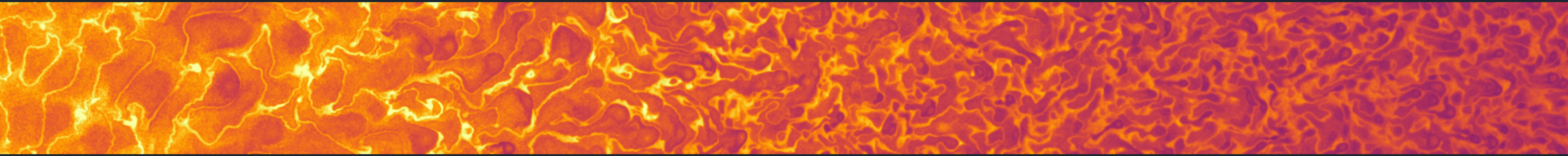
Mereology of Relativistic Blast Waves
- Heating, Acceleration, and Radiation -

Arno Vanthieghem



HEPRO VIII: High Energy Phenomena in Relativistic Outflows

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Thanks to:

M. Lemoine (IAP), L. Gremillet (CEA), G. Pelletier (IPAG),
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Non-thermal spectra in extreme astrophysical environments originates from collective plasma effects

Source

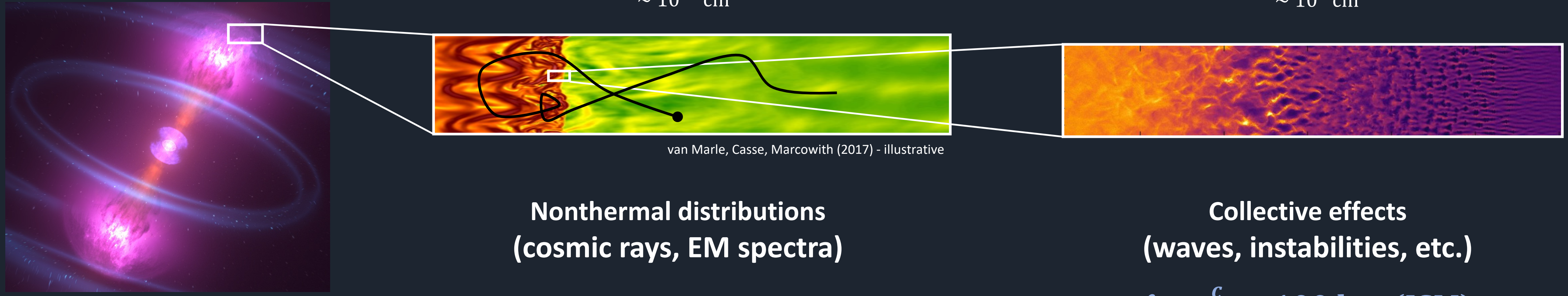
pc ~ 10^{19} cm

Accelerated particles

~ 10^{12} cm

Ambient plasma

~ 10^{8} cm



van Marle, Casse, Marcowith (2017) - illustrative

Free energy (kinetic, magnetic)

$\lambda \simeq L$

(dynamical scale)

Nonthermal distributions (cosmic rays, EM spectra)

Multimessenger observations

Collective effects (waves, instabilities, etc.)

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

(kinetic scale)

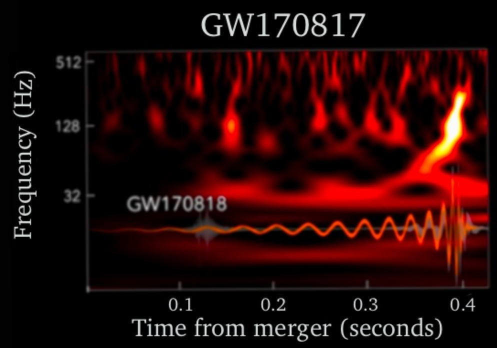
Motivations

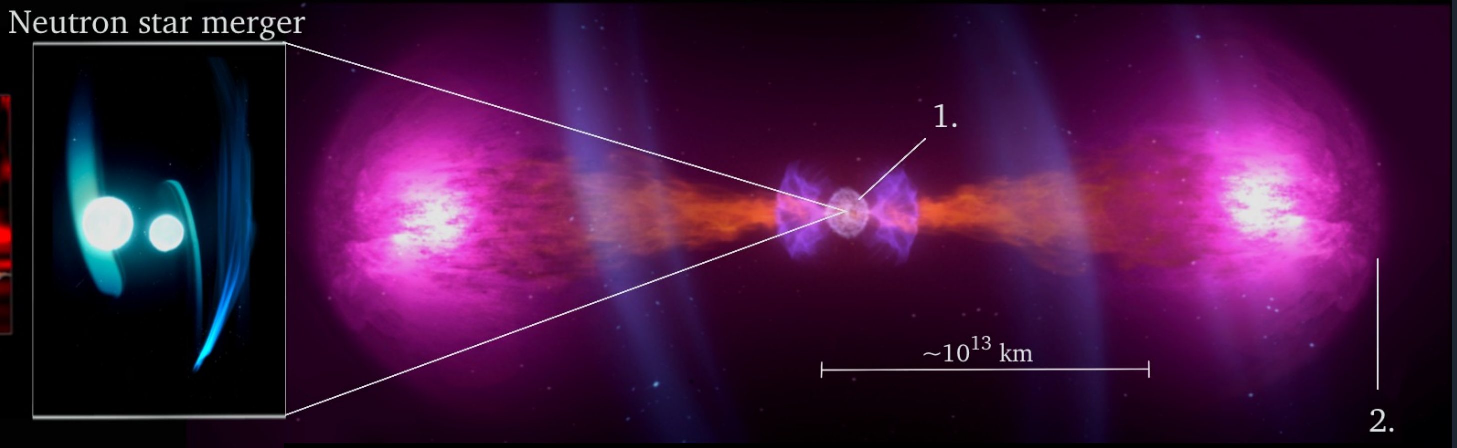
Self-consistent dynamics of extreme astrophysical environments

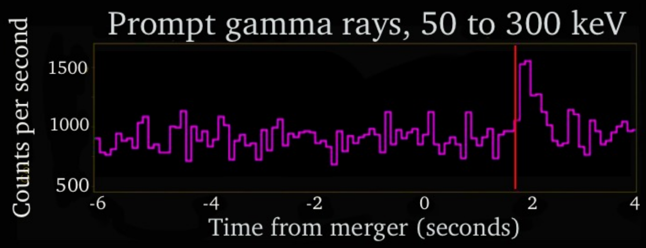
- Self-generation and amplification of magnetic field
- Partition of energy between species
- Mechanisms of particle acceleration and feedback

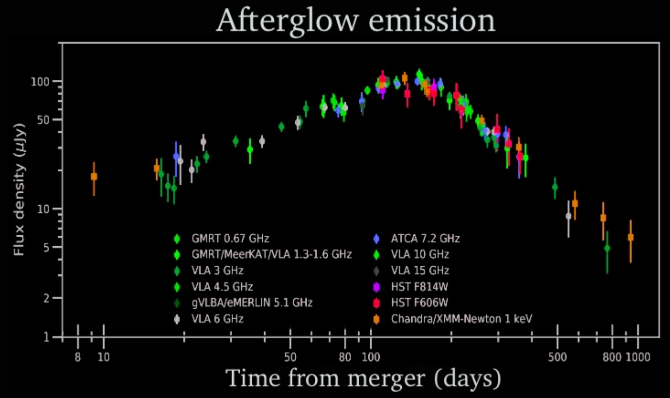
$\Rightarrow$ kinetic description of the plasma process (Particle-In-Cell here)

Relativistic ejecta from binary neutron star mergers – A rich source of information for extreme plasma physics

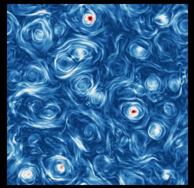






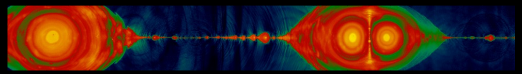


1. Prompt emission
   - Relativistic turbulence



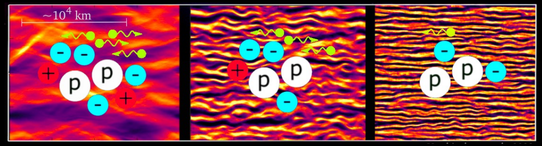
Comisso+, 2019

   - Collisionless reconnection



Sironi+, 2014

   - Radiation-mediated shocks
     see Filip Alamaa's talk
   - Internal shocks, …



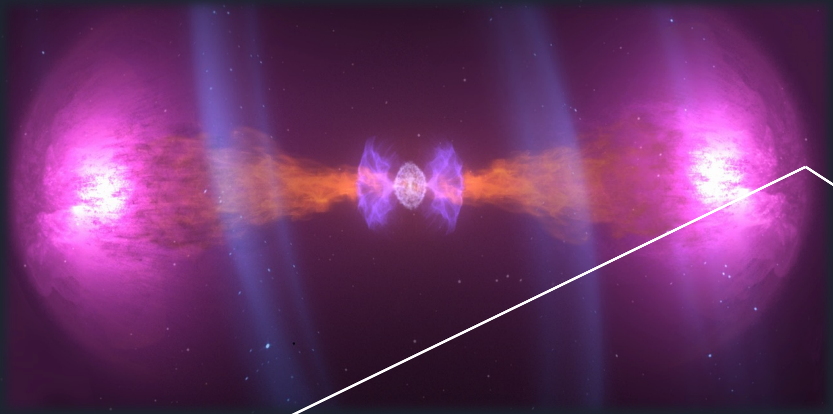
Vanthieghem+, 2022; Mahlmann+, 2023

2. Afterglow emission

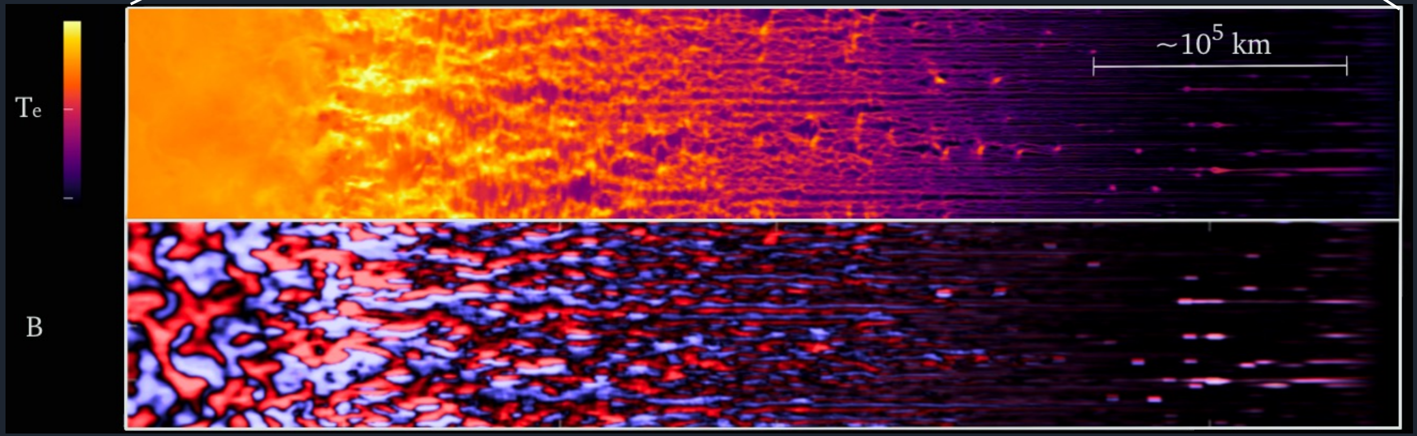
"Synchrotron self-Compton emission from electrons accelerated at a relativistic collisionless shock propagating at the interface with the ISM"

NASA's Goddard Space Flight Center/CI Lab; LIGO & Virgo /Georgia Tech/S. Ghonge & K. Jani; Mahkatini et al., 2020

Physics and Phenomenology of Collisionless Blast Waves



Collisionless relativistic shock ($\Gamma_{sh} = 173$)



Toward a self-consistent modeling of relativistic shock dynamics

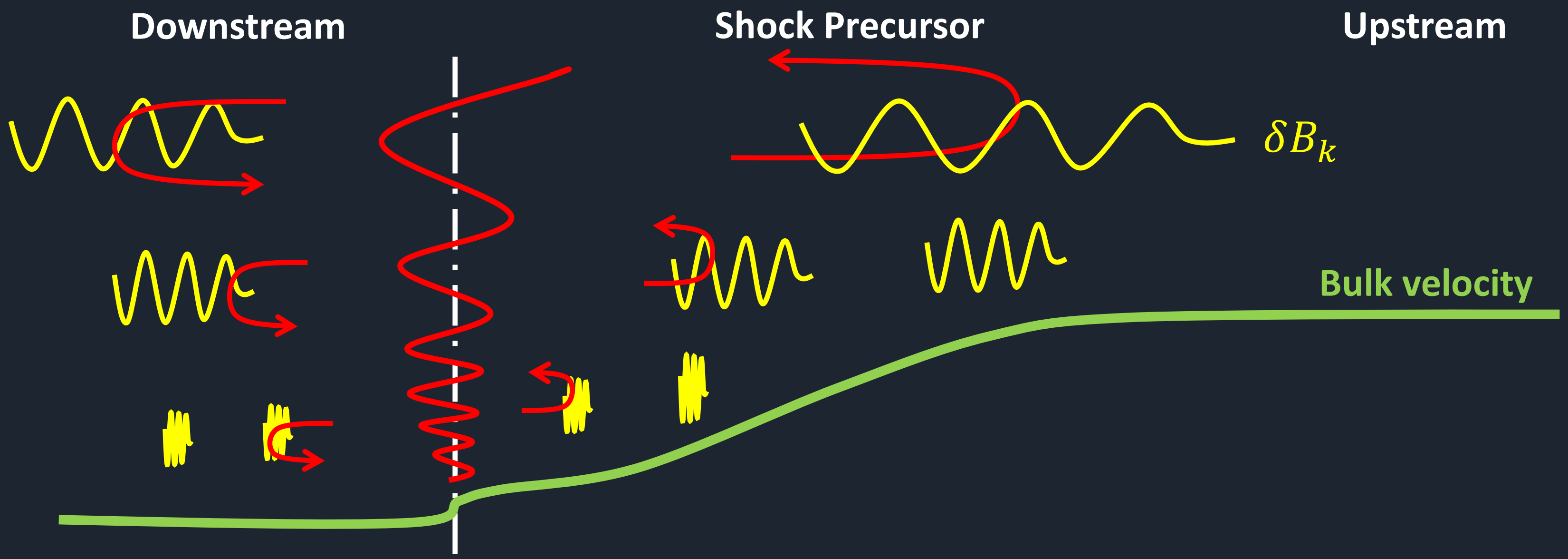
- Shock wave structure
  - Nature of the turbulence
  - Deceleration and heating of the flow

- Energy partition between electrons and ions
  - Relativistic
  - Non-relativistic

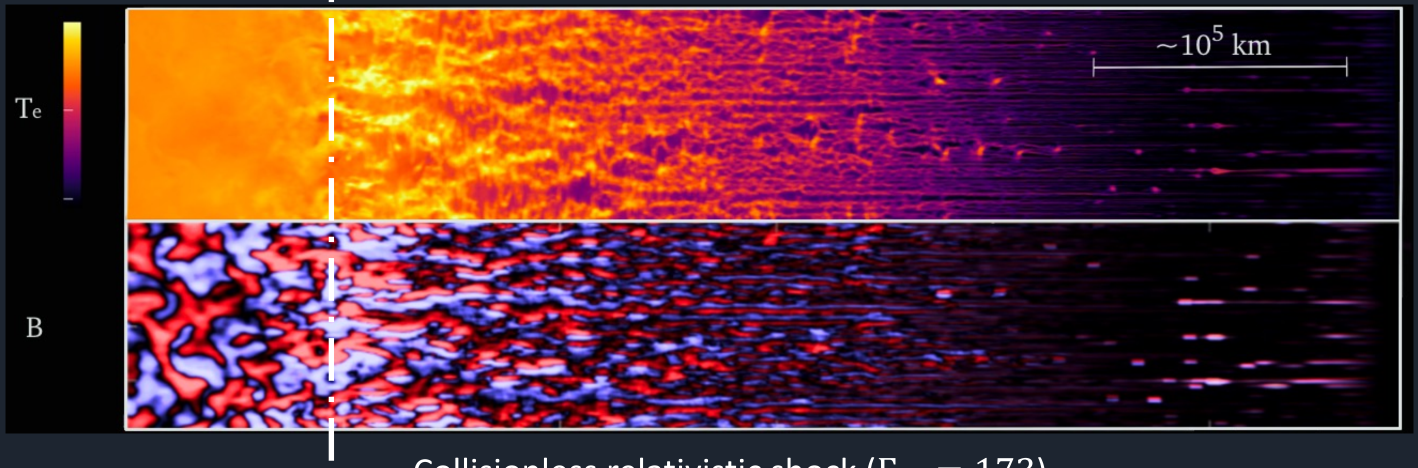
- Particle Acceleration
  - Acceleration time
  - Effect of upstream pair creation

Structure of a relativistic collisionless shock wave in an unmagnetized environment

A general picture in the shock front frame



- Supersonic plasma flow
- Accelerated beam
- Microturbulent (+ coherent) EM field

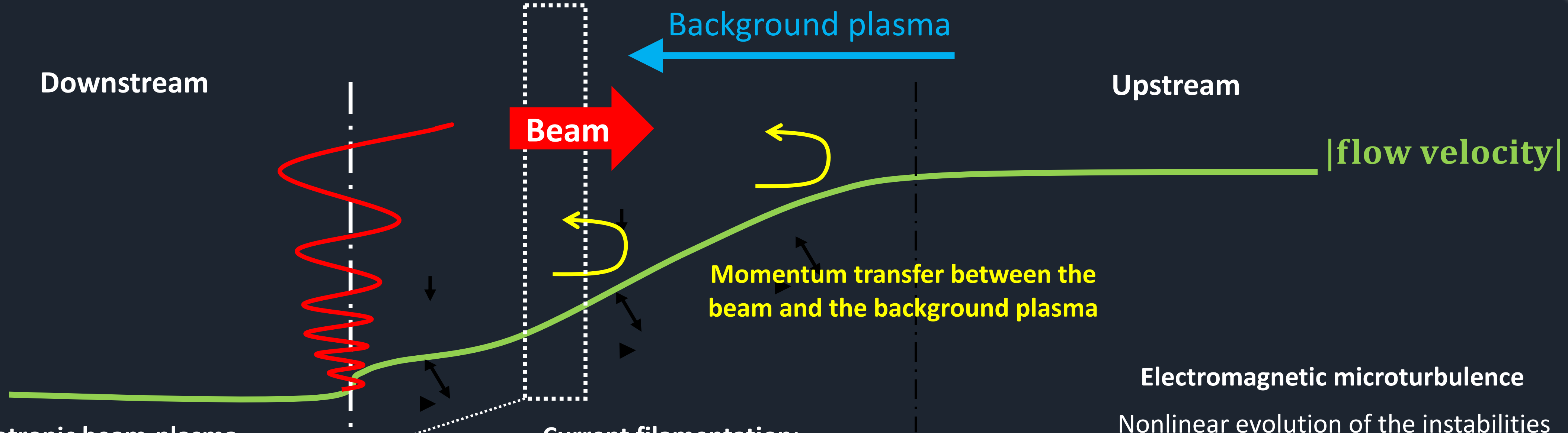


Collisionless relativistic shock ($\Gamma_{sh} = 173$)

Relativistic collisionless shock wave

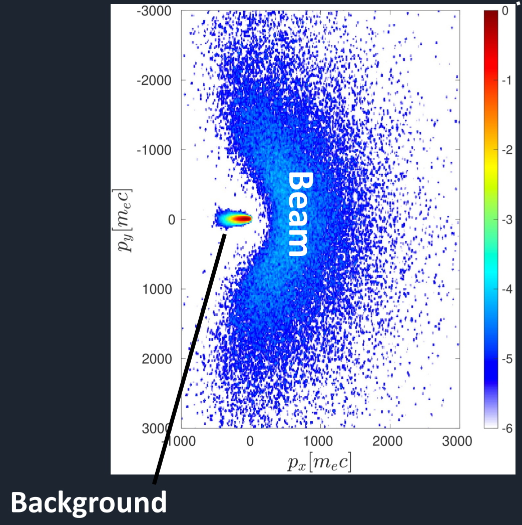
The interplay between a beam of Fermi-accelerated particles and the background plasma generates an electromagnetic microturbulence at kinetic scales

The beam-plasma interplay generates a kinetic scale electromagnetic turbulence via the Weibel instability

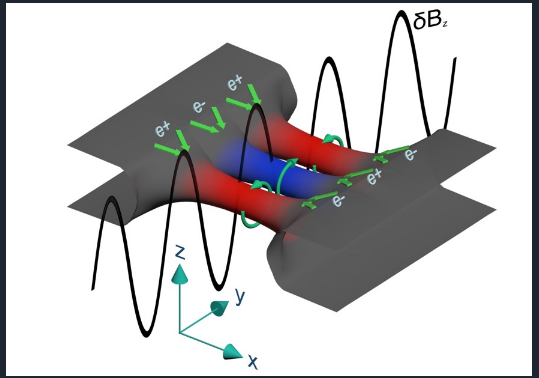


Momentum transfer between the beam and the background plasma

Anisotropic beam-plasma in phase space



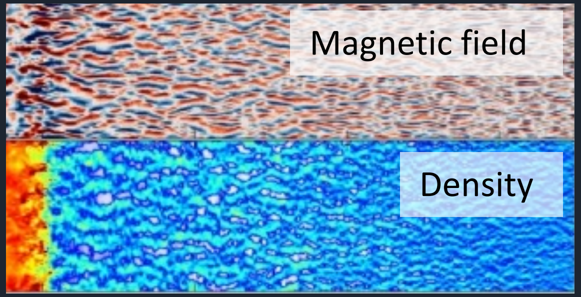
Current filamentation: Weibel instability



A transverse δB generate a net current with 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

Cosmic ray-modified shock – Deceleration of the background flow through the beam ram pressure

Lemoine, Vanthieghem, Pelletier, Gremillet, Phys. Rev. E (2019)

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

Lorentz factor of background flow

Pressure of accelerated particles

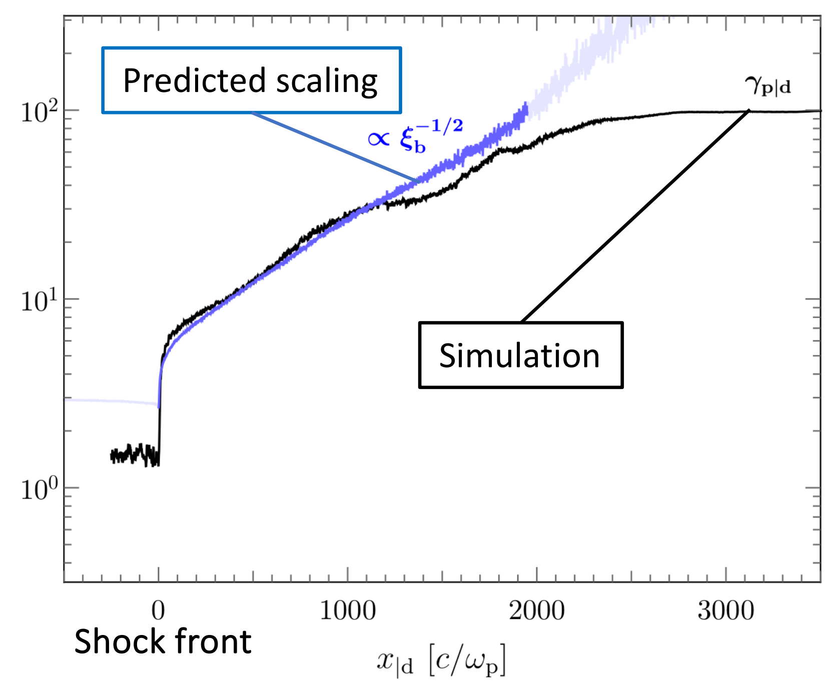
with

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

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



PIC simulation (Calder)
$\gamma = 173; m_p/m_e = 1$

The turbulence is magnetically dominated, and drifts close to the electron/positron bulk velocity

Pelletier, Gremillet, Vanthieghem, Lemoine, Phys. Rev. E (2019)

The turbulence frame: the Weibel frame

- The Weibel instability dominates the precursor of the shock

$$\Rightarrow\ \boldsymbol{E}^2 - \boldsymbol{B}^2 < 0$$

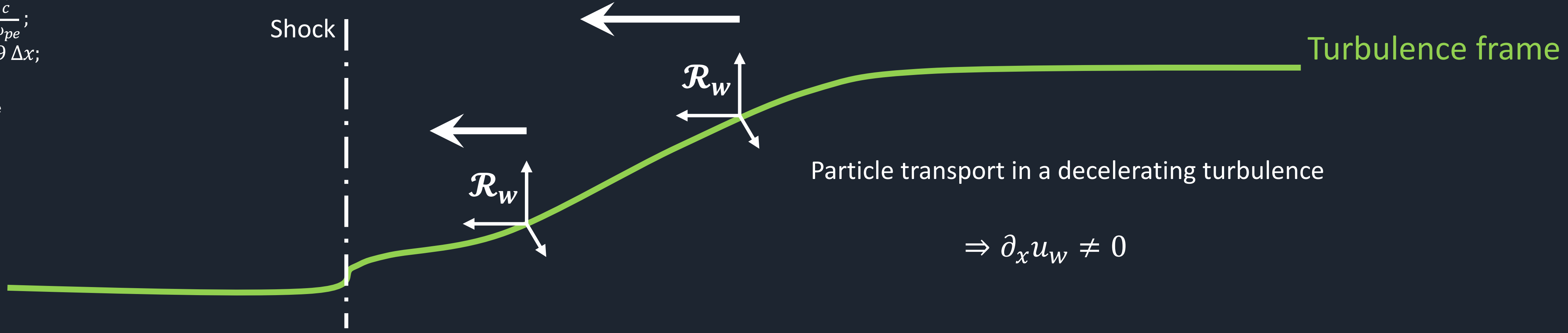
- At each point, one can define a local quasi-magnetostatic reference frame $\mathcal{R}_w$[1,2]

$$\Rightarrow\ u_w \sim \frac{E\times B}{B^2} \sim \frac{\omega}{k}\frac{\epsilon_{xy}}{\epsilon_{yy}} \sim u_e$$

- Electrons drift close to the Weibel frame in the shock precursor

- $u_{sh} = 17.3$;
- $\Delta x = 0.3\frac{c}{\omega_{pe}}$;
- $c\Delta t = 0.99\,\Delta x$;
- 10 ppc;
- $\mathrm{m_i} = 1\ \mathrm{m_e}$

Calder



Particle transport in a decelerating turbulence

$$\Rightarrow \partial_x u_w \neq 0$$

The decelerating turbulence introduces a noninertial force leading to nonadiabatic heating of the plasma

Lemoine, Vanthieghem, Pelletier, Gremillet, Phys. Rev. E (2019)

Semi-dynamical approach to electron-ion transport

For a white noise with isotropic scattering, the transport equation reduces to

$$\dot{\boldsymbol{p}}^i = \underset{1.}{\left(\boldsymbol{p}\cdot\delta\widehat{\boldsymbol{\Omega}}_t\right)^i} - \underset{2.}{\Gamma^i_{ab}\,p^a\,\beta^b}$$

1. **Pitch-angle scattering:** Gaussian white-noise process
In the scattering center frame

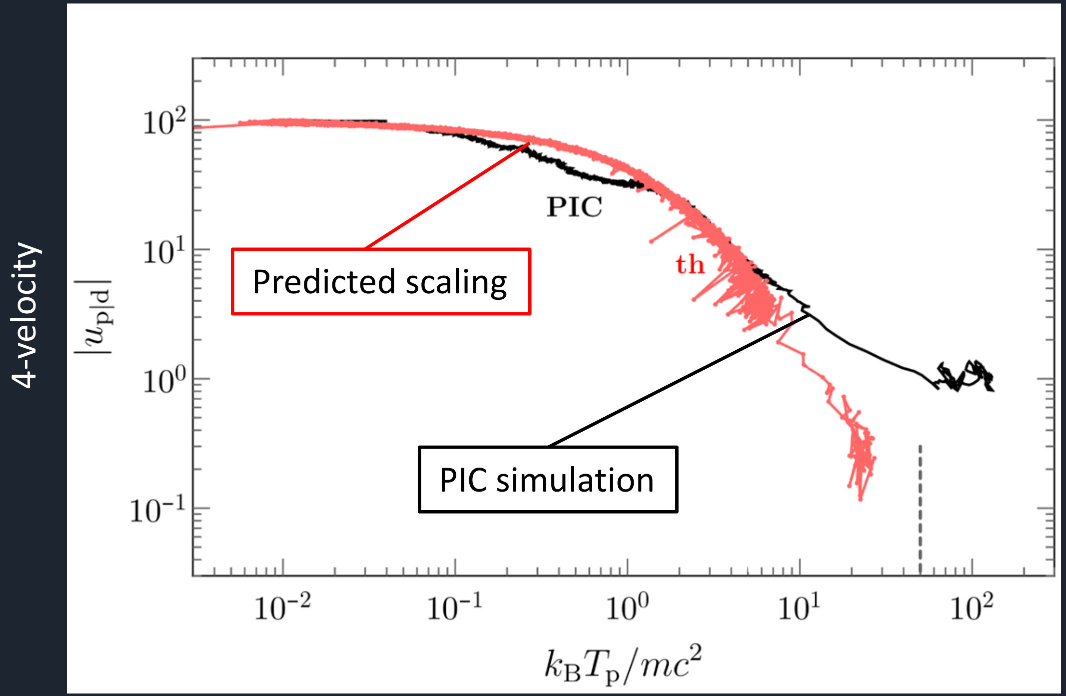
$$<\delta\widehat{\Omega}_t> = 0 \qquad <\delta\widehat{\Omega}_t\,\delta\widehat{\Omega}_{t'}> = 2\,\delta(t'-t)$$

2. Stationary scattering center frame deceleration

$$\partial_x u_w \neq 0$$

Successfully accounts for plasma heating in relativistic pair plasmas

Free parameters: ν, L_{sh}



Background plasma temperature

⇒ Linear Fokker-Planck equation

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

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

~ shearing acceleration (see F. Rieger's talk)

Joule-type heating cannot account for the electron temperature in electron-ion collisionless shocks

Lemoine, Vanthieghem, Pelletier, Gremillet, Phys. Rev. E (2019)

Semi-dynamical approach to electron-ion transport

For a white noise with isotropic scattering, the transport equation reduces to

$$\dot{\boldsymbol{p}}^i = \underbrace{\left(\boldsymbol{p}\cdot\delta\widehat{\boldsymbol{\Omega}}_t\right)^i}_{1.} \underbrace{- \Gamma^i_{ab}\, p^a\, \beta^b}_{2.}$$

1. **Pitch-angle scattering:** Gaussian white-noise process
In the scattering center frame

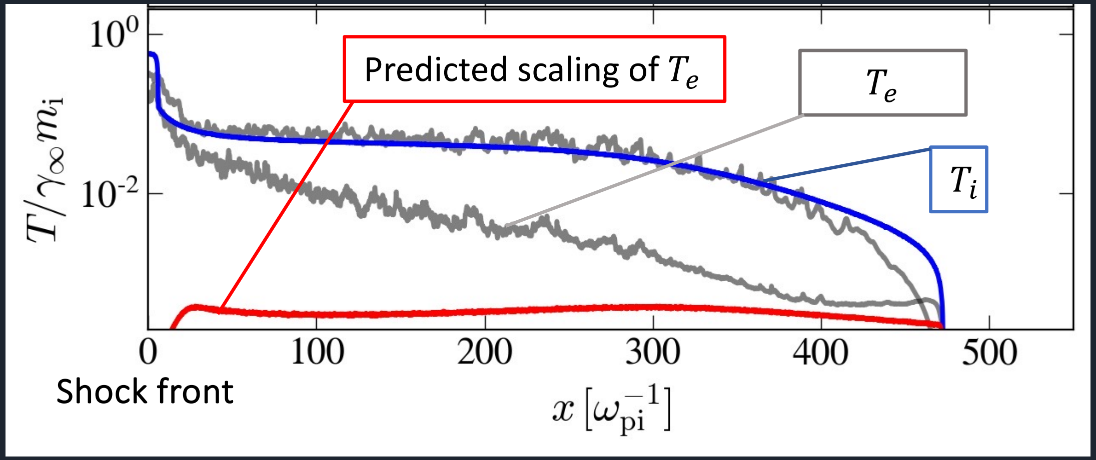
$$<\delta\widehat{\Omega}_t> = 0 \qquad <\delta\widehat{\Omega}_t\,\delta\widehat{\Omega}_{t'}> = 2\,\delta(t'-t)$$

2. Stationary scattering center frame deceleration

$$\partial_x u_w \neq 0$$

Free parameters: ν, L_{sh}

Comparison between model and numerical simulation

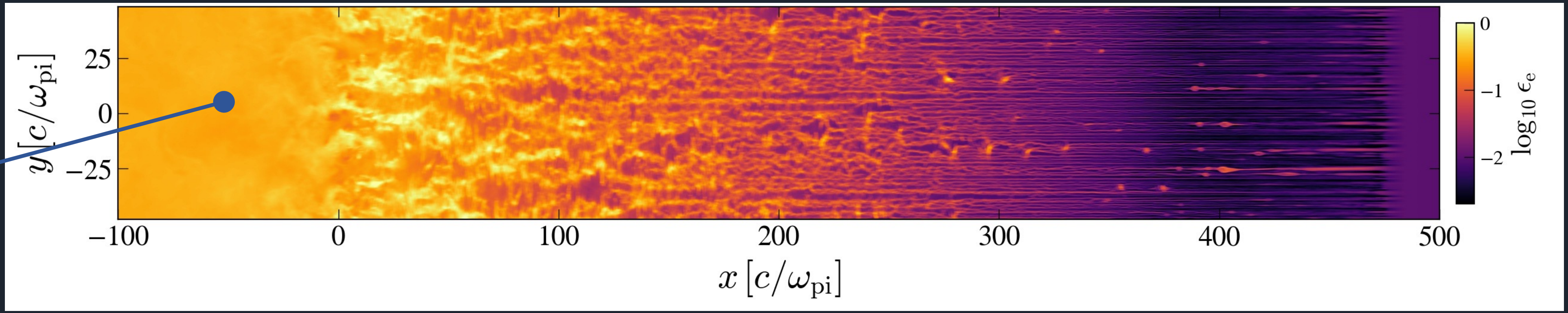


Collisionless friction with the Weibel-mediated turbulence leads to pure adiabatic compression of the electrons

What is the source of strong electron energization?

Electron energy fraction (ϵ_e)

$\Gamma_{sh} = 173$



Downstream

$T_{\rm e} \simeq 0.5\,T_{\rm i}$

Vanthieghem, Lemoine, Gremillet, ApJ Lett. (2022)

- Modeling of gamma-ray burst afterglows indicate equipartition between electrons and ions – Freedman+2001

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

- Equipartition observed in PIC simulations – Spitkovsky 2008; Martins et al., 2009, Haugbölle 2011, Sironi 2011
- Different sources of electron heating in the microturbulence have been identified – Milosavljevic et al., 2006; Gedalin et al., 2008; Gedalin et al., 2012; Plotnikov et al., 2013; Kumar et al., 2015

Differential scattering of electrons and ions off of a decelerating turbulence leads to ambipolar heating

Vanthieghem, Lemoine, Gremillet, ApJ Lett. (2022)

Semi-dynamical approach to electron-ion transport

For a white noise with isotropic scattering, the transport equation reduces to

$$\dot{\boldsymbol{p}}^i = \left(\boldsymbol{p}\cdot\delta\widehat{\boldsymbol{\Omega}}_t\right)^i - \Gamma^i_{ab}\, p^a\, \beta^b + q\, E_\parallel$$

1.   2.   3.

1. **Pitch-angle scattering:** Gaussian white-noise process

In the scattering center frame

$$< \delta\widehat{\Omega}_t > = 0 \qquad < \delta\widehat{\Omega}_t\, \delta\widehat{\Omega}_{t'} > = 2\,\delta(t'-t)$$

2. Stationary scattering center frame deceleration

$$\partial_x u_w \neq 0$$

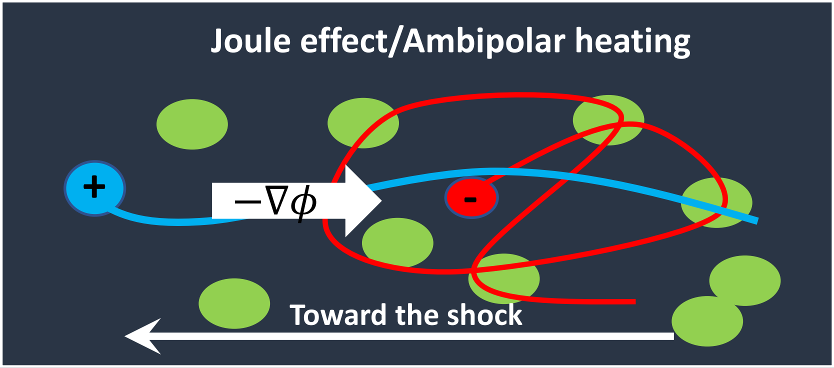
3. **Poisson solver**: self-consistent solution to the electrostatic field

In the shock front frame

$$\nabla^2\phi = -4\,\pi\,\rho$$

Free parameters: ν, L_{sh}

Electric field induced by charge separation in a decelerated plasma



⇒ Linear Fokker-Planck equation

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

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

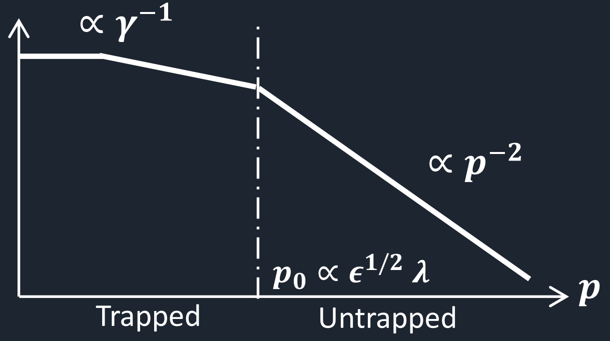
Particle-In-Cell simulations (Calder)

$\gamma = 173; m_i/m_e = 25$ $\gamma = 173; m_i/m_e = 100$ $\gamma = 17; m_i/m_e = 100$

Energy-dependent pitch-angle scattering frequency is fundamental to electron-ion equipartition

Vanthieghem, Lemoine, Gremillet, ApJ Lett. (2022)

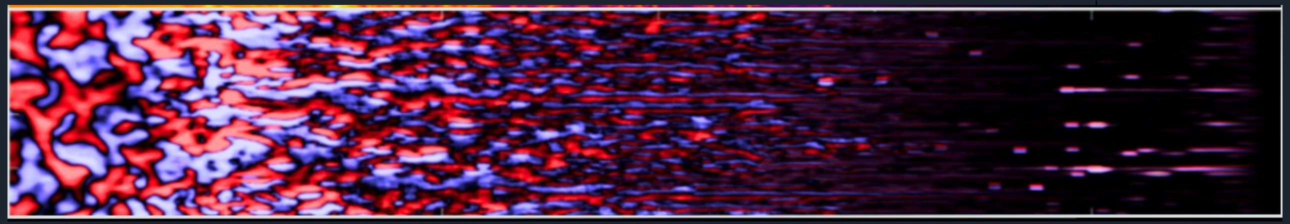
The scattering frequency of the electron varies by order of magnitude from the far upstream to the shock transition



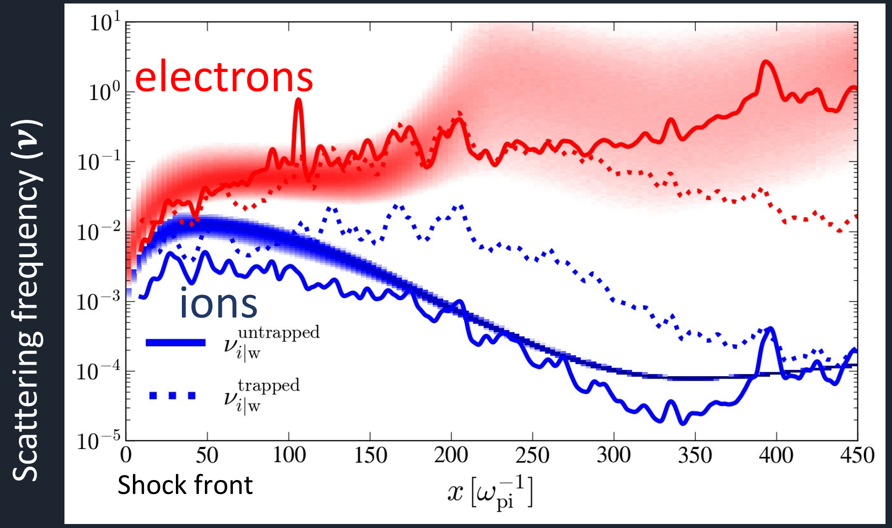
With $\nu \sim \nu_{0|w}\, \beta_{|w} \left(p_{|w}/m_i\right)^{-2}$ for $p_{|w} > \epsilon_B^{1/2}\, \omega_{pi}/k_\perp$

$$\nu_{0|w} \propto \epsilon_B / k_\perp$$

$\lambda \sim d_e \sim d_i$ ⟵ $\lambda \sim d_e$

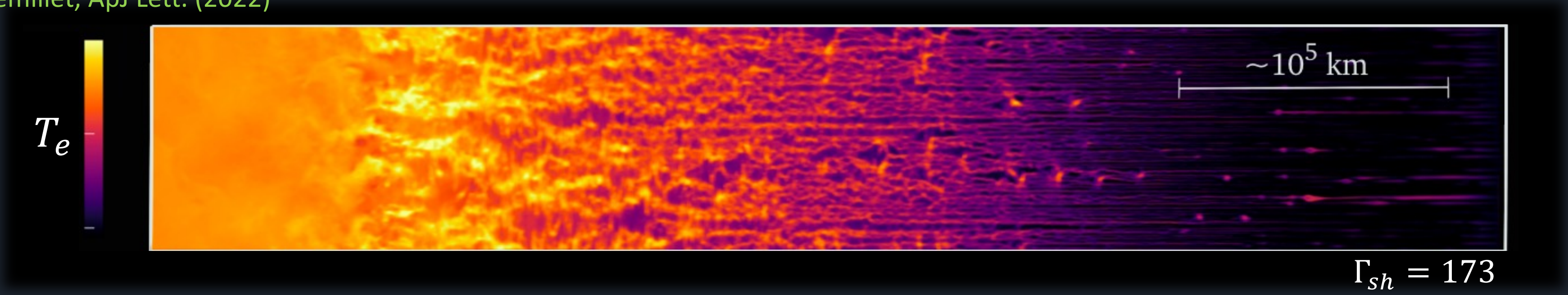


Comparison between the scattering frequency estimated from kinetic simulations and by solving the transport equation (shaded area)



The radiative signature consistent with ambipolar heating in a decelerating microturbulence

Vanthieghem, Lemoine, Gremillet, ApJ Lett. (2022)

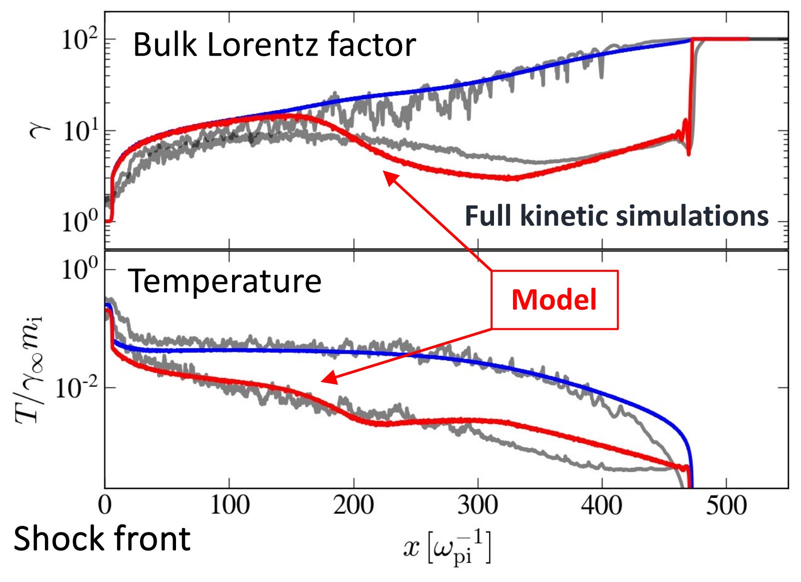


Monte Carlo pitch-angle scattering in a decelerating turbulence couple to a self-consistent Poisson solver

Blue/**Red** : Reconstructed trajectories of ions and electrons from the transport equation

Red : T_e from theoretical model **with longitudinal electrostatic field**

⇒ Overall, satisfactory reconstruction of velocity and temperature, with electron heating up to equipartition



$\gamma = 173; m_i/m_e = 25$

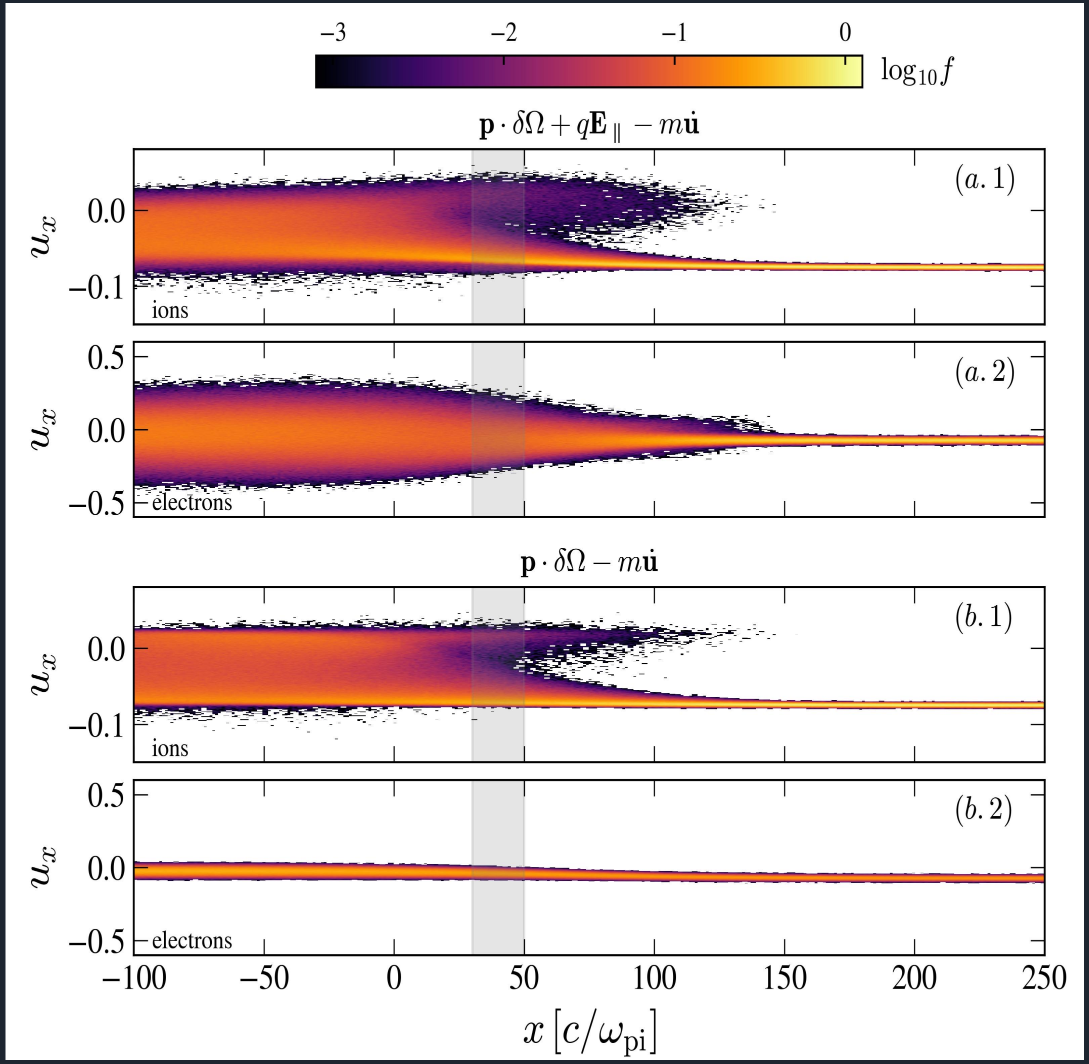
$\gamma = 173; m_i/m_e = 100$

$\gamma = 17; m_i/m_e = 100$

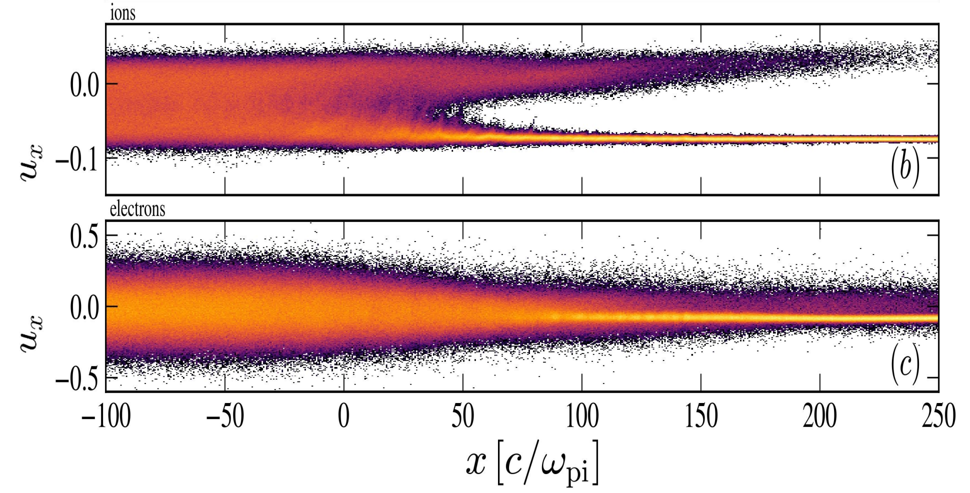
Ambipolar heating accounts for the energy partition in the nonrelativistic regime of blast waves

Vanthieghem, Tsiolis, Spitkovsky, Todo, Skiguchi, Fiuza, To be submitted

Theory



Particle-In-Cell



$u_{sh} = 0.075; \mathrm{m_i} = 49\ \mathrm{m_e}$ (**Tristan-mp**)

For strongly magnetized electrons and weakly magnetized ions

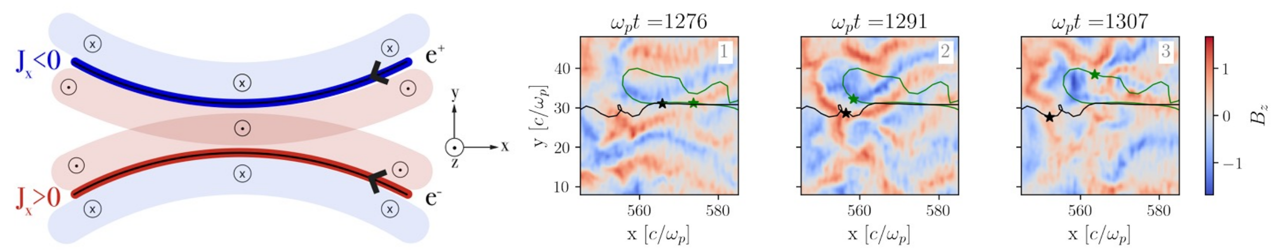
$$\boxed{\Rightarrow \frac{T_e}{T_i} \sim 0.2 - 0.5}$$

Weibel-mediated shock naturally leads to efficient electron heating

$$m_i = 49\, m_i\ ;\ \nu_i = \frac{|u_\infty|}{L_{sh}}; \nu_e = \frac{m_i \nu_i}{m_e}; L_{sh} = 150\frac{c}{\omega_{pi}}$$

The upstream turbulence dictates the acceleration timescale for the nonthermal injected particles

Injection of ~1% of particles in number and ~10% in energy
⇒ See A. Spitkovsky’s talk



Parsons, Spitkovsky, Vanthieghem, submitted, 2023

Lemoine, Pelletier, Vanthieghem, Gremillet, Phys. Rev. E (2019)

Downstream turbulence

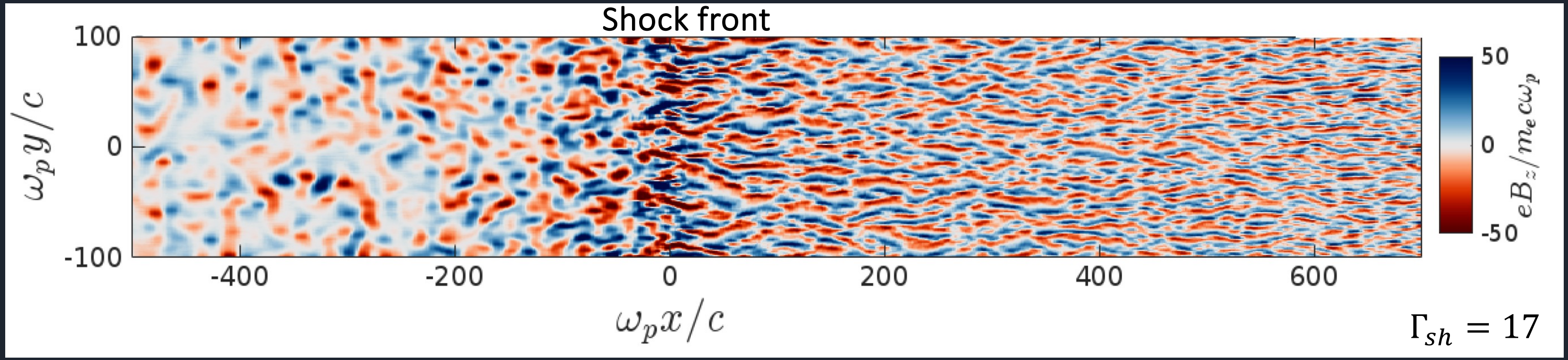
- Isotropic in the suprathermal particle frame

$$\Rightarrow l_{scatt}(p) \sim \epsilon_B^{-1} \left(\frac{p}{\gamma_\infty\, m\, c}\right)^2 c/\omega_p$$

Upstream turbulence

- Strongly anisotropic in the suprathermal particle frame

$$\Rightarrow l_{scatt}(p) \sim \gamma_p\, \epsilon_B^{-1} \left(\frac{p}{\gamma_\infty\, m\, c}\right)^2 c/\omega_p$$

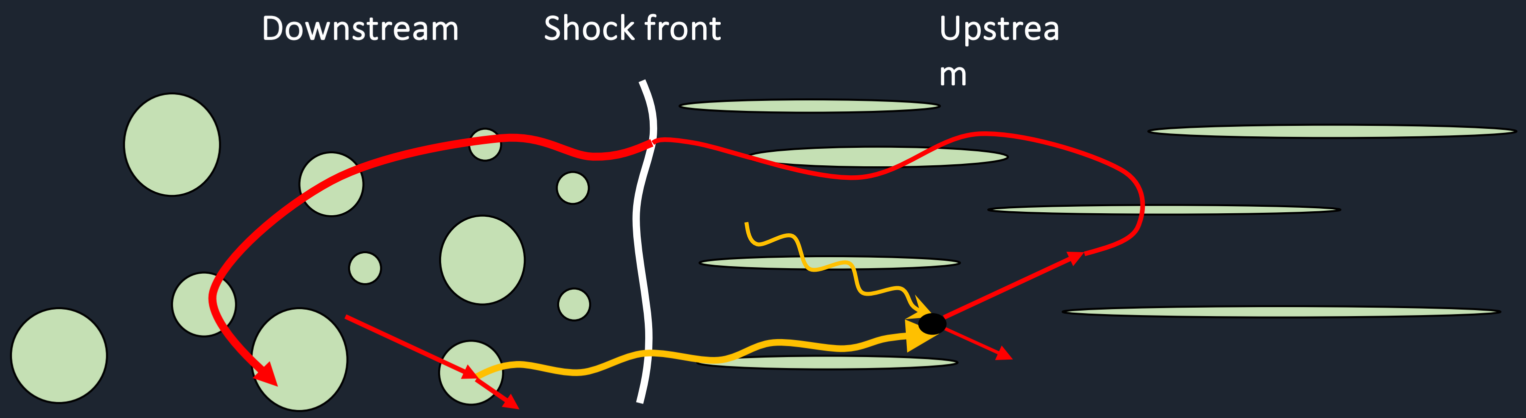


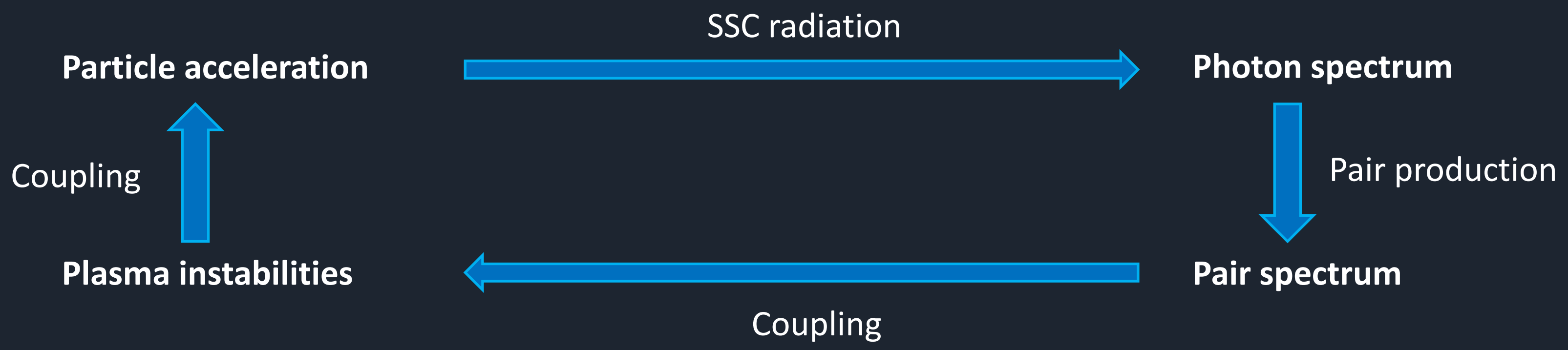
Retroaction of pair creation upstream of the shock from SSC photons emitted in the downstream

In Progress

Converter mechanism: efficient Fermi cycles via a neutral agent crossing the shock boundary. The Fermi accelerated pairs radiate SSC emission that cross the shock and pair produce in the upstream

Derishev et al., 2003, Stern 2003, Derishev & Piran 2016





Particle acceleration

SSC radiation

Photon spectrum

Pair production

Pair spectrum

Coupling

Plasma instabilities

Coupling

Hydrodynamics with pair loading

In Progress

Stationary state with pair injection

- Fraction of energy collected by the plasma $\eta_\pm = \frac{2}{3}\frac{\dot{u}_\pm R}{\Gamma^3 w c}$
- Fraction of mass collected by the plasma $\rho_\pm = \frac{4}{3}\frac{\dot{n}_\pm R}{\Gamma^2 n m_p c}$

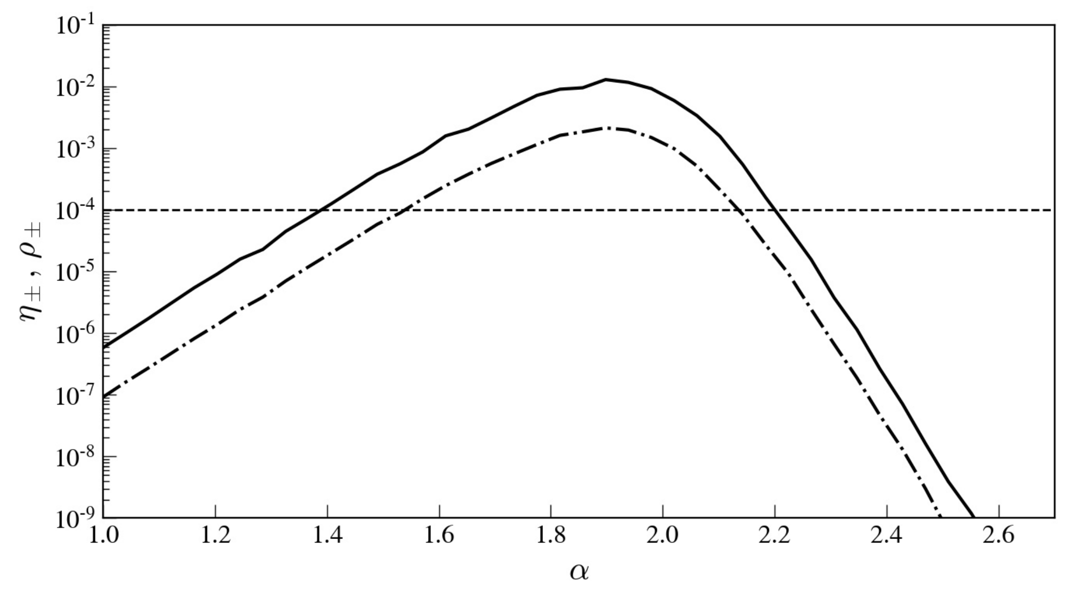
- If $\eta_\pm \gg 1/\Gamma^2 \Rightarrow$ Affect the precursor dynamics
- If $\eta_\pm \gg 0.1 \Rightarrow$ No shock solution

Derishev, Piran, MNRAS, 2016

Regime

- t_{acc} is negligible compared to all other times
- $t_{acc} \ll t_{cool} \ll t_{dyn}$

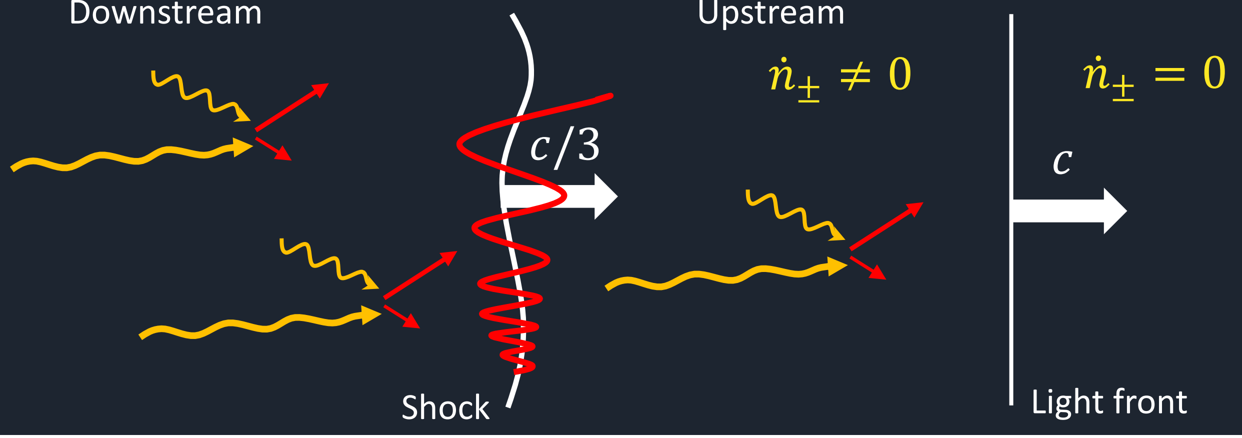
$R = 10^{17}$ cm; $\Gamma_{sh} = 100; n_0 = 1$ cm^{-3}; $\epsilon_{\min} = 10^{-8}; \epsilon_{\max} = 10^4$

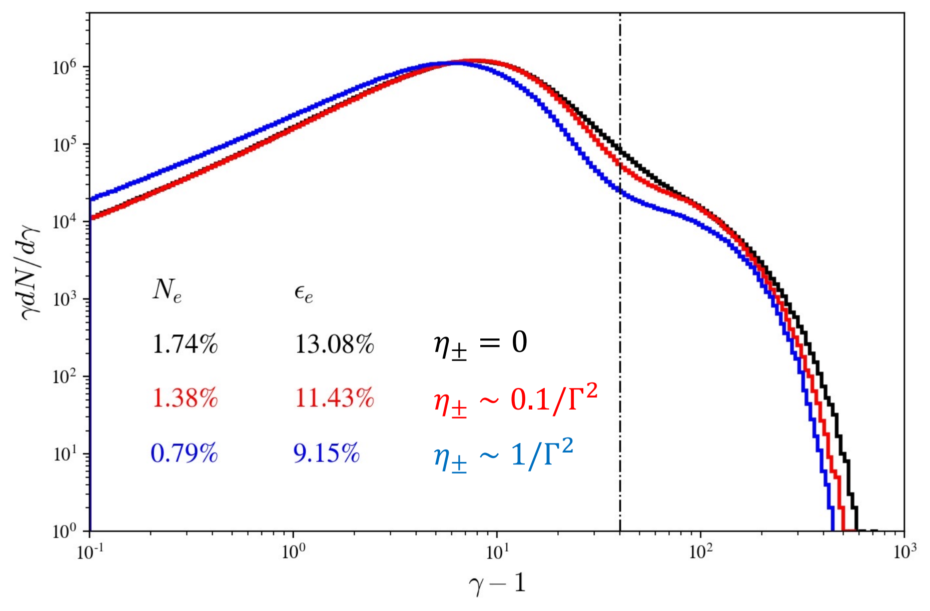


Photon spectral index

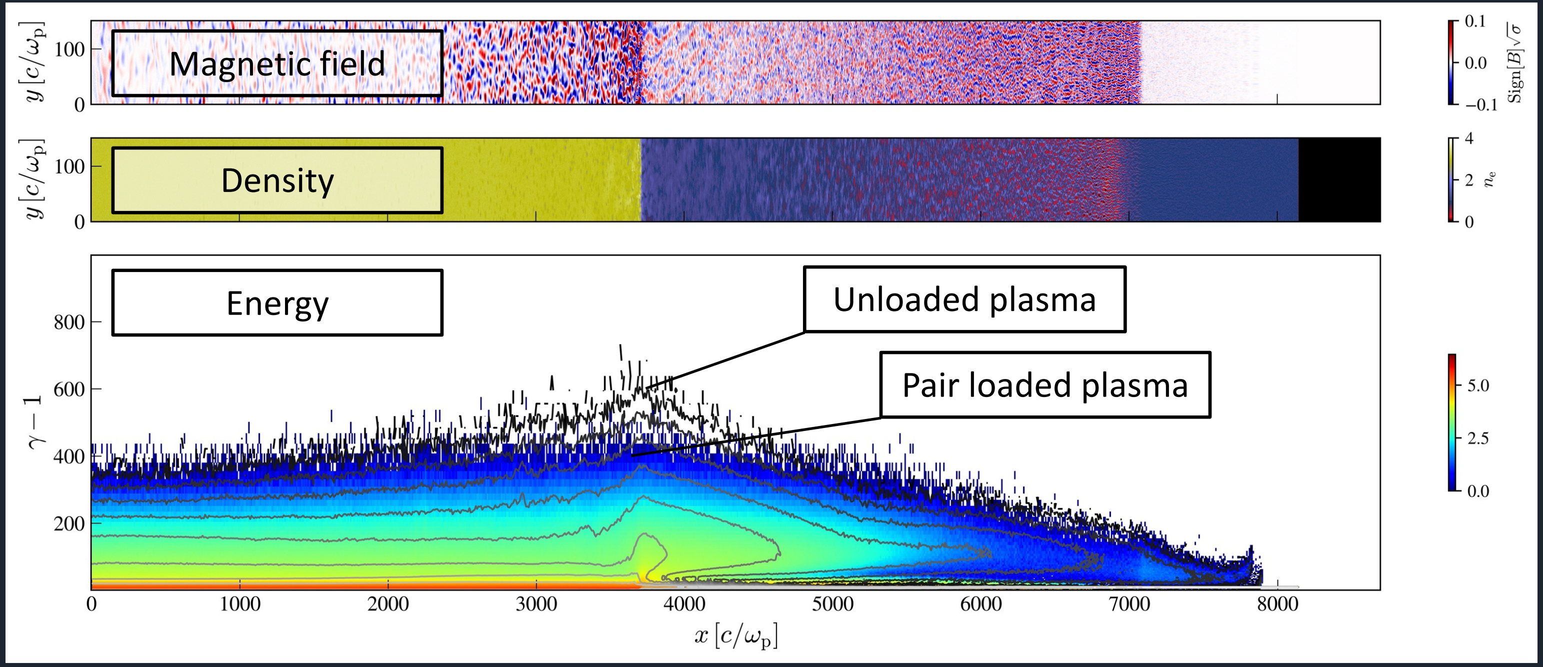
Pair-loading leads to kinetic instabilities coupling species and affecting particle acceleration

In Progress





N_e	ϵ_e	
1.74%	13.08%	$\eta_{\pm} = 0$
1.38%	11.43%	$\eta_{\pm} \sim 0.1/\Gamma^2$
0.79%	9.15%	$\eta_{\pm} \sim 1/\Gamma^2$



$\boldsymbol{\eta_{\pm} \gtrsim 1/\gamma^2}$

- Coupling through Weibel instability
- Significant upstream heating
- Enhanced deceleration of the flow
- Reduced suprathermal particle injection

Take away message

Summary

- Plasma deceleration obeys a cosmic-ray modified-type profile from the pressure of the accelerated particles
- The turbulence defines a preferential frame that is of non-inertial nature
- In pair plasma shock waves, the background heats non-adiabatically in a Joule-like process
- For electron-ion plasma, Weibel-mediated shocks efficiently heat electrons through ambipolar diffusion
- The acceleration timescale of the nonthermal particles is dominated by the upstream residence time
- Pair loading from SSC-photons radiated in the shock downstream modifies the shock structure and reduces the acceleration efficiency

Thank you!