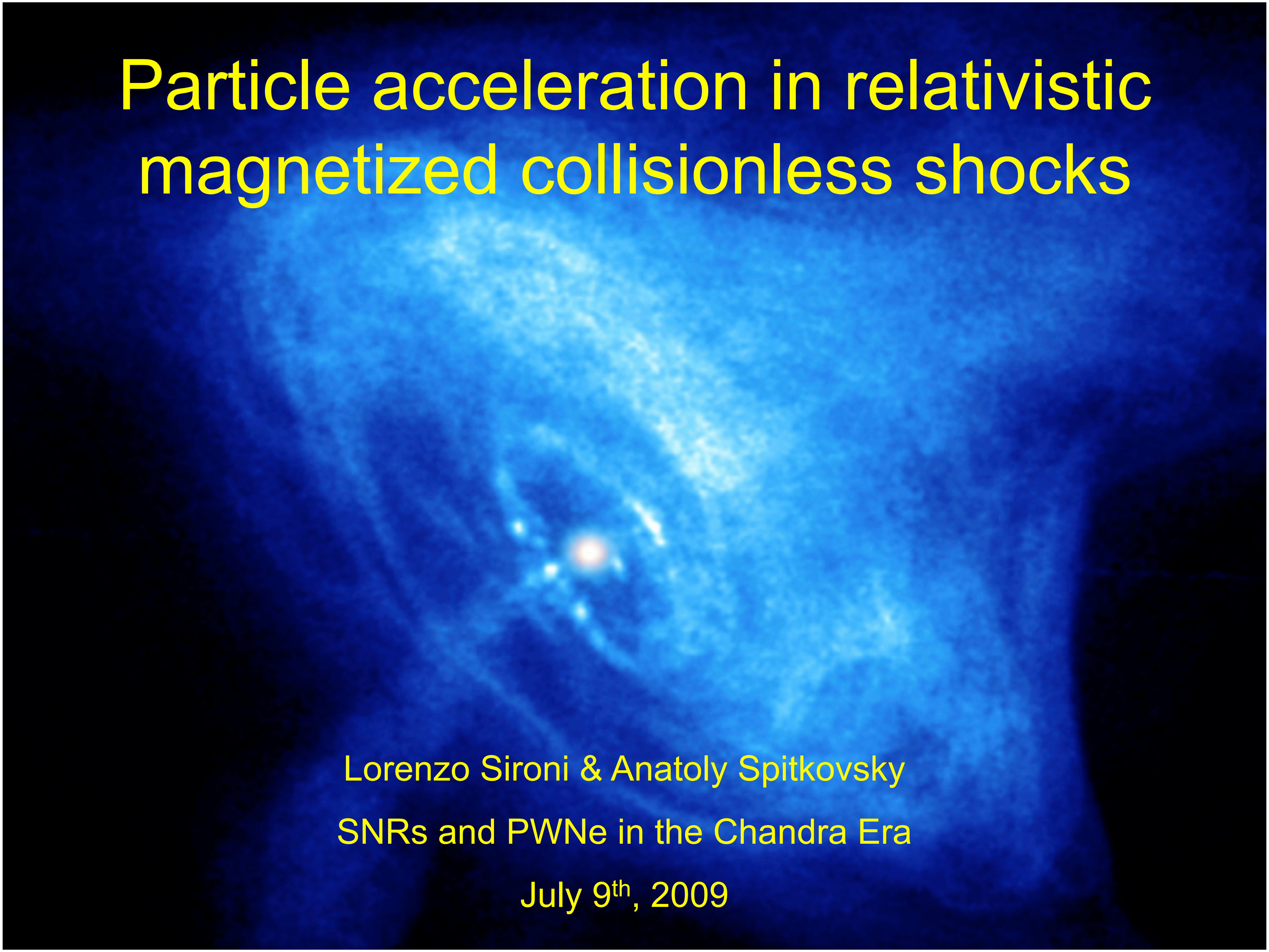

Particle acceleration in relativistic magnetized collisionless shocks

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SNRs and PWNe in the Chandra Era

July 9th, 2009

Astrophysical shocks

• In SNRs, GRBs, AGN jets, PWNe: how do collisionless shocks work? How do they produce the observed non-thermal radiation?

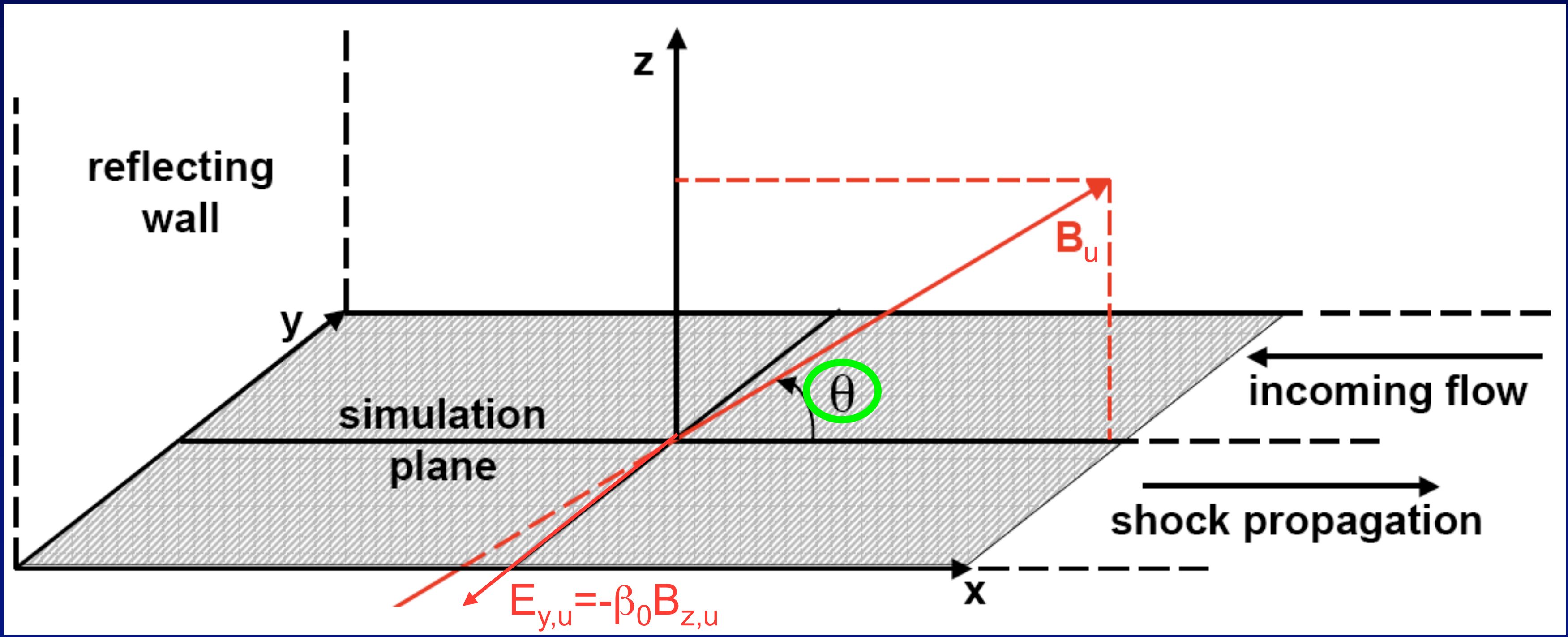
• Basic ingredients:

1. Magnetic fields
2. Accelerated particles

How does the efficiency of particle acceleration depend on the magnetic field strength and inclination and the flow composition?

Method: Self-consistent first-principle particle-in-cell (PIC) numerical simulations…

Simulation setup

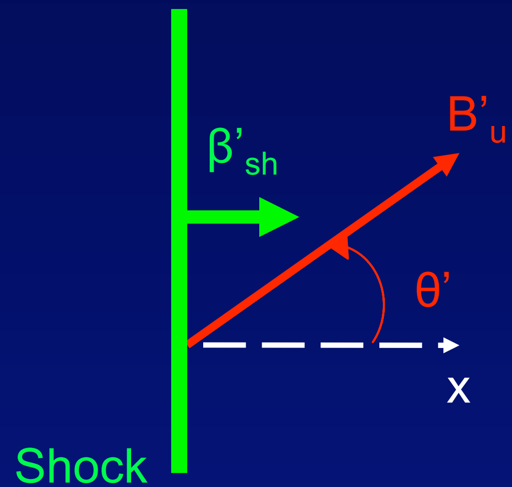


- Injected flow is reflected by a wall; simulation in the wall frame

- Upstream flow is $e^- - e^+$ or $e^- - p^+$ ($m_p/m_e=16$) cold plasma with bulk Lorentz factor $\gamma_0=15$ and magnetization $\sigma = B_u^2/(4\pi\gamma_0 n_u m_p c^2) = 0.01-0.1$. We vary the wall-frame magnetic obliquity θ.

- 2.5D simulations (100 c/ω_{pe} X 9000 c/ω_{pe}) with out-of-plane magnetic field; main results confirmed by 3D simulations

Subluminal vs superluminal shocks



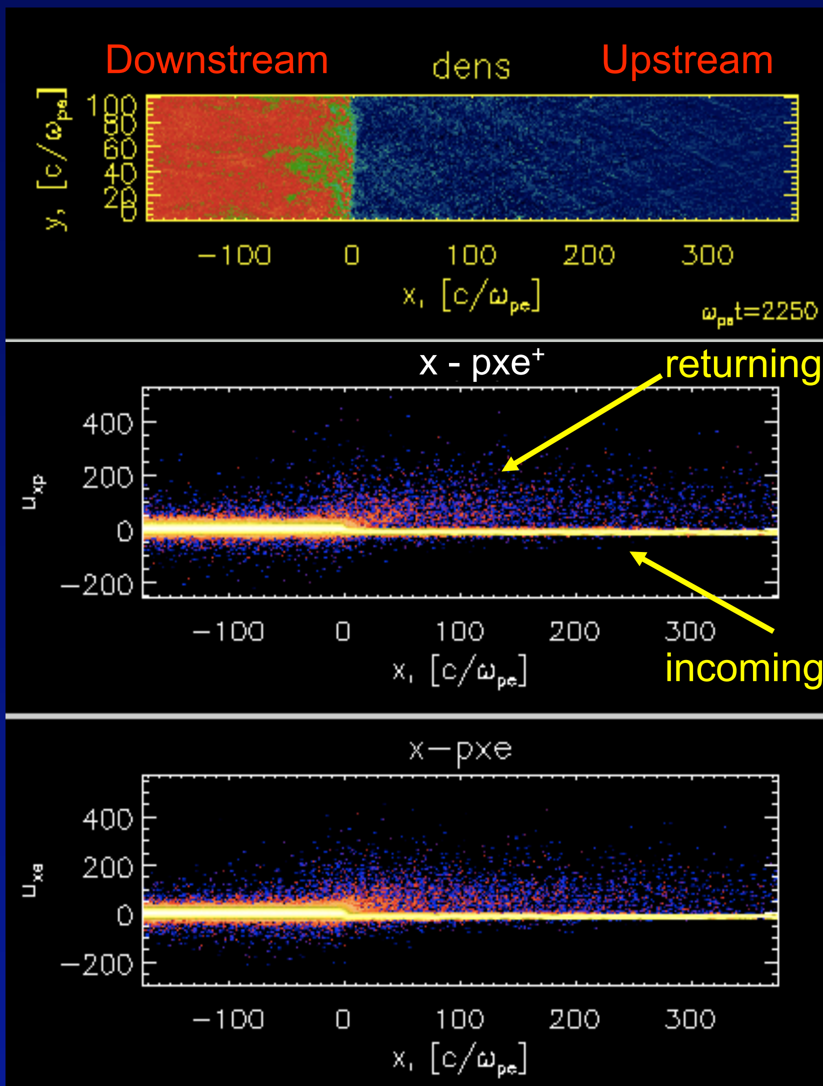
In the upstream frame

$$\theta'_{\rm crit} = \arccos(\beta'_{\rm sh})$$

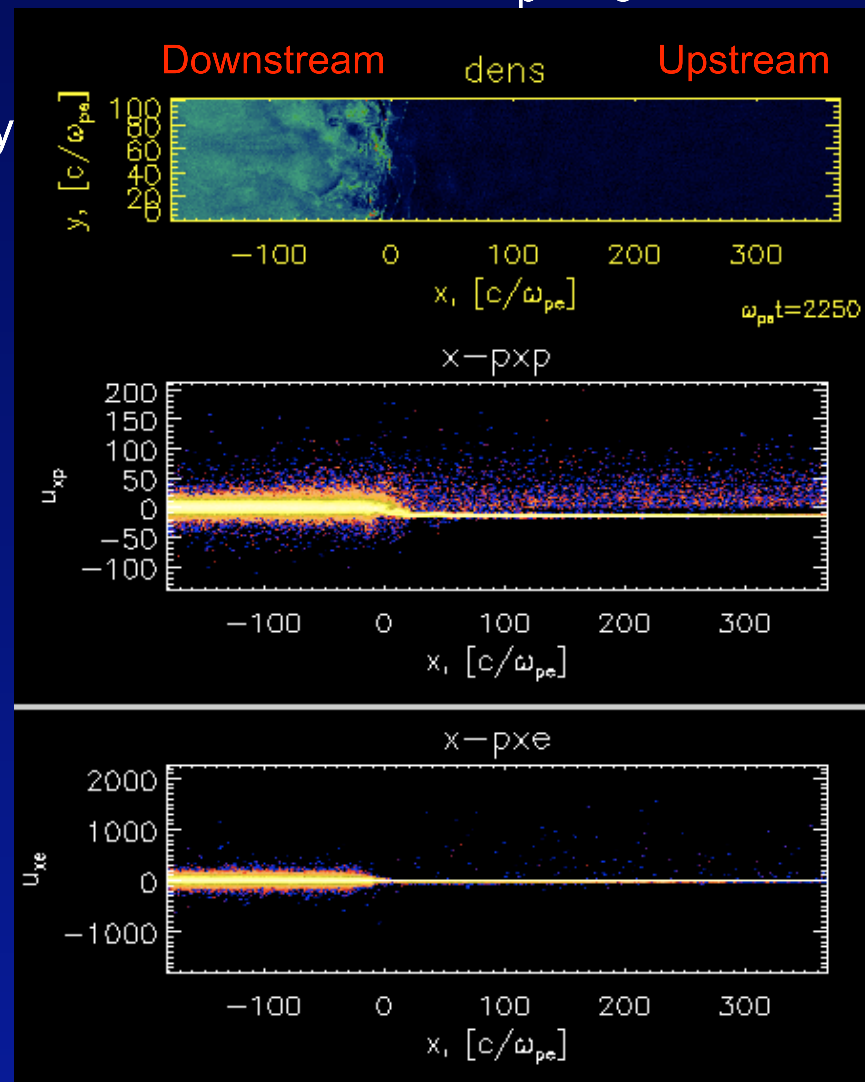
- In superluminal (vs subluminal) shocks, a particle sliding along magnetic field lines CANNOT (vs CAN) return upstream
- For γ_0=15 and σ=0.1, the critical obliquity is $\theta_{crit} \approx 34°$ in the wall frame; in the upstream frame $\theta'_{crit} \approx 34°/\gamma_0$
- θ_{crit} weakly depends on both γ_0 ($\geq$5) and σ ($0.01<\sigma<0.3$)
- We expect particle acceleration to be suppressed in superluminal shocks, unless there is strong magnetic turbulence. But is strong turbulence self-consistently produced by the shock?

θ=15°: a subluminal shock

e^--e^+ shock



e^--p^+ shock (m_p/m_e=16)



Density

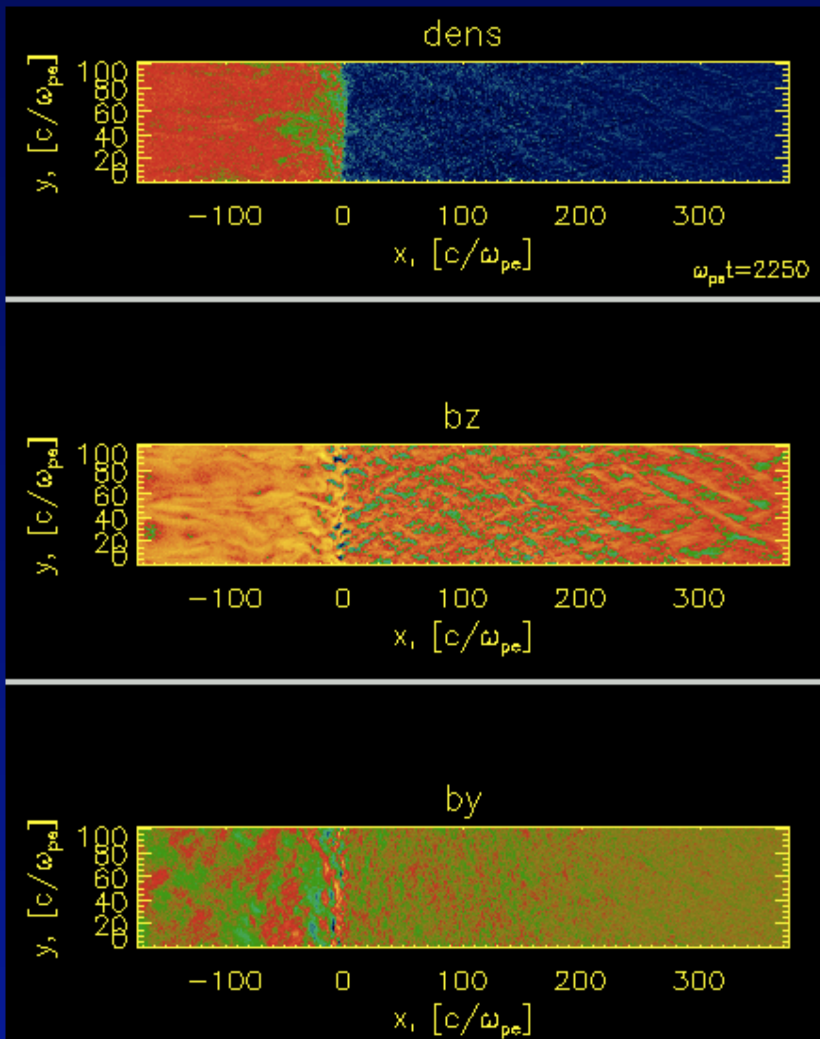
$\gamma_p\beta_{xp}$

$\gamma_e\beta_{xe}$

Subluminal ➔ Returning particles (mostly IONS for e^--p^+ shock)

θ=15°: a subluminal shock

e^--e^+ shock

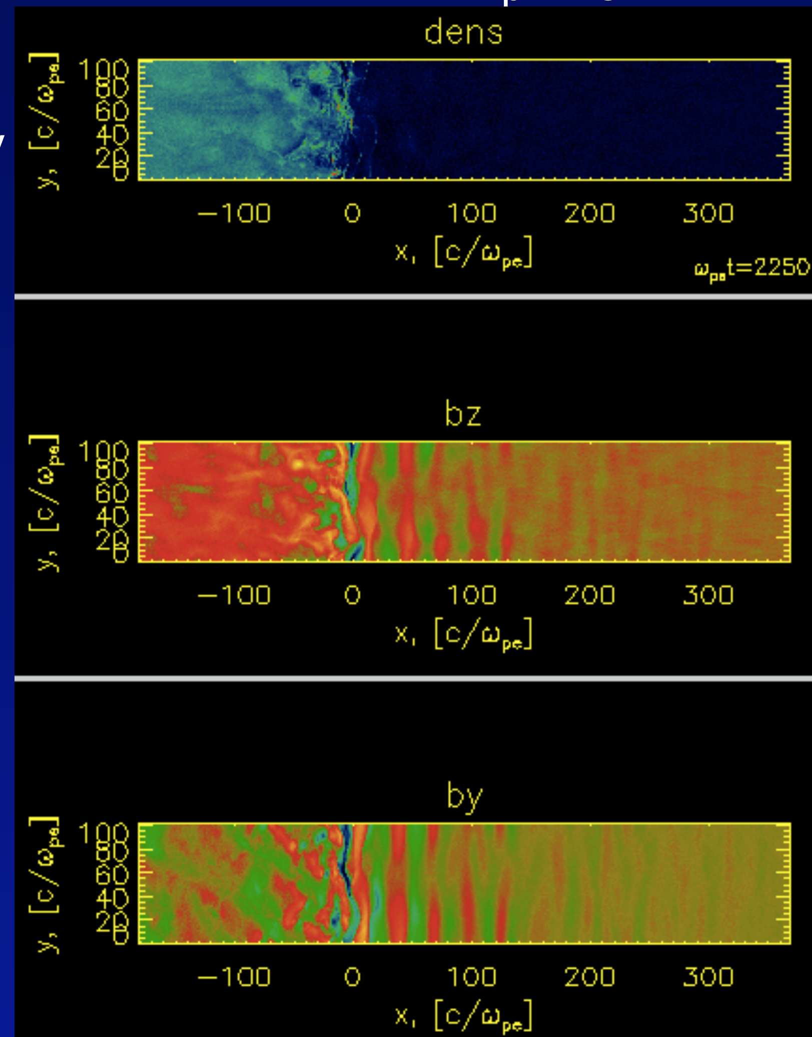


Density

B_z

B_y

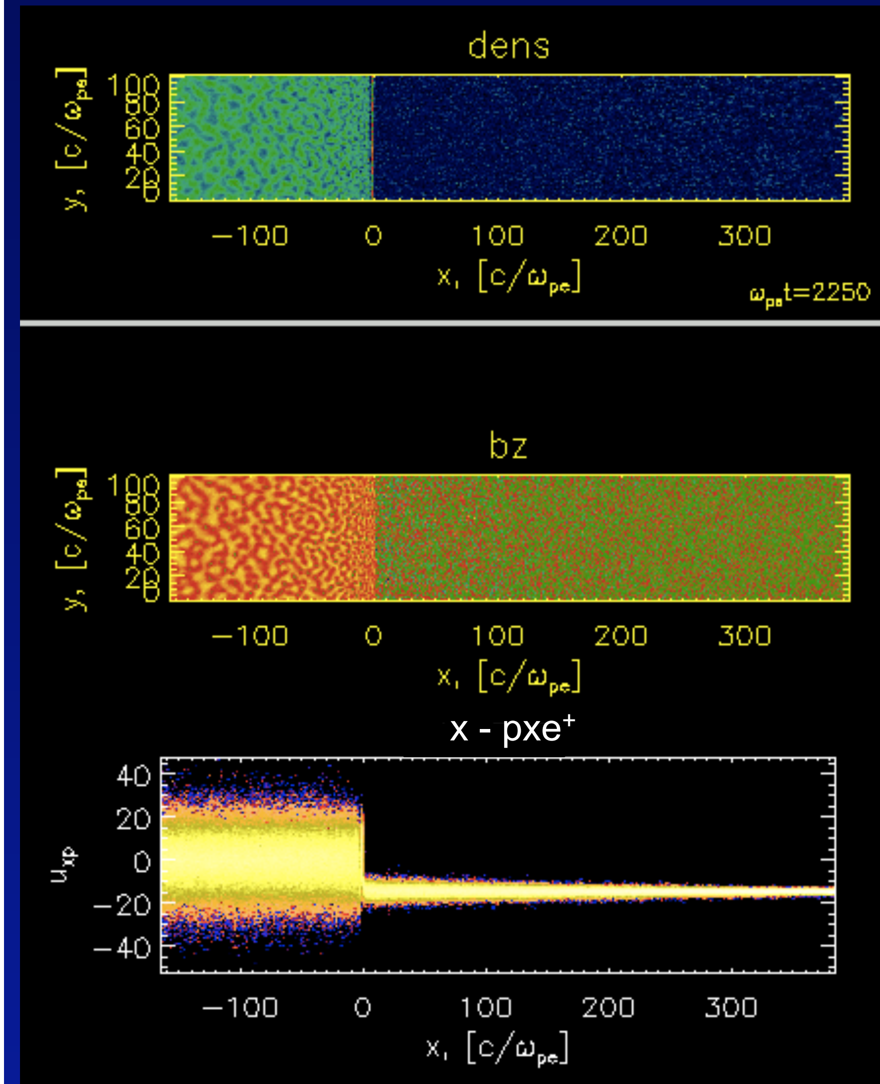
e^--p^+ shock (m_p/m_e=16)



Returning particles ➔ Upstream waves (oblique vs longitudinal wavevector, linear vs circular polarization)

θ=45°: a superluminal shock

e^--e^+ shock

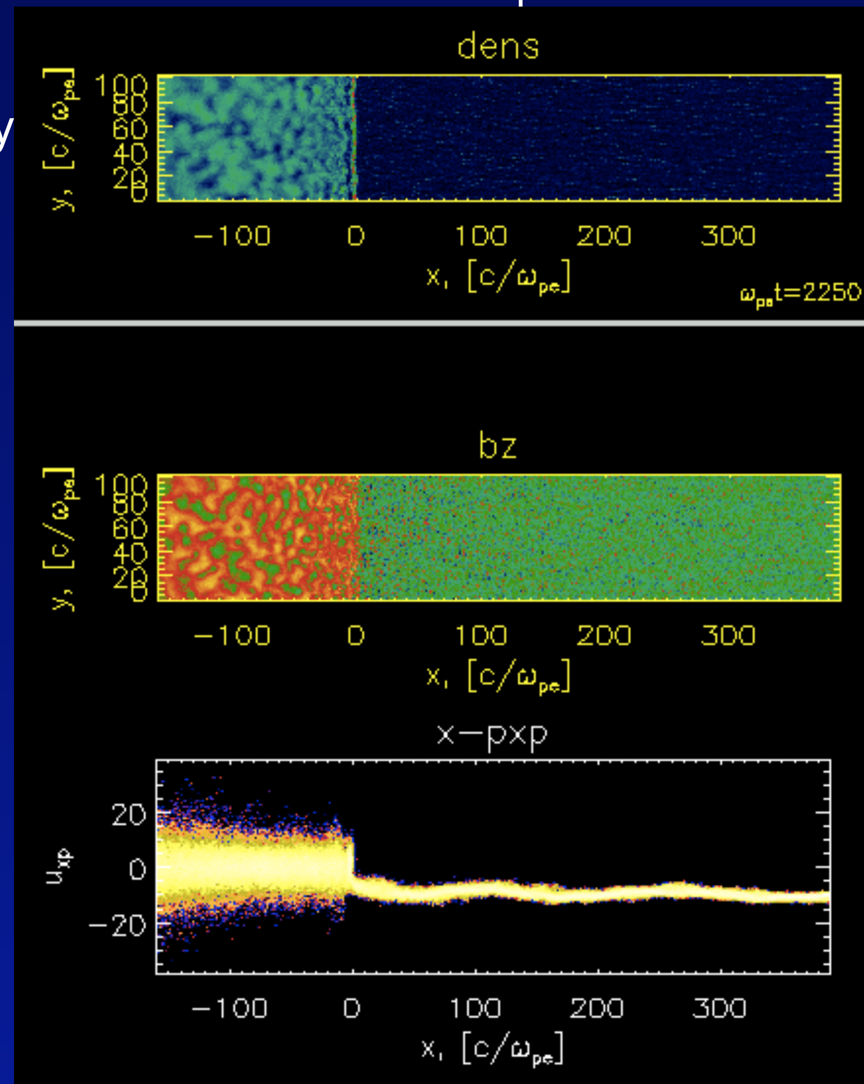


Density

B_z

$\gamma_p\beta_{xp}$

e^--p^+ shock (m_p/m_e=16)



Superluminal → No returning particles → No upstream waves

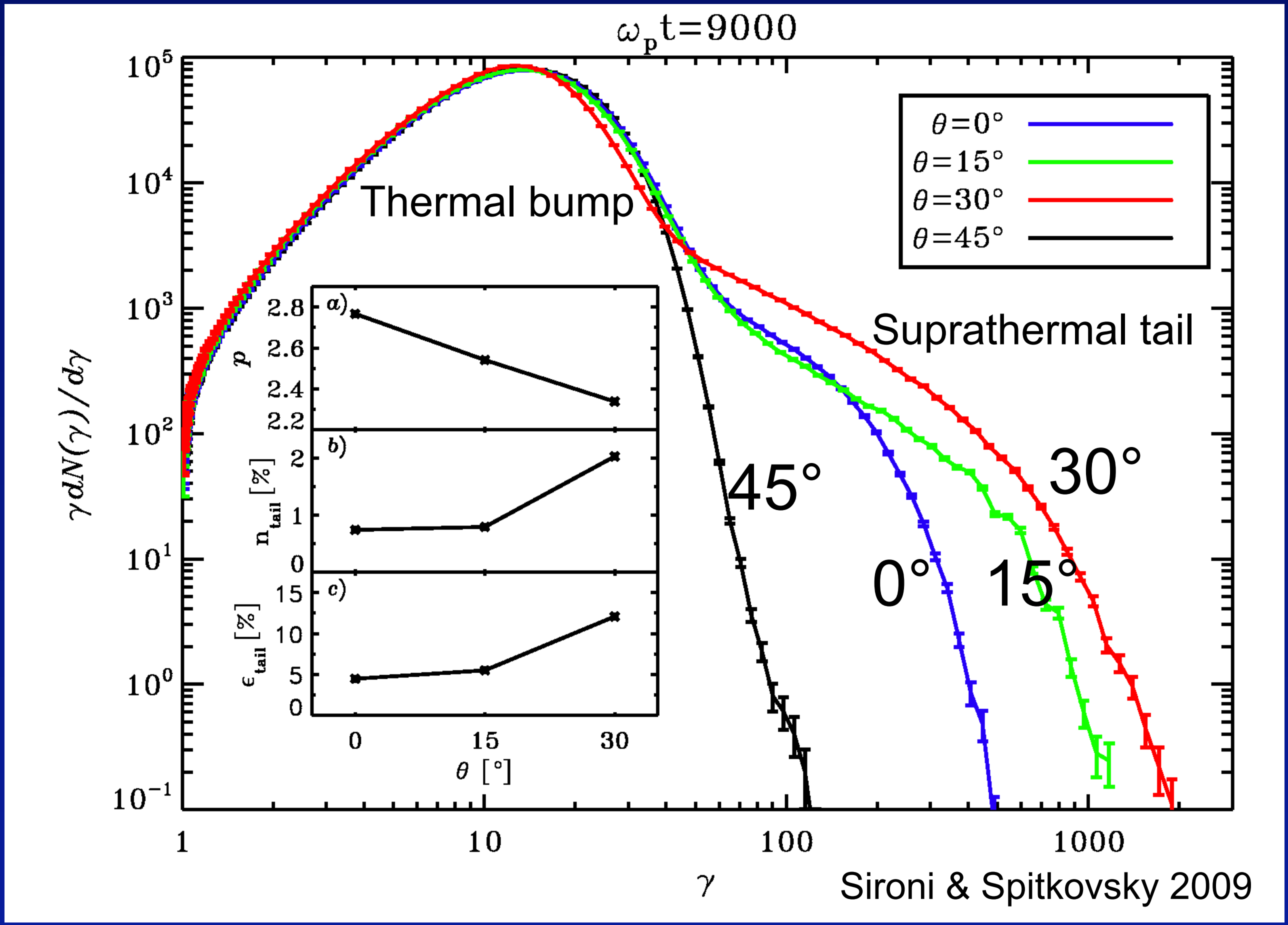
Downstream particle spectra: e^--e^+ shock

- Superluminal shocks DO NOT significantly accelerate, subluminal shocks DO accelerate, the more efficient the closer to $\theta_{crit} \approx 34°$
- In subluminal shocks, spectra well fitted by 3D low-energy Maxwellian + high-energy power-law tail with exponential cutoff

e^--e^+ shock

As θ increases from 0° to 30°:

- Power-law slope from -2.8 to -2.3
- Number fraction from 1% to 2%
- Energy fraction from 5% to 13%



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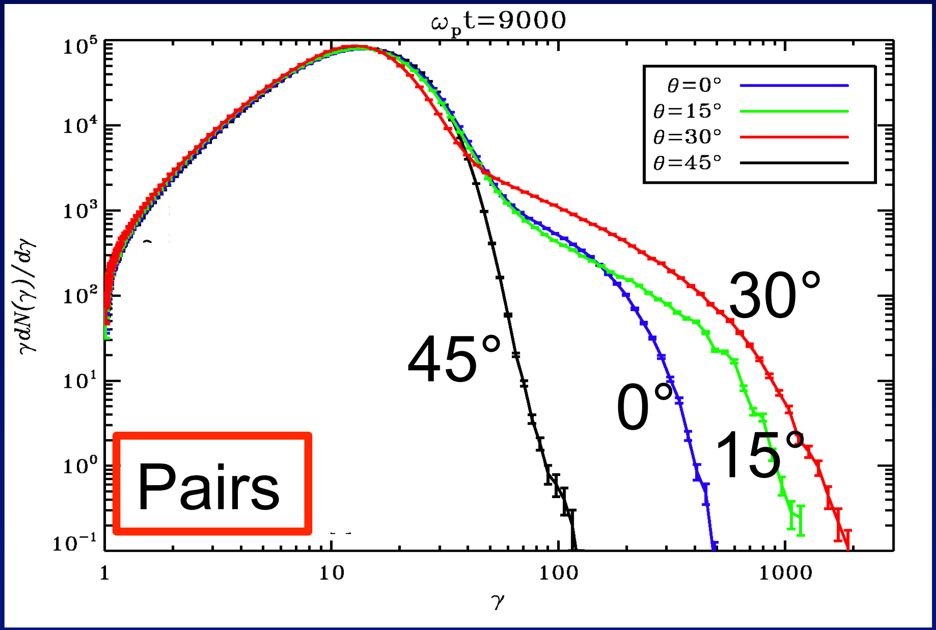
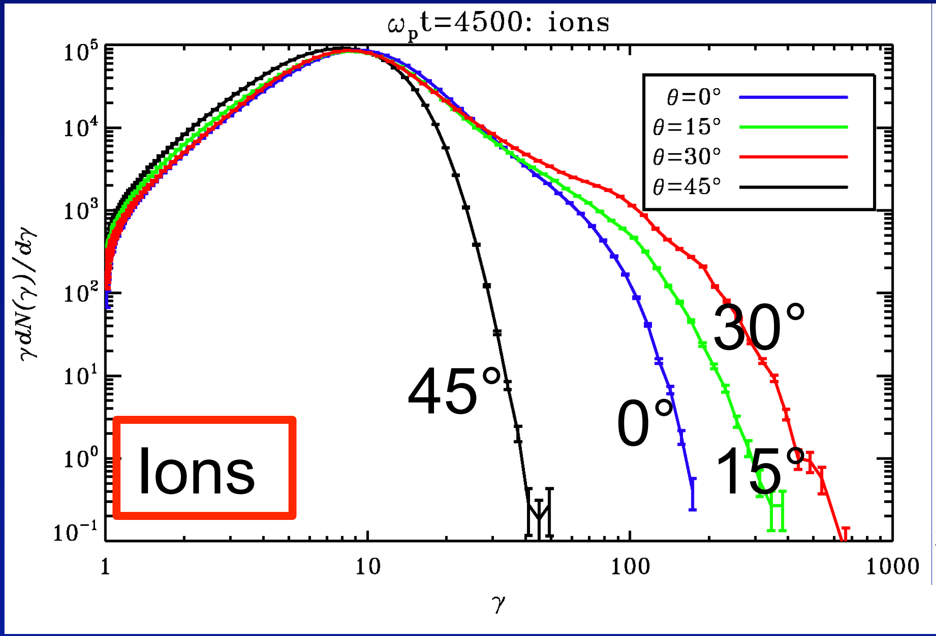
Downstream particle spectra: e^--p^+ shock

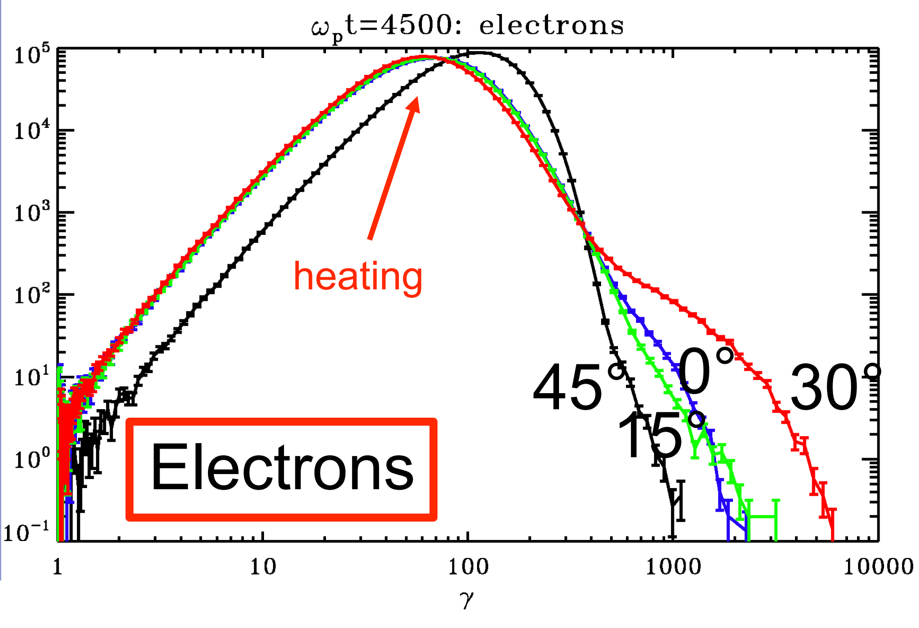


Ions are accelerated, and their spectra resemble pair spectra in e^--e^+ shocks:

- negligible acceleration in superluminal shocks
- with increasing θ from 0° to 30°, slope from -3.0 to -2.2, number fraction from 2% to 5%, energy fraction from 10% to 25%

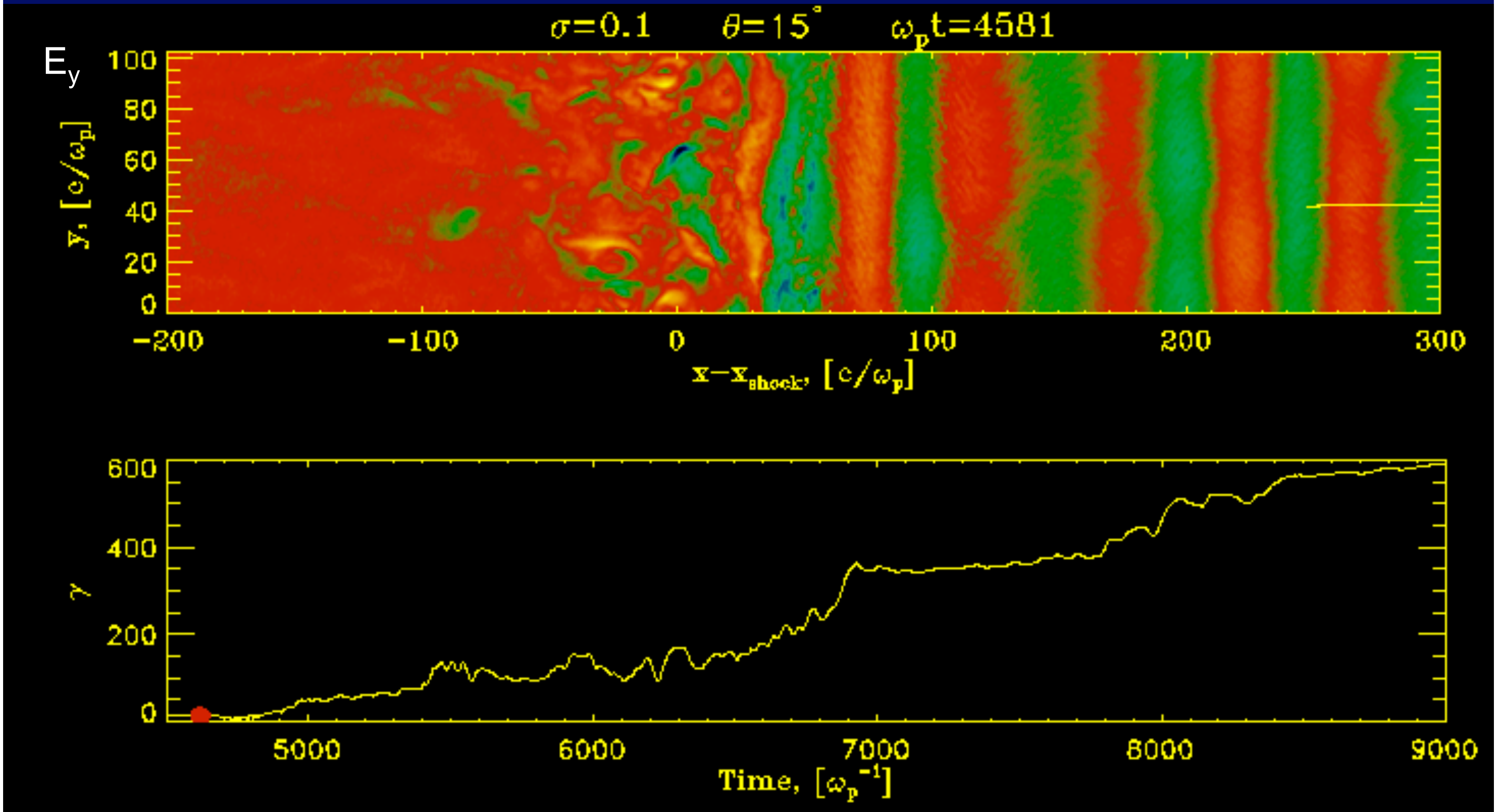
Electron acceleration in e^--p^+ shocks is a factor of 5-10 less efficient than ions





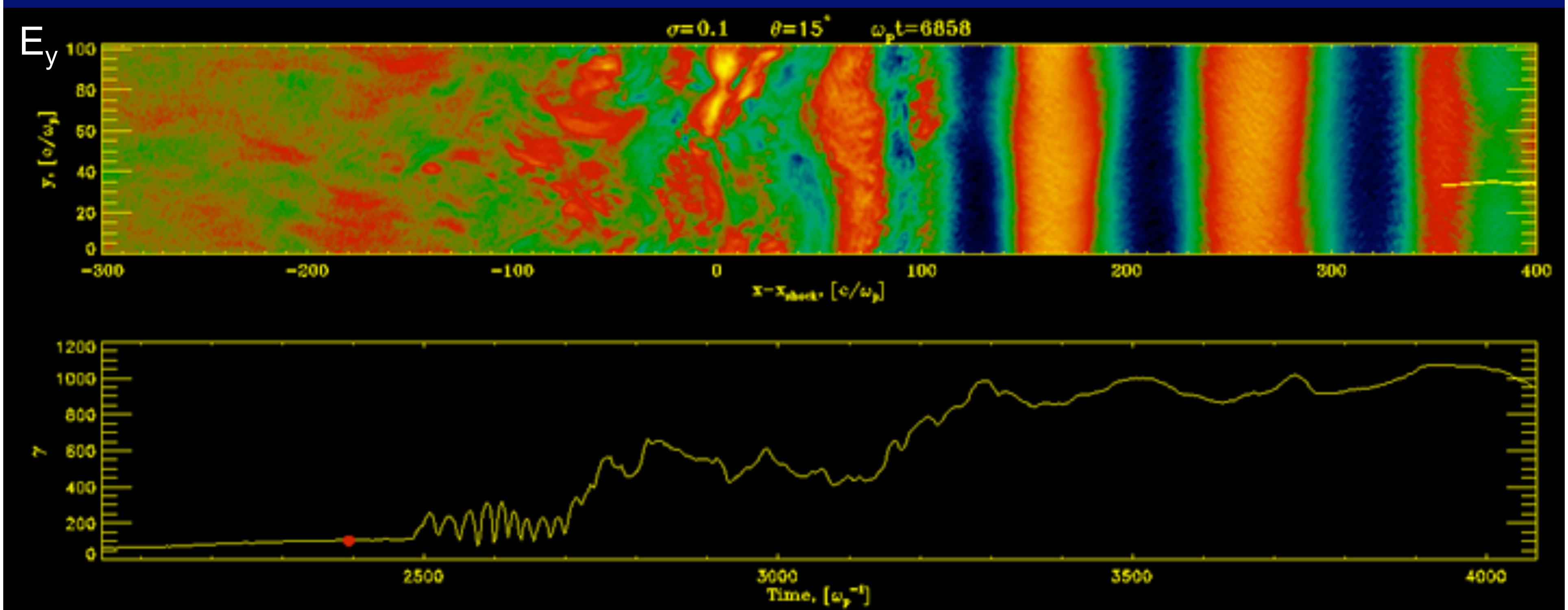
Ion vs electron acceleration (1/2)

σ=0.1 θ=15° e^--p^+ shock: IONS get accelerated by scattering off the self-generated upstream longitudinal waves

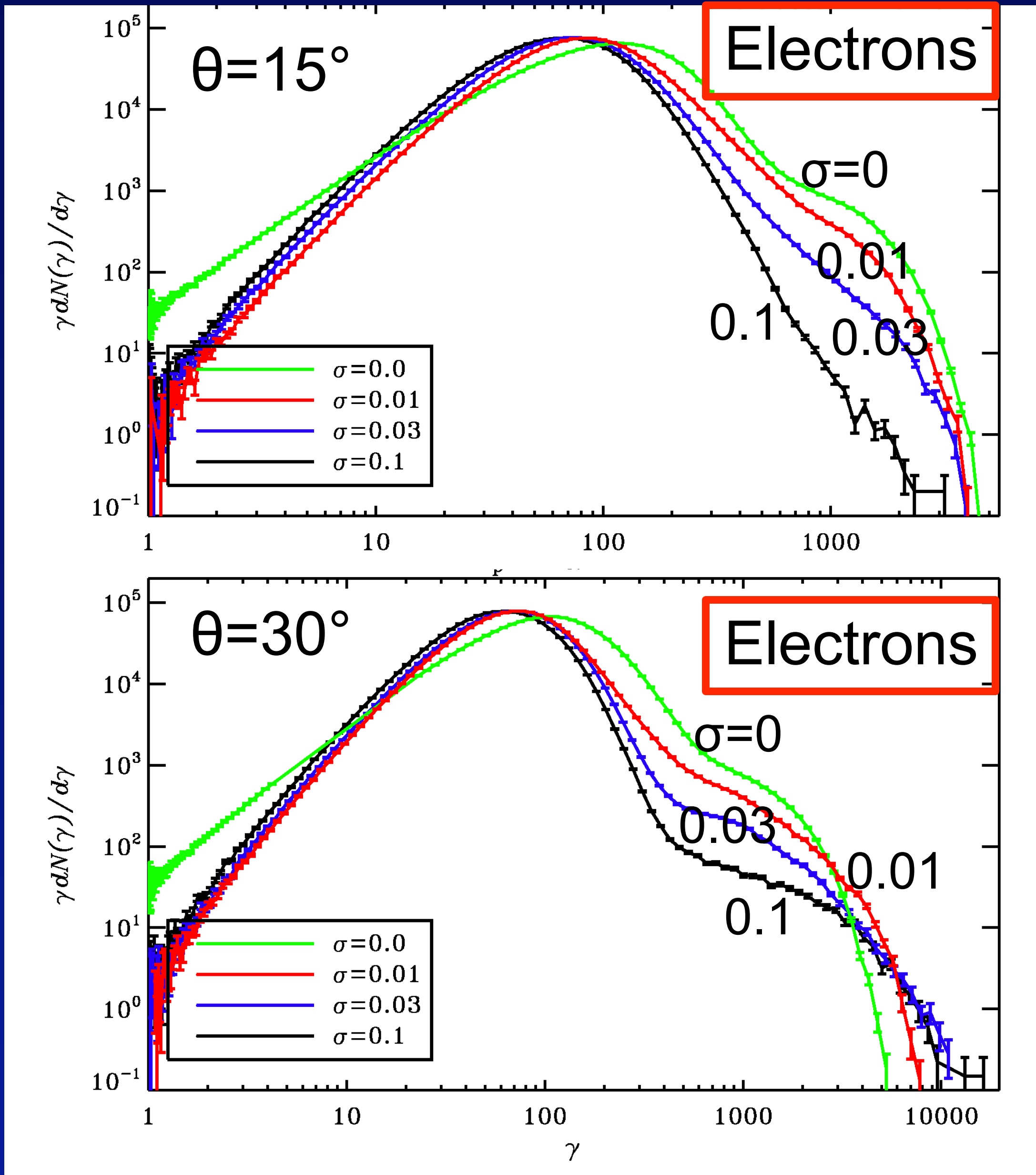


Ion vs electron acceleration (2/2)

σ=0.1 θ=15° e^--p^+ shock: ELECTRONS are more strongly tied to the magnetic field lines and get quickly advected downstream



Varying σ in e^--p^+ shocks



With increasing σ, electrons are more tied to magnetic field lines

➔ Once advected downstream, it is harder for them to come back upstream

➔ Lower efficiency of electron acceleration, independent of θ

Summary

- Relativistic magnetized (σ=0.01-0.1) collisionless shocks do exist
- For fixed magnetic field strength, the shock structure and acceleration efficiency critically depend on the magnetic inclination (subluminal vs superluminal shocks):
  - Subluminal pair shocks ($\theta<\theta_{crit}\approx34°$) are efficient particle accelerators (~1% by number, ~10% by energy), superluminal shocks are not.
  - IONS are efficiently accelerated in subluminal electron-ion shocks, with ~3% of particles and ~20% of energy stored in a suprathermal tail.
  - ELECTRON acceleration in subluminal electron-ion shocks is ~5-10 times less efficient than for ions, especially for high magnetizations (σ~0.1).

Implications

Constraints on the composition and magnetization of pulsar winds:

- If electron-positron plasma, then nearly-parallel shocks (in the upstream fluid frame $\theta'_{crit} \approx 34°/\gamma_0$) are required for efficient particle acceleration; or magnetization must be $\sigma \leq 10^{-3}$
- If electron-ion plasma, magnetization must be $\sigma \leq 10^{-2}$ regardless of the magnetic obliquity, since for $\sigma \sim 0.1$ shocks, electron acceleration is inefficient even for subluminal configurations.

Caveats:

- Long-term shock evolution? Results from 3D simulations? Realistic mass ratios?
- Different magnetic field geometry in the upstream flow: Magnetic turbulence? Striped wind? ➔ Acceleration via reconnection?
- Different composition of the upstream flow: Ion-doped pair plasma? ➔ Acceleration via Resonant Cyclotron Absorption (Elena’s talk)?