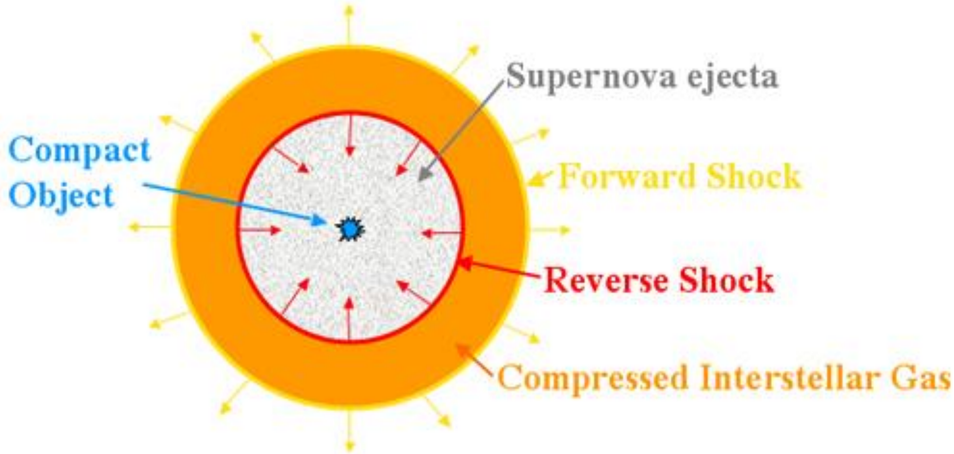
The Henryk Niewodniczański
Institute of Nuclear Physics
Polish Academy of Sciences

Kinetic Approach to Nonlinear Evolution of the Non-resonant Instability Upstream of a Young Supernova Remnant Shock

Oleh Kobzar, Jacek Niemiec, Martin Pohl

Supernova remnant

SNR is a diffuse, expanding nebula resulting from a supernova explosion



***Shock waves*:**

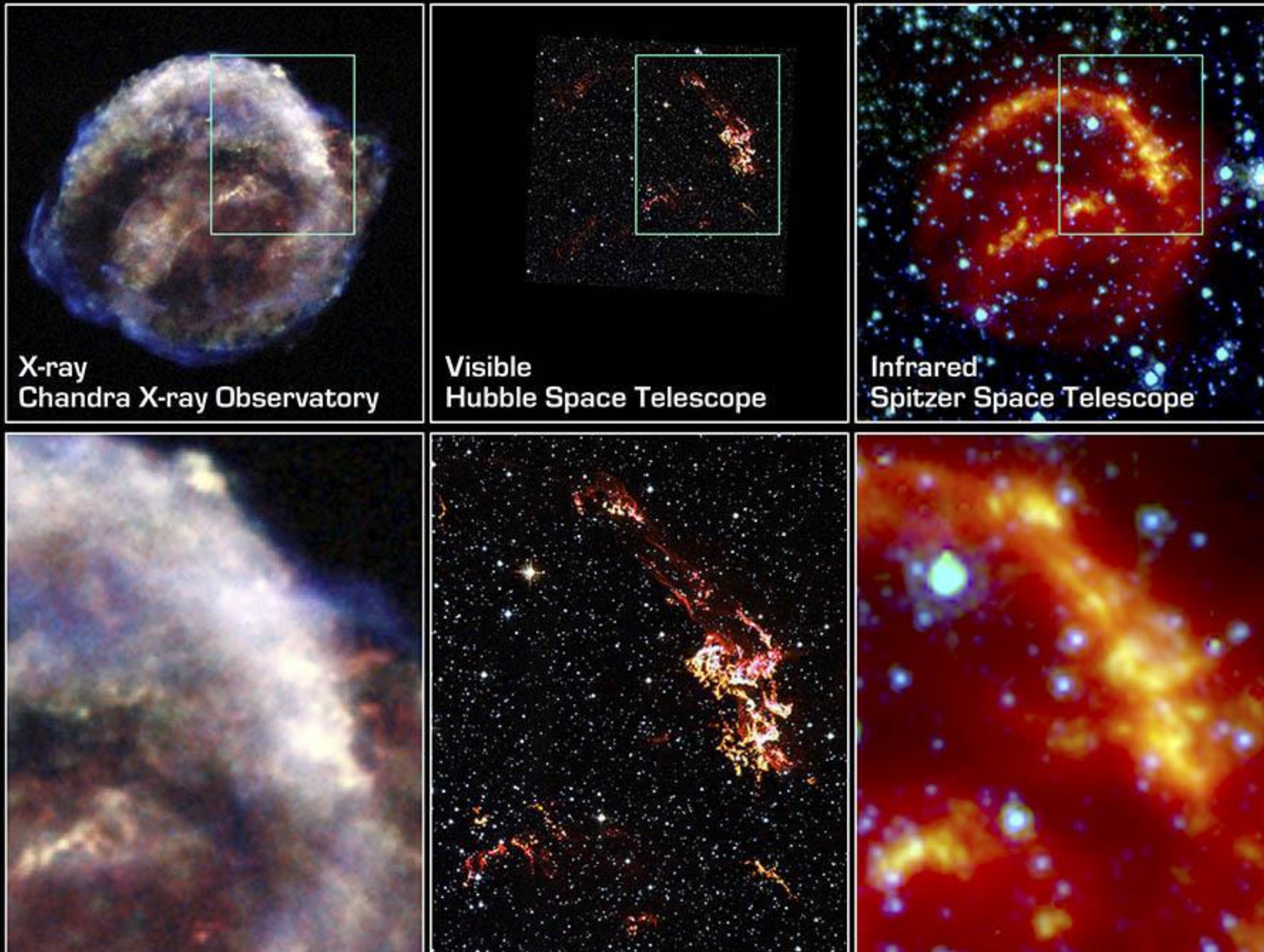
- Turn kinetic streaming energy into random thermal particle energy
- Accelerates particles
- MF amplification needed for efficient particle energization
- Young SNRs host fast shocks and are assumed to be efficient high-energy particle accelerators

***Peculiarities of young SNRs*:**

- Formation of the shock waves
- Shocked material is heated to millions of Kelvins
- Emission of thermal X-rays

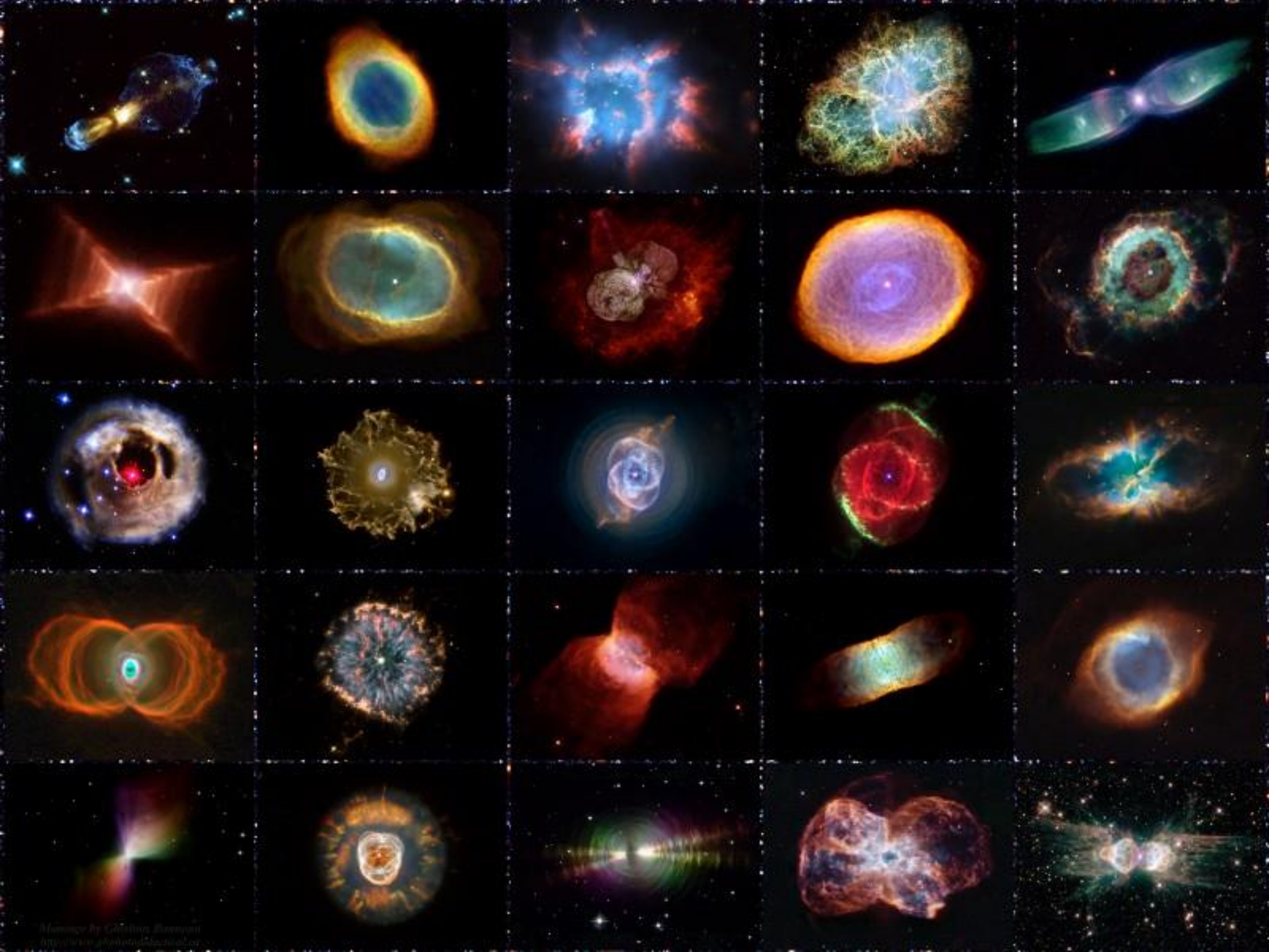
Role of the magnetic fields

- Efficient particle production in the diffusive shock acceleration process requires turbulent amplified magnetic fields in the shock's precursor
- Field amplification can be provided through the CR current driven non-resonant instability
- Effective growth of non-resonant instability requires the shock with high Mach numbers, typical for the young SNR-s



Kepler's Supernova Remnant • SN 1604 ssc2004-15b

NASA, ESA / JPL-Caltech / R. Sankrit & W. Blair (Johns Hopkins University)



Kinetic PIC simulations for SNR astrophysics

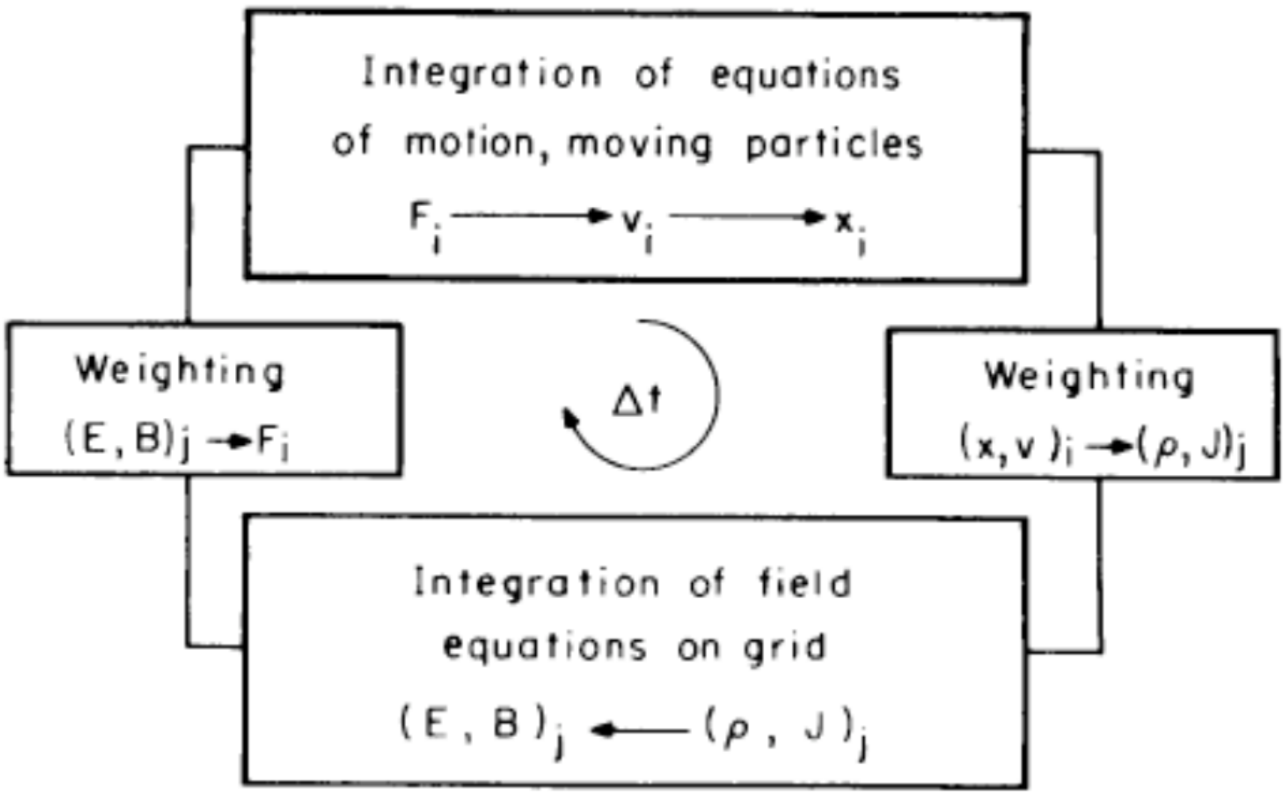
Topics today:

- Particle-In-Cell simulation method
- Applications
  - magnetic field turbulence amplification near shocks with efficient particle acceleration
  - global modeling of shock formation and particle (pre-)acceleration processes

Particle-In-Cell simulations

An ***ab-initio*** method for collisionless plasma

- solving Maxwell's equations on the numerical grid
- integrating relativistic equations of motion for particles in the self-consistent electromagnetic field



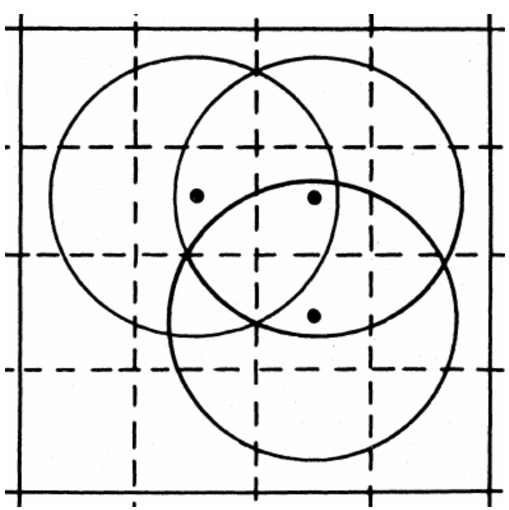
Numerical model of collisionless plasma

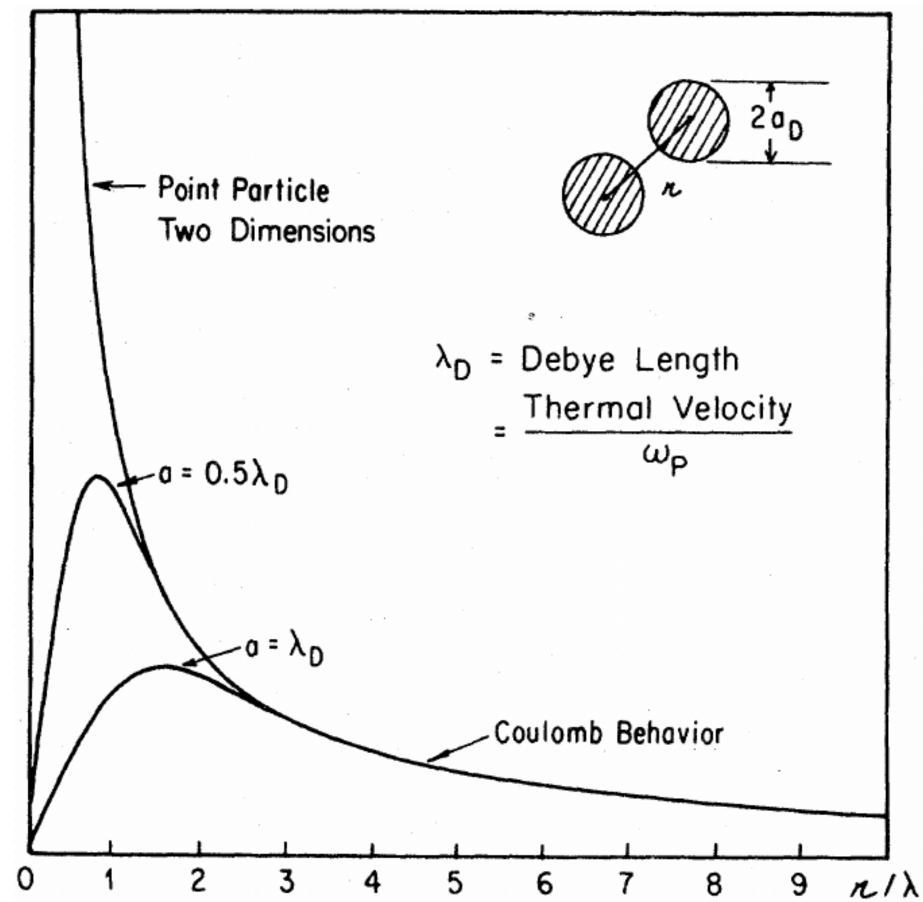
Definition of plasma $L >> \lambda_D$

Typical astrophysical system $N_D >> 1$

Basic physical condition for plasma $\frac{\langle E_{kin} \rangle}{\langle E_{pot} \rangle} \gg 1$

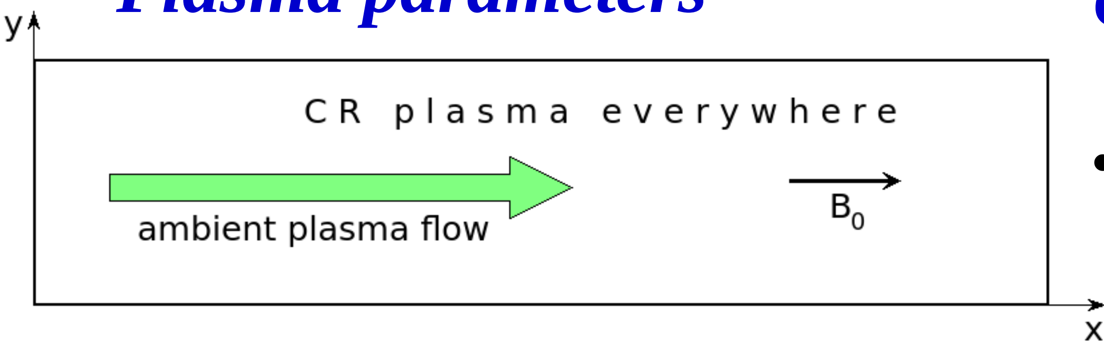
- numerical grid for E-M fields
  - filtering short-range forces
- finite-size particle model
  - cutting-off of short-range Coulomb scattering





Simulation setup

Plasma parameters



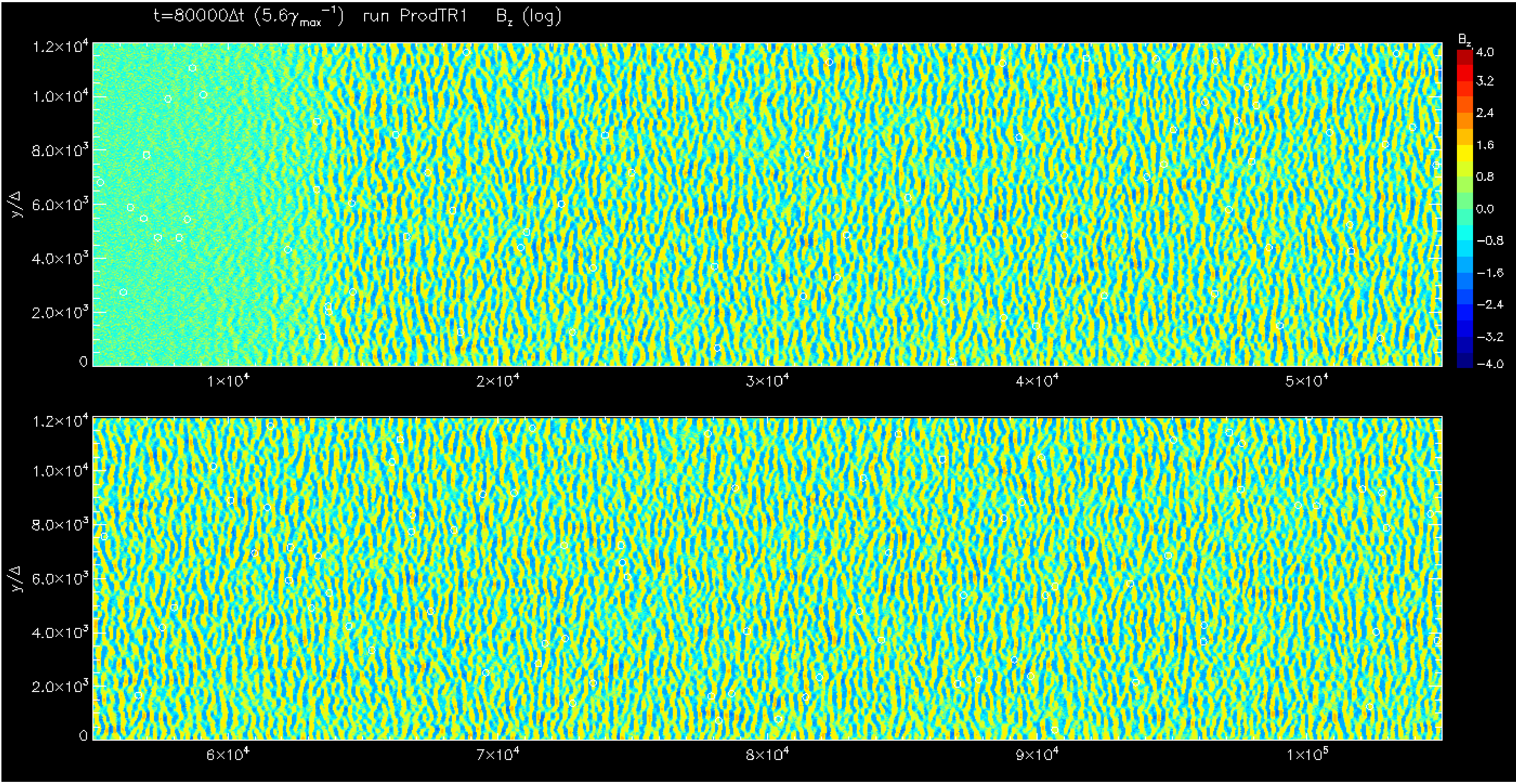
- Reduced ion to electron mass ratio $m_i/m_e = 50$
- CR to ambient plasma relative speed $v_{rel} = 0.4\, c$
- CR to ambient plasma density ratio 1/50
- Initial CR relativistic Lorentz factor $\gamma = 50$
- Initial plasma is cold and weakly magnetized

Computation

- 2D3V kinetic PIC simulation with box size $130{,}000 \times 12{,}000$ cells
- 5.6×10^{10} macroparticles
- ~1 month wall-time of parallel code execution with 9600 CPU-s

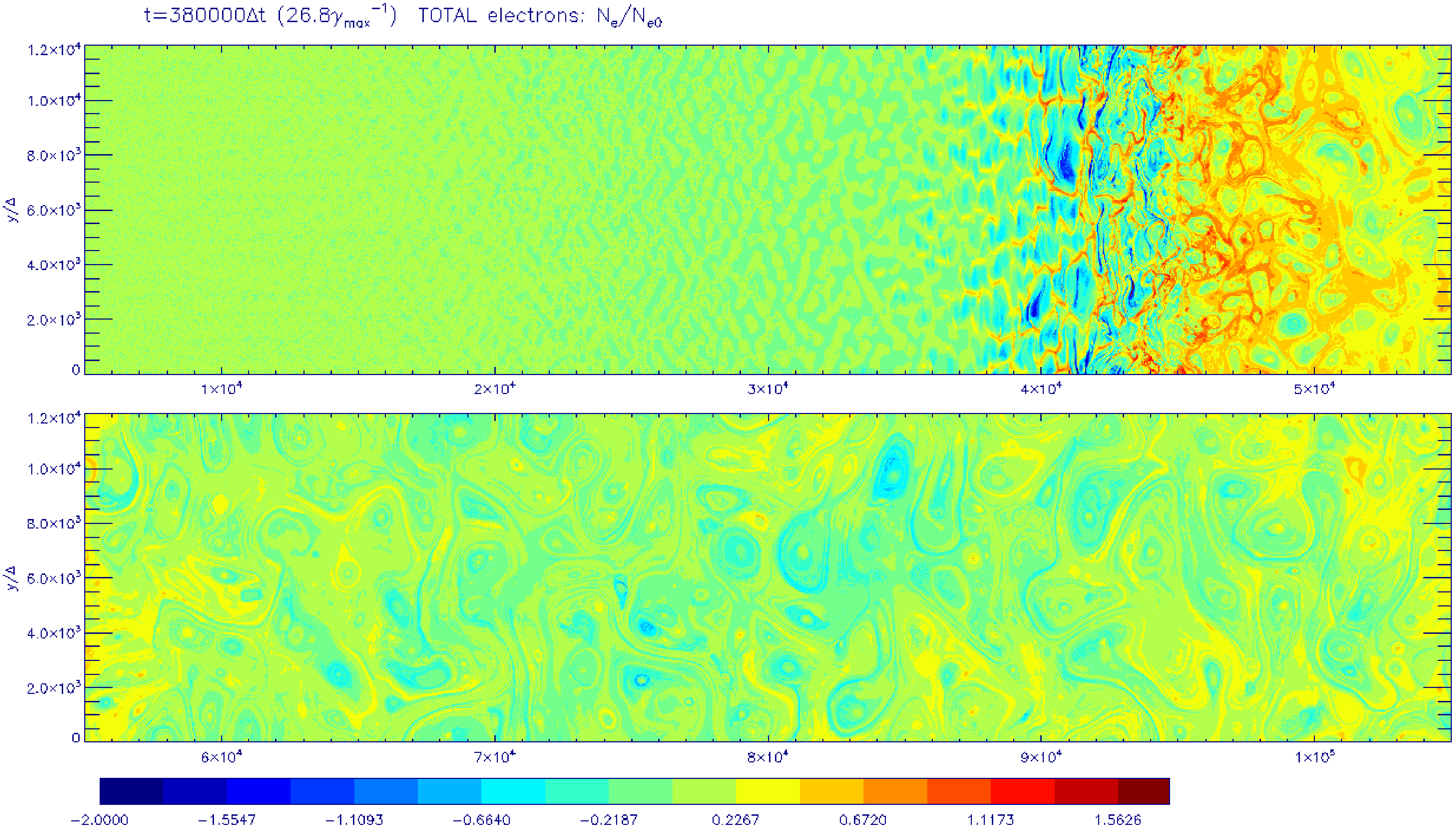
Global evolution of the nonresoant instability

(B_Z, tracing of arbitrary chosen 200 CR particles)



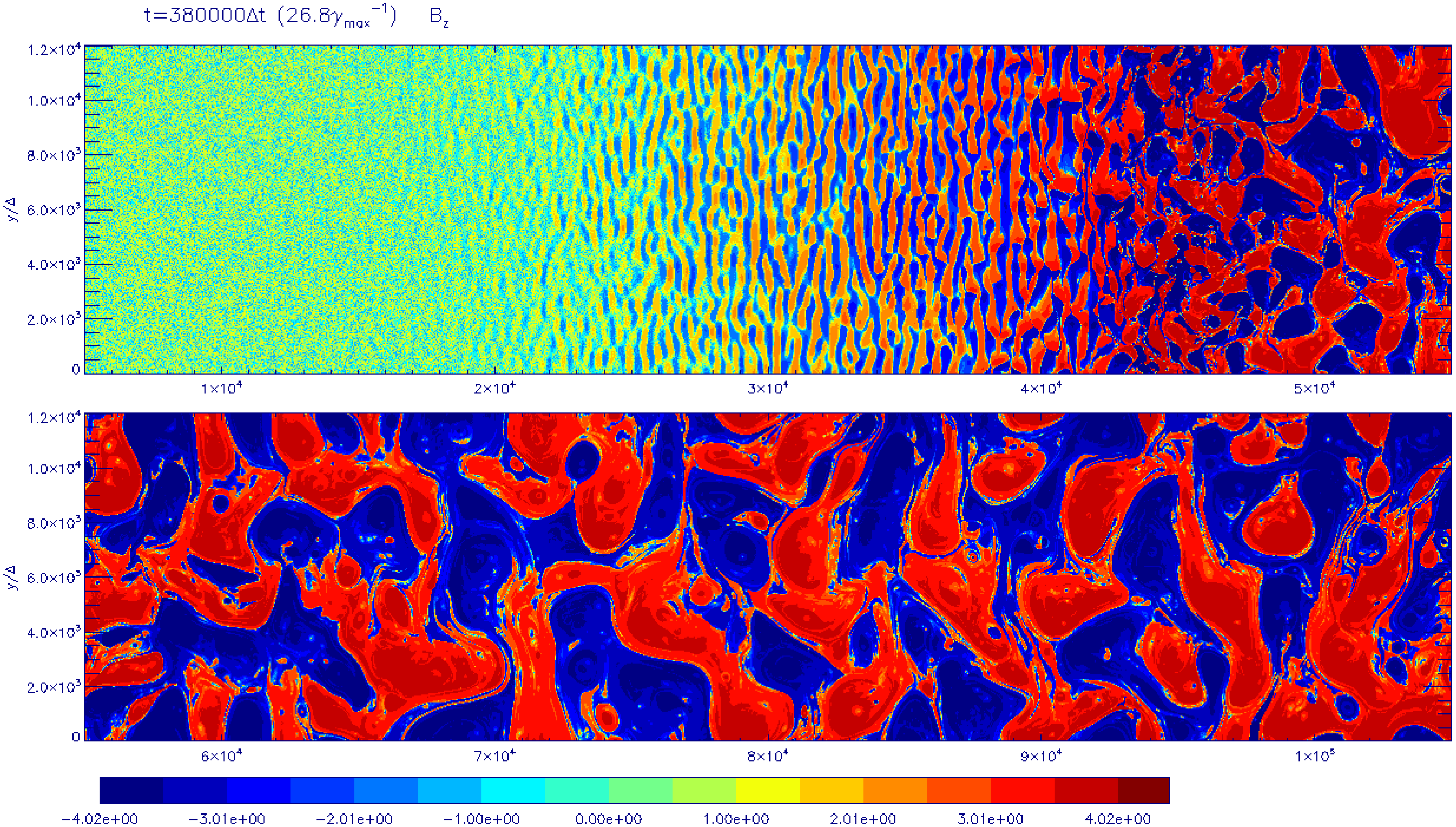
2-D map of electron density

snapshot for t = 380,000 Δt (**26.8** $\gamma_{\mathbf{max}}^{-1}$)



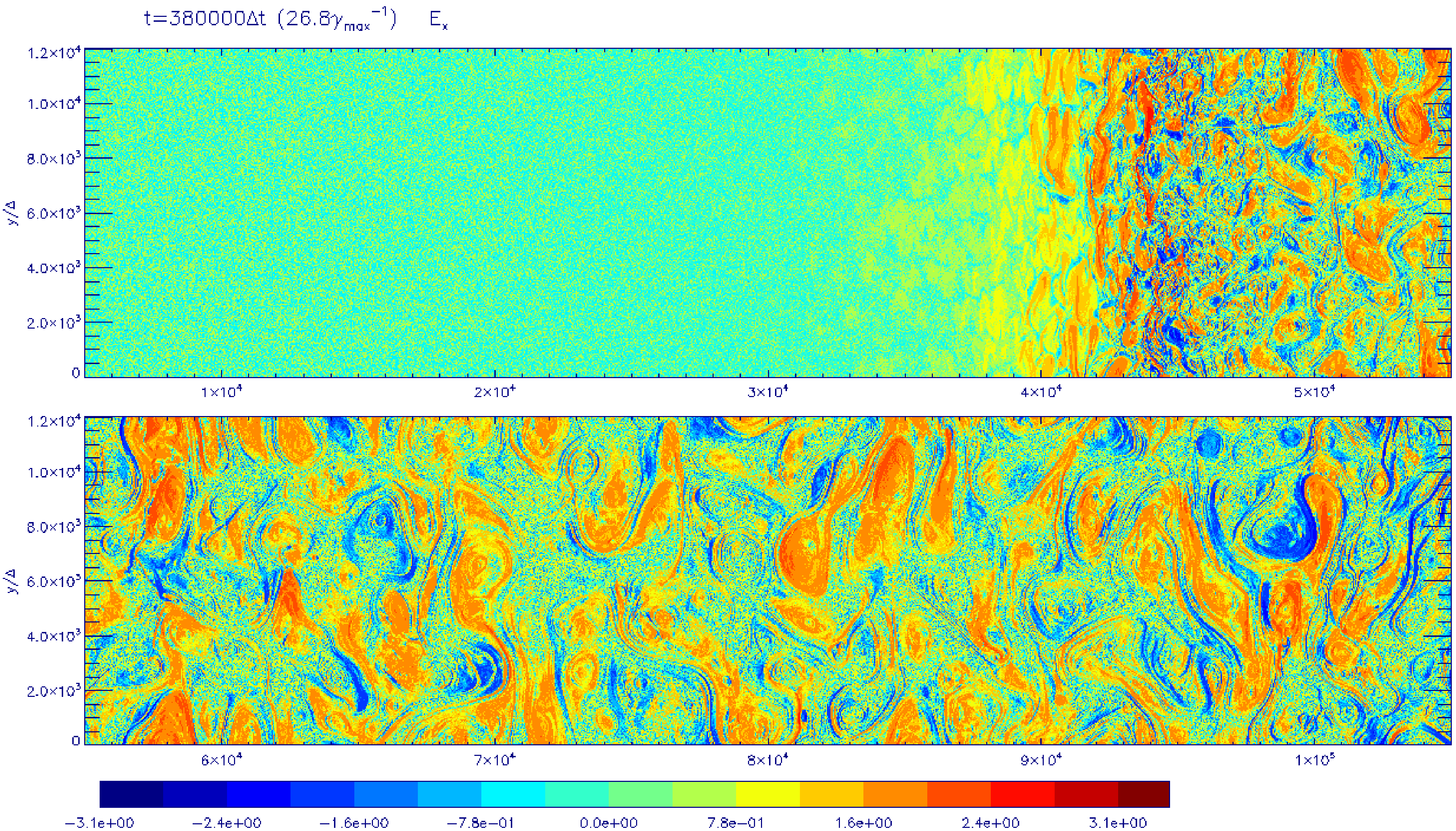
2-D map of magnetic field (B_z)

snapshot for t = 380,000 Δt (**26.8** $\gamma_{\mathbf{max}}^{\mathbf{-1}}$)



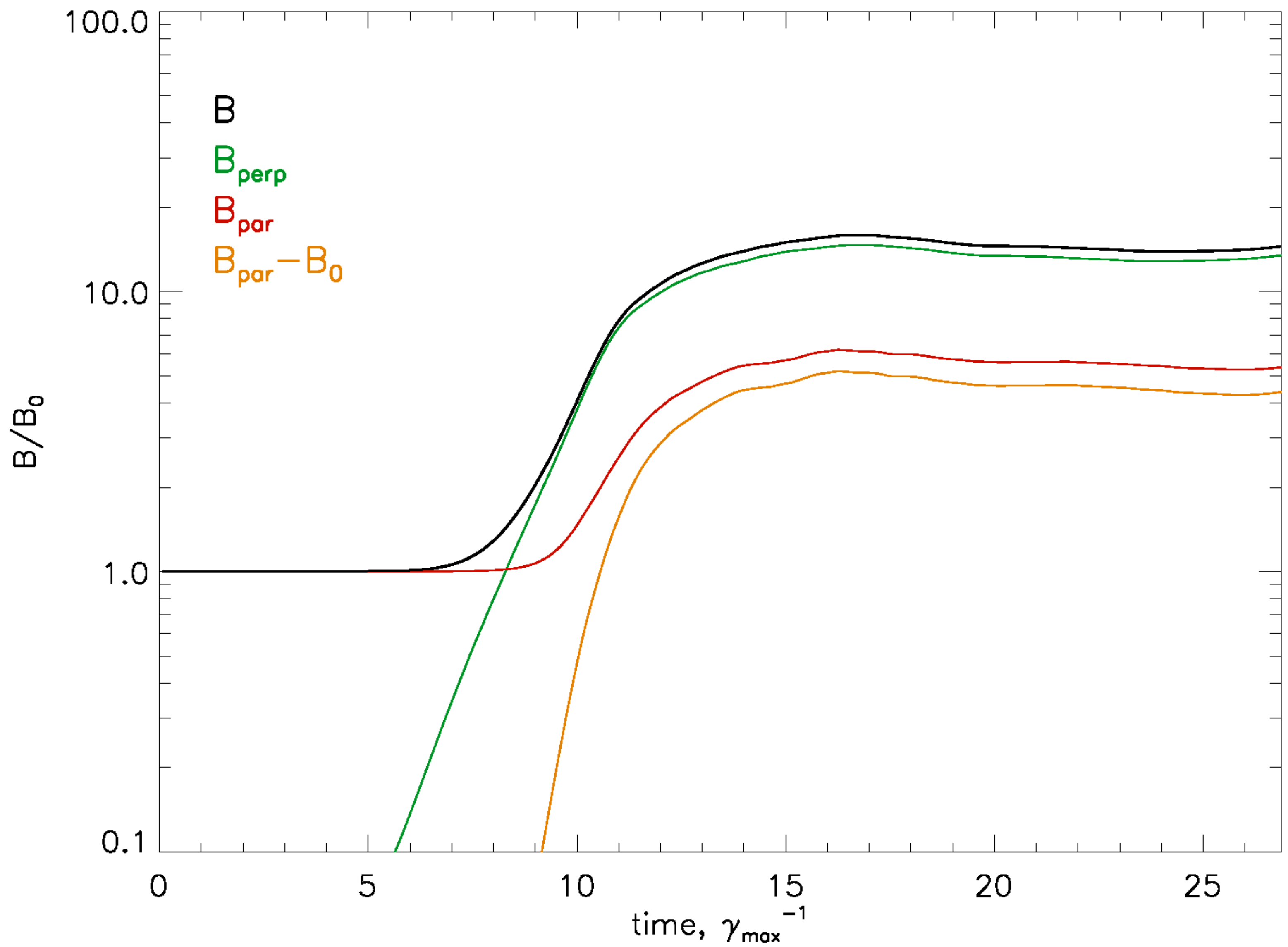
2-D map of electric field (E_x)

snapshot for t = 380,000 Δt (**26.8** $\gamma_{\mathbf{max}}^{\mathbf{-1}}$)

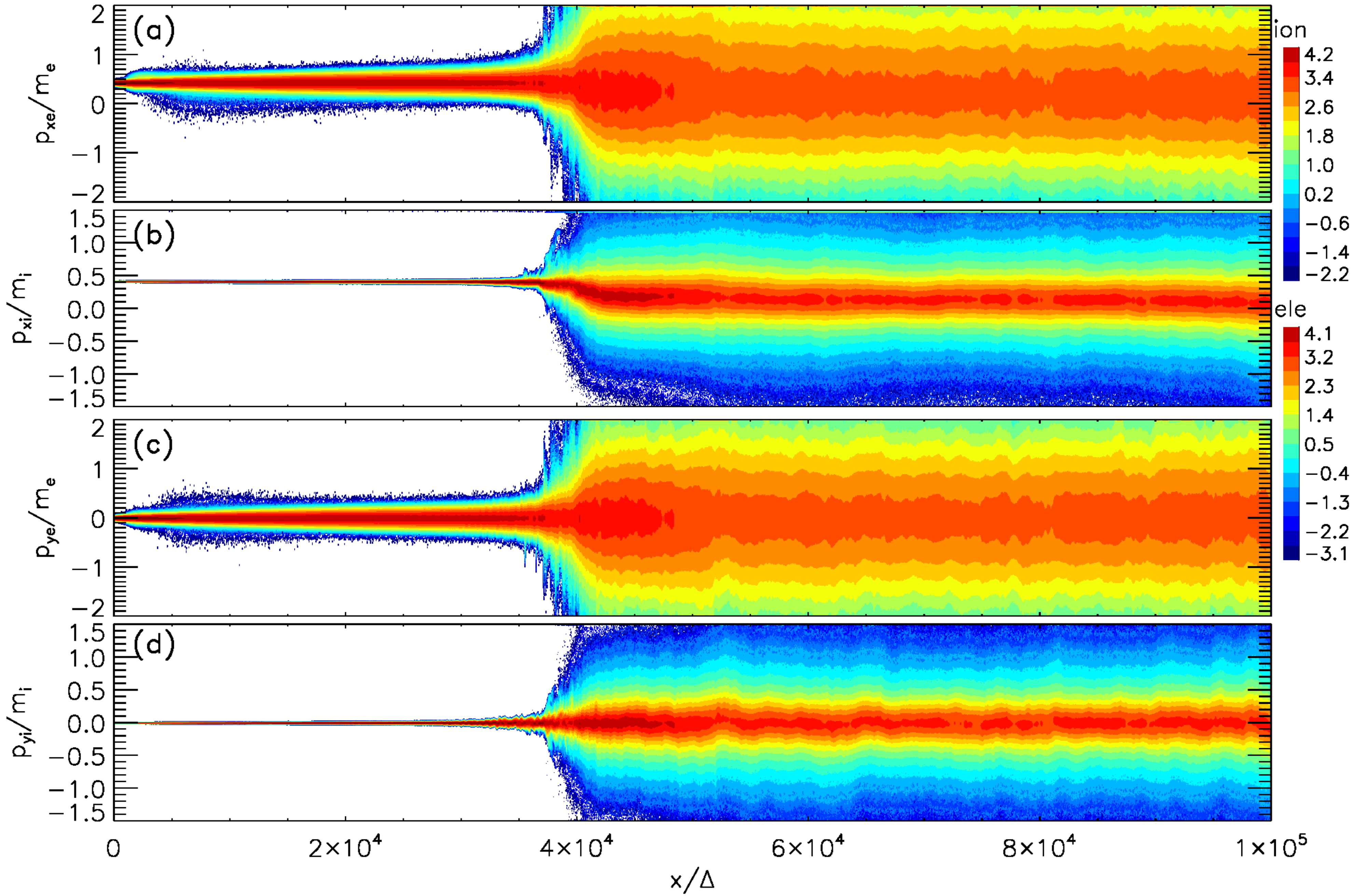


Growth of the turbulent magnetic field

(non-resonant instability upstream of the shock)

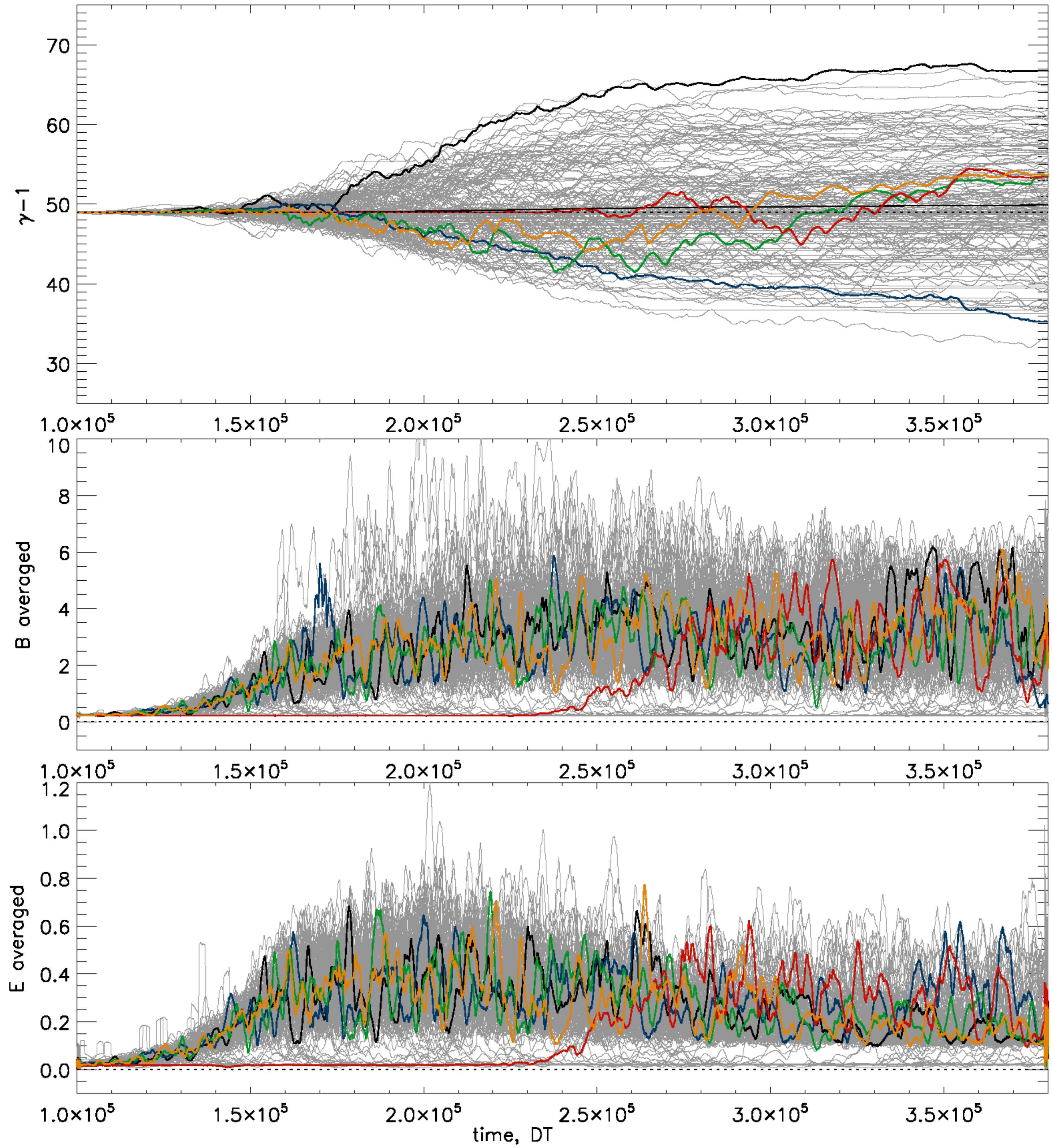


Phase-space distributions t = 320,000 Δt (**22.6** γ_{max}^{-1})



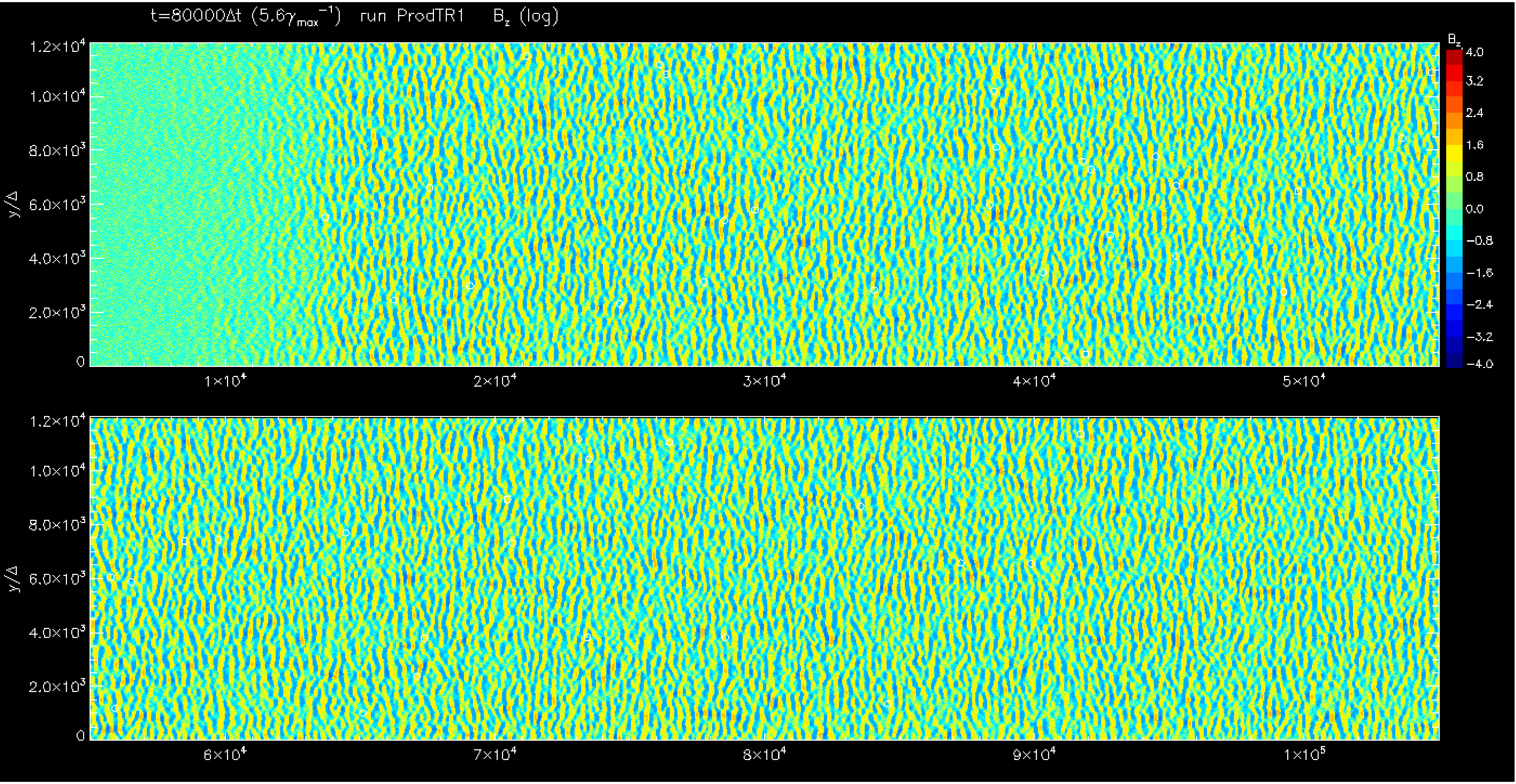
CR distribution

- Back-reaction of magnetic turbulence upon CRs is observed
- CR distribution strongly modified
- Average CR Lorentz factor increases in the simulation frame (momentum exchange between CR and ambient plasma)
- Individual CR particles can be accelerated or



Tracing of accelerated CRs

(54 particles reaching Lorentz factor γ **> 68**)



Conclusions

- Application of open boundary conditions in our setup allows us to investigate both the spatial properties of non-resonant instability and its temporal evolution in the precursor of a young SNR parallel shock
- We re-confirm the effects of the saturation of magnetic field growth due to the back-reaction of CRs on the background plasma, observed earlier in simulations with periodic boxes
- New features in the flow (e.g., a shock-like compression structure) are observed at later stages of the system evolution
- Tracing individual particle trajectories enable detail study of the saturation processes, CR interactions with electro-magnetic turbulence, ambient plasma heating, etc.

Dziękuję za uwagę!