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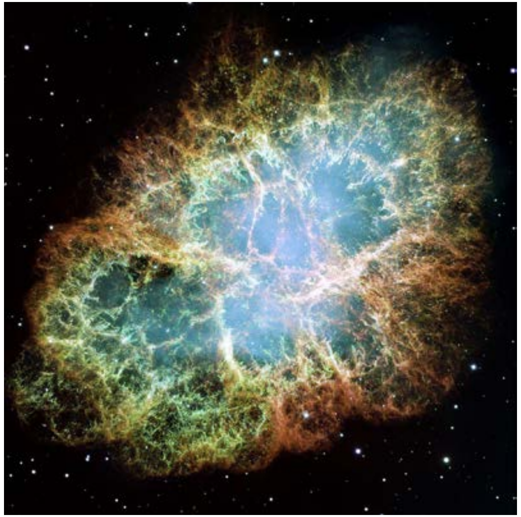
Investigating Mildly Relativistic Magnetized Perpendicular Shocks with Kinetic Simulations

CGW2018 - Krakow

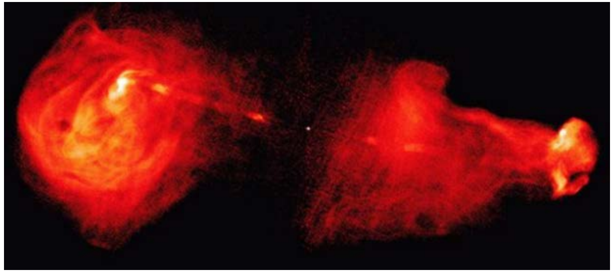
Astrophysical shocks

Shocks in many astrophysical environments

SNRs → non-relativistic shocks

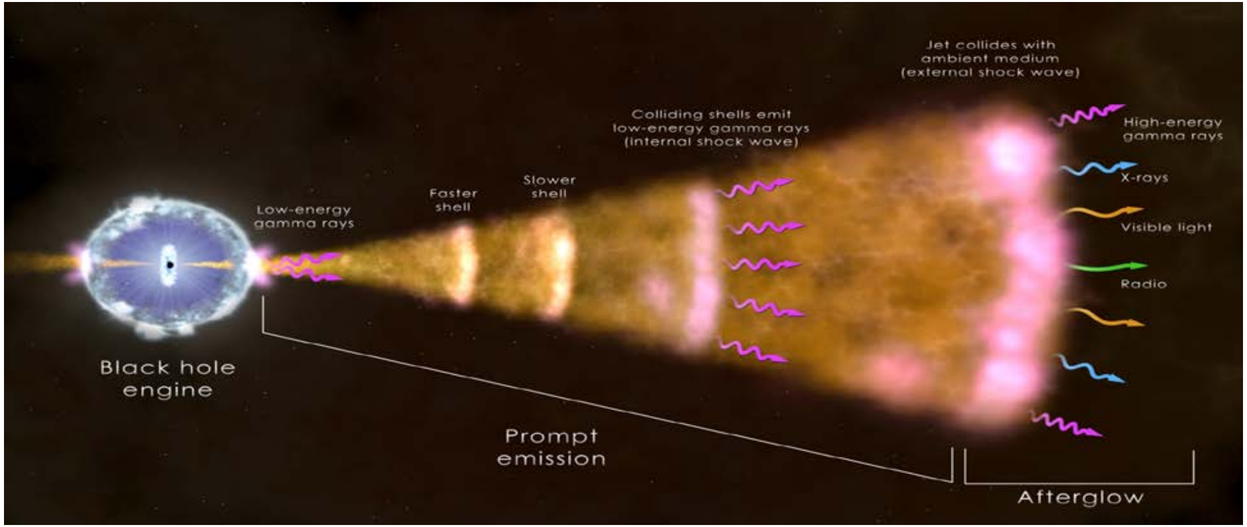


Active Galactic Nuclei, Pulsars, Gamma Ray Burst, Blazars → relativistic shocks



Astrophysical shocks: Blazars

AGN with relativistic jets seen approx head on



Dissipation → Internal Shock Model

We study the model for **mildly relativistic (γ~2) regime**

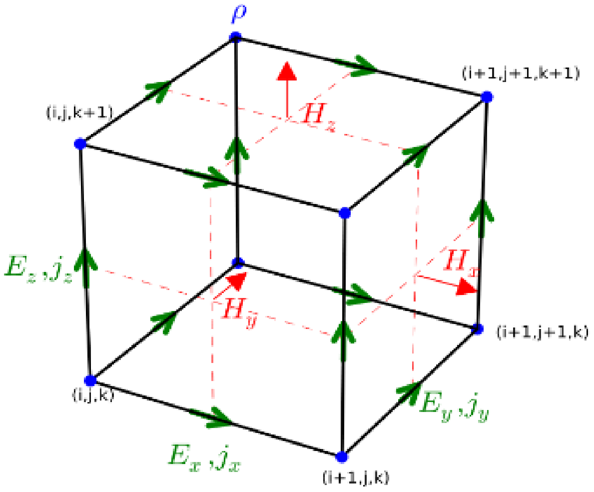
- perpendicular magnetic field
- total magnetization σ = 0.1

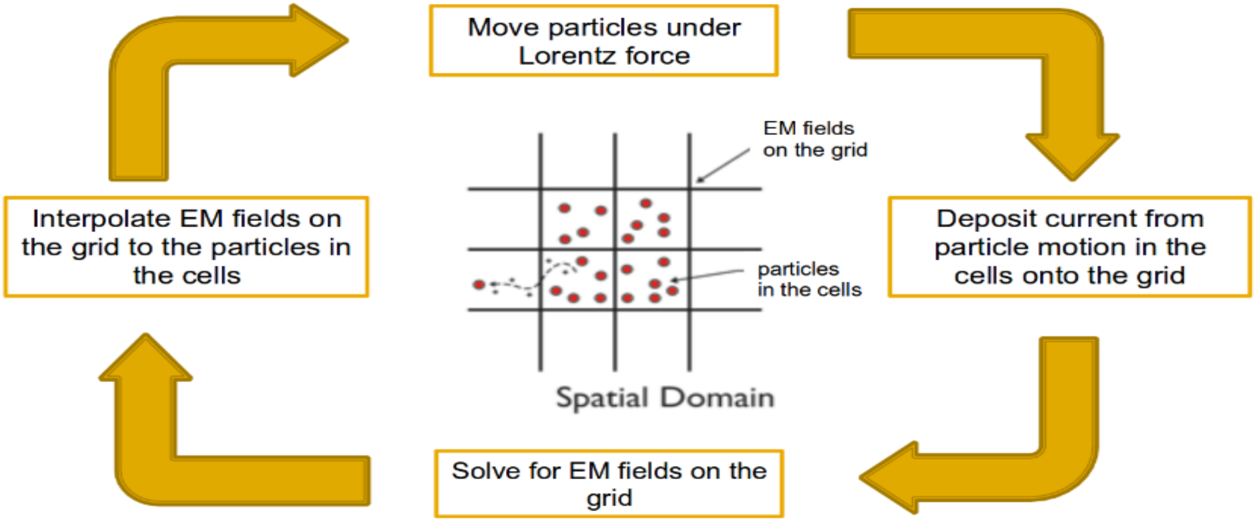
Sikora, 2013
Sikora, 2016

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





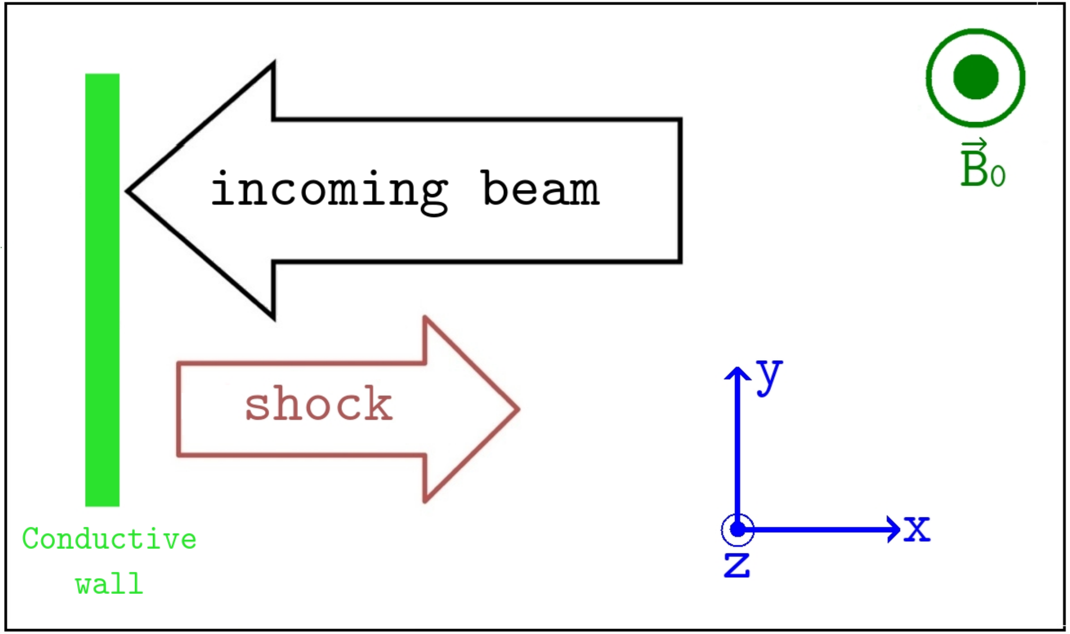
Particle-In-Cell Simulations

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:
→ 2D (2D3V)
→ ~ 74TB of storage
→ > 9 mil of walltime hours

Simulation setup

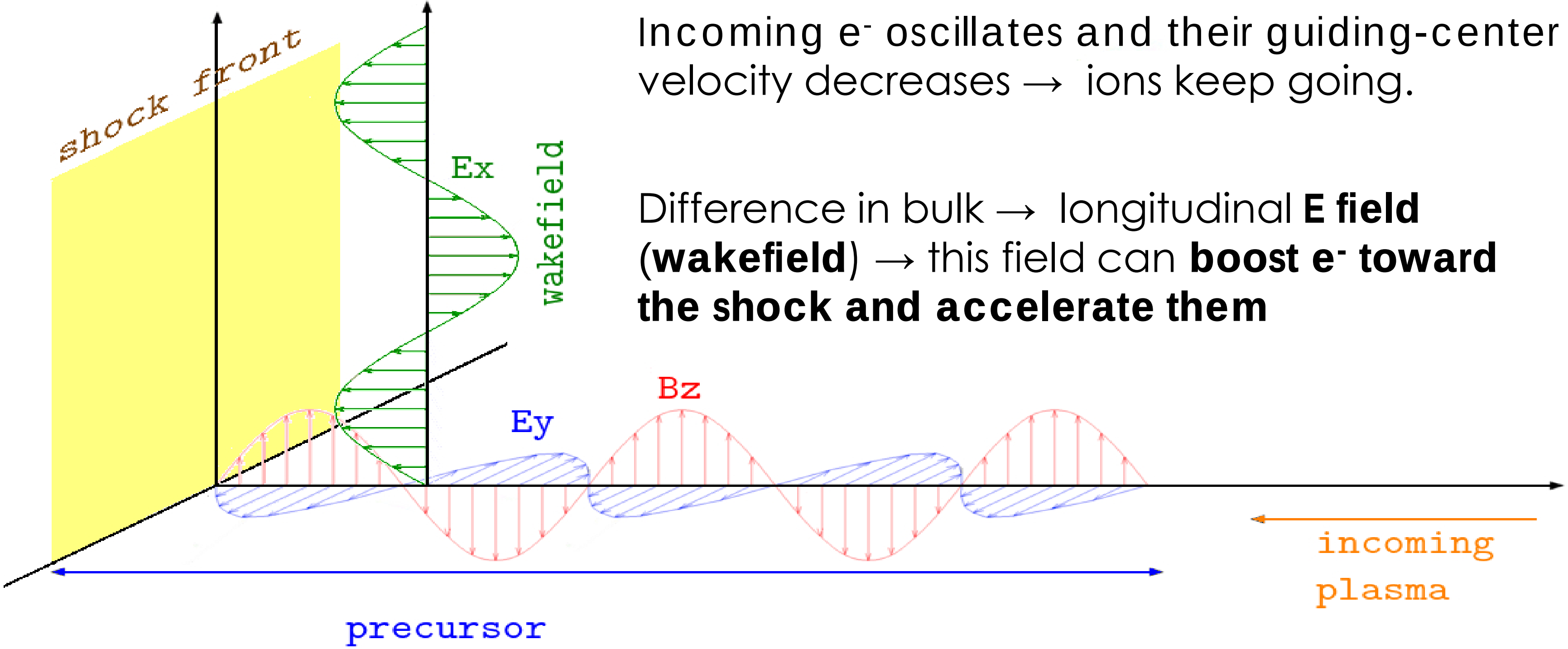


Ions and electrons cold plasma

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

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.

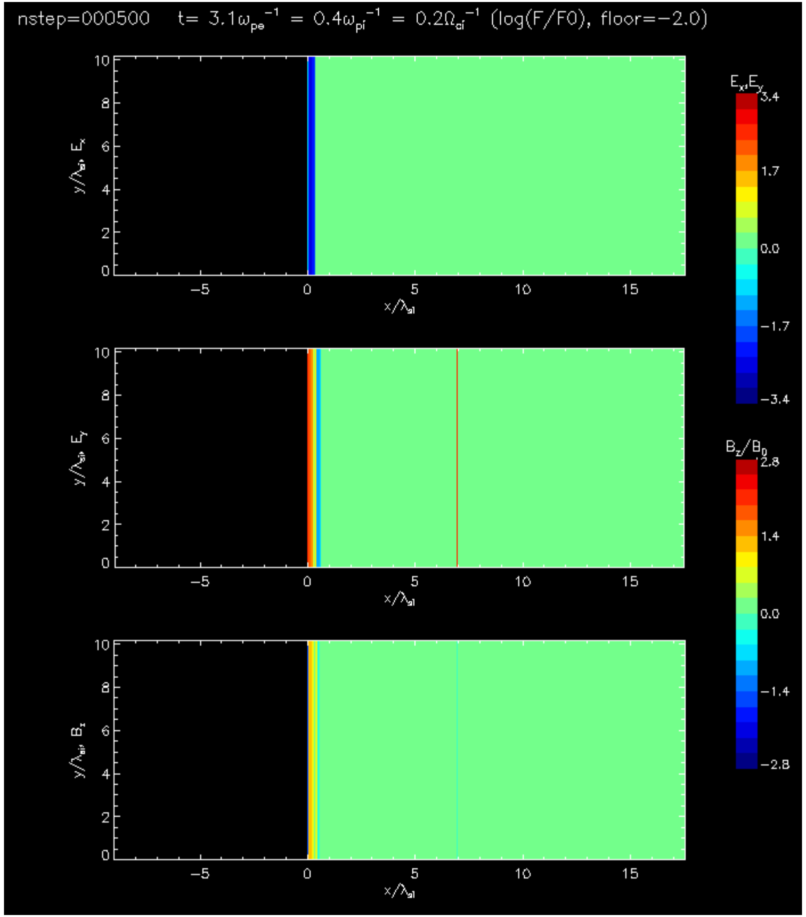
Difference in bulk → longitudinal **E field** (**wakefield**) → this field can **boost e^- toward the shock and accelerate them**

Large scale simulation: field movie

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

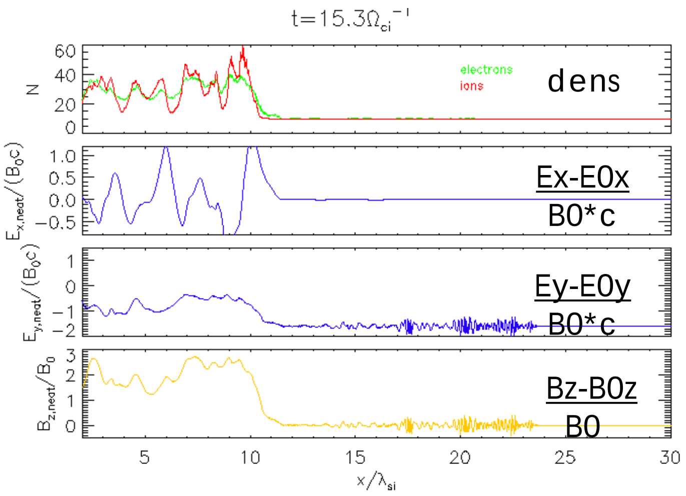
$\frac{E_y - E_{0y}}{B_0 * c}$

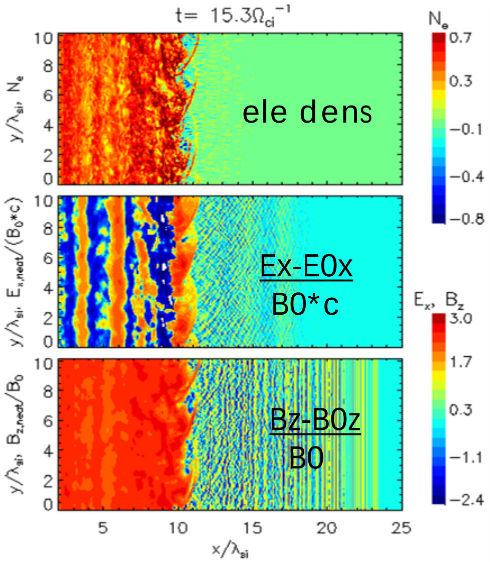
$\frac{B_z - B_{0z}}{B_0}$

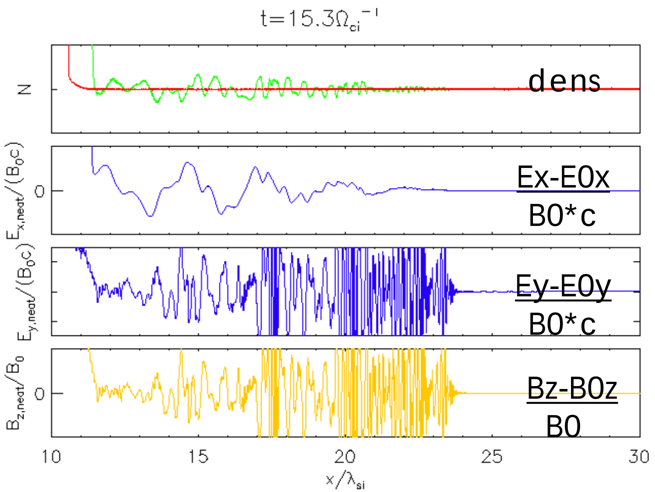


Evidence of a linear early stage + rippled stage

Linear stage: $t\Omega_{ci}$=15.3

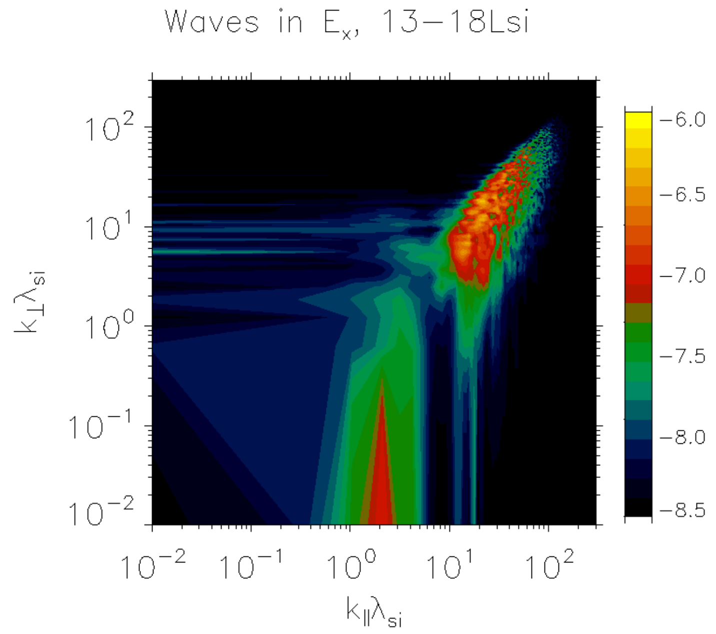






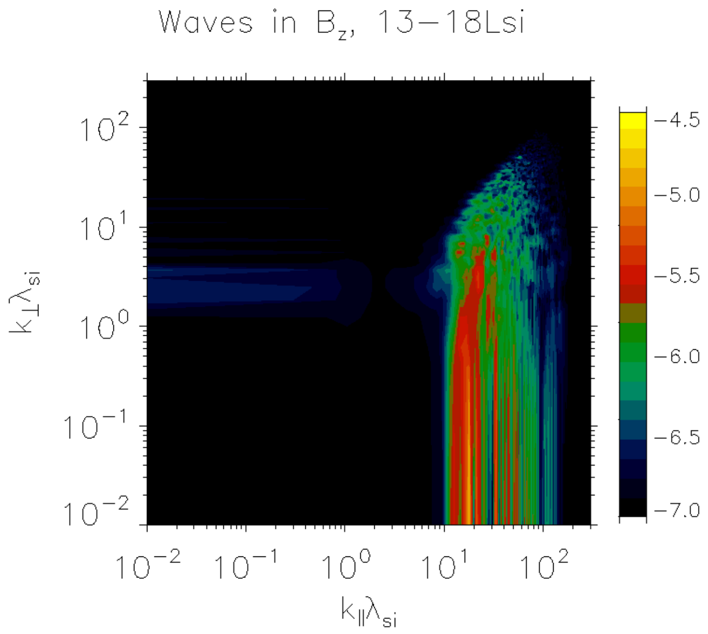
1. Shock at ~10.5 x/ λ_{si}, average downstream density compression factor ~ 3
2. Precursor waves in Bz and Ey, velocity ~ c → **X-mode EM waves**
3. **Wakefield** in Ex, λ_{Ex} ~ 3/ λ_{si} (in accord with Hoshino 2008)

Linear stage: $t\Omega_{ci}^{-1}$=15.3



More accurate estimate of wavelenghts:

Very good agreement with theory!

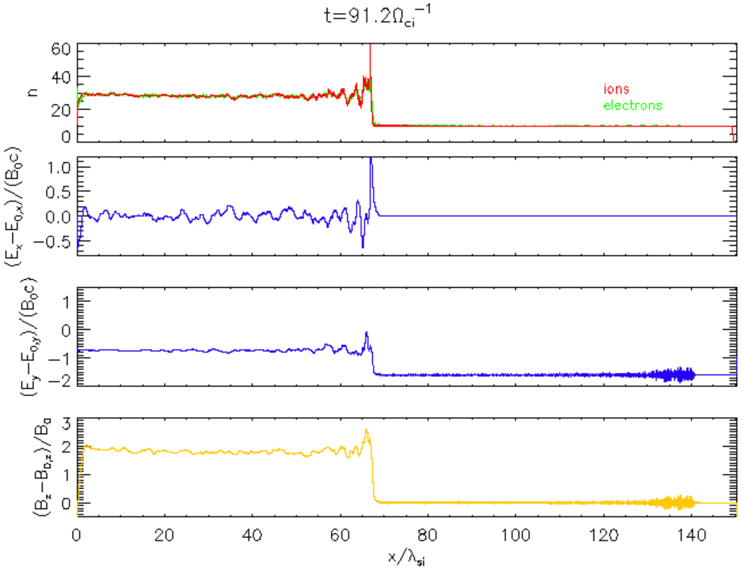


λ_{Ex} ~ $2.9\lambda_{si}$ (cfr. Theory: $\lambda_{Ex,th}$ ~ $3.1\lambda_{si}$)

λ_{Bz} ~ $0.37\ \lambda_{si}$ (cfr. Theory: $\lambda_{Bz,th}$ ~ $0.37\lambda_{si}$)

oblique component → first phases of the rippling

Late stage: $t\Omega_{ci}$=91.2

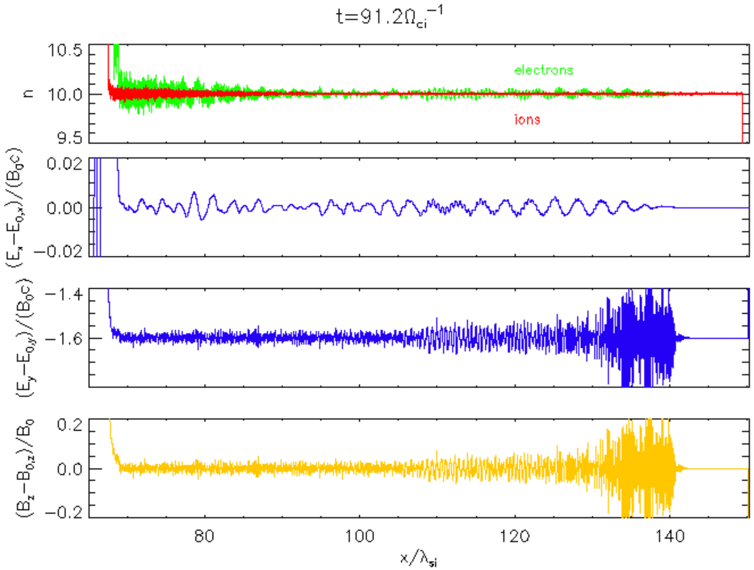


dens

Ex-E0x / B0*c

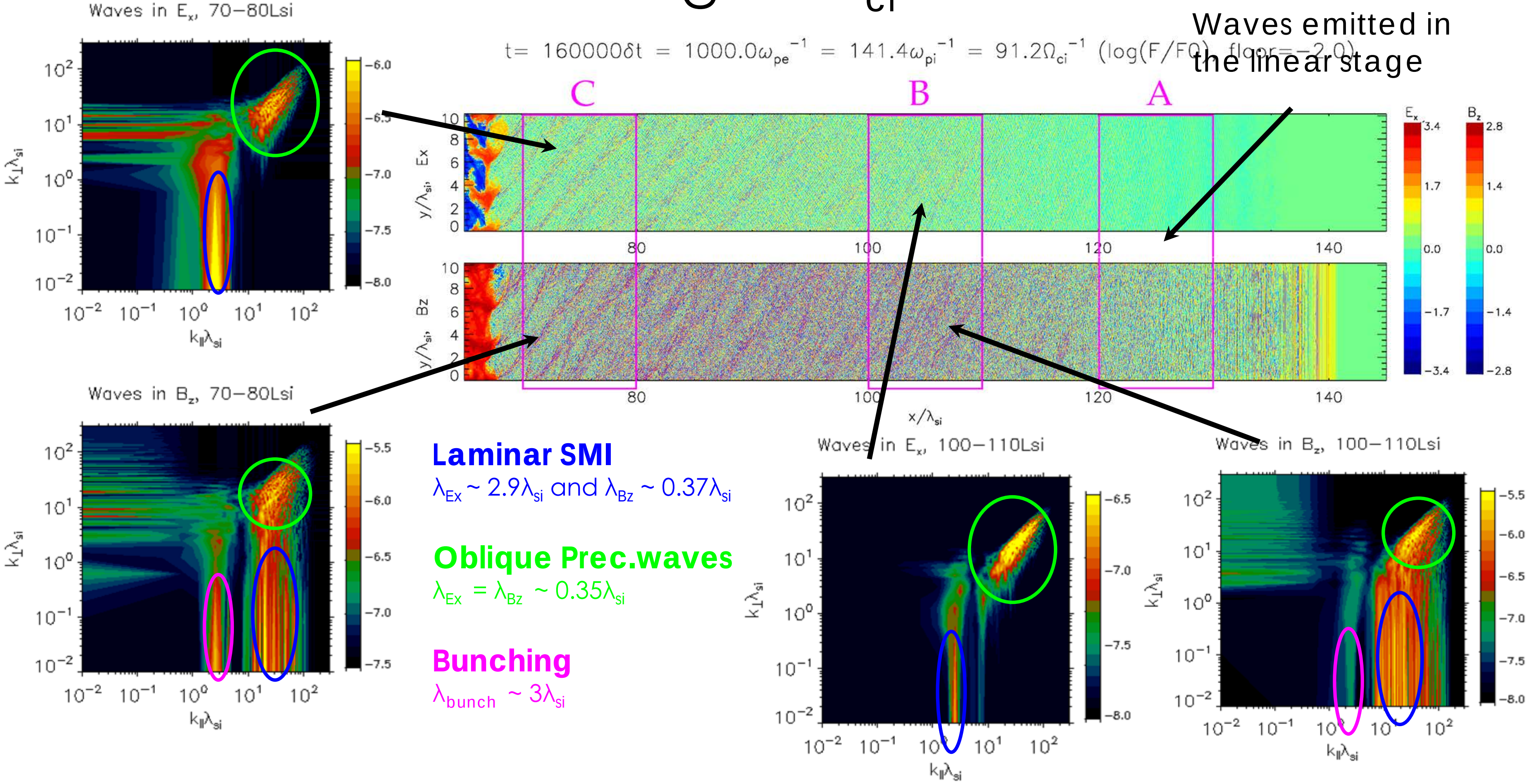
Ey-E0y / B0*c

Bz-B0z / B0



1. Shock at ~67 x/λ_{si}, downstream density compression factor ~ 3
2. Precursor waves in Bz and Ey, velocity ~ c → **X-mode EM waves**
3. **Wakefield** in Ex, λ_{Ex} ~ 3/ λ_{si} (again, in accord with Hoshino 2008)

Late stage: $t\Omega_{ci}$=91.2



Laminar SMI

$\lambda_{Ex} \sim 2.9\lambda_{si}$ and $\lambda_{Bz} \sim 0.37\lambda_{si}$

Oblique Prec.waves

$\lambda_{Ex} = \lambda_{Bz} \sim 0.35\lambda_{si}$

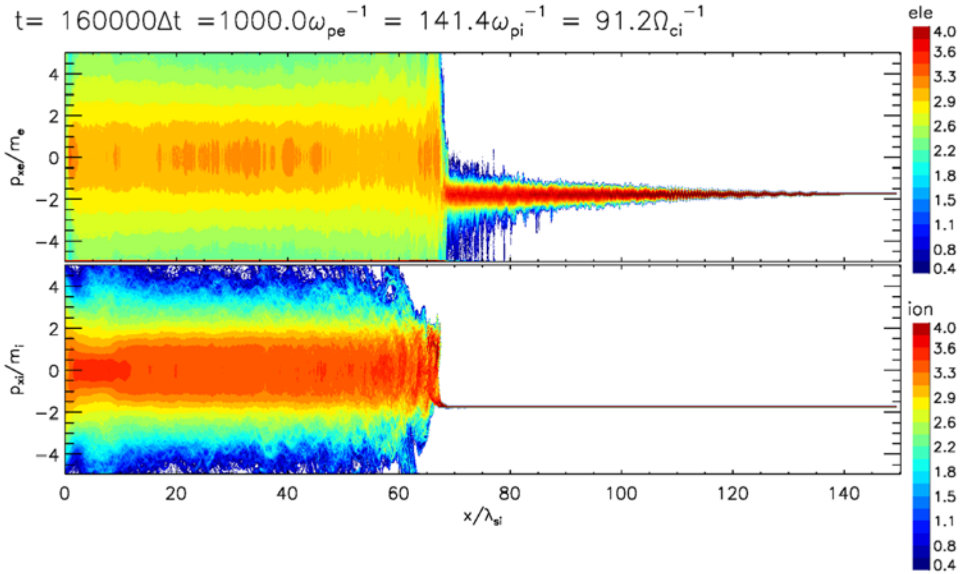
Bunching

$\lambda_{bunch} \sim 3\lambda_{si}$

Late stage: $t\Omega_{ci}$=91.2

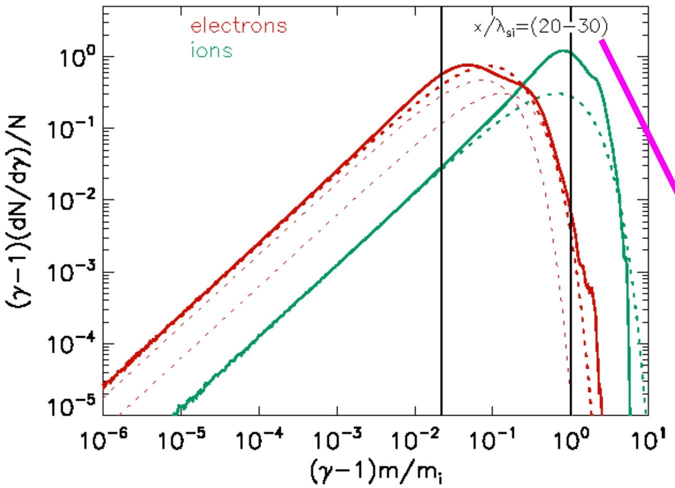
p_{xe}/m_e

p_{ye}/m_e

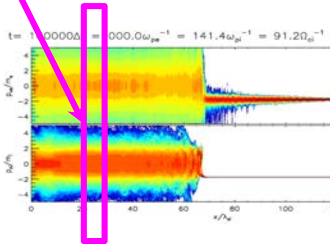


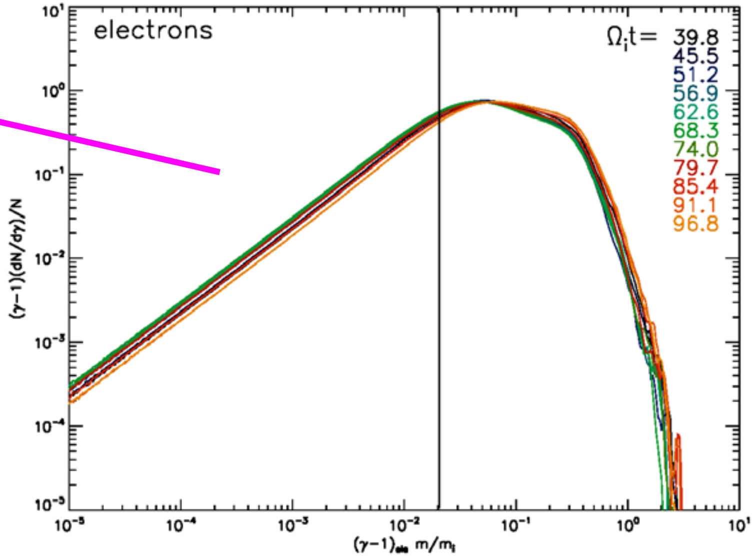
1. **Ring-like feature** at the shock in ion phase space
2. Faint **downstream oscillations** in e^- phase space
3. **e^- upstream phase space is modulated by Ex** → precursor waves affect the plasma
4. **e^- are boosted towards the shock** (i.e., in negative x-momentum)

Particle distribution spectra



Fixed distance ($17\lambda_{si}$) from the shock, time evolution





1.Downstream ions are isotropizing around their initial energy

2. e^- are heated in bulk, but show asymmetry (double maxwellian fit): it may depend on **upstream acceleration by wakefield**

3. Heating of e^- is still progressing: equipartiton can then be reached?

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. Evidence of the rippling feature (new for PIC simulation)

3. Particle-wave interactions in the precursor → **plasma thermalization and limited ion-to-e^- energy transfer: can equipartition be reached?**

4. More analysis will be performed in the near future with introduction of a positron component

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

Thank you
for your attention