Micro- and multi-scale simulations of particle acceleration

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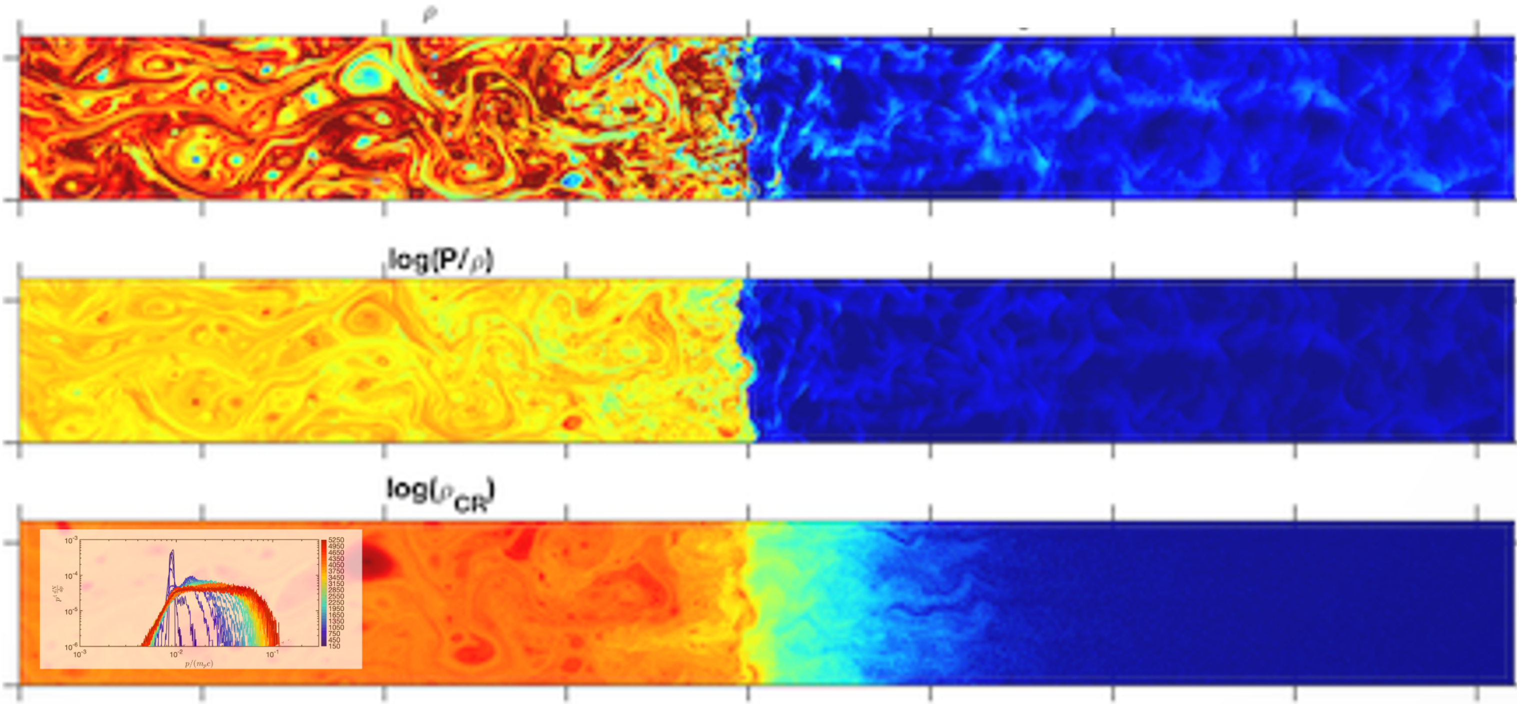
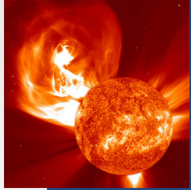
Atéliers Astroplasma IRAP, 10 Feb 2021



Examples of involved environments

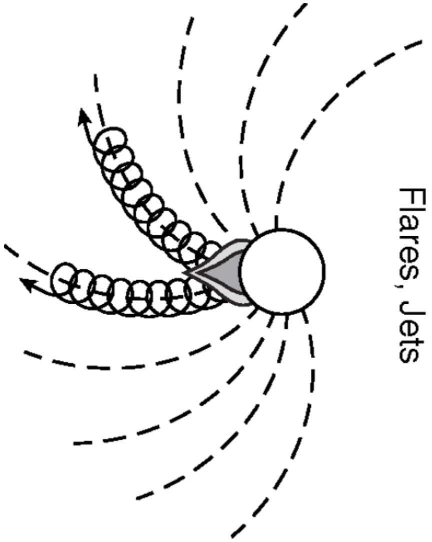
Astro context

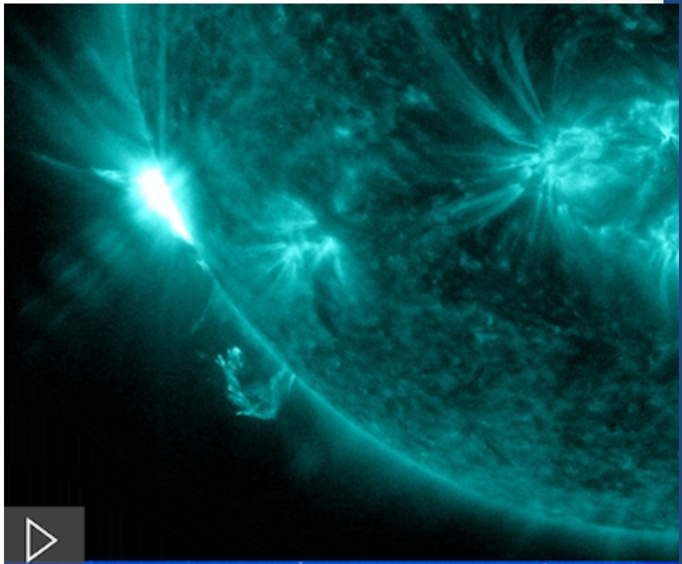


Flavors of particle acceleration in space/astrophysics

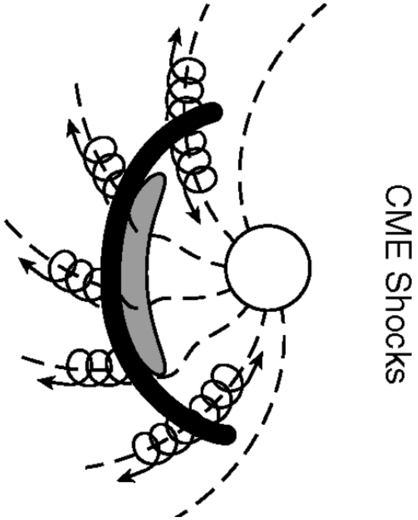
- Solar flares / CMEs

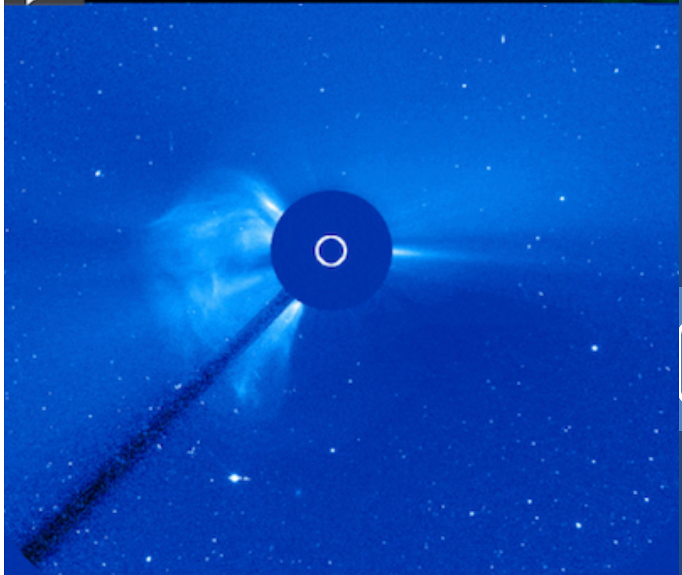
Measured in-situ as
impulsive event
(acceleration in
the small flare region)



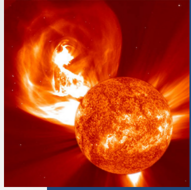


Measured in-situ as
gradual event
(acceleration in
the large CME region)



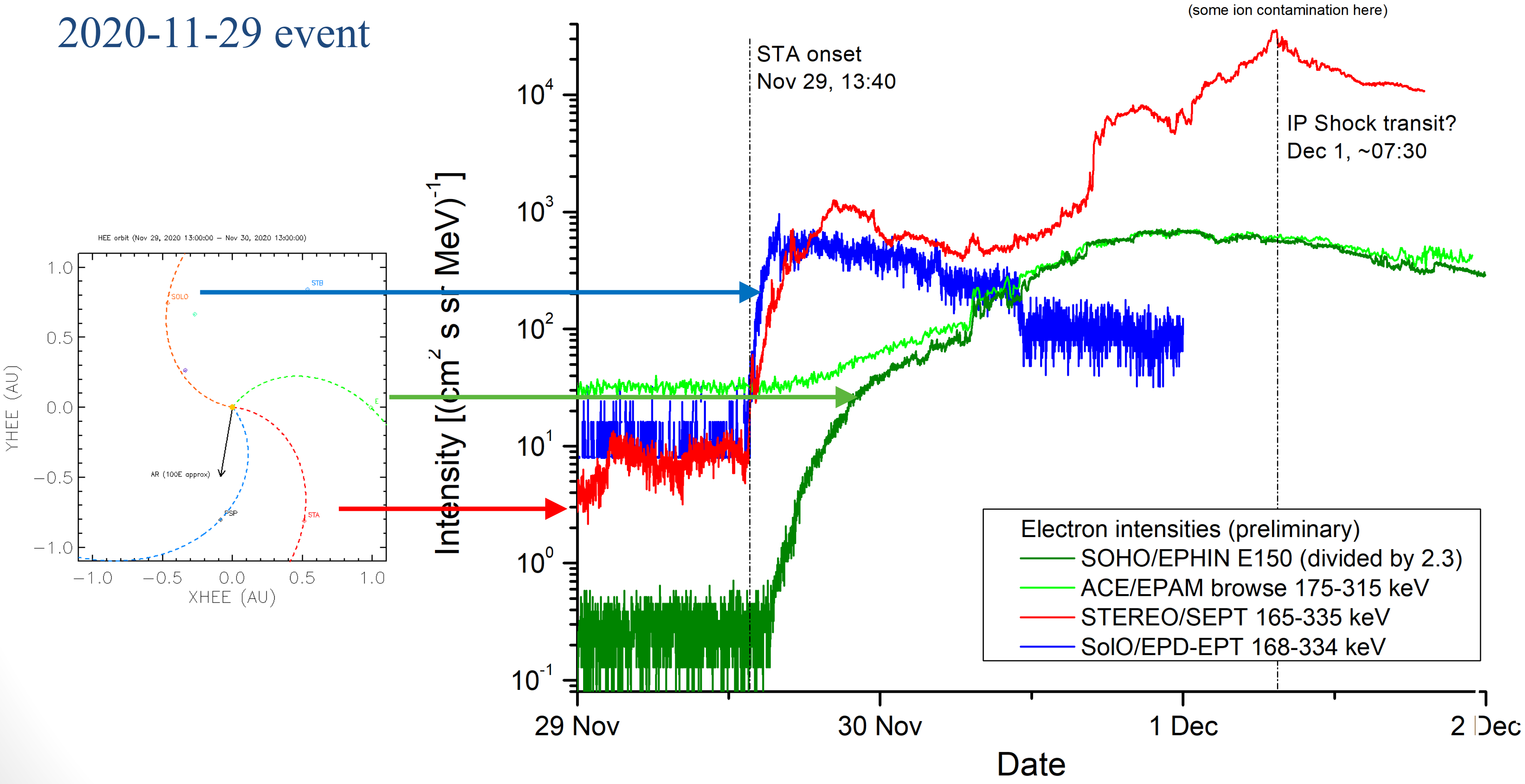


Astro context



Flavors of Fermi acceleration in space/astrophysics

- Solar flares / CMEs:
  2020-11-29 event

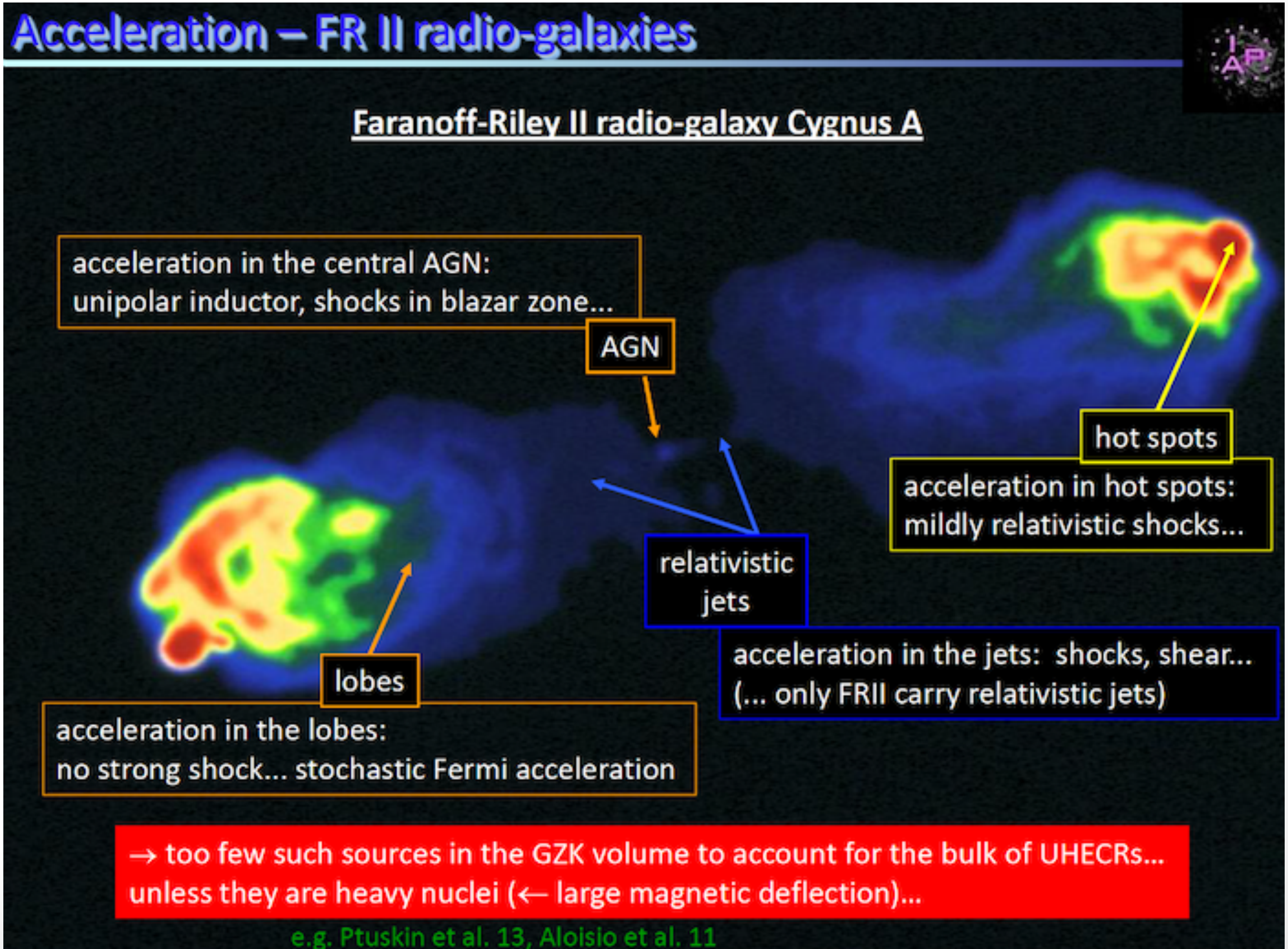


Times delays : evolving magnetic connectivity of the expanding shock to remote probes
Max intensity: history of shock strength & local plasma density ?

Astro context

Slide by Martin Lemoine, IAP

Flavors of Fermi acceleration in space/astrophysics



Acceleration – FR II radio-galaxies

Faranoff-Riley II radio-galaxy Cygnus A

acceleration in the central AGN:
unipolar inductor, shocks in blazar zone...

acceleration in hot spots:
mildly relativistic shocks...

acceleration in the jets: shocks, shear...
(... only FRII carry relativistic jets)

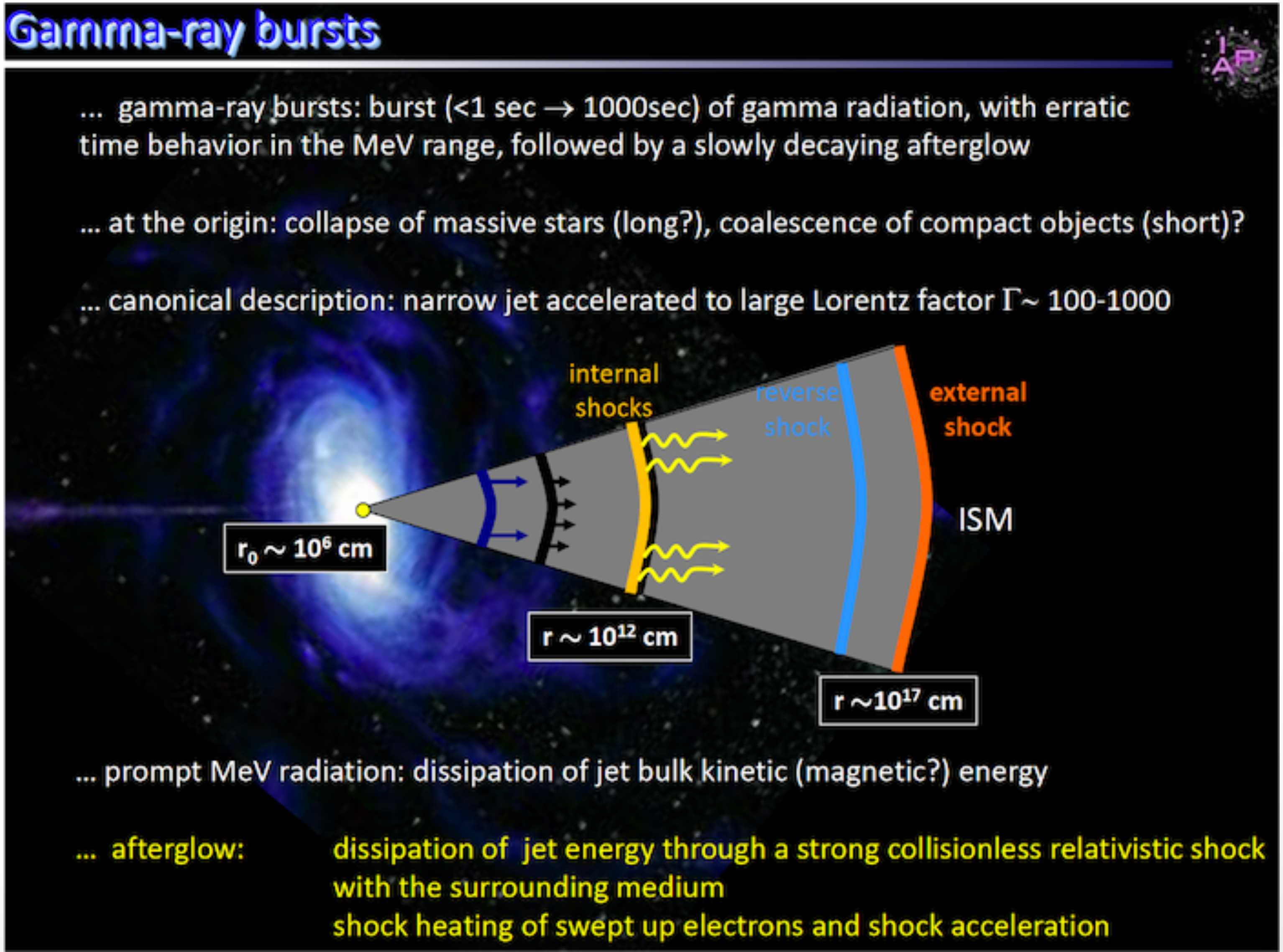
acceleration in the lobes:
no strong shock... stochastic Fermi acceleration

→ too few such sources in the GZK volume to account for the bulk of UHECRs... unless they are heavy nuclei (← large magnetic deflection)...

e.g. Ptuskin et al. 13, Aloisio et al. 11

Slide by Martin Lemoine, IAP

Flavors of Fermi acceleration in space/astrophysics



Gamma-ray bursts

… gamma-ray bursts: burst (<1 sec → 1000sec) of gamma radiation, with erratic time behavior in the MeV range, followed by a slowly decaying afterglow

… at the origin: collapse of massive stars (long?), coalescence of compact objects (short)?

… canonical description: narrow jet accelerated to large Lorentz factor $\Gamma \sim 100\text{-}1000$

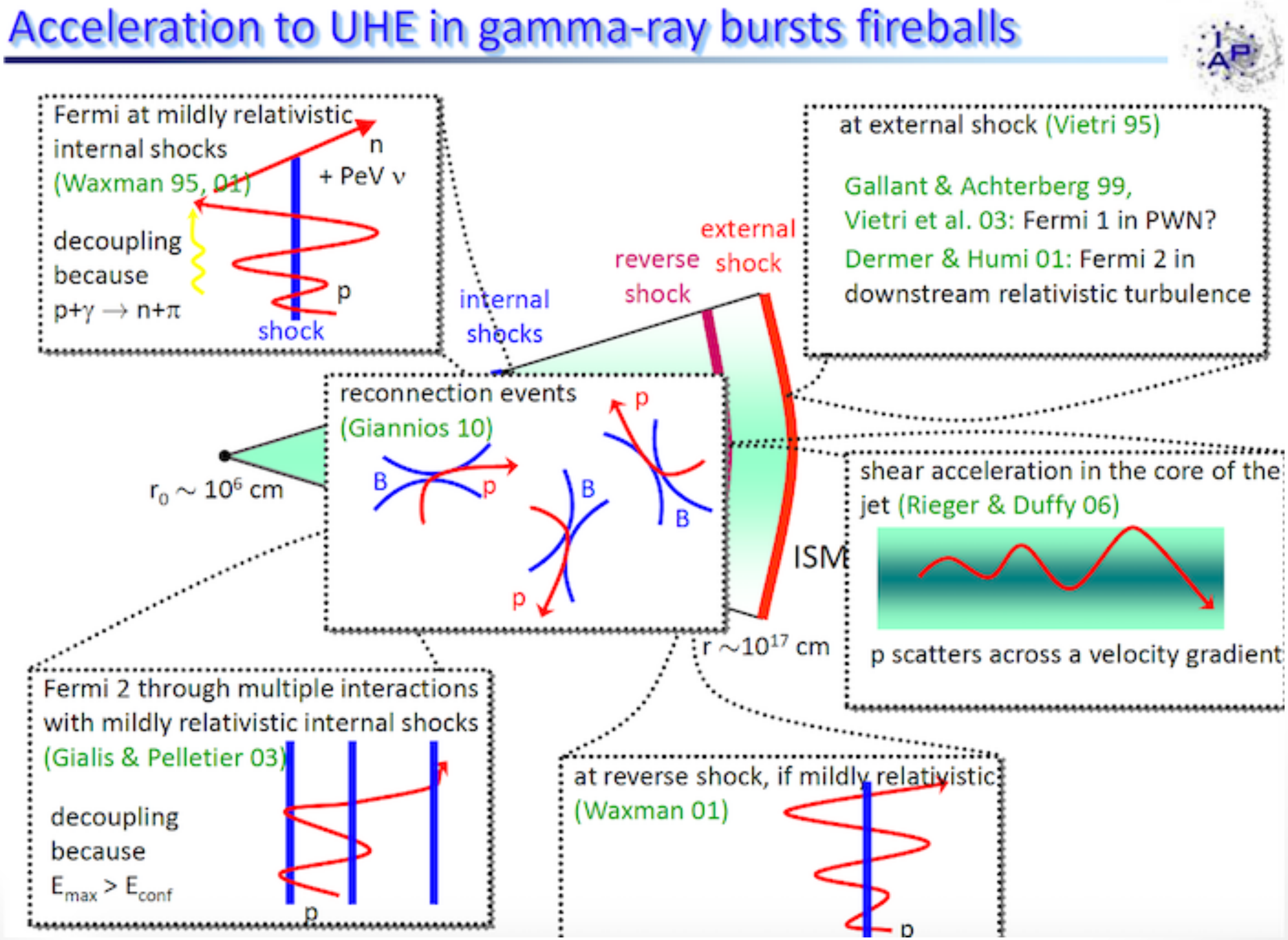
… prompt MeV radiation: dissipation of jet bulk kinetic (magnetic?) energy

… afterglow: dissipation of jet energy through a strong collisionless relativistic shock with the surrounding medium
shock heating of swept up electrons and shock acceleration

Astro context

Slide by Martin Lemoine, IAP

Flavors of Fermi acceleration in space/astrophysics



Acceleration to UHE in gamma-ray bursts fireballs

Fermi at mildly relativistic internal shocks (Waxman 95, 01)

decoupling because $p+\gamma \rightarrow n+\pi$

at external shock (Vietri 95)

Gallant & Achterberg 99,
Vietri et al. 03: Fermi 1 in PWN?
Dermer & Humi 01: Fermi 2 in downstream relativistic turbulence

reconnection events (Giannios 10)

shear acceleration in the core of the jet (Rieger & Duffy 06)

p scatters across a velocity gradient

Fermi 2 through multiple interactions with mildly relativistic internal shocks (Gialis & Pelletier 03)

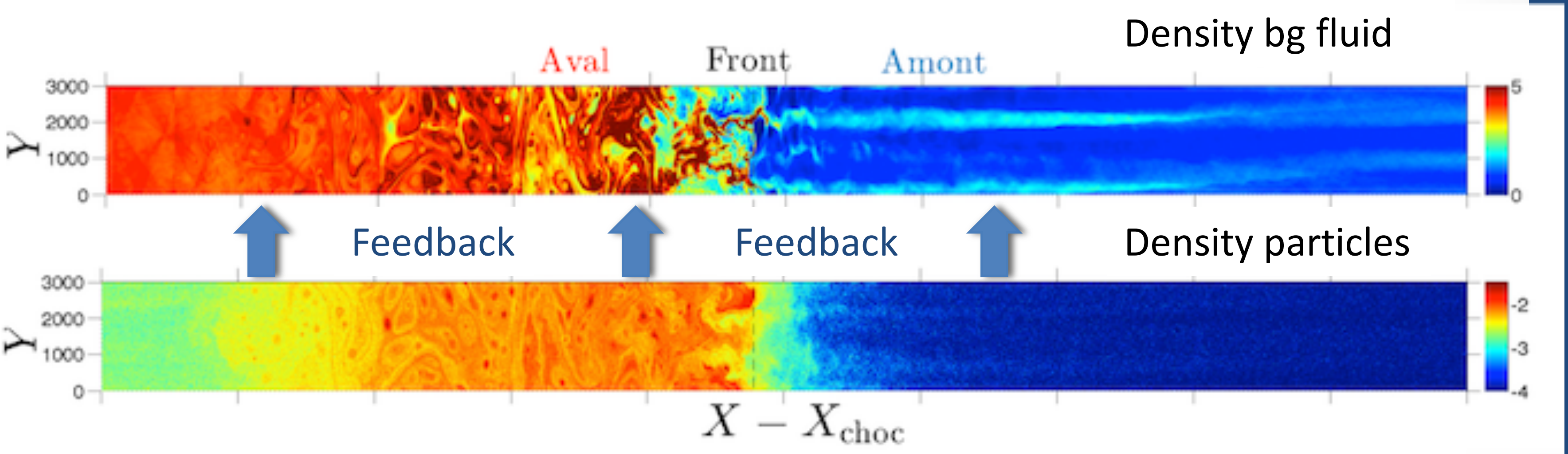
decoupling because $E_{max} > E_{conf}$

at reverse shock, if mildly relativistic (Waxman 01)

Why numerical simulations?

Goal: understand non-linear plasma physics of particle acceleration

Beyond standard DSA: non-linearities



Density bg fluid

Feedback

Feedback

Density particles

If no strong feedback -> test-particle DSA is valid.
BUT, in general, we do expect strong feedback from accelerated particles…

Different plasma simulation approaches

Types of numerical simulations

1. Fully kinetic: Particle-In-Cell or Vlasov codes
2. Hybrid-PIC or hybrid-Vlasov: electrons are fluid, ions are macro-particles
3. Hybrid-MHD: either supra-thermals are test-particles (not very interesting…) or coupled through PIC algorithm to the background fluid (MHD+CR as particles from supra-thermals).

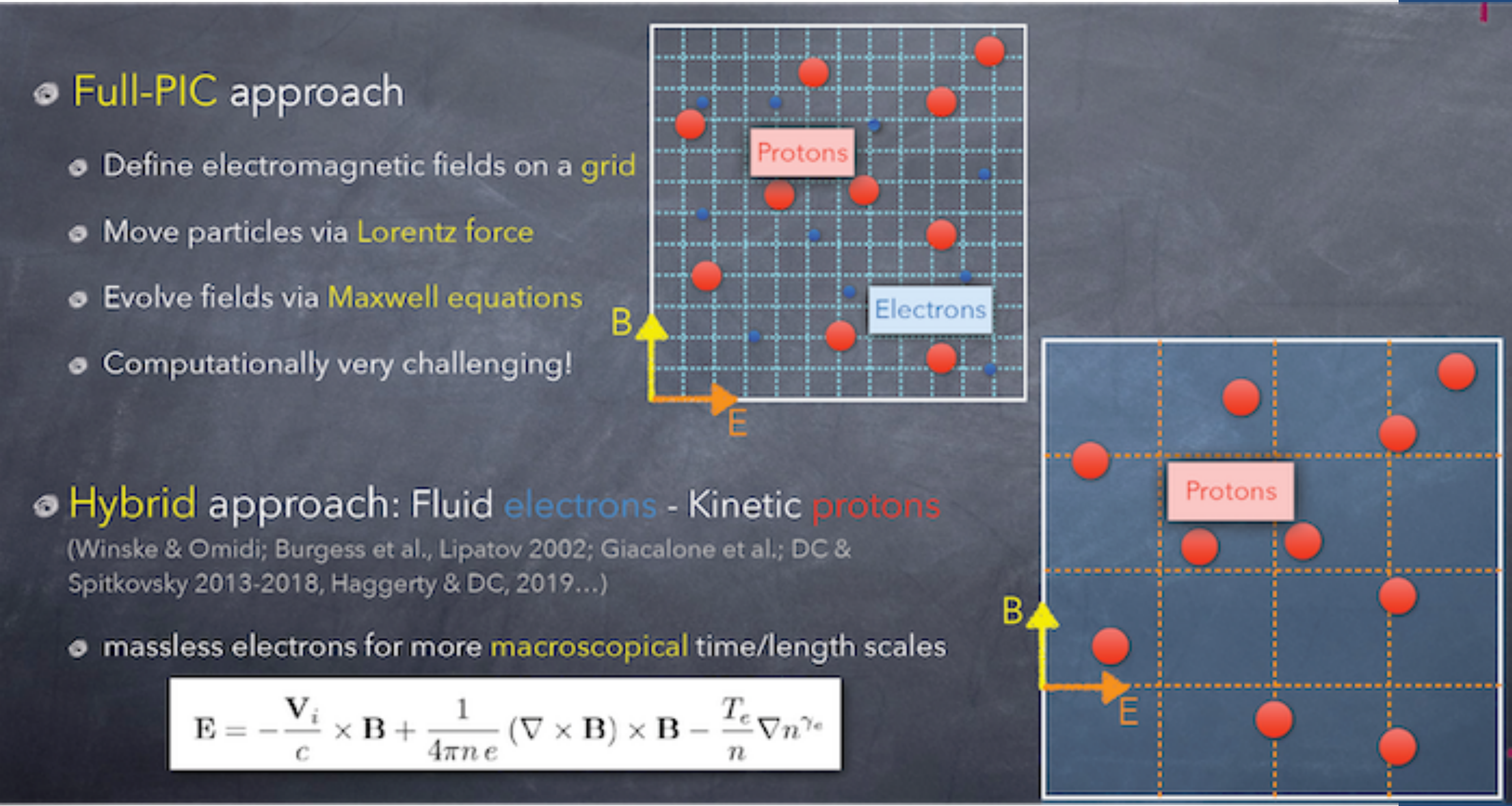
See, e.g., review by Marcowith et al, LRCA, 2020

Full-PIC and Hybrid-PIC

Method

Classical textbooks: Birdsall & Langdon (PIC)
Lipatov (Hybrid-PIC)

Full-PIC and Hybrid-PIC techniques



- Full-PIC approach
  - Define electromagnetic fields on a grid
  - Move particles via Lorentz force
  - Evolve fields via Maxwell equations
  - Computationally very challenging!

- Hybrid approach: Fluid electrons - Kinetic protons

(Winske & Omidi; Burgess et al., Lipatov 2002; Giacalone et al.; DC & Spitkovsky 2013-2018, Haggerty & DC, 2019…)

  - massless electrons for more macroscopical time/length scales

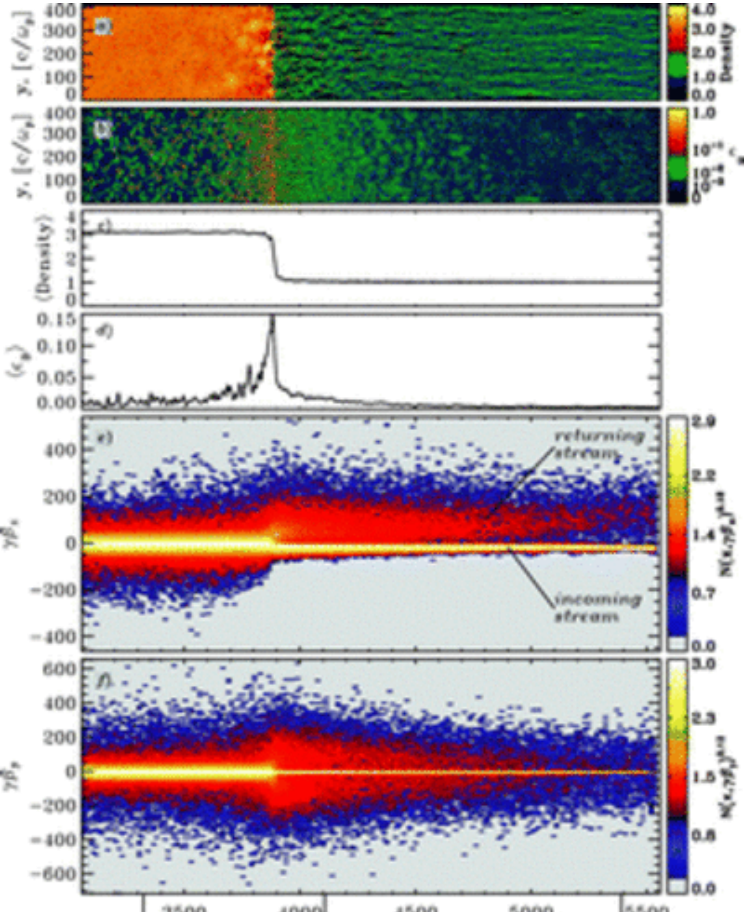
$$\mathbf{E} = -\frac{\mathbf{V}_i}{c}\times\mathbf{B} + \frac{1}{4\pi n e}(\nabla\times\mathbf{B})\times\mathbf{B} - \frac{T_e}{n}\nabla n^{\gamma_e}$$

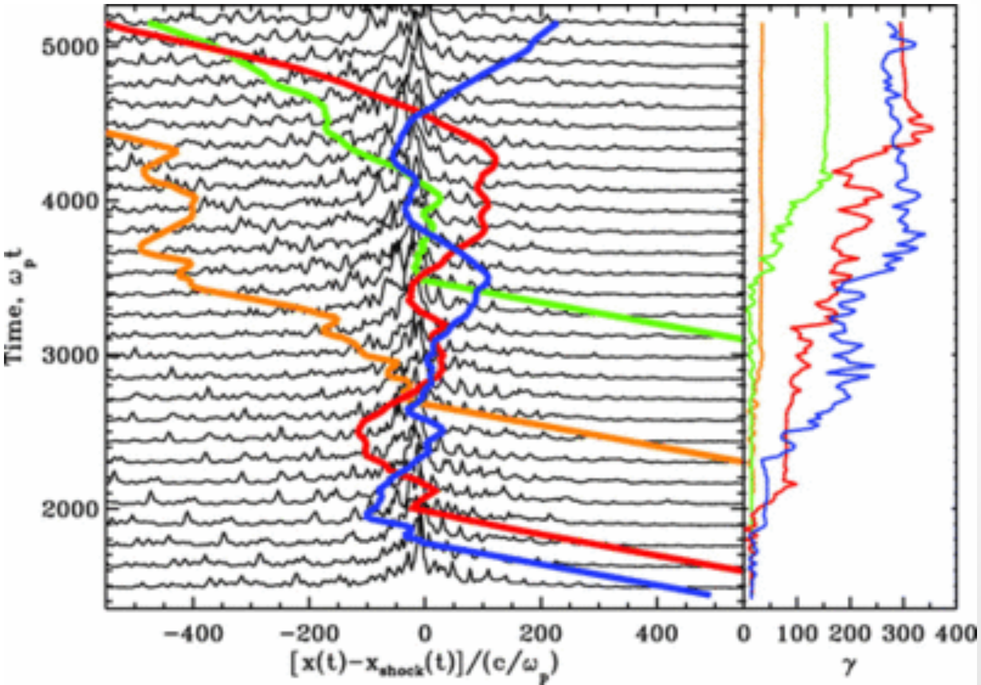
Credits: D. Caprioli

Relativistic shocks simulations

First ab-initio demonstration of Fermi I process

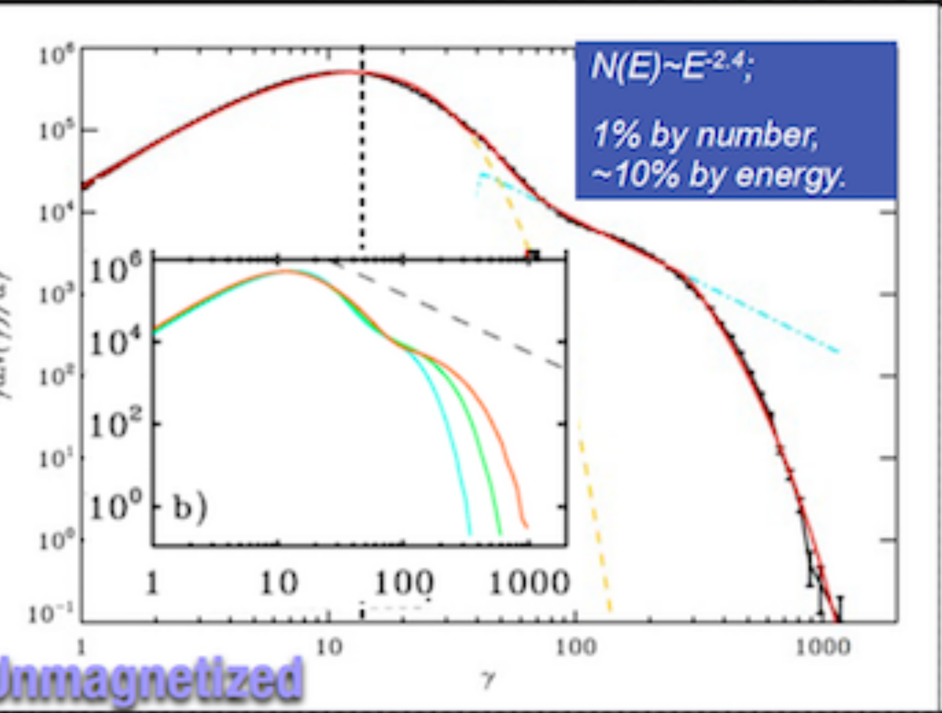
Spitkovsky, ApJL, 2008





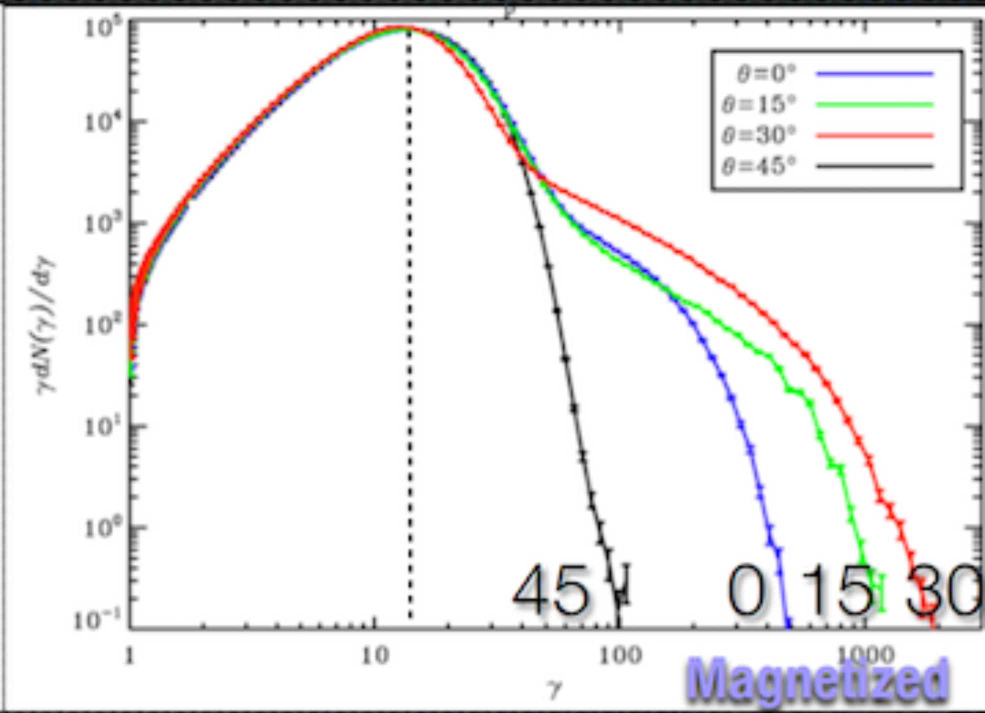
Particle acceleration:

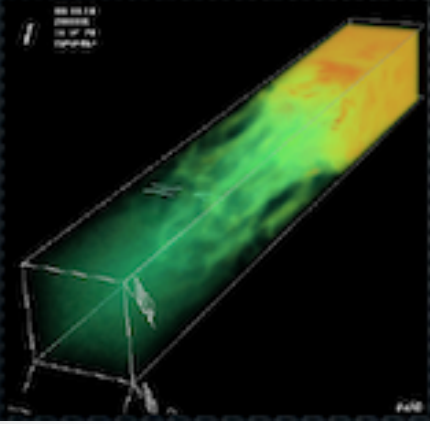
Sironi & AS 09



$N(E) \sim E^{-2.4}$;

1% by number,
~10% by energy.

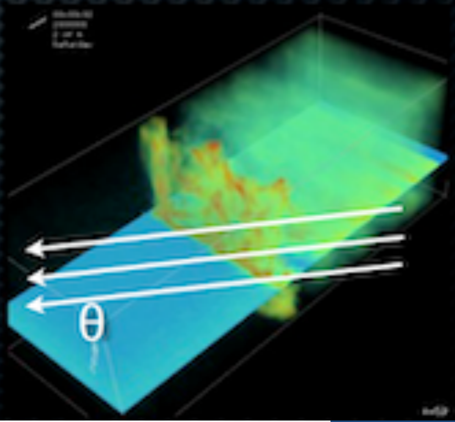




Conditions for acceleration in relativistic shocks:

low magnetization of the flow

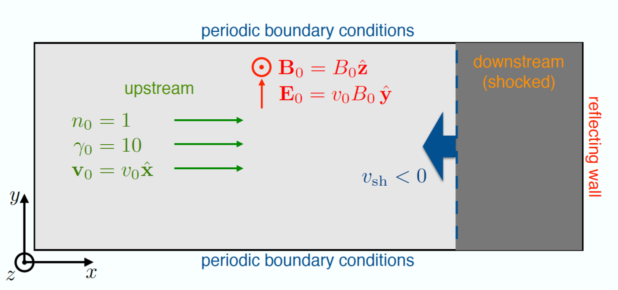
or quasi-parallel B field.



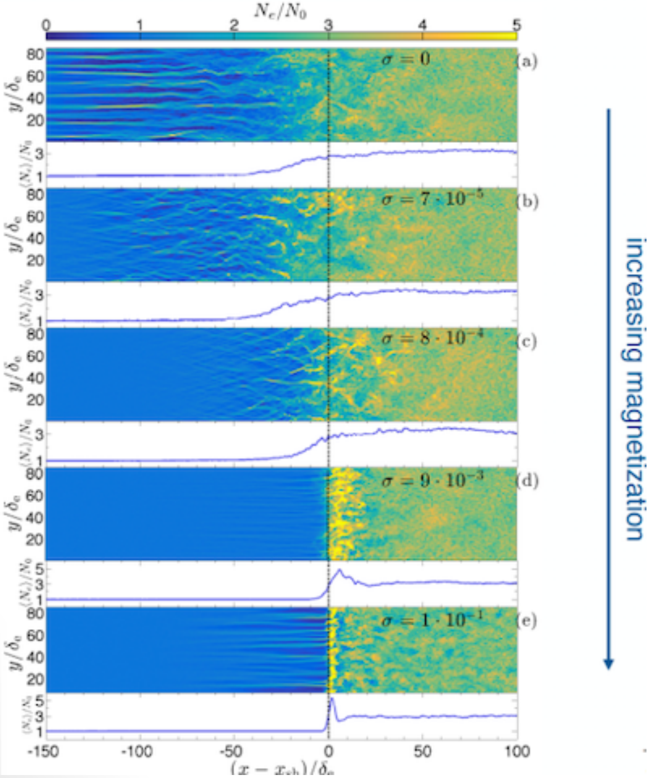
Credits: A. Spitkovsky,
L. Sironi

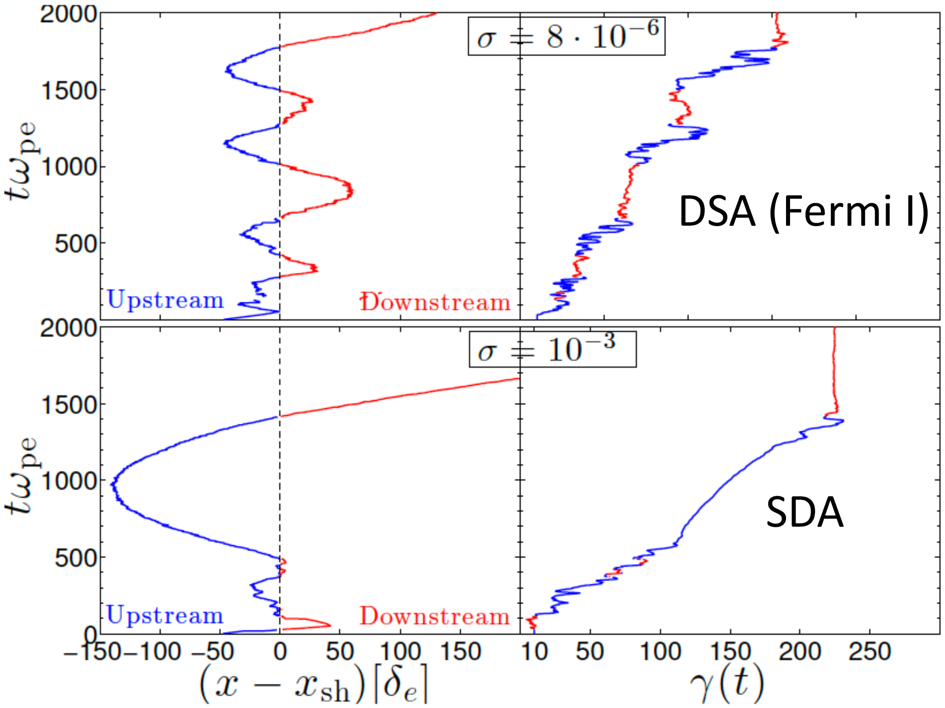
Relativistic shocks simulations

Fermi I process: dependence on magnetization



Sironi, Sptikovsky, Arons, ApJ, 2013
Plotnikov, Grassi, Grech, MNRAS, 2018
-> Dependence on upstream plasma magnetization

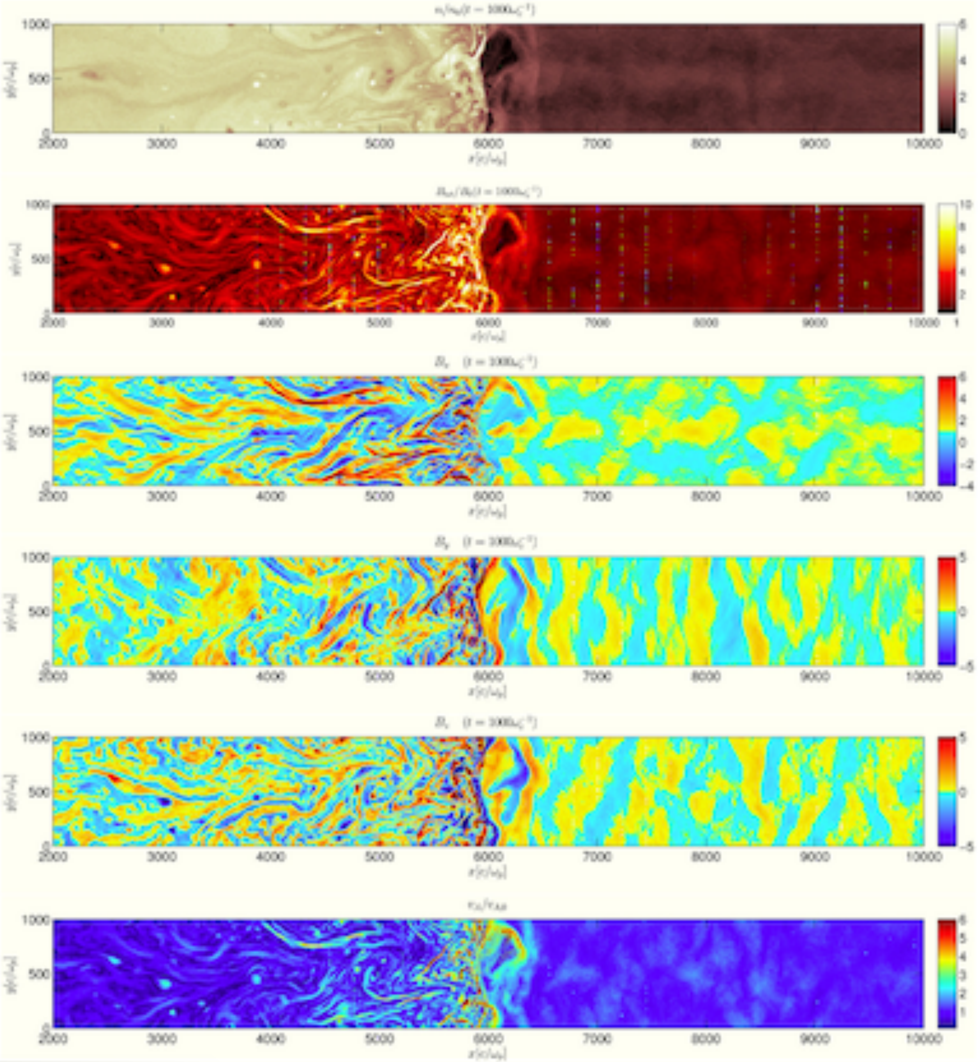




Hybrid-PIC simulation of shock

Global view: $M_A = 20$

Caprioli & Spitkovsky 2014b



Dsty

B_{tot}

$B_x - 1$

By

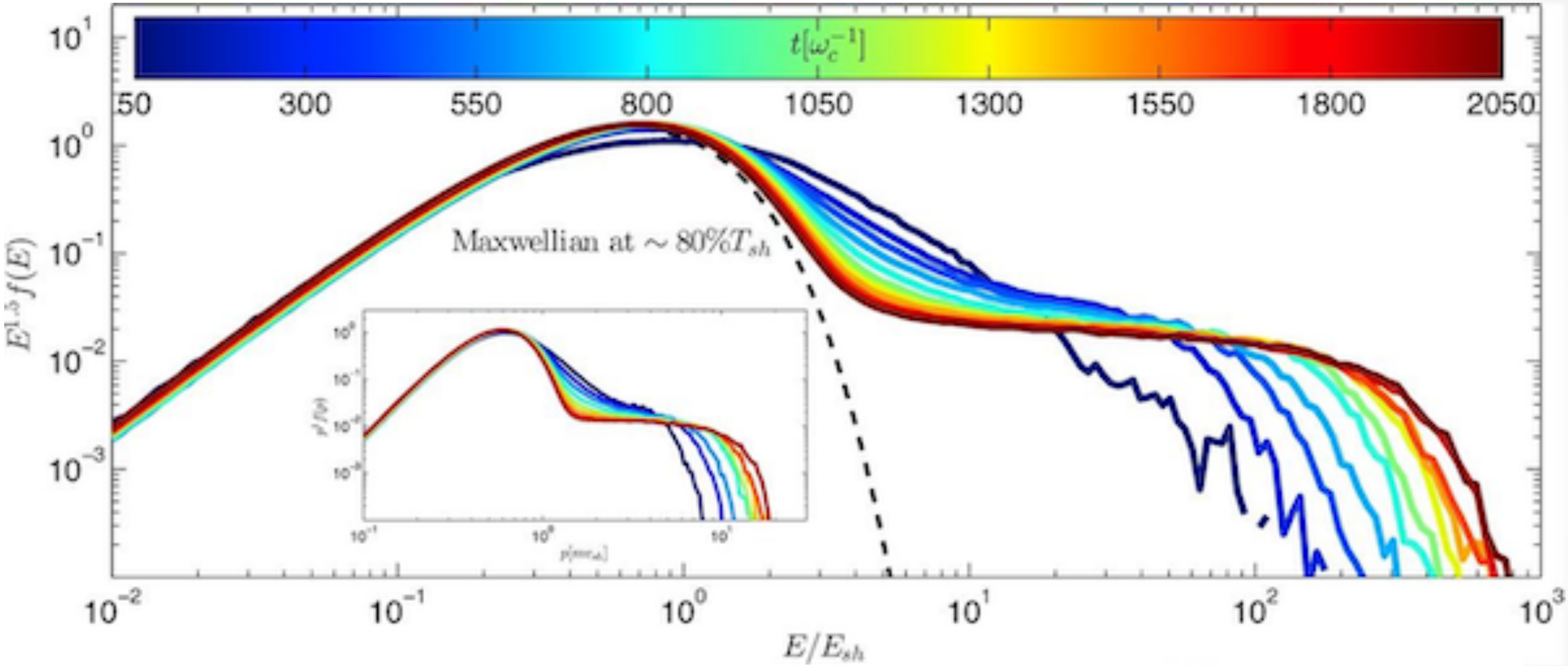
Bz

V_A

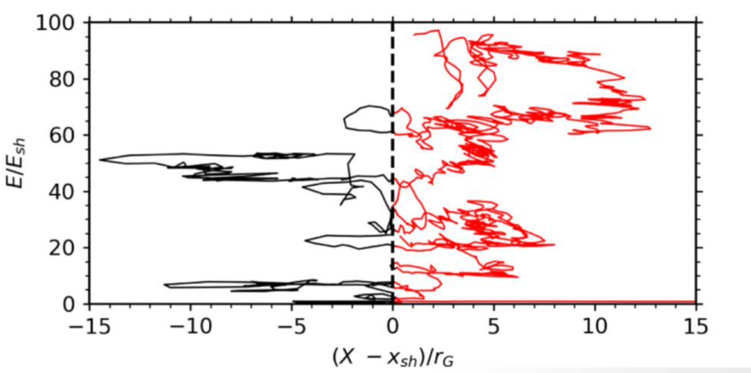
Amplification in the precursor
-> Main non-linearity

Hybrid-PIC simulation of shock

Particle accleration properties



As particles are accelerated, they escape upstream of the shock.
Leads to efficient B-field amplification.

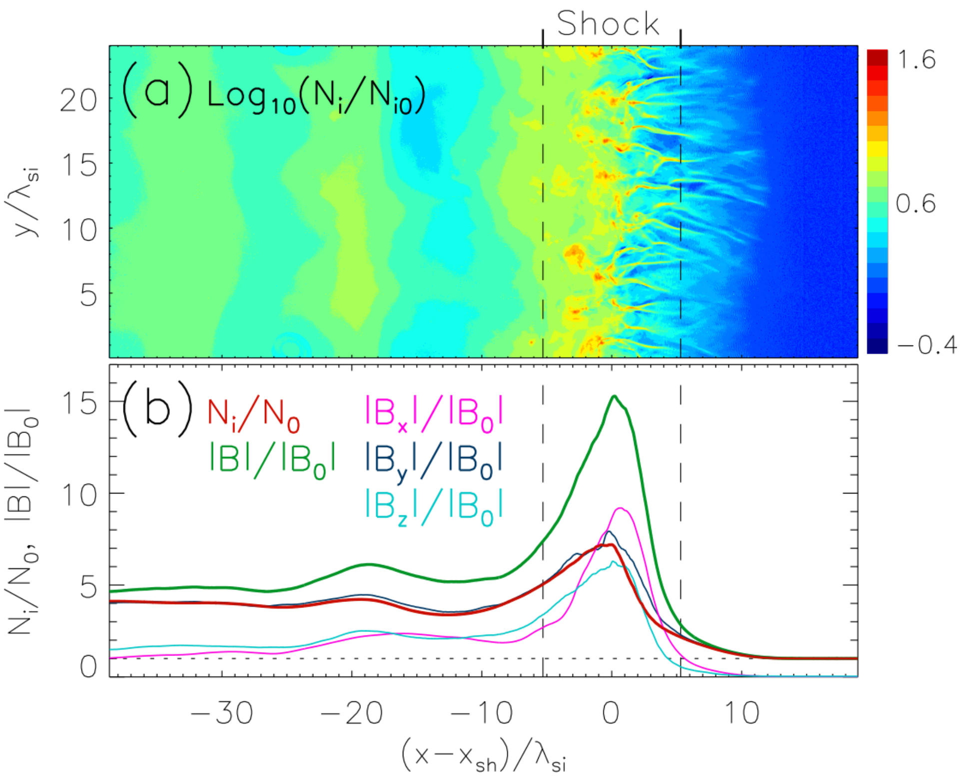


Caprioli & Spitkovsky 2014a,b,c;
Haggerty et al, 2020; Caprioli et al, 2020

Shocks plasma physics: Not only particle accelearion.

Related question: Magnetic field amplification at shocks

Quasi-perp shocks studied by PIC simulations (Bohdan et al, PRL, 2021)
Evidence of the role of Weibel instability even in non-relativistic shocks.
(Here compared to Saturn’s bow shock crossings)



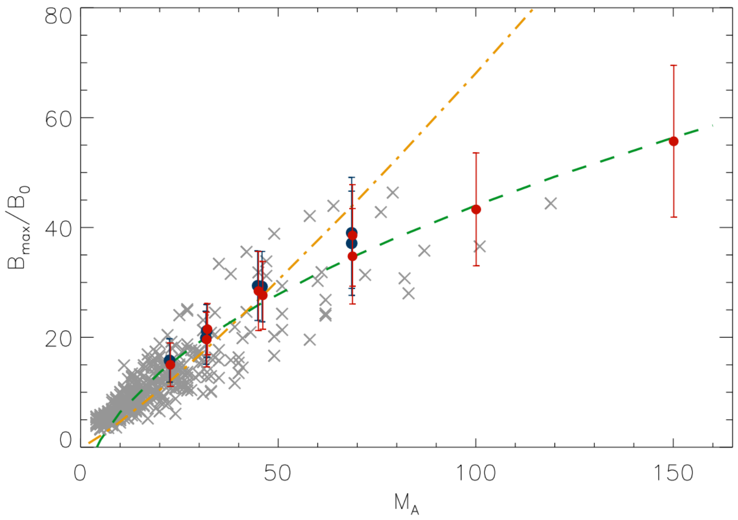


FIG. 4. Cassini measurements [25] indicated by gray crosses and PIC simulation data displayed with blue and red dots for *left* ($\beta = 5 \cdot 10^{-4}$) and *right* ($\beta = 0.5$) shocks, respectively. The yellow dash-dotted line is an earlier prediction, $B_{\rm over}/B_0 \approx 0.4 M_{\rm A}^{7/6}/1.26$ (cf. Eq. 1), corrected for shock reformation. The green dashed line is the behavior found in our PIC simulations, $B_{\rm max}/B_0 = 5.5\left(\sqrt{M_{\rm A}} - 2\right)$.

MHD-PIC

MHD-PIC summary: MHD with CR particles

Full equations for the CR particles:

$$\frac{d(\gamma_j \boldsymbol{u}_j)}{dt} = \frac{q_j}{m_j}\left(\boldsymbol{E} + \frac{\boldsymbol{u}_j}{c} \times \boldsymbol{B}\right)$$

Relativistic Boris pusher, subcycling (~10 particle steps per MHD).

Specify the numerical speed of light c >> any velocities in MHD.

Full equations for the gas:

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B} + \mathbf{P}^*) = \text{- Lorentz force on the CRs}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P^*)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B} \cdot \boldsymbol{v})] = \text{- energy change rate of the CRs}$$

Momentum and energy source terms reflect Newton's 3rd law.

Bai et al, 2015 ; van Marle, Casse & Marcowith, 2018; Mignone et al. 2018, Amano 2018

CR-induced Hall effect

Electrons are force-free: $\boldsymbol{E} + \frac{\boldsymbol{v}_e}{c} \times \boldsymbol{B} = 0$

Decomposition of current density:

$$\frac{c}{4\pi} \nabla \times \boldsymbol{B} = \boldsymbol{J}_{\mathrm{tot}} = n_i q_i \boldsymbol{v}_i - n_e e \boldsymbol{v}_e + n_{\mathrm{CR}} q_{\mathrm{CR}} \boldsymbol{u}_{\mathrm{CR}}$$

$$e n_e = q_i n_i + q_{\mathrm{CR}} n_{\mathrm{CR}}$$

Generalized Ohm's law:

$$\boldsymbol{E} = -\frac{\boldsymbol{v}_i}{c} \times \boldsymbol{B} + \frac{1}{e n_e c} \boldsymbol{J}_{\mathrm{tot}} \times \boldsymbol{B} - \frac{q_{\mathrm{CR}} n_{\mathrm{CR}}}{e n_e} \frac{(\boldsymbol{u}_{\mathrm{CR}} - \boldsymbol{v}_i)}{c} \times \boldsymbol{B}$$

inductive term

normal Hall term

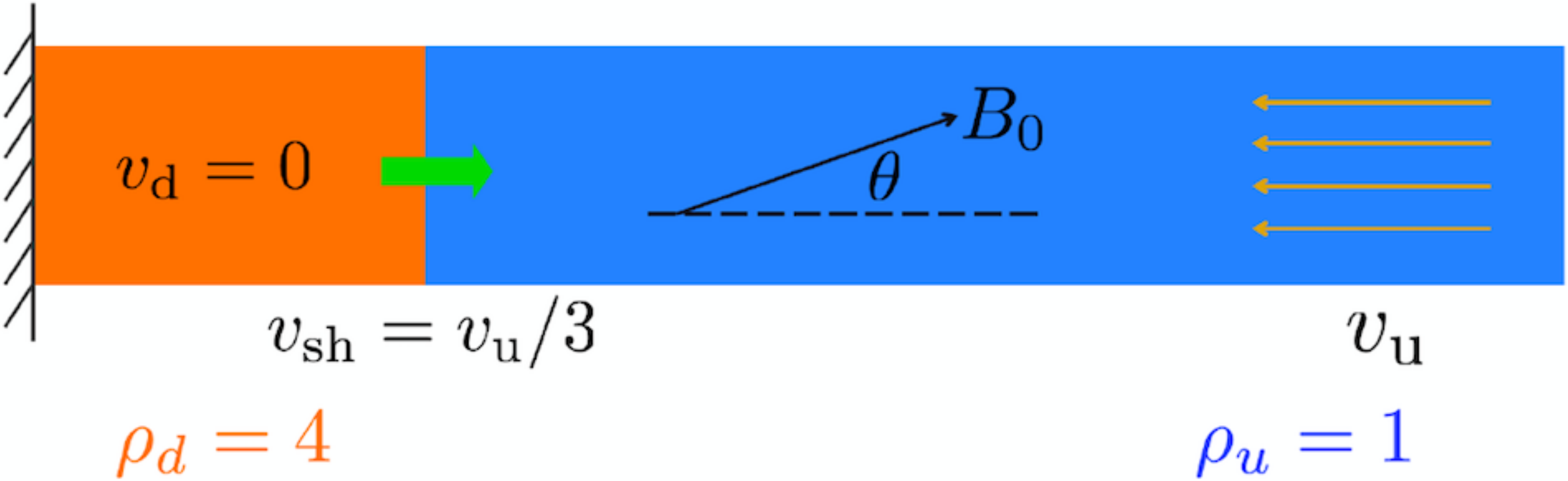
CR-induced Hall term

Important on scales < ion skin depth

scale independent

Bai et al, 2015 ; van Marle, Casse & Marcowith, 2018; Mignone et al. 2018, Amano 2018

Setting up the shock problem



- Inject CR particles at the shock with some efficiency η.
- They are injected at energy of 10 Eshock isotropically.
- Escaping CRs drive upstream waves, and acceleration ensues.

Credits: X.-N. Bai

MHD-PIC simulation: oblique shock, no particle injection

Density

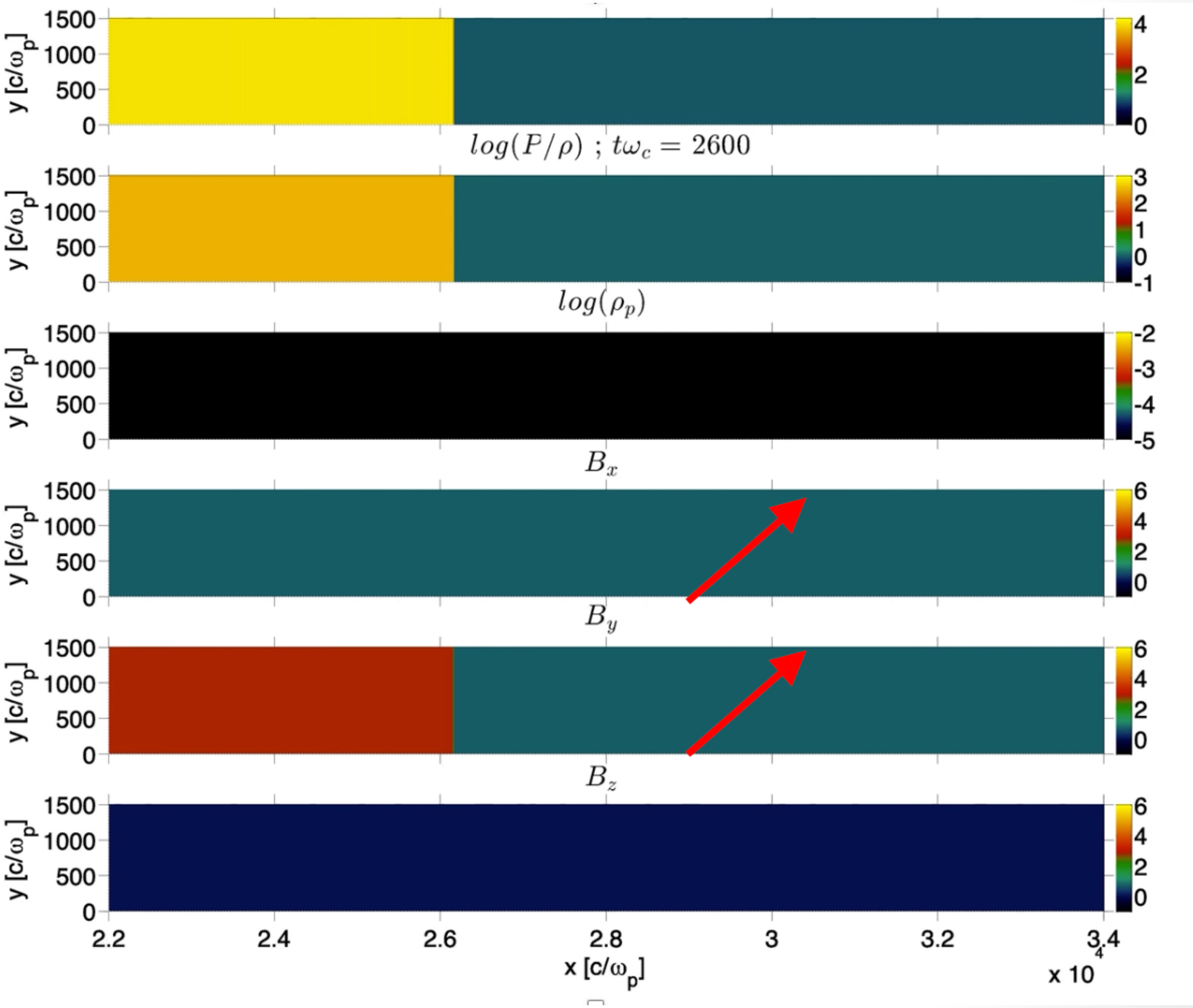
log(T)

log(CR density)

Bx

By

Bz



The shock is a jump between two fluid states, consistent with RH conditions

MHD-PIC simulation: injection at front (MA=30 and η_{inj} =2 10^{-3})

Density

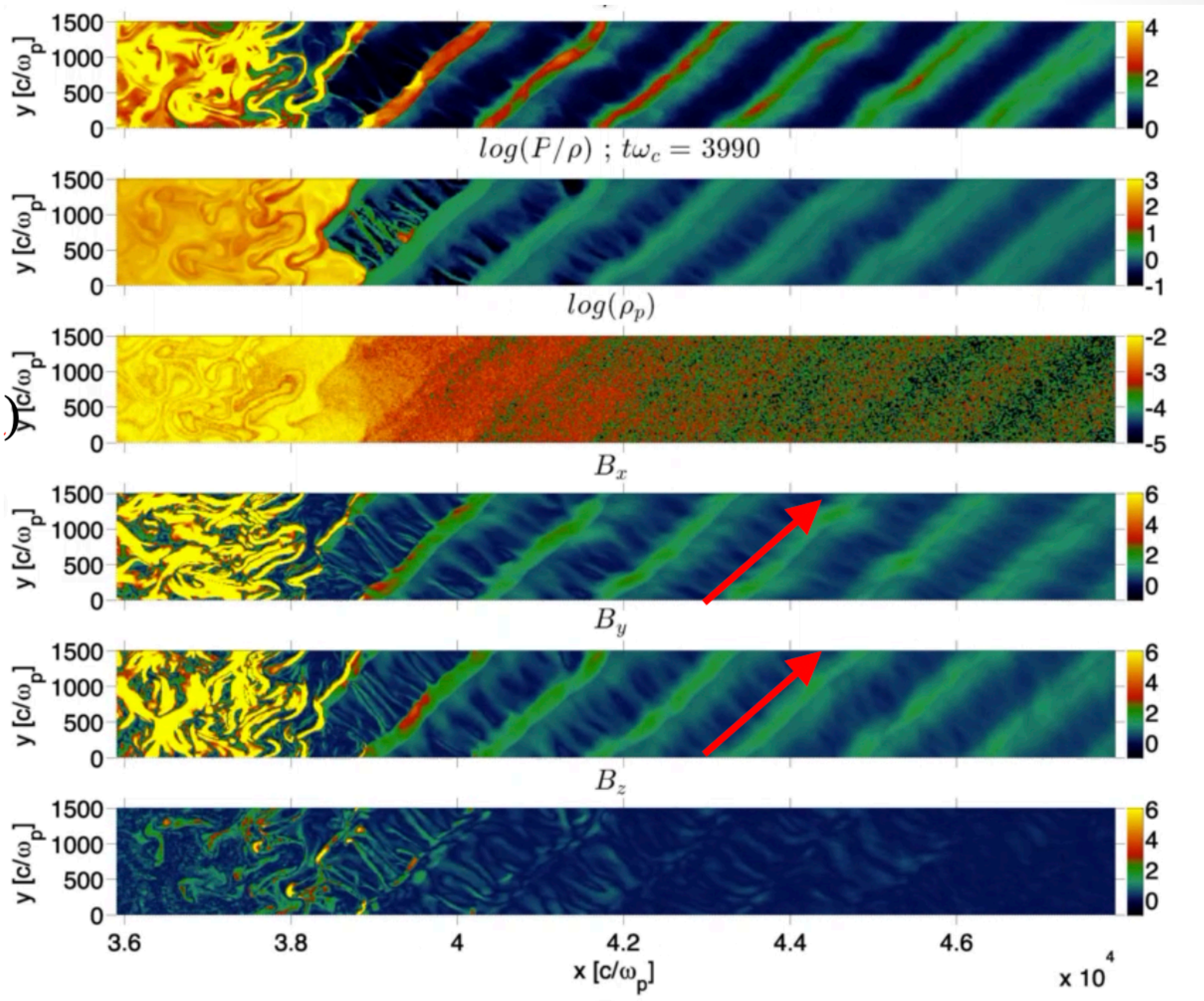
log(T)

log(CR density)

Bx

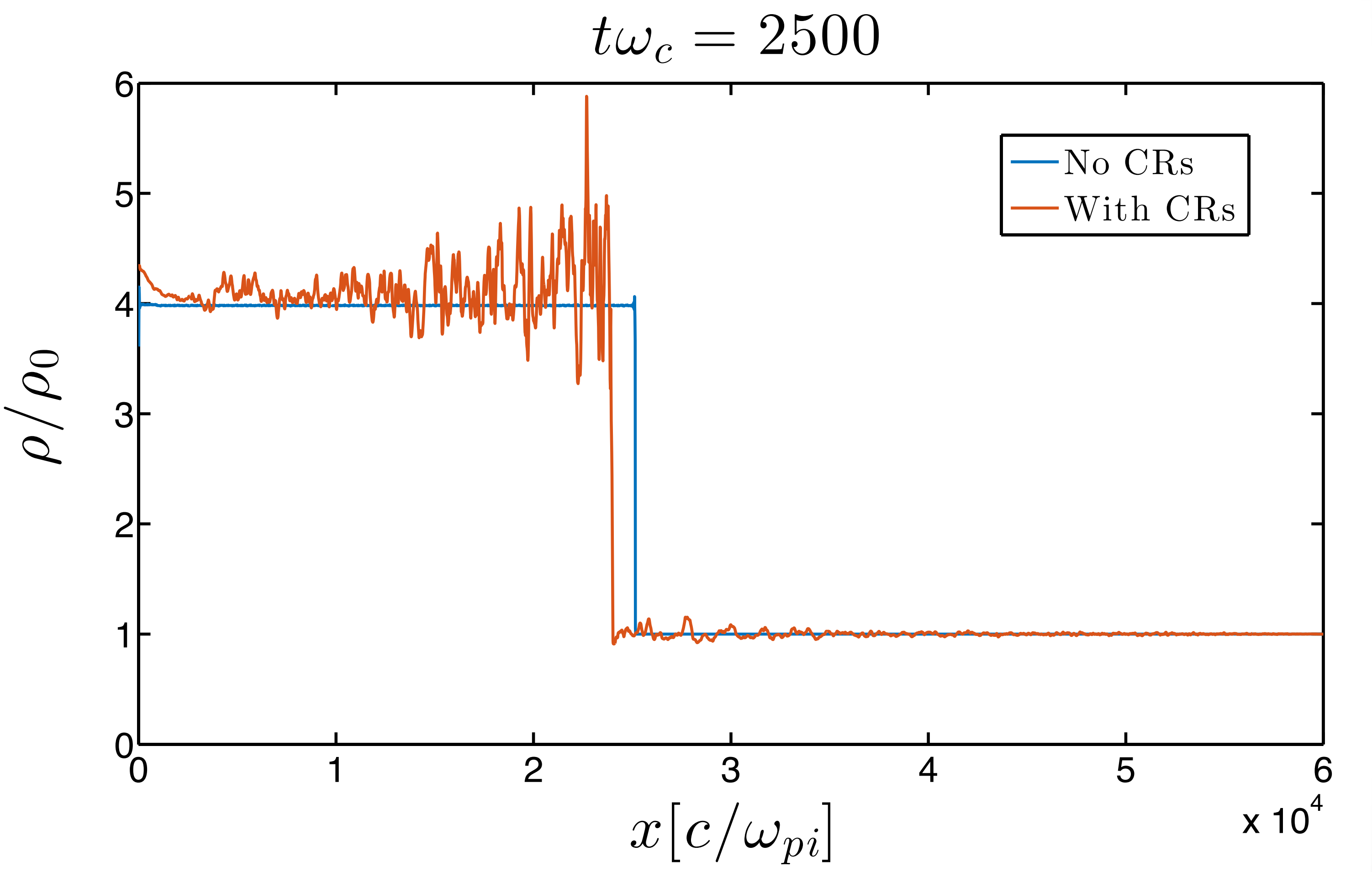
By

Bz



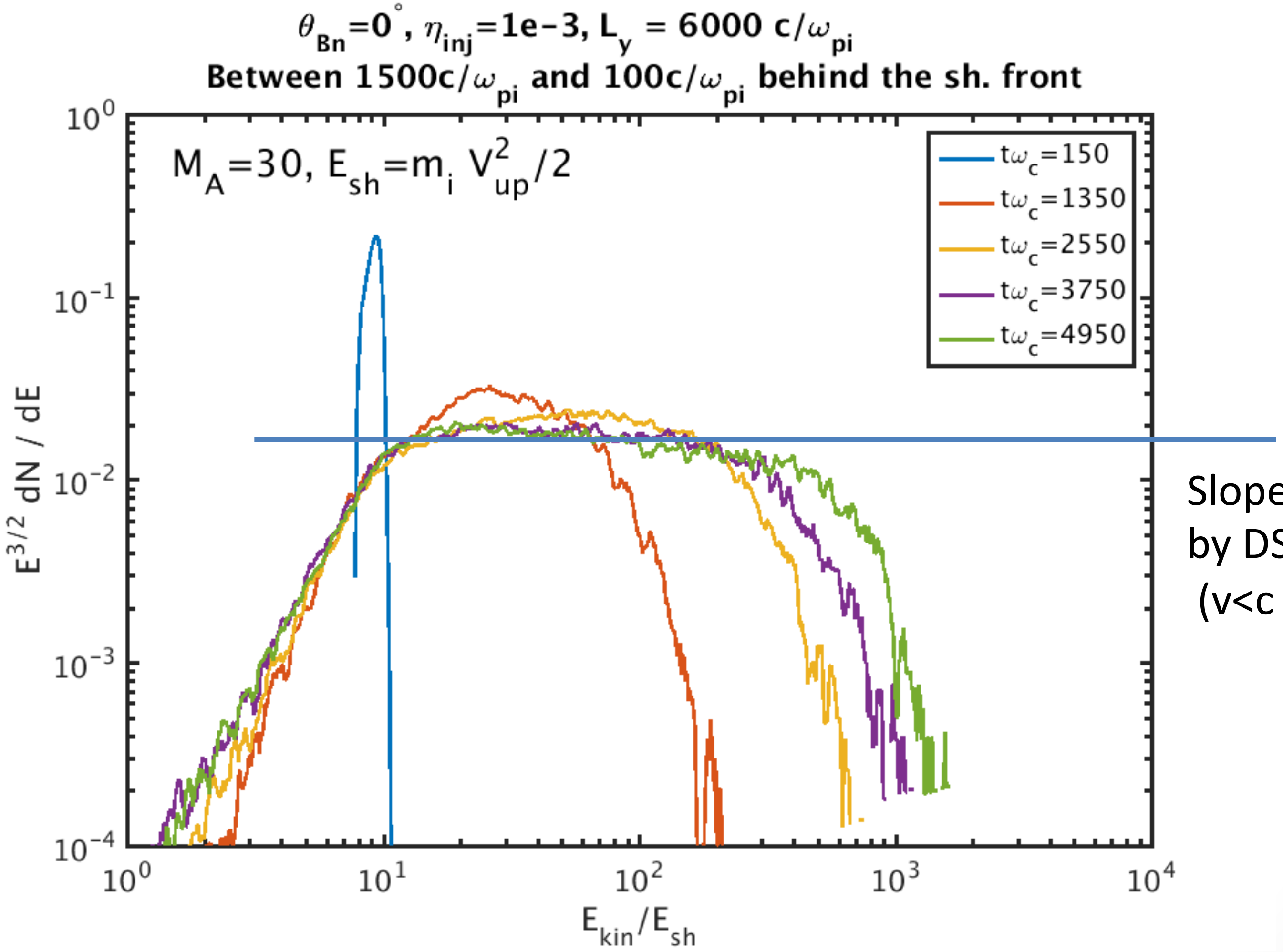
Modified shock: wave amplification upstream, modified jump conditions…

Shock modification by particle acceleration



If efficient acceleration, density compression ratio is enhanced, front slows down

Particle acceleration: power-law build-up



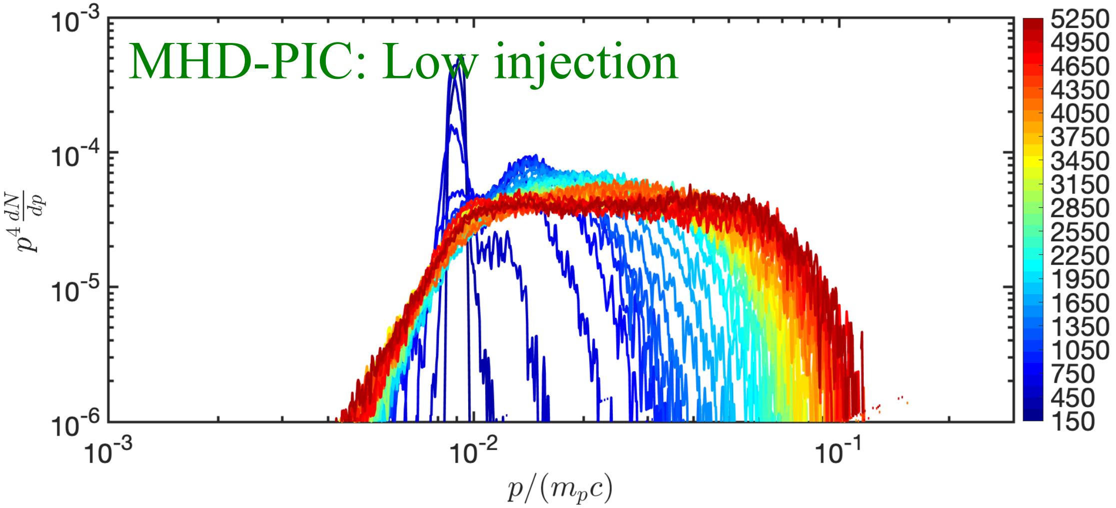
Slope predicted by DSA
(v<c regime)

Prominent power-law build up, but no sign of spectrum concavity.

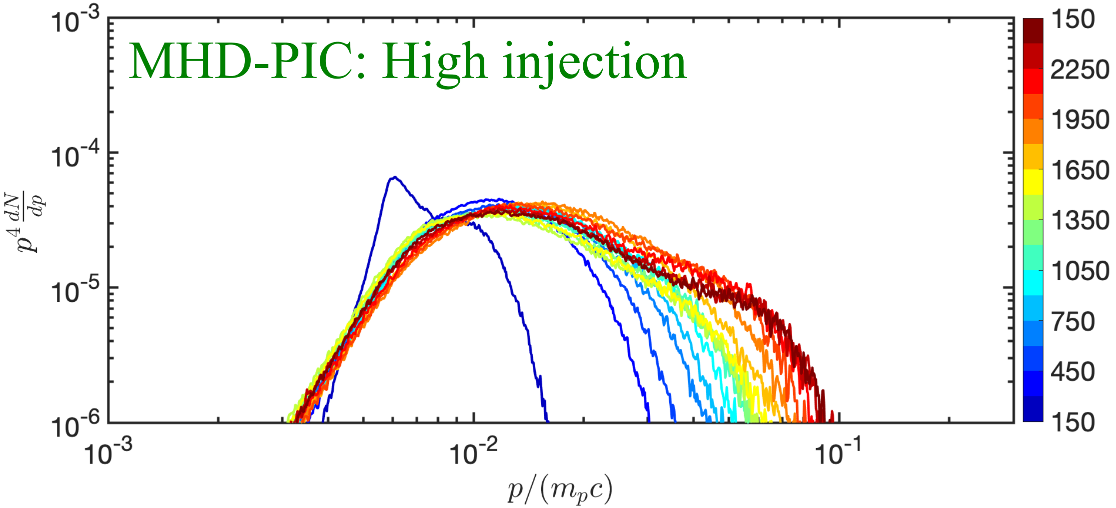
CR quantities

Post-shock F(p): dependence on injection recipe

Low injection:
in good agreement with standrad DSA $dN/dp \propto p^{-4}$, see Caprioli & Spitkovsky 2014a, Bai et al. 2015



Steeper spectrum in the High injection run.
$dN/dp \propto p^{-5}$ roughly, at late times.



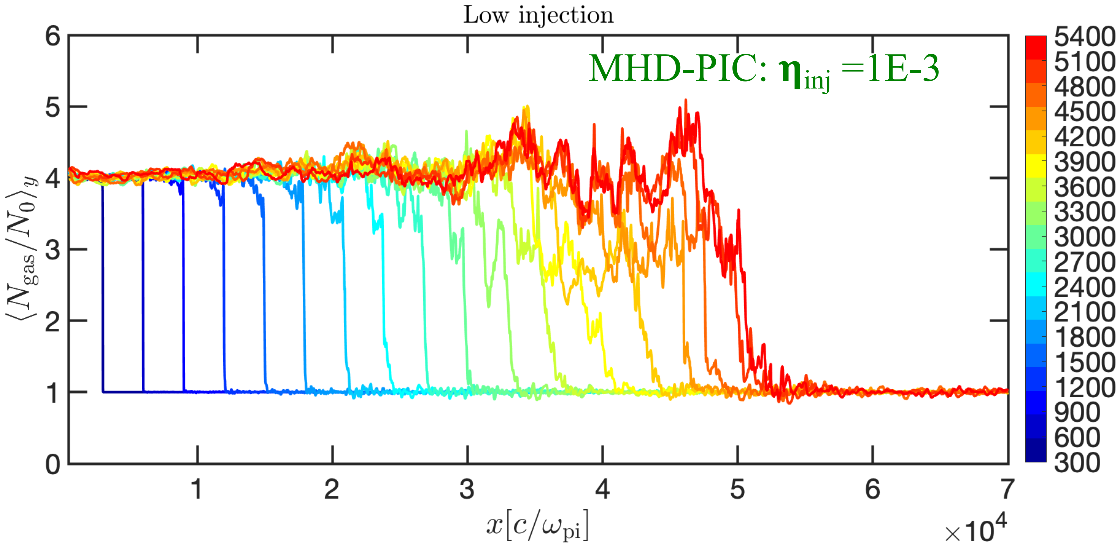
Fluid quantities

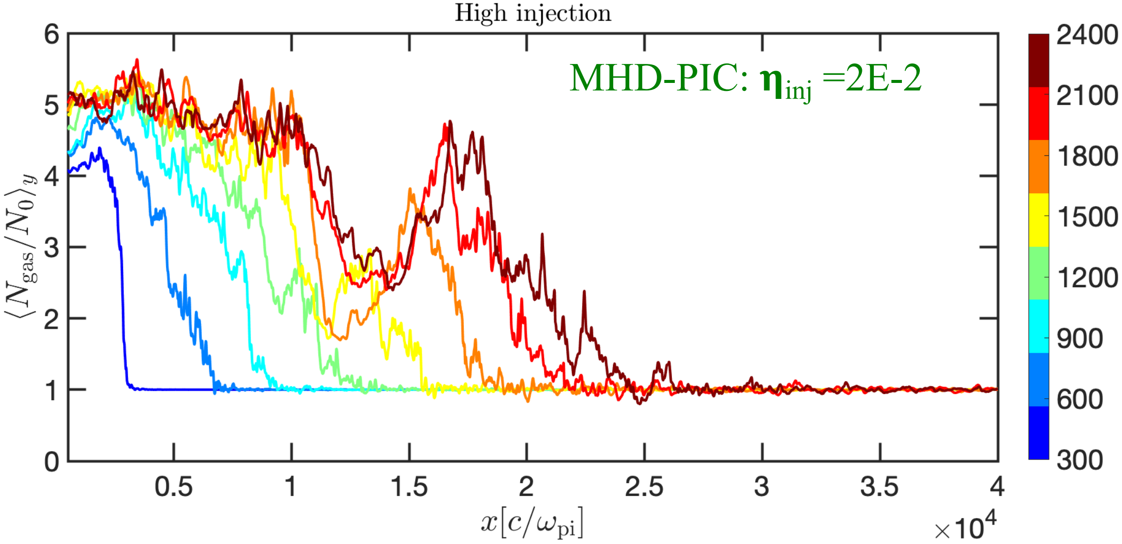
Compression ratio: MHD-PIC runs

- Y-averaged Gas number density at different simulation times (see colorbar in units of cyclotron)

- Low injection here (η_{inj} = 1e-3): Far downstream : ratio 4 conserved as in standard picture. Close downstream: starts to increase at late times (t > 3000)

- High injection (bottom panel, η_{inj} = 2e-2). Far downstream : increase to 5. Close downstream : strong modification leads to poor definition of the shock front

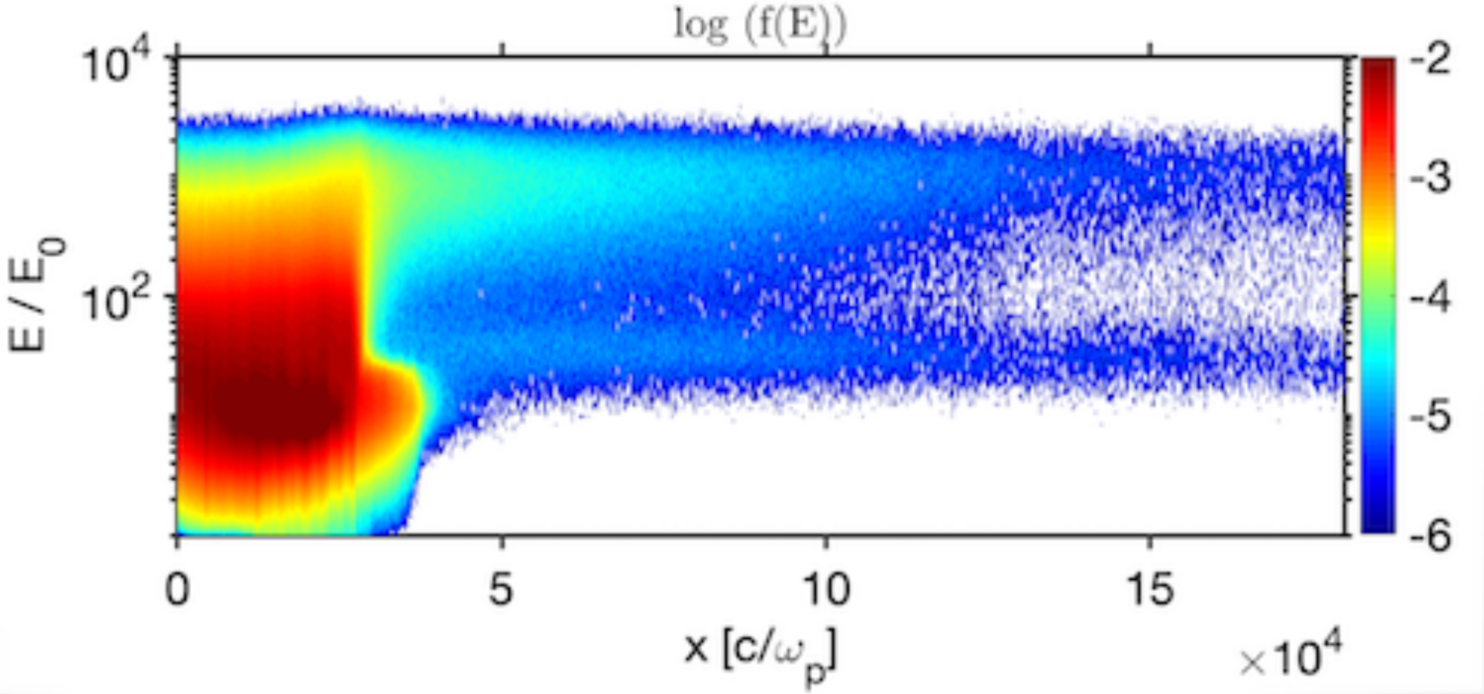




CR quantities

Phase space evolution of CRs

- Injected behind the front with E = 10*E0
- Movie below
- CRs escape upstrame and produce waves
- Self-confinement at late times



Summary and open questions

Summary

Micro and multi-scale simulations of particle acceleration

- Micro scale: powerful ab-initio plasma simulation techniques. Important to study intial stages but fail to bridge the gap with astrophysical scales.
- MHD-PIC: aims to bridge the gap in almost self-consistent way. The difficulty consists in a few prescriptions.
- A lot of open questions to be investigated.

Further reading:

- Marcowith et al, 2020, LRCA, 6, 1
  « Multi-scale simulations of particle acceleration in astrophysical systems »

} Review on multi-scale simulations

Some links to public PIC codes

PIC codes

- TRISTAN-MP (Princeton group)
  https://ntoles.github.io/tristan-mp-pitp/

- SMILEI (French, Polytechnique + Maison de la Simulation)
  https://smileipic.github.io/Smilei/

- ZELTRON (B. Cerutti)
  https://ipag.osug.fr/~ceruttbe/Zeltron/

- EPOCH (UK)
  https://github.com/Warwick-Plasma/epoch

- OSIRIS (not open-source…)
  https://picksc.idre.ucla.edu/software/software-production-codes/osiris/