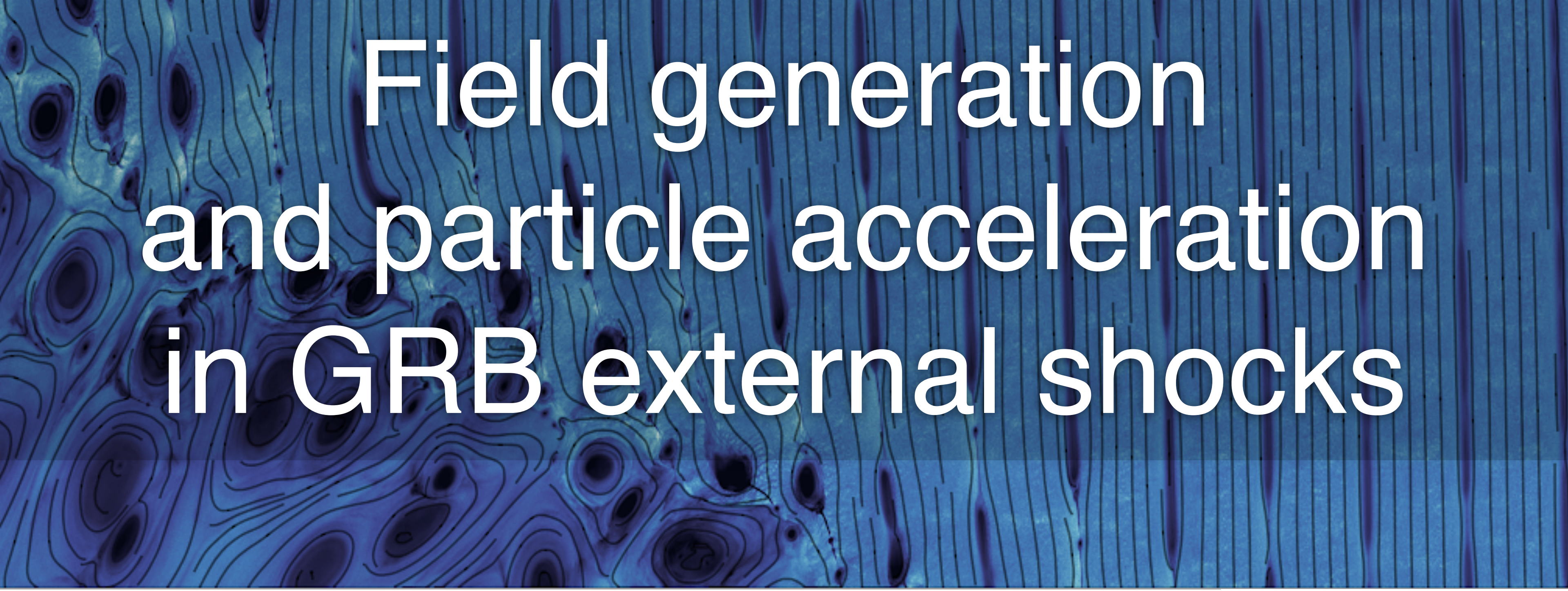
Field generation and particle acceleration in GRB external shocks



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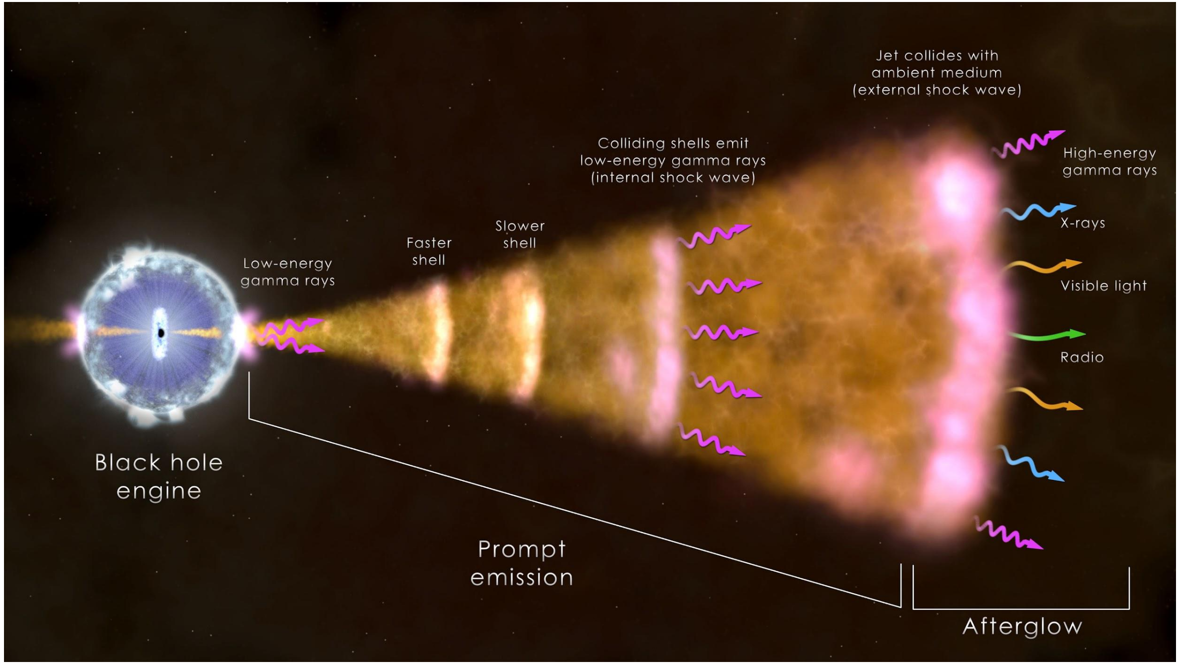
Relativistic shocks: whence the fields? [WTF?]

arXiv.2401.02392

with Daniel Groselj and Anatoly Spitkovsky

Gamma Ray Burst (GRB) external shocks



External GRB shocks are:

- Collisionless
- Ultra-relativistic: $\gamma_0 \sim 10^2$
- Weakly magnetized:

$$\sigma = \frac{B_0^2}{4\pi\gamma_0\rho c^2} \sim 10^{-9}$$

- $B_0 \perp$ shock normal

What is the long-term evolution of relativistic unmagnetized shocks?

The Weibel instability

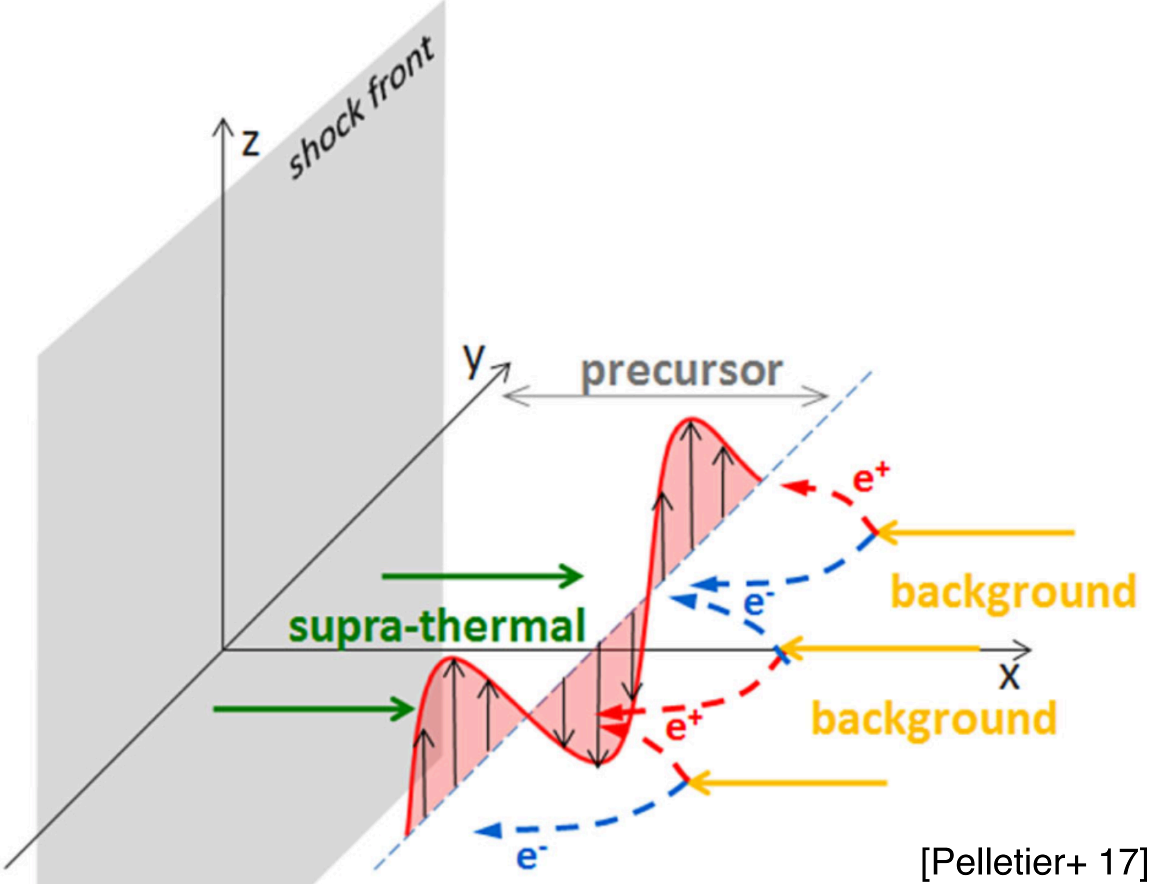
The Weibel instability converts the free energy of counter-streaming flows into self-generated magnetic fields.

[Weibel 1959, Medvedev & Loeb 1999]

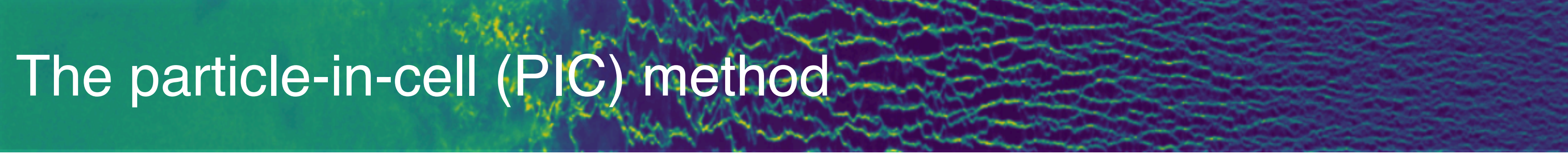
The growth of Weibel fields from scratch *cannot* be captured in MHD:

$$\boxed{\frac{\partial \mathbf{B}}{\partial t} = \underbrace{\nabla \times (\mathbf{V} \times \mathbf{B})}_{\text{advection}} + \underbrace{D_\eta \nabla^2 \mathbf{B}}_{\text{diffusion}}}$$

In MHD, the field stays zero.

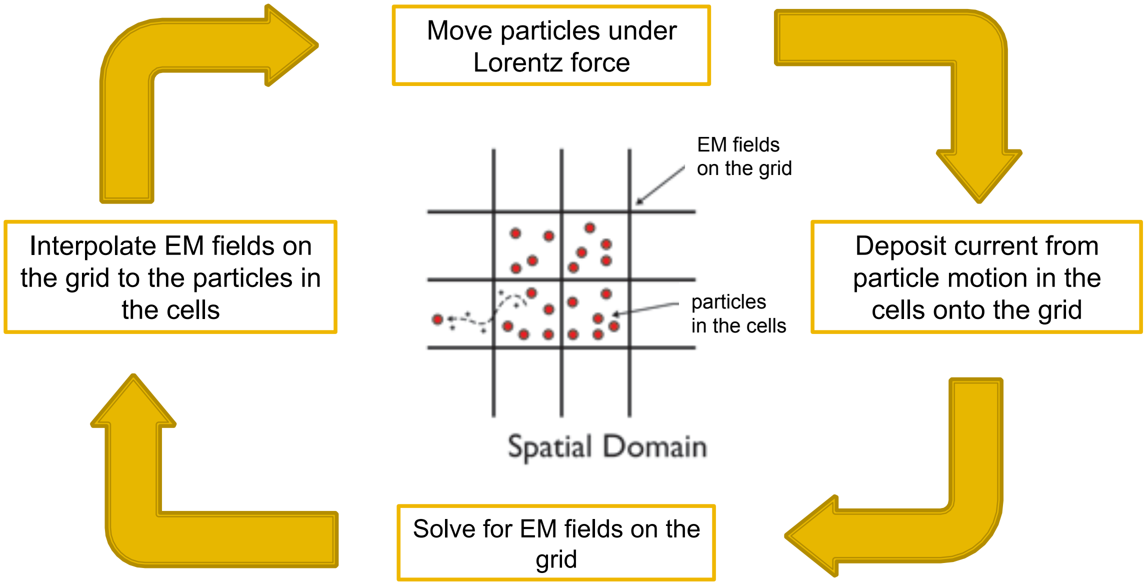


[Pelletier+ 17]



The particle-in-cell (PIC) method

It is the most fundamental way of capturing the interplay of charged particles and electromagnetic fields.



Move particles under Lorentz force

Deposit current from particle motion in the cells onto the grid

Solve for EM fields on the grid

Interpolate EM fields on the grid to the particles in the cells

Plasma length scale:

$$\frac{c}{\omega_{\rm pe}} \simeq 5 \times 10^5 \left(\frac{n}{1\,{\rm cm}^{-3}}\right)^{-1/2} \,{\rm cm}$$

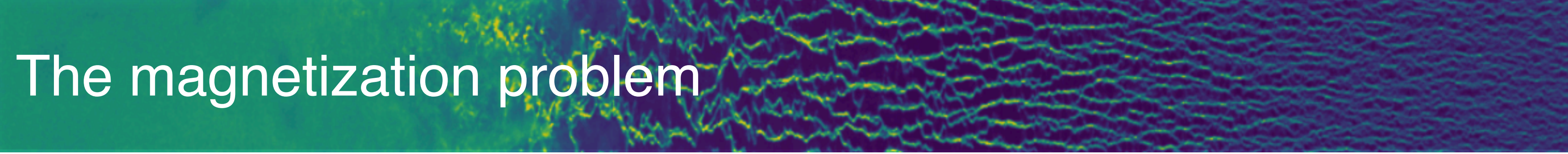
Plasma time scale:

$$\frac{1}{\omega_{\rm pe}} \simeq 2 \times 10^{-5} \left(\frac{n}{1\,{\rm cm}^{-3}}\right)^{-1/2} \,{\rm s}$$

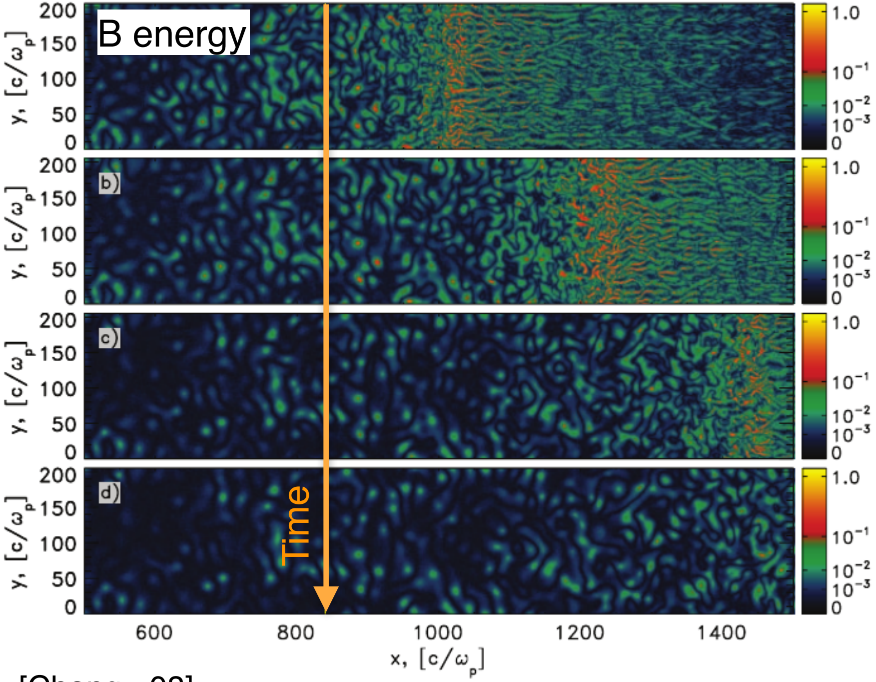
$$\left[\omega_{\rm pi} = \omega_{\rm pe}\sqrt{m_e/m_i}\right]$$

The *microscopic* scales resolved by PIC simulations are much smaller than *astronomical* scales.

The magnetization problem

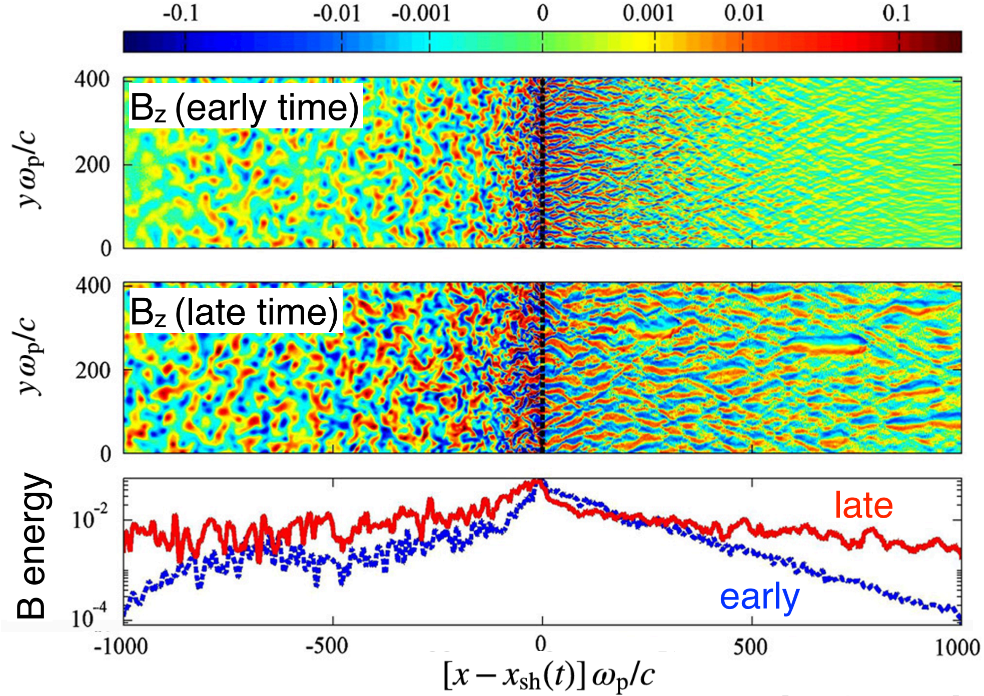


Weibel fields grow on small scales, thus they quickly decay.



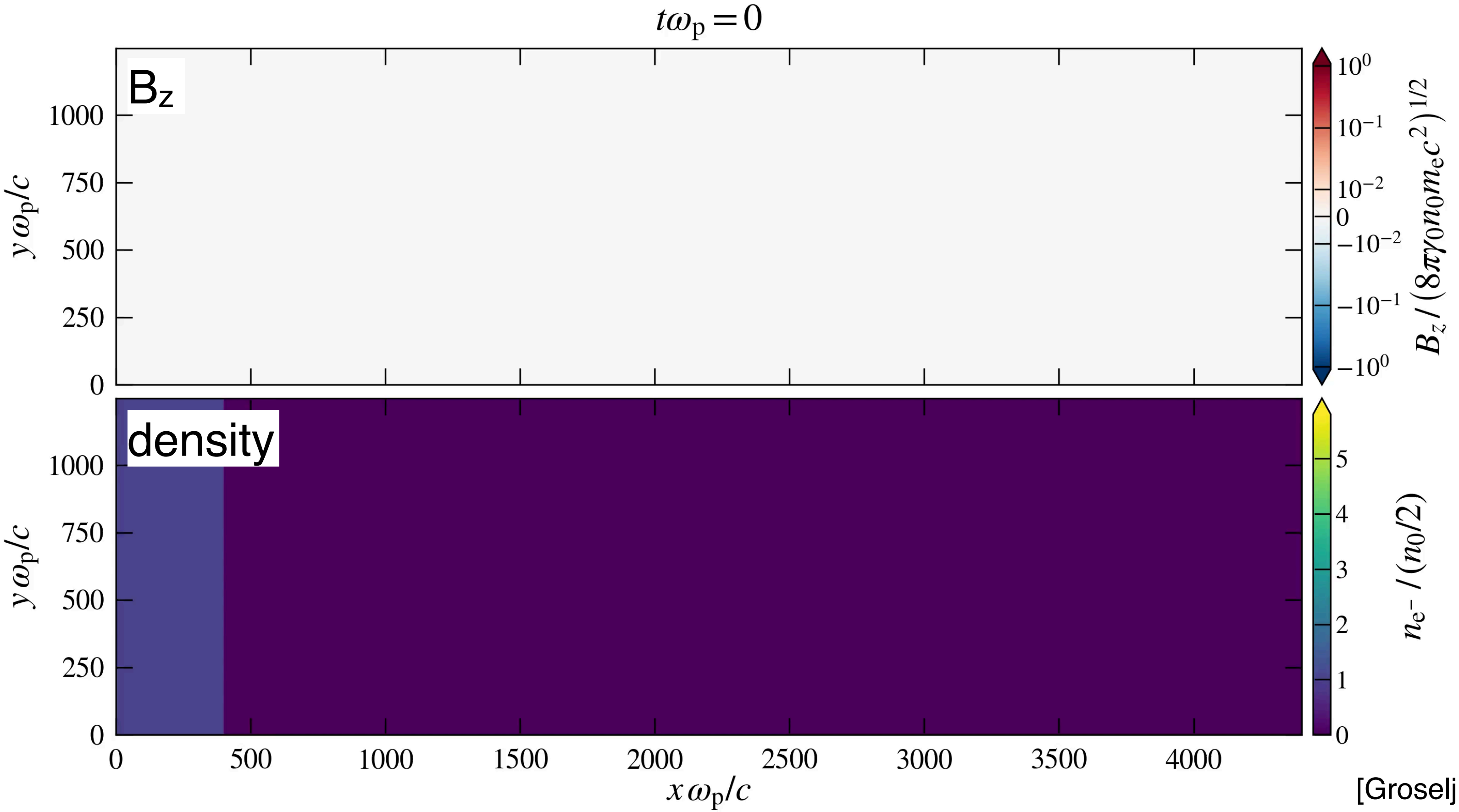
[Chang+ 08]

As particles are accelerated to higher energies, the field coherence scale increases.



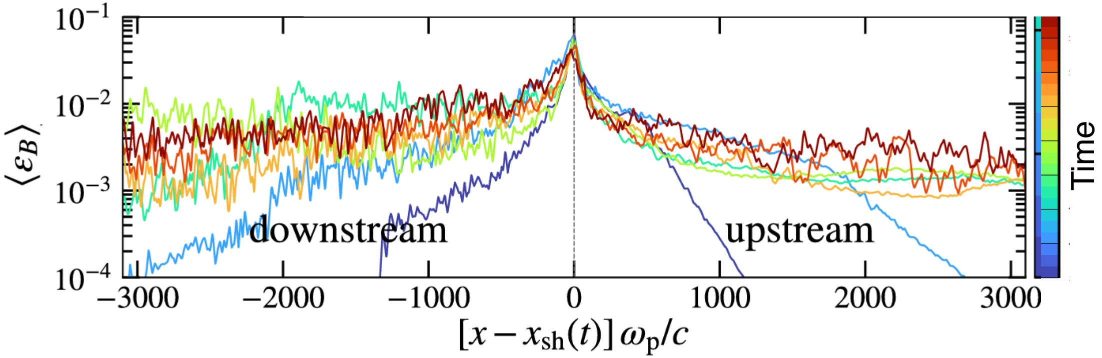
[Keshet+ 09]

The long-term evolution [electron-positron shock]



[Groselj, LS & Spitkovsky 24]

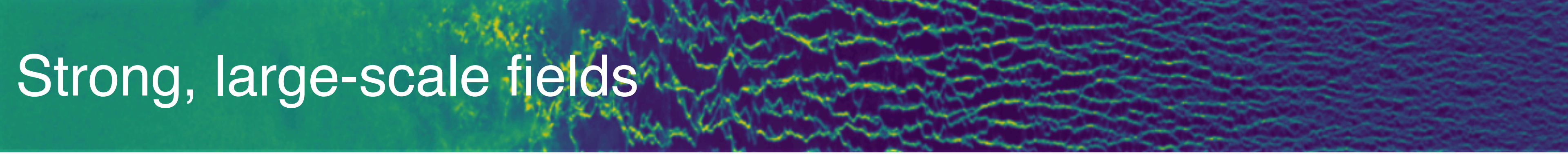
Strong, large-scale fields



- The mean post-shock magnetic energy fraction is

$$\langle \epsilon_B \rangle = \frac{\langle B^2 \rangle}{8\pi\gamma_0\rho c^2} \sim 0.003$$

- The magnetic energy fraction does not appreciably decay downstream.



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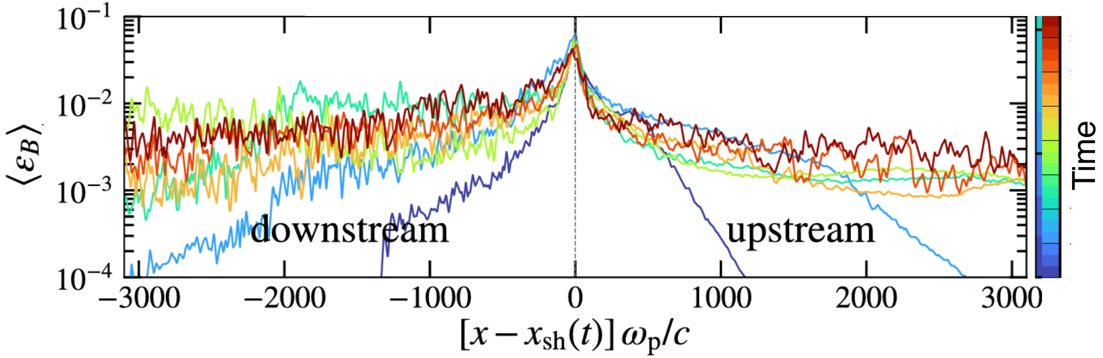

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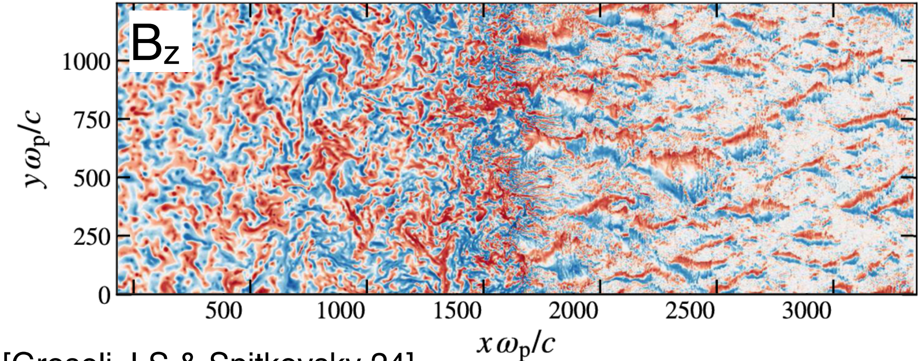
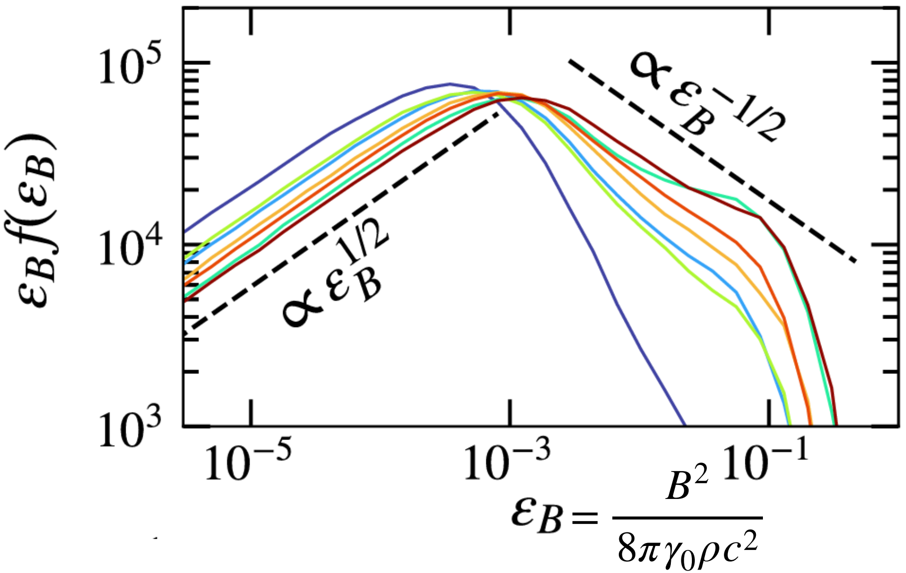


[Groselj, LS & Spitkovsky 24]

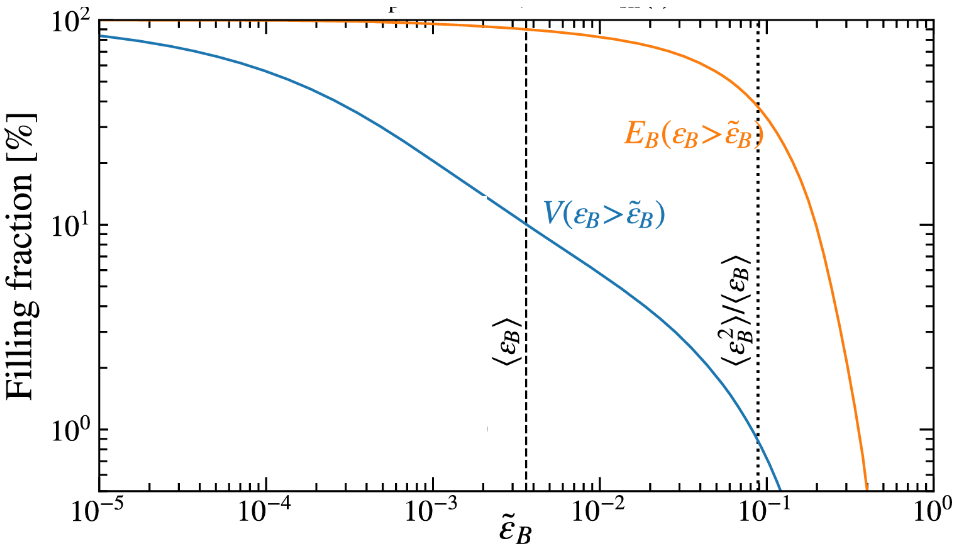
- The transverse coherence scale increases beyond $\sim 100\ c/\omega_{\rm p}$
- A large fraction of the B energy is localized in intense, non-volume-filling magnetic structures.

[Peterson & Fiuza 21, 22; Bresci & Lemoine 22;
Parsons, Spitkovsky & Vanthieghem 23]

The PDF of magnetic energy

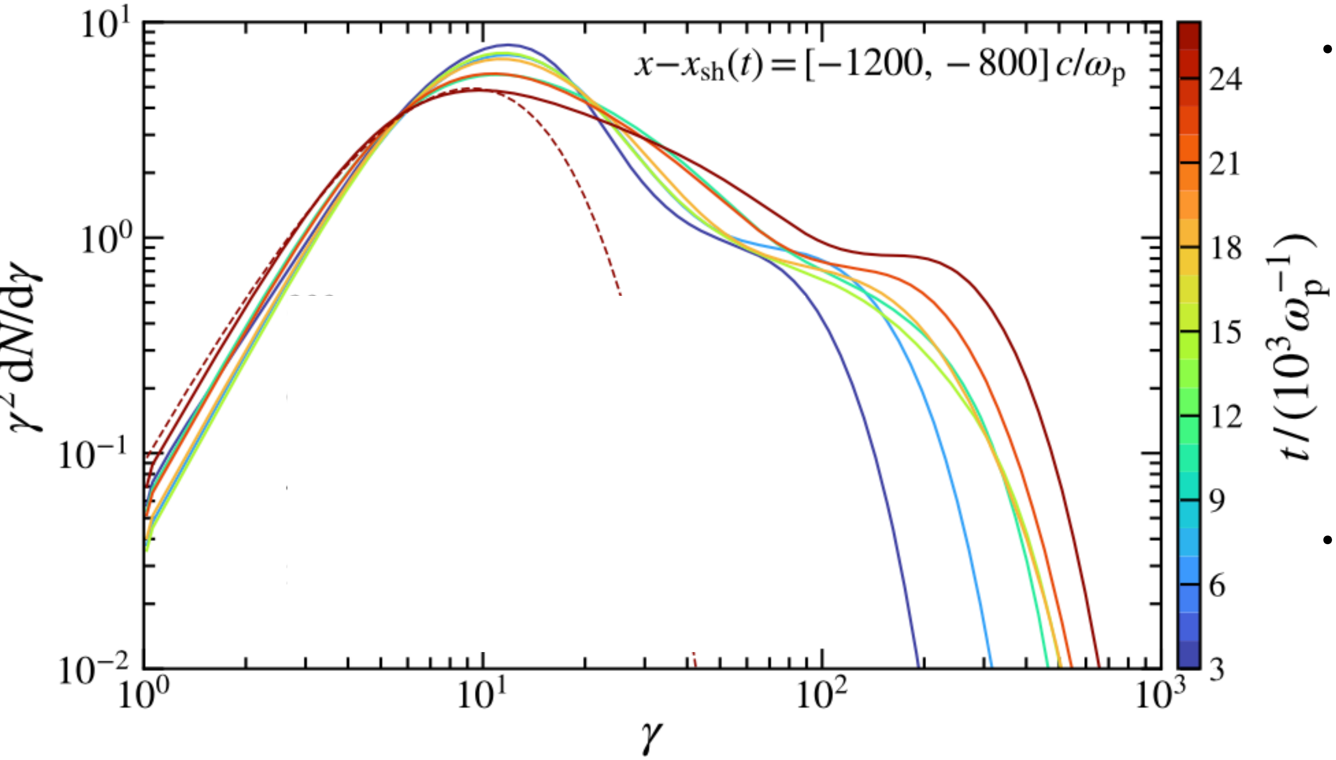


- The magnetic energy fraction PDF peaks at ~ 0.003, but it shows a tail extending up to ~ 0.1



- 50% of the magnetic energy, and so of the synchrotron power, is contributed by structures with $\epsilon_B \sim 0.1$, which occupy only 1% of the downstream volume.

The particle energy spectrum



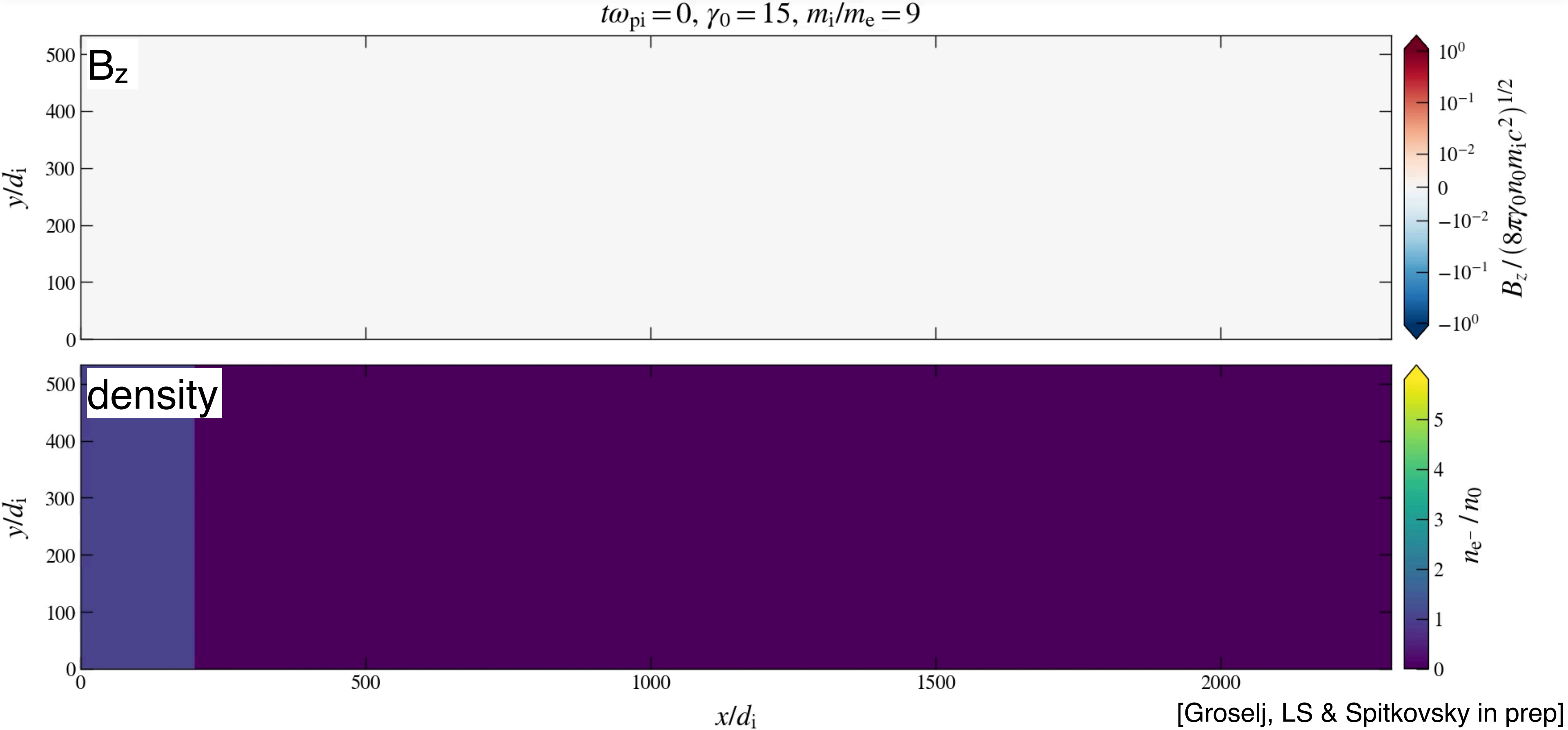
- A pronounced supra-thermal population emerges at late times, between the Maxwellian peak and the non-thermal tail.

- The maximum energy grows as $\gamma_{\rm max} \propto t^{1/2}$, as expected for small-angle scattering.

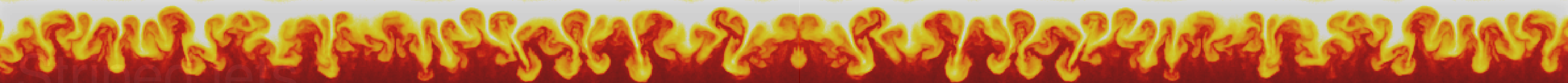
[Lemoine & Pelletier 13, Sironi+ 13]

[Groselj, LS & Spitkovsky 24]

The long-term evolution [electron-ion shock]



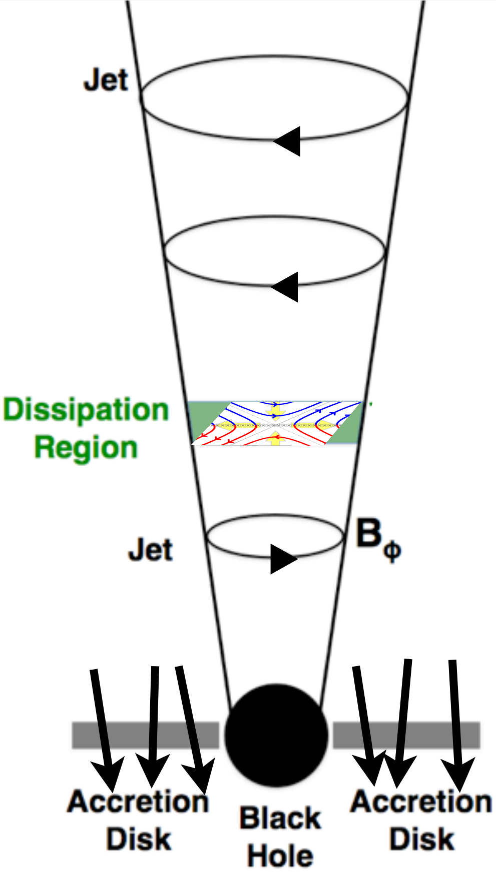
[Groselj, LS & Spitkovsky in prep]



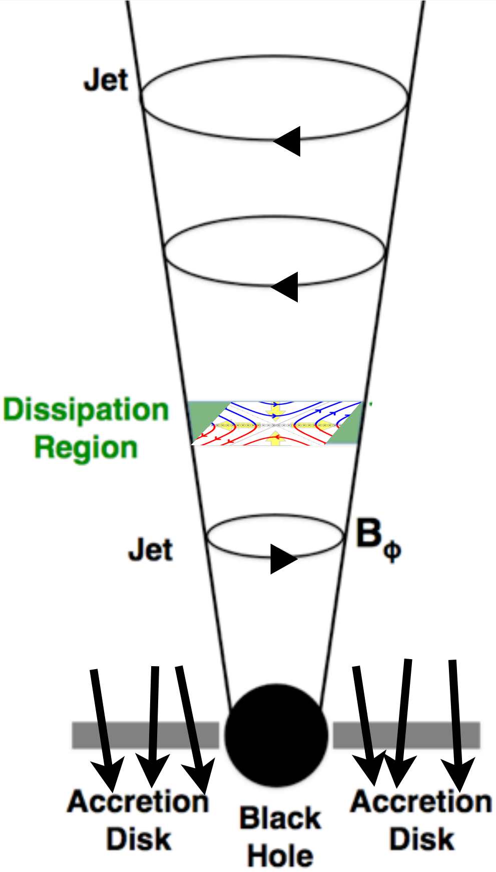
Dissipation in striped jets

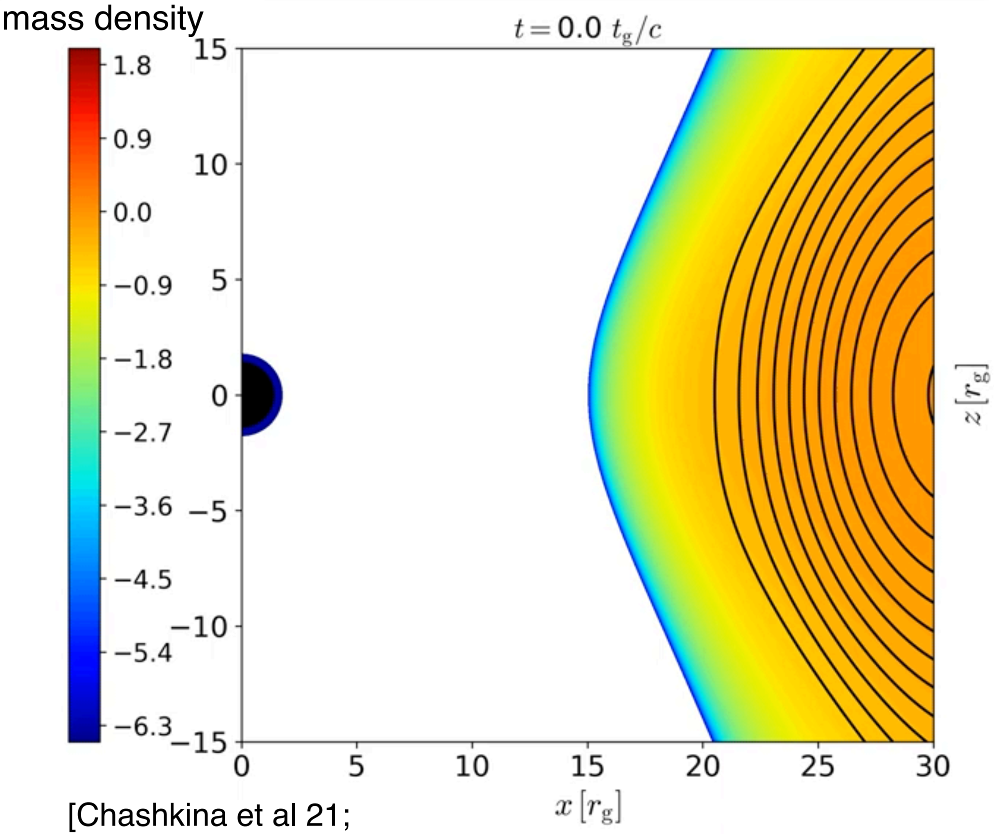
with William Groger and Hayk Hakobyan

Striped jets



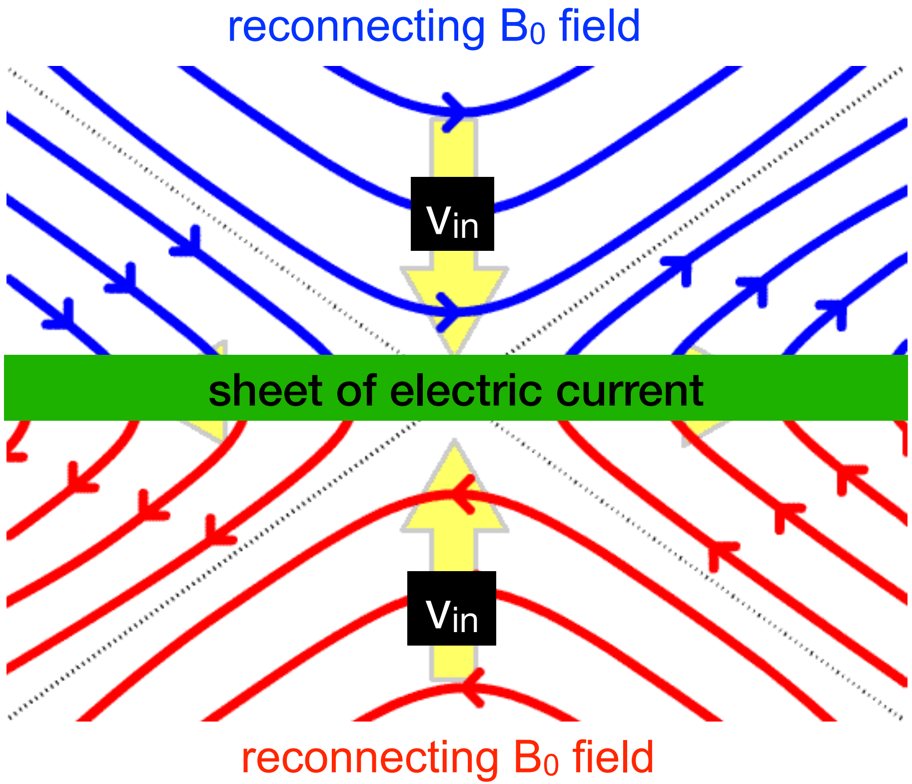
Striped jets





[Chashkina et al 21;
foundational works by Aloy, Giannios, Tchekhovskoy]

Interlude: relativistic magnetic reconnection



Relativistic reconnection:

$$\sigma = \frac{B_0^2}{4\pi \rho c^2} \gg 1 \qquad v_A \sim c$$

- The plasma flows into the layer with

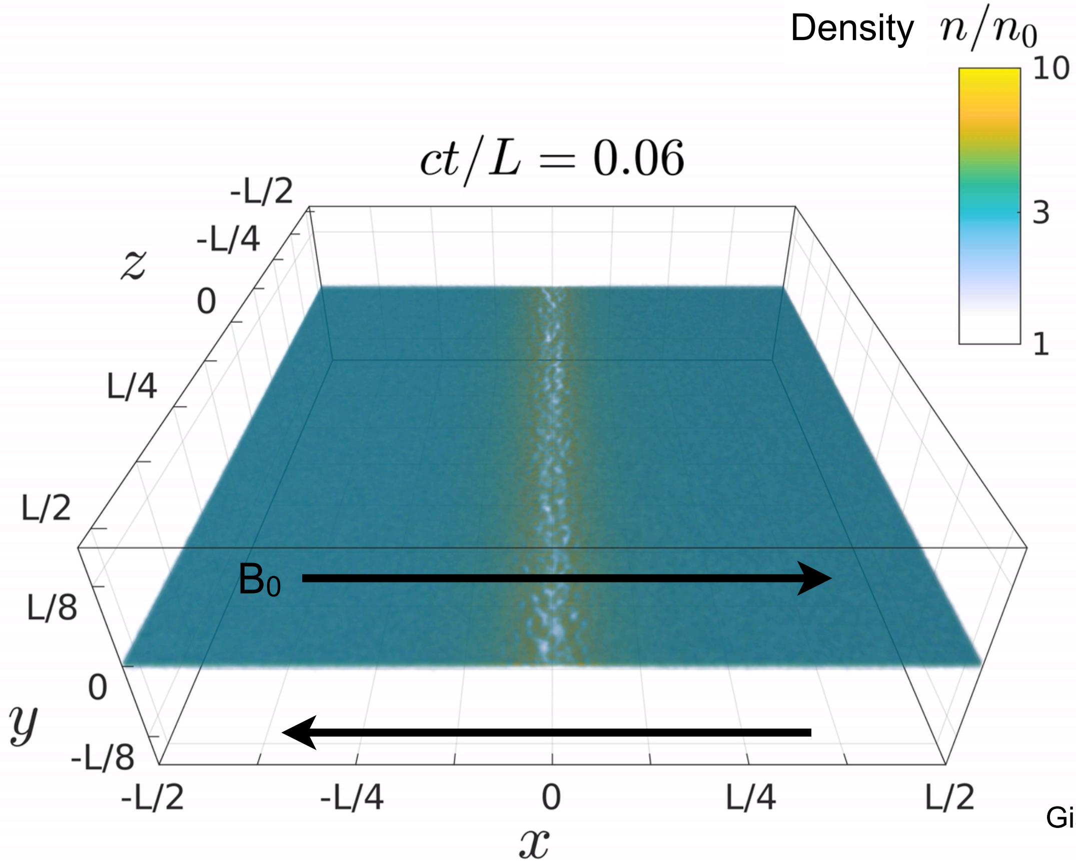
$$v_{\rm in} \sim 0.1 v_A \sim 0.1c$$

→ Rel. reconnection can efficiently dissipate the field energy

→ Rel. reconnection can efficiently accelerate particles, via

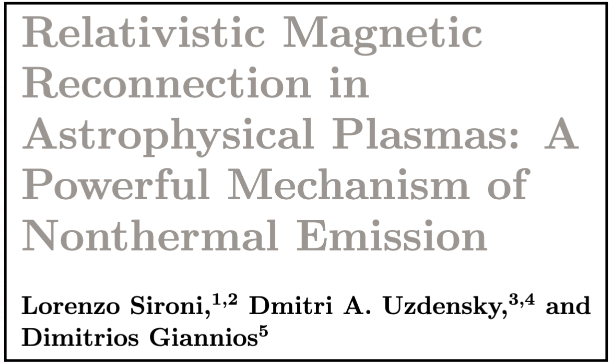
$$E_{\rm rec} \sim (v_{\rm in}/c) B_0 \sim 0.1 B_0$$

Interlude: relativistic magnetic reconnection



The reconnection layer breaks into a chain of flux ropes / plasmoids

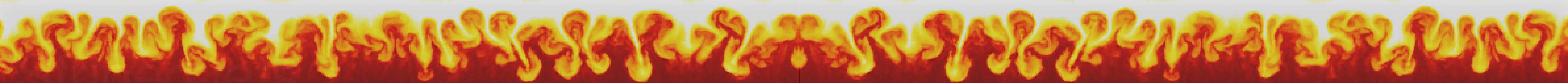
upcoming ARAA review:



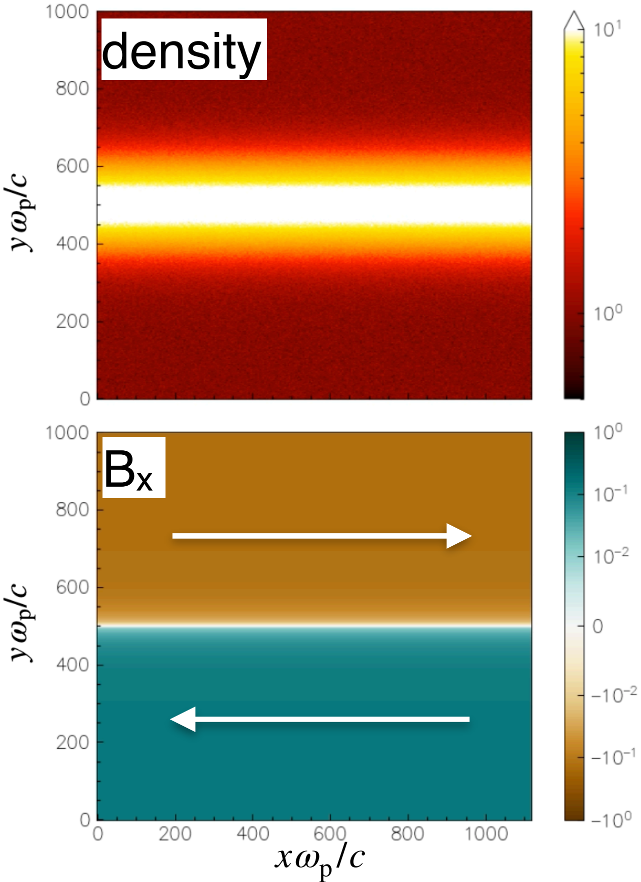
Relativistic Magnetic Reconnection in Astrophysical Plasmas: A Powerful Mechanism of Nonthermal Emission

Lorenzo Sironi,[1,2] Dmitri A. Uzdensky,[3,4] and Dimitrios Giannios[5]

[Zhang, LS, Giannios 21,23]

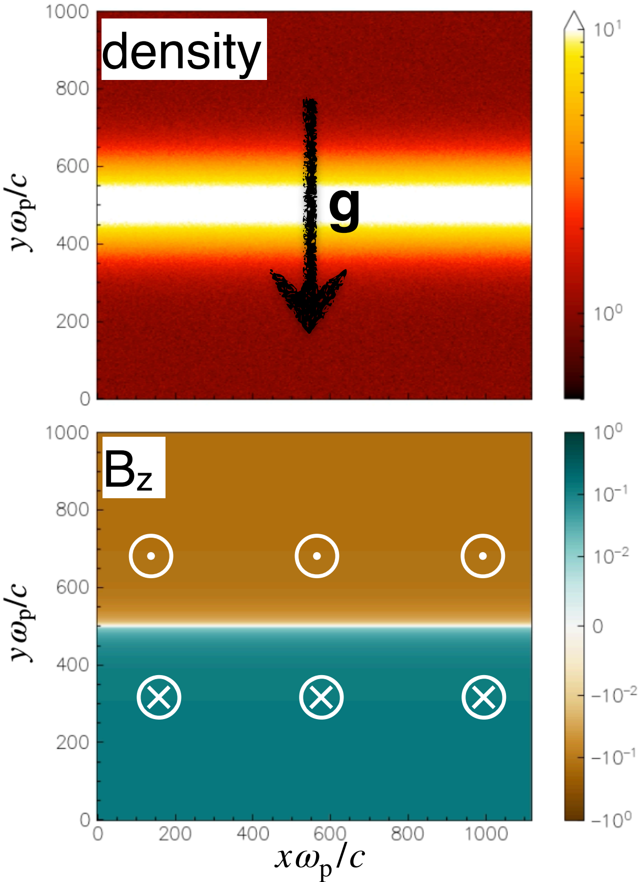


How to dissipate in striped jets?



- The sheet is too thick, so reconnection does not spontaneously occur (onset problem).

How to dissipate in striped *accelerating* jets?



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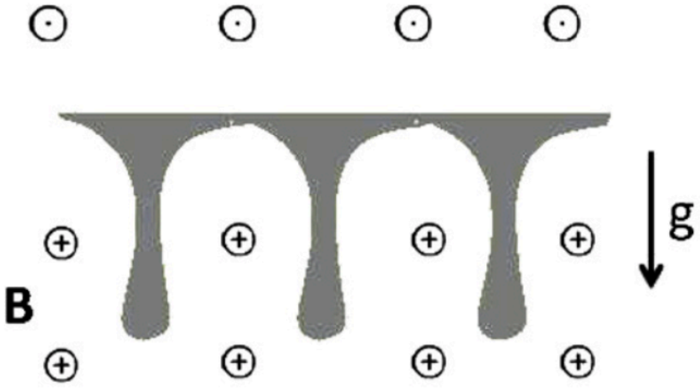
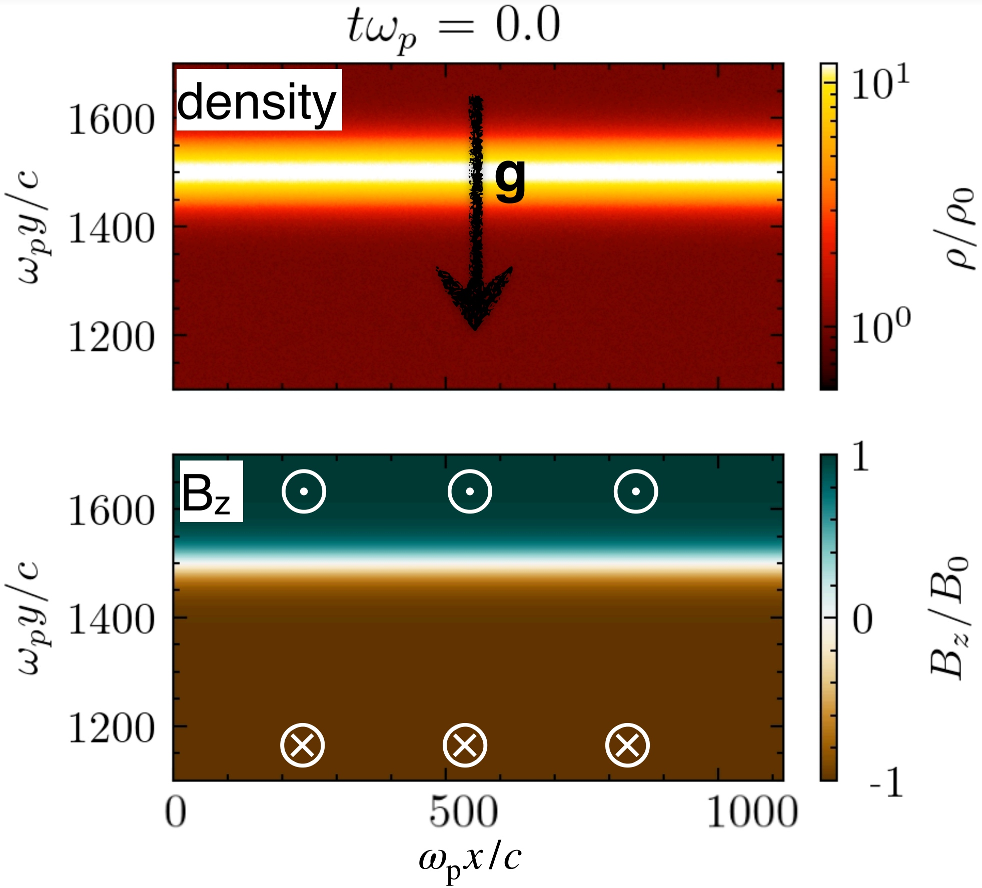


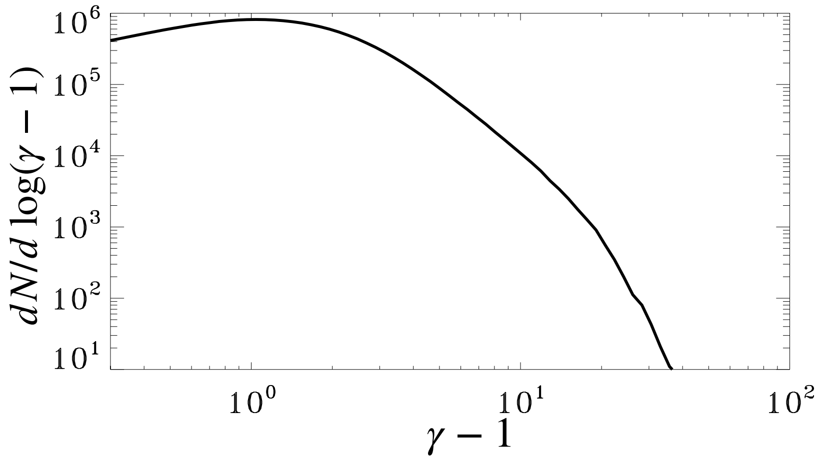
[Lyubarsky 10, Gill+17, Zhdankin+23]

- **Kruskal–Schwarzschild instability**: in the presence of an effective gravity force, the plasma drips out of the current sheet.

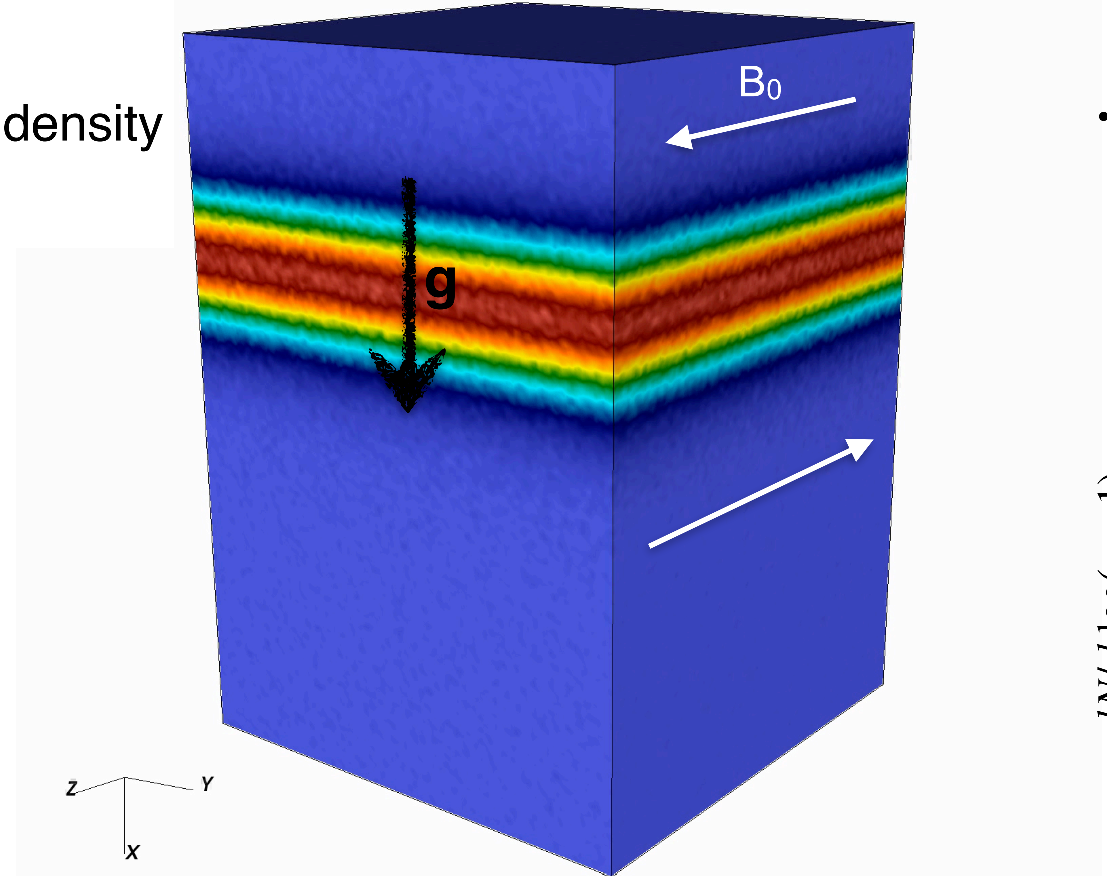
PIC simulations of the KS instability: 2D



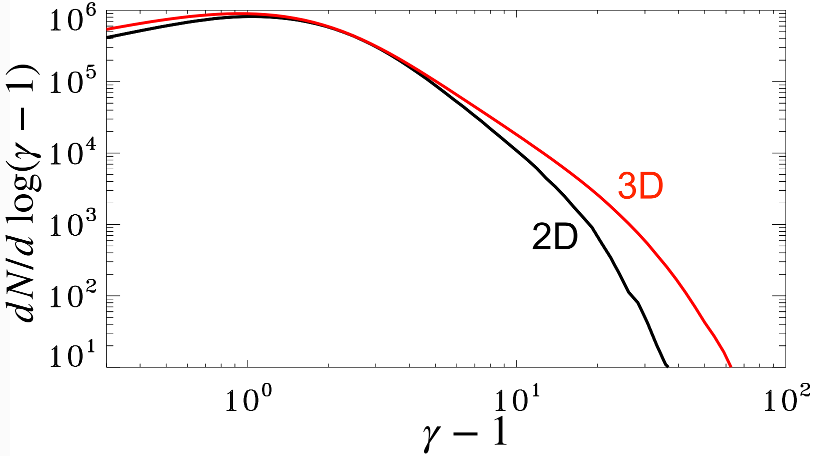
- Due to the KS instability, the plasma drips out of the current sheet, facilitating field dissipation.
- In 2D with out-of-plane fields, reconnection is inhibited, and the particle spectrum is nearly thermal.

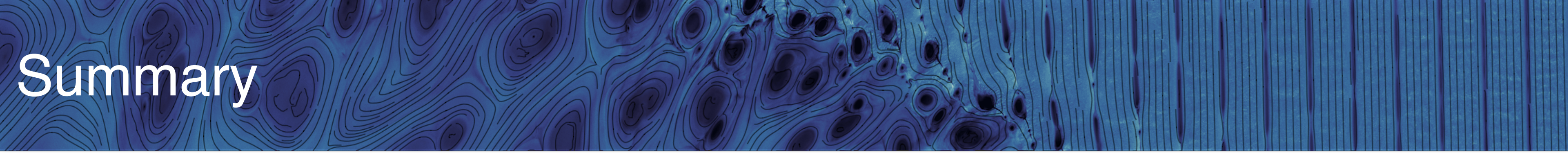


PIC simulations of the KS instability: 3D



- In 3D, both the KS instability and the reconnection mode can grow, mediating efficient reconnection-powered particle acceleration.





Summary

GRB afterglow:

- GRB external shocks produce large-scale magnetic filaments (coherence length $> 100\,c/\omega_{\rm p}$, and still growing), with synchrotron-weighted $\epsilon_B \sim 0.1$. Having a large coherence length, the field does not decay much in the post-shock region.
- In addition to the mean $\langle\epsilon_B\rangle \sim 0.003$, the post-shock PDF of ϵ_B — that extends up to $\epsilon_B \sim 0.1$ — is key for predicting the emission signatures.
- The late-time particle energy spectrum shows a supra-thermal population, which may hide the contribution of the thermal Maxwellian in afterglow synchrotron spectra.

GRB prompt:

- The Kruskal-Schwarzschild instability provides a promising mechanism for field dissipation and particle acceleration in striped *accelerating* jets.