Efficient non-thermal particle acceleration mediated by the kink instability in jets

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Jets from active galactic nuclei (AGN) are among the most powerful cosmic accelerators

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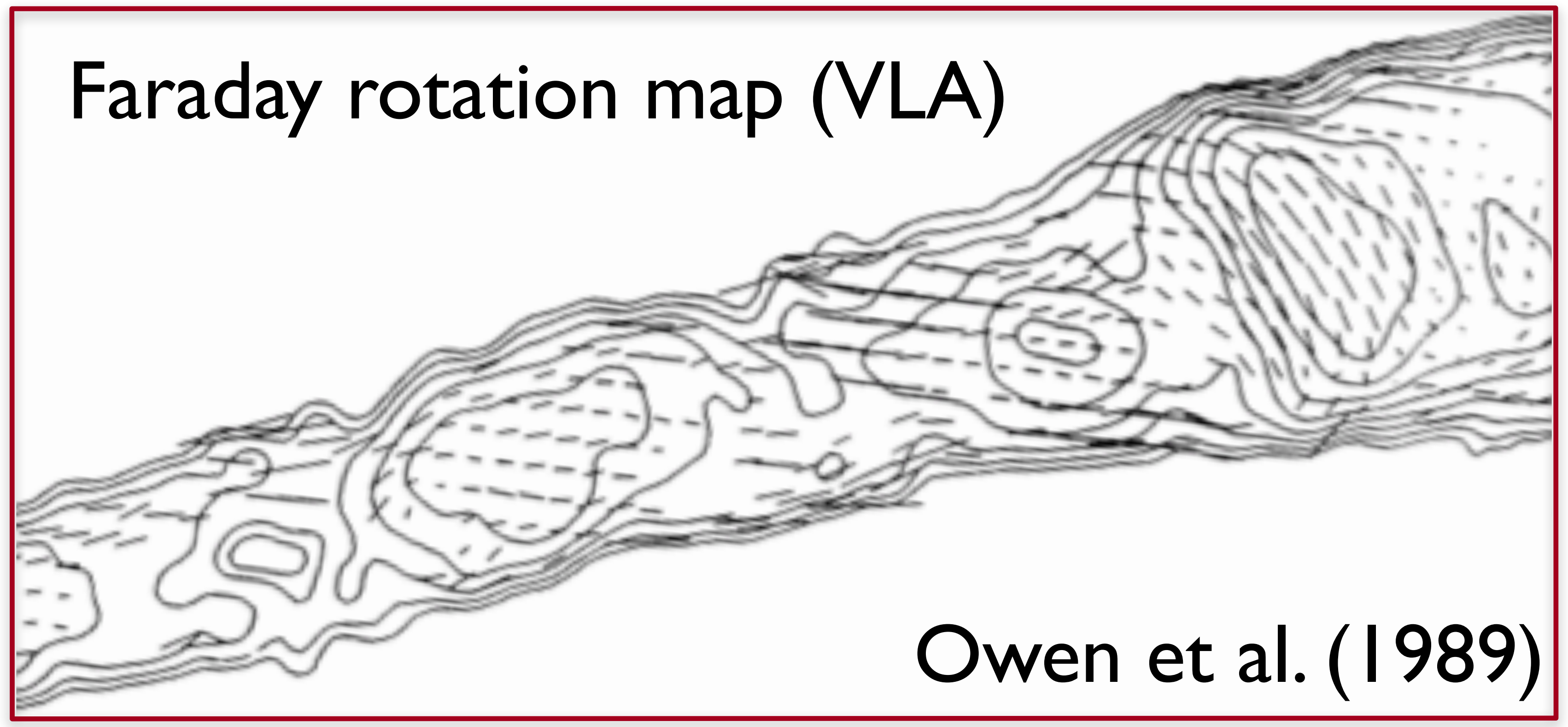
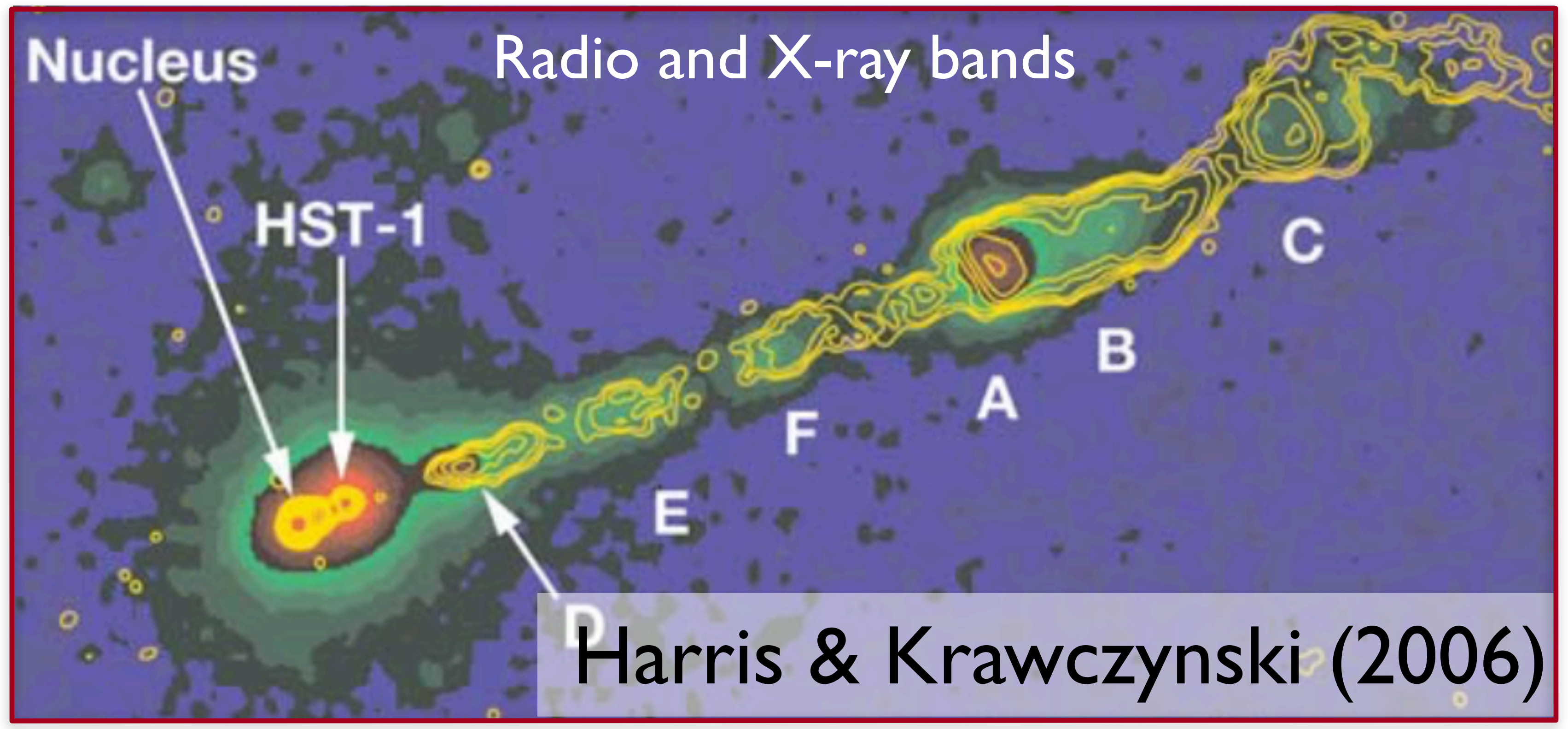
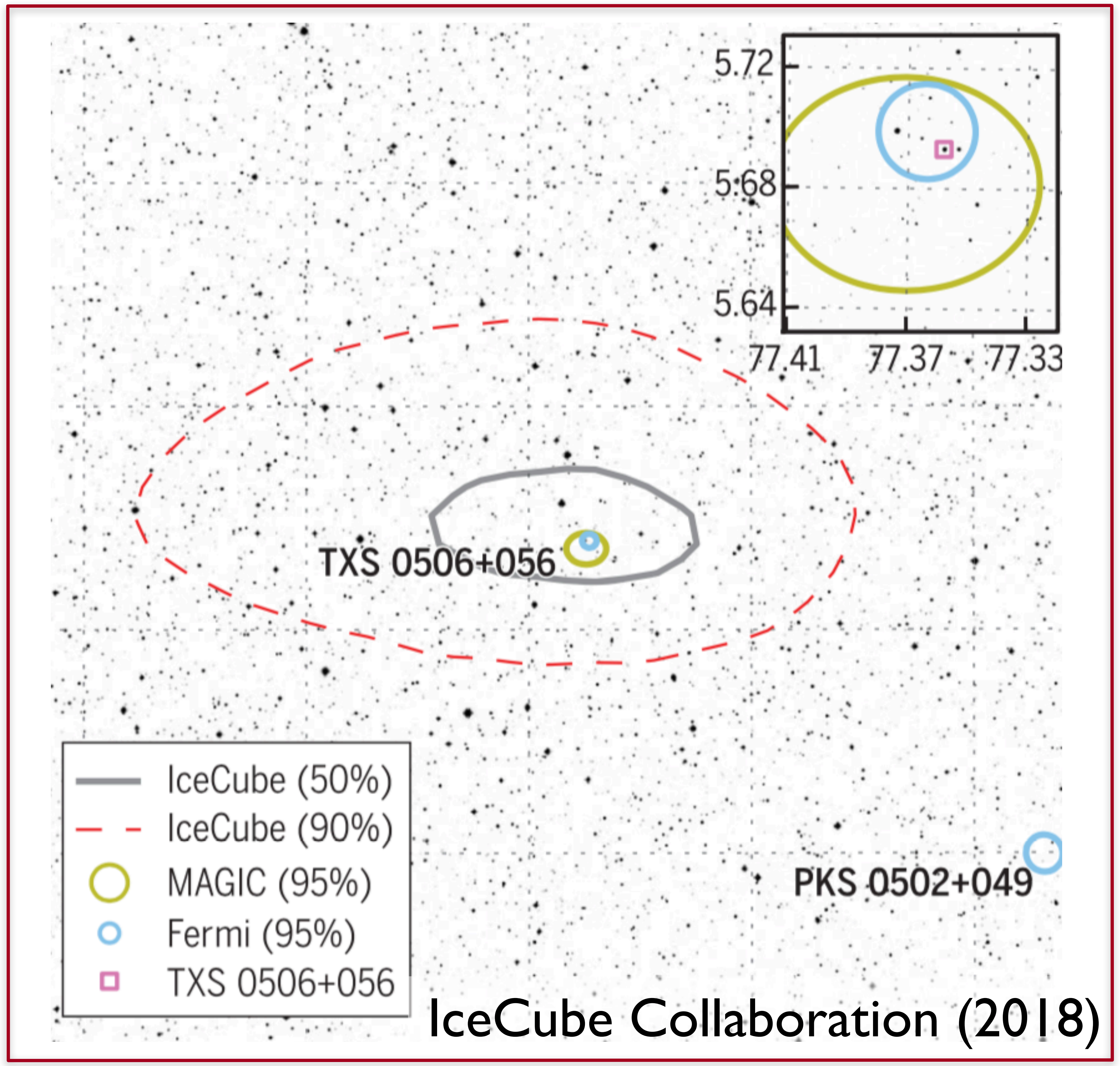
Magnetized outflows with helical B-fields



Emission across the e.m. spectrum



Sources of very high energy cosmic rays



Their particle acceleration mechanisms remain poorly understood

Shocks* and magnetic reconnection** are often invoked but it is not clear how they would operate efficiently in jet environments

* Bell (1978, 2018), Blanford & Eichler (1987), Sironi et al. (2013)

** Drake et al. (2006), Sironi et al. (2014), Guo et al. (2014)

Global MHD simulations indicate that the KI can efficiently dissipate the jet's B-field at recollimation

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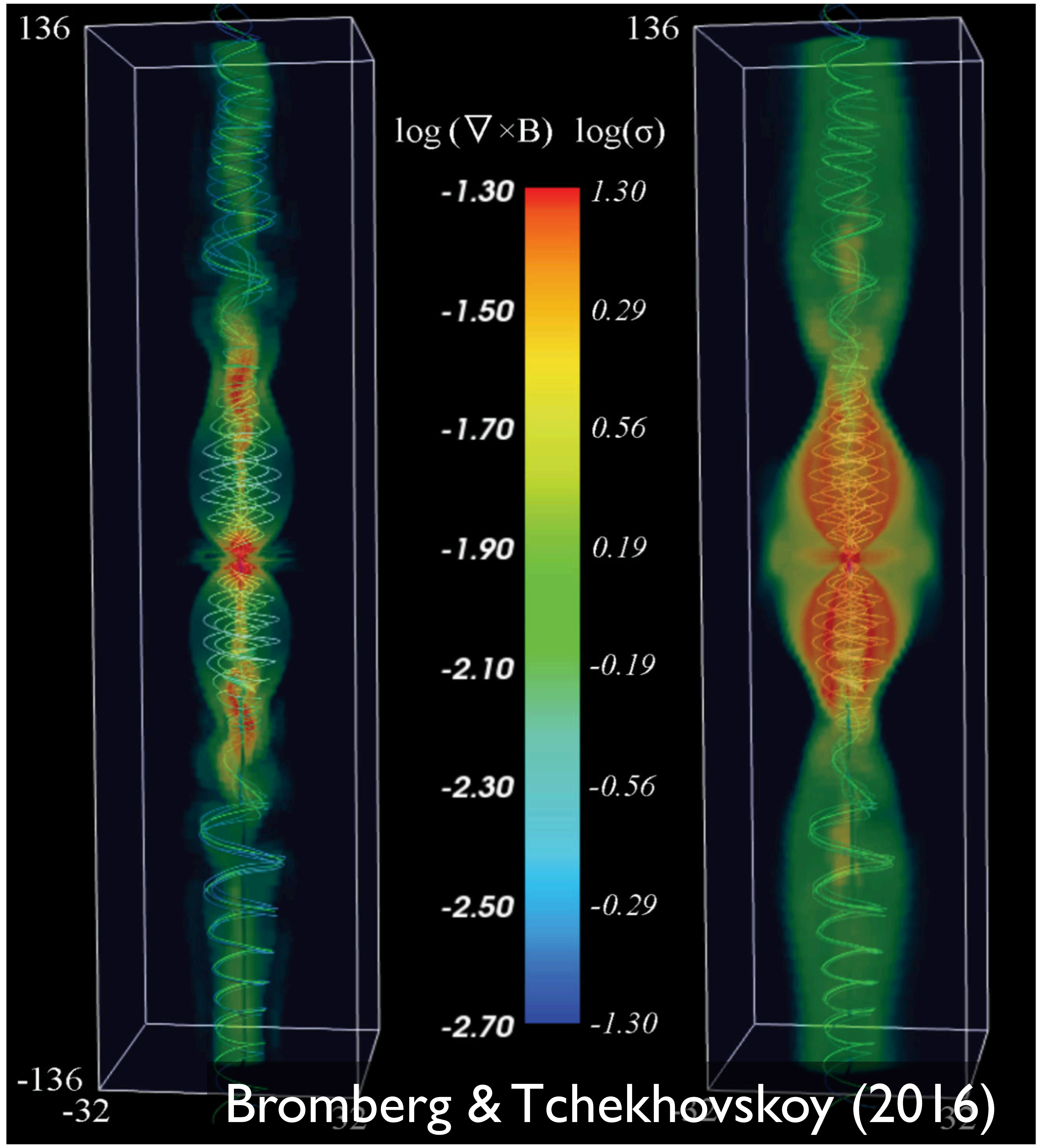
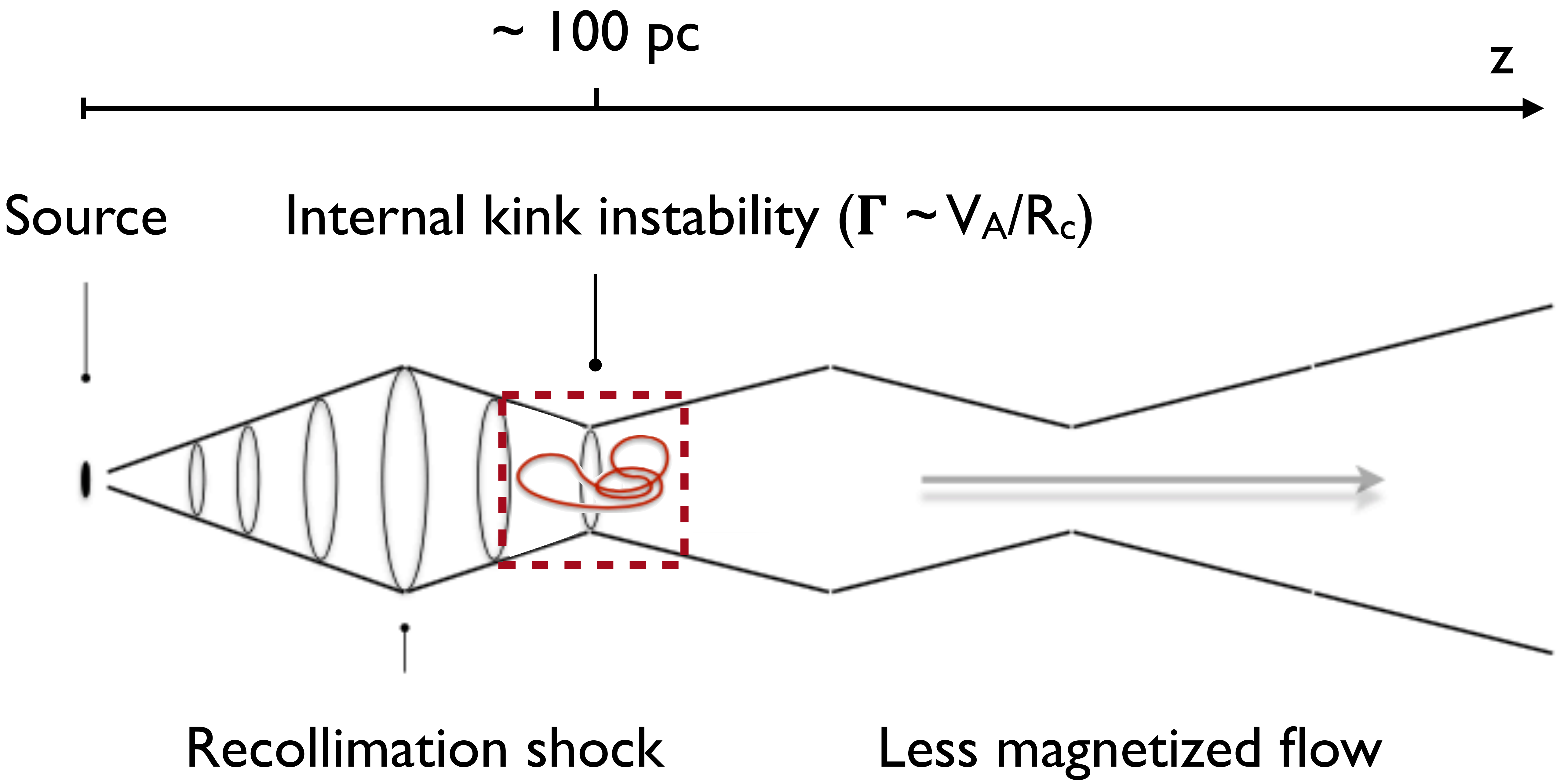
* Internal KI is triggered at jet recollimation



Bromberg & Tchekhovskoy (2016)



$B_z/B_\phi \sim 1/z$ — Magnetic field predominantly toroidal where jet recollimates

***If* and *how* the dissipated magnetic energy is channeled into non-thermal particles is unknown**

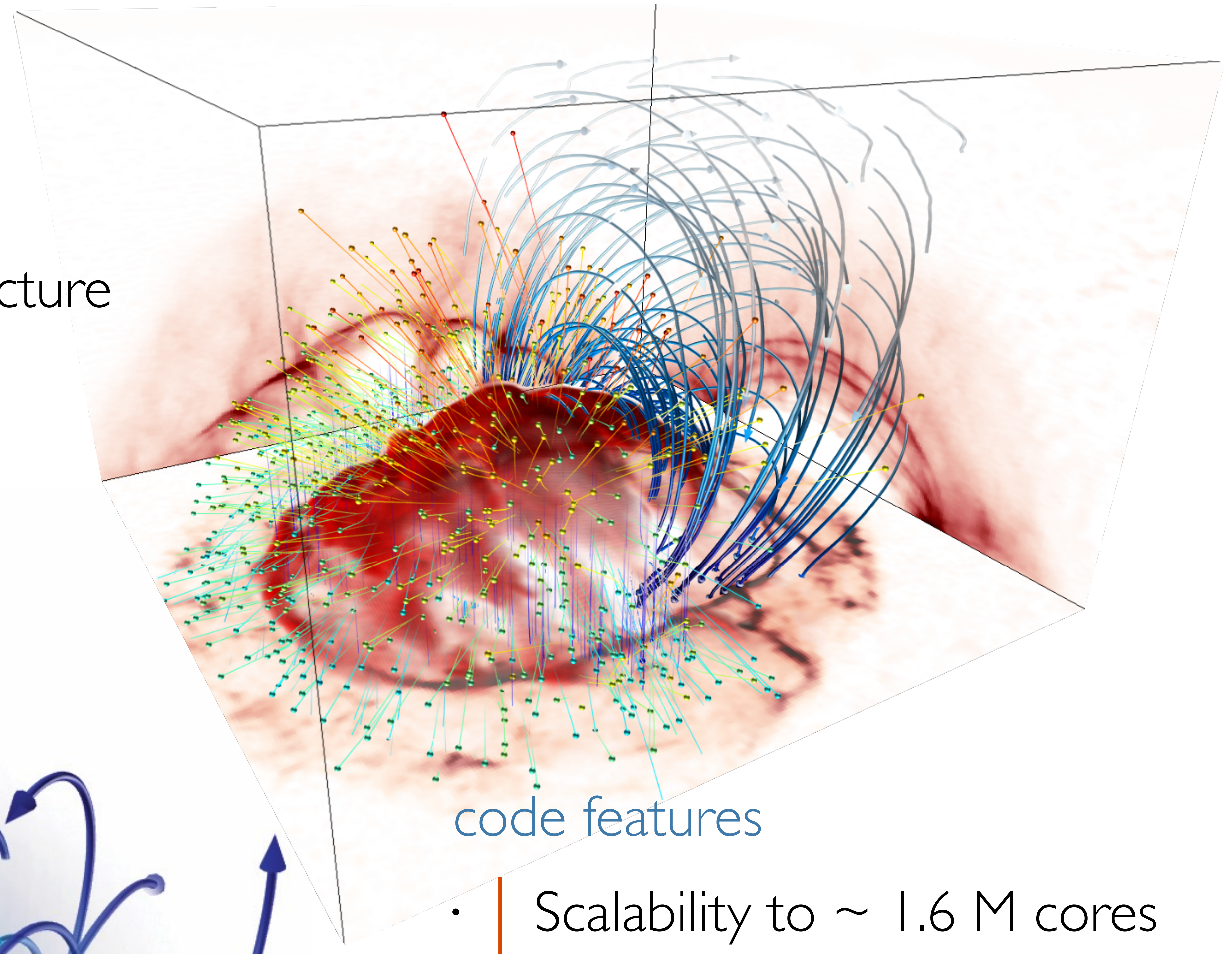
* Begelman (1998), Giannios & Spruit (2006), Porth & Komissarov (2015), Tchekhovskoy & Bromberg (2016), Duran et al. (2016)

OSIRIS: a state-of-the-art PIC code for the modeling of plasmas

Osiris 3.0

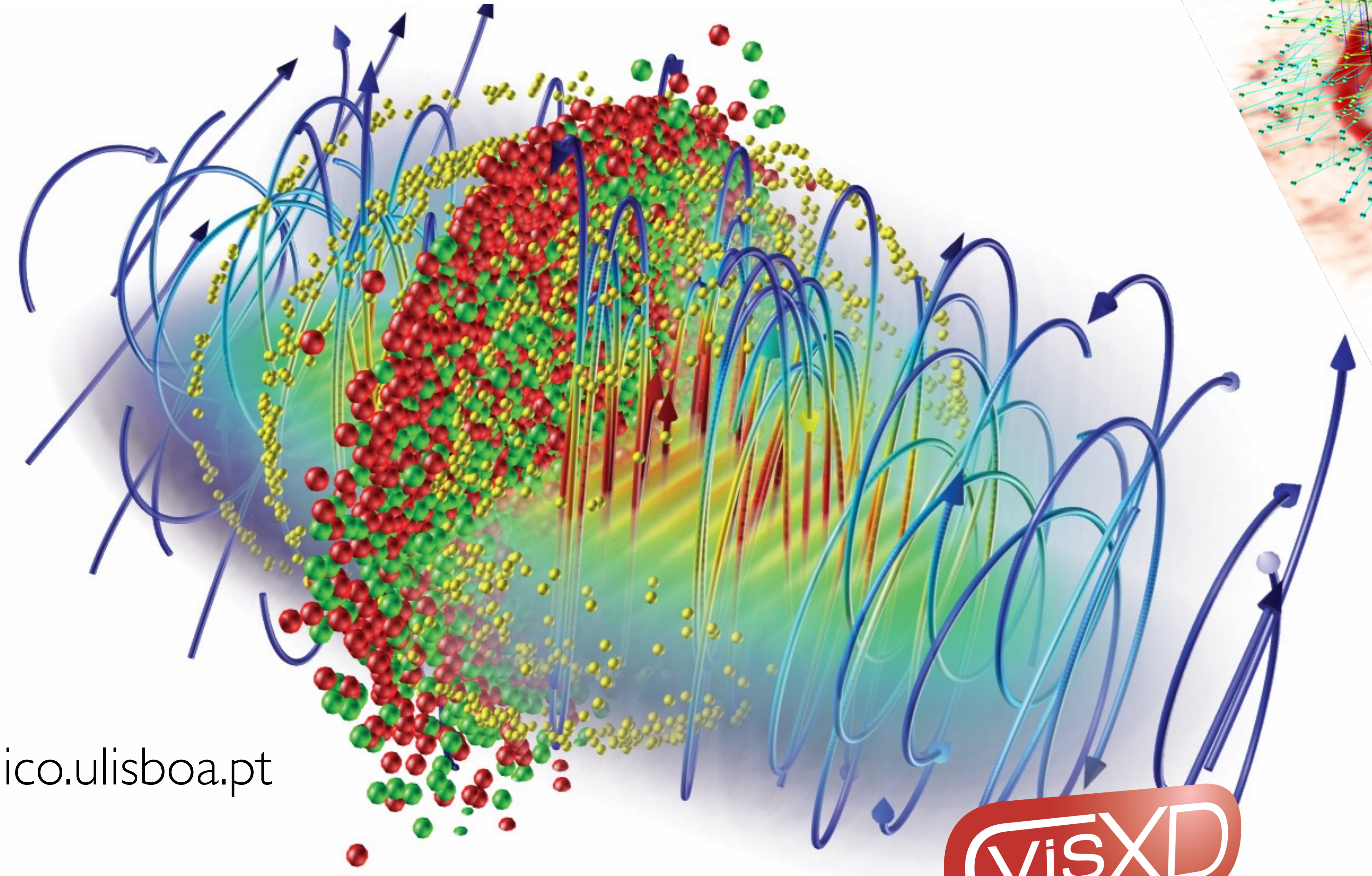
osiris framework

- Massivelly Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  ⇒ UCLA + IST



TÉCNICO LISBOA

UCLA



code features

- Scalability to ~ 1.6 M cores
- SIMD hardware optimized
- Parallel I/O
- Dynamic Load Balancing
- QED module
- Particle merging
- GPGPU support
- Xeon Phi support

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We model a 3D volume of the jet's KI unstable region as a relativistic electron-positron plasma in hydromagnetic equilibrium

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Toroidal B-field*

$$\mathbf{B}(r) = B_0 \frac{r}{R_c} e^{1-r/R_c} \mathbf{e}_\phi + B_z \mathbf{e_z}$$

Density profile

$$n(r) = n_0 + \frac{n_c - n_0}{\cosh(2r/R_c)}$$

Current density

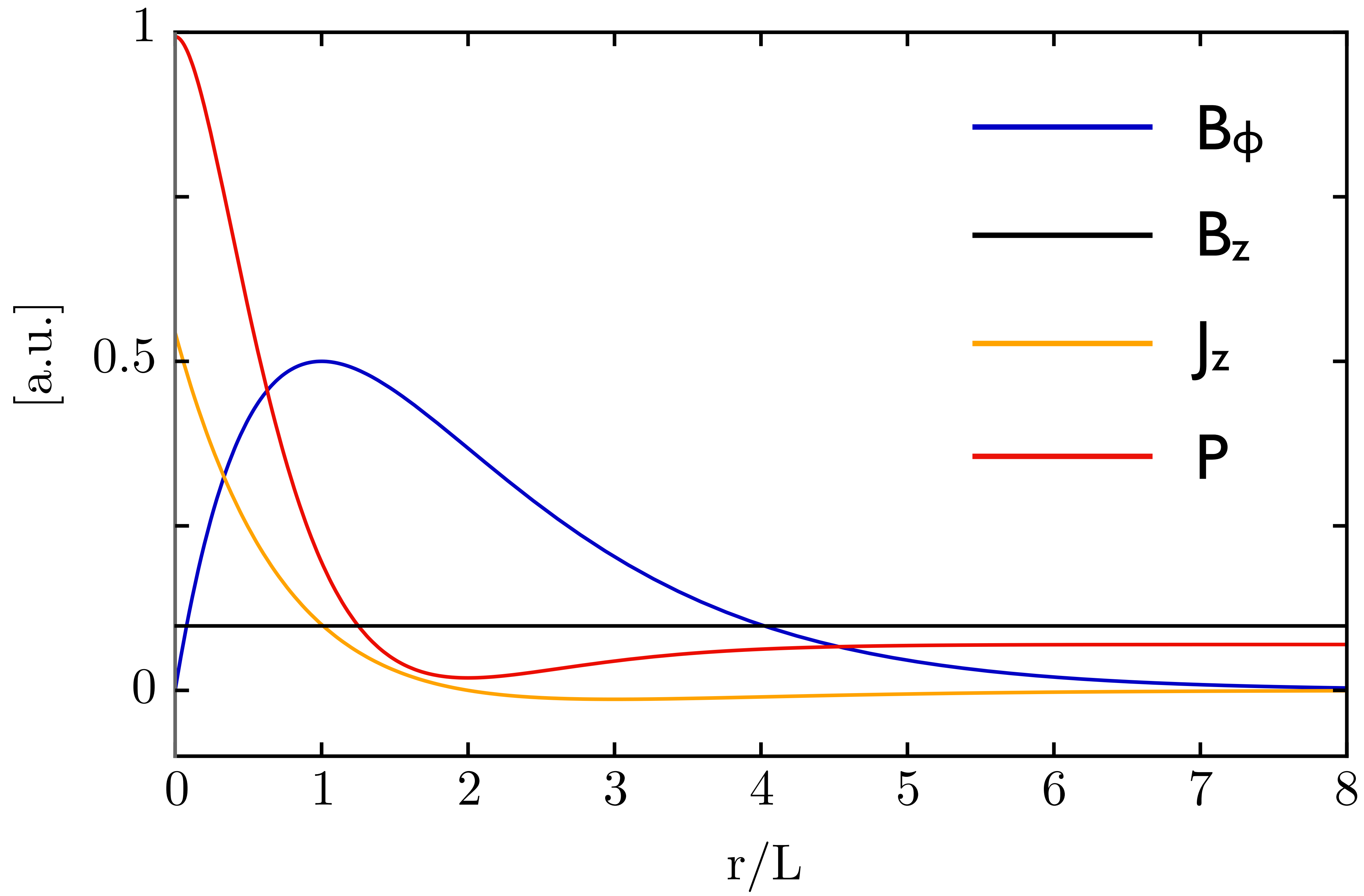
$$\mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{B}$$

Pressure balance

$$\nabla P = \mathbf{J} \times \mathbf{B}$$

* The particle acceleration physics is the same for B-field profiles that decay as $r^{-\alpha}$ (with $\alpha \gtrsim 1$)

Equilibrium profiles



Characteristic dimensionless parameters

$$\sigma = \frac{B_0^2}{4\pi n_c m_e c^2} \qquad P \equiv B_z/B_\phi \qquad \bar{R} \equiv \frac{R_c}{\langle \rho_g \rangle} = \frac{R_c \omega_{pe}}{c} \sqrt{\frac{n_c}{9\sigma n_0}}$$

Development of coherent E-field embedded in tangled B-field during nonlinear phase of the KI

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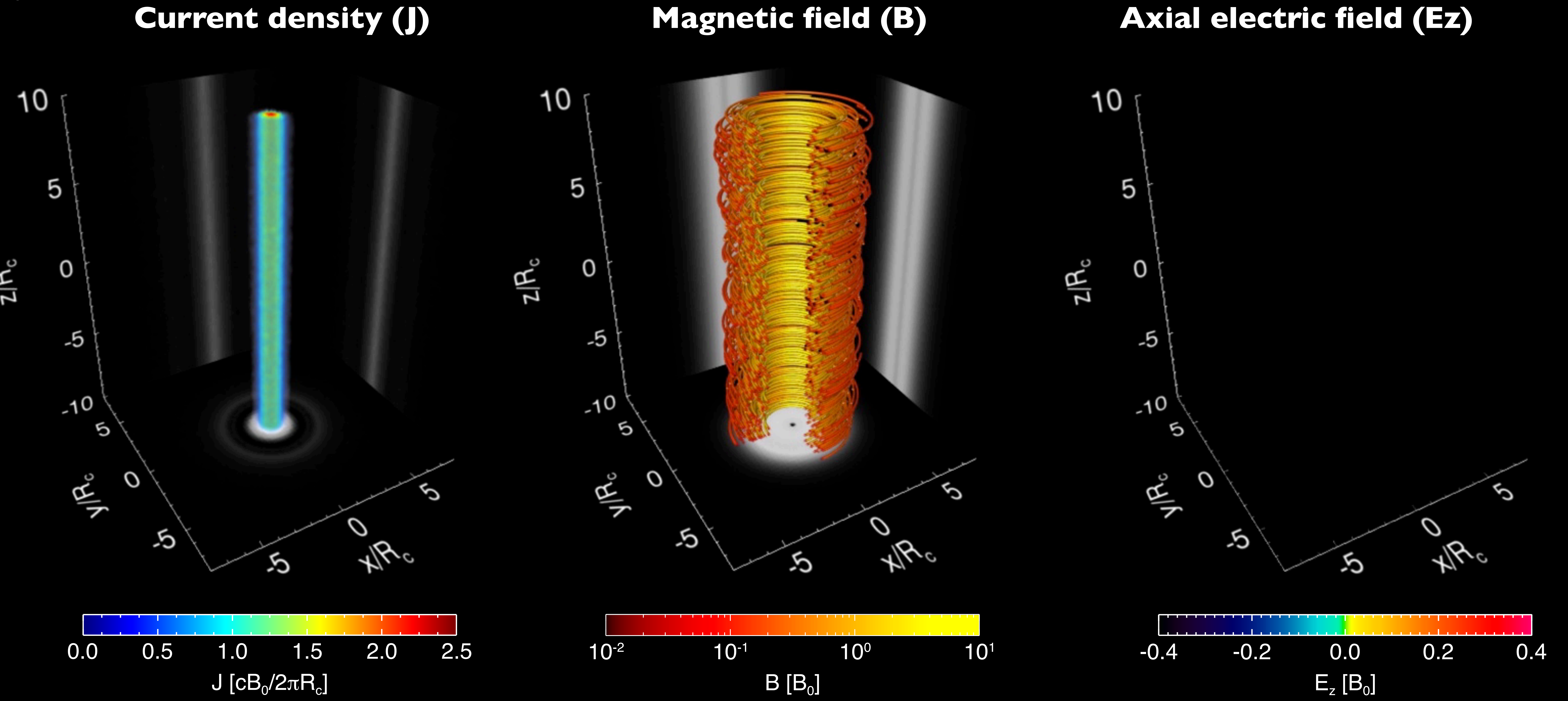
$ct/R_c = 0.0$



Physical parameters: $\sigma = 5$, $R_c/\langle\rho_g\rangle = 8.3$

Development of coherent E-field embedded in tangled B-field during nonlinear phase of the KI

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Physical parameters: $\sigma = 5$, $R_c/\langle\rho_g\rangle = 8.3$

Efficient transfer of the magnetic field energy into non-thermal particles

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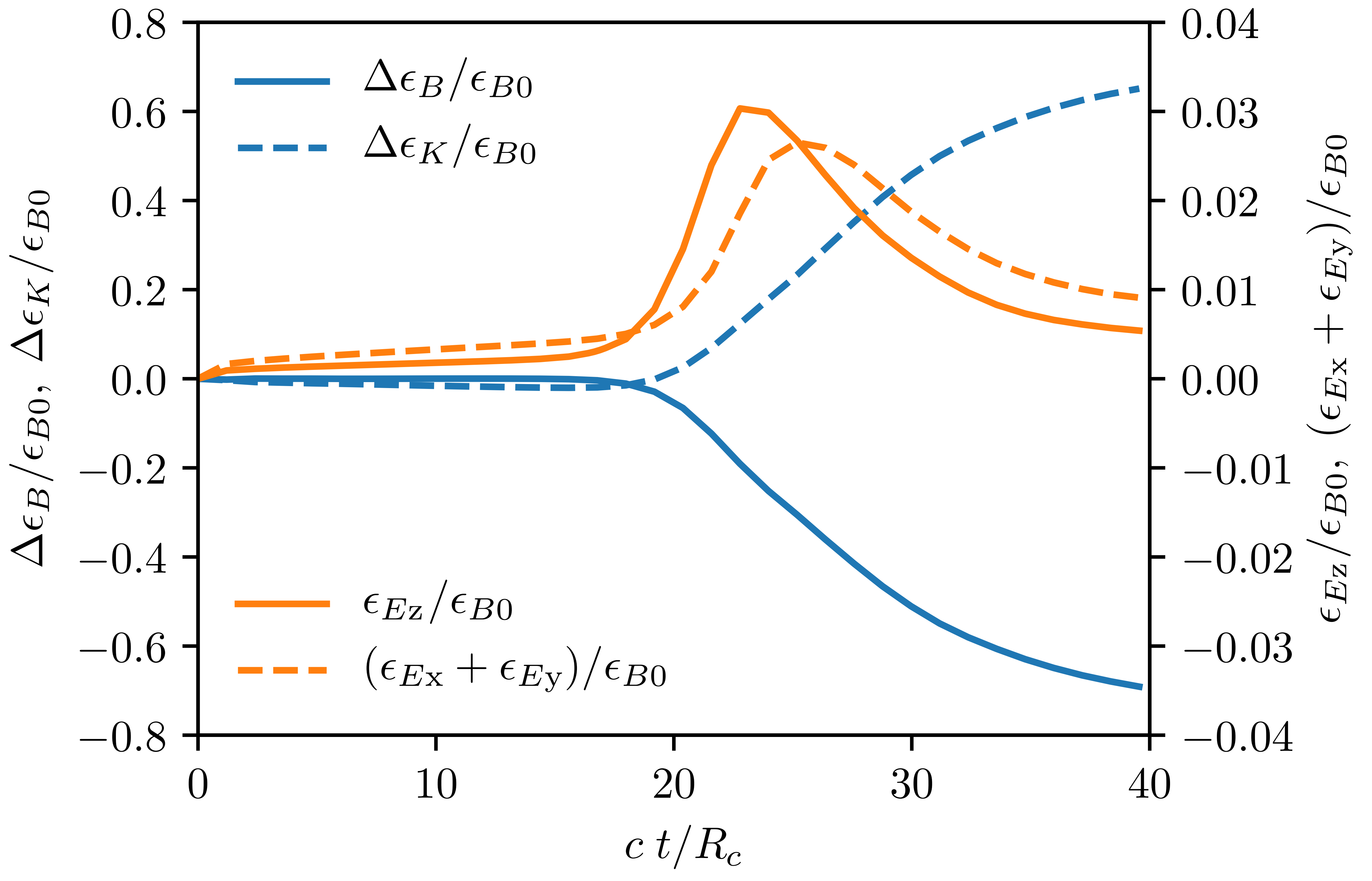
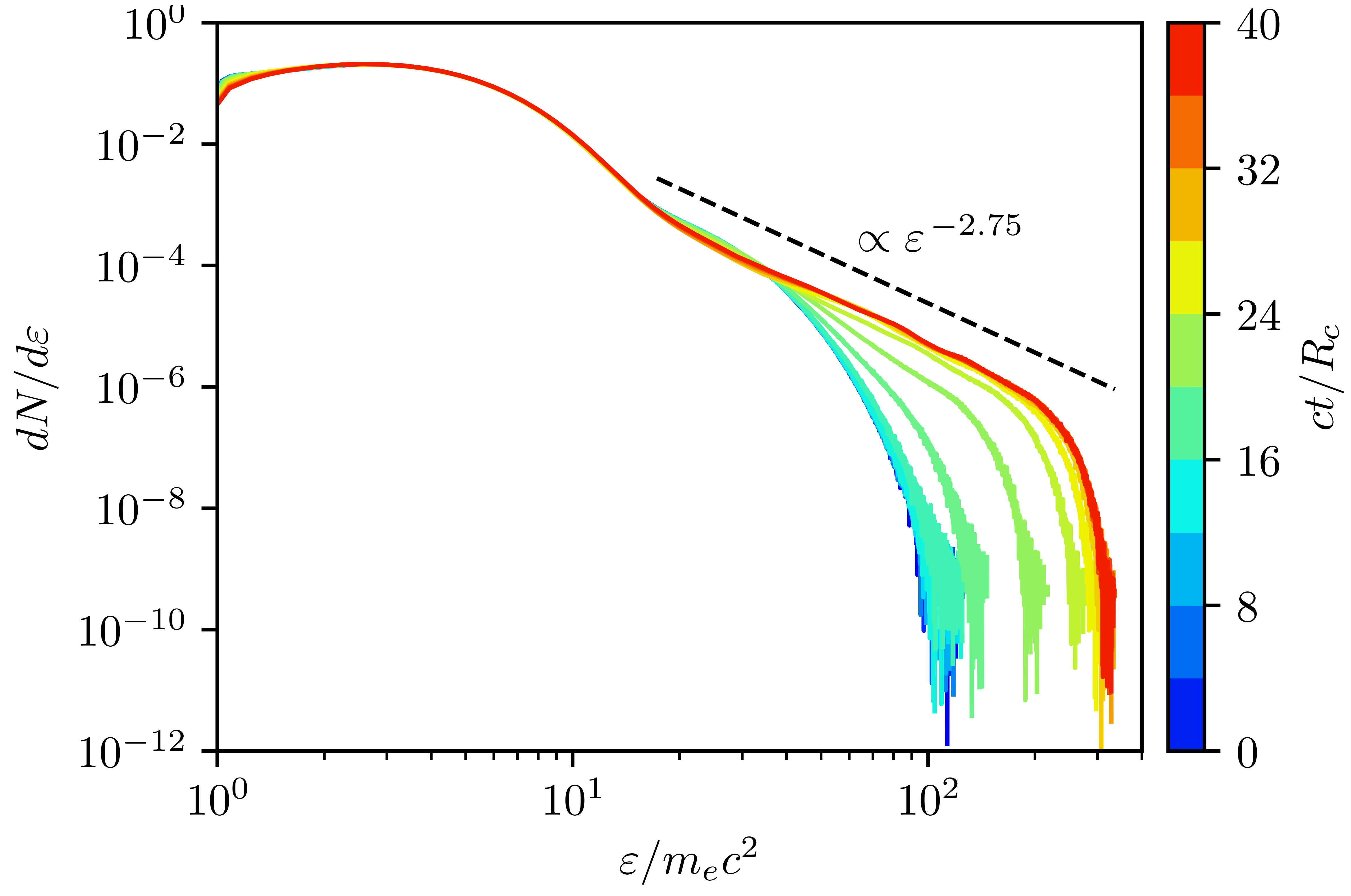
Evolution of system energetics



Evolution of particle energy spectrum

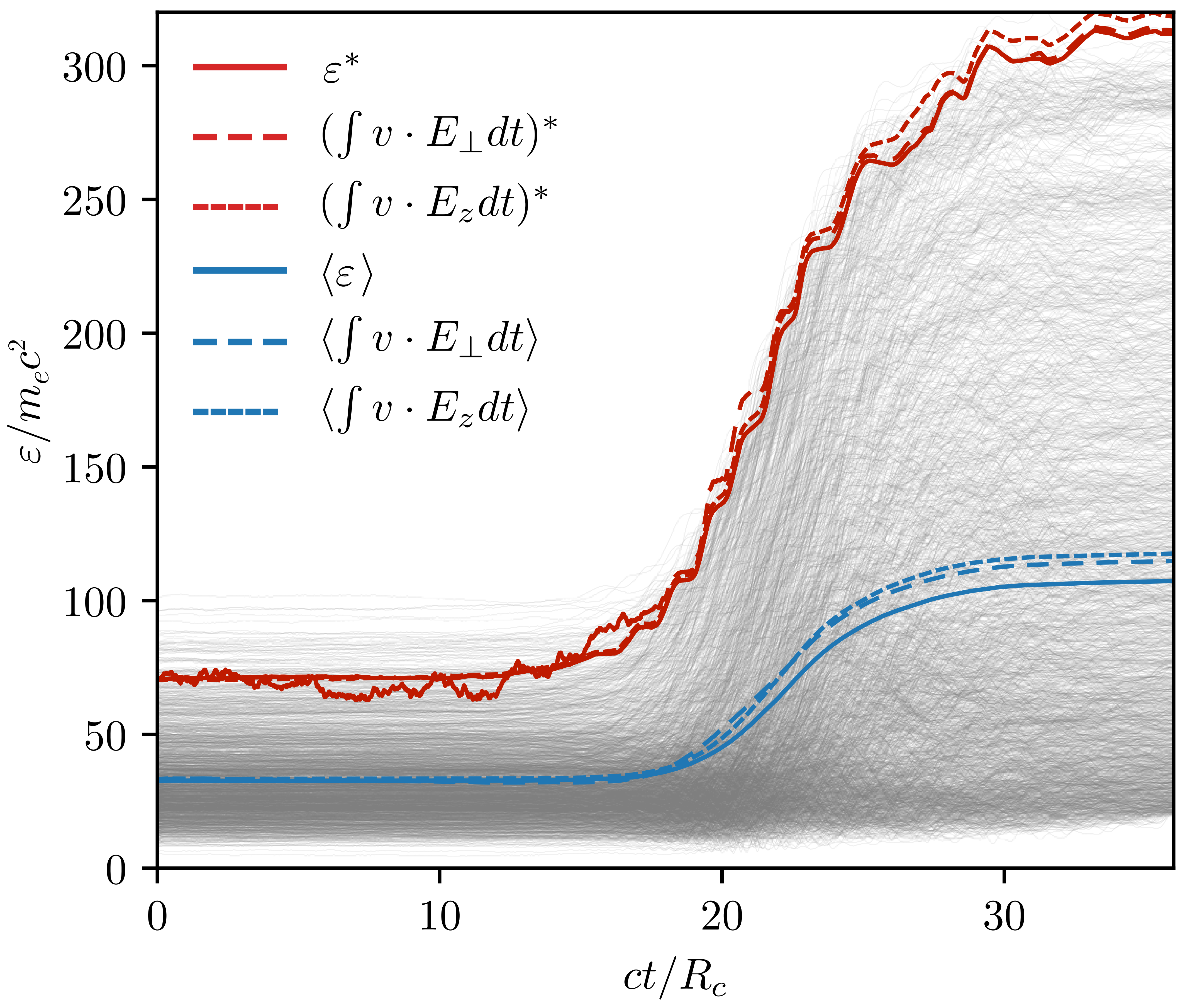


~ 50% of the total magnetic energy is transferred to the power-law tail

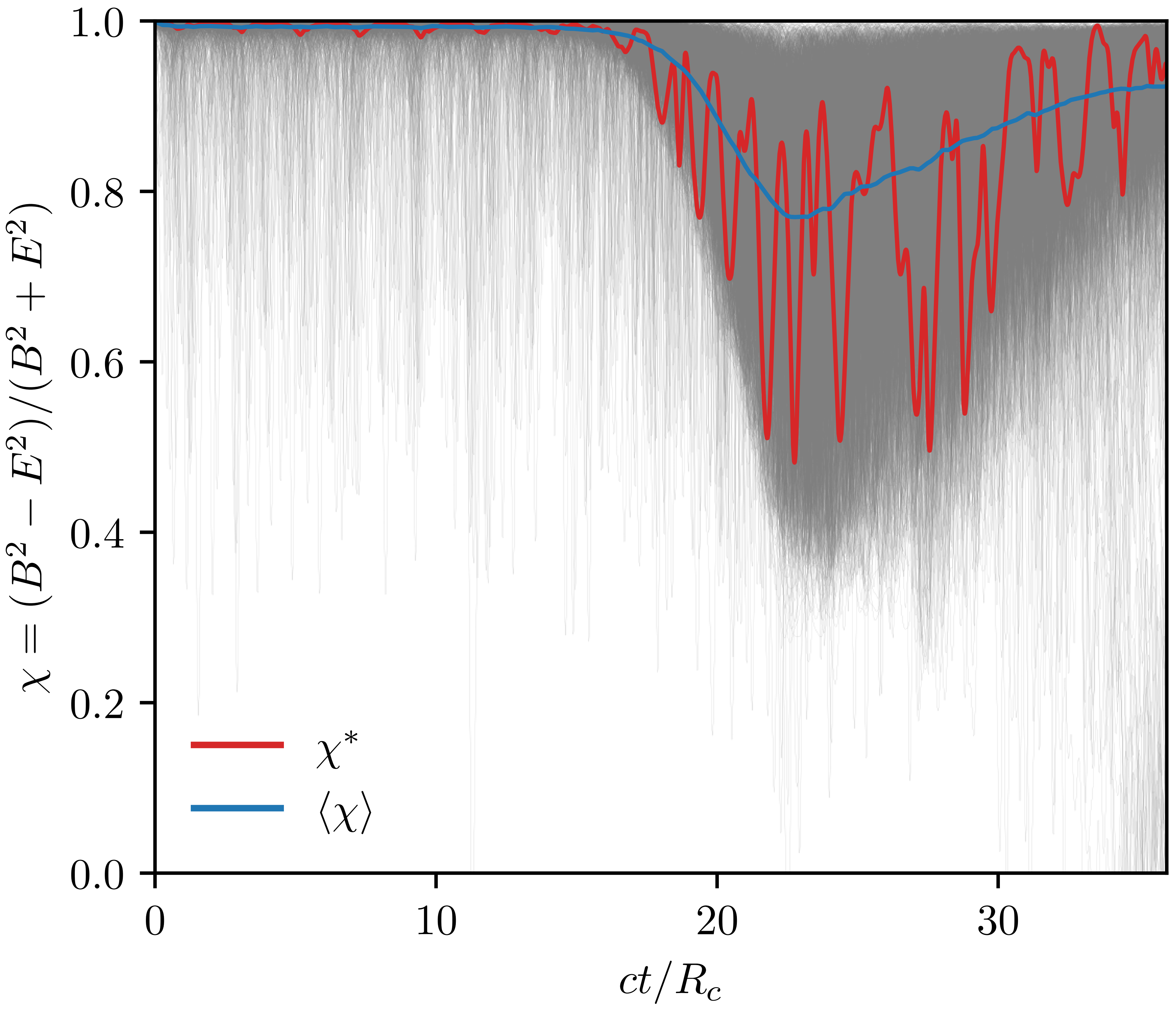
Physical parameters: $\sigma = 5$, $R_c/\langle\rho_g\rangle = 8.3$

The accelerating field structure is dominated by E ≅ $E_\perp$ and |E|<|B|

Particle energization due to $E_\perp$ work



|E|<|B| throughout acceleration process



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Efficient acceleration is enabled by the highly tangled B-field produced by the nonlinear KI

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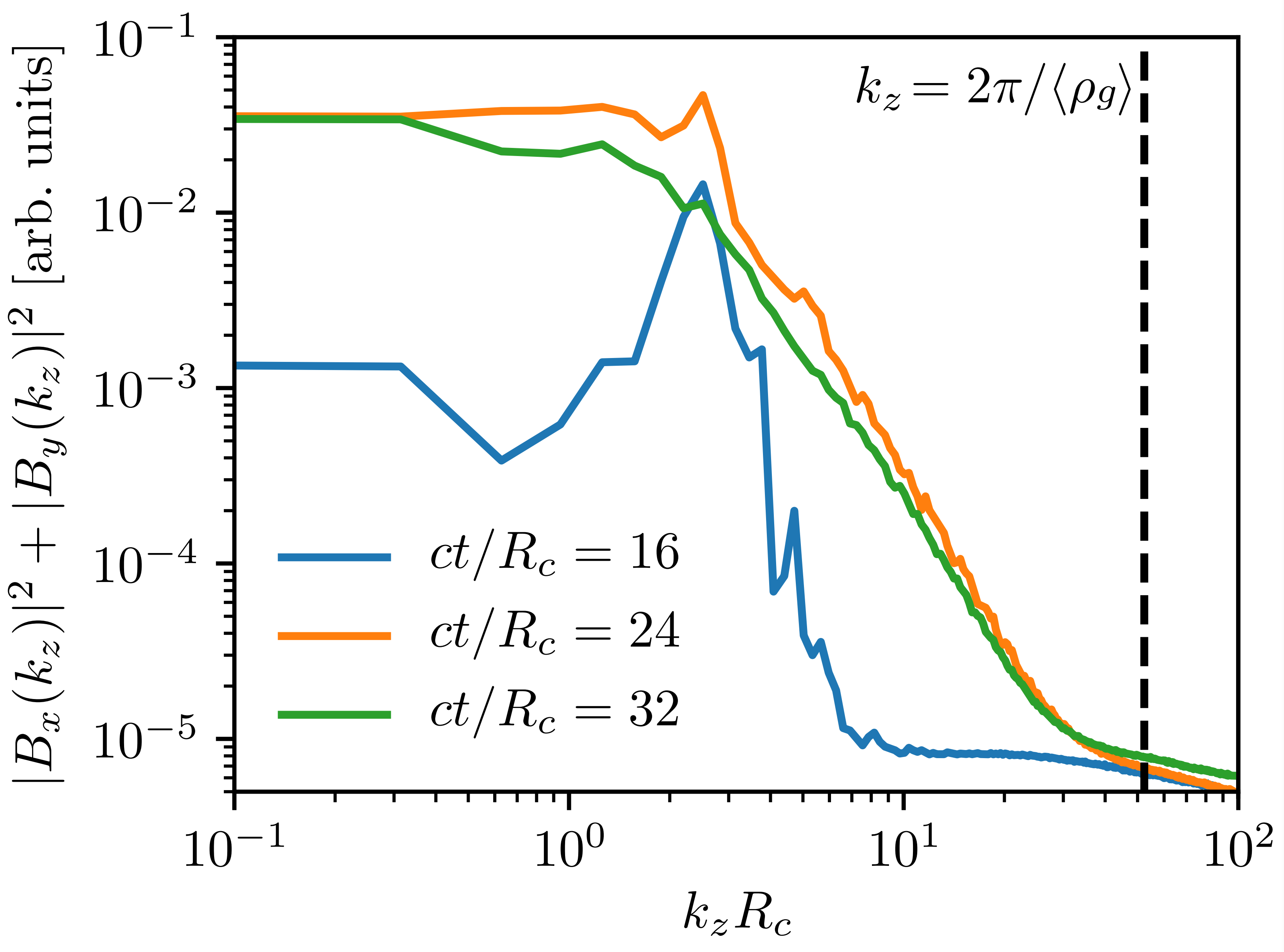
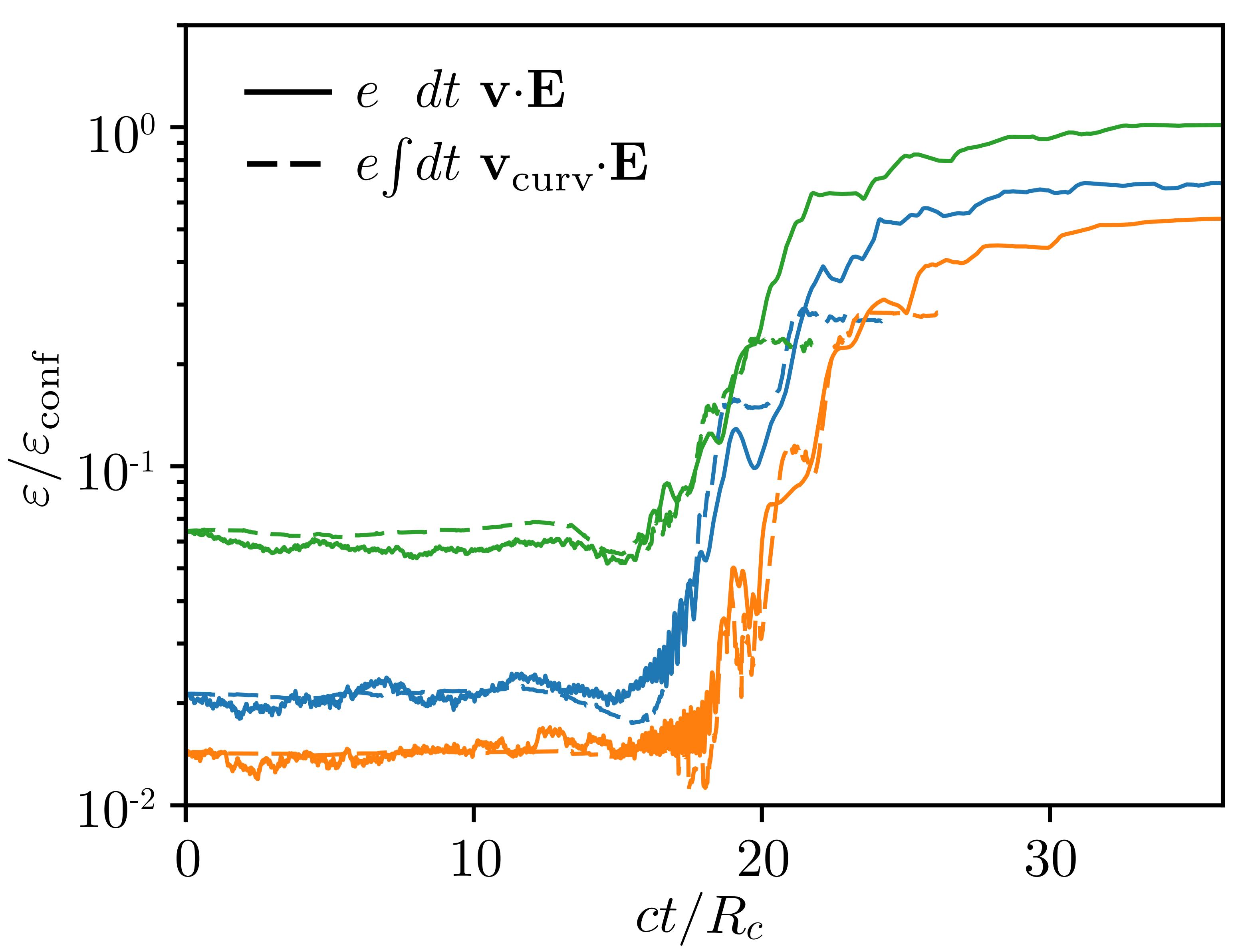
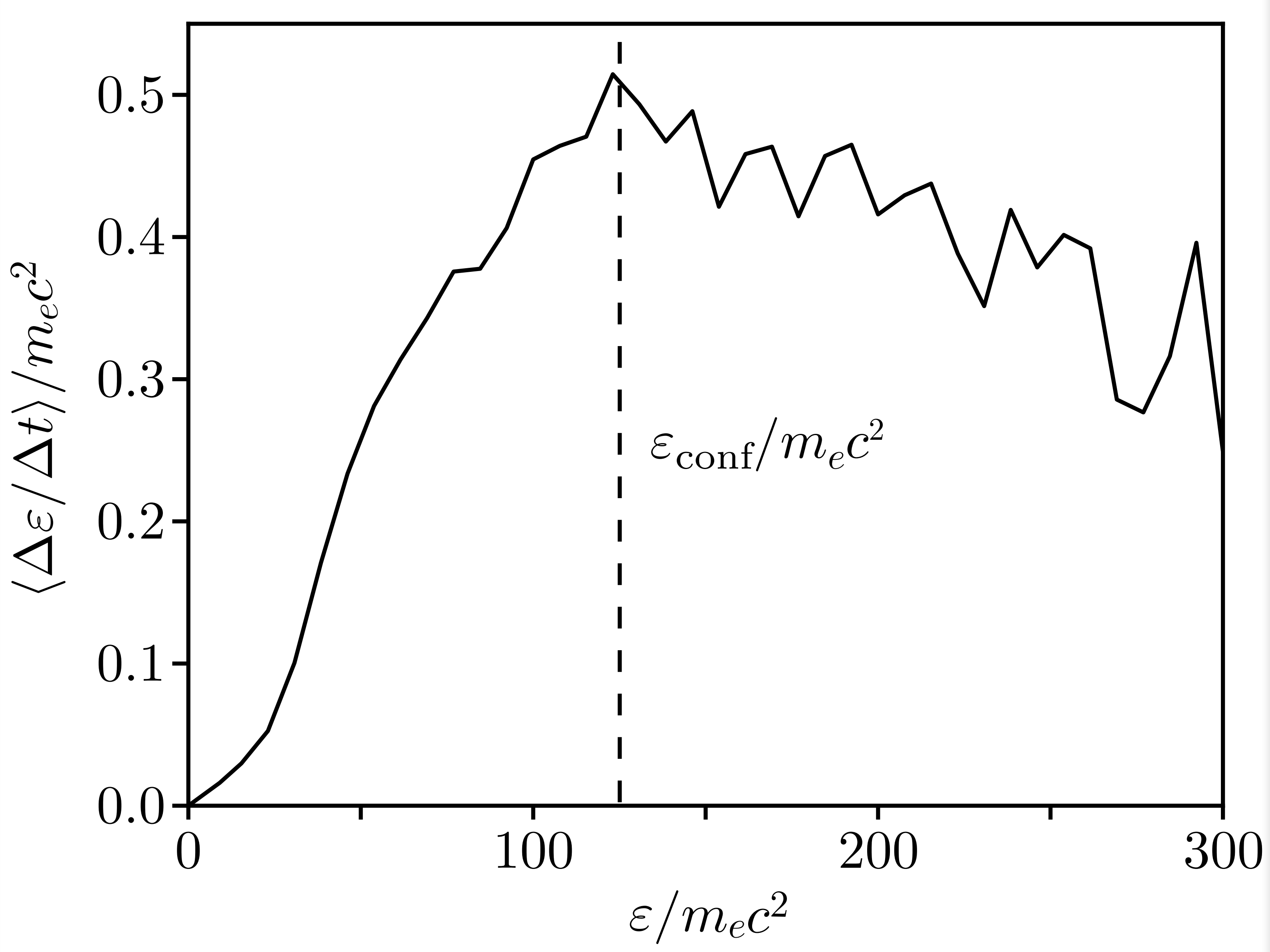
Nonlinear KI leads to highly tangled B-field that extends down to the mean particle Larmor radius



Highly tangled B-field facilitates rapid curvature drift motion across field lines, enabling efficient acceleration



Mean energization rate increases with particle energy indicating 1st order Fermi acceleration



Highly tangled B-field promotes rapid curvature-drift motion across field lines, enabling efficient particle acceleration by E⊥

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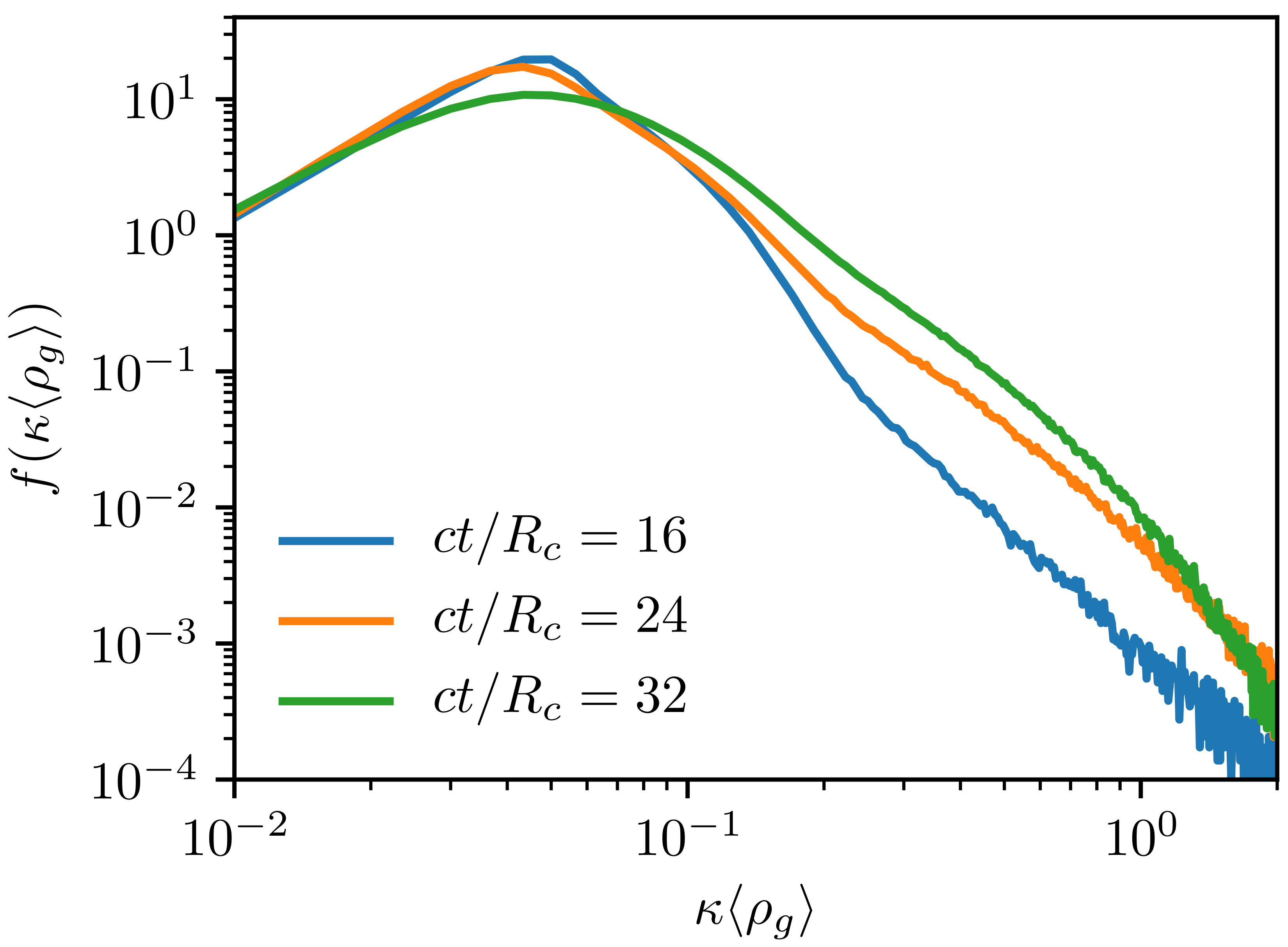
Nonlinear KI leads to highly tangled B-field that extends down to the mean particle Larmor radius



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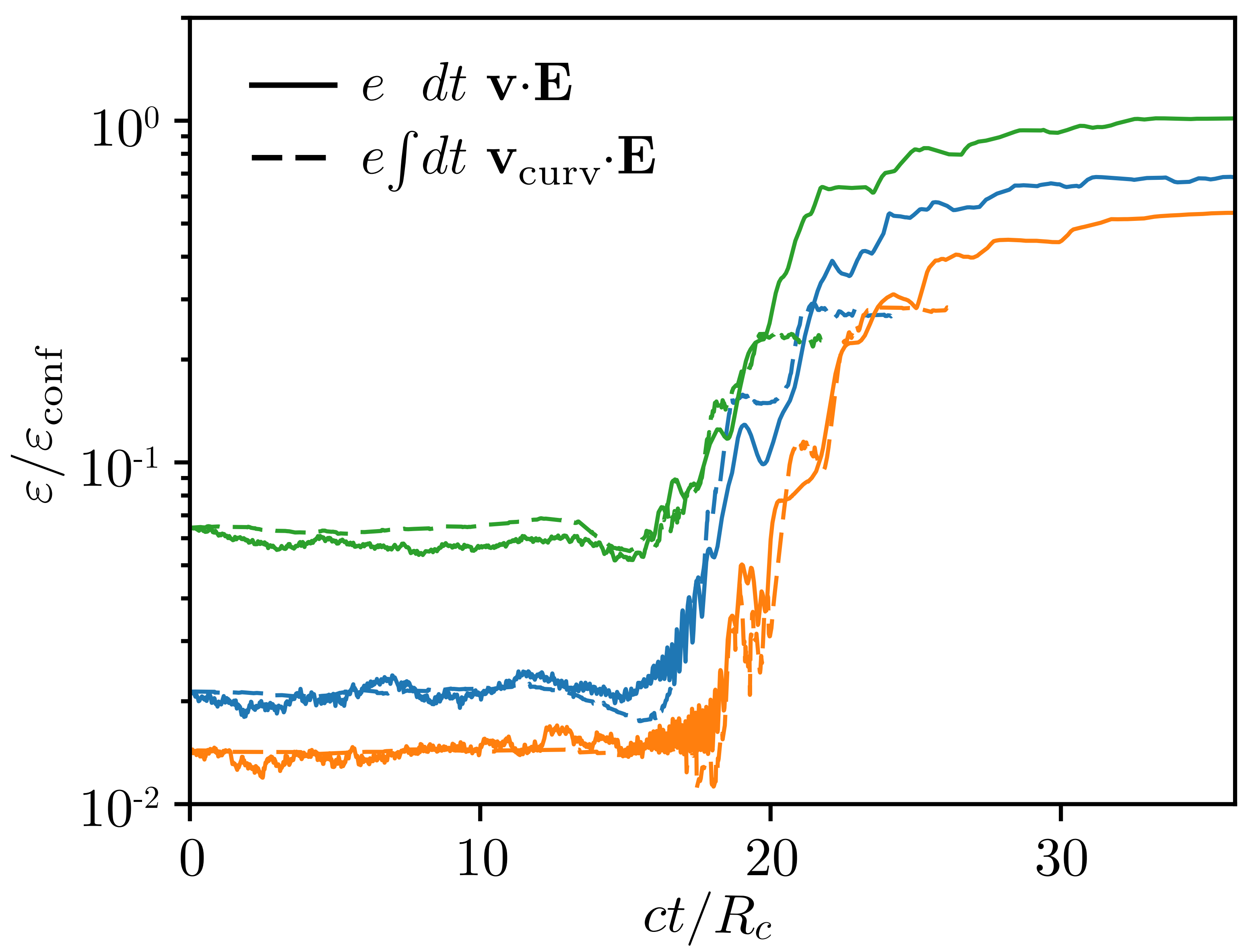

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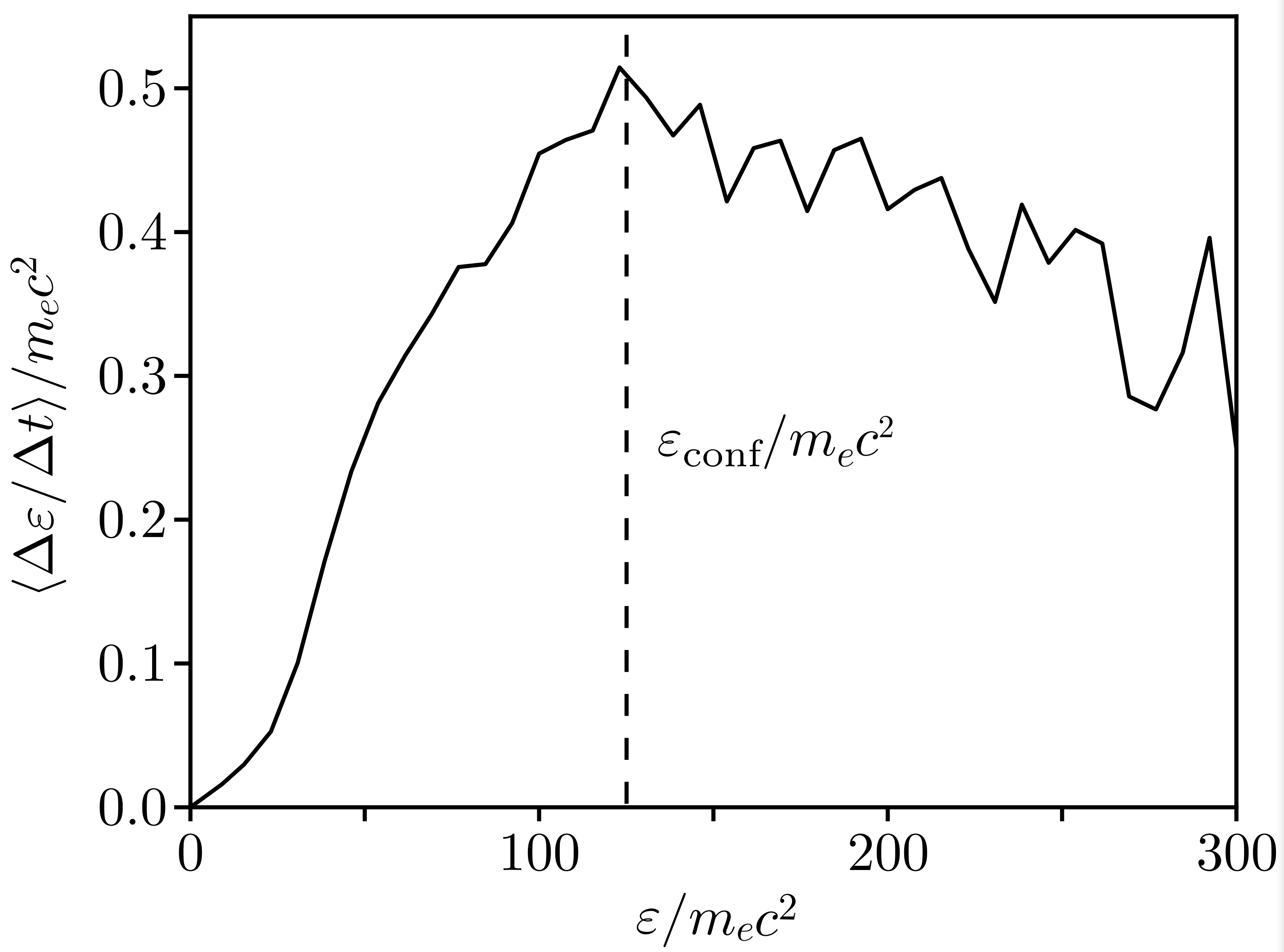

Highly tangled B-field promotes rapid curvature-drift motion across field lines, enabling efficient particle acceleration by E⊥

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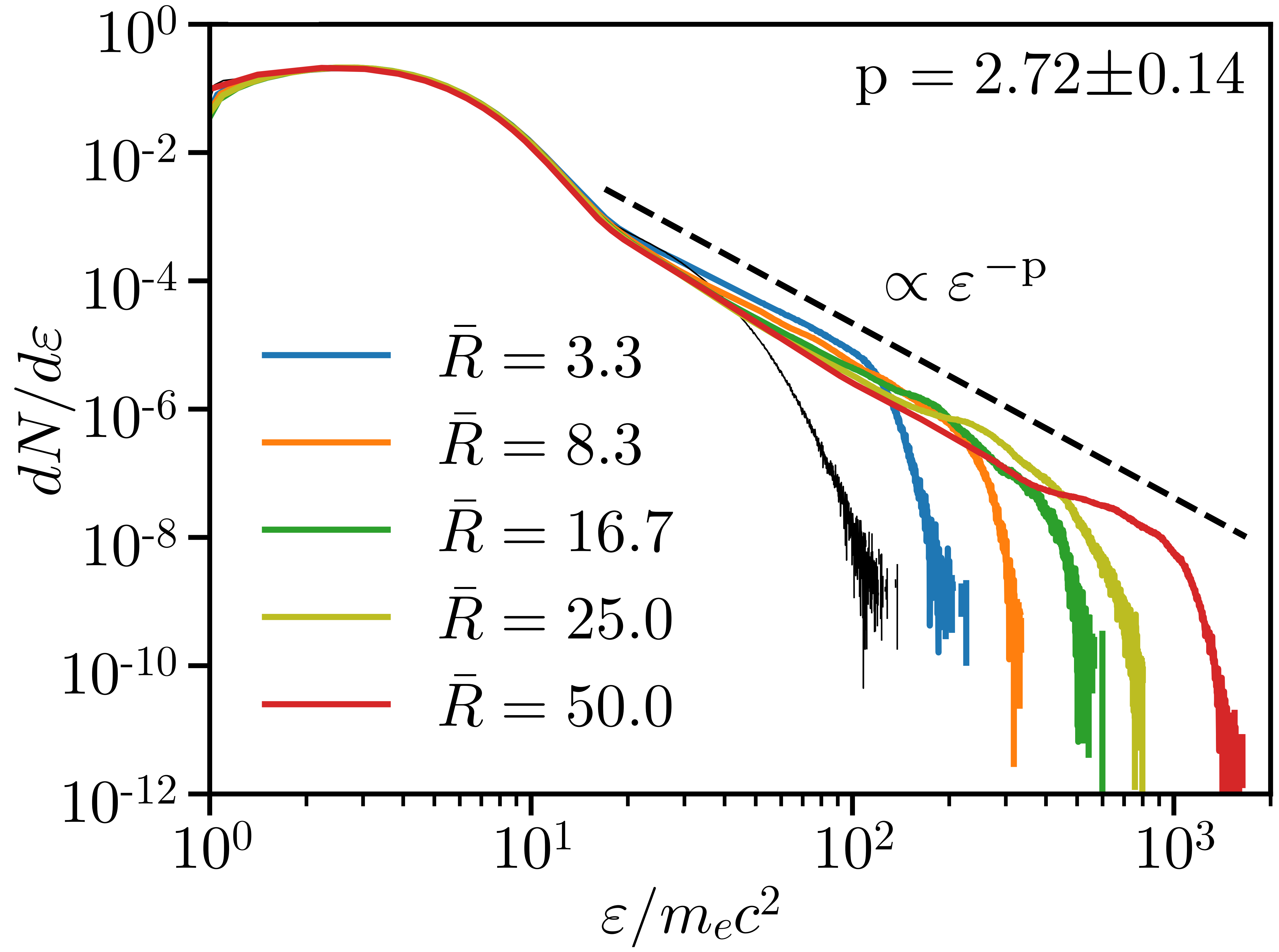
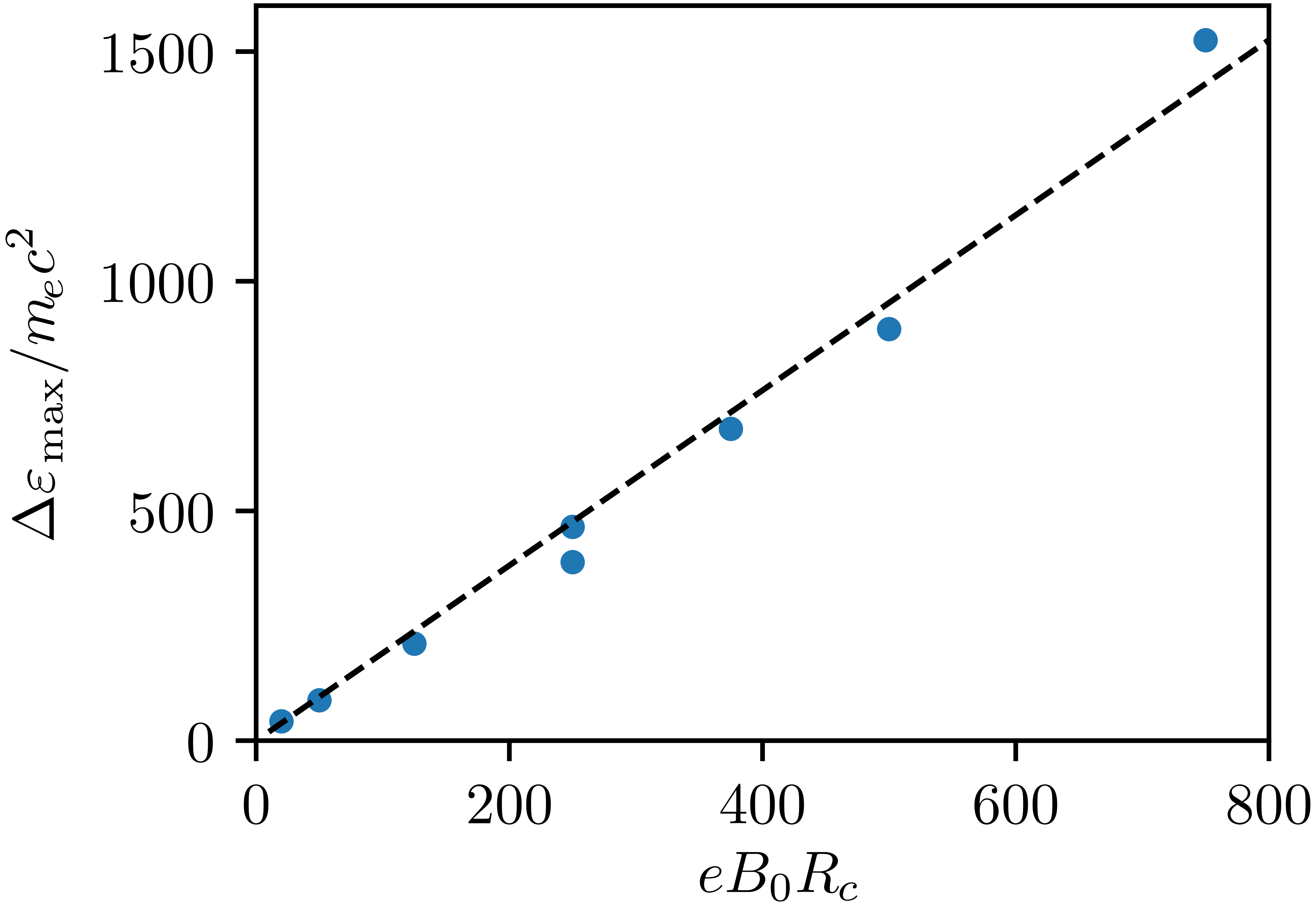
KI-induced acceleration dynamics can scale to very large system sizes ($\bar{R}$ >> 1)

p-index is preserved for increasing $\bar{R}$ (fixed σ = 5)



Particles are accelerated to confinement energy



Increasing R_c (at fixed σ) extends maximum particle energy while preserving p-index
p-index varies between 2-3 for σ between 1-10

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This mechanism can account for non-thermal synchrotron emission and also accelerate UHECRs

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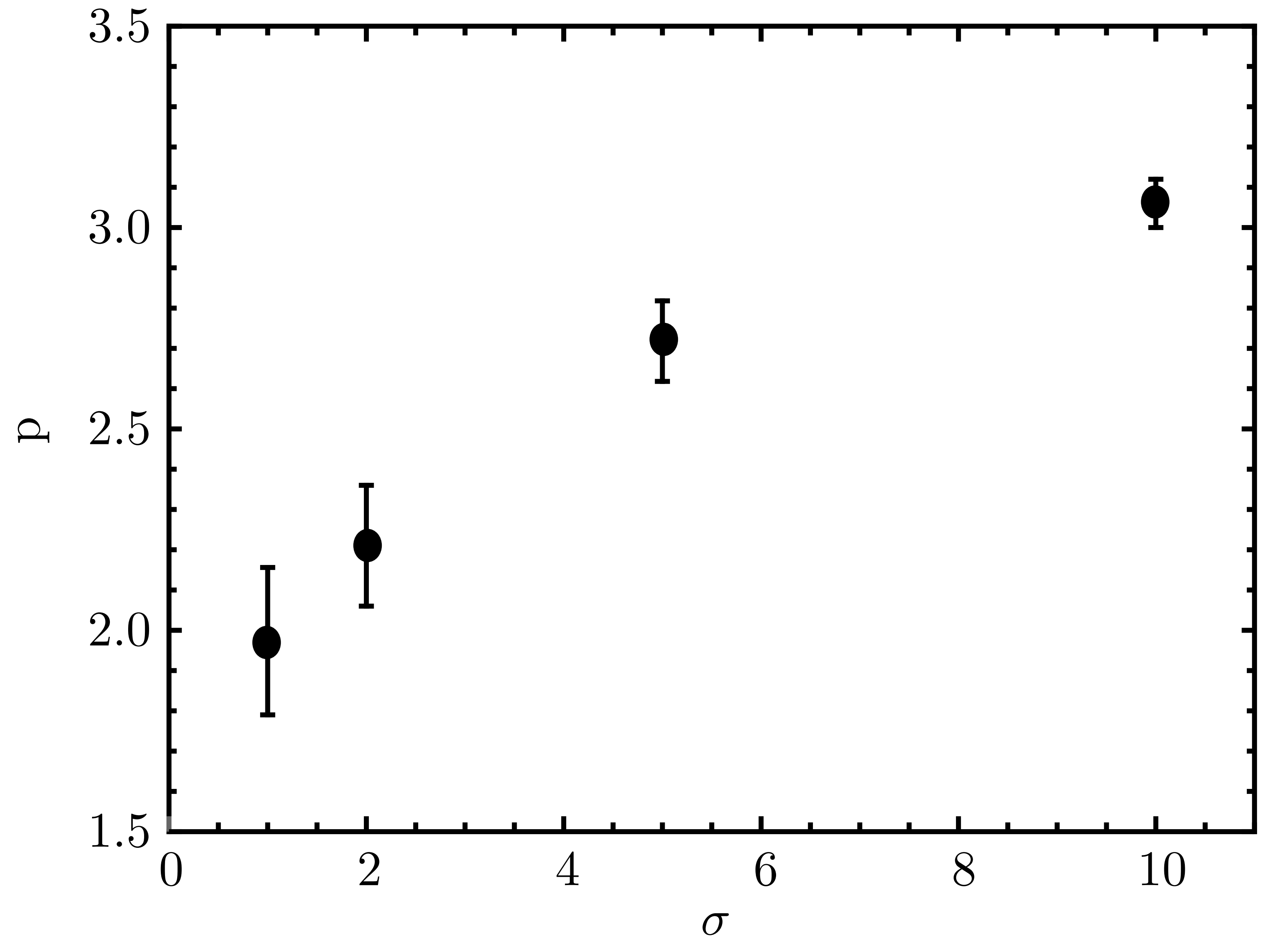
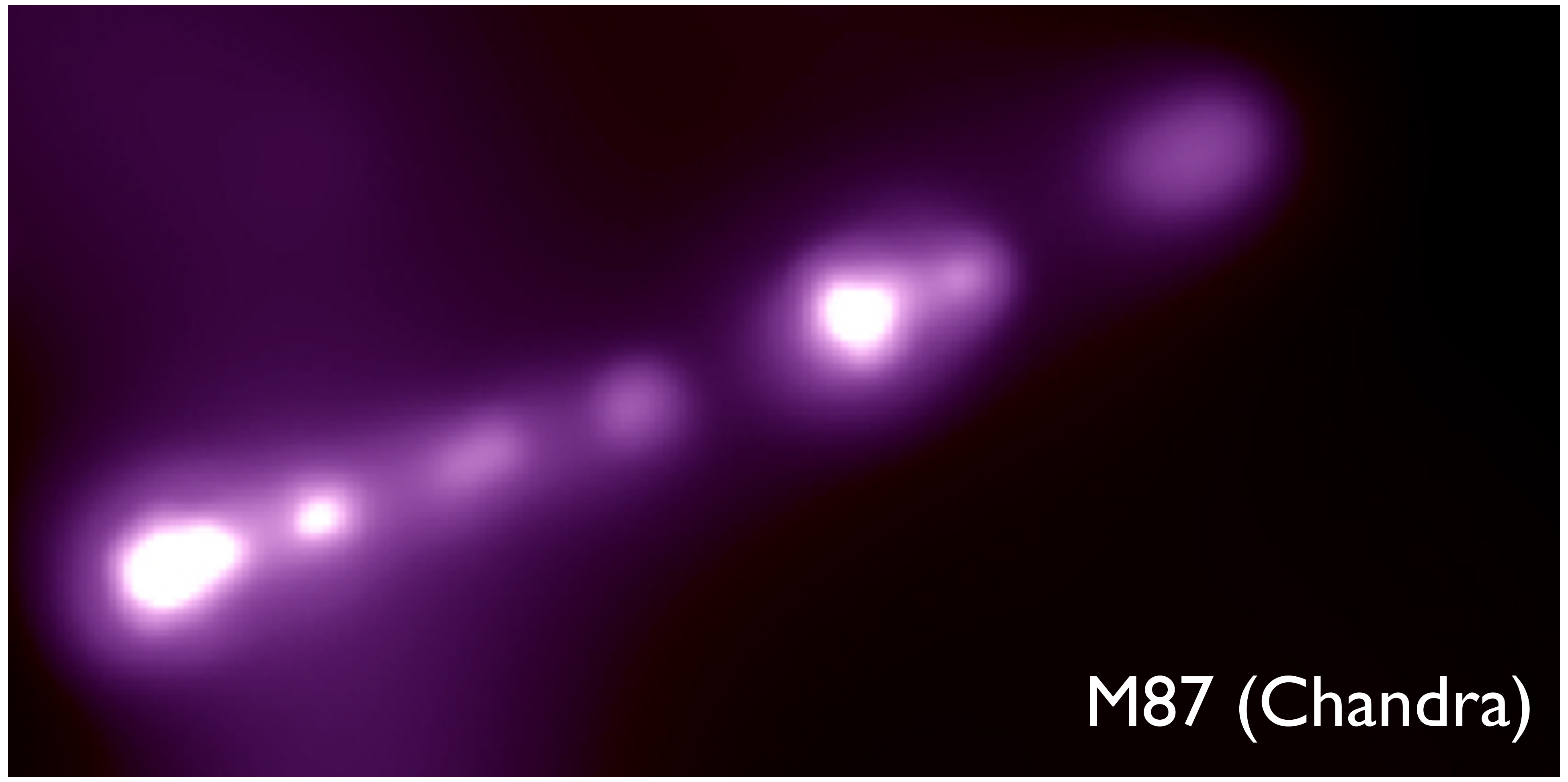
Non-thermal particle spectra produced by KI is consistent with synchrotron X-ray spectra of HST-1



- X-ray spectral index (α_X) = p/2 in fast cooling regime
- HST-1 observations* reveal α_X=1-1.5 which is consistent with p=2-3 found for the KI at σ = 1-10

Maximum particle acceleration by the KI



For HST-1 (M87): R_c ~ pc, B_0 ~ 1- 10 mG

- τ_{KI} ~ 30 yr (co-moving frame)
- Synchrotron-limited lepton energy ~ 0.6PeV
- Maximum proton energy = 10^{18}-10^{19} eV

Knot A (M87): R_c ~ 100 pc, B_0 ~ 1mG

- Maximum proton energy = 10^{20} eV

The development of the KI provides a viable means of accelerating UHECRs in AGN jets

* Harris et al. (2003, 2006)

Conclusions

- Self-consistent development of the KI leads to efficient conversion of the jet's toroidal magnetic field energy (40%) into non-thermal particles over a dynamical time ($\tau_{KI} \sim 10\ R_c/c$)

- Particle acceleration by large-scale inductive E-field is made efficient by the presence of a highly tangled B-field structure in nonlinear phase of KI, which enables rapid curvature drifts

- This mechanism can produce non-thermal particles consistent with synchrotron spectra of AGN jets, and can accelerate protons and heavier ions to UHECR energies

- This mechanism may also operate in other electromagnetically dominated astrophysical outflows such as PWNE and GRBs