Particle acceleration at pulsar wind termination shocks revisited : shear, reconnection and giant plasmoids

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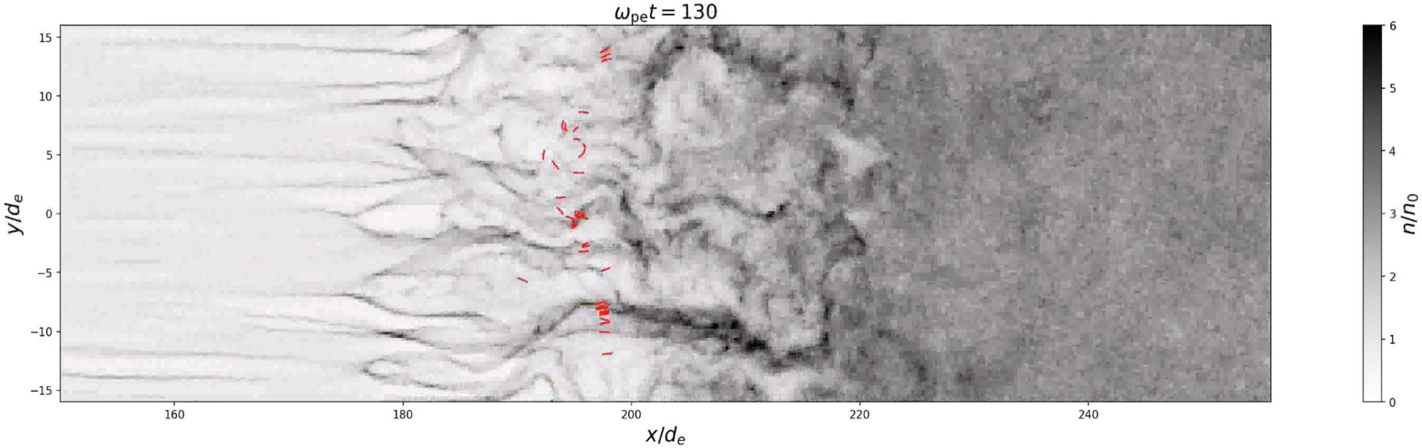
Relativistic unmagnetized shocks are good accelerators… but slow !

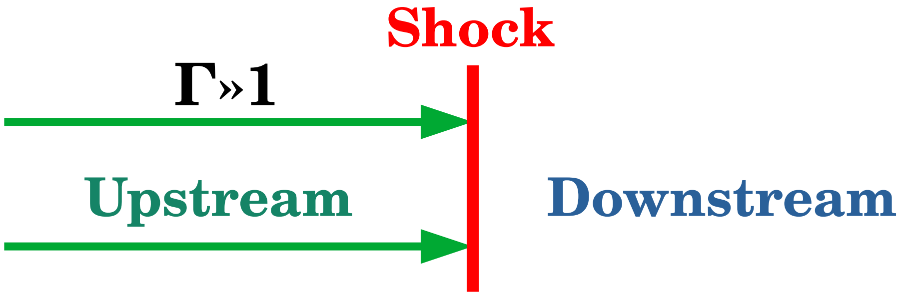
[e.g. Spitkovsky 2008 ; Sironi +2013 ; Plotnikov +2018 ; Lemoine+2019]

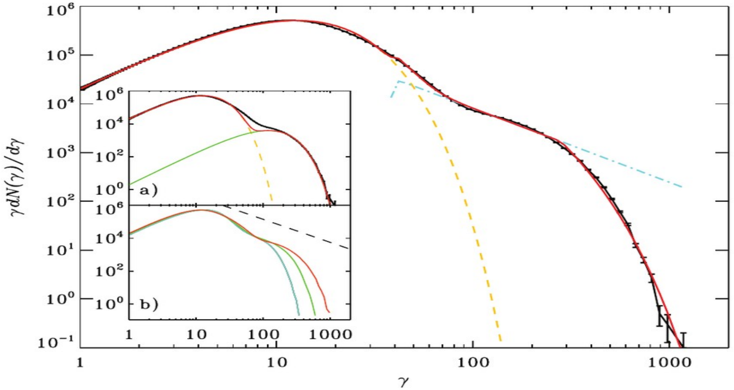
Particle trajectories
Plasma density

PIC simulation



Spitkovsky 2008



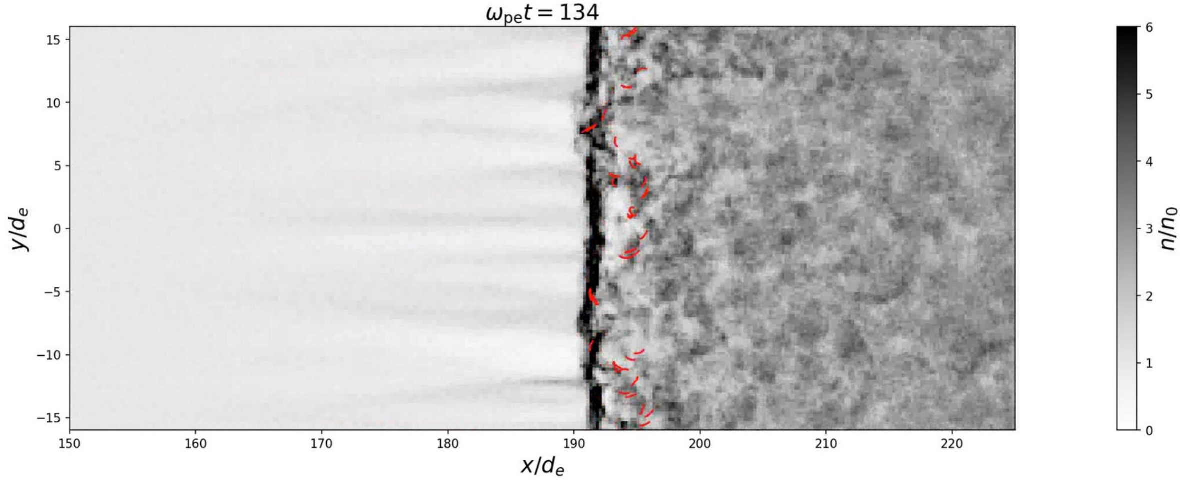


Relativistic magnetized shocks are poor accelerators

Even **modest magnetization (σ>~10^{-3})** is enough to **quench** particle acceleration.

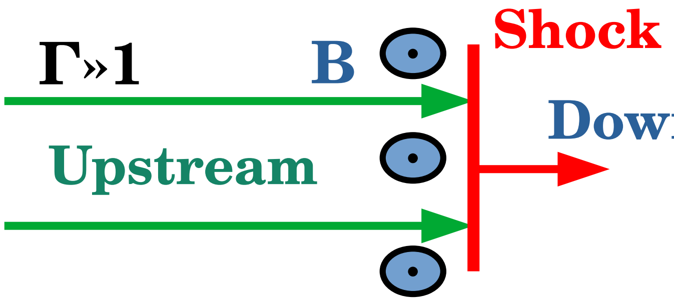
Particle trajectories
Plasma density

PIC simulation

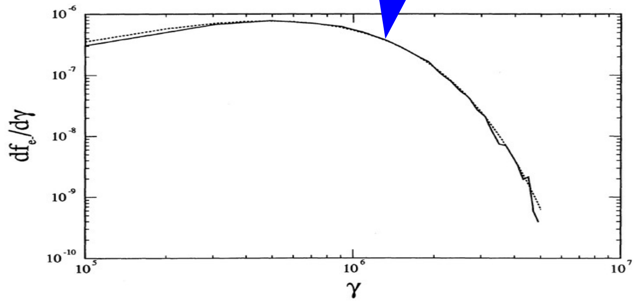


Magnetization parameter:

$$\sigma = \frac{B_0^2}{4\pi \Gamma n m c^2}$$



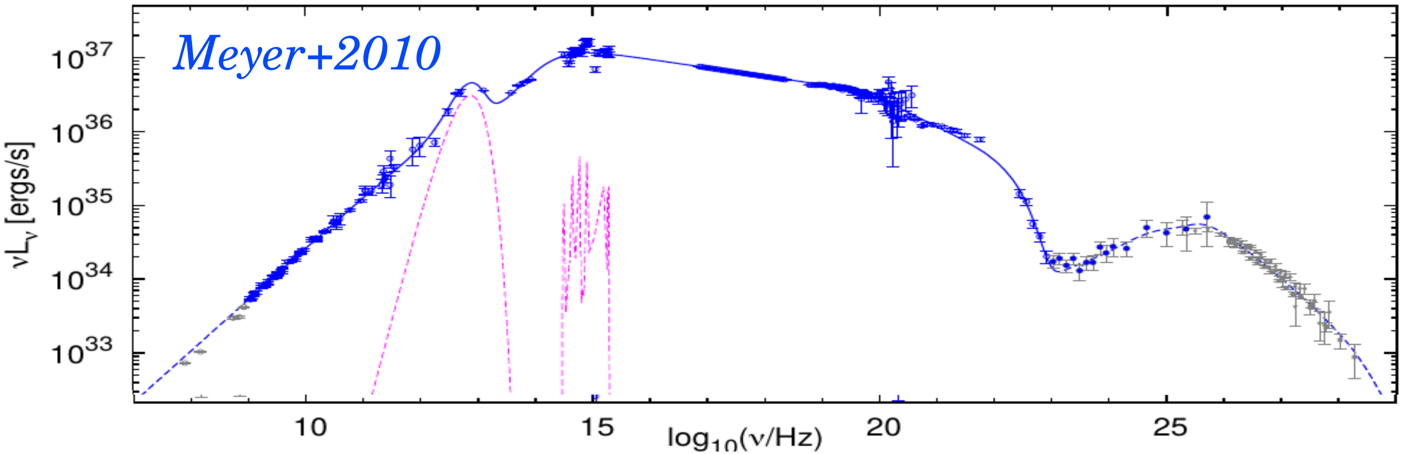
Downstream spectrum is **Maxwellian**

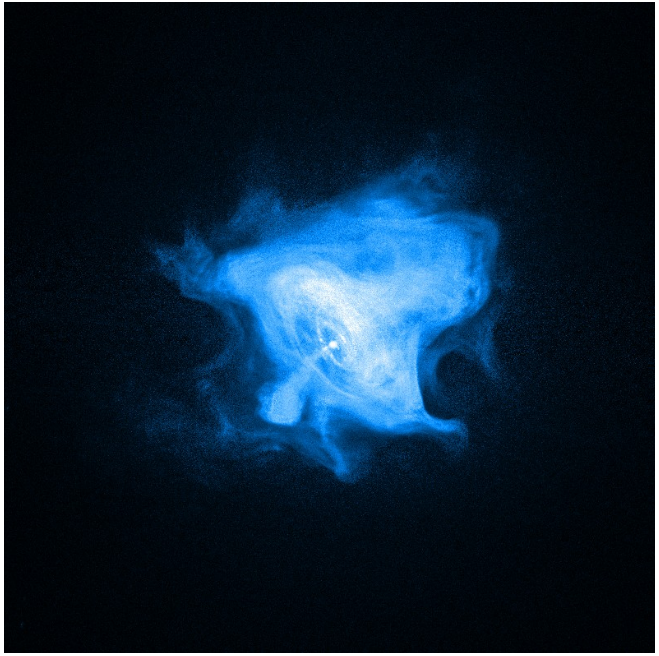


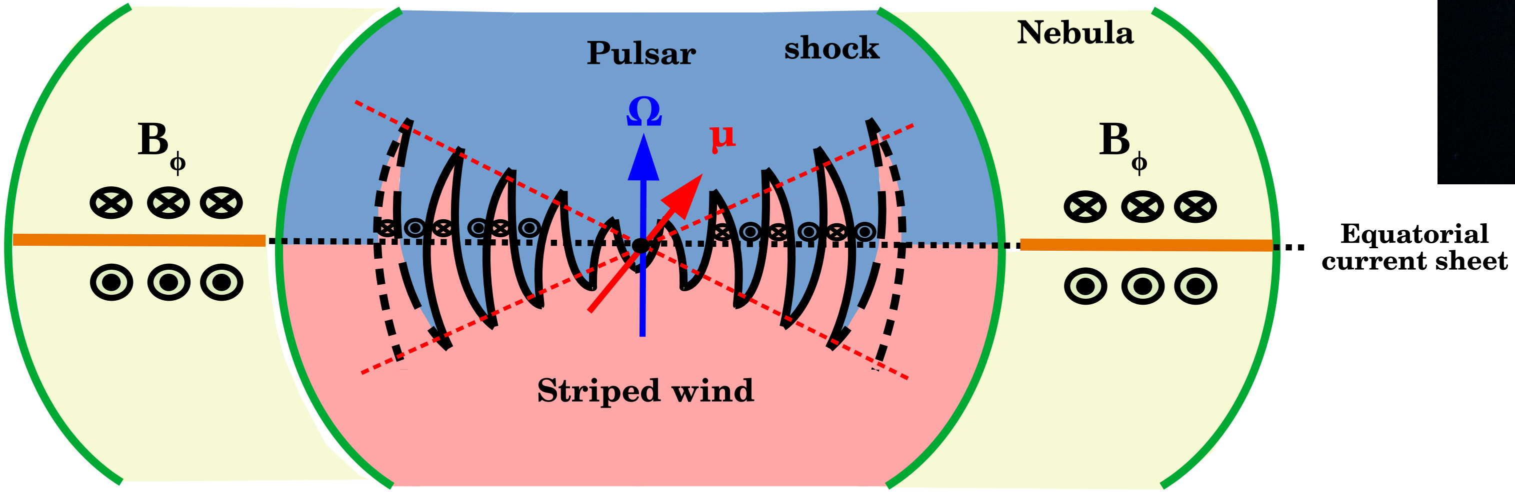
[Gallant+ 1992]

Yet, particle acceleration is efficient in PWNe

Crab Nebula : σ~>1 (*Porth+2013, 2014*) => no acceleration !

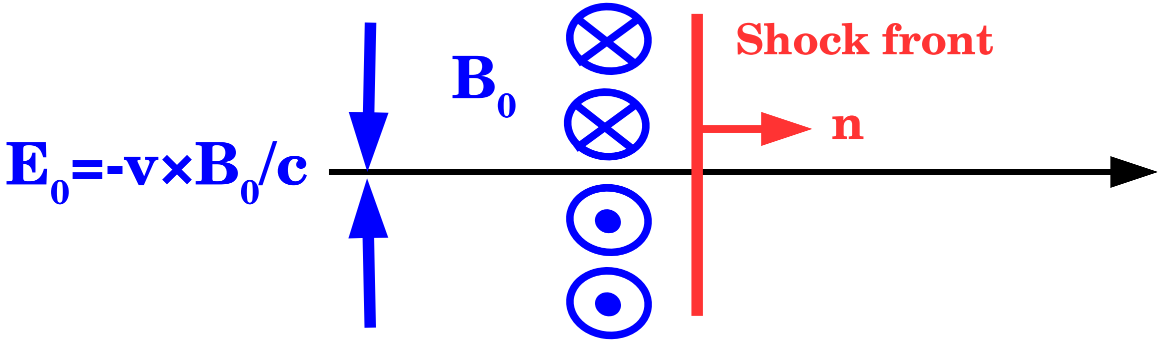


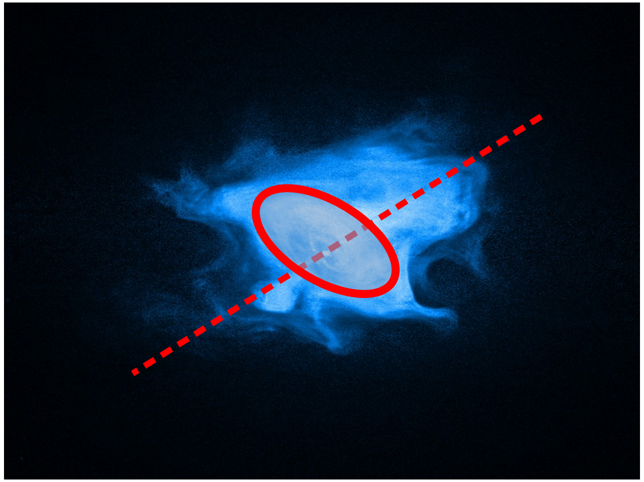


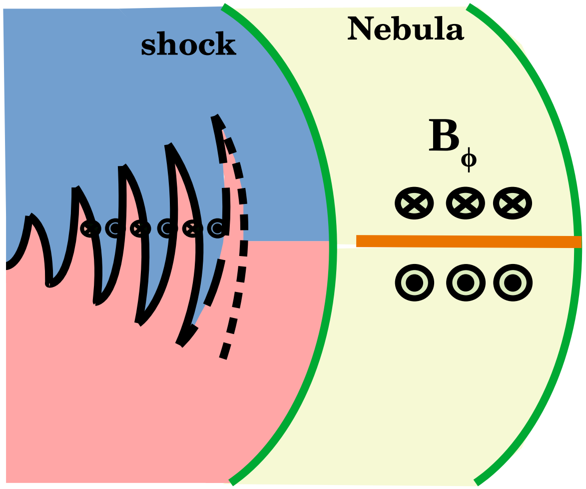


The anisotropic nature of the wind is the key !

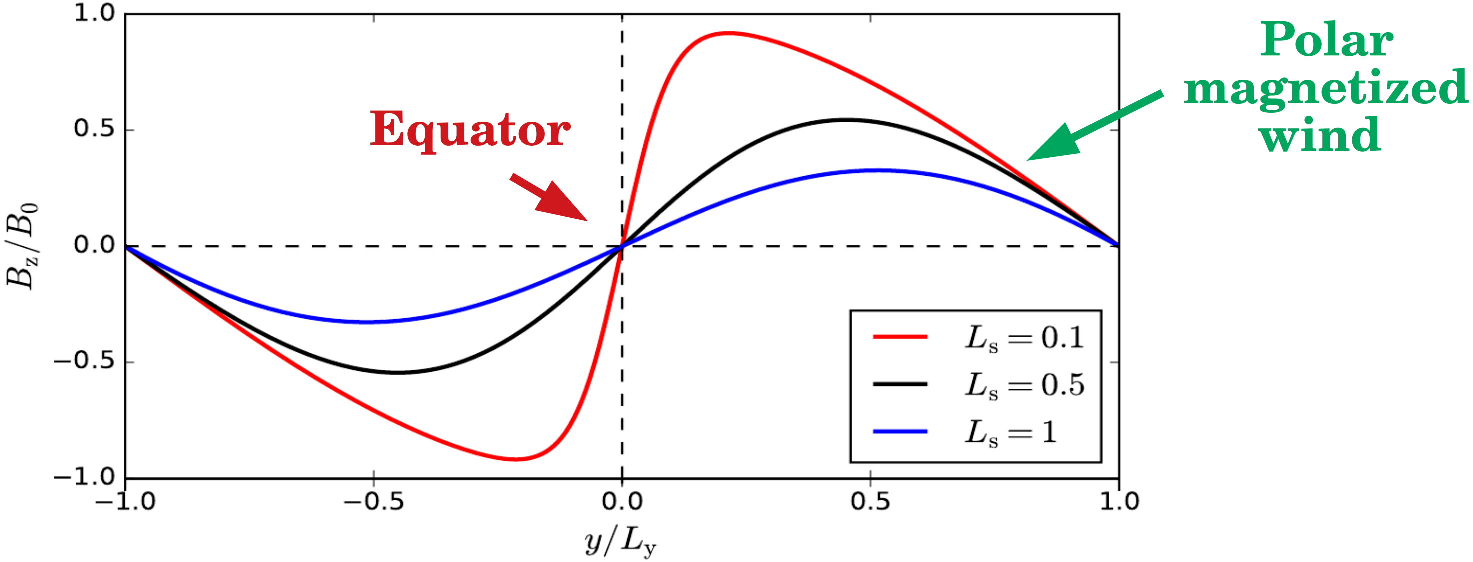
Giacinti & Kirk 2018







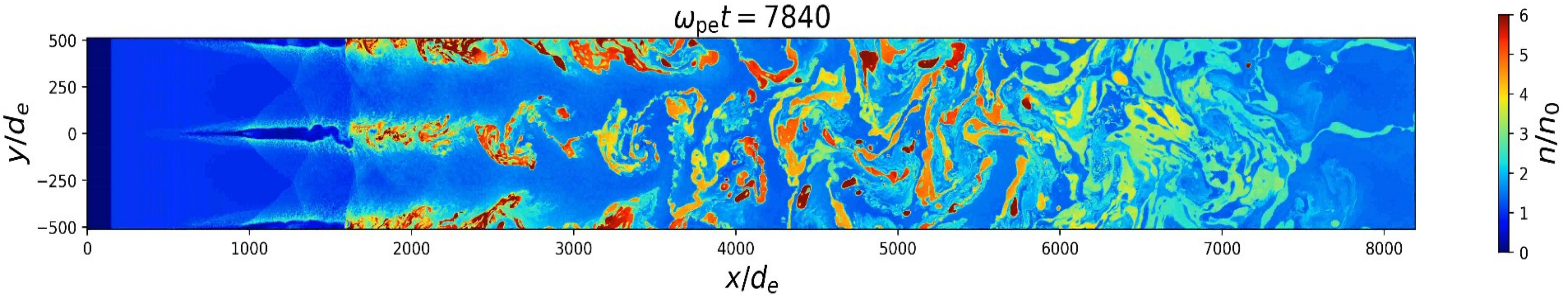
Magnetic field latitudinal profile



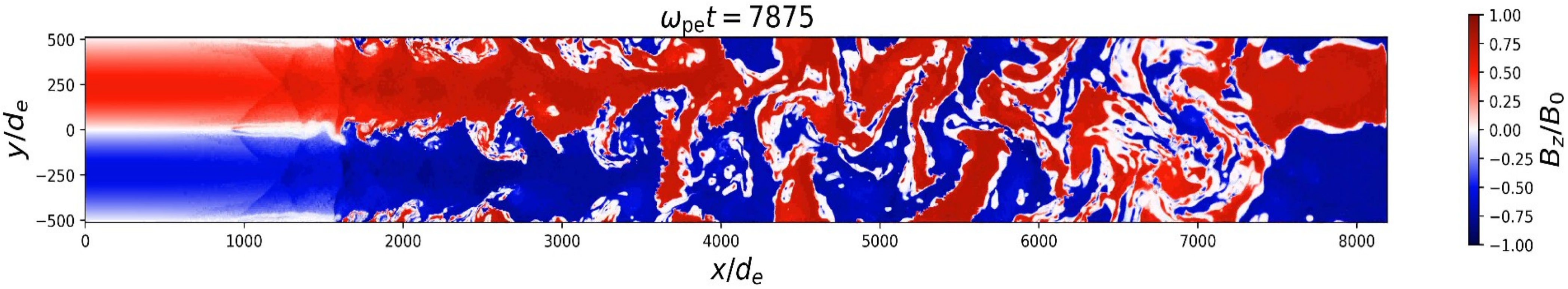
Shear-driven turbulence and reconnection

σ_0=30

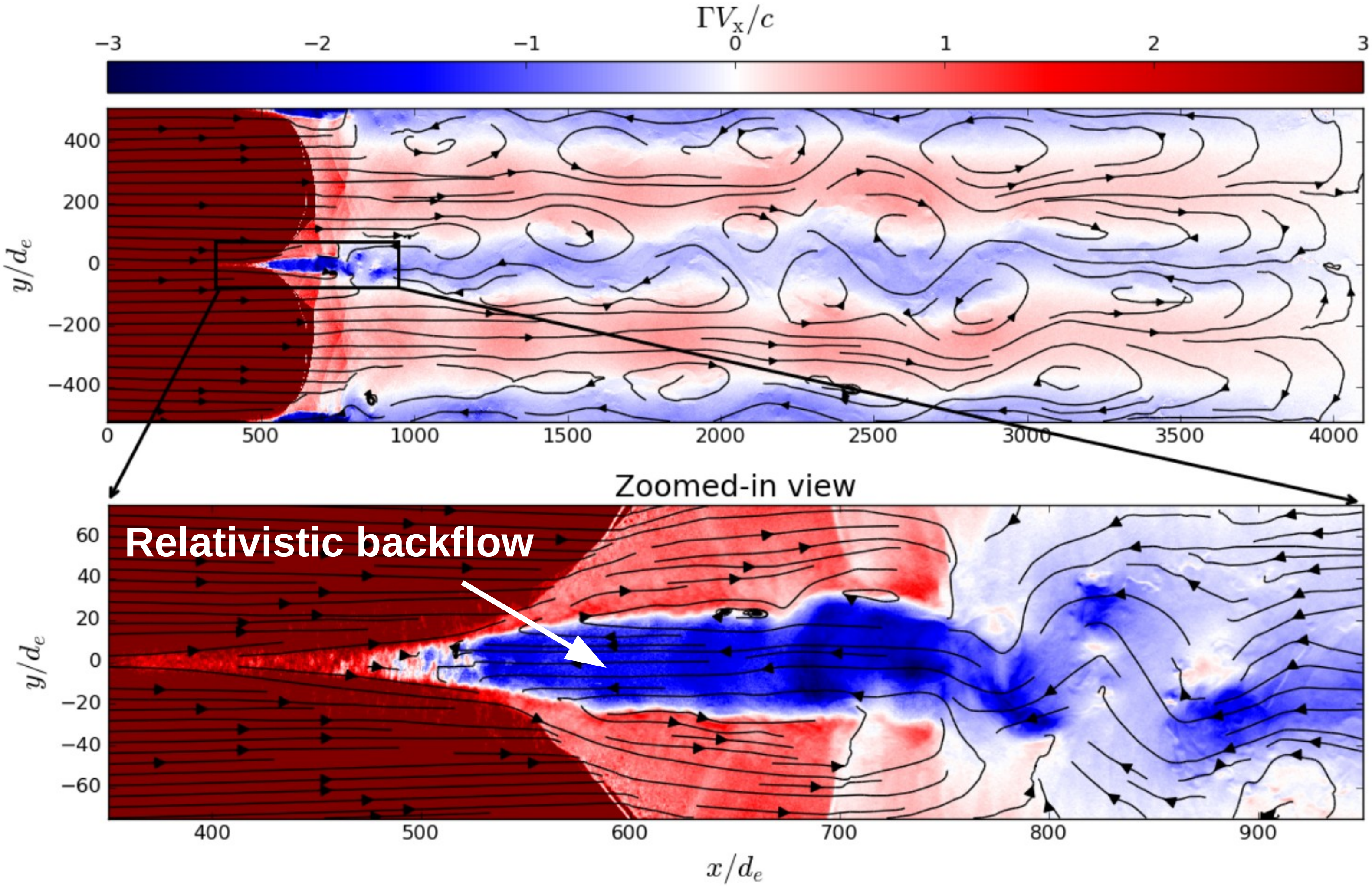
Density



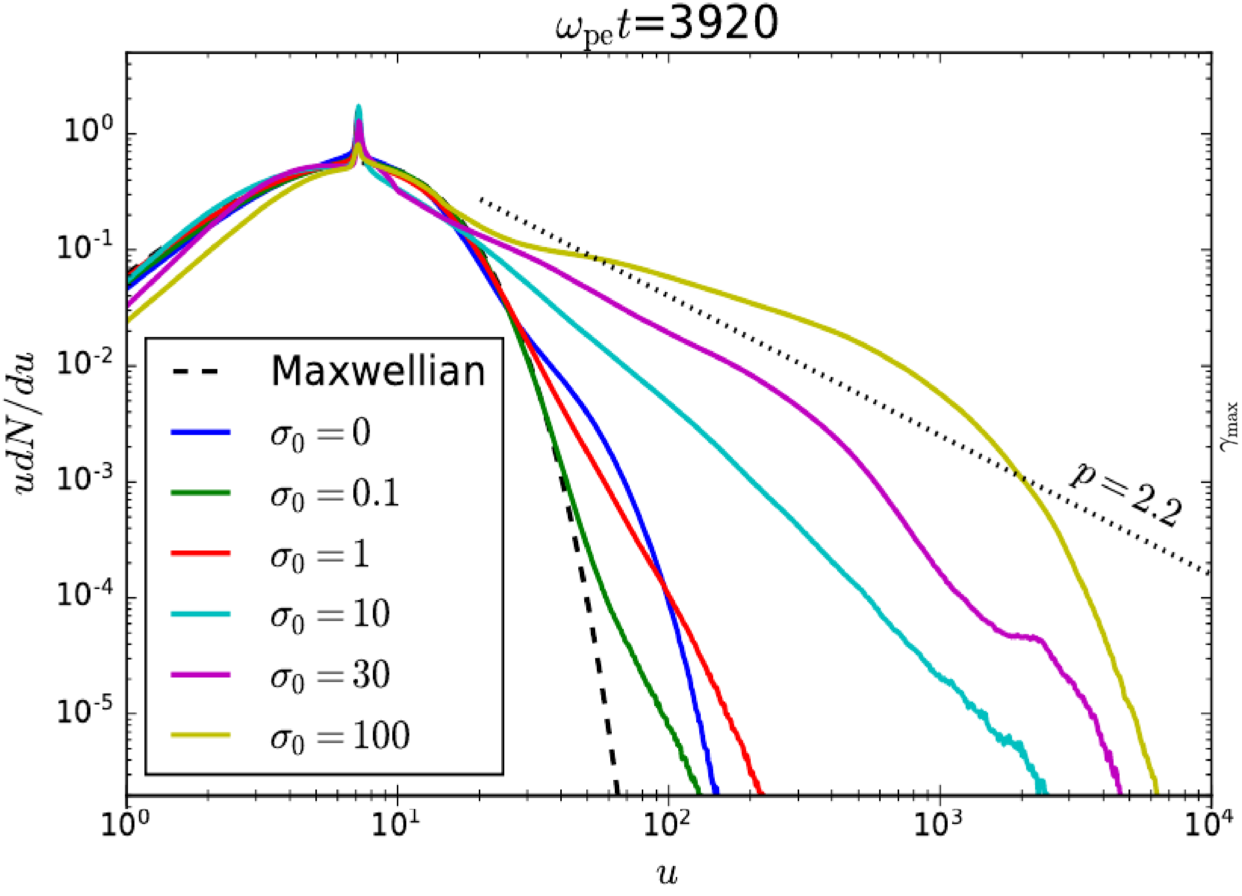
Magnetic field



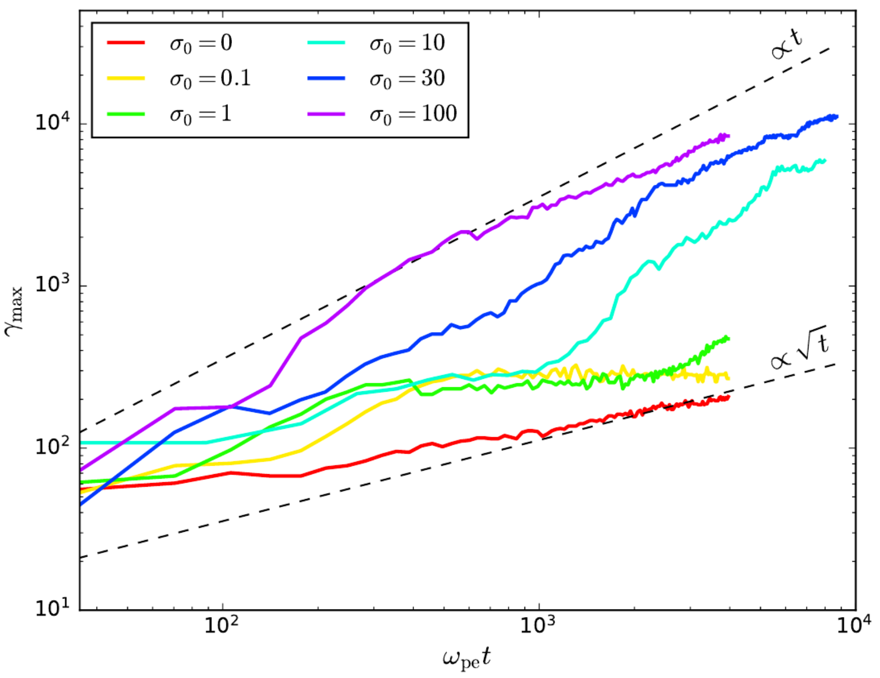
Flow pattern



Particle spectrum : acceleration near the Bohm limit



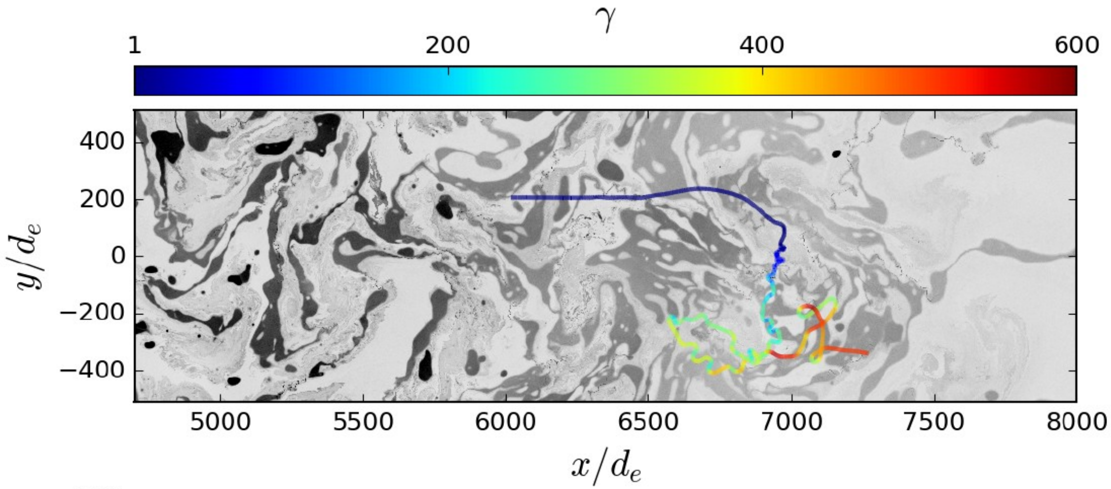
$\gamma_{max} \propto t$

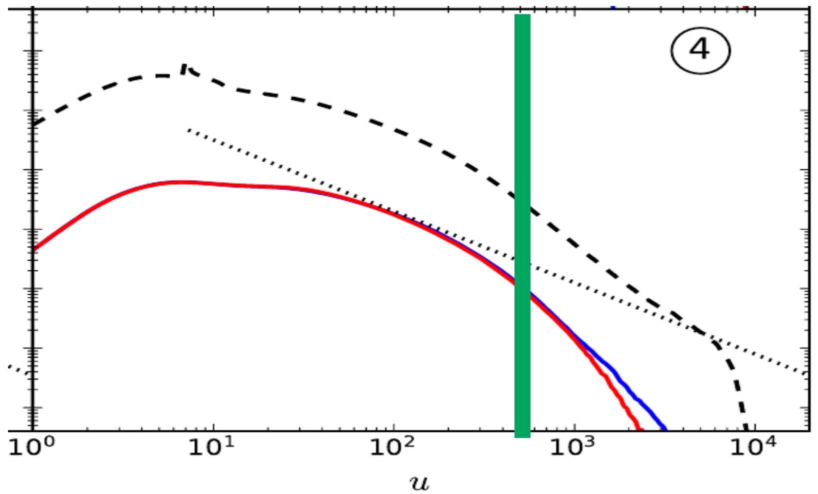


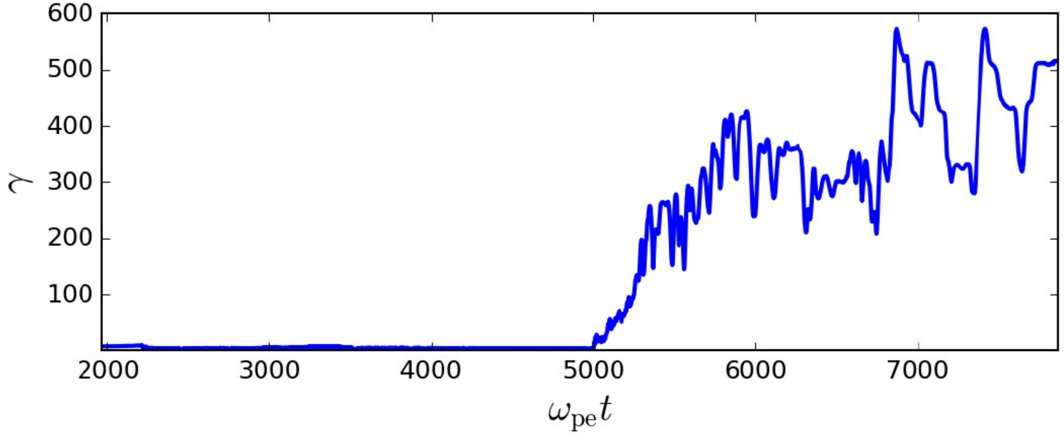
Particle acceleration : I. Reconnection & kinetic turbulence

[e.g., Cerutti+2012 ; Werner+2016 ; Sironi & Spitkovsky 2014]

[e.g., Zdhankin+2016-2020 ; Comisso & Sironi 2016]







1. Capture by the current sheet

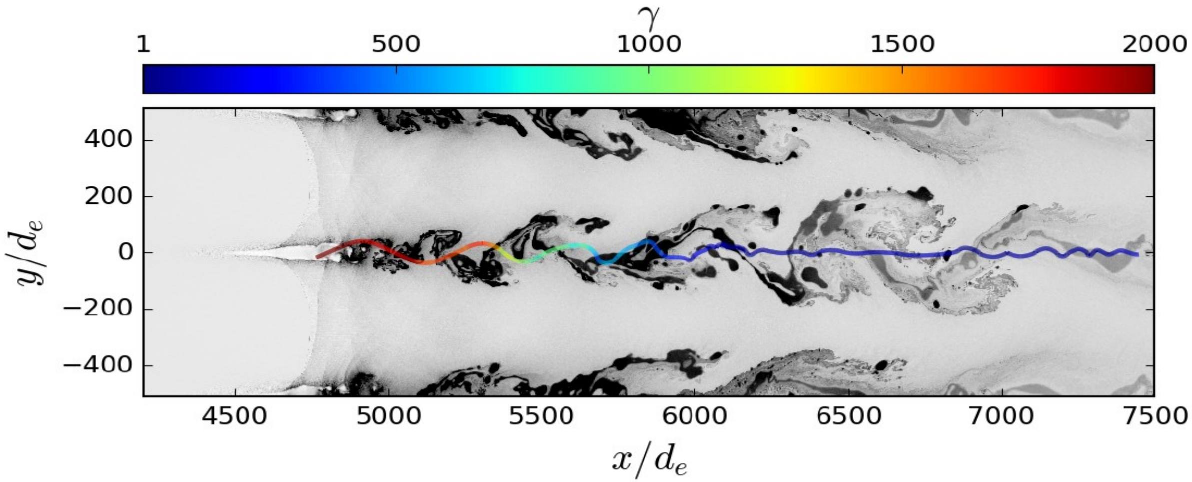
2. Impulsive acceleration via reconnection

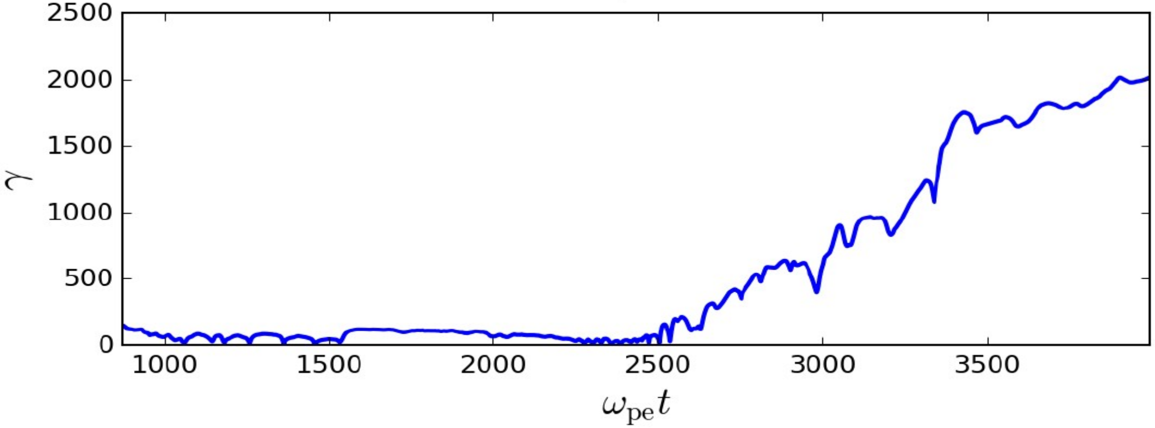
3. Stochastic acceleration in turbulent flow (Fermi Type-II acceleration)

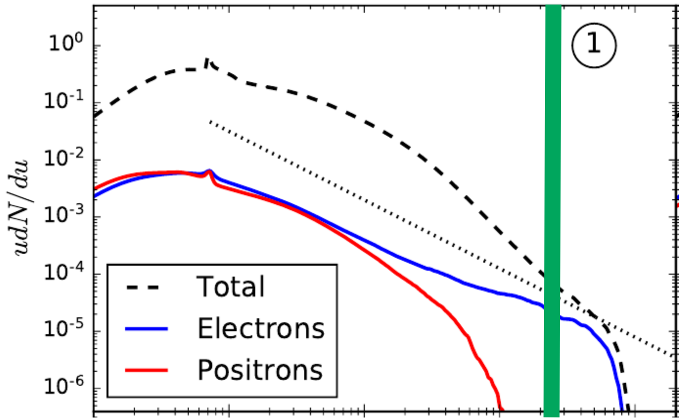
Particle acceleration : II. Macroscopic shear-flow acceleration

Particle "wake surfing"
Formation of a bubble

[e.g., Ostrowski 1990 ; Rieger & Duffy 2004 ; Sironi et al. 2021]

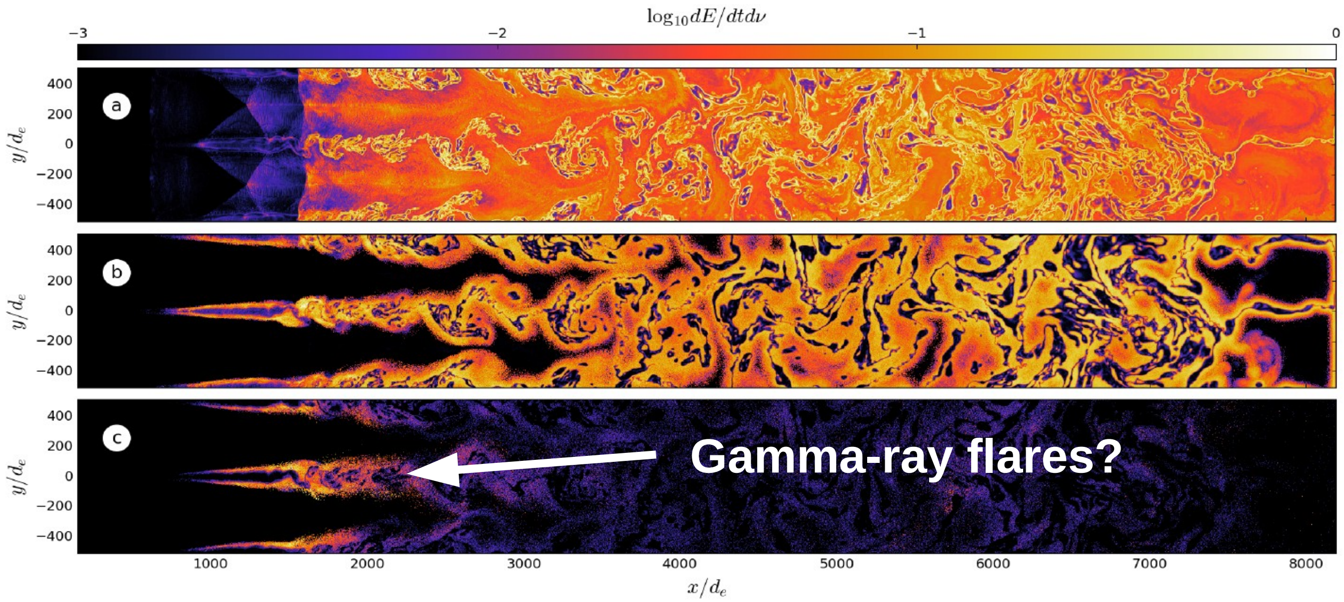






Highest energy particles

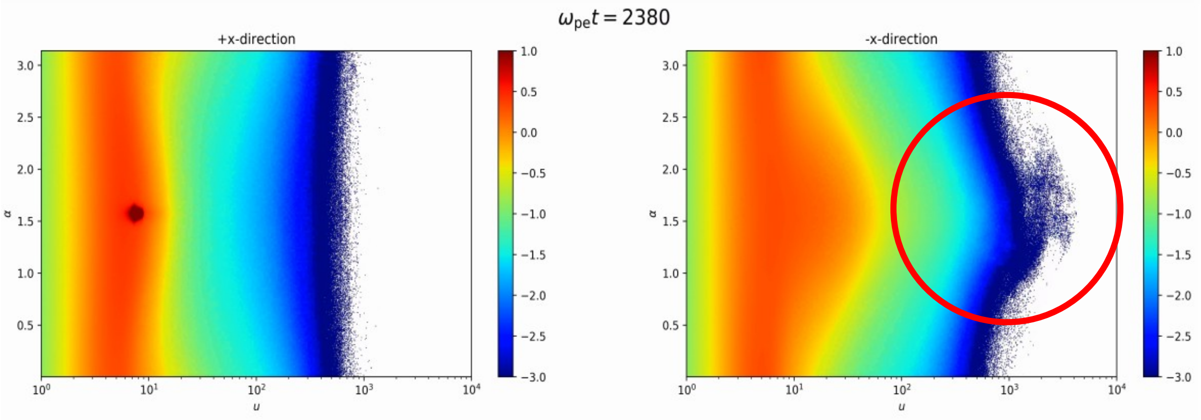
Origin of the synchrotron emission



Low-energy band

High-energy band

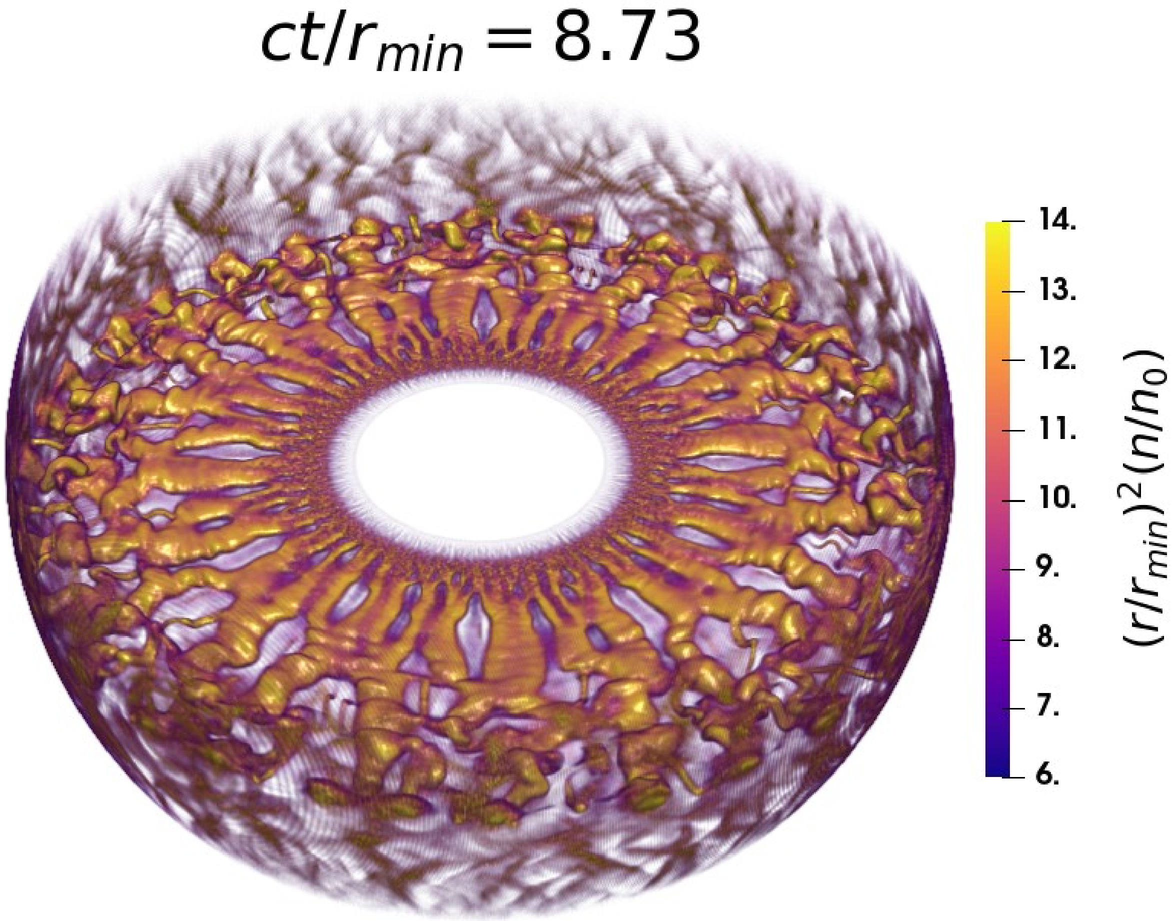
Highest-energy band

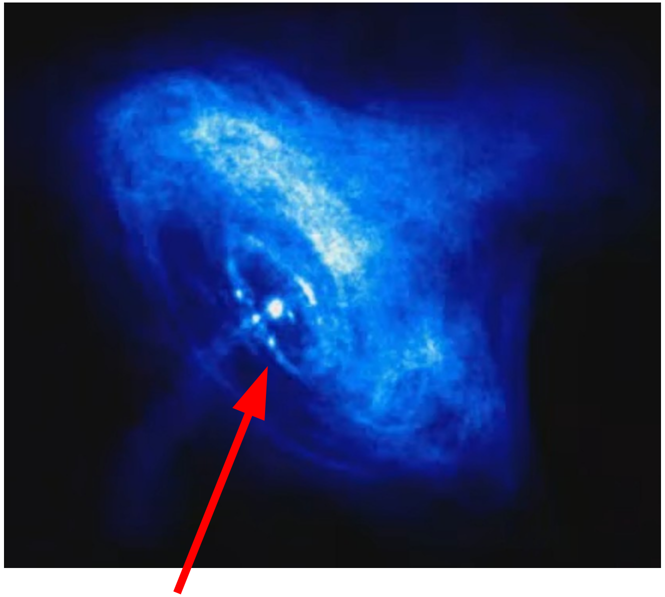


<u>Prediction :</u>

Gamma-ray flares coming from the inner ring, or base of the jet (one-sided emission)

3D spherical simulations : giant plasmoid formation





Origin of the Crab/Vela knotty inner ring ?

=> reconnection smoking gun

Conclusion & perspectives

The key is the anisotropic nature of the upstream B field !

Plasma turbulence and particle acceleration driven by currents and velocity shear (reconnection & KH-vortices).

Fast particle acceleration (near Bohm !) for magnetized shocks (σ>1)

Possible applications to gamma-ray bursts, AGN jets (lobes), galactic Pevatrons ?