Physics of Weibel-Mediated Relativistic Collisionless Shock Waves

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Kinetic description in high-energy astrophysics

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Free energy
(kinetic, magnetic)

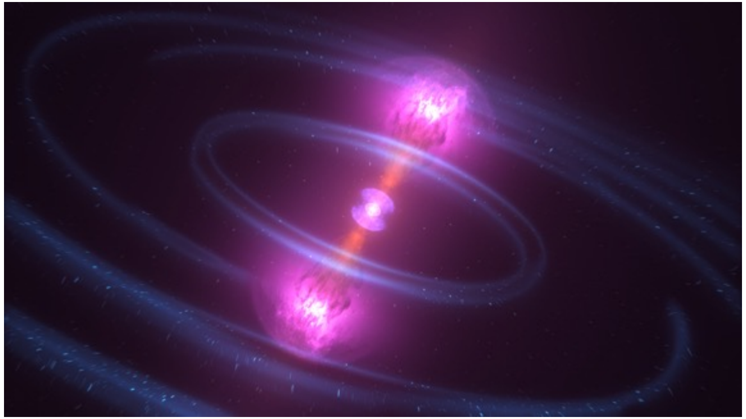
$\lambda \simeq L$
(dynamical scale)

Collective effects
(waves, instabilities, etc.)

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

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

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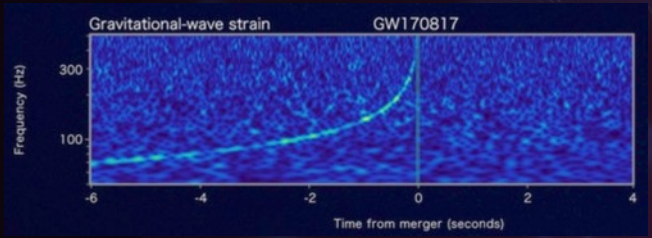
Gravitational wave emission

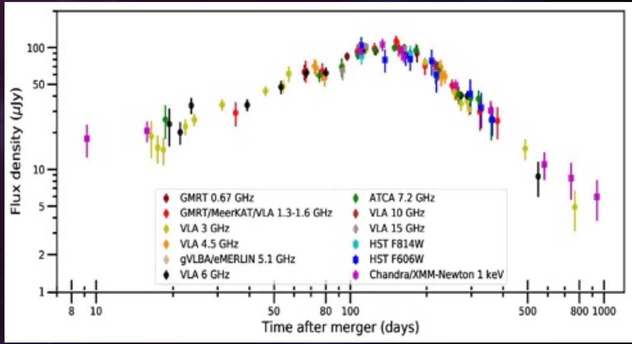


GW170817 and its EM counterpart as a perfect example…

Prompt gamma emission

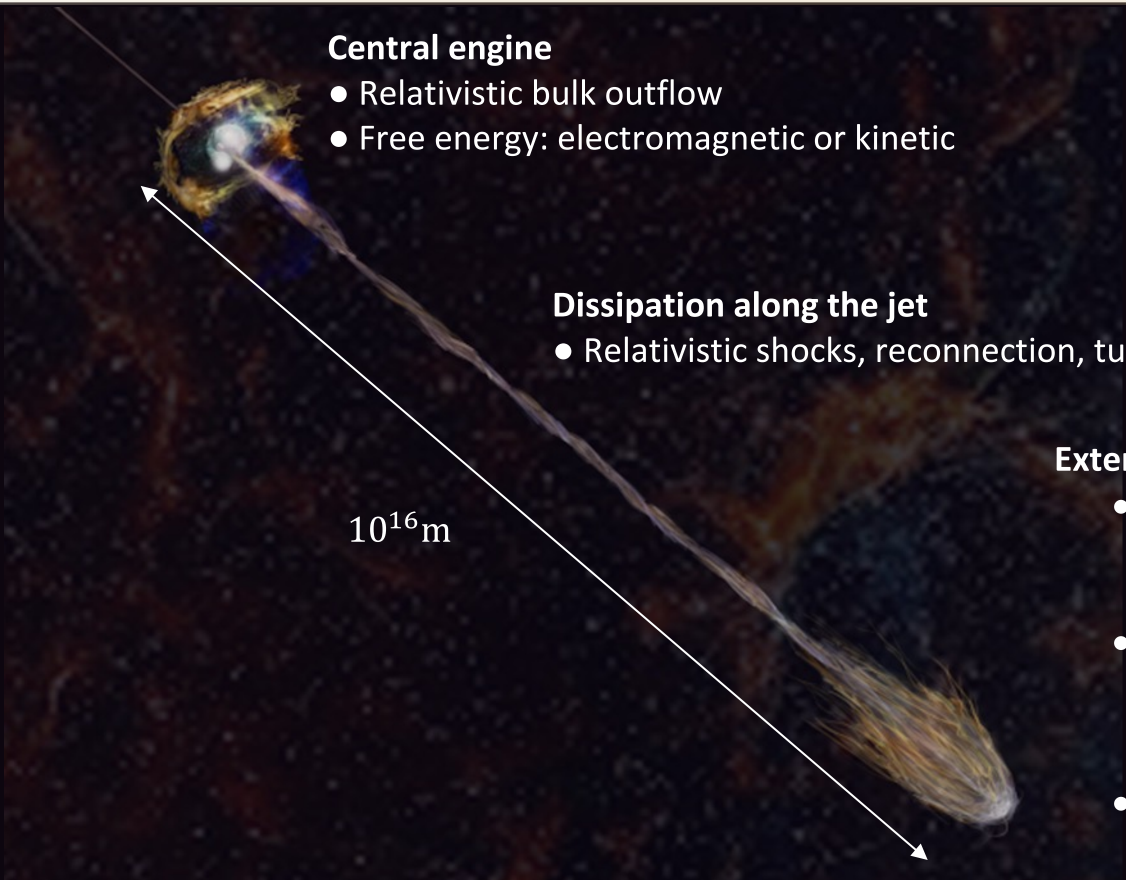
Fermi-GBM

Afterglow emission



Mahkatini et al. 2020

Motivations
Relativistic jets - Gamma Ray Burst Afterglows



Central engine
- Relativistic bulk outflow
- Free energy: electromagnetic or kinetic

Dissipation along the jet
- Relativistic shocks, reconnection, turbulence etc.

External shock
- Relativistic

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

- Unmagnetized

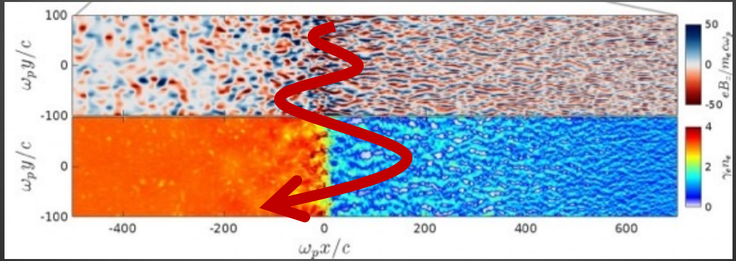
$$\sigma = \frac{u_A^2}{c^2} \ll 1$$

- Collisionless

Motivations

Relativistic jets: Gamma Ray Burst Afterglows

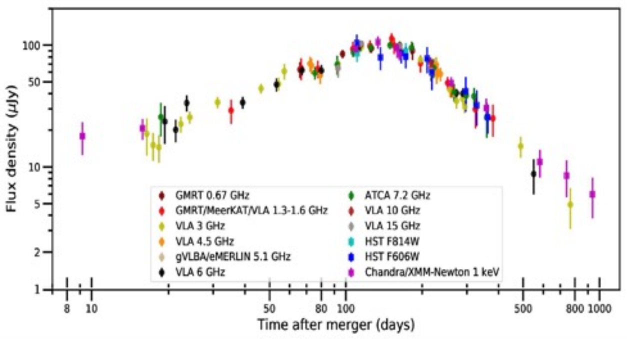
Fermi Acceleration in Relativistic Collisionless Shock Wave



Particle-In-Cell simulation - Calder

Afterglow emission

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



Mahkatini et al. 2020

External shock

- Relativistic

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

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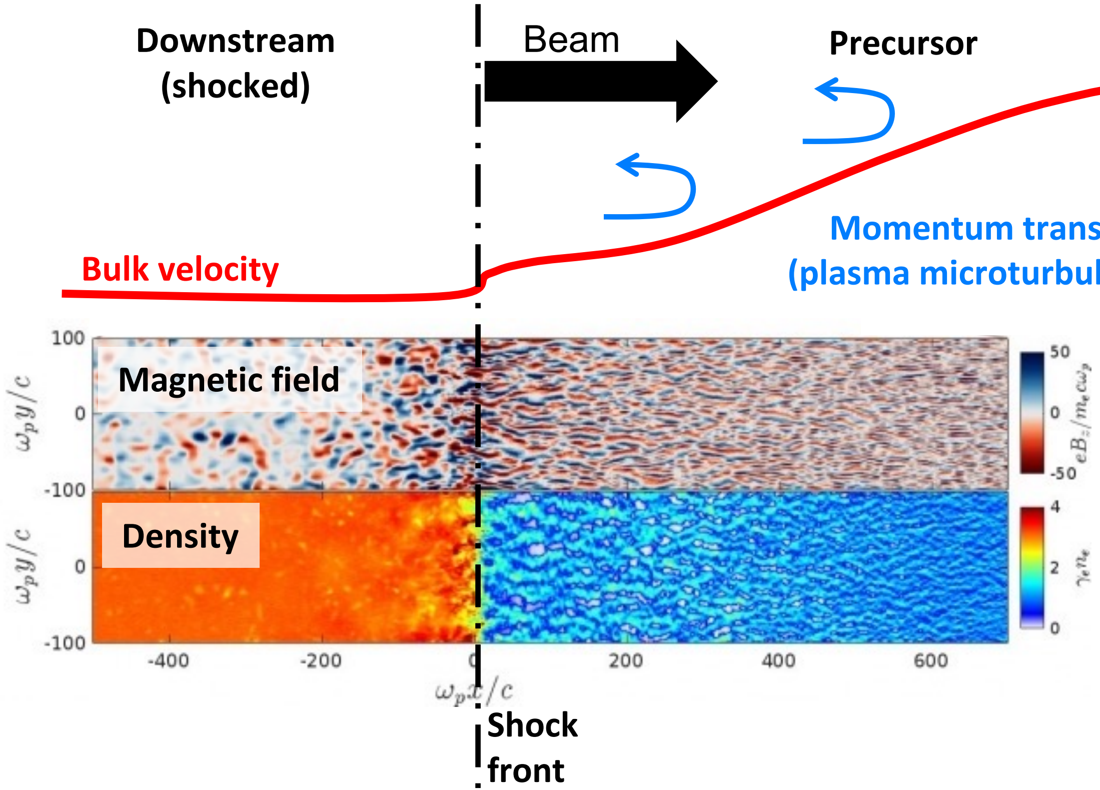
$$\sigma = \frac{u_A^2}{c^2} \ll 1$$

- Collisionless

Momentum transfer from a beam of accelerated particles to the background plasma via a self-generated microturbulence



- **Collisionless shock waves**

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

⇒ **scale:** $c/\omega_p \sim \gamma^{1/2}\, n_{15}^{1/2}$ cm

The Weibel turbulence frame in a pair plasma
The electromagnetic turbulence as scattering agent for the particles

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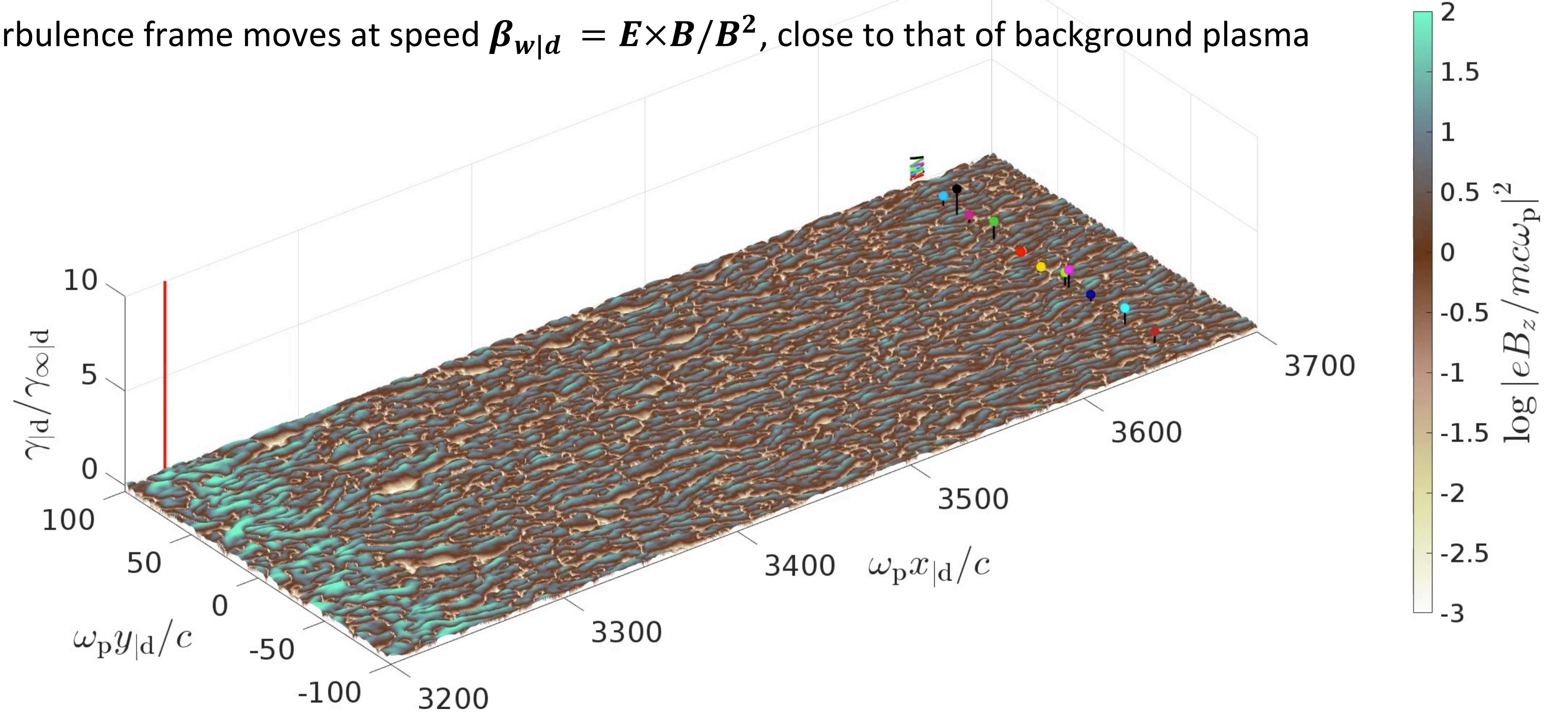
At each point, one can define a local reference frame $\mathcal{R}_w$ in which the turbulence is quasi-magnetostatic

- Turbulence frame moves at speed $\boldsymbol{\beta}_{w|d} = \boldsymbol{E}\times\boldsymbol{B}/B^2$, close to that of background plasma



Pelletier+2019

γ = 100; mi/me = 100; $k_BT = 0.01\ m_ec^2$; Nx = 6×10^4; Ny = 3.4×10^3; Nt = 3.6×10^4; 10ppm/species (~10^{10} macro-particles)

Deceleration of the background is modeled as energy-momentum transfer from the beam in a perfect fluid picture

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

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

- Electromagnetic turbulence hardly contributes to the fluid conservation equations

⇒ Background plasma deceleration law

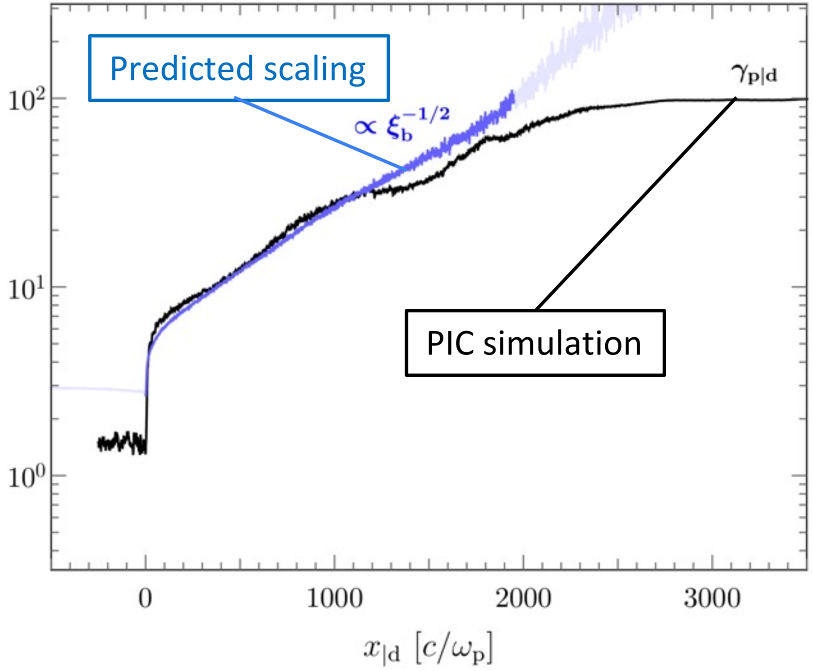
Lorentz factor $\gamma_p \propto \xi_b^{-1/2}$

with

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

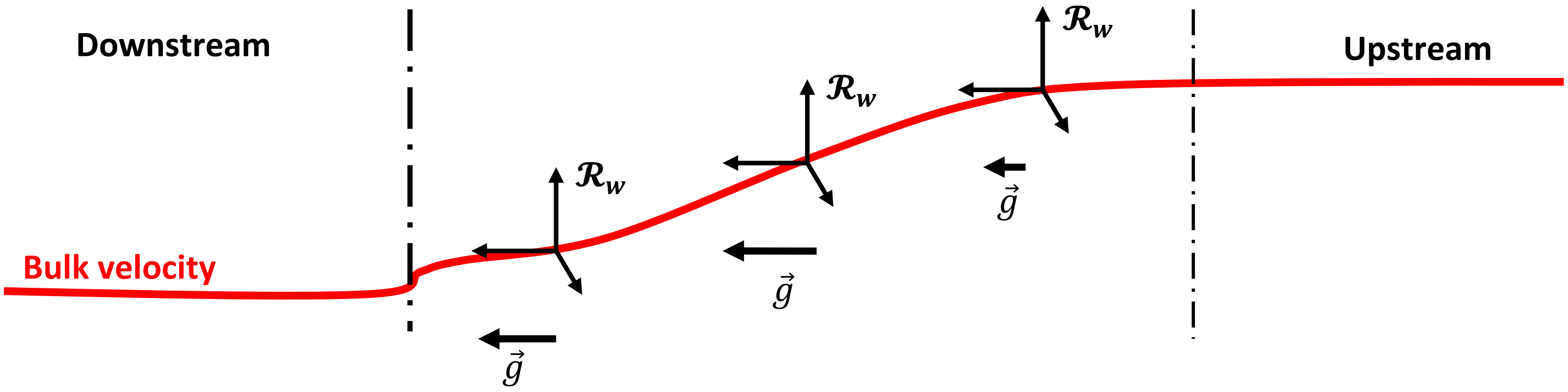
P_b - Suprathermal particle pressure
$\mathcal{F}_\infty$ - Incoming ram pressure

Background plasma Lorentz factor



Lemoine+2019a

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



The noninertial turbulence frame acts as an effective gravity ($\vec{g} = -\vec{a}$) for the particles scattering in pitch angle with scattering frequency $\nu \Rightarrow$ nonadiabatic heating of the background plasma in a Joule-like process

Diffusion coefficient

$$D_{pp} \propto \frac{1}{\nu}\left(\frac{du_w}{dx}\right)^2$$

Linear analytical estimate for a pair plasma

- Perturbative transport equation
- Slow deceleration regime

u_w - turbulence frame velocity in shock front frame

ν - scattering frequency in turbulence frame

Lemoine+2019a

The transport equation is solved as a stochastic differential equation in a general Monte Carlo-Poisson approach

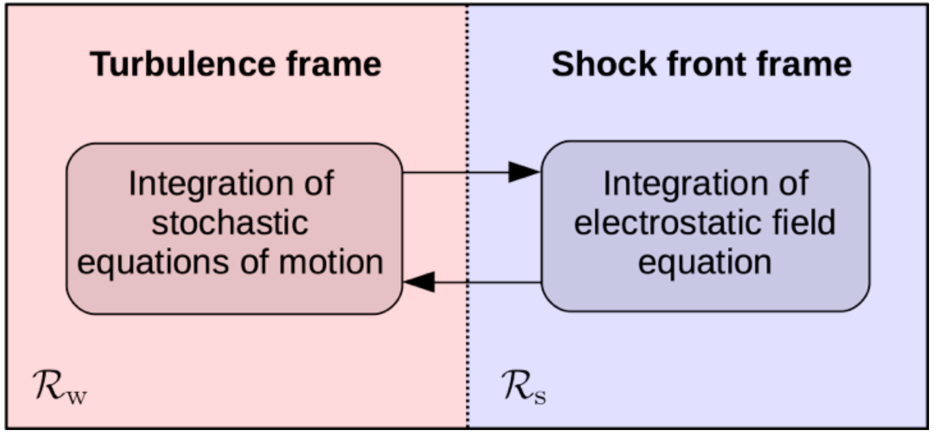
How to extract the relevant physics from full PIC simulations?
⇒ Need for a reduced description accounting for the relevant physics – *i.e.*, pitch angle scattering in the turbulence frame and stationary shock

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.)

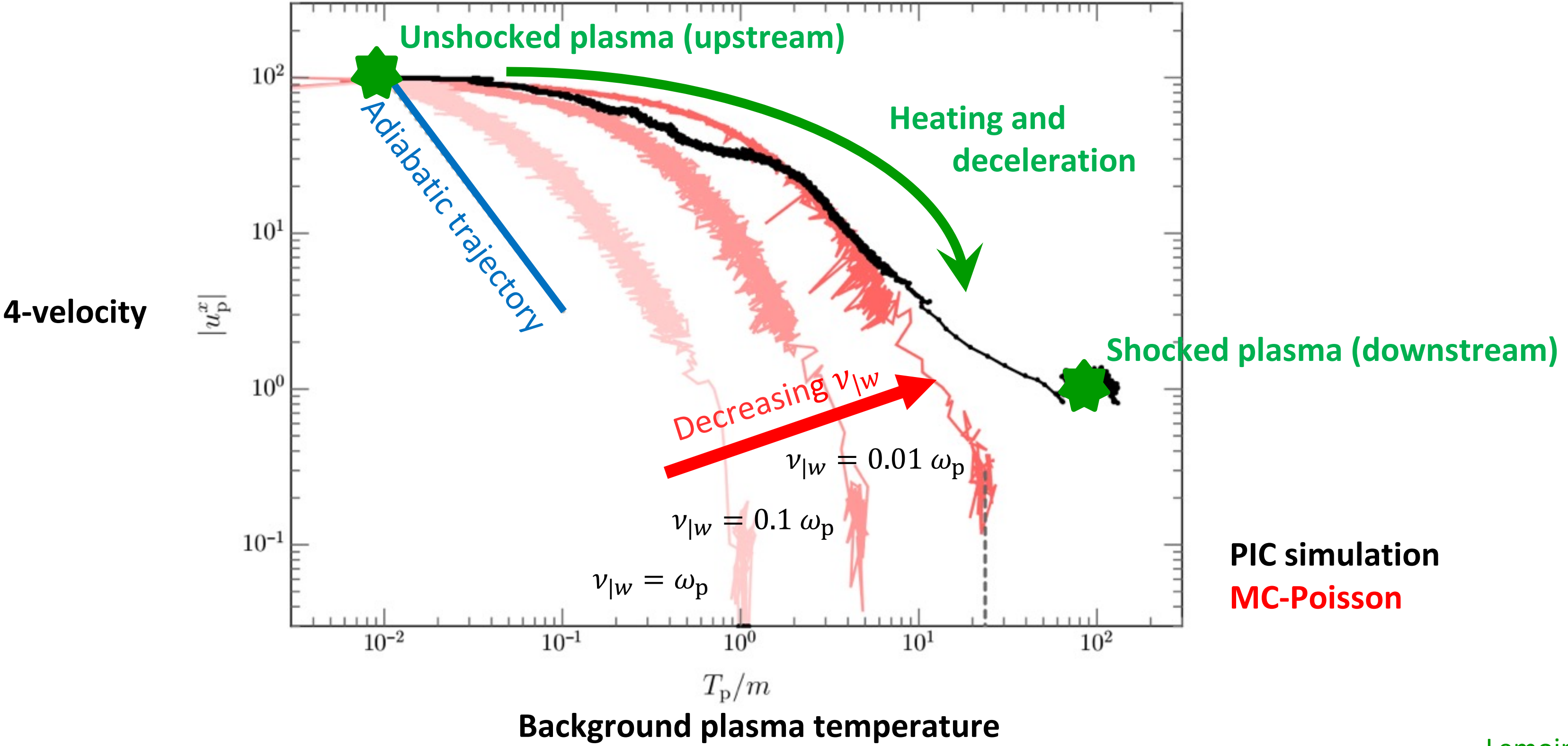
Momentum coordinates
turbulence frame

Space coordinates
shock front frame



Vanthieghem+2021 (In prep.)

In a pair plasma, pure pitch angle scattering in a noninertial turbulence frame is sufficient to describe the background dynamics



Lemoine+2019a

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

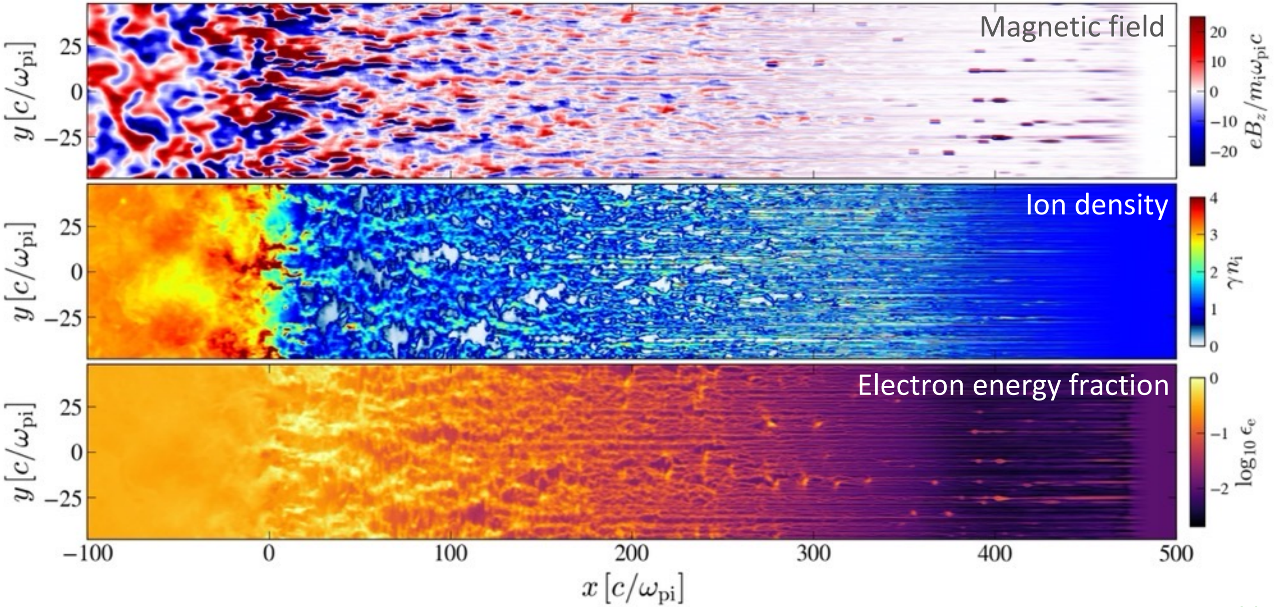
- Modeling of gamma-ray burst afterglows indicate equipartition between electrons and ions - Freedman+01

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

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

Downstream

$E_e \sim E_i$



Upstream

$E_e \sim \frac{m_e}{m_i} E_i$

Vanthieghem+2021 (In prep.)

What is the source of strong electron heating?

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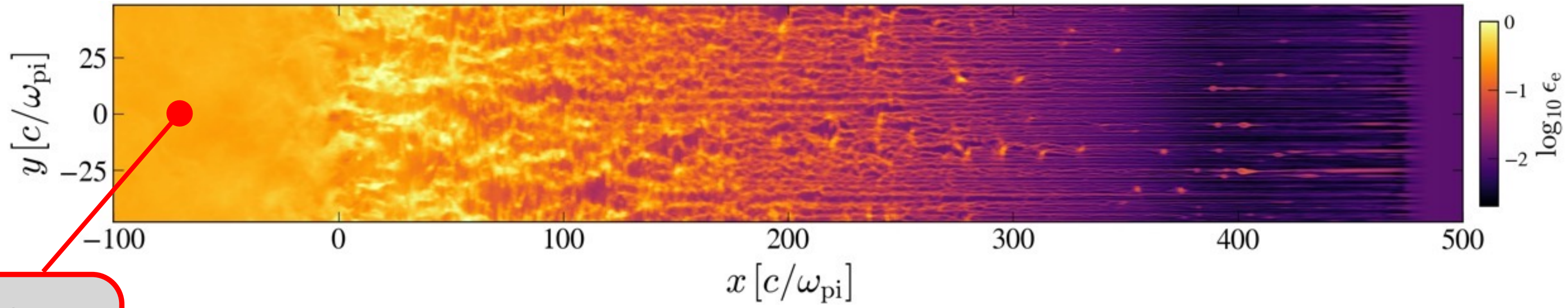
γ = 100; mi/me = 100; $k_B T = 0.01\, m_e c^2$; Nx = 10^5; Ny = $1.2\text{x}10^4$; Nt = $9\text{x}10^4$; 10ppm/species (~10^{10} macro-particles)



Downstream

$T_e \simeq 0.5\, T_i$

Different models have been proposed

- Inductive E-field from the Weibel growth – Gedalin+2012, Kumar+2015
- Break up of the filaments through kink unstable modes – Milosavljevic+2006
- Electrostatic/transverse modes – Gedalin+2008, Plotnikov+2013, Kumar+2015

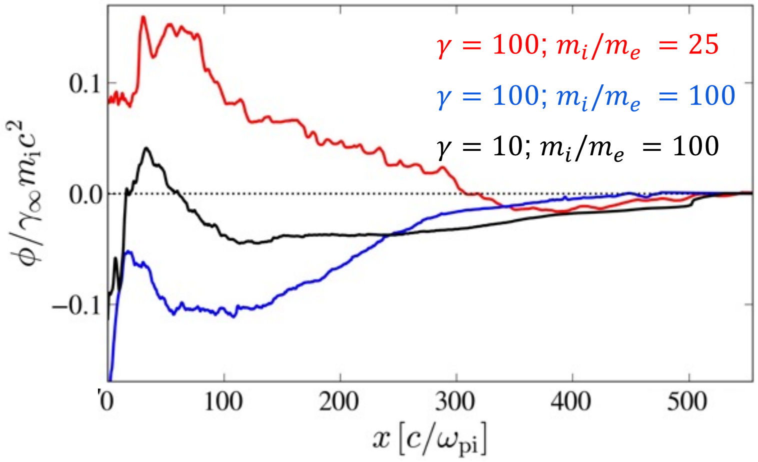
Probe the electron heating with ab initio PIC simulations (+ reduced model)

$\gamma = 100;\ m_i/m_e = 25$ $\gamma = 100;\ m_i/m_e = 100$ $\gamma = 10;\ m_i/m_e = 100$

Vanthieghem+2021 (In prep.)

The electrostatic potential in the shock precursor originates from the mixed contribution of the beam and background plasma

Electrostatic potential



Coherent electric field

$$\langle \phi \rangle_y = -\int \langle E_x \rangle_y \, dx$$

Components

- Charge separation in the **background plasma**
  $\nabla\phi < 0$
- Net charge carried by the **beam**
  $\nabla\phi > 0$

Stochastic heating through the **electrostatic potential** from **both components**

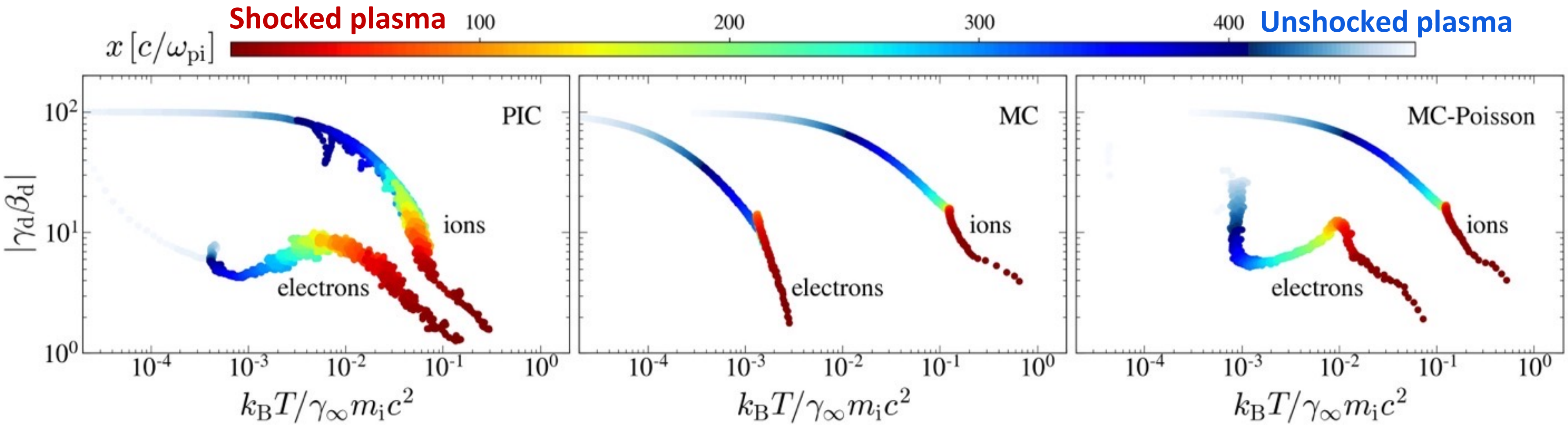
$$D_{pp} \propto \frac{1}{v}\left(\frac{2}{3}\frac{du_w}{dx} + \frac{q\,E_x}{p}\right)^2$$

Microturbulence deceleration

Electrostatic field

Vanthieghem+2021 (In prep.)

Equipartition requires the contribution of strong heating by the electrostatic field



Pure pitch angle scattering

Pitch angle scattering + E-field

The heating and deceleration of the background plasma is qualitatively described by the joint contribution of the electrostatic field and pitch angle scattering of trapped and untrapped populations

Vanthieghem+2021 (In prep.)

To summarize

Take home message

- The dynamics of a pair plasma is well modeled by pure pitch angle scattering in a noninertial turbulence frame
- The noninertial nature of the turbulence frame leads to nonadiabatic heating in a Joule-like process
- The electrostatic field in the shock precursor of electron-ion shocks accounts for equipartition in the downstream
- Both the charged beam and background plasmas contribute to the electrostatic potential

Future perspective
Microturbulence in Relativistic Radiation Mediated Shocks

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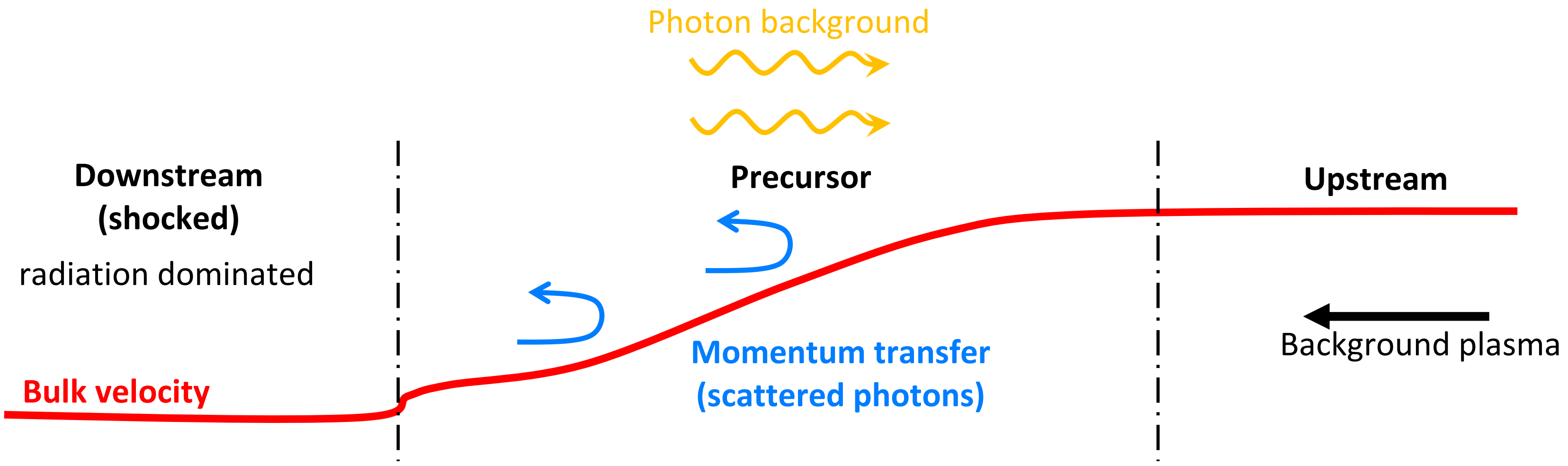

- RRMS are mediated by Compton scattering and pair production
- The system is unstable to electromagnetic modes, seeding a microturbulence
- The microturbulence is leads to species coupling and nonadiabatic heating // Weibel-mediated shocks

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Vanthieghem+2021 (In prep.)