Origin of intense electron heating in relativistic blast waves

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Collaborators

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Mainly based on

A. Vanthieghem et al., “Origin of intense electron heating in relativistic blast waves”, submitted to ApJL, 2022

A. Vanthieghem et al., “*The role of plasma instabilities in relativistic radiation mediated shocks: stability analysis and particle-in-cell simulations*”, MNRAS, 2022

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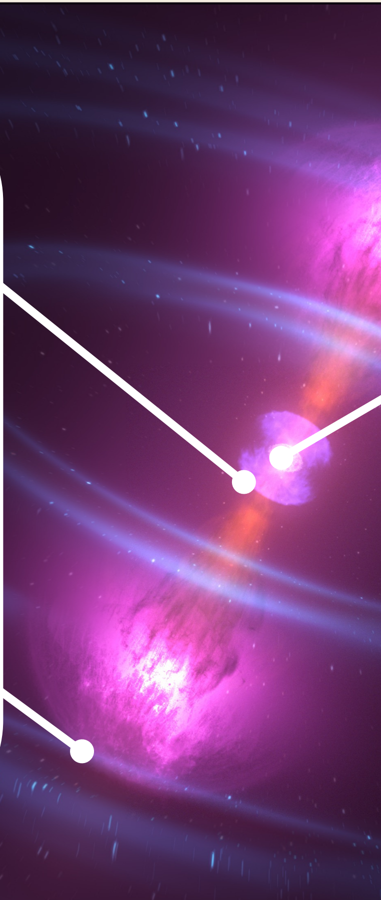
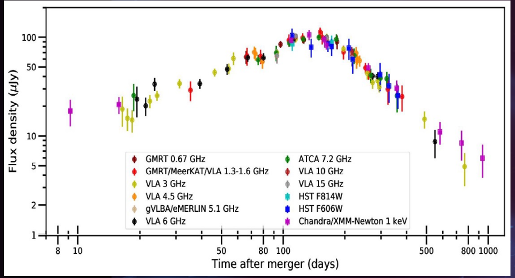
Multimessenger signature of GRBs are emitted in vastly different astrophysical conditions that we need to model



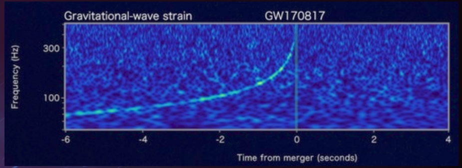
Prompt gamma emission

Afterglow emission



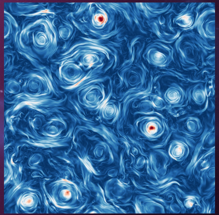
Mahkatini et al. 2020

Gravitational wave signal

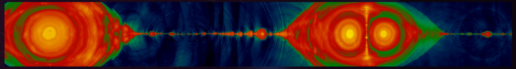


Kinetic processes are essential to model nonthermal emission

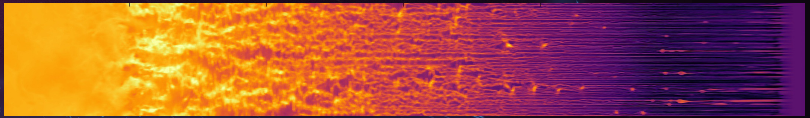
- Collisionless shock waves
- Collisionless reconnection
- Turbulence
- Radiation mediated shock waves
- …



Comisso+, 2019



Sironi+, 2014



Vanthieghem+, 2022

Kinetic description is essential to phenomenology in high-energy astrophysics

Free energy
(kinetic, magnetic)

$\lambda \simeq L$
(dynamical scale)

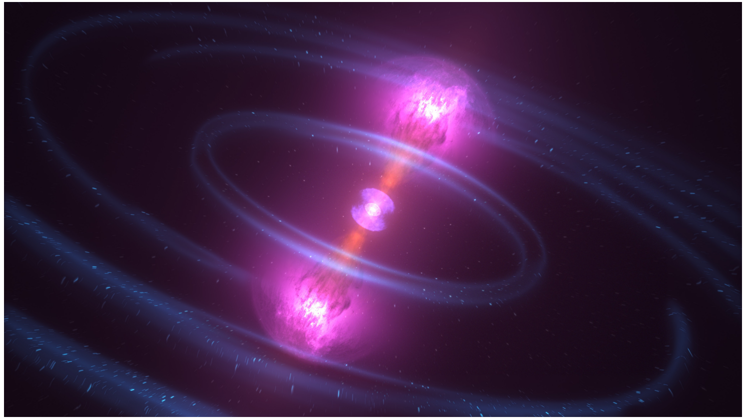
Collective effects
(waves, instabilities, etc.)

$\lambda \simeq \frac{c}{\omega_{\mathrm{p}}} \sim 100\ \mathrm{km}\ (\mathrm{ISM})$
(kinetic scale)

Nonthermal distributions
(cosmic rays, EM spectra)

Multimessenger observations

Particle-In-Cell simulation + reduced theoretical description



Motivations

- **Dynamics of extreme astrophysical environments**
- **Mechanisms of particle acceleration**

Motivations (and notations)
Gamma Ray Burst Afterglows

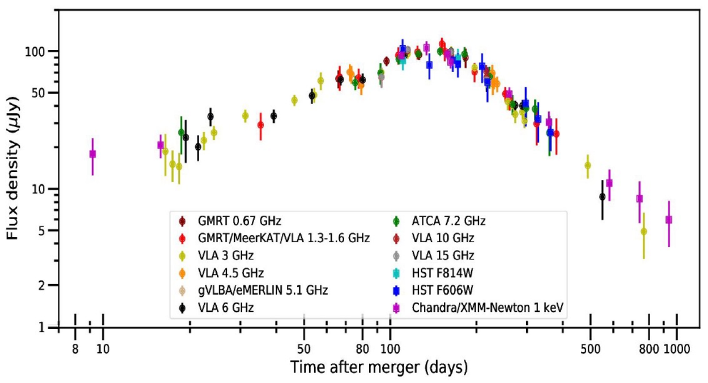
Central engine

- Relativistic bulk outflow
- Free energy: electromagnetic or kinetic

Afterglow emission

Synchrotron Self Compton radiation of electrons accelerated at a relativistic shock front

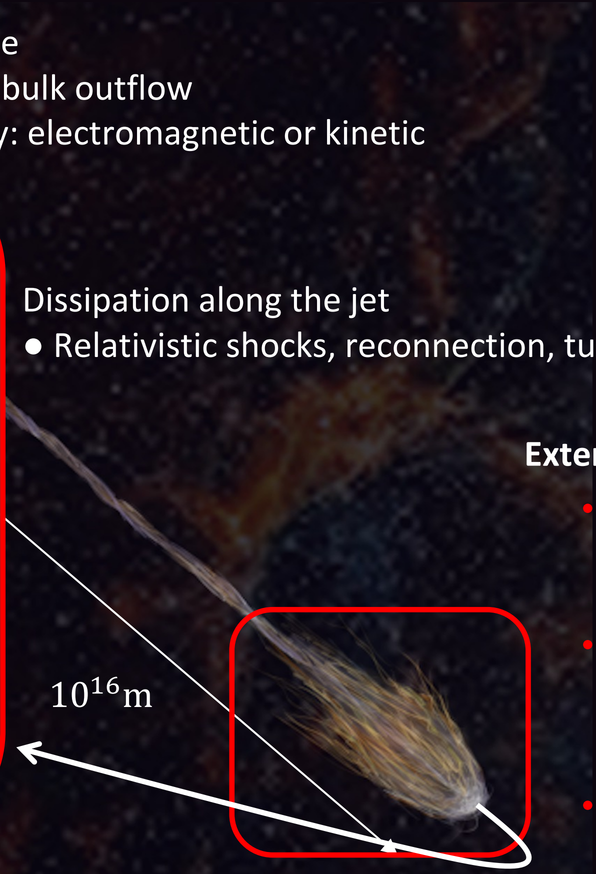
Afterglow of GW170817



Mahkatini et al. 2020

Dissipation along the jet

- Relativistic shocks, reconnection, turbulence etc.



External shock

- **Relativistic**

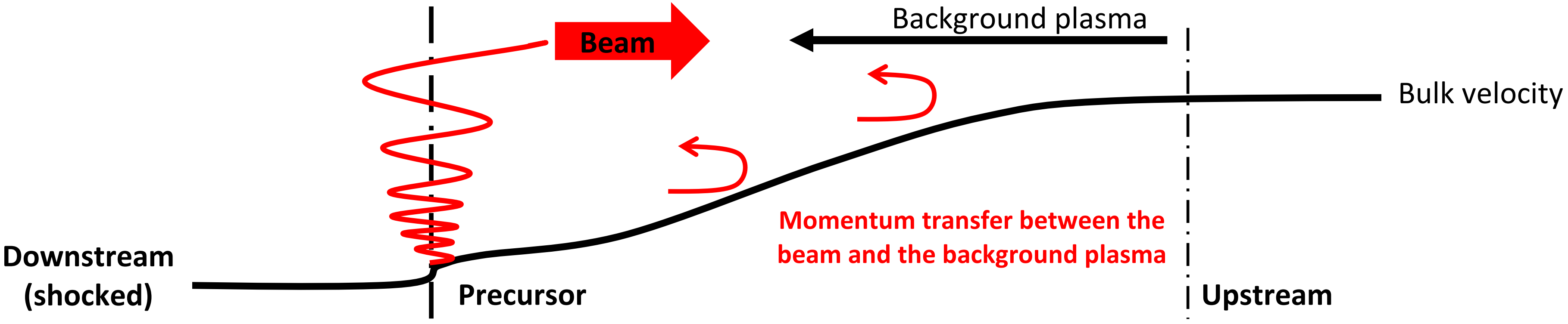
$$\gamma_{sh} = 1/\sqrt{1-\beta_{sh}^2} \sim 100-1000$$

- **Unmagnetized**

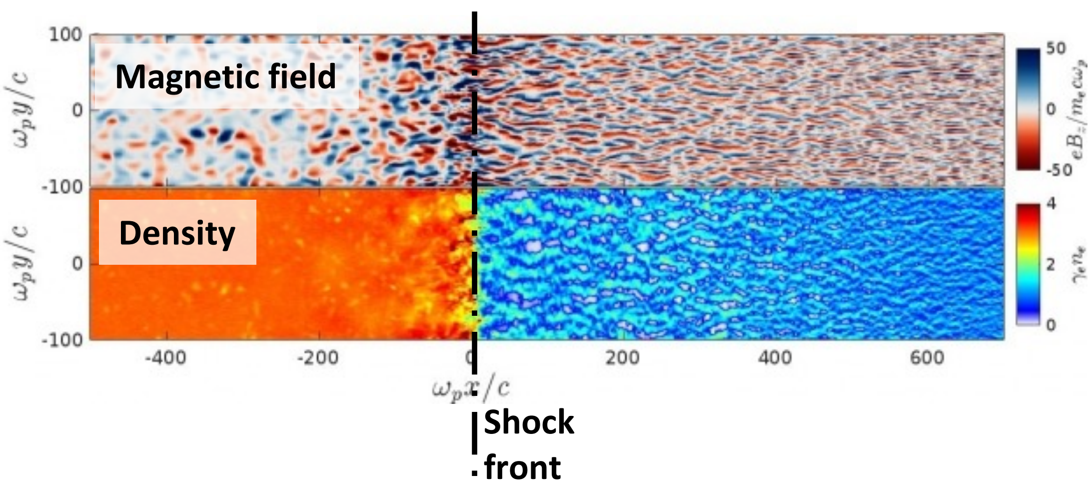
$$\sigma = \frac{B^2}{4\pi\, \gamma_{sh}^2\, nmc^2} \ll 1$$

- **Collisionless**

Structure of a relativistic collisionless shock wave without external magnetic field



Momentum transfer between the beam and the background plasma



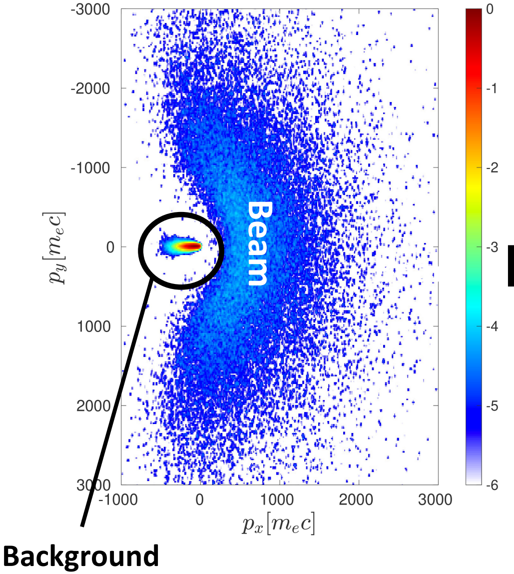
- **Collisionless shock waves**

The interplay between a beam of Fermi-accelerated particles and the background plasma generates an electromagnetic microturbulence at kinetic scales

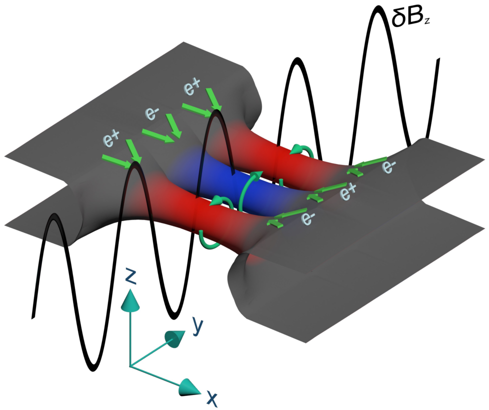
⇒ **scale:** $\frac{c}{\omega_p} \sim 100\ \mathrm{km}$

The microturbulence is generated by the interaction between the beam and the background plasma via the Weibel Instability

Anisotropic beam-plasma in phase space



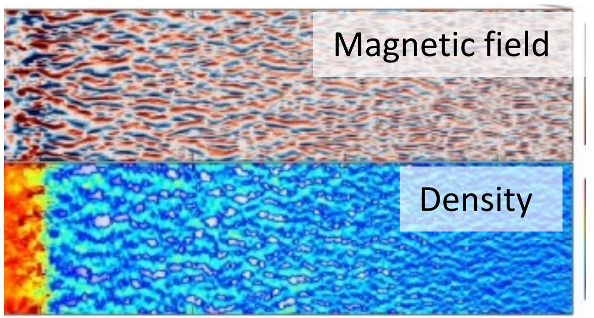
Current filamentation: Weibel instability



A transverse δB generate a net current which have a positive feedback on δB

Electromagnetic microturbulence

Nonlinear evolution of the instabilities shapes the microturbulence dynamics



The microturbulence rules

- Momentum exchange and heating
- Particle acceleration efficiency
  ⇒ sustain phase-space anisotropy

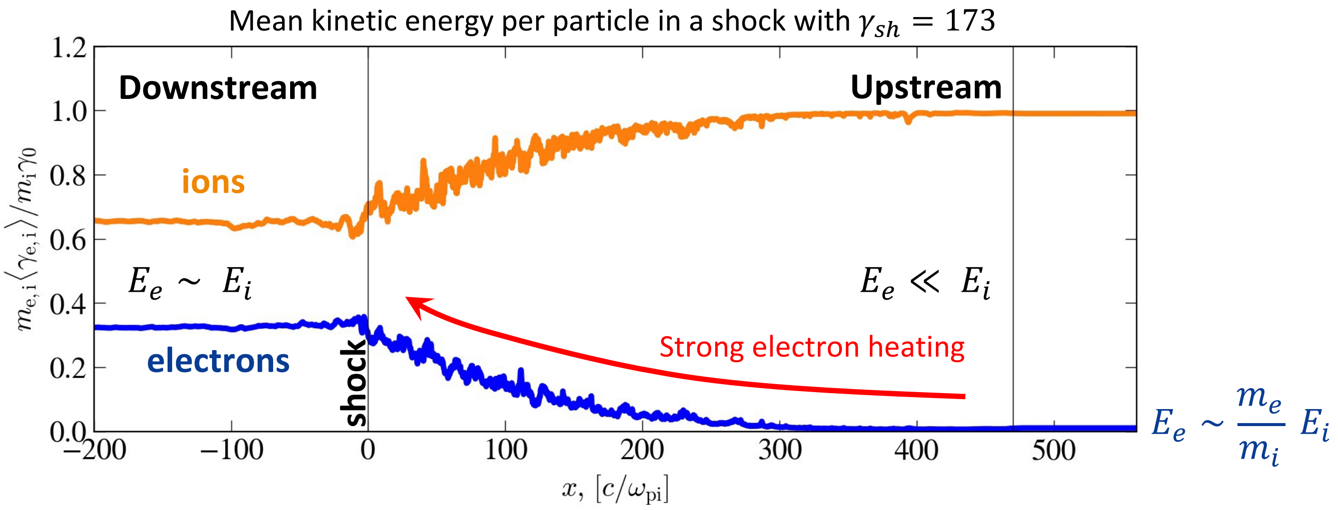
The cold background plasma interacts the hot beam of accelerated particles and generates a microturbulence

Relativistic electron-ion plasmas shock waves reach equipartition in the shock downstream

- Modeling of gamma-ray burst afterglows indicate equipartition between electrons and ions - Freedman+01

$$E_e \sim E_i \Rightarrow \langle \gamma_e \rangle \sim \frac{m_i}{m_e} \langle \gamma_i \rangle \sim 10 \text{ GeV}$$

- Equipartition observed in PIC simulations – Spitkovsky08, Martins+09, Haugbölle11, Sironi+11



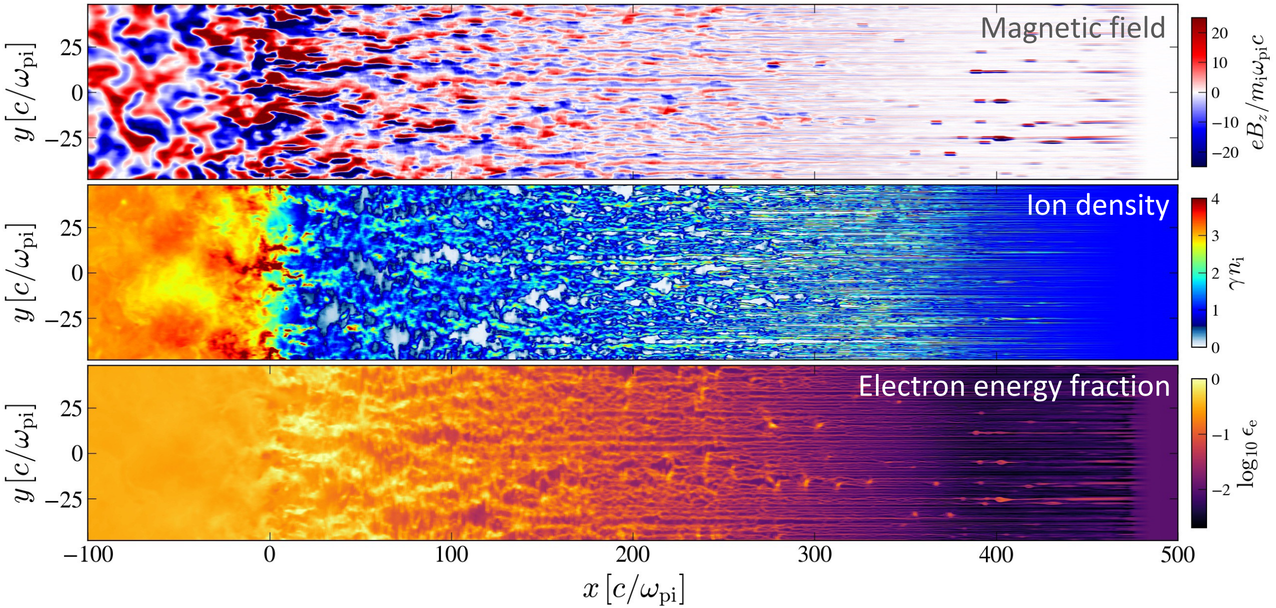
Mean kinetic energy per particle in a shock with $\gamma_{sh} = 173$

What is the origin of this strong electron energization?

Vanthieghem+2022

What is the source of strong electron heating?

Probe the electron heating with large-scale ab initio N-body simulations



$\gamma = 100;\ m_i/m_e = 25$

$\gamma = 100;\ m_i/m_e = 100$

$\gamma = 10;\ m_i/m_e = 100$

Different sources of electron heating in the microturbulence have been identified (Milosavljevic+2006, Gedalin+2008, Gedalin+2012 , Plotnikov+2013, Kumar+2015)

⇒ Need to build a reduced model that can disentangle them and identify a dominant source of electron heating

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The pressure of the beam on the background leads to a deceleration of the background plasma across the precursor

- System composed **of background plasma** + **suprathermal particles** + **electromagnetic turbulence**
- Conservation of energy-momentum

$$\partial_\mu \left(T^{\mu\nu} + T_{\mathrm{b}}^{\mu\nu} + T_{\mathrm{EM}}^{\mu\nu} \right) = 0$$

- Electromagnetic turbulence hardly contributes to the fluid conservation equations

⇒ Background plasma deceleration law

Lorentz factor $\gamma_p \propto \xi_b^{-1/2}$

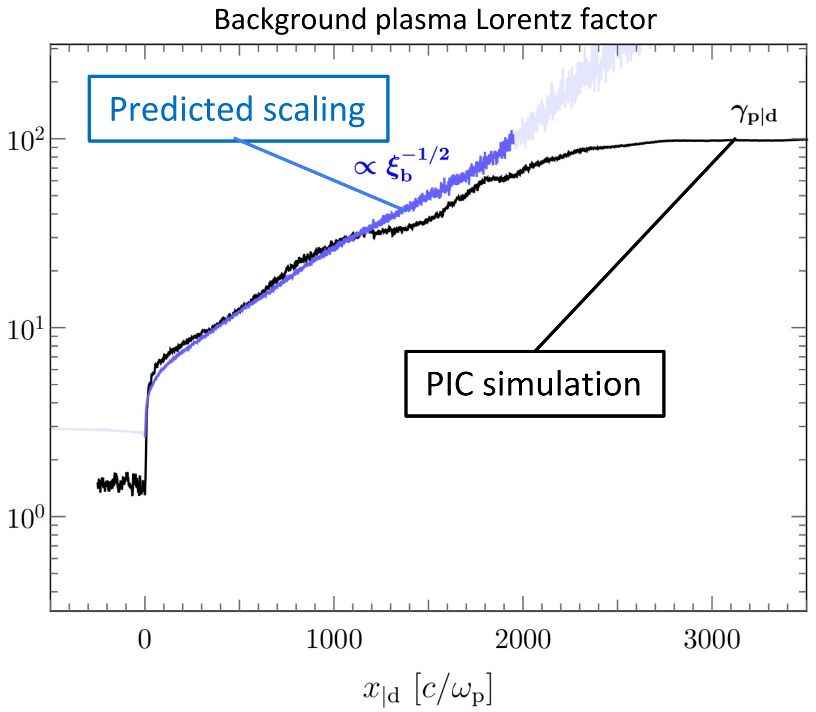
with

$$\xi_b = P_b / \mathcal{F}_\infty$$

P_b - Suprathermal particle pressure

$\mathcal{F}_\infty$ - Incoming ram pressure

The pressure of the beam is mediated to the background by the microturbulence

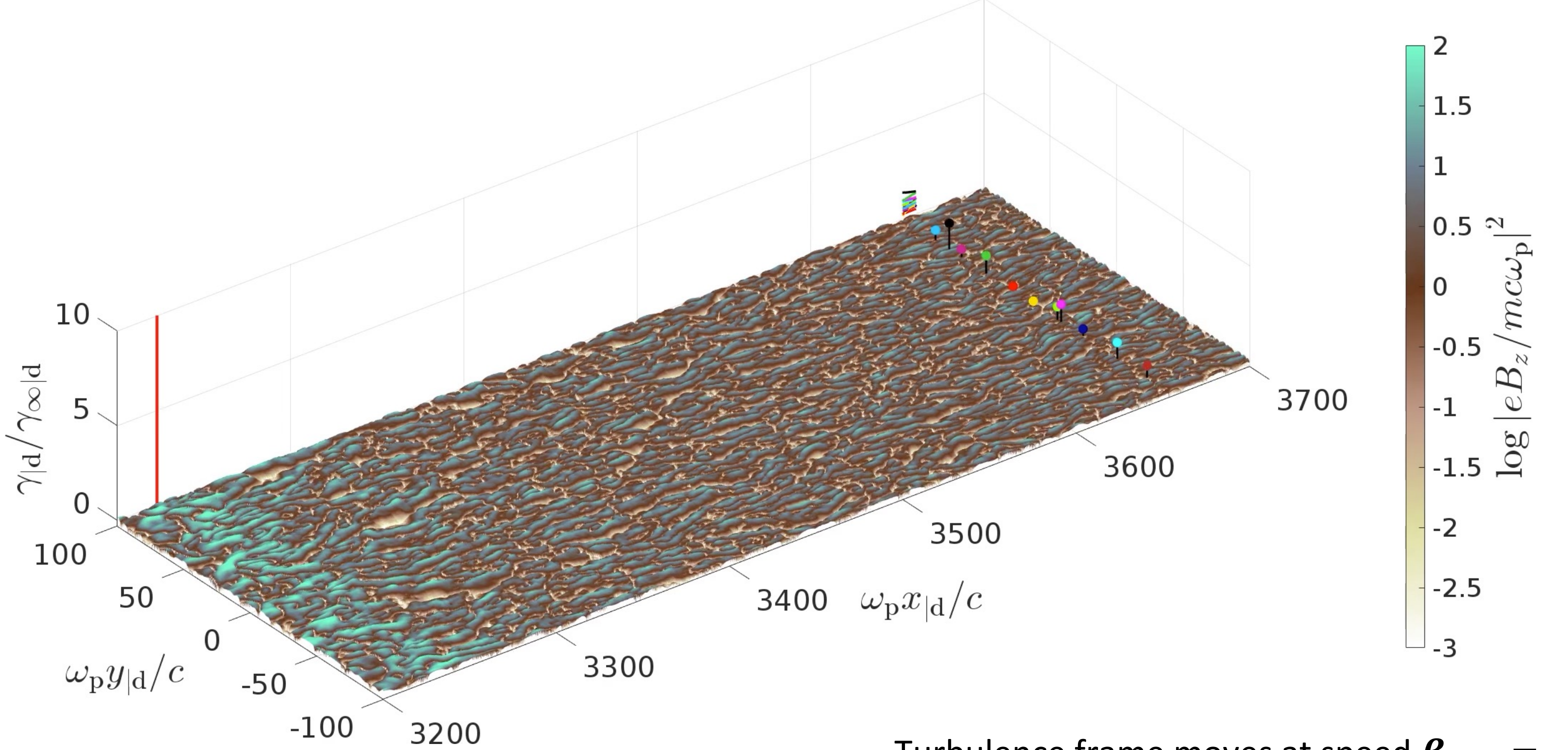


Background plasma Lorentz factor

Lemoine+2019a

The Weibel microturbulence is quasi-magnetostatic in a preferential frame: the Weibel frame

At each point, one can define a local reference frame $\mathcal{R}_w$ in which the turbulence is quasi-magnetostatic



$\gamma_{sh} = 173$

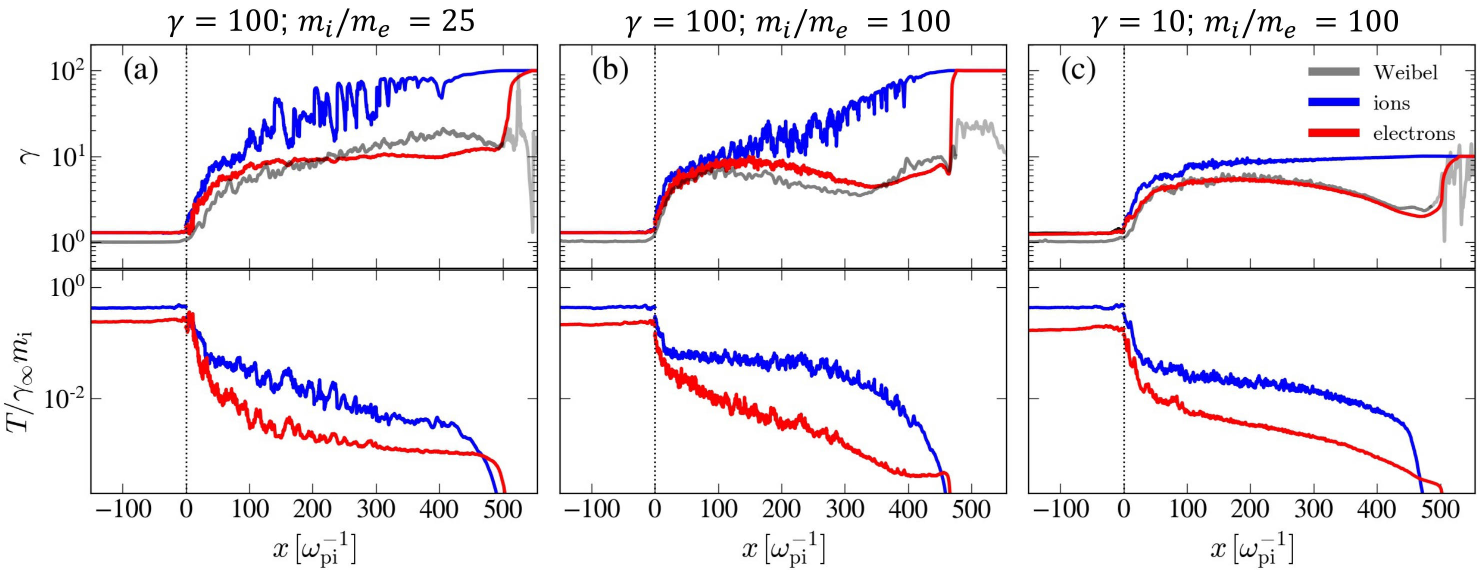
Turbulence frame moves at speed $\boldsymbol{\beta}_{\boldsymbol{w|d}} = \boldsymbol{E}\times\boldsymbol{B}/\boldsymbol{B}^2$

Pelletier+2019

Due to their large difference in inertia, electrons and ions have largely different dynamics in the shock precursor

Lorentz factor

Temperature



- Large difference of inertia between ions and electrons in the precursor ⇒ background charge separation
- Electrons are strongly coupled to the microturbulence ⇒ $\mathcal{R}_w \sim \mathcal{R}_e$
- Ions are drifting at relativistic speed in the Weibel frame ⇒ $\nu_i \ll \nu_e$ (ν : scattering frequency)

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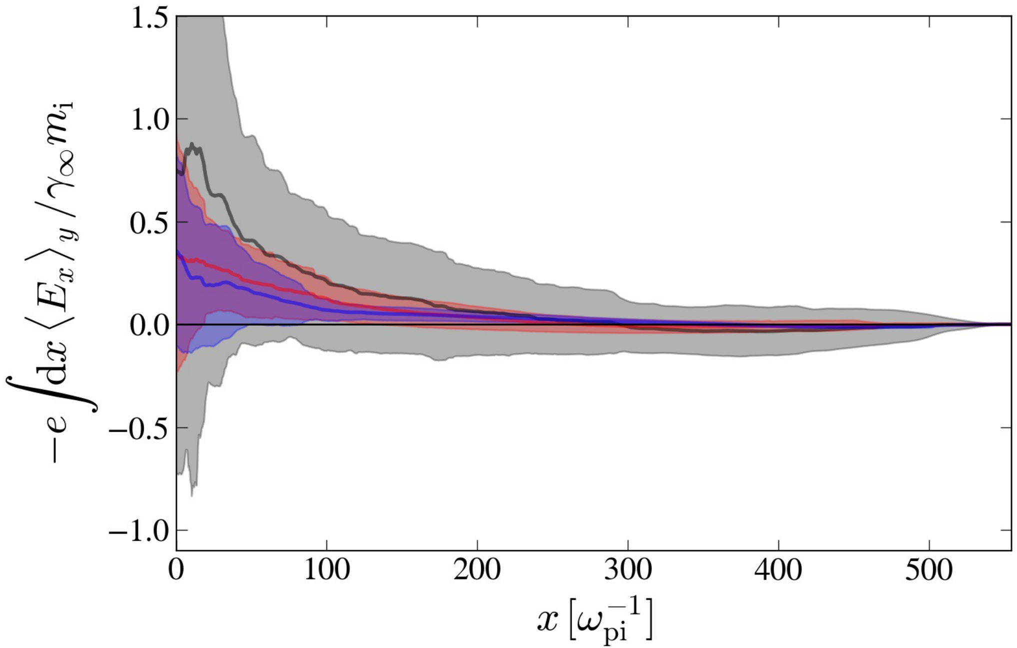
Build up of an electric potential in the shock precursor of the shock



Coherent electric field

$$\langle\, \phi \,\rangle_y = -\int \langle\, E_x \,\rangle_y \;\mathrm{d}x$$

Charge separation in the **background plasma**

$$\nabla\phi < 0$$

Estimate of the electric potential in the shock precursor shows evidence of a coherent electric field of sufficient amplitude to explain the strong electron energization

$$\Delta\phi \sim 0.5\,\gamma\, m_i \sim T_e$$

What is the nature of this electric field?

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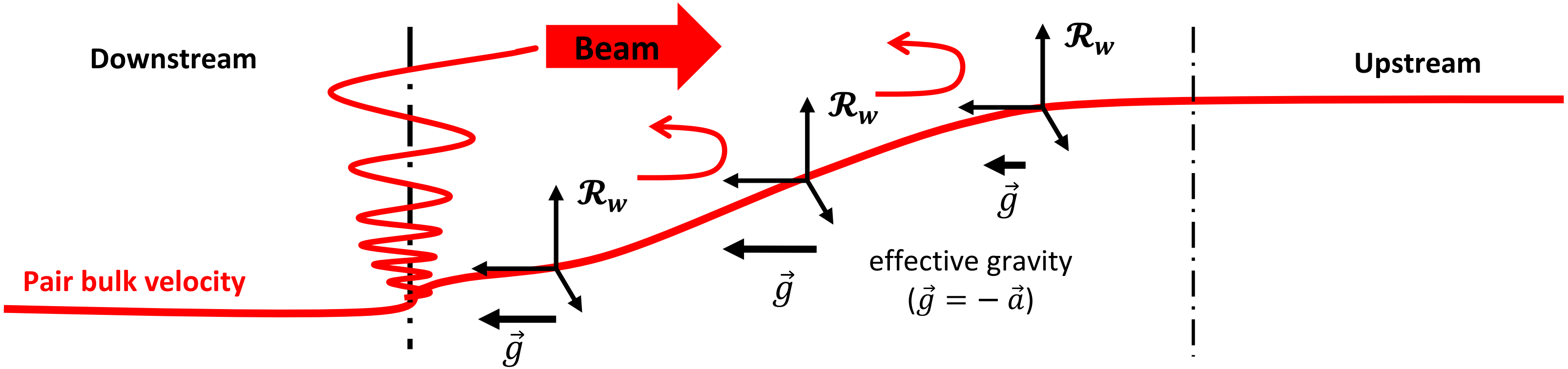
The decelerating turbulence frame introduces noninertial forces leading to nonadiabatic heating of the plasma



Transport equation in a noninertial turbulence with

- pitch angle scattering
- Electrostatic field

Vanthieghem+2022

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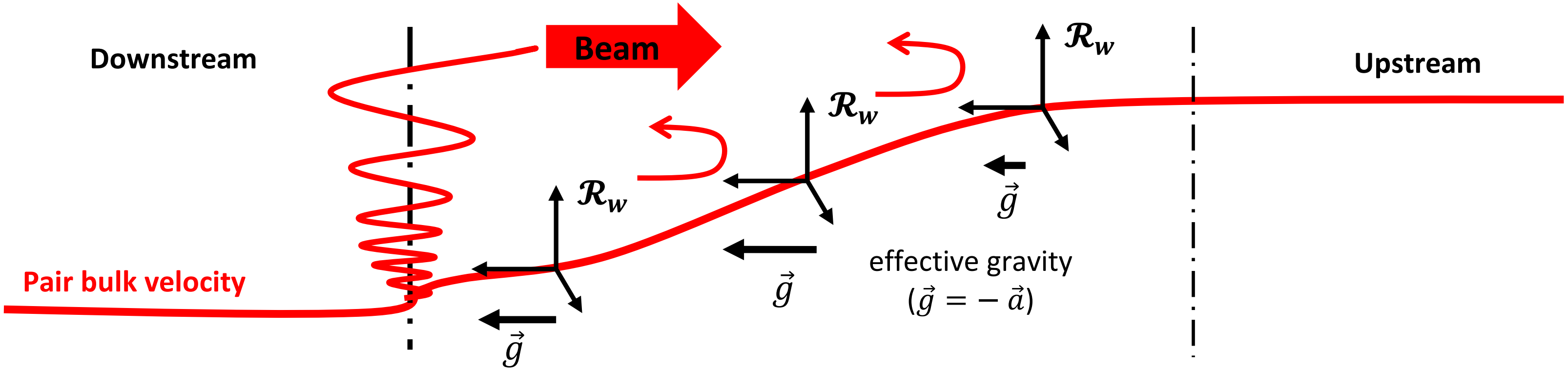

Transport equation in a noninertial turbulence with
- pitch angle scattering
- Electrostatic field

Linearized
Fokker-Planck equation

$$\sim \partial_x f + \cdots \underbrace{\frac{du_w}{dx}\, \partial_p f}_{\text{Advection}} + \cdots \underbrace{\partial_p \left(D_{pp}\, \partial_p f \right)}_{\text{Diffusion}} = 0$$

Vanthieghem+2022

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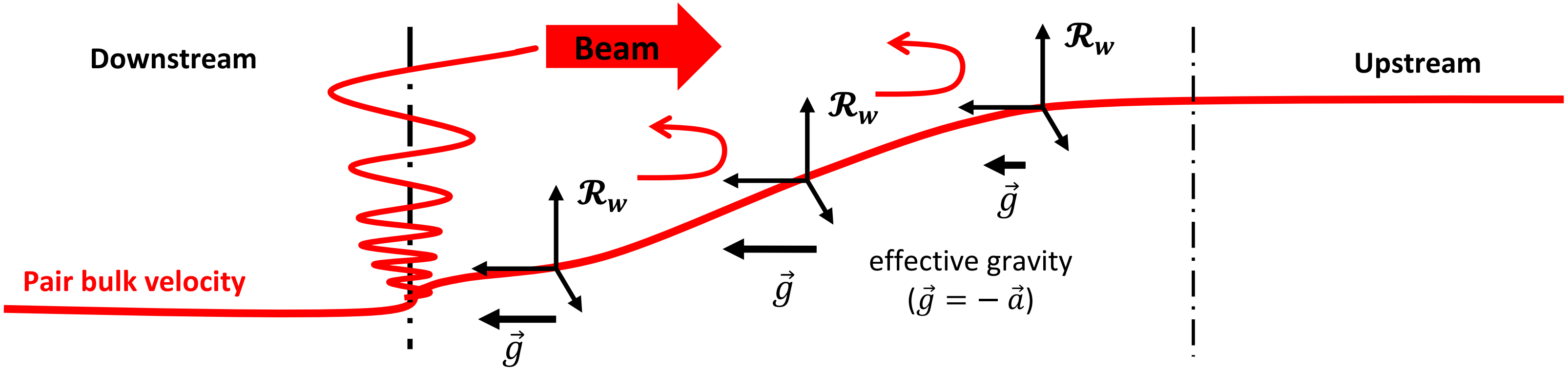

effective gravity
($\vec{g} = -\vec{a}$)

Transport equation in a noninertial turbulence with
- pitch angle scattering
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Linearized
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Diffusion coefficient

$$\boxed{D_{pp} \propto \frac{1}{\nu}\left(\frac{2}{3}\,\frac{du_w}{dx} + \frac{q\,E_{\parallel}}{p}\right)^2}$$

Scattering frequency

Microturbulence deceleration

Electrostatic field

Vanthieghem+2022

The transport equation is solved using a Monte Carlo approach for turbulence and a Poisson solver for electrostatic field

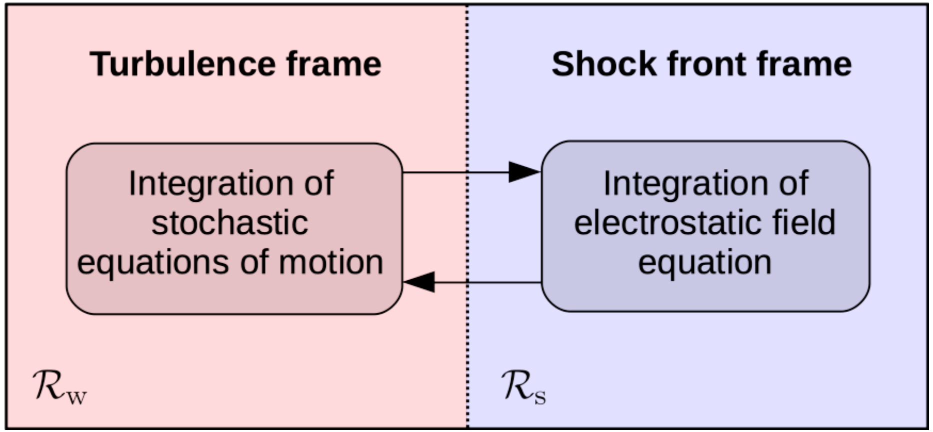
How to extract the relevant physics from full PIC simulations?
⇒ Need for a reduced description accounting for the relevant physics – *i.e.*, pitch angle scattering in the turbulence frame and stationary shock

Forces in the turbulence frame

- Stochastic **pitch angle scattering** at **frequency $\boldsymbol{\nu}$**
  ⇒ via Monte Carlo (for $\delta\boldsymbol{B}$)
- **Electrostatic field**
  ⇒ via Poisson solver (for $\delta\boldsymbol{E}_\parallel$)
- \+ other forces (**radiation**, etc.)

Momentum coordinates
turbulence frame

Space coordinates
shock front frame



Turbulence frame

Shock front frame

Integration of stochastic equations of motion

Integration of electrostatic field equation

$\mathcal{R}_\mathrm{W}$

$\mathcal{R}_\mathrm{S}$

Free parameter : scattering frequency in the turbulence

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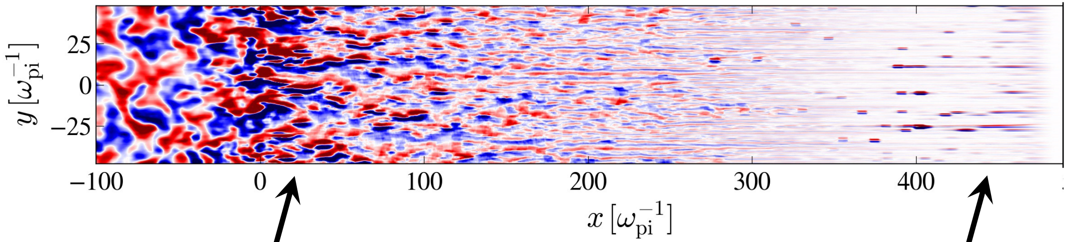
The scattering frequency can be estimated from the structure of the microturbulence

The scattering frequency is determined by the magnetization ($\boldsymbol{\sigma}$) and local typical size of a scattering center ($\boldsymbol{\lambda}$)

$$\boldsymbol{\nu} \propto \boldsymbol{\sigma}\,\boldsymbol{\lambda}\;\boldsymbol{f}(\boldsymbol{p}) \qquad \text{with } \boldsymbol{\sigma} \sim \mathbf{10}^{-(\mathbf{2-3})}$$



$\boldsymbol{d_i} \gg \boldsymbol{d_e}$

$\boldsymbol{\lambda} \sim \boldsymbol{d_i}$

$\boldsymbol{\lambda} \sim \boldsymbol{d_e}$

The microturbulence transitions from electron scale ($\boldsymbol{d_e}$) in the far precursor to ion scales close to the shock ($\boldsymbol{d_i}$)

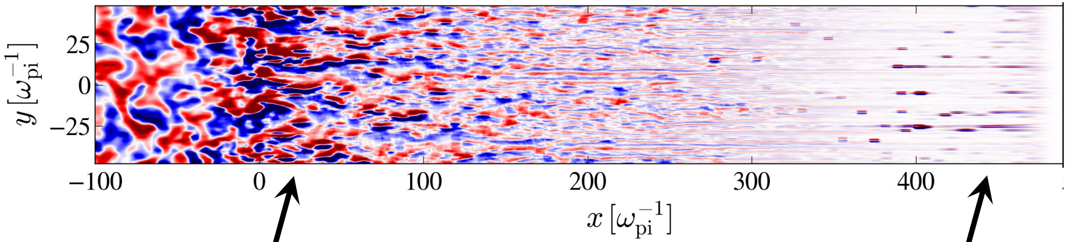
Vanthieghem+2022

The scattering frequency can be estimated from the structure of the microturbulence

The scattering frequency is determined by the magnetization ($\boldsymbol{\sigma}$) and local typical size of a scattering center ($\boldsymbol{\lambda}$)

$$\boldsymbol{\nu} \propto \boldsymbol{\sigma}\, \boldsymbol{\lambda}\ \boldsymbol{f(p)} \qquad \text{with } \boldsymbol{\sigma} \sim \mathbf{10^{-(2-3)}}$$

Comparison between the scattering frequency estimated from kinetic simulations and by solving the transport equation (shaded area)



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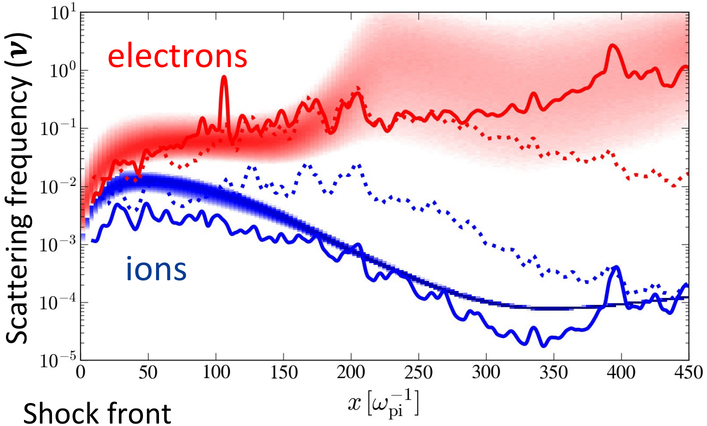

Shock front

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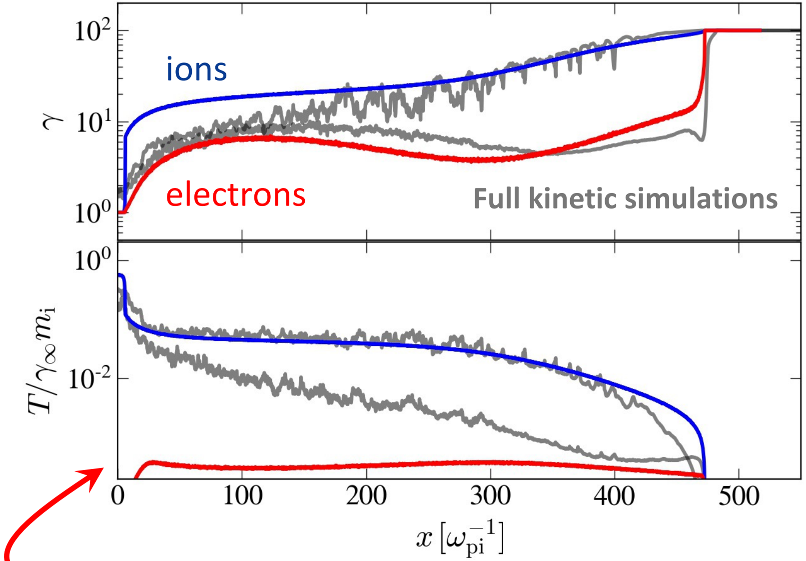
The electrostatic potential is essential to account for the strong electron energization

Comparison between fully kinetic simulations and Monte Carlo-(Poisson) solutions to the transport equation

Dynamics of the plasma without electrostatic potential

Pure pitch-angle scattering in the turbulence ($E_\parallel = 0$)



Cold electrons ⇒ pitch-angle scattering cannot explain strong equipartition

Vanthieghem+2022

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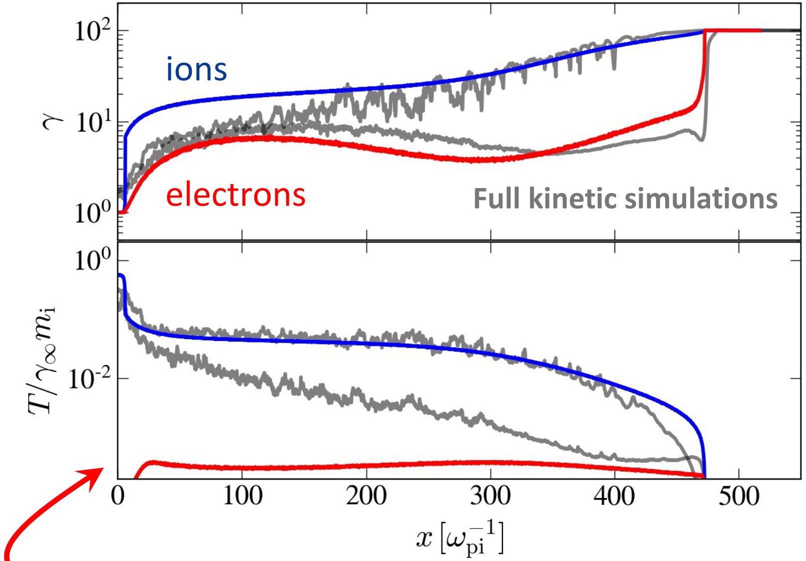
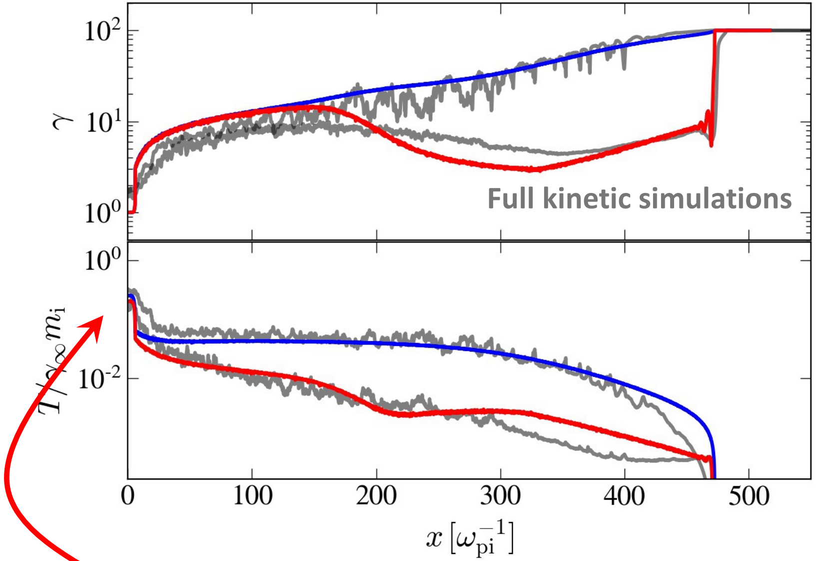


Cold electrons ⇒ pitch-angle scattering cannot explain strong equipartition

Dynamics of the plasma with electrostatic potential

pitch-angle scattering + electrostatic field



Electron-ion equipartition

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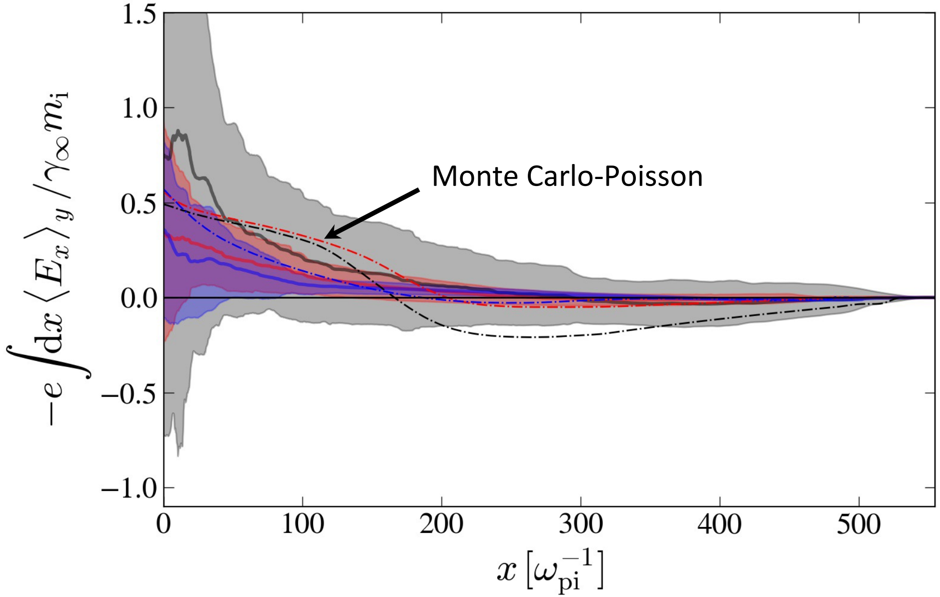
Electron heating proceeds through a Joule-like process in the decelerating microturbulence and coherent electric field

Comparison between the electric potential (from kinetic simulation) and the electrostatic potential from the Monte Carlo-Poisson solution to the transport equation



Equipartition is associated with the self-consistent generation of a coherent (along the transverse direction) longitudinal electric field across the shock precursor coupled with scattering in microturbulence

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To summarize

Take home message

- Strong electron energization, up to near equipartition, is observed in unmagnetizaed relativistic collisionless shock waves
- The noninertial nature of the turbulence frame and electrostatic potential lead to nonadiabatic heating in a Joule-like process
- The ions dynamics is mainly governed by the pitch angle scattering in the decelerating microturbulence
- The electrostatic field in the shock precursor of electron-ion shocks accounts for equipartition in the downstream