PIC Simulations of relativistic transverse magnetosonic shocks

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Outline

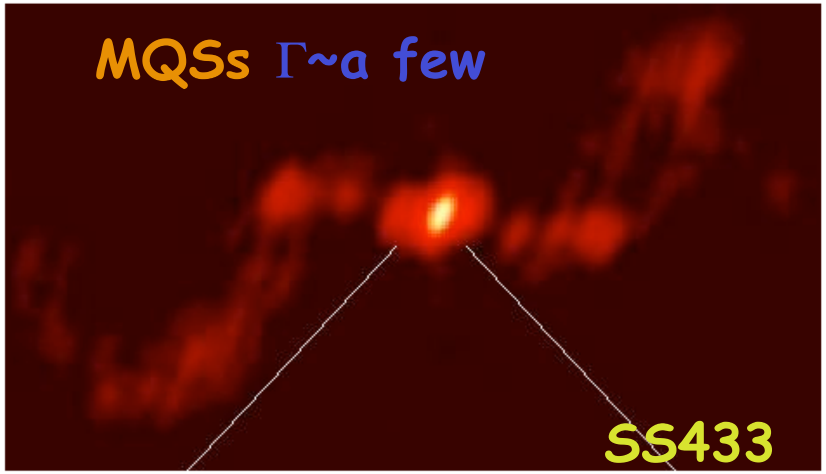
- **Astrophysical relevance of the subject**

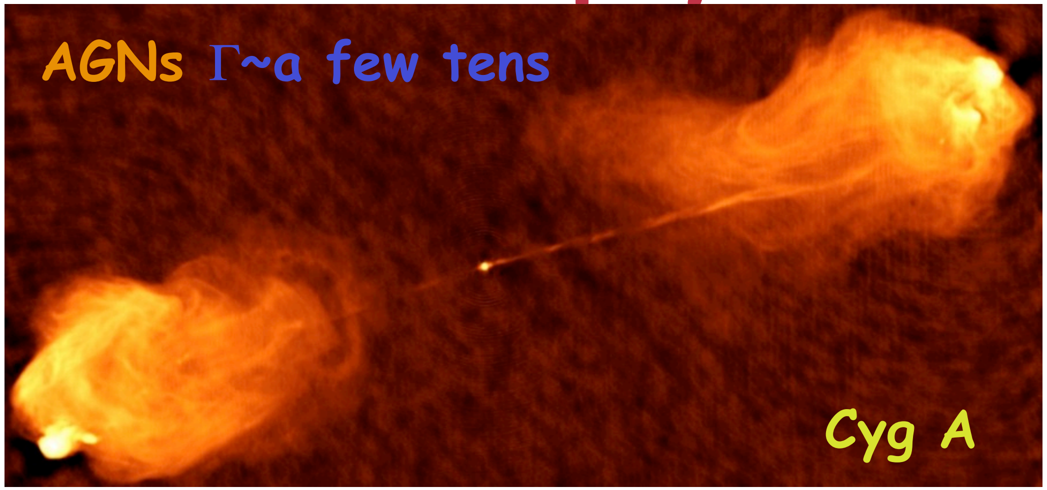
- **PIC simulations of relativistic transverse magnetosonic shocks in e^--e^+-p plasmas**
  - Resonant cyclotron absorption
  - Questions left open by previous work on the subject
  - What can still be learned from 1D PIC

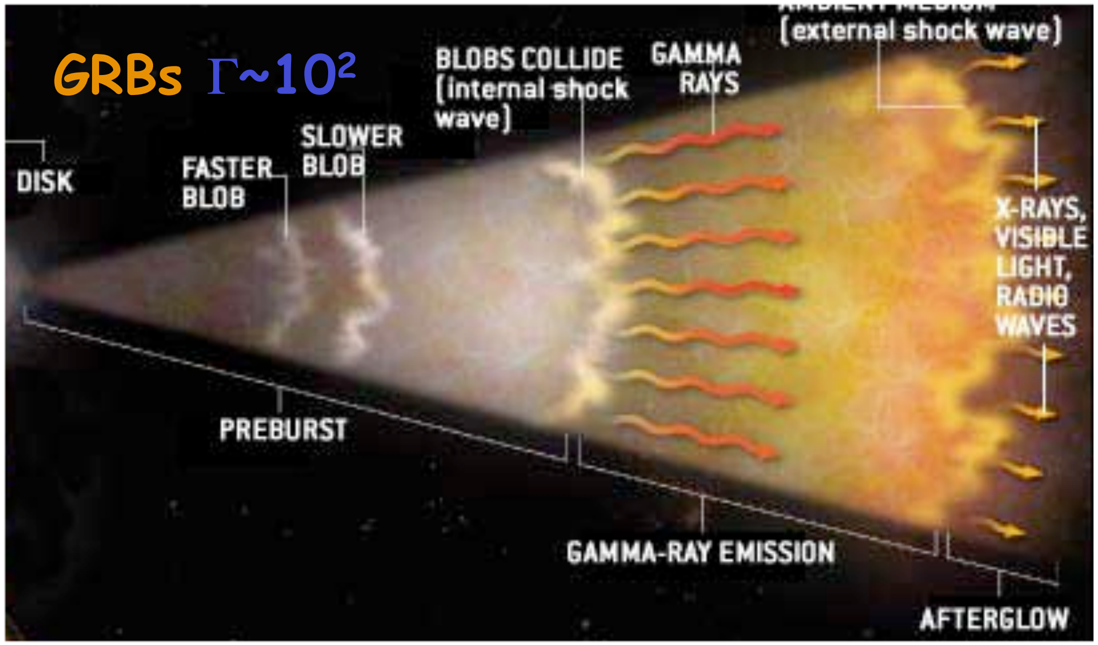
- **Simulations with increased mass-ratio between ions and pairs (up to 100): now outdated**
  - Acceleration mechanism still effective
  - Electron acceleration seen for the first time
  - Effects of finite temperature of the plasma

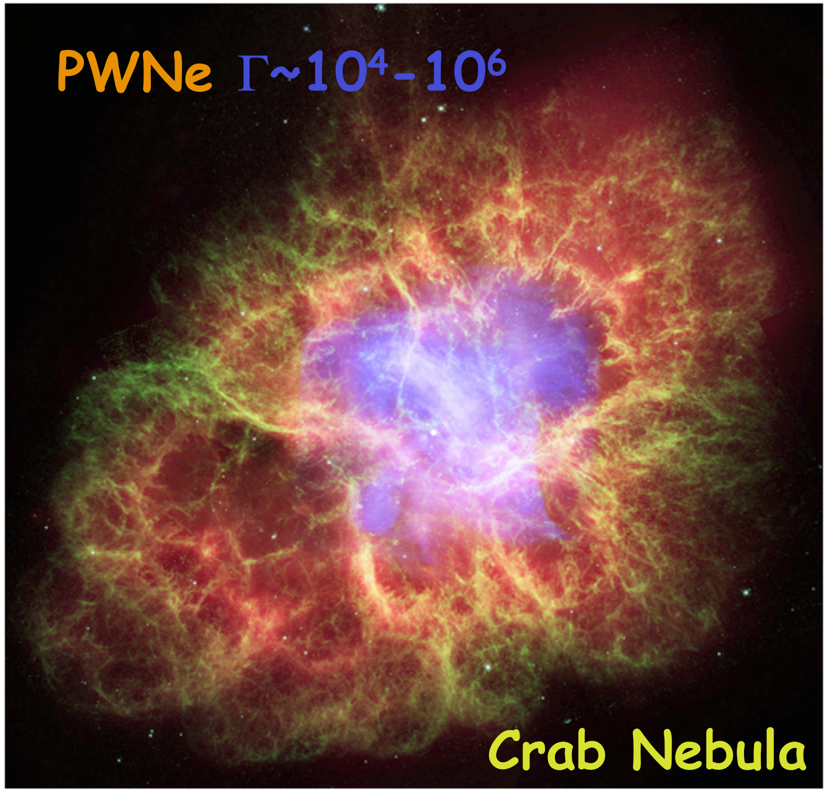
- **Summary and Conclusions**

Relativistic shocks in astrophysics









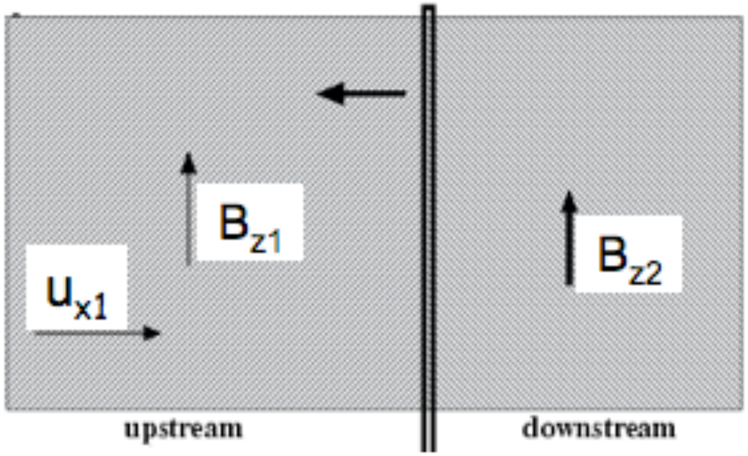
Properties of the flow and particle acceleration

- These shocks are collisionless: transition between non-radiative (upstream) and radiative (downstream) takes place on scales too small for collisions to play a role
- They are generally associated with non-thermal particle acceleration but with a variety of spectra and acceleration efficiencies

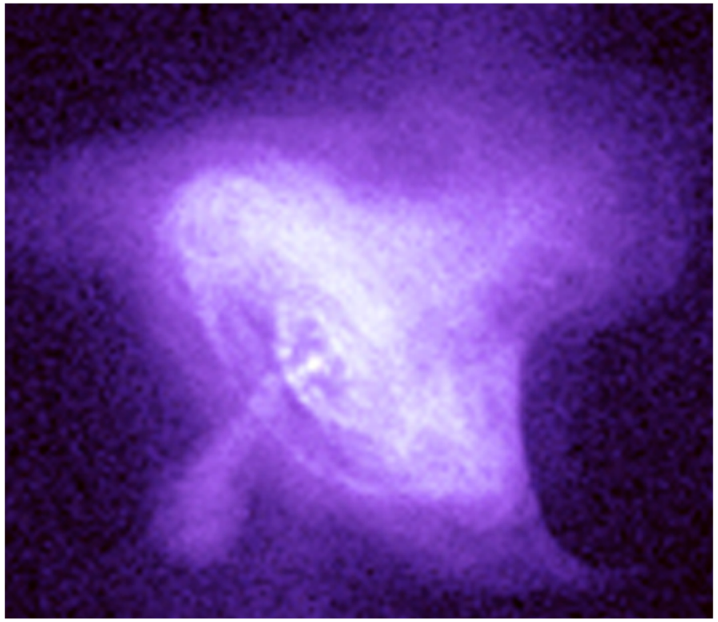
Self-generated electromagnetic turbulence mediates the shock transition: it must provide both the dissipation and particle acceleration mechanism

The detailed physics and the outcome of the process strongly depend on
composition (e^--e^+-p?)
magnetization ($\sigma=B^2/4\pi n\Gamma mc^2$)
and geometry ($\Gamma \times \Theta(\mathbf{B}\cdot\mathbf{n})$)
of the flow, which are usually unknown….

Relativistic transverse magnetosonic shocks



$\Theta(\mathbf{B}\cdot\mathbf{n}) \gg 1/\Gamma$
Geometry
Common for Magnetized Relativistic shocks



Magnetized relativistic shocks in PWNe accelerate particles very efficiently!!!

Look at the Crab Nebula:
✓Efficiency >20% of total L_{sd}
✓Maximum energy: for Crab ~few x 10^{15} eV (close to total available ΔV at the PSR)

3D PIC of magnetized pair shocks hint at low efficiency (Spitkovsky 08)

Magnetic reconnection ?

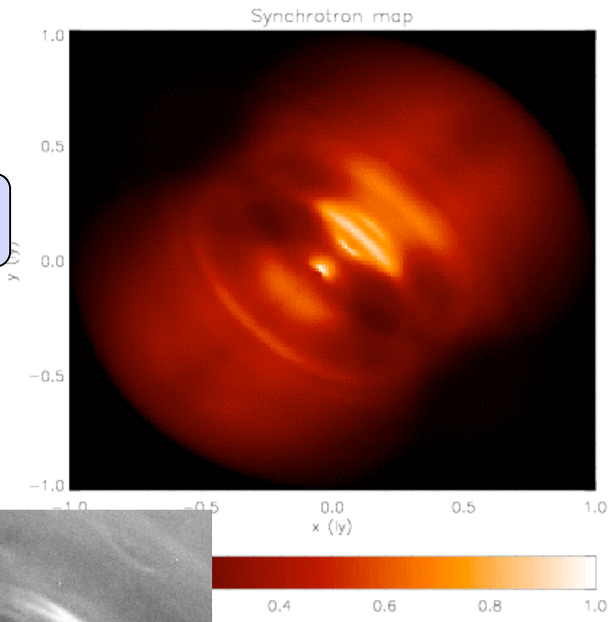
Or maybe ions?

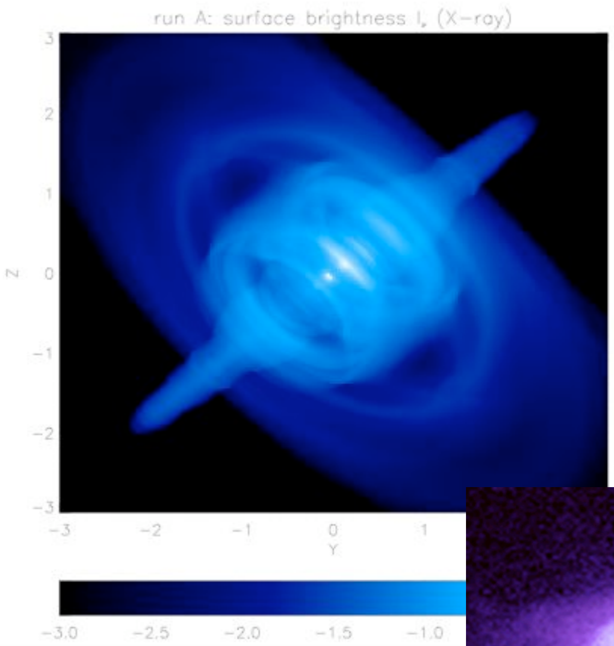
- unmagnetized shock: efficient Fermi I (Spitkovsky 08)
- acceleration associated to reconnection (Lyubarsky & Petri 07)

Resonant cyclotron absorption

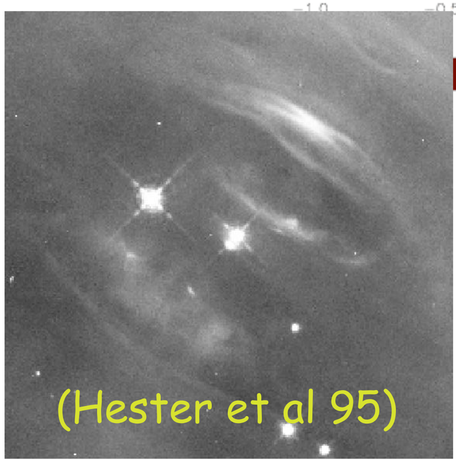
Synchrotron Emission maps from 2D MHD simulations of PWNe

optical



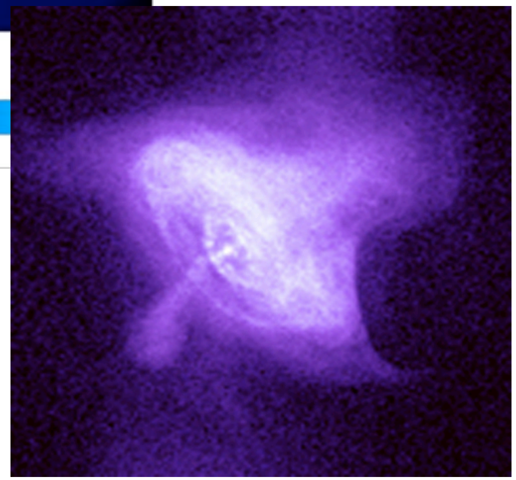


X-rays



σ=0.025, b=10

(Del Zanna et al. 06)



Particle In Cell Simulations

The method:

✓Collect the current at the cell edges
✓Solve Maxwell's eqs. for fields on the mesh
✓Compute fields at particle positions
✓Advance particles under e.m. force

Approximations

In principle only cloud in cell algorithm

Powerful investigation tool for collisionless plasma physics: allowing to resolve the kinetic structure of the flow on all scales

But Computational limitations force:

Reduced spatial and time extent

Mistaken transients

Far-from-realistic values of the parameters

An example of the effects of reduced m_i/m_e in the following

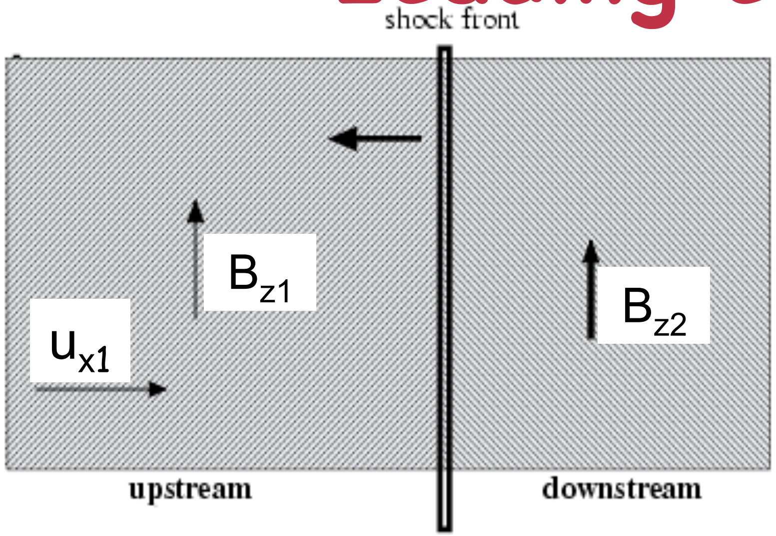
reduced dimensionality of the problem

e^--e^+ plasma flow:

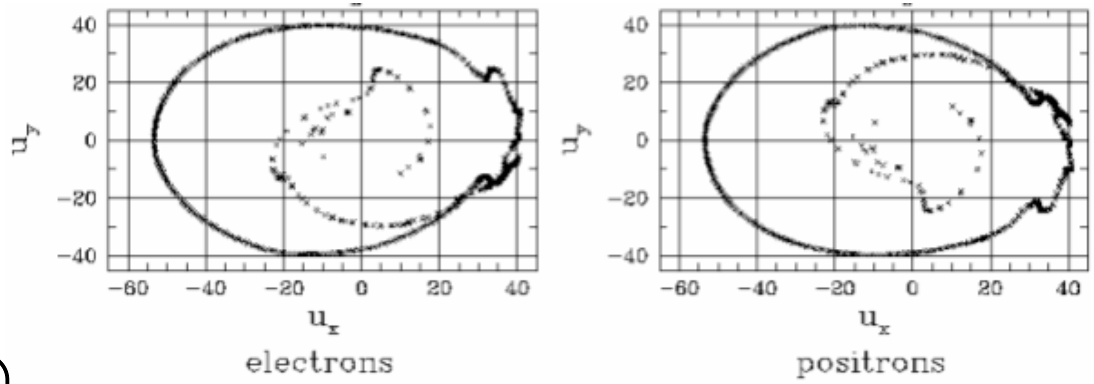
- **in 1D:**
  - No shock if σ=0
  - No accel. for any σ
- **in 3D**
  - Shock for any σ
  - Fermi accel. for σ=0

For some aspects of problems involving species with different masses 1D WAS still the only way to go

Leading edge of the shock



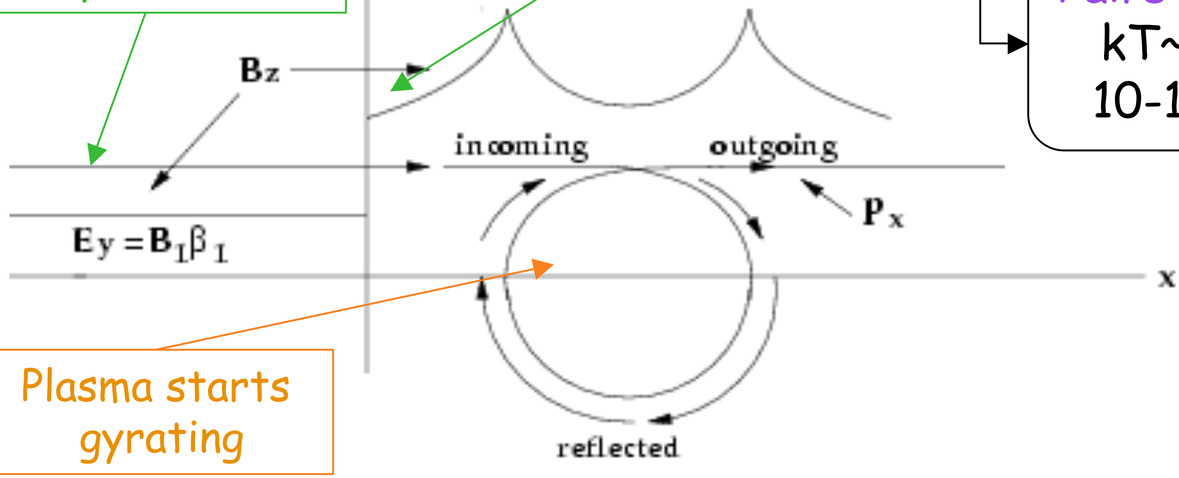
Configuration at the leading edge
~ cold ring in momentum space



Magnetic reflection mediates the transition

Drifting e^+-e^--p plasma

B increases



Plasma starts gyrating

Coherent gyration leads to collective emission of cyclotron waves

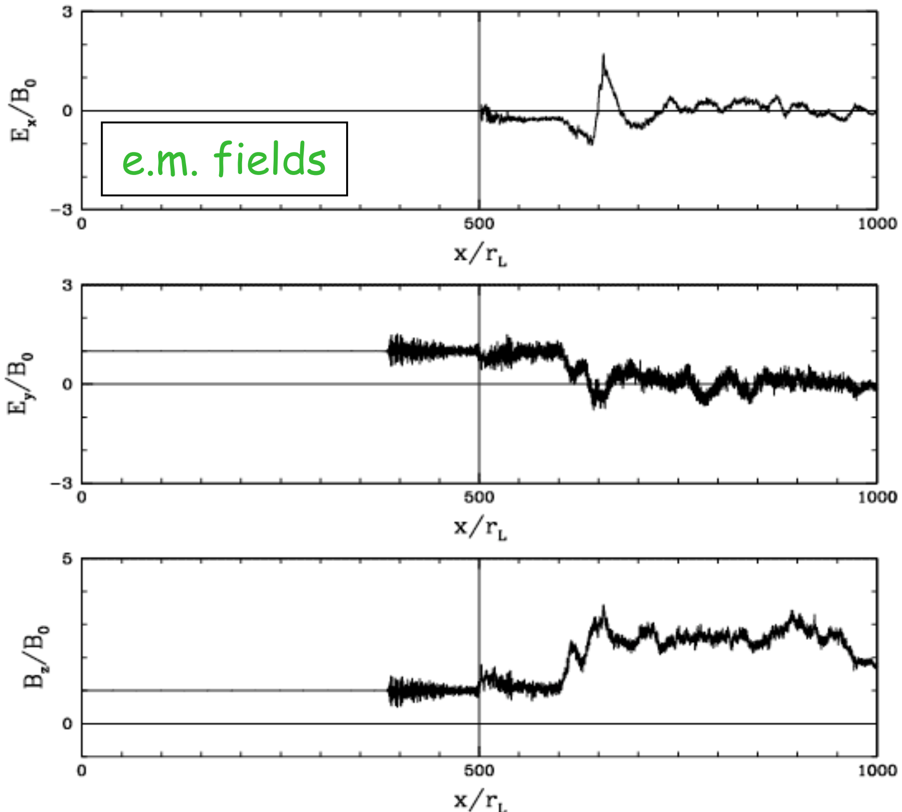
Pairs thermalize to $kT \sim m_e \Gamma c^2$ over $10\text{-}100 \times (1/\Omega_{ce})$

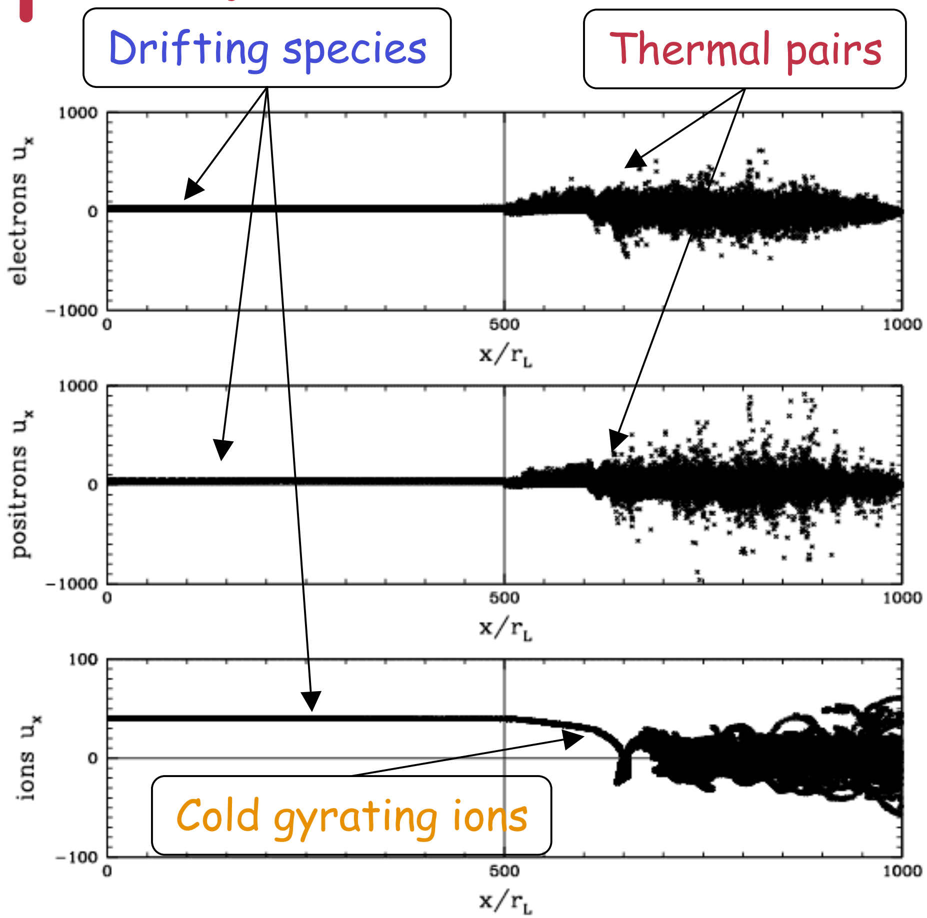
Ions take their time: m_i/m_e times longer

Pairs can absorb ion radiation resonantly

1D PIC Simulations of shocks in $e^- - e^+ - p$ plasmas

From 1D PIC with $m_i/m_e=100$
(Amato & Arons 06)
Using XOOPIC (Verboncouer et al. 95)



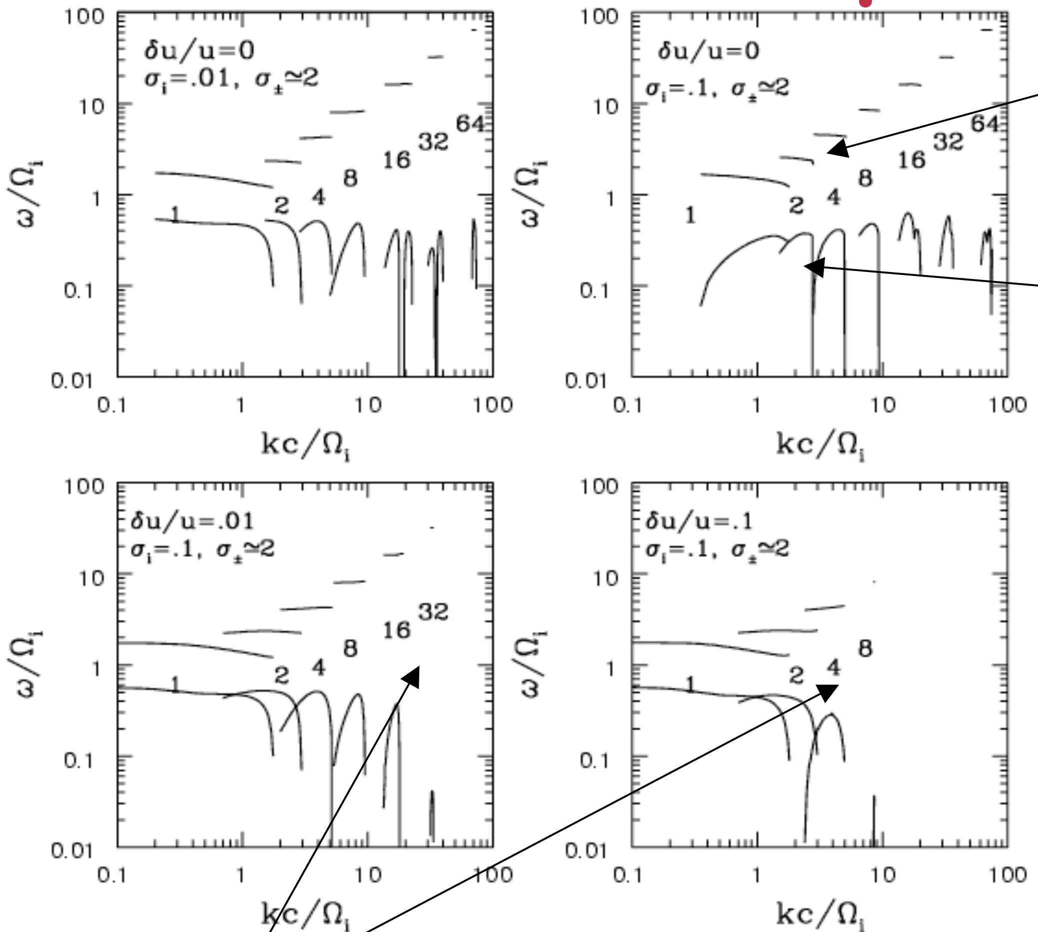


- Particles enter simulation box from left
- Impact on a wall on the right
- Wait until shock far from right boundary

1D PIC sim. with m_i/m_e up to 20
(Hoshino & Arons 91, Hoshino et al. 92)
e^+ effectively accelerated
if $U_i/U_{tot}>0.5$

Resonant cyclotron absorption in ion-doped plasma

$\Omega_{ci} = m_e/m_i \Omega_{ce}$



frequency

Growth-rate

Pairs initially need $n \sim m_i/m_e$ for resonant absorption!!!
Then lower n

Growth-rate~independent of n
(Hoshino & Arons 91)

m_i/m_e much lower than reality implies n_i/n_- correspondingly larger to guarantee sufficiently large U_i/U_{tot}

⇓

Elliptical polarization of ion waves

⇓

Preferential absorption by e^+

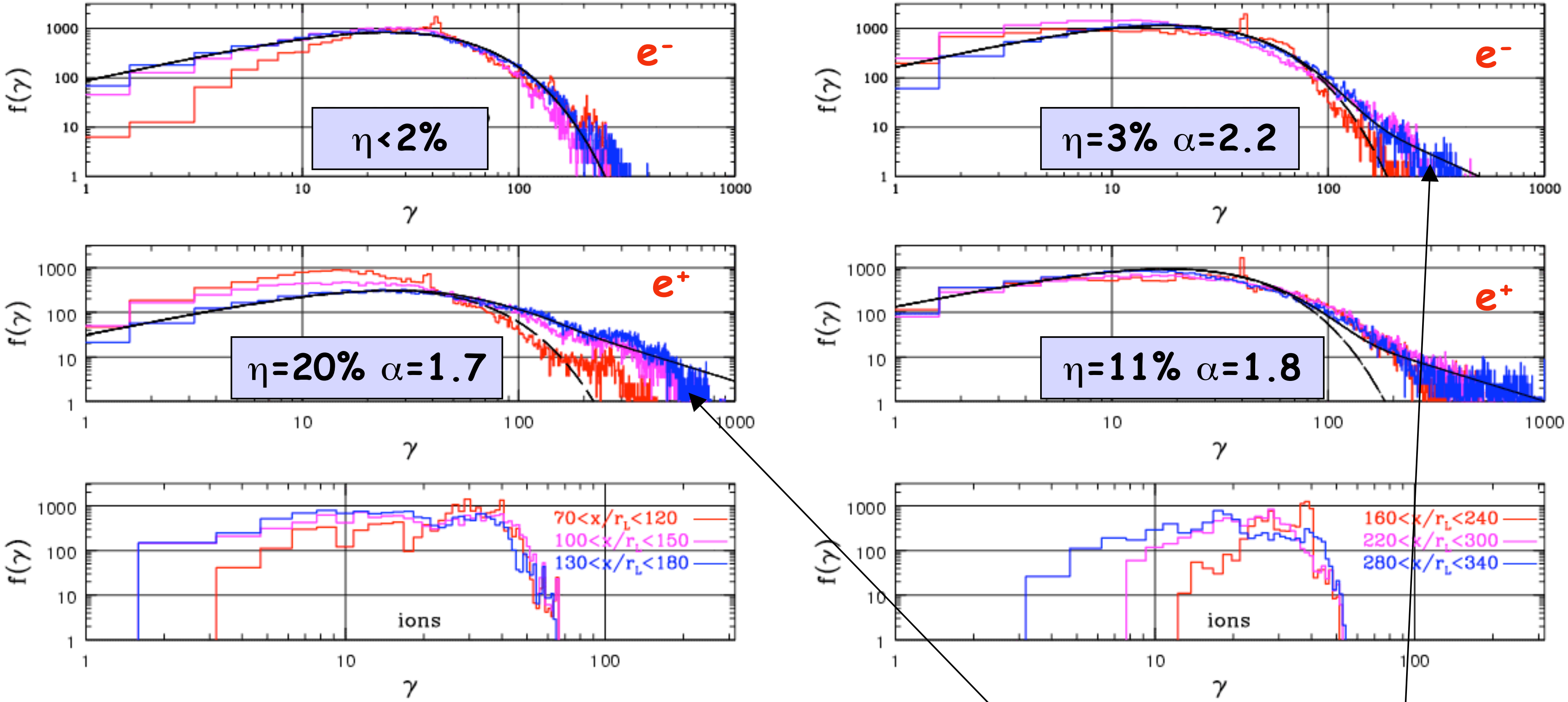
Spectrum is cut off at $n \sim u/\delta u$

⇒

growth-rate ~ independent of n if plasma cold (Amato & Arons 06)

Polarization of the waves

m_i/m_e=20, n_i/n_-=0.4 | m_i/m_e=40, n_i/n_-=0.2



Upstream flow:
Lorentz factor: Γ=40
Magnetization: $\sigma_\pm$=2

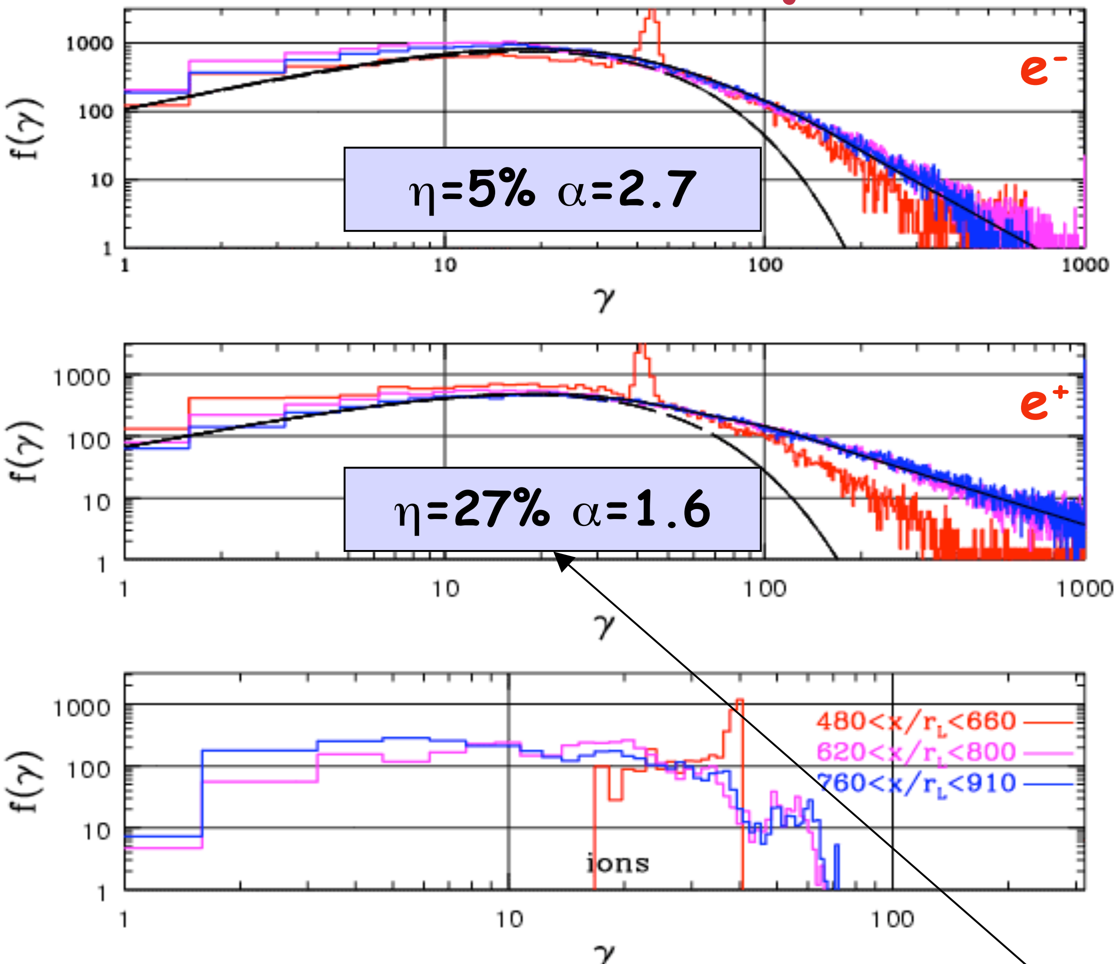
Simulation box:
$\Delta x=r_{Le}/10$
$Lx=r_{Li}\times 10$

Positron tail extends to $\gamma_{max}=m_i/m_e\Gamma$

First evidence of electron acceleration

U_i/U_{tot}=0.7 same in both simulations

Particle spectra and acceleration efficiency for m_i/m_e=100



Acceleration efficiency:
~few% for U_i/U_{tot}~60%
~30% for U_i/U_{tot}~80%

Spectral slope:
>3 for U_i/U_{tot}~60%
<2 for U_i/U_{tot}~80%

Maximum energy:
~20% $m_i c^2 \Gamma$ for U_i/U_{tot}~60%
~80% $m_i c^2 \Gamma$ for U_i/U_{tot}~80%

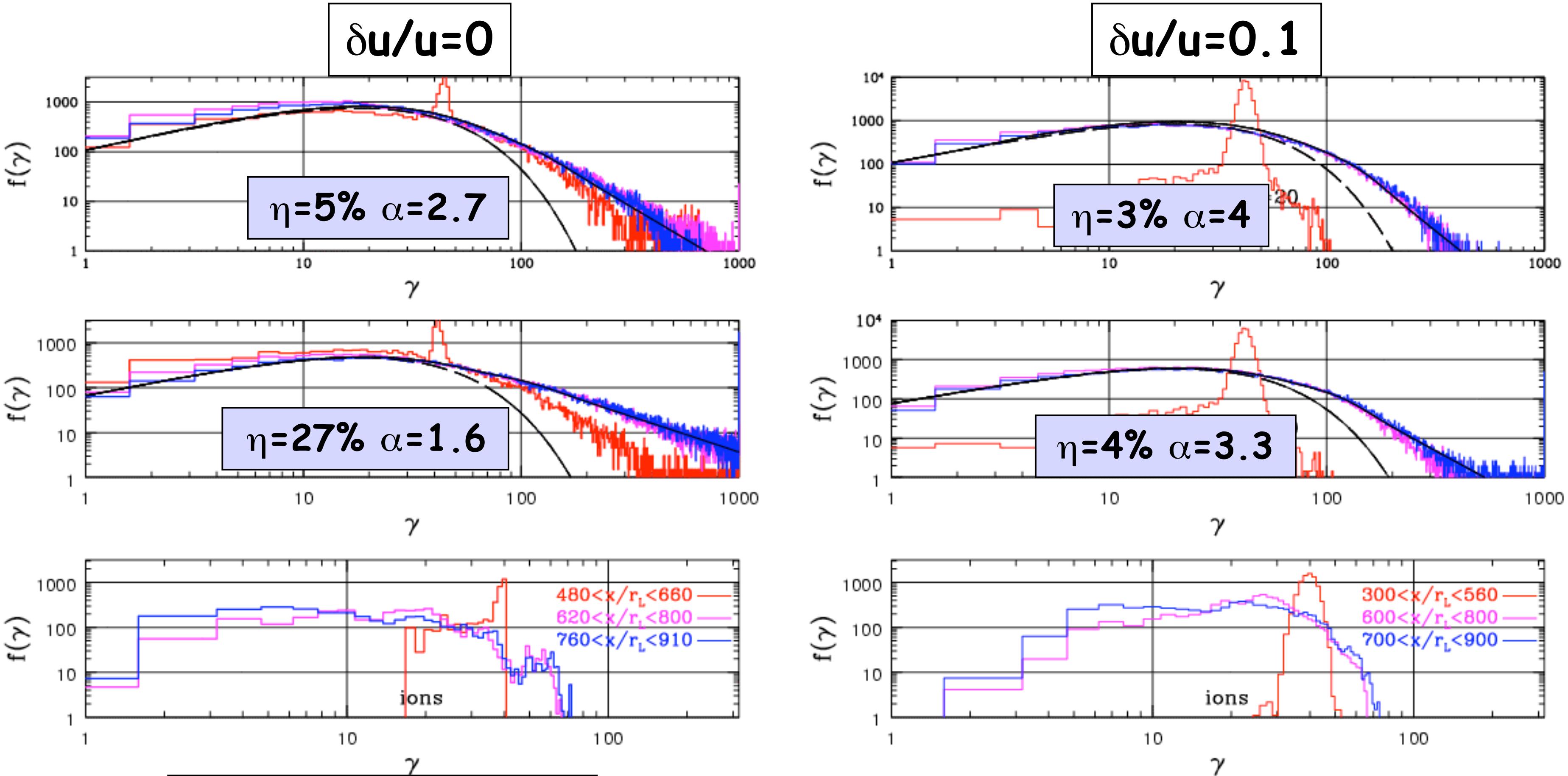
Mechanism still works at large m_i/m_e for both e^+ and e^-

Upstream flow:
Lorentz factor: Γ=40
Magnetization: $\sigma_\pm$=2

Simulation box:
$\Delta x = r_{Le}/10$
$Lx = r_{Li} \times 10$

n_i/n_-=0.2
U_i/U_{tot}=0.8

Effects of thermal spread



$n_i/n_- = 0.2$ $m_i/m_e = 100$
$U_i/U_{tot} = 0.8$

Initial particle distribution function is a gaussian of width δu

Upstream flow:
Lorentz factor: $\Gamma = 40$
Magnetization: $\sigma_\pm = 2$

Simulation box:
$\Delta x = r_{Le}/10$
$Lx = r_{Li} \times 10$

Acceleration effectively suppressed!!!

Summary and Conclusions

We have explored the physics of
relativistic transverse magnetosonic shocks in ion-doped plasmas
through 1D PIC simulations: still about the only possibility to explore the behaviour of the system for large m_i/m_e

Aims:

- Checking whether RCA would still provide any particle acceleration
- Checking whether any electron acceleration for larger mass-ratios (upstream plasma closer to quasi-neutrality)

Results:

- Pairs are efficiently accelerated even for m_i/m_e=100 if U_i/U_{tot}>0.5
- Electron acceleration finally seen!!!
- Less efficient than for positrons due to elliptical polarization of the waves (forced by low m_i/m_e which implies large n_i/n_e to ensure U_i/U_{tot}>0.5)
- Extrapolation to realistic m_i/m_e predicts same efficiency for accelerating e^+ and e^-
- Efficiencies and spectra as observed in PWNe can be obtained depending on ion fraction
- The acceleration is effectively suppressed if initial thermal spread larger than m_e/m_i