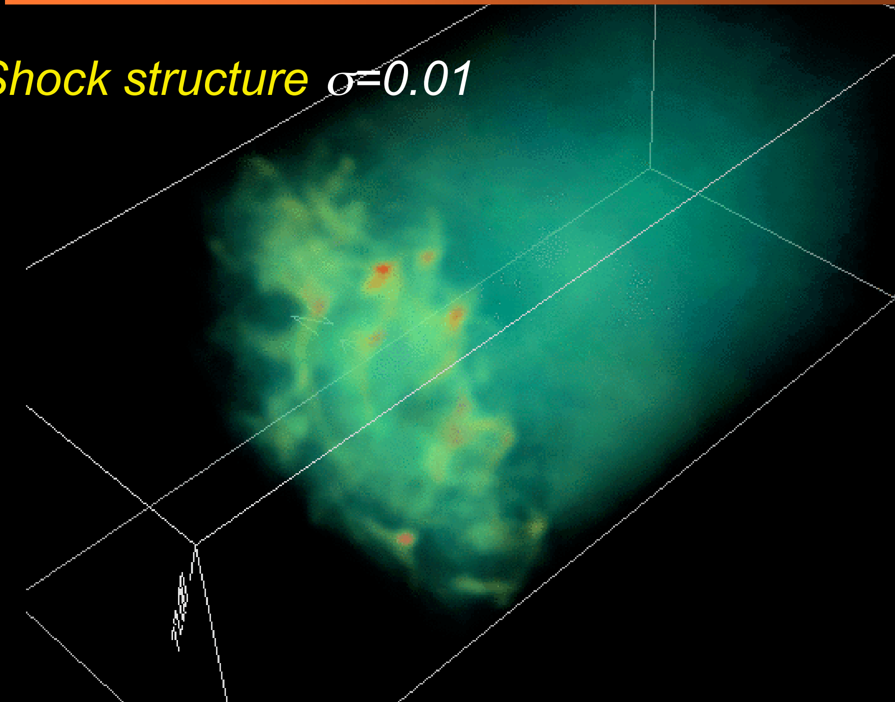
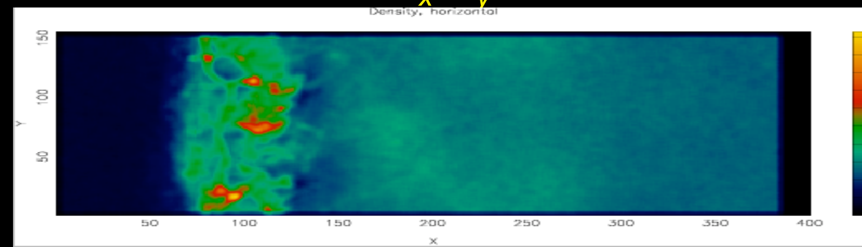
Magnetized perpendicular pair shock

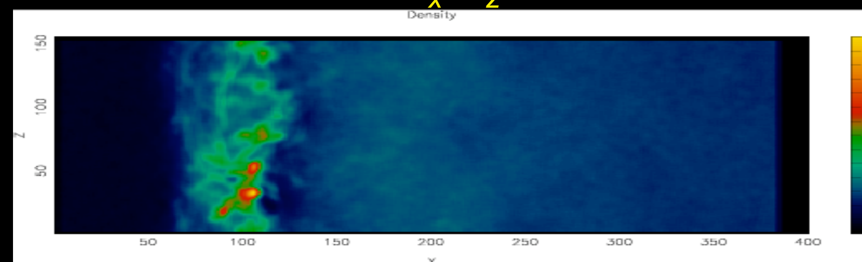
Shock structure σ=0.01

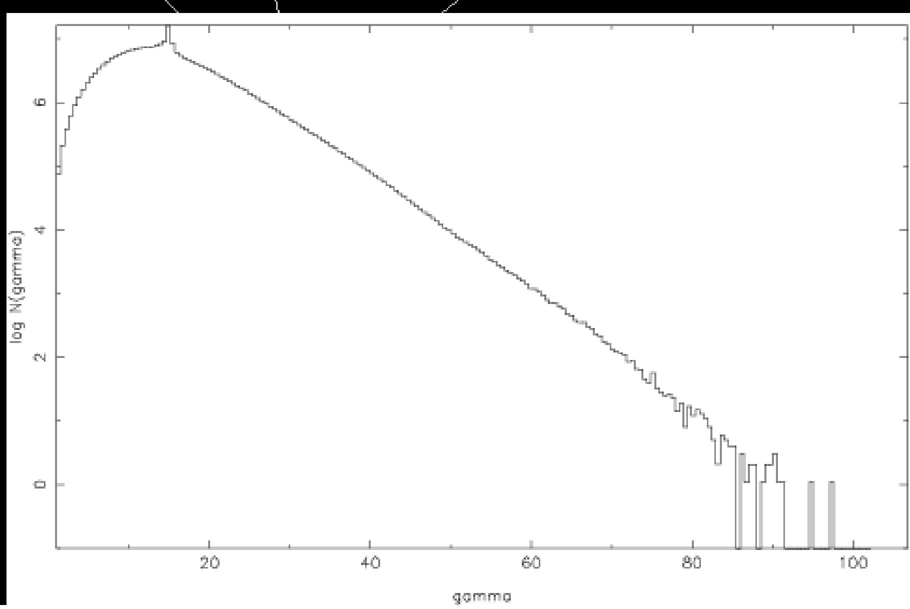


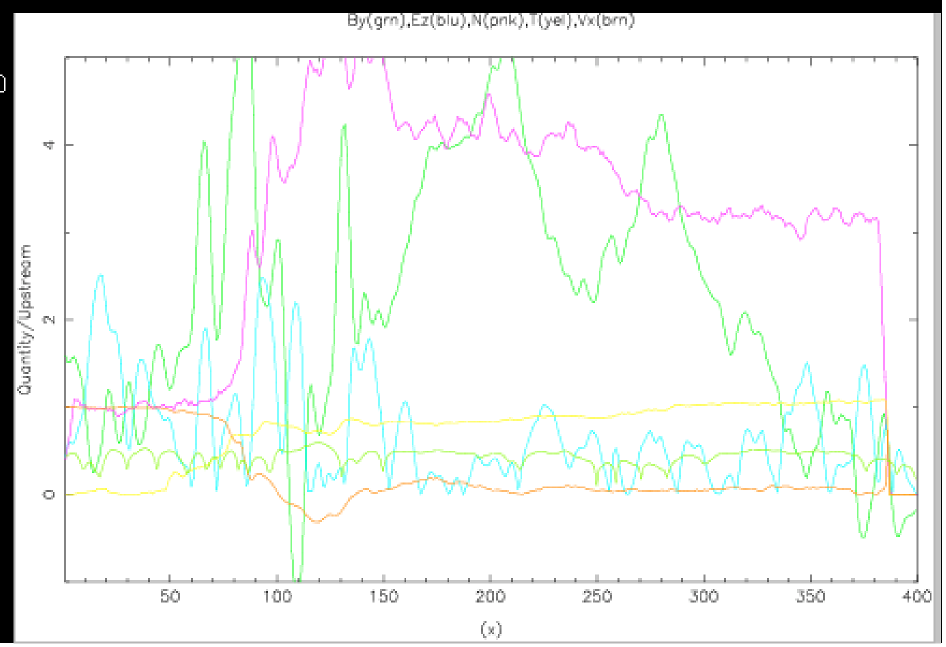
Plane of v_x-B_y



Plane of v_x-E_z

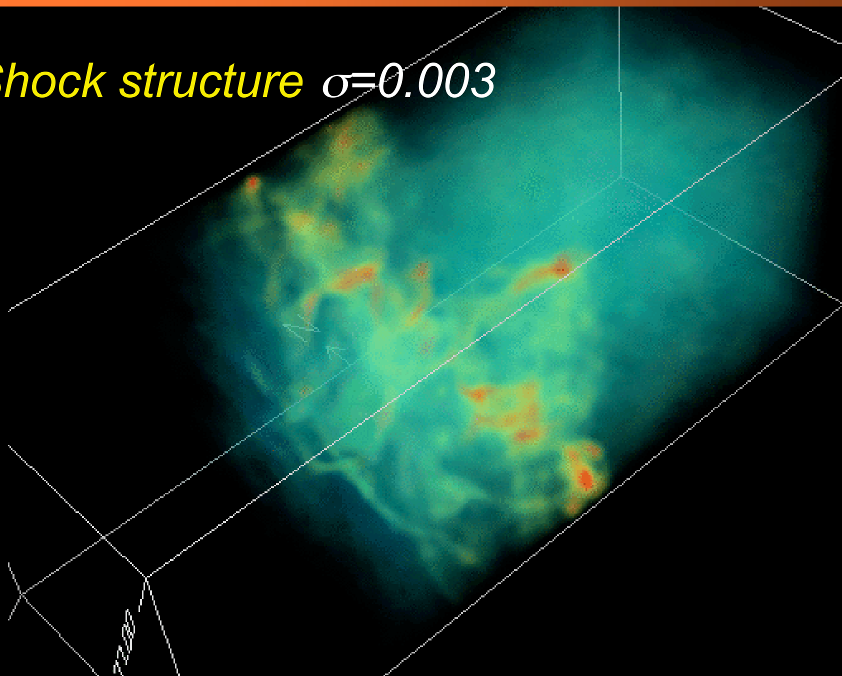




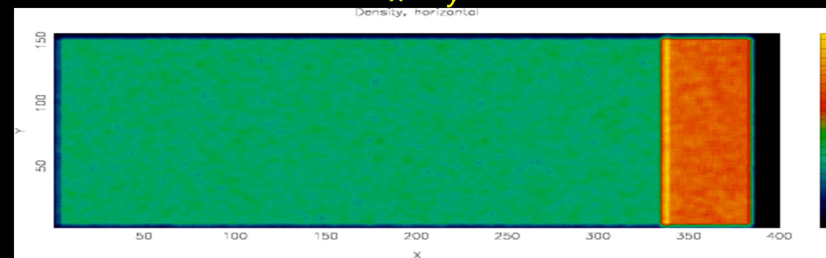


Magnetized perpendicular pair shock

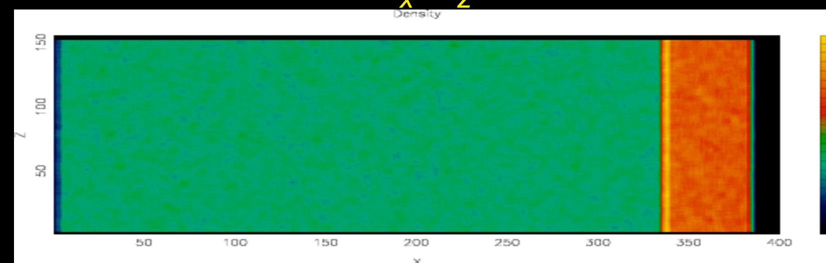
Shock structure σ=0.003

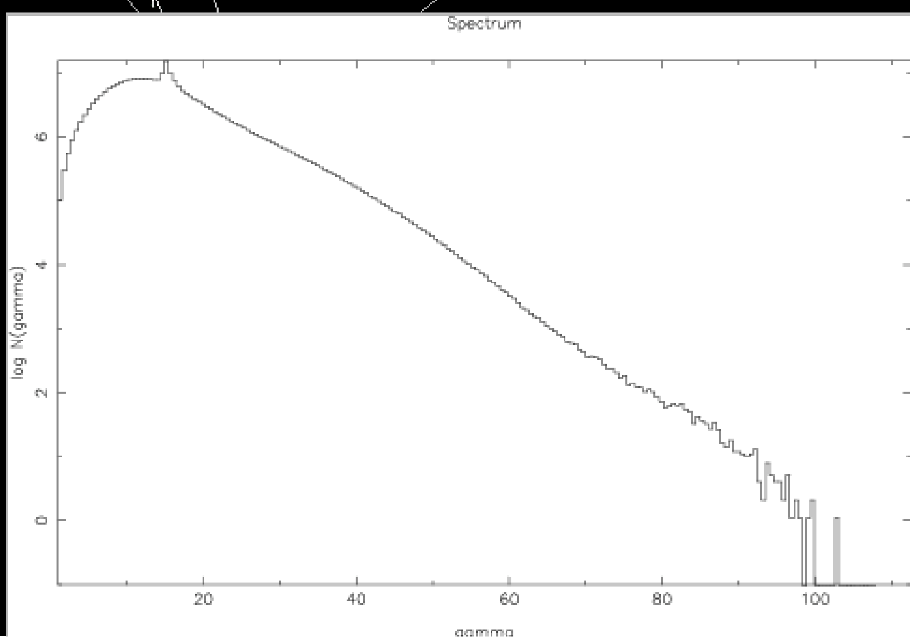


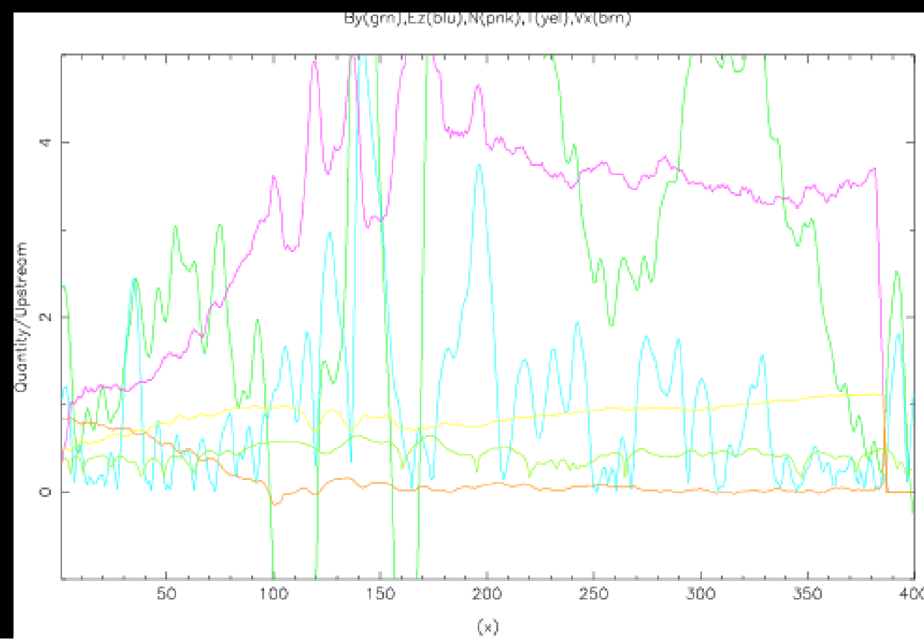
Plane of v_x-B_y



Plane of v_x-E_z







Perpendicular pair shocks: conclusions

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

σ<0.001 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. Self-generated Weibel field exceeds background field.

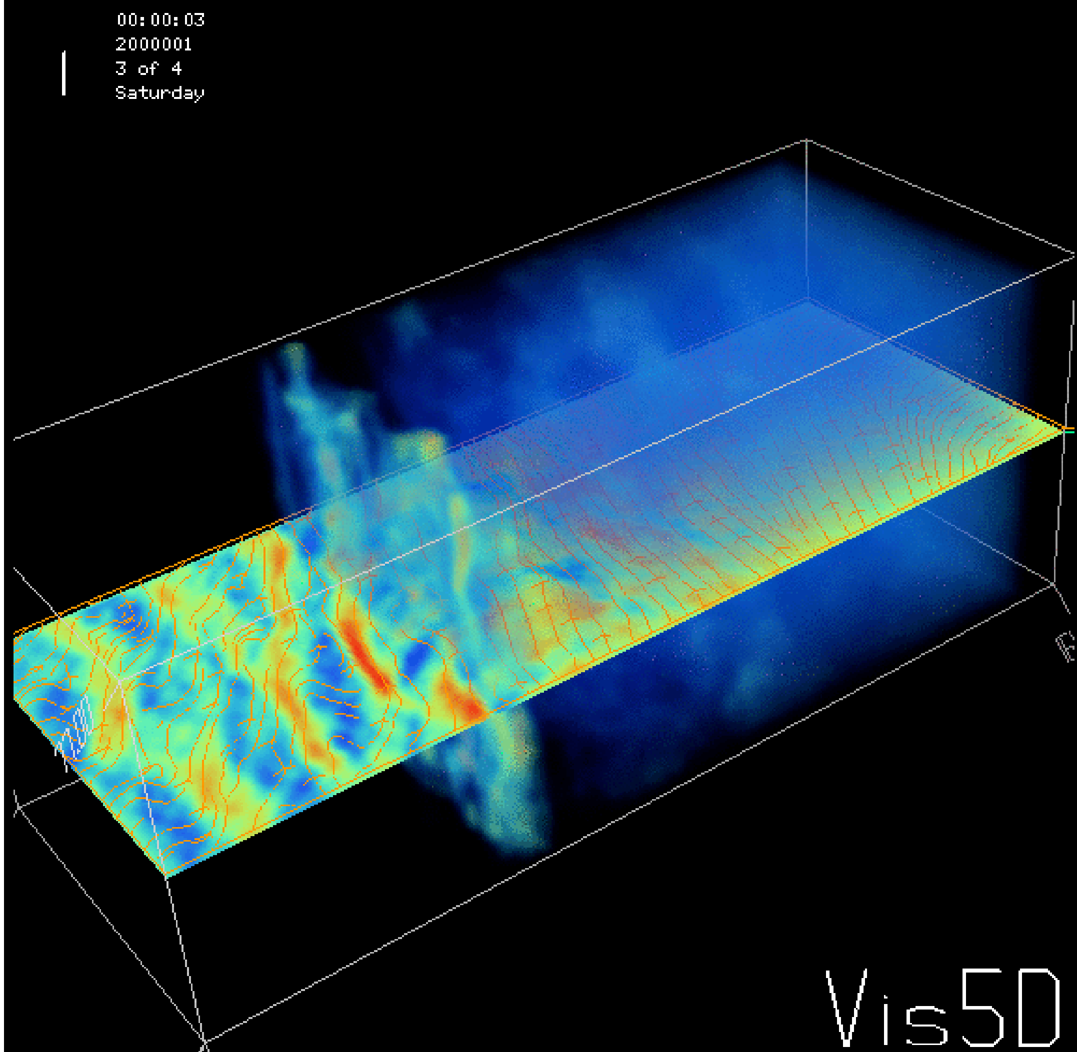
Interestingly, even though in 1D coherent low magnetization shocks are possible, in 3D they cannot exist -- Weibel instability dominates and significantly perturbs the field.

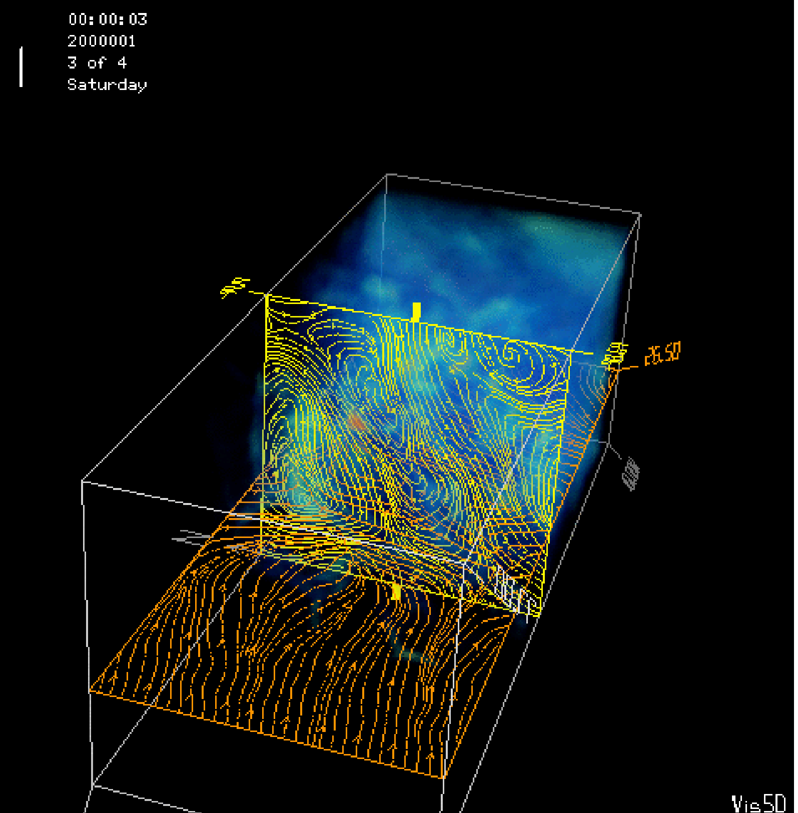
1D studies of shock-drifting acceleration in low-sigma shocks are suspect because of this (e.g. Hoshino et al 03). 1D maser-modulated shocks (Lyubarsky 06) can be overwhelmed by Weibel in multi-D.

Oblique pair shocks

45 degrees -- like magnetized shocks

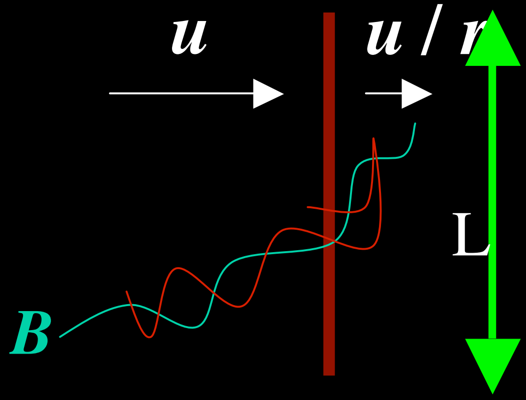
15 degrees -- like unmagnetized

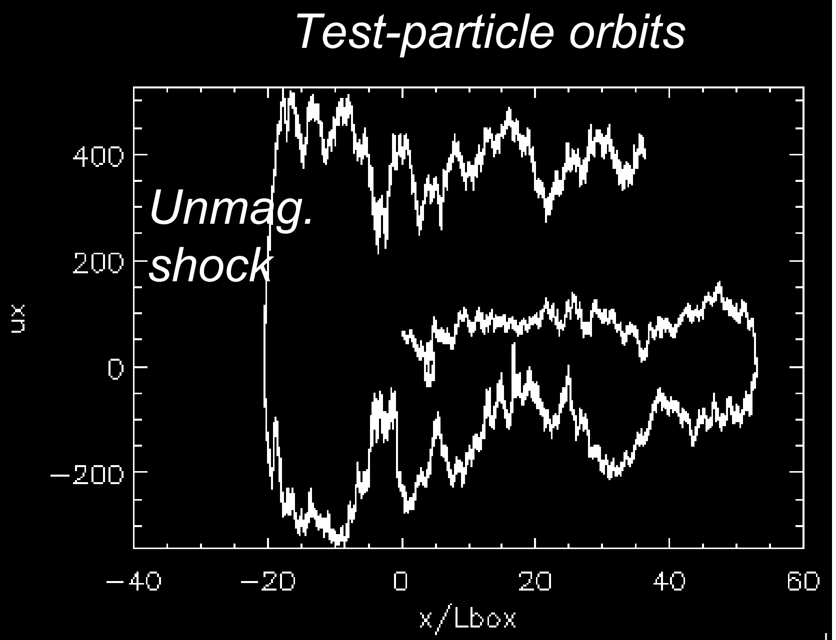


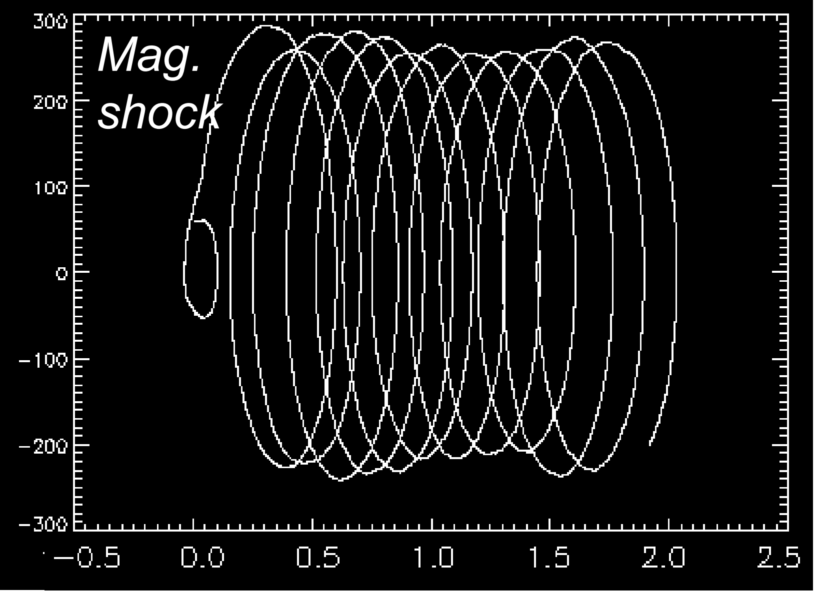


Shock structure is determined by the effective transverse σ. Oblique simulations so far too short to talk about Fermi acceleration in oblique shocks

Where is Fermi accelleration?







Both test-particle and analytic analysis of Fermi I assumes efficient diffusion and scattering.

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

Unmagnetized shocks show more promise, if B field survives far enough downstream, and upstream turbulence exists, or is self-generated.

Can Fermi I accel. be seen in PIC simulations?

2D: back to the future

Test-particle orbits suggest turbulence in unmagnetized shocks.

To see if this turbulence can be tapped we need

a) To reach a steady-state shock;

b) Give it enough time;

Full 3D is prohibitive even for pair plasma. At 3000x320x320x12 particle/cell -- 150Gb of memory. (300 x32 x 32 c/ω_p). And this should be increased by a factor of 10 at least to see steady state. Not impossible, but prohibitive.

To explore the parameter space we go back to 2D.

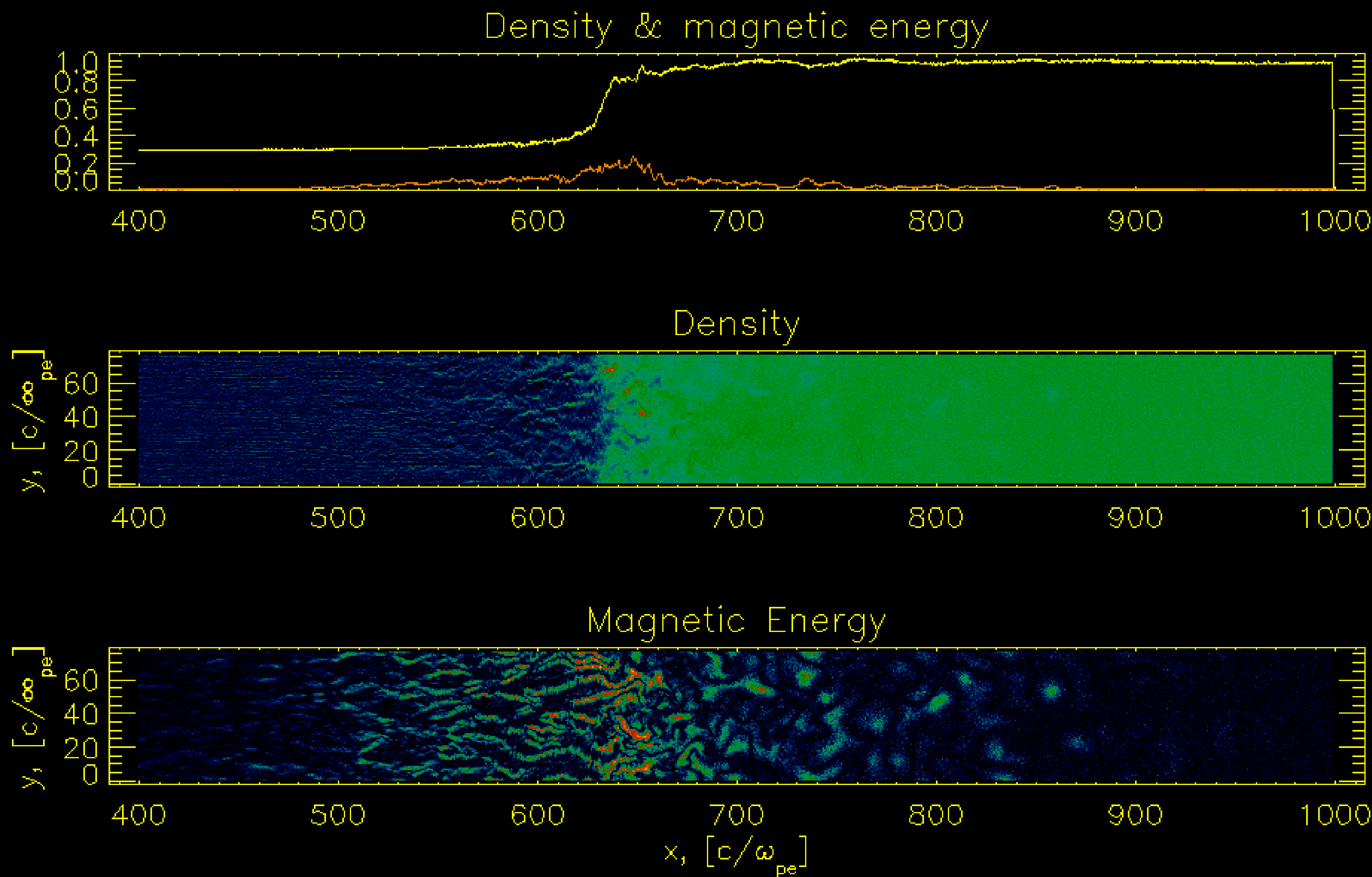
We checked that early evolution is very similar between 2D and 3D.

2D allows both Weibel (transverse) and longitudinal / magnetic modes.

Evolution of magnetic field is suspect in 2D. Downstream may behave differently in 3D.

Tentative detection of self-consistent Fermi acceleration

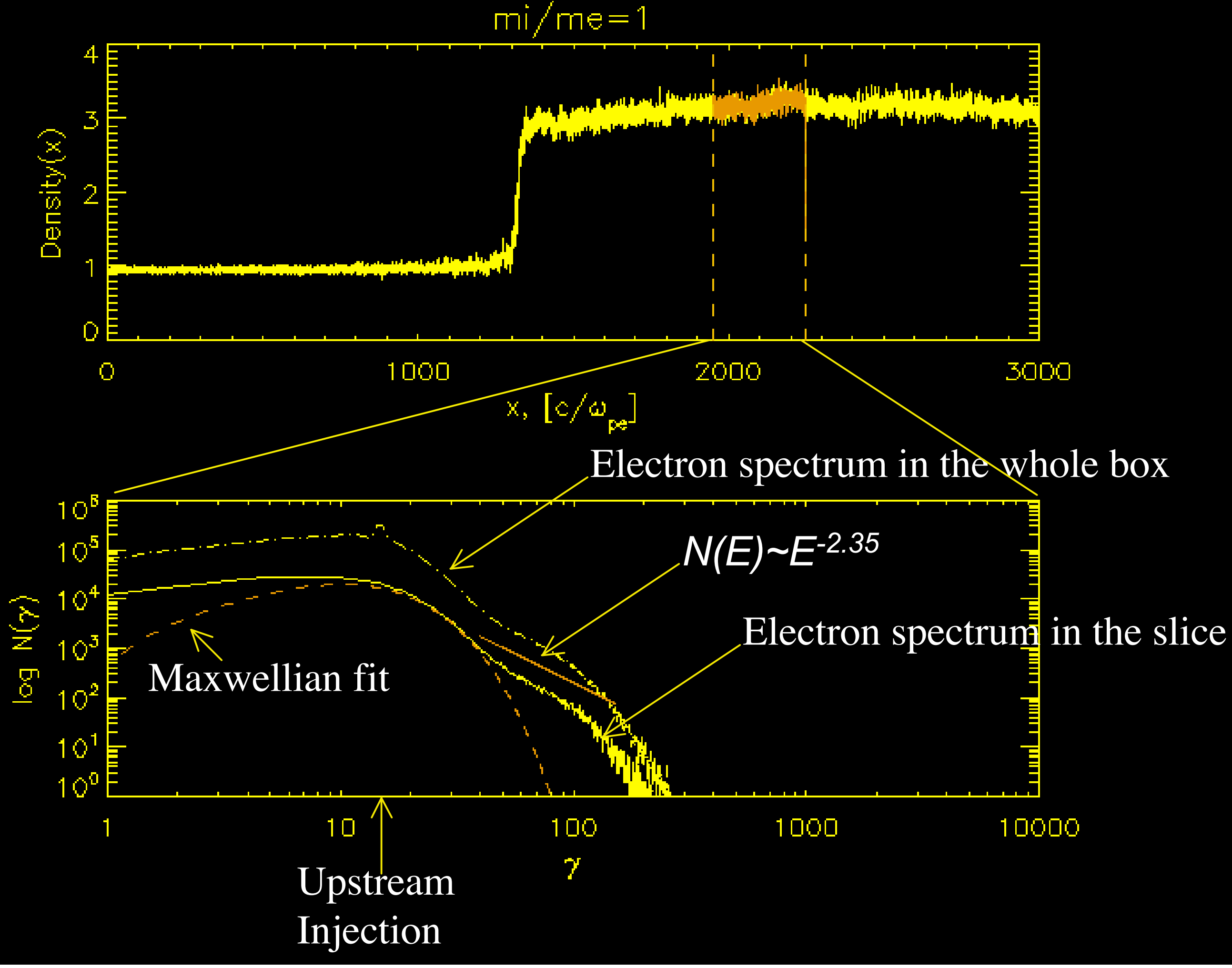
2.5D simulation on large domain (1000x80 c/ω_p).



Tentative detection of self-consistent Fermi acceleration

Use 2.5D simulation on large domain (3000x80 c/ω_p). Verified that initial evolution is very similar to 3D. Run long enough to establish steady state. Nonthermal tail deveolps, $N(E) \sim E^{-2.4}$. Nonthermal contribution is 5% by number, 20% by energy.

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



Tentative detection of self-consistent Fermi acceleration

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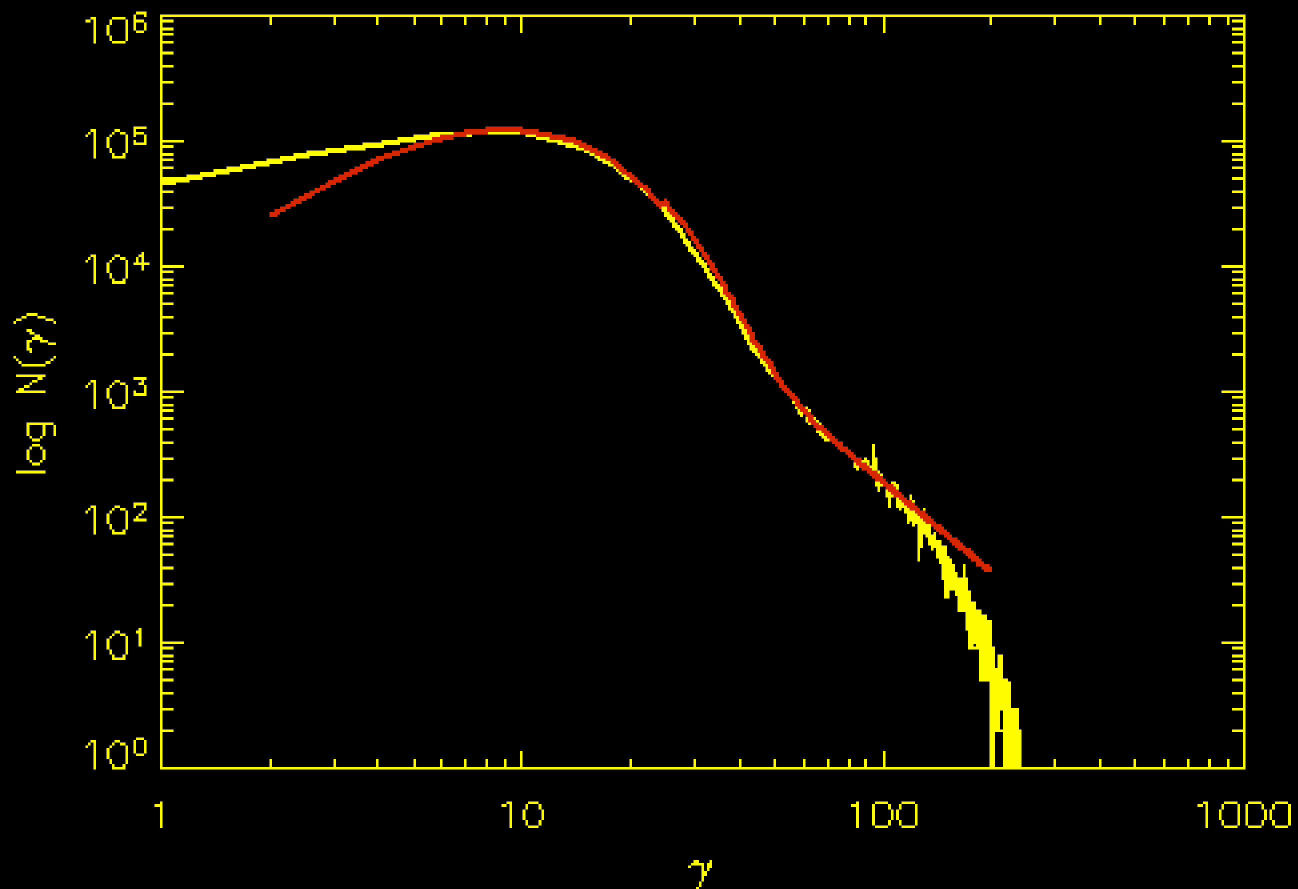
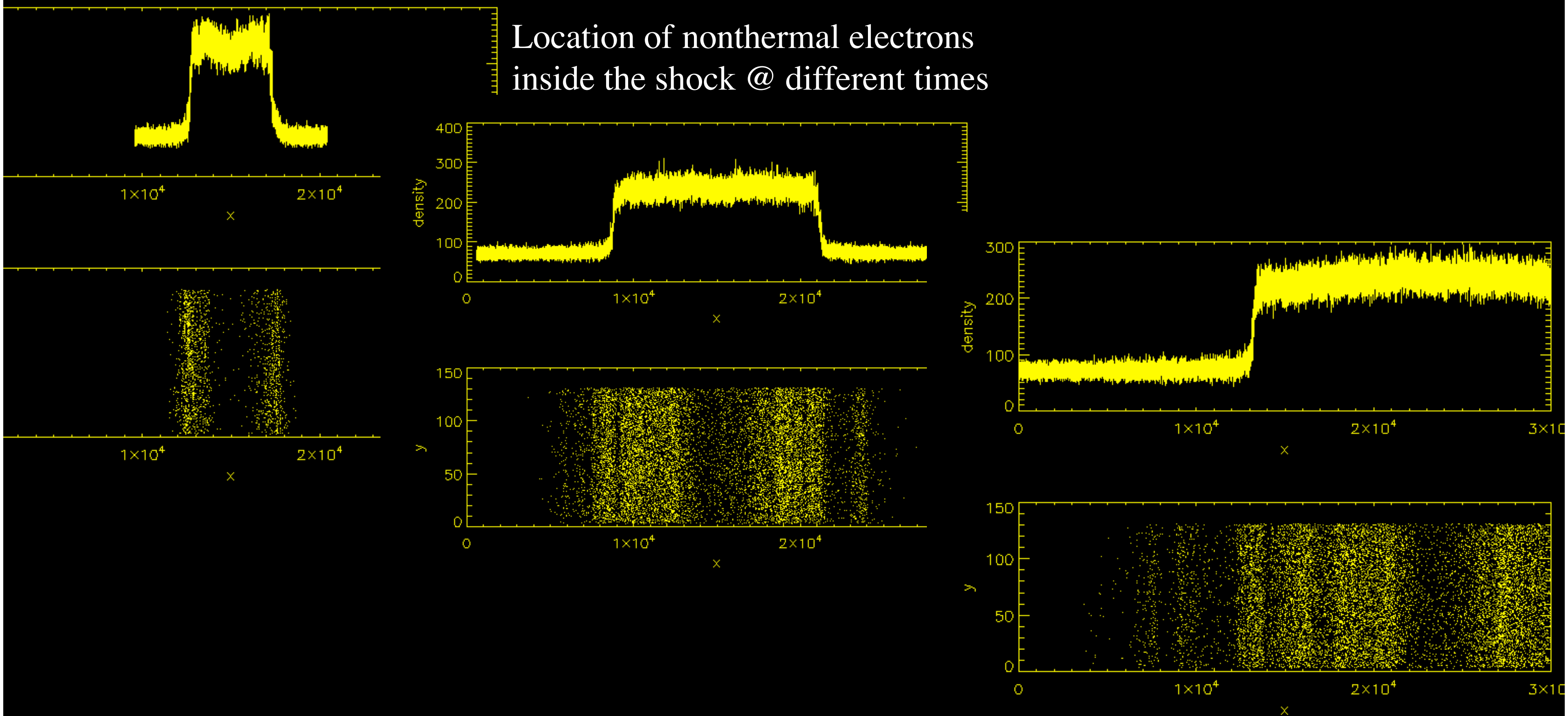


Tentative detection of self-consistent Fermi acceleration

High energy particles are accelerated while moving along the shock front, and sampling upstream and downstream. At early times (3D sim) they haven't spread downstream yet, so they didn't appear in the 3D downstream spectra.

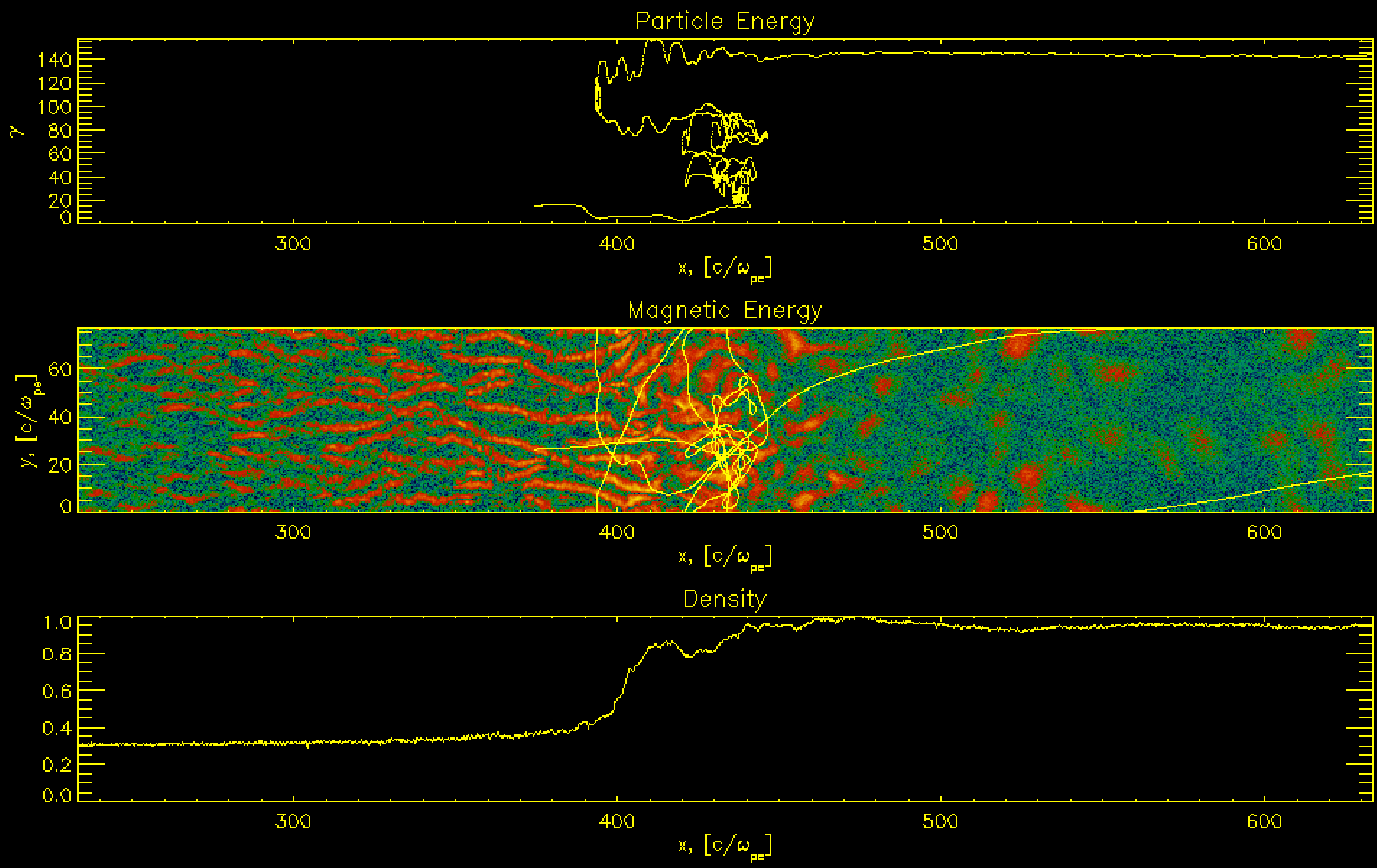
There is a cap on gamma factor, presumably when the shock becomes transparent even at high obliqueness angle. Electrostatics is not ruled out yet.



Location of nonthermal electrons inside the shock @ different times

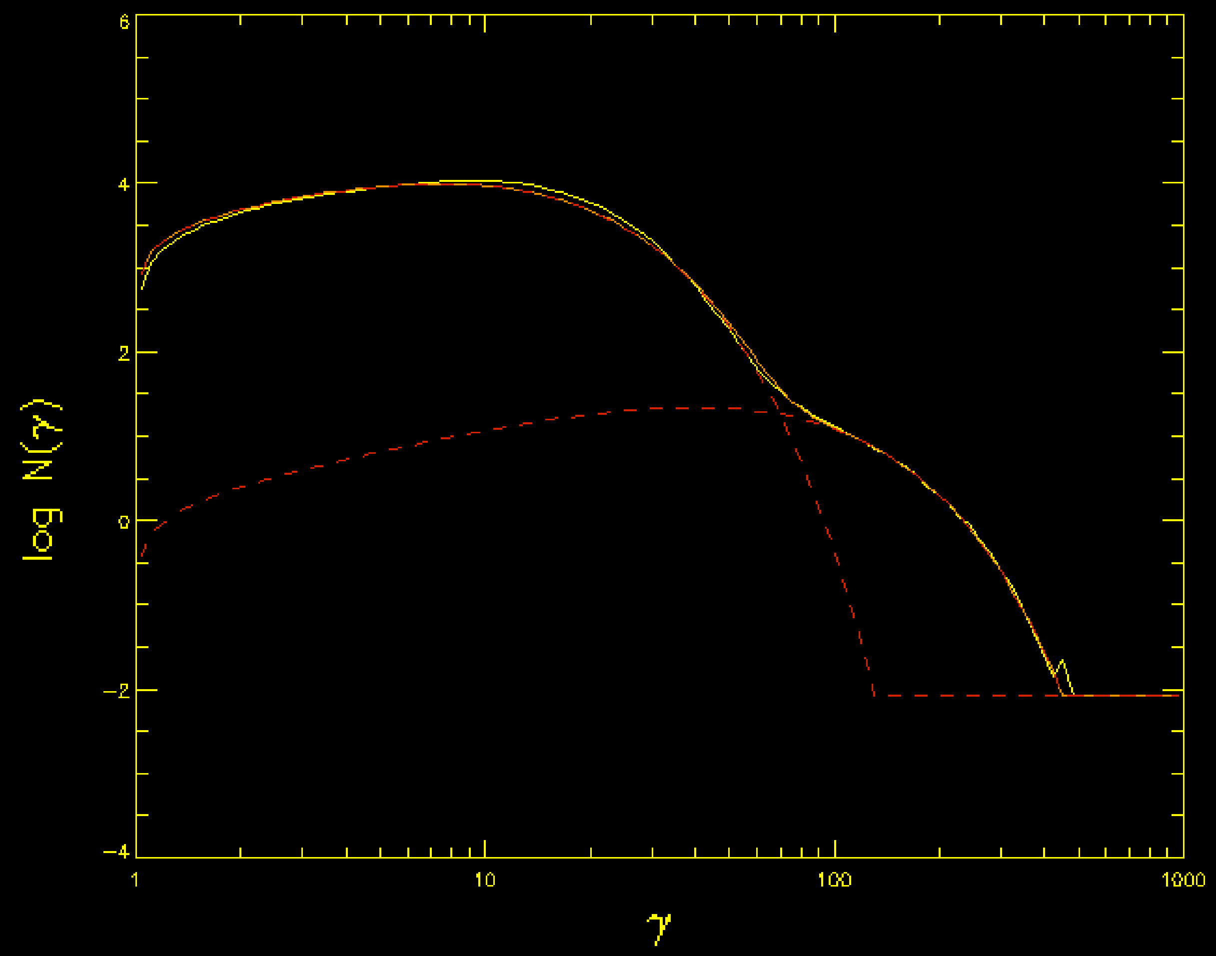
Tentative detection of self-consistent Fermi acceleration

Trace particles that end up in the tail.



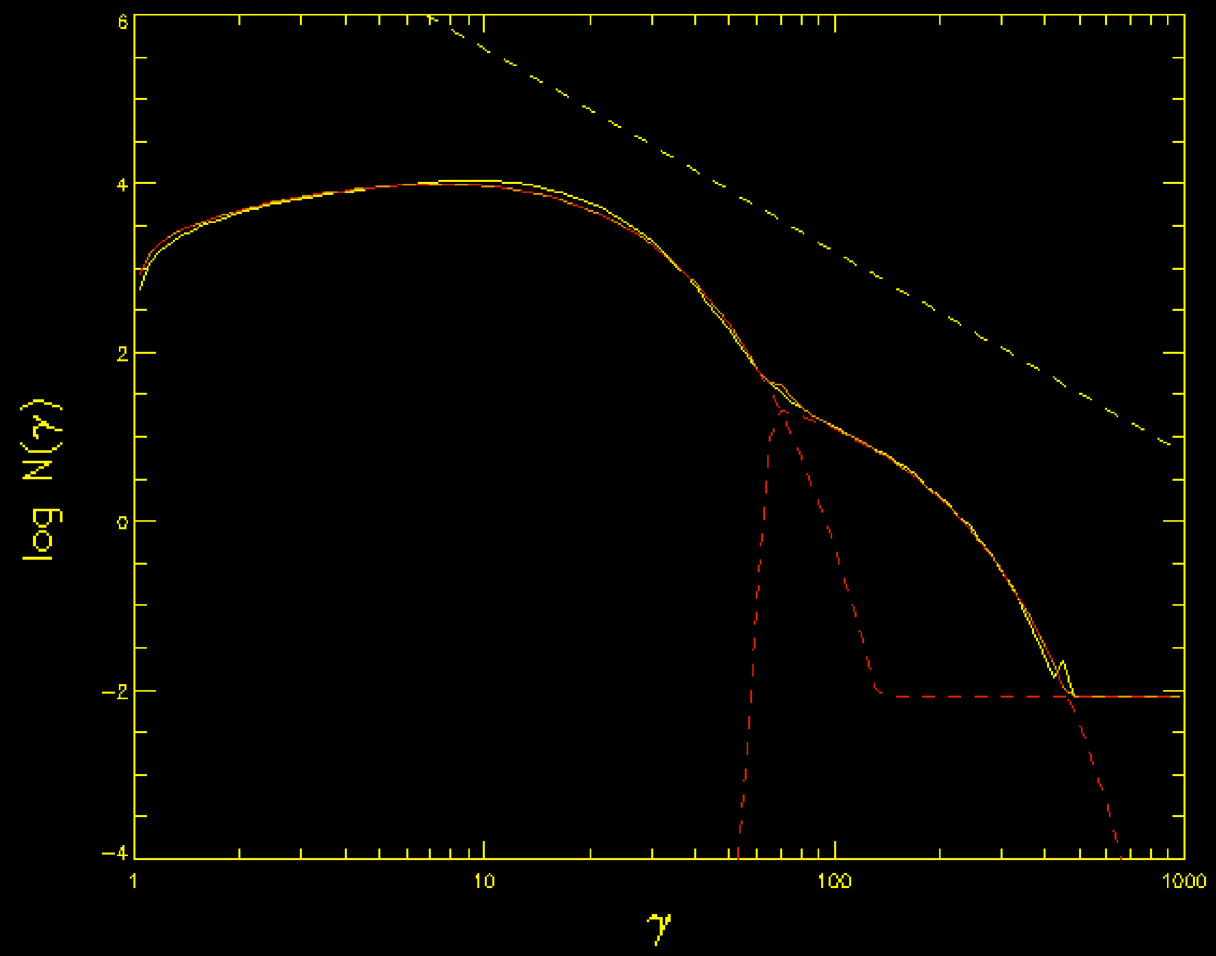
Nonthermal or just hot?

Can fit two maxwellians, one with $T=\gamma_{up}/2$, another with $T_1=3\ \gamma_{up}$. Hot distribution is ~1% by number, ~6% by energy, max γ is 40 times upstream

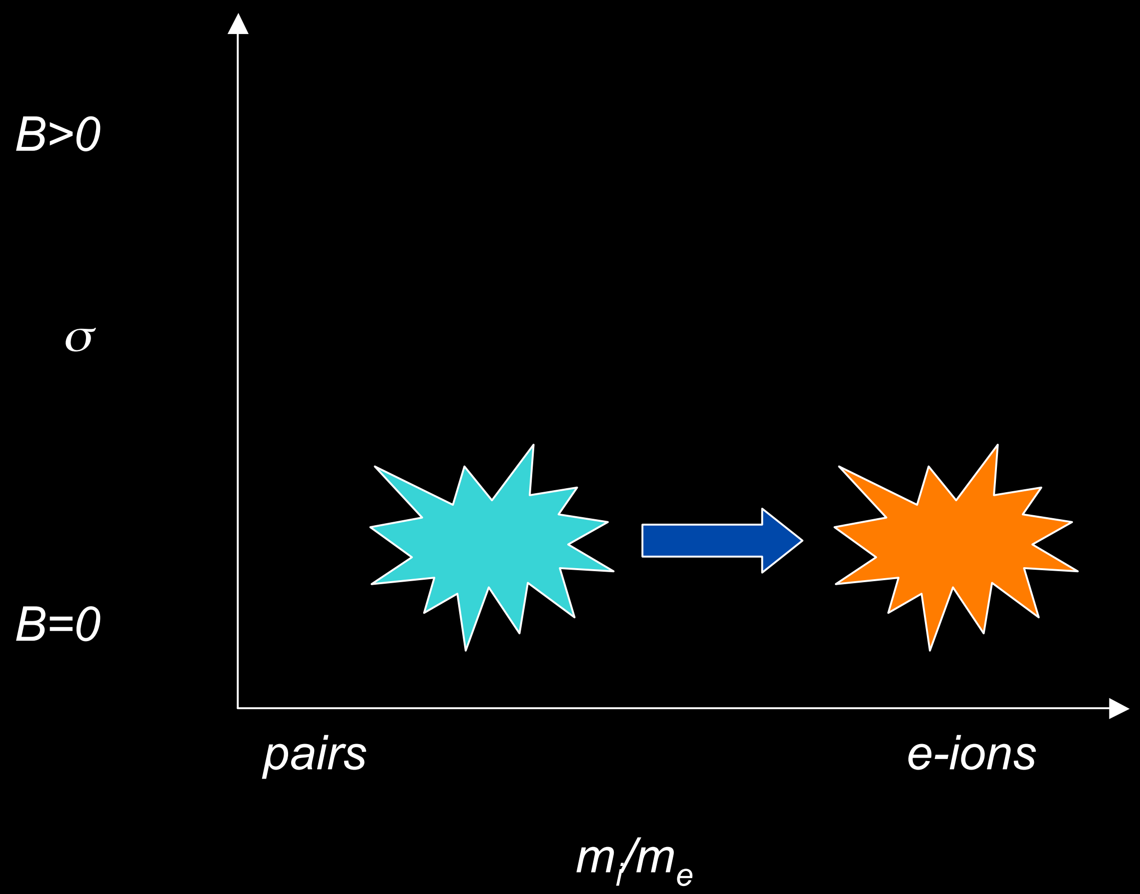


Nonthermal or just hot?

Power-law with index 2.4 can be fit with a strong exponential cutoff, sometimes leaving small dynamic range for the powerlaw.



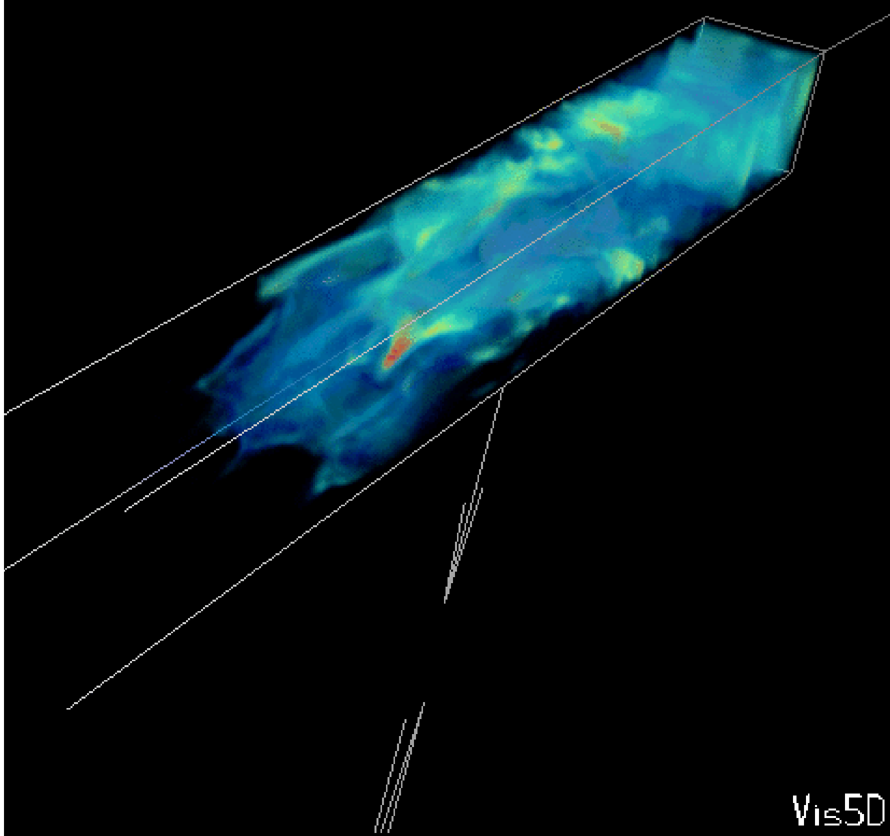
Chapter IV: Unmagnetized electron-ion shocks

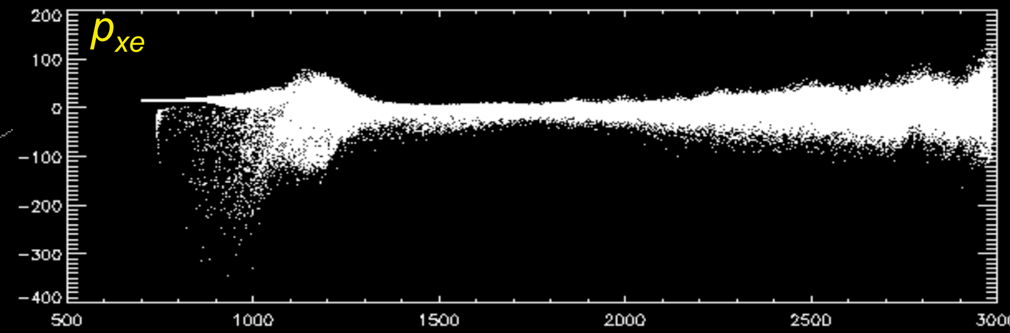


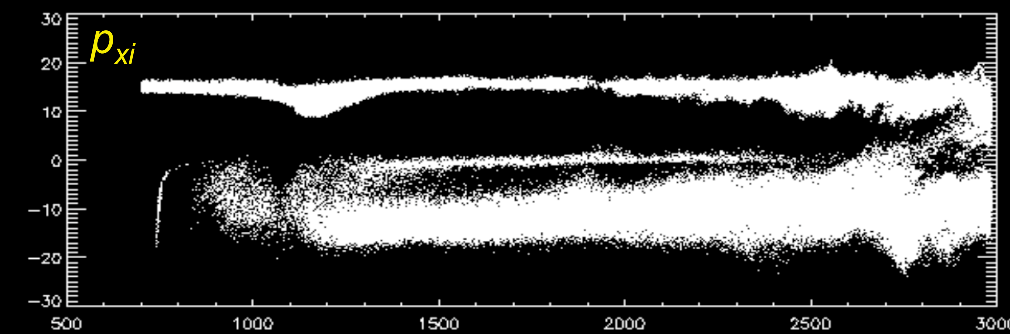
Electron-ion shocks

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

Electron density



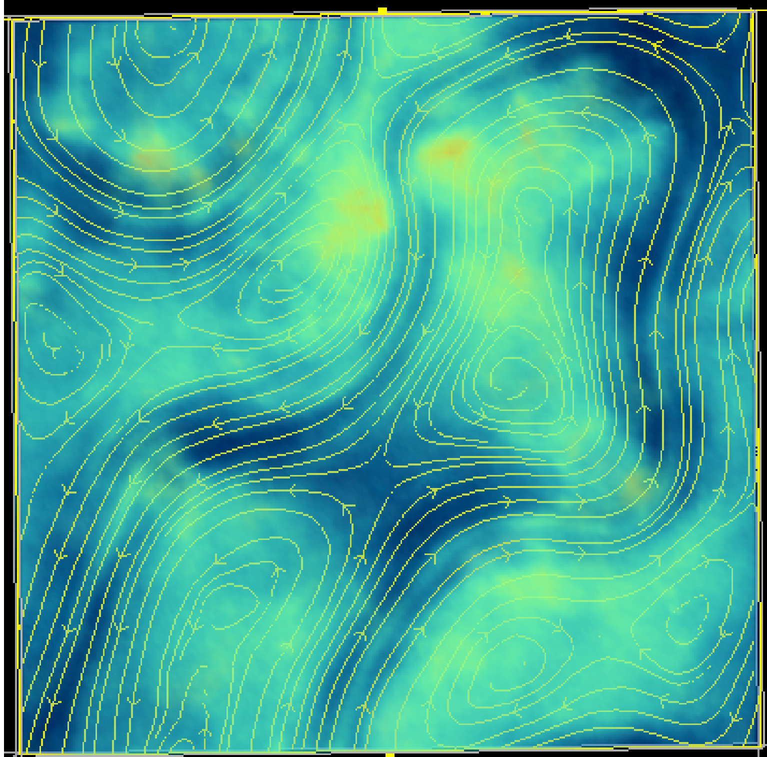




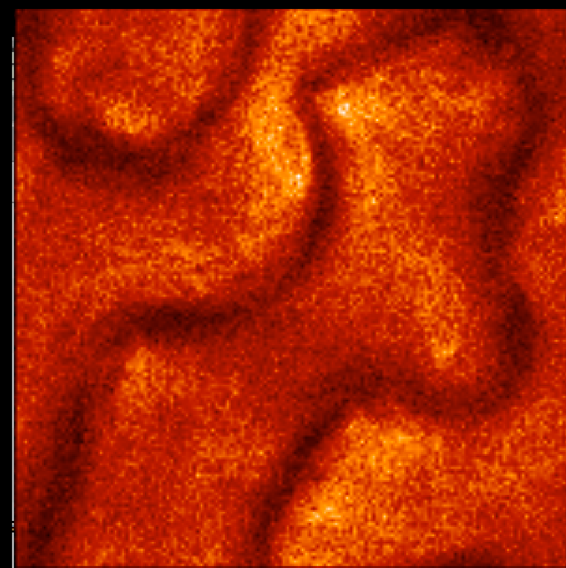
After 300 c/ω_{pe} ions are still not thermalized. Weibel instability works very fast in electrons but slow in ions (see also simulations of Nordlund et al).

Electron-ion shocks: shielding

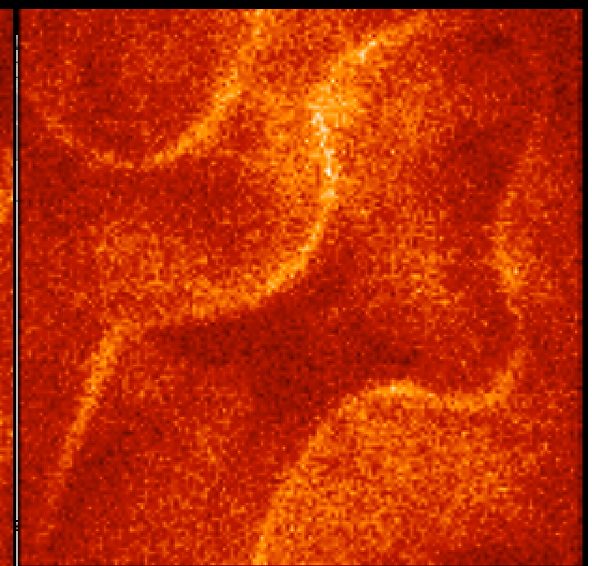
Unmagnetized ion-electron shock: $\sigma=0$, $m_i/m_e=16$



Ion density



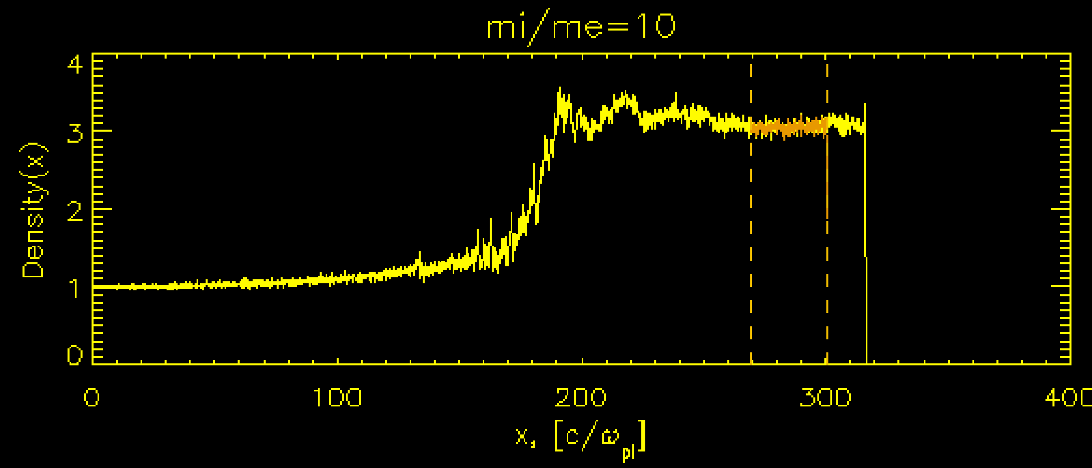
Electron density



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

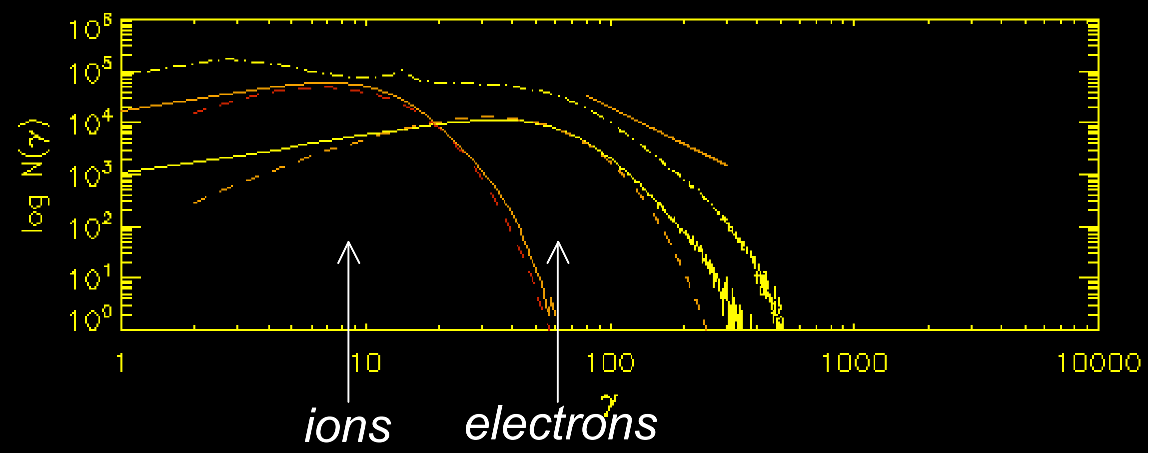
Formation of unmagnetized electron-ion shocks

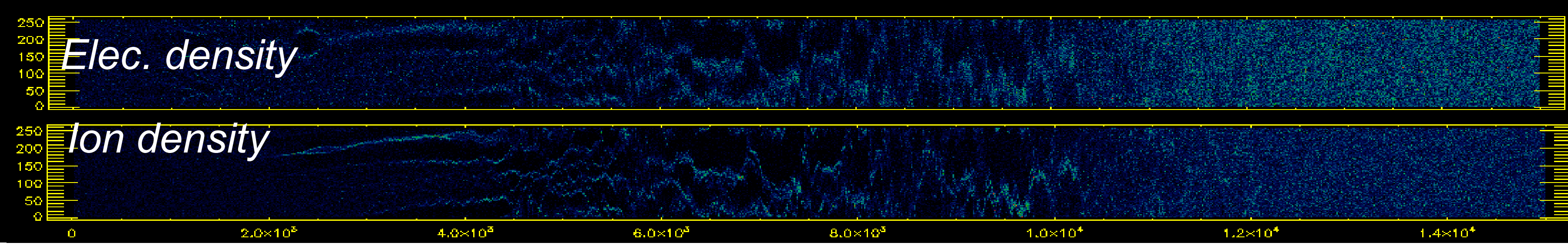
2.5-dimensional simulations are better suited for long term, large size evolution of electron-ion plasma. We find steady state shocks mediated through ion Weibel instability.



Try different mass ratios:

m_i/m_e=10



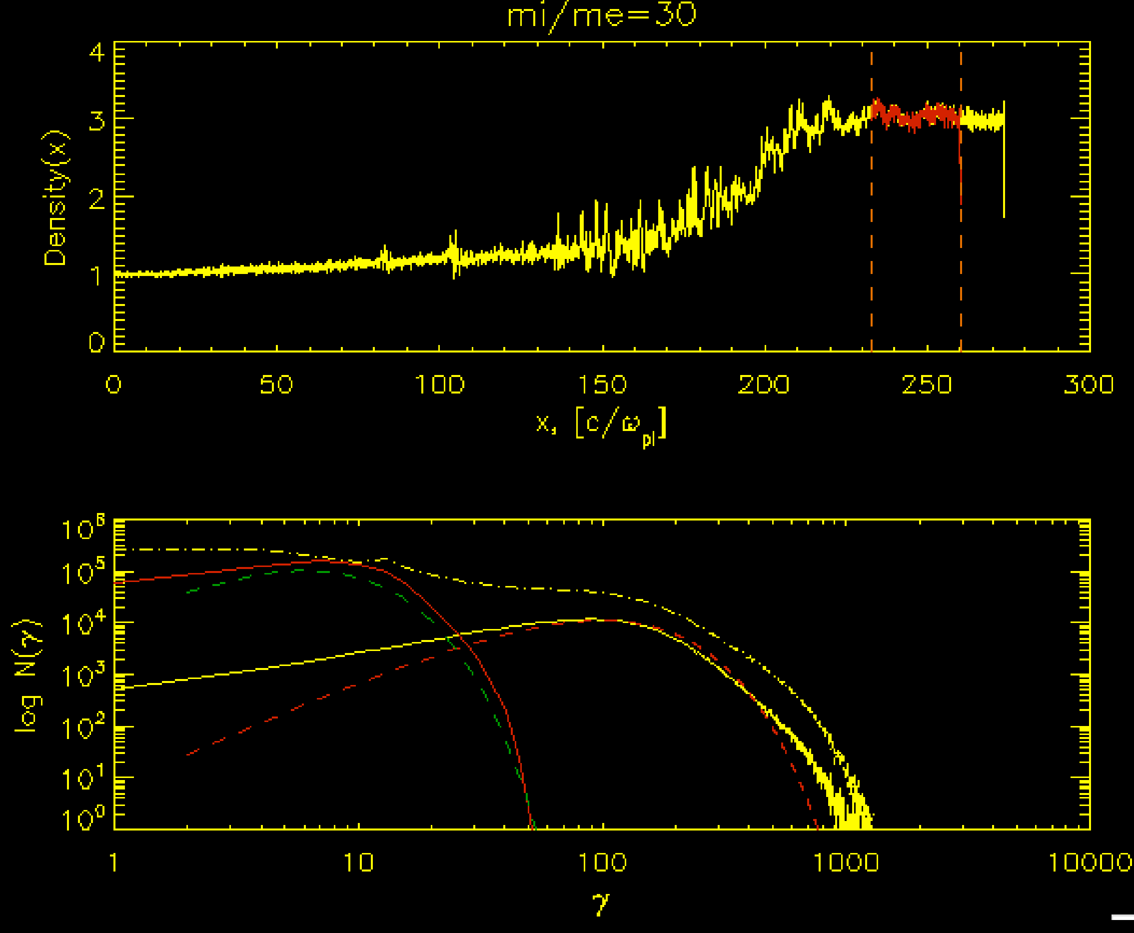


Formation of unmagnetized electron-ion shocks

2.5-dimensional simulations are better suited for long term, large size evolution of electron-ion plasma. We find steady state shocks mediated through ion Weibel instability.

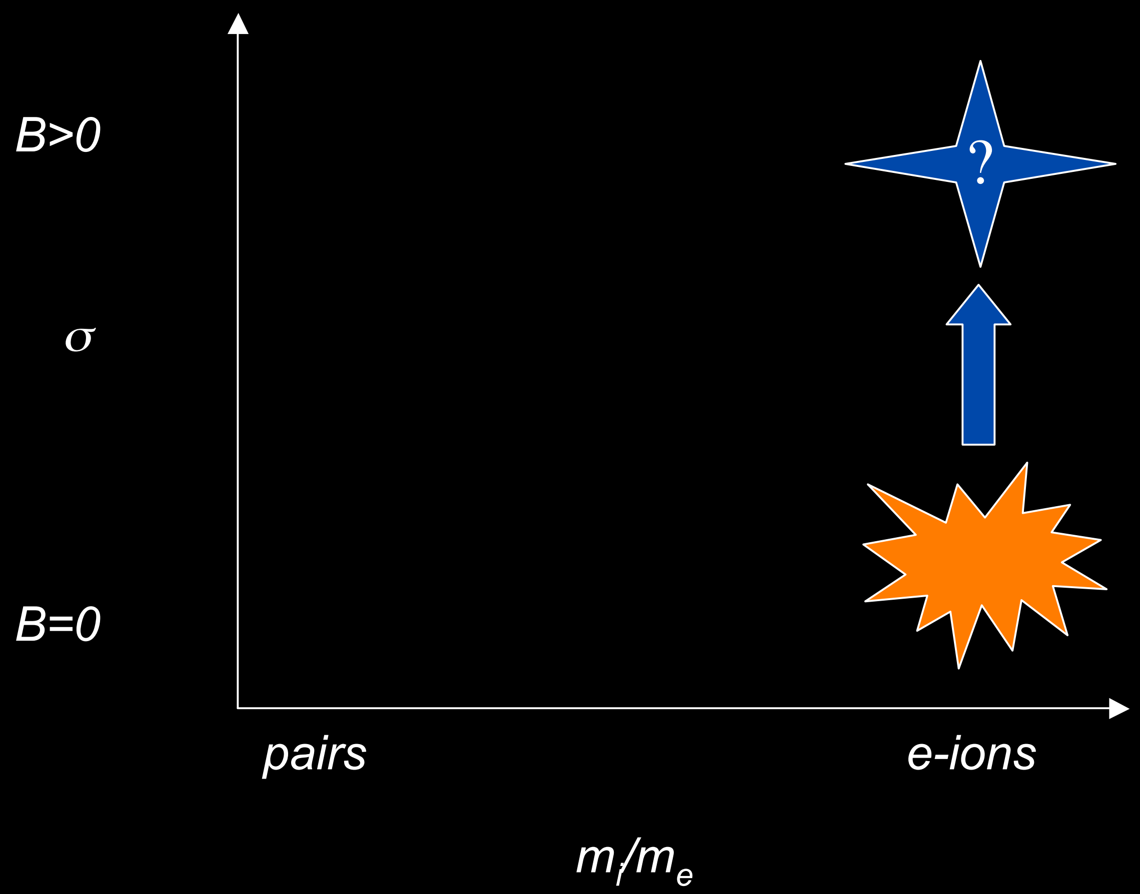
Try different mass ratios:

m_i/m_e=30



Width of the shock (in units of $c/\omega_{p\ ion}$), peak Lorentz factor of electrons and magnetic energy density all scale with the mass ratio. Electrons and ions reach equipartition in energy, so that $\gamma_e \approx \gamma_{shock} \frac{m_i}{m_e}$. *Ion shocks are possible through Weibel (cf Lyubarsky & Eichler 06). Simulations of Nordlund et al are too short.*

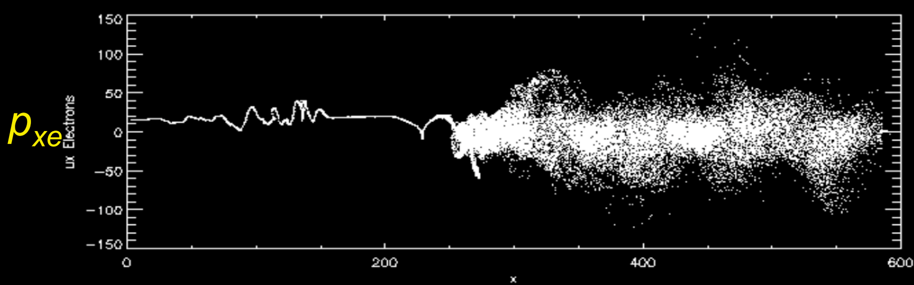
Chapter V: Magnetized electron-ion shocks

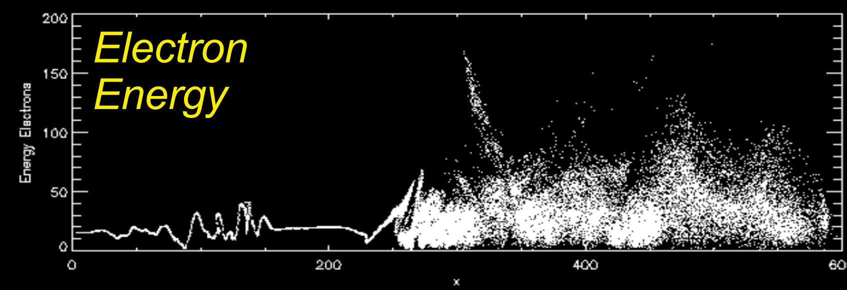


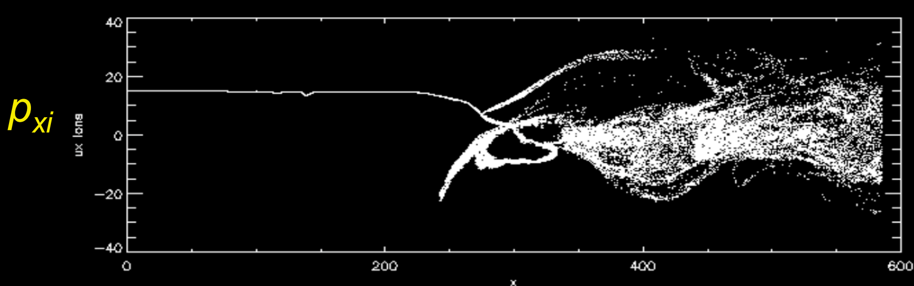
Electron-ion shocks

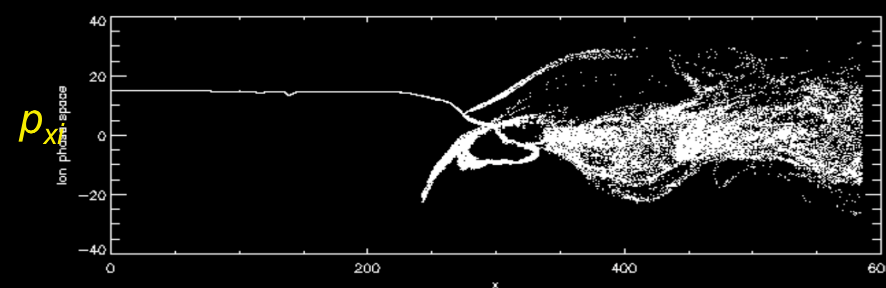
Magnetization is mainly determined by ion energy density $\sigma = B^2/(4\pi n\gamma(m_i+m_e)c^2)$

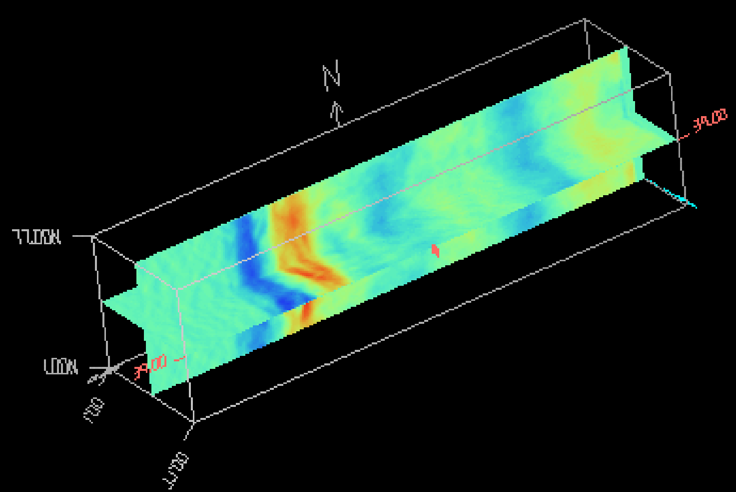
Electrons are magnetized much stronger than ions. $\sigma=0.1$

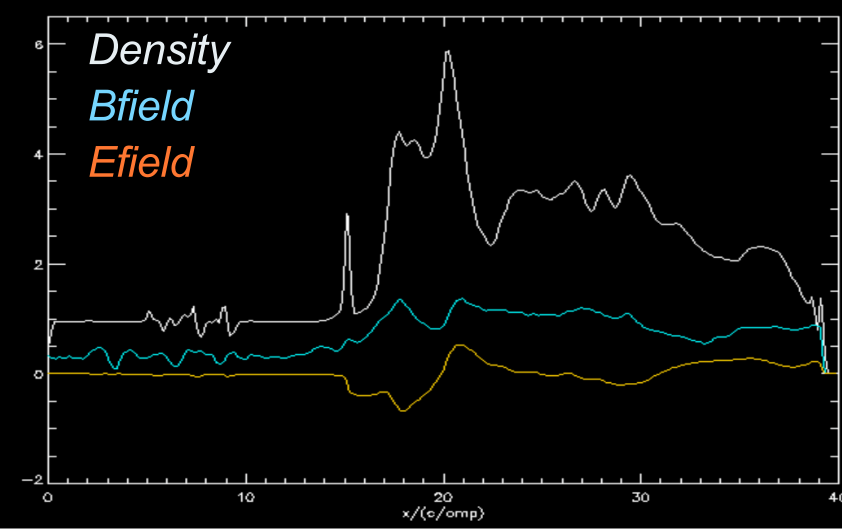












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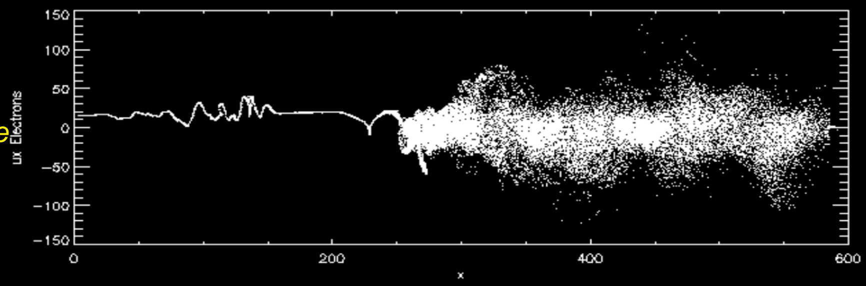
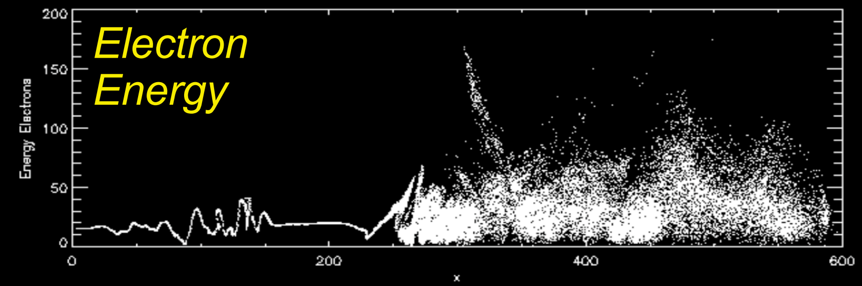
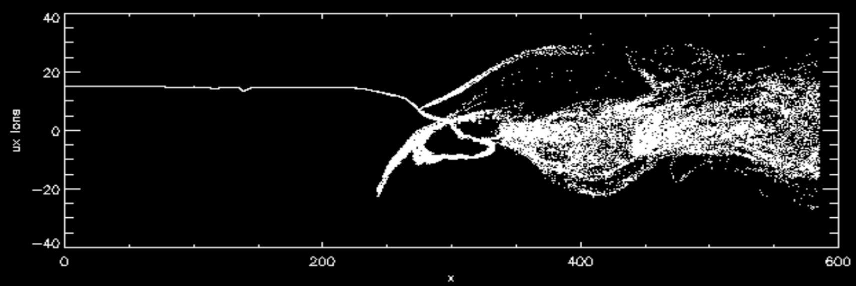
Electrons are magnetized much stronger than ions. $\sigma=0.1$

p_{xe}

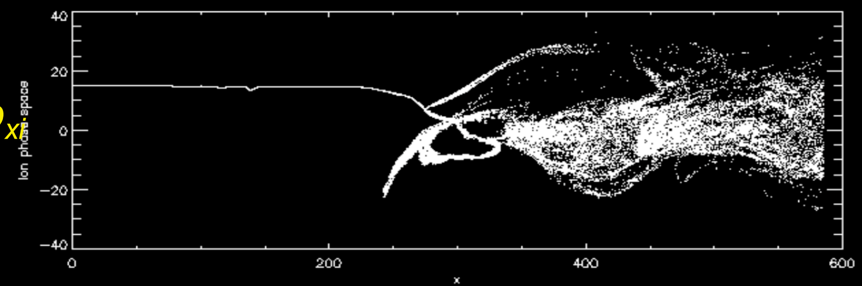


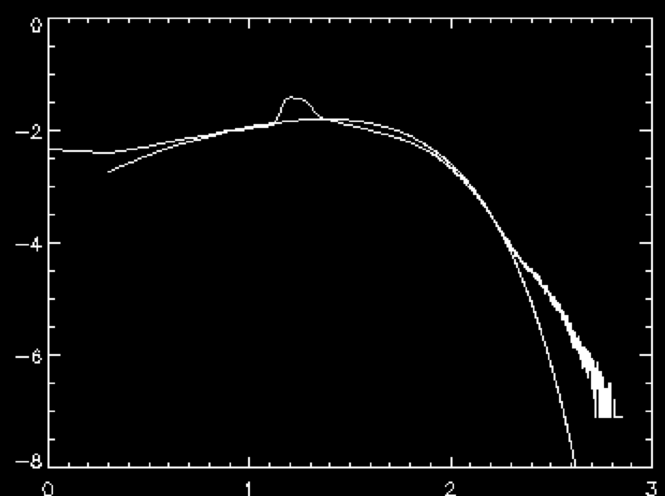


p_{xi}



p_{xi}





Log $N(\gamma)$

Log γ

Even with ions acceleration is non-Fermi: thermalization and electrostatics at the head of the shock.

More work remains to understand all effects.

Conclusions

- Collisionless shocks exist in 3D, 2D, and sometimes in 1D.
- 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. Composition also important.
- Very low-sigma shocks do not exist as magnetic shocks in more than 1D, shocks with ions can also be mediated by Weibel.
- Magnetized pair shocks do not efficiently produce nonthermal particles, unmagnetized shocks and oblique shocks show more promise.
- First evidence of self-consistent Fermi-type process operating near the unmagnetized shock. For pairs it cuts off very early -- no extended powerlaws. Need to understand magnetic turbulence decay.
- Electron-ion temperature equilibration for any B. Can we see thermal component in the observations?
- Short and small simulations can be very misleading.
- What about nonthermal generation for electron-ion or ion-pair case?
- Do pure pair plasmas *really* exist in astrophysics? (very feeble accelerators!!!)

Conclusions

- Hunting for Fermi (nonthermal) acceleration. What are the options?
  - Main difficulty for both magnetized and unmagnetized shocks is the absence of sufficient turbulence/magnetic field downstream. Can self-consistent shock structure with high-energy component amplify turbulence?
  - Possibility of Bell's instability: high energy particles (effectively unmagnetized) don't respond in the same way as a magnetized upstream plasma to fluctuations. Current can be unbalanced, leading to instability. Need parallel electric field, and bulk of the high-energy particles to be of one sign of charge, e.g. protons (won't work for pairs)
  - Resonant and nonresonant amplification of Alfven waves.
  - Composition -- e.g., only electorn-ion shocks can do this.
  - Perhaps only shocks with certain magnetic geometry in the upstream accelerate. What is it?