Aperiodic magnetic turbulence produced by streaming cosmic rays

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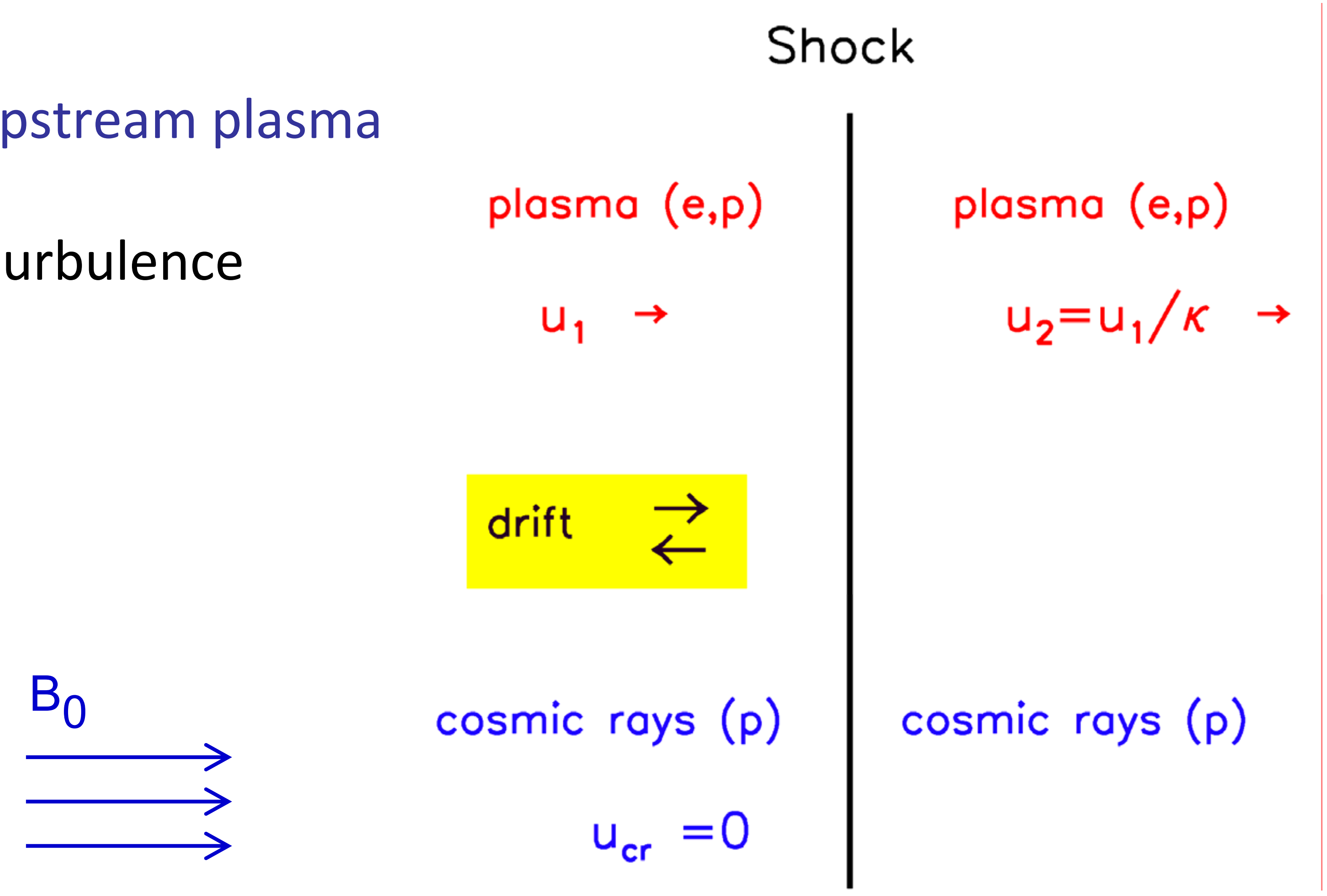
Scientific motivations

- Existence of amplified magnetic fields inferred from observations (e.g., supernova remnants, gamma-ray bursts)
- Collisionless shocks assumed to be acceleration sites of energetic particles (cosmic rays) responsible for high-energy emission of these objects
- Magnetic turbulence must be self-generated at the shock by accelerated particles ➔upstream (precursor) region

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

- cosmic ray-upstream plasma relative drift

→ magnetic turbulence



Shock

plasma (e,p)

u_1 →

plasma (e,p)

$u_2=u_1/\kappa$ →

drift $\rightleftarrows$

B_0

cosmic rays (p)

u_{cr} =0

cosmic rays (p)

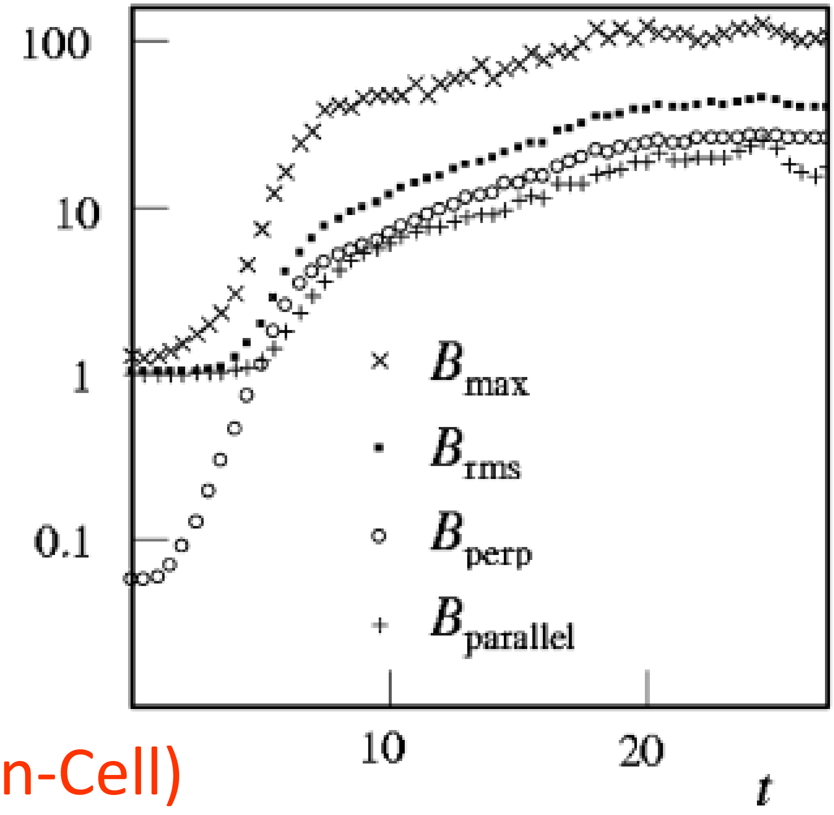
Earlier work: isotropic CRs drifting upstream of nonrelativistic SNR shocks

Analytical theory (Bell 2004, Winske& Leroy 1984):

- streaming cosmic rays produce purely growing, nonresonant ($\lambda \ll r_{gCR}$) modes of magnetic turbulence
- wave-vector parallel to streaming (**$k \parallel B_0$**)

MHD simulations (Bell 2004, Zirakashvili et al. 2008, Reville et al. 2008):

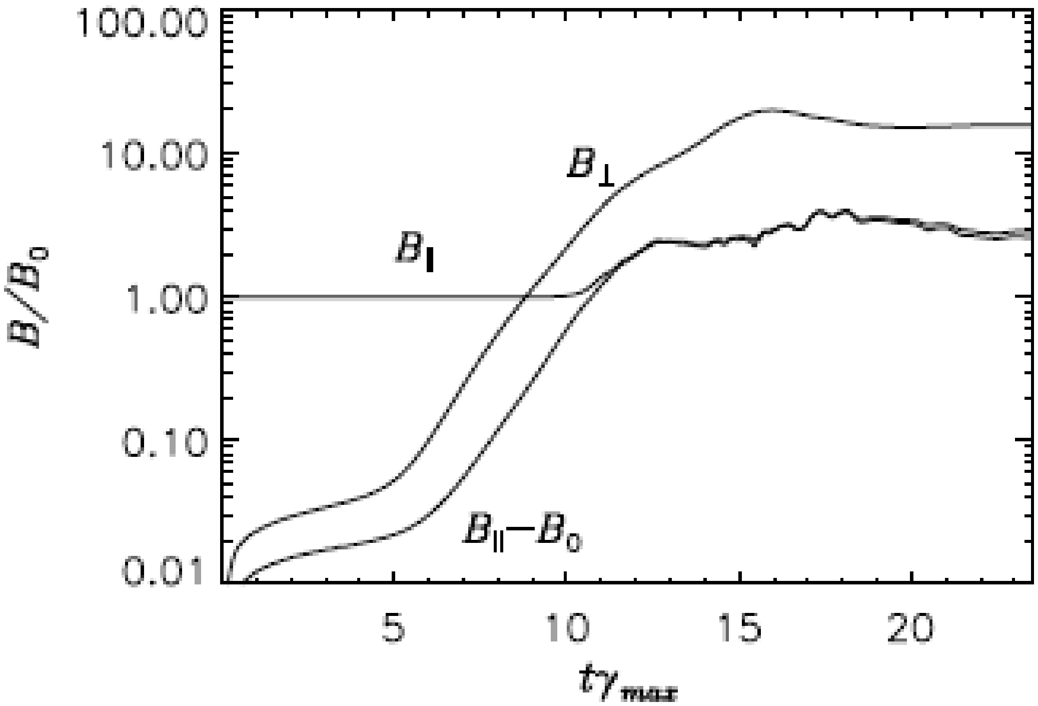
- magnetic field growth to $\delta B/B_0 \gg 1$
- cosmic-ray current constant – no backreaction on CRs
- MHD can't do vacuum



⟶ kinetic plasma simulations (Particle-In-Cell)

PIC simulations of magnetic turbulence production by drifting CRs

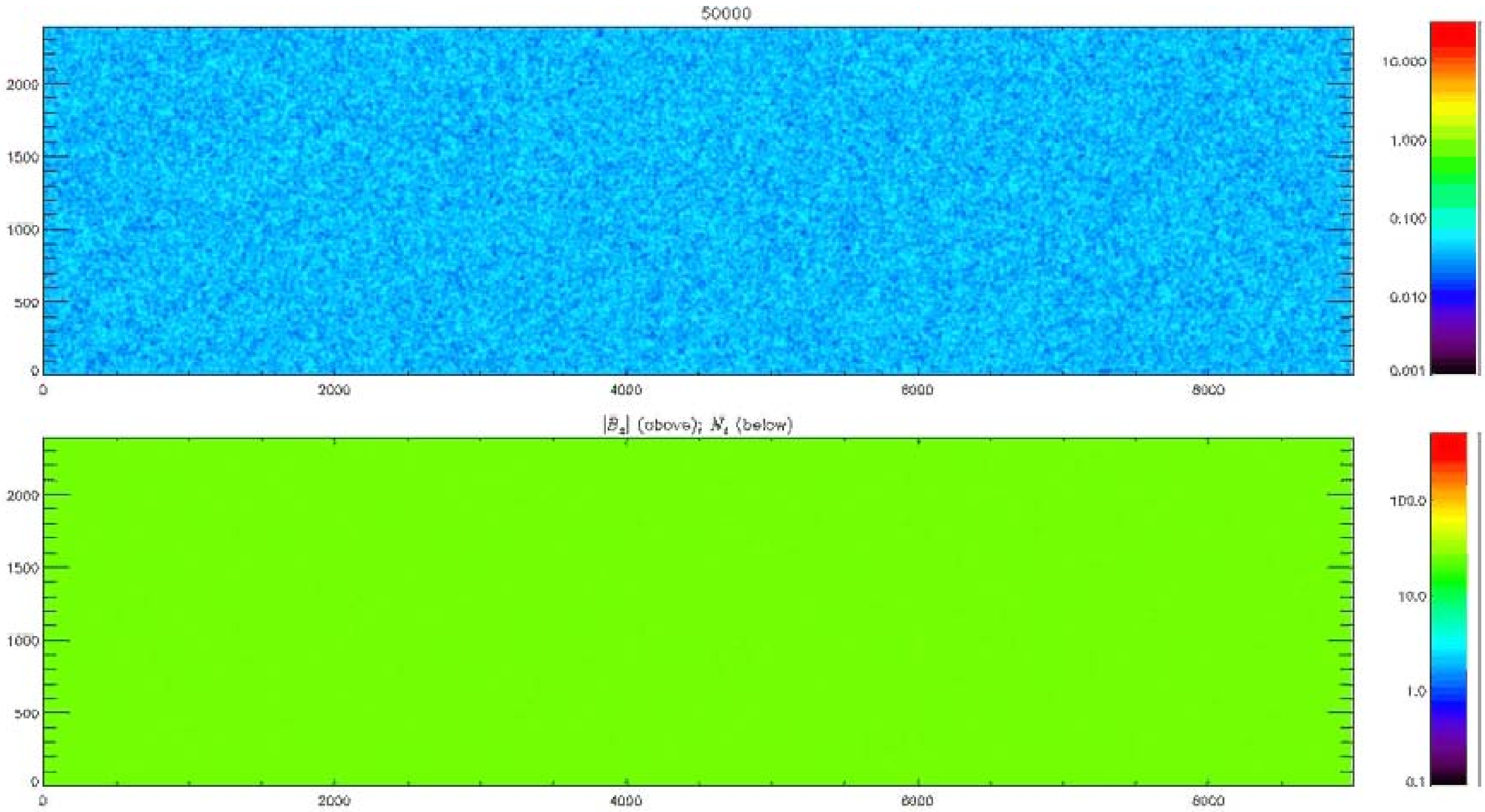
Niemiec et al. (2008)
Riquelme&Spitkovsky (2009)
Ohira et al. (2009)
Stroman et al., in preparation
Gargate et al., in preparation(hybrid)



2.5D simulations
$\gamma_{max}/\Omega_i=0.4$, $v_{drift}=0.4c$, $M_A=40$, $\gamma_{CR}=50$

- magnetic field turbulence excited in components transverse to the cosmic-ray drift direction
- parallel mode (***k* // *B$_0$***) with theoretically predicted growth rate observed
- field amplitude saturates at *$\delta B \approx 10\text{-}20 B_0$*
- turbulence is nearly isotropic and highly nonlinear at later stage

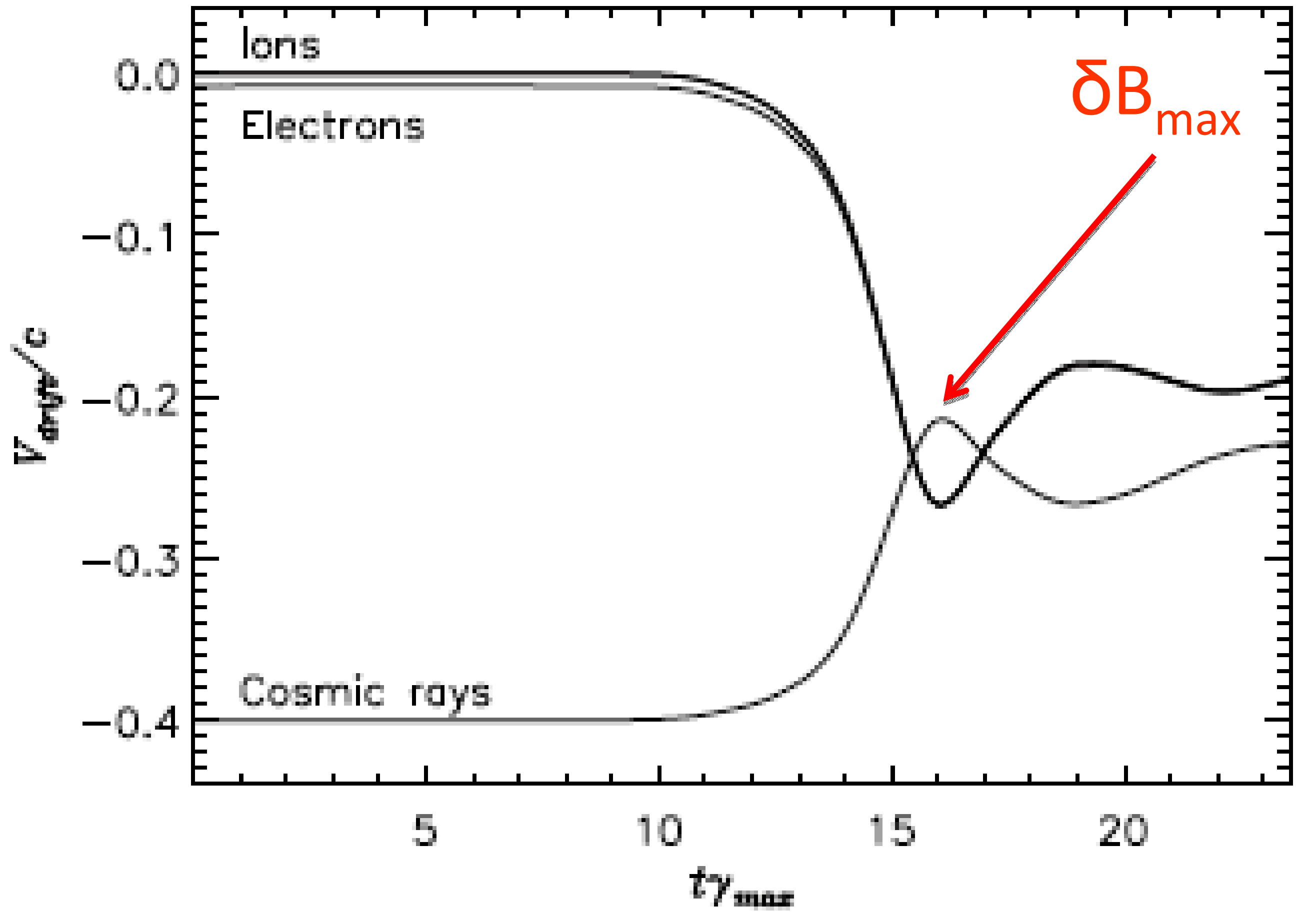
Evolution of magnetic turbulence



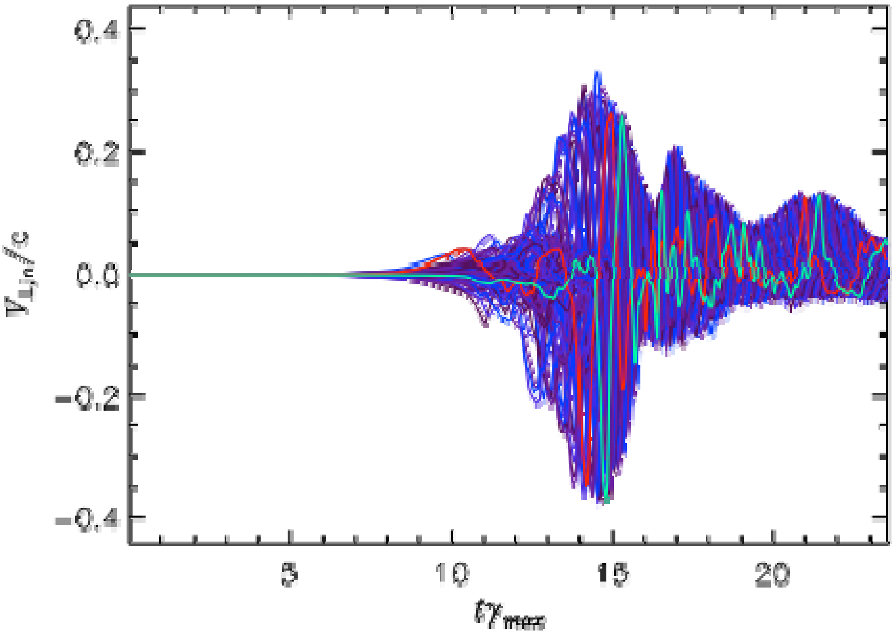
← CR drift

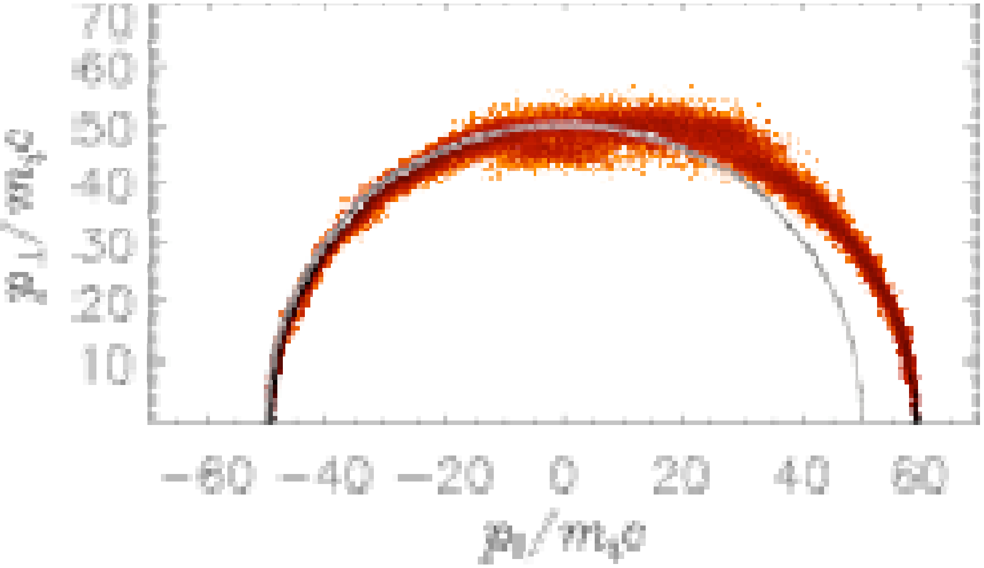
Top: turbulent magnetic field $|B_z|$ - nonresonant mode, $k \parallel B_0$
Bottom: ambient plasma density

Saturation of the turbulence growth



- bulk CR momentum transferred to the ambient plasma
- relative drift between cosmic rays and ambient plasma disappears– no source for the streaming instability
- saturation mechanism is independent of the initial linear instability





- strong plasma density and transverse velocity fluctuations in nonlinear stage

➔ possibly non-negligible impact on injection processes and CR scattering downstream thus also on resulting particle spectra

➔upstream plasma heating due to collisions of plasma parcels at superalfvenic speeds – increased injection rate? (Vladimirov et al. 2008)

- (rest-frame) anisotropy in CR distribution

Aperiodic turbulence produced by a relativistic CR ion beam in electron-proton plasma

System:

- cold, dilute, relativistic ion beam propagating along background magnetic field B_0 in cold electron-proton ambient medium

Astrophysical applications:

- SNR shocks: most energetic CRs streaming far upstream of the free-escape boundary
- GRB and AGN relativistic foreshock region:
  - strongly anisotropic particle distributions inherent to the shock acceleration processes ($p_{perp} \leq p_{parallel}/\Gamma_{sh} << p_{parallel}$)
  - CR ion energies larger than the "CR electron" energy limit imposed by radiation cooling

Analytical analysis:

- dispersion relations for $\boldsymbol{k} \,||\, \boldsymbol{B}_0$ in the limit $\gamma_{max}/\Omega_i << 1$ (Reville et al. 2006)

\- nonresonant modes dominant

- CR-driven turbulence may account for magnetic field amplification inferred from GRB sources (Milosavljevic&Nakar 2006)

Relativistic CR ion beam in electron-proton plasma: linear analysis

System parameters:

$\gamma_{CR}=\infty$, 300, 20; $v_A=c/20$, $c/50$; $N_{CR}/N_i=1/50$, $1/125$

$\gamma_{max}/\Omega_i=0.2$, $m_i/m_e=20$

Growth rates for arbitrary orientation of ***k*** (zero temperature limit):

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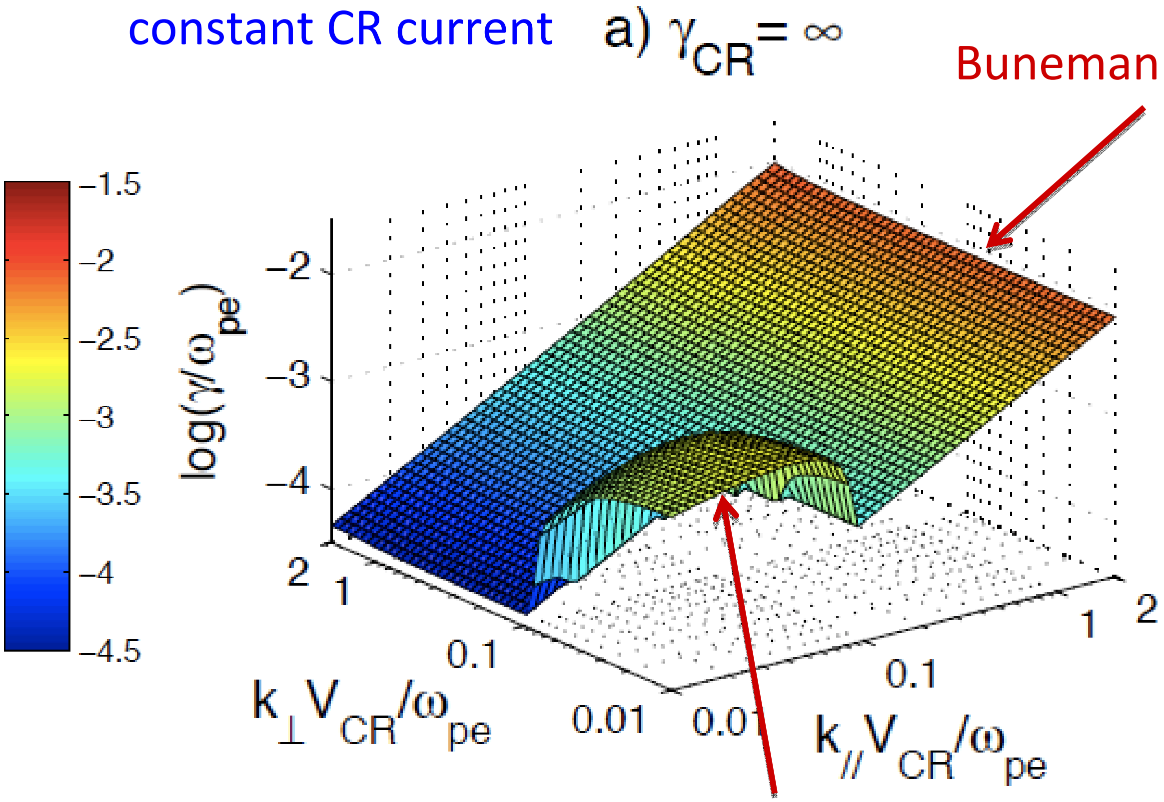
Growth rates for arbitrary orientation of ***k*** (zero temperature limit):

constant CR current



Buneman mode (ambient ions-drifting electrons)

nonresonant mode

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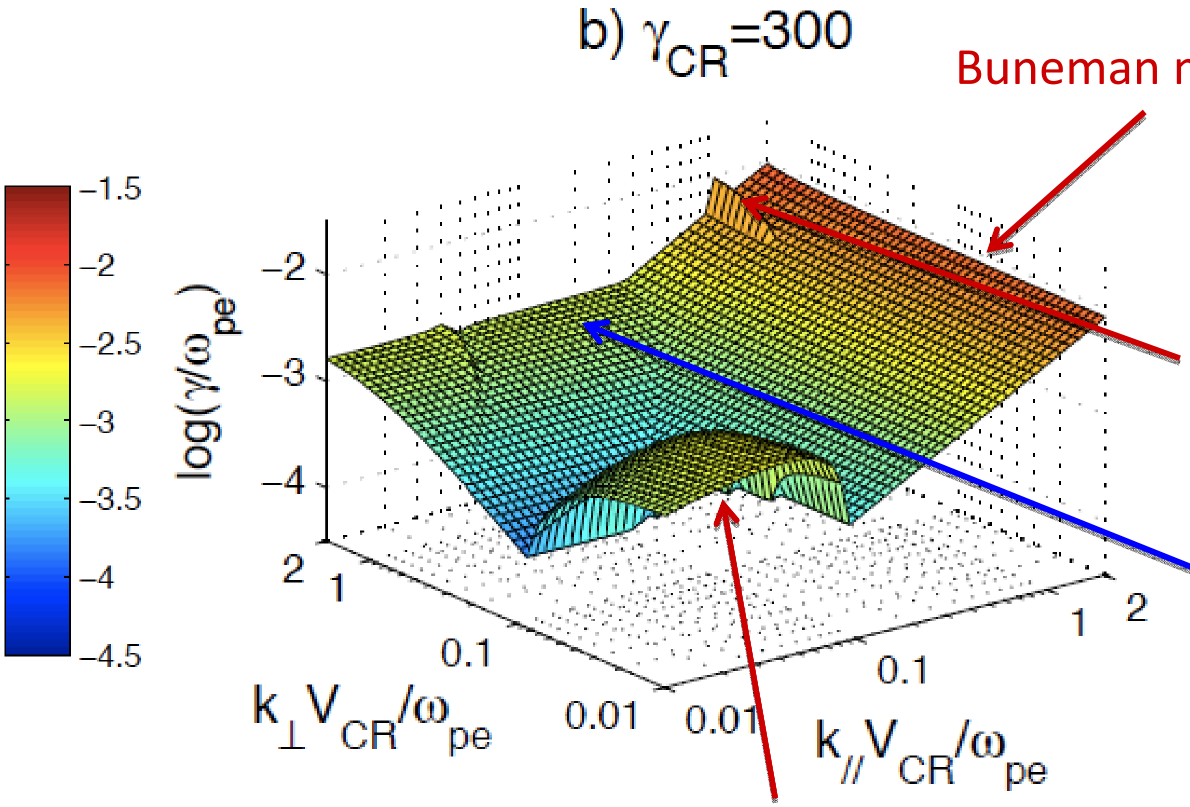

Buneman mode (ambient ions-drifting electrons)

Buneman mode (CR beam-electrons)

filamentation modes!

nonresonant mode

Relativistic CR ion beam in electron-proton plasma: linear analysis

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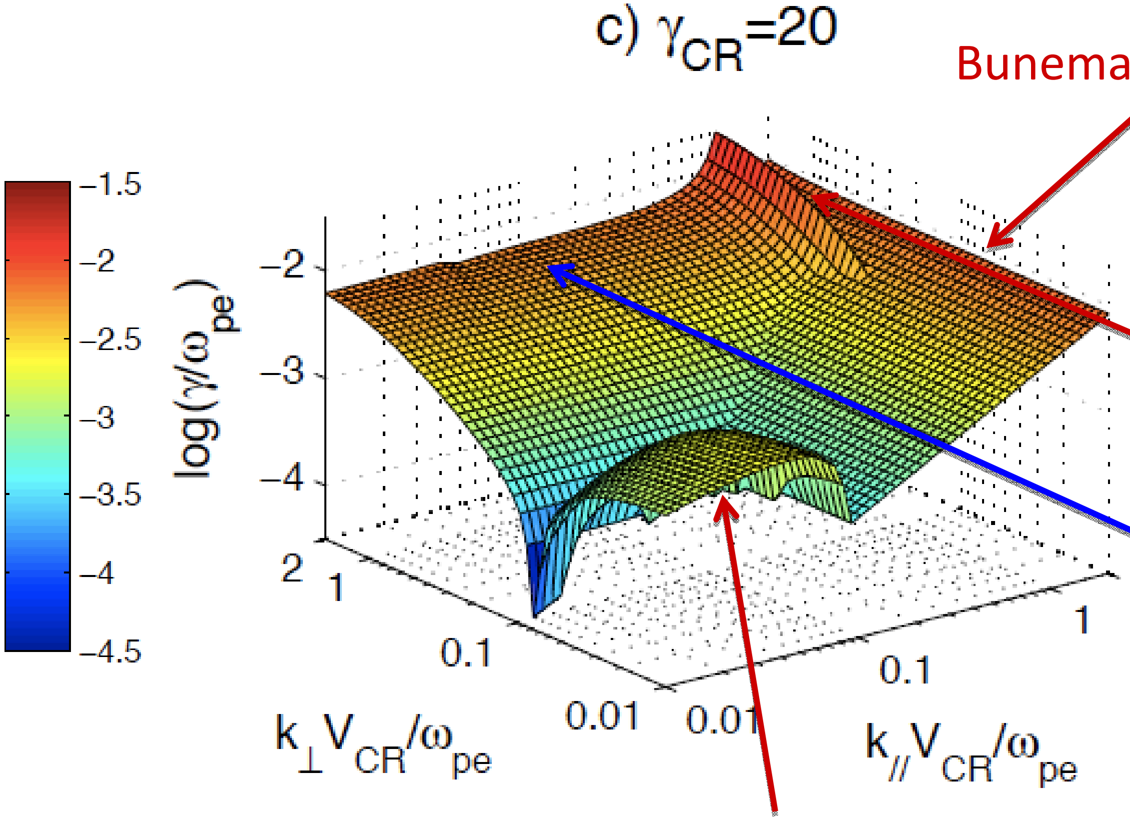


Buneman mode (ambient ions-drifting electrons)

Buneman mode (CR beam-electrons)

filamentation modes dominant over nonresonant modes!

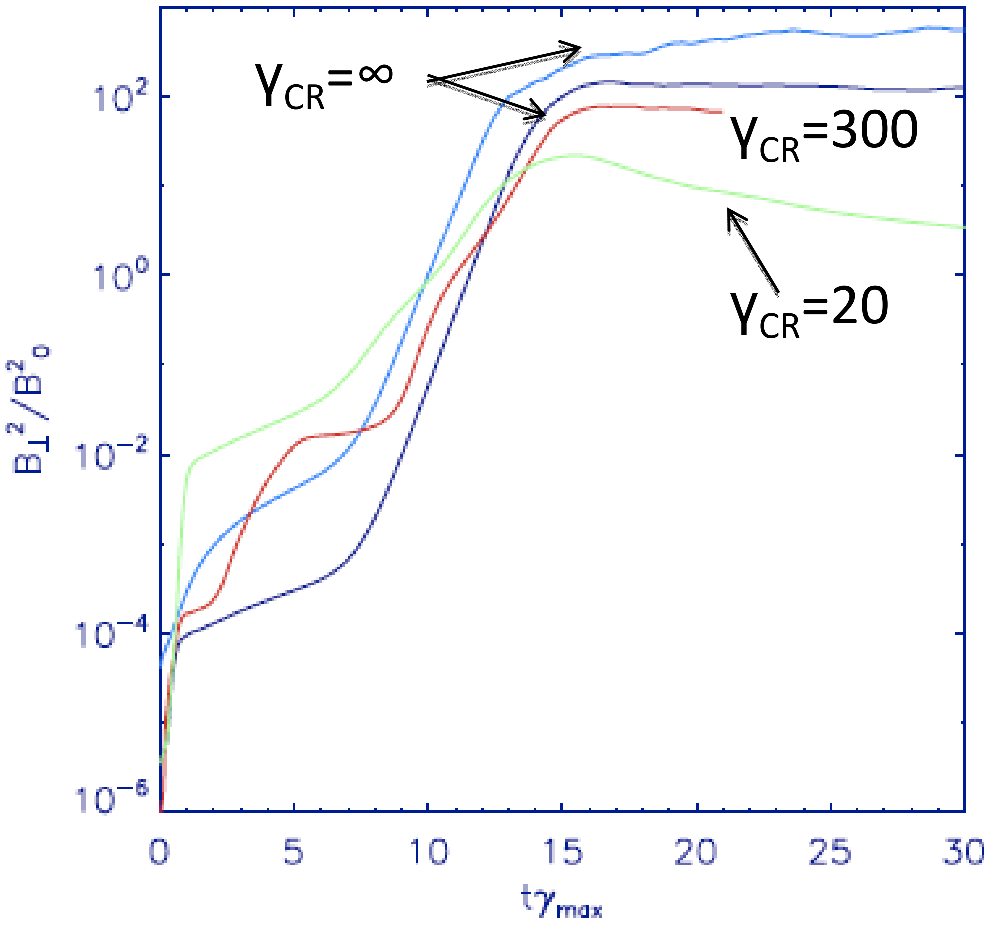
nonresonant mode

Relativistic CR ion beam in electron-proton plasma: Particle-In-Cell simulations

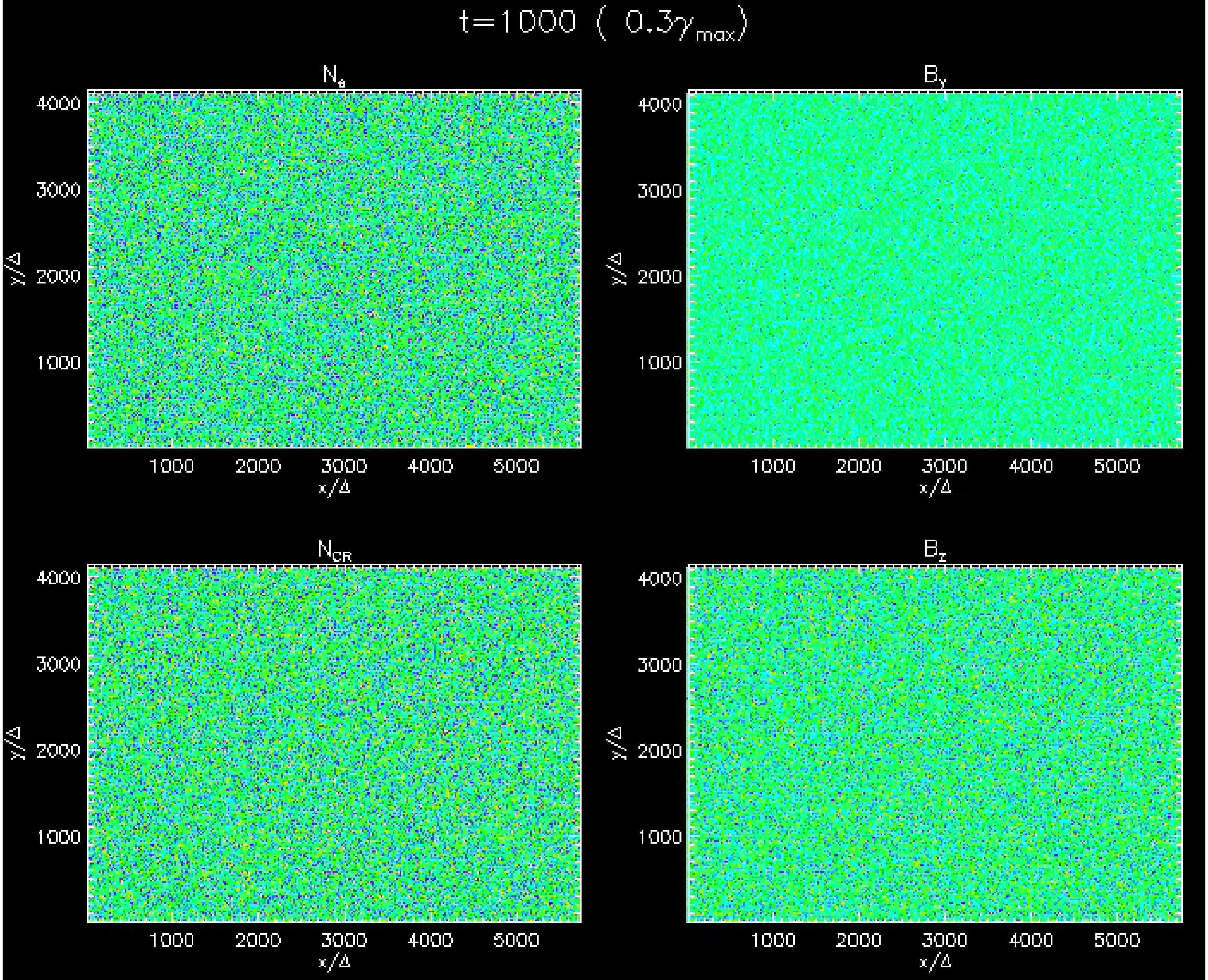
2.5D simulation parameters:

$\gamma_{CR}=\infty, 300, 20$; $v_A=c/20, c/50$; $N_{CR}/N_i=1/50, 1/125$

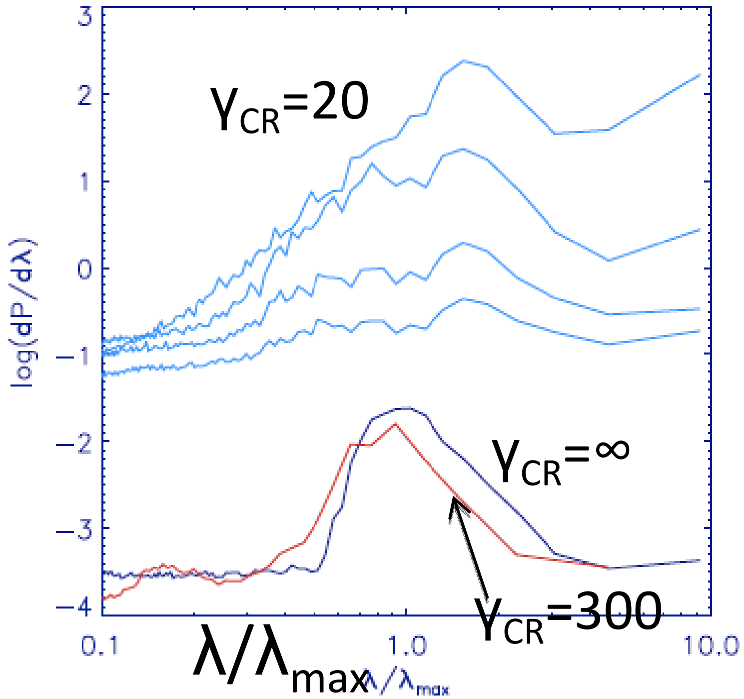
$\gamma_{max}/\Omega_i=0.2$, $m_i/m_e=20$



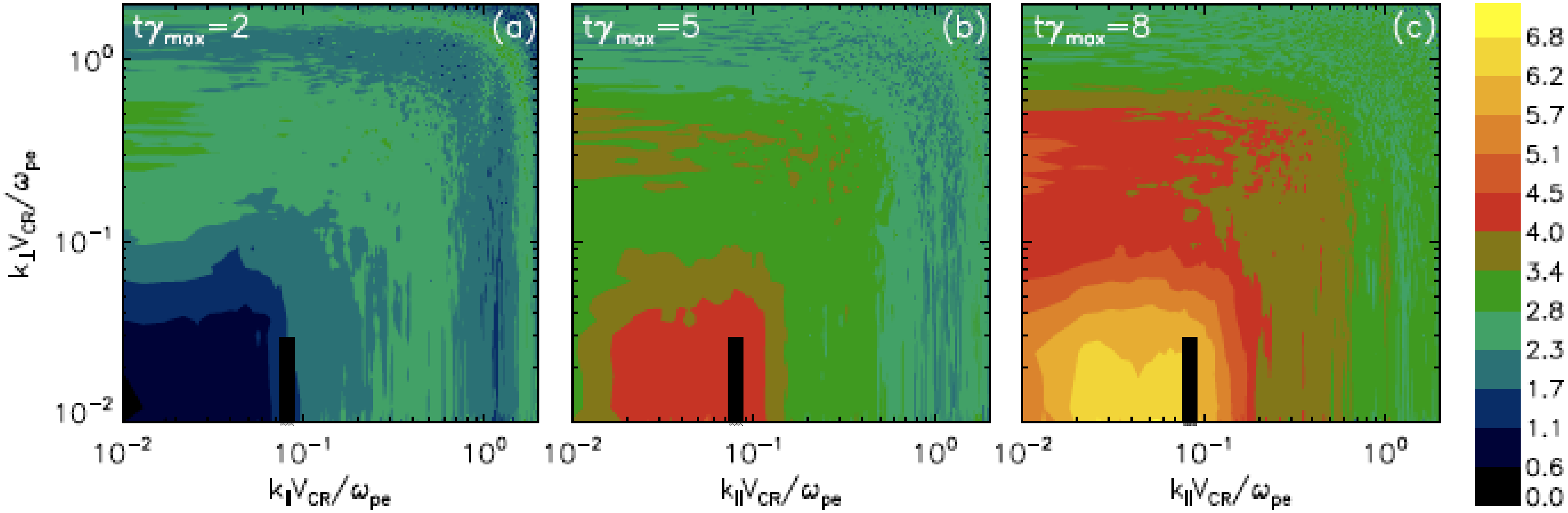
- perfect agreement with linear analysis results during initial evolution
- constant CR current ($\gamma=\infty$)
  - nonresonant modes with γ_{max}
- CR backreaction ($\gamma=300, 20$)
  - ambient plasma and beam filamentation in initial stage
  - nonresonant modes strongly modified by filamentation for mildly relativistic beams ($\gamma_{CR}=20$) and $\delta B_{max} \approx$ 5-9 B_0
- nonlinear saturation similar to nonrelativistically driftingCR case


$t=1000$ ($0.3\gamma_{max}$)
N_e
B_y
N_{CR}
B_z
y/Δ
x/Δ
1000
2000
3000
4000
5000

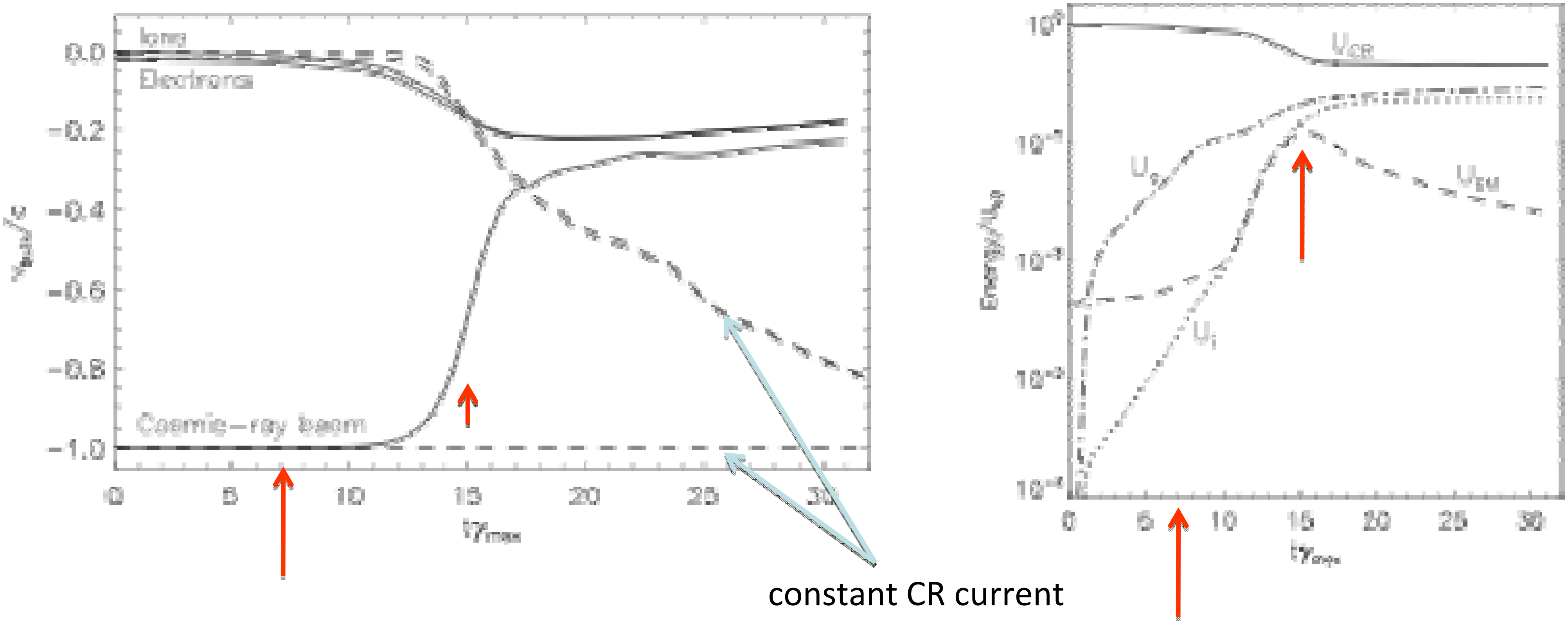
Properties of turbulence for mildly relativistic beams



- nonresonant parallel modes in a broad range of wavelengths around λ_{max}
- slow growth rate (~0.4 γ_{max})
- backreaction of magnetic turbulence on particles enhances the filamentation
  - saturation of turbulence growth
  - CR beam “randomization”



Particle distributions – saturation of the instability



constant CR current

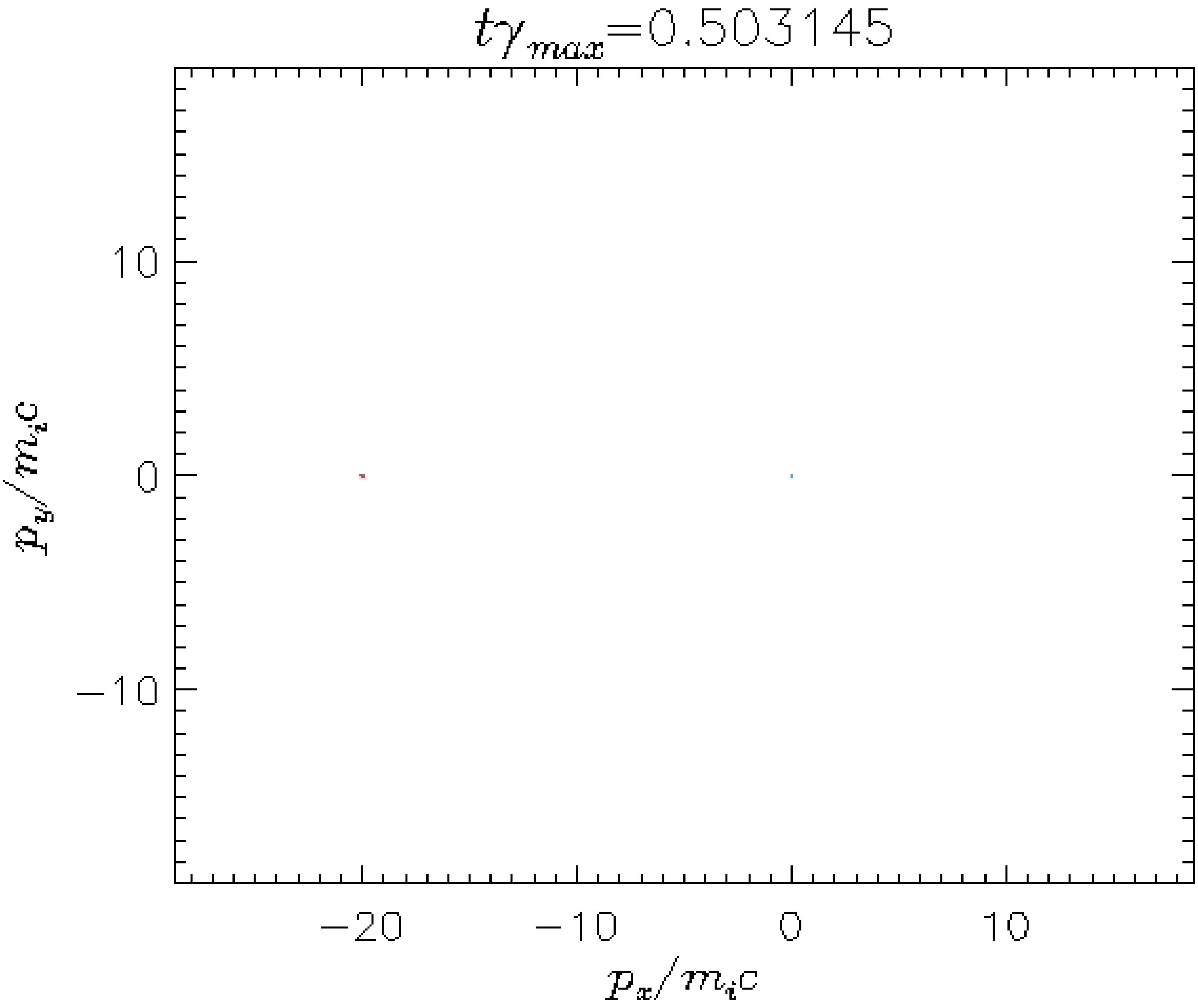
- energy of decelerating ion beam transferred in about equal parts to the ambient ions and magnetic field (Winske& Leroy 1984; nonrelativistic beams)
- validity of simulations assuming a constant CR current restricted to early phases of system evolution

Particle phase-space distributions

CR ions

ambient ions

$\gamma_{\mathrm{CR}} = 20$



Particle phase-space distributions

•CR beam momentum randomization through ,,pitch-angle" scattering in conditions allowing for an efficient magnetic field amplification through nonresonant modes

•scattering mean free path:

$$\lambda_{\rm mfp} \approx 5000\Delta$$

compatible with Bohm diffusion (a rough estimate)

$$\lambda_{\rm Bohm} \approx 3000\Delta$$

Conclusions

- Properties of the relativistic cosmic-ray ion beam-plasma system determined by a close competition of the nonresonant mode with filamentation instability and Buneman modes
- The system is capable of producing highly nonlinear magnetic turbulence
    - representation of the CR beam by a constant current is suboptimal, since it suppresses part of the nonlinear response of the system, delays saturation, and significantly overestimates the amplitude of the generated magnetic field
- Magnetic turbulence leads to efficient CR scattering even for moderate field amplification levels