Hadronic processes in SNR

Jacek Niemiec

Institute of Nuclear Physics PAN, Kraków

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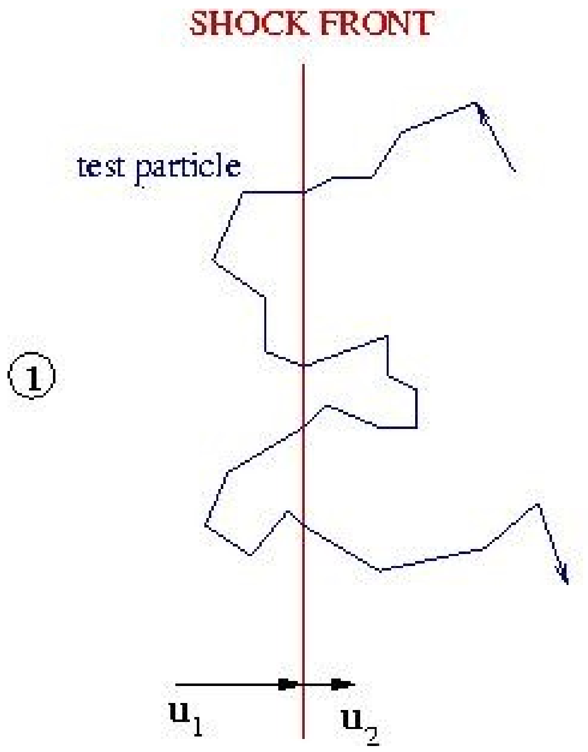
Production of magnetic turbulence by streaming cosmic rays upstream of SNR shocks

Martin Pohl, Thomas Stroman (Iowa State University, Ames, IA)
Ken-Ichi Nishikawa (NSCA, Huntsville, AL)

Scientific motivations

- interpretation of X-ray and γ-ray emission observed from young SNR
- origin of (Galactic) cosmic rays
- DSA at Supernova Remnants paradigm for CR production

First-order Fermi process
(Diffusive Shock Acceleration)



diffusion in pitch angle - elastic scattering off static irregularities of the magnetic field

energy gains ⟺ diffusive escape

power-law particle spectrum

First-order Fermi process
Nonrelativistic shocks

- particle distribution function: $f(p) \sim p^{-\alpha}$ $(N(E) \sim E^{-\sigma})$

$$\alpha = \frac{3R}{R-1}$$

$R = \frac{u_1}{u_2}$ compression ratio

- nonrelativistic matter (strong shock): $R = \frac{\Gamma+1}{\Gamma-1} = \frac{5/3+1}{5/3-1} = 4$

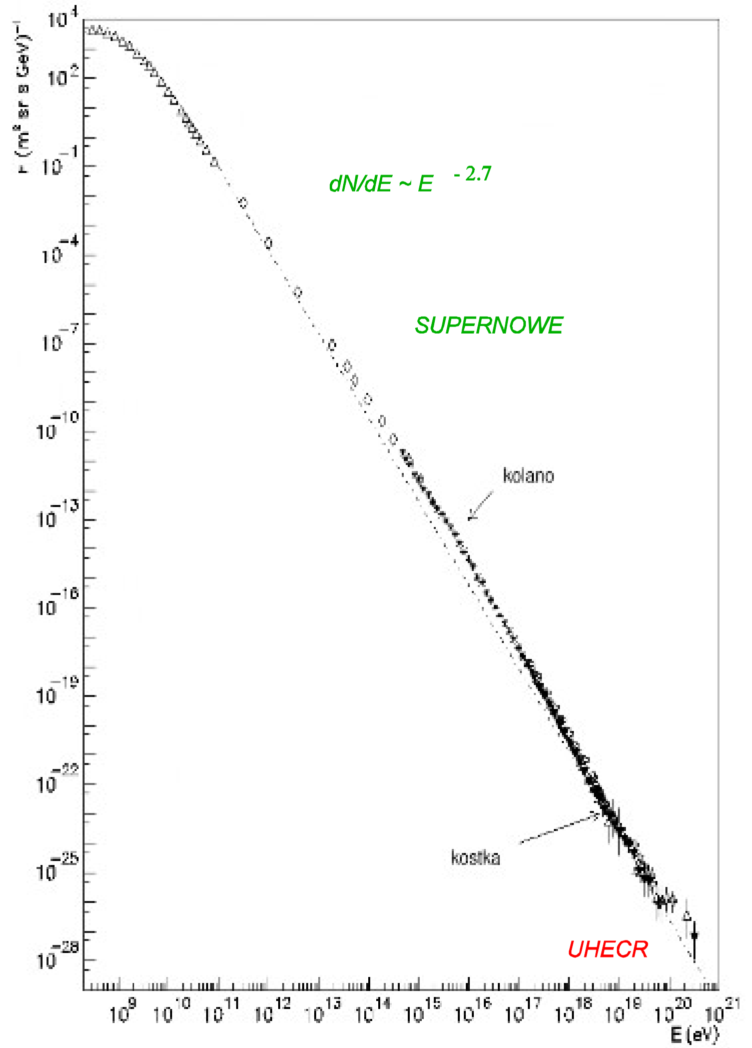
$$\Longrightarrow \alpha = 4 \quad (\sigma = 2)$$

Origin of Galactic cosmic rays – supernova remnants (SNR)

• nonrelativistic shocks in SNR are sources of Galactic cosmic rays

• acceleration process must be efficient – 10-30% energy of a supernova must go into cosmic ray ions to account for the cosmic ray flux at Earth

complete description of the shock acceleration requires fully nonlinear theory!



Nonrelativistic shocks – nonlinear effects

- particle spectrum

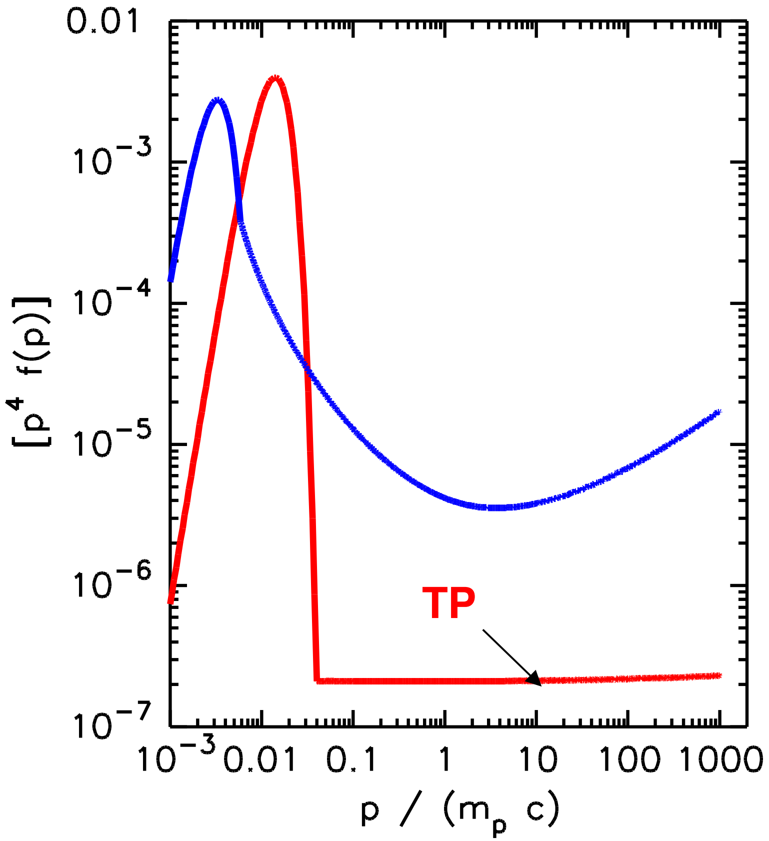
- cutoff at high energies E_{max}

- smaller adiabatic index for energetic particles → ($\Gamma = 4/3$ → $R = 7$)

- escape of highest-energy particles leads to higher compression – flat particle spectrum ($R \rightarrow \infty$, $\alpha \rightarrow 3$)

⇩

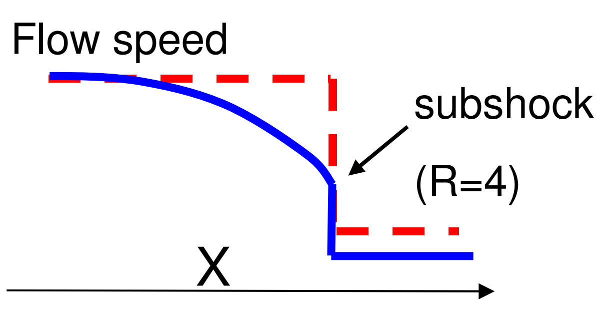
concave particle spectrum



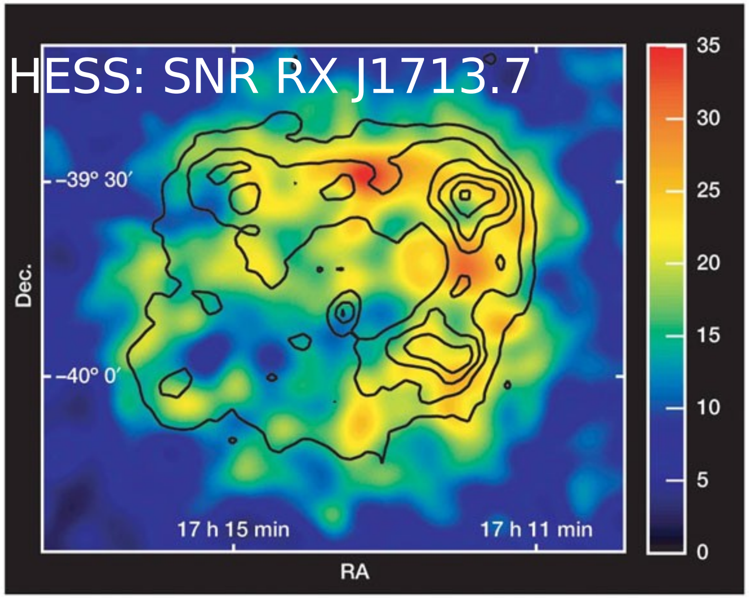
- shock structure

- shock becomes smooth from backpressure of CR – precursor to the shock wave is formed

- cosmic rays generate turbulent magnetic field; amplitude of turbulence determines E_{max}



Supernova remnants – observations



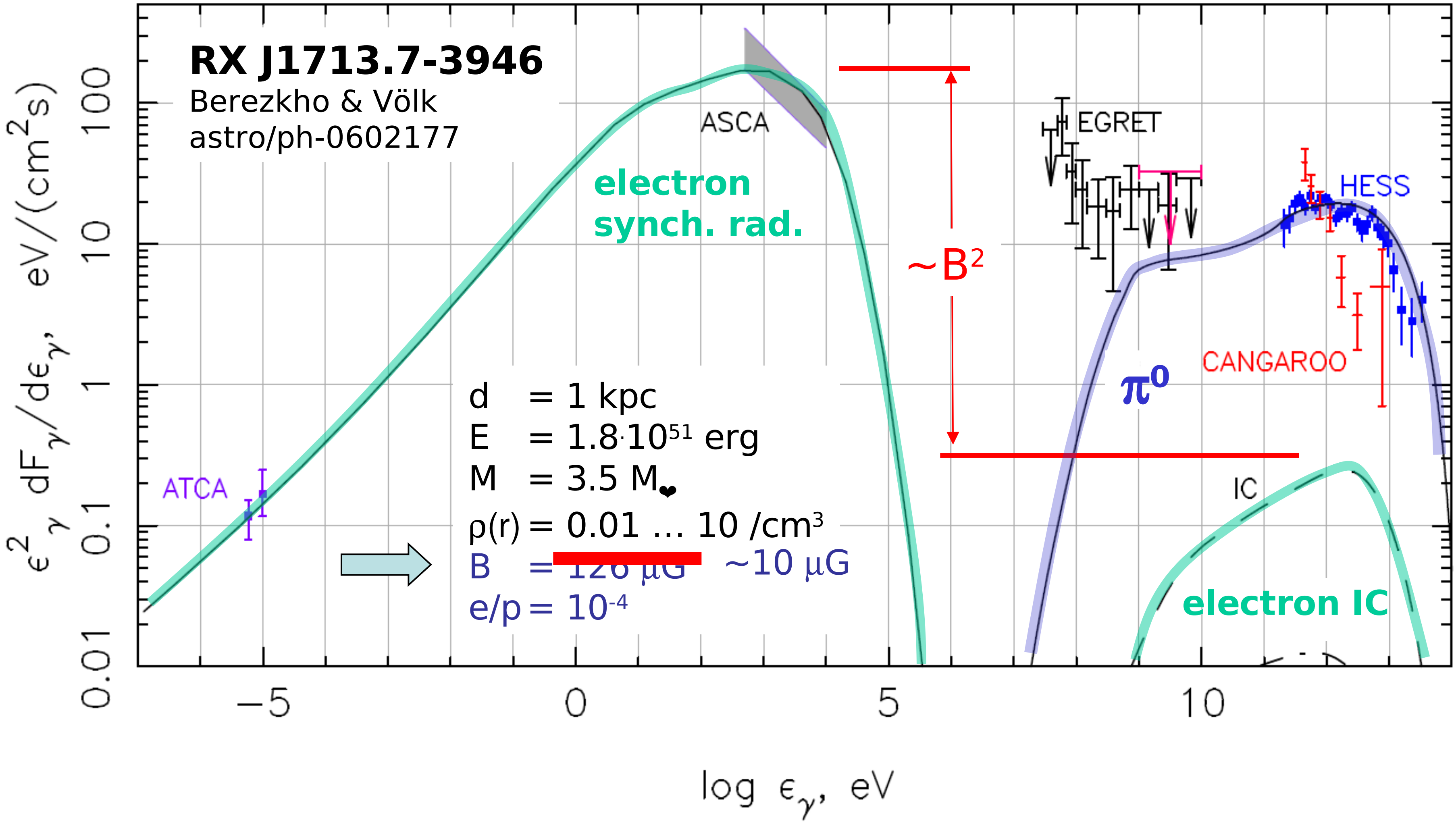
- X-ray and γ emission observed from young SNR – evidence for the production of high-energy electrons

But:

- are hadrons (cosmic rays) accelerated to high energies?
- how efficiently and with what properties is magnetic turbulence produced by energetic particles upstream of the shock?
- what is E_{max}?

γ–ray production in hadronic processes?

$$p + \text{nucleus} \rightarrow \pi + X, \quad \pi^0 \rightarrow \gamma\gamma$$



Supernova remnants – observations


SN 1006 (Chandra)

- filamentary structures seen at the rims of young SNR – the presence of strong magnetic fields? (large compression ratios as in shocks modified by accelerated particles?)

Unambiguous evidence for hadron acceleration requires good understanding of the nonthermal radiation – spatial distribution of magnetic field and phase-space distribution of high-energy electrons needed to accurately model leptonic contribution to X-ray and γ-ray emission.

Precursor to a SNR shock with efficient particle acceleration – Physical picture

- Isotropic cosmic ray ions stream through upstream medium

- Cosmic rays carry electric current j_{CR} along the background magnetic field

- upstream plasma provides charge neutrality and a return current j_{ret}

- $\boldsymbol{j}_{ret}$ x $\boldsymbol{B}$ force should drive strong magnetic turbulence

Dispersion relation for parameters of young SNRs

$$\omega^2 - v_A^2 k^2 + \zeta v_s^2 k / r_g = 0, \qquad \zeta = n_{CR} c \gamma_{CR} / n_b v_s \qquad (k \parallel B_0)$$

Bell (2004)

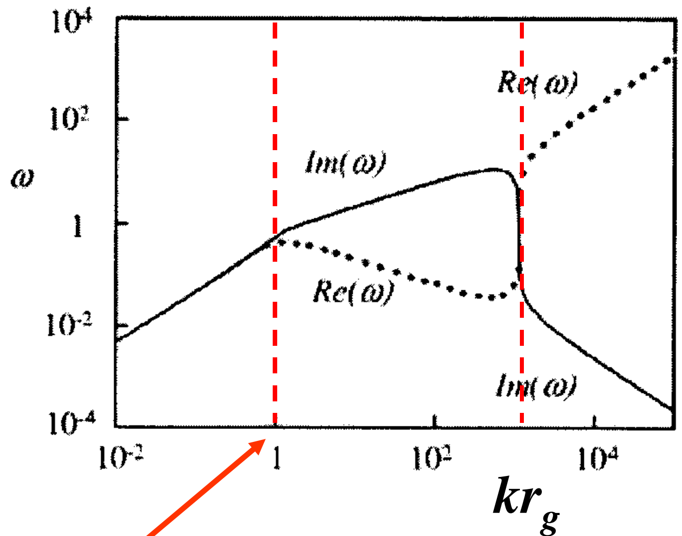


Figure 2. Dispersion relation for the mode with the largest maximum growth rate; $v_A = 6.6 \times 10^3$ m s^{-1}, $v_s/c = 1/30$, $\zeta = 4.8 \times 10^{-4}$. ω is in units of v_s^2/cr_{g1} and k in units of r_{g1}^{-1}.

$$e^{i(kx - \omega t)}, \ \omega = \omega_R + i\omega_I$$

$kr_g = 1$ – resonant production of Alfven waves with wavelength of CR Larmor radius ($\lambda \sim r_g$)

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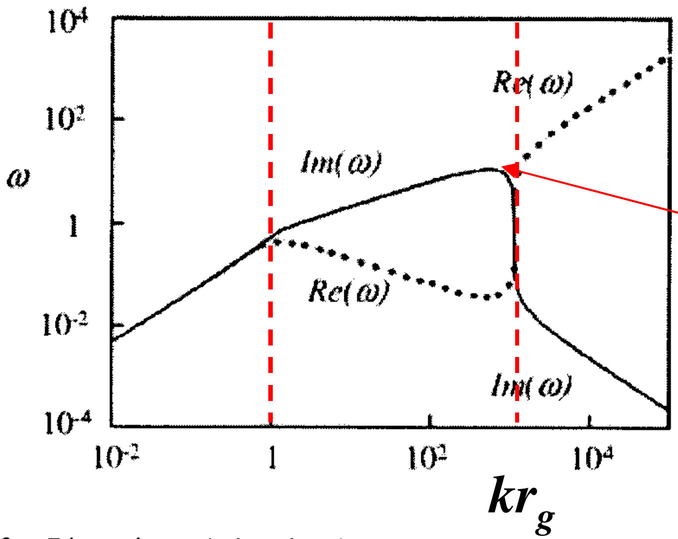

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maximum growth rate at

$$k_{max} = \zeta v_s^2 / 2 v_A^2 r_g$$

- $1 < kr_g < \zeta v_s^2/v_A^2$ – strongly driven, nonresonant, short wavelength ($\lambda < r_g$), nearly purely growing modes !

- $\delta B/B \gg 1$ – supported with MHD simulations (Bell 2004, 2005)

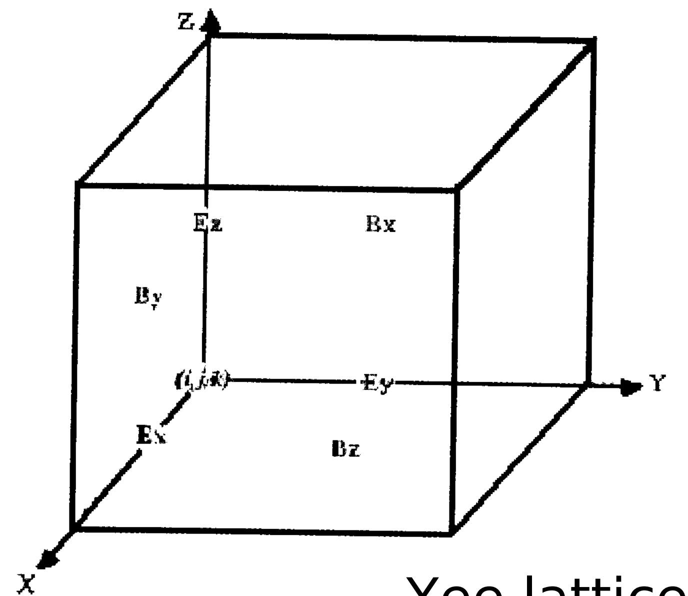
Particle-In-Cell modeling

$$\frac{\partial \boldsymbol{E}}{\partial t} = c\nabla \times \boldsymbol{B} - \boldsymbol{J},$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\nabla \times \boldsymbol{E},$$

$$\frac{d\gamma m \boldsymbol{V}}{dt} = \boldsymbol{F} = q\left(\boldsymbol{E} + \boldsymbol{V} \times \frac{\boldsymbol{B}}{c}\right), \qquad \frac{d\boldsymbol{x}}{dt} = \boldsymbol{V},$$

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot \boldsymbol{J}$$



Yee lattice

- solves differential equations using finite-difference method with leapfrogging scheme on the Yee lattice
- rigorous charge conservation method – no need to solve Poisson equation
- TRISTAN code: 3D, relativistic, Cartesian coordinates, modified MPI version

Motivations:

- verify the existence of Bell's non-Alfvenic turbulence in the presence of kinetic particle effects
- explore its properties: nonlinear evolution, saturation, particle heating
- account for backreaction on CR trajectories

Particle-In-Cell modeling

Setup:

- computational grid: 992 x 304 x 304 cells + periodic boundary conditions

- 1.5 billion particles

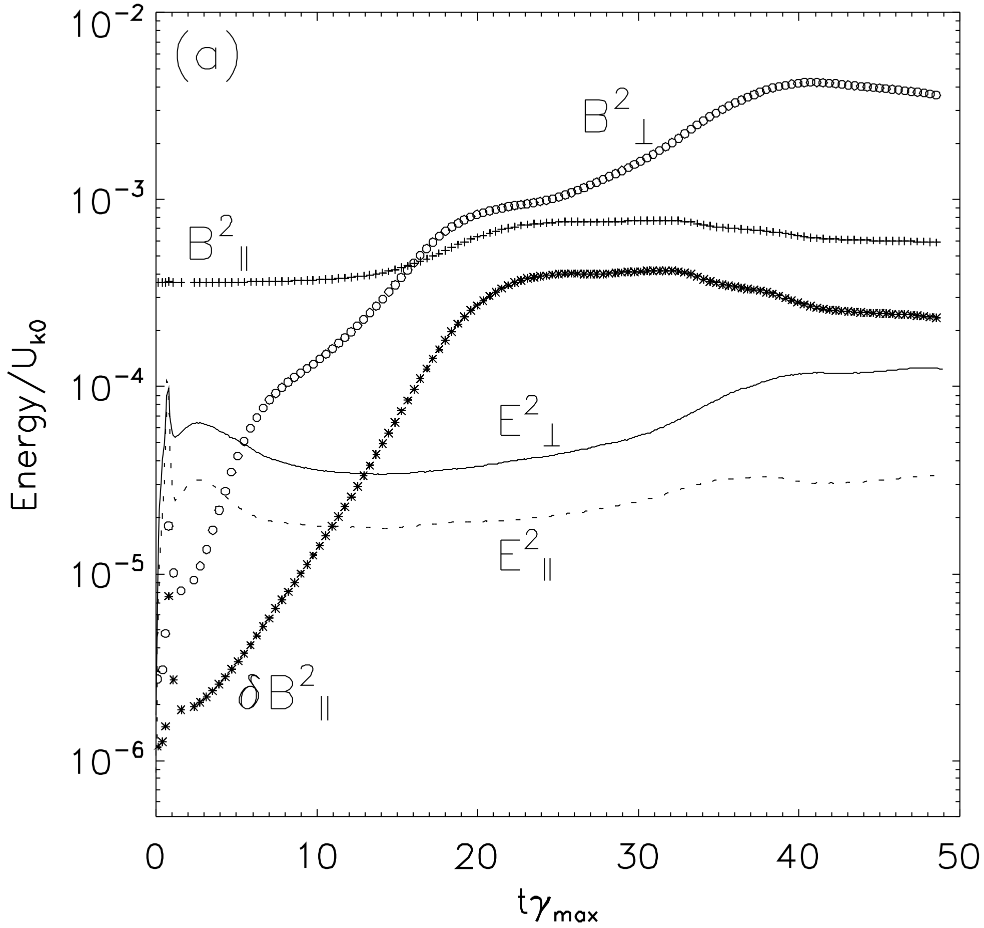
- particle density ratio: N_{CR}/N_i = 1/3
- CR ions drift velocity: v_s = 0.3c
- CR ions Lorentz factor: γ_{CR} = 2

- ion/electron mass ratio: m_i / m_e = 10
- plasma skindepths: $\lambda_{se} = 7\ \Delta$ $\lambda_{si} = 25.6\ \Delta$

$\zeta\, v_s^2/v_A^2$ = 826

- wavelength of the most unstable mode: $\lambda_{max} = 50\ \Delta$

Results

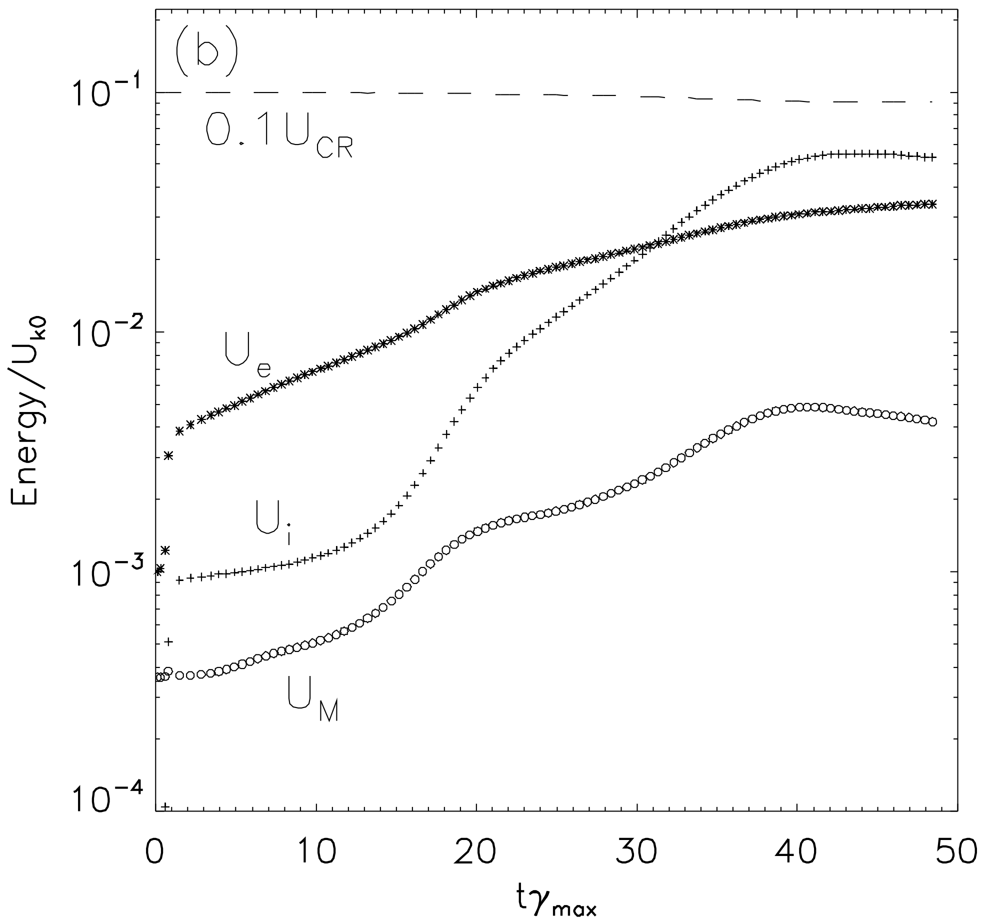


- magnetic field turbulence excited mainly in components transverse to the CR drift direction

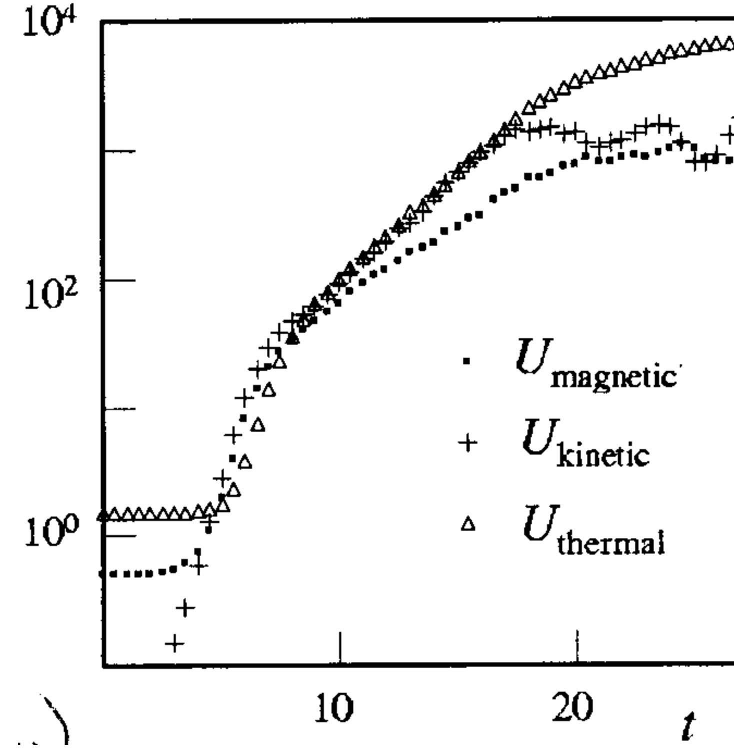
- the growth of perturbations is much slower than estimated by Bell (1/5 of γ_{max})

- field amplitude saturates at

$$\delta B \approx B_0$$



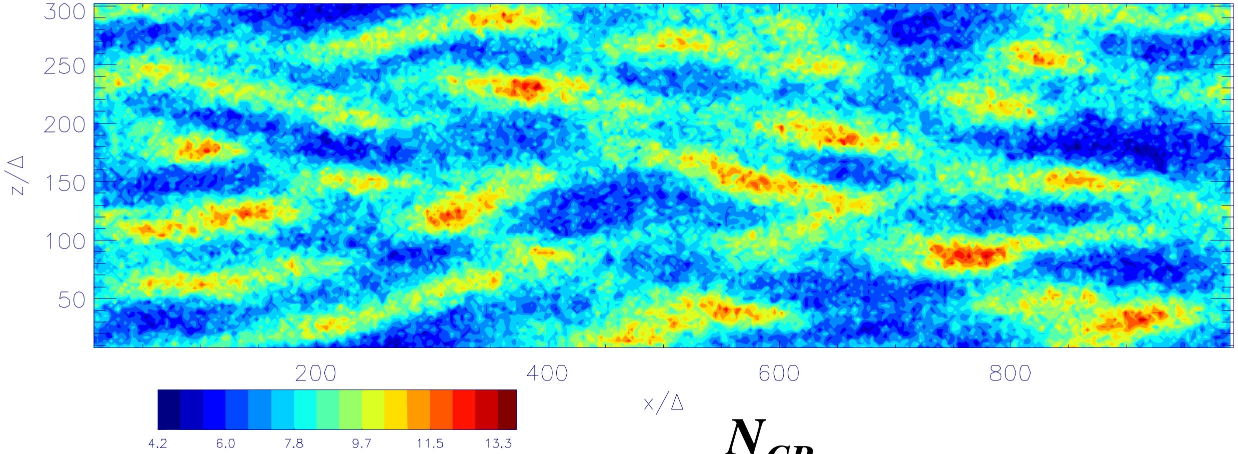
Bell (2004)



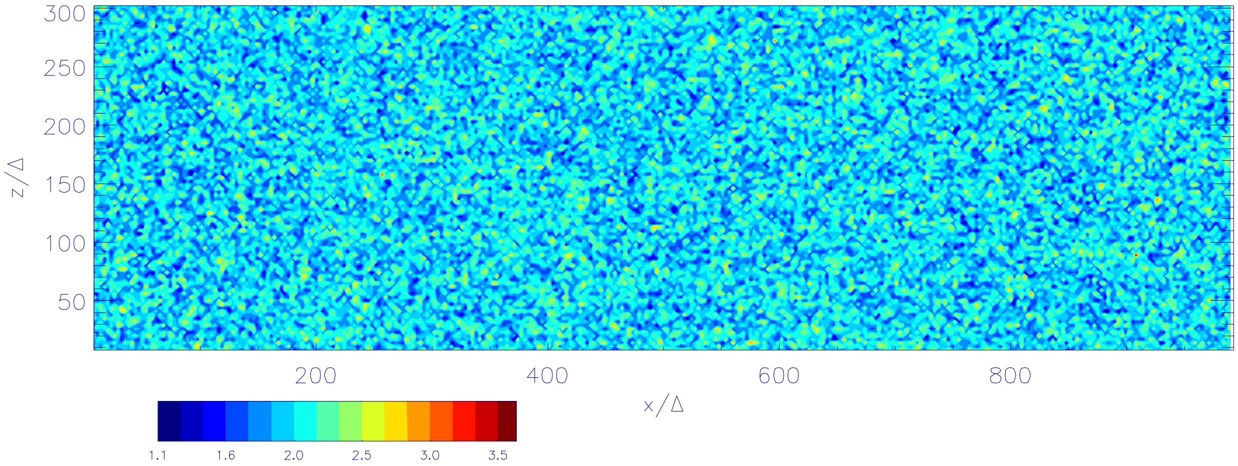
- turbulence becomes isotropic at nonlinear stage
- field remains below equipartition with plasma

Filamentation-like modes

$t\gamma_{max} \sim 5$ N_e **CR drift plane (X, Z)**



N_{CR}



Dominant wave mode is oblique ($\boldsymbol{k} \neq k_{||}$) at 75° to CR drift direction (x)

$\lambda_{\perp} \approx 50\Delta = \lambda_{max}$

$\lambda_{||} \approx 250\Delta$

In theoretical analysis

$\boldsymbol{k} = k||$

Bell (2004)

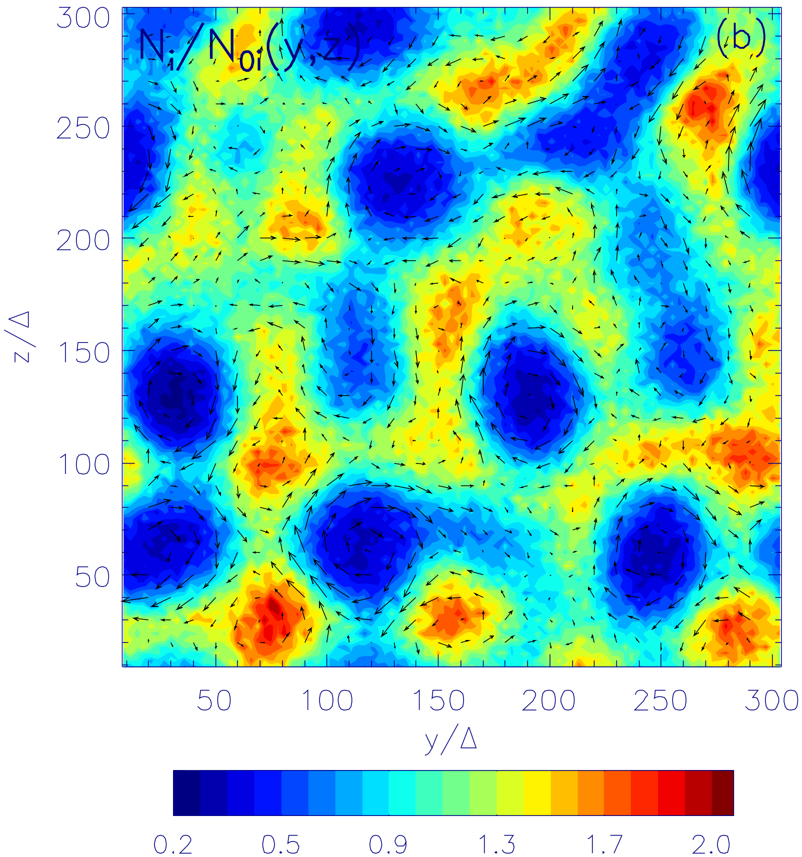
Initial evolution of magnetic turbulence

Plane perpendicular to CR drift direction

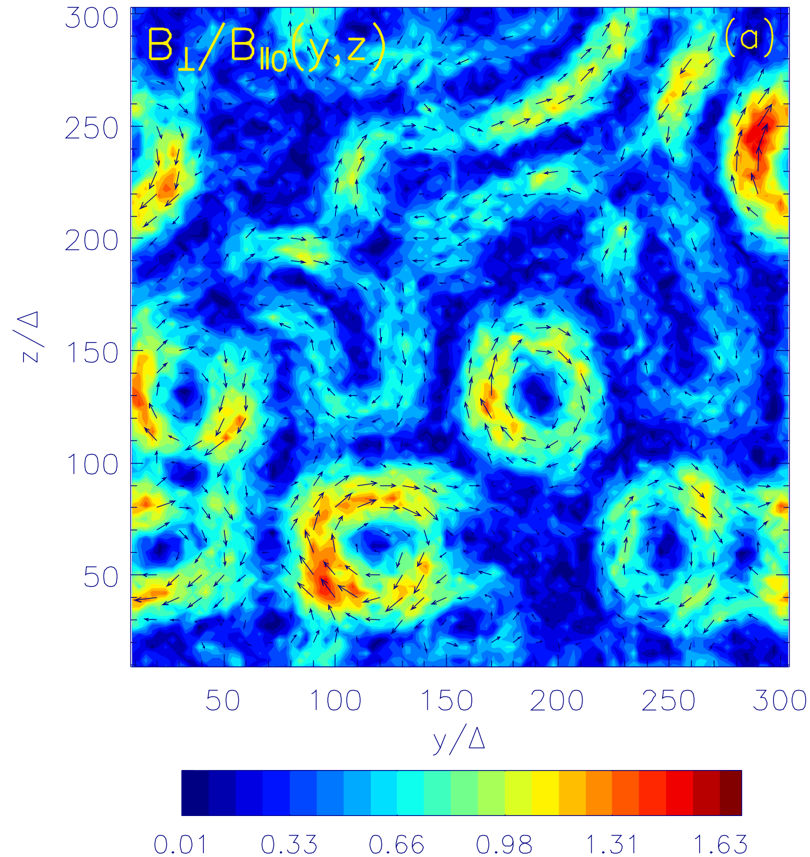
Long-time evolution of magnetic turbulence

In the plane of CR drift

$N_i \sim N_e$



B



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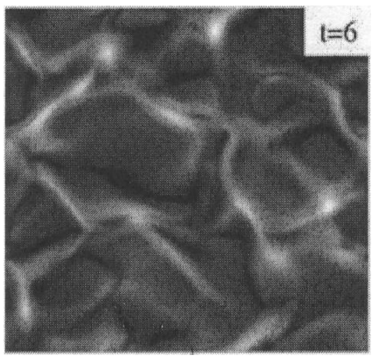
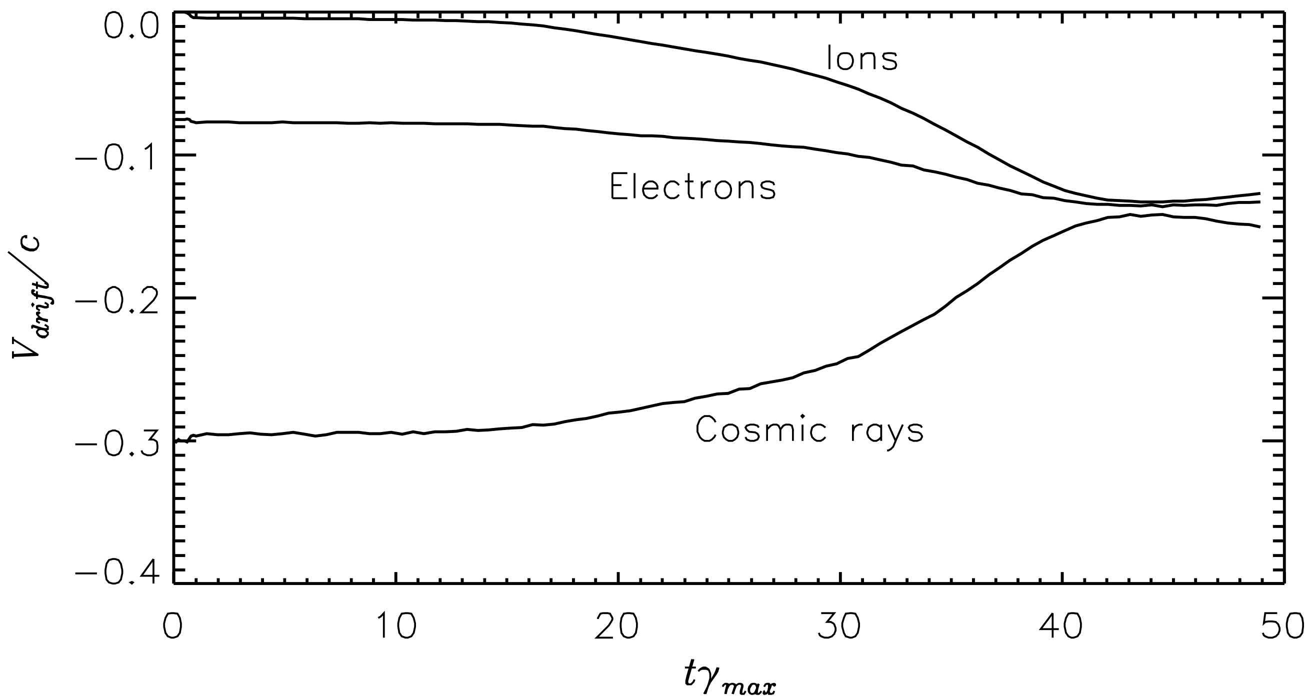


- perpendicular field concentrated around the regions of low plasma density – associated with strong net CR current flowing inside the voids (Ampere's law)

- growth of turbulent structures associated with $\boldsymbol{j}_{CR}$ x $\boldsymbol{B}$ force



- drift velocities of all particle species converge – effects of a cosmic-ray modified shock occur without a significant magnetic field amplification and with instability modes different from those usually invoked in the studies

Summary

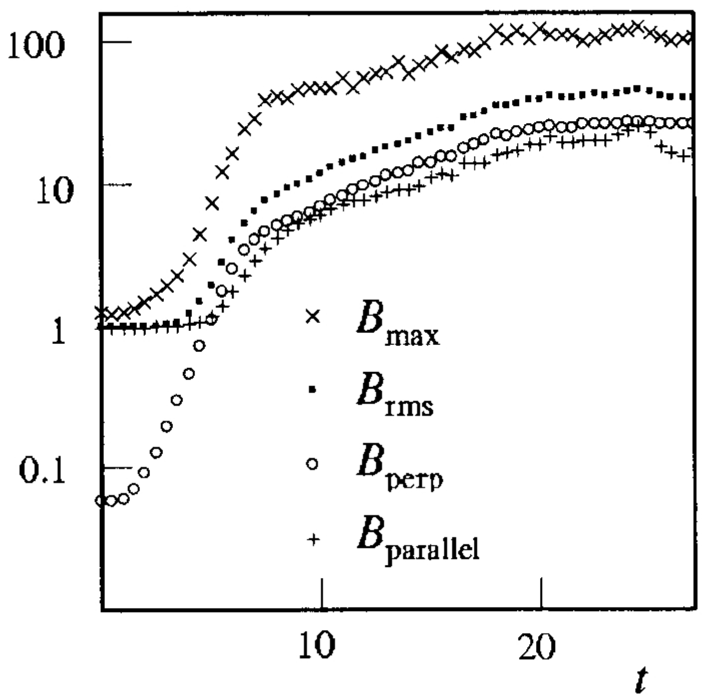
- Particle-In-Cell modeling of cosmic-ray ions streaming in the plasma upstream of the nonrelativistic shocks confirms the production of magnetic turbulence
  - growth of turbulence is much slower than estimated with MHD approach
  - amplitude of turbulence is not much larger than B_0

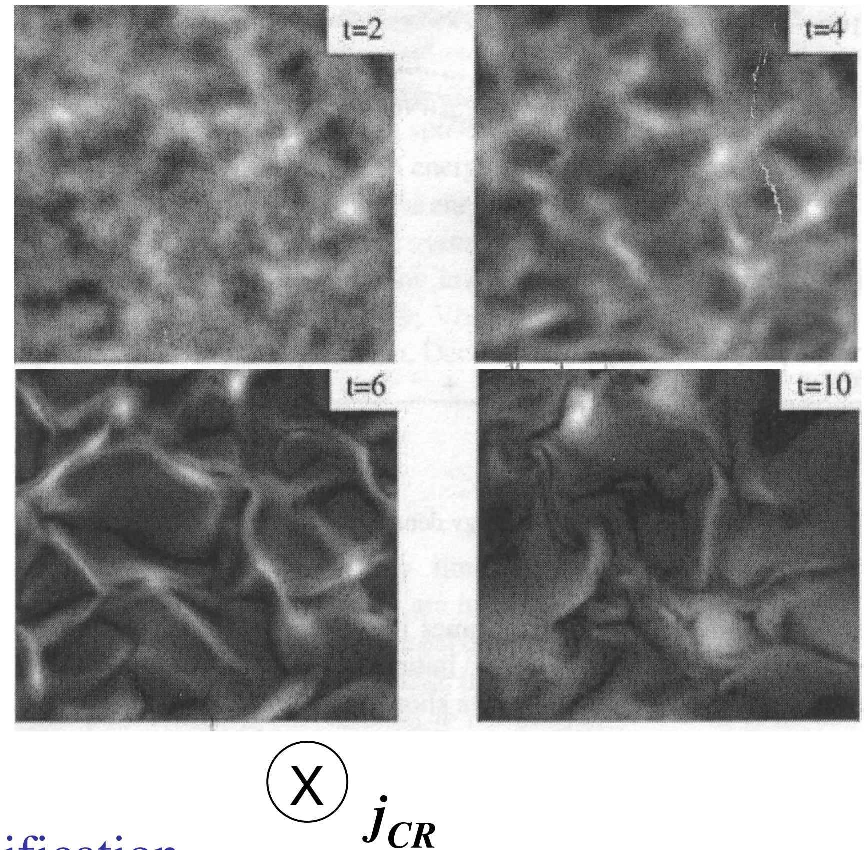
- efficiency of magnetic field generation might not be sufficient to account for high magnetic fields observed in some young SNRs

- the question of the ability of DSA at SNR shocks to produce cosmic rays with energies beyond the “knee” in CR spectrum remains open

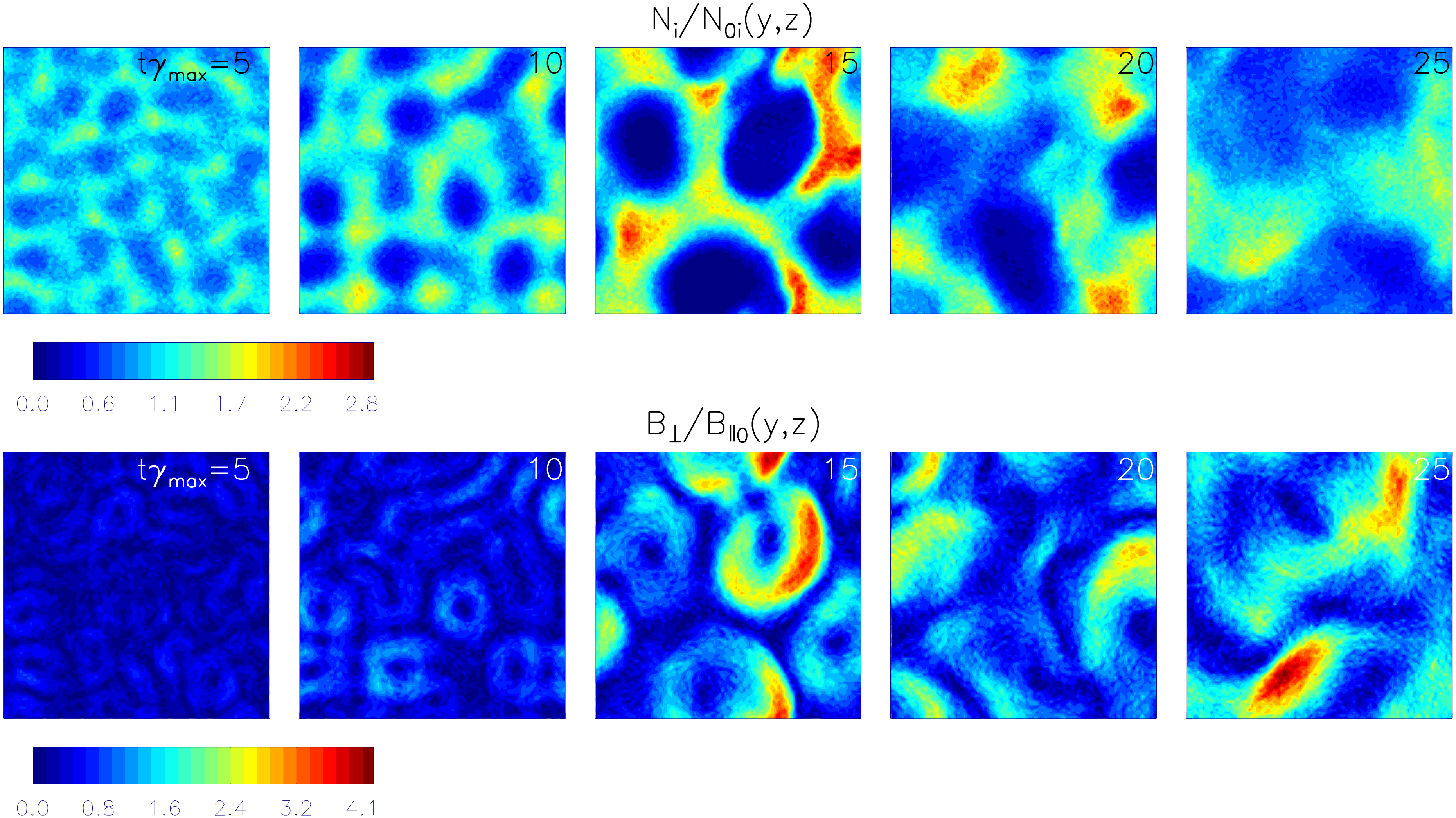
- interpretation of X-ray and γ-ray observations remains model- dependent

Nonlinear MHD simulations – Bell (2004)





- strong transverse magnetic field amplification
- $\boldsymbol{j}_{CR}$ x $\boldsymbol{B}$ force leads to formation of cavities with low plasma density and low magnetic field strength – resembles filamentation instability
- return current not included self-consistently
- backreaction of the magnetic field on CR trajectories not taken into account



- plasma voids expansion is accompanied by the growth of the magnetic field amplitude