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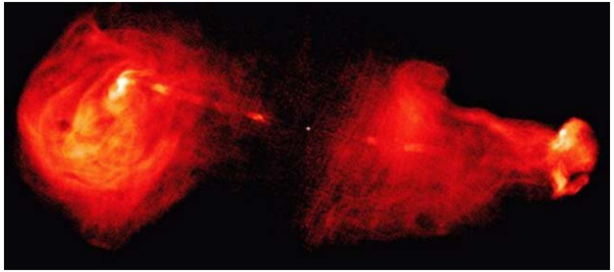
Mildly Relativistic Magnetized Perpendicular Shocks: a Study with Kinetic Simulations

KUKDM 2018 - Zakopane

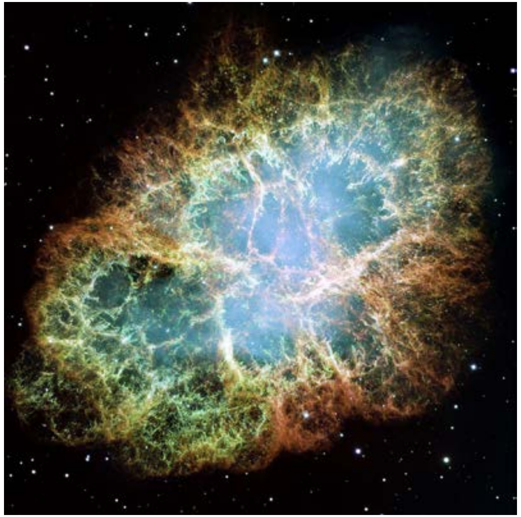
Astrophysical shocks



Shocks in many astrophysical environments

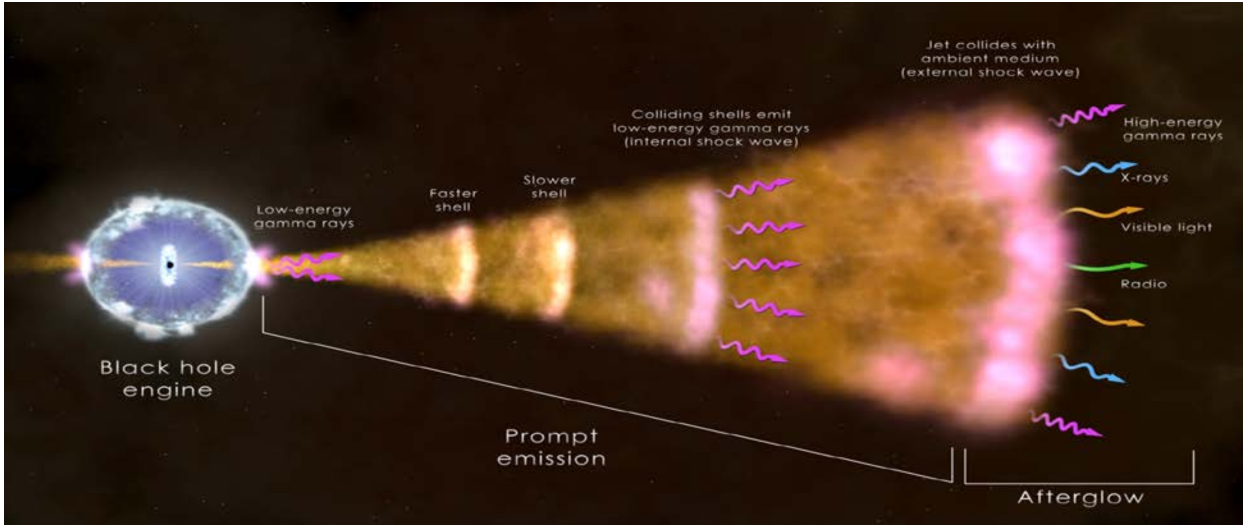
<ins>SNRs</ins> → non-relativistic shocks

<ins>Active Galactic Nuclei, Pulsars, Gamma Ray Burst, Blazars</ins> → relativistic shocks



Astrophysical shocks: Blazars

AGN with relativistic jets seen approx head on



Dissipation → Internal Shock Model

We study the model for **mildly relativistic ($\gamma \sim 2$) regime**

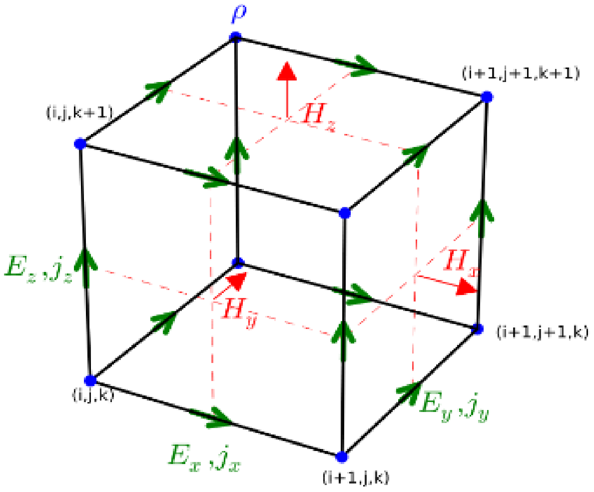
- perpendicular magnetic field
- total magnetization $\sigma = 0.1$

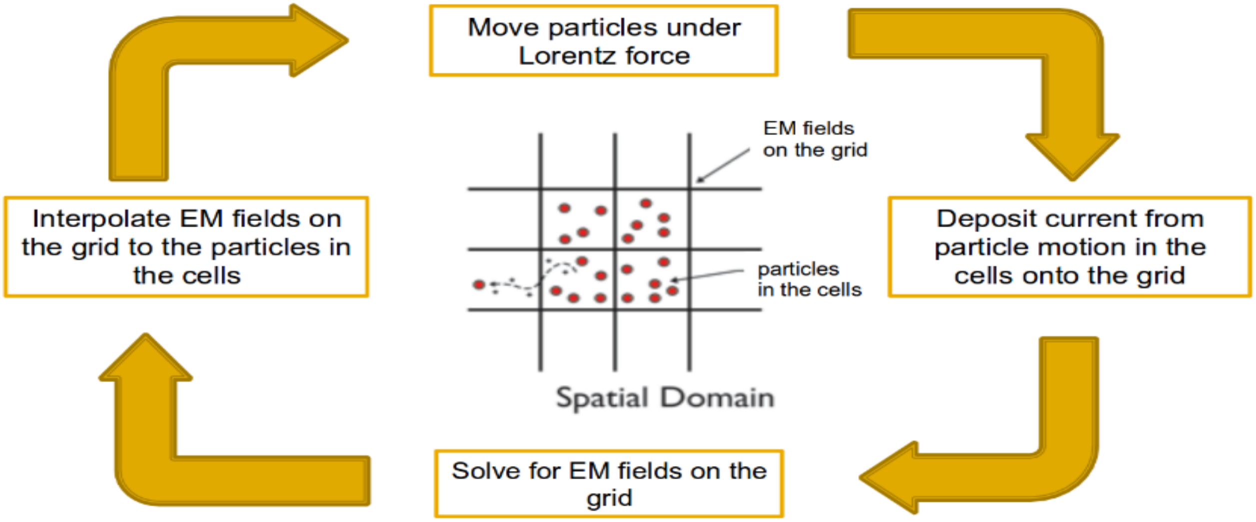
Sikora, 2013
Sikora, 2016

Particle-In-Cell Simulations

PIC simulations → ab-initio method of solving Vlasov equation:

1. Solving of Maxwell's equations on a numerical grid
2. Integration of rel. particle eq. of motion in self-consistent EM field





Particle-In-Cell Simulations

Large-scale high-resolution PIC simulations must be performed at high-performance supercomputing centers

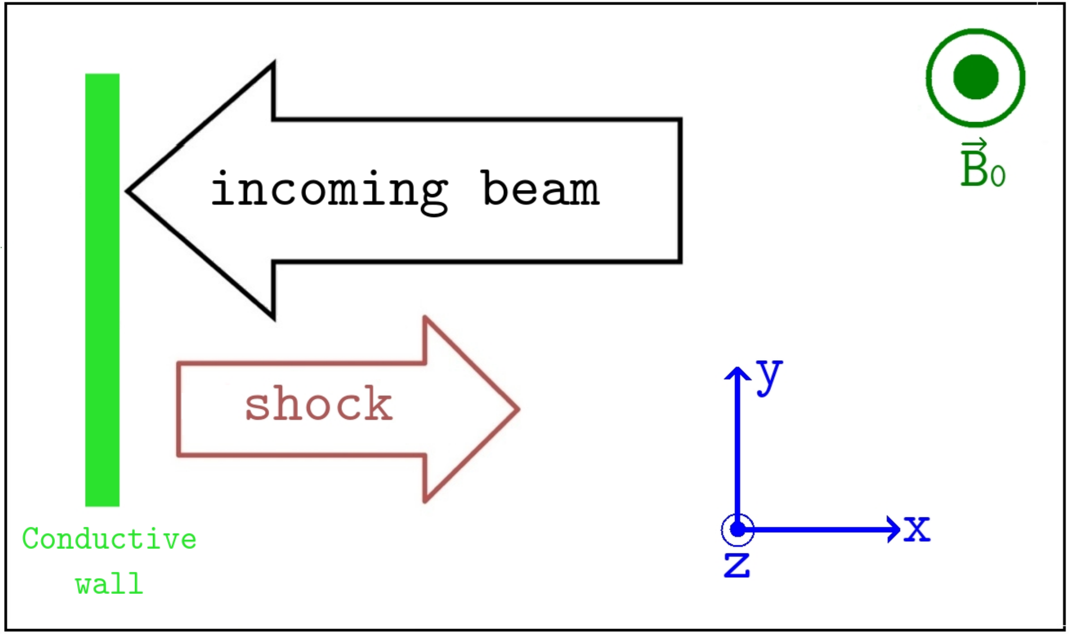
Prometheus (Poland, Intel Xeon E5-2680v3, 53,568-core, 2.4 Pflop/s)

Main simulations:

→ 1D-like, (1D3V)

→ 2D (2D3V)

Simulation setup

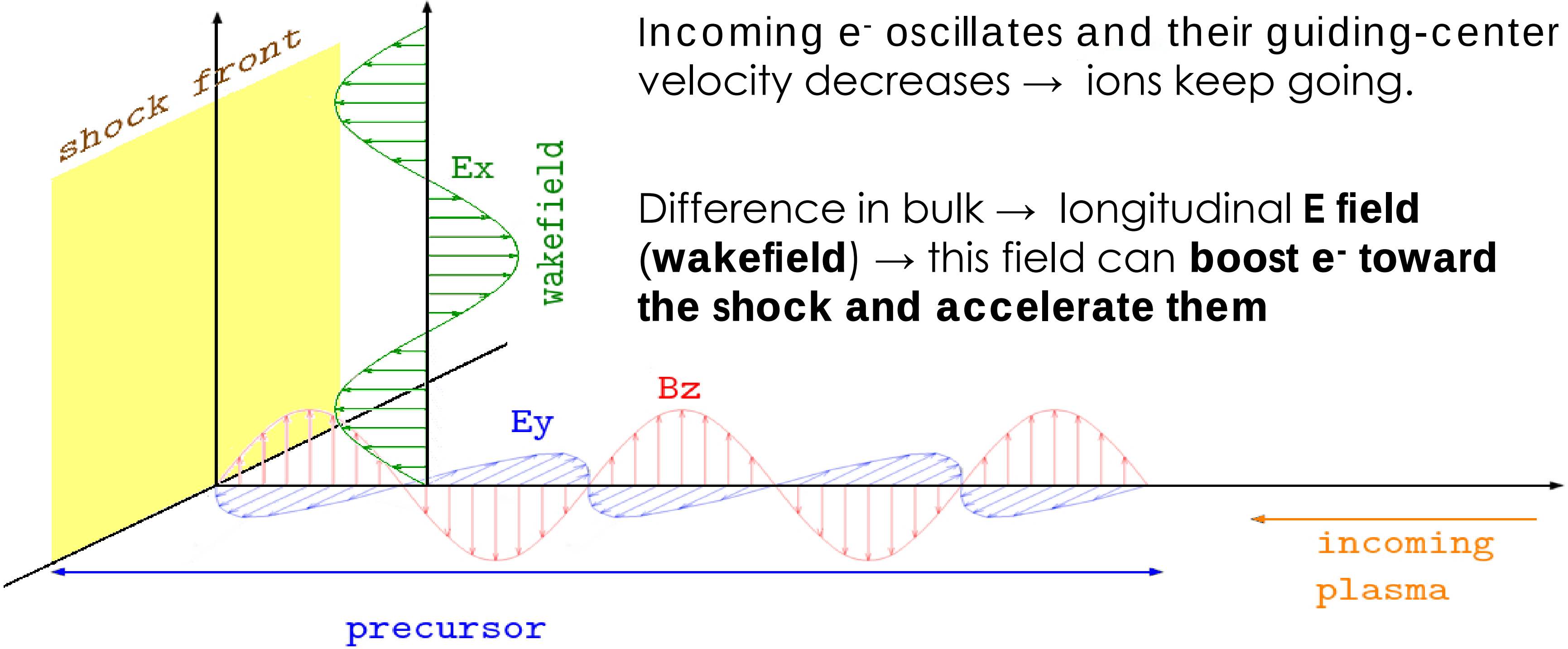


Ions and electrons cold plasma

$m_i/m_e = 50$, $\sigma = 0.1$, $\lambda_{se} = 80$, $\lambda_{si} = 566$

The Synchrotron Maser Instability

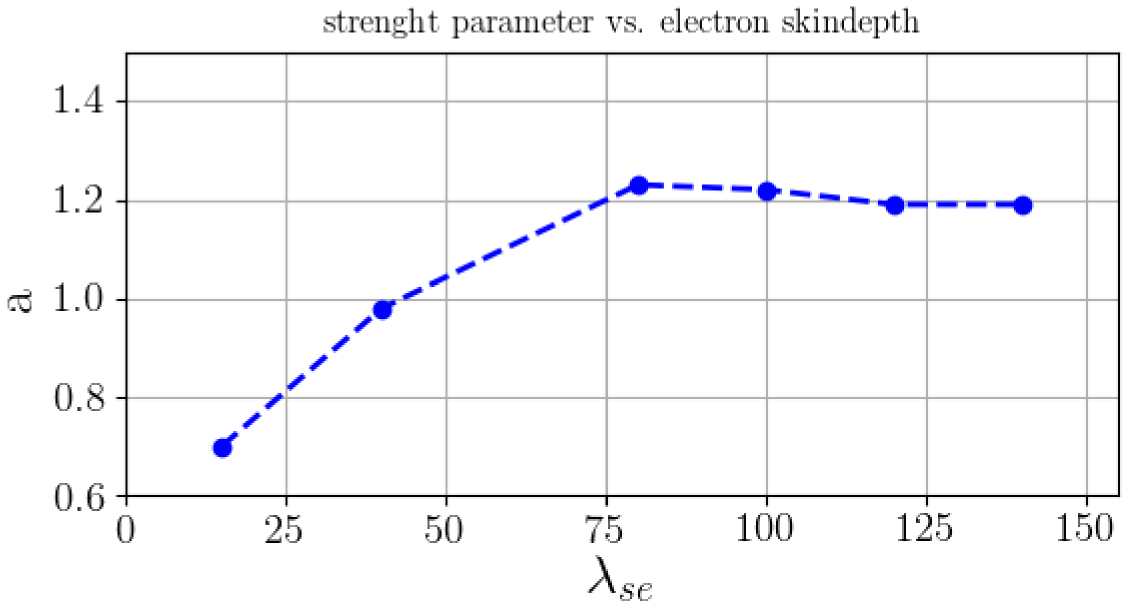
A ring of particles gyrating in the shock transition zone breaks up in bunches of charge → they radiate a coherent train of **transverse EM waves** of the X-mode in the **upstream (precursor).**



Incoming e^- oscillates and their guiding-center velocity decreases → ions keep going.

Difference in bulk → longitudinal **E field** (**wakefield**) → this field can **boost e^- toward the shock and accelerate them**

Some test: choosing fiducial parameter

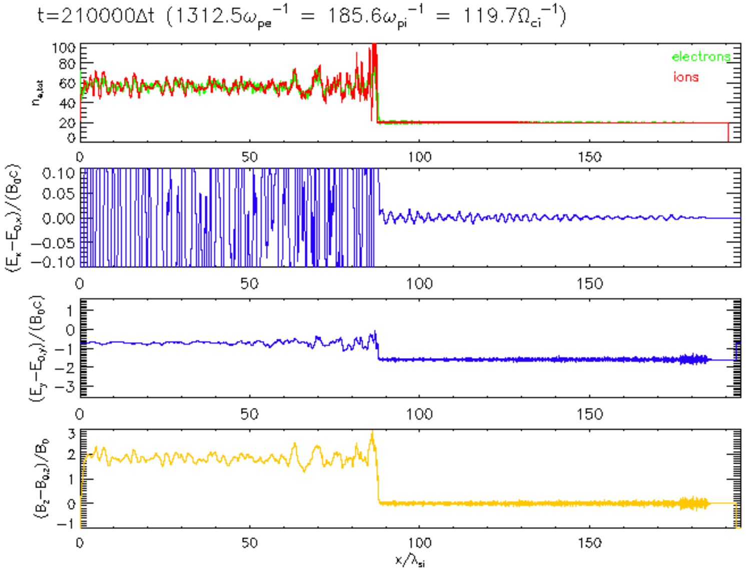


(a~ ωpe/ω δB/B0)

1D simulations, measure of the amplitude of EM waves in the shock precursor

Saturation at λ_{se} =80

Fiducial simulation: shock structure

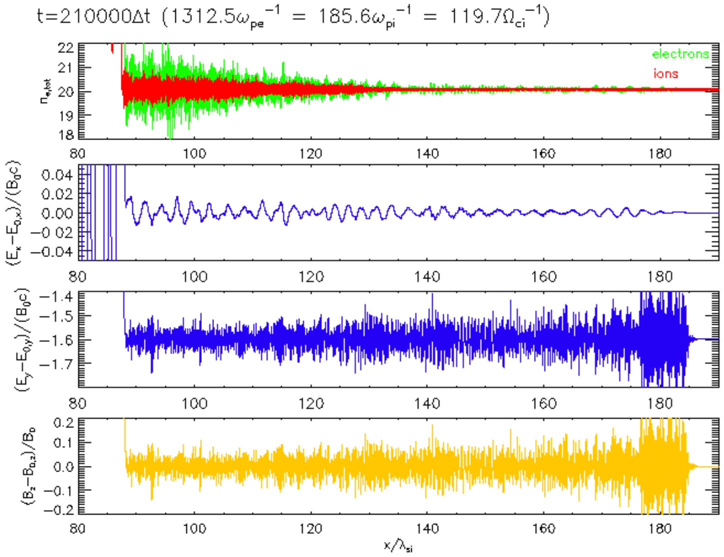


dens

Ex-E0x
B0*c

Ey-E0y
B0*c

Bz-B0z
B0



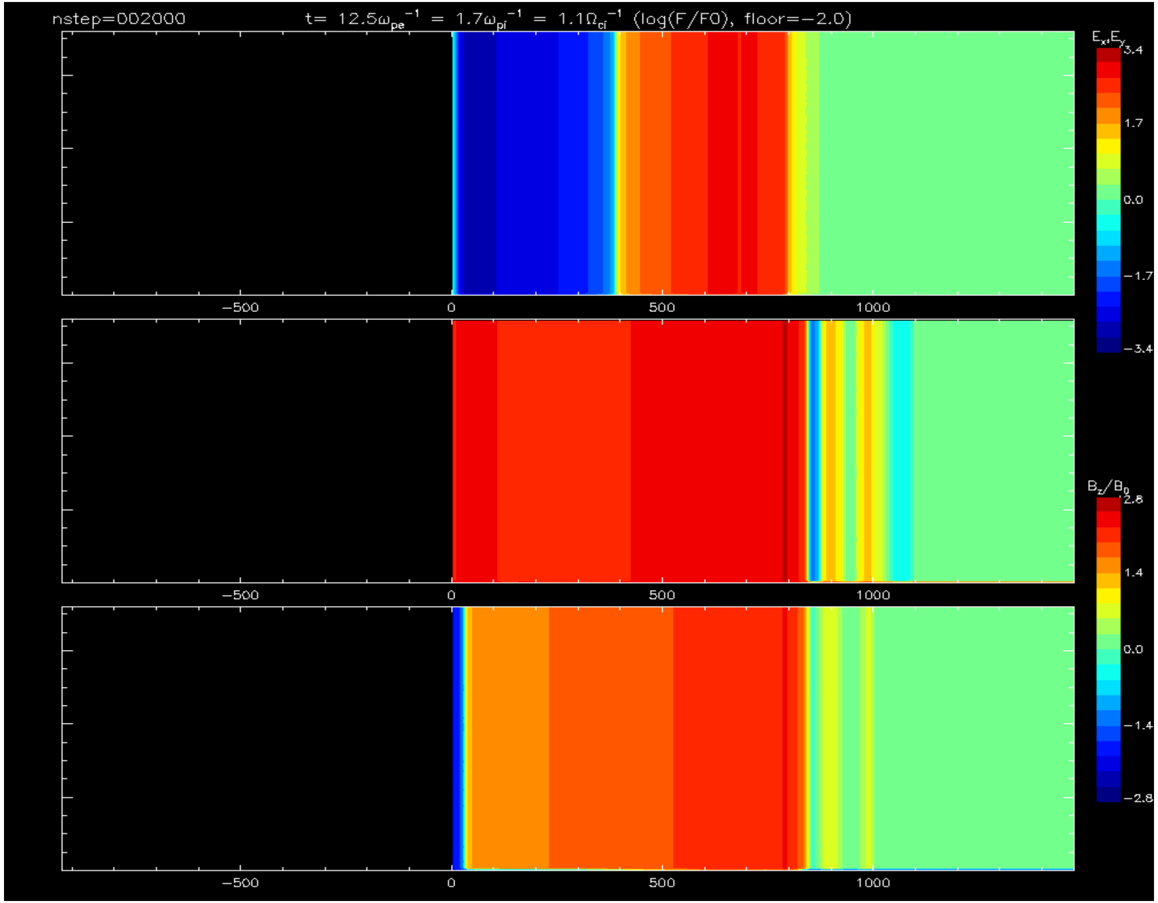
1. Shock at ~87 x/ λ_{si}, density compression factor ~3
2. Precursor waves in B_z and E_y, velocity ~ c → **X-mode EM waves**
3. **Wakefield** in E_x, λ_{Ex} ~ 3/ λ_{si} (in accord with Hoshino 2008)

Fields movie

$\frac{E_x - E_{0x}}{B_0 * c}$

$\frac{E_y - E_{0y}}{B_0 * c}$

$\frac{B_z - B_{0z}}{B_0}$



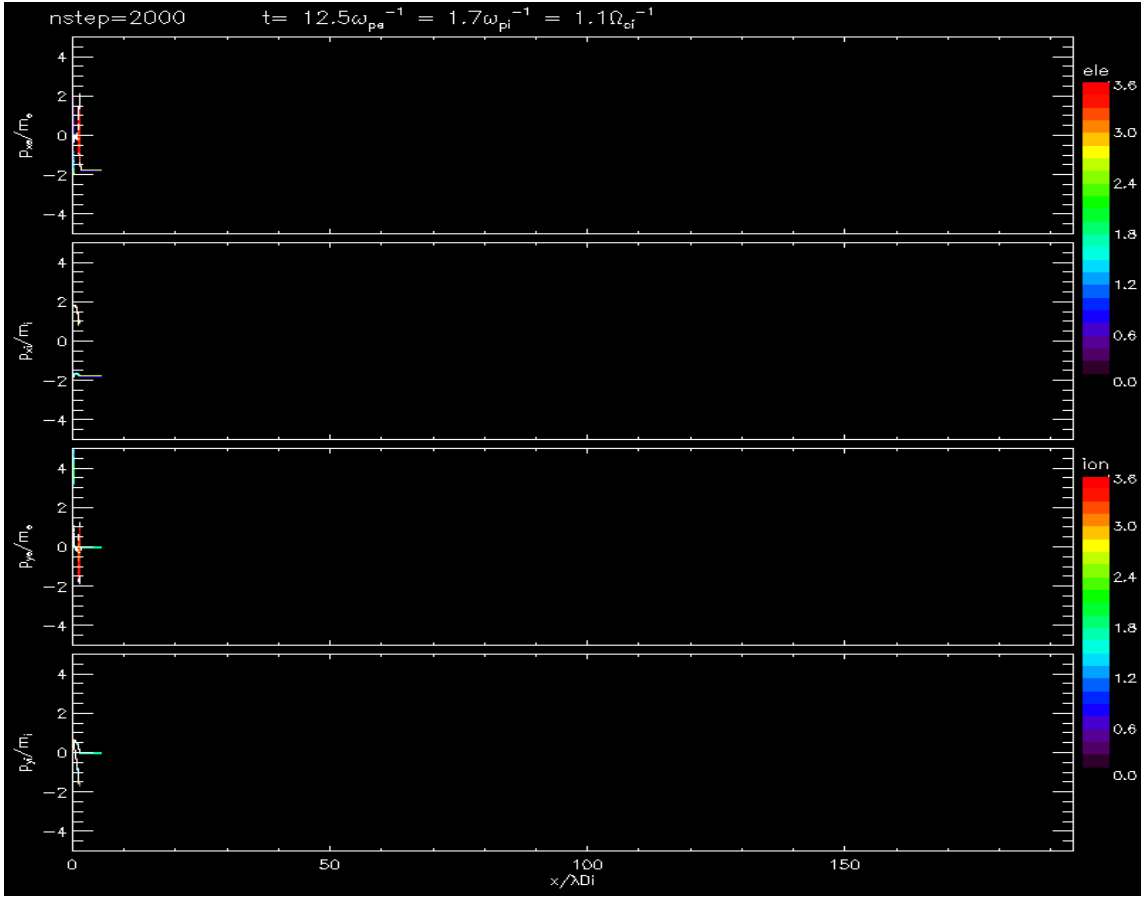
Phase space movies

p_{xe}/m_e

p_{ye}/m_e

p_{xi}/m_i

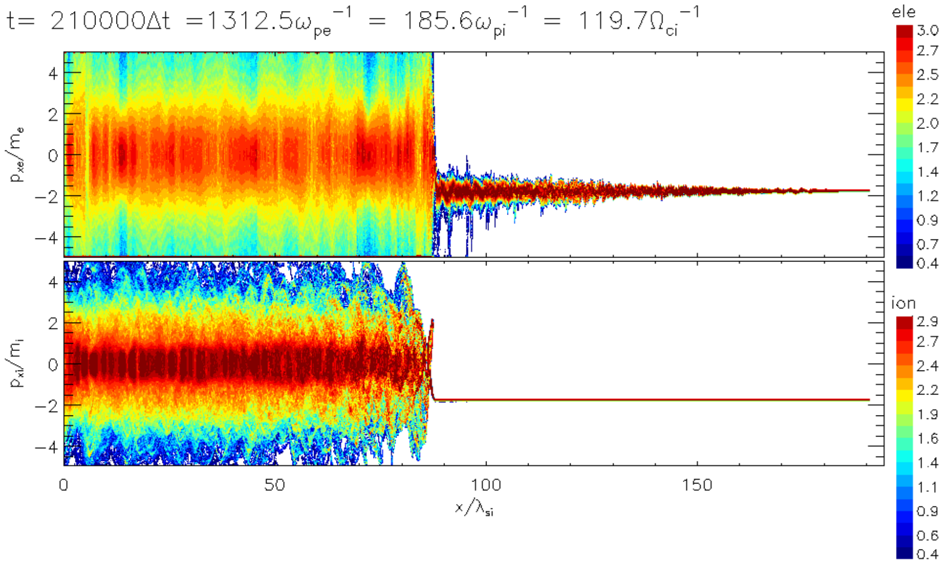
p_{yi}/m_i



Phase space maps

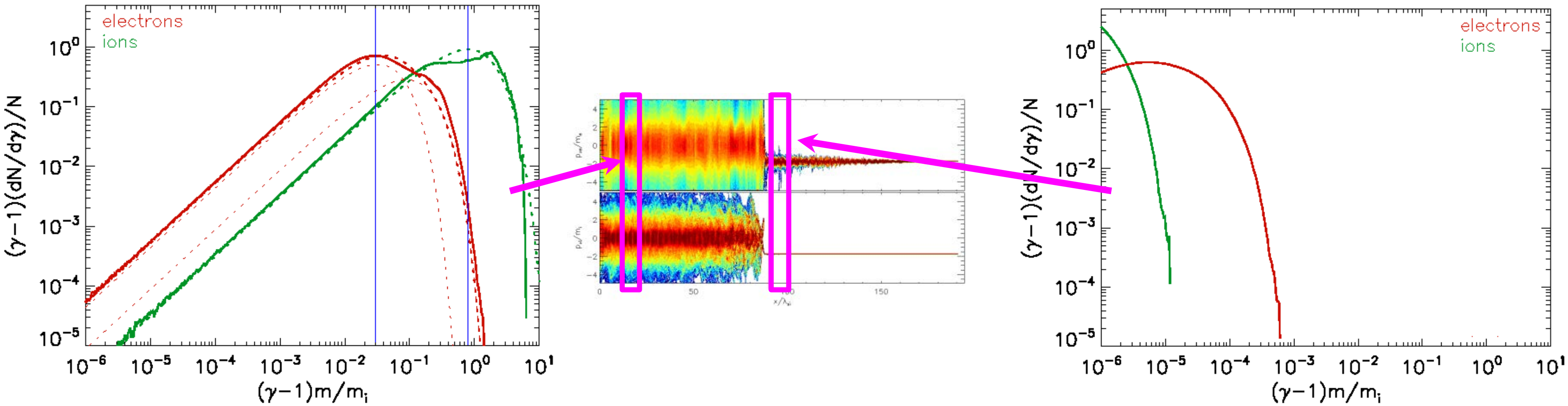
p_{xe}/m_e

p_{ye}/m_e



1. **Ring-like feature** at the shock in ion phase space
2. Faint **downstream oscillations** in e^- phase space
3. **e^- upstream phase space is modulated by Ex** → precursor waves affect the plasma
4. **e^- are boosted towards the shock** (i.e., in negative x-momentum)

Particle distribution spectra



1.Downstream ions are isotropized around their initial energy
2. e^- also thermalized close to their initial energy and are only slightly heated in bulk (double maxwellian fit).
3. Asymmetry in high energies e^- may depend on **upstream acceleration by wakefield.**

Summary

1. We presented preliminary results of PIC simulations of a poorly explored regime of **mildly relativistic magnetized shocks in ion-e^- plasma**.

2. We show **consistent evidence for Synchrotron Maser Instability**(precursor waves, wakefields)

3. Particle-wave interactions in the precursor → **plasma thermalization and limited ion-to-e^- energy transfer**

4. More analysis will be performed in the near future:
   (a) larger box to investigate features in the ion scale
   (b) higher value for the mass ratio (closer to the real one)
   (c) introduction of a positron component

5. A far greater amount of computation time will be necessary (up to 20 million CPU hours)

Thank you
for your attention