Magnetic-field amplication near non-relativistic shocks

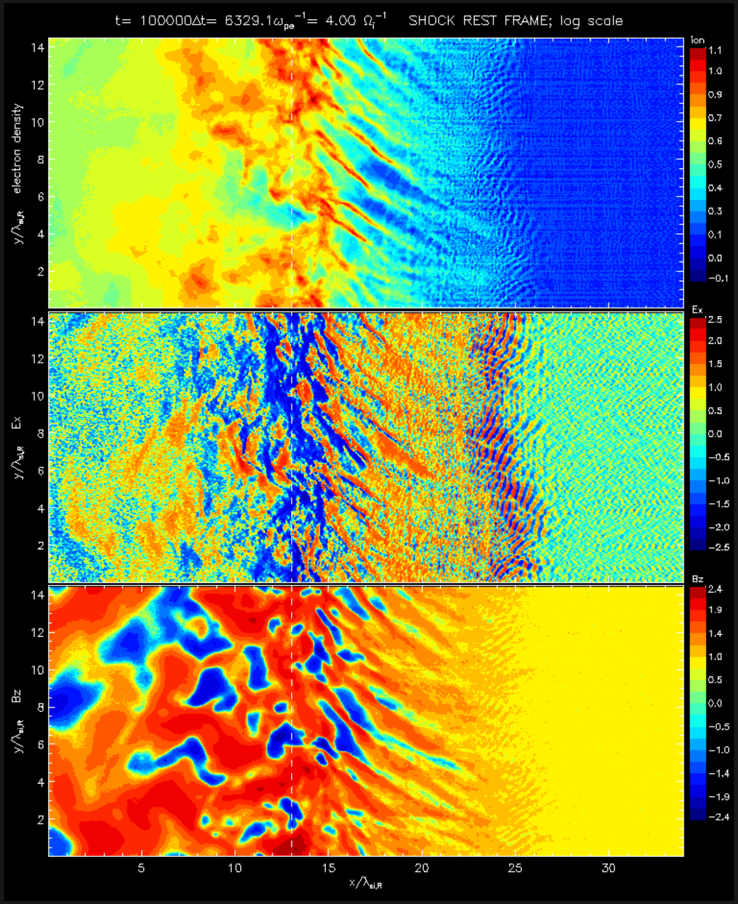
Martin Pohl

with Jacek Niemiec, Oleh Kobzar, and Artem Bohdan

Introduction

- Introduction
- Shock acceleration
- Magnetic turbulence
- New simulations of Bell‘s mode

Shock acceleration



Ion density

E_x

B_z

Injection relates to shock structure

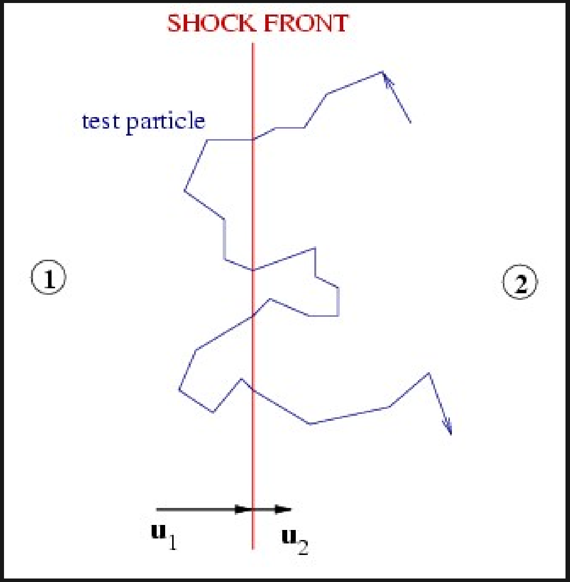
Structure of a perpendicular Shock

Thickness: Ion Larmor radius

2.5D PIC Simulation

(Wieland et al.)

Shock acceleration



Elastic scattering on both sides of shock

→ Pre-acceleration required

→ Energy gain per cycle $\delta E/E = v_s^2$ (Shock speed v_s)

→ Acceleration rate depends on scattering rate on both sides

→ How is the magnetic turbulence produced?

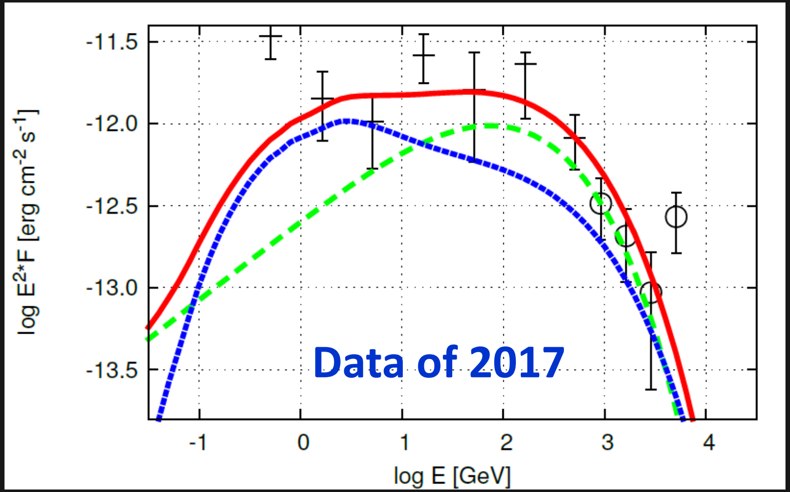
Shock acceleration

Is there evidence for strong magnetic turbulence?

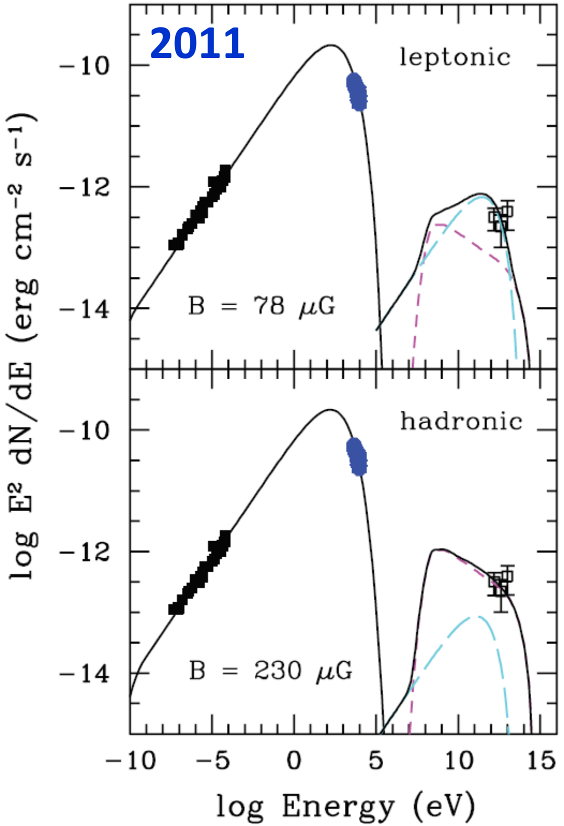
Yes: Tycho's SN remnant

γ-ray / X-ray ratio → magnetic field

With damping B>170 μG



VERITAS papers



Shock acceleration

Radiation modelling indicates (turbulently) amplified magnetic field

Most radiation is produced downstream

➔ a strong magnetic field downstream is sufficient

Shock acceleration relies on turbulent magnetic field upstream

Magnetic turbulence

Efficient shock acceleration requires

- Build-up of turbulence far upstream
- High scattering efficiency of the turbulence
- Very rapid build-up of turbulence

Magnetic turbulence

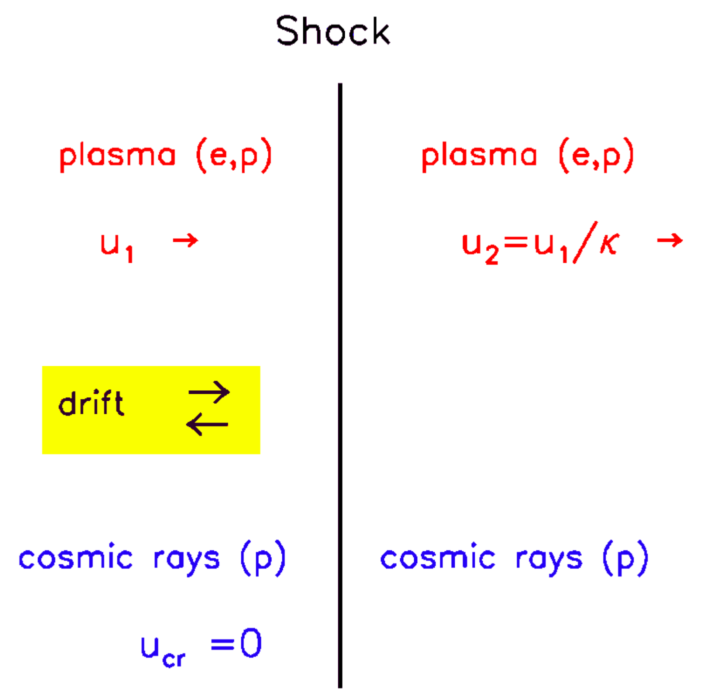
What drives strong magnetic turbulence?

Upstream:

Relative motion

of cosmic rays

and cool plasma



Magnetic turbulence

Isotropic, slowly drifting cosmic rays

PIC simulations in periodic box

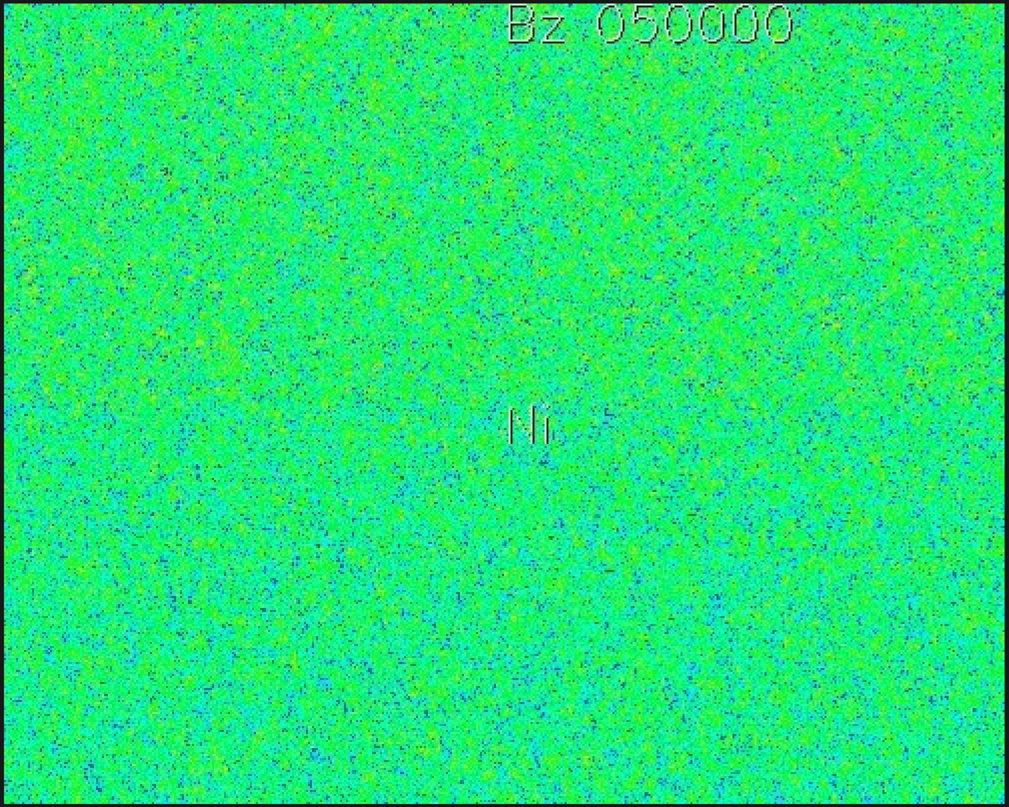
2.5D only!

Non-resonant parallel mode seen!

(predicted by Bell 2004)

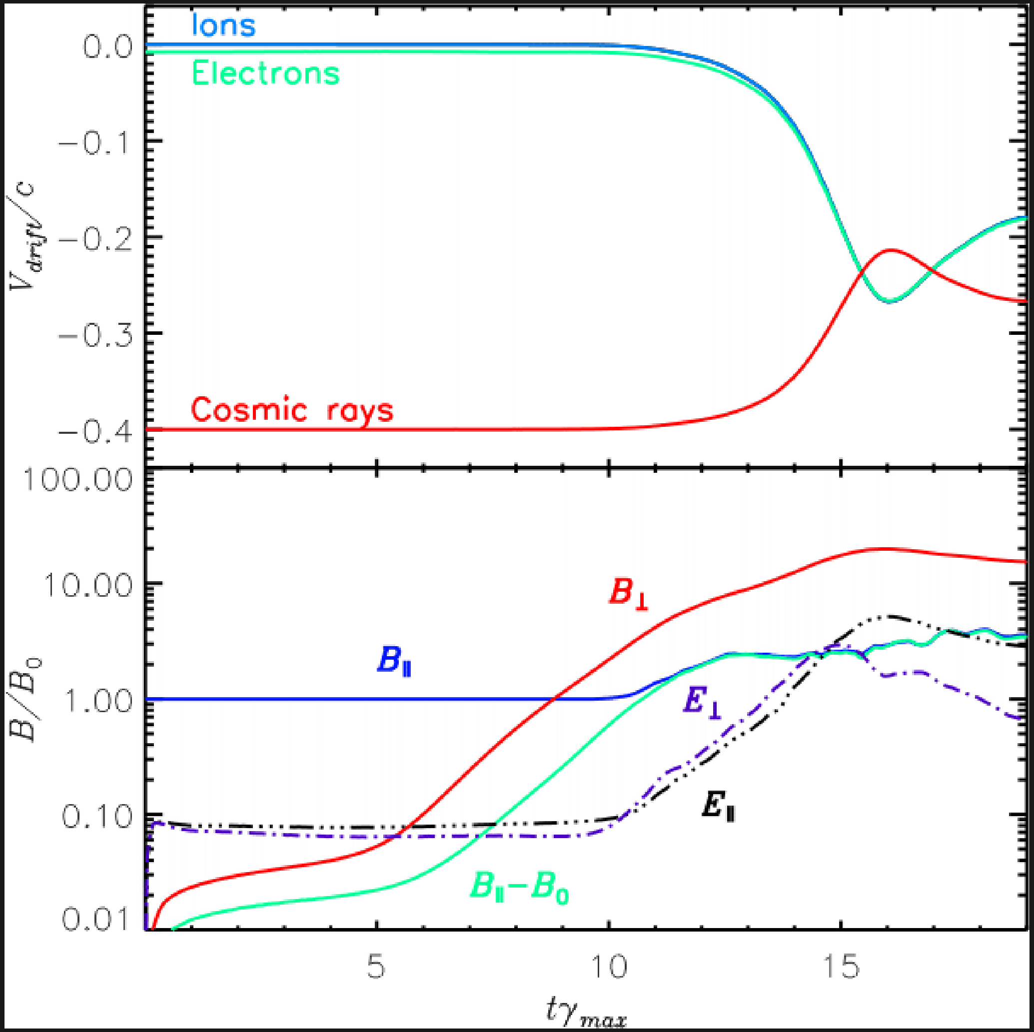
B_z

N_i



Magnetic turbulence

Bell’s wave mode



- Drifts speeds align
- Peak MF ~ 20 B_0
- Decays after peak
- Fast turbulent motion

Stroman et al. 2009

Magnetic turbulence

Earlier simulations of Bell‘s mode used periodic boundaries

Issues:

Spatial structure ignored

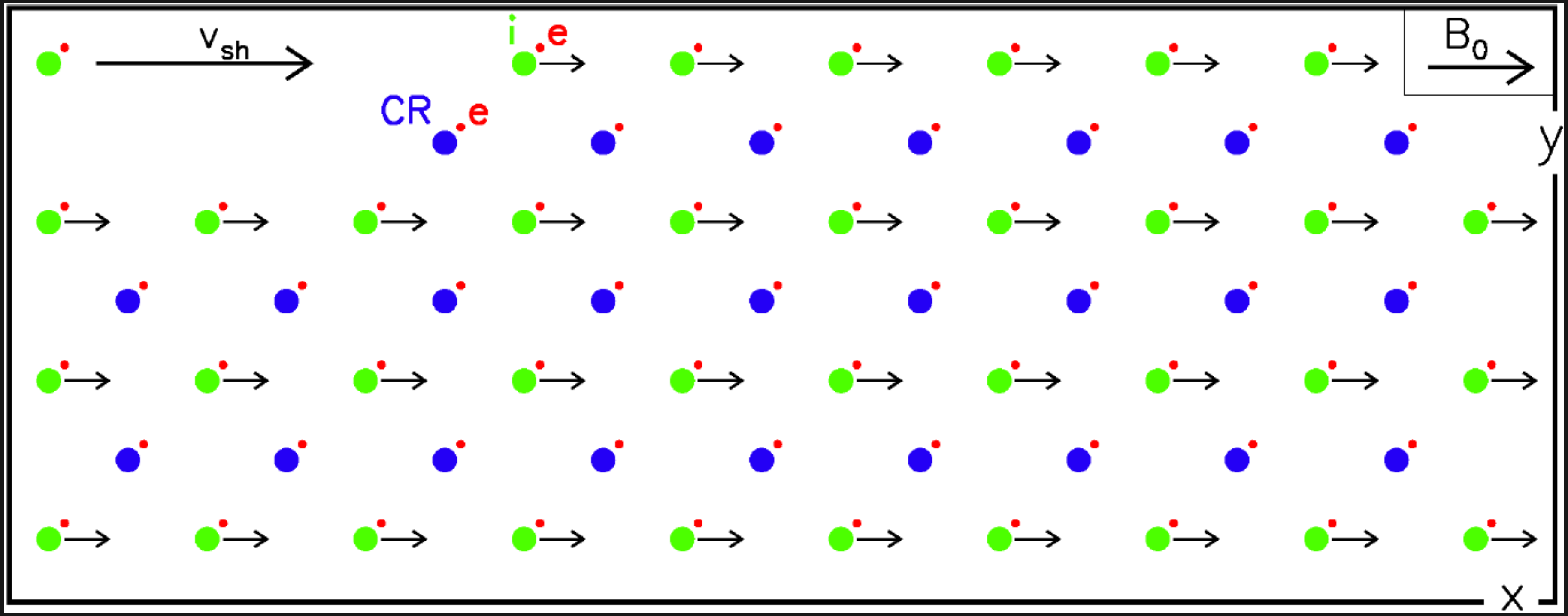
Violation of continuity by bulk deceleration

Neglect of interaction with „fresh“ plasma

Can we run PIC simulations with open boundaries?

Bell‘s mode

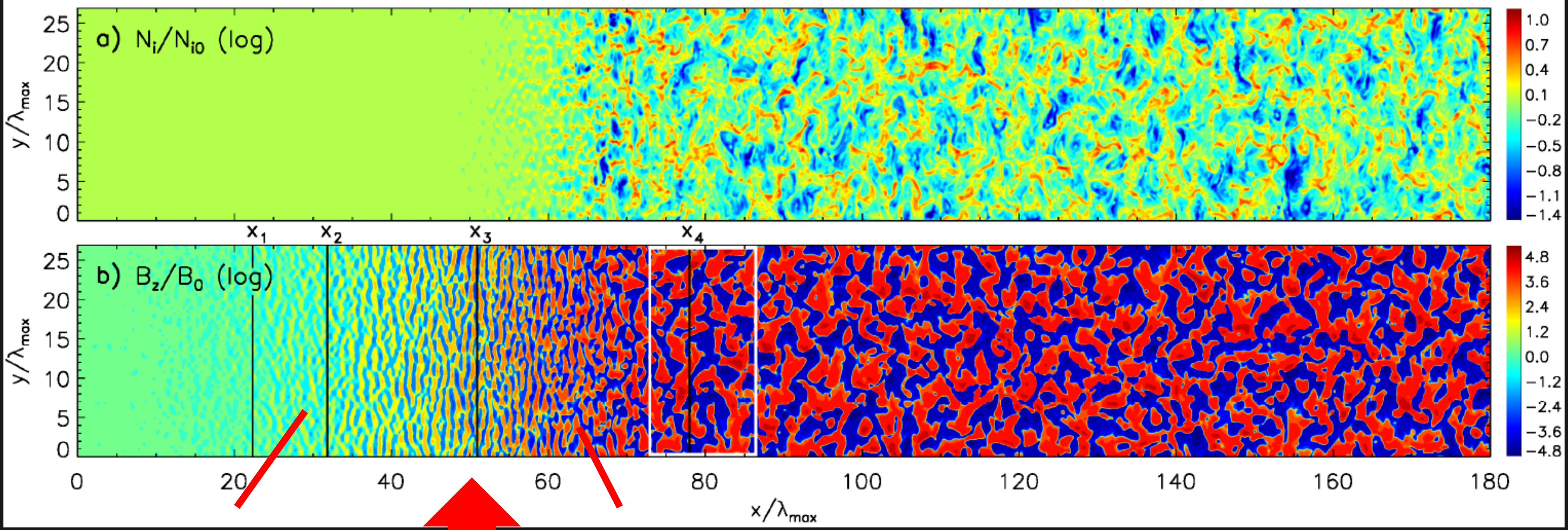
Setup of simulation



Kobzar et al. 2017

Bell‘s mode

Ion density and magnetic field B_z at time close to saturation



Linear phase

Transition to saturation

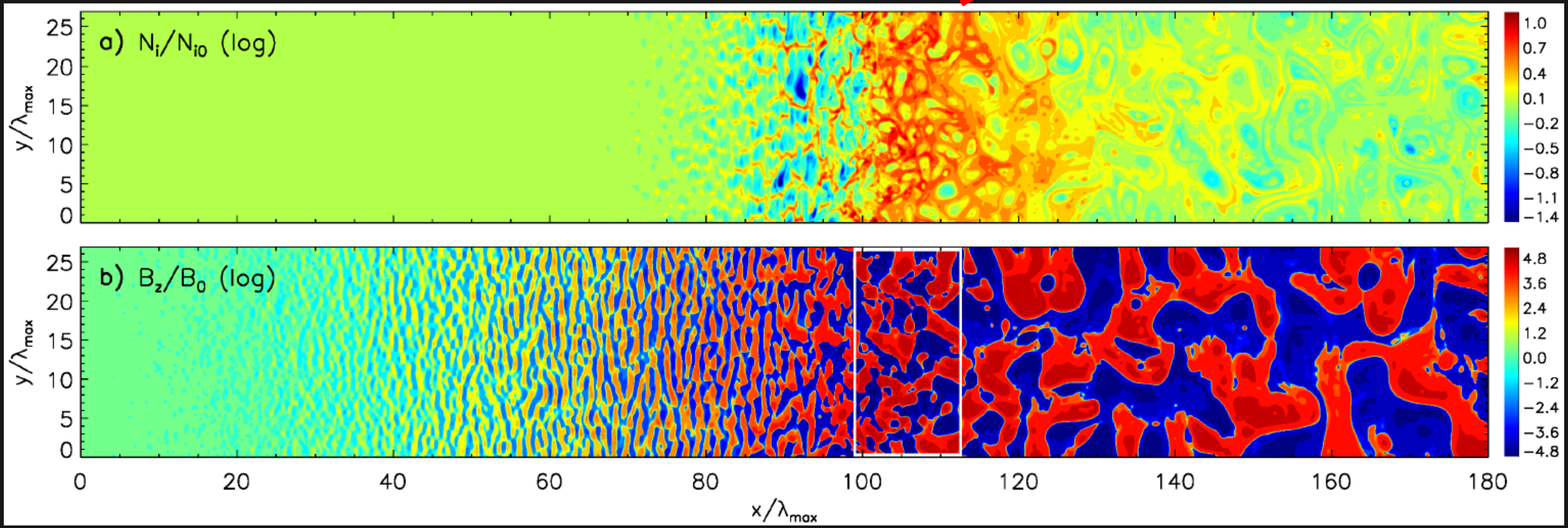
Temporal development mapped spatially

Bell‘s mode

Ion density and magnetic field B_z at the end of the simulation

$T=26.9\ \gamma_{max}^{-1}$

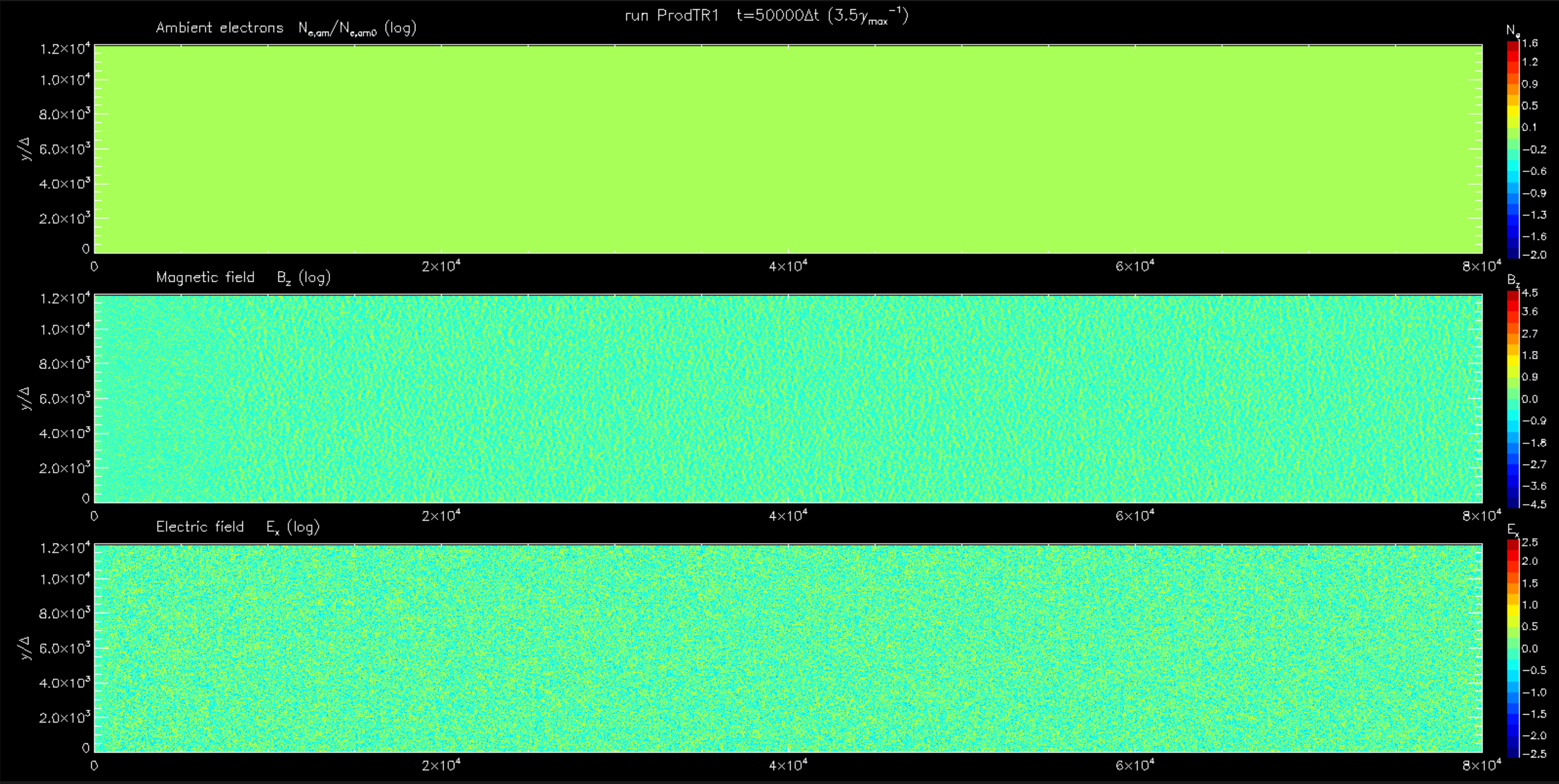
Compression region



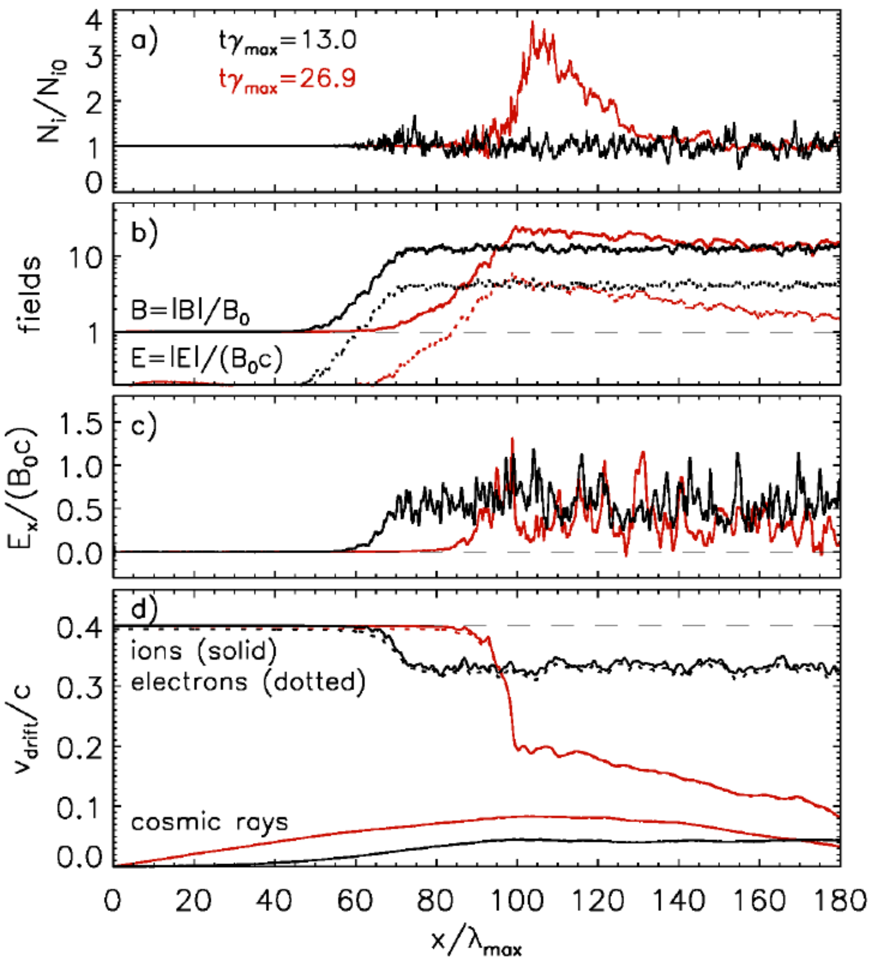
λ_{max} is wavelength of fastest growing wave

Bell‘s mode

Movie of electron density, magnetic field B_z, and electric field E_x



Bell‘s mode



Profiles of moments of the distributions

Localized bulk deceleration

Compression results
from bulk deceleration

Compression increases magnetic field

Electric field is largely motional

Bell‘s mode

Plasma deceleration may be not as strong in real precursors

Estimate:

Cosmic-ray pressure $\Pi_{CR} = U_{CR}/3$

Pressure loss by kinetic work $\delta\Pi_{CR} = -\rho_{up} V_{up} \delta V$

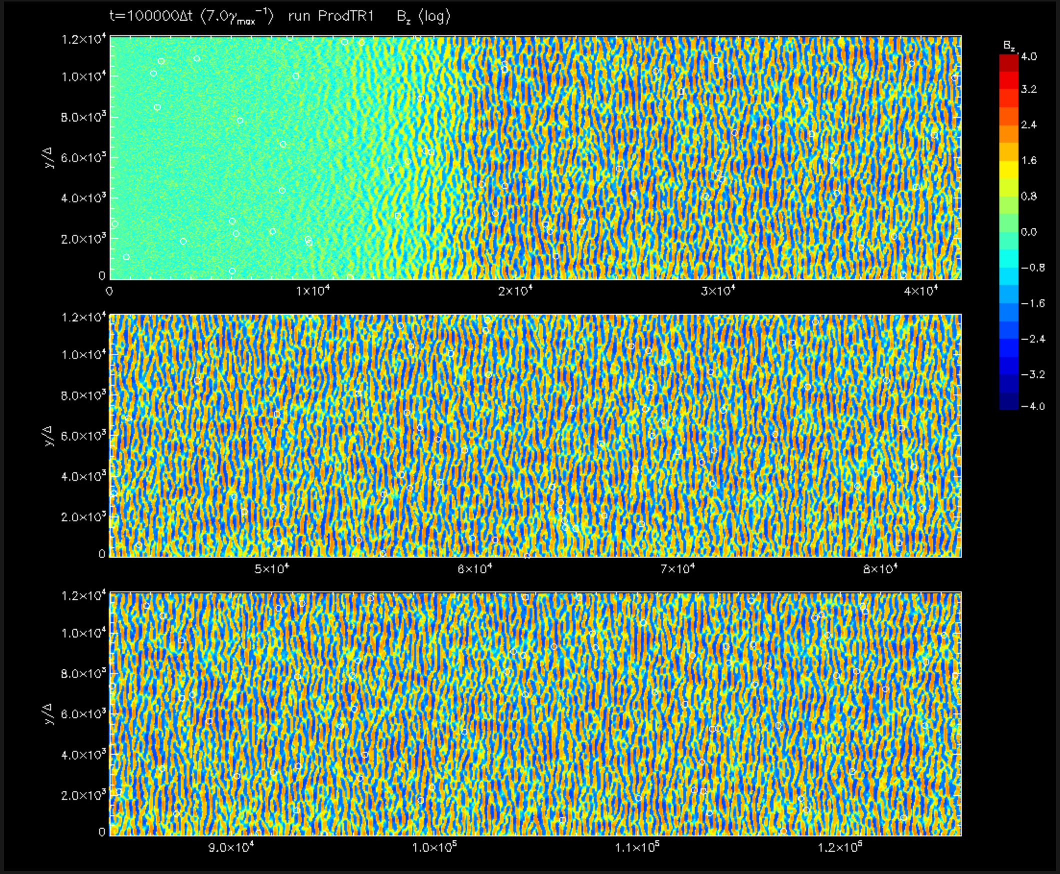
Expected velocity change $\delta V = \frac{V_{up}}{6} \frac{U_{CR}}{U_{up}} = 2 v_A N_{e-fold}$

With v_A=30 km/s and $N_{e\text{-}fold}$=15 we find $\delta V = 900\ \mathrm{km/s}$

Much more than sound speed ➔ Steepening to a compression front?

Effect on cosmic rays

We can follow individual cosmic rays



Effect on cosmic rays

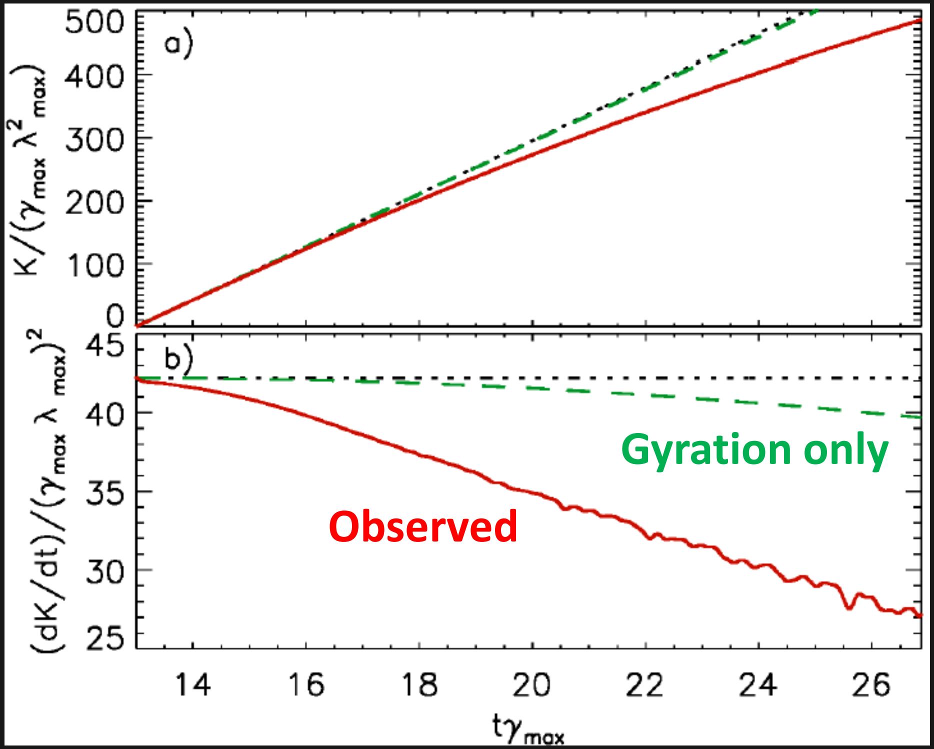
Calculate running diffusion coefficient

$$K(t) = \frac{\langle (x - x_0)^2 \rangle + \langle (y - y_0)^2 \rangle}{4\,t}$$

Estimate diffusion coefficient by extrapolating to K=const.

Value commensurate with

$$D = \frac{{r_{CR}}^2}{\tau}$$



Bohm diffusion for cτ = coherence length

Effect on plasma

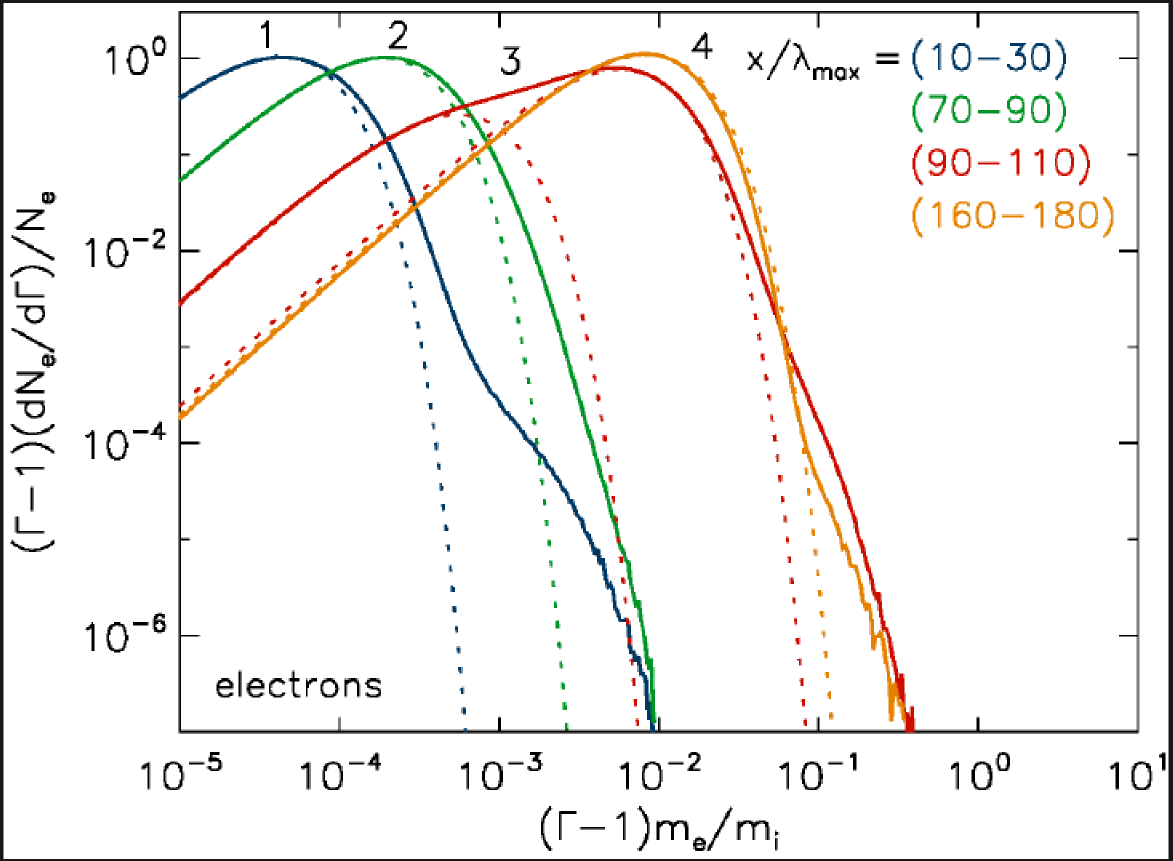
Kinetic-energy spectra in local flow frame

Strong bulk heating

High-energy tails

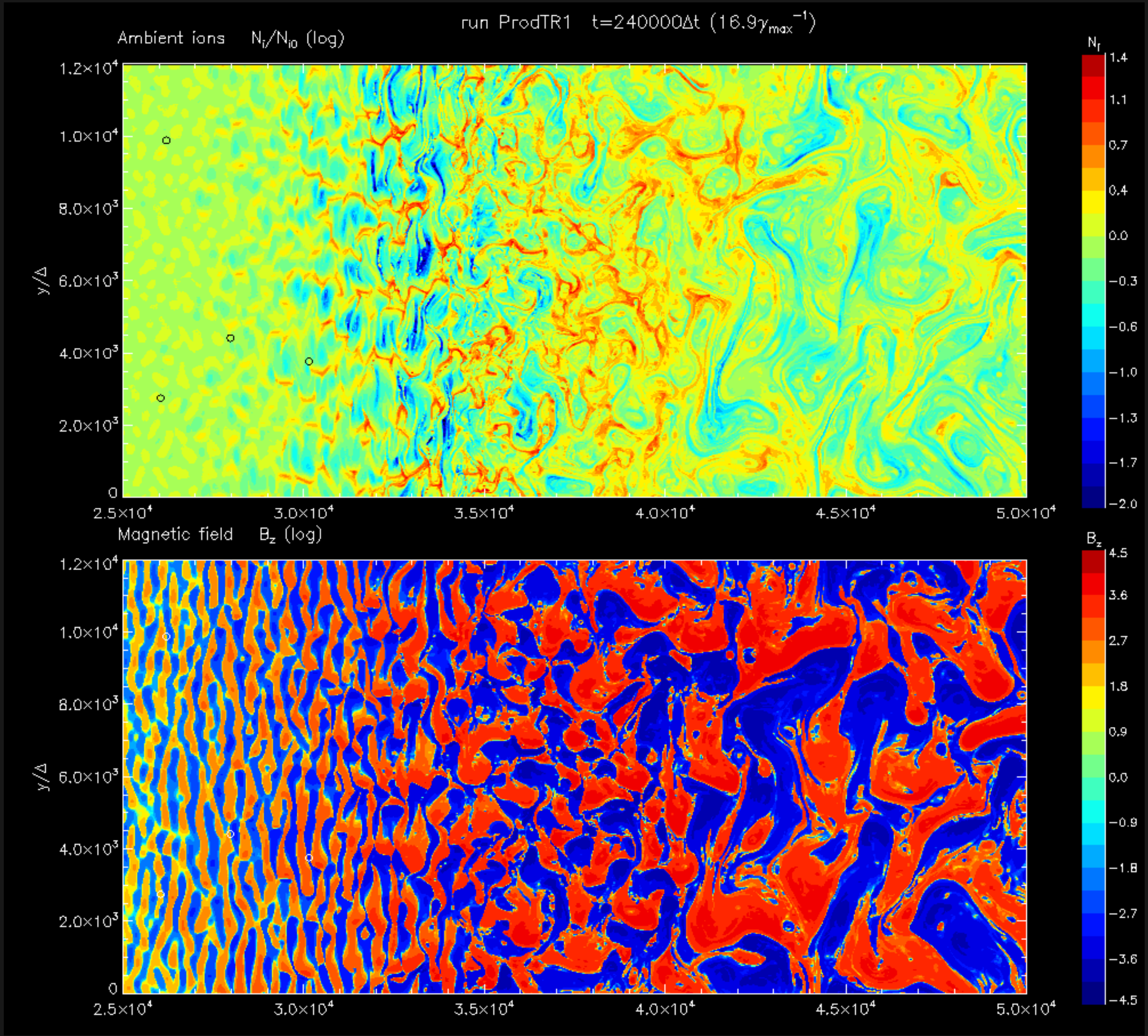
Similar for ions

Effect on shock!



Effect on plasma

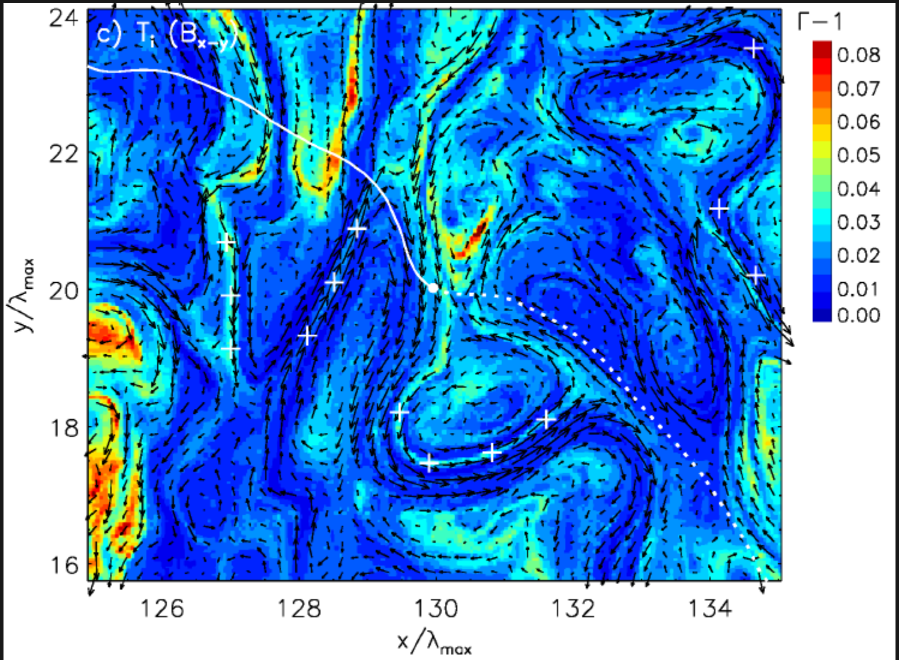
Follow individual plasma ions



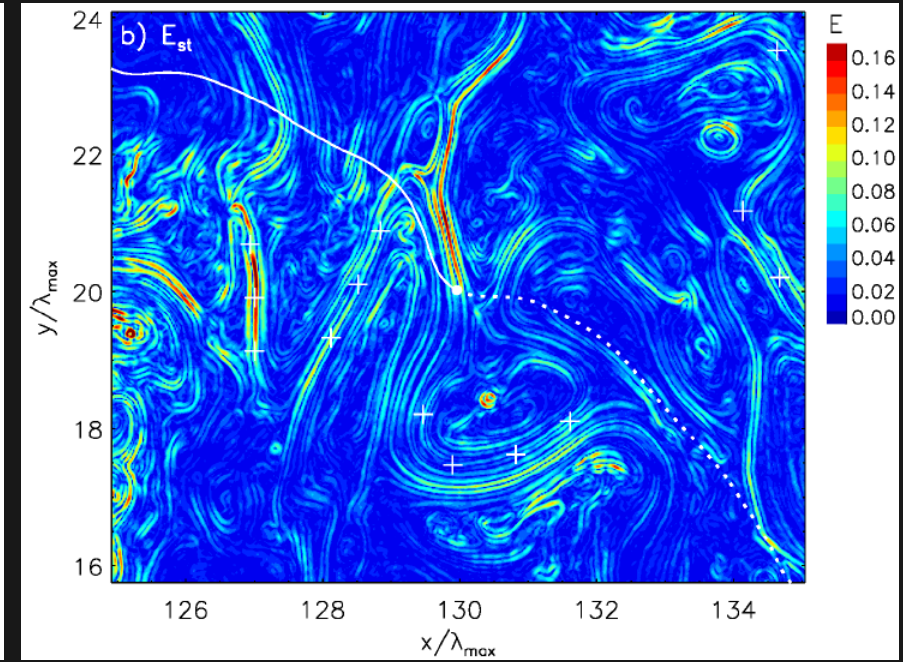
Effect on plasma

Highest temperature in regions of strong electrostatic fields
→ Non-adiabatic heating by electric work

Ion temperature



Electrostatic field amplitude



Summary

Turbulent magnetic field needed upstream of SNR shocks

Bell‘s mode is an interesting candidate

New PIC simulations with open boundaries

- Fast magnetic-field amplification possible
- Bulk deceleration as feedback can create a compression front
- Quasi-Bohmian cosmic-ray diffusion
- Strong plasma heating

Significant modification of thermal shock must be expected