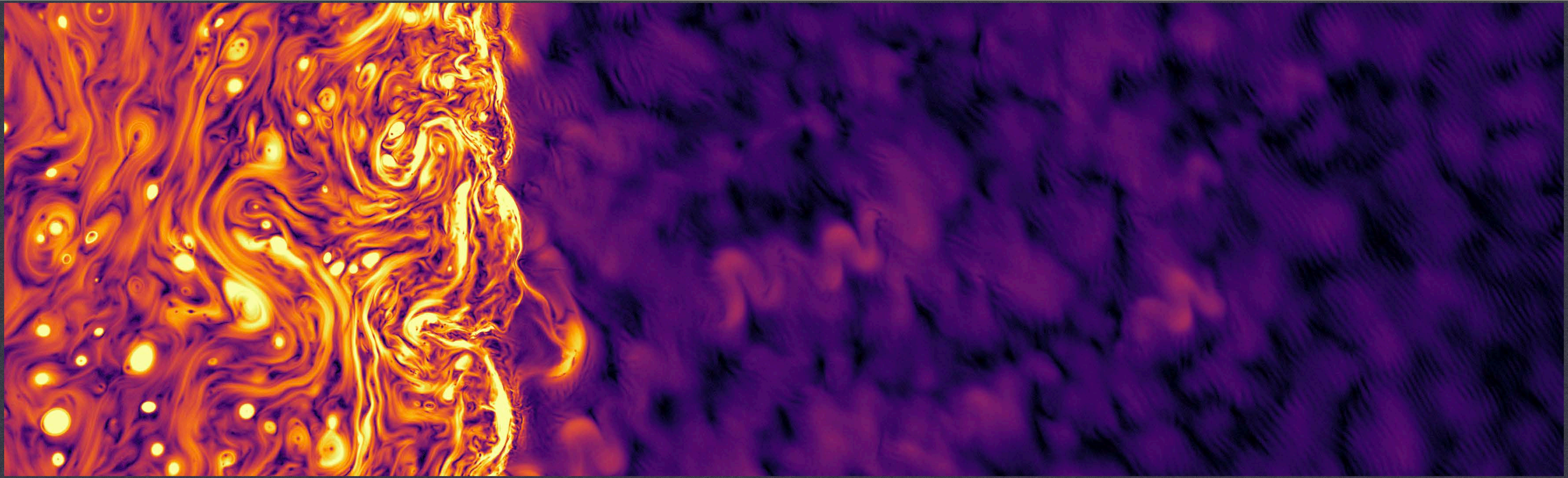


Heating, Maxwellianization, and Nonthermal Tails in Violently Collisionless Plasmas

Anatoly Spitkovsky
(Princeton University)

with much help from D. Caprioli, J. Park, V. Zekovic, A. Vanthieghem, A. Galishnikova, V. Tsiolis, Z. Hemler, M. Riquelme, L. Sironi, P. Crumley, R. Kumar, X. Bai, H-S. Park, F. Fiuza

OUTLINE

"Violently Collisionless": plasma element considerably changing its state on scales << Coulomb mfp (usually as a result of supersonic motion against background)

1. Collisionless shocks: basic properties

2. Shock formation, heating, and internal structure

3. Role of shock structures in plasma heating and acceleration

4. Open questions and connections to dynamics

Physics of collisionless shocks

$$[\varrho u_n] = 0$$

$$\left[\varrho u^2 + P + \frac{B^2}{8\pi}\right] = 0$$

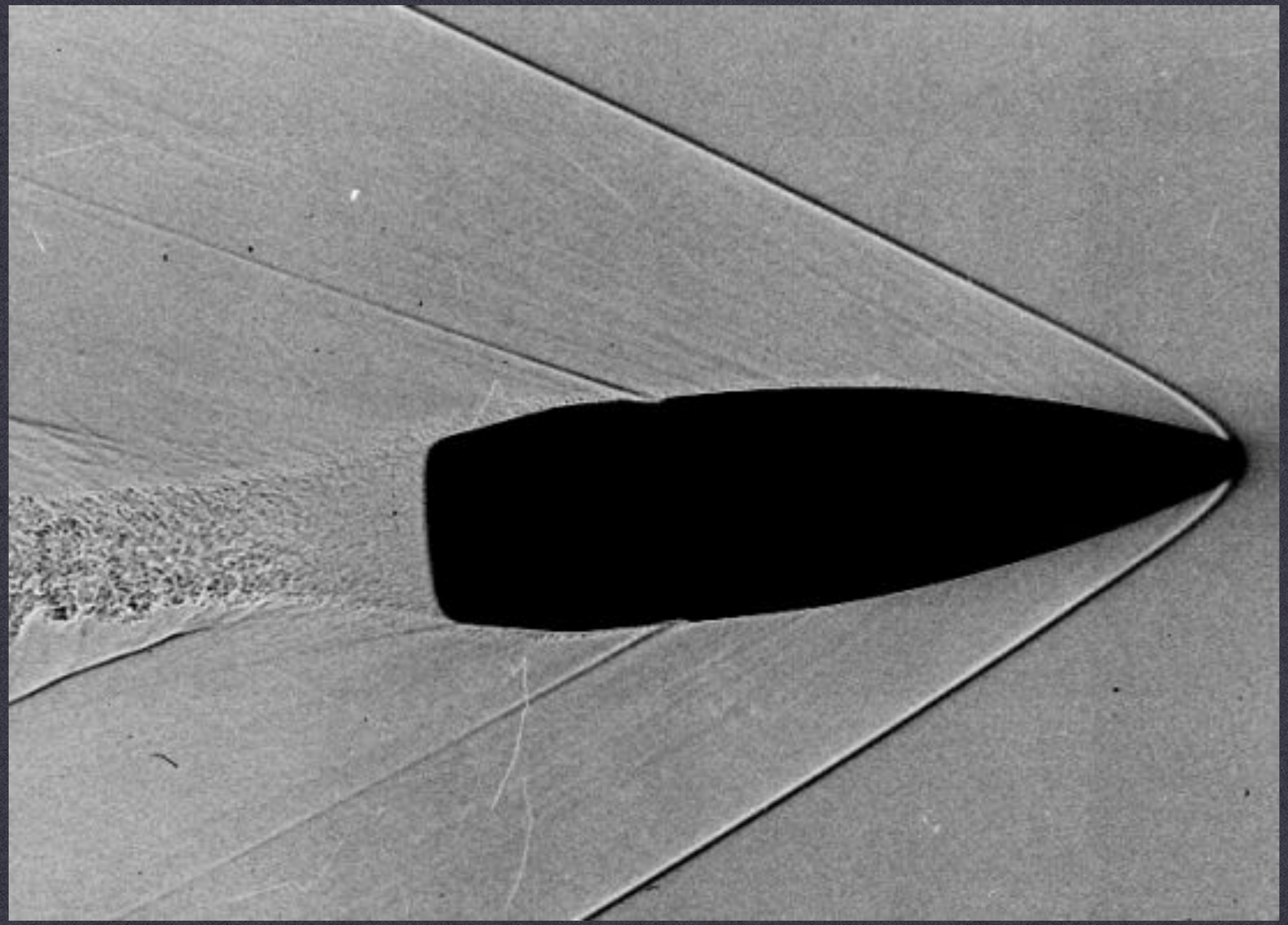
$$\left[\varrho u_n \boldsymbol{u}_t - \frac{B_n}{4\pi}\boldsymbol{B}_t\right] = 0$$

$$\left[\varrho u_n\left(\frac{1}{2}u^2 + \frac{\gamma}{\gamma-1}\frac{P}{\varrho}\right) + u_n\frac{B^2}{4\pi} - \frac{\boldsymbol{u}\cdot\boldsymbol{B}}{4\pi}B_t\right] = 0$$

$$[u_n\boldsymbol{B}_t - B_n\boldsymbol{u}_t] = 0$$

$$P = P_0\left(\frac{\varrho}{\varrho_0}\right)^{\gamma}$$

Shock: sudden change in density, temperature, pressure that decelerates supersonic flow



Thickness ~mean free path
in air: mean free path ~micron

On Earth, most shocks are mediated by collisions

$$\left[r^2\frac{2-\gamma}{M_A} + r\left(\frac{\gamma}{M_A^2} + \frac{2}{M_s^2} + \gamma - 1\right) - (\gamma+1)\right](r-1) = 0$$

As $M_s \to \infty,\, r \to 4$

Astro: Mean free path to Coulomb collisions in enormous: 100pc in supernova remnants, ~Mpc in galaxy clusters

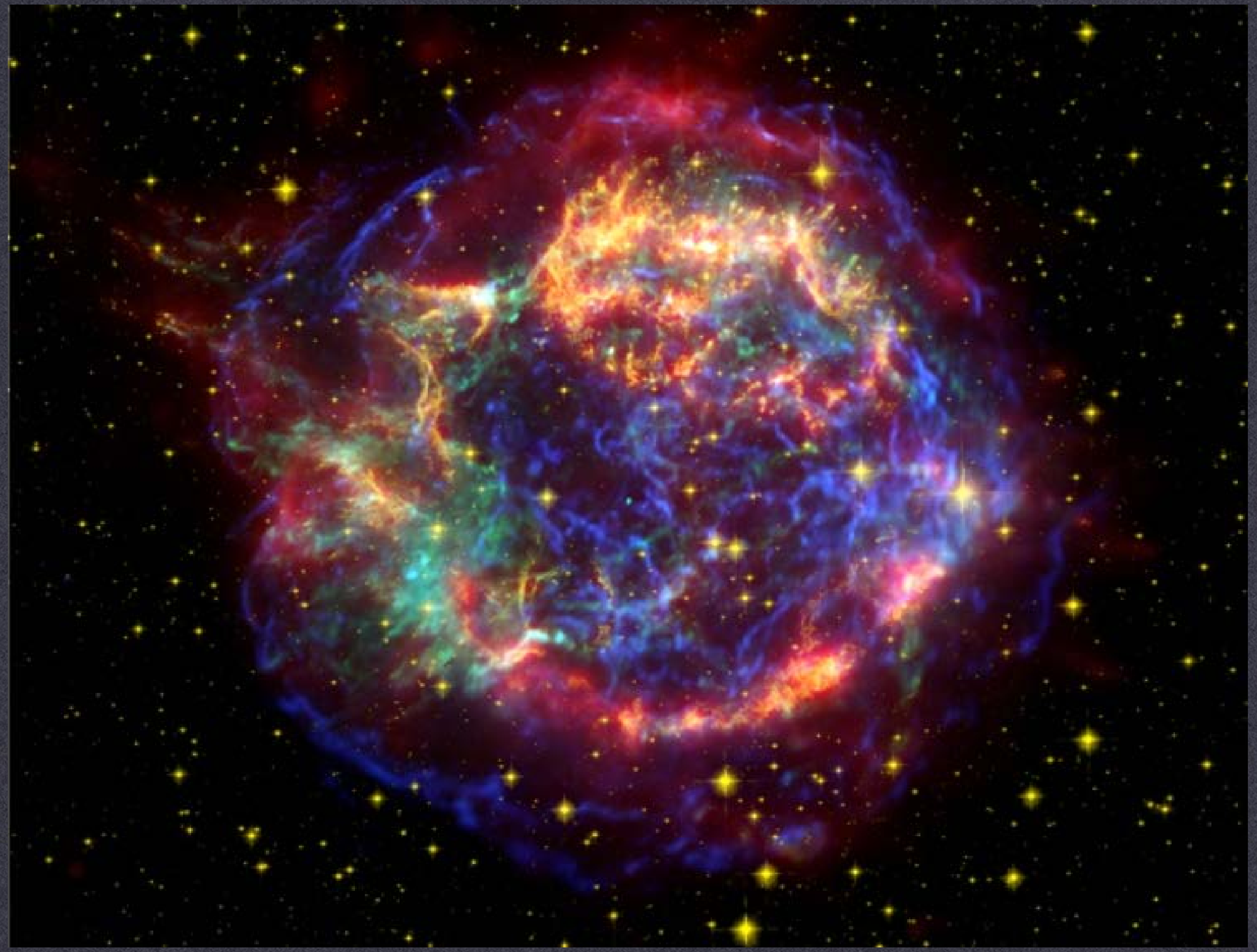
Mean free path > scales of interest

shocks must be mediated without direct collisions, but through interaction with collective fields

collisionless shocks

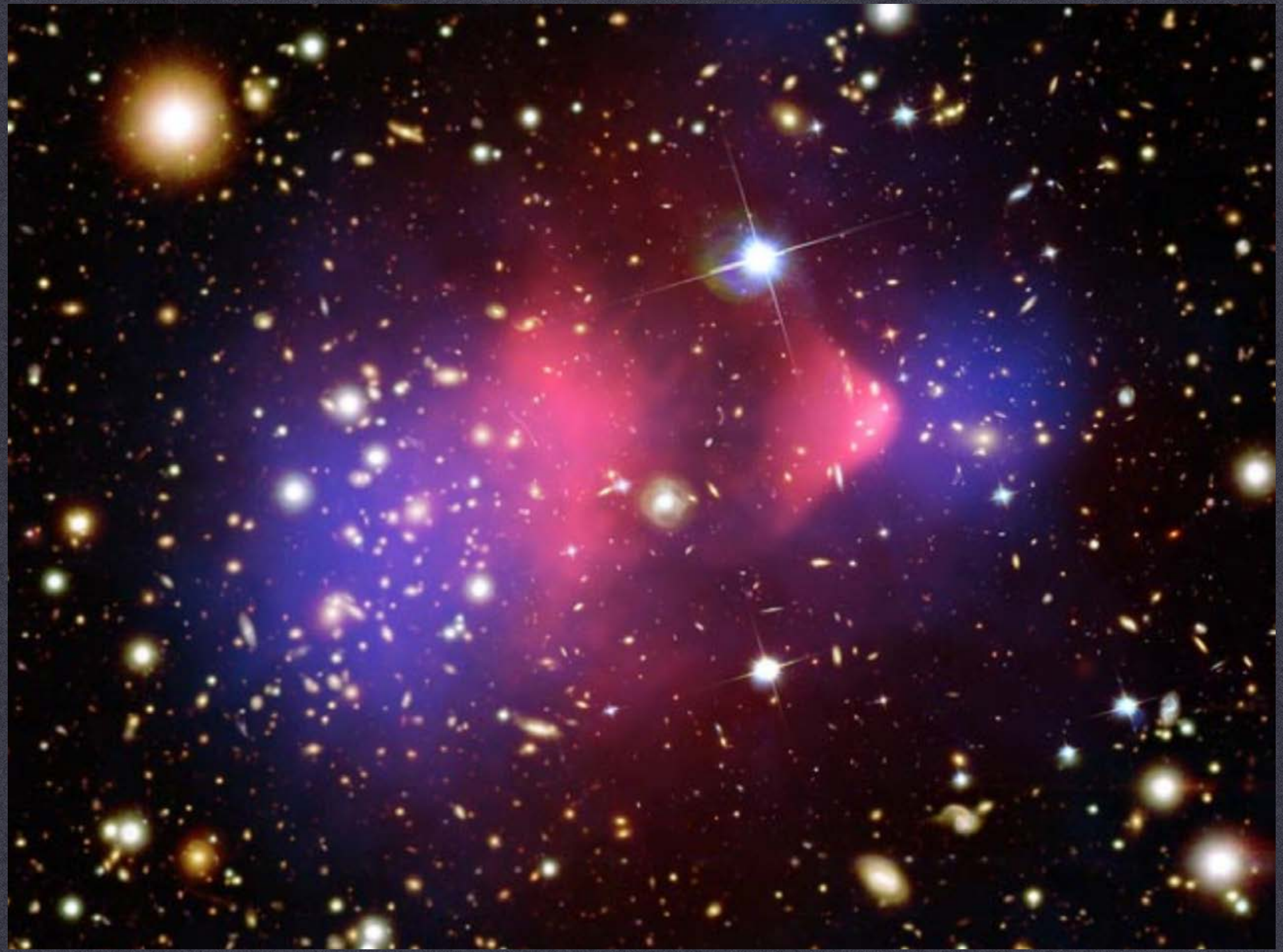
Physics of collisionless shocks

Shock: sudden change in density, temperature, pressure that decelerates supersonic flow



Thickness ~mean free path
in air: mean free path ~micron

On Earth, most shocks are mediated by collisions

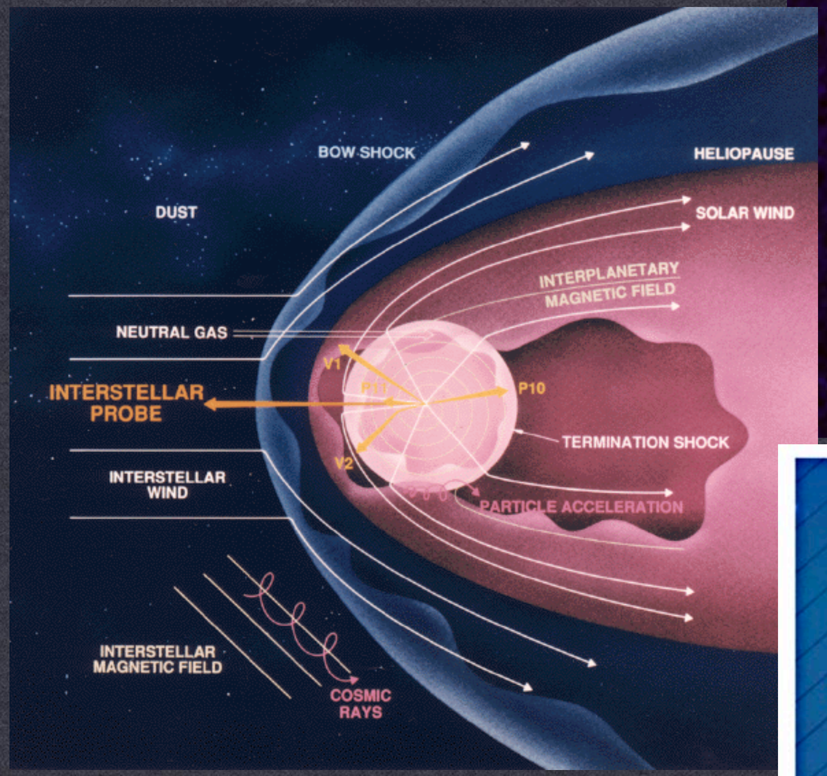


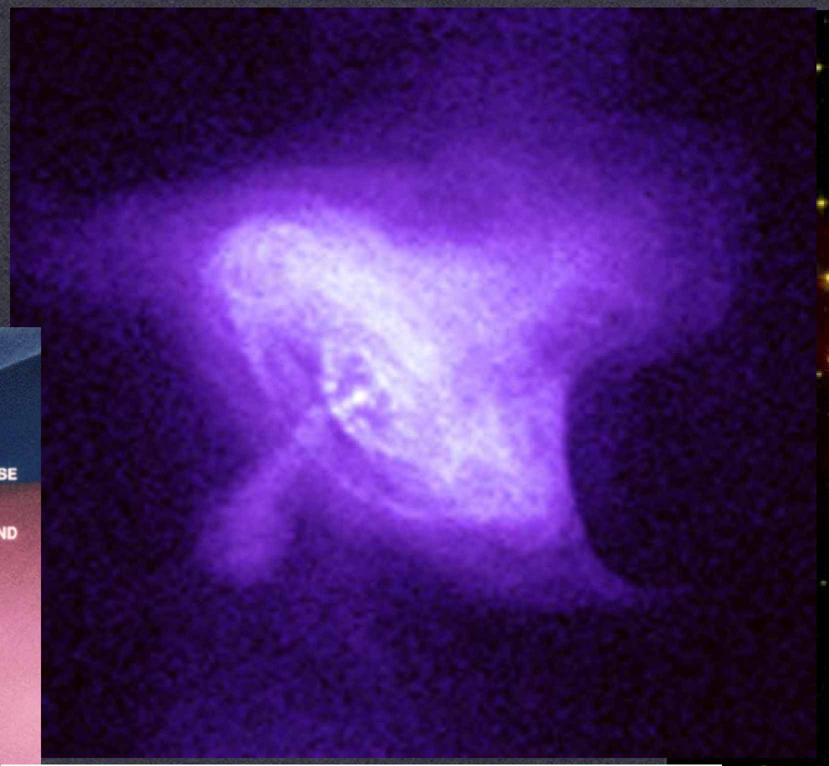
Astro: Mean free path to Coulomb collisions in enormous: 100pc in supernova remnants, ~Mpc in galaxy clusters
Mean free path > scales of interest

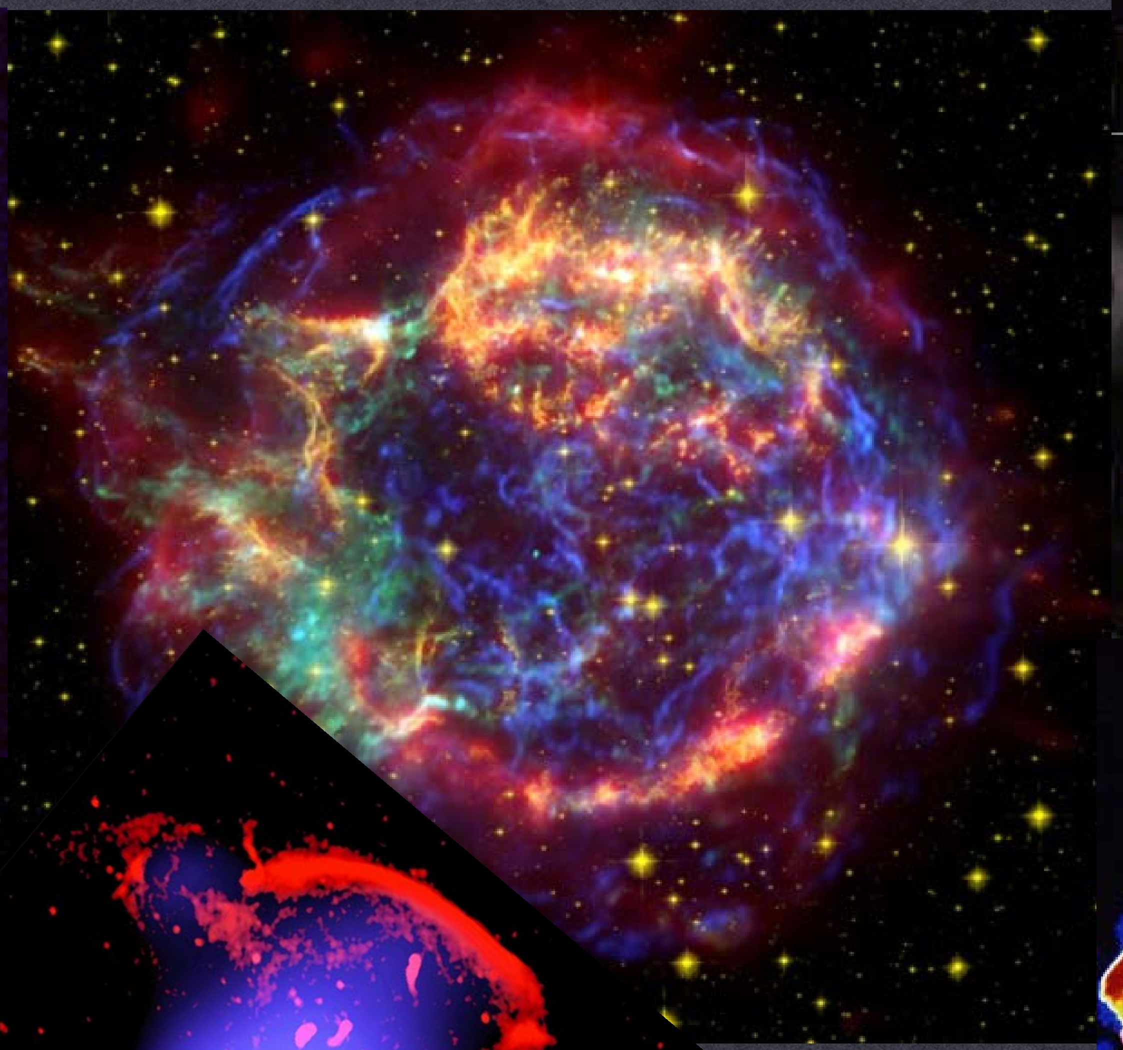
shocks must be mediated without direct collision, but through interaction with collective fields

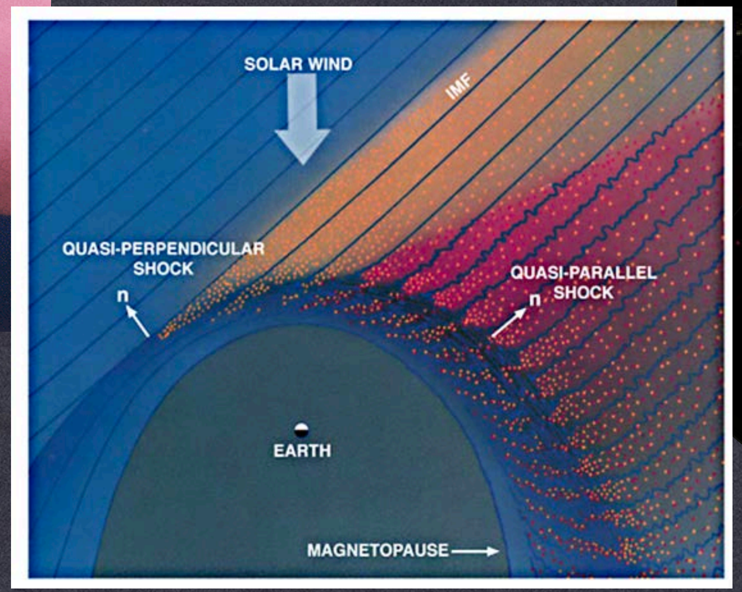
collisionless shocks

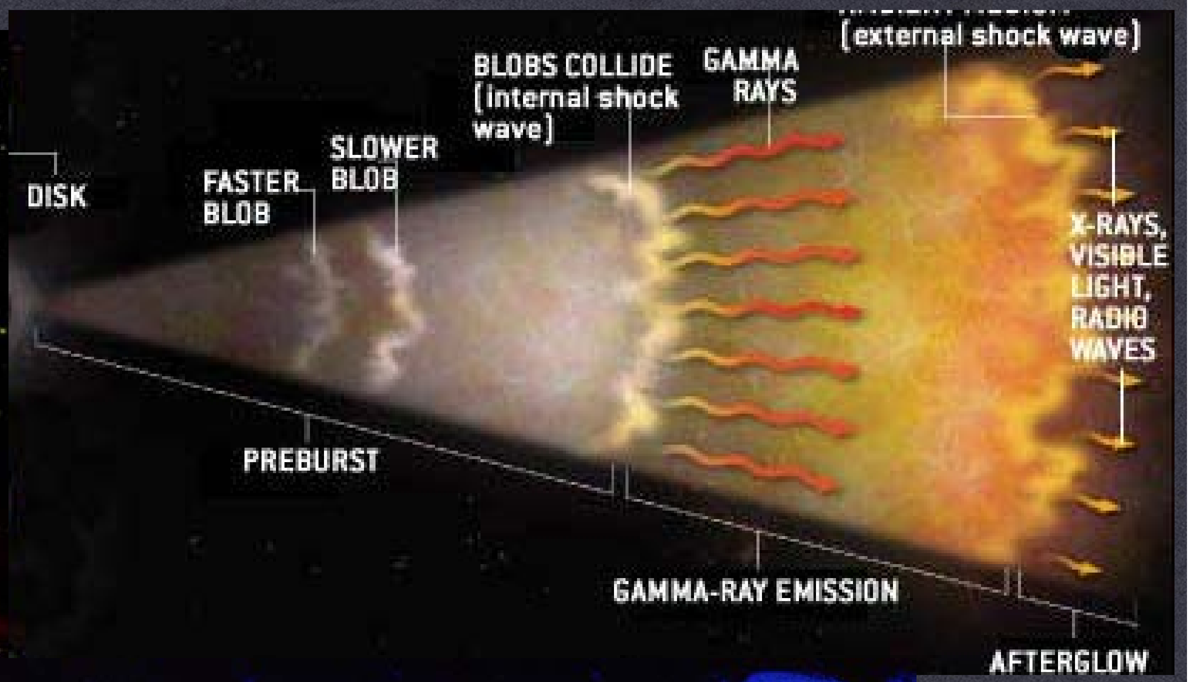
Shocks & power-laws in astrophysics

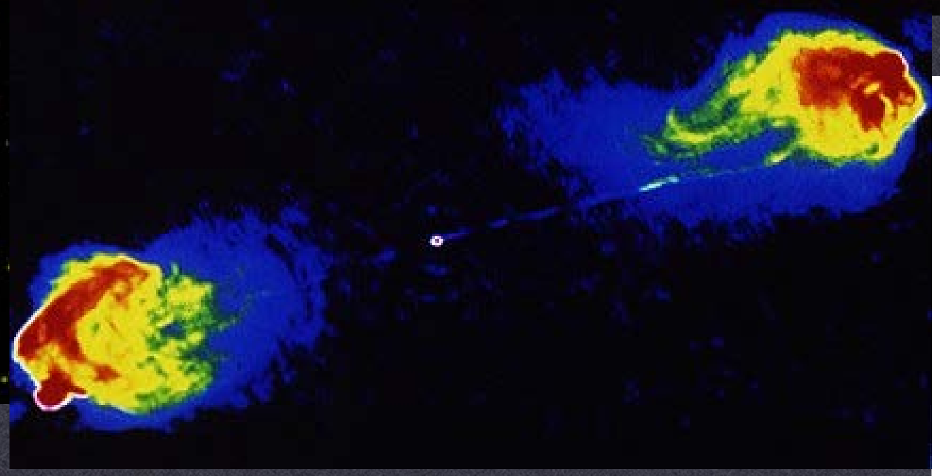


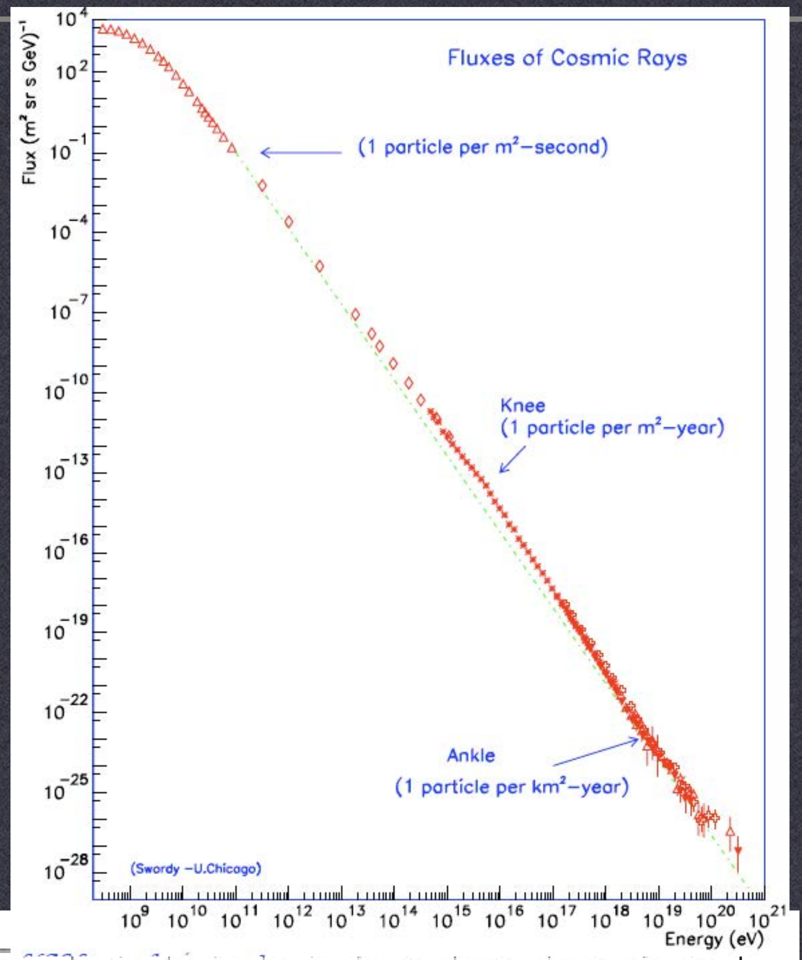


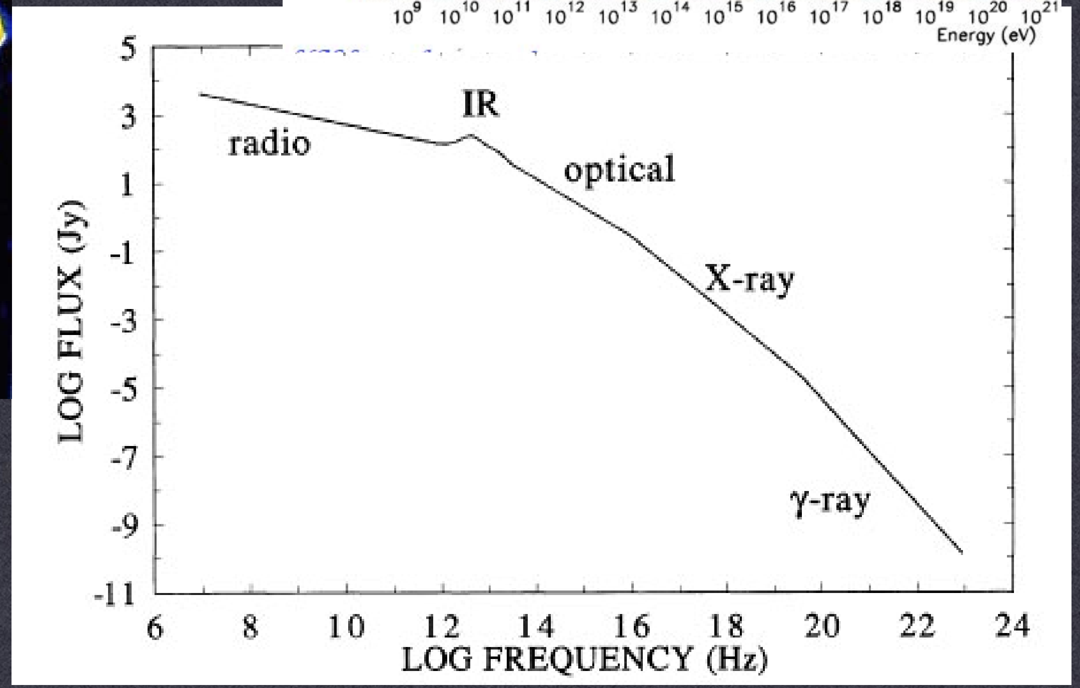












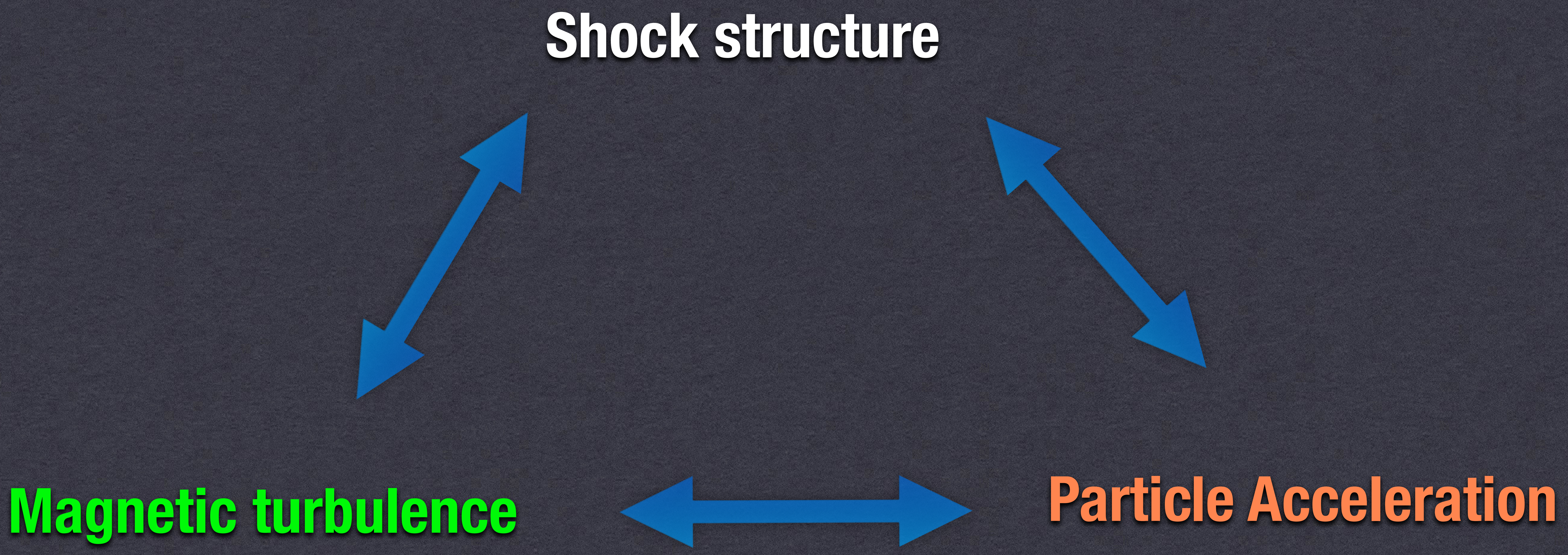
Astrophysical shocks are typically collisionless (mfp >> shock scales).
Many astrophysical shocks are inferred to:

1) satisfy jump conditions (* with caveats)
2) accelerate particles to power-laws
3) amplify magnetic fields
4) exchange energy between electrons and ions

Mechanisms? Efficiencies? Conditions for operation?

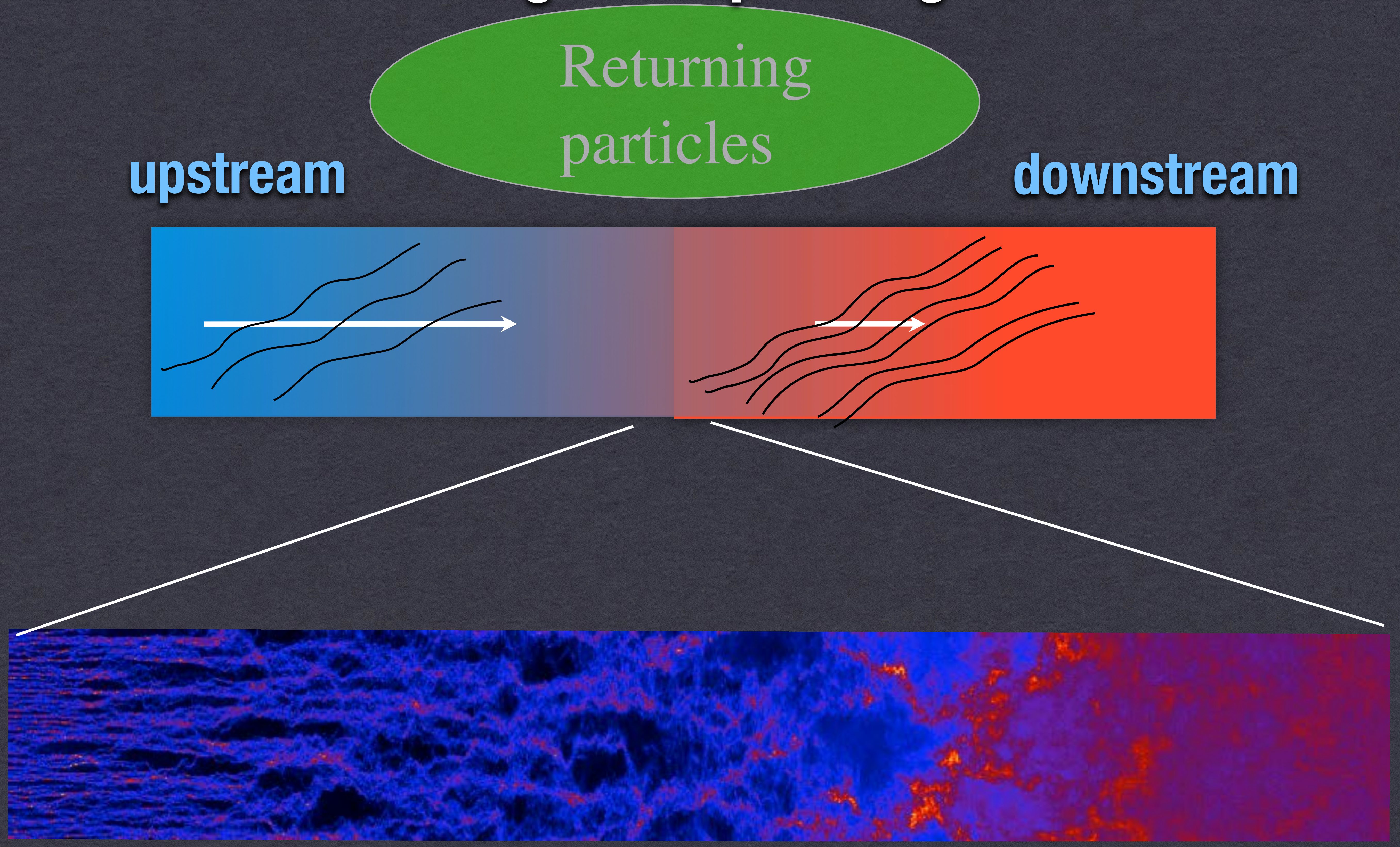
Collisionless shocks

- Complex interplay between micro and macro scales and nonlinear feedback: self-sustaining and replicating nonlinear structure



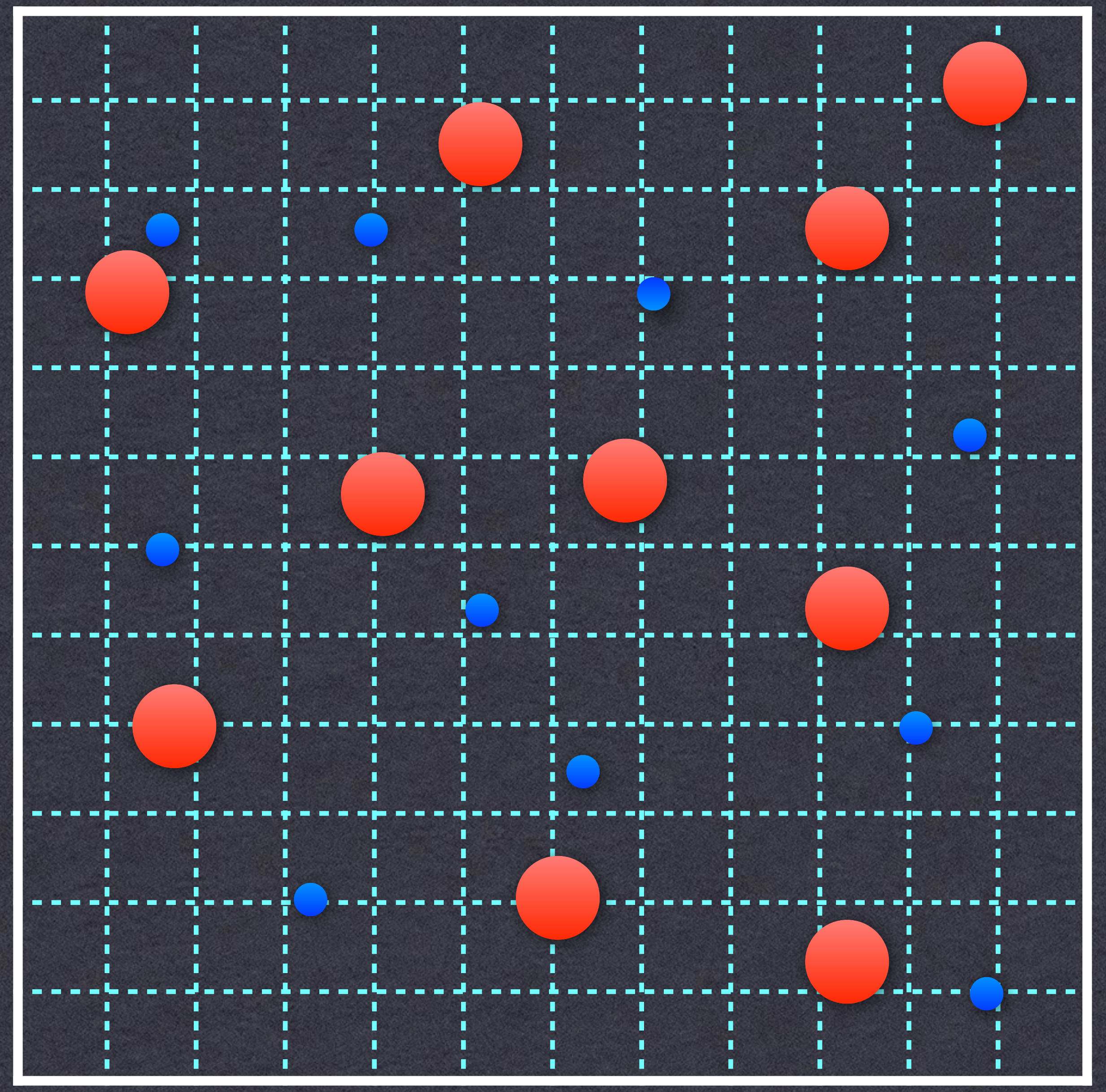
Collisionless shocks

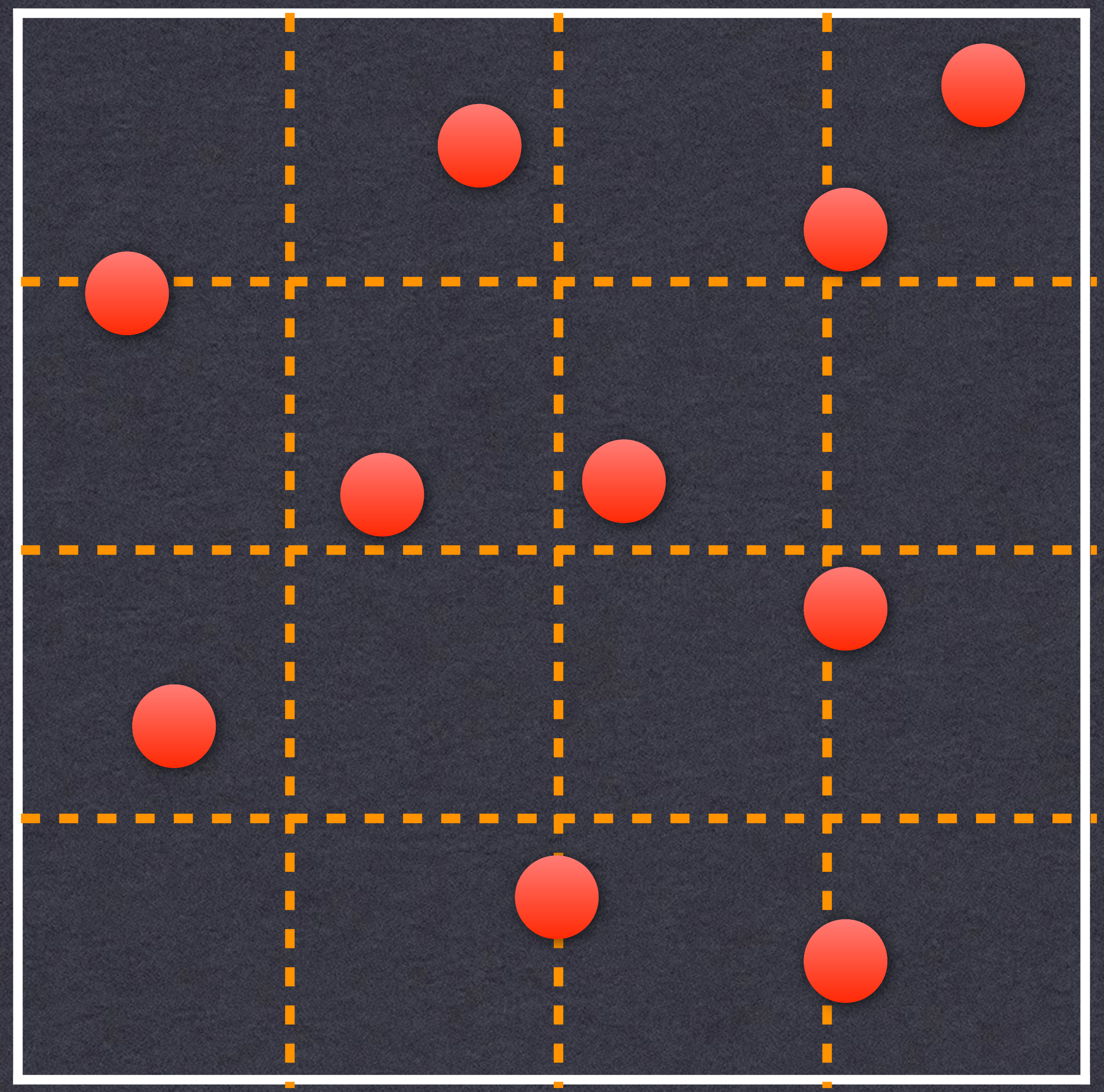
- Complex interplay between micro and macro scales and nonlinear feedback: self-sustaining and replicating nonlinear structure



Collisionless plasma physics on computers

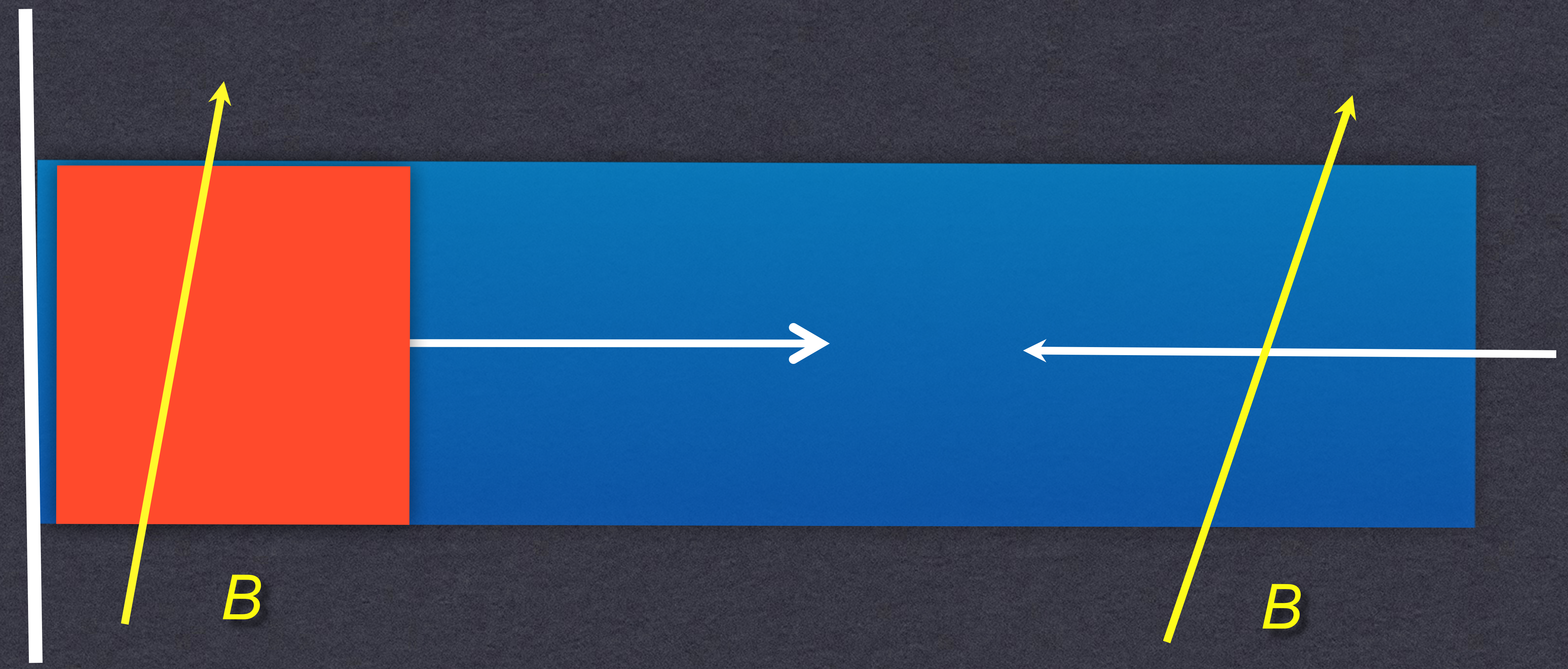
- **Full particle in cell**: TRISTAN-MP code
  (Spitkovsky 2008, Niemiec+2008, Stroman+2009, Amano & Hoshino 2007-2010, Riquelme & Spitkovsky 2010, Sironi & Spitkovsky 2011, Park+2012, Niemiec+2012, Guo+14,...)
  - Define electromagnetic field on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally expensive!
- **Hybrid approach**: dHybrid code
  Fluid electrons - Kinetic protons
  (Winske & Omidi; Lipatov 2002; Giacalone et al.; Gargaté & Spitkovsky 2012, Caprioli & Spitkovsky 2013, 2014)
  - massless electrons for more macroscopic time/length scales





Simulation setup

Supersonic plasma impinging on reflective wall. Equivalent to two streams crossing.

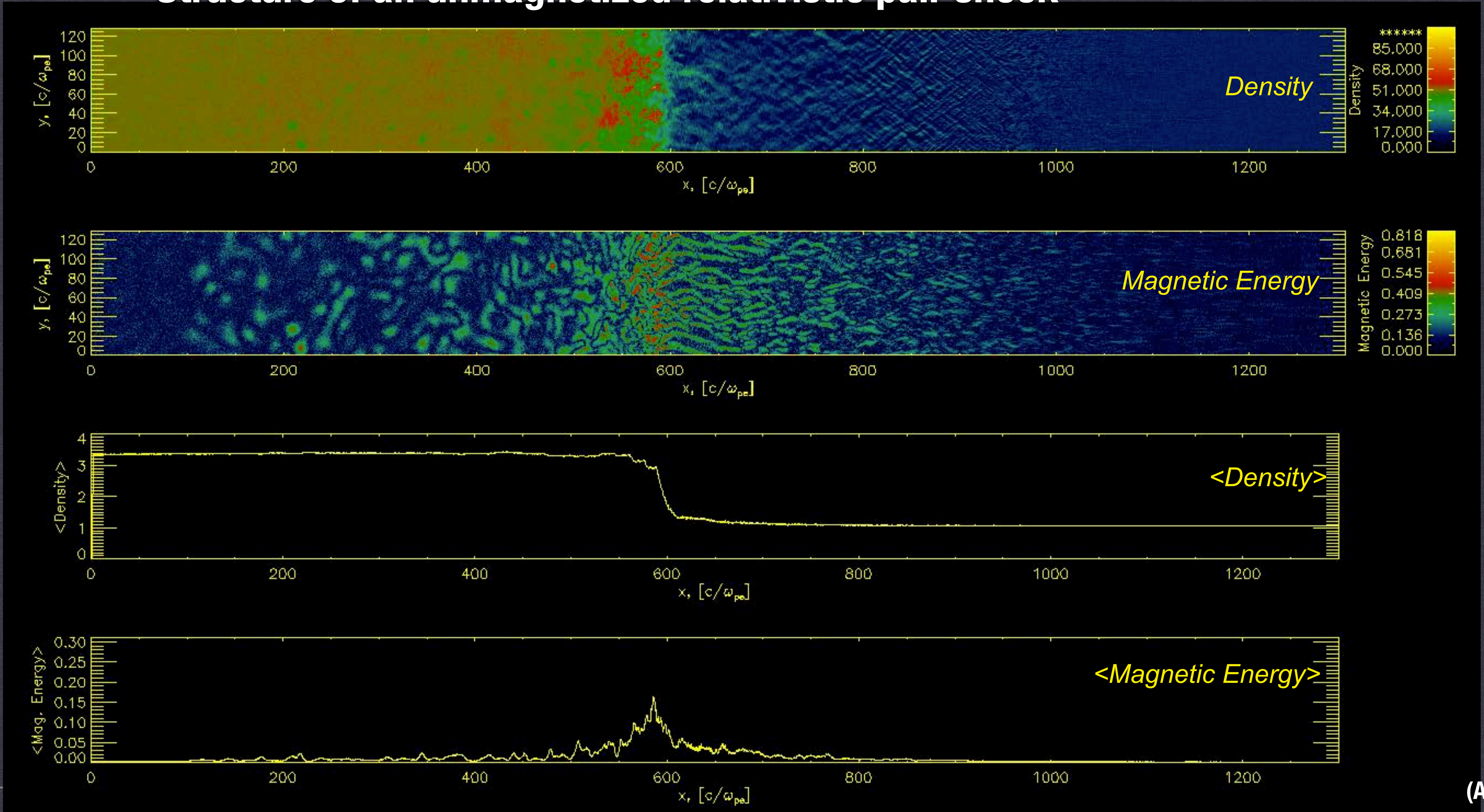


Initial magnetic field can vary strength and direction (including be 0).

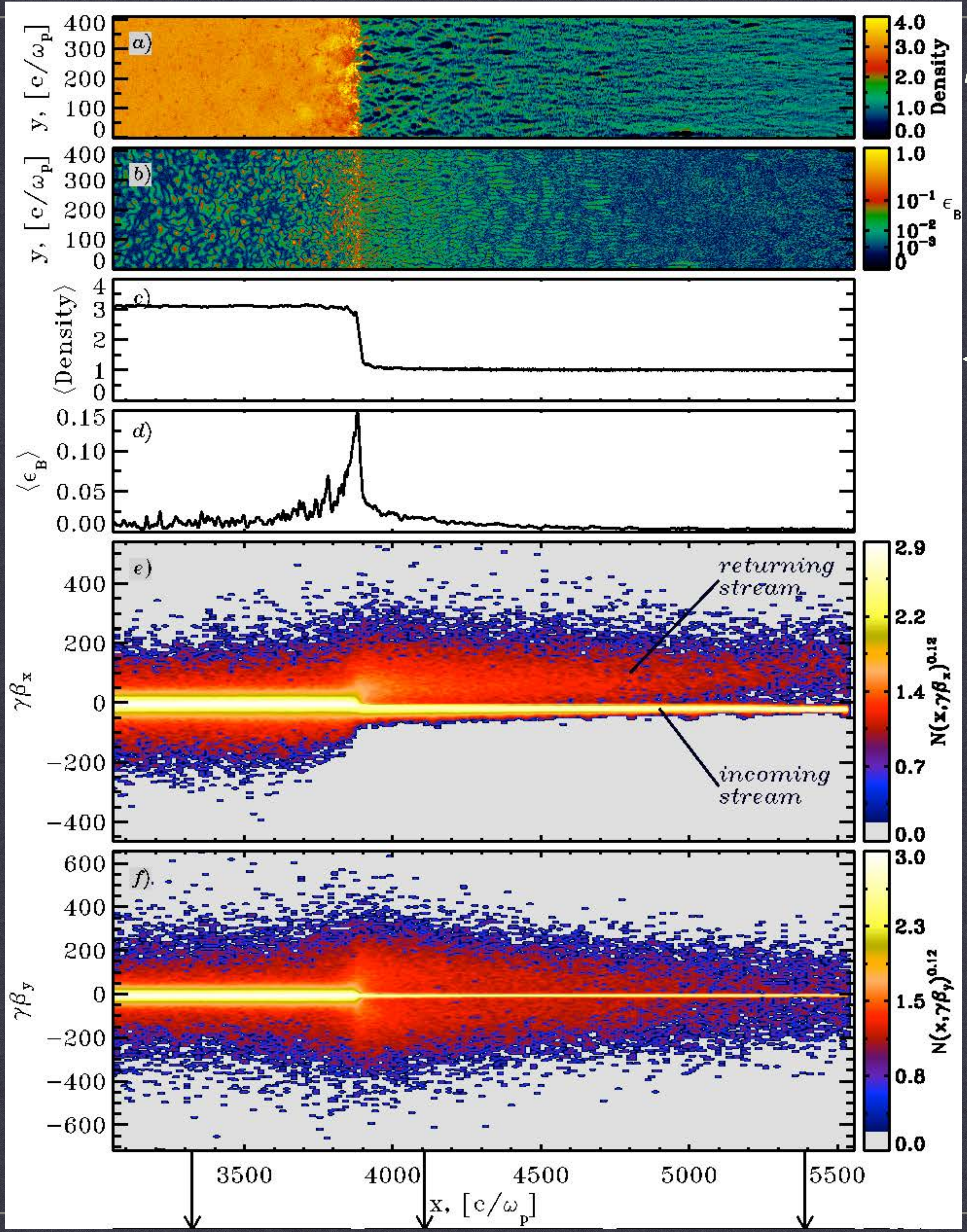
For simplicity in this talk will use electron-positron pair plasma only.

Collisionless shocks

Structure of an unmagnetized relativistic pair shock



(AS 2008)



Density

<Density>

<B²>

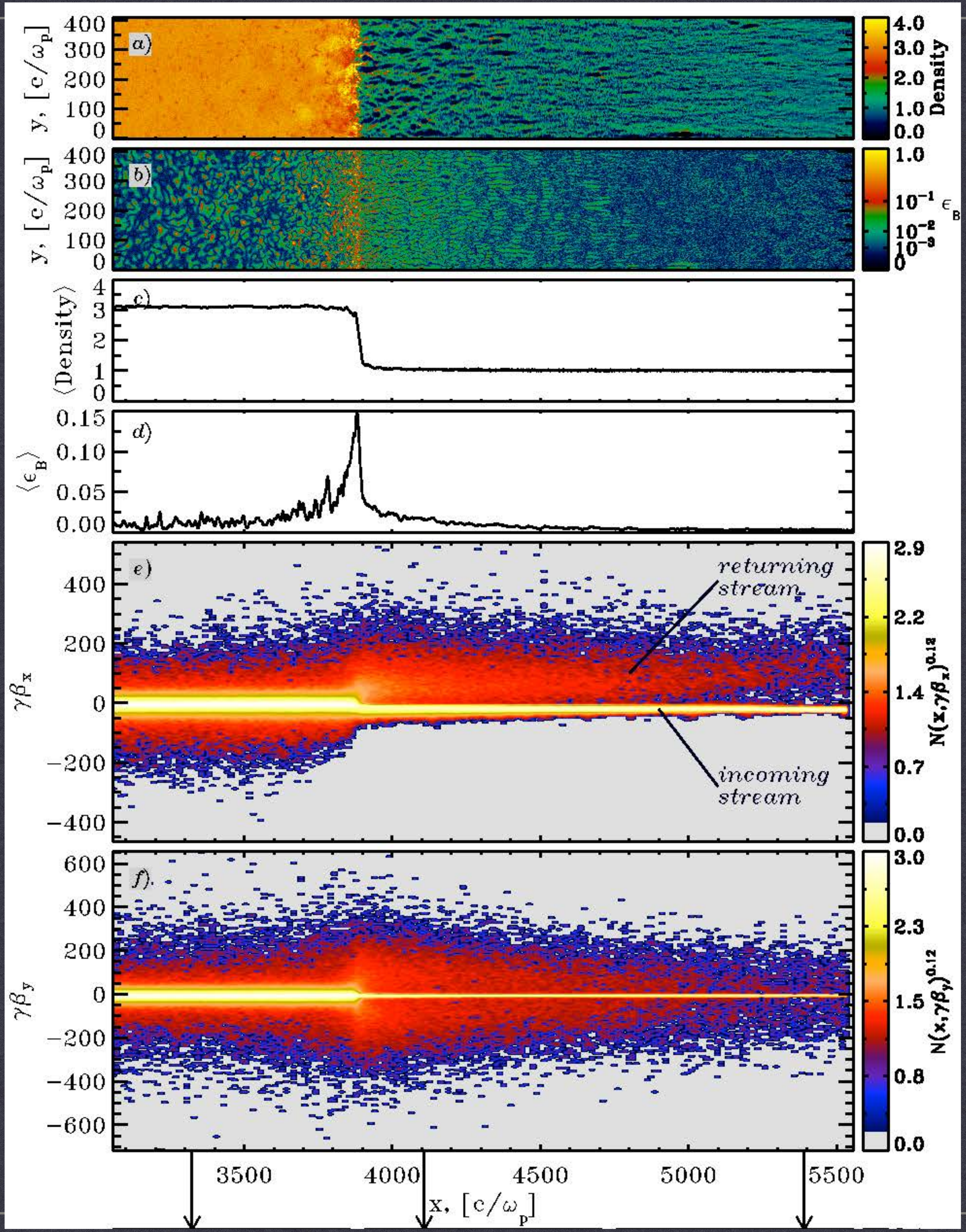
Shock formation from counterstreaming

shock is driven by returning particle precursor

x- px momentum space

x- py momentum space

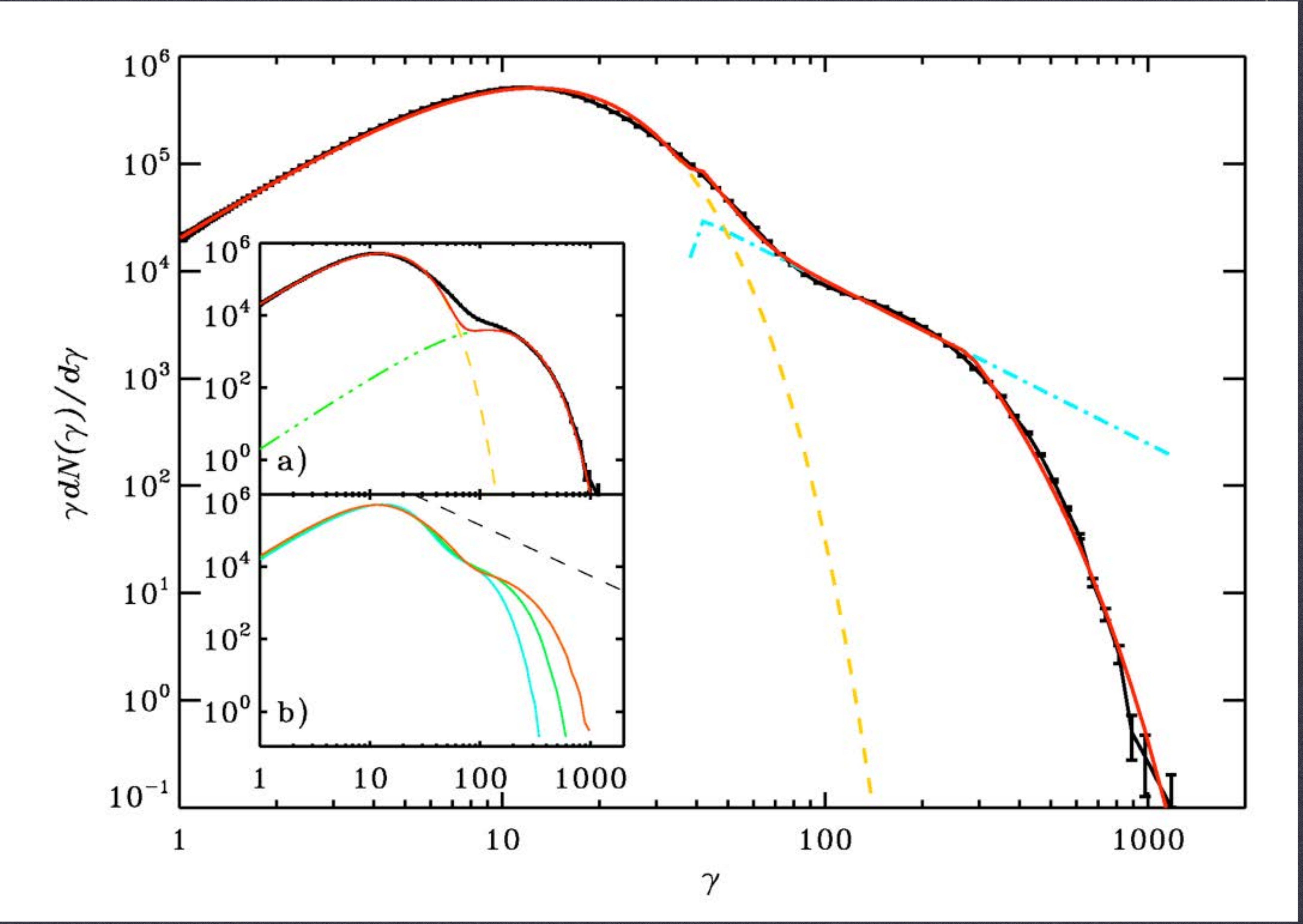
Shock structure for B=0 *(AS '08)*



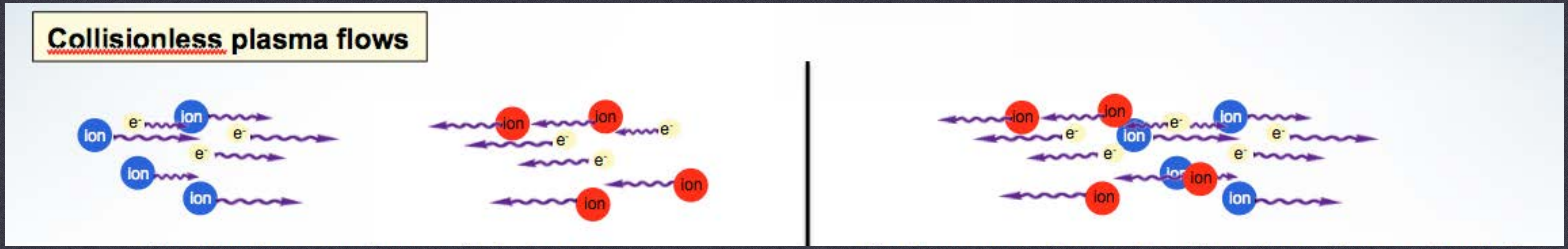
downstream spectrum: development of nonthermal tail

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

Bulk of the distribution is Maxwellian



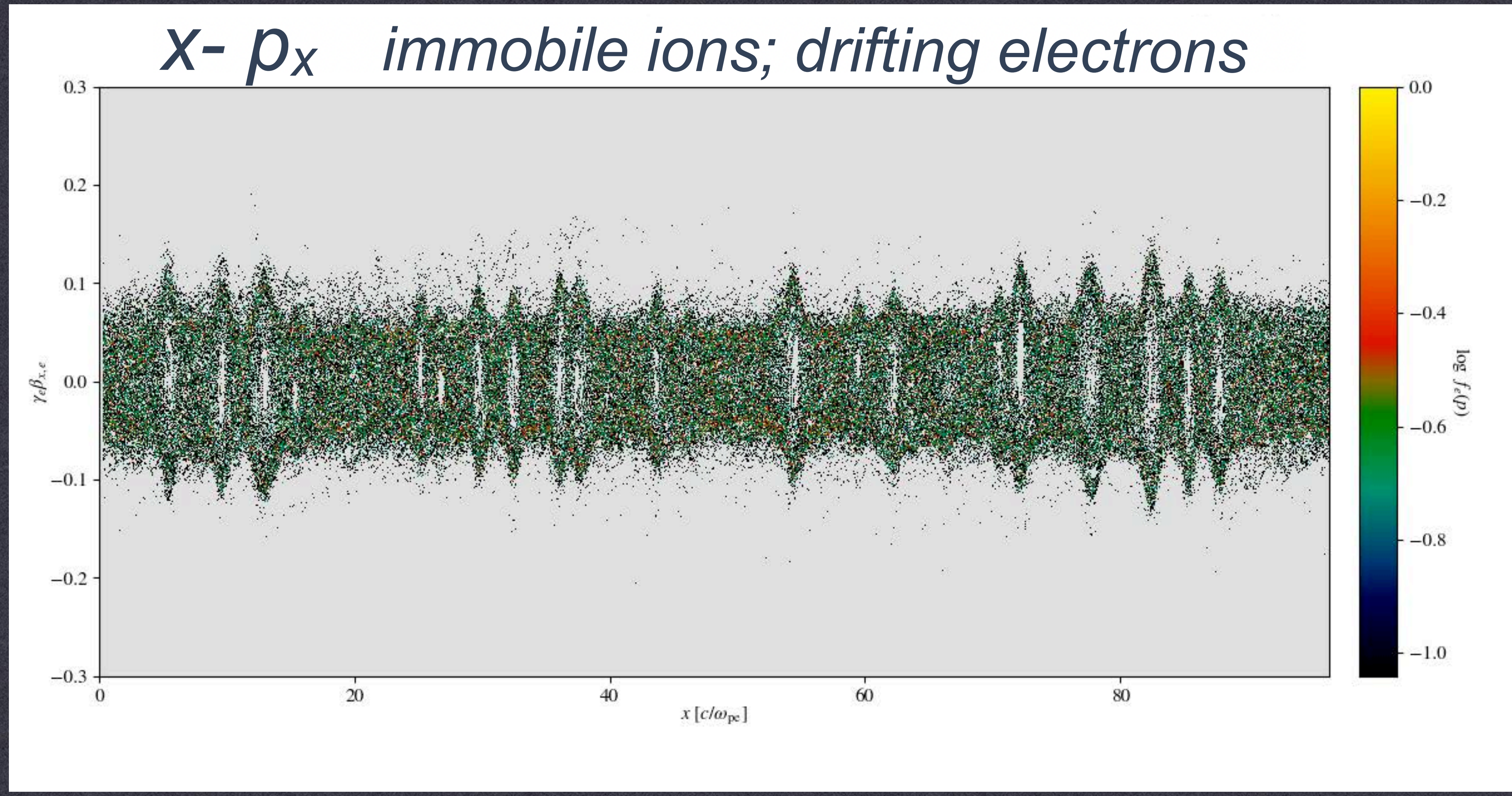
COUNTERSTREAMING INSTABILITIES



Two main mechanisms for creating collisionless shocks:

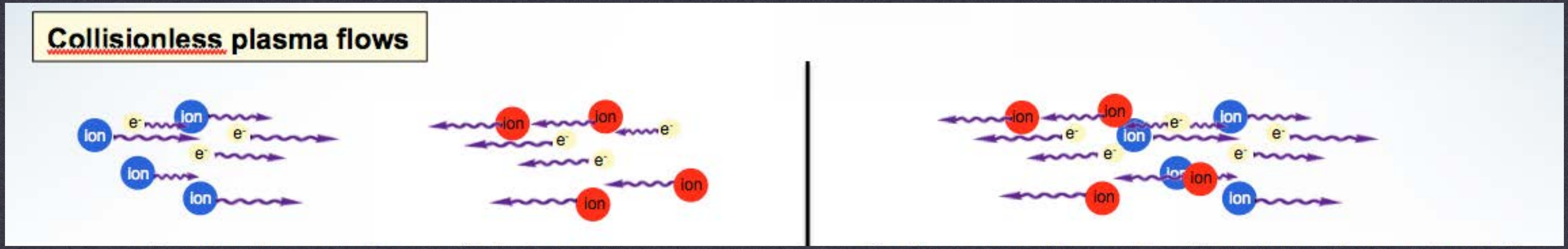
Electrostatic two-stream instability (1D+)

Filamentation instability (Weibel, 2D+)



Additional processes in magnetized shocks: magnetic reflection and gyration

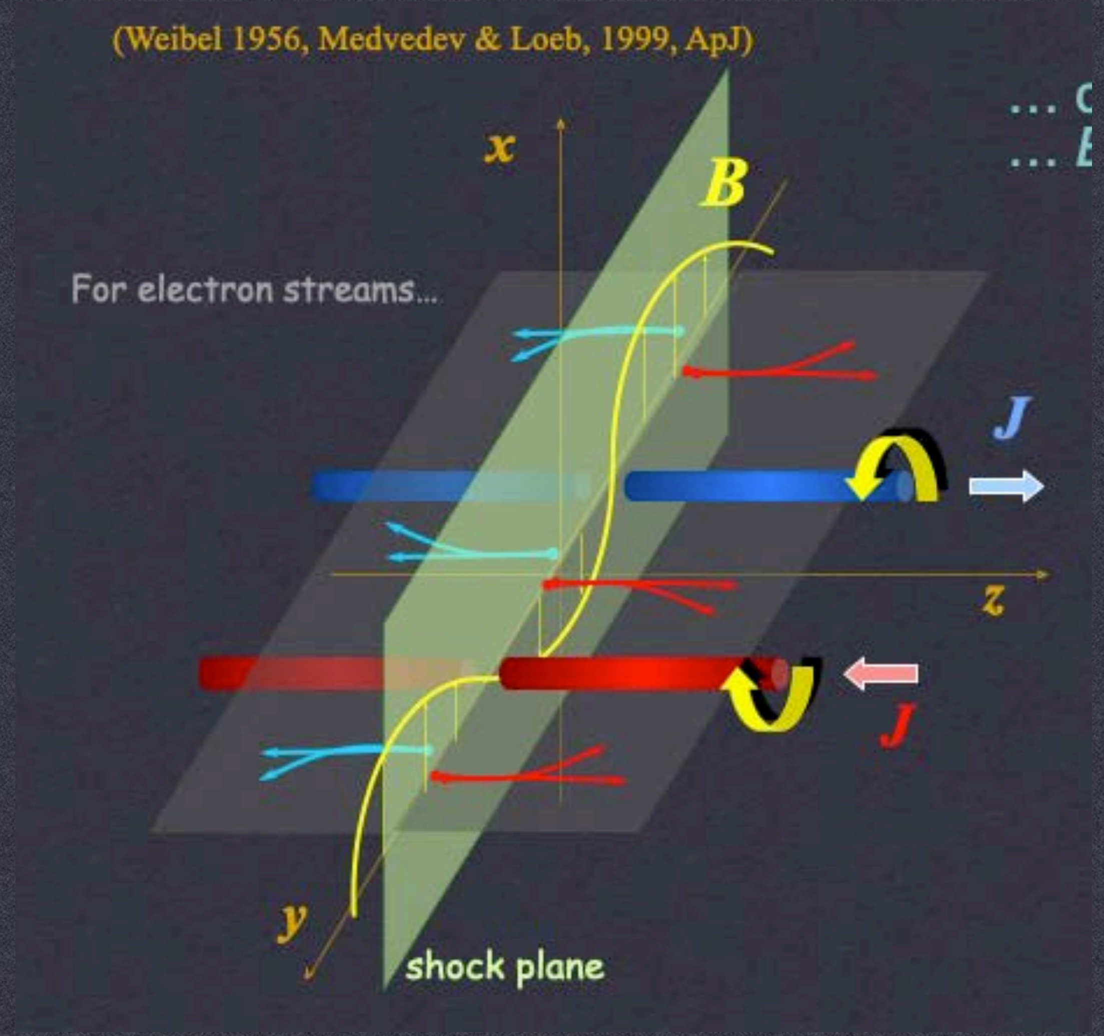
COUNTERSTREAMING INSTABILITIES

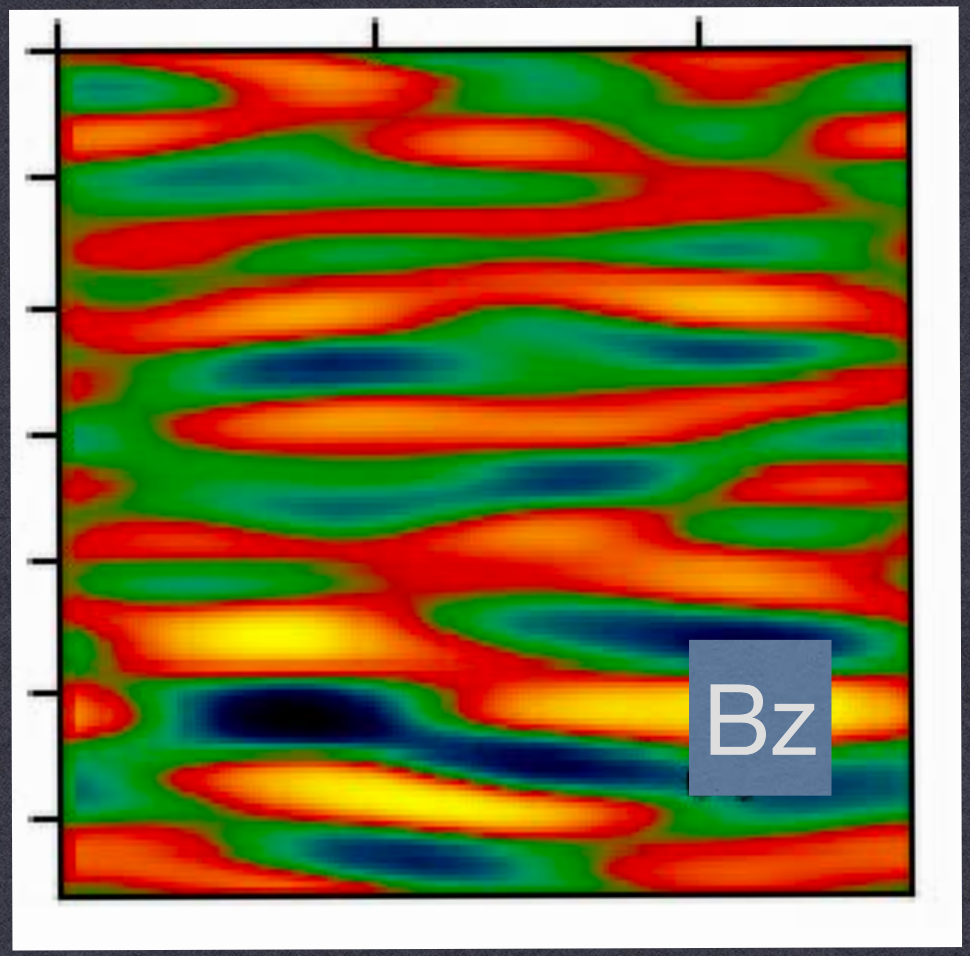


Two main mechanisms for creating collisionless shocks:

Electrostatic two-stream instability (1D+)

Filamentation instability (Weibel, 2D+)



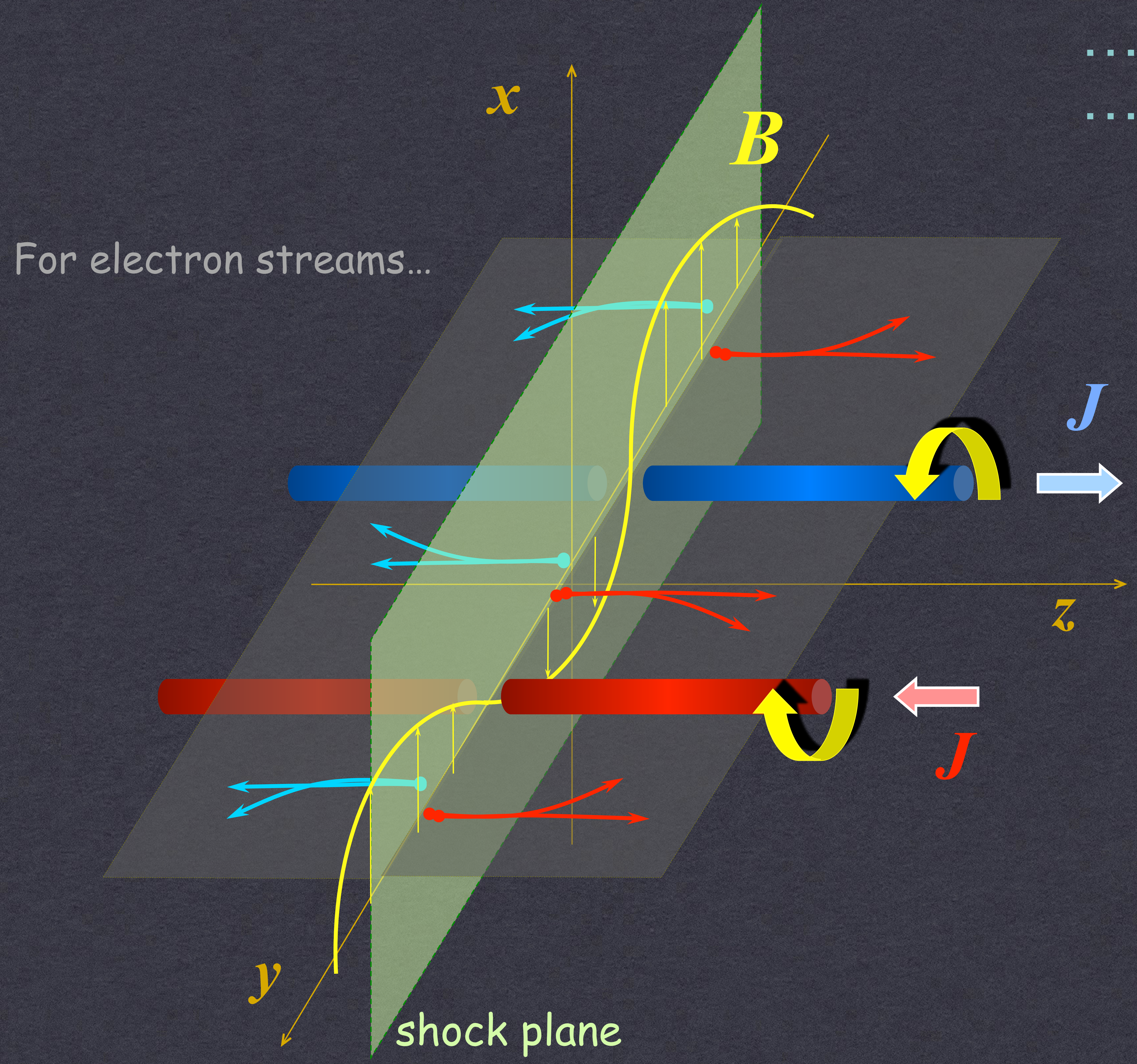


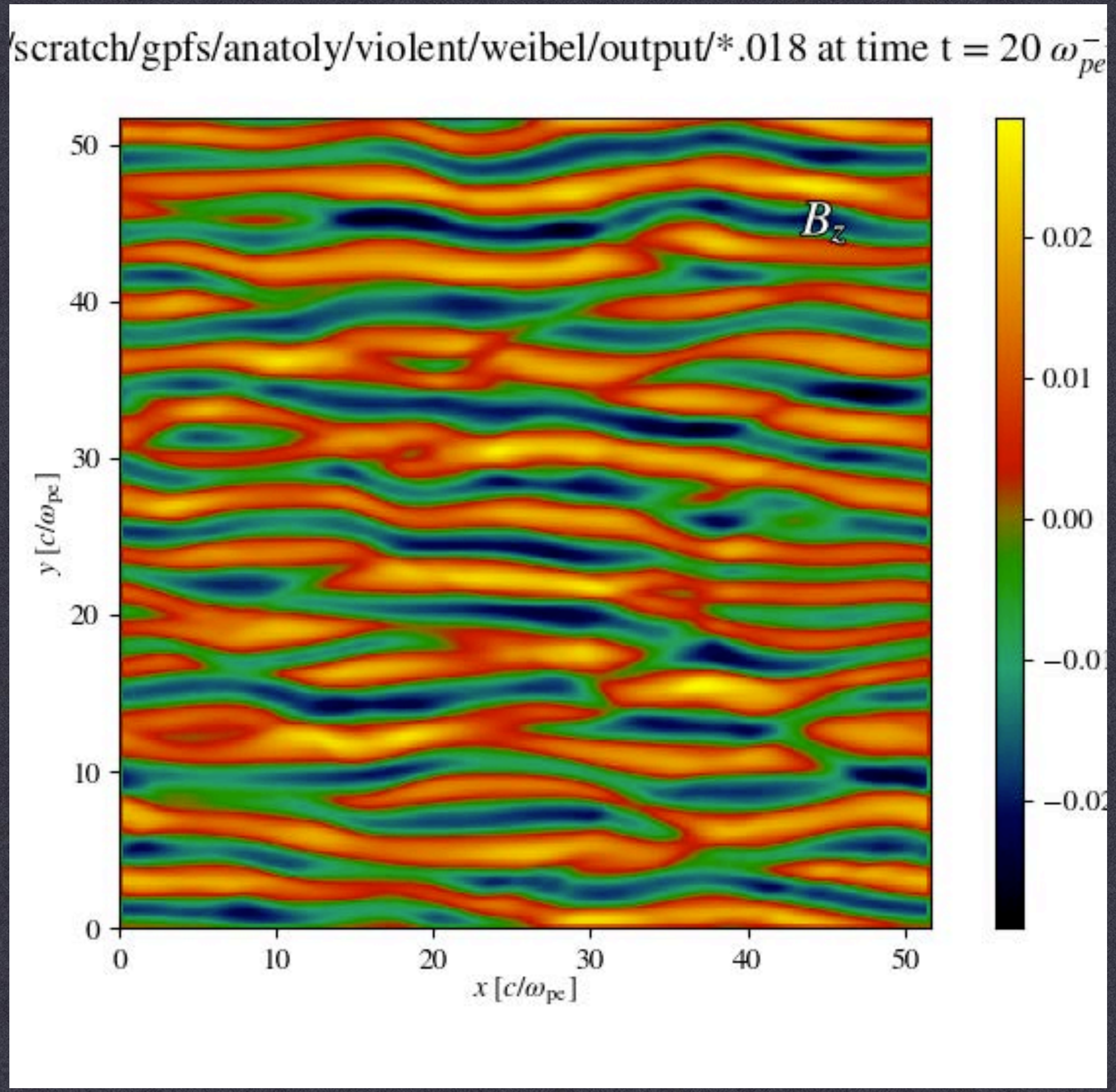
Additional processes in magnetized shocks: magnetic reflection and gyration

Weibel instability

(Weibel 1956, Medvedev & Loeb, 1999, ApJ)

… current filamentation …
… B – field is generated …

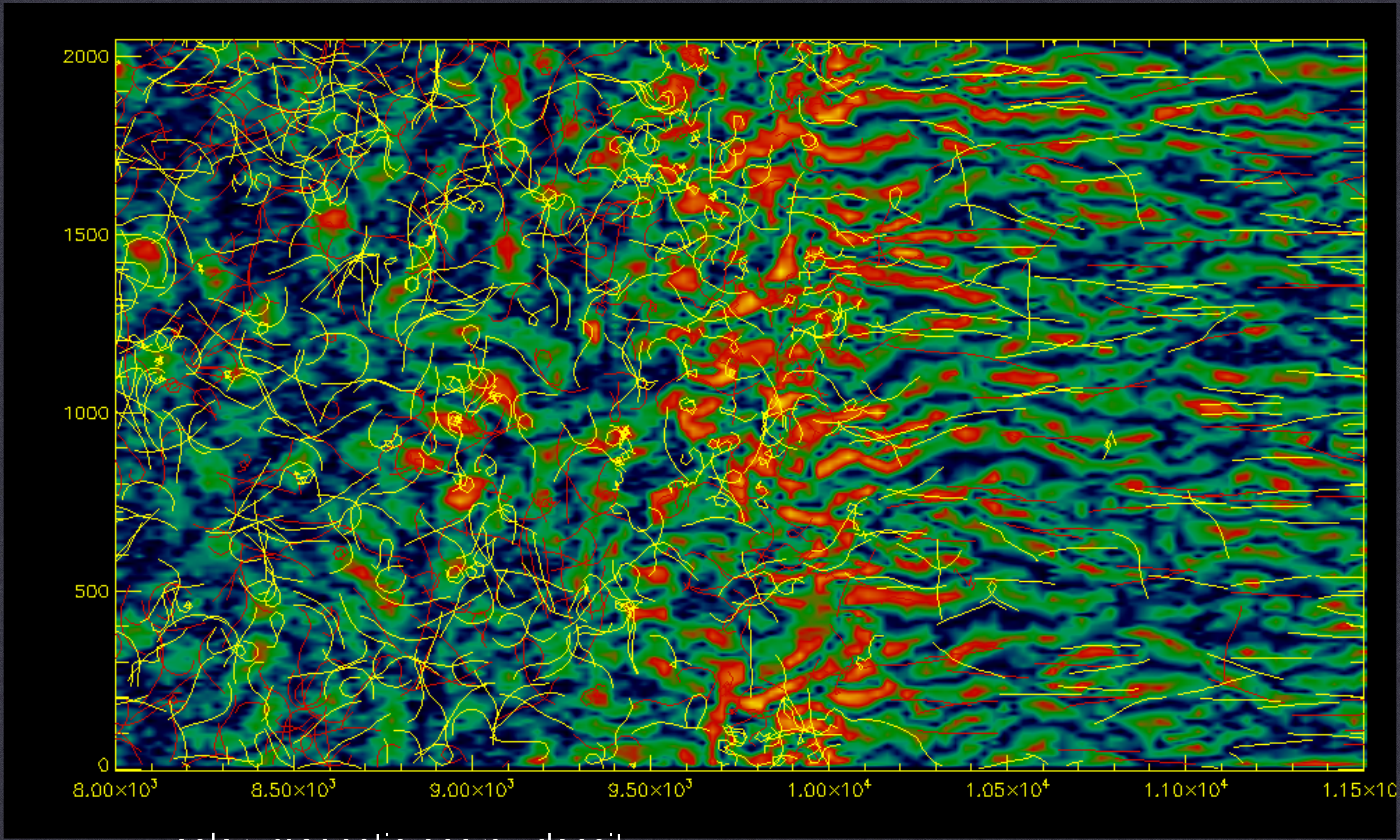




$$\Gamma^2_{\max} \simeq \frac{\omega_p^2}{\gamma} \qquad k^2_{\max} \simeq \frac{1}{\sqrt{2}} \frac{\omega_p^2}{\gamma_\perp c^2}$$

Cartoon from Misha Medvedev

Effective collisionality: particle orbits



color: magnetic energy density

Study of heating

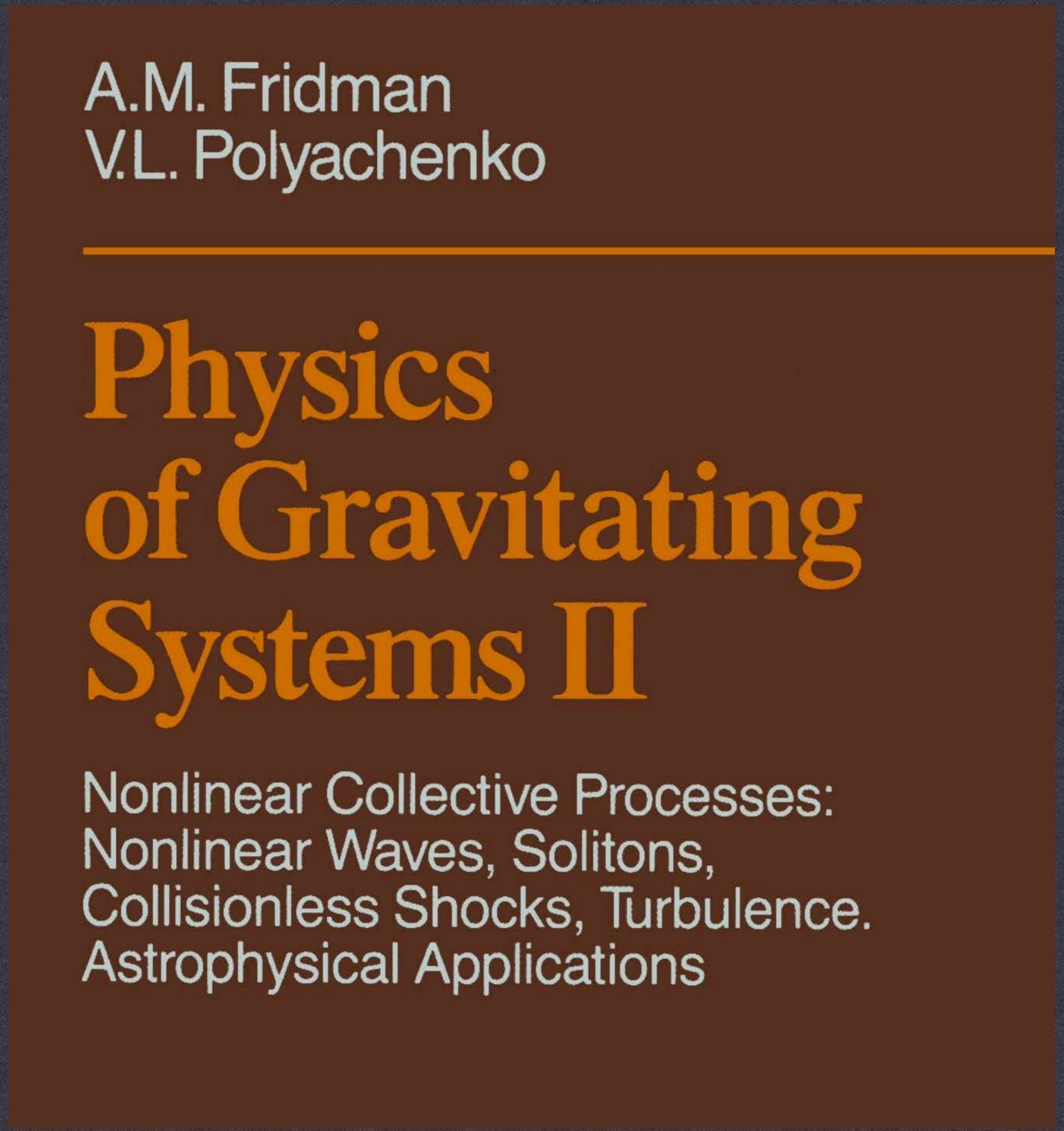
Relativistic shocks generally heat extremely well.

For the purposes of this meeting, we want to (potentially) connect to less extreme systems, so let's look at non-relativistic shocks.

We want to minimize electromagnetic effects (are there analogs in gravity?), so low v/c

Electrostatic 2-stream is most important. However, most non-relativistic plasmas are e-ion, which limits 2-stream instabilities.

Consider non-relativistic pair plasmas. Not that important in the lab, but probably best connection to gravitational systems.



Heating and Maxwellianization in shock transition

Simple non-relativistic unmagnetized pair shock, v/c=0.2: downstream Maxwellian

x- p_x

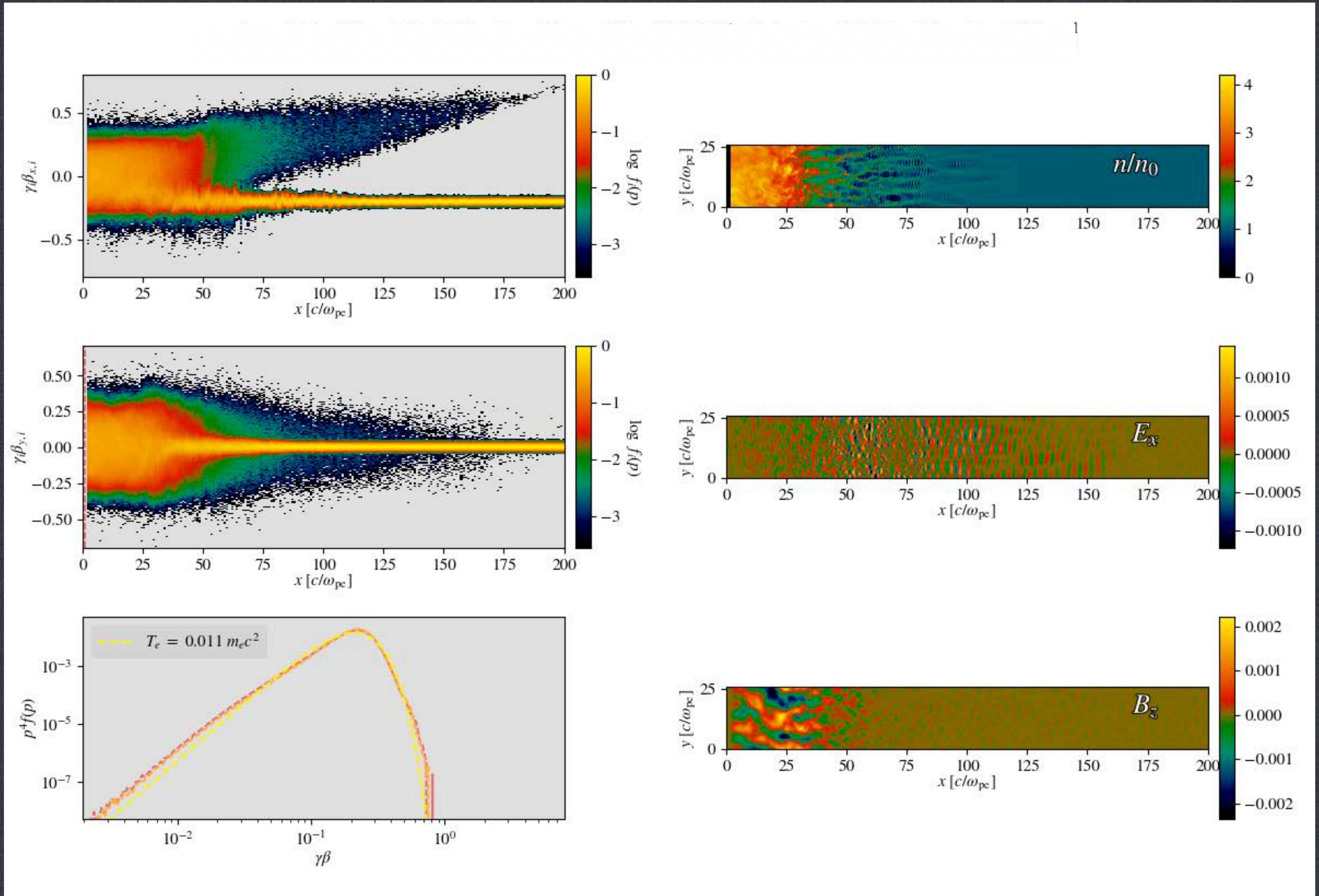
Density

x- p_y

E_x

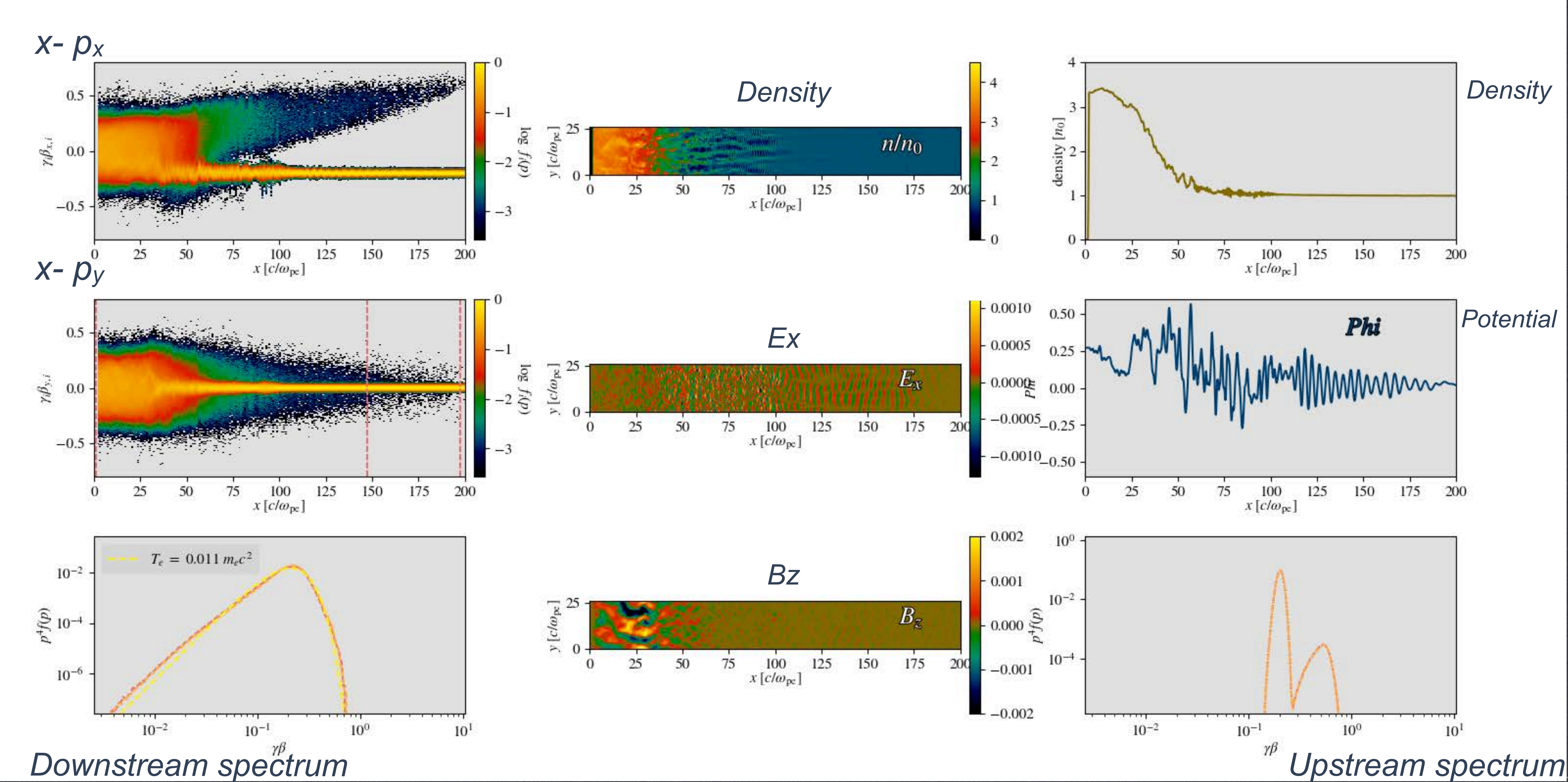
Spectrum

B_z



Heating and Maxwellianization in shock transition

Simple non-relativistic unmagnetized pair shock, v/c=0.2: downstream Maxwellian



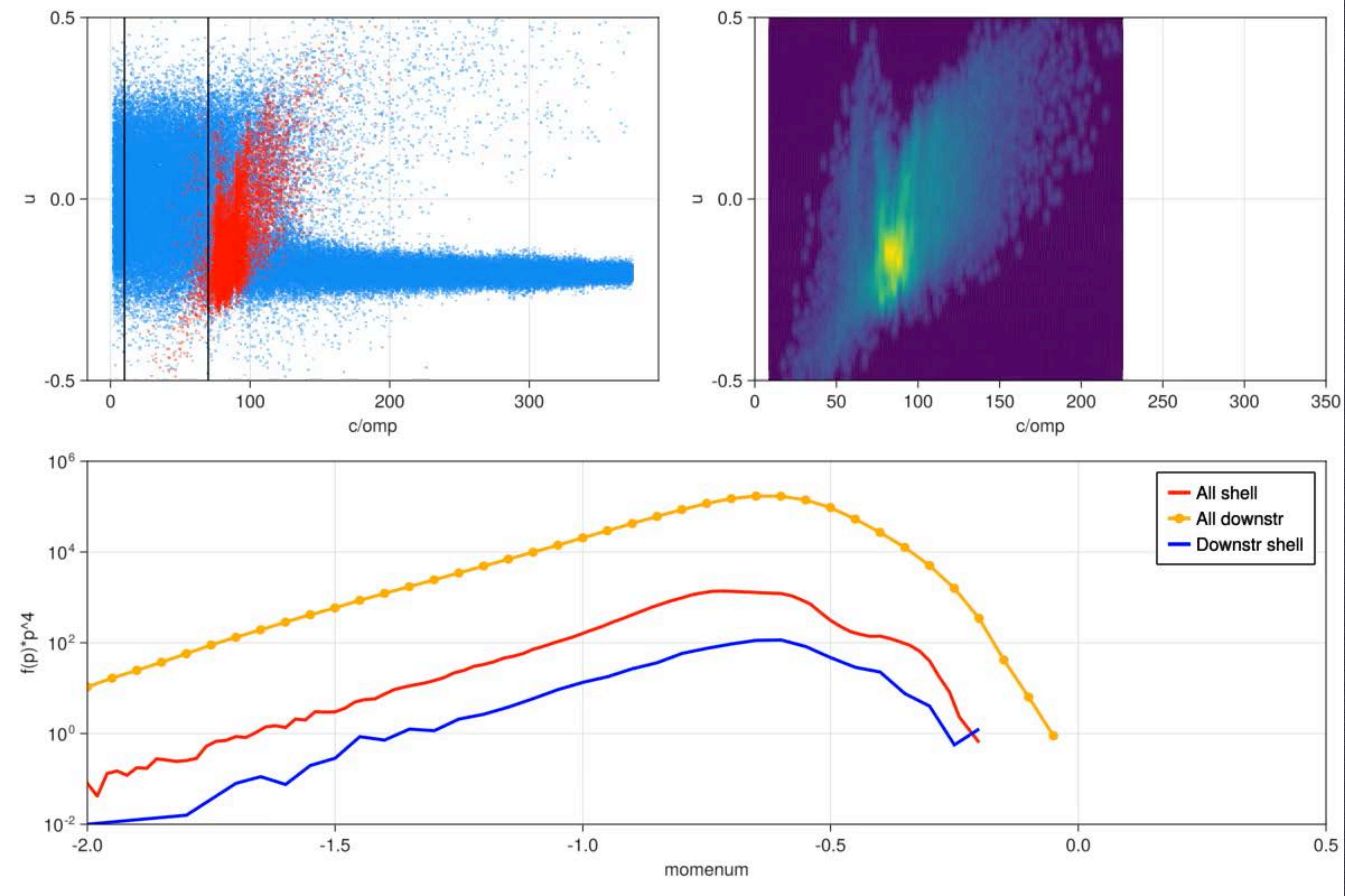
Heating and Maxwellianization in shock transition

Simple non-relativistic unmagnetized pair shock, v/c=0.2: downstream Maxwellian

x- p_x

x- p_x

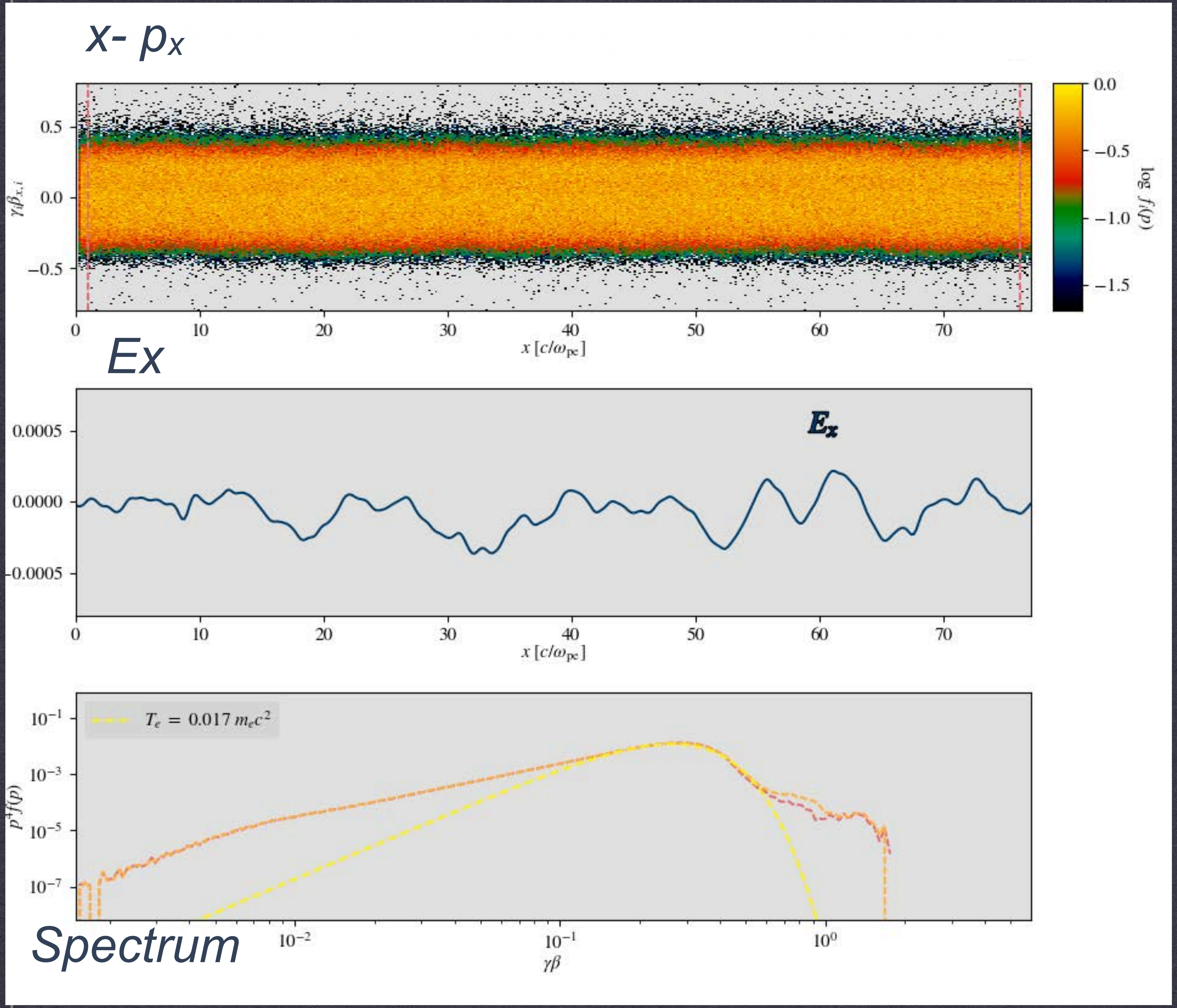
Spectrum



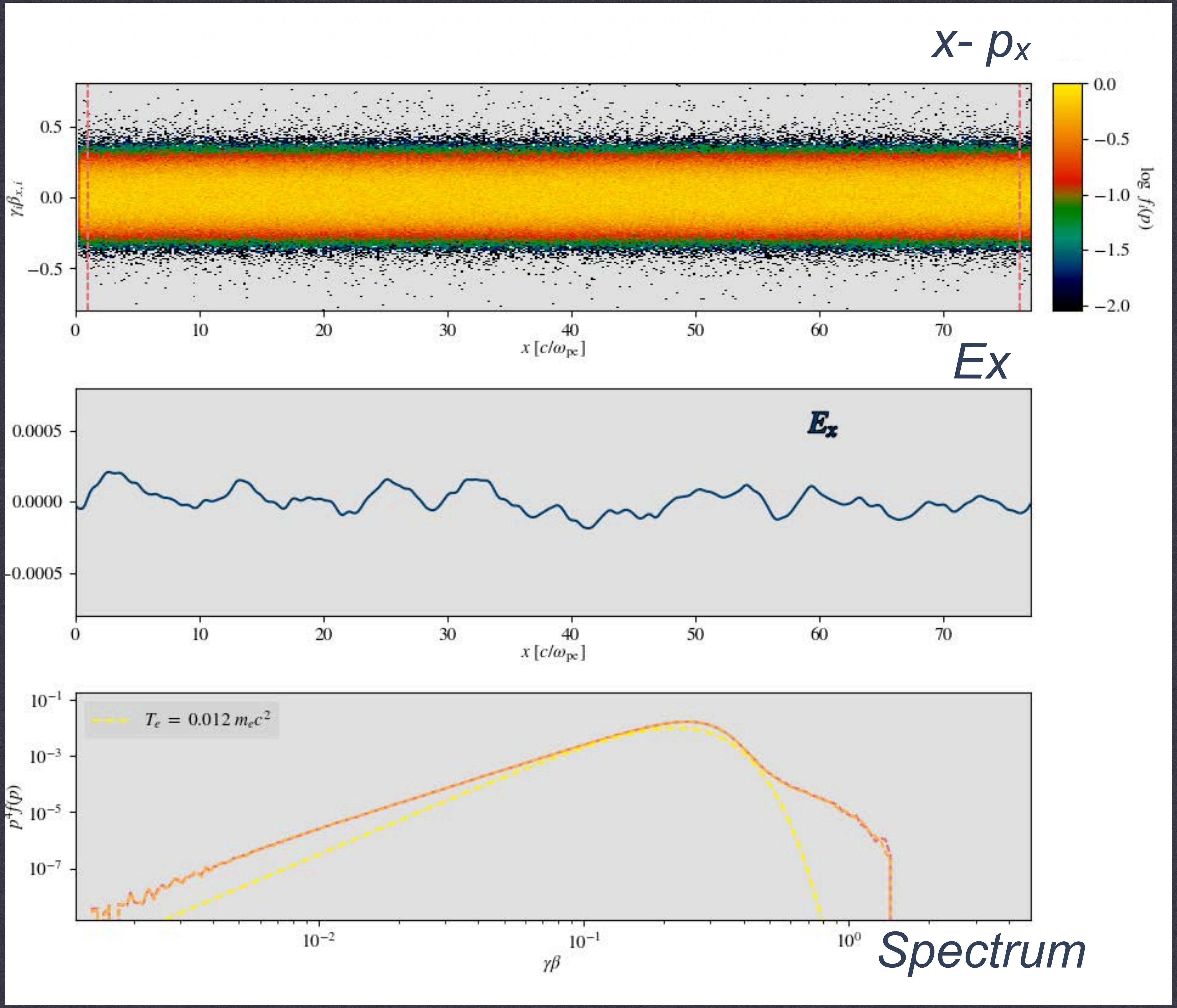
Heating and Maxwellianization in shock transition

Is it a simple two-stream instability?

1D:



2D:



Not quite! Shock structure is important for heating!

Study of heating

Electrostatic two-stream can mediate a shock in pair plasma.

Maxwellian core is produced fast due to (?) rapidly oscillating electric fields at the shock which scatter and isotropize the distribution.

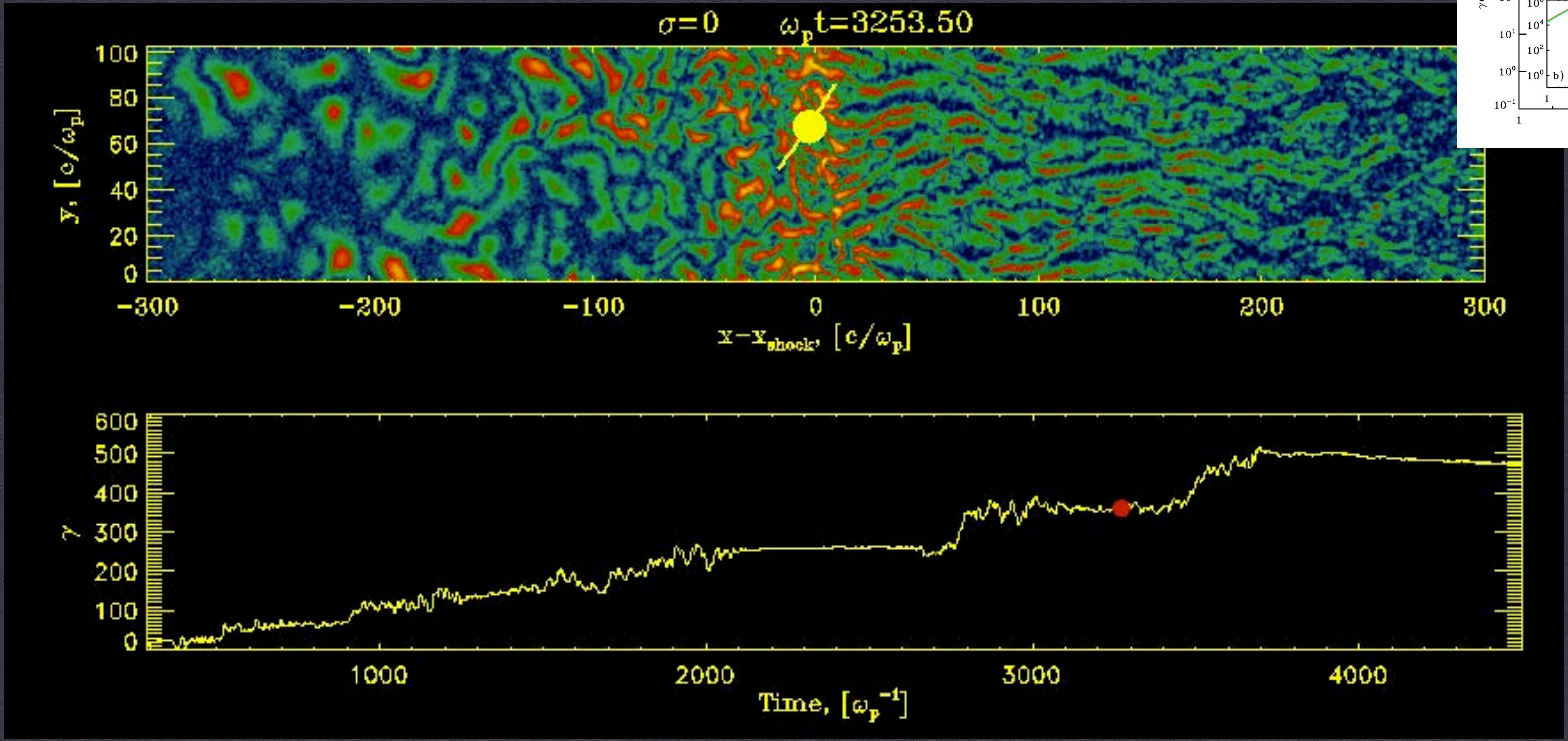
By itself two-stream can produce nothermal tails in pair plasma (origin tbc), or under-Maxwellianize (low energy tail).

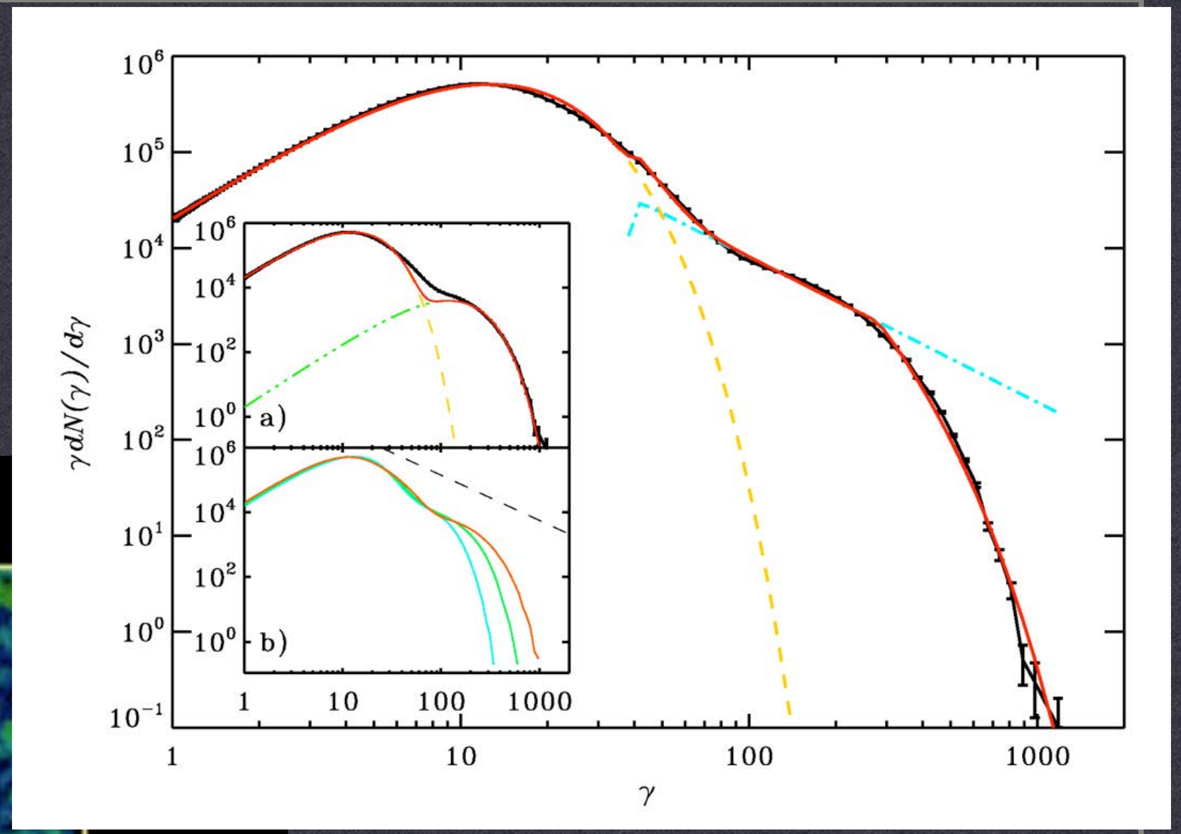
Multidimensional effects are needed to fully isotropize the distribution downstream (both 2D ES and EM Weibel effects).

Shock seems to bleed off high energy particles into the upstream, retaining downstream Maxwellian.

Nonthermal tails at long time are much weaker than in relativistic case (if they are present at all). Is ES turbulence inherently not conducive to shock acceleration?

WHAT ABOUT THE TAILS?



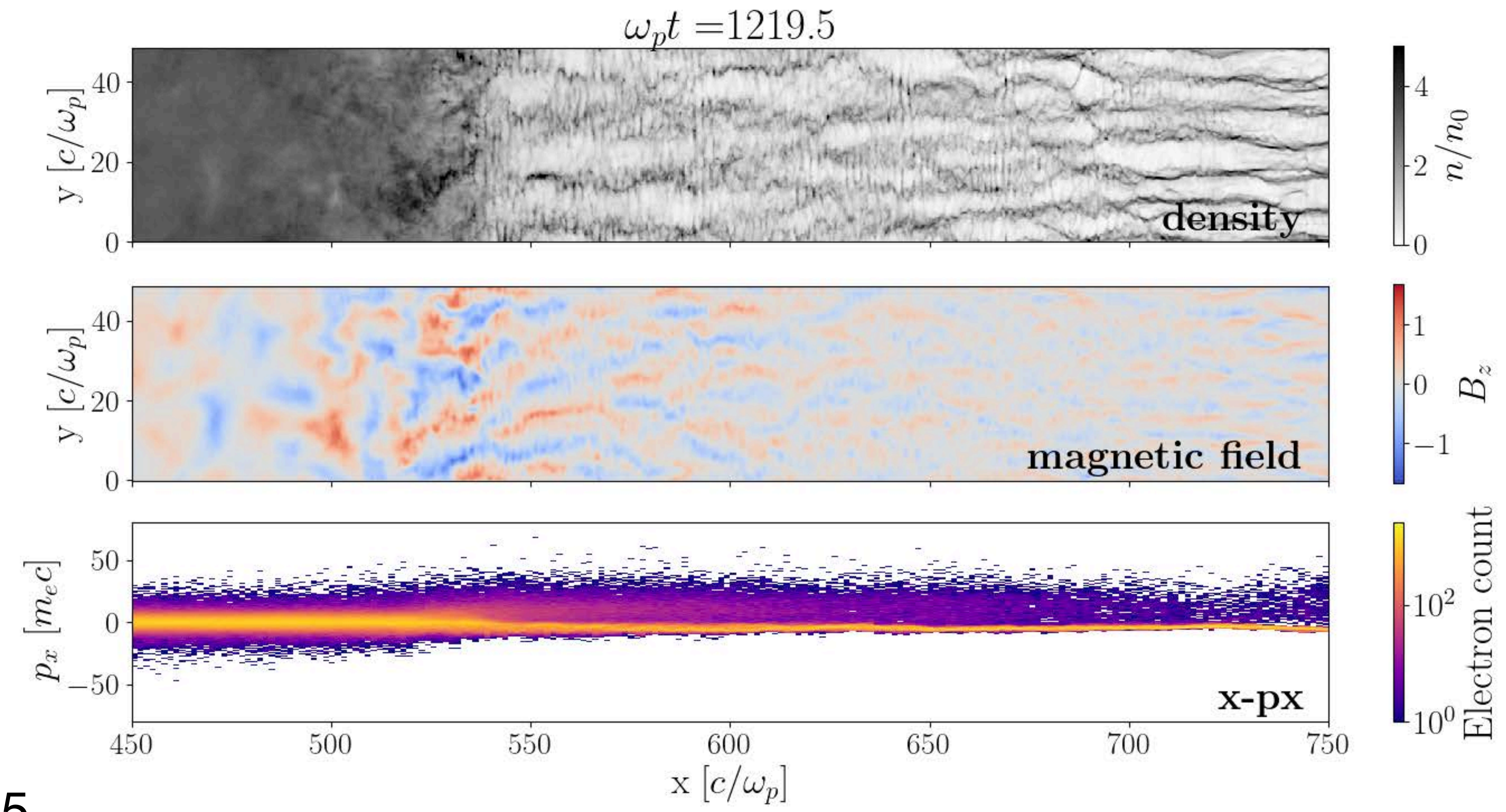


Magnetic Energy

Particle Energy

Fermi acceleration between two converging walls: appears stronger in relativistic shocks. What sets normalization?

Role of shock substructure (clumping) in determining reflection



Γ=5

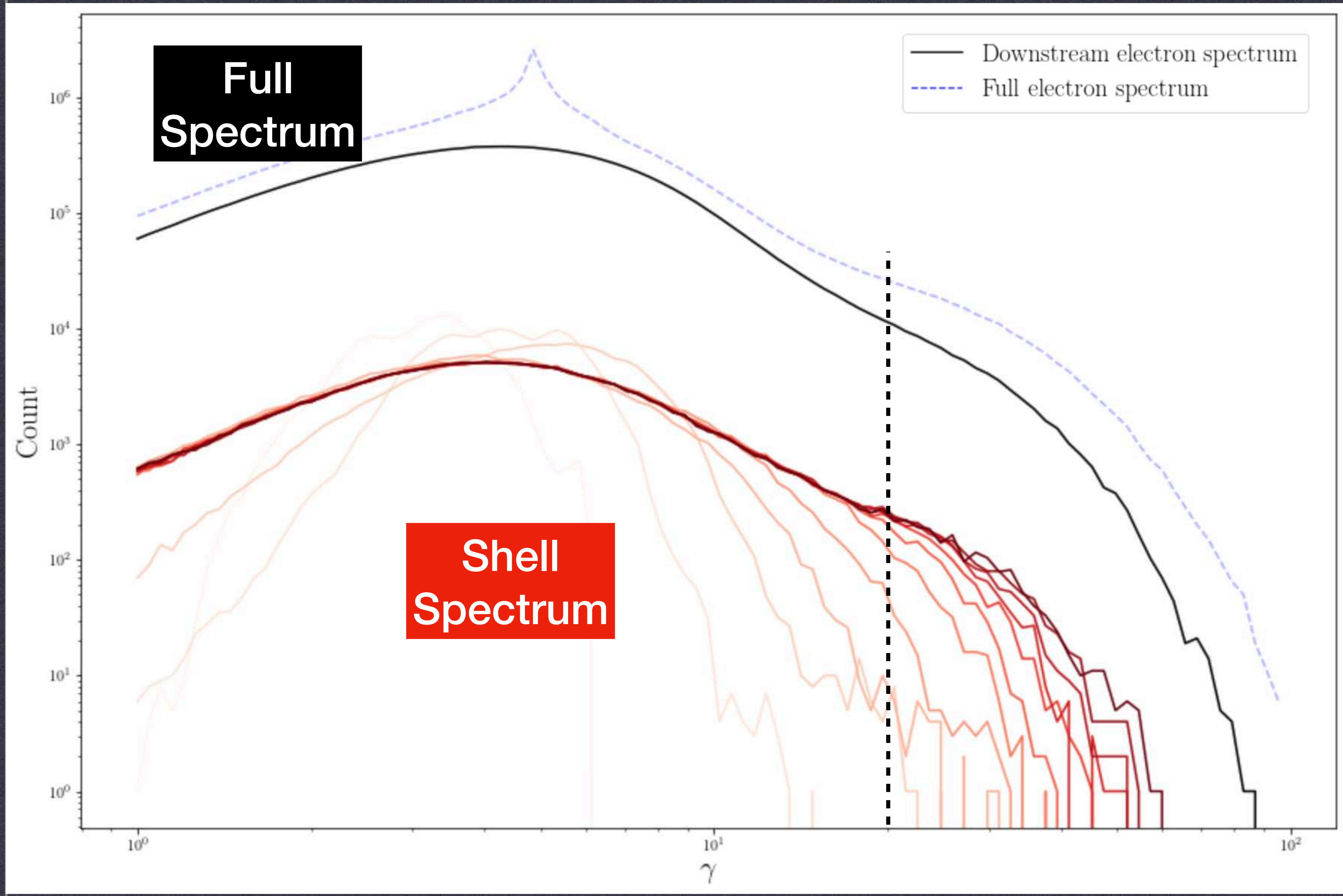
Weibel-dominated relativistic pair shock

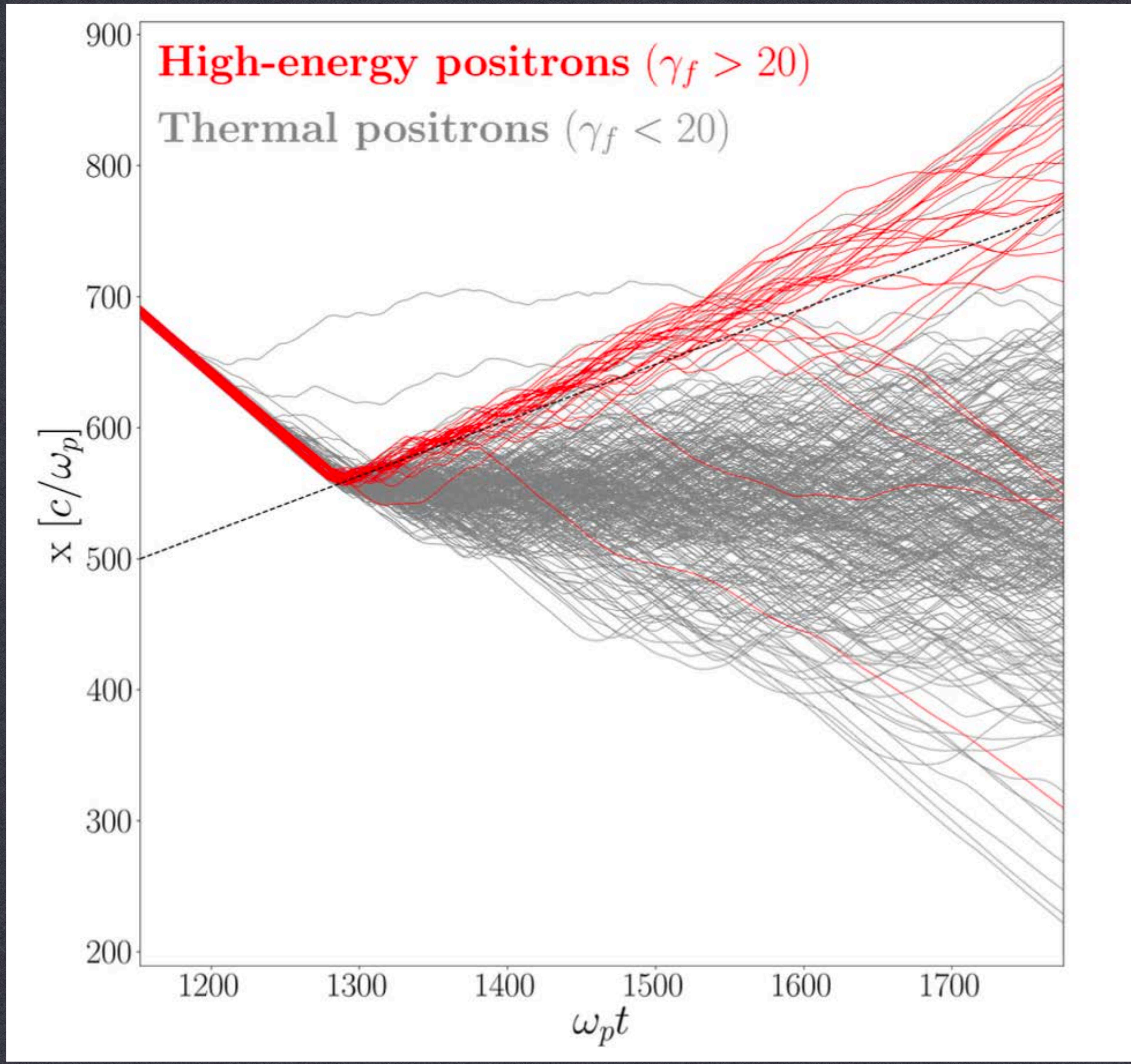
Jasmine Parsons, AS, A. Vanthieghem '23, arXiv:2310.12950

Reflectivity at the shock: the role of structures

About 1% particles in the tail. How did they get into the tail?

We track a shell of particles through the shock, marking those that eventually reach high energy

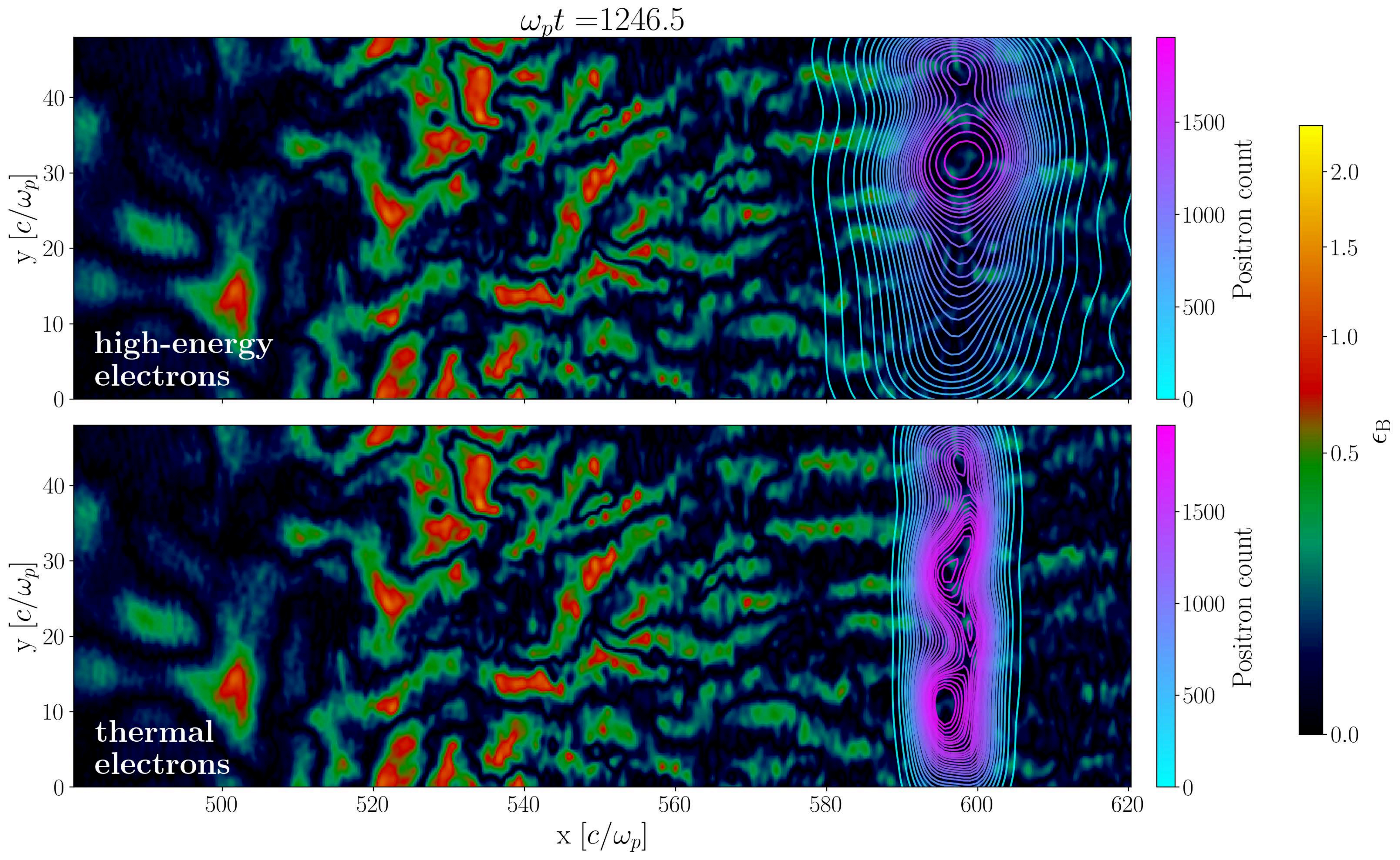




- If $\gamma_f > 20$, particle is considered to be 'high-energy' (ends simulation with high energy)
- If $\gamma_f < 20$, particle is considered to be 'thermal' (does not end simulation with high energy)
-

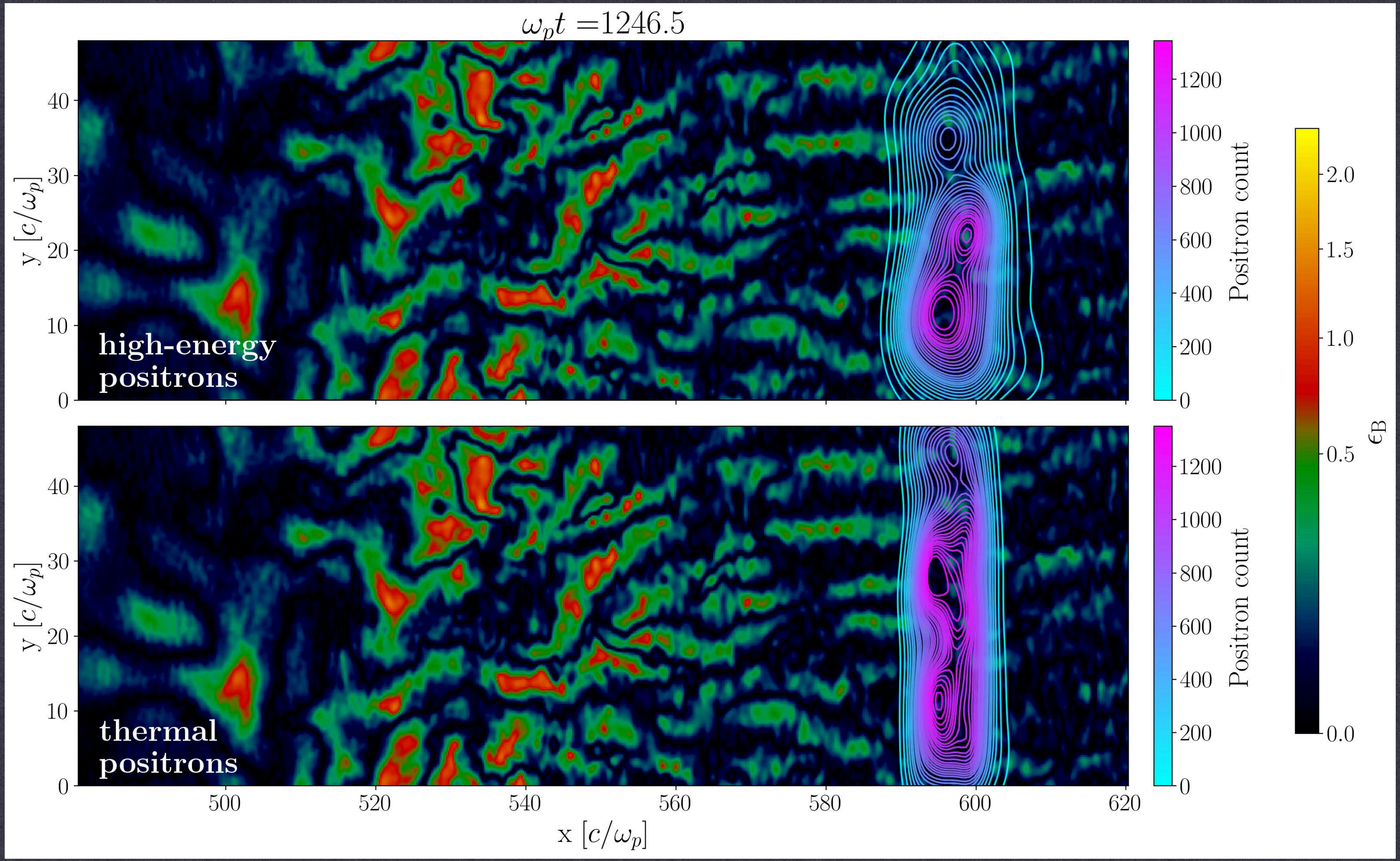
Behavior of high-energy electron subshell vs thermal electron subshell

High-energy electrons are not evenly distributed amongst thermal electrons



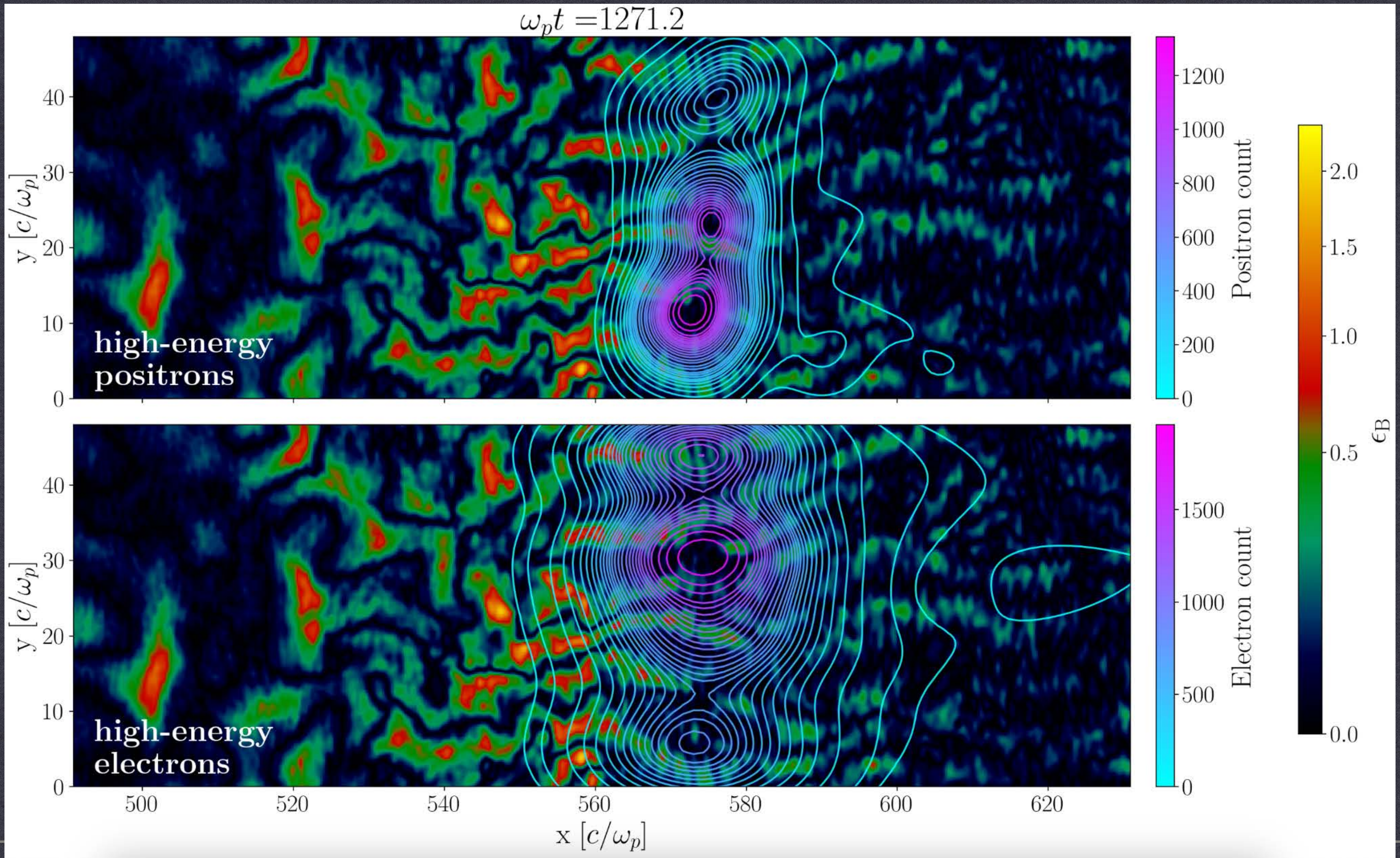
Behavior of high-energy positron subshell vs thermal positron subshell

- Same thing: high-energy positrons are not evenly distributed amongst thermal positrons



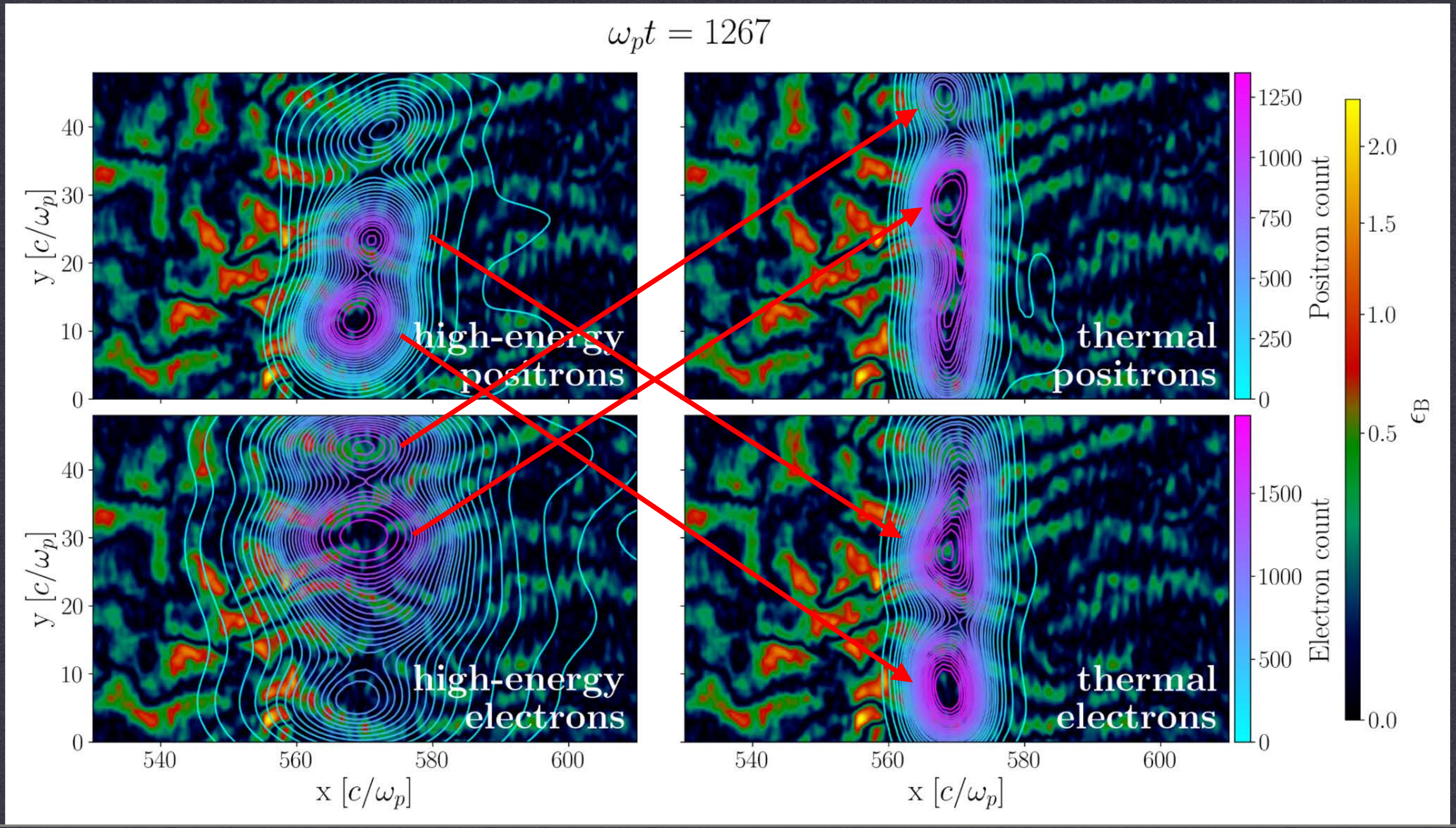
Behavior of high-energy positron subshell vs high-energy electron subshell

- But location of the high-energy electrons and positrons also aren't correlated when hitting the shock



Behavior of high-energy subshells vs thermal subshells

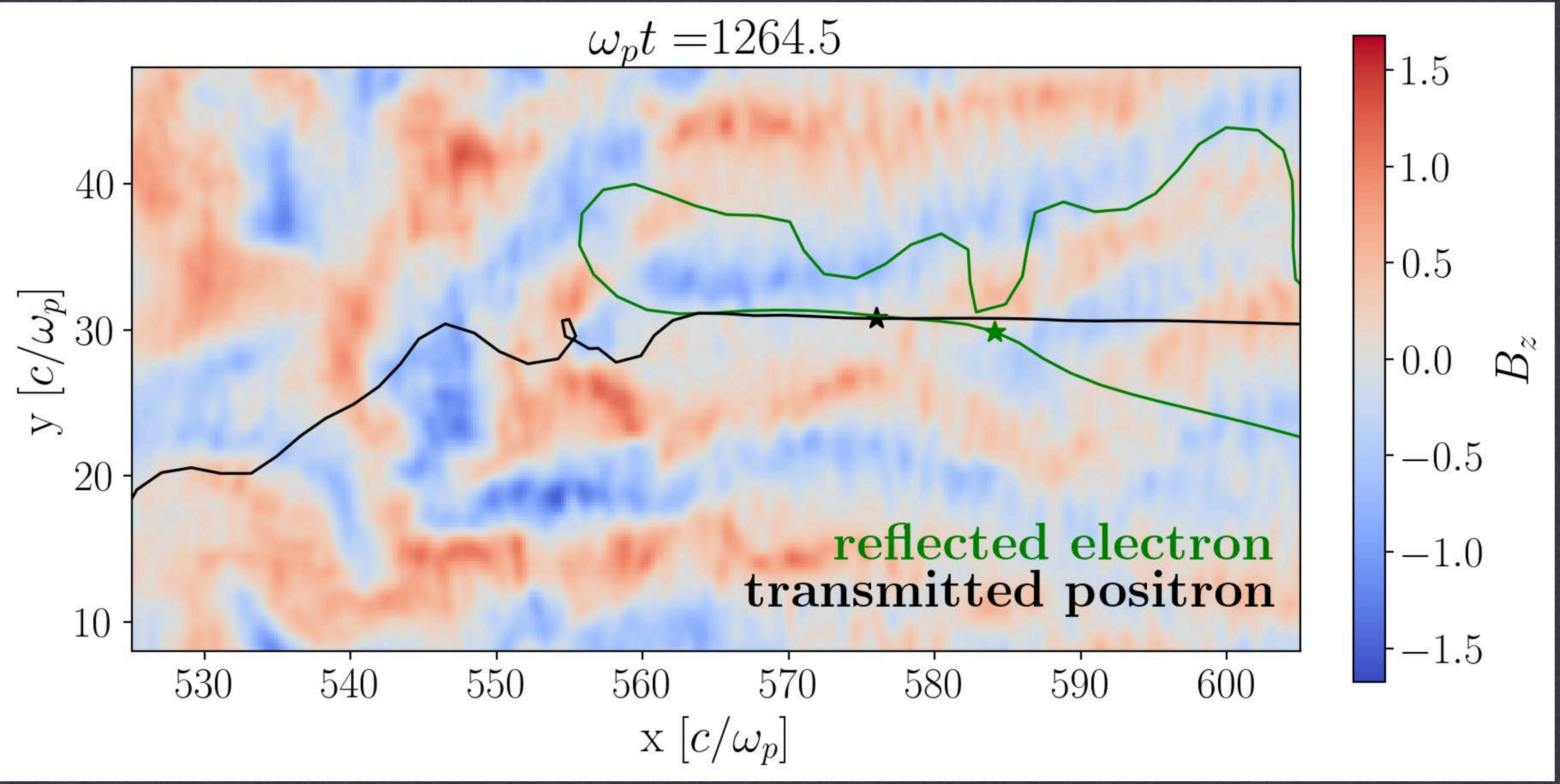
- When comparing high-energy vs thermal **across species**: high-energy particles of one species hit the shock at the same place as the thermal particles of the opposite species



Particle reflection and transmission

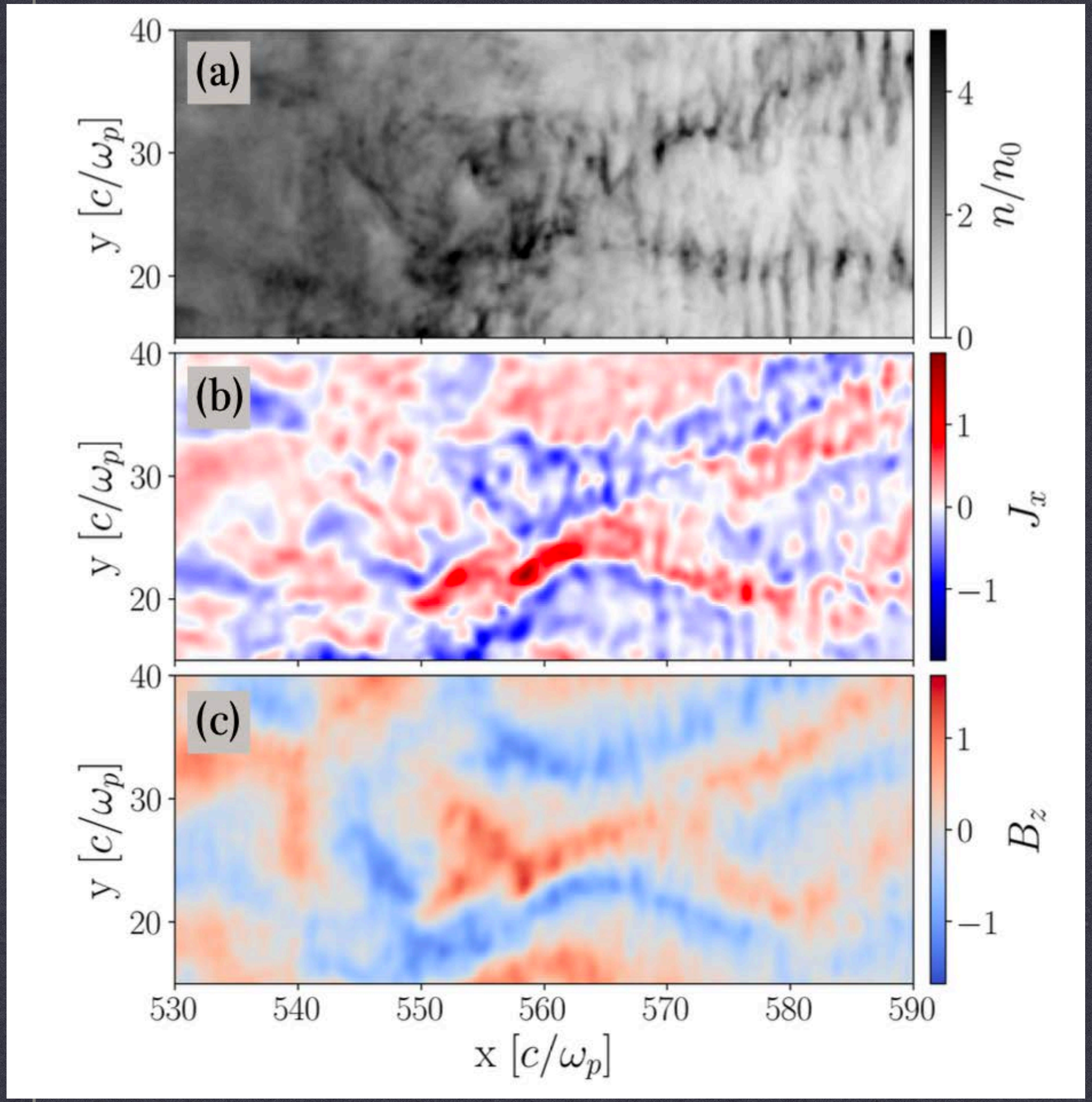
Orbits of electron and positron from same filament hitting shock at same place, same time

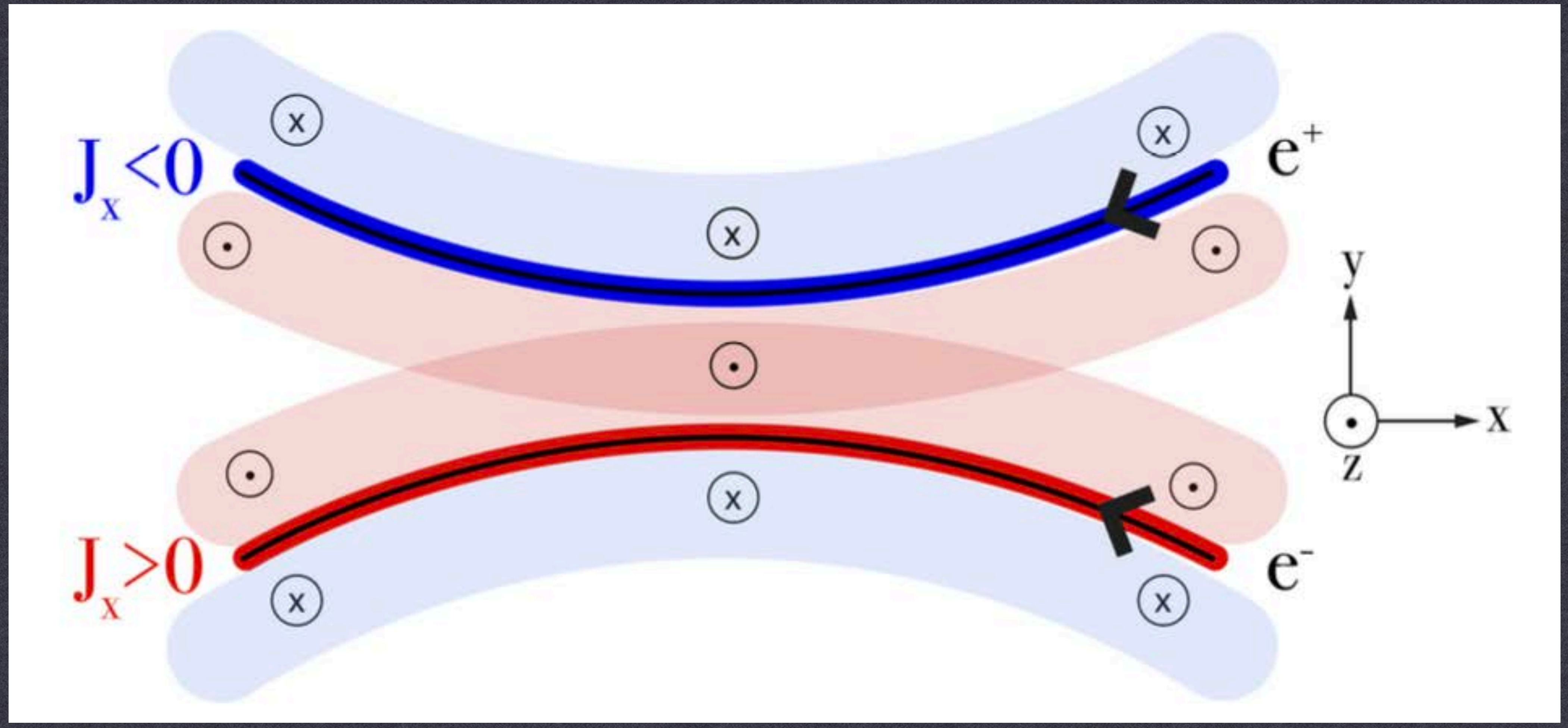
- Electron is reflected, positron is transmitted

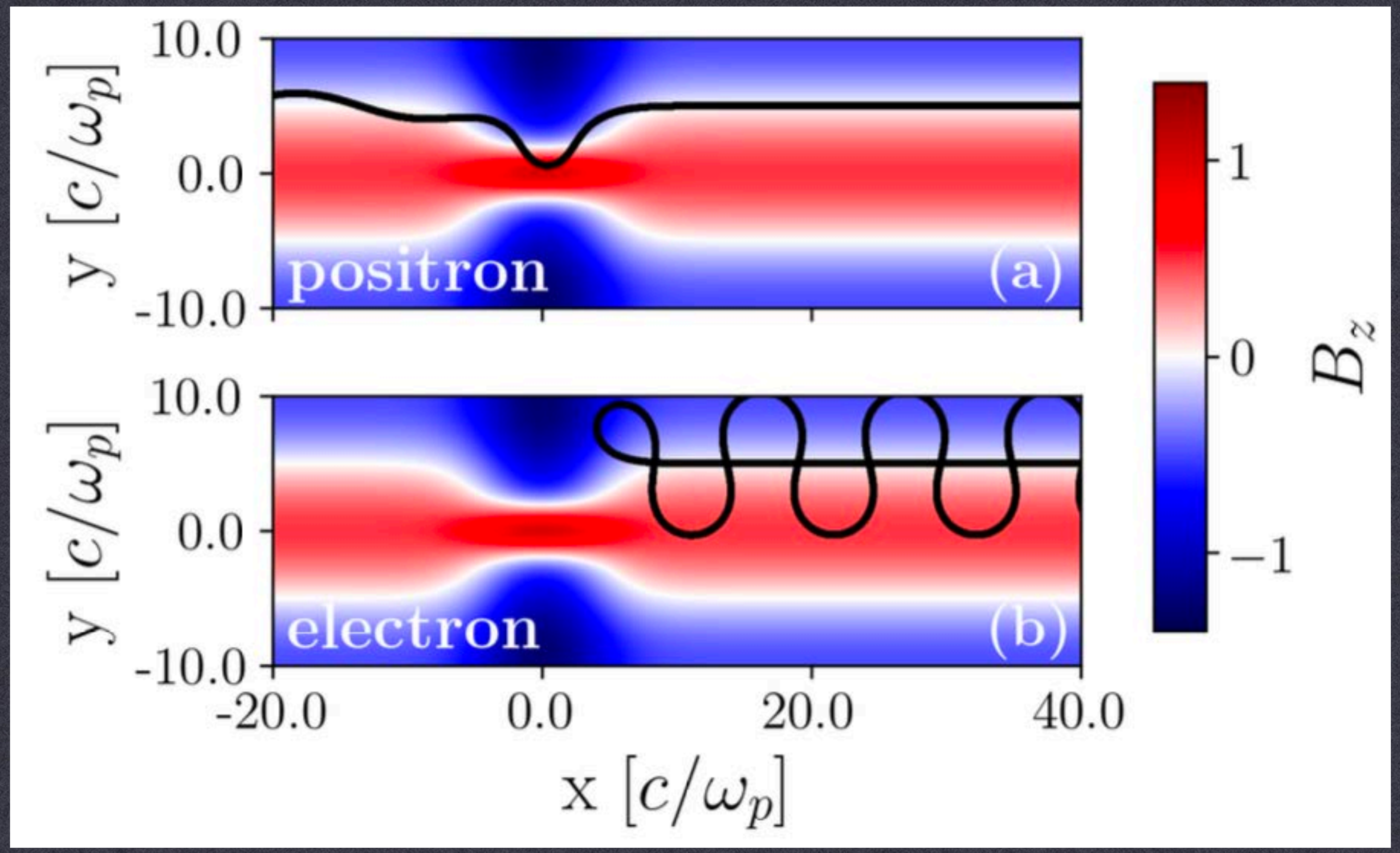


Nonlinear structures reflect (and transmit)!

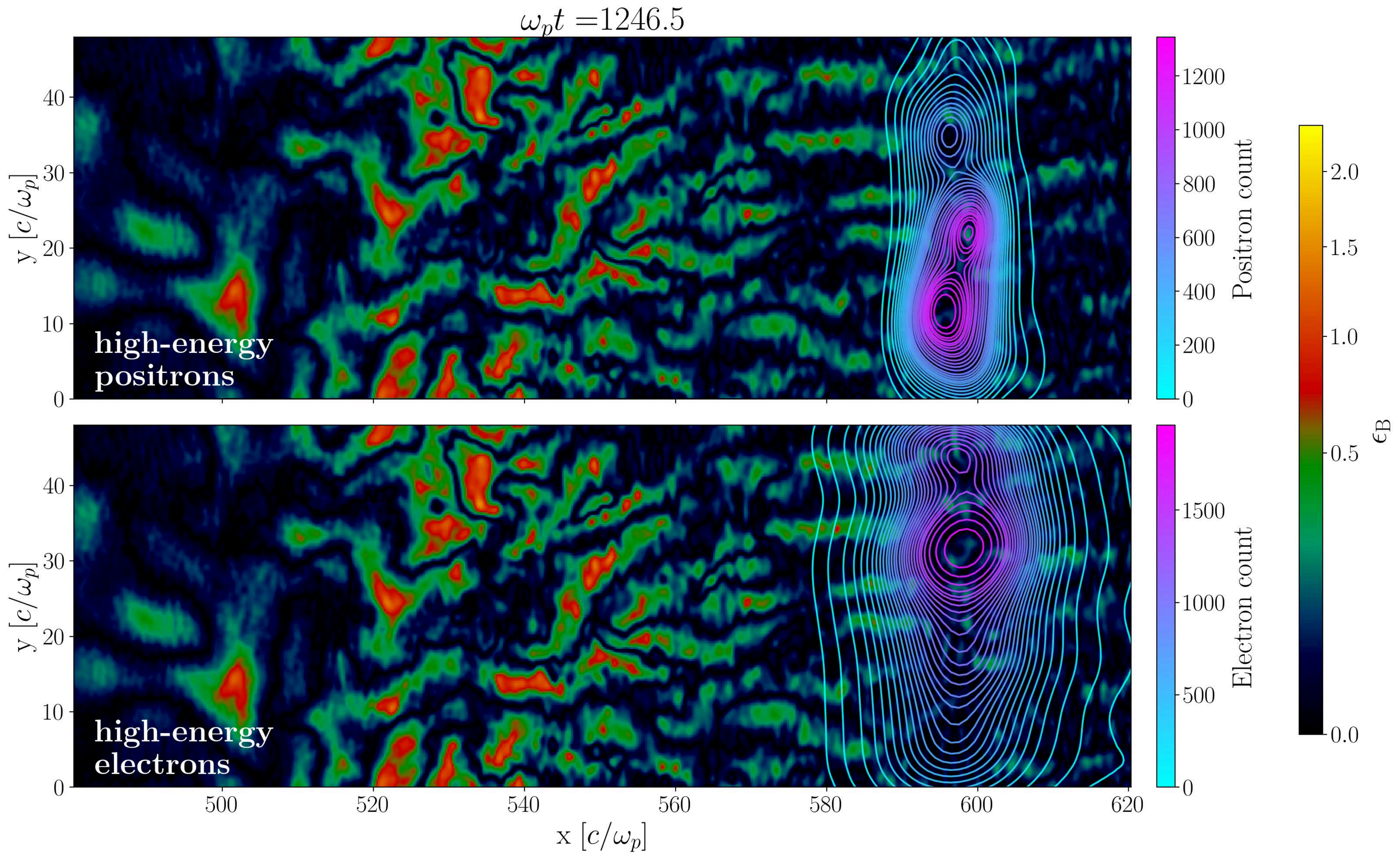
Opposite currents pushed together at the shock. Particles of “wrong sign” reflect. “Right sign” transmit.





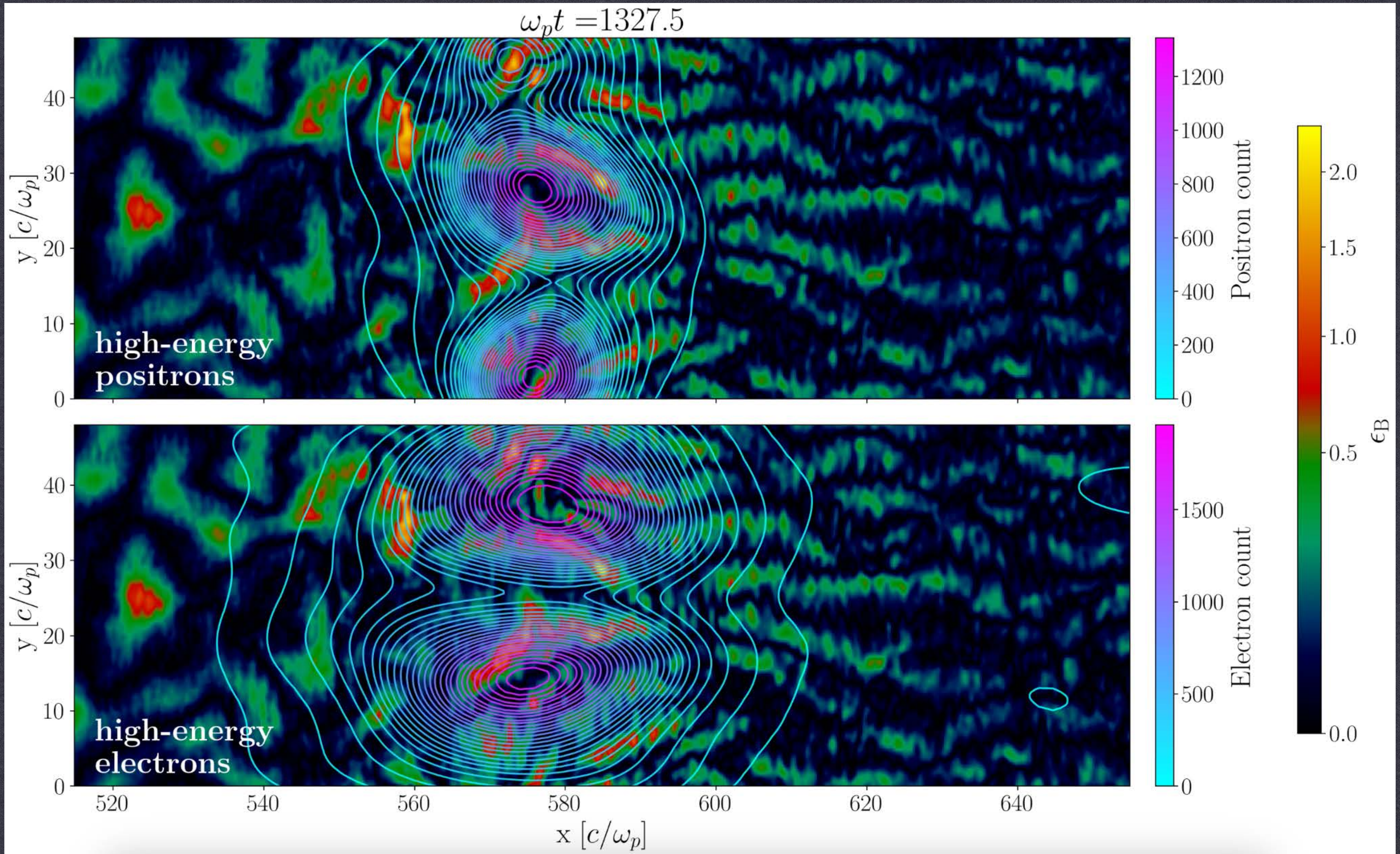


Behavior of high-energy subshells post-reflection

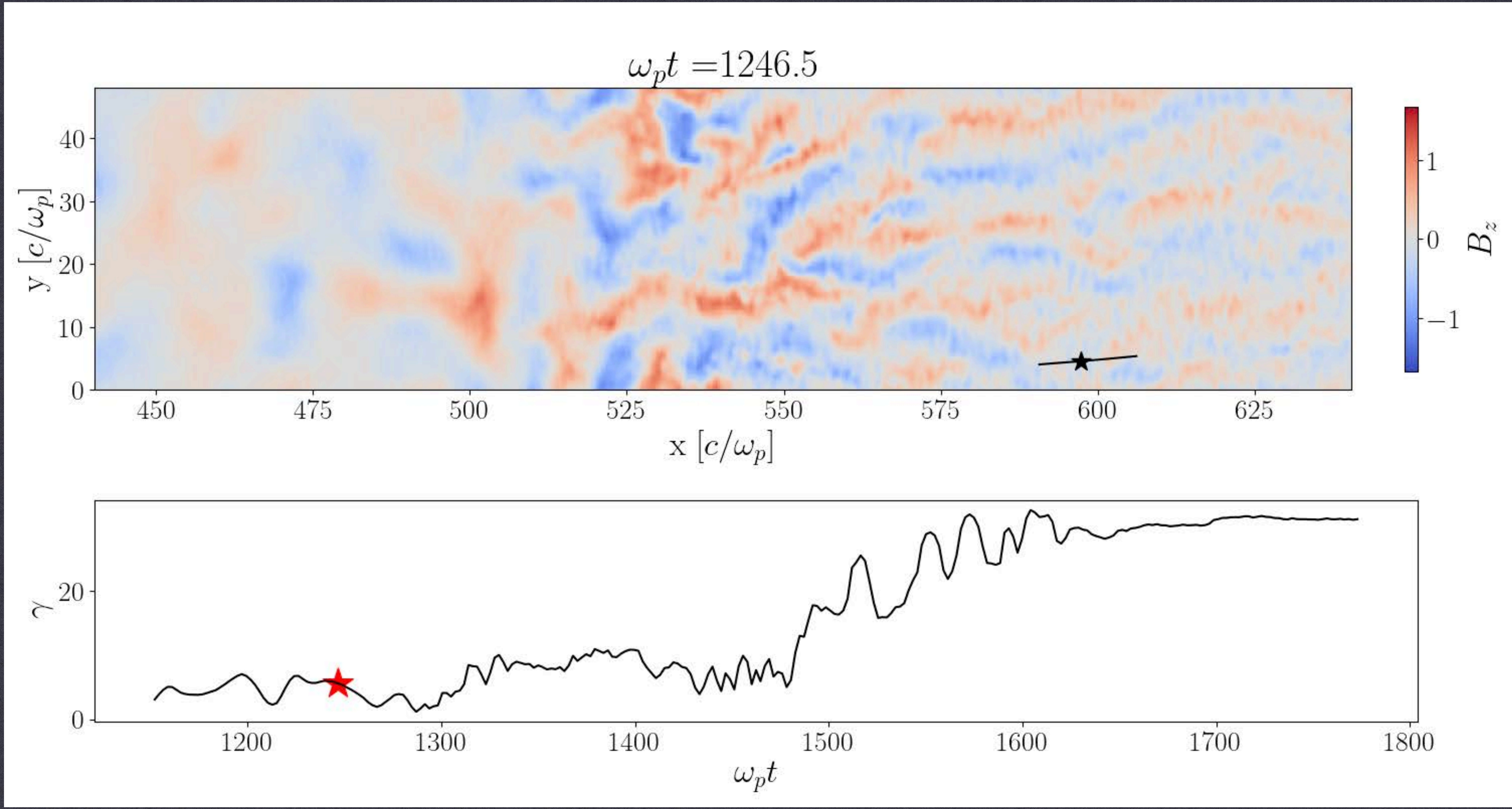


Behavior of high-energy subshells post-reflection

- High-energy electrons and high-energy positrons in incoming filaments of same sign of current that they're carrying (hence anti-correlated)

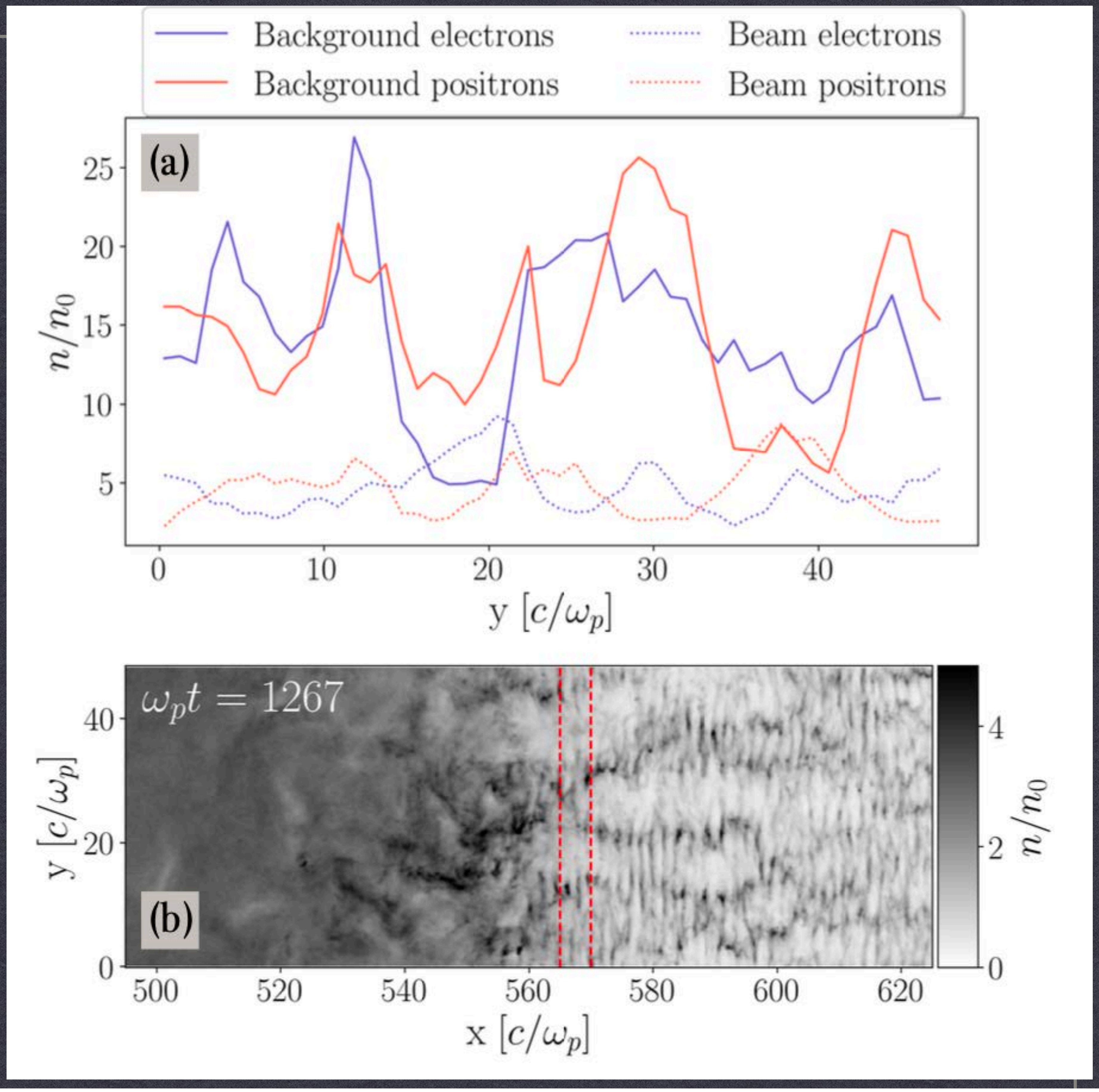


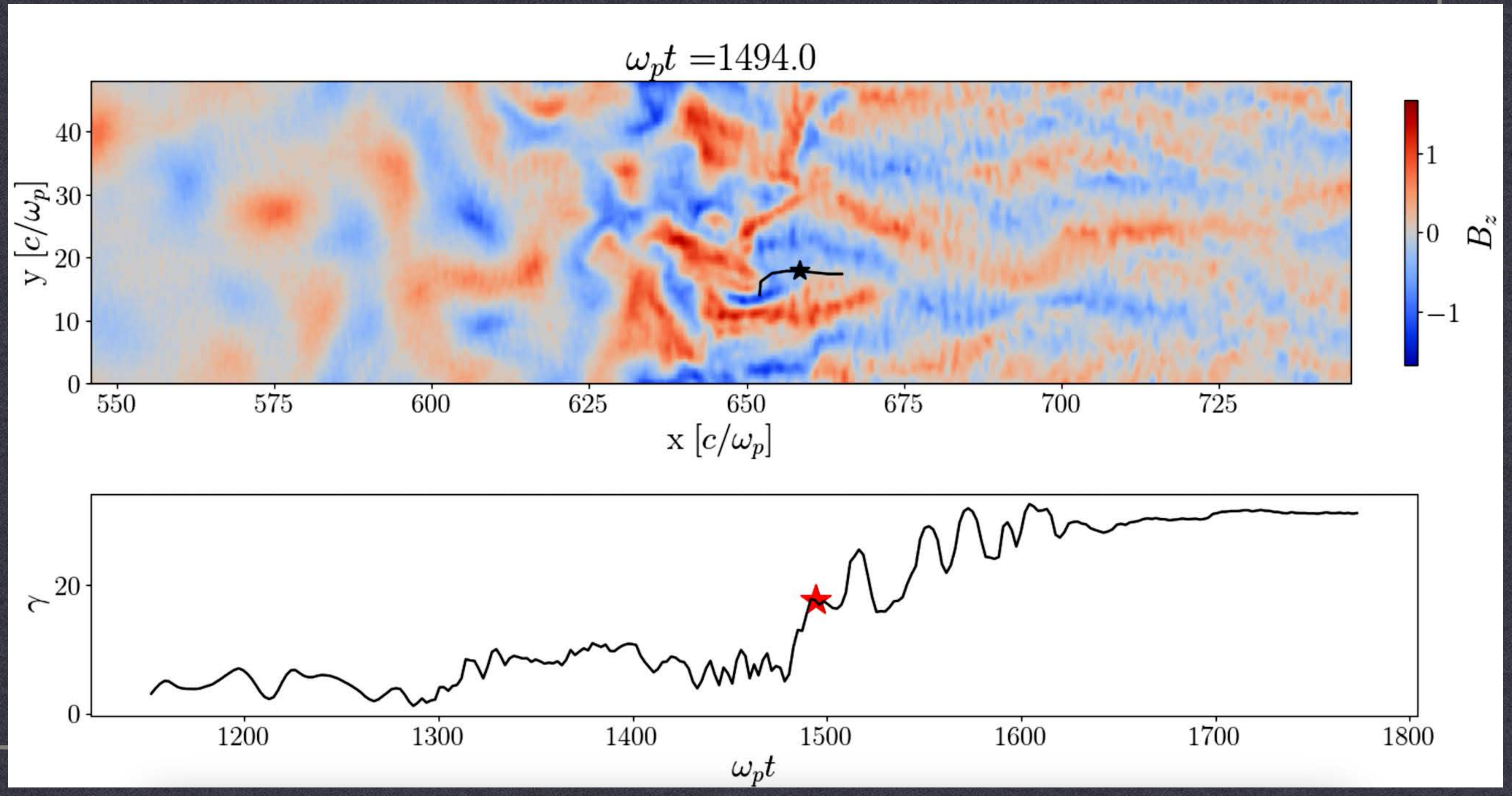
Behavior of high-energy particles post-reflection: filament swimming



Model for shock injection

- Two step process:
- Incoming density filaments are non-neutral, about 35% of particles are in the “wrong” filaments, and are reflected.
- To join Fermi accleration, particles need to stay ahead of the shock and accelerate so they can cross filaments.
- To stay in the upstream, they have to find filaments of the right sign of current, “swim in them”, and switch them when filaments stop. 4-5 switches, each lossy with ~50% probability, 0.1 factor.
- Result: ~35% * 0.1 ~ few %





Conclusions

- Collisionless shocks redistribute flow energy into heat, EM fields, and non thermal particles.
- Shock is a spatially non-uniform and highly nonlinear structure. This leads to additional sources of instabilities (e.g. reflected particles) and scattering (2D and 3D shocks heat better).
- Downstream Maxwellians are commonly observed.
- Instabilities lead to thermalization. If not all space is accessible, heating may saturate at non-Maxwellian shape.
- Tails develop from incomplete thermalization and direct Fermi acceleration in converging flows.
- Long-term feedbacks are subject of current research.
- Are shocks analogs of galaxy collisions? Are there shock-like features in these collisions?
- Are filamentation instabilities in gravity working like plasma analogs?