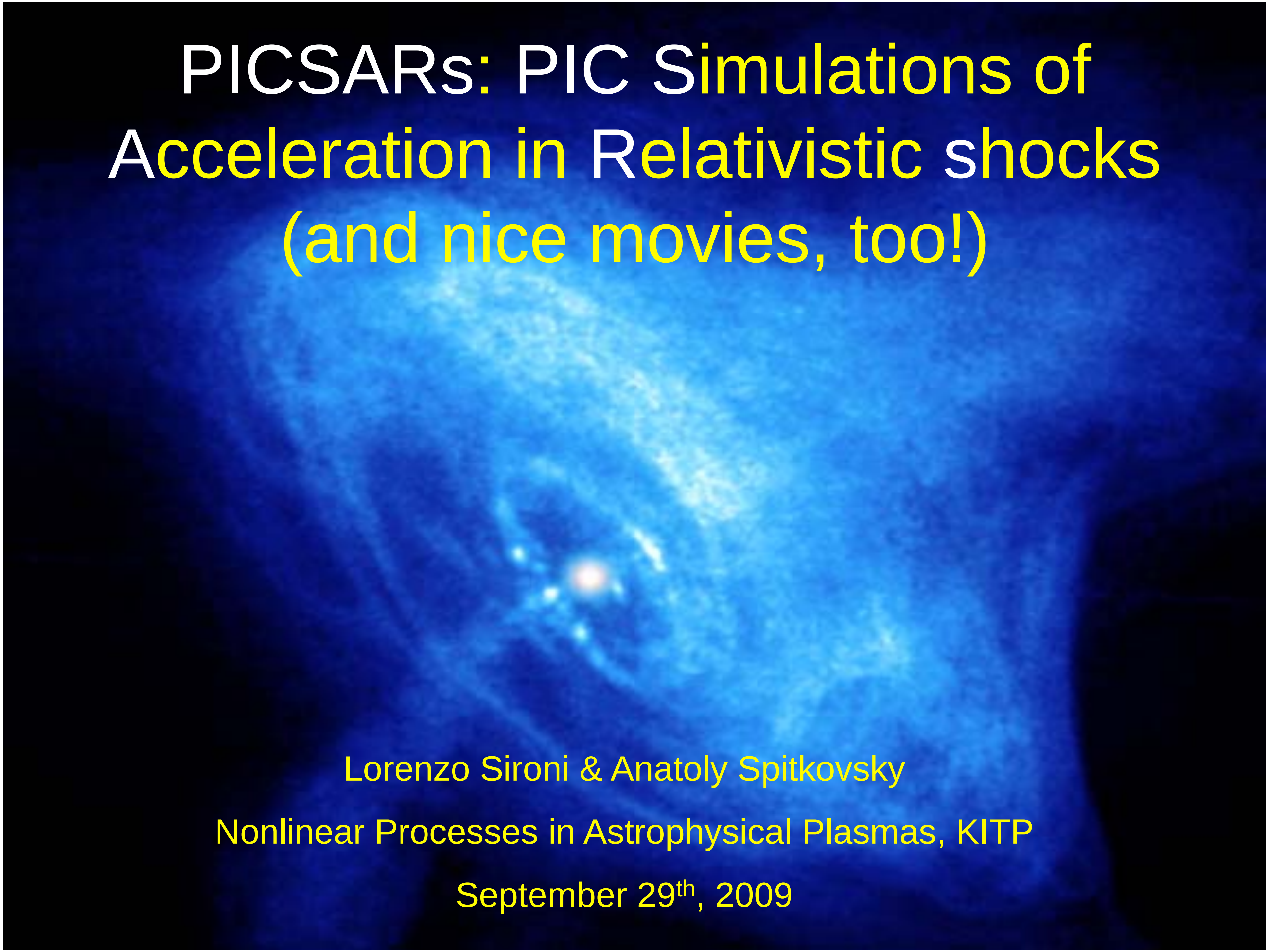

PICSARs: PIC Simulations of Acceleration in Relativistic shocks (and nice movies, too!)

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Nonlinear Processes in Astrophysical Plasmas, KITP

September 29th, 2009

Relativistic shocks in astrophysics

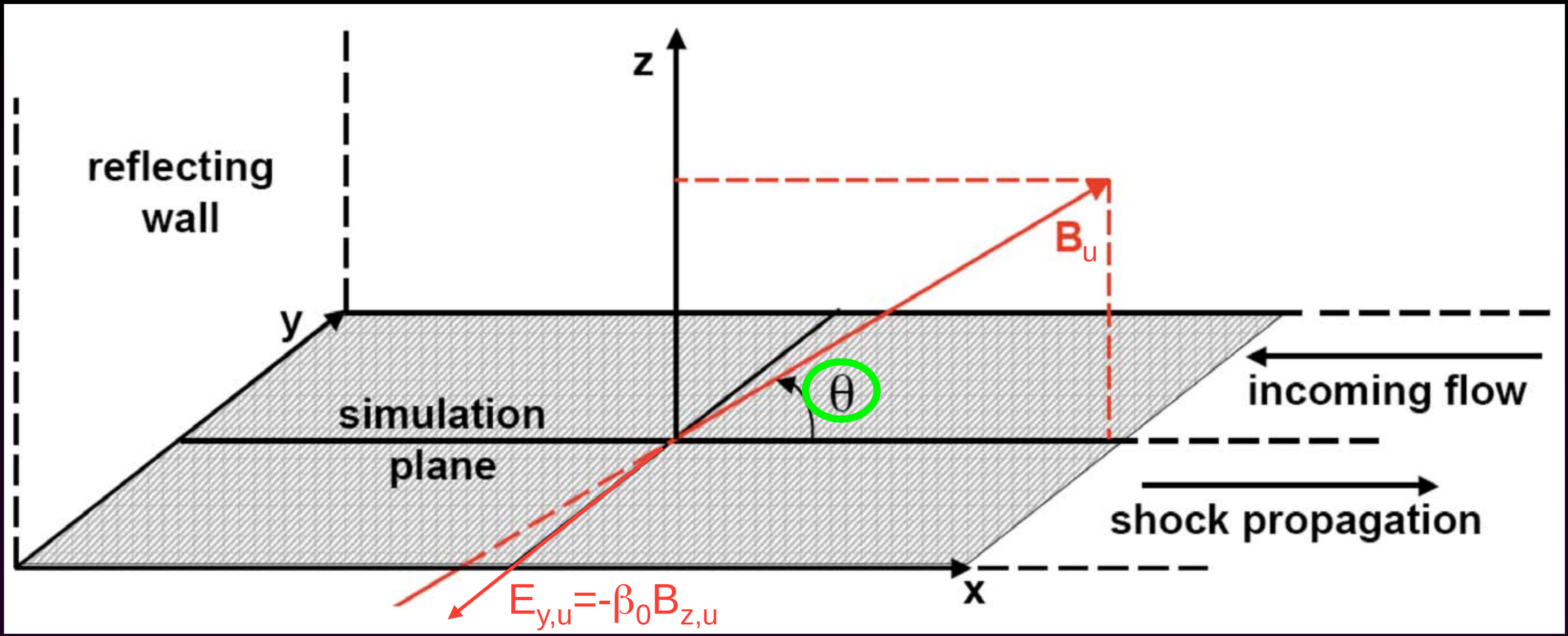
- Are shocks responsible for the nonthermal emission from GRBs, PWNe and AGN jets and for the acceleration of CRs?

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

- How do particle acceleration and magnetic field generation in shocks translate into the observed emission signatures?

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

Simulation setup



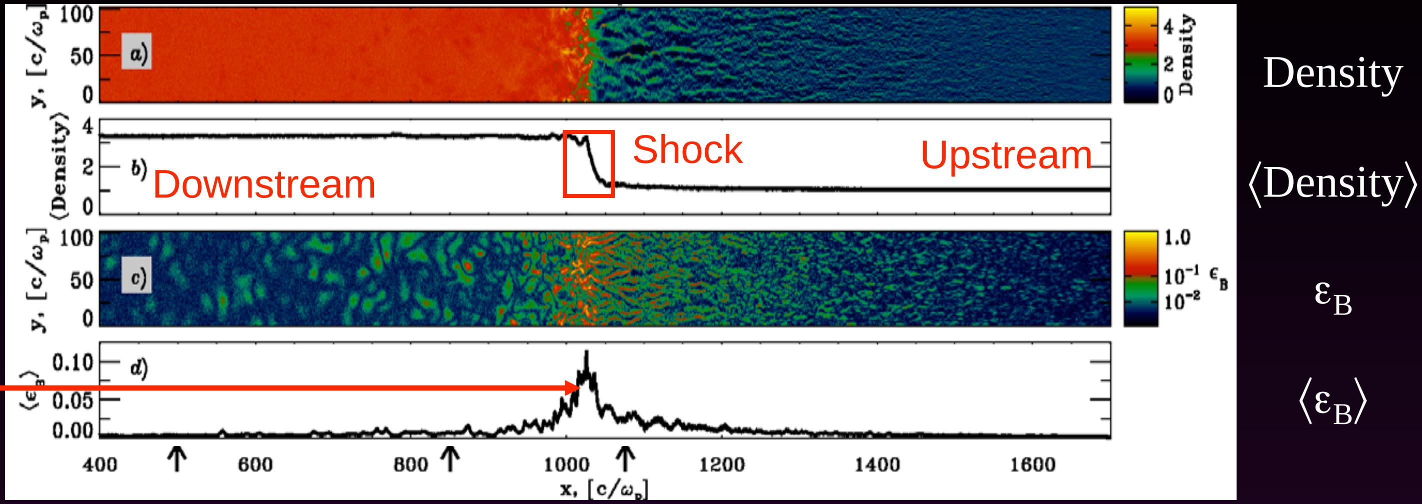
- Upstream flow is $e^- - e^+$ or $e^- - p^+$ (m_p/m_e=16-100) cold plasma with bulk Lorentz factor $\gamma_0=15$ and magnetization $\sigma = B_u^2/(4\pi\gamma_0 n_u m_p c^2) = 0\text{-}0.1$. We also vary the wall-frame magnetic obliquity θ.

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

Which magnetization regime?

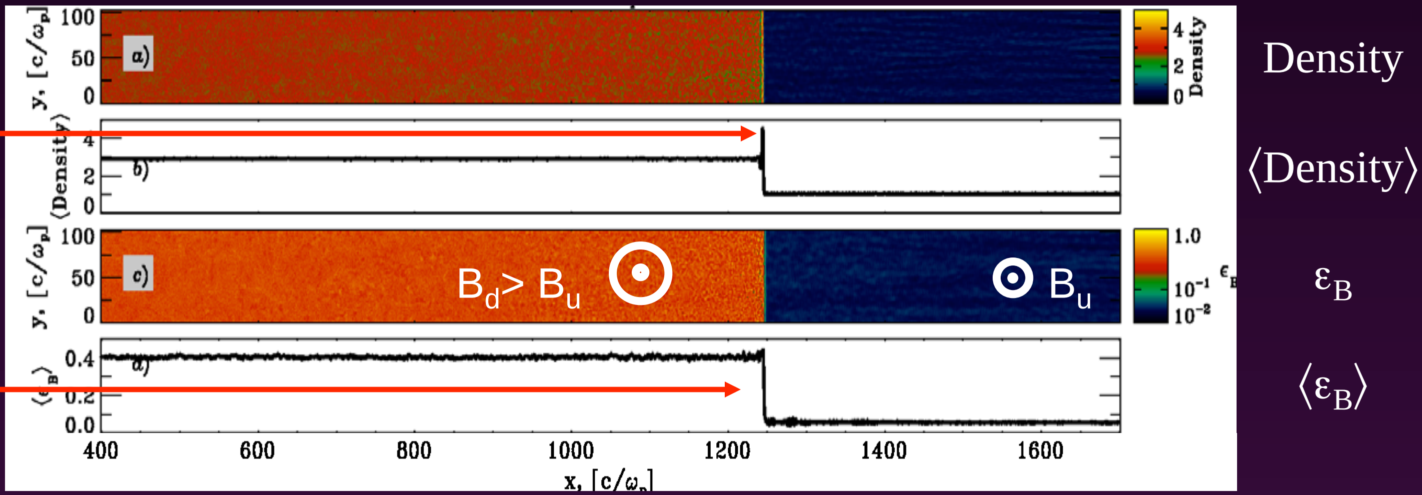
- Unmagnetized shocks (σ=0): mediated by the Weibel instability

  - Upstream (Weibel) filaments in density and ε_B
  - Magnetic energy generation at the shock



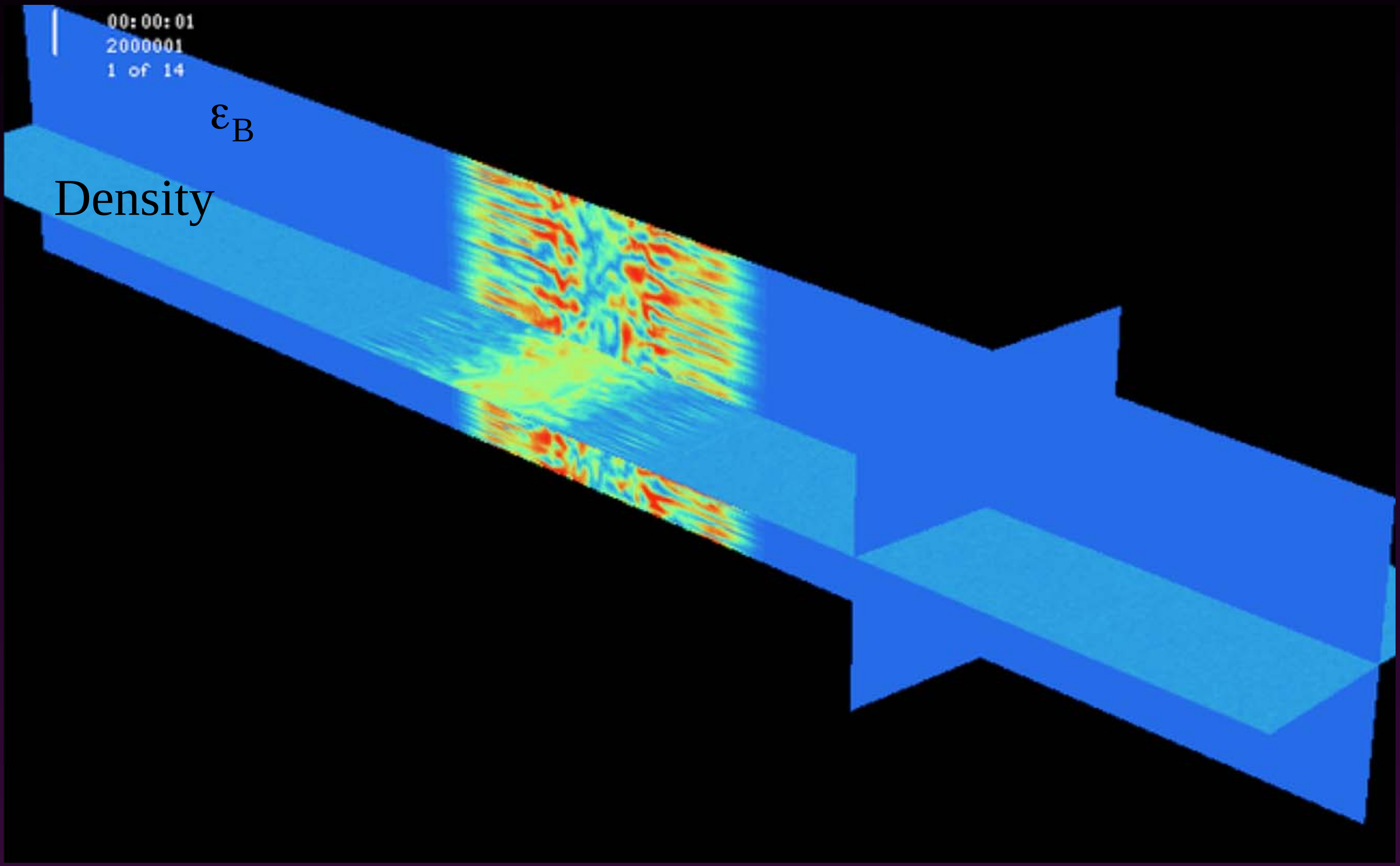
- Magnetized perpendicular shocks (σ=0.1 & θ=90°): mediated by magnetic reflection

  - Density peak due to coherent Larmor gyration
  - Transverse magnetic field compression



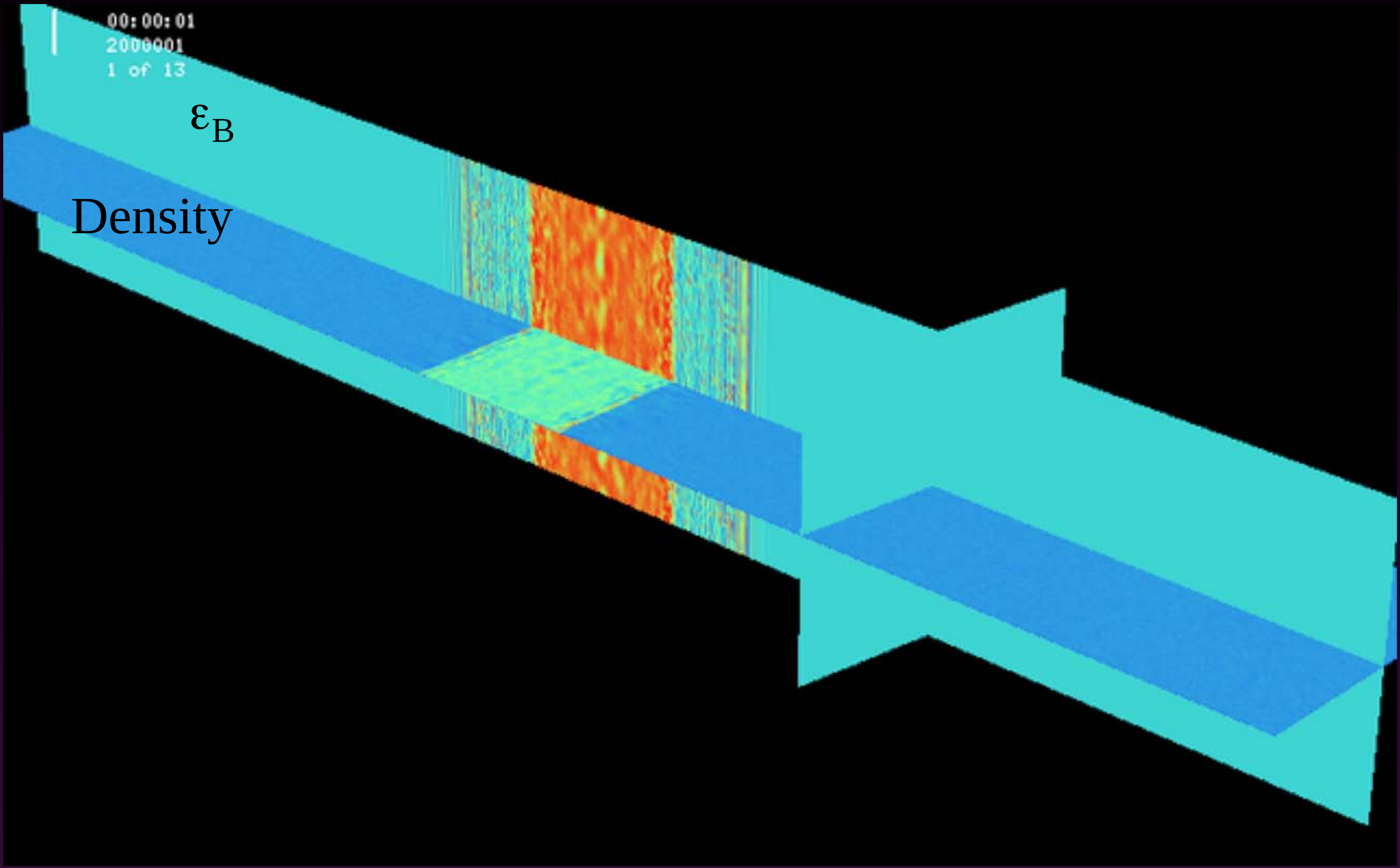
σ=0 vs σ=0.1 & θ=90°: shock structure

σ=0



σ=0 vs σ=0.1 & θ=90°: shock structure

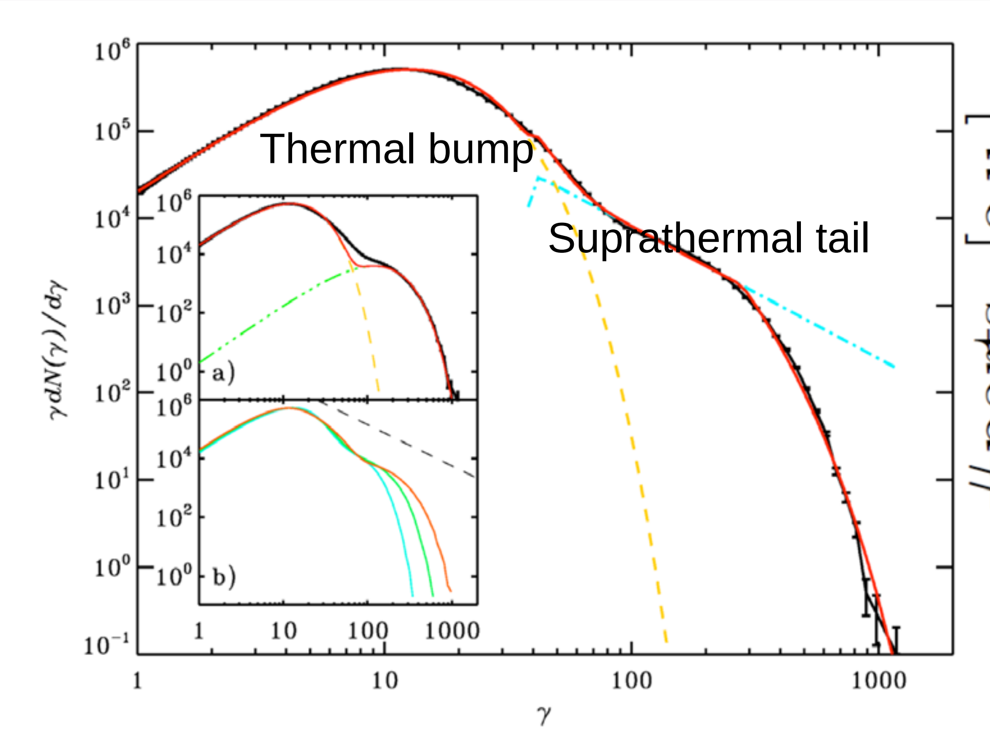
σ=0.1 & θ=90°



σ=0 vs σ=0.1 & θ=90°: particle acceleration

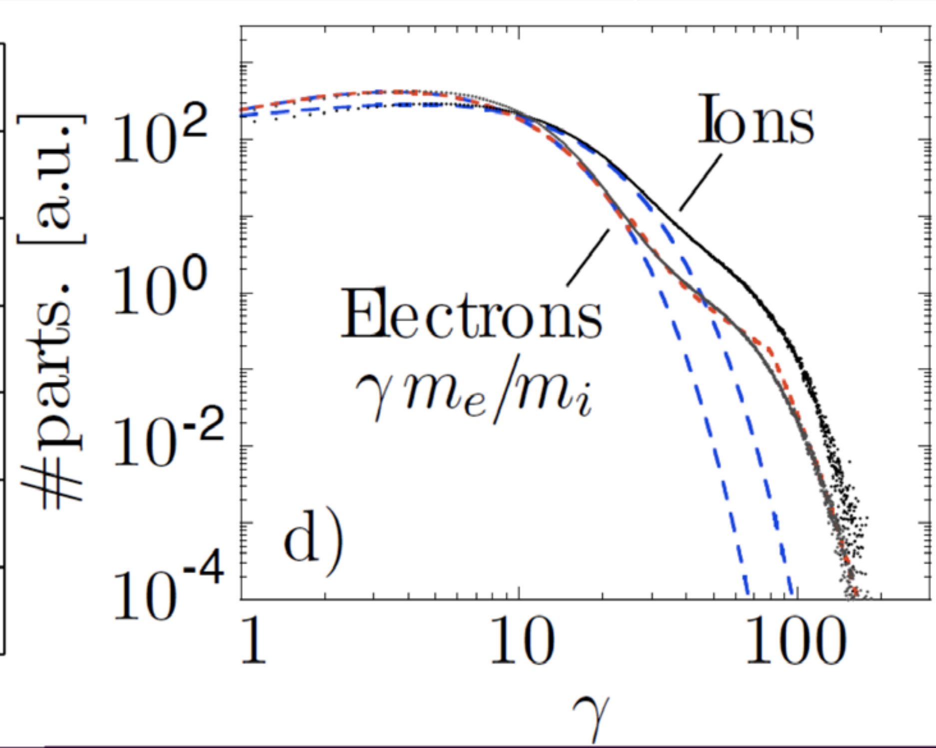
- For σ=0.1 & θ=90° shocks, downstream spectrum is purely thermal
- In σ=0 shocks, downstream spectrum well fitted by low-energy Maxwellian + high-energy power-law tail with exponential cutoff
- The nonthermal tail has slope -2.4±0.1 and contains ~1% of particles and ~10% of energy

σ=0 e^--e^+ shock



(Spitkovsky 2008)

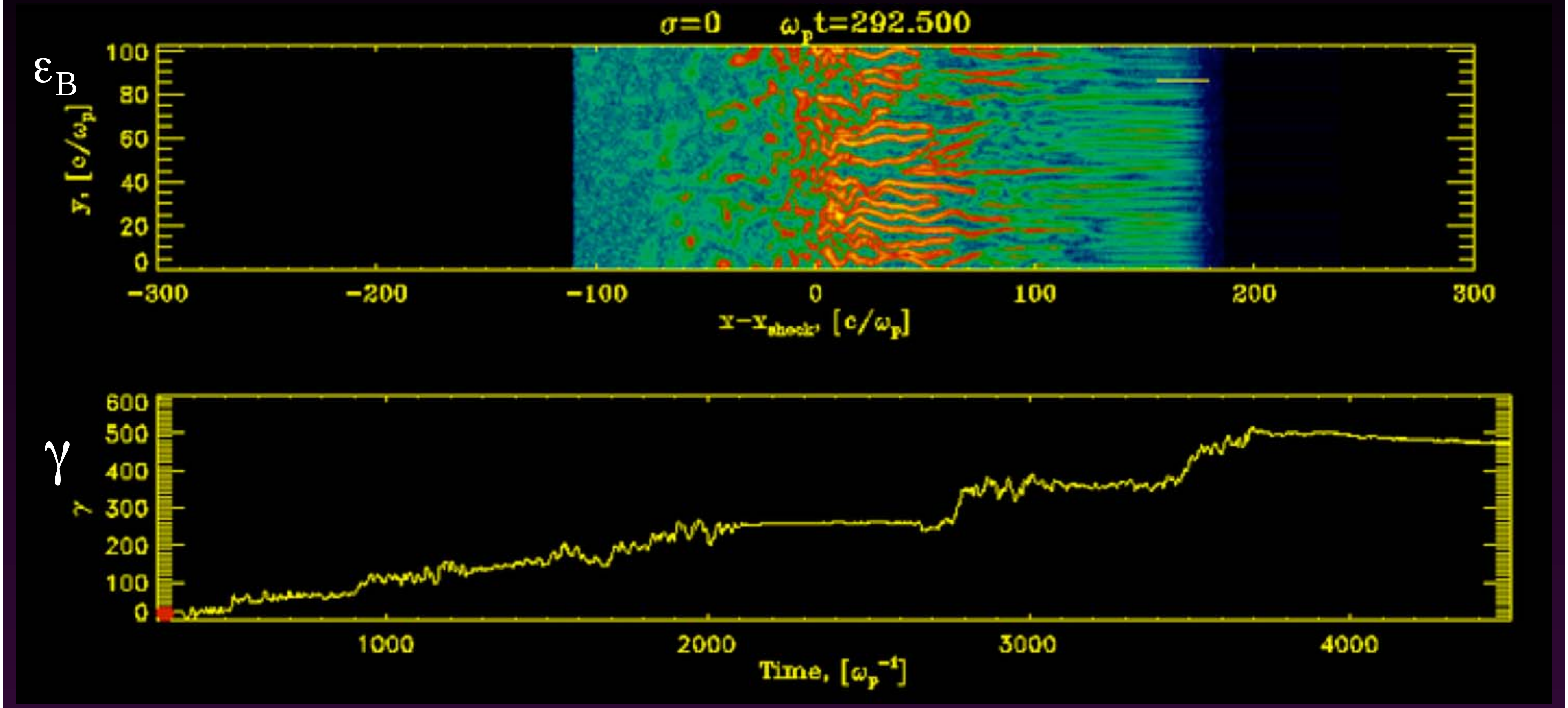
σ=0 e^--p^+ shock (m_p/m_e=32)



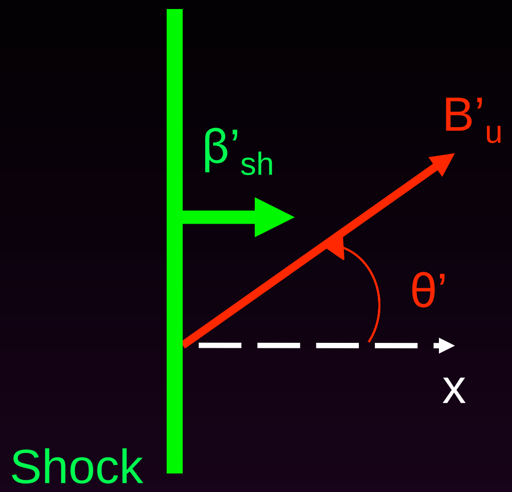
(Martins et al. 2009)

Acceleration mechanism in σ=0 shocks

Fermi-like process: particles get accelerated by scattering off the self-generated Weibel filaments



What about changing the field obliquity?



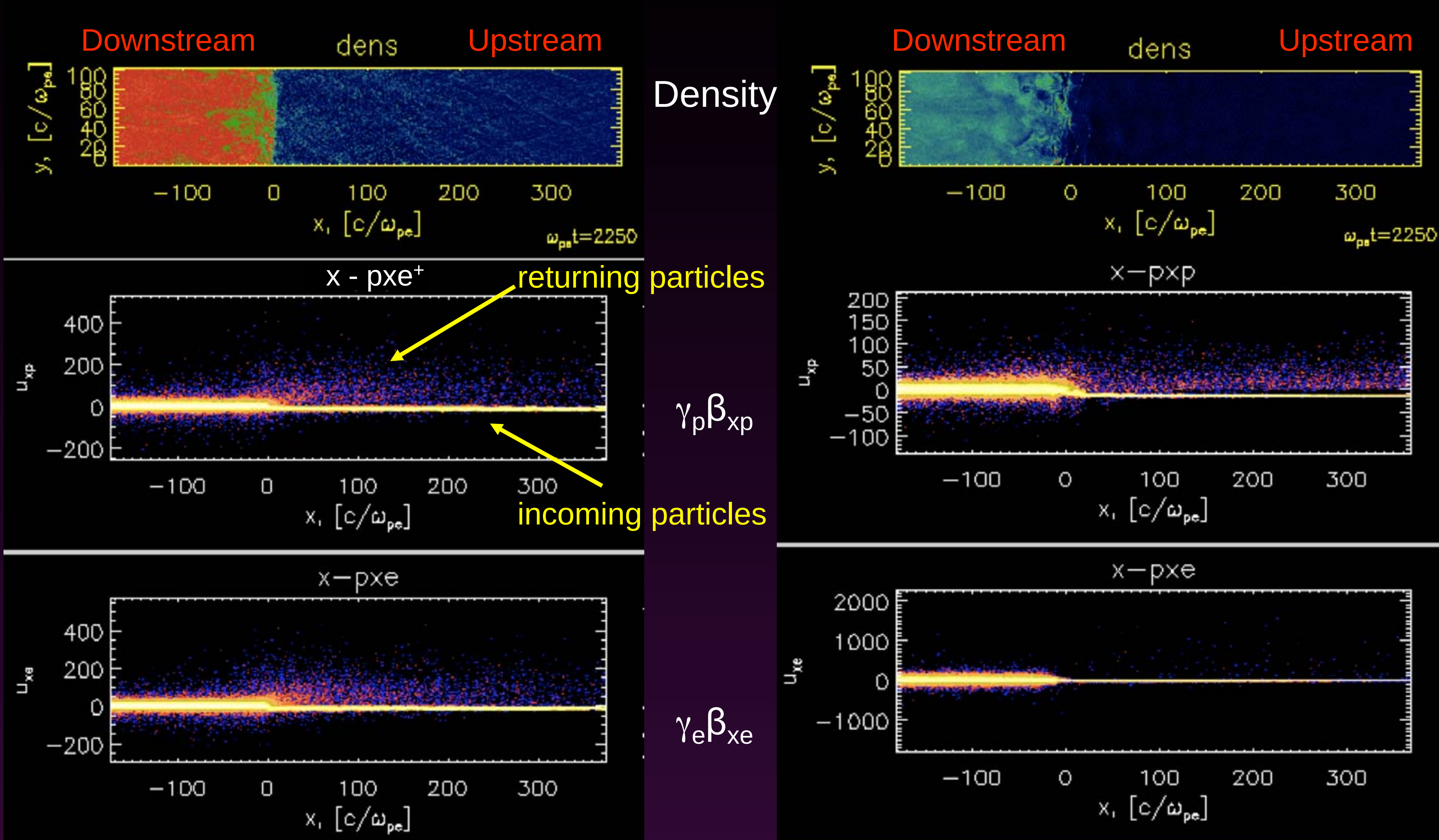
In the upstream frame

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

- 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 ($0.01<\sigma<0.3$)
- How does the field obliquity affect the shock structure and the efficiency of particle acceleration?

σ=0.1 & θ=15°: a subluminal shock

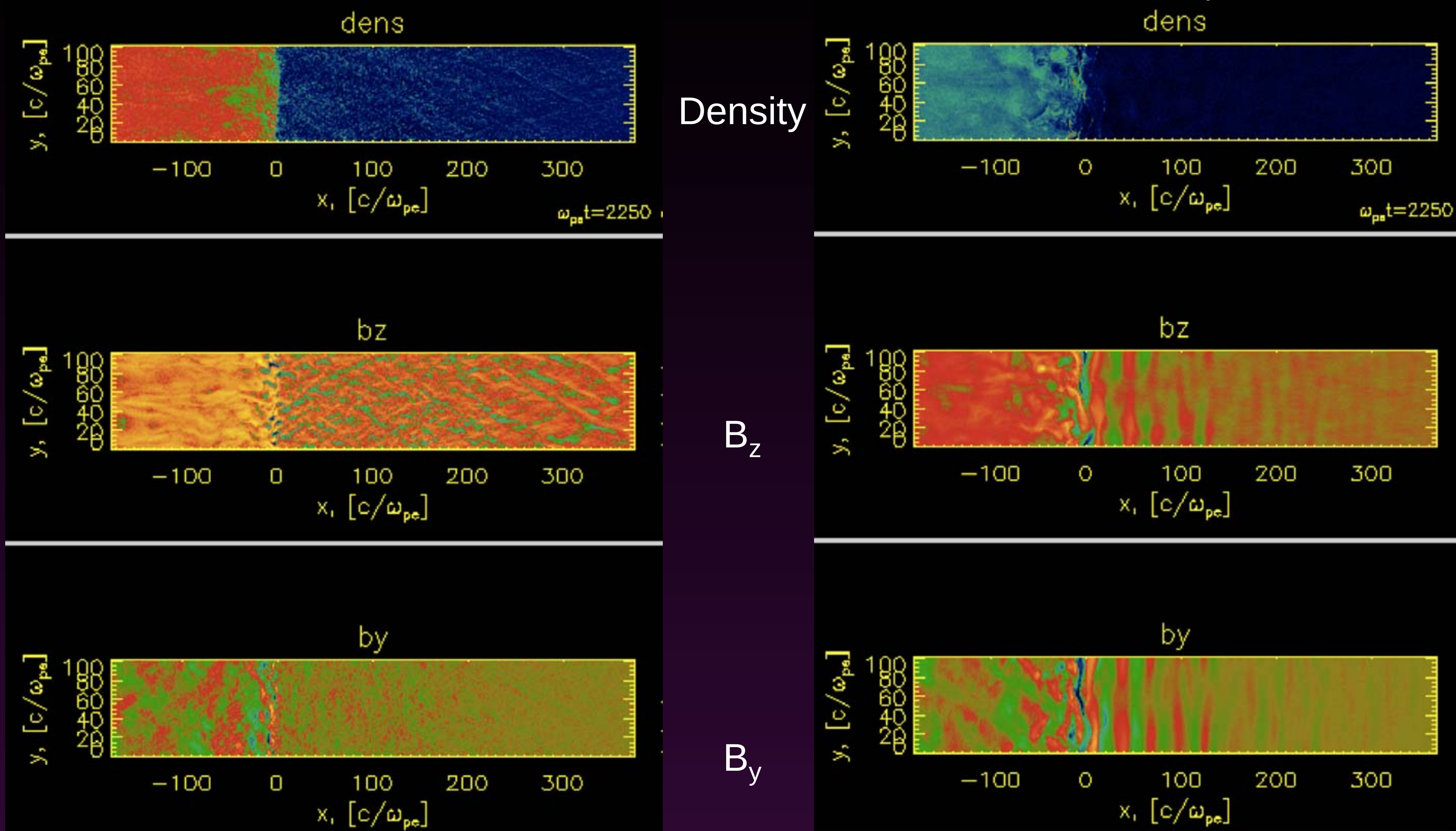
e^--e^+ shock | e^--p^+ shock (m_p/m_e=16)



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

σ=0.1 & θ=15°: a subluminal shock

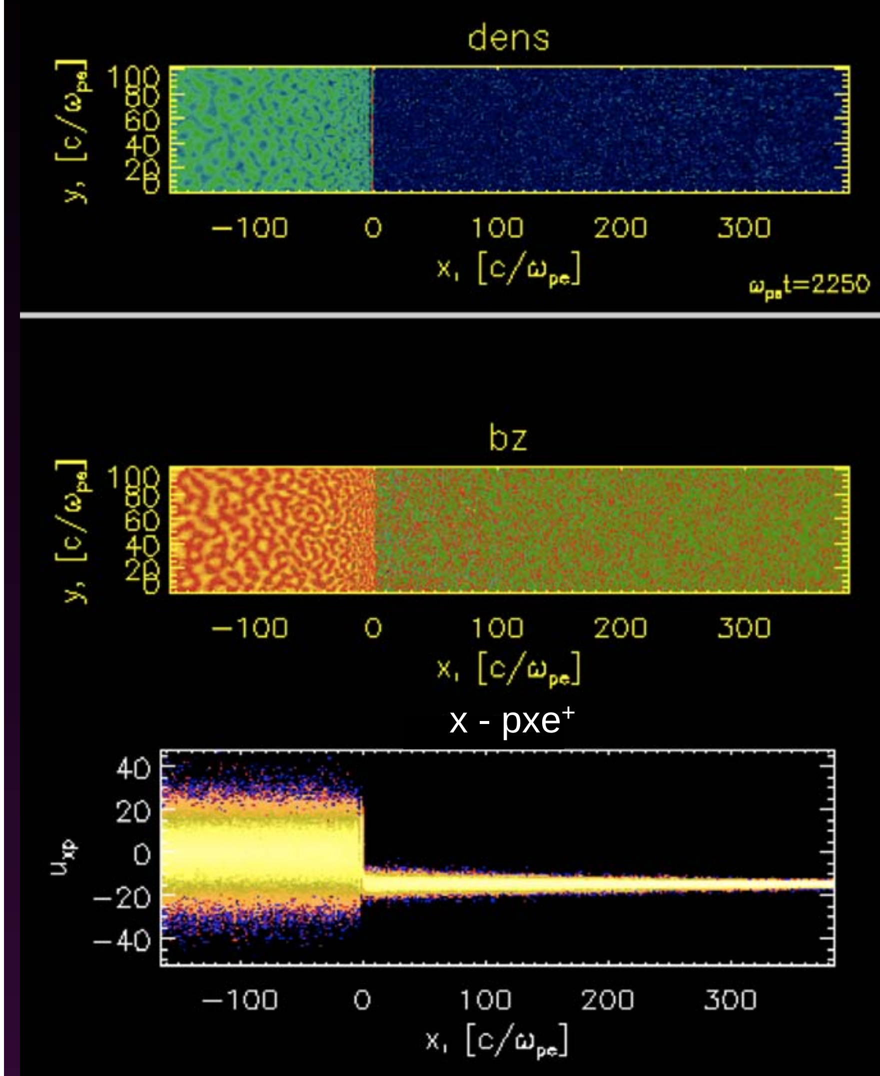
e^--e^+ shock $\qquad$ e^--p^+ shock (m_p/m_e=16)



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

σ=0.1 & θ=45°: a superluminal shock

e^--e^+ shock

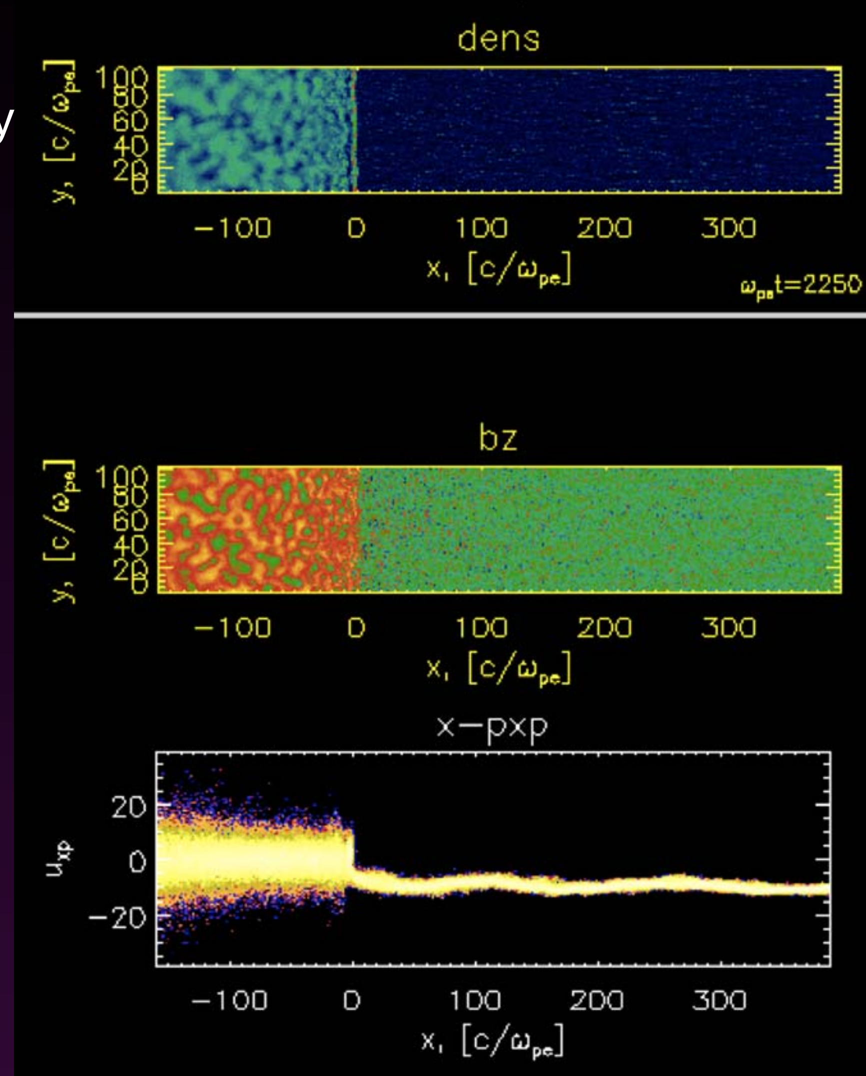


Density

B_z

$\gamma_p\beta_{xp}$

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



Superluminal ➔ No returning particles ➔ No upstream waves

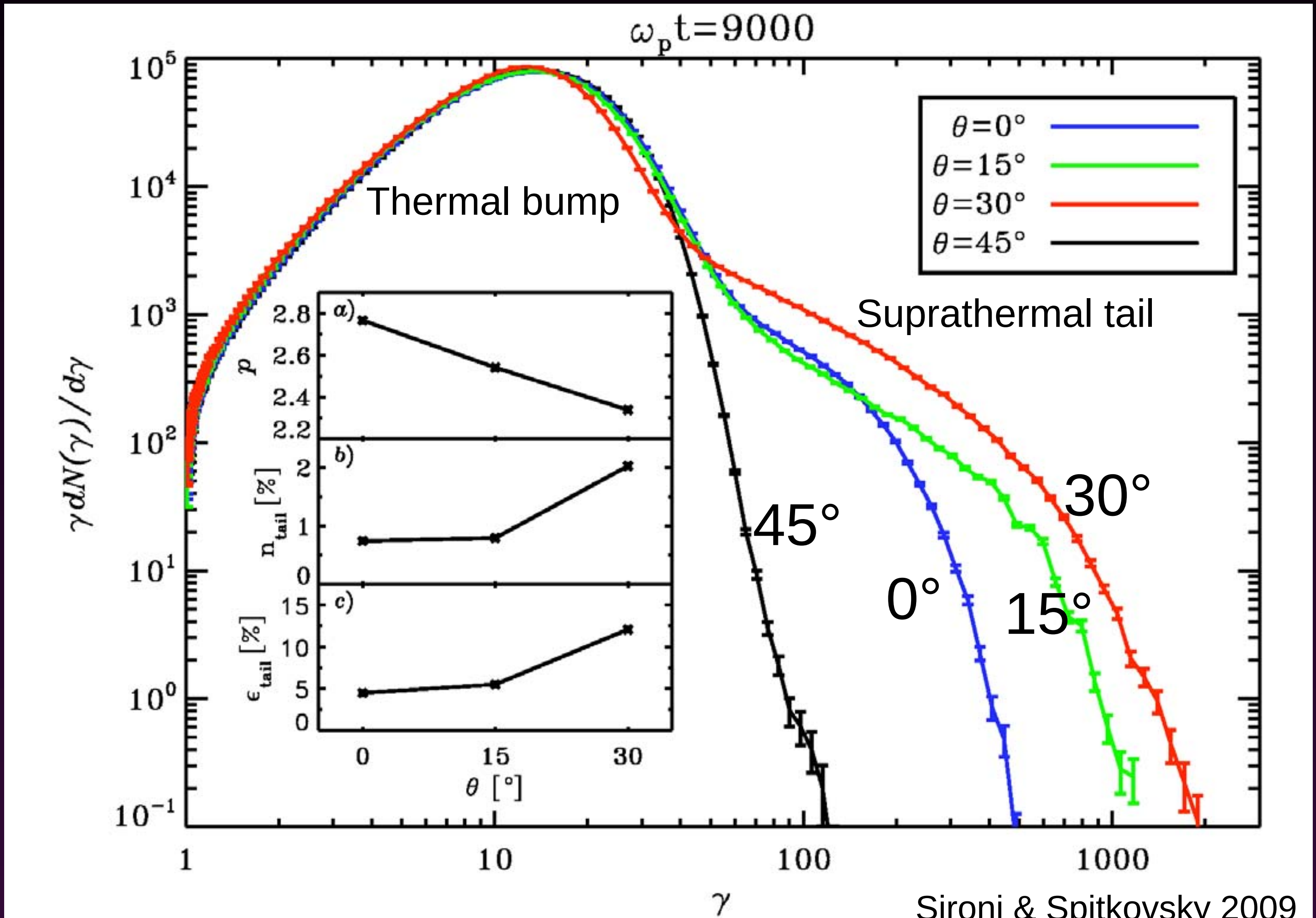
σ=0.1 downstream spectra: e^--e^+ shock

- Superluminal magnetized shocks DO NOT significantly accelerate, subluminal shocks DO, the more efficiently the closer to $\theta_{crit}\approx 34°$

σ=0.1 e^--e^+ shocks

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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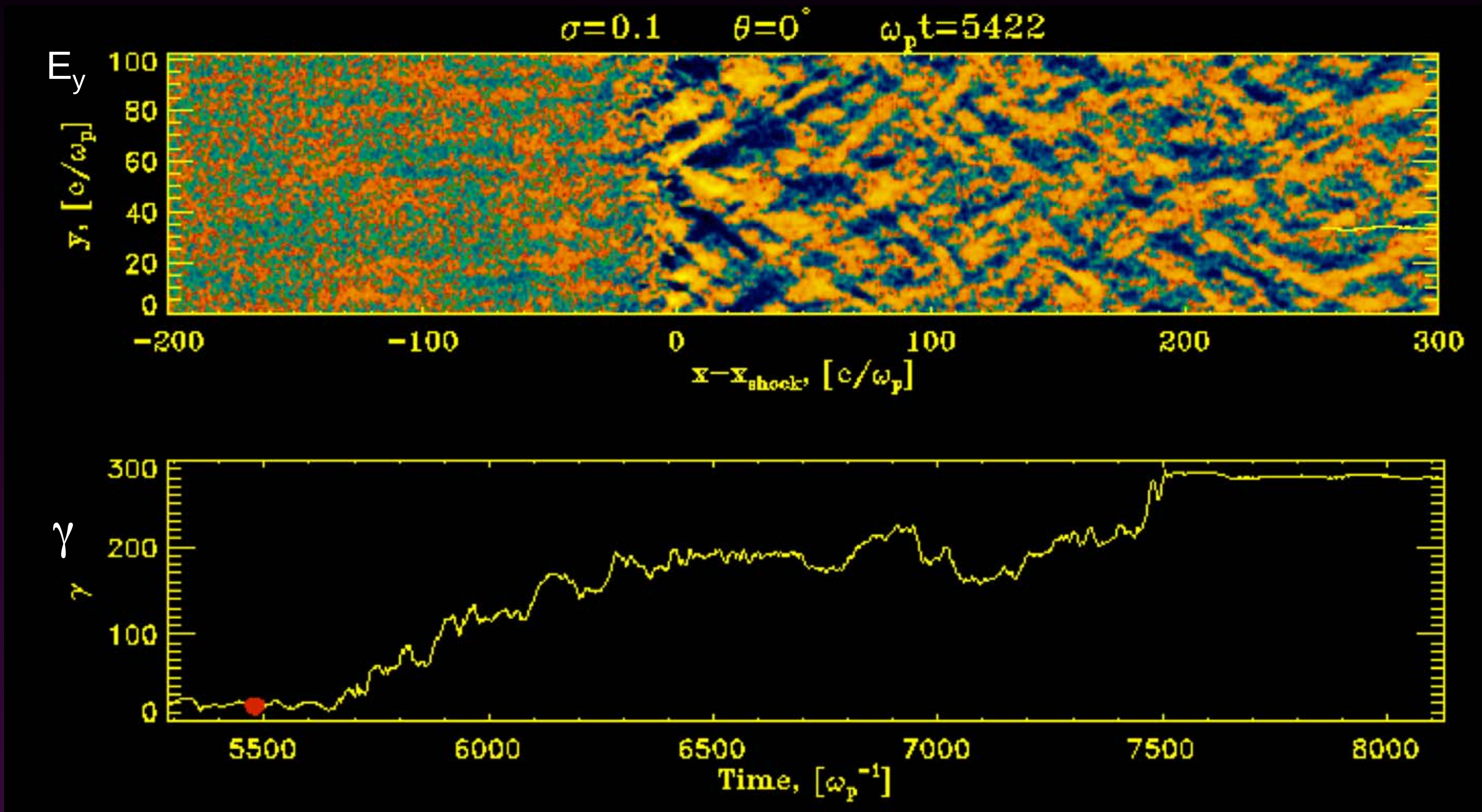
Acceleration mechanism: low obliquity

- Diffusive Shock Acceleration (DSA) by stochastic scattering between the shock layer and the upstream oblique waves

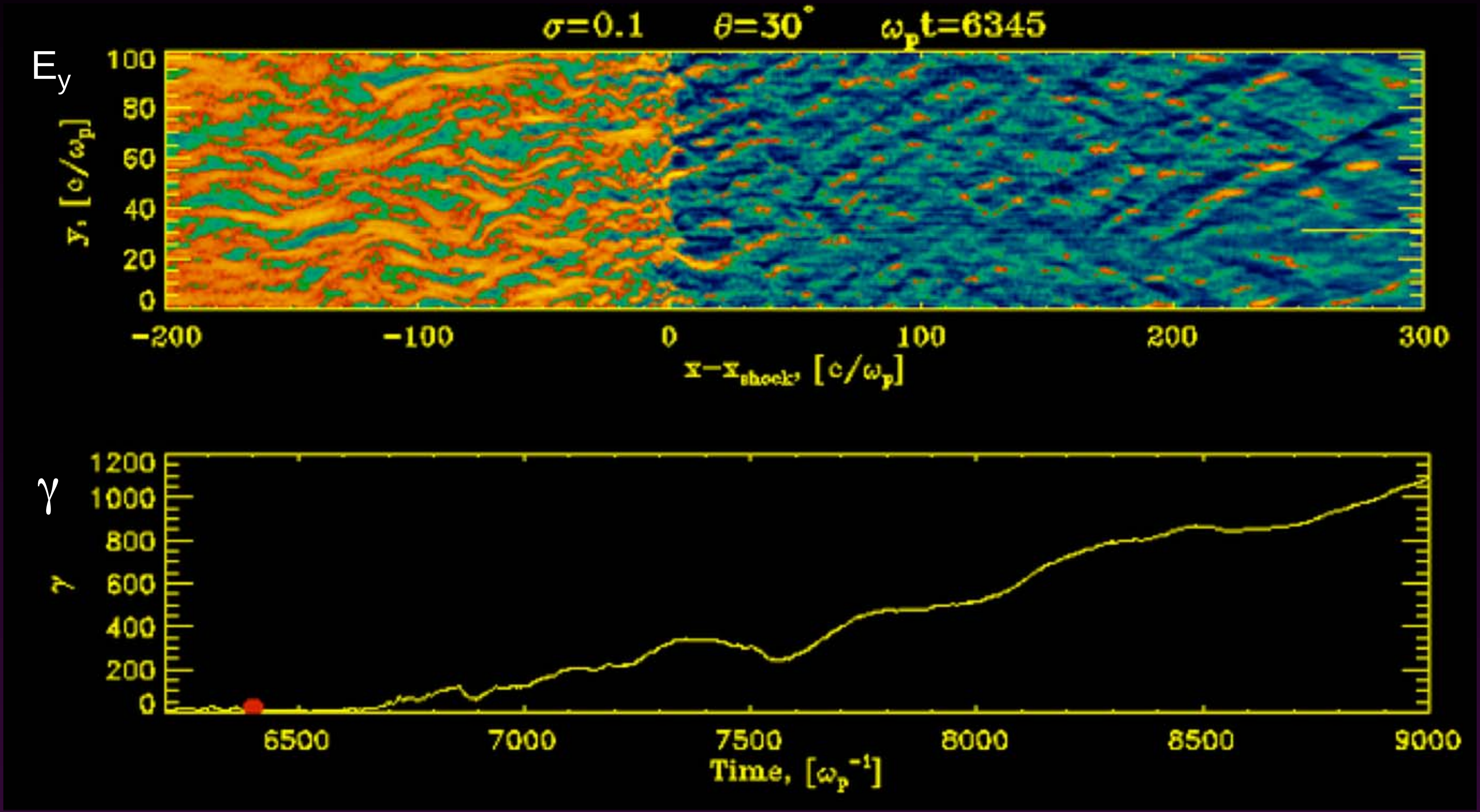
σ=0.1 θ=0° e^--e^+ shock



Acceleration mechanism: high obliquity

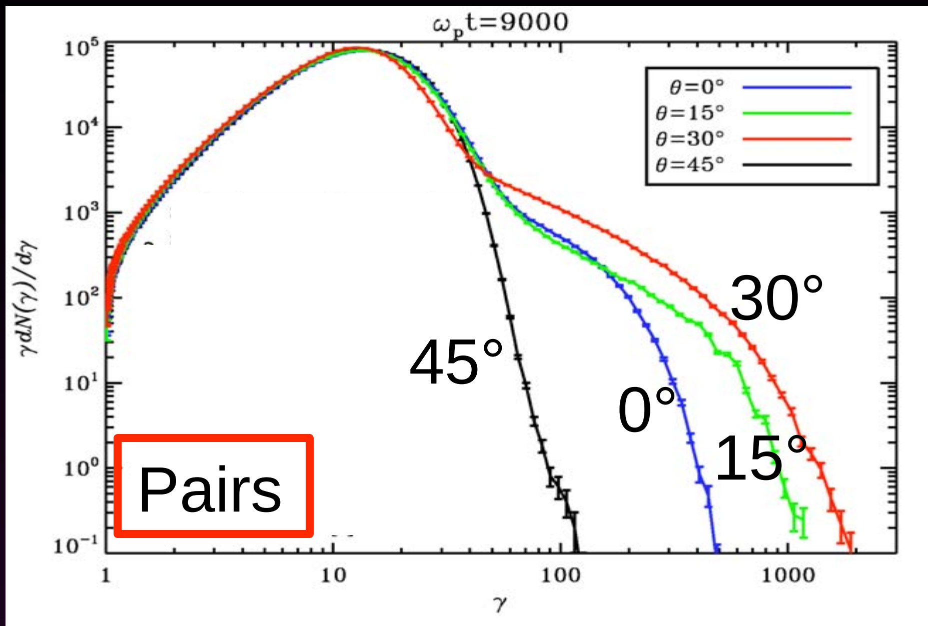
- $\theta \leq \theta_{crit}$: Shock-Drift Acceleration (SDA) by the background E_u after particles are reflected upstream along the oblique background B_u

σ=0.1 θ=30° e^--e^+ shock



- Upstream oblique waves mediate the injection process

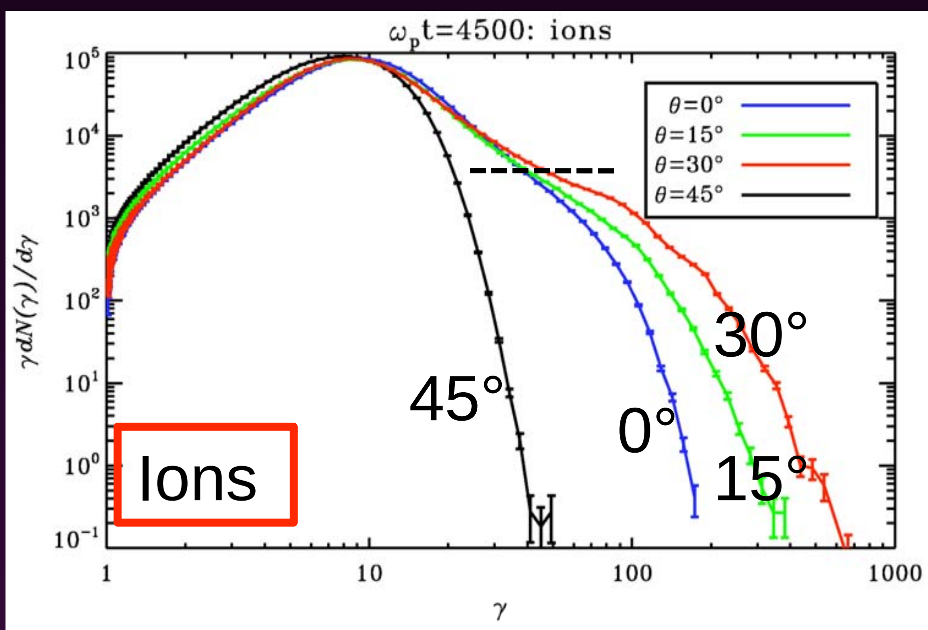
σ=0.1 downstream spectra: e^--p^+ shock

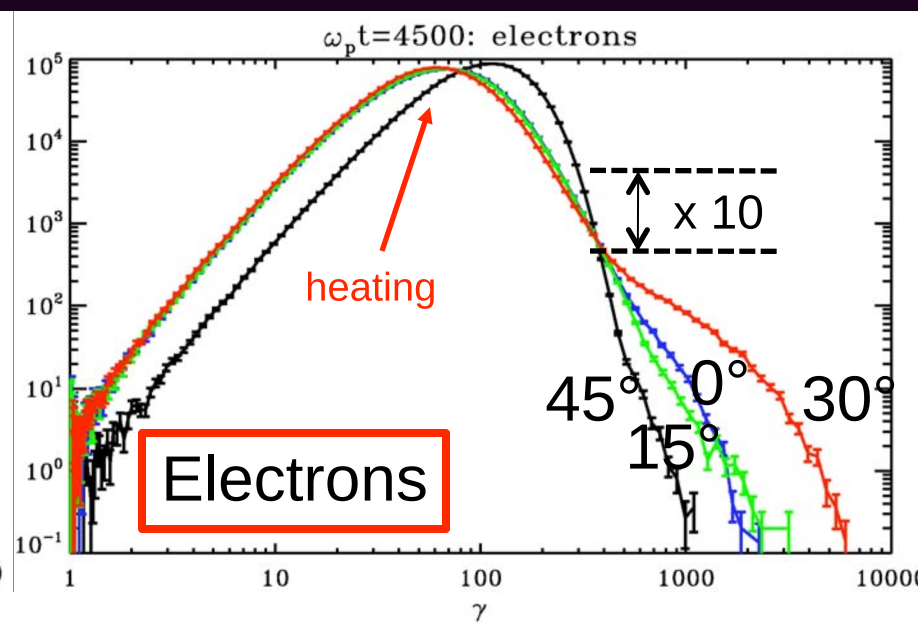


Ion spectra resemble pair spectra of e^--e^+ shocks:

- negligible acceleration for superluminal configurations
- 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%

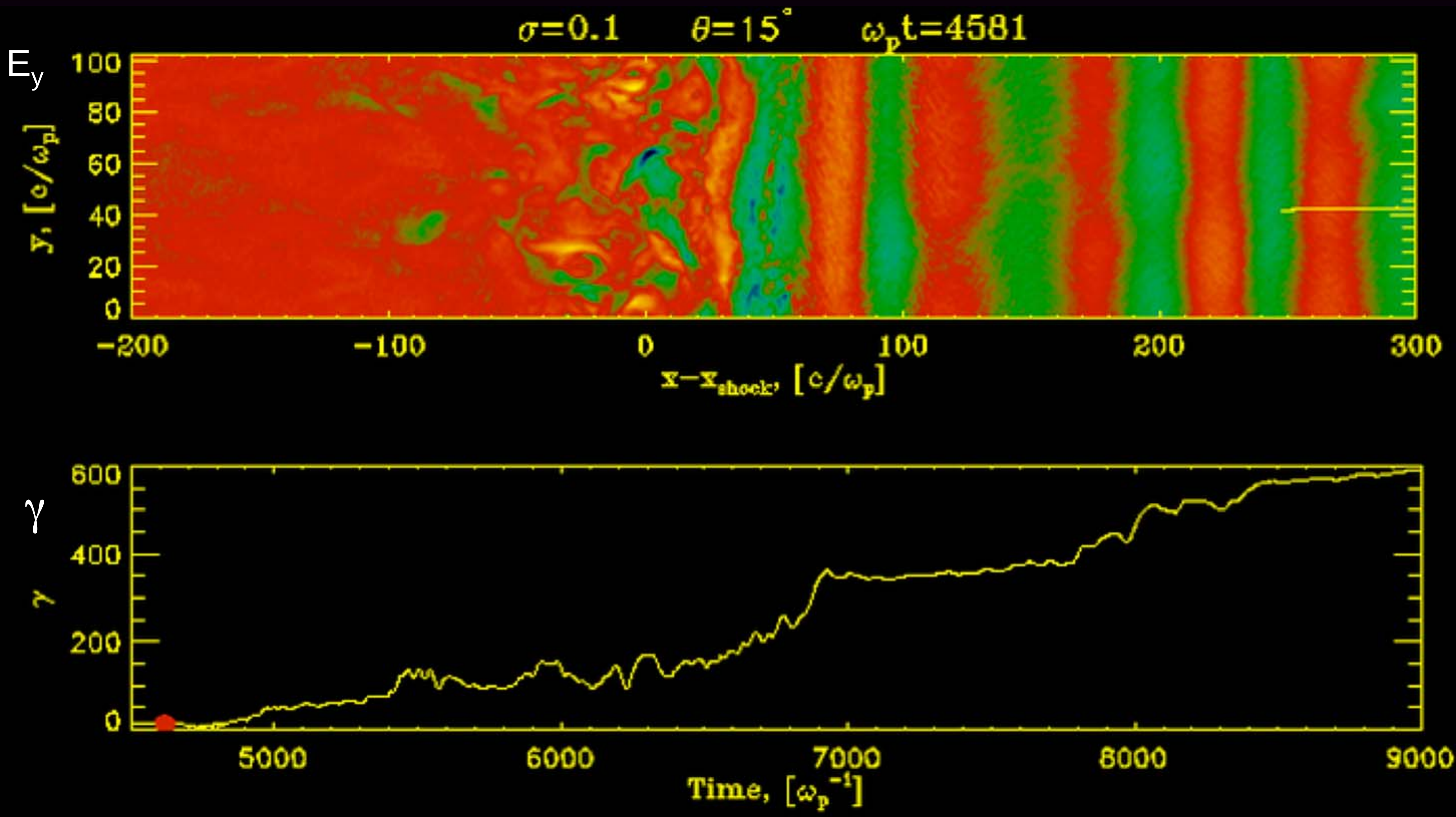
Electron acceleration in e^--p^+ shocks is a factor of 5-10 less efficient than ions





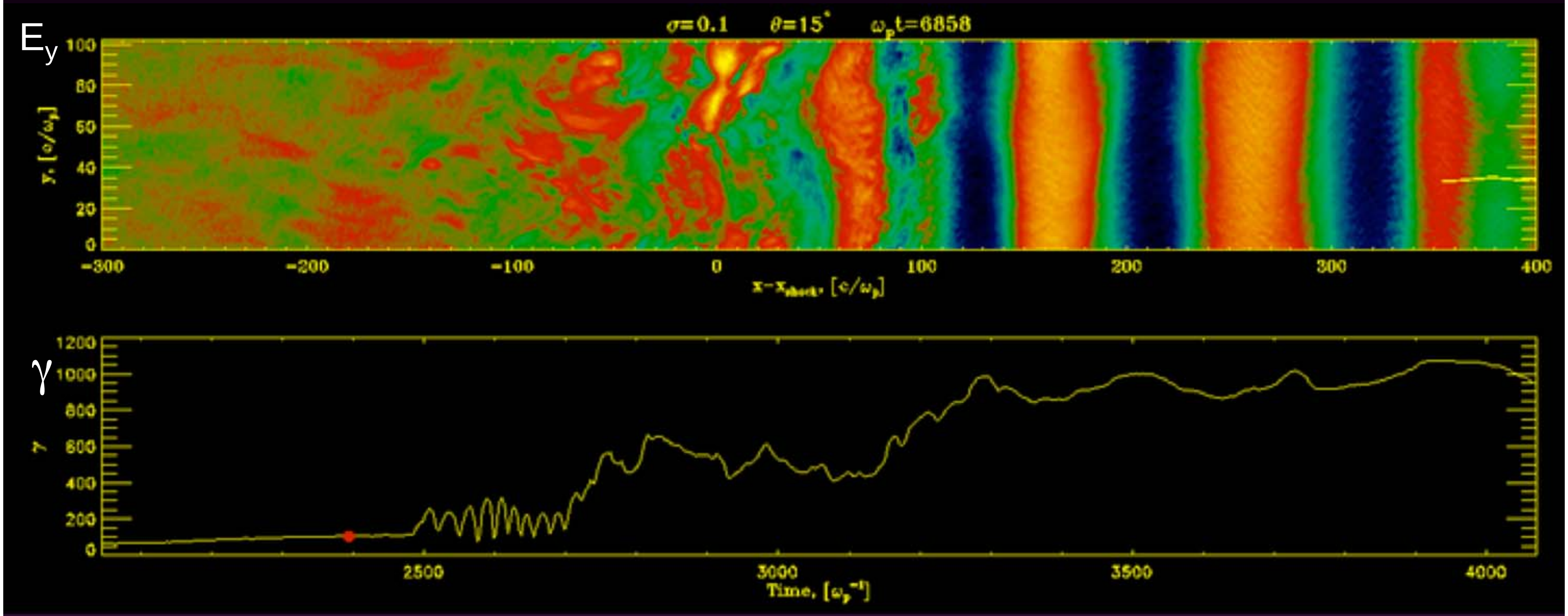
Ion vs electron acceleration (1/2)

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

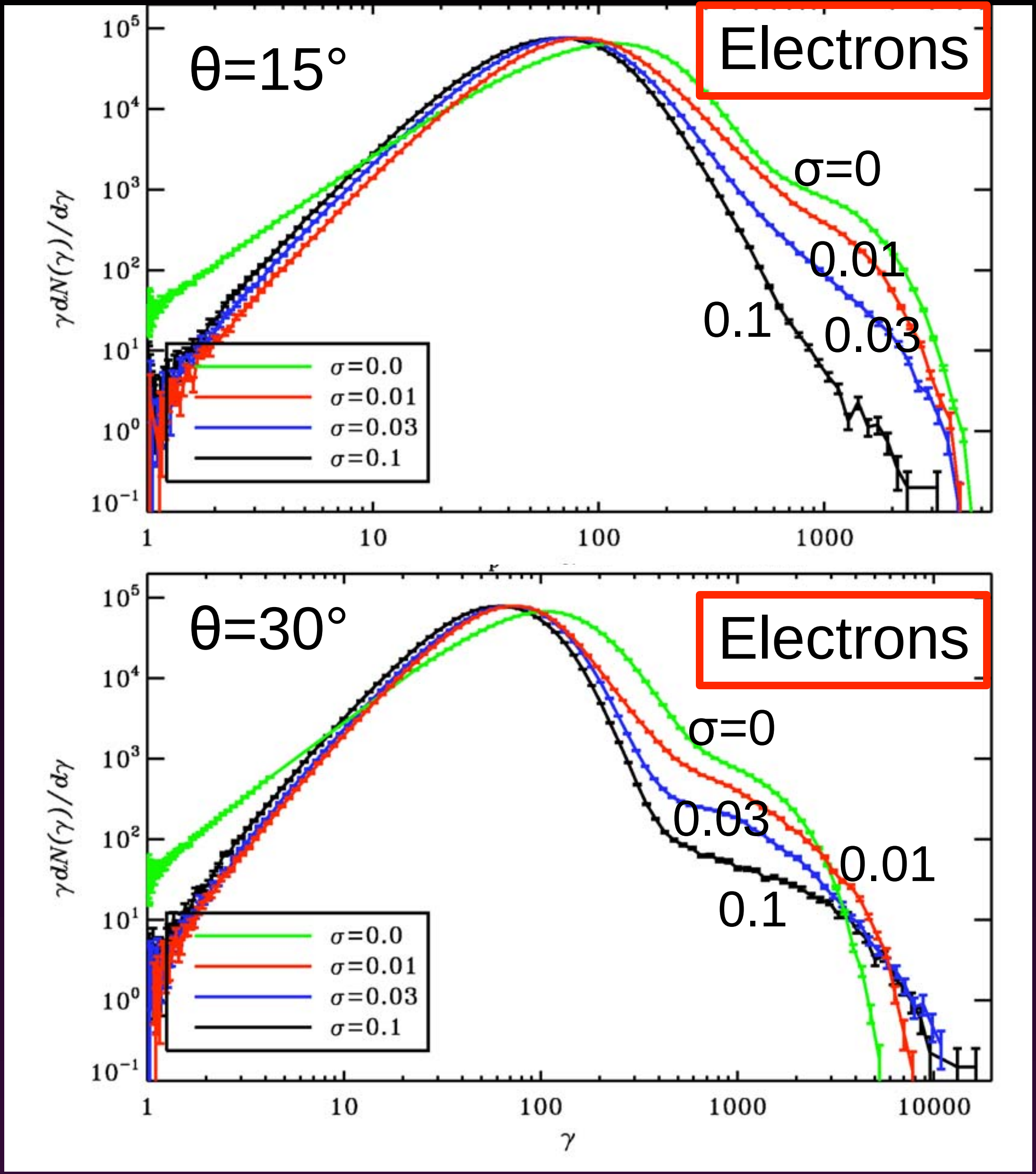


Ion vs electron acceleration (2/2)

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

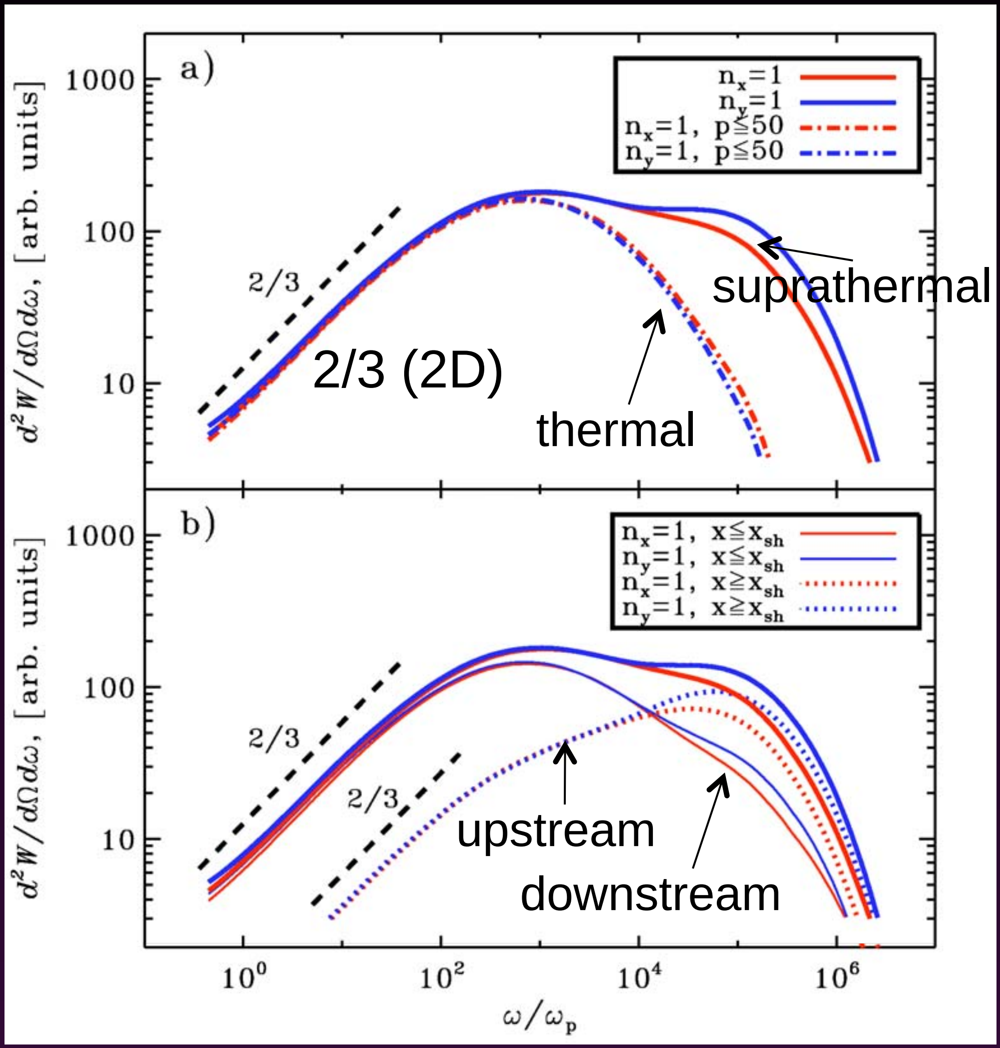
➔ Lower efficiency of electron acceleration, independent of θ

Radiation signatures of σ=0 shocks

Radiation spectrum from simulation particles traced in the self-consistent fields

- Low-frequency spectral slope is consistent with synchrotron theory: Line-of-Death puzzle in GRB prompt spectra cannot be solved by the jitter paradigm

- Significant contribution to the radiation spectrum by upstream particles



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Summary (1/2)

- Relativistic unmagnetized shocks are mediated by the Weibel instability, magnetized (σ=0.01-0.1) perpendicular shocks by magnetic reflection
- If σ=0, ~1% of particles and ~10% of energy are stored in a suprathermal tail (both for e^--e^+ and e^--p^+ shocks)
- If $\sigma \geq 0.01$:

  e^--e^+ shocks are efficient accelerators (~1% by number, ~10% by energy) only for subluminal field obliquities ($\theta<\theta_{crit}\approx 34°$)

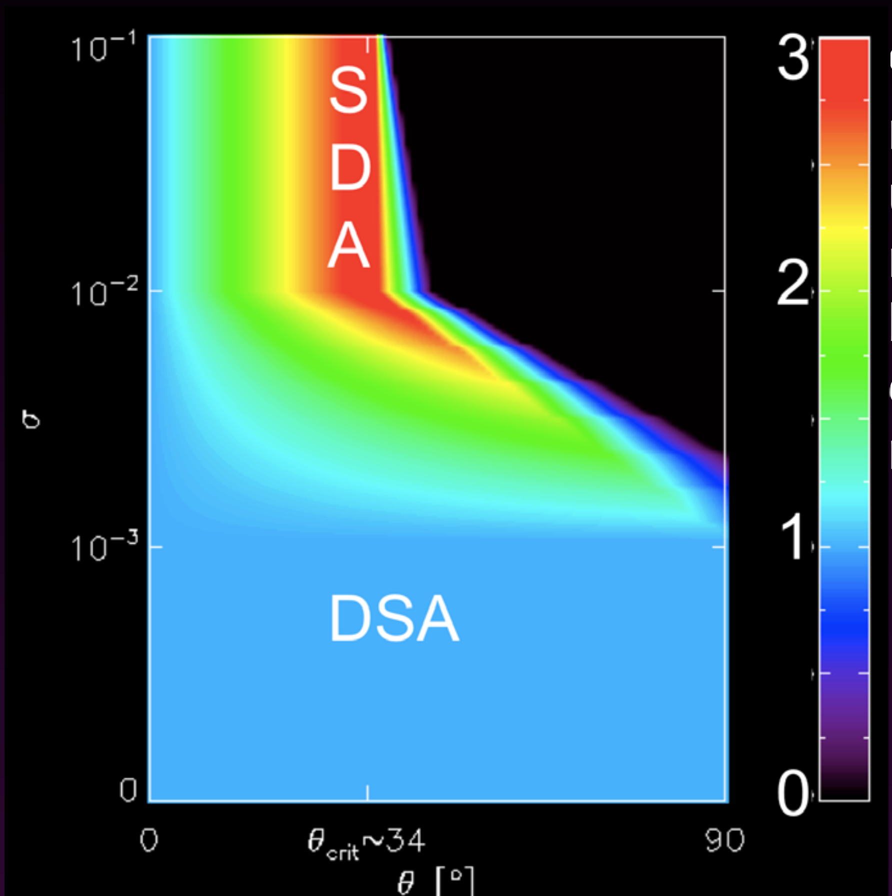
  e^--p^+ shocks:

    ion acceleration only for subluminal configurations (~3% by number, ~20% by energy)

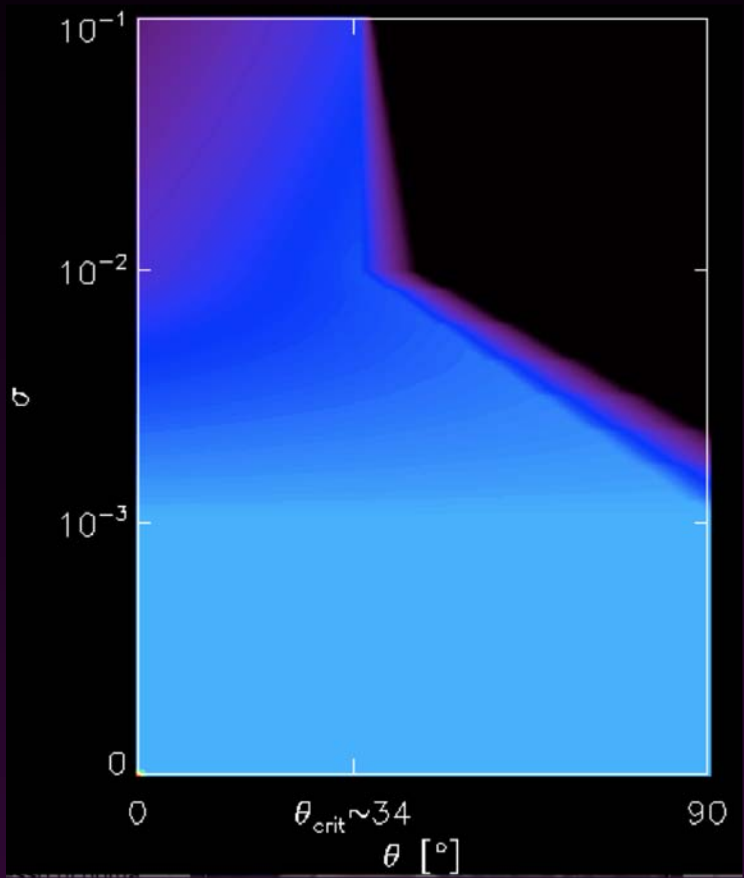
    electron acceleration suppressed by a factor of 5-10 wrt ions even for subluminal obliquities, especially for high magnetizations (σ~0.1).

Summary: particle acceleration (2/2)

e^--e^+ shock
($ions$ in e^--p^+ shocks)



electrons in e^--p^+ shocks



- Acceleration via a Fermi-like mechanism for unmagnetized or quasi-parallel shocks, via Shock-Drift for $\theta \leq \theta_{crit}$ magnetized shocks

Implications

Constraints on the composition and magnetization of the flow:

- 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?