Arianna Ligorini
Jacek Niemiec
Oleh Kobzar
Department of Gamma-ray Astrophysics, IFJ-PAN, Krakow

Masanori Iwamoto
Takanobu Amano
Masahiro Hoshino
Department of Earth and Planetary Science, University of Tokyo

Yosuke Matsumoto
Department of Physics, Chiba University

Martin Pohl
Institute of Physics and Astronomy, University of Potsdam and DESY

Kinetic simulations of mildly relativistic magnetized perpendicular shocks in astrophysics

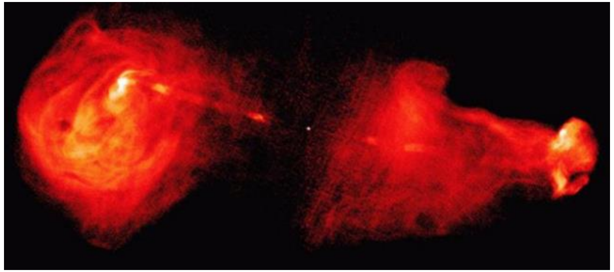
KUKDM 2019 - Zakopane

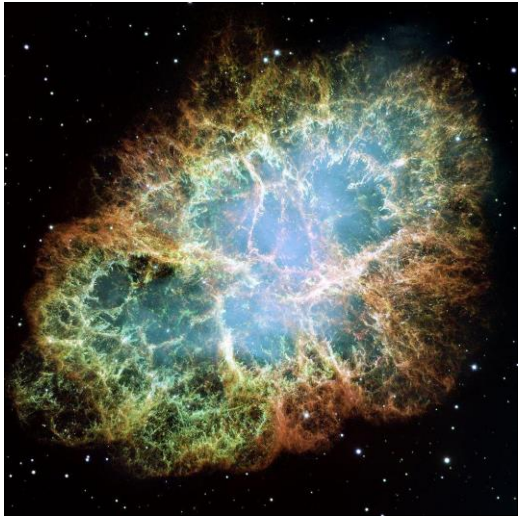
Astrophysical shocks

Shocks in many astrophysical environments

SNRs → non-relativistic shocks

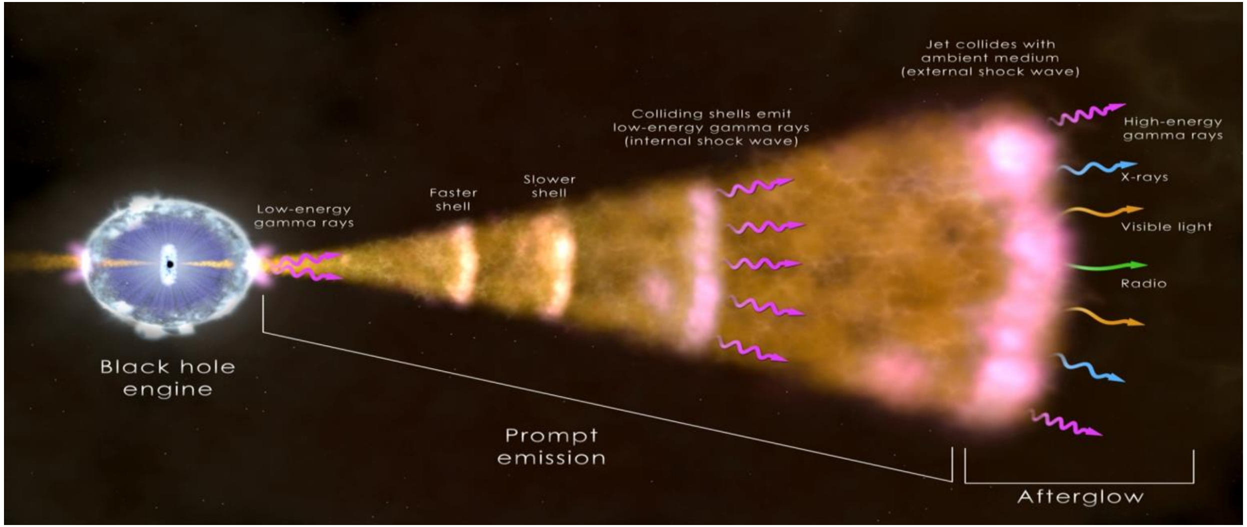
Active Galactic Nuclei, Pulsars, Gamma Ray Burst, Blazars → relativistic shocks





Astrophysical shocks: Blazars

AGN with relativistic jets seen approx head on



Dissipation → Internal Shock Model

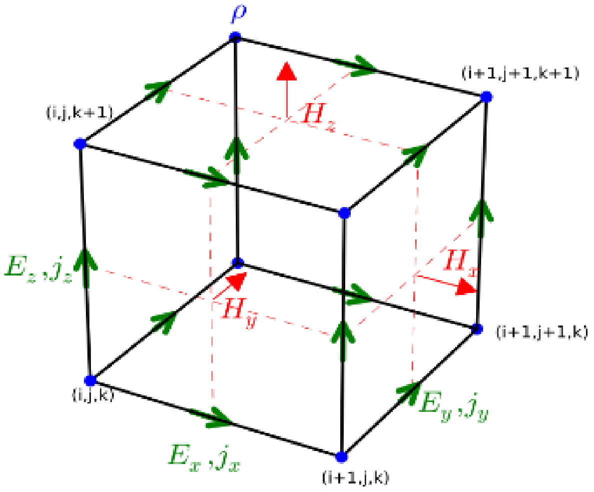
We study the model for **mildly relativistic (γ~2) regime**
- perpendicular magnetic field
- total magnetization σ = 0.1

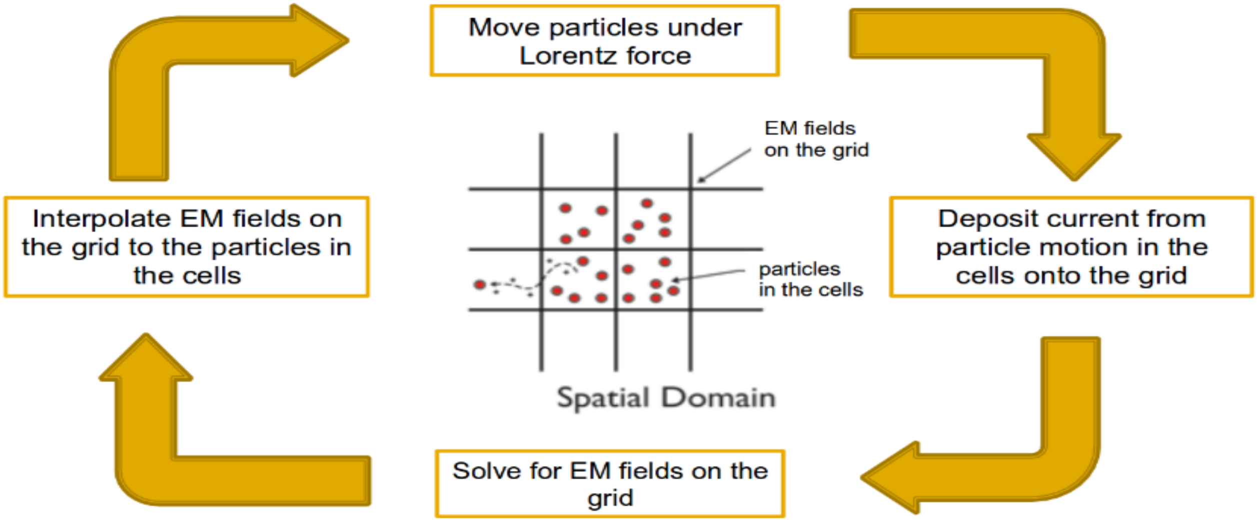
Sikora, 2013
Sikora, 2016

Particle-In-Cell Simulations

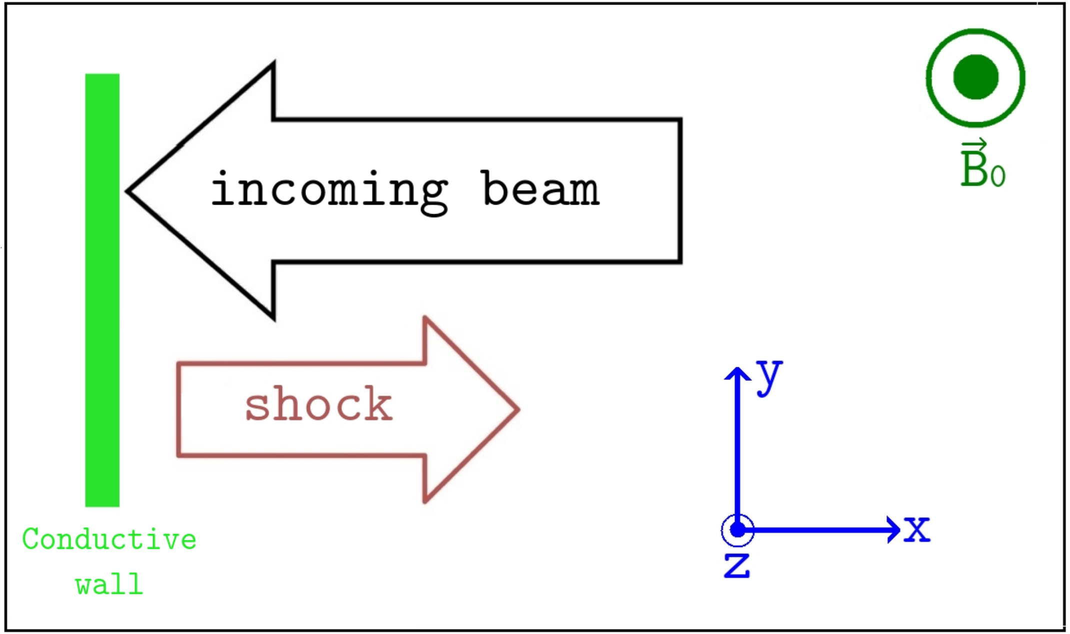
PIC simulations → ab-initio method of solving Vlasov equation:

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





Simulation setup



Ions and electrons cold plasma

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

Particle-In-Cell Simulations

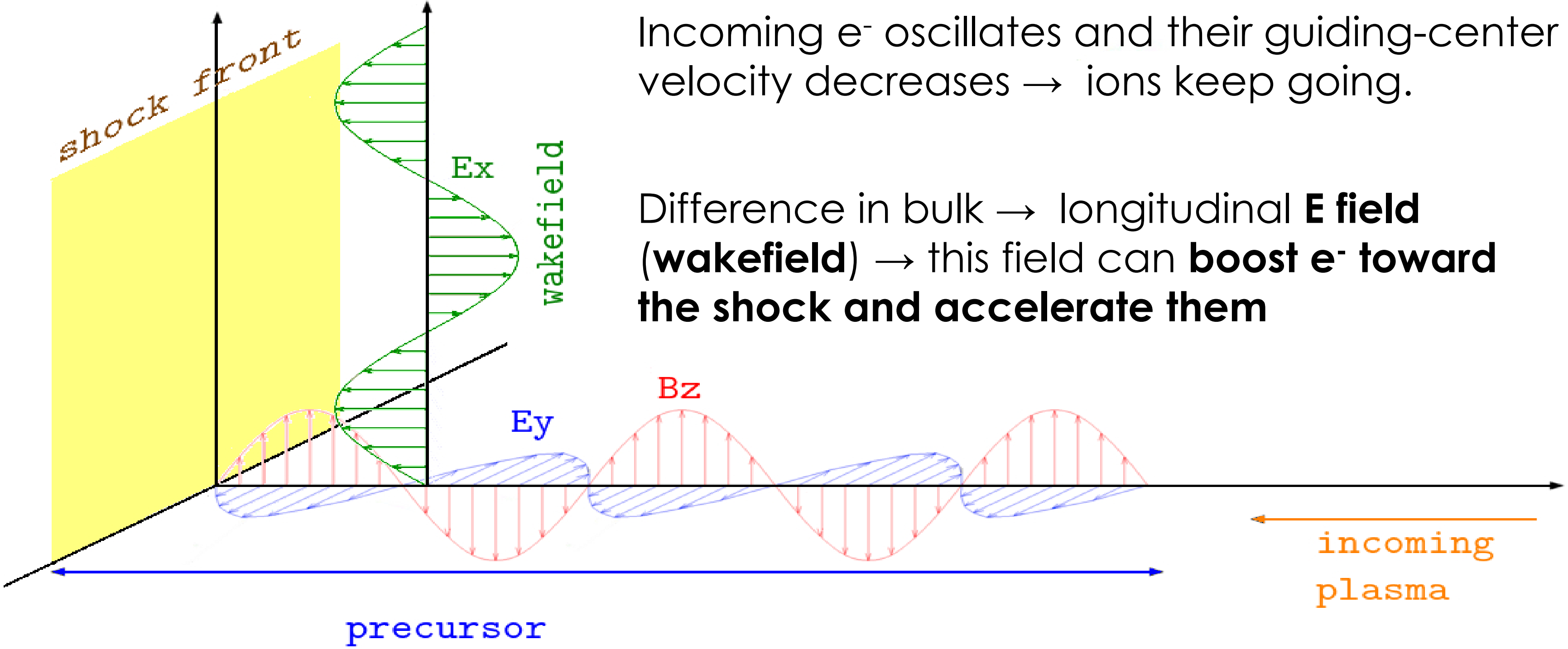
Large-scale high-resolution PIC simulations must be performed at high-performance supercomputing centers

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

Main simulations:
→ 2D (2D3V)
→ ~ 74TB of storage
→ > 12 mil of walltime hours

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).**



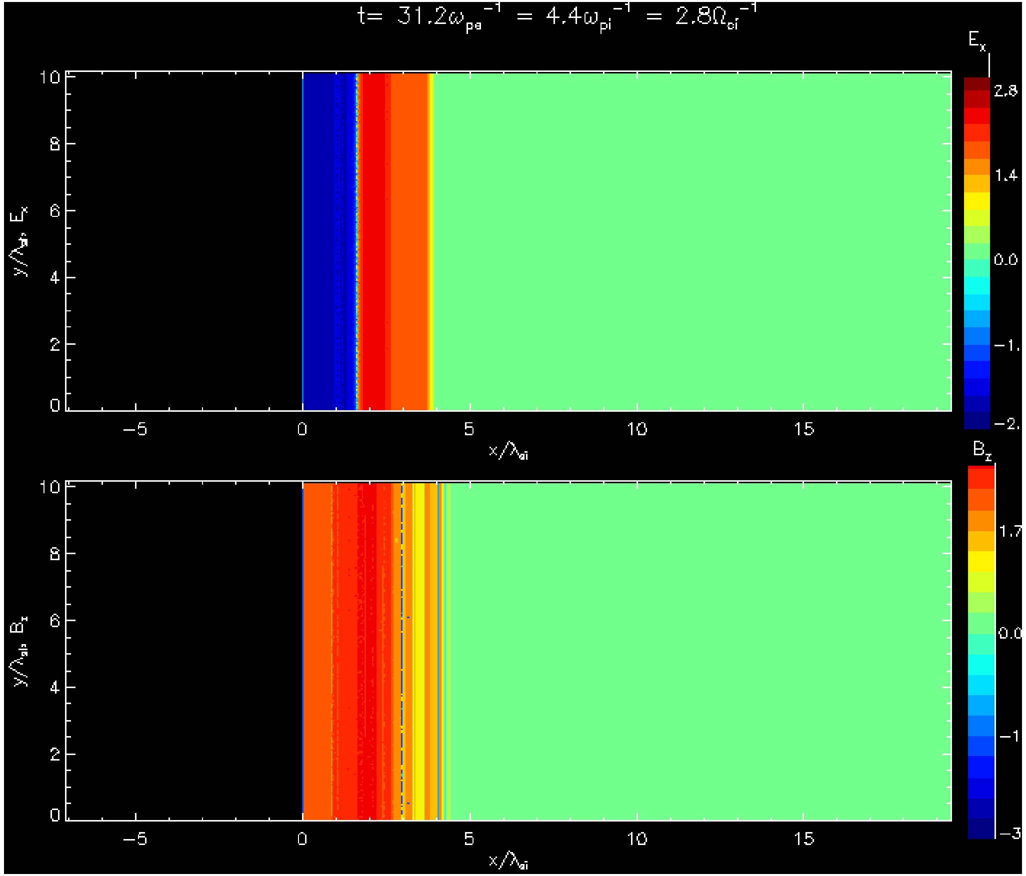
Incoming e^- oscillates and their guiding-center velocity decreases → ions keep going.

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

Large scale simulation: field movie

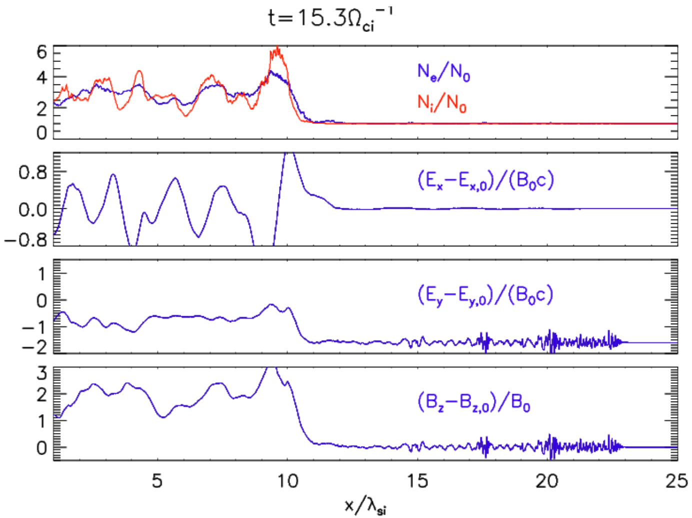
$\frac{E_x - E_{0x}}{B_0 * c}$

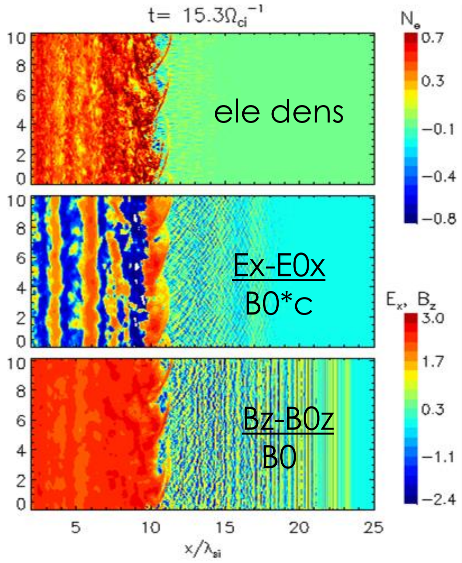
$\frac{B_z - B_{0z}}{B_0}$

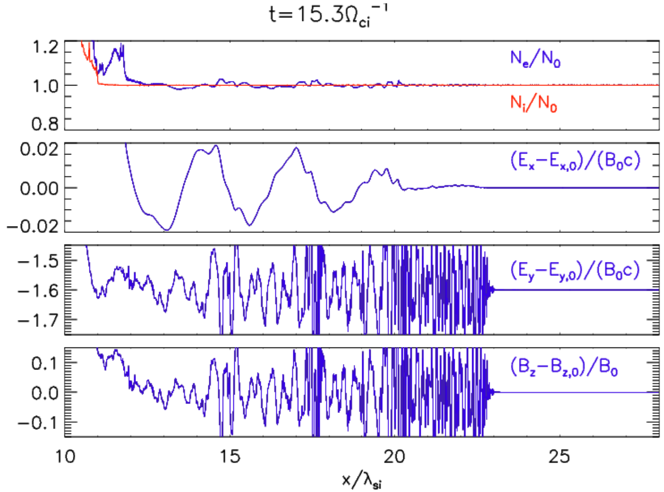


Evidence of a linear early stage + rippled stage

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

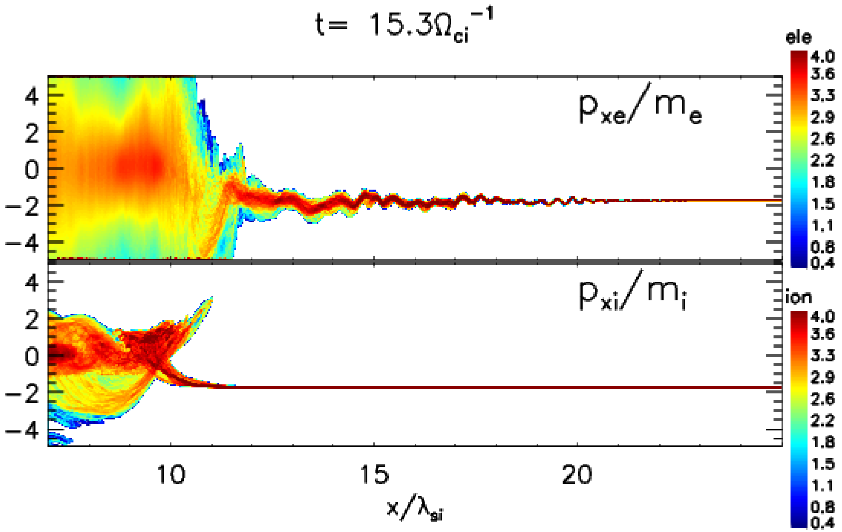






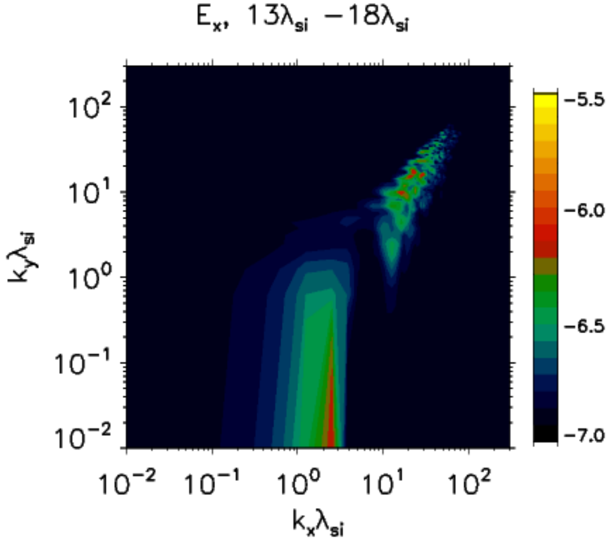
1. Shock at ~10.5 x/ λ_{si}, average downstream density compression factor ~ 3
2. Precursor waves in Bz and Ey, velocity ~ c → **X-mode EM waves**
3. **Wakefield** in Ex, λ_{Ex} ~ 3/ λ_{si} (in accord with Hoshino 2008)

Linear stage: $t\Omega_{ci}$=15.3 - phase space maps (px)



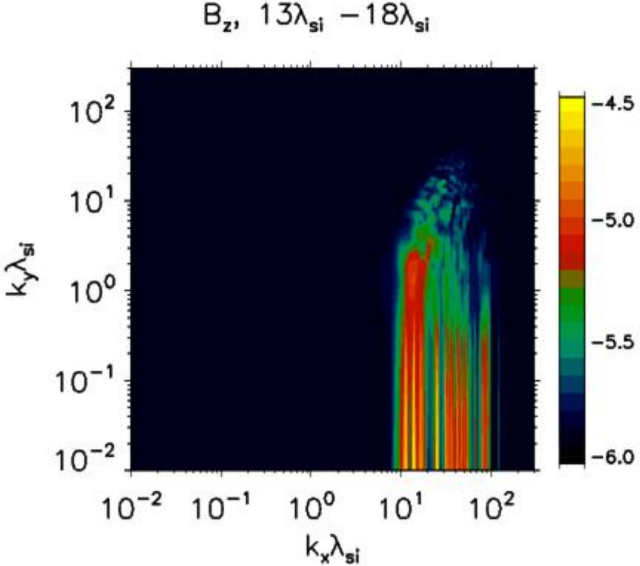
1. **Sort of ring-like feature** at the shock in ion phase space
2. **e^- upstream phase space is modulated by E_x** → precursor waves affect the plasma
3. **Still no evidence of e^- boosted towards the shock** (i.e., in negative x-momentum)

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



More accurate estimate of wavelenghts:

Very good agreement with theory!

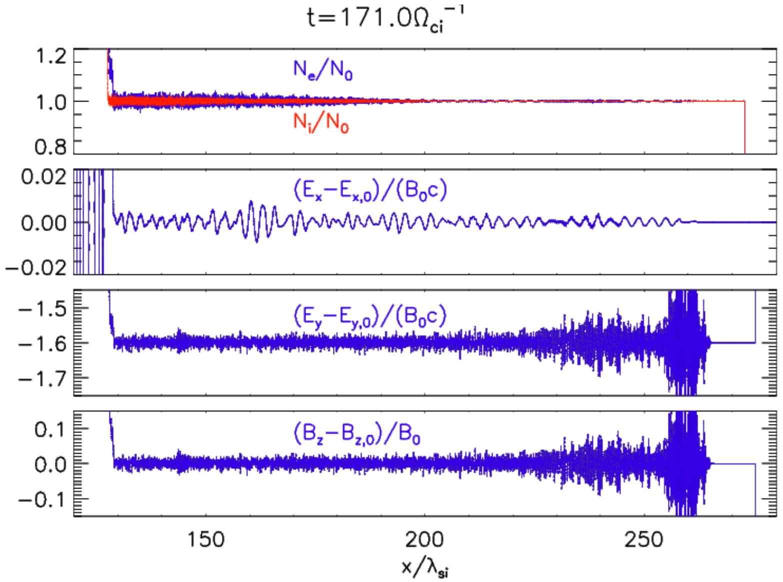


λ_{Ex} ~ $2.9\lambda_{si}$ (cfr. Theory: $\lambda_{Ex,th}$ ~ $3.1\lambda_{si}$)

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

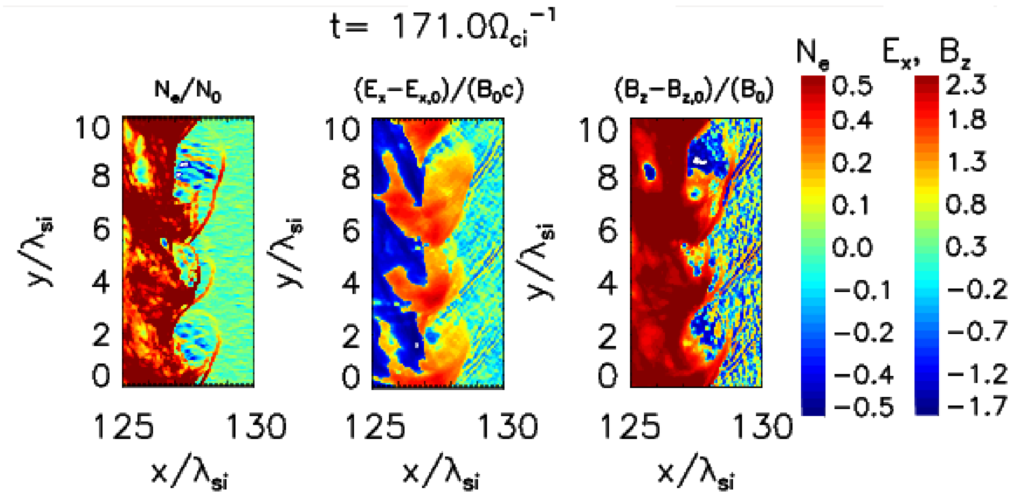
oblique component → first phases of the rippling

Late stage: $t\Omega_{ci}$=171.0



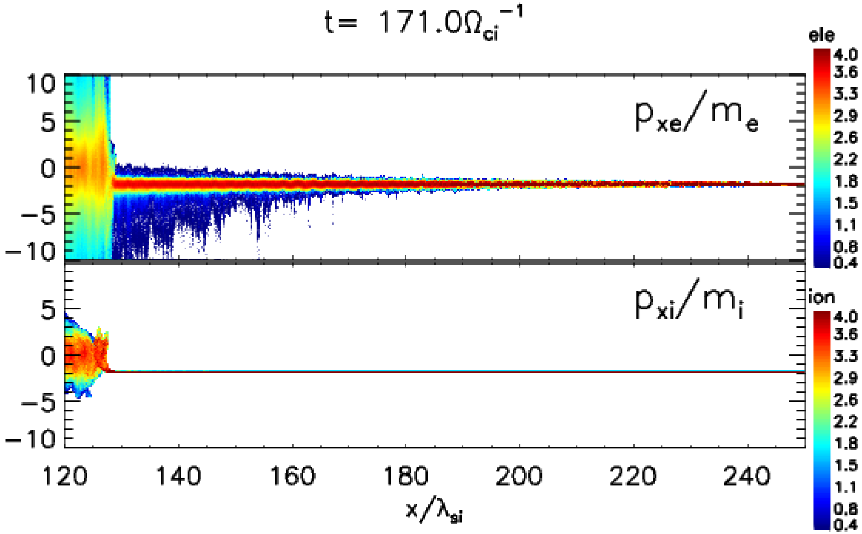
1. Shock at ~127 x/ λ_{si}, downstream density compression factor ~ 3
2. Precursor waves in Bz and Ey, velocity ~ c → **X-mode EM waves**
3. **Wakefield** in Ex, λ_{Ex} ~ 3/ λ_{si} (again, in accord with Hoshino 2008)

Late stage: $t\Omega_{ci}$=171.0 - Rippling



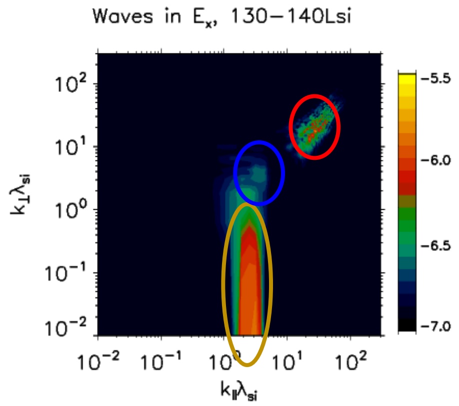
- ➢ **Proposed origin**: ions gyrating at the shock → scales and directions are compatible!
- ➢ Also we see gyratin ions in ph.space

Late stage: $t\Omega_{ci}$=171.0 - Phase space maps (px)



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 E_x** → precursor waves and wakef. affect the plasma
4. **e^- are boosted towards the shock** (i.e., in negative x-momentum)

Late stage: $t\Omega_{ci}$=171.0 - Fourier spectra

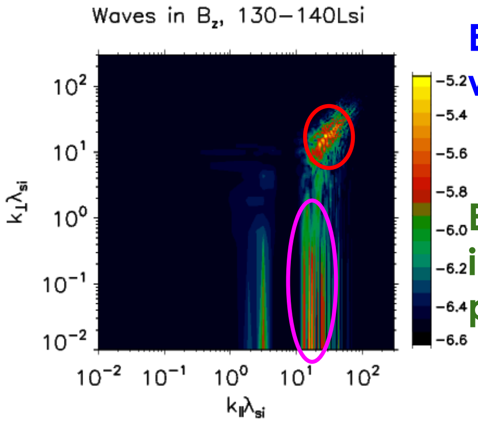


Comp.with standard SMI wakefield

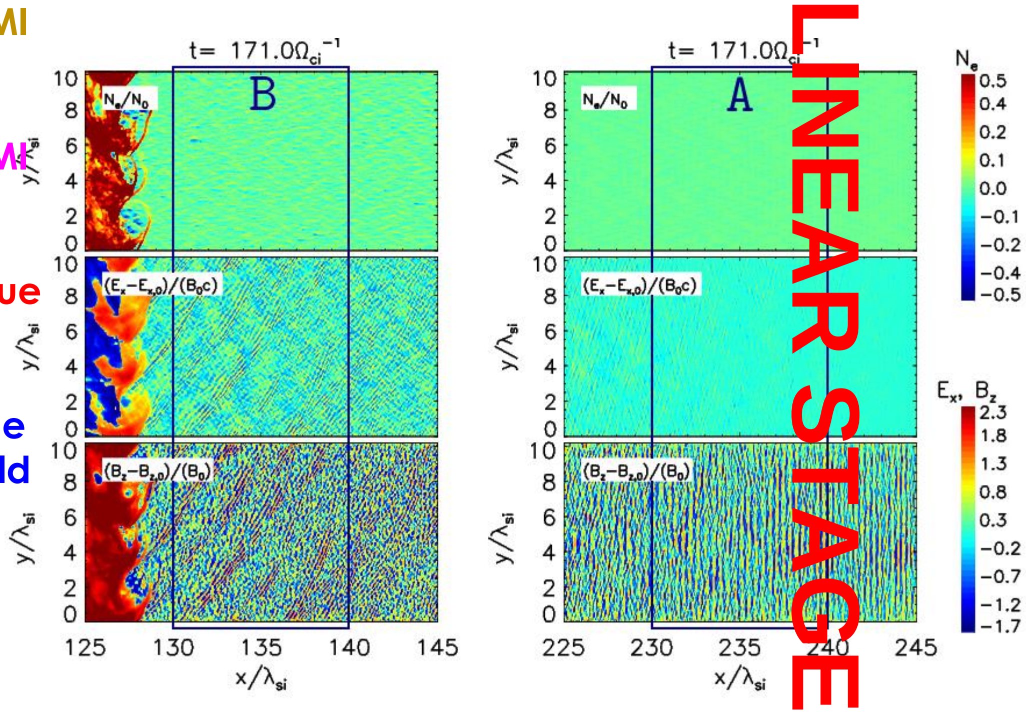
Comp.with standard SMI prec

Compatible with Oblique SMI precursors

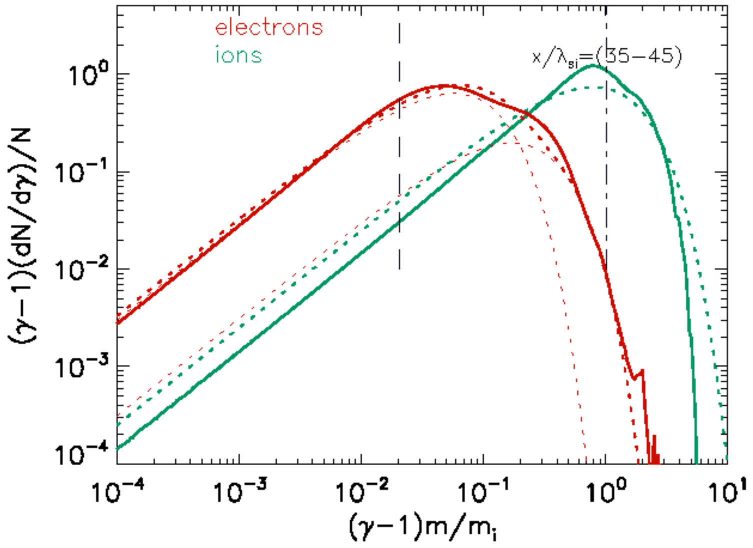
ES in nature, compatible with a oblique wakefield



BUNCHING: is it an interference phenomenon?

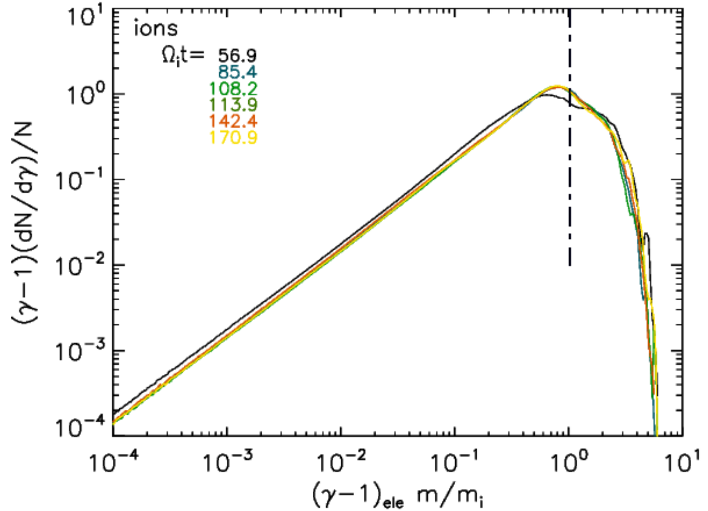


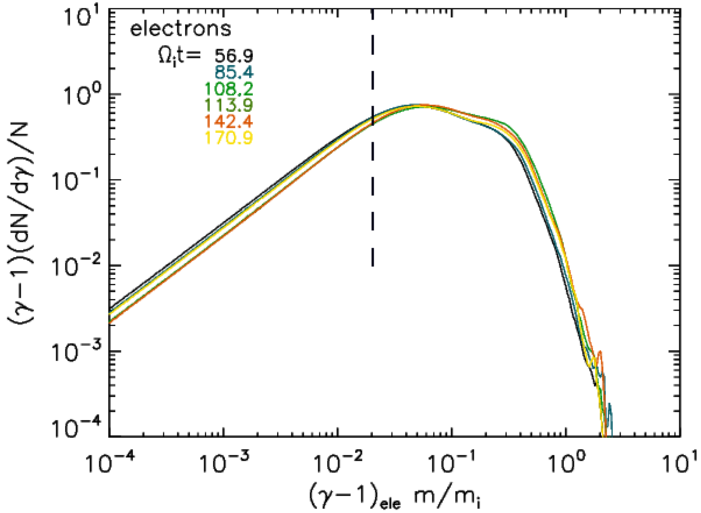
Late stage: $t\Omega_{ci}$=171.0 - Spectra



1. Ions are still isotropizing around their initial energy
2. e^- are heated in bulk, but show asymmetry
3. Double maxwellian → population of heated electrons

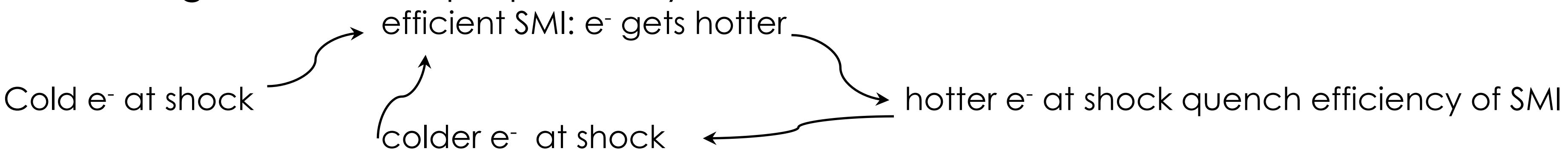
Late stage: $t\Omega_{ci}$=171.0 - Spectra in time



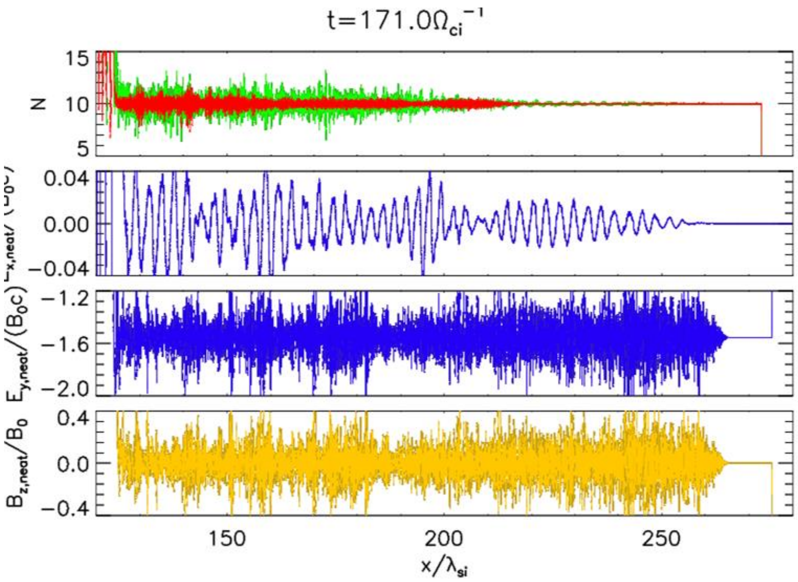


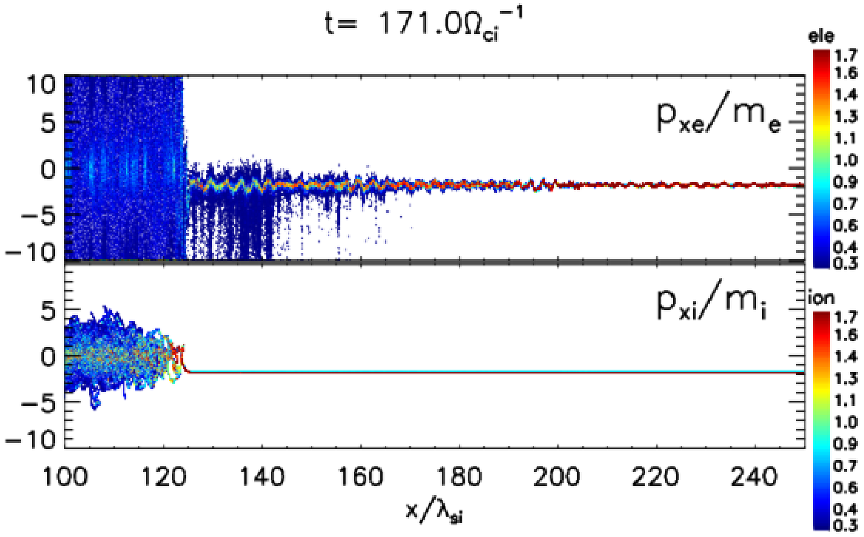
Heating of e^- progresses for a while, then gets lower

Quenching mechanism proposed by Sironi2011?



1D Late stage: $t\Omega_{ci}$=171.0

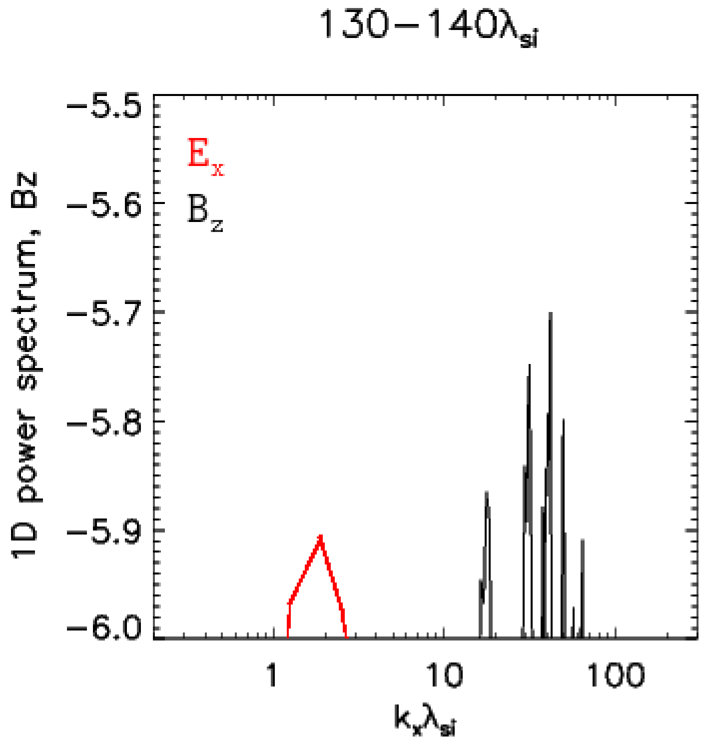




1. Shock at ~127 x/ λ_{si}
2. **Higher intensity of prec. and wakefield**

1. **Ring-like feature** at the shock in ion phase space
2. **e^- upstream phase space is modulated by E_x**
3. **e^- are boosted towards the shock** (negative px)

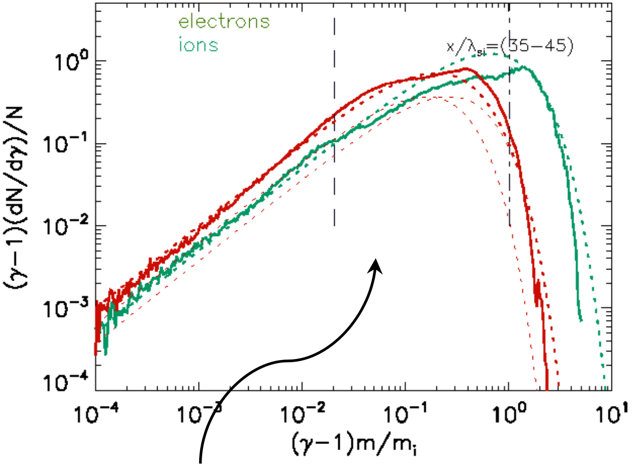
1D Late stage: $t\Omega_{ci}$=171.0 - Fourier spectra

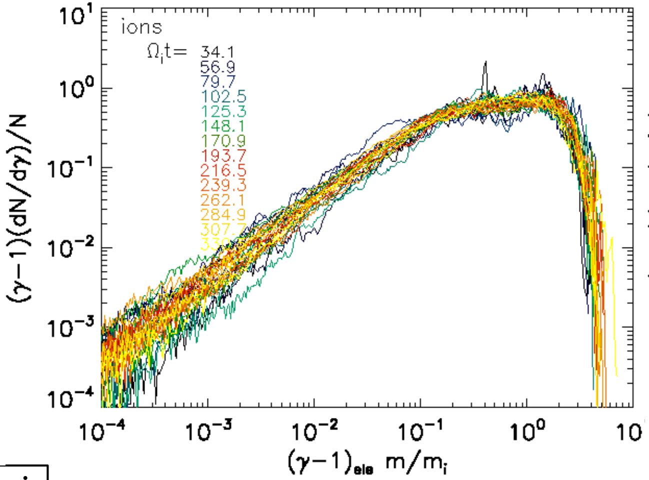


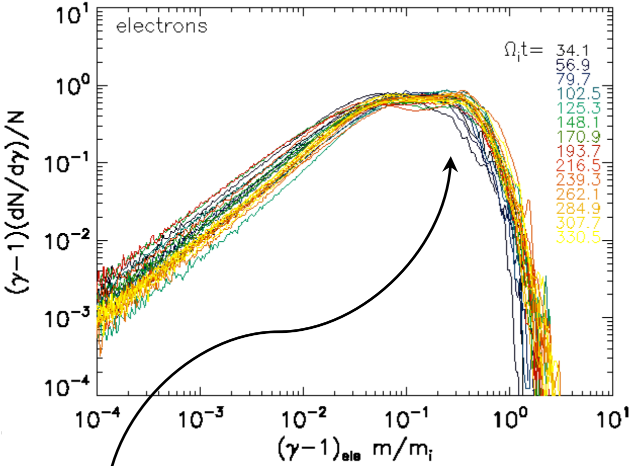
Compatible with standard SMI precursor (+some noise)

Compatible with standard SMI wakefield

1D VERY Late stage: $t\Omega_{ci}$=330.0 - Spectra







1. Ions are still isotropizing around their initial energy

2. e^- double maxwellian → population of heated e^-

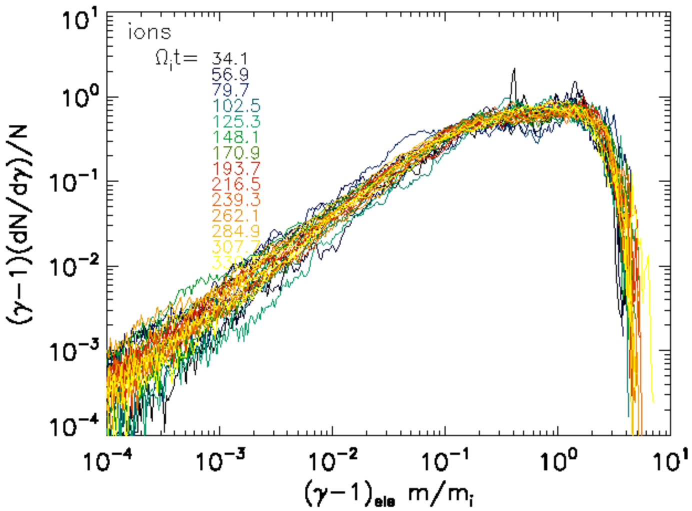
3. **Higher coupling!** → correlated with higher efficiency of SMI

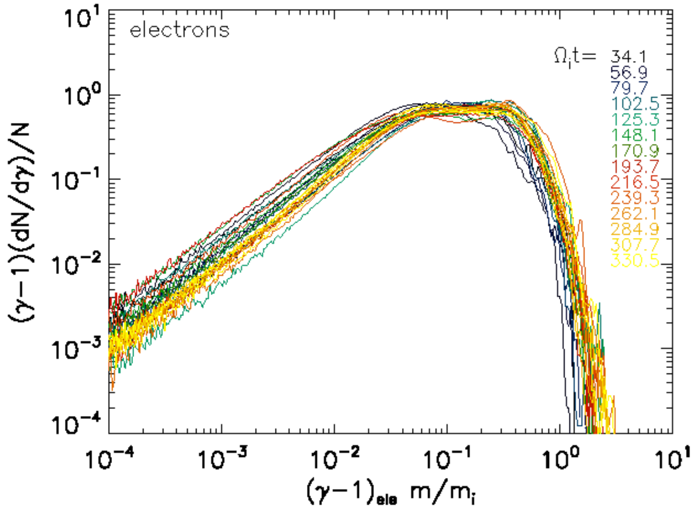
Again heating of e^- progresses for a while, then gets lower.

No higher heating but a sort of “up-and-down” behaviour

This seems to agree with quenching mechanism proposed by Sironi2011!

1D VERY late stage: $t\Omega_{ci}$=330.0 - Spectra in time





Again heating of e^- progresses for a while, then gets lower.

No higher heating but a sort of “up-and-down” behaviour

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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: is it due to waves efficiency?**

4. 1D simulation proves that!

5. Further study: the in-plane magnetic field setup (need of ~15 million CPU hours)

Thank you
for your attention