Particle-In-Cell Simulations of Nonresonant Instability in the Shock Precursor of a Young Supernova Remnant

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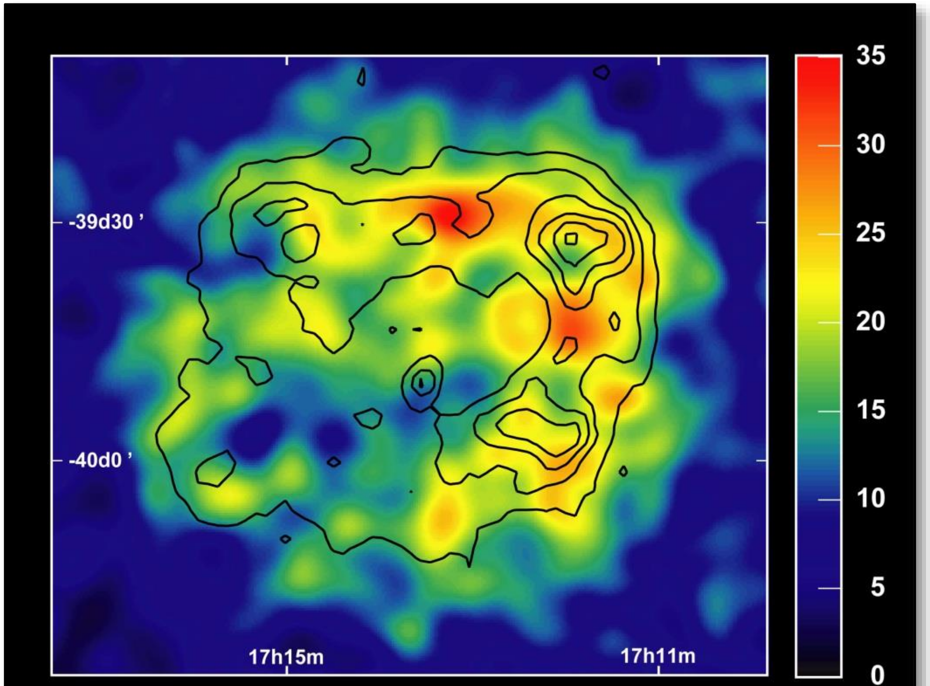
Physical picture

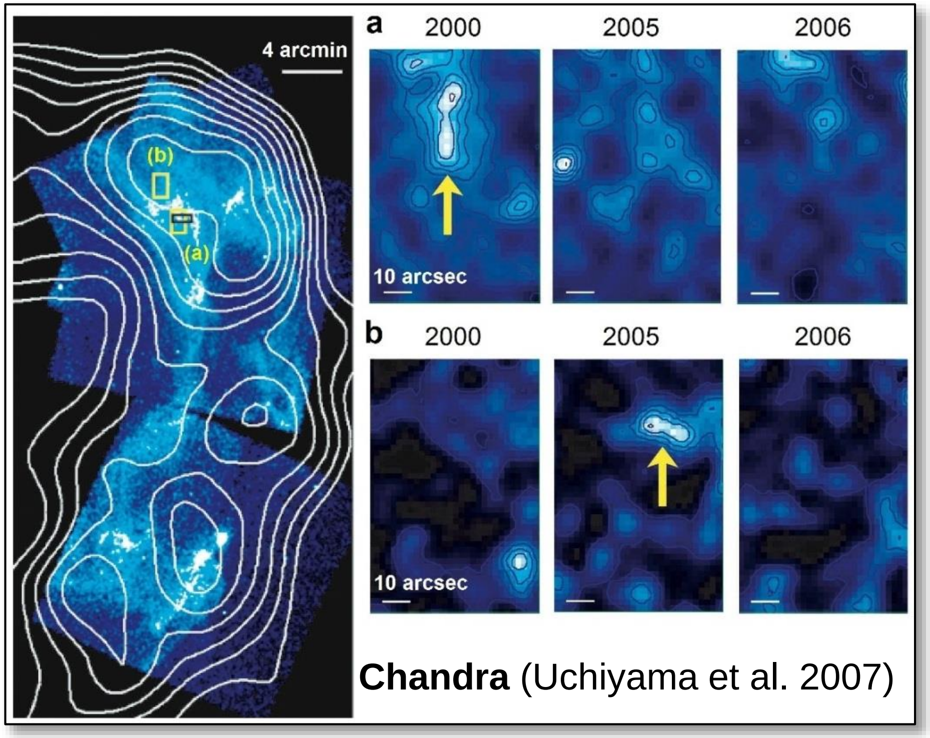
Cosmic Rays (CR) are the extremely high-energetic particles coming from different sources in space.

The main part of Galactic CR flux with energies up to few PeV is assumed to be provided by Diffusive Shock Acceleration (DSA) processes at young SNR shocks.

- Magnetic field is required for efficient acceleration: E_{max} is determined by the amplitude of magnetic turbulence.
- Bright X-ray filaments of synchrotron emission coincident with outer shocks of SNRs and variability of X-ray filaments on time scales ~1 year: evidence for strong magnetic fields.
- Magnetic field amplitudes $B \sim 100\ \mu G - 1\ mG$ ($B_{ISM} \sim 3\ \mu G$).



HESS image: ***SNR RXJ1713.7***



Chandra (Uchiyama et al. 2007)

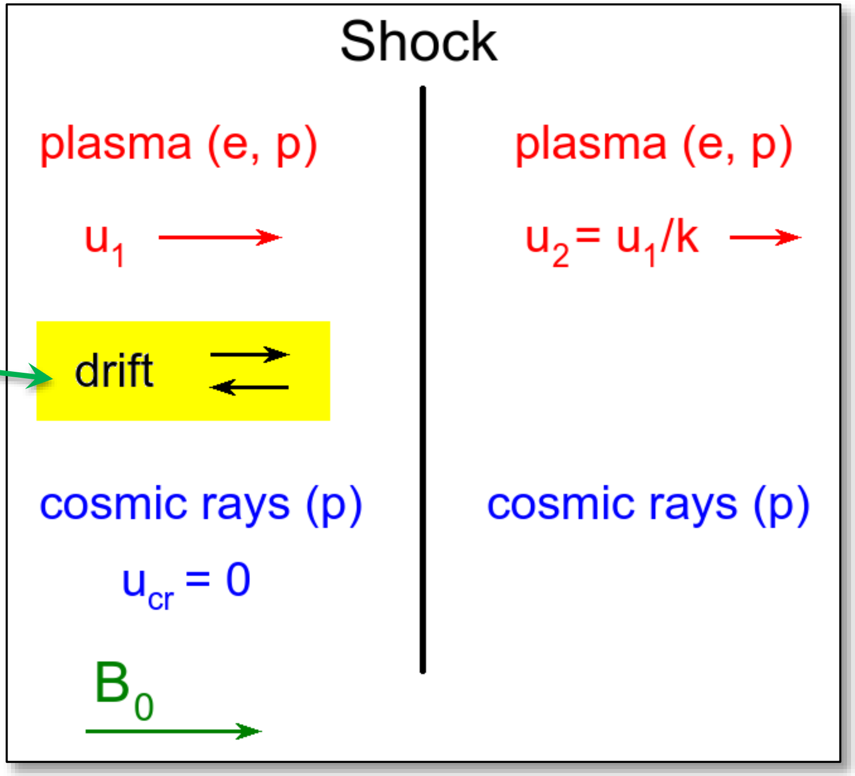
Magnetic field amplification

- How and where is the magnetic turbulence produced?
- How do particle interact with magnetic turbulence?

Precursor:

- Slow relative motion of cosmic rays and cold plasma.
- Electromagnetic turbulence is self-generated by accelerated particles via ***Bell's instability*** (*Bell* 2004, *Zirakashvili et al.* 2008, *Niemiec et al.* 2008, *Riquelme & Spitkovsky* 2009, *Stroman et al.* 2009).

it acts here

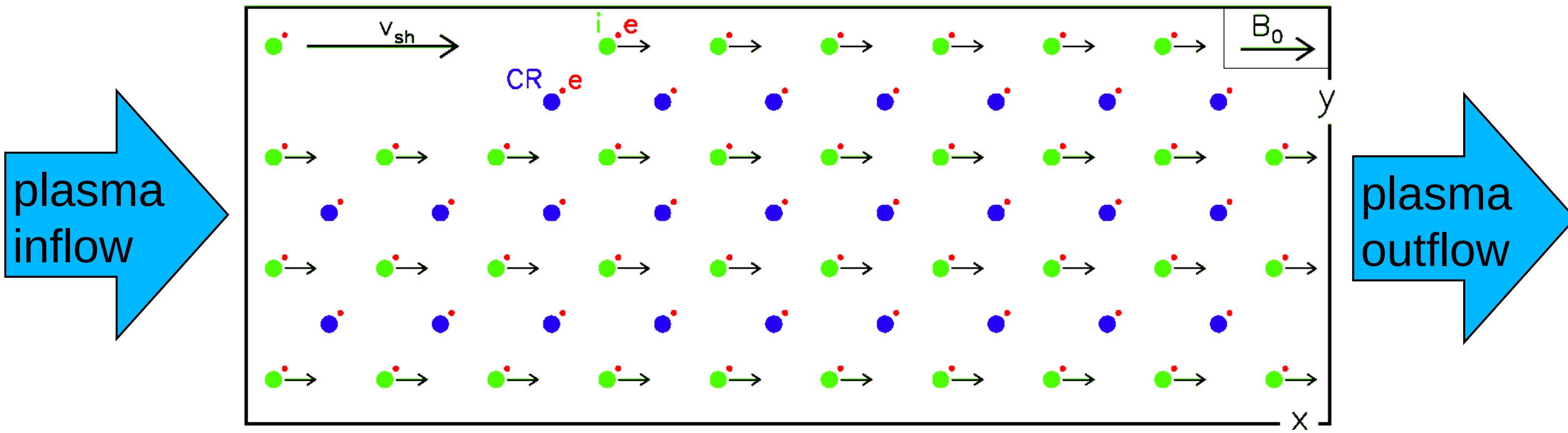


Shock propagates from right to left. The shock rest frame is used in this picture.

Important:

- saturation process and level

Very large-scale Particle-In-Cell simulation



$L_x = 130{,}000\ \Delta \approx 293\ \lambda_{max}$ $L_y = 12{,}000\ \Delta \approx 27\ \lambda_{max}$

2D-3V

Open boundaries account for mass conservation in the plasma flow.

***Simulation frame*:**

Isotropic population of relativistic CR ions at rest.

Electron-ion plasma beam moves with the shock velocity v_{sh} from left to right.

***Physical parameters*:**

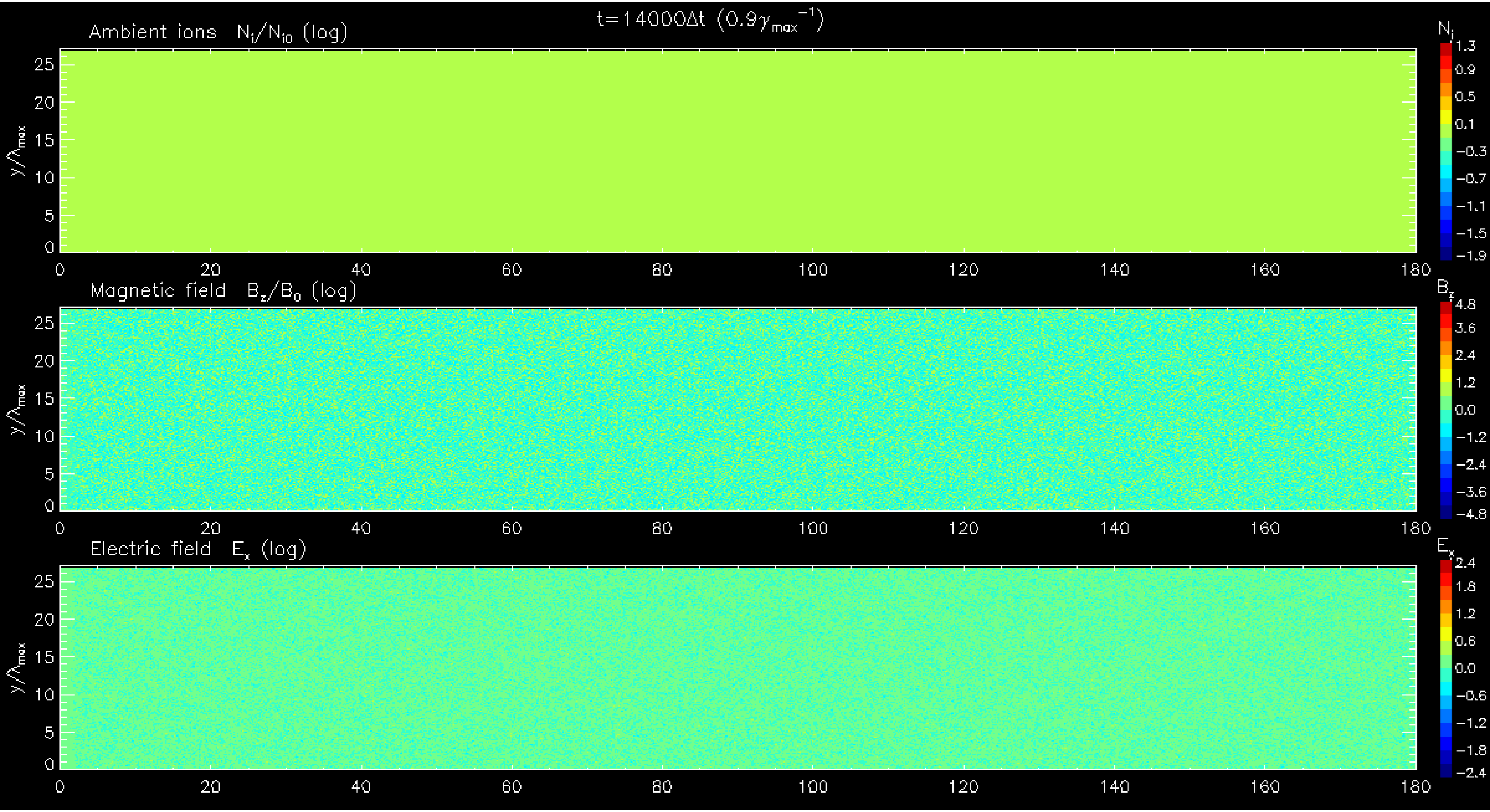
- Reduced ion to electron mass ratio $m_i/m_e = 50$
- CR-to-ambient plasma relative speed $v_{rel} = 0.4c$ (electron thermal velocity $v_{e,th} = 0.01c$)
- CR-to-ambient plasma density ratio 1/50
- Initial CR relativistic Lorentz factor $\Gamma = 50$
- Alfven Mach number of the shock $M_A = 40$

***Computation*:**

- 9600 CPU cores,
- ~ 1 month wall-time of simulation
- on *PROMETHEUS* cluster
- ~ 1 year of data analysis

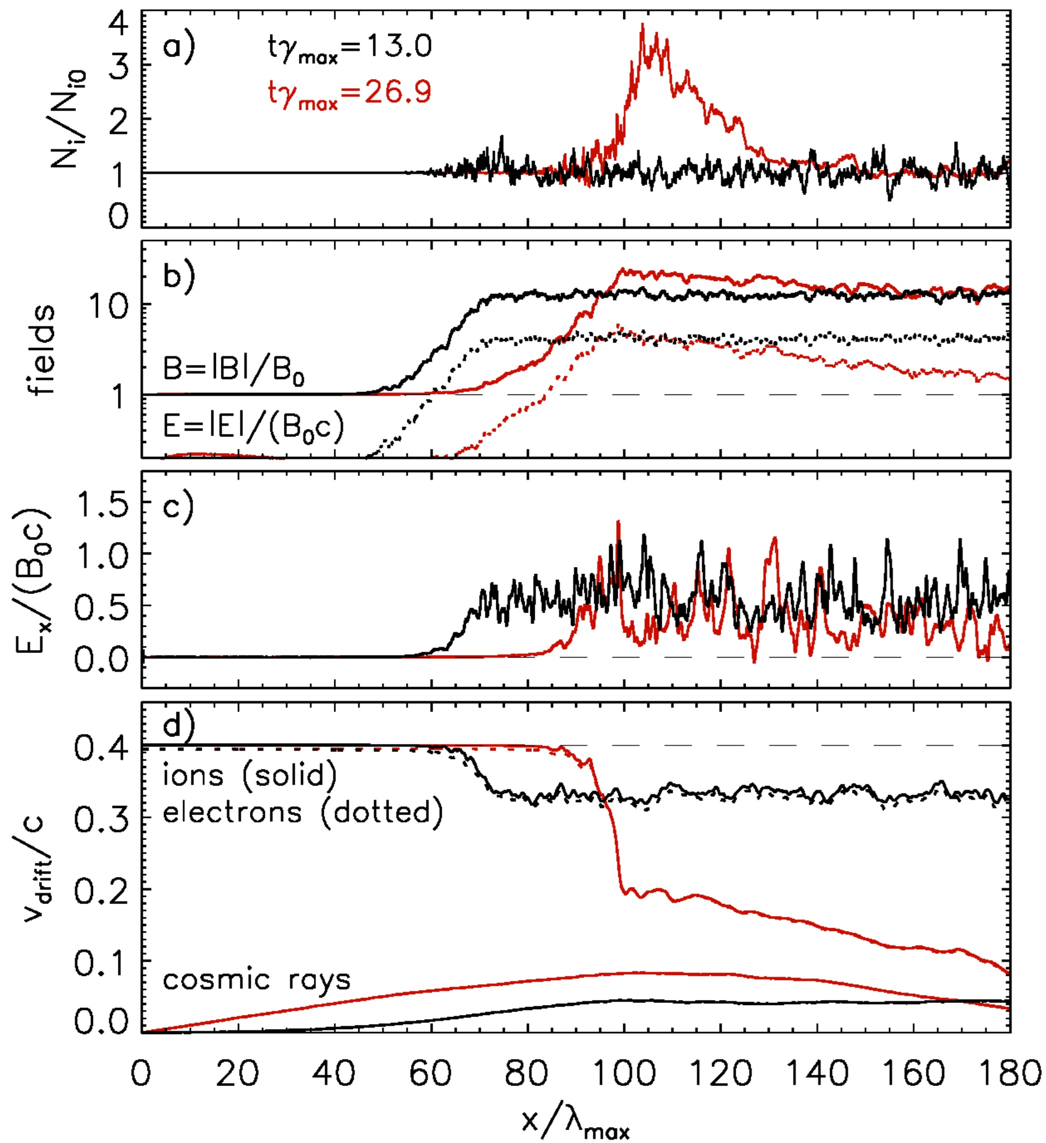
Global evolution of the nonresonant instability

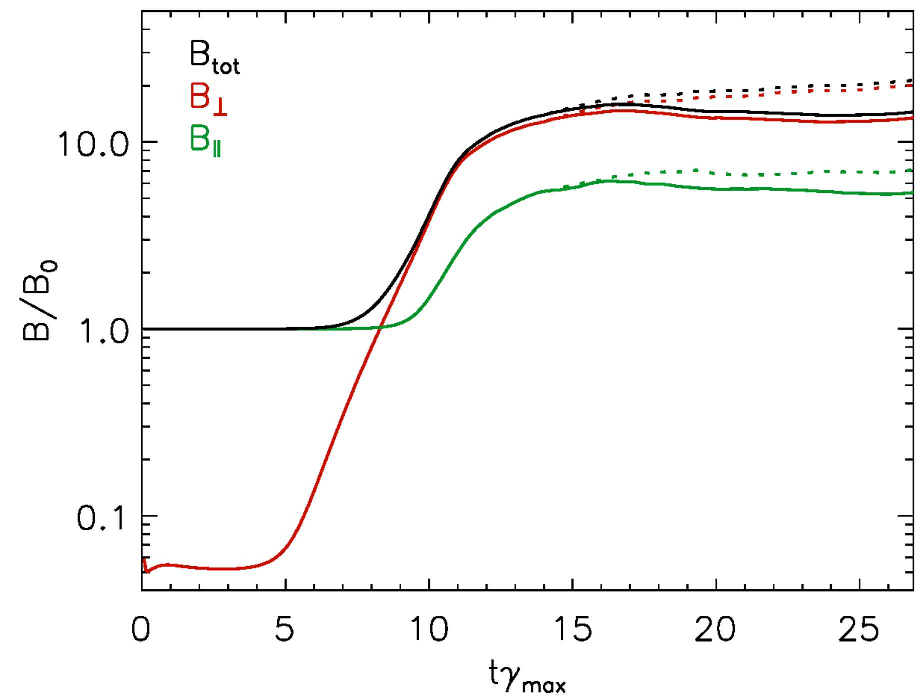
(From top to bottom: ambient ion density, B_z magnetic field, E_x electric field)



Global evolution of the nonresonant instability

(Profiles of densities and fields, growth of magnetic turbulence)

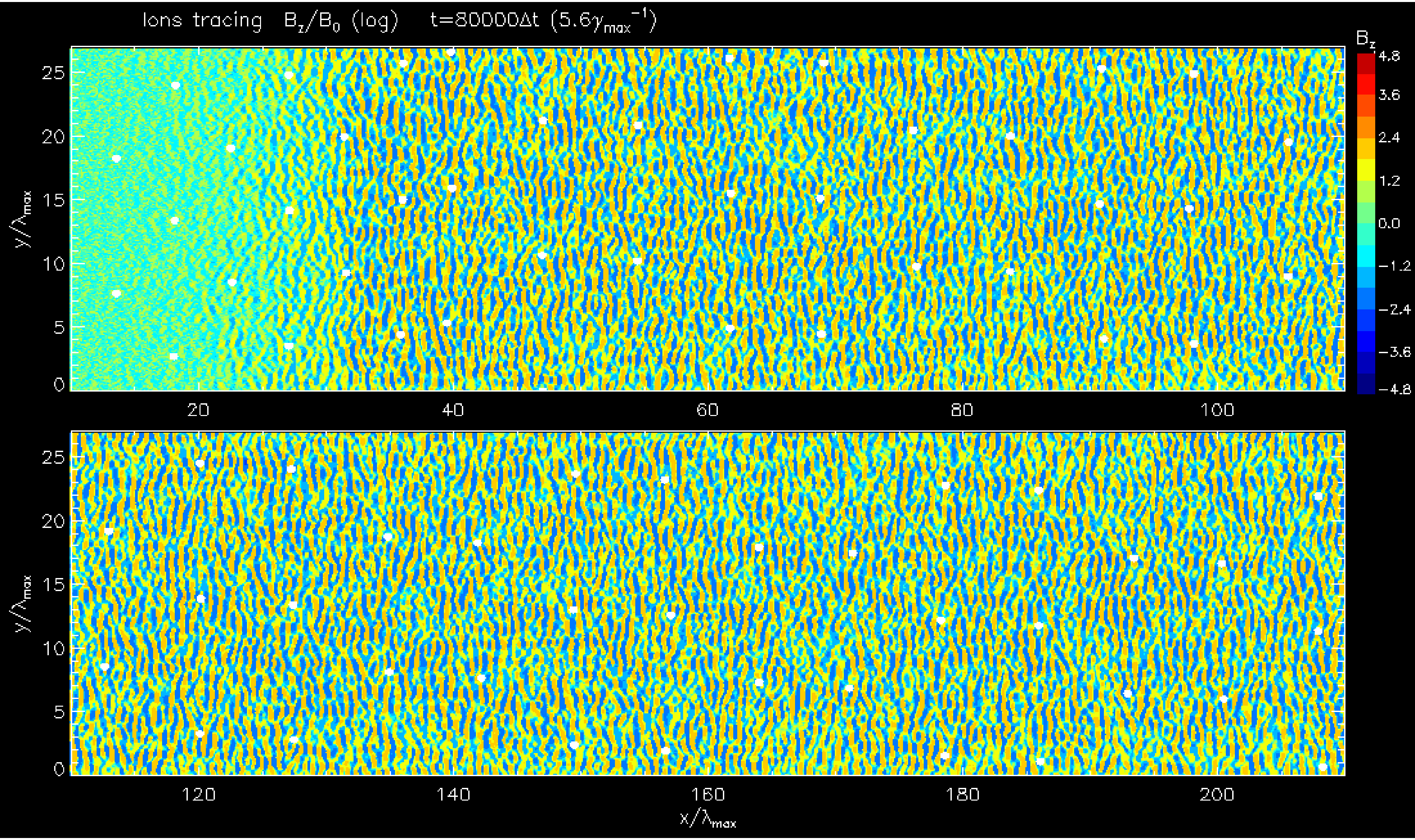




- Turbulent MF amplified and saturated at $\delta B \approx 15\ B_0$ as in studies with periodic boxes.
- Additional amplification by about 30% through compression in shock-like structure.
- Saturation through deceleration of bulk motions – relative CR-ambient plasma drift velocity decreases from $0.4c$ to $\sim 0.05c$.
- Averaged E_x component is positive in the turbulent region.

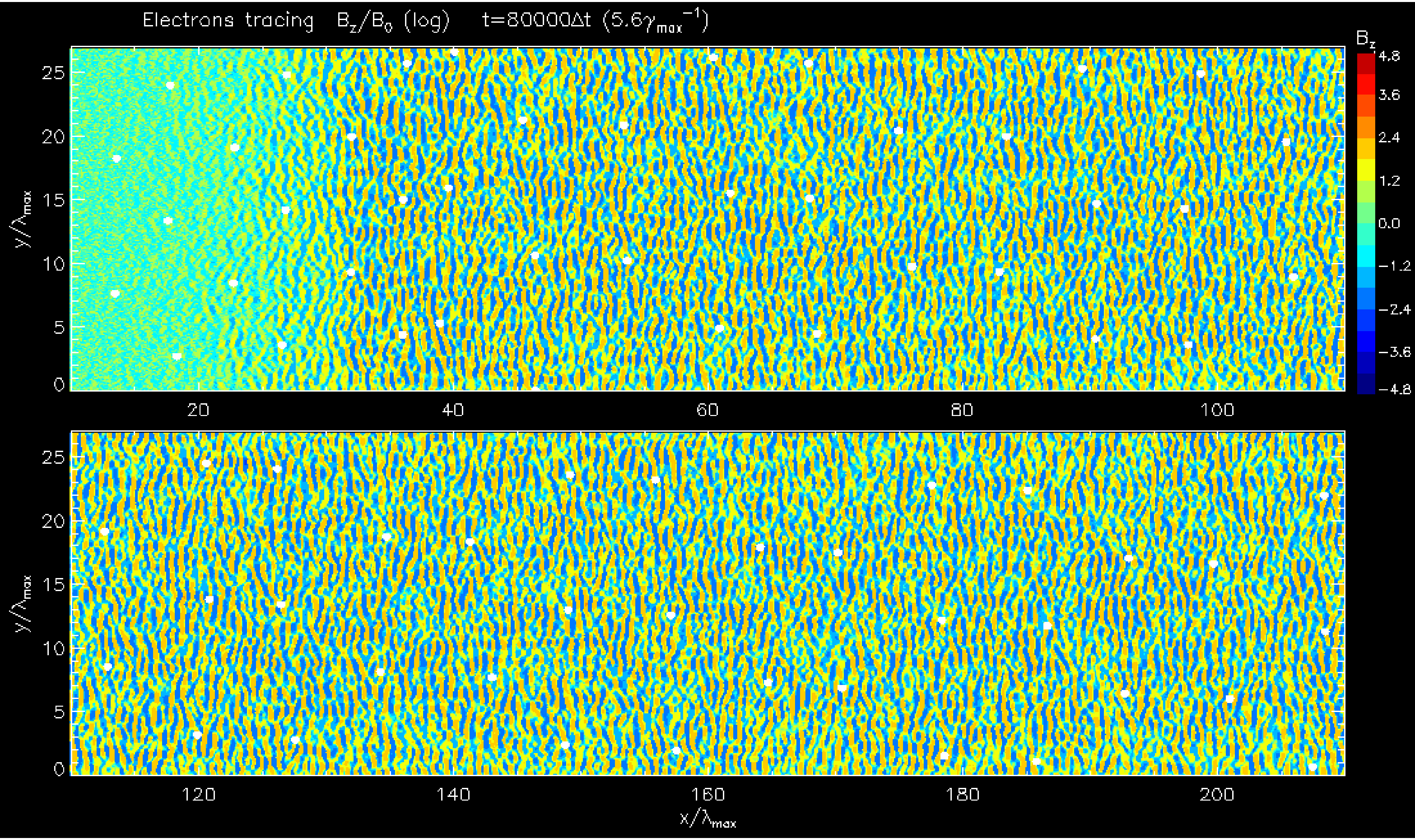
Tracing of the particles

(Ambient plasma **ions**)



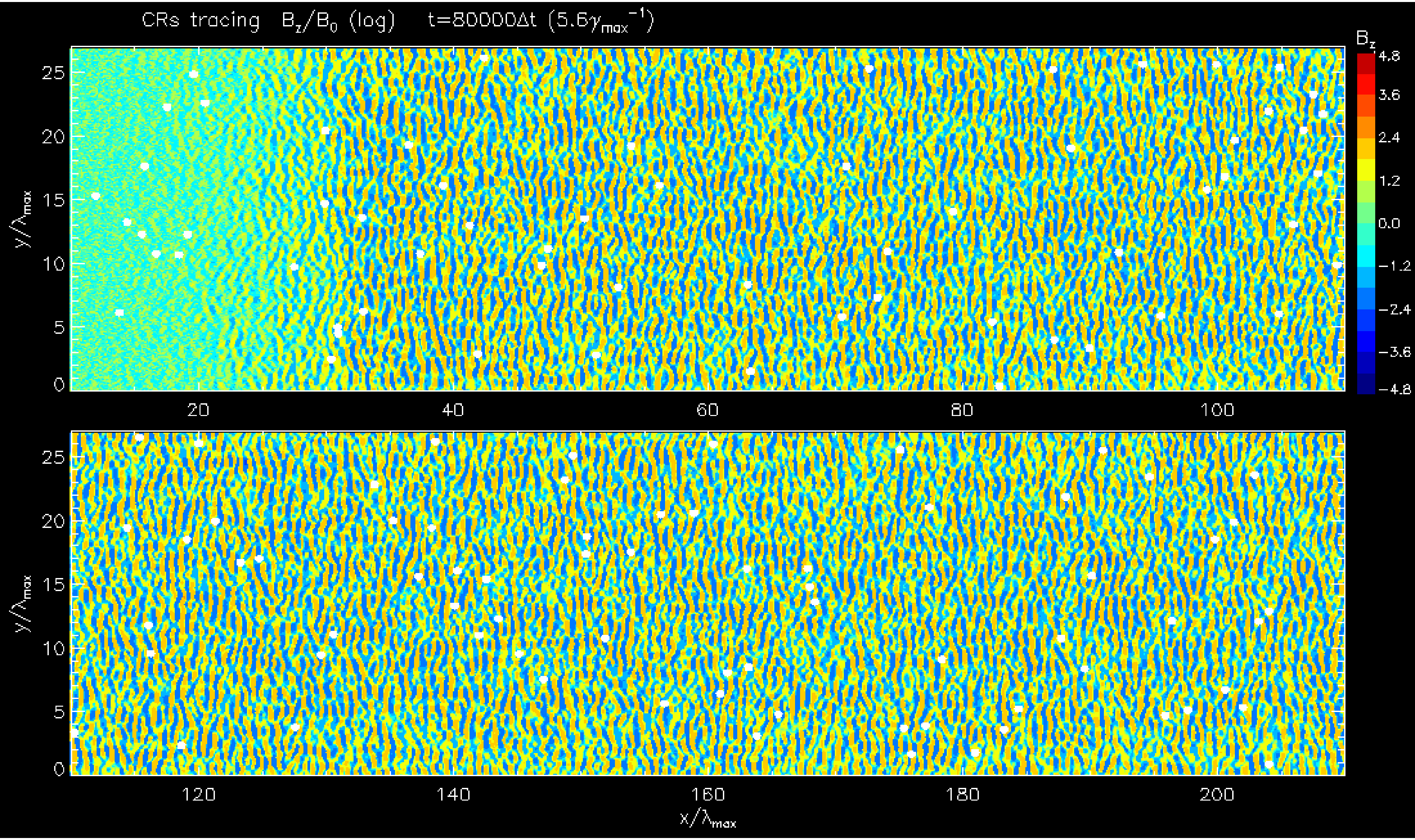
Tracing of the particles

(Ambient plasma **electrons**)

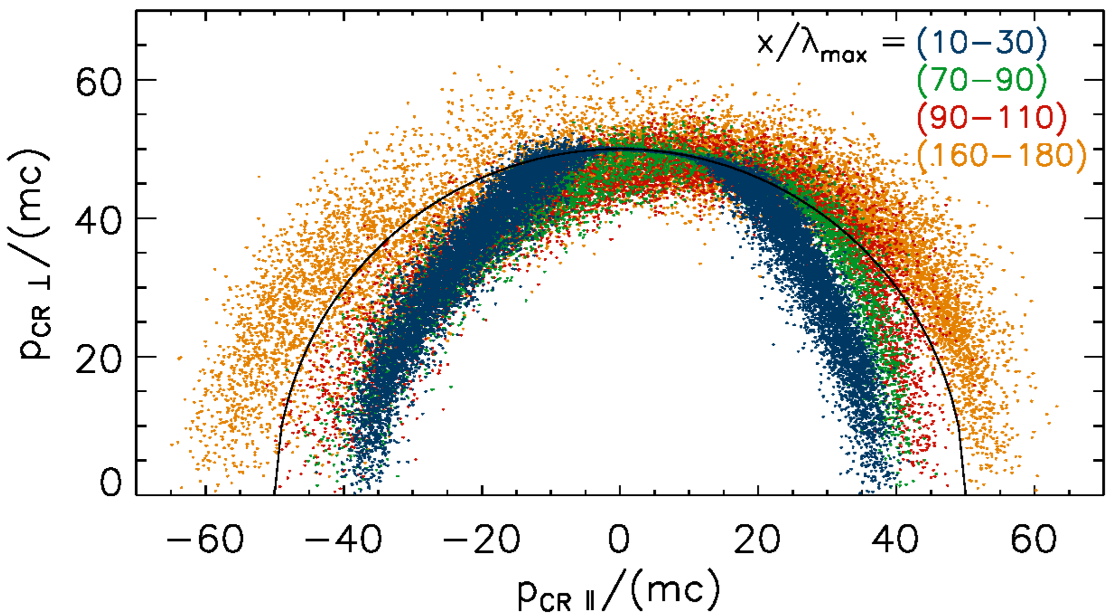


Tracing of the particles

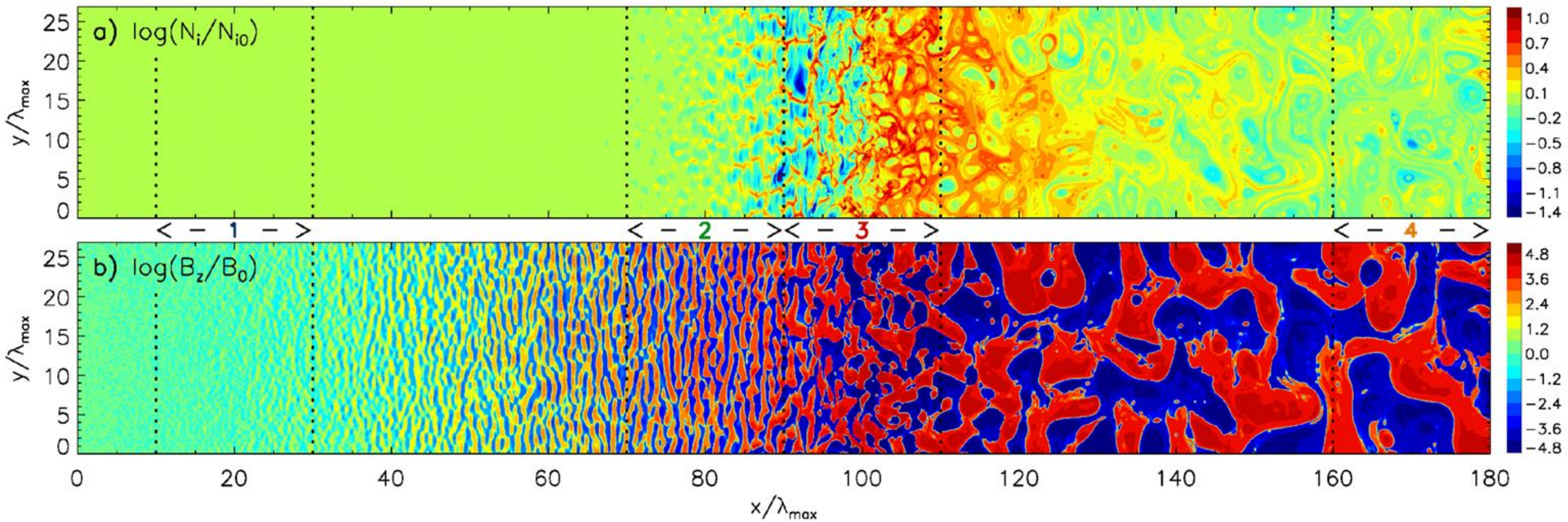
(**C**osmic **R**ays)



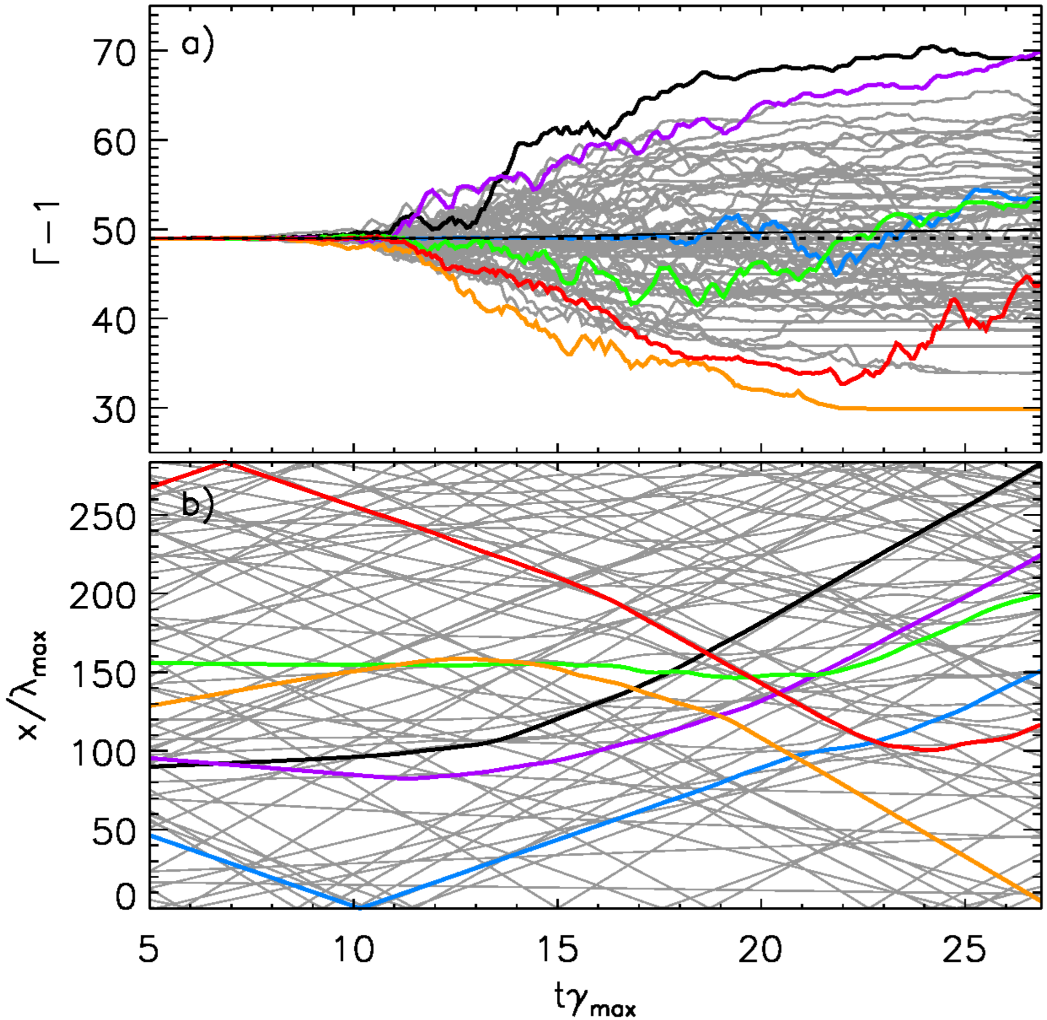
Evolution of the CR energy distribution



- CRs are scattered by electromagnetic turbulence.
- Most of the scattering is inelastic, due to turbulent electric field, and results in either acceleration or deceleration of individual CR particles.
- Significant modification of CR distribution; strong anisotropy is introduced.

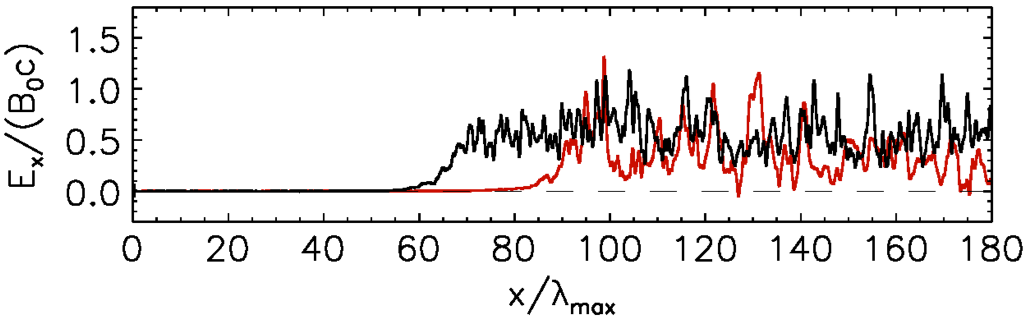


Evolution of the CR energy distribution

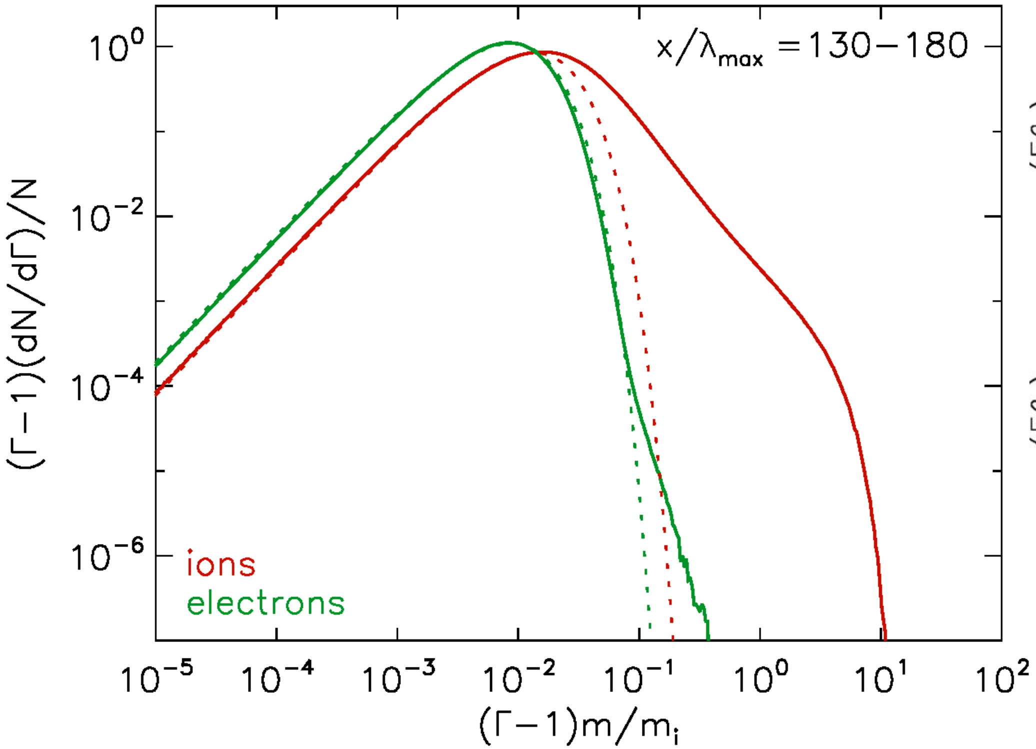


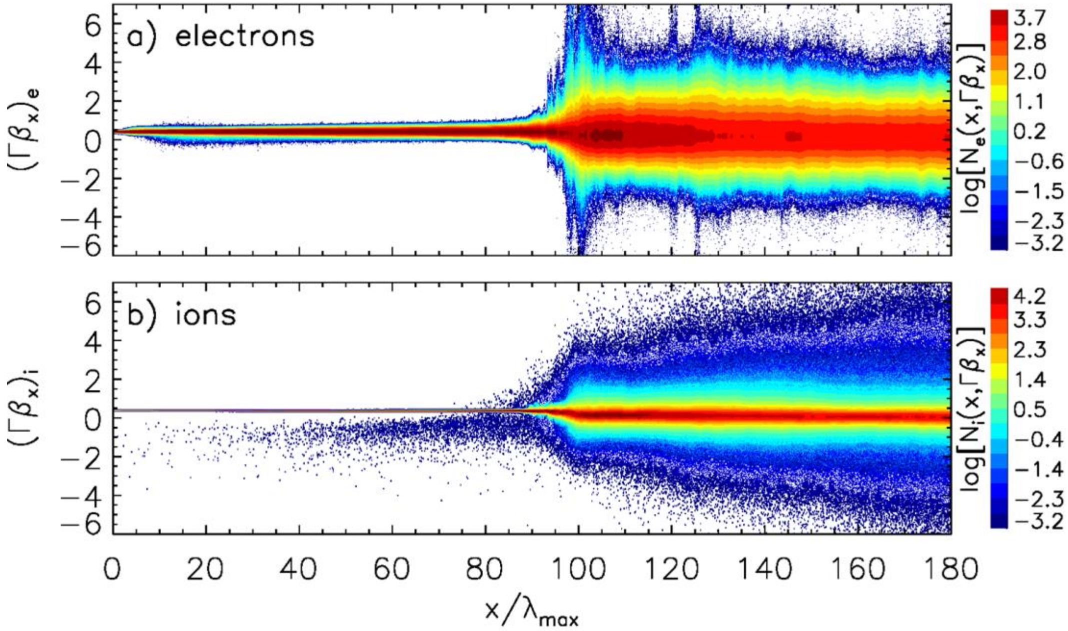
- The mean CR energy increases from the initial $\Gamma - 1 = 49$ to appr. 50.
- CRs traveling along the plasma flow are accelerated,
- whereas those moving against the flow become decelerated.

- E_x component is on average positive in the turbulent region – energy transfer rate $-E_x j_{ret}$.



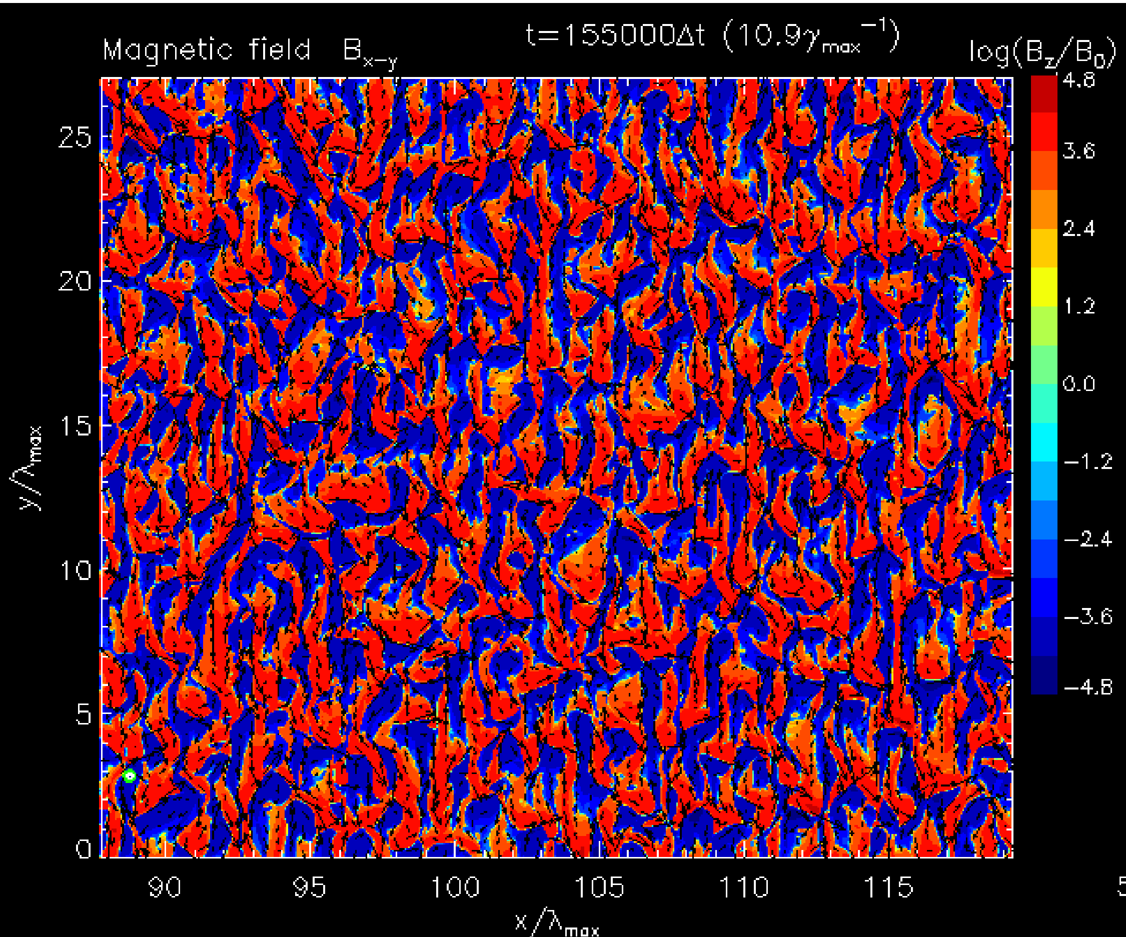
Ambient plasma heating



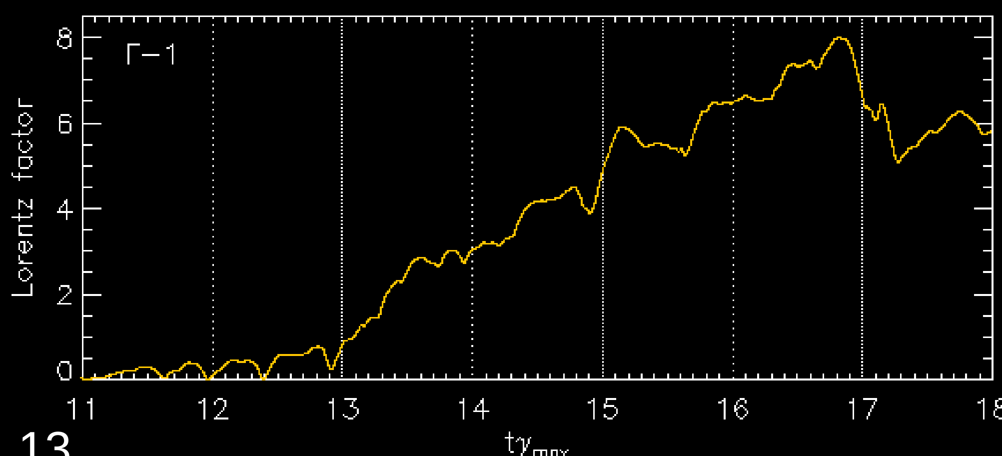


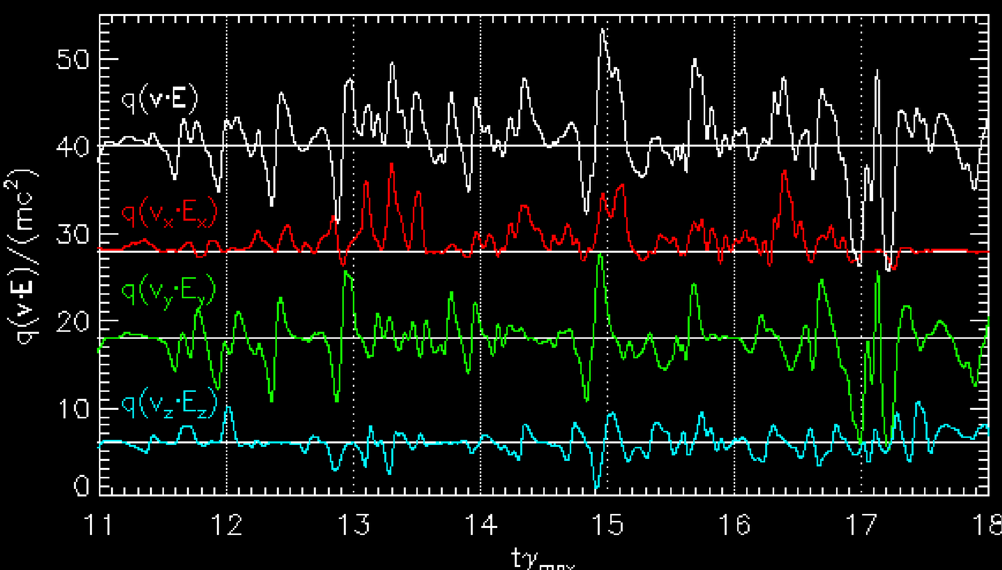
- Plasma is strongly heated by the electromagnetic turbulence.
- There is a bulk equipartition between electrons and ions.
- Electron energy distributions are close to thermal.
- Ion energy spectra have supra-thermal tails.
- A fraction of plasma ions are reflected from the shock-like structure generating additional turbulence through filamentation instabilities.

Ambient ion scattering

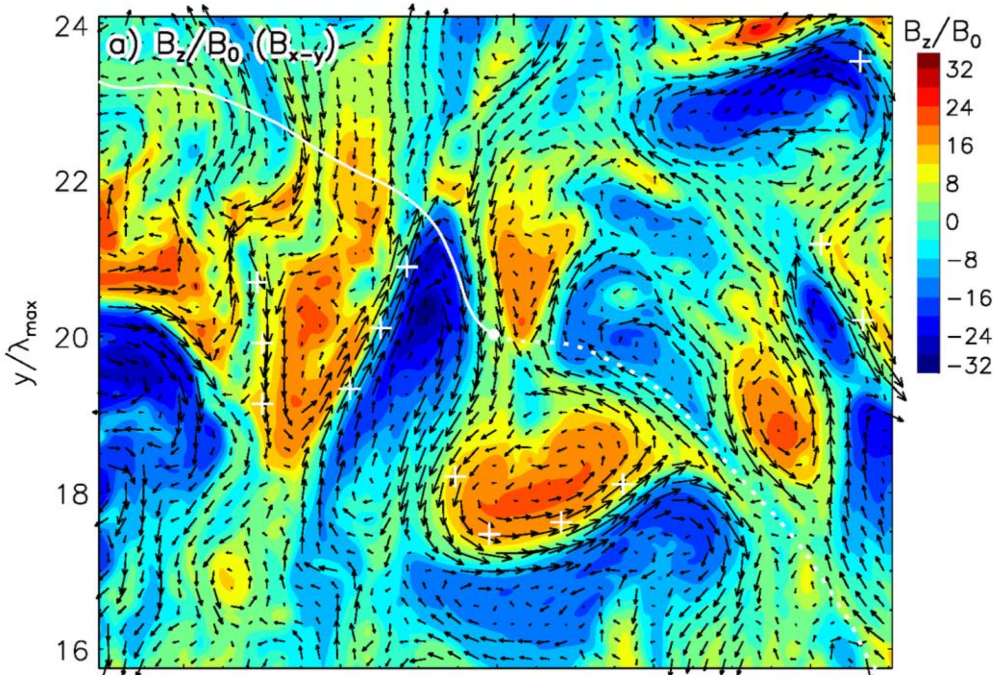


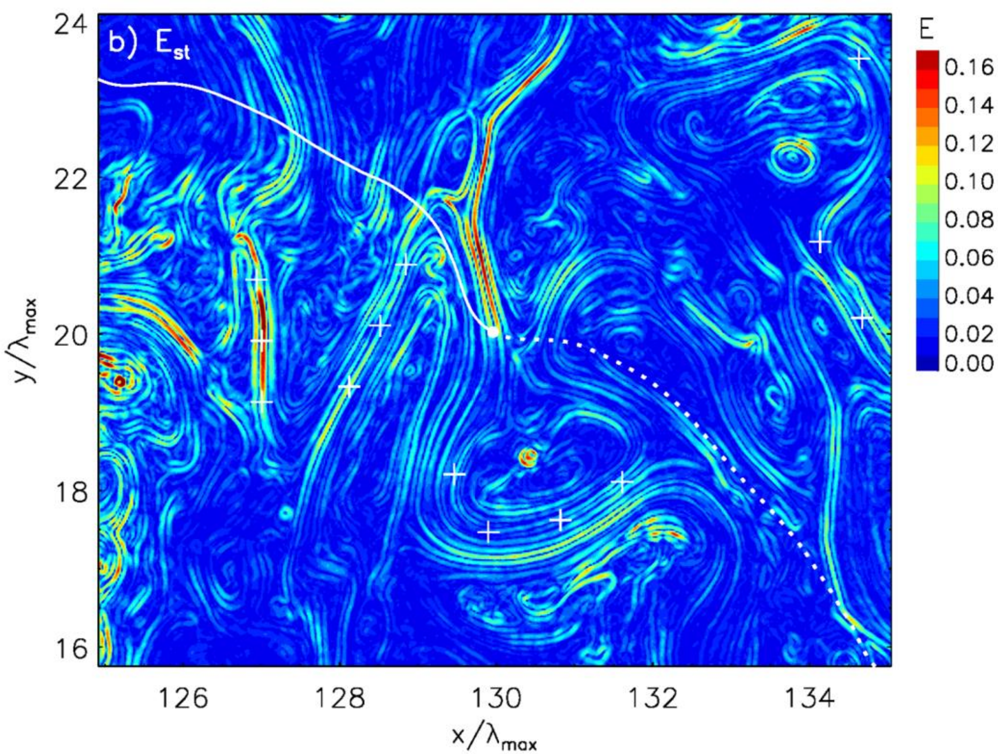
- Energy growth rate $d\Gamma/dt$ is strictly coincident with dot product $q(\boldsymbol{v}\cdot\boldsymbol{E})$.
- x-component of the dot product $q(v_x\cdot E_x)$ has an averaged positive value (like averaged E_x field).
- Plasma ions moving in positive x-direction are therefore accelerated.
- Positive motional electric field E_x is responsible for bulk particle acceleration.

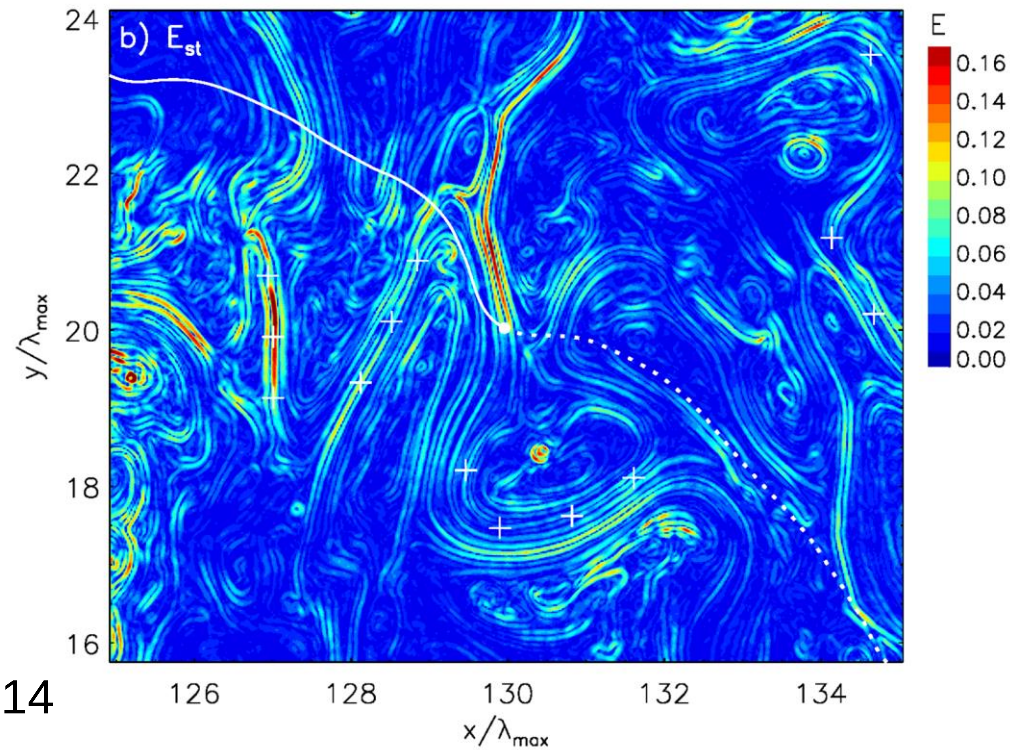




Microphysics of plasma heating







- Particles are scattered in energy by the turbulent electric field.
- Bulk plasma heating is not due to compression (nonadiabatic).
- Highest temperatures are reached in plasma cavities – at sites of large-amplitude electrostatic charge-separation field.

Summary

- MF is amplified to $\delta B \approx (15 - 20)\, B_0$ and saturates through deceleration of relative CR-to-plasma drifts.
- MF can be amplified to large amplitudes in SNR shock precursors before it is overtaken by the approaching shock.
- Additional amplification through compression in the shock-like structure, that should be present in realistic SNR shocks.
- SNR shock precursors are highly turbulent. Particles are heated efficiently by electromagnetic turbulence. Second-order Fermi processes lead to stochastic scattering of plasma ions.
- Turbulent electric field also inelastically scatters CRs, introducing significant anisotropy and modifying their energy distribution.

Thank you!