Simulations of cosmic ray acceleration near astrophysical shocks: Particle In MHD Cells approach

Fabien CASSE

Laboratoire Astroparticule & Cosmologie (APC)

Université de Paris — CNRS/IN2P3

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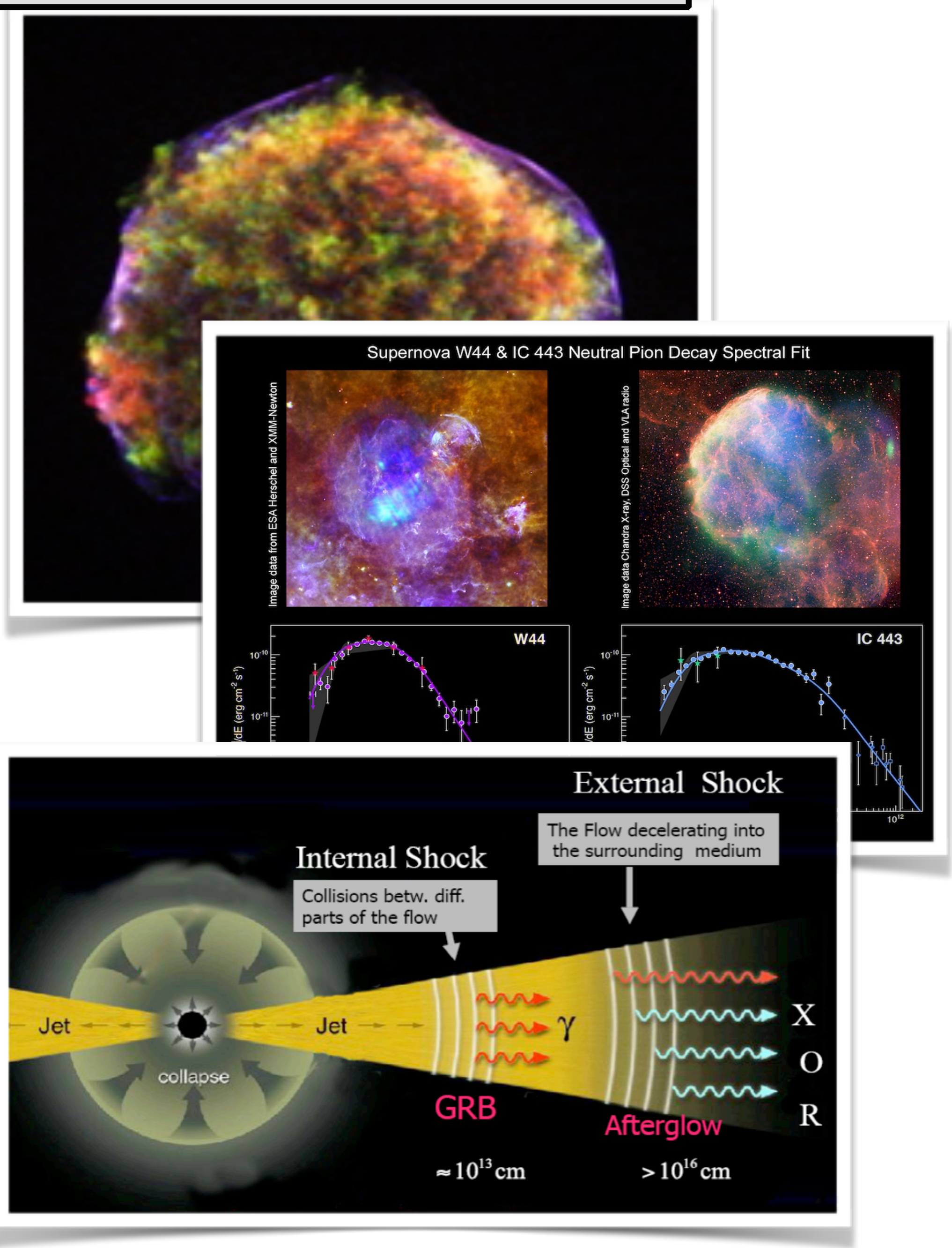
Particle acceleration near astrophysical shocks

•Thin bright X-ray rims are observed at the location of SNR forward shock (e.g. Bamba et al 2006) with a localized magnetic field amplification ($\sim 10^2$ B_{ISM}, e.g. Parizot et al 2006).

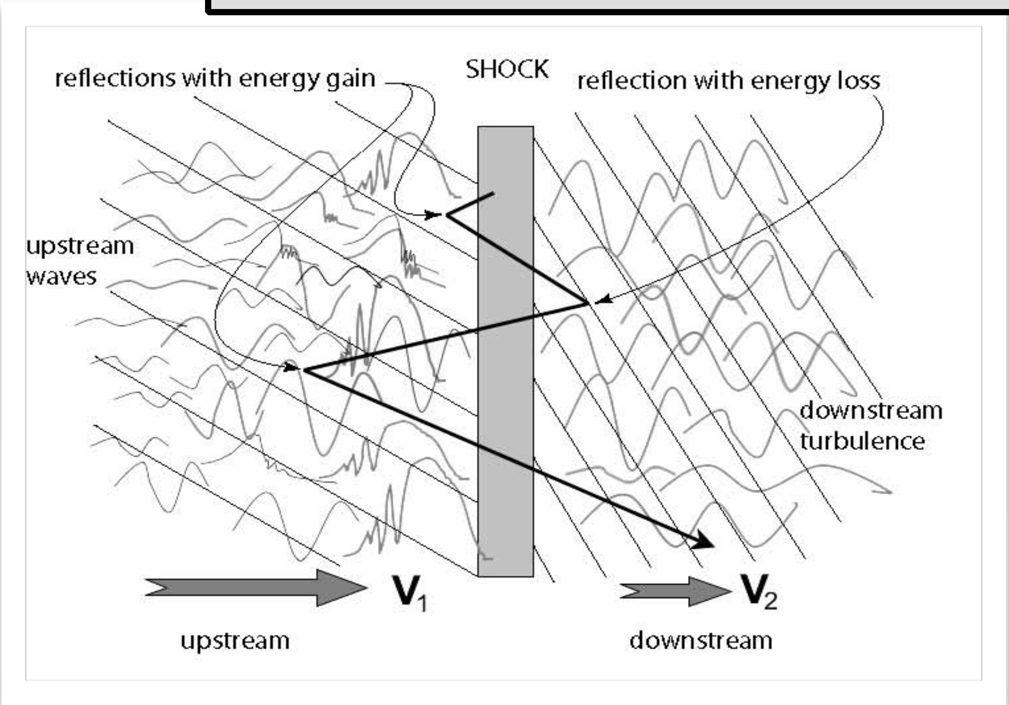
•Cosmic-rays are detected through γ-rays emission (collision with ambient material).

•Similar magnetic amplification is likely to occur in γ-ray bursts (external relativistic shocks, e.g. Li & Waxman 2006).

• Relativistic shock fronts are also present in pulsar wind nebula and AGN (e.g. blazars) with Lorentz factor ranging from a few units up to 10^6.

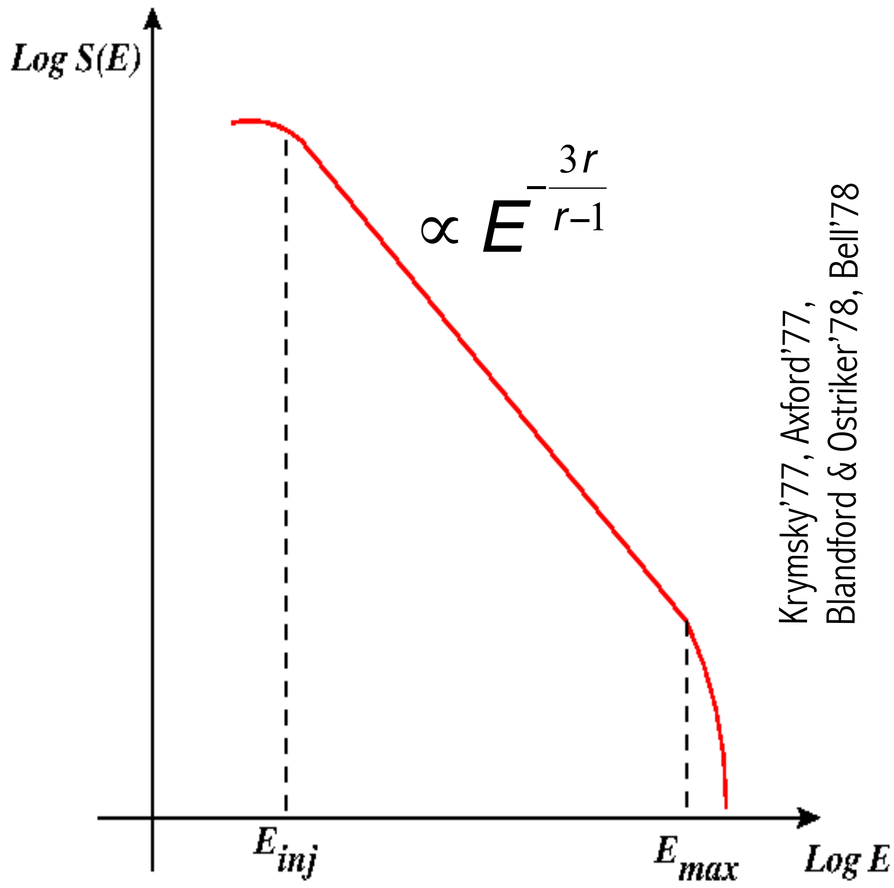


The Diffusive Shock Acceleration (DSA)



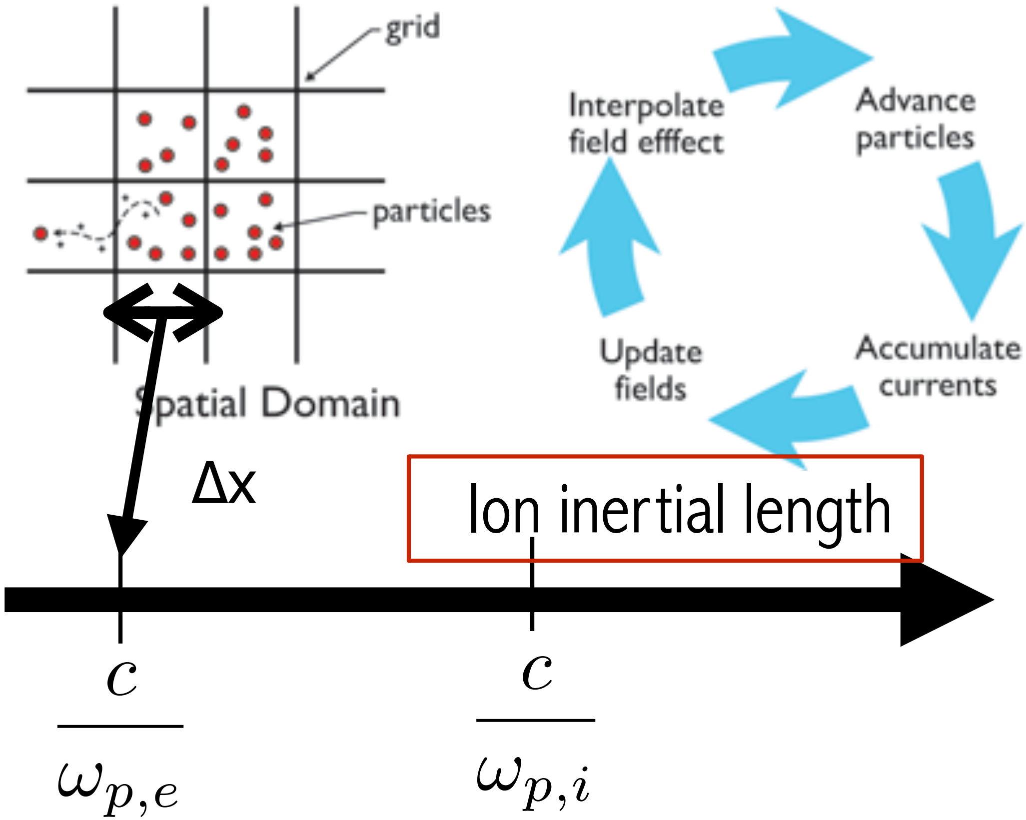
- DSA is likely the acceleration process of galactic cosmic-rays.
- Magnetic turbulence is a key element to ensure non-thermal particle diffusion.
- The streaming of supra-thermal particles into the plasma triggers magnetic instabilities.
- The nature of the instability driving the magnetic turbulence depends on the magnetization.

$$r = \frac{\rho_d}{\rho_u}$$



Krymsky'77, Axford'77, Blandford & Ostriker'78, Bell'78

Particle-In-Cells 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)

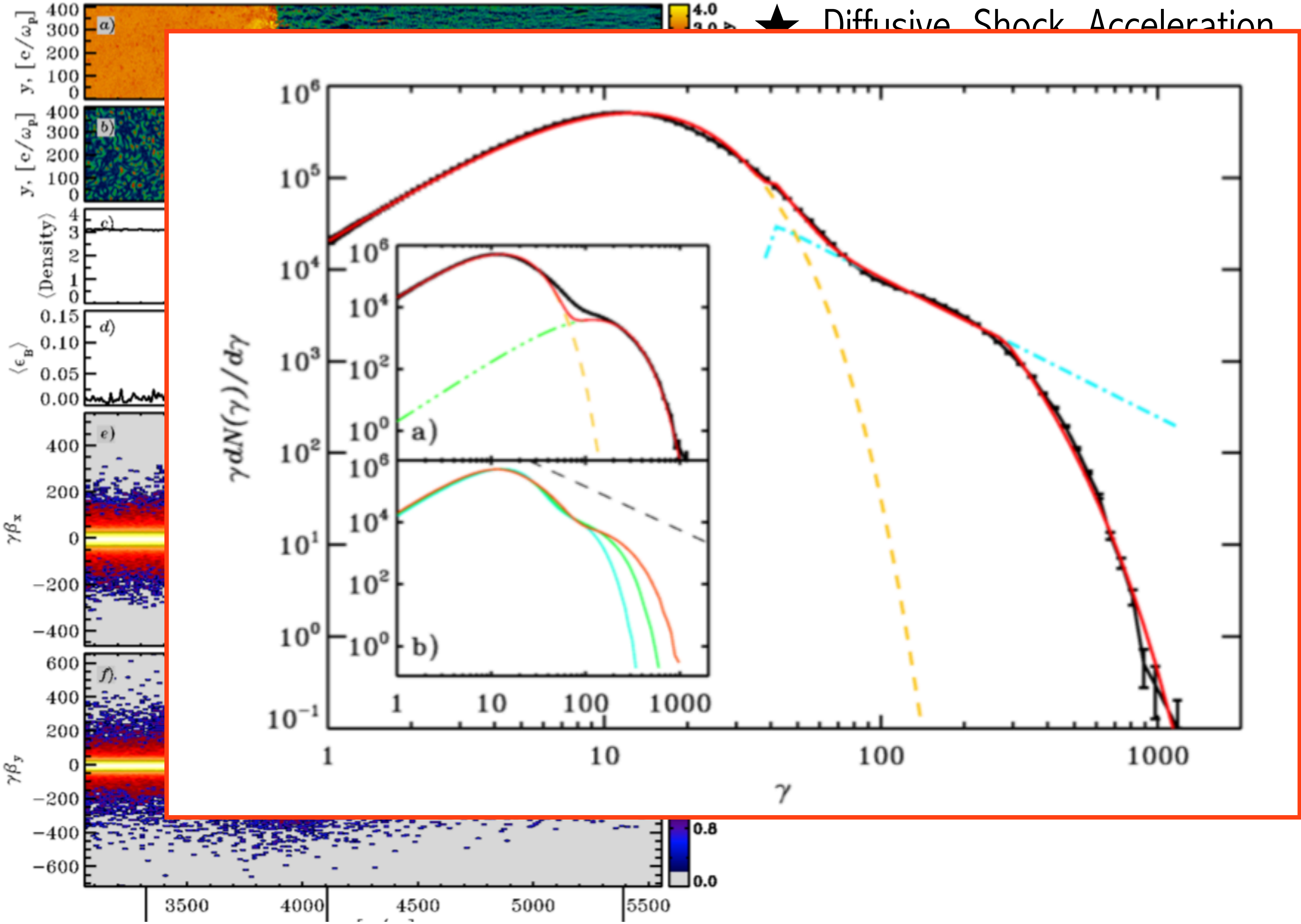
➡ Very noisy method so handle with extreme care !!

Numerical constraints

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

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

PIC: DSA in pair plasma shocks



★ Diffusive Shock Acceleration (DSA) has

...ivistic pair

...Spitkovsky

... with bulk

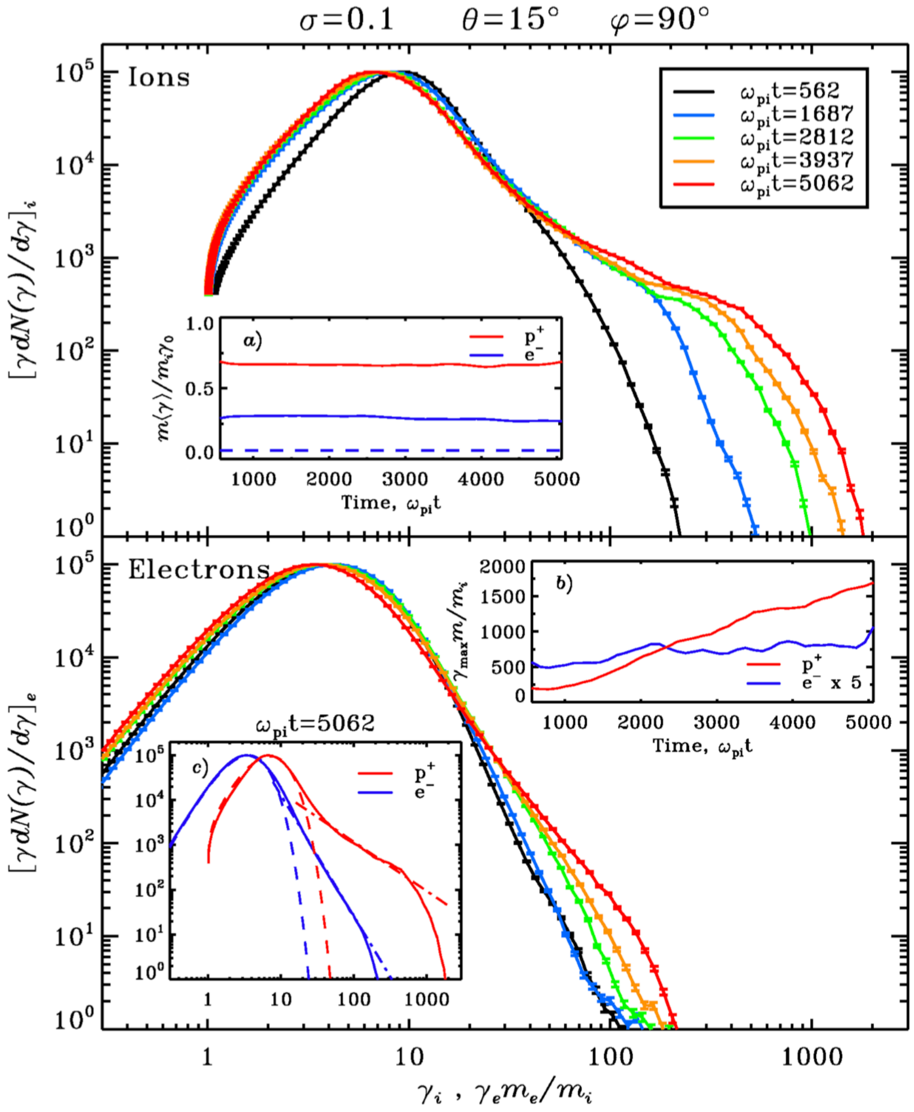
...ng plasma

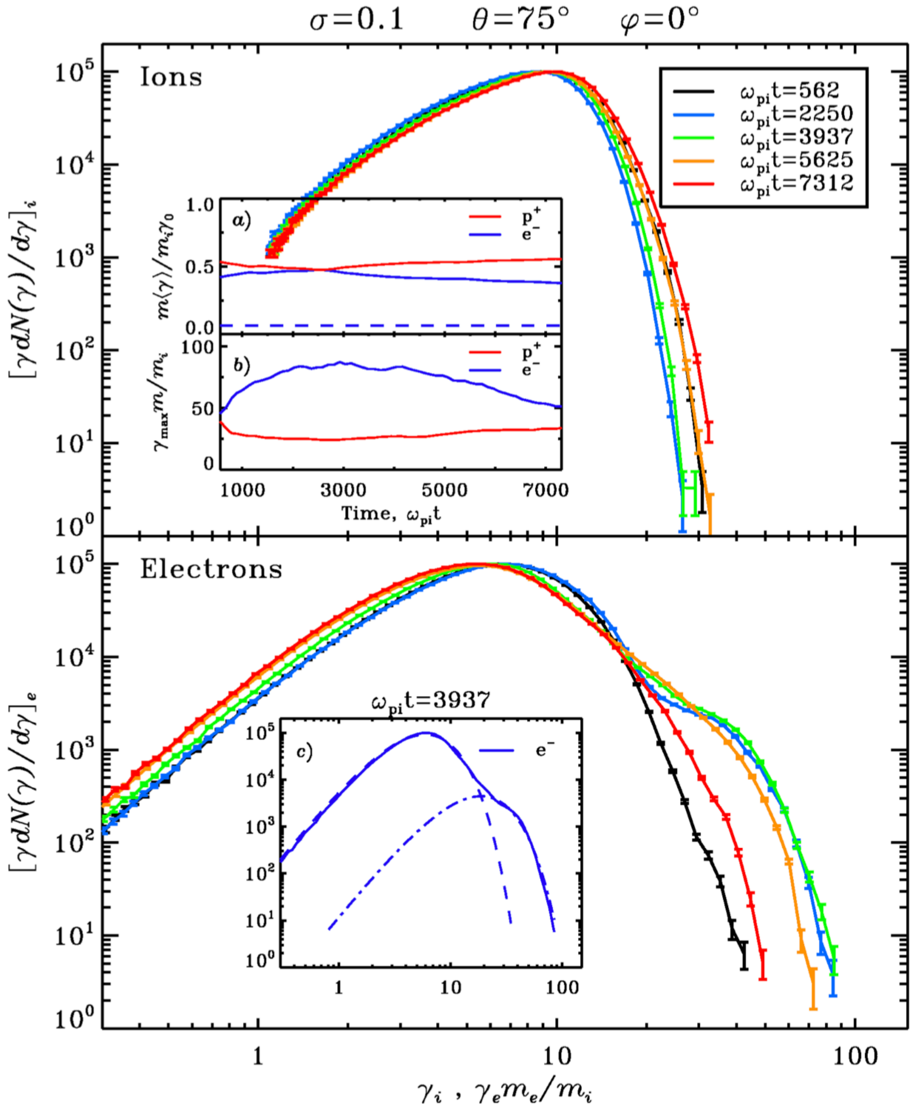
... thanks to

... magnetic

...wer law ?

PIC: DSA in relativistic p+/e- plasmas





Sironi & Spitkovsky (2011)

Subluminal shock vs Superluminal shock

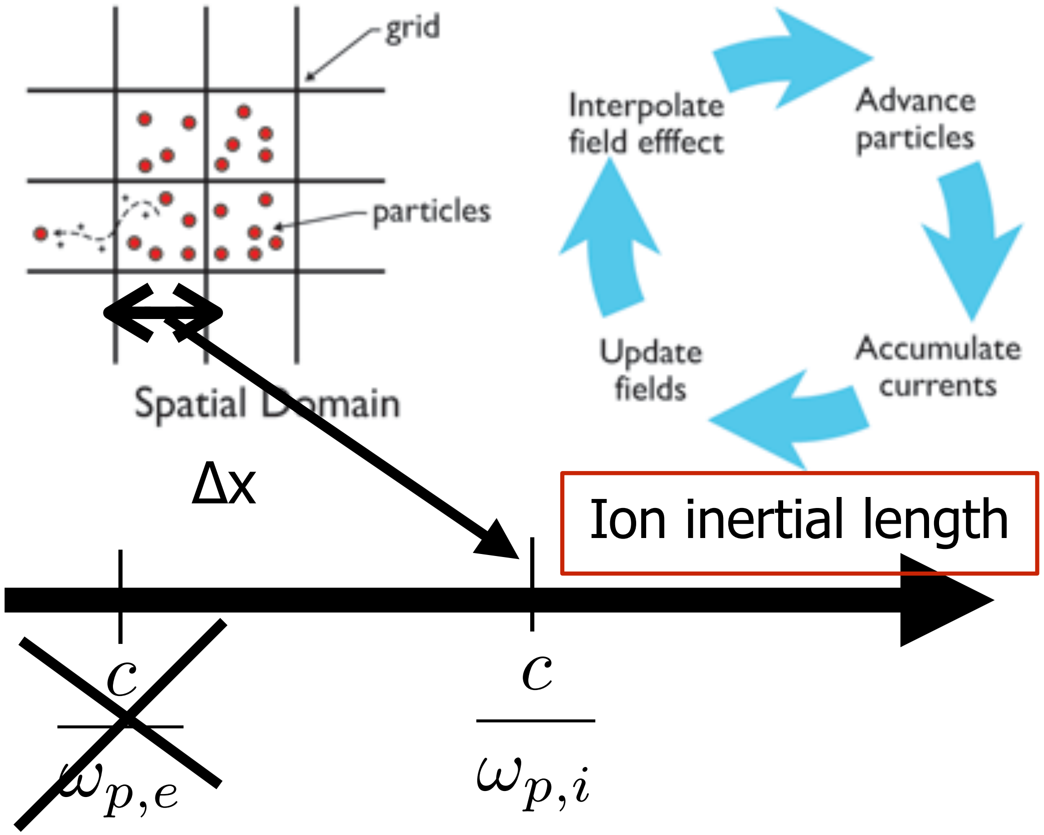
Alternatives to PIC:
Hybrid-PIC vs Particle in MHD Cells

- Particle-In-Cells (PIC) simulations requires huge computational ressources to assess the very beginning of DSA near astrophysical shocks.

- PIC simulations describe a tiny fraction of the precursor of shocks (box size $<$ 1% precursor size).

- Alternative methods to PIC have been developped to partially alleviate these issues.

Hybrid-PIC simulations



➡ 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)

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

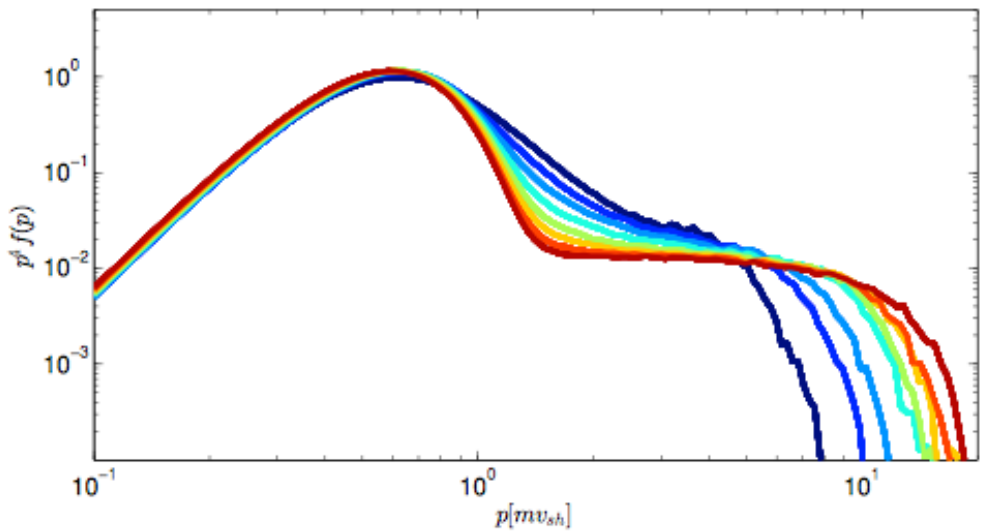
Numerical constraints

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

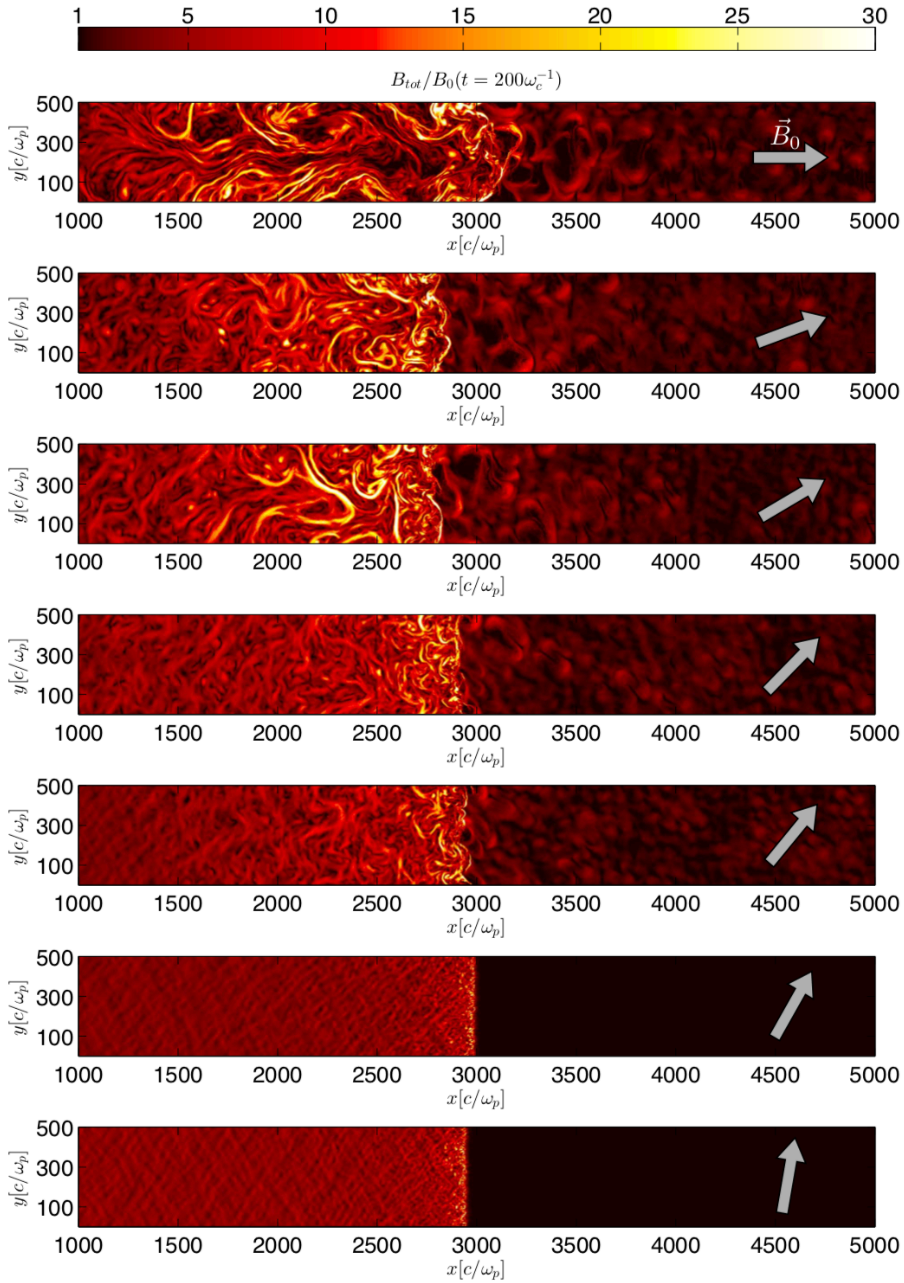
Hybrid-PIC: DSA & magnetic field obliquity

➡ 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 ($\boldsymbol{\theta}$>50°) but yet <u>subluminal</u>!

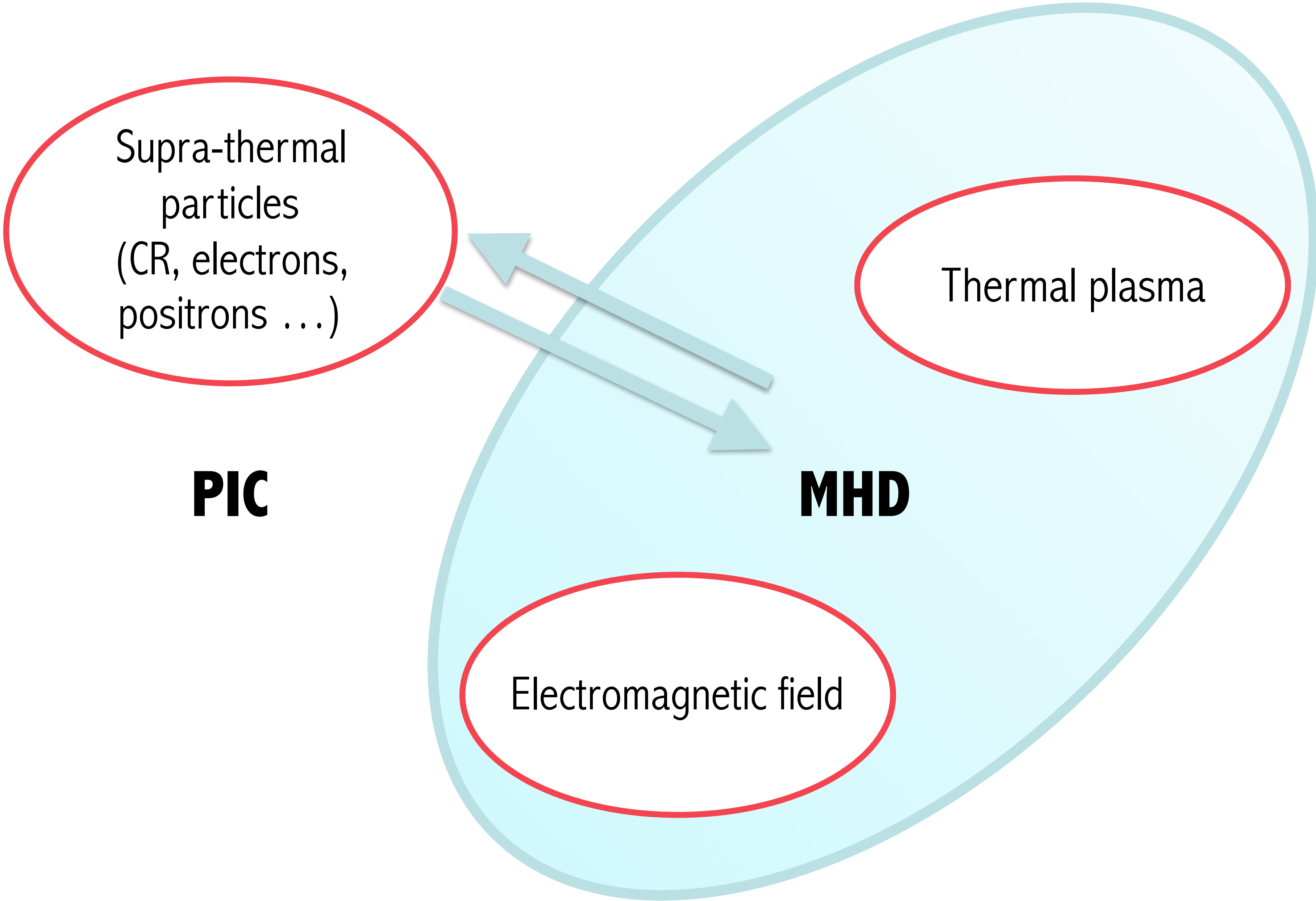


DSA near parallel shock ($\boldsymbol{\theta}$=0)



Caprioli & Spitkovsky (2014a,b,c)

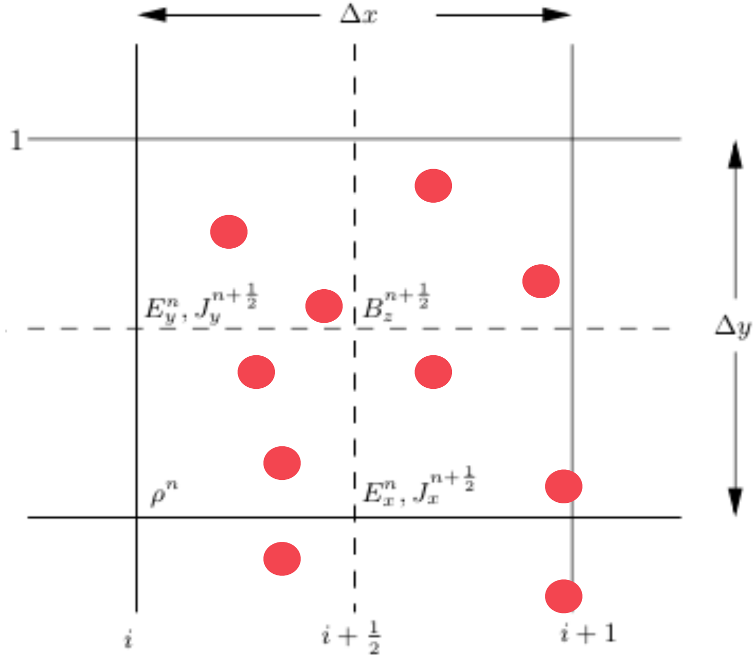
An alternative approach

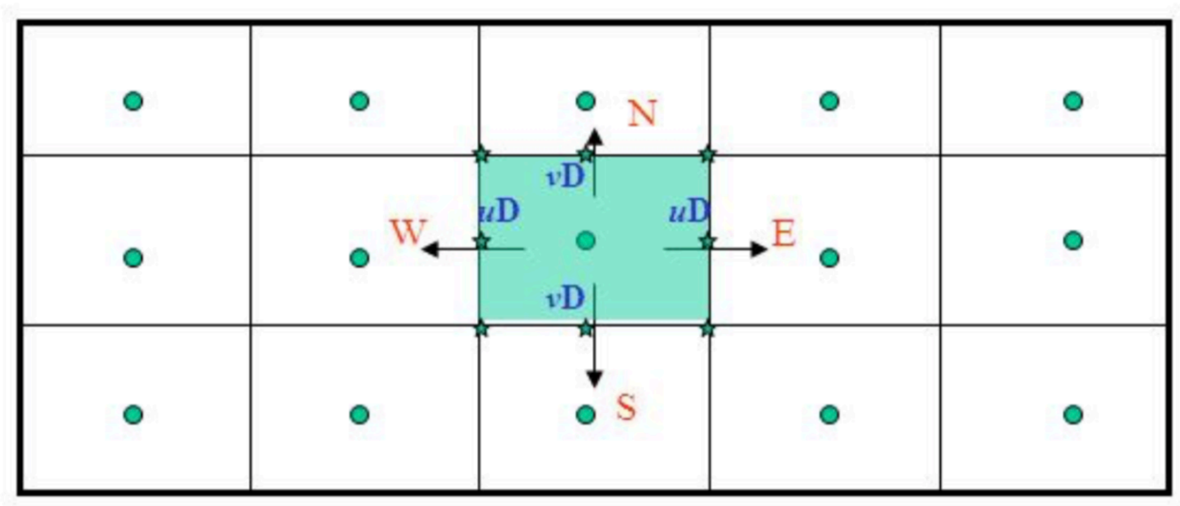


PIC versus MHD

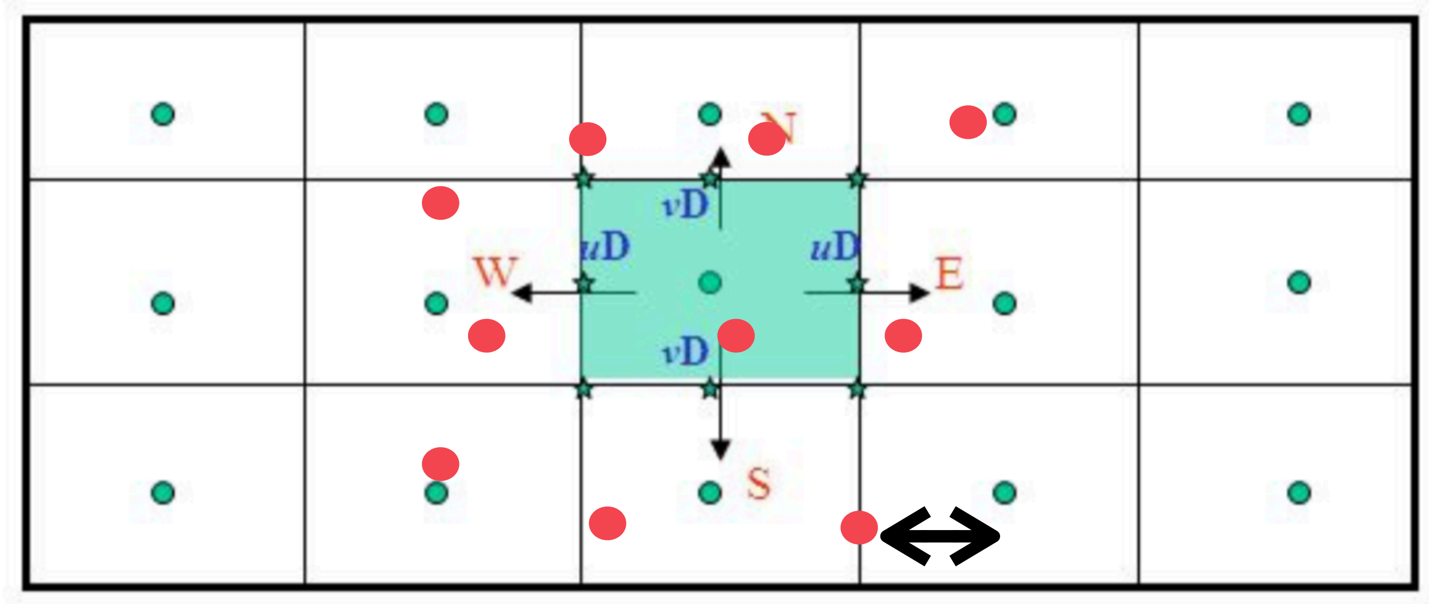
PIC: Supra-thermal particles + Maxwell Eqs

MHD : volume averaged quantities + conservation Eqs





Particle In MHD Cells simulations



Ion inertial length

$$\partial_t D + c\partial_j \left(D\beta^j \right) = 0$$

$$\partial_t S^i + c\partial_j \left\{ S^i \beta^j - (E \times B)^i \beta^j - E^i E^j - B^i B^j + \left(P + \frac{B^2 + E^2}{2} \right) \delta^{ij} \right\} = -\rho_{\rm CR} E^i - (\vec{J}_{\rm CR} \times \vec{B})^i$$

$$\partial_t \mathrm{B}^i + \varepsilon_k^{ij} \partial_j E^k = 0$$

$$\partial_t \tau + c\partial_j \left[\left(\tau + P + \frac{B^2 - E^2}{2} \right) \beta^j - ((\vec{E} - \vec{E}_O) \times \vec{B})^j \right] = -\vec{J}_{\rm CR} \cdot \vec{B}$$

Modified Relativistic MHD eqs

$$\frac{d\gamma \vec{v}_k}{dt} = -\frac{q_k}{m_k} \left(\left\{ 1 - \frac{n_{cr}}{n_g} \right\} \vec{U} + \frac{n_{cr}}{n_g} \vec{U}_{cr} - \vec{v}_k \right) \times \vec{B}$$

Modified motion eqs

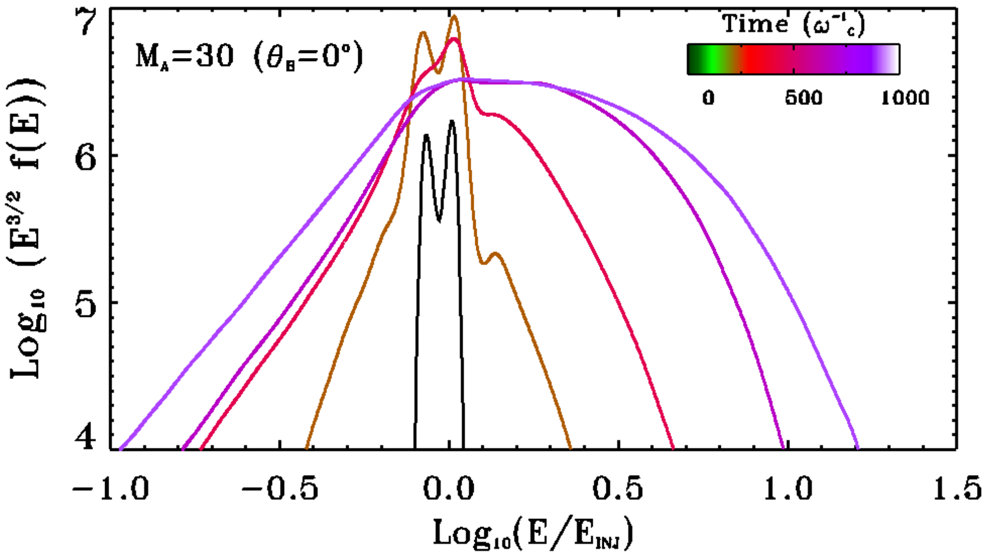
Ohm's law

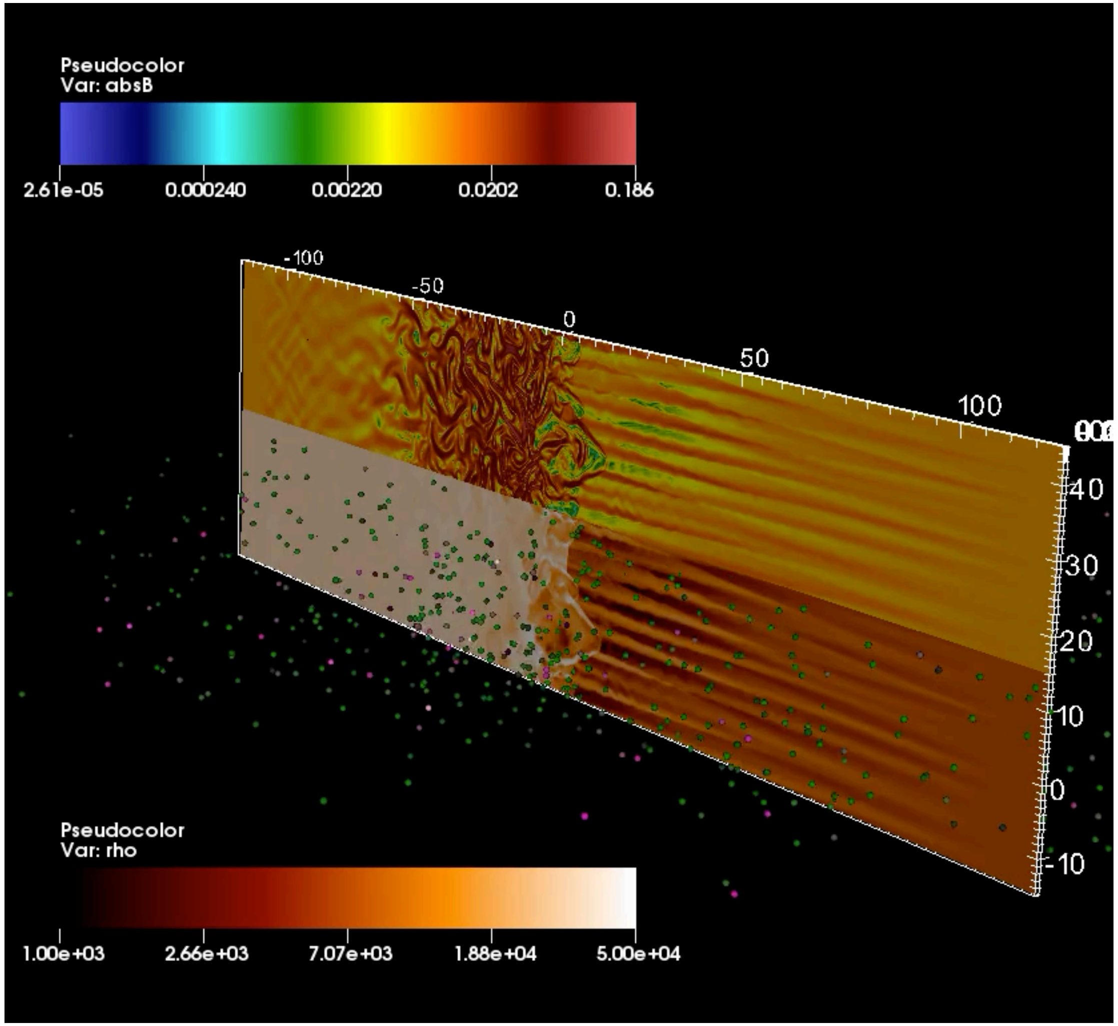
$$\vec{\mathbf{E}} = -\left(\left(1 - \frac{n_{CR}}{n_e}\right) \vec{\mathbf{U}} + \frac{n_{CR}}{n_e} \vec{\mathbf{U}}_{CR} \right) \times \vec{\mathbf{B}}$$

PI[MHD]C: DSA near parallel non-relativistic shocks

➡ Following full-PIC injection recipe at the shock one recover all results from Hybrid-PIC simulations on parallel shocks (code mPIC-AMRVAC).

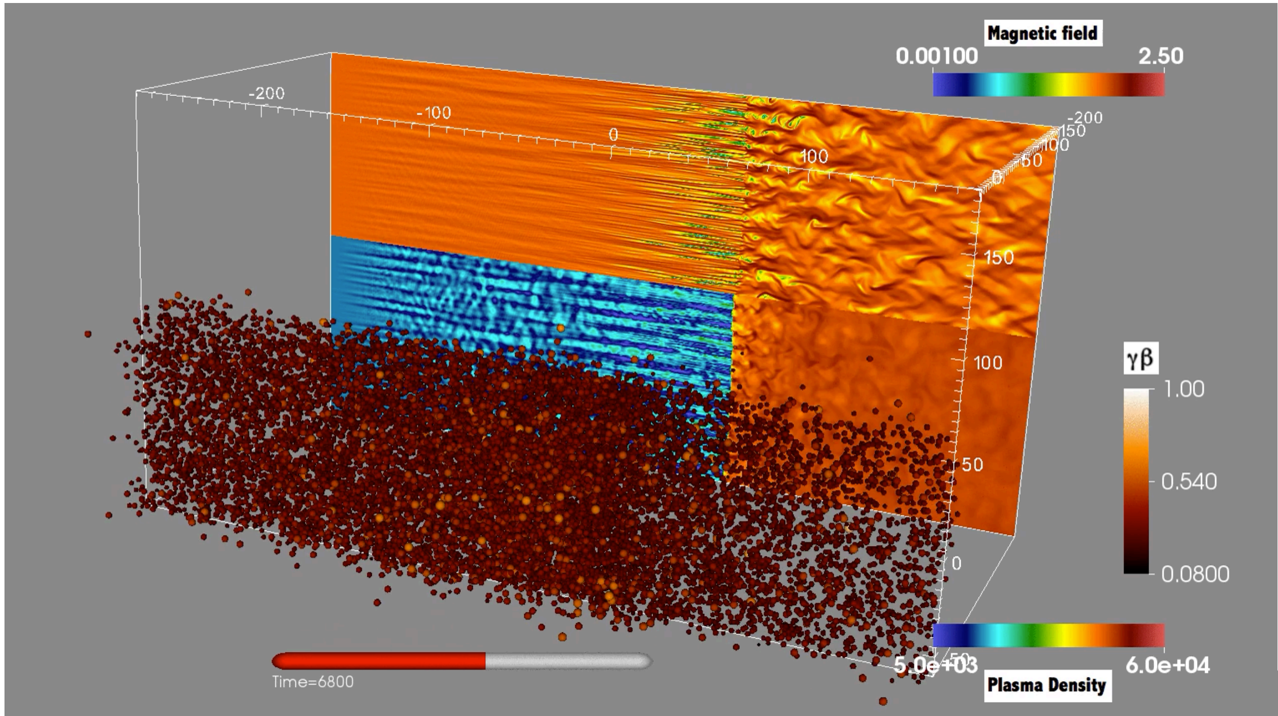
➡ Recovering Hybrid-PIC simulations results on DSA for non-relativsitic shocks…



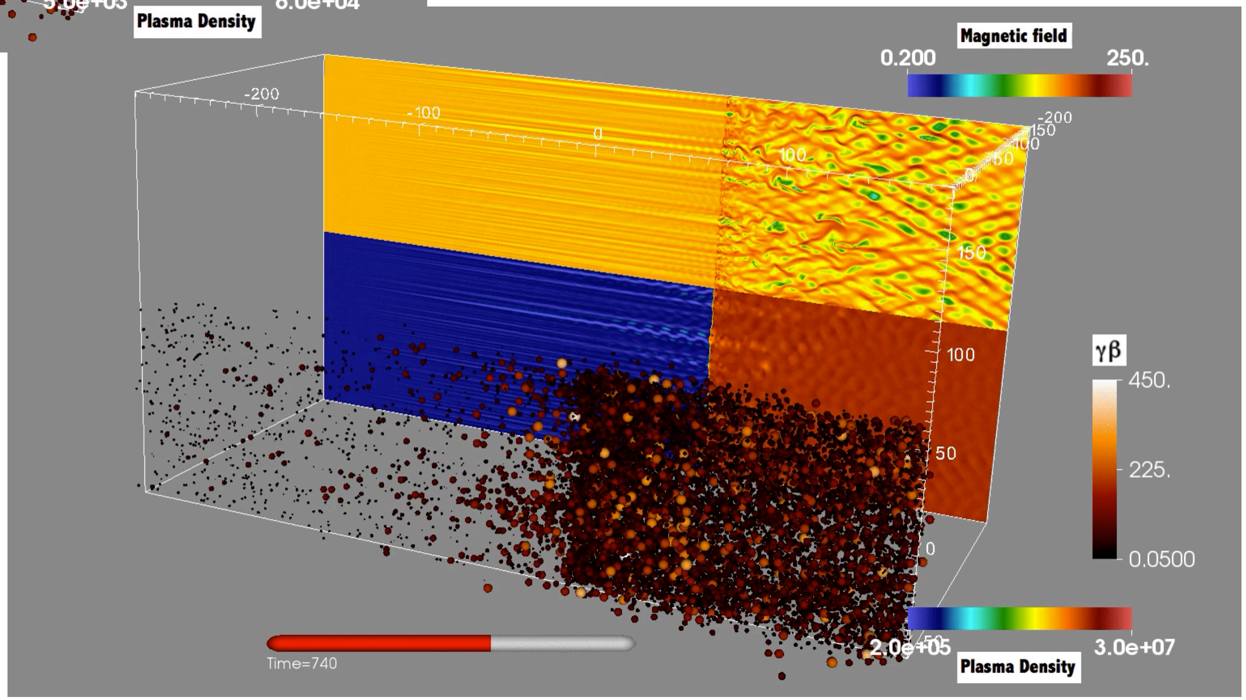


van Marle, Casse & Marcowith (2018)

DSA near parallel shocks:
Non-relativistic versus ultra-relativistic shocks



γ_{SH}=1.005



γ_{SH}=10

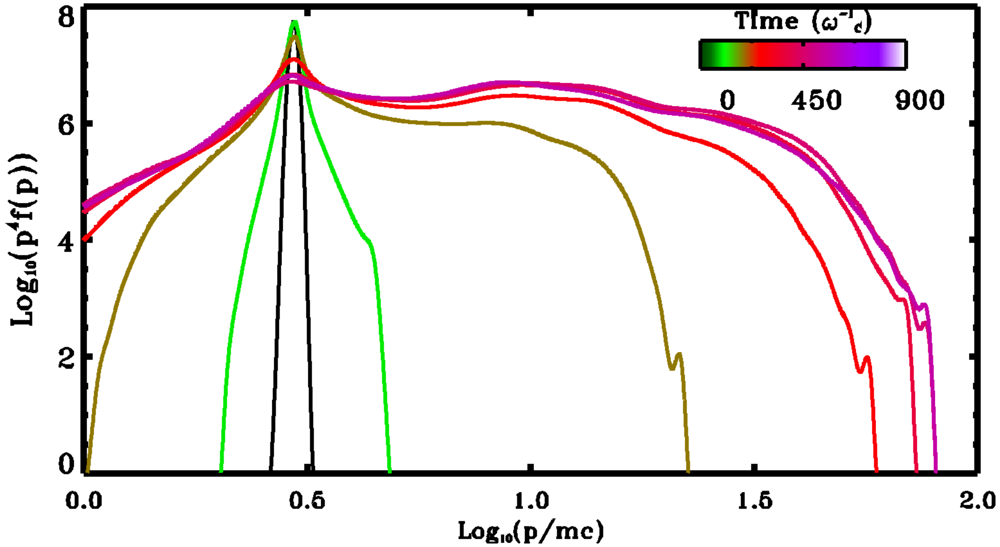
Casse, van Marle & Marcowith (prep)

DSA in parallel shocks:
CR acceleration from classical to relativistic regime

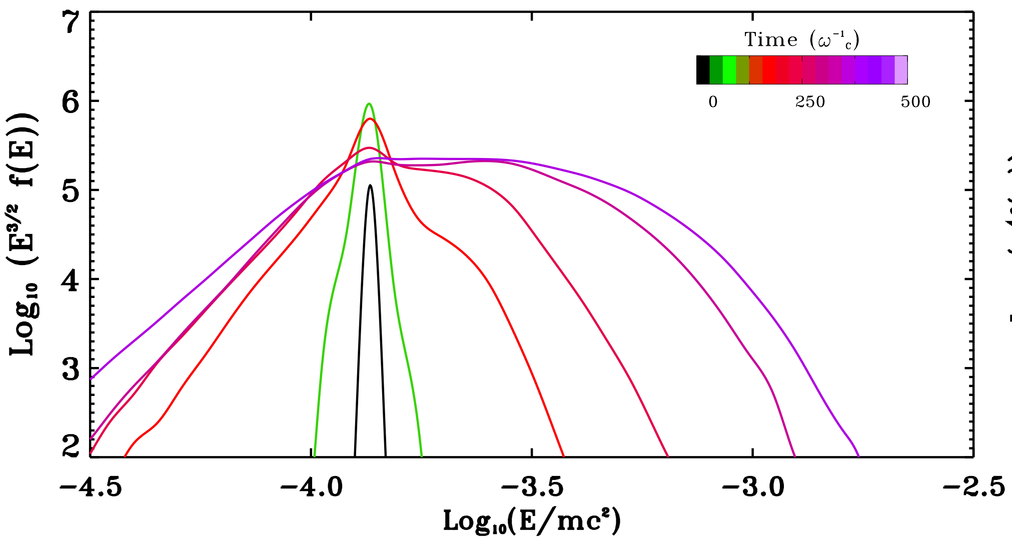
➡ More efficient Fermi-like acceleration for mildly relativistic shocks as upstream CR losses decreases.

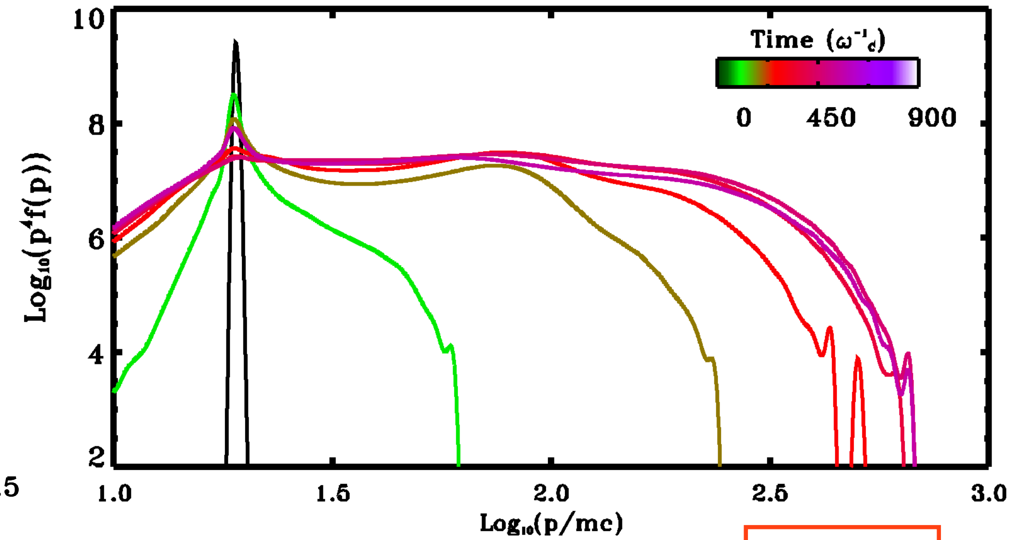
➡PI[RMHD]C simulations reach a better statistics but <u>still</u> rely on PIC injection recipe.

$\gamma_{SH}=2$



$\gamma_{SH}=1.0001$

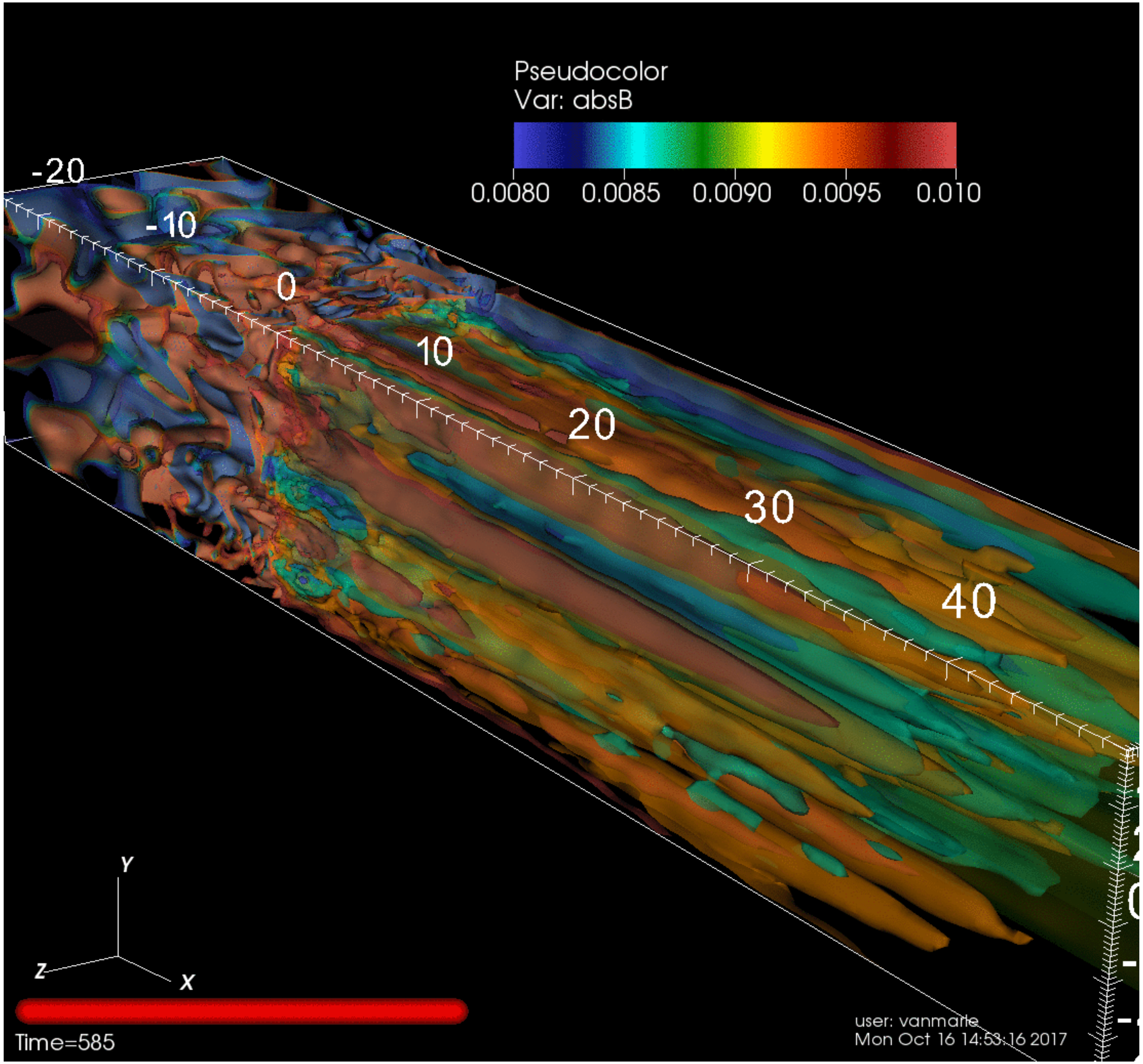




$\gamma_{SH}=10$

Casse, van Marle & Marcowith (prep)

PI[MHD]C: 3D DSA near parallel non-relativistic shocks

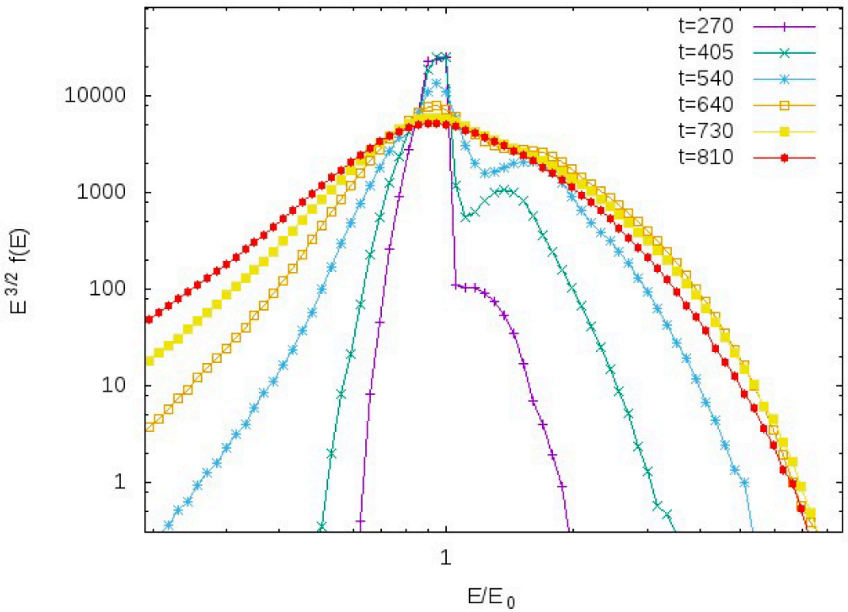


van Marle et al (2019)

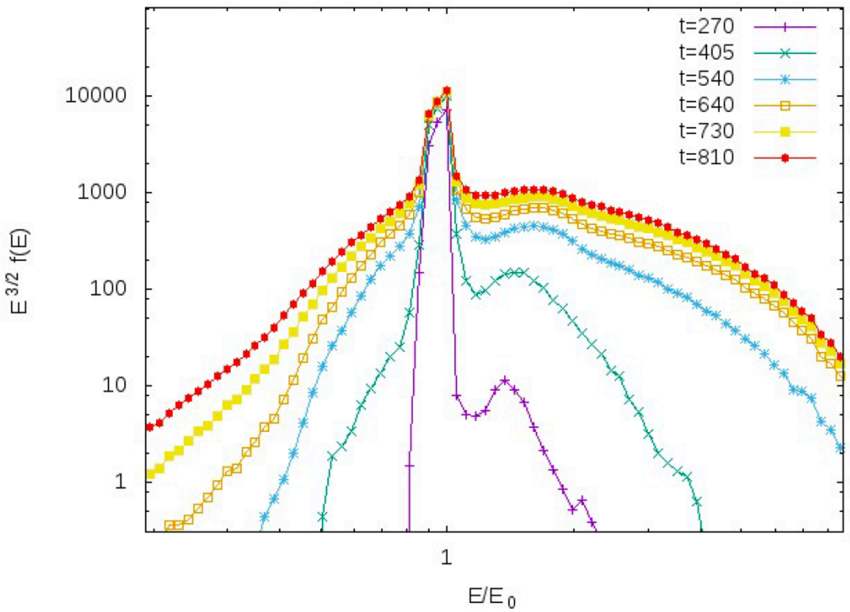
PI[MHD]C: 3D DSA near parallel non-relativistic shocks

➡ 3D3V simulations recover the basic trends regarding plasmas quantities and large-scale magnectic field (i.e. the same turbulence spectrum).

➡ Particle acceleration is less efficient in 3D due to the full filamentation process that prevent the trapping of particles in 2D current sheets.



3D



2D

van Marle, Casse & Marcowith (2019)

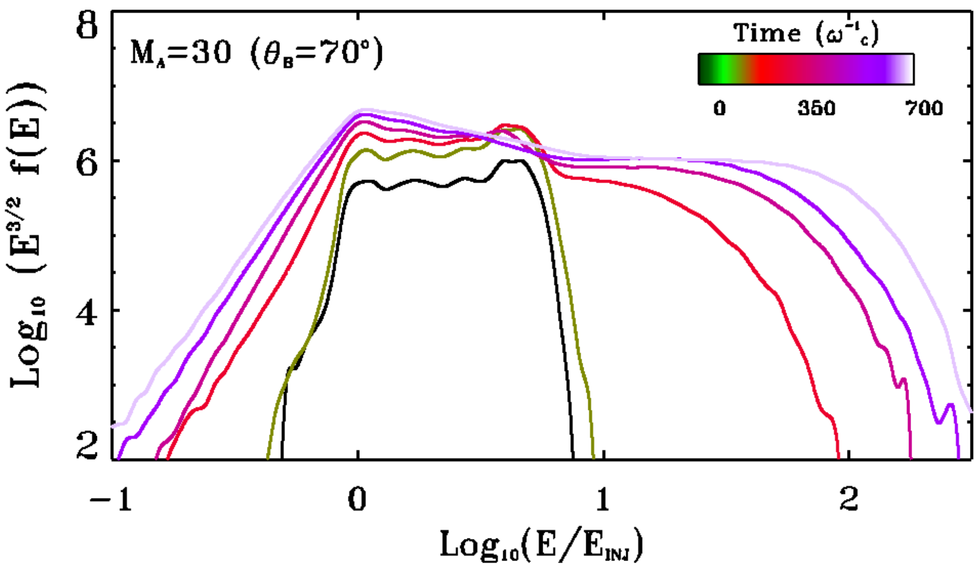
PI[MHD]C: DSA near-perpendicular non-relativistic shocks

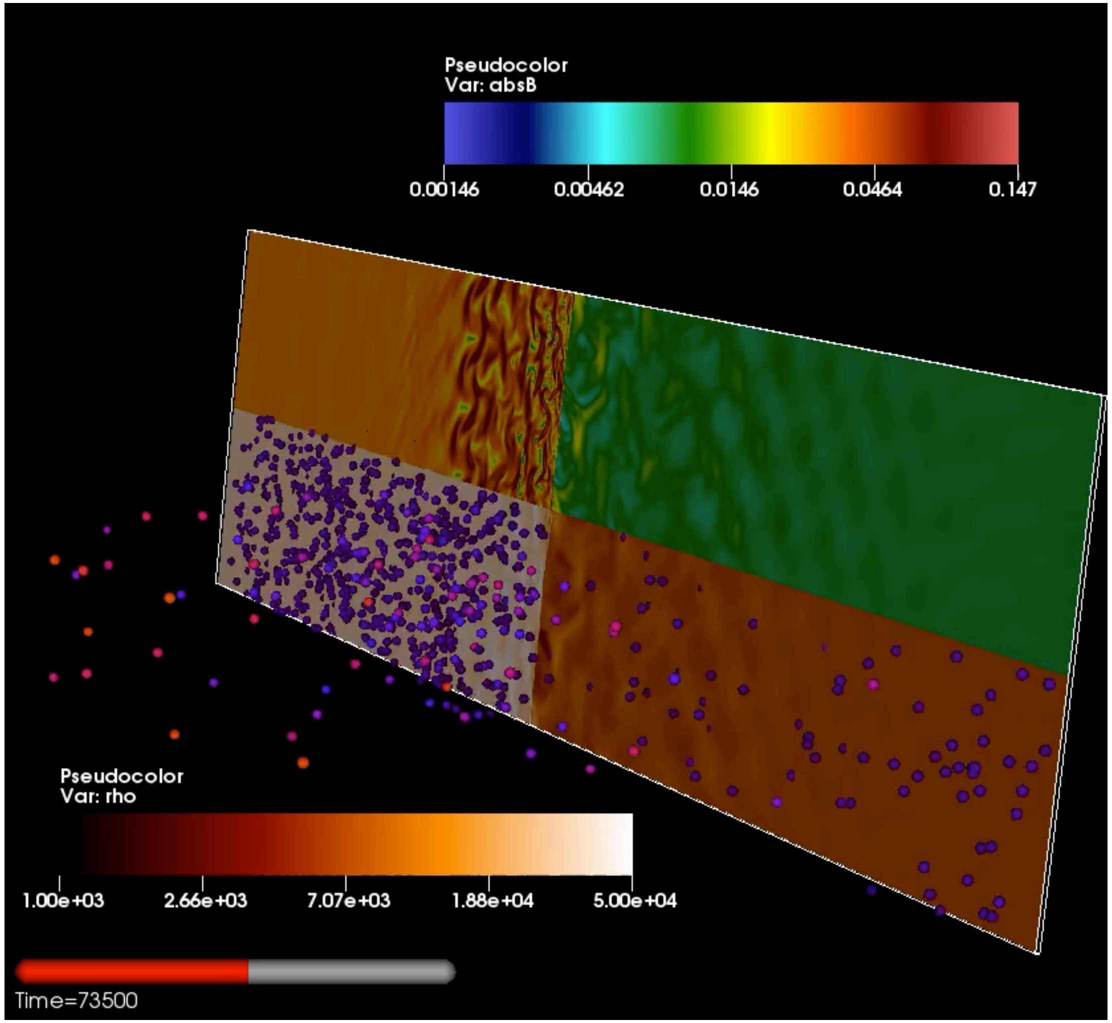
➡ Large scale Bell's instability leads to corrugation of the shock front

➡ DSA and magnetic amplification is triggered by the corrugation of the shock

➡ Shock Drift Acceleration is pre-heating particles before entering DSA.

➡**Contradiction with Hyb.-PIC sim. !**





van Marle, Casse & Marcowith(2018)

Summary and outlook

😀 ◉ PI[RMHD]C simulations can complement full-PIC simulations as they enable us to reach larger spatial extension and larger time-scale.

😀 ◉ PI[RMHD]C simulations provides better statistics regarding non-thermal accelerated particles and spectra.

😠 ◉ However PI[RMHD]C simulations rely on particle injection recipes and cannot describe microphysics (e.g. electron skin depth) nor unmagnetized plasmas…

◉ PIC, Hybrid-PIC & PI[RMHD]C simulations agree on DSA near magnetized parallel shocks (efficient ion acceleration).

◉ Disagreement arises when dealing with magnetized non-relativistic perpendicular shocks: no ion acceleration (Hybrid-PIC) vs ion acceleration after shock corrugation (PI[MHD]C)…

Summary and outlook

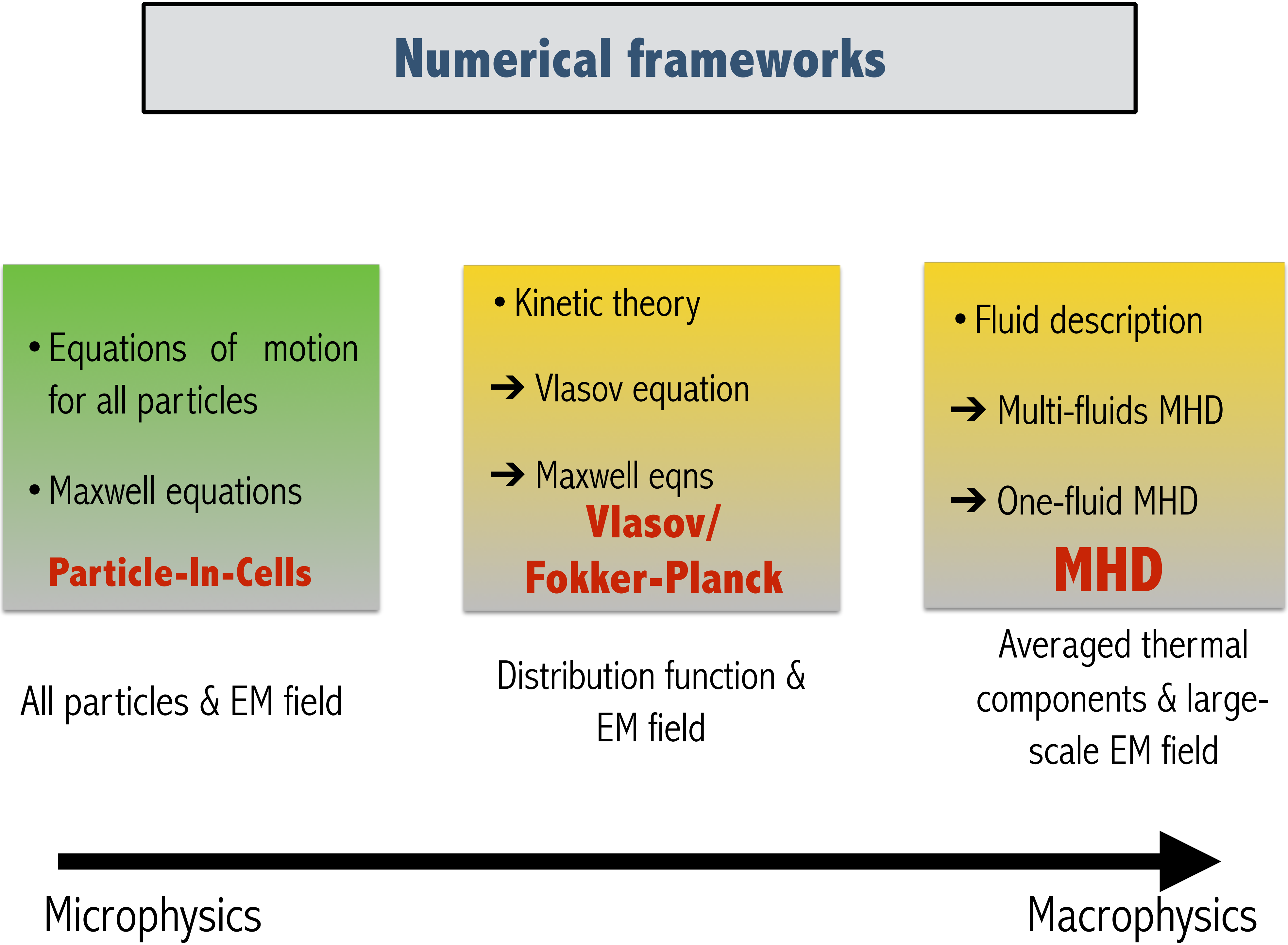
◉ We need to understand the particle injection process at the shock in order to get a reliable recipe for injection at perpendicular shocks.

◉ Adressing this issue may require to mix a full-PIC description of the shock region with PI[RMHD]C computations of the upstream and downstream media.

◉ PI[RMHD]C simulations can be a way to model large-scale astrophysical jets and the associated non-thermal cosmic-ray/leptonic emissions.

◉ Including general relativistic effects is possible as GRMHD codes are now well working when dealing with plasmas near compact objects (ion/electron jet with Blandford-Znajek process ?).

BackUp Slides


Numerical frameworks
• Equations of motion for all particles
• Maxwell equations
Particle-In-Cells
• Kinetic theory
→ Vlasov equation
→ Maxwell eqns
Vlasov/ Fokker-Planck
• Fluid description
→ Multi-fluids MHD
→ One-fluid MHD
MHD
All particles & EM field
Distribution function & EM field
Averaged thermal components & large-scale EM field
Microphysics
Macrophysics

Questions & open issues

Perpendicular shocks

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 ?

- Hybrid-PIC simulations are performed with very limited proton density (4 particle/cell and 2 cell/ion skin depth) and it is not clear what are the effects of hybrid assumptions upon the perpendicular shock structure (overestimate of the electrical barrier).

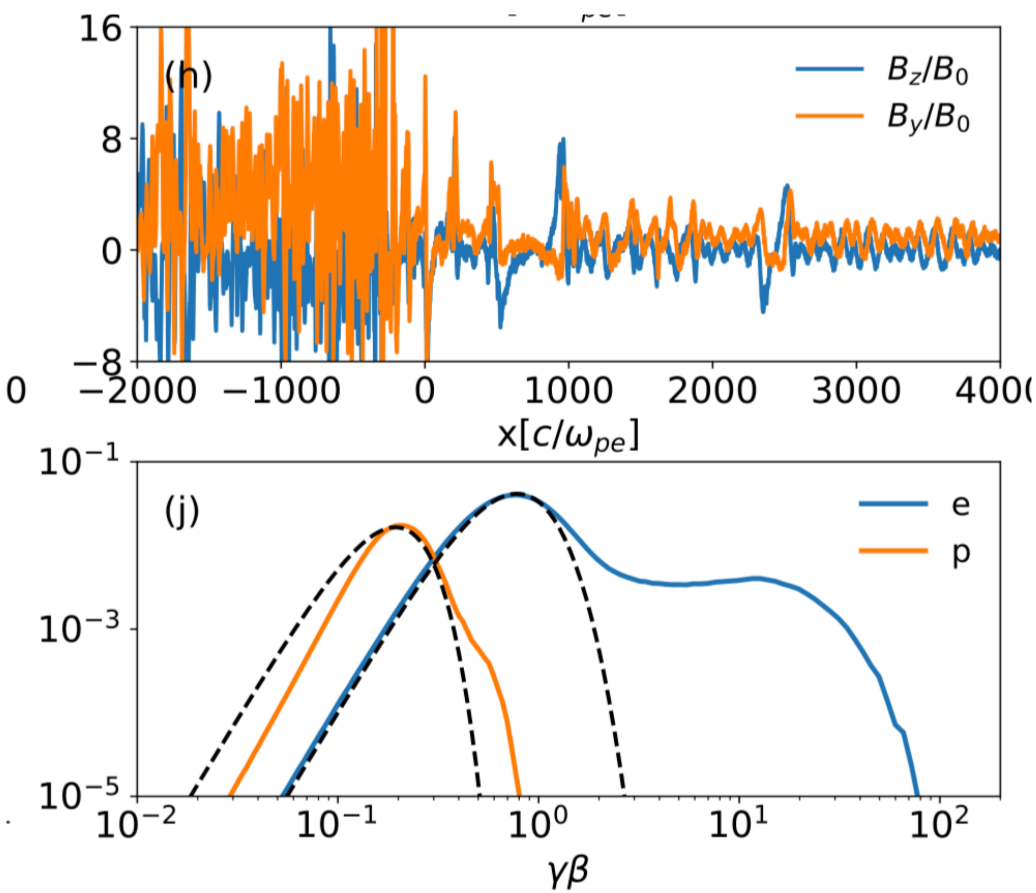
- PI[MHD]C simulations do not self-consistently inject non-thermal particles but rely on recipes from PIC simulations and do not depict the microphysics of the shock.

Questions & open issues

Perpendicular shocks

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

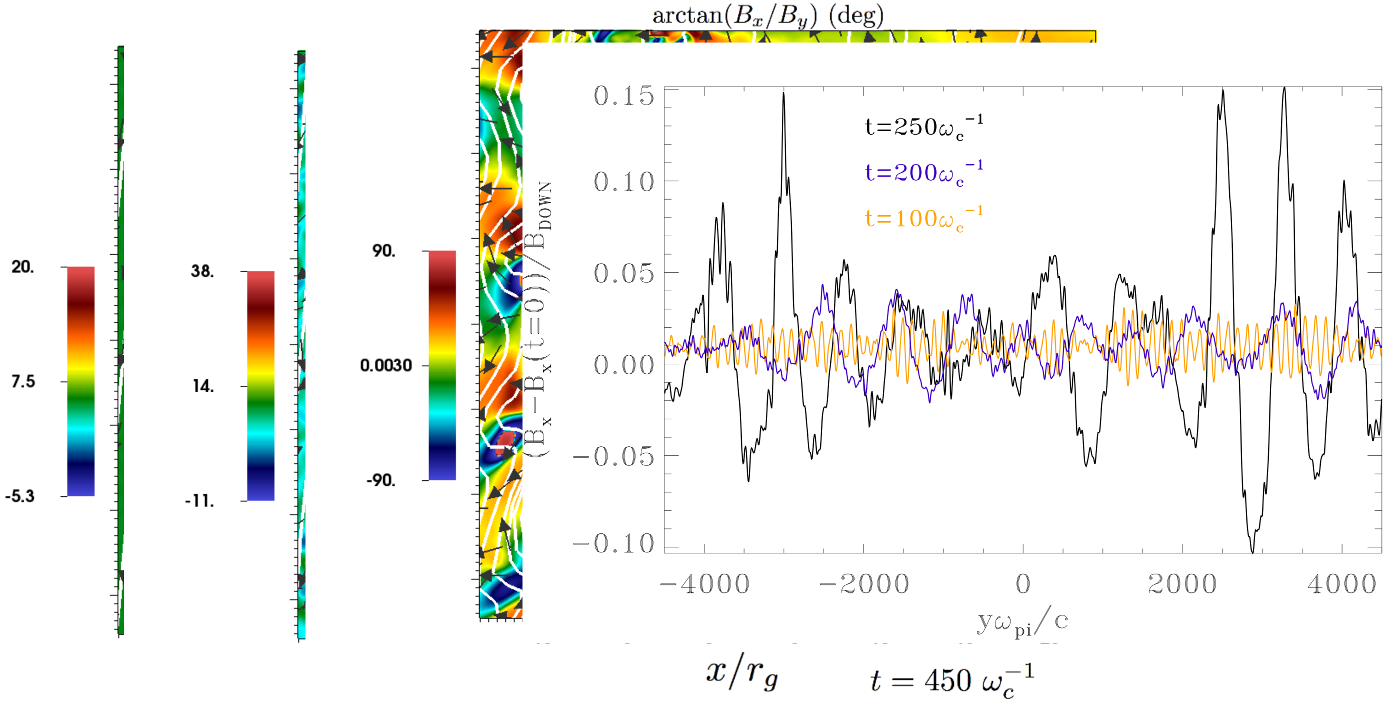
➡ 1D3V Full-PIC simulations shows that electrons can trigger DSA by generating uptream magnetic turbulence via Bell instability (Xu, Spitkovsky & Caprioli 2019) ➜ Ion injection into DSA, Corrugation of the shock ?



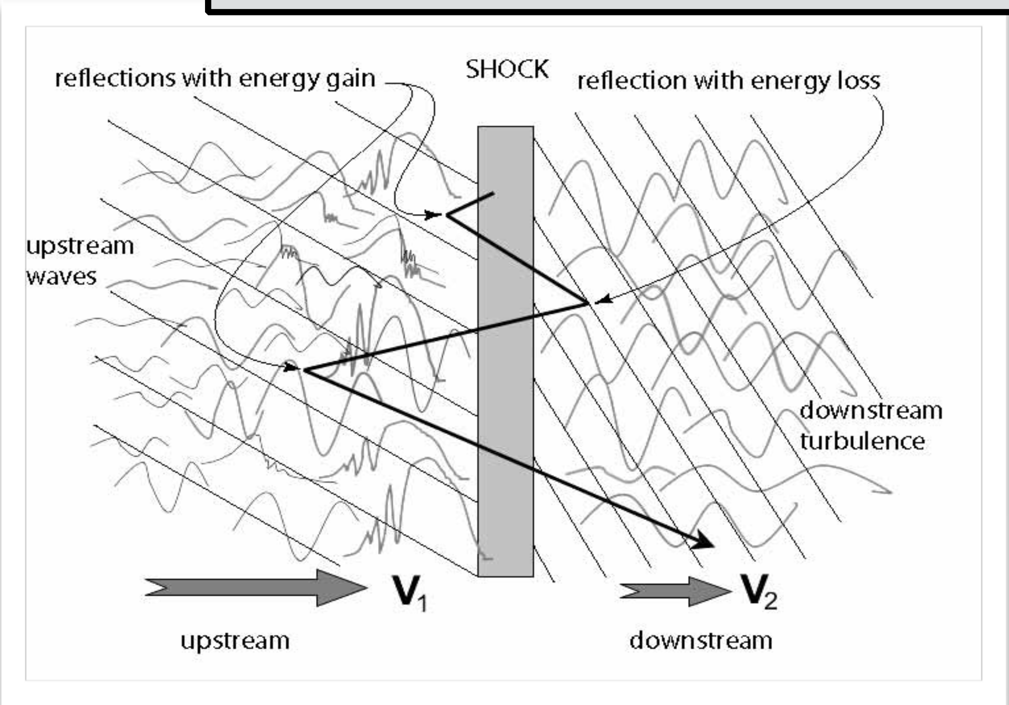
CR-induced corrugation of oblique shocks

➡ A long wavelength current-driven instability arises just behind the shock

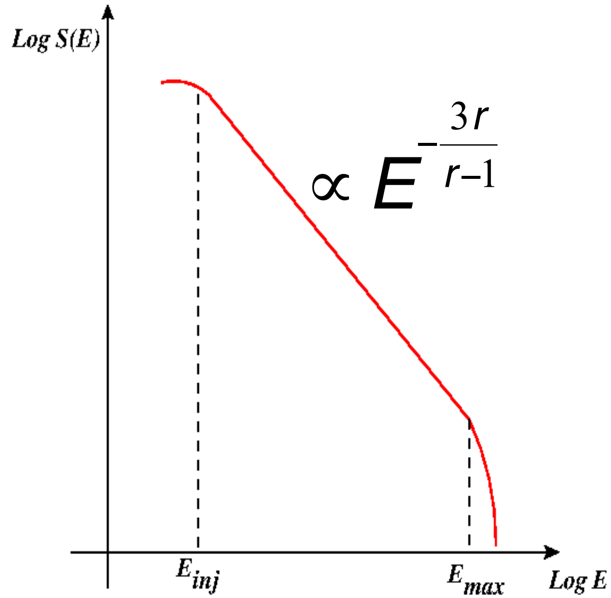
➡ Wavelength and growth rate are compatible with a downstream Bell instability …



The Diffusive Shock Acceleration (DSA)



$$r = \frac{\rho_d}{\rho_u}$$



Krymsky'77, Axford'77,
Blandford & Ostriker'78, Bell'78

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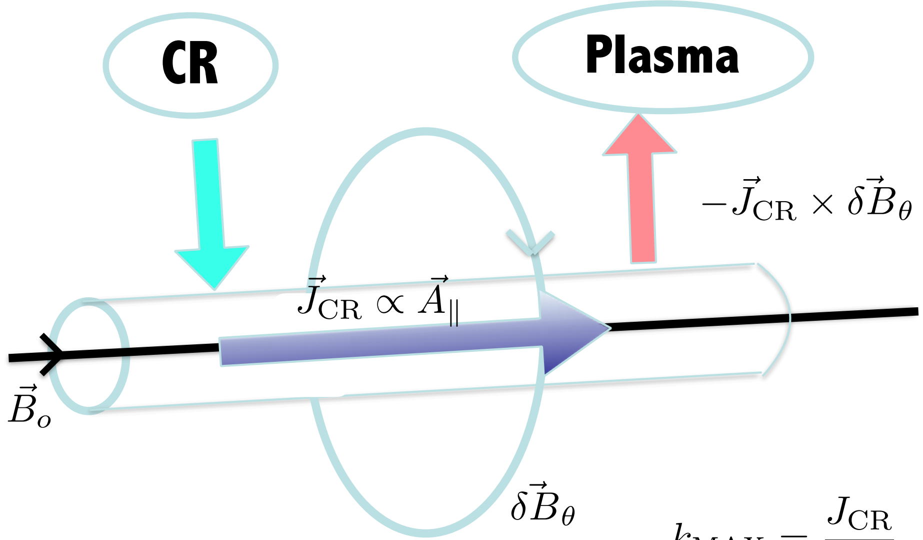
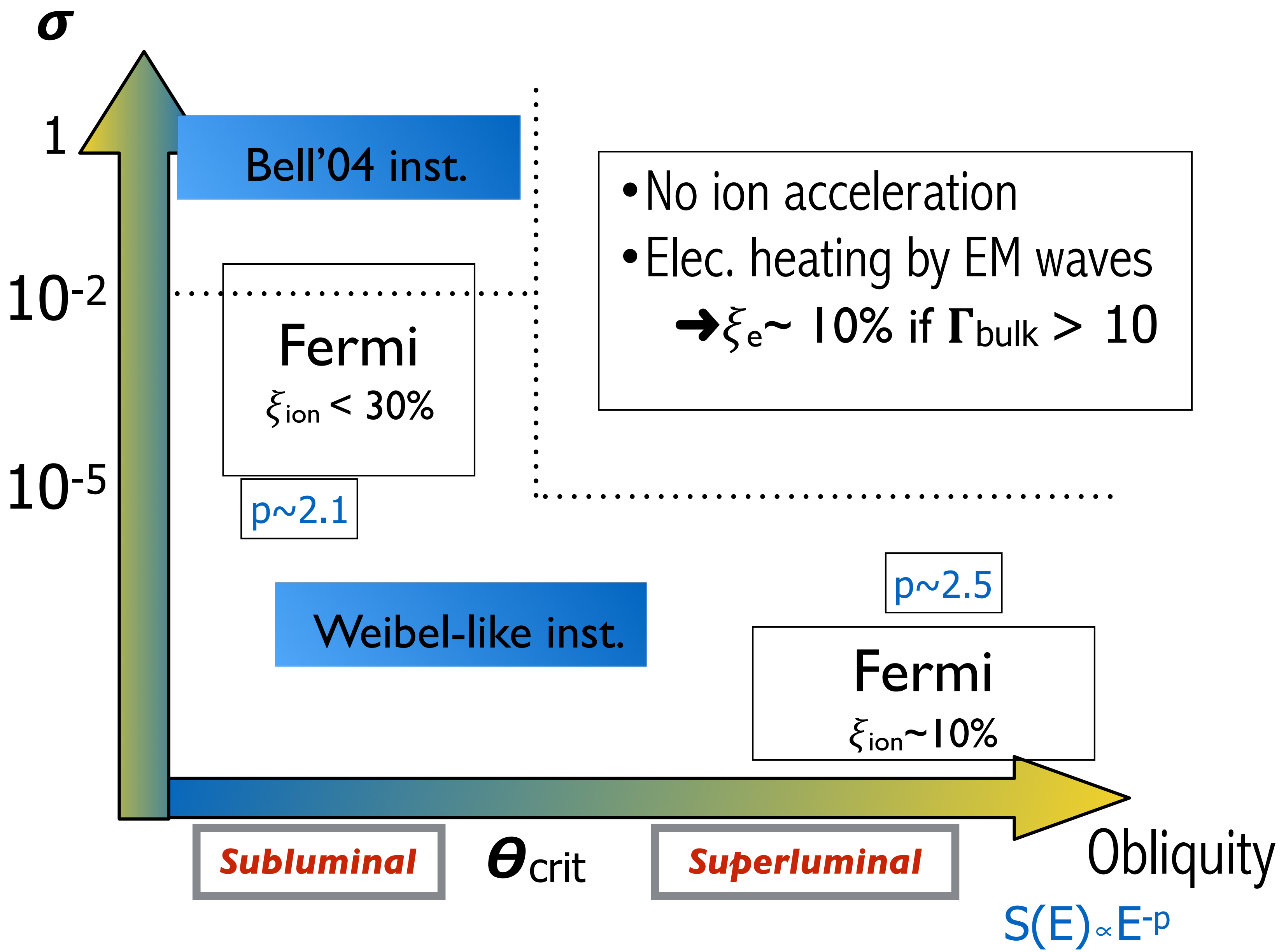


$$k_{\rm MAX} = \frac{J_{\rm CR}}{2B_o}$$

Non-resonant streaming instability
(Bell 2004)

PIC: DSA in relativistic p+/e- plasmas



Relativistic astrophysical shocks

• Similar magnetic amplification is likely to occur in γ-ray bursts (external relativistic shocks, e.g. Li & Waxman 2006).

• Relativistic shock fronts are also present in pulsar wind nebula and AGN (e.g. blazars) with Lorentz factor ranging from a few units up to 10^6.

• Fermi acceleration upon planar ultra-relativistic shock is very efficient but return probability is very weak since most shocks are quasi-perpendicular !

➜ Strong downstream magnetic turbulence is required ! Corrugation ?

• Astrophysical shocks are usually strong shocks ($M_{FM} \gg 1$) ➜ Non-resonant streaming instability should drive large scale turbulence (Bell'04).