Numerical simulations of particle acceleration in astrophysical plasmas

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Laboratoire Astroparticule & Cosmologie (APC)

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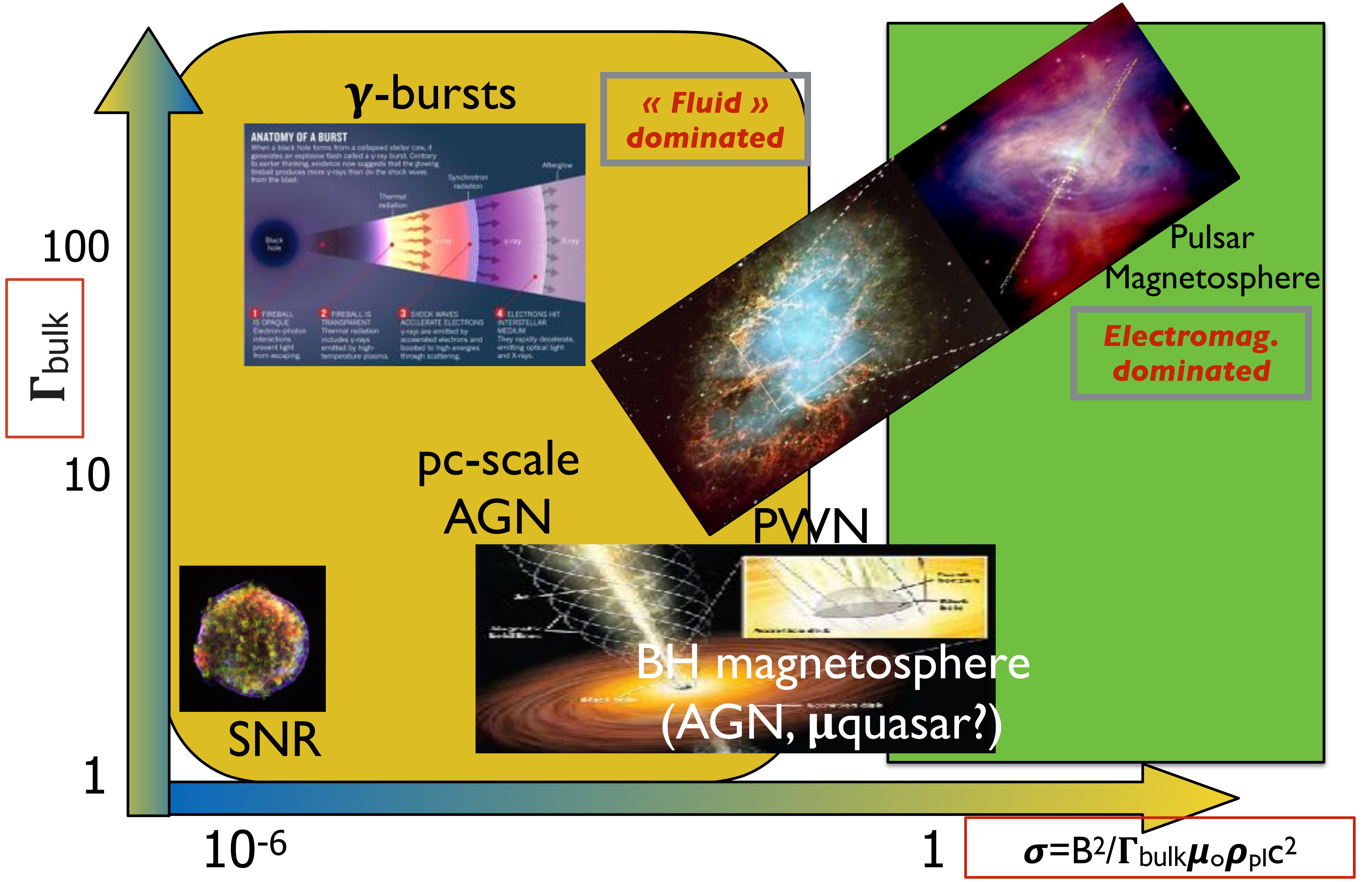
High-energy particles sources



Theoretical frameworks

- In low-σ systems, acceleration is likely to arise from the interaction between supra-thermal particles and strong shocks via the electromagnetic field.

- In high-σ systems, magnetic reconnection is also a plausible way to energize particles.

Can be derived from previous with approximation (less physics)

PIC
- Equations of motion for all particles
- Maxwell equations

All particles+EM field

Vlasov/ Fokker-Planck
- Kinetic theory

➔ Vlasov equation

➔ Maxwell eqns

Averaged thermal AND non-thermal distribution + EM field

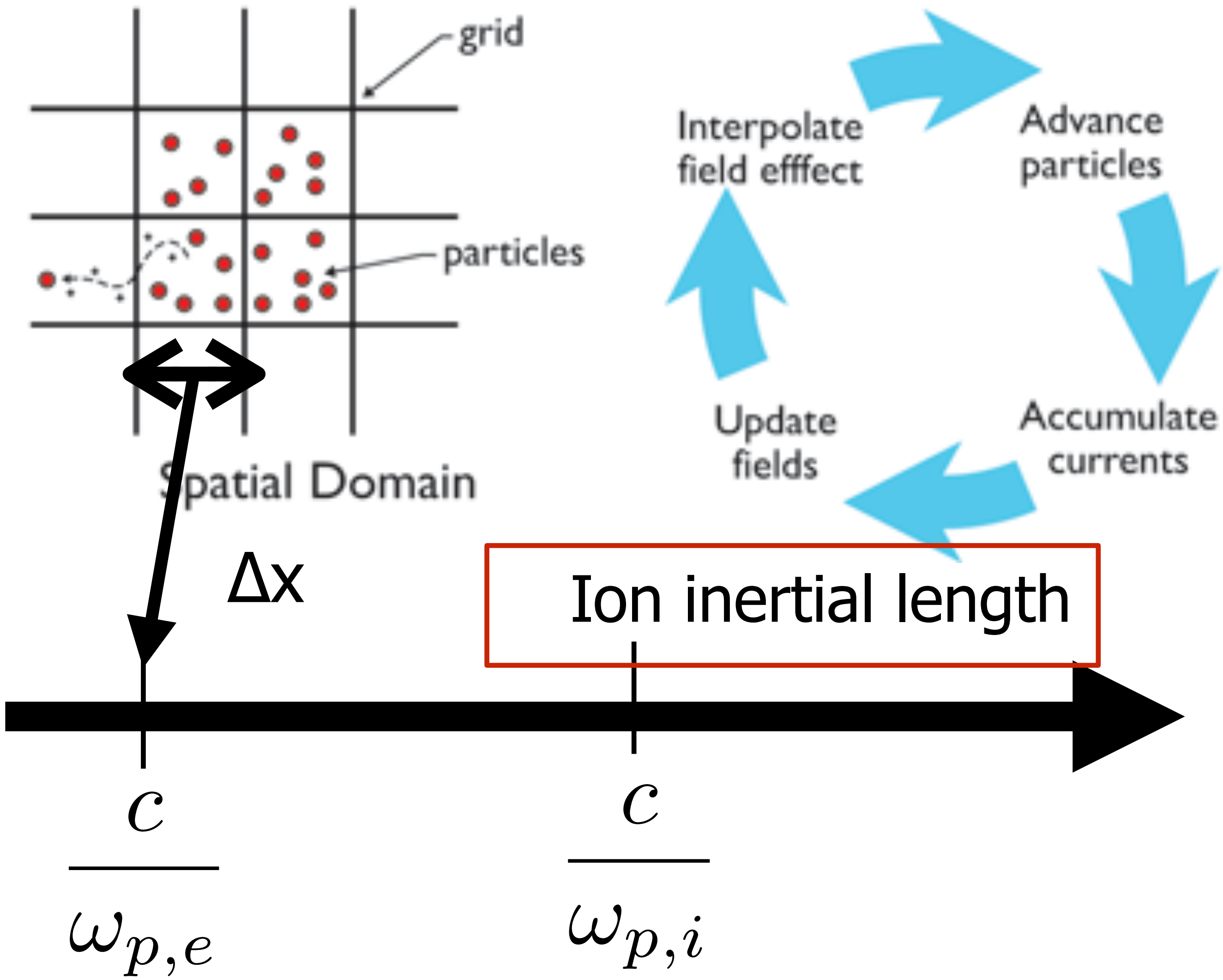
MHD
- Fluid description

➔ Multi-fluids MHD

➔ One-fluid MHD

Averaged thermal components + large-scale EM field

Basics of Particle-In-Cell simulations



- ➡ In PIC simulations, particles are moved solving motion equations of **EVERY** particles including the electromagnetic force (Boris pusher).
- ➡ EM field is time advanced at **vertices of a regular grid** solving the Maxwell equations (Yee algorithm)
- ➡ Very noisy method so handle with great care !!

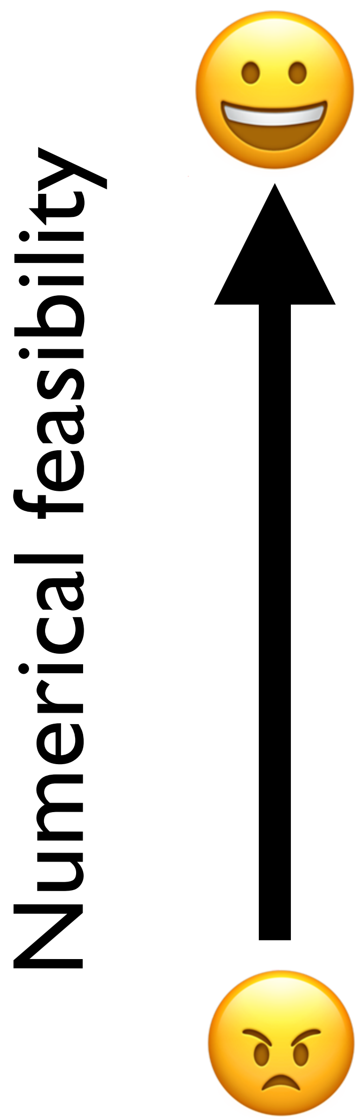
Numerical constraints

- Spatial resolution $\Delta x \sim$ Electron skin depth
- Temporal resolution imposed by CFL condition or gyro-period in high-σ plasmas.

$$\Delta t < \min\left(\frac{c}{v_{\rm part}\omega_{p,e}}, \frac{1}{4\omega_{L,e}}\right)$$

Particle acceleration: PIC applications

- Particle-In-Cells (PIC) approach is the most accurate numerical description of the interaction between particles (thermal and non-thermal) and EM field
- State of the art PIC simulations: $<10^{11}$ particles and 3000^3 cells (~ x10 TBytes data and running time ~few months on 10,000 cores).



➡ Pair plasmas (ultra and mildly relativistic)

- Mass ratio = 1 and all particles have similar velocities
- **OK** for any magnetization

➡ Relativistic electron/ion plasmas

velocity of electrons ~ velocity of ions

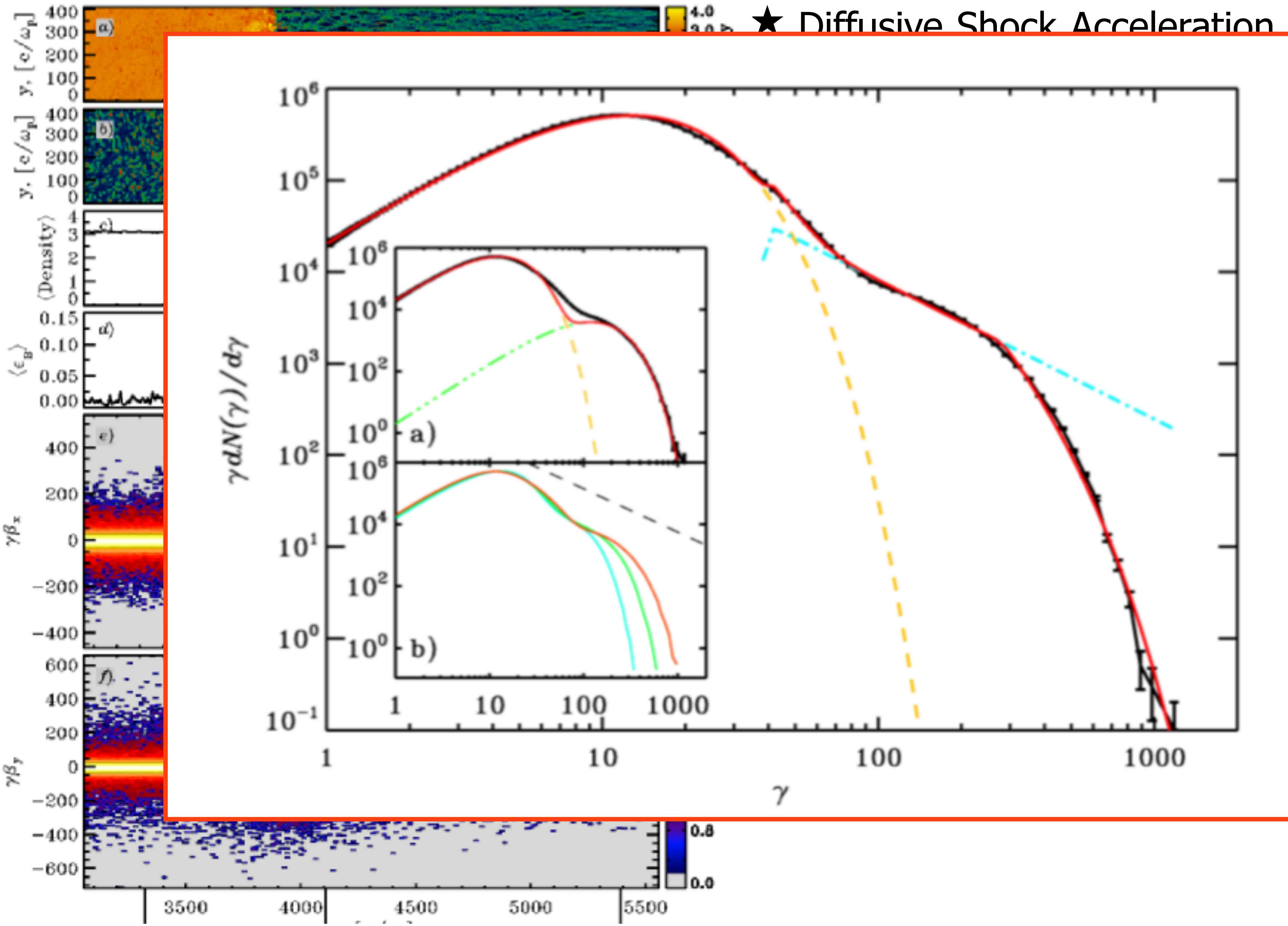
- **OK** for any magnetization

➡ Non relativistic electron/ion plasmas are often very low-σ and thermal velocity of electrons >> thermal velocity of ions

PIC simulations of relativistic shocks

- **Pair plasma shocks**
- Electron/ion shocks

DSA in unmagnetized pair plasma



★ Diffusive Shock Acceleration (DSA) has
…vistic pair
…Spitkovsky

…sma with

…slamming
…wall.

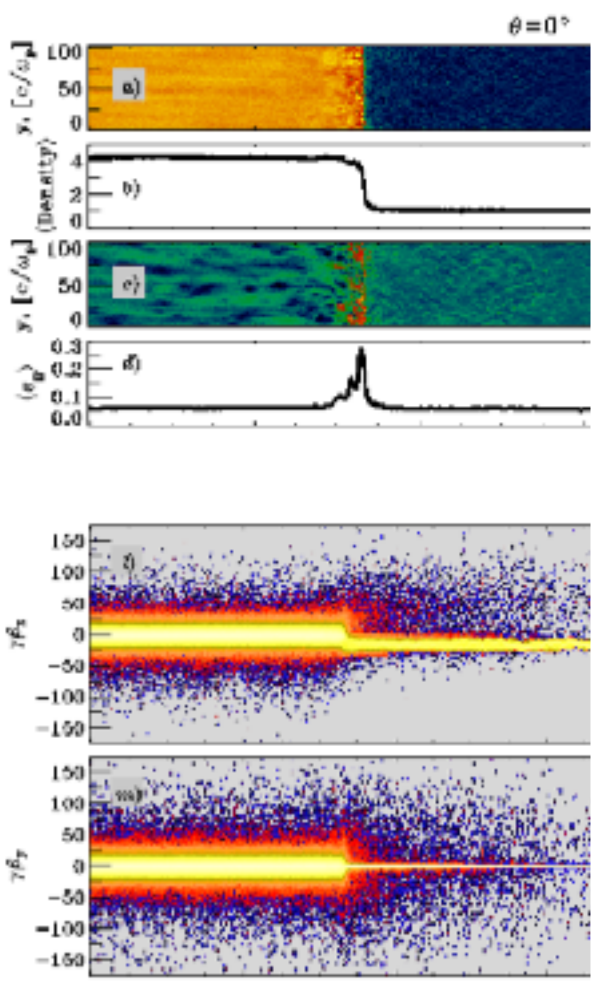
…ed thanks
…enerating

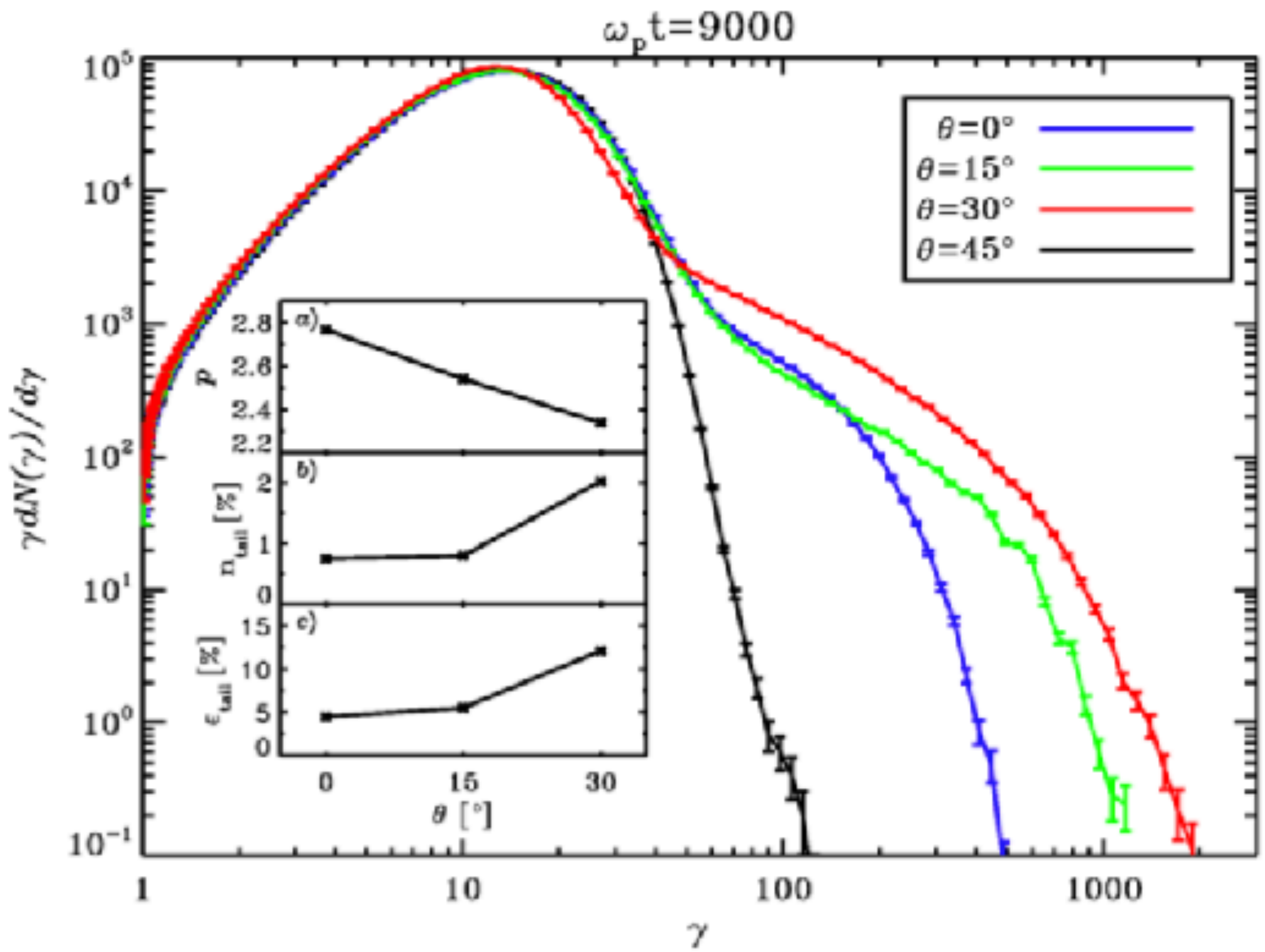
…al power
…?

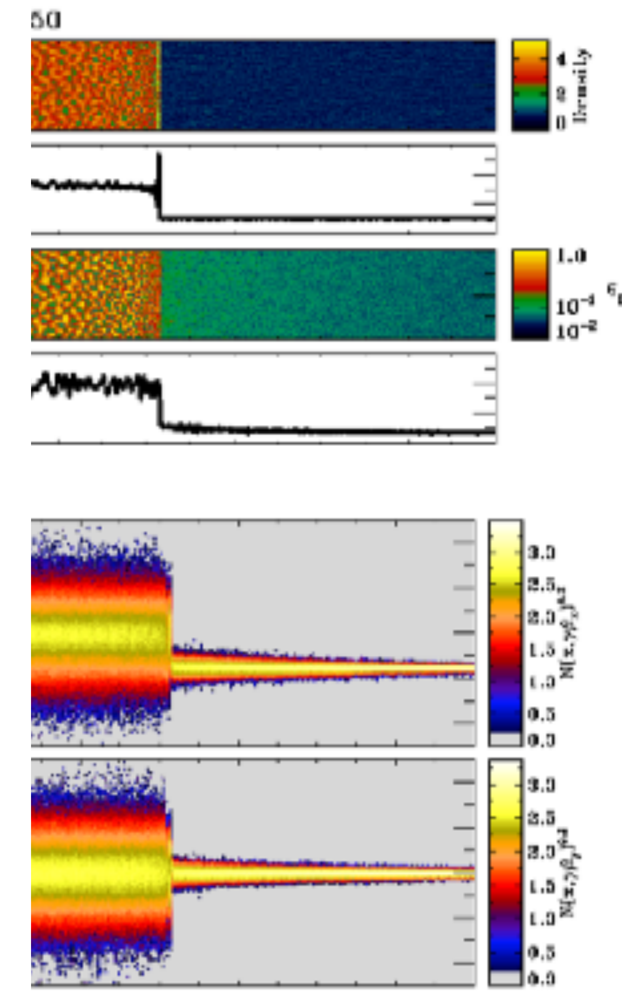
DSA-SDA & magnetic obliquity in pair plasmas

★ In highly magnetized pair plasma shock (**σ**=0.1), only subluminal shocks are efficient particle accelerator

Sironi & Spitkovsky (2009)





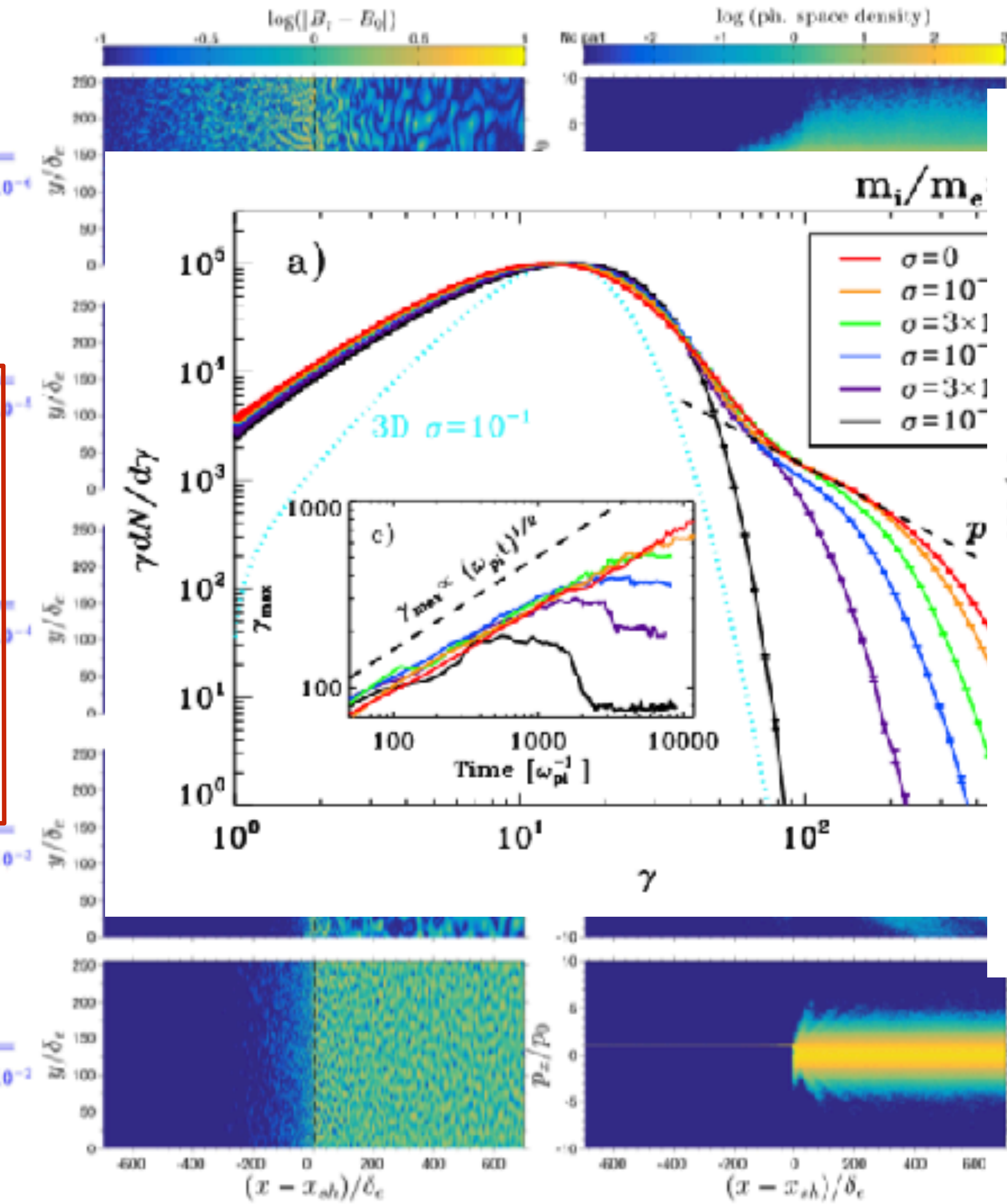


Subluminal shock

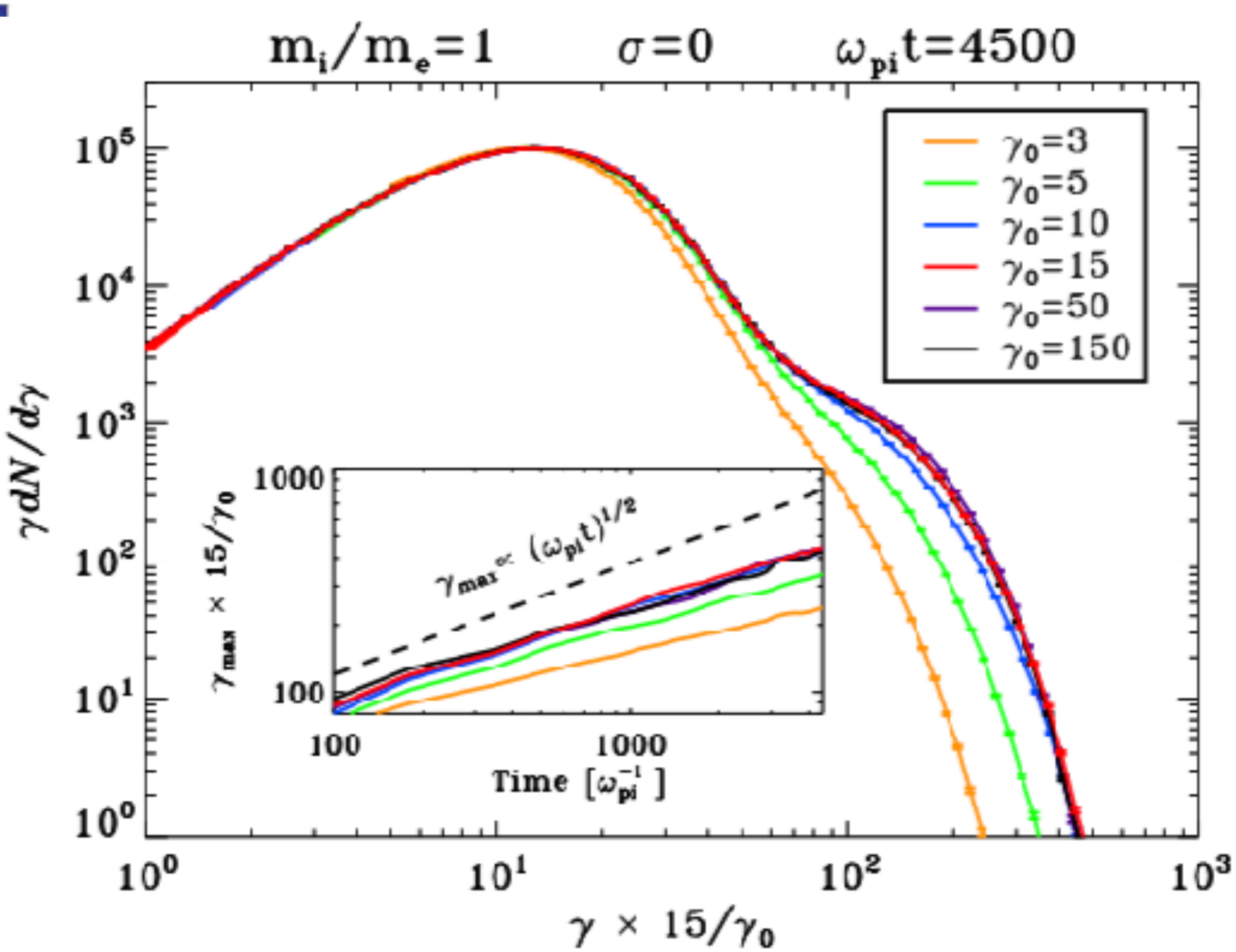
Superluminal shock

DSA-SDA & shock magnetization

★ Low-**σ** perpendicular pair shocks (**σ**<10^{-3}) are efficient particle accelerator



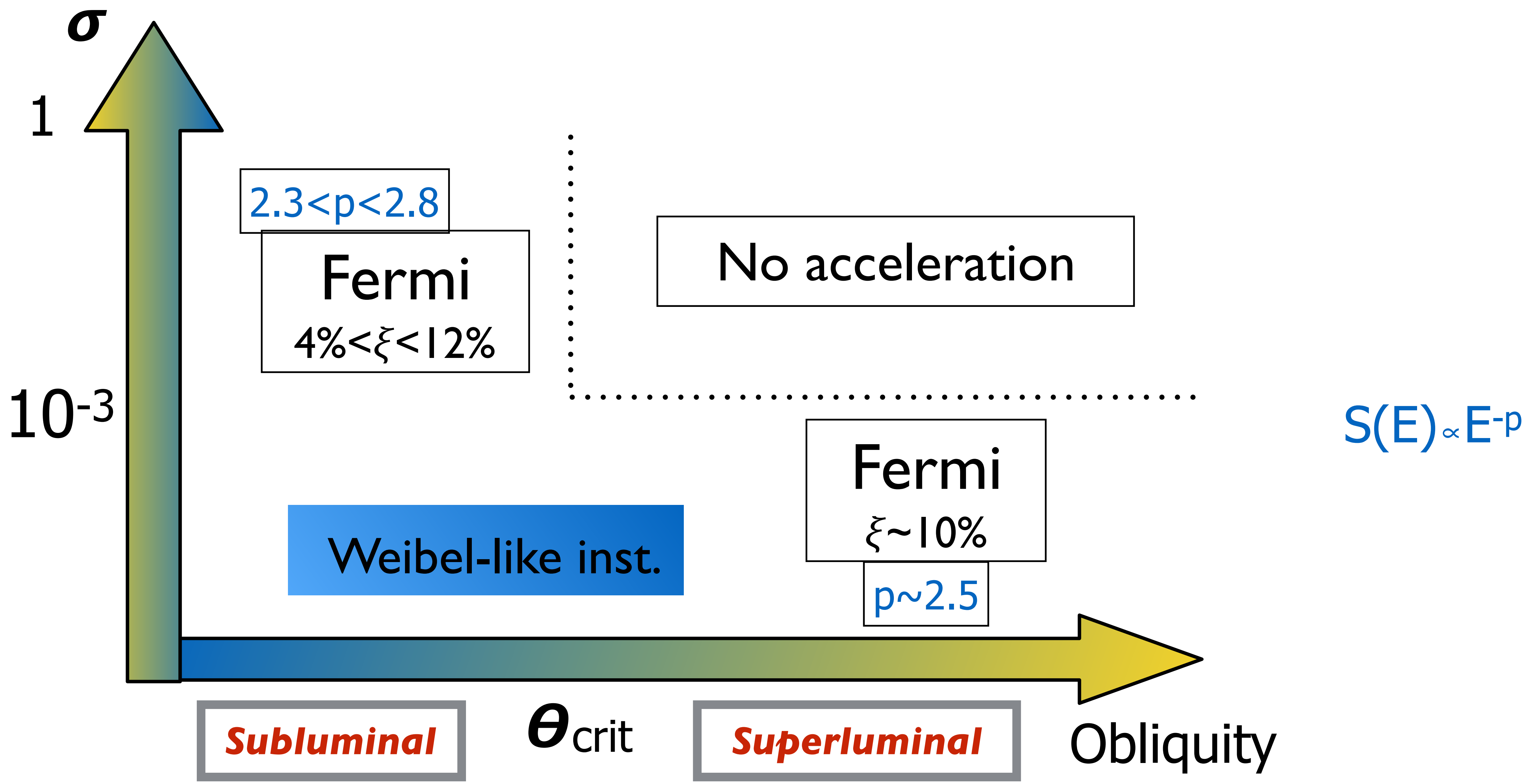
Plotnikov et al (2018)



Sironi et al (2013)

Acceleration at pair shocks

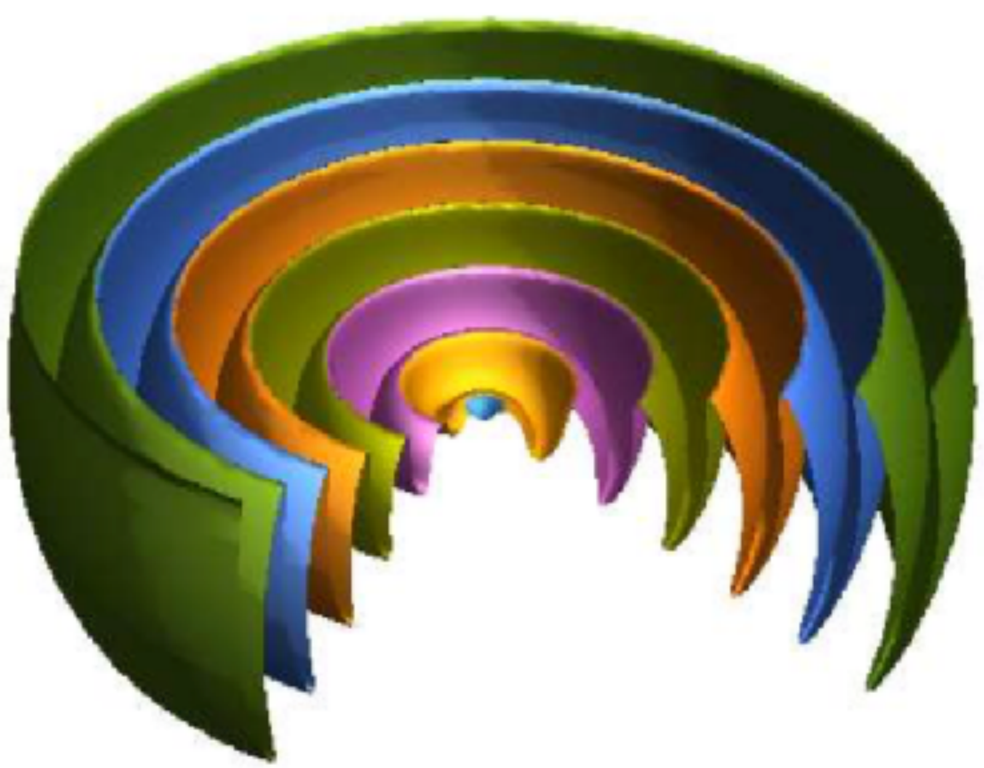
- Relativistic shocks are likely to be superluminal.
- Some of them are likely to be high-σ shocks (PWN, AGN Jets, …)
- Magnetic reconnection may contribute to particle acceleration.



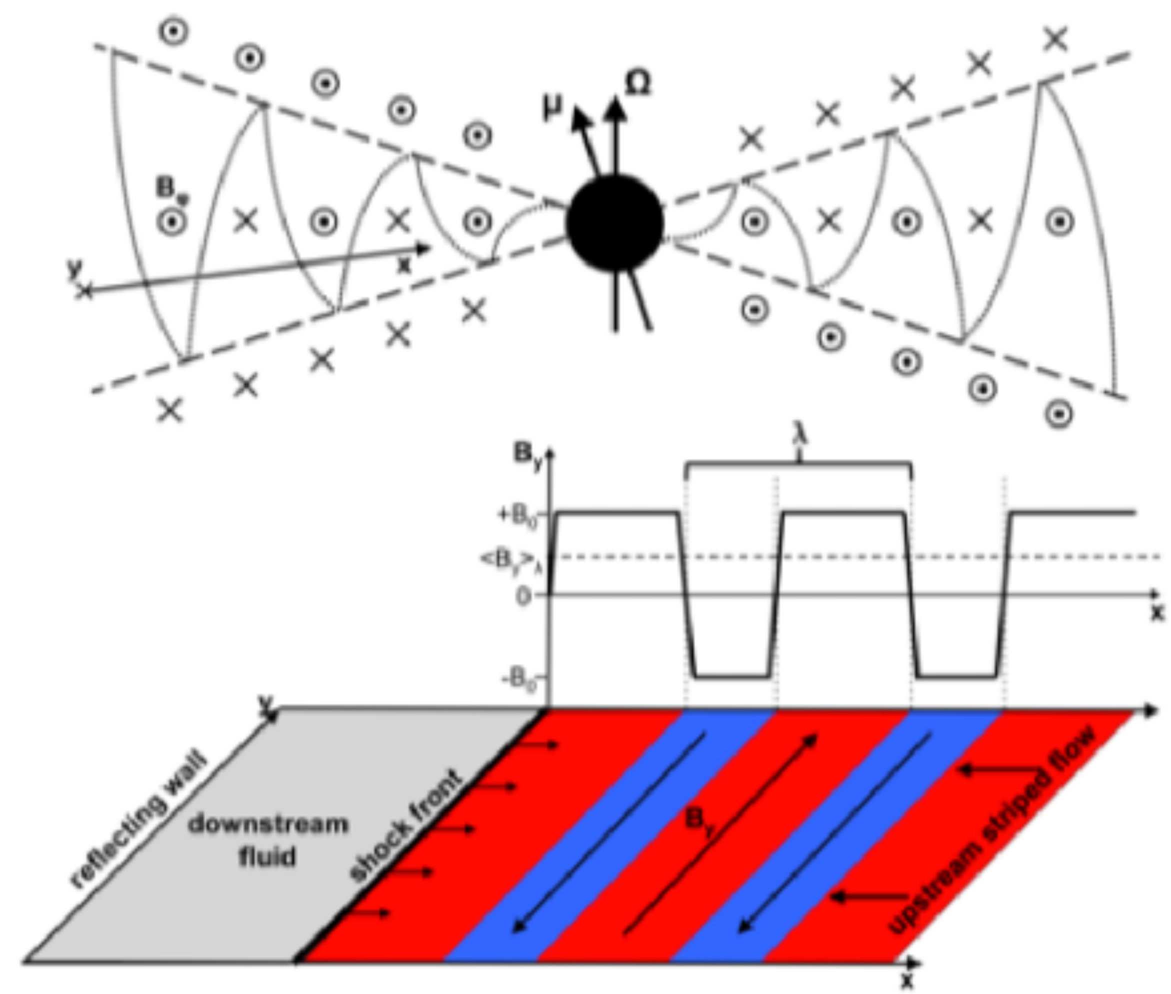
Pulsar Wind Nebulae

➡ Striped Wind model provides a description of PWNe (Lyubarsrsky & Kirk 2001, Petri & Kirk 2005, Petri & Lyubarsky 2007, …)

➡ RMHD simulations provides the overall magnetic structure of the outflow (Mixed MPI code RMHD finite volume & spectral)



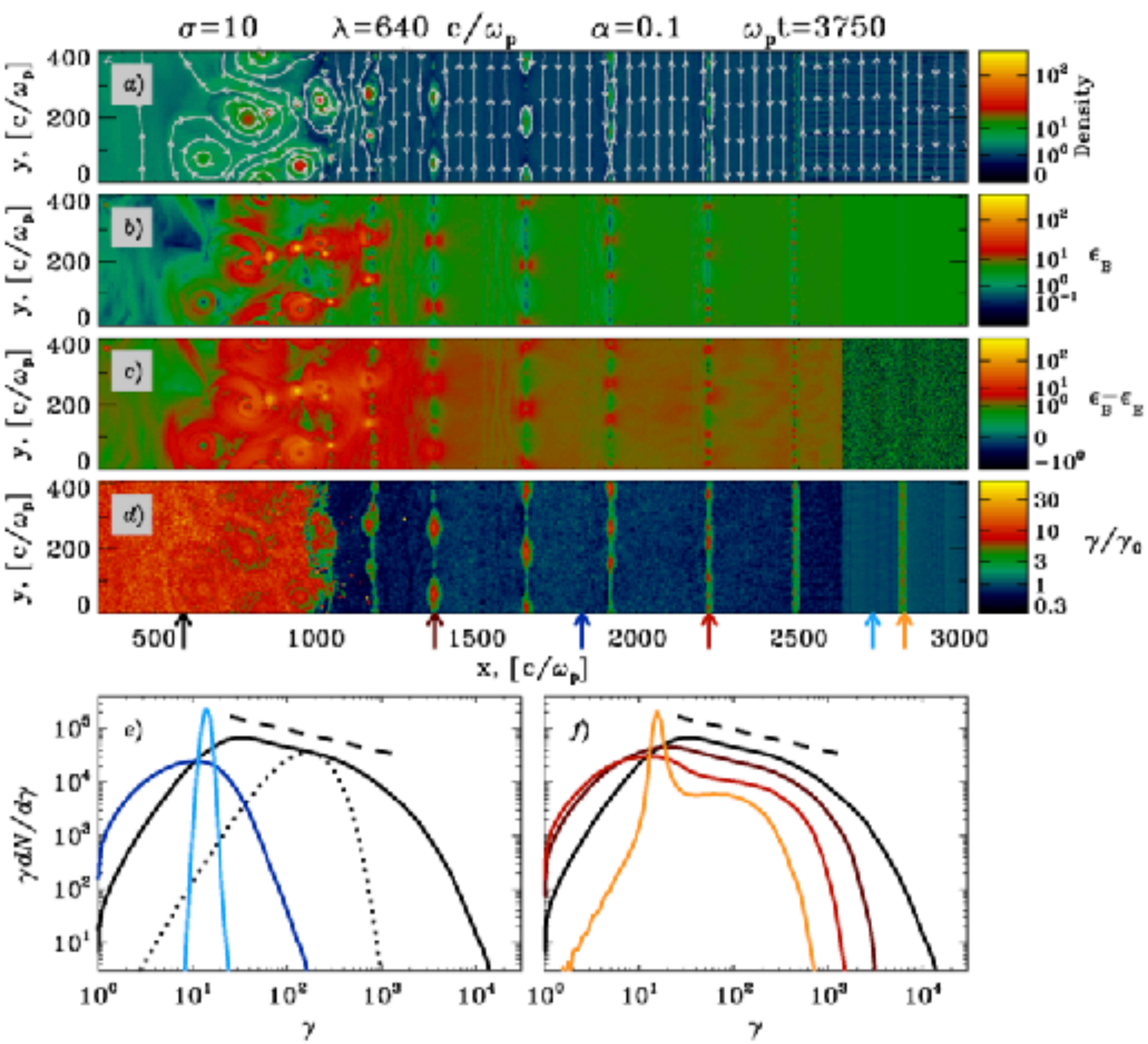
Pétri (2012)

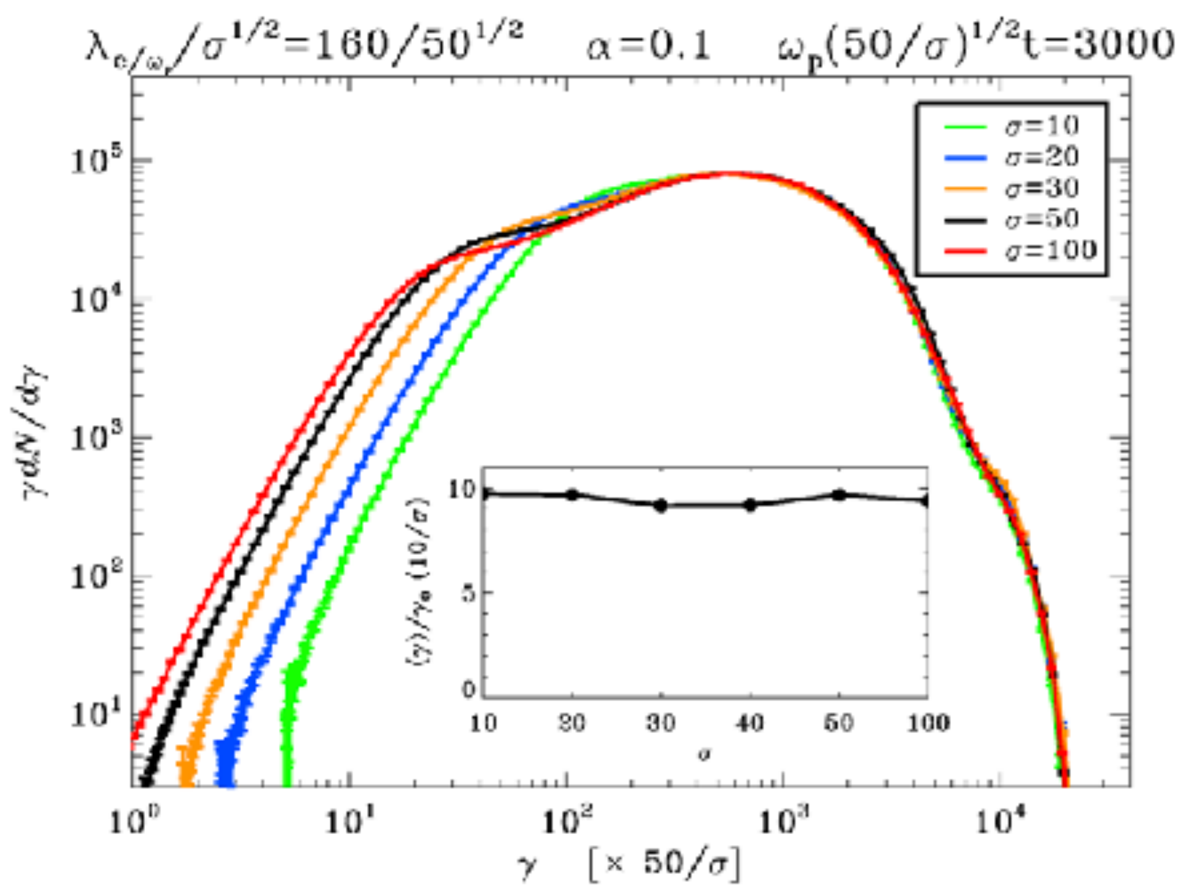


Magnetic reconnection in a striped wind

➡ Magnetic reconnection in a pair plasma has been adressed in the context of the striped wind near the terminal shock.

➡ Hard particle spectrum is obtained (p~1.5) and max energy depends on magnetization.



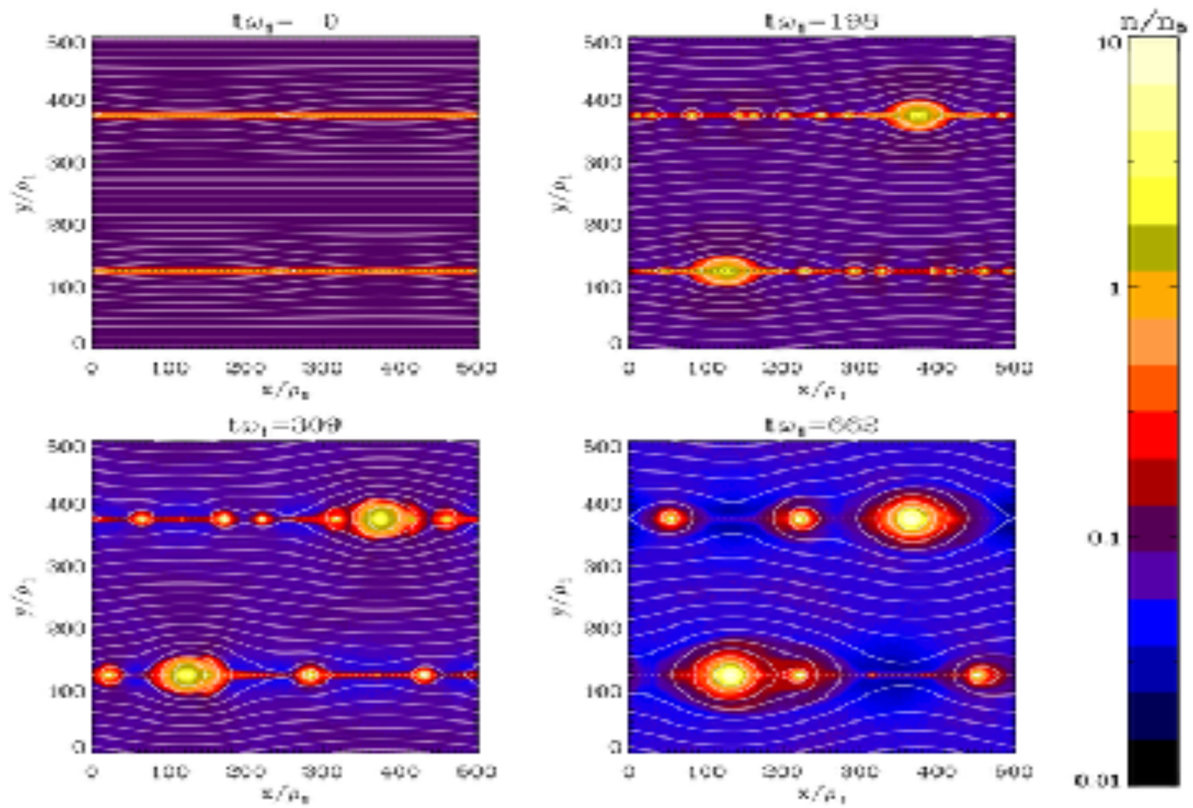


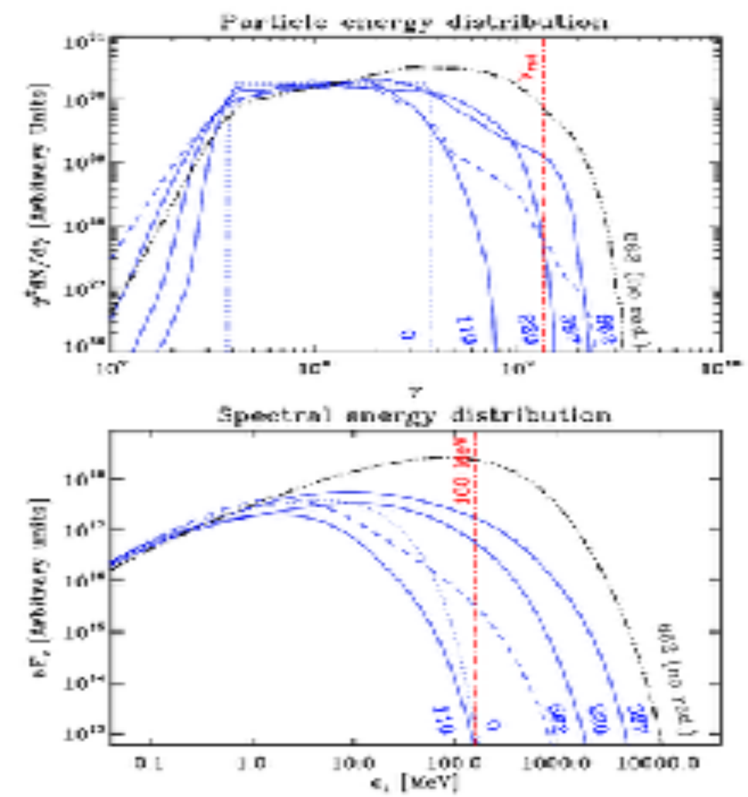
Sironi & Spitkovsky (2012)

Magnetic reconnection in relativistic plasmas

- ➡ **γ**-ray flares in PWNe require p<2 spectrum !
- ➡ Magnetic reconnection is also studied in electron/ion relativistic plasmas

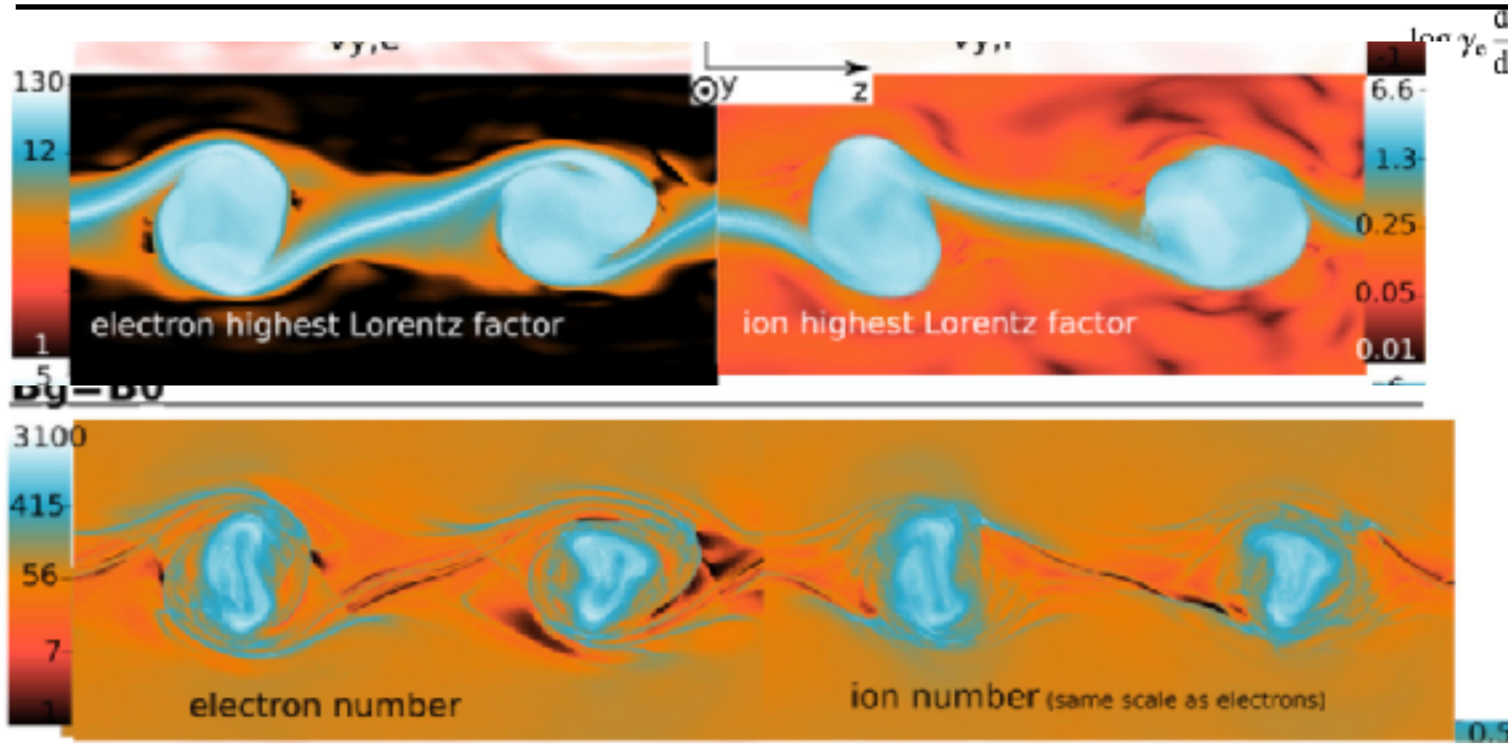
Pair plasma e+-e-

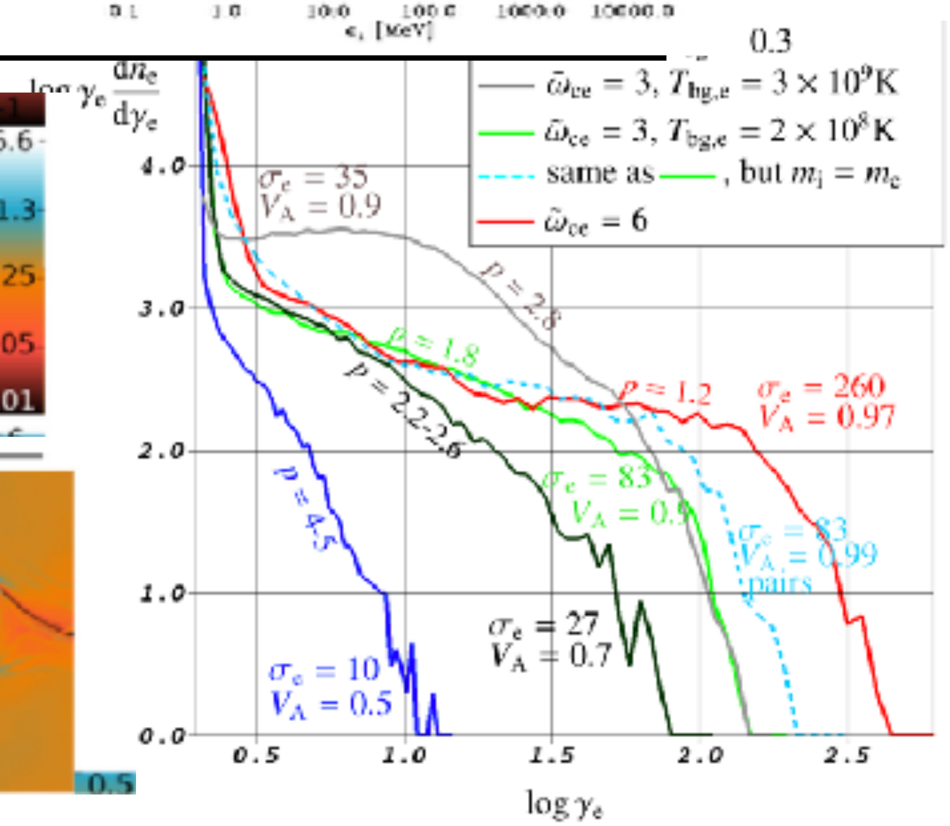




Cerutti et al. (2013,14)

Ion-electron plasma



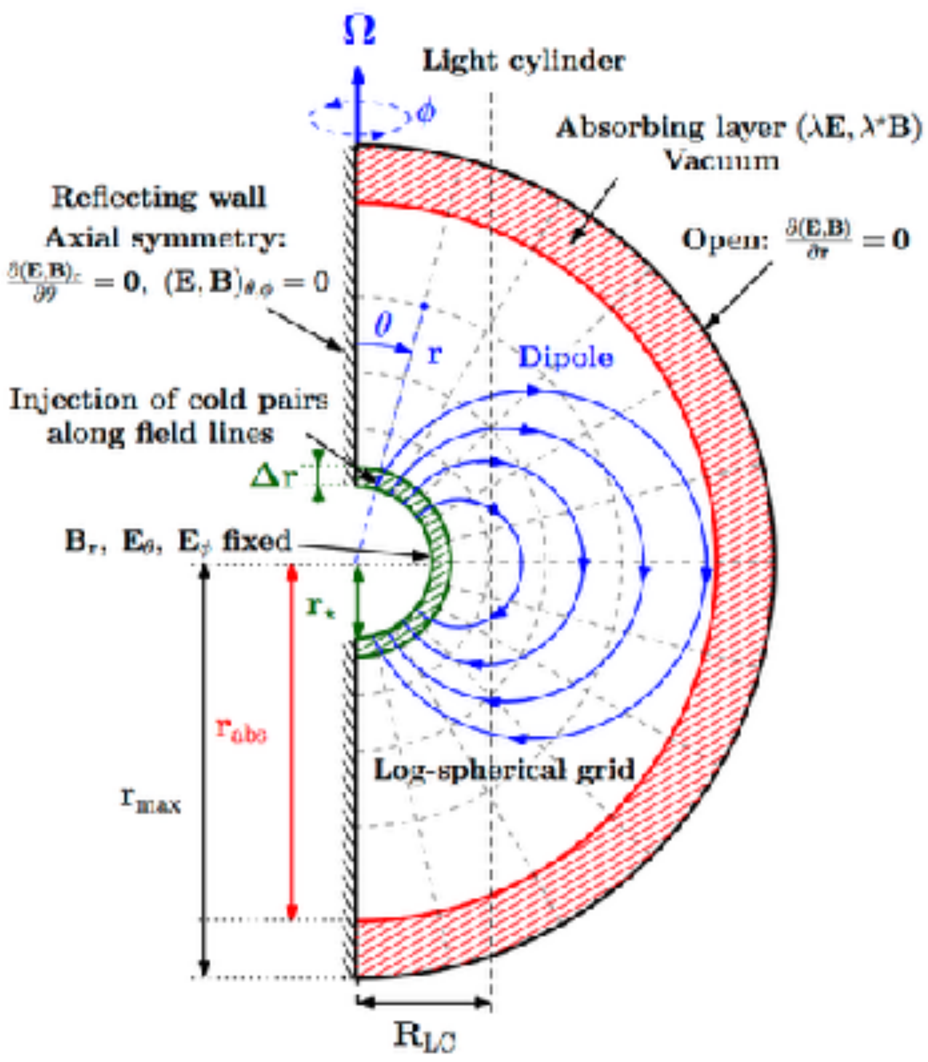


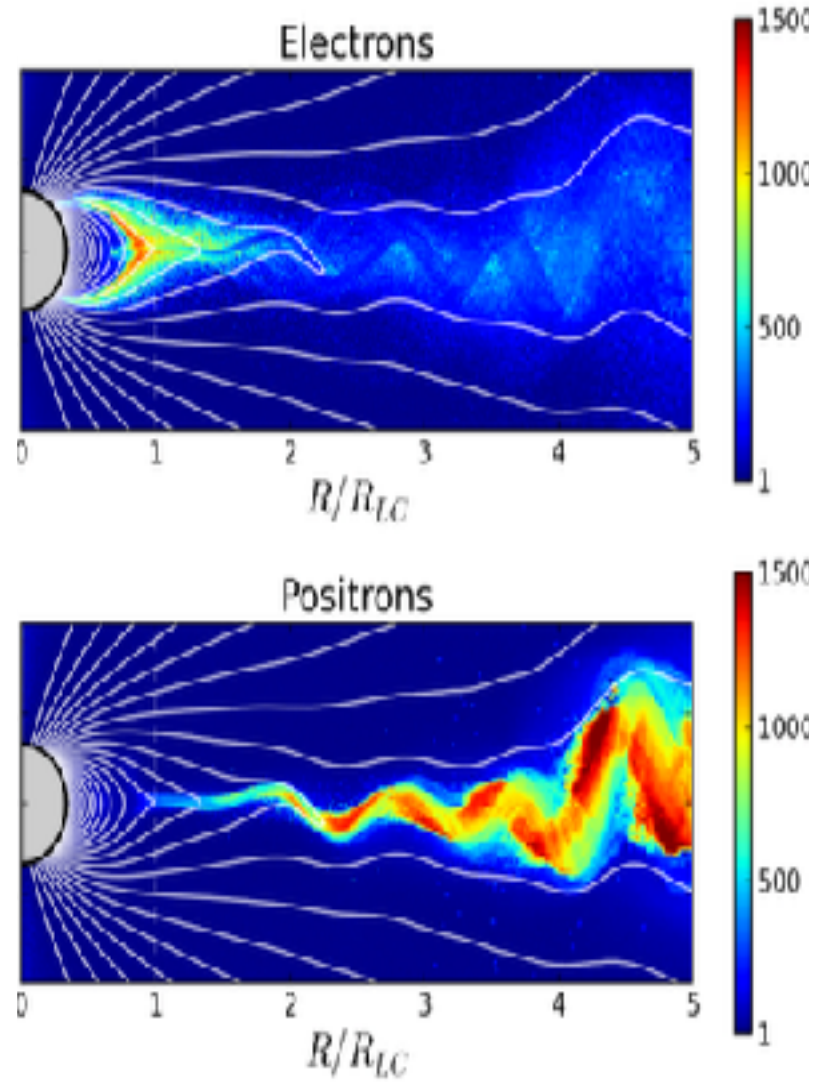
Melzani et al. (2014a,b)

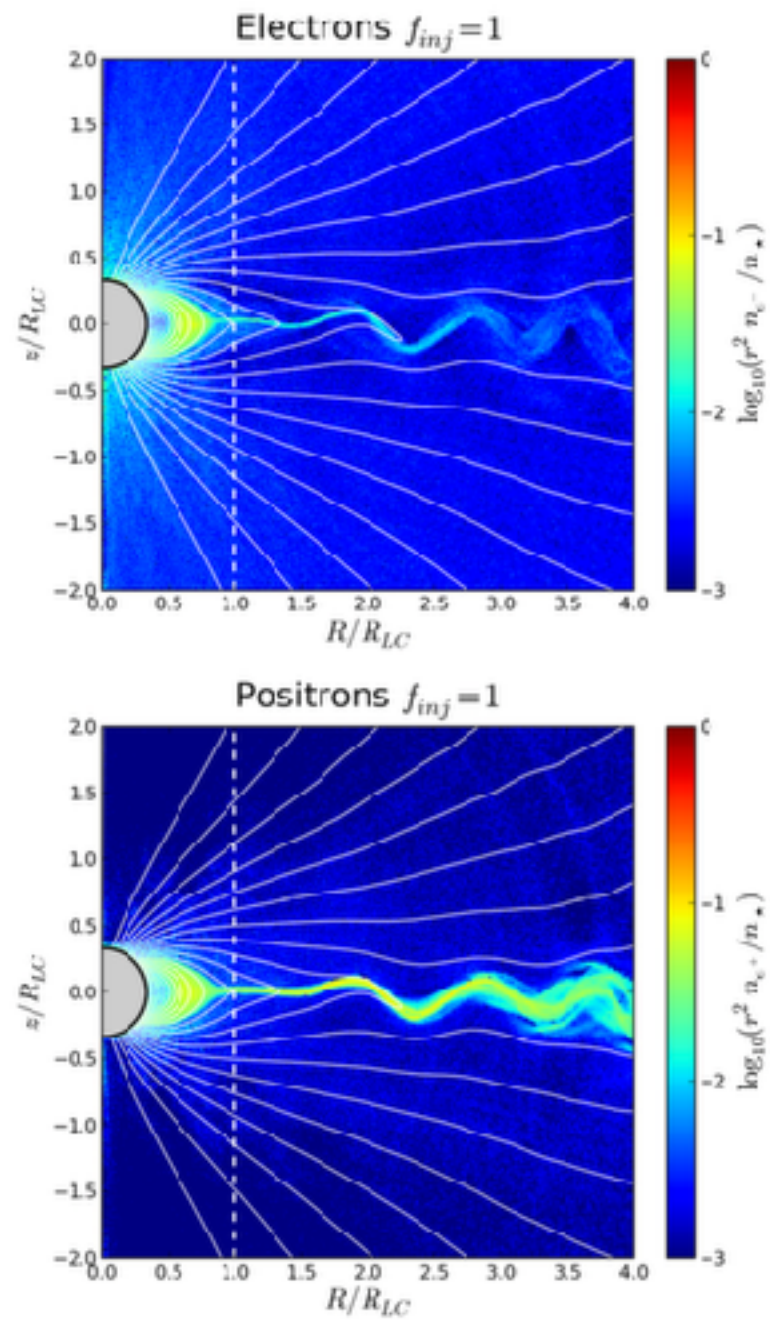
Particle acceleration in PWNe

➡ Magnetic magnetosphere of pulsar are now been addressed using global PIC simulations

➡ MPI PIC Zeltron code (logarithmic scale - Cerutti et al 2013)







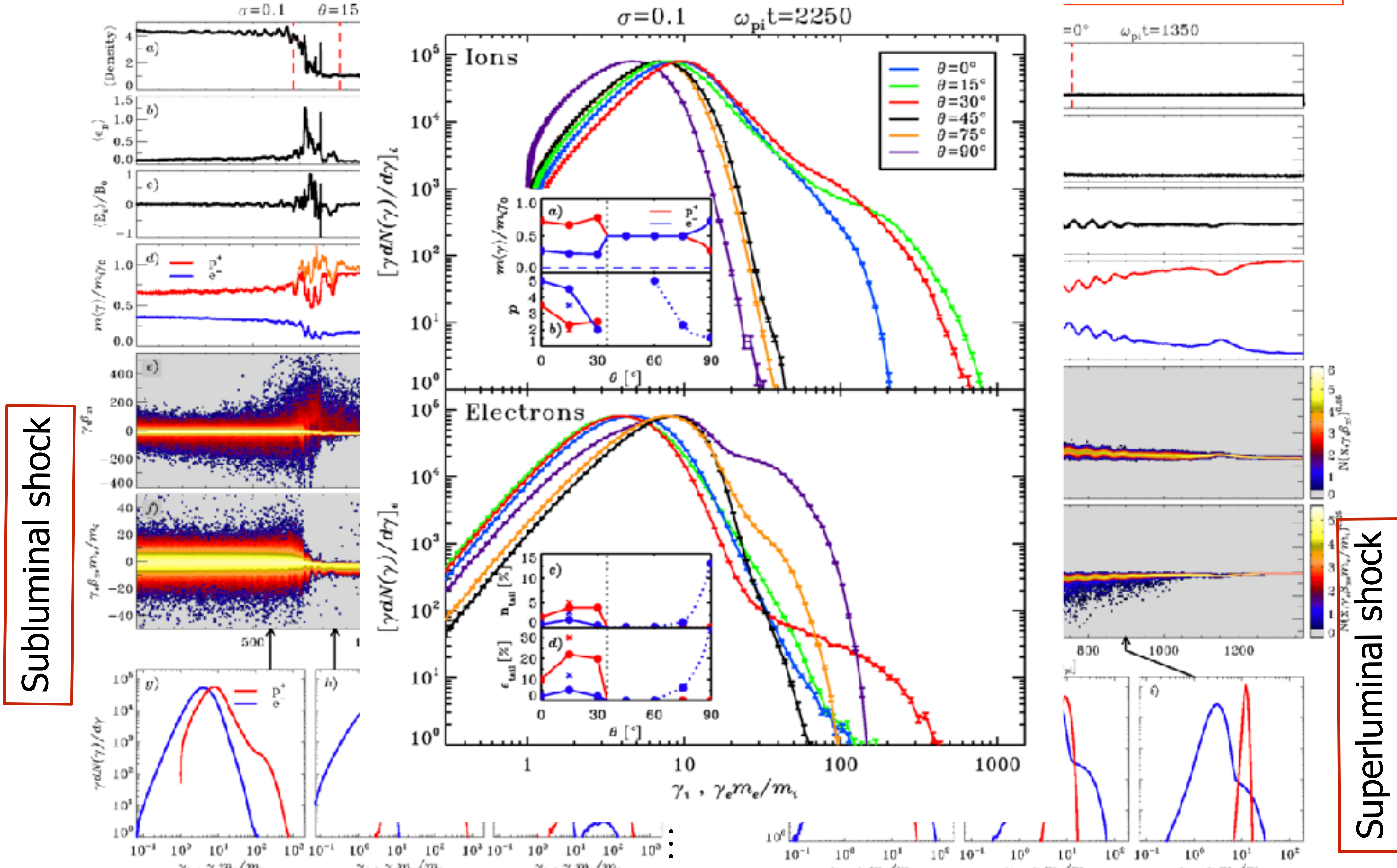
Cerutti et al. (2015)

PIC simulations of relativistic shocks

- Pair plasma shocks
- **Electron/ion shocks**

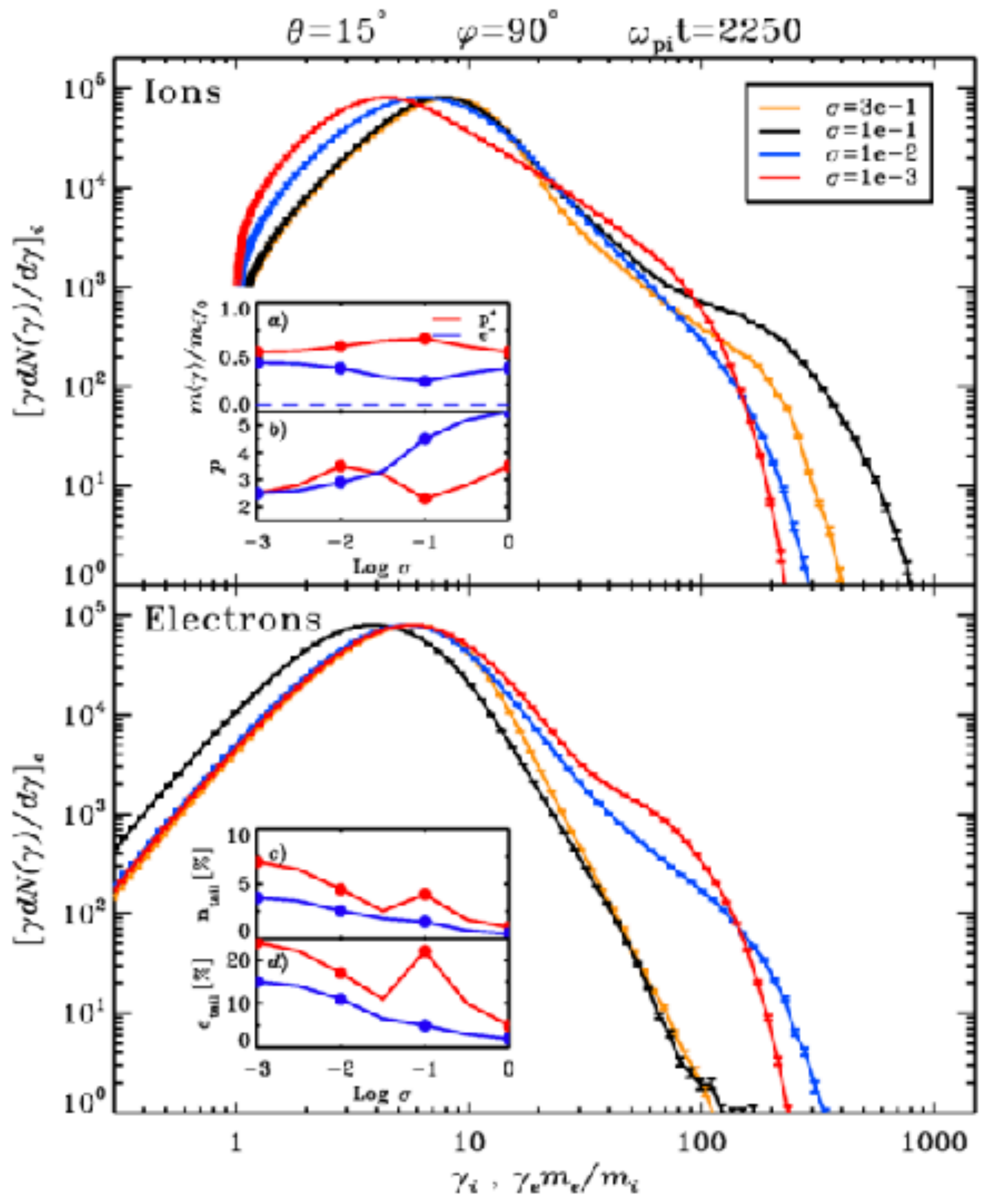
Acceleration in relativistic e-p⁺ shocks

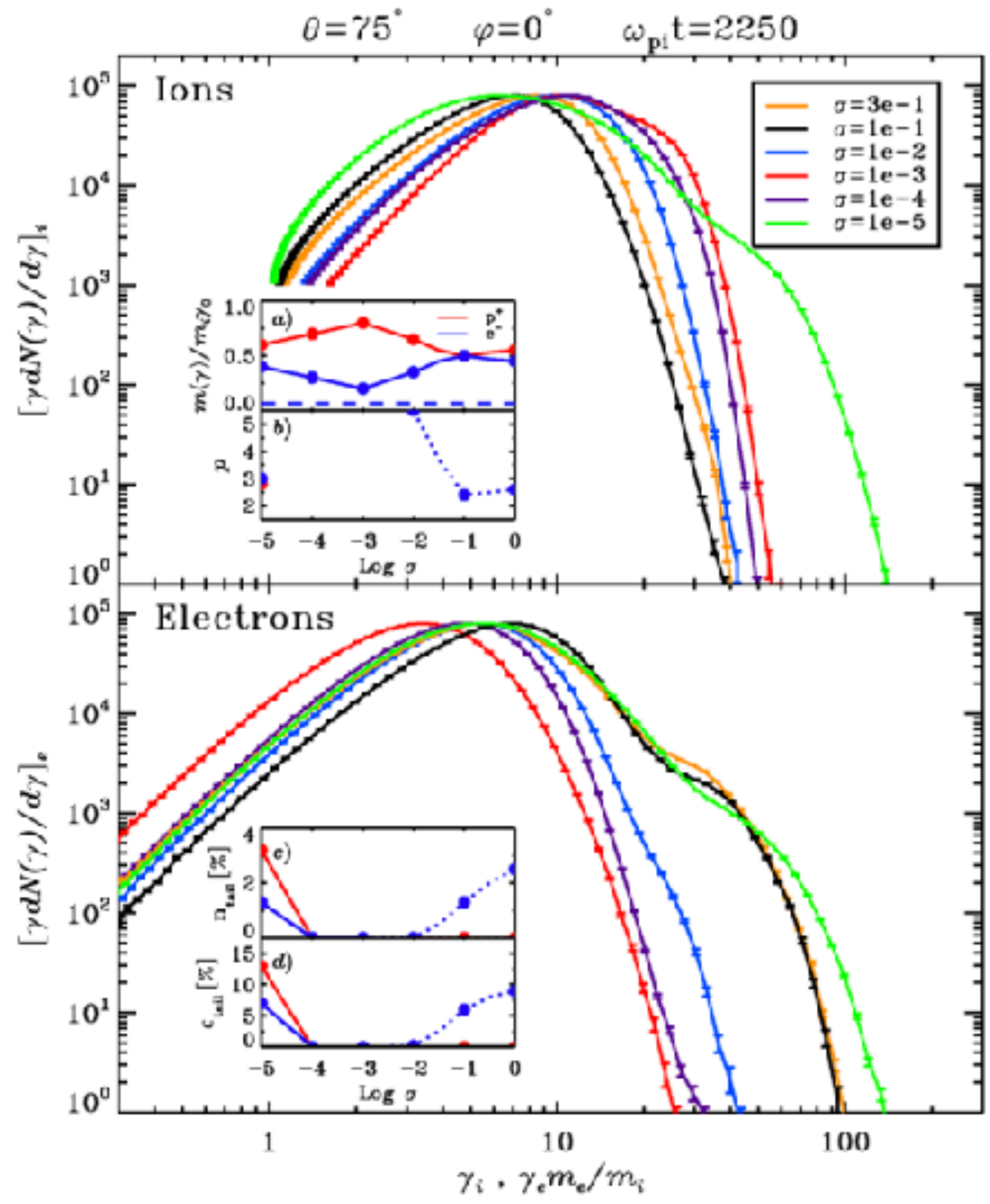
Sironi & Spitkovsky (2011)



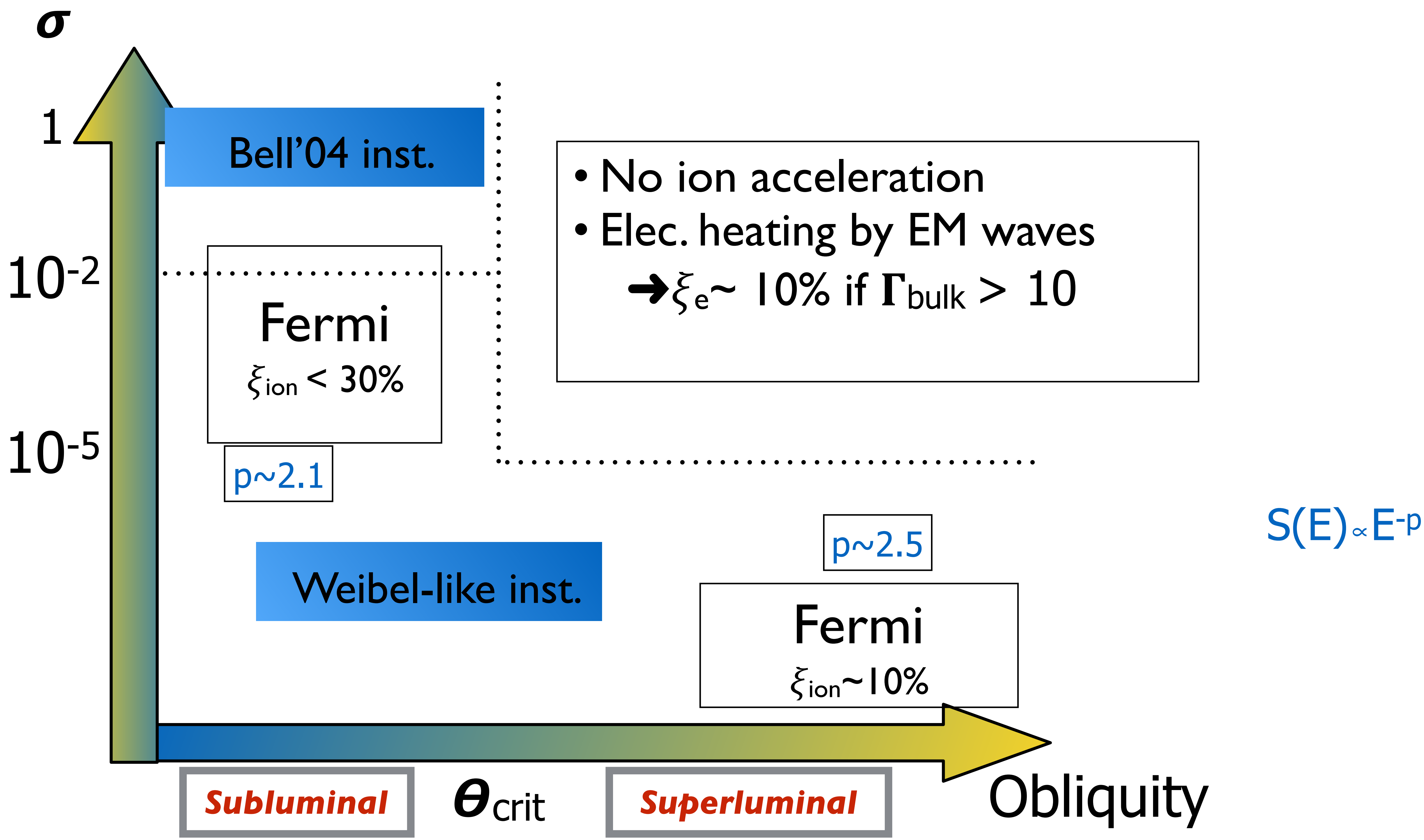
Acceleration in relativistic e-p+ shocks

Sironi & Spitkovsky (2011)





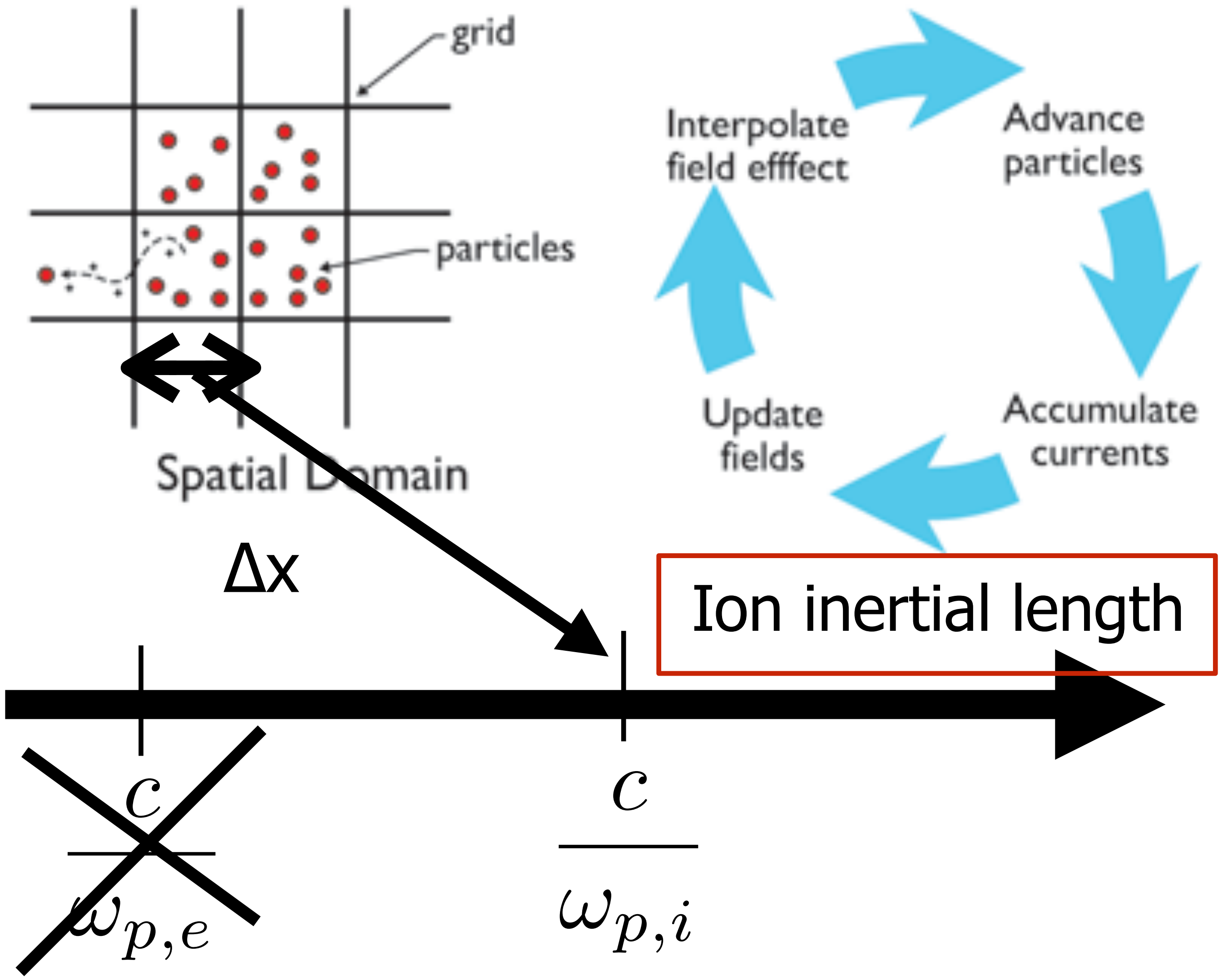
Acceleration at electron/ion shocks



Simulations of particle acceleration in non-relativistic shocks

- Hybrid PIC
- Mixing PIC & MHD

Basics of Hybrid PIC



- ➡ In Hybrid PIC simulations, particles are moved solving motion equations but electrons are considered as a massless and temperatureless fluid
- ➡ EM field is time advanced using an Ohm's law and Maxwell-Faraday equation.
- ➡ Ion current is used to compute the electric field (e.g. Gargaté et al 2007)

$$\vec{E} = -\vec{V}_{\rm ion} \times \vec{B} + \frac{\vec{\nabla} \times \vec{B}}{n_{\rm ion} e \mu_o} \times \vec{B}$$

<u>Numerical constraints</u>

- Spatial resolution Δx ~ Ion skin depth
- Temporal resolution imposed by ion CFL condition or gyro-period in high-**σ** plasmas.

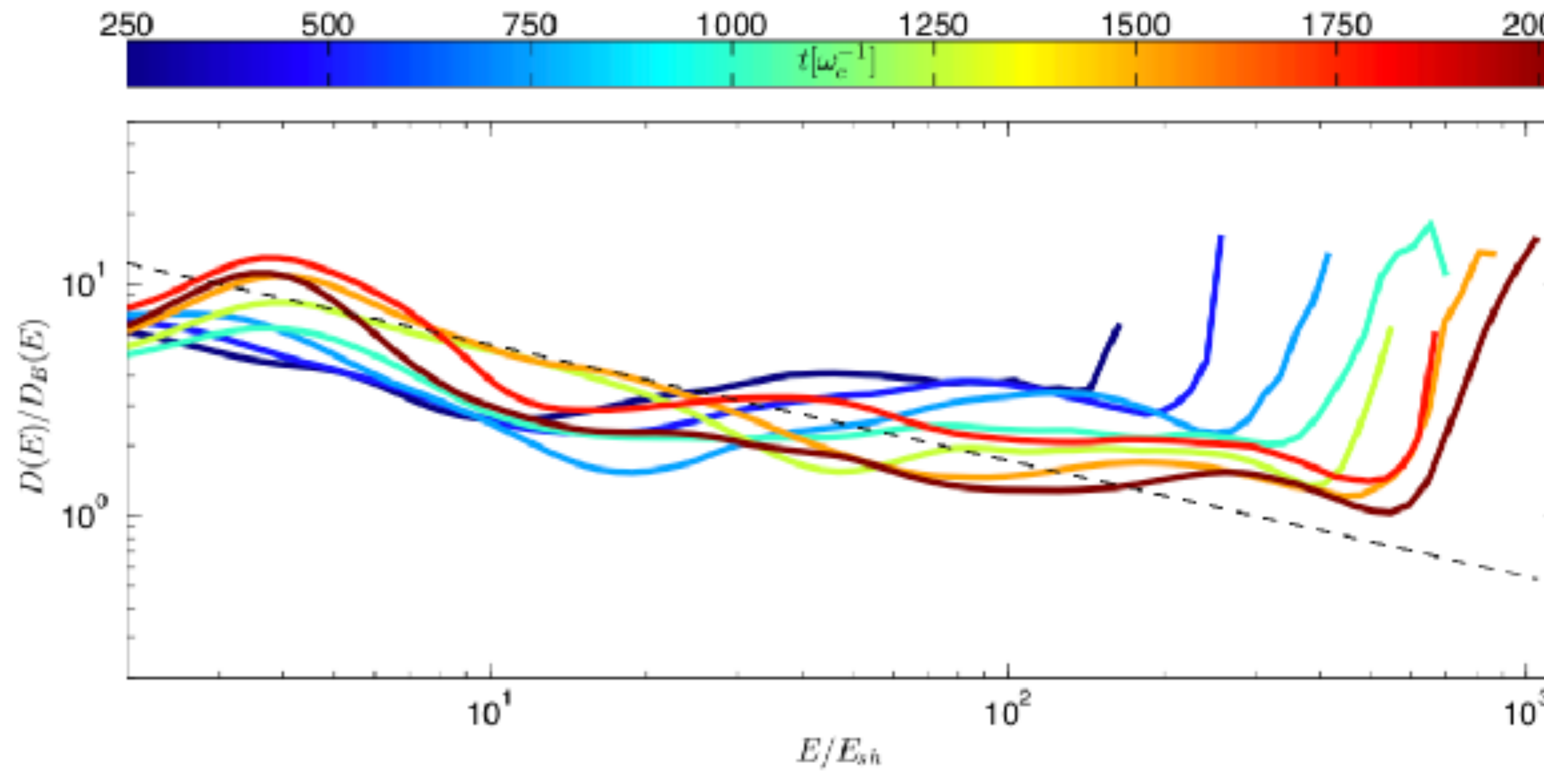
DSA in parallel non-relativistic shocks

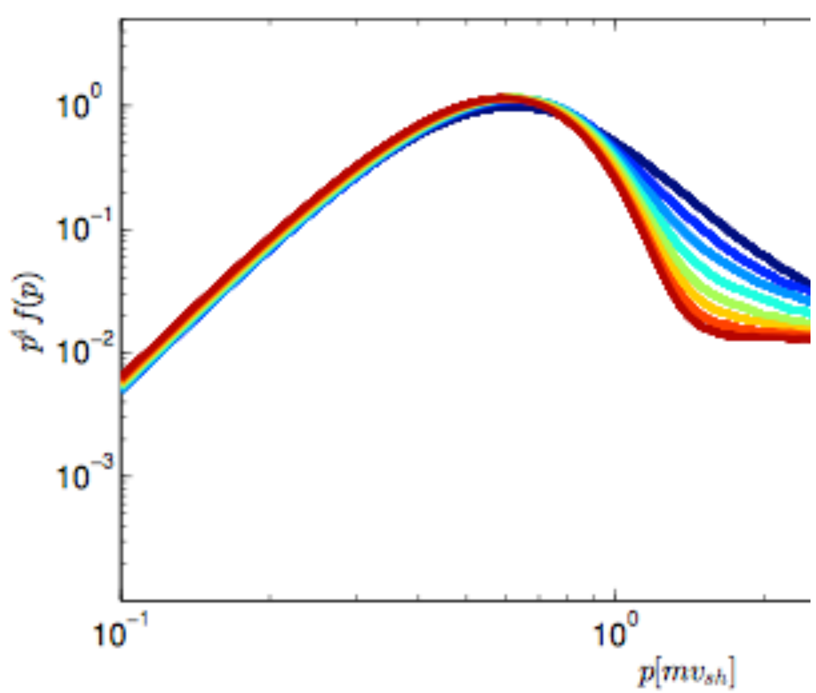
➡ Use of Hybrid PIC code (2D3V) provided the first self-consistent description of the DSA in non-rela

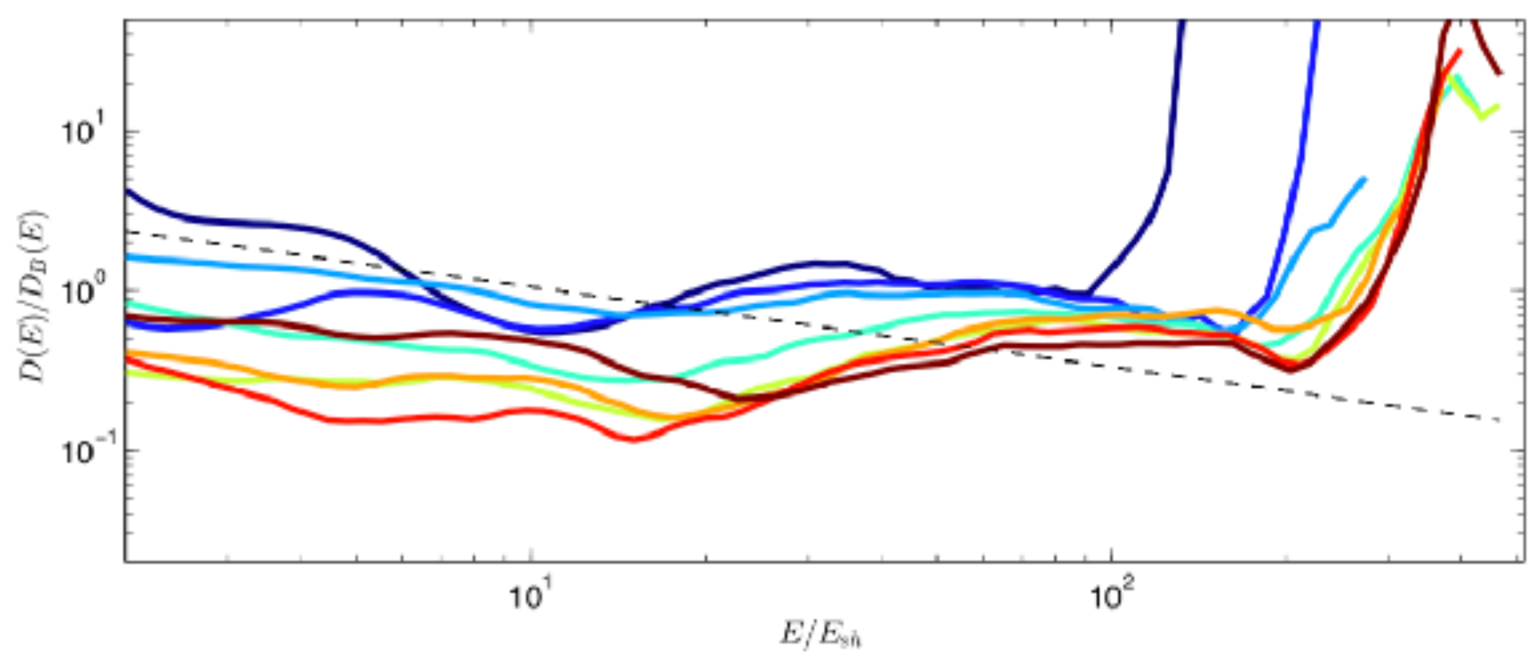
➡ In parallel superal consistantly generate

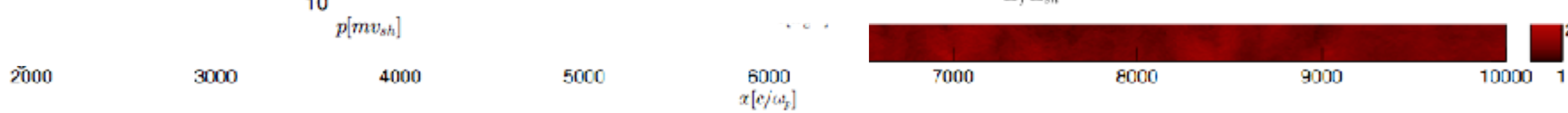
➡ Energy spectrum w (ξ_{CR}~10-20%).

➡Spatial diffusion consi





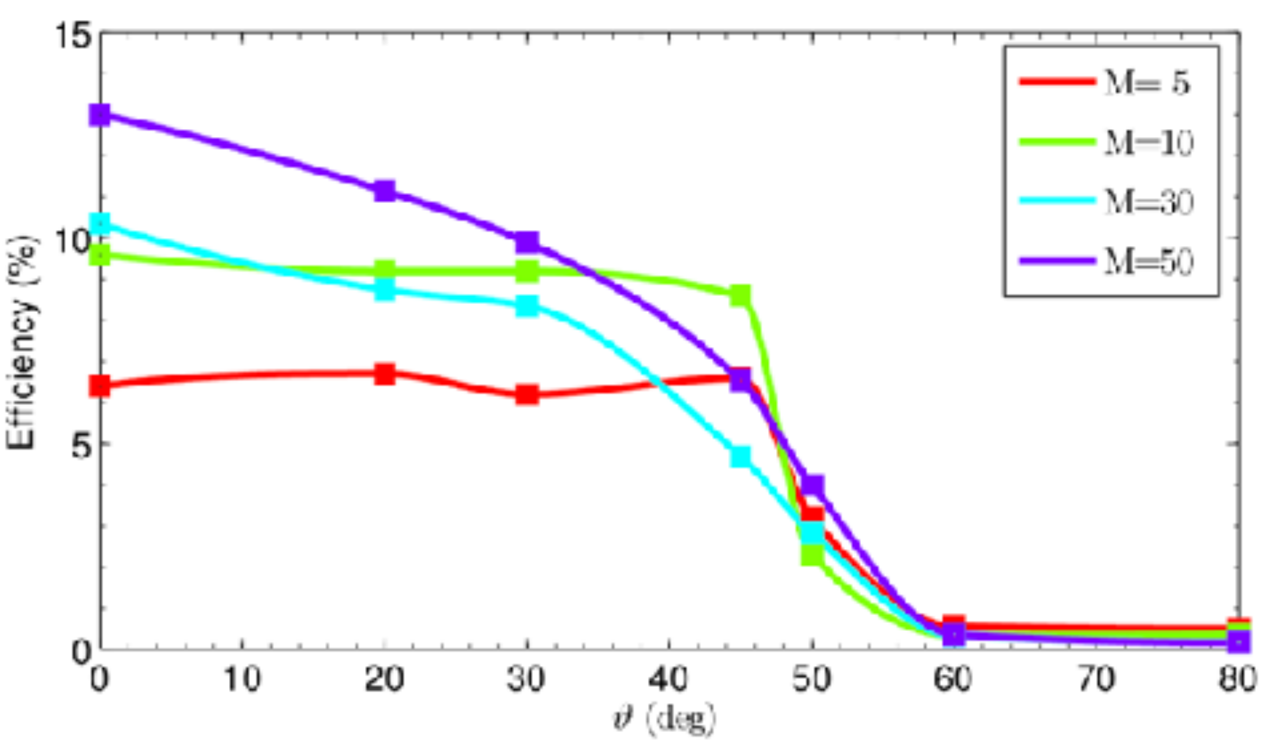


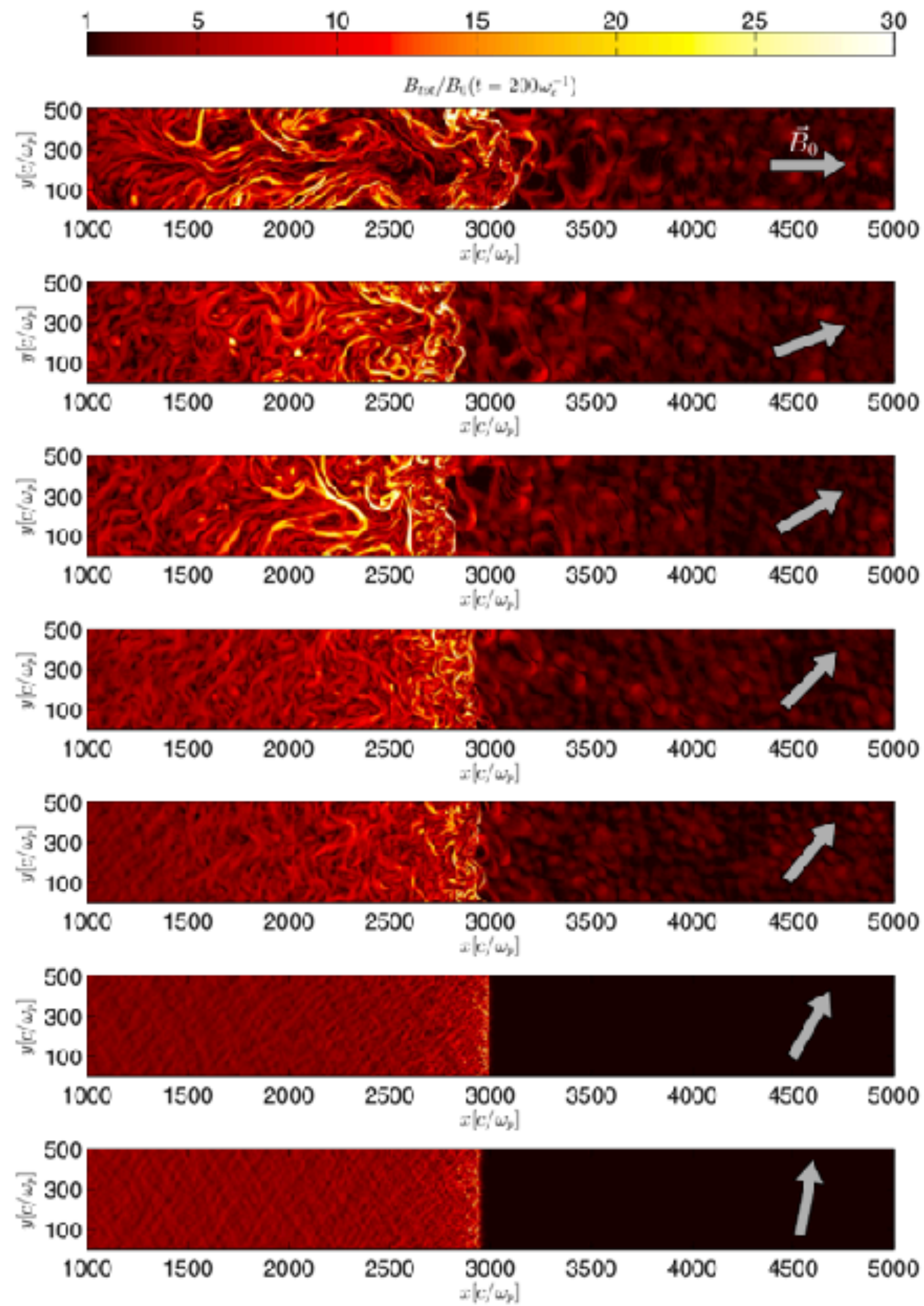


Caprioli & Spitkovsky (2014a,c)

DSA in perpendicular non-relativistic shocks

- ➡ In perpendicular non-relativistic shocks the ion acceleration efficiency drops to zero for Hybrid -PIC simulations.
- ➡ No magnetic turbulence nor particle acceleration is obtained in high obliquity shocks (θ>50°) !





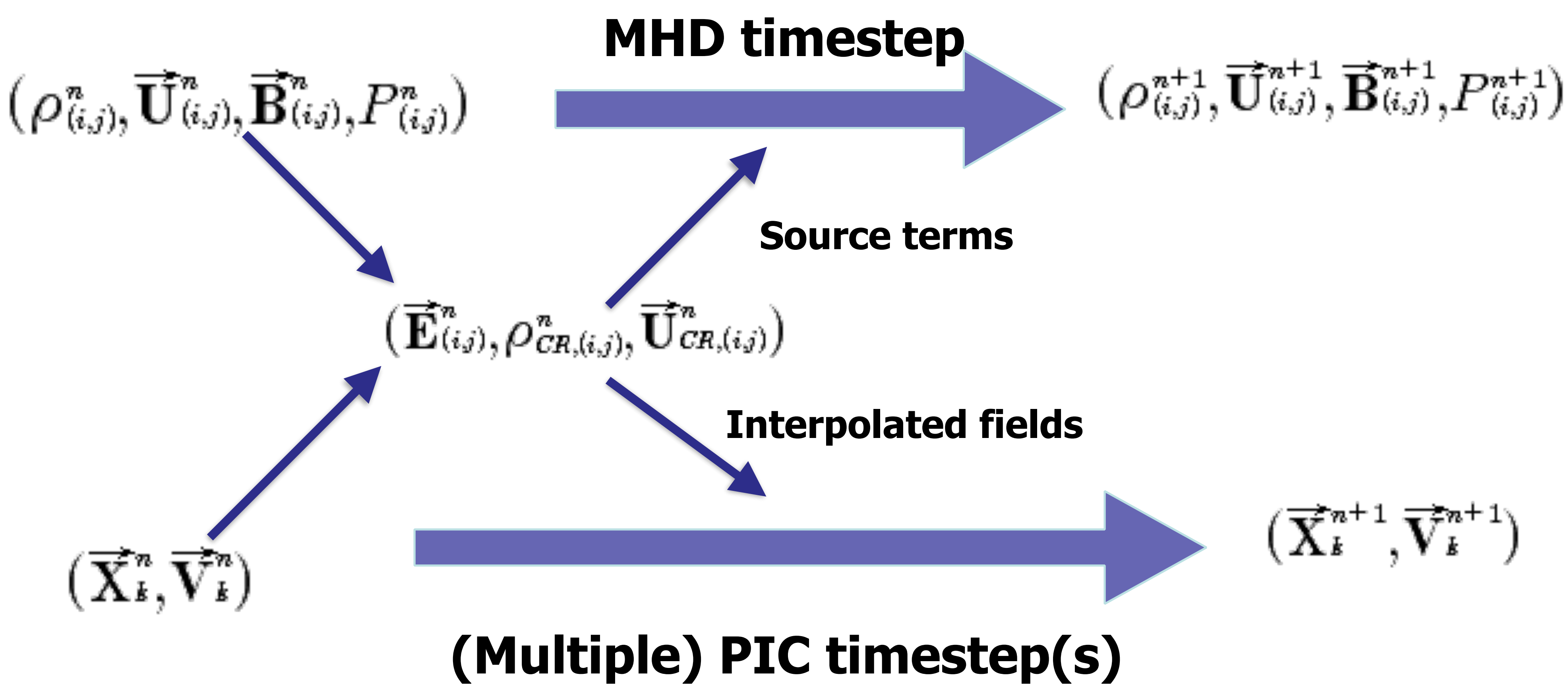
Caprioli & Spitkovsky (2014a)

Basics of Particle In MHD Cells

➡ MHD describes the evolution of thermal fluid and EM field while PIC takes care of supra-thermal particles **only** (Bai et al 2015, van Marle et al 2018).

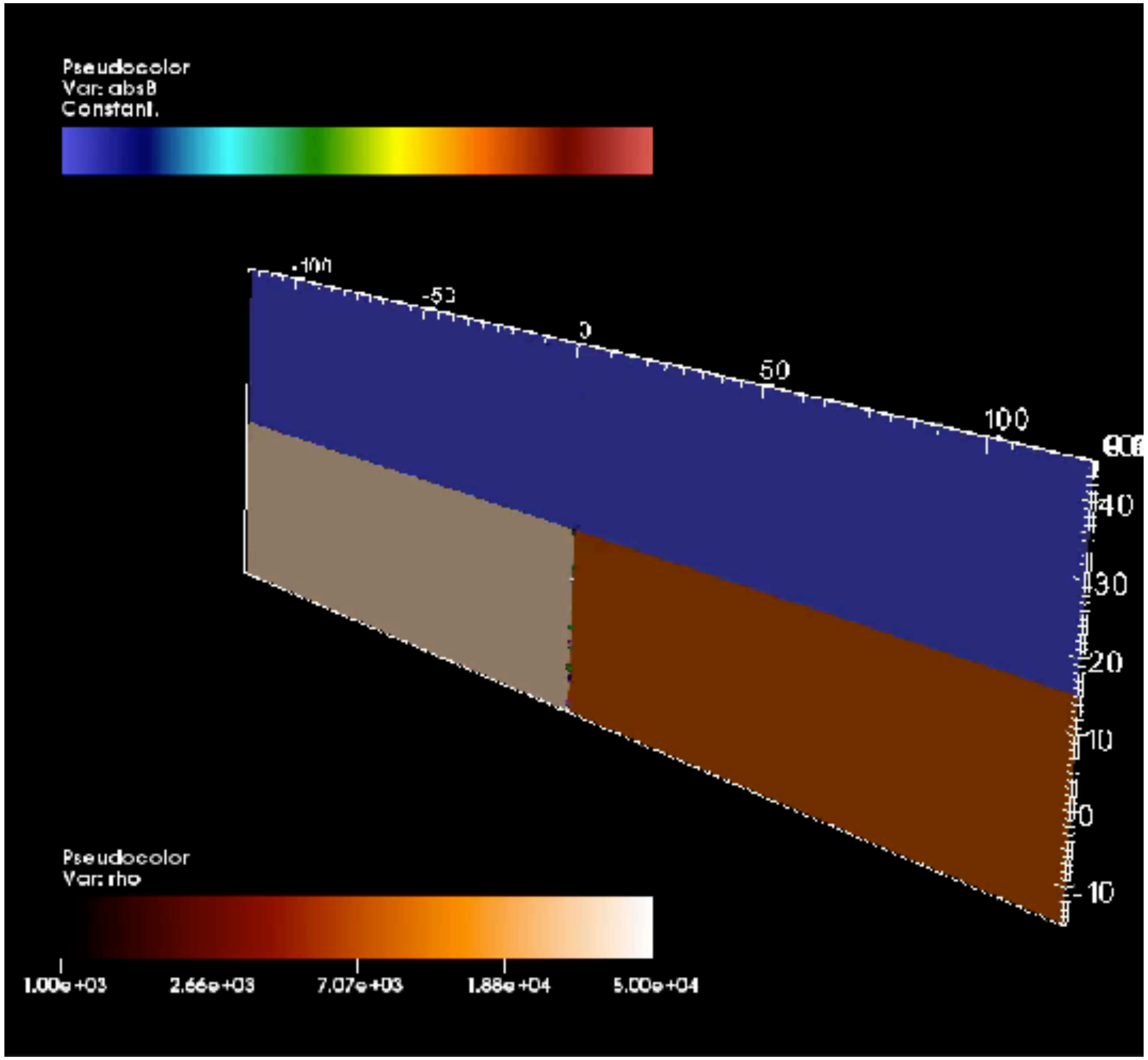
➡ Modified Ohm's law provides E field incorporated in MHD **AND** Boris pusher.

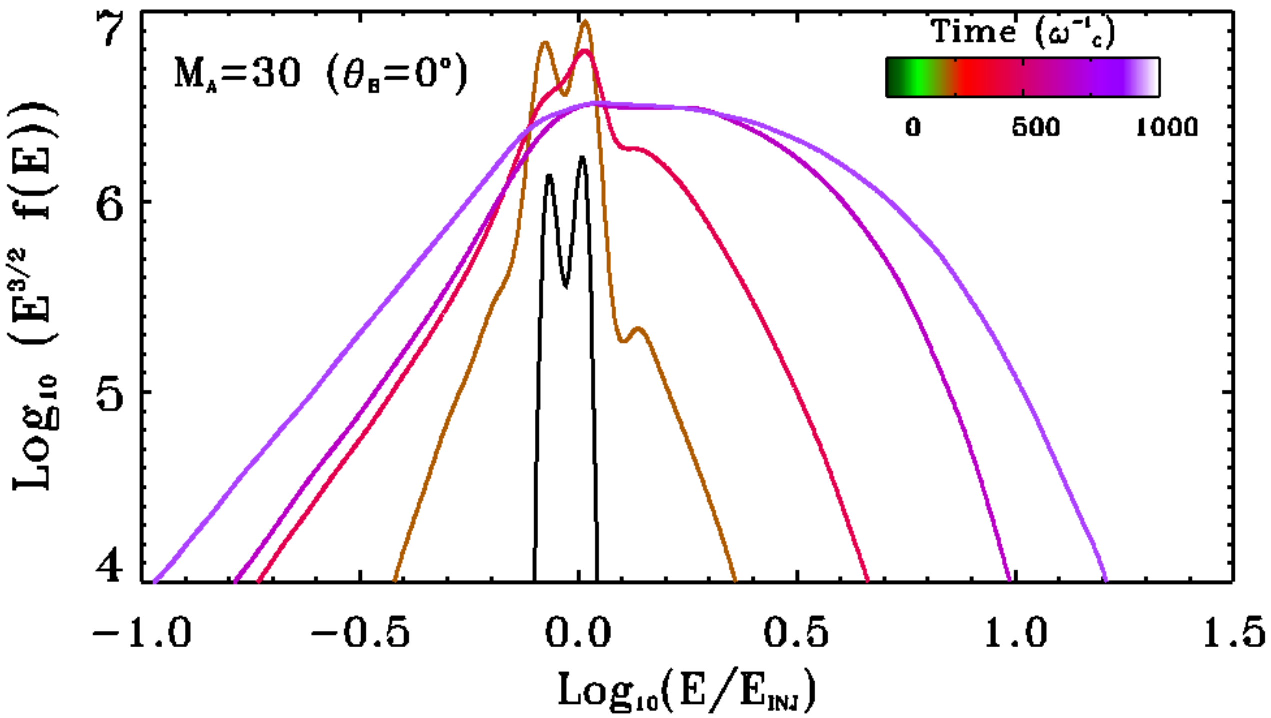
➡ Requires particle injection recipe but enables large-scale system description.



Non-relativistic shocks: PI[MHD]C approach

- ➡ Following full PIC injection recipe at the shock one recover all results from Hybrid PIC simulation on **parallel** shocks.
- ➡ Bell's non resonent streaming instability is at work in the precursor.

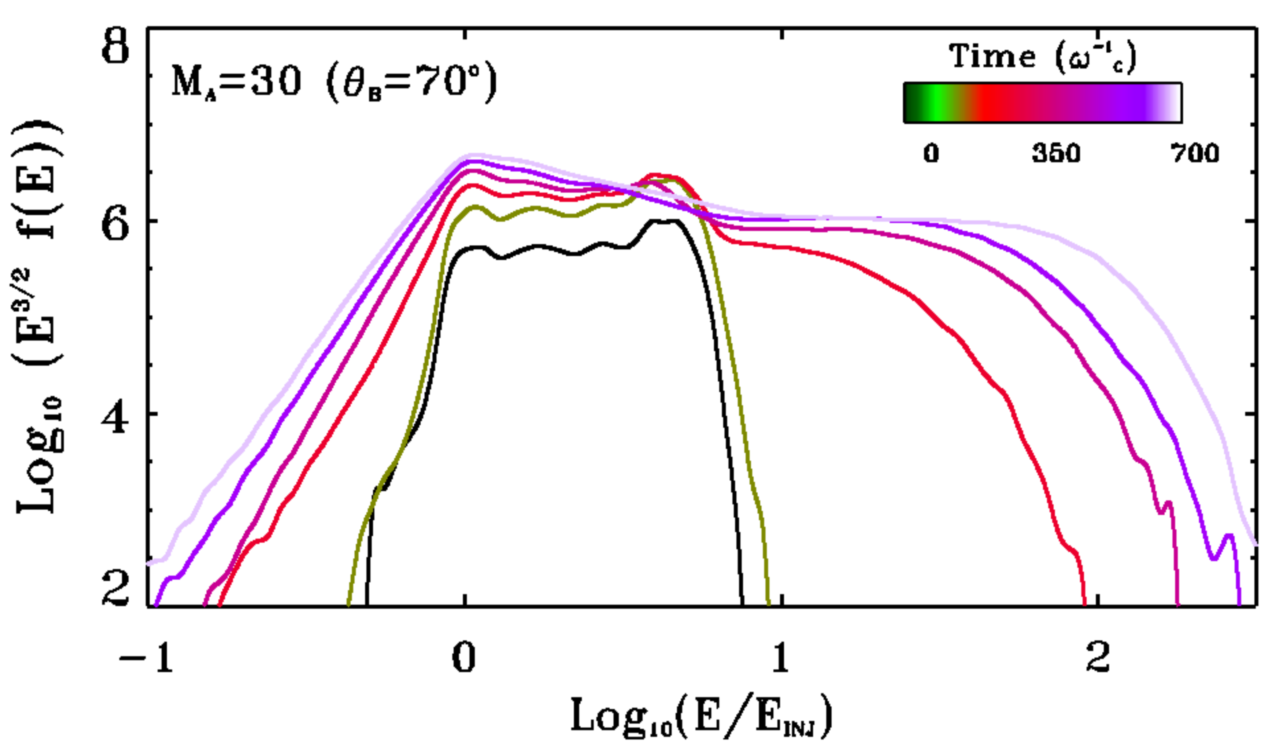


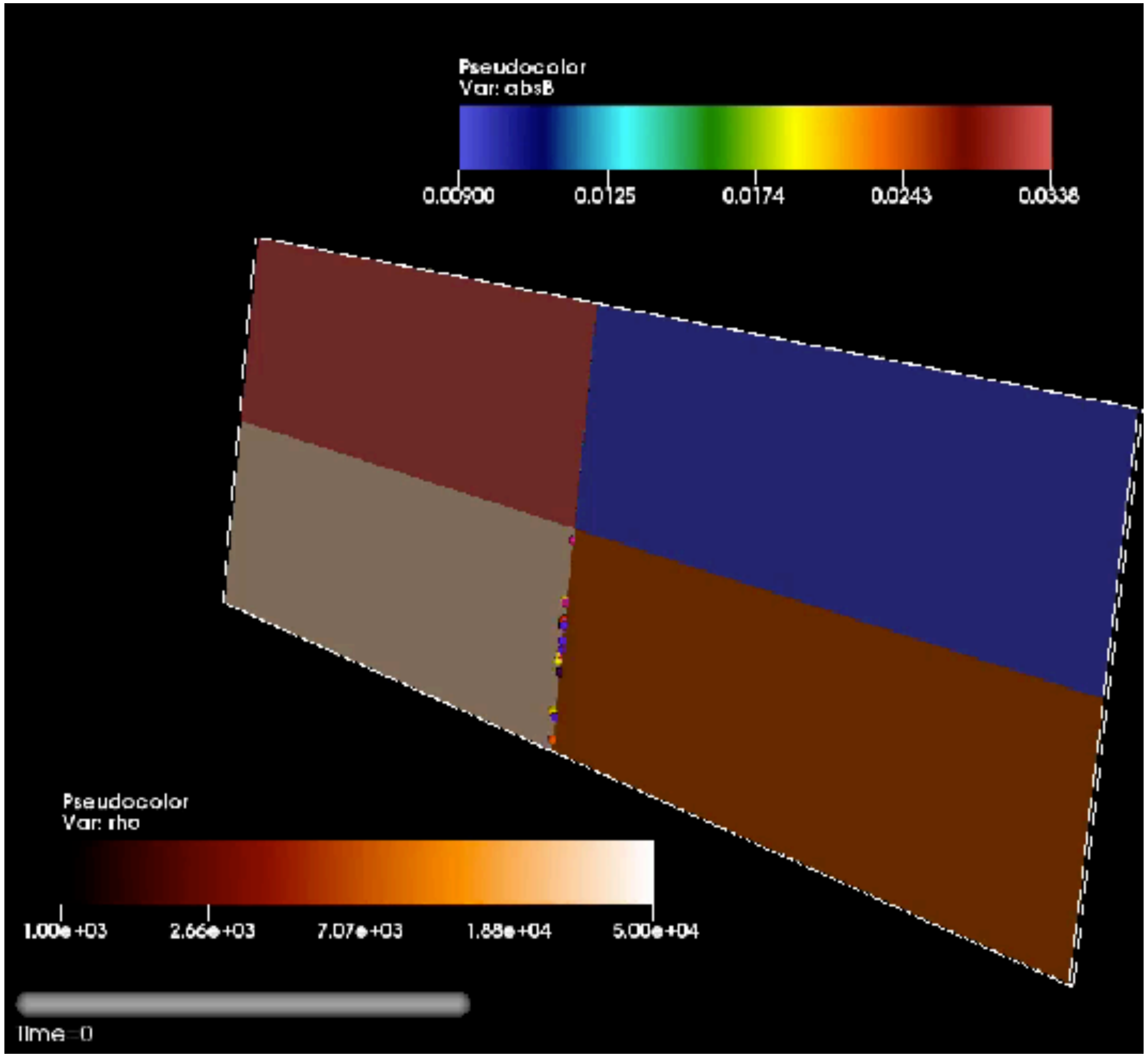


van Marle et al (2018)

PI[MHD]C : near-perpendicular shocks

- ➡ Large scale Bell's instability leads to corrugation of the shock front
- ➡ DSA and magnetic amplification is triggered by the corrugation of the shock
- ➡ SDA is pre-heating particles before entering DSA.





van Marle et al (2018)

Some issues & open questions

➡ Over the last decade full-PIC simulations brought new insight on particle acceleration in astrophysical environments.

➡ **Parallel shocks** are efficient particle accelerators

- ⊙ Relativistic parallel pair shocks are mediated by Weibel-like instabilities but such turbulence relaxes over a short distance:

  ➜ How to accelerate higher energy particles ? How to address larger simulations (huge cost in full-PIC) ?

- ⊙ NR shocks: Ion injection in DSA process is not yet clearly understood

- ⊙ NR shocks: Electron injection is efficient for low M_A (SDA, SSA, Whistler)

  ➜ How to heat electrons in order to make them entering DSA in strong shocks ?

Some issues & open questions

➡ **Perpendicular shocks**

⊙Low-σ perpendicular relativistic shocks can trigger DSA through Weibel mediated shock ➜ How to accelerate higher energy particles ?

⊙High-σ perpendicular relativistic shocks cannot trigger DSA.

➜ Is magnetic reconnection able to trigger particle acceleration and the turbulence needed to drive DSA ?

⊙ Discrepencies arise between Hybrid PIC and PI[MHD]C simulations on NR perpendicular simulations (e.g. Caprioli et al 2018). Can ion injection be adressed including electrons (full-PIC) over long time-scale ?

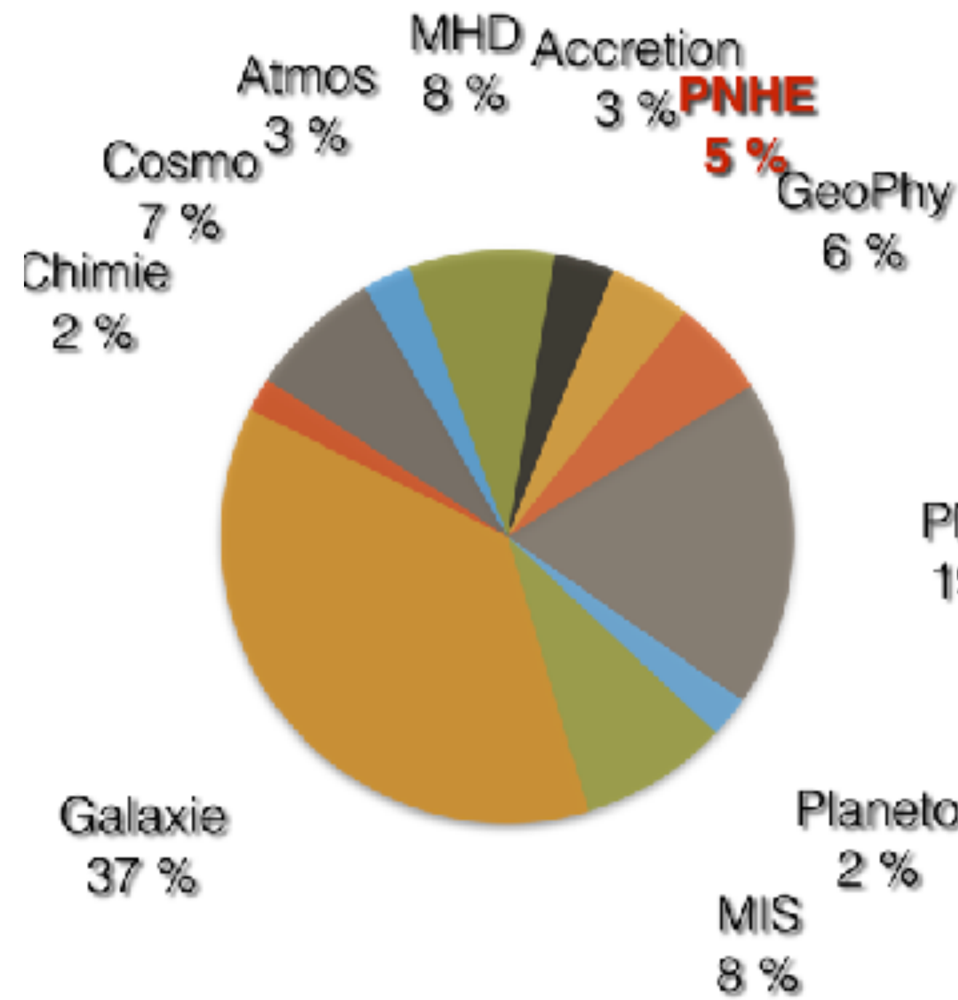
⊙ We are in need of simulations linking full-PIC simulation on limited spatial extension (shock vicinity) to larger MHD-Kinetic describing the shock precursor.

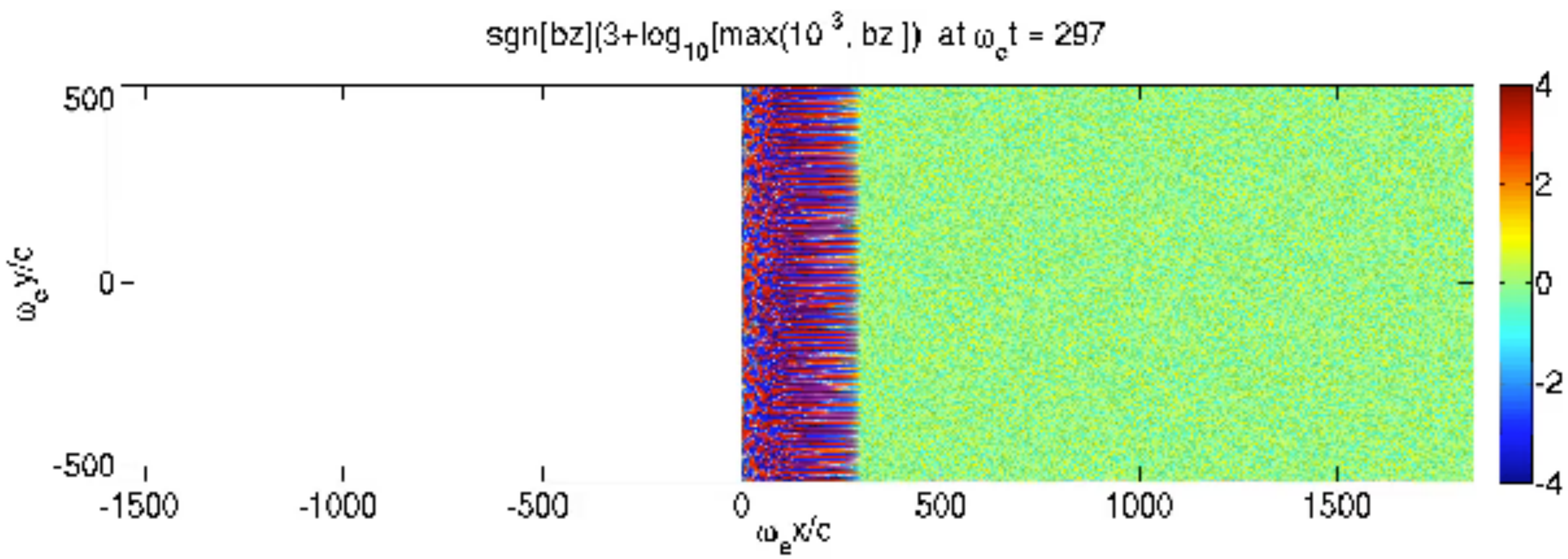
➡ We have a lot to learn from Laser-plasma community as they have a huge experience with PIC and other type of simulations.

CR french community on the numerical side

- ➡ GENCI = Grand Equipement National de Calcul Intensif —> Regrouping IDRIS (CNRS), TGCC (CEA) and CINES (Universités).
- ➡ PNHE's tcompting time grant represented 5% of total astrophysical computing time in 2016 (but rising).
- ➡ French numerical codes for particle acceleration :

- Full-PIC: CALDER, SMILEI, ZELTRON, Apar-T
- PI[MHD]C: mPIC-AMRVAC
- MHD bi-fluid (thermal+CR) : RAMSES





CALDER (Vanthieghem et al.,IAP/CEA)

Simulation numérique & PNHE

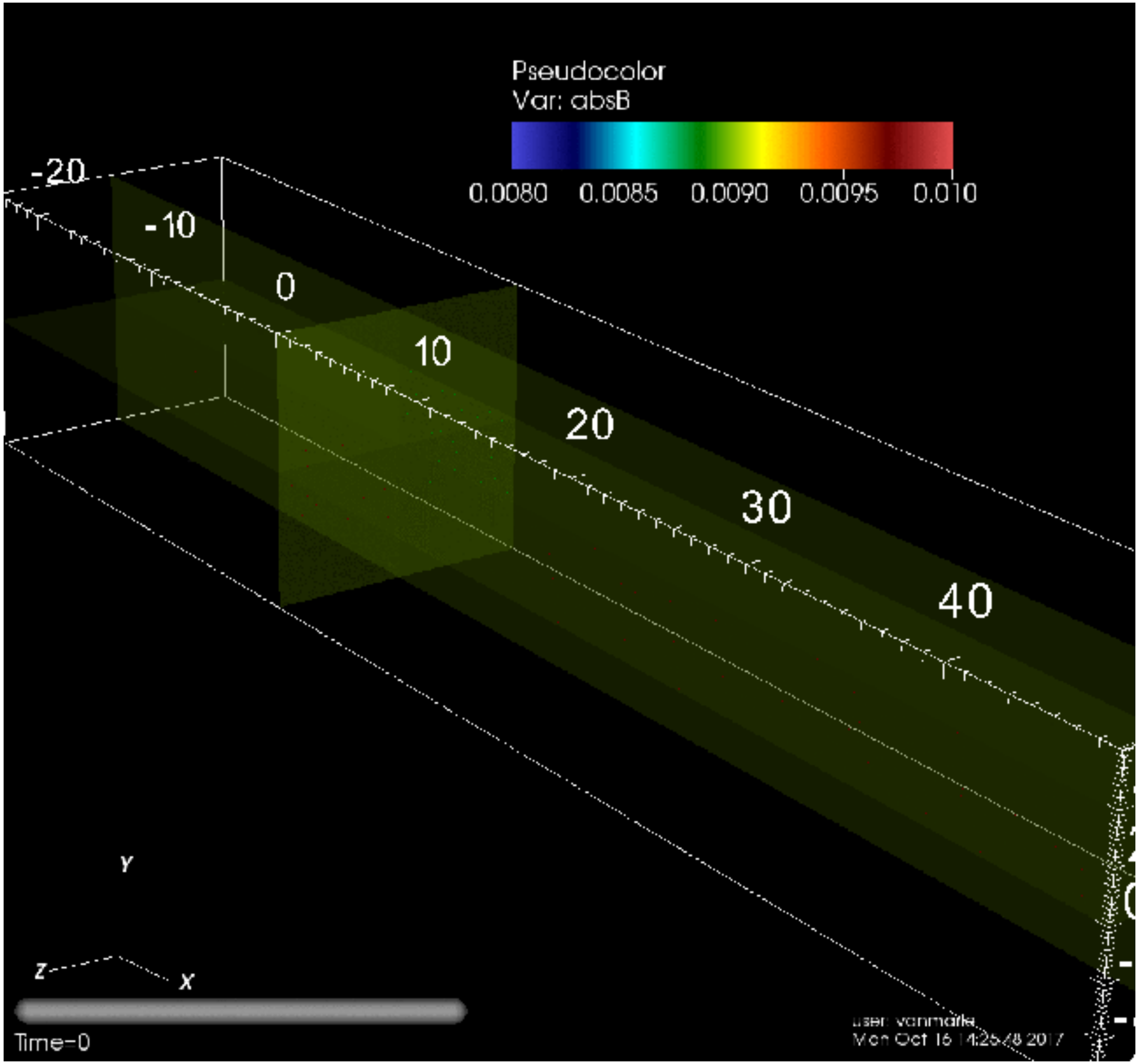
➡ Le PNHE a soutenu l'activité de simulation au travers du financement de projets/collaborations dont c'est quelque fois le seul financement.

➡ Ouverture à d'autres communautés plasma grâce à l'organisation de conférences (ex: Workshop sur accélération de particules avec communauté Laser-Plasma et la communauté plasma magnétosphériques).

➡ Appui du PNHE pour l'organisation d'une école sur les techniques numériques en HE —> Intérêt pour former à l'utilisation de codes des étudiants en thèse pour développer des liens simulations-modélisation-observations.

➡ Nécessité de maintenir un savoir-faire en accord avec les innovations technologiques (ex. GPGPU) —> Formations professionnelles au calcul scientifique financées par le PNHE (Maisons de la Simulation) ?

3D PI[MHD]C



van Marle et al (in prep)