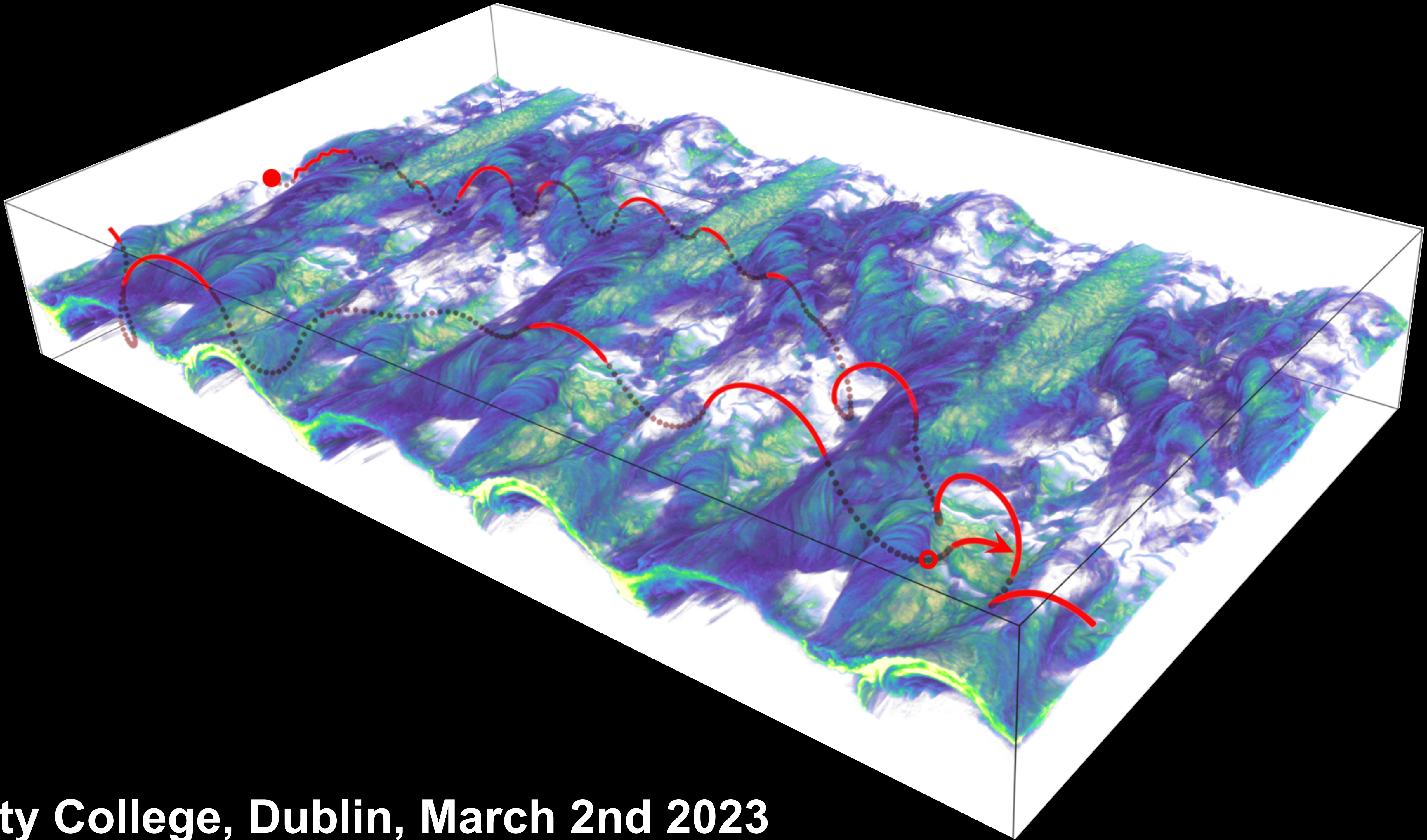
Reconnection-powered emission in BH jets and coronae

Lorenzo Sironi (Columbia)

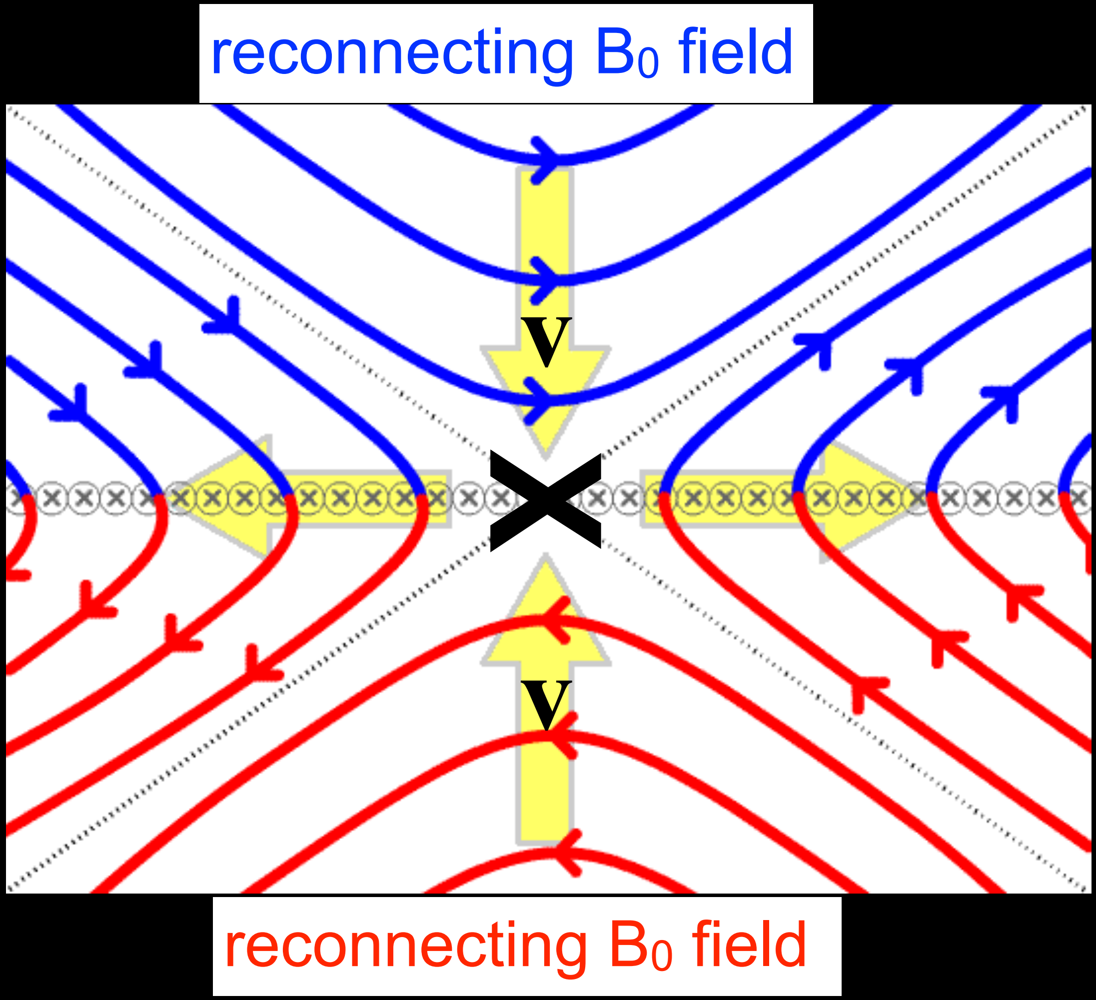


Trinity College, Dublin, March 2nd 2023

Relativistic reconnection

$$\sigma = \frac{B_0^2}{4\pi\rho c^2} \gg 1$$

$$v_A \sim c$$



⊙ ⊙ ⊙

“Guide” (out-of-plane) uniform magnetic field B_g

⊙ ⊙ ⊙

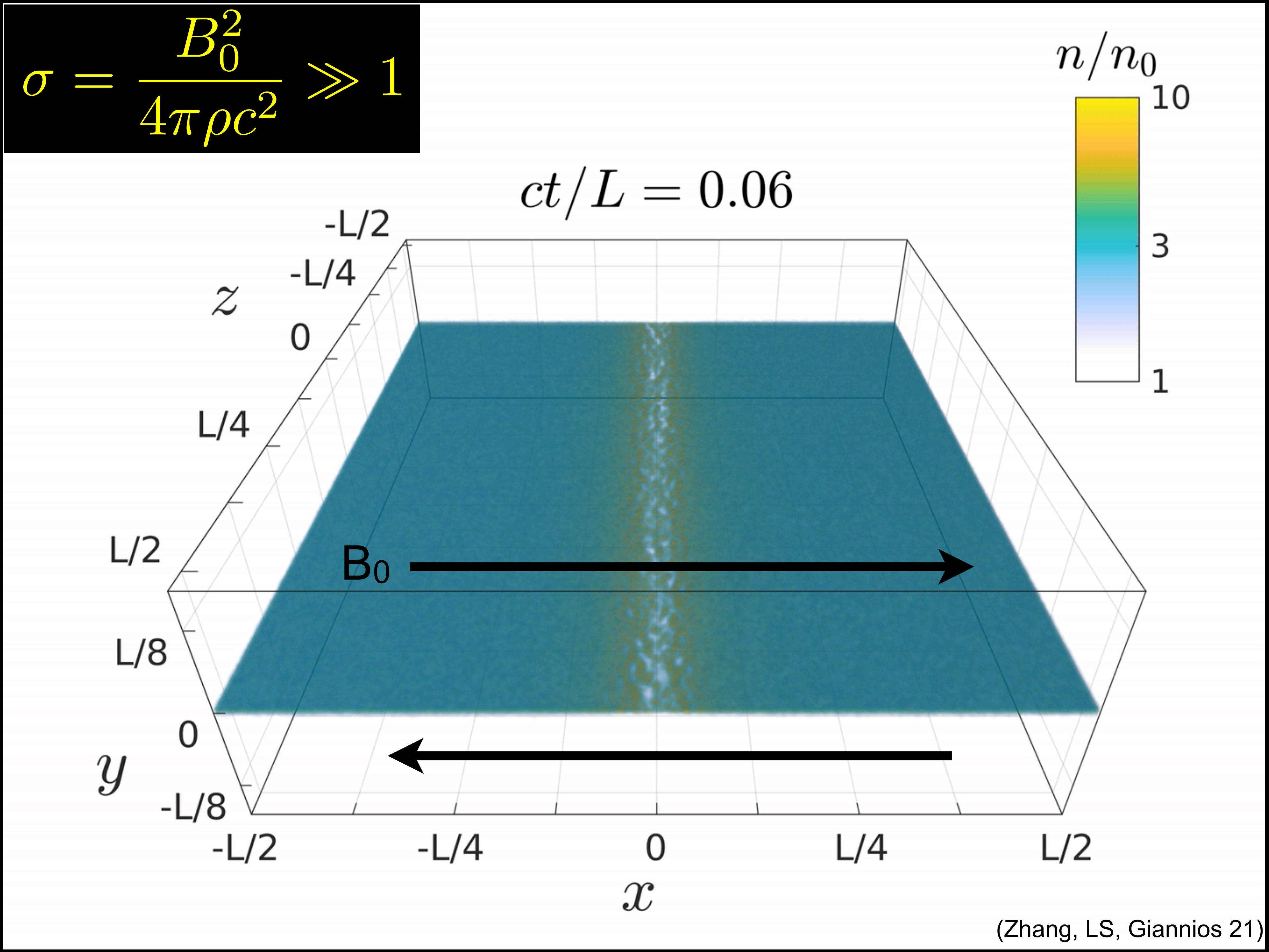
- The plasma flows into the reconnection region with $\frac{v_{\rm in}}{v_A} = \frac{E_{\rm rec}}{B_0} \sim 0.1$

→ Rel. reconnection can efficiently dissipate the field energy (at rate ~ 0.1 c).

→ Rel. reconnection may accelerate particles, via $E_{\rm rec} \sim 0.1 B_0$.

PIC simulation of σ=10 (relativistic) reconnection

$$\sigma = \frac{B_0^2}{4\pi\rho c^2} \gg 1$$



(Zhang, LS, Giannios 21)

The reconnection layer breaks into a chain of flux ropes / plasmoids

Particle acceleration in relativistic reconnection

Zhang, LS & Giannios 2023, arXiv:2302.12269

LS 2022, PRL, 128, 145102

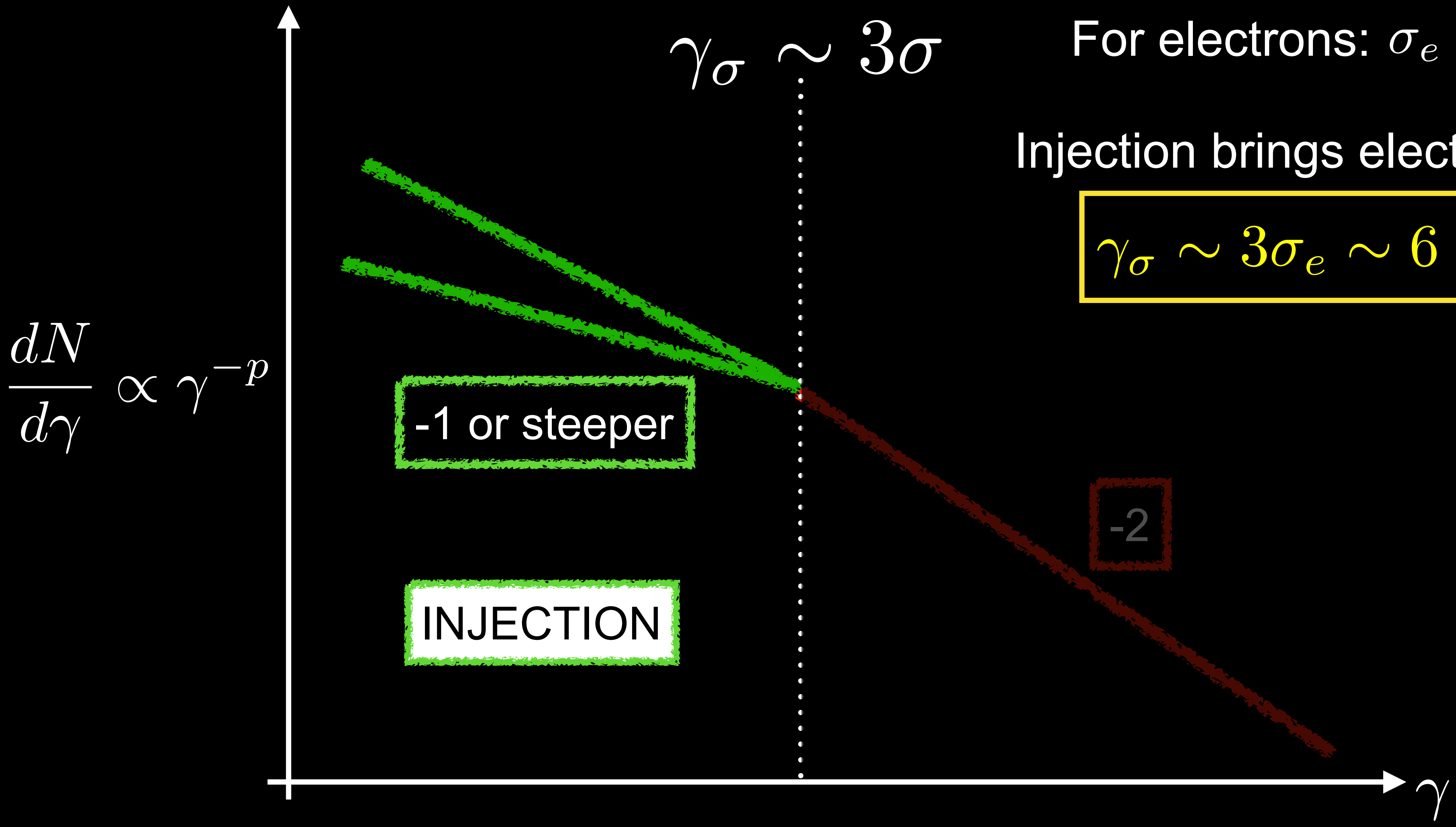
Zhang, LS & Giannios 2021, ApJ, 922, 261

Hao Zhang

M. Petropoulou

D. Giannios

Reconnection makes broken power laws



For electrons: $\sigma_e = \frac{m_p}{m_e}\sigma$

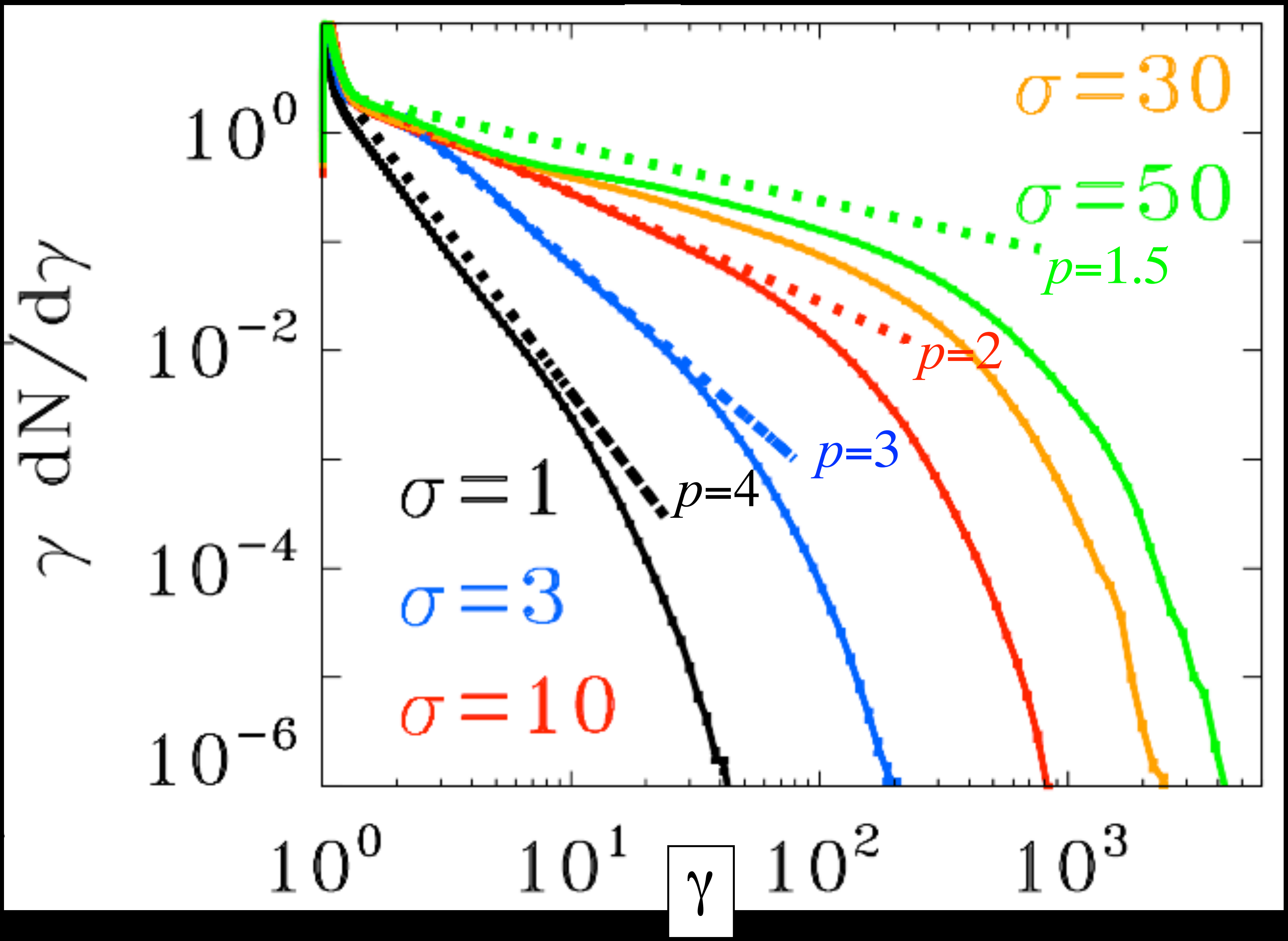
Injection brings electrons up to

$$\boxed{\gamma_\sigma \sim 3\sigma_e \sim 6 \times 10^3\sigma}$$

At $\gamma \lesssim 3\sigma$ “injection” in reconnection leads to σ-dependent slopes, with *p*≳*1*.

At $\gamma \gtrsim 3\sigma$ 3D reconnection leads to a universal (~ σ-independent) slope of *p*~2.

Particle injection, from γ~1 to γ~3σ



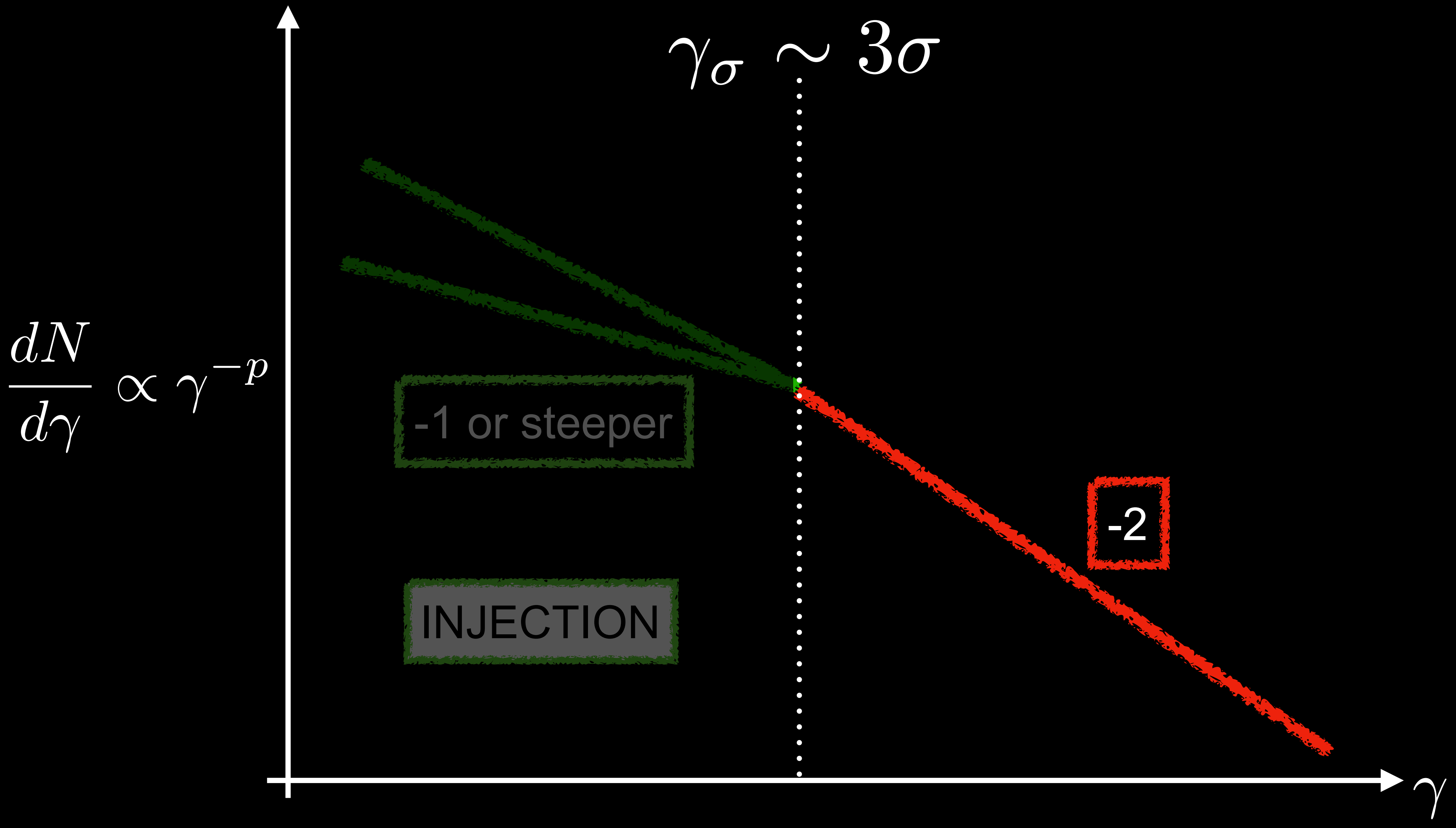
$$\sigma = \frac{B_0^2}{4\pi\rho c^2}$$

(LS & Spitkovsky 14; also Melzani+14, Guo+14,15, Werner+16)

At $\gamma \lesssim 3\sigma$ “injection” in reconnection leads to σ-dependent slopes, with *p*≳*1*.

This holds in electron-positron (e.g., LS & Spitkovsky 14), electron-proton (e.g., Ball, LS & Ozel 18) and electron-positron-proton plasmas (Petropoulou, LS et al 19).

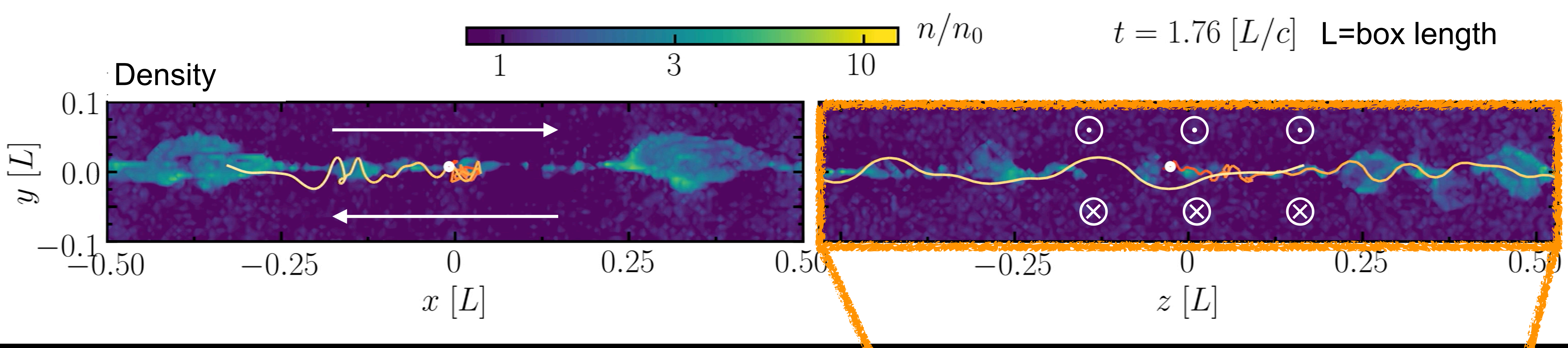
Reconnection makes broken power laws



At $\gamma \lesssim 3\sigma$ “injection” in reconnection leads to σ-dependent slopes, with $p \gtrsim 1$.

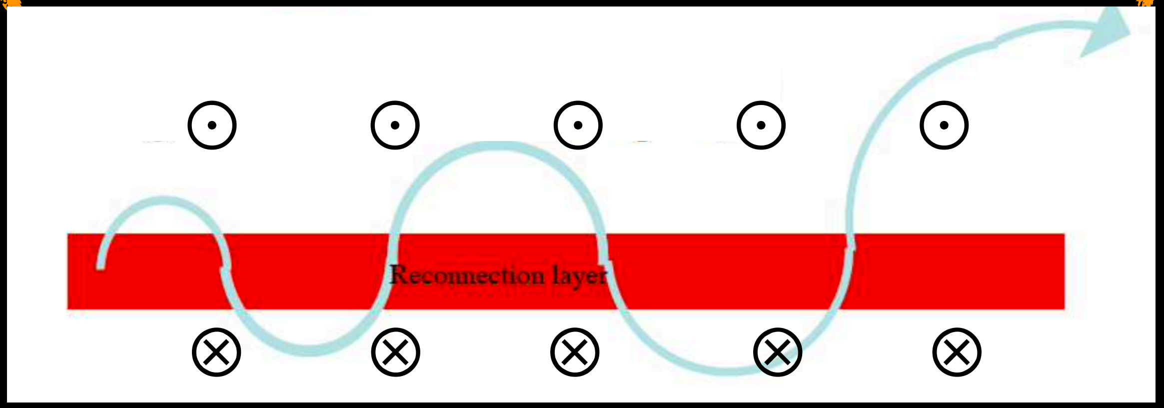
At $\gamma \gtrsim 3\sigma$ 3D reconnection leads to a universal (~ σ-independent) slope of $p \sim 2$.

Particle acceleration to $\gamma \gg 3\sigma$ (in 3D)



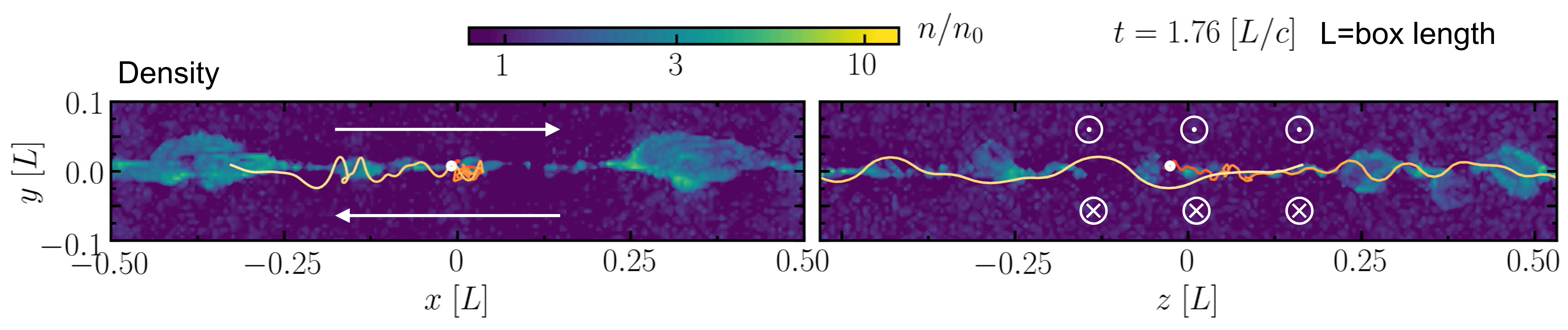
L=box length

- In 3D, lucky particles escape from plasmoids (Dahlin+15) and wiggle "free" around the layer (via grad-B drift).



(Lazarian +12)

Particle acceleration to γ≫3σ (in 3D)

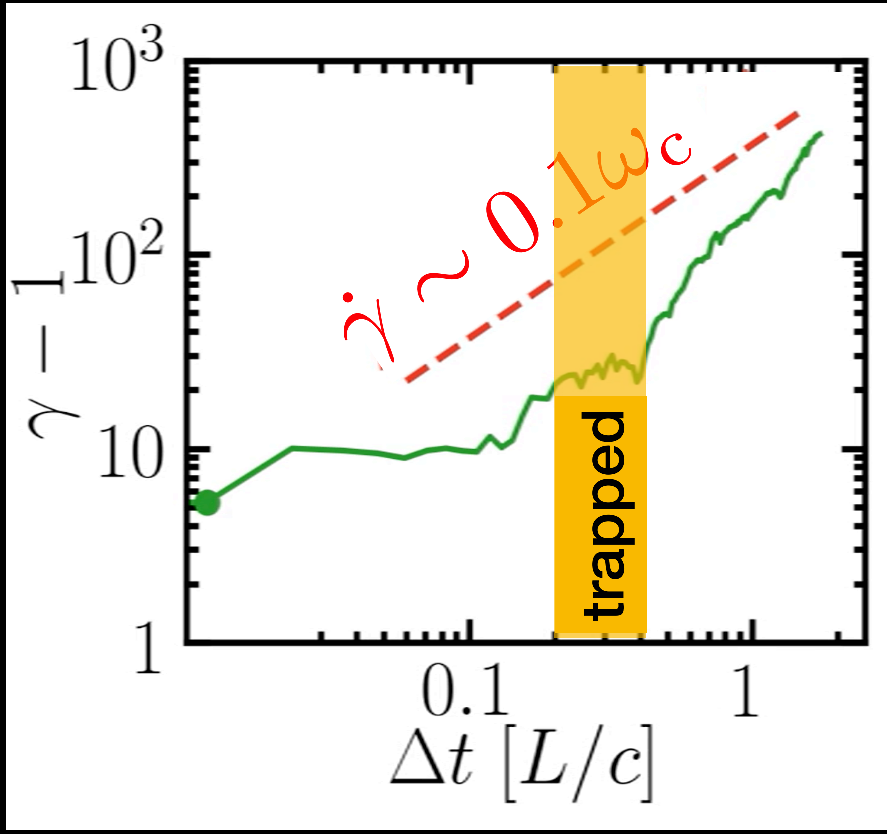


- In 3D, lucky particles escape from plasmoids (Dahlin+15) and wiggle "free" around the layer (via grad-B drift).

- They get accelerated linearly in time, γ ∝ t, by the large-scale <u>ideal</u> electric field in the upstream.

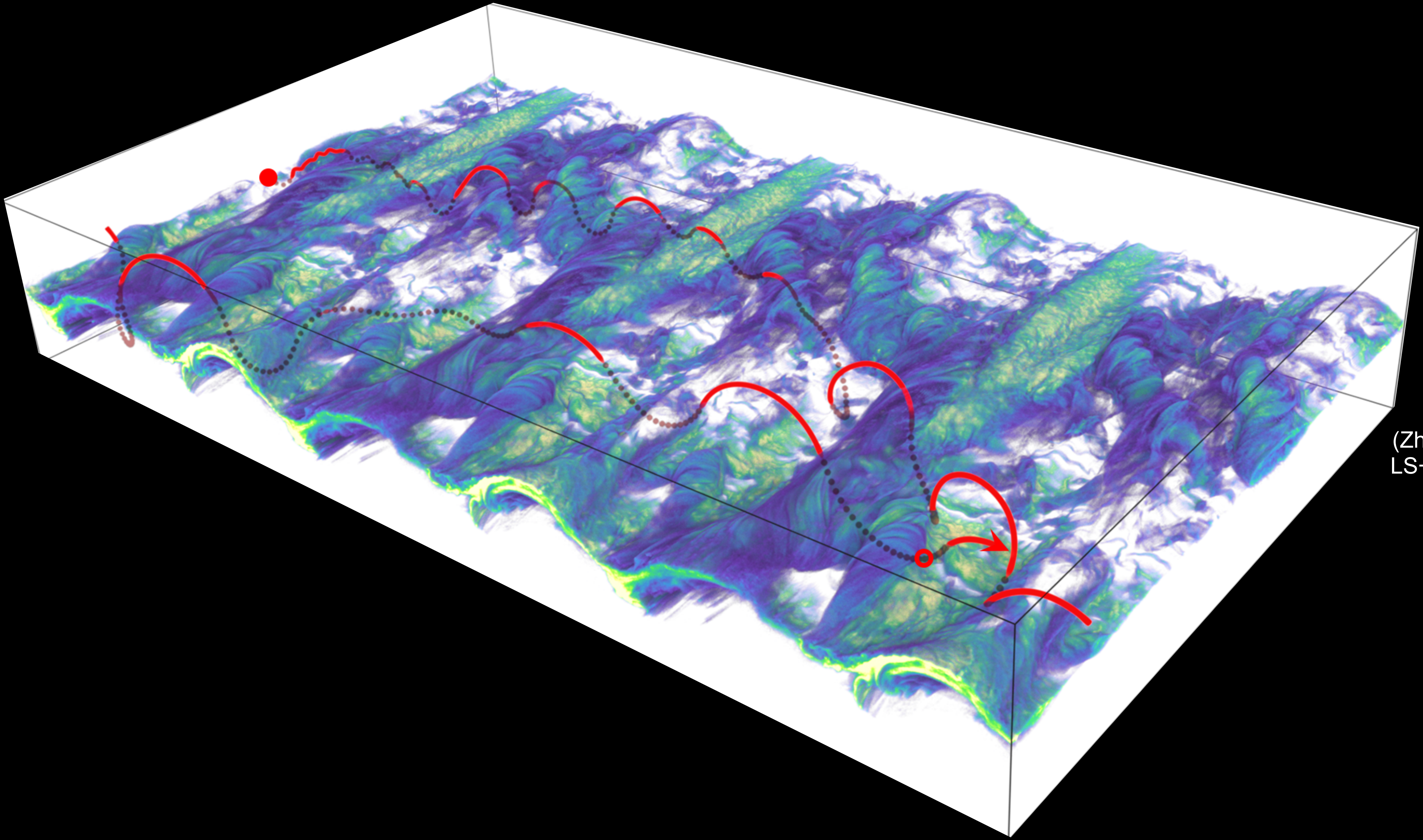
- The energy gain rate approaches $\sim eE_{\rm rec}c$
$$\sim 0.1eB_0c$$

- Reconnection in AGN jets can accelerate UHECRs.



(Zhang, LS, Giannios 21)

What does it take to be a lucky particle?



(Zhang, LS+ 23)

- Most of the high-energy particles experience a “free” phase in the upstream.
- Most of their energy is acquired while upstream.

A 3D model of power-law formation

- In steady state, $$\frac{\partial}{\partial\gamma}\left(\frac{\gamma}{t_{\rm acc}}f\right)+\frac{f}{t_{\rm esc}}=Q_0\delta(\gamma-3\sigma)$$ $$f=\frac{dN}{d\gamma}$$

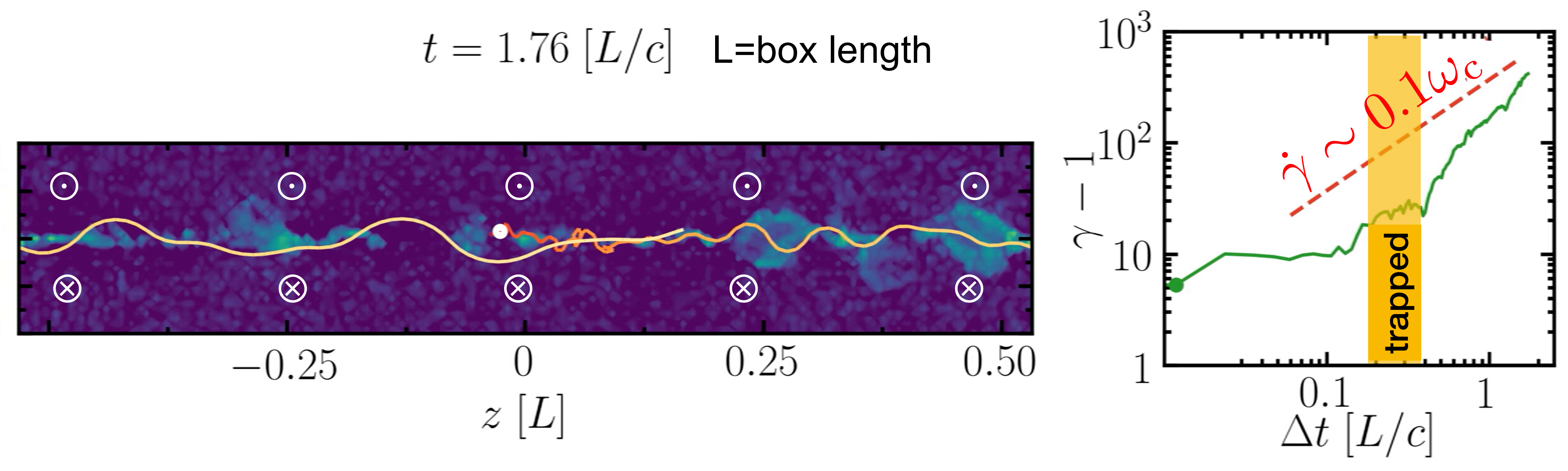
assuming injection at $\gamma = 3\sigma$

- If $t_{\rm acc}$ and $t_{\rm esc}$ depend linearly on γ, the solution is

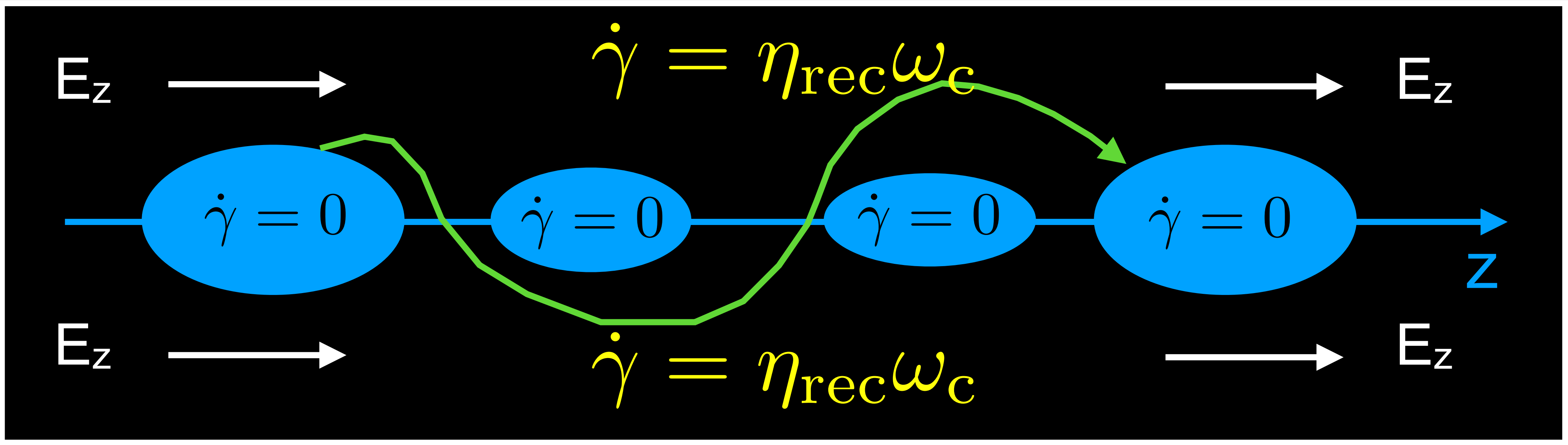
$$f\propto\gamma^{-t_{\rm acc}/t_{\rm esc}}$$

- What is the acceleration time $t_{\rm acc}=\gamma/\dot{\gamma}$?
- What is the escape time $t_{\rm esc}$?

A 3D model of power-law formation



(Zhang, LS, Giannios 21)

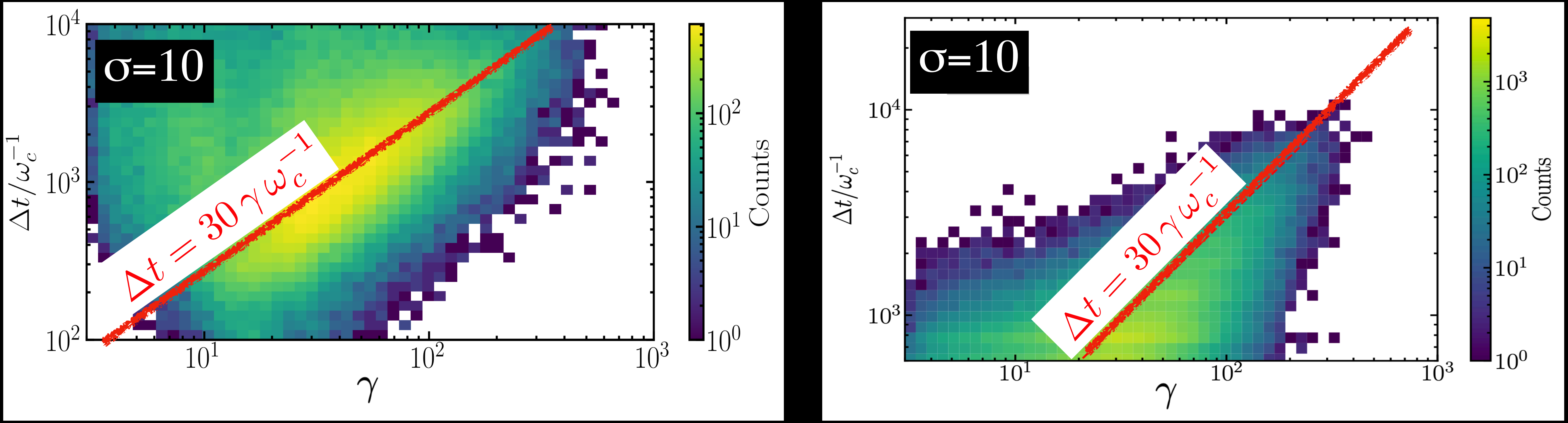


- Active acceleration only in the “free” stage while particles are in the upstream.
- Acceleration ceases when particles are captured by plasmoids (escape term).

Acceleration and escape times

Acceleration time $t_{acc} = \gamma/\dot{\gamma} \sim \boxed{\gamma\omega_c^{-1}/(\eta_{\rm rec}\beta_z)}$

Escape/trapping time t_{esc}



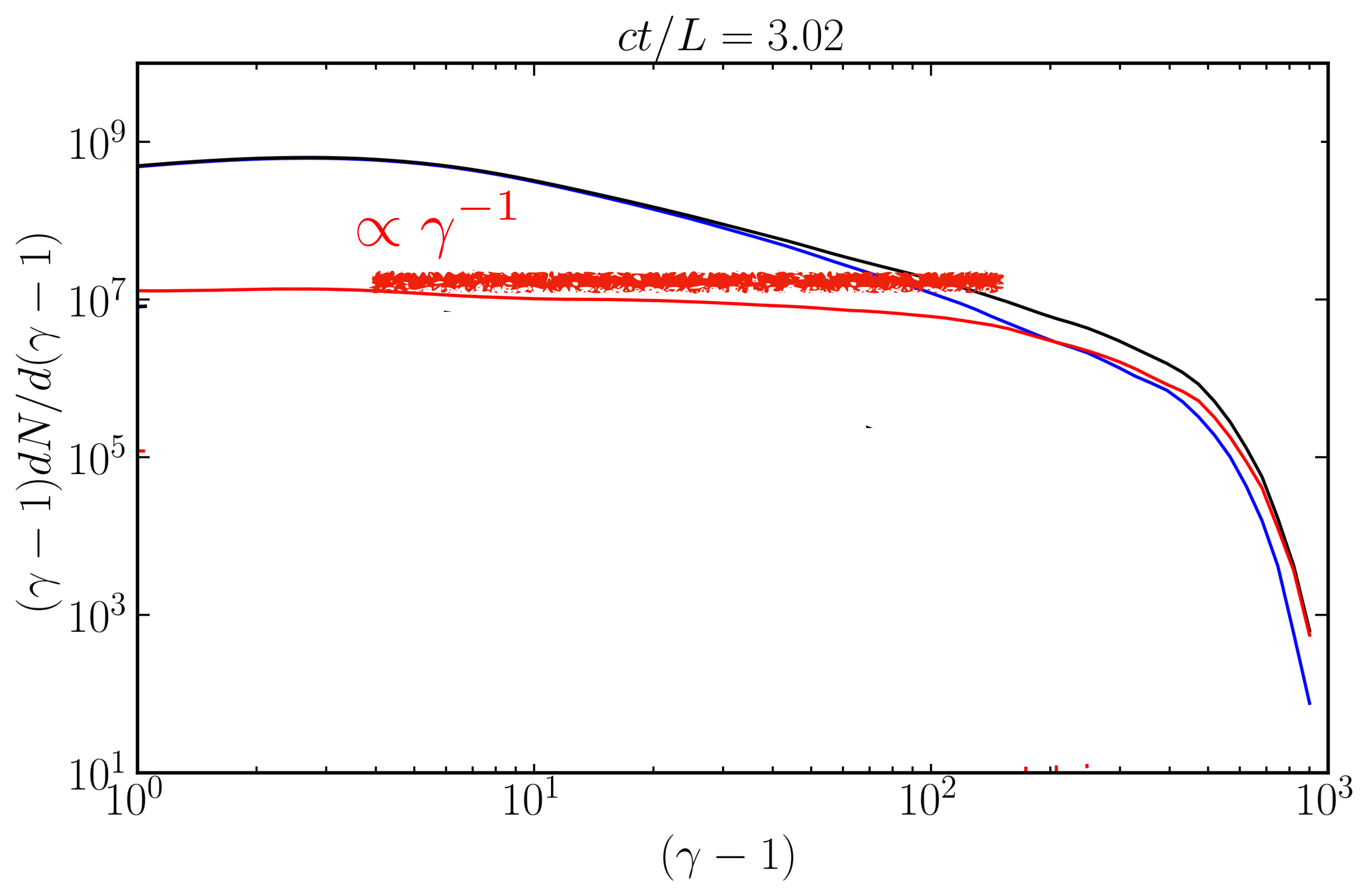
(Zhang, LS+ 23)

The two timescales are comparable, so

$$f_{\rm free} = \frac{dN_{\rm free}}{d\gamma} \propto \gamma^{-t_{\rm acc}/t_{\rm esc}} \propto \gamma^{-1}$$

Free vs trapped vs all

σ=10



red:free

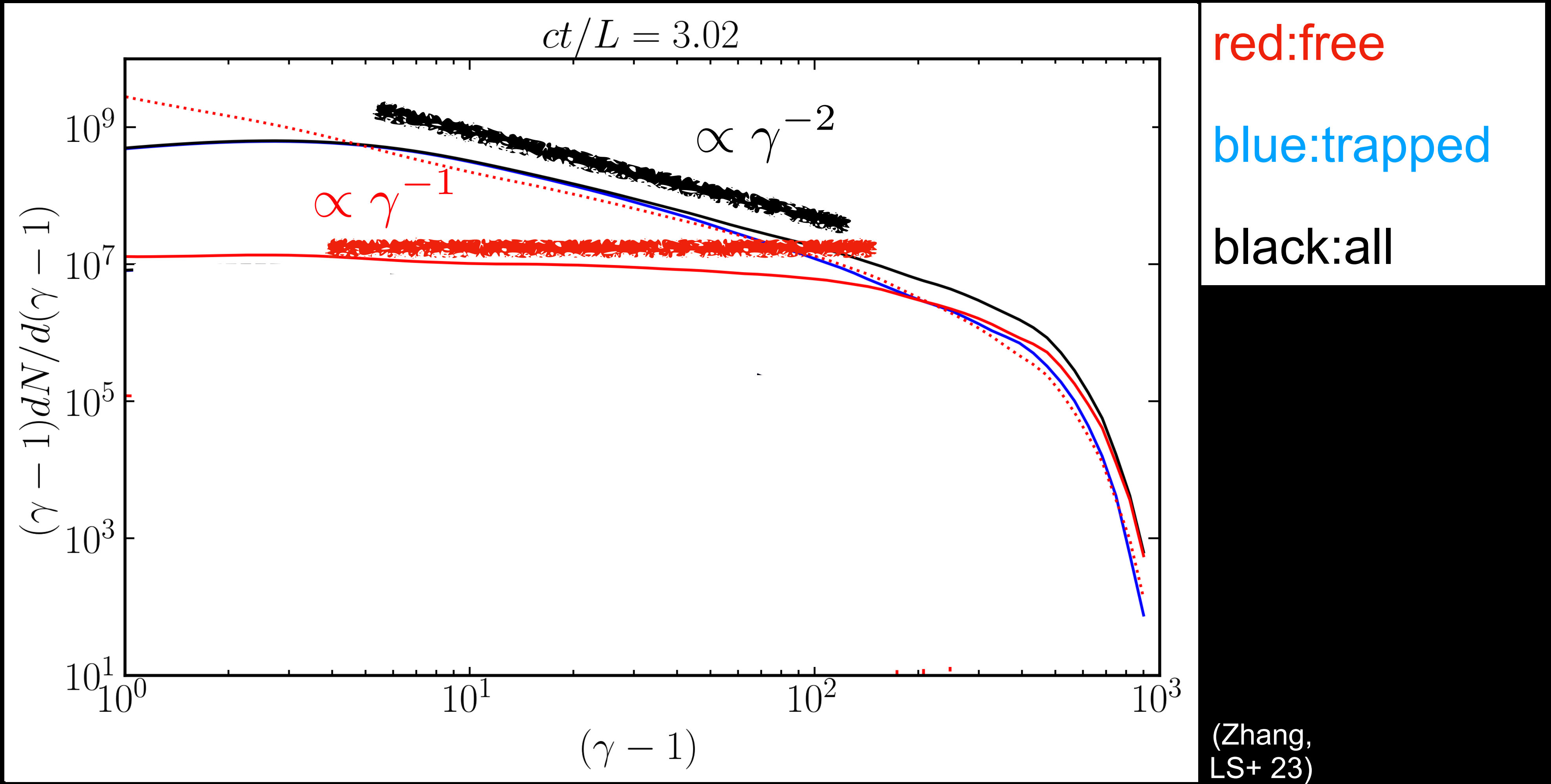
blue:trapped

black:all

(Zhang, LS+ 23)

Free vs trapped vs all

σ=10



(Zhang, LS+ 23)

<u>In steady state:</u>

rate of free particles getting trapped = rate of trapped particles being advected out

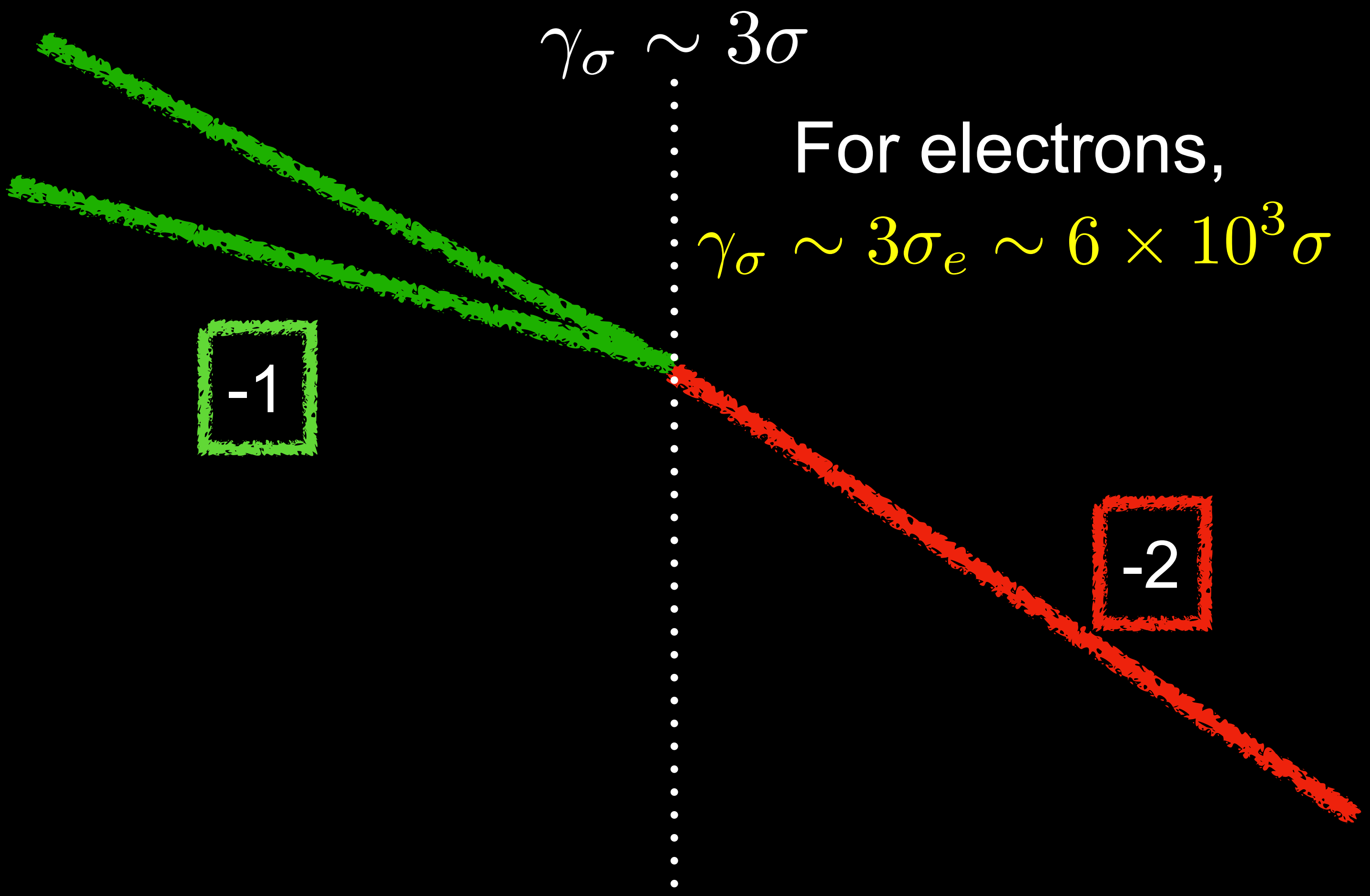
$$f_{\rm trap} = f_{\rm free}\frac{t_{\rm adv}}{t_{\rm esc}} \propto f_{\rm free}\gamma^{-1} \propto \gamma^{-2}$$

At $\gamma \gtrsim 3\sigma$ 3D reconnection leads to a universal (~ <u>σ-independent</u>) slope of *p*=2.

Two-stage acceleration in reconnection

- Particle injection in the range $\gamma \lesssim 3\sigma$ leads to σ-*dependent* power laws, with slope *p≳1.*

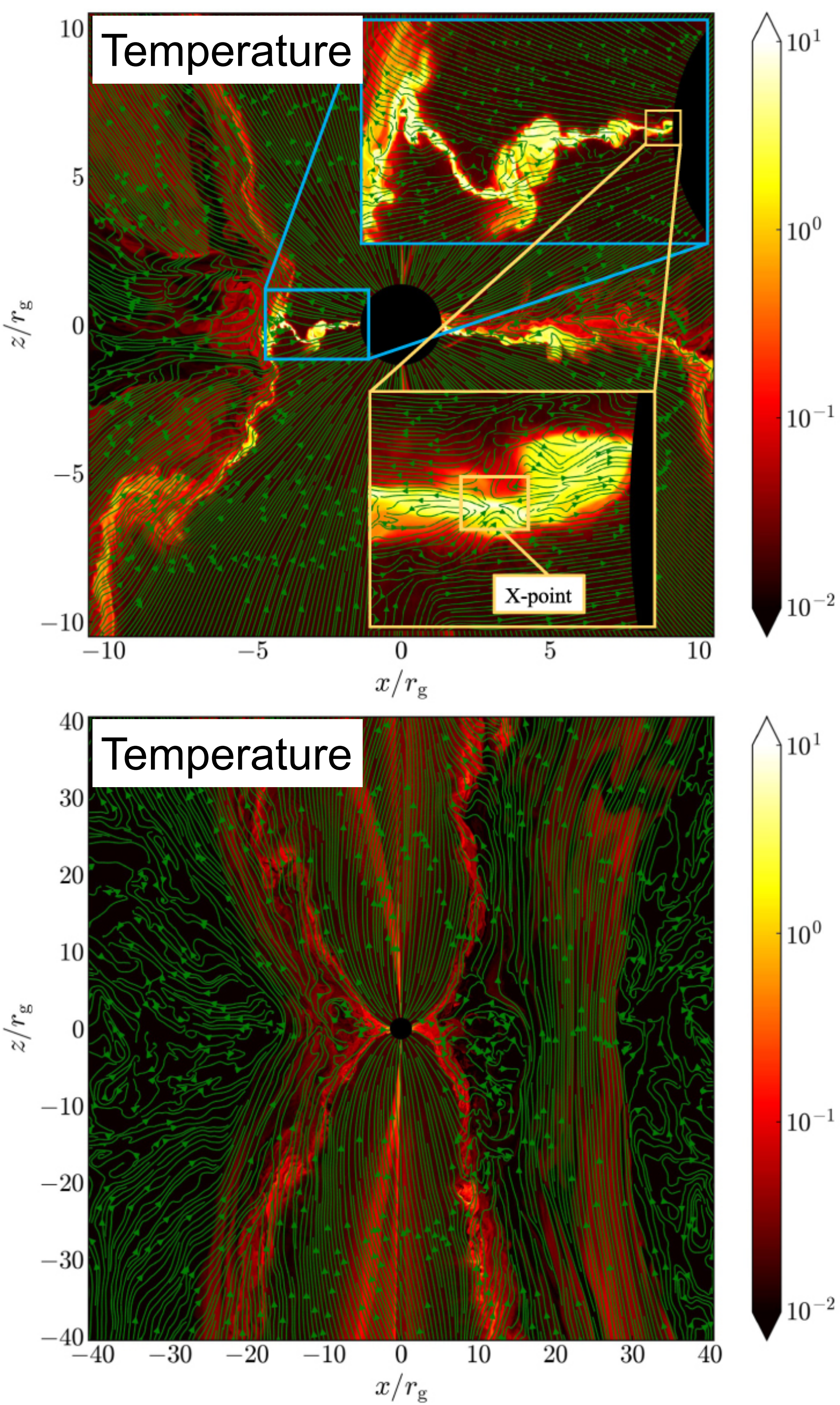
- Further acceleration beyond injection ($\gamma \gtrsim 3\sigma$) leads (in 3D!) to a nearly universal (~ σ-*independent*) slope of *p~2.*



For electrons,

$\gamma_\sigma \sim 3\sigma_e \sim 6 \times 10^3 \sigma$

Reconnection near BHs



Equatorial current sheet in the magnetically-arrested (MAD) state

Jet boundary

“Corona”

(Ripperda+22)

Reconnection at jet boundaries

Chow, Davelaar, Rowan, LS 2022, arXiv:2209.13699

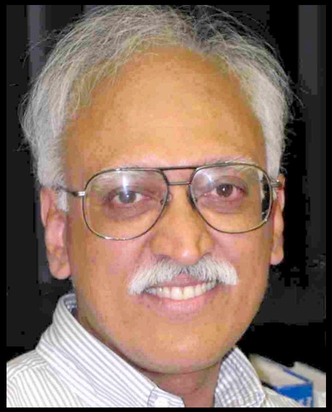
LS, Rowan & Narayan 2021, ApJL, 907, L44

A. Chow

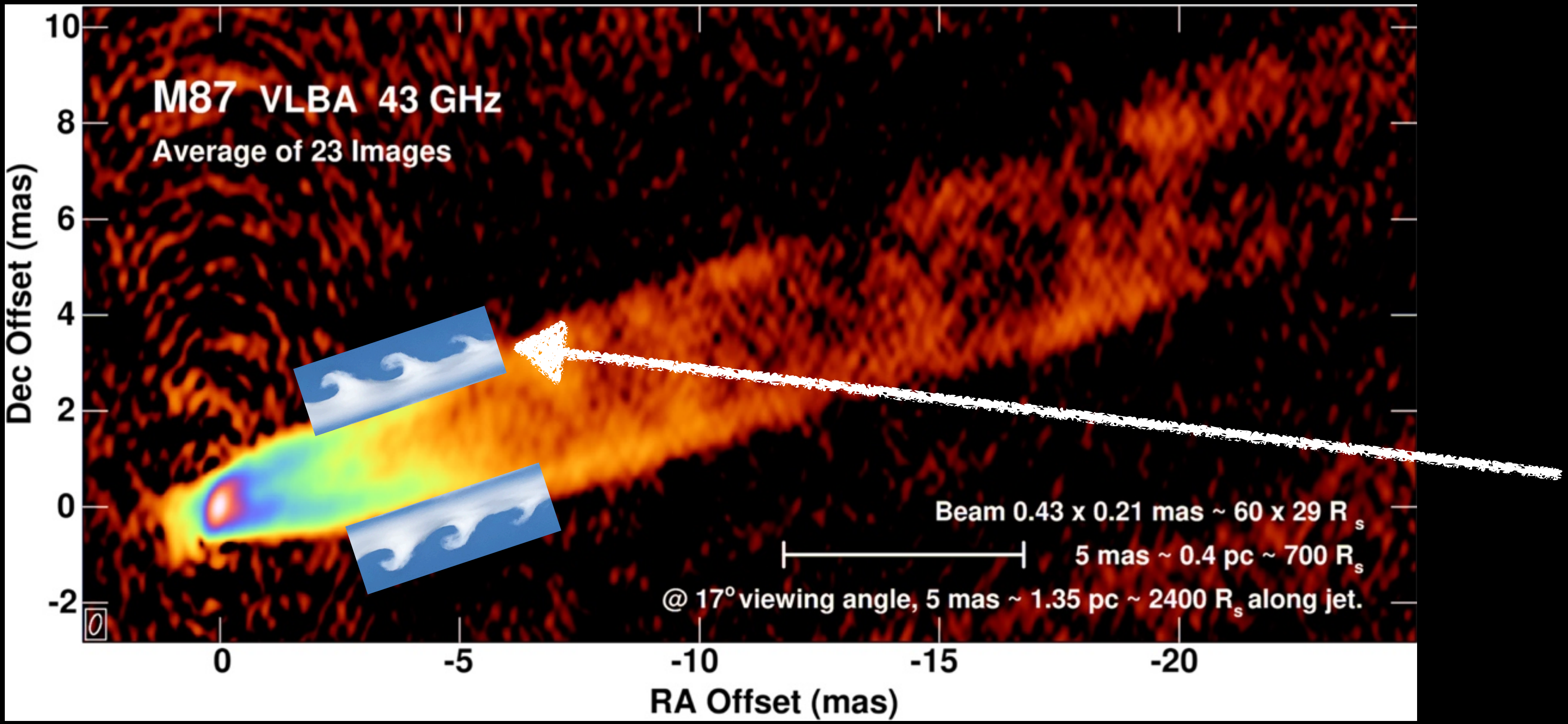
M. Rowan

J. Davelaar

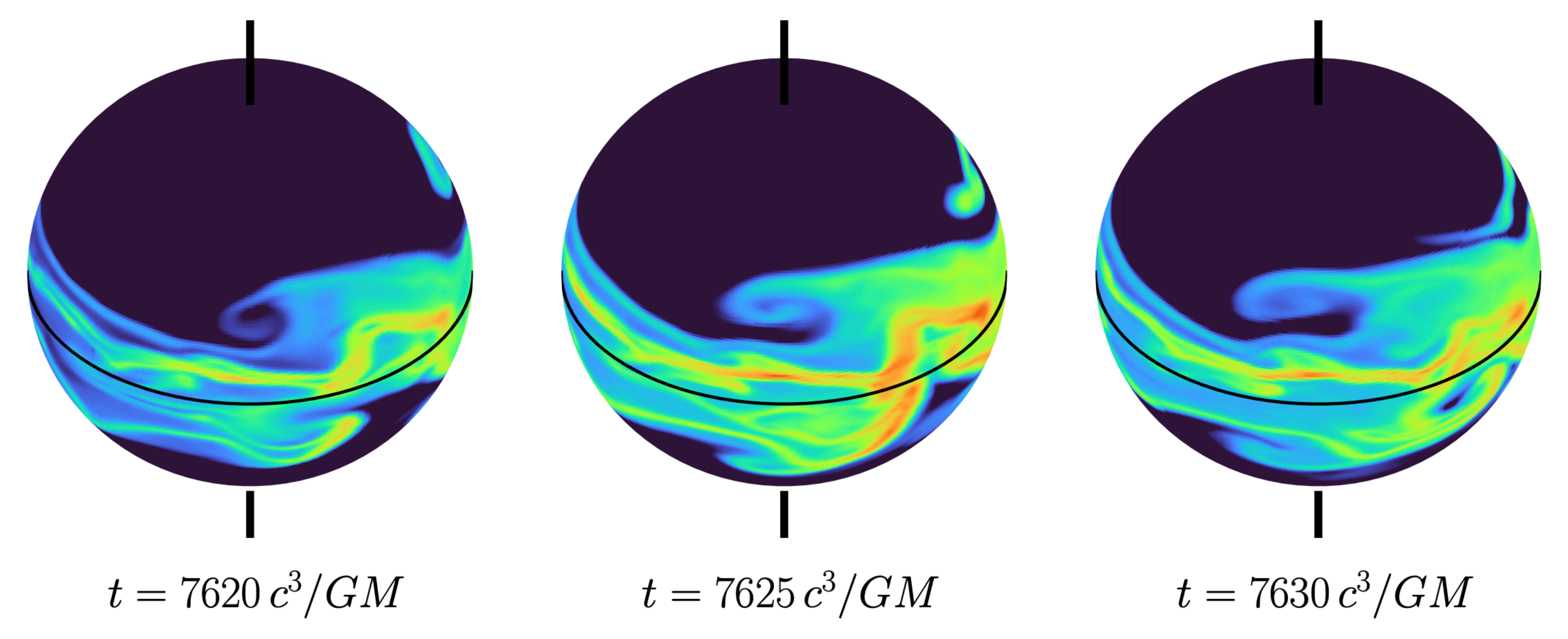
R. Narayan



The boundary of M87 jet



Kelvin-Helmholtz (KH) instability at the jet boundary

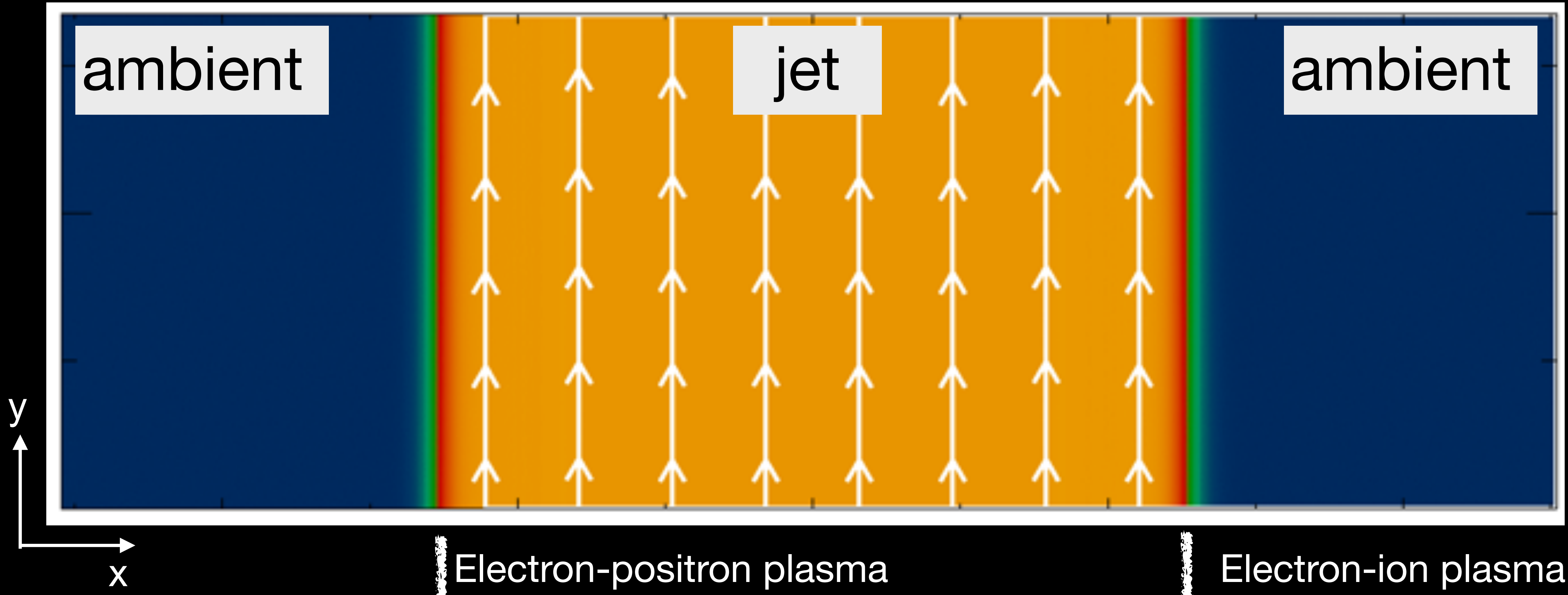


(Wong+21; see also Chatterjee+19)

What is the nonlinear outcome of KH at the jet boundary?

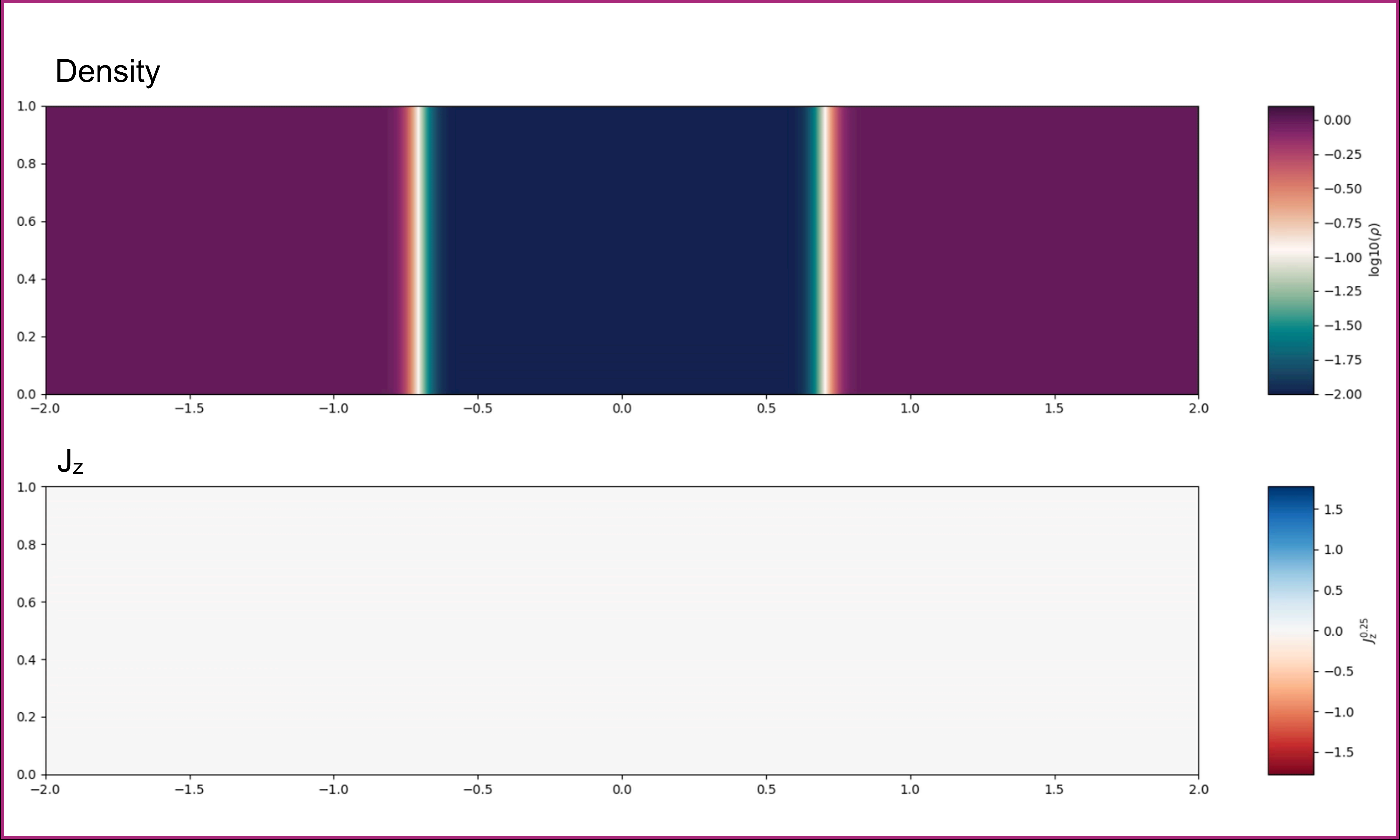
The jet / ambient system

2D PIC with TRISTAN-MP (Spitkovsky 2005)



Electron-positron plasma	Electron-ion plasma
Relativistic bulk motion: $\Gamma_0\beta_0 = 1.3$	Stationary
Dominant B_y (poloidal) and B_z (toroidal) $\sigma_{\mathrm{j},y} = B_{\mathrm{j},y}^2/(4\pi n_0 m_\mathrm{e} c^2) = 6.7$ Field obliquity $\theta = 75^\circ$	Plasma-pressure dominated, weak B_z

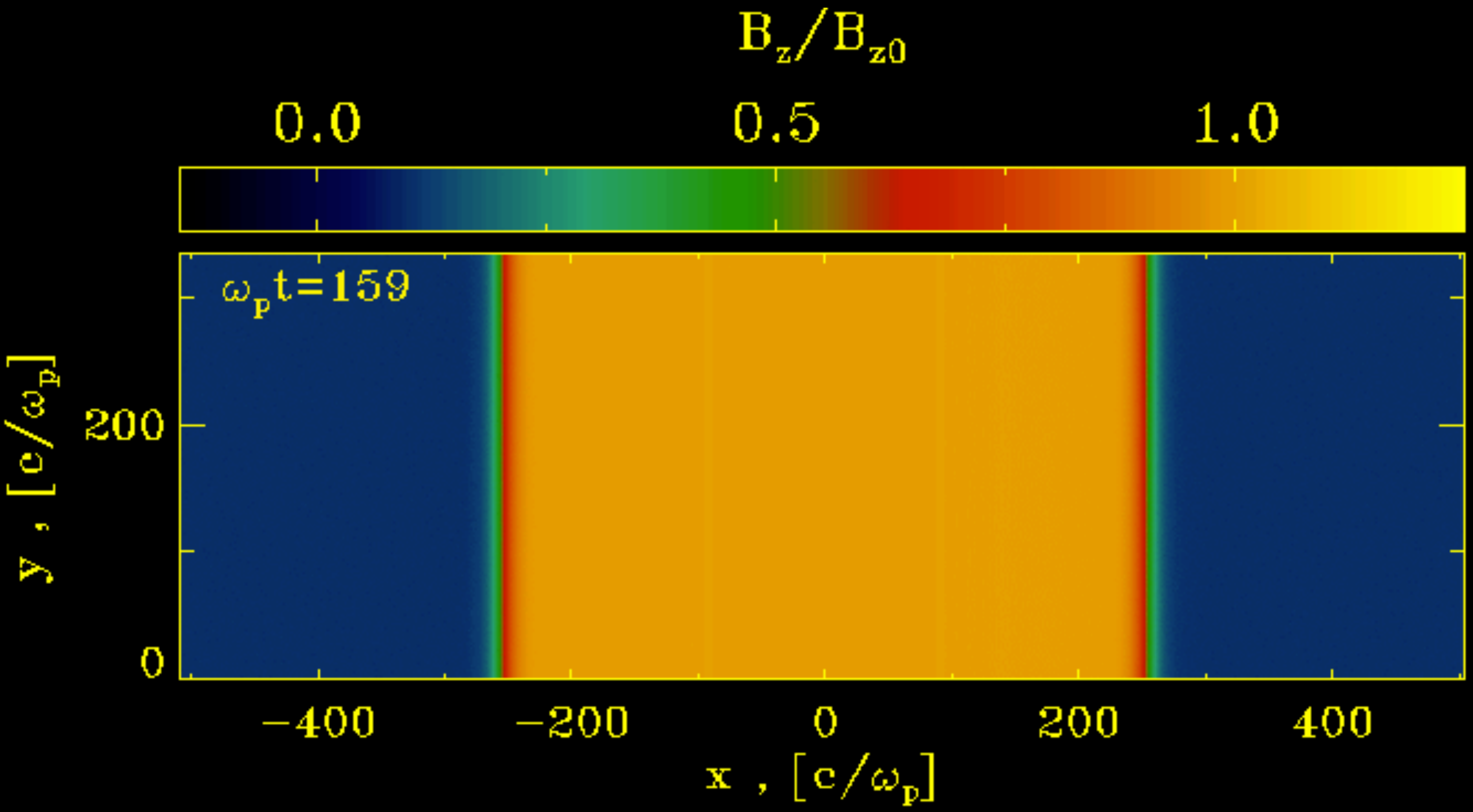
Kelvin-Helmholtz (KH) instability



(Davelaar+23, in prep)

- For realistic jet and ambient plasma conditions, the interface is KH unstable.
- The KH growth rate matches well with linear MHD expectations (Chow+ 22).

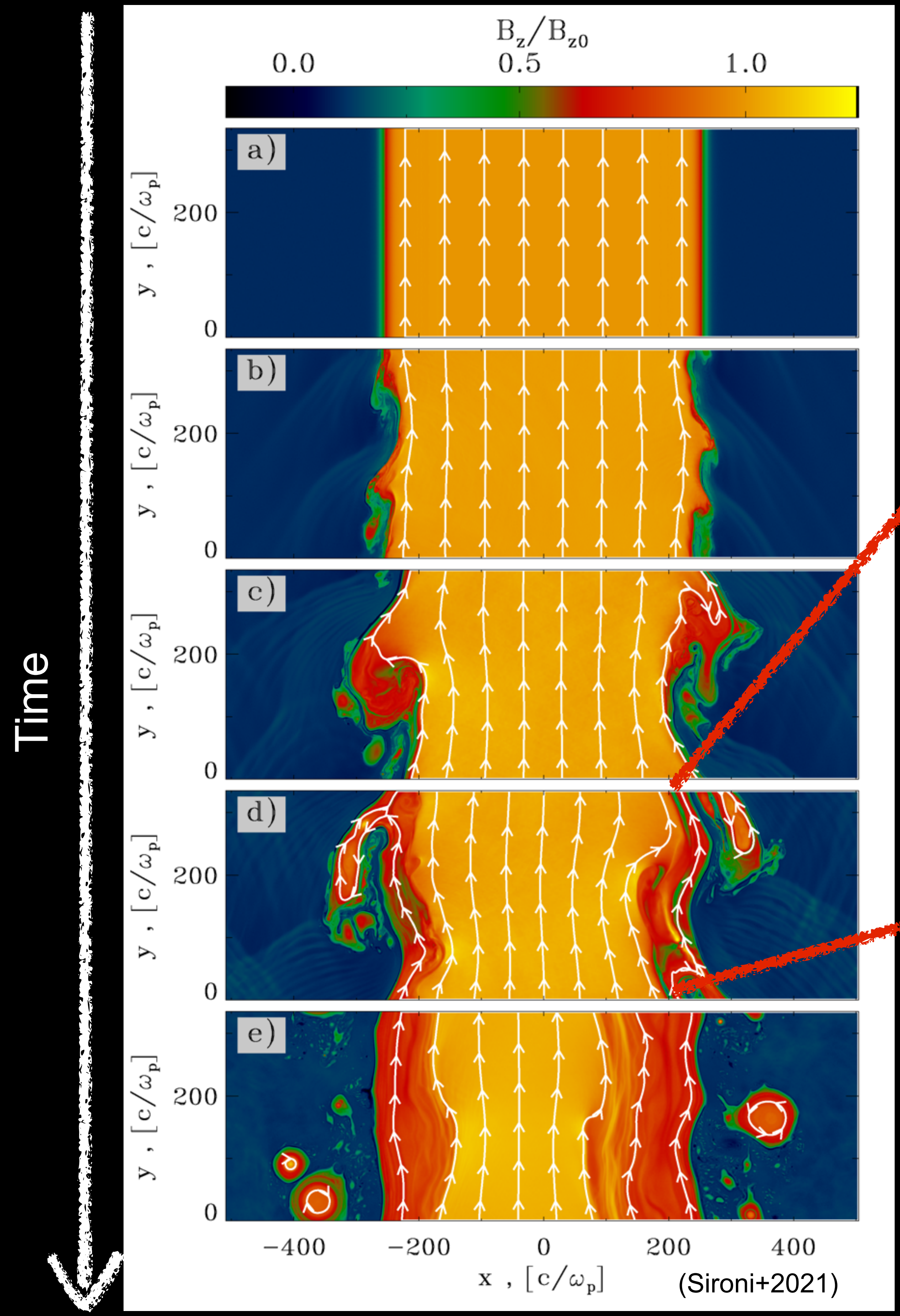
Kelvin-Helmholtz (KH) instability



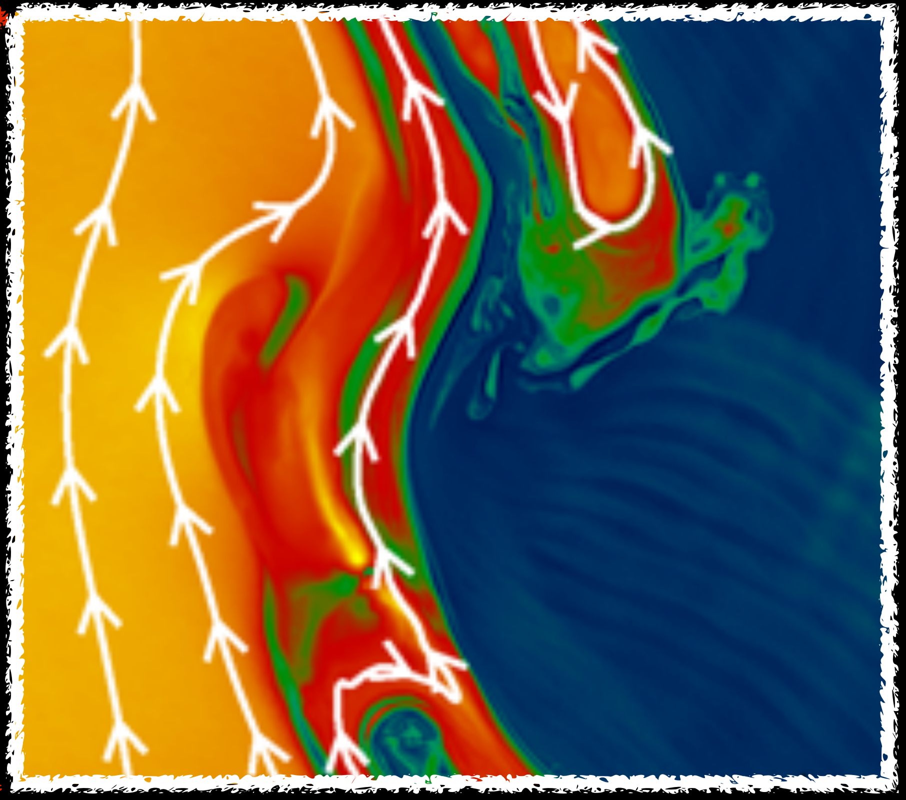
(Sironi+21)

- The linear and non-linear evolution is the same in PIC and resistive MHD.

KH → reconnection

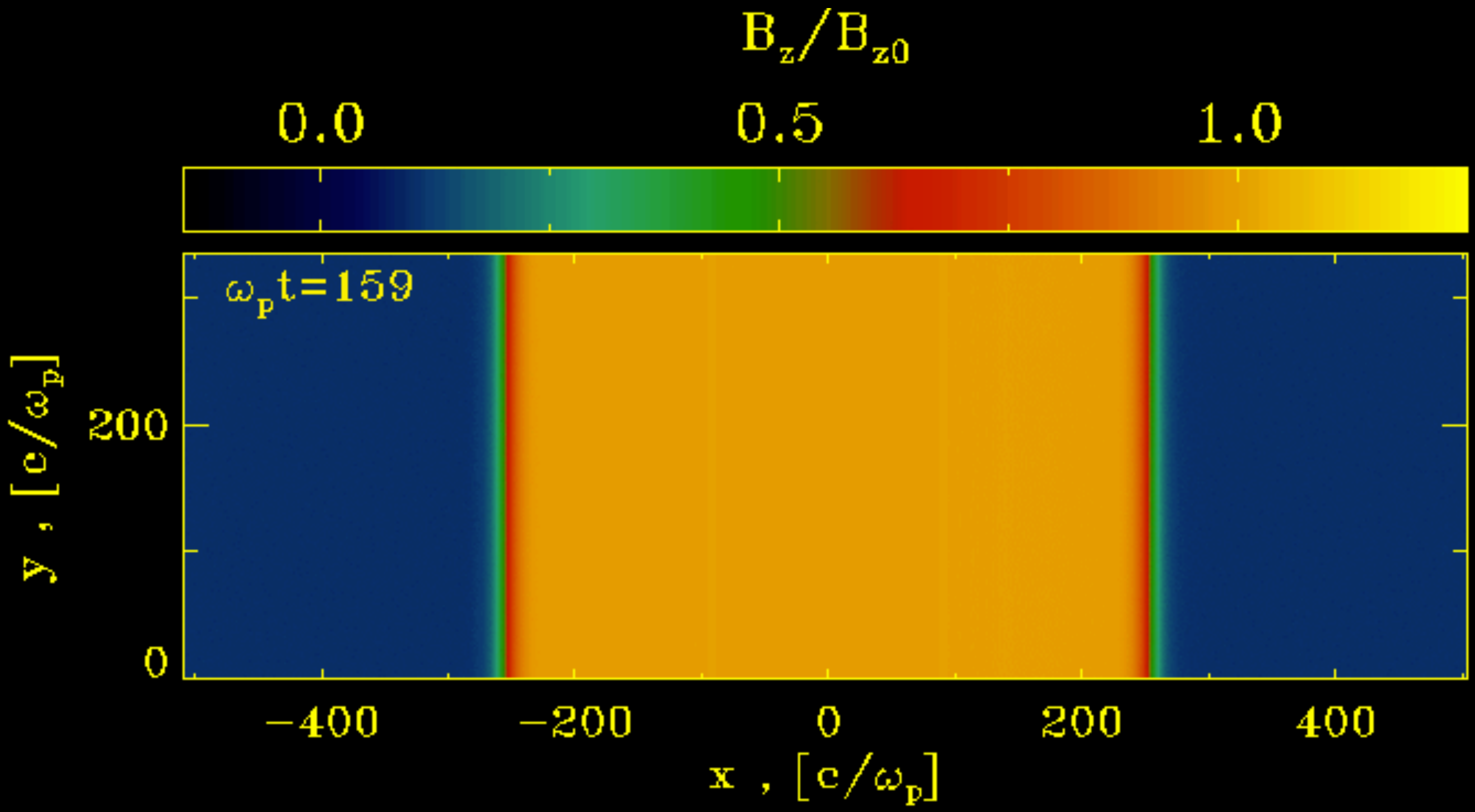


(Sironi+2021)

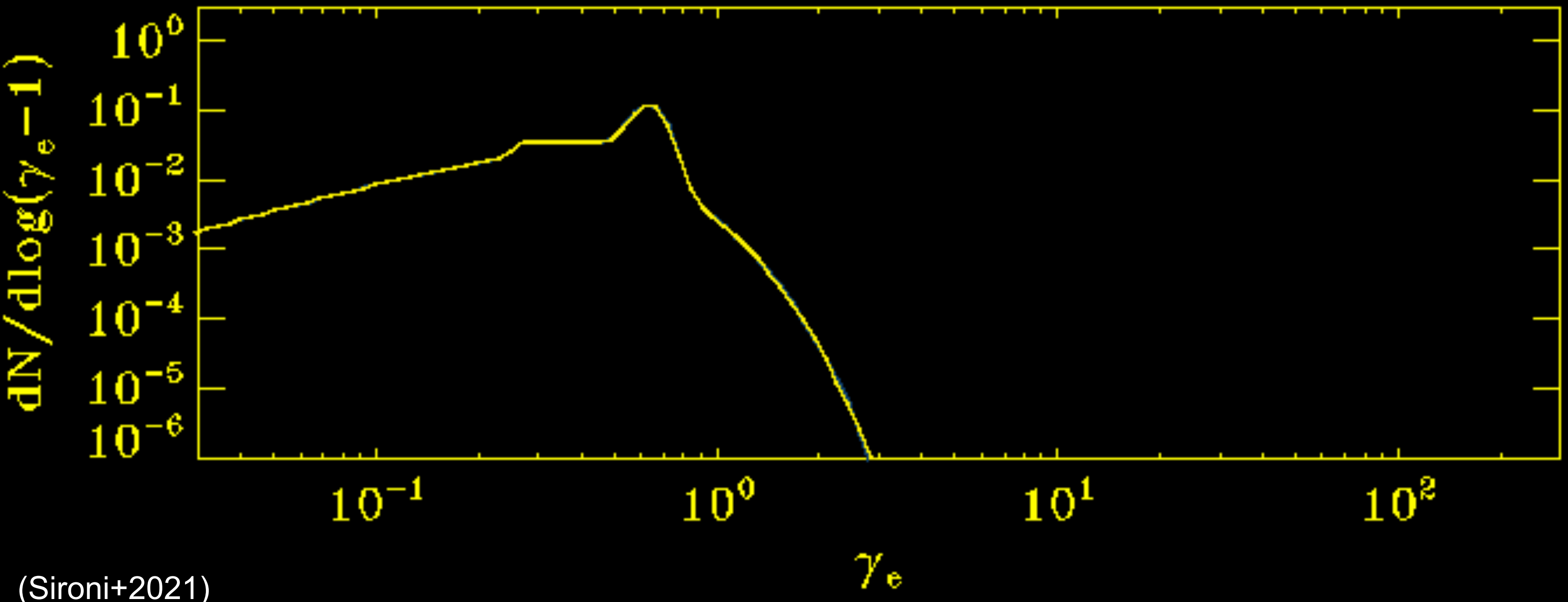


Magnetic reconnection (with $B_g \sim B_0$) is a natural by-product of nonlinear KH evolution.

KH → reconnection → particle acceleration



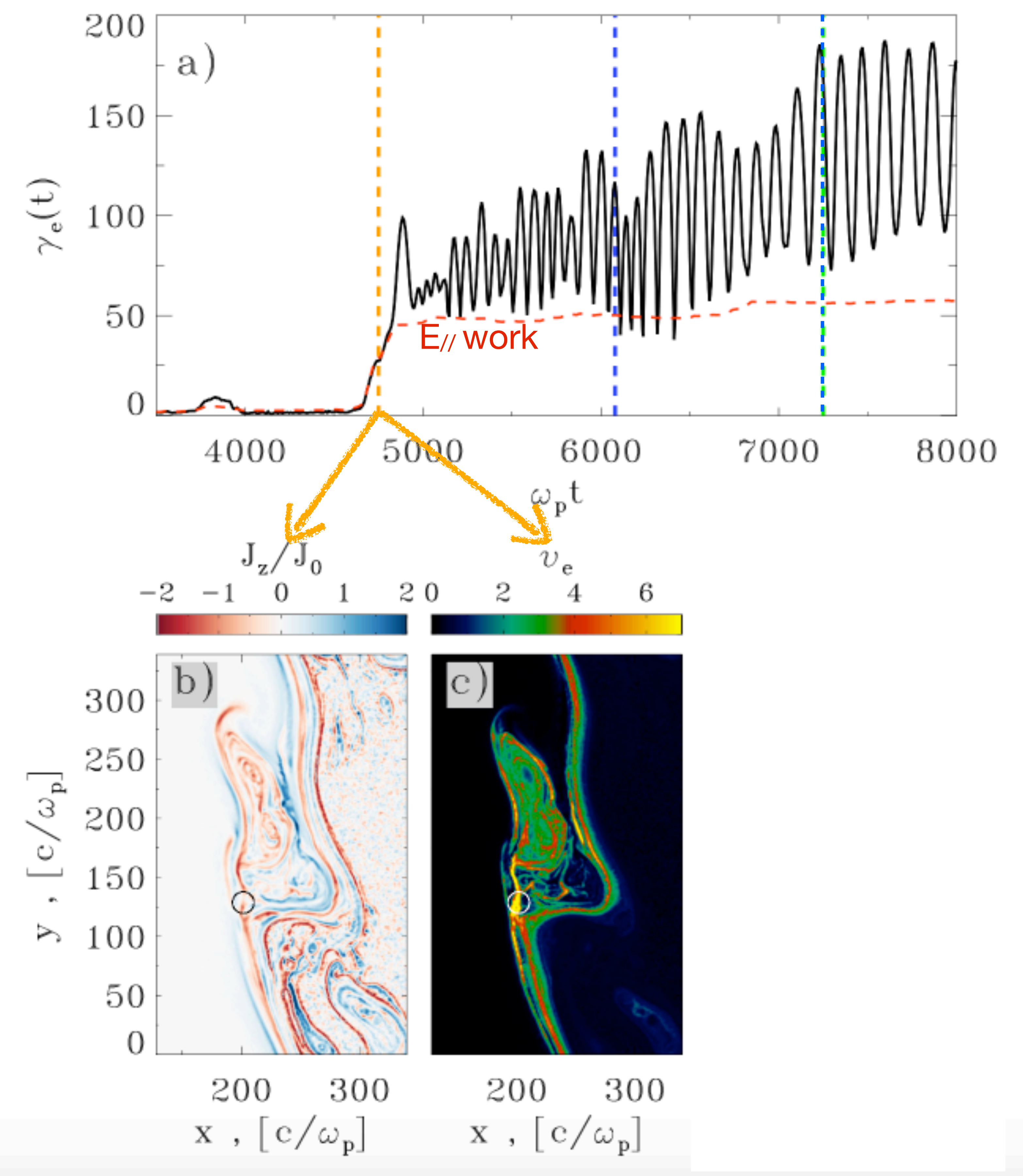
KH-driven reconnection leads to efficient acceleration of jet particles.



The high-energy cutoff increases at each nonlinear stage of KH.

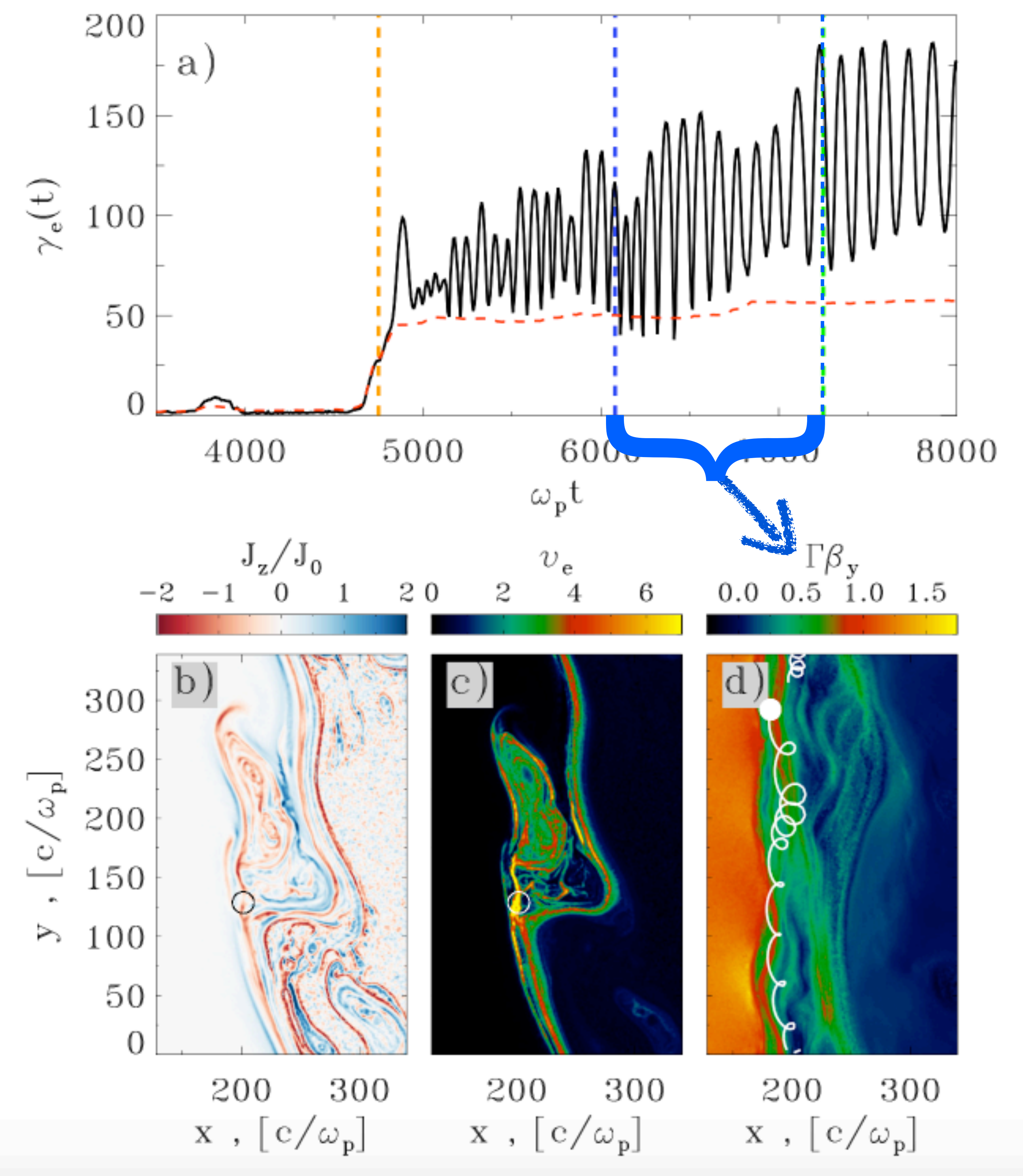
(Sironi+2021)

Two-stage acceleration



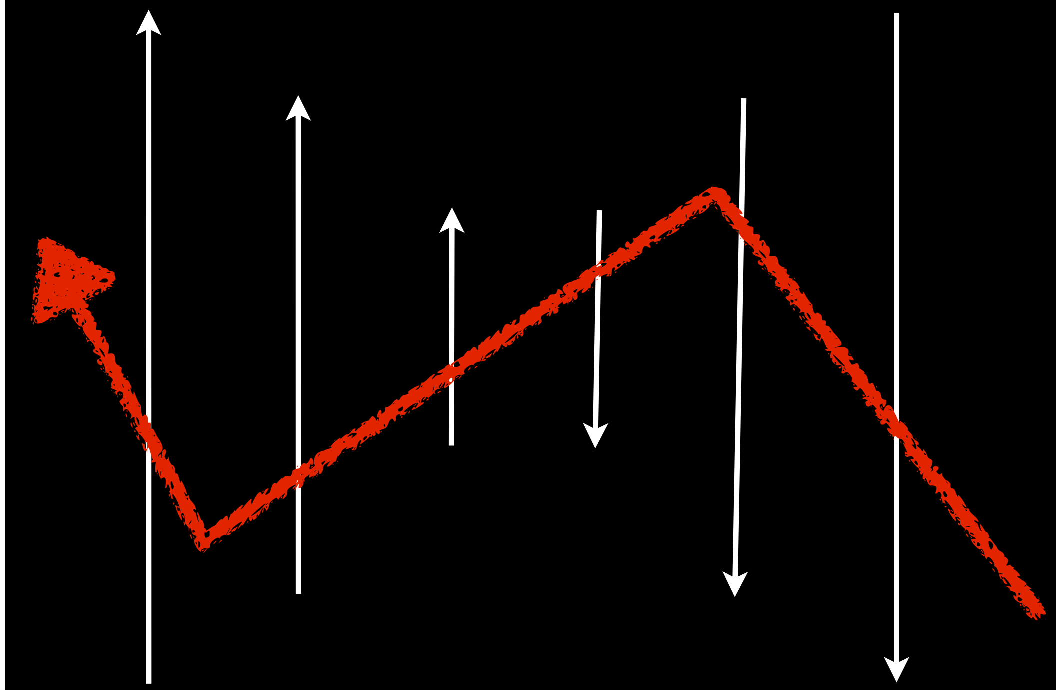
(1) The early acceleration stages (injection) are powered by $E_{//}$ at reconnection layers.

Two-stage acceleration



(1) The early acceleration stages (injection) are powered by $E_{//}$ at reconnection layers.

(2) Reconnection-accelerated particles then experience shear-driven acceleration.



Astrophysical implications

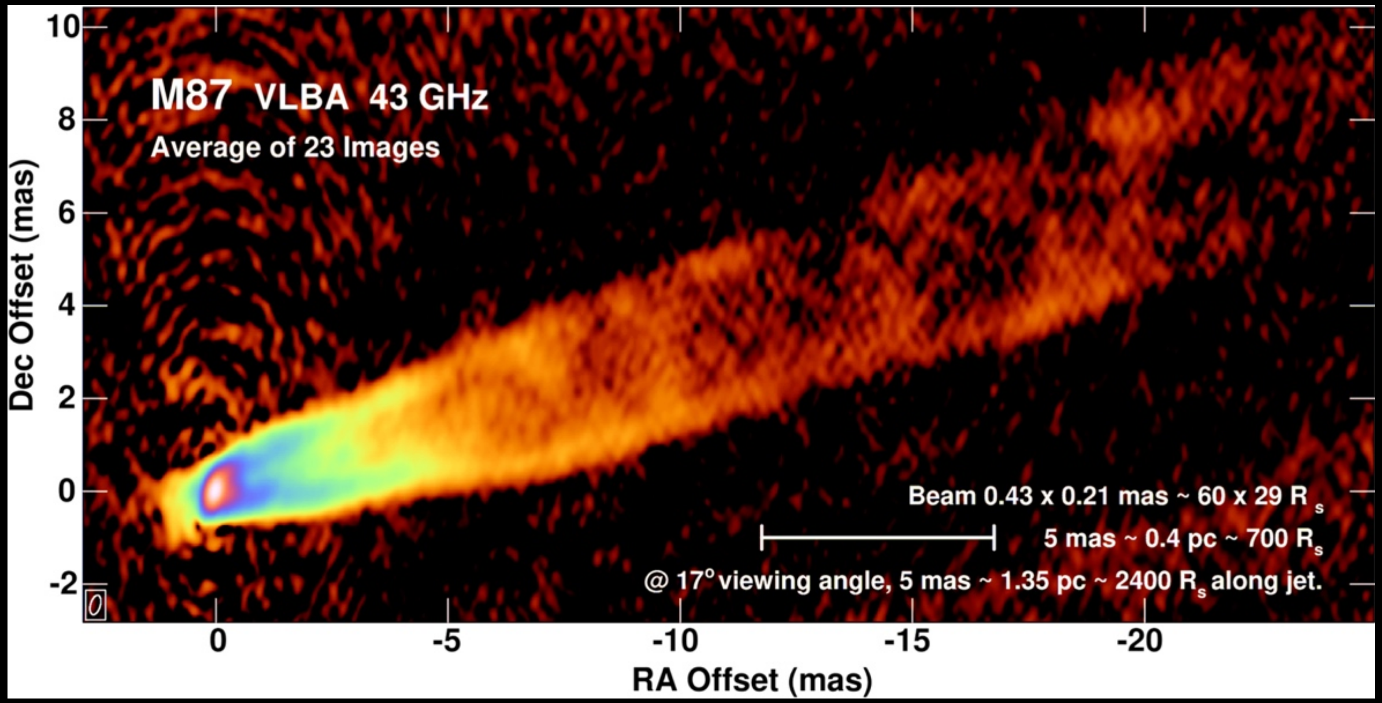
KH instability:

→ relativistic reconnection

→ particle injection

→ shear-driven acceleration

→ limb-brightened jets

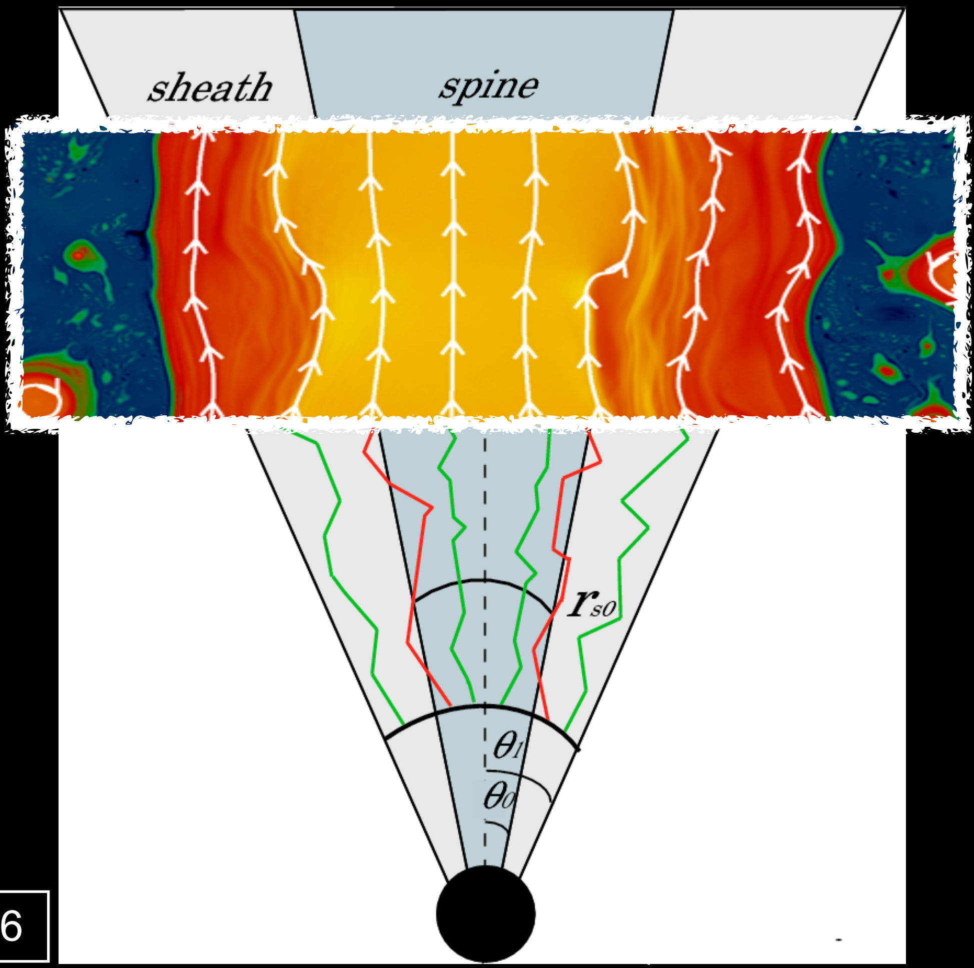


Walker+2018

The final stage presents:

- a fast core/spine
- a slower sheath with plasma beta~1

as assumed by spine-sheath models of blazar emission (e.g., Sikora 16).



Sikora+2016

Reconnection in BH X-ray coronae

Groselj, Hakobyan + 2023, arXiv:2301.11327

Sridhar, LS et al. 2022, MNRAS, 518, 1301

Sridhar, LS et al. 2021, MNRAS, 507, 5625

LS & Beloborodov 2020, ApJ, 899, 52

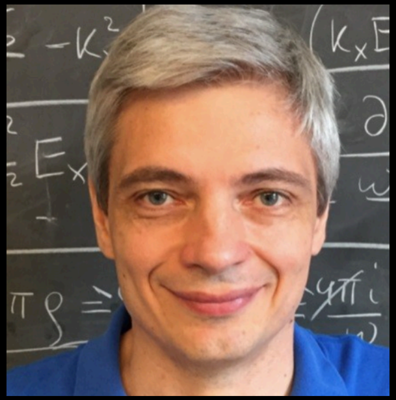
N. Sridhar

D. Groselj

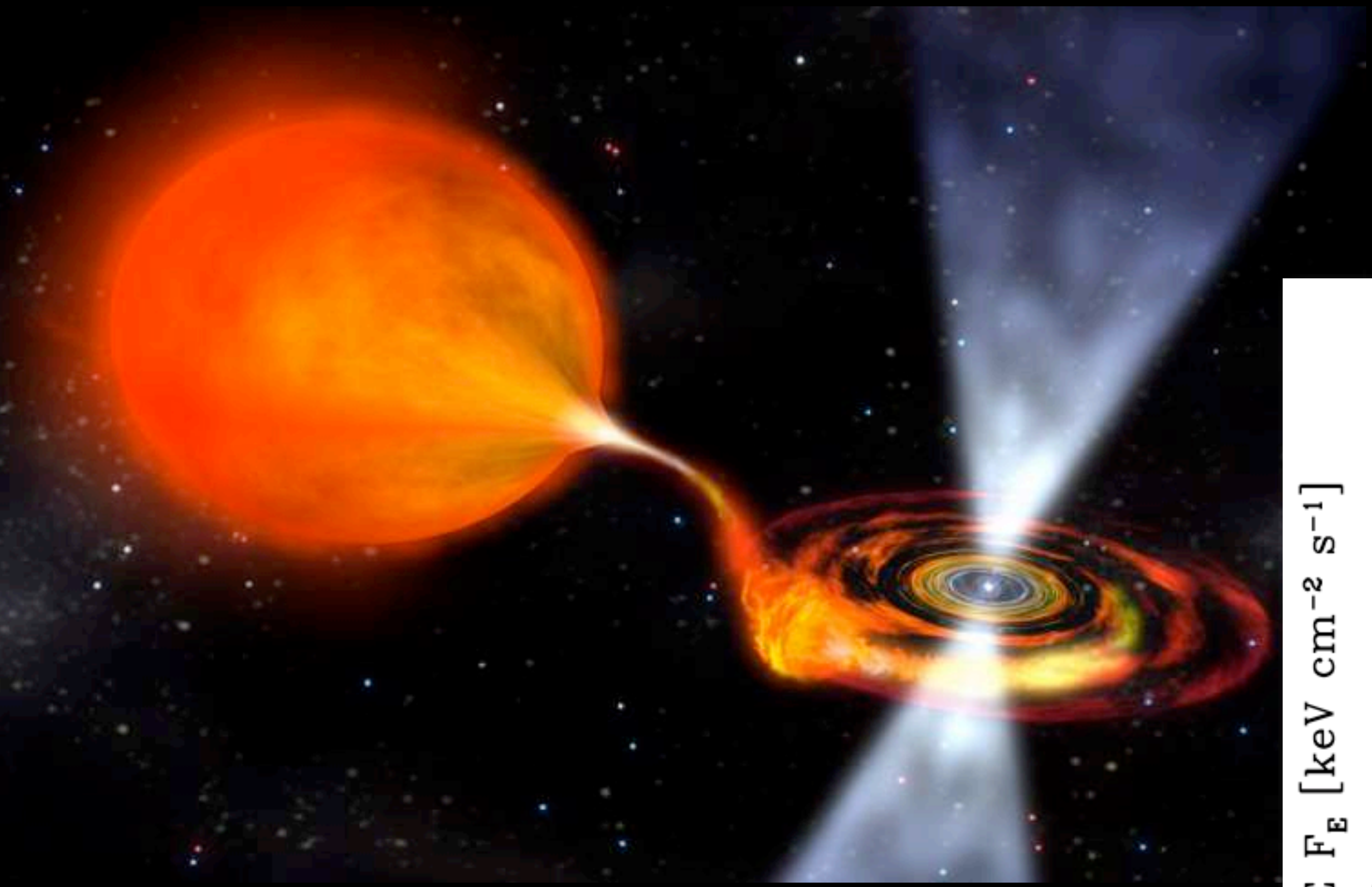
H. Hakobyan

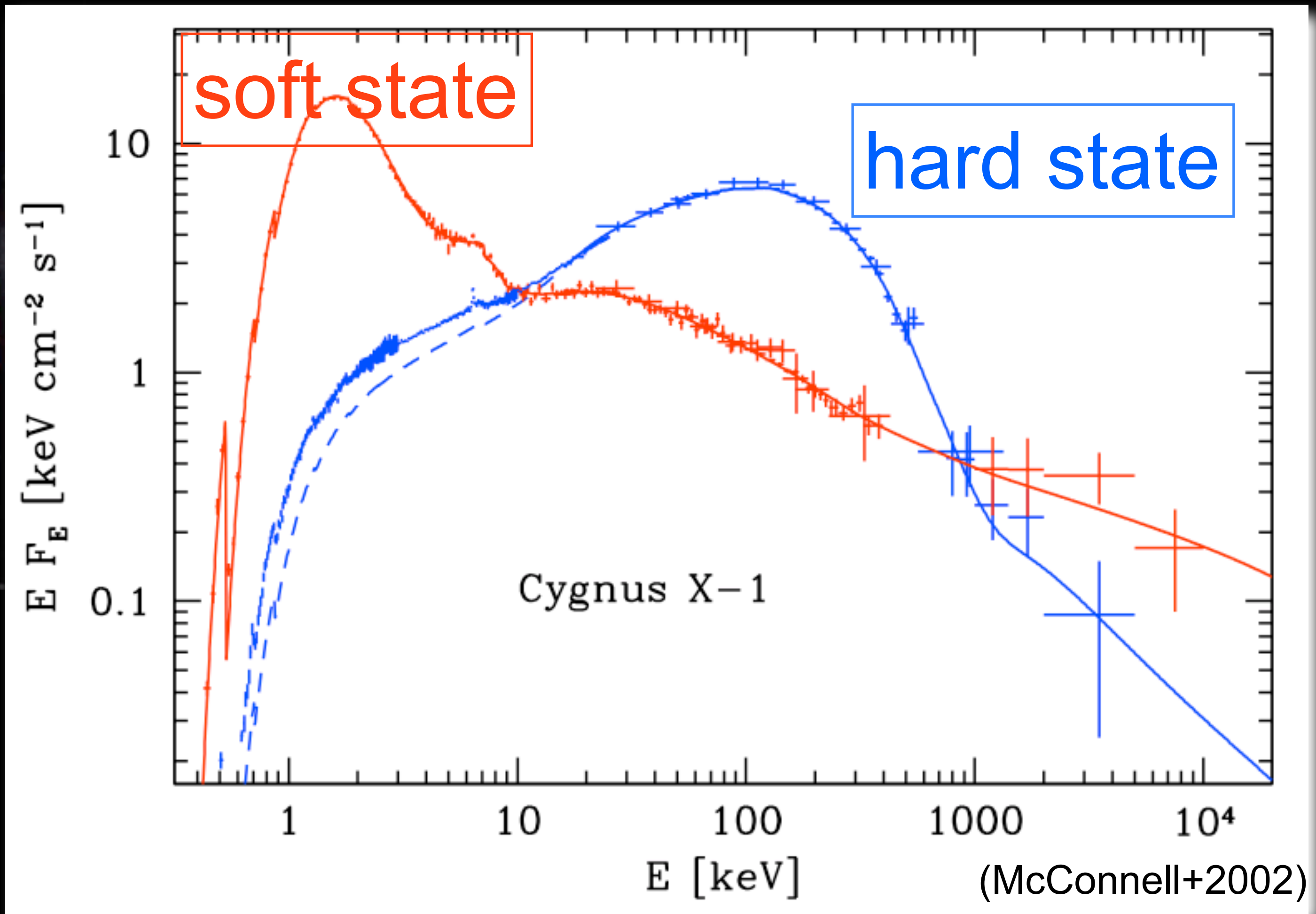
A. Philippov

A. Beloborodov



The hard state of X-ray binaries





(McConnell+2002)

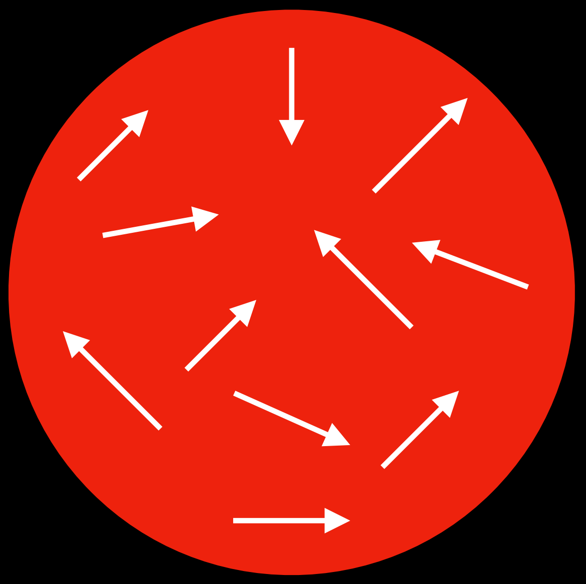
Hard state: interpreted as thermal Comptonization by “coronal” plasma with electron temperature ~100 keV and moderate optical depth.

Can the emitting electrons in BH coronae stay hot?

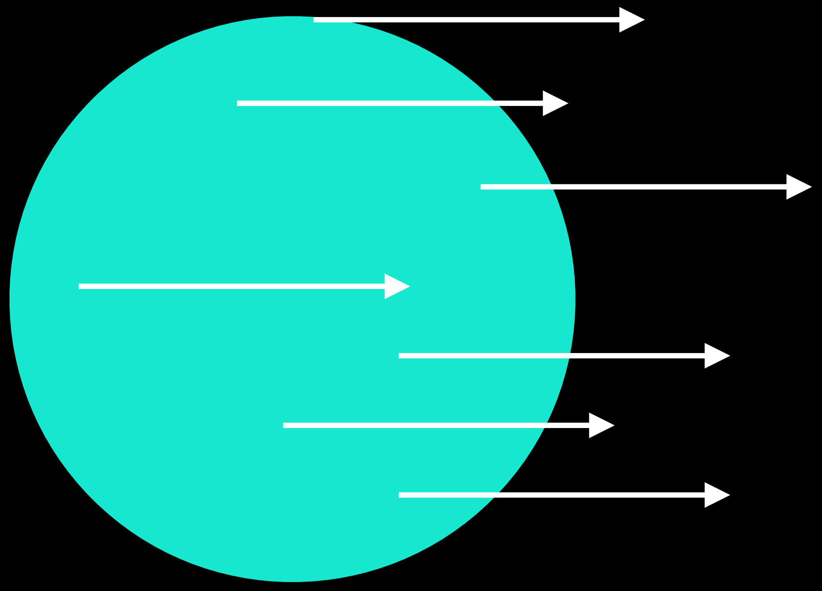
Internal vs bulk motions

Can the emitting electrons in BH coronae stay hot?

In BH coronae, $t_{cool} \ll t_{dyn} \rightarrow$ internal motions (temperature) are suppressed



Internal motions (random)

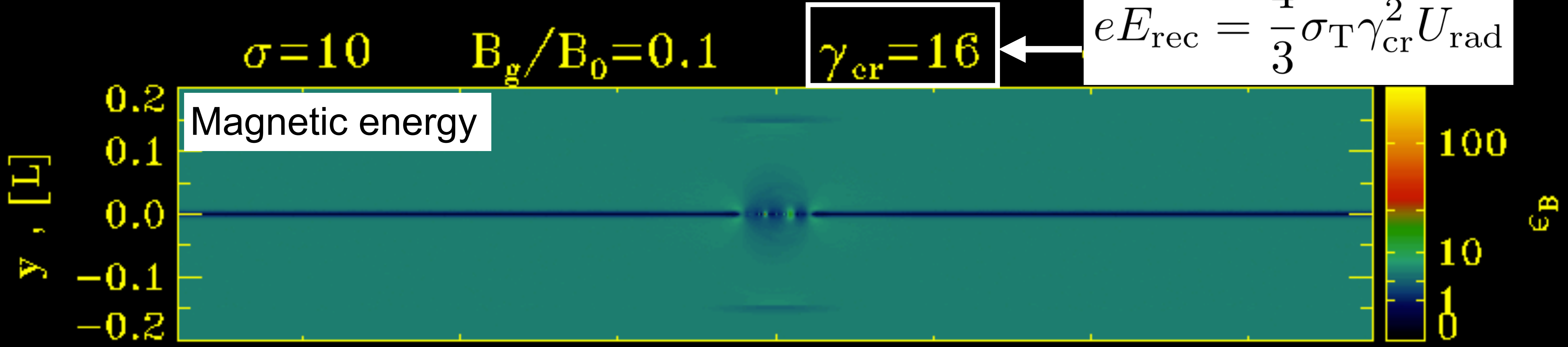


Bulk motions (ordered)

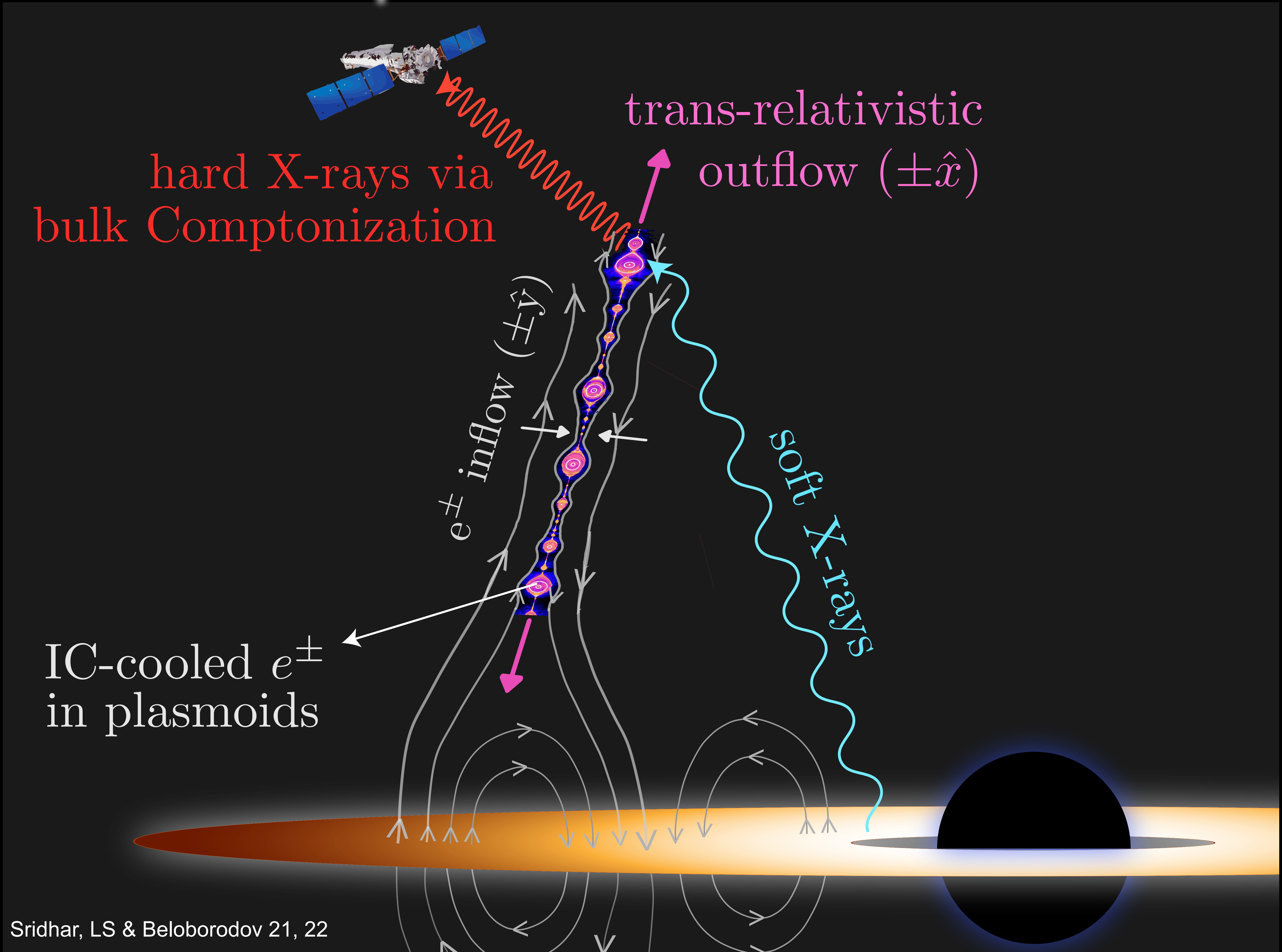
What provides ordered/bulk motions for Comptonization?

Option 1: reconnection

$$eE_{\rm rec} = \frac{4}{3}\sigma_{\rm T}\gamma_{\rm cr}^2 U_{\rm rad}$$



Option 1: reconnection



hard X-rays via bulk Comptonization

trans-relativistic outflow ($\pm\hat{x}$)

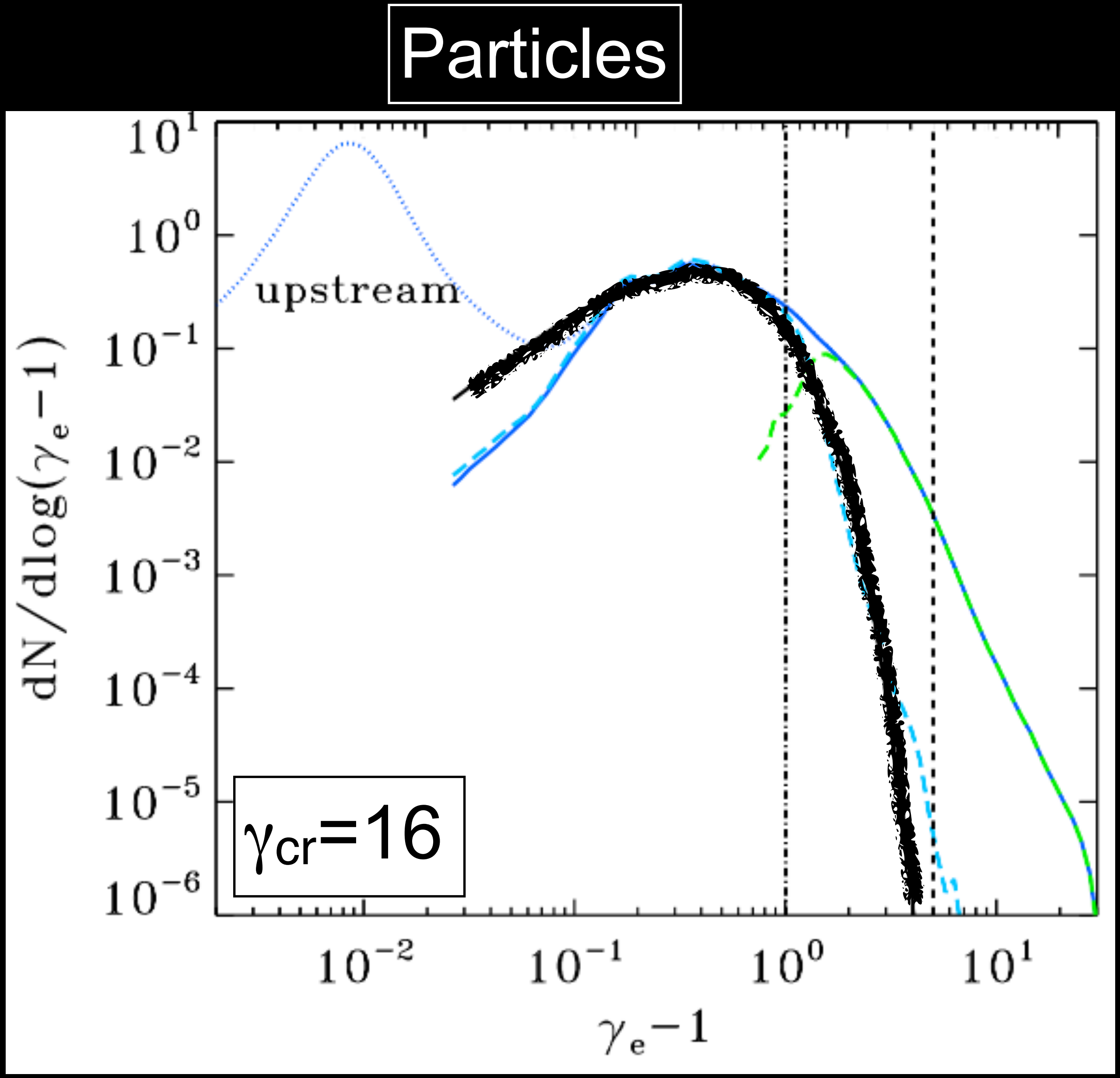
$e^{\pm}$ inflow ($\pm\hat{y}$)

soft X-rays

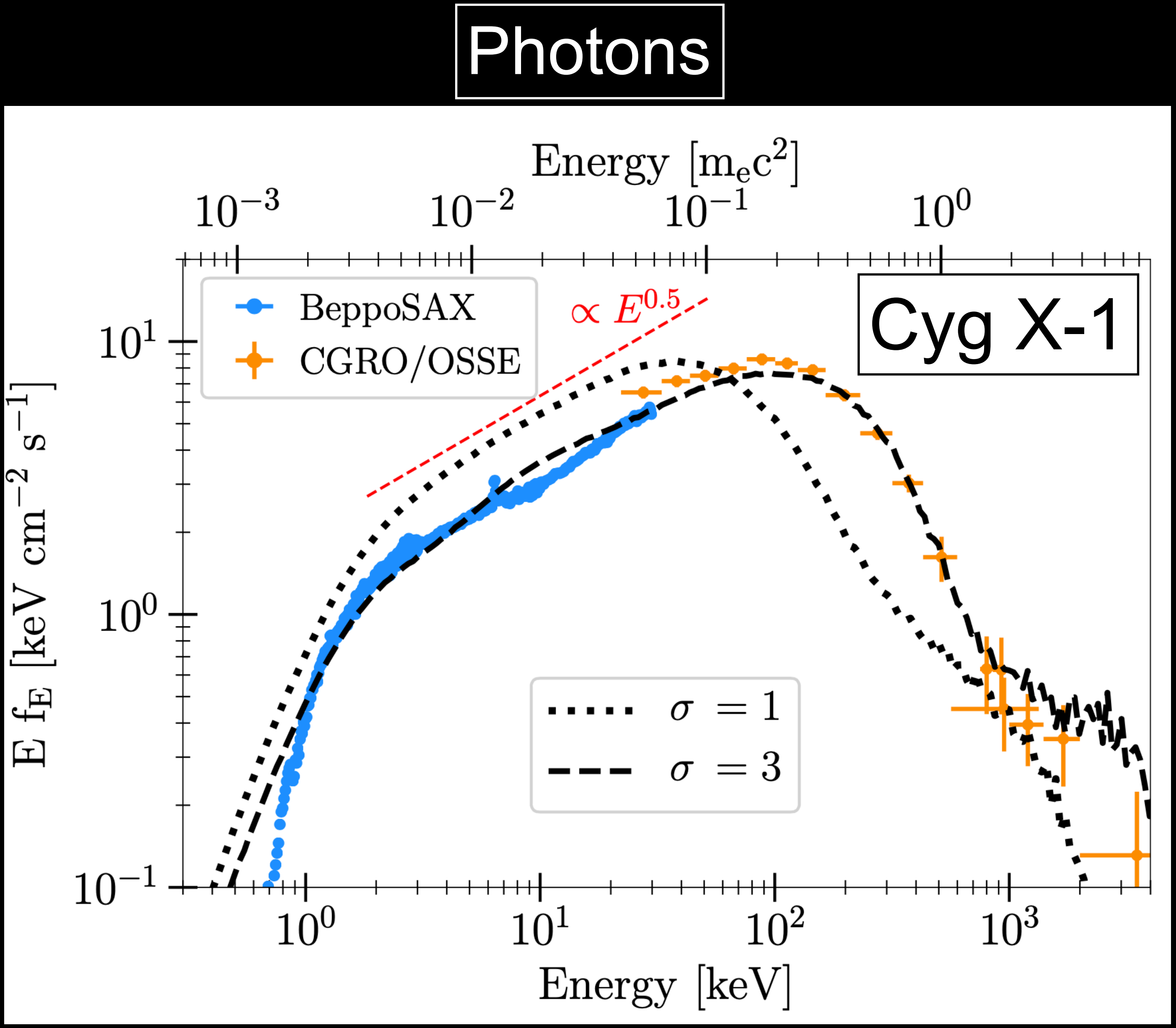
IC-cooled $e^{\pm}$ in plasmoids

Sridhar, LS & Beloborodov 21, 22

Option 1: reconnection



(Beloborodov 17; LS & Beloborodov 20; Sridhar, LS & Beloborodov 21, 22)



(Sridhar, LS & Beloborodov 21, 22)

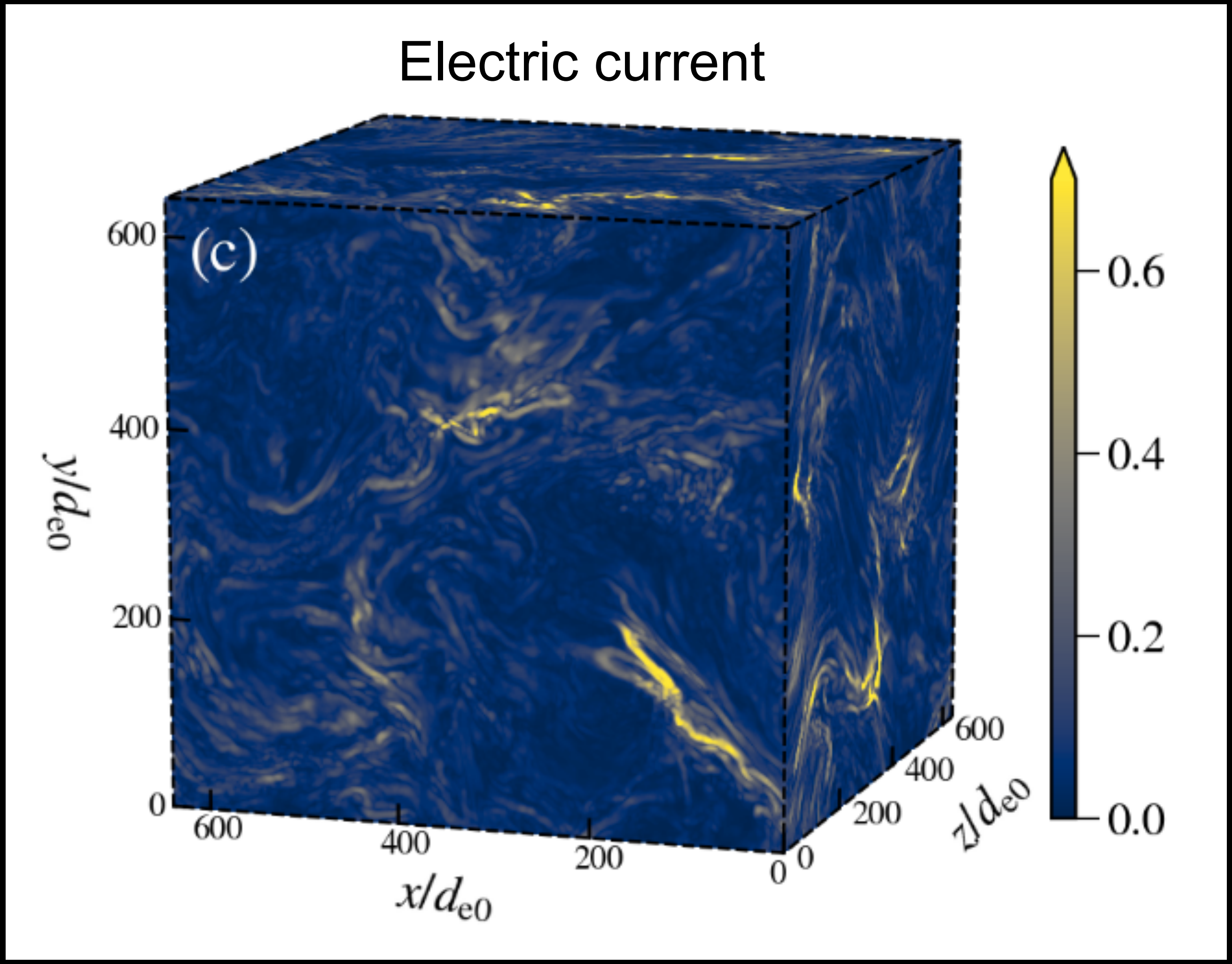
- The particle <u>bulk</u> energy spectrum resembles a <u>Maxwellian</u> with T~100 keV

- For optical depth ~ 1 and σ ~ few, our photon spectrum matches the observations.

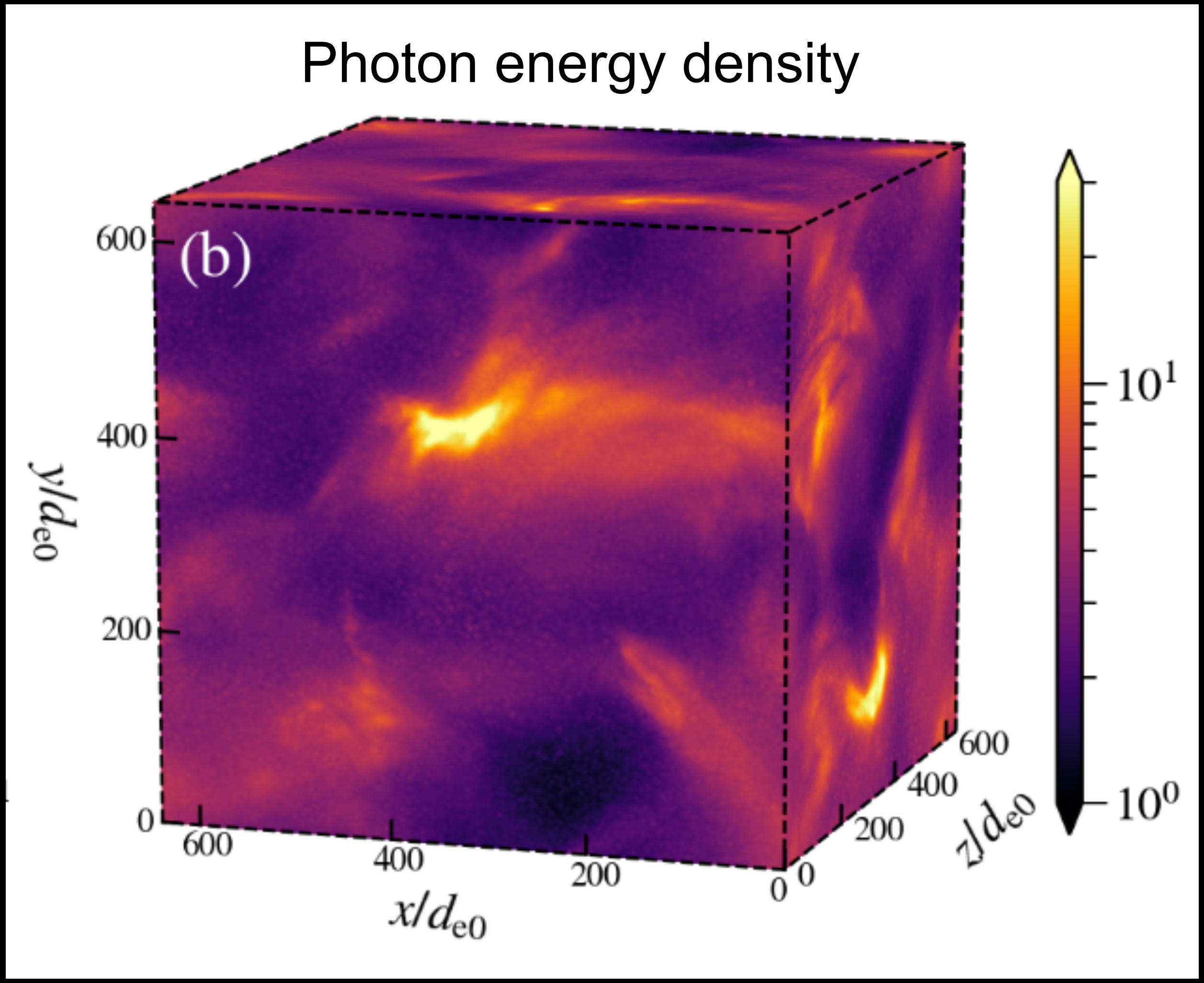
Option 2: turbulence

First simulations of kinetic turbulence with self-consistent radiative transfer:

- Injection of soft seed photons from a thermal bath at ~ 1 keV
- Photon escape
- Spatially-resolved Compton scattering with full Klein-Nishina cross-section (Monte-Carlo method)



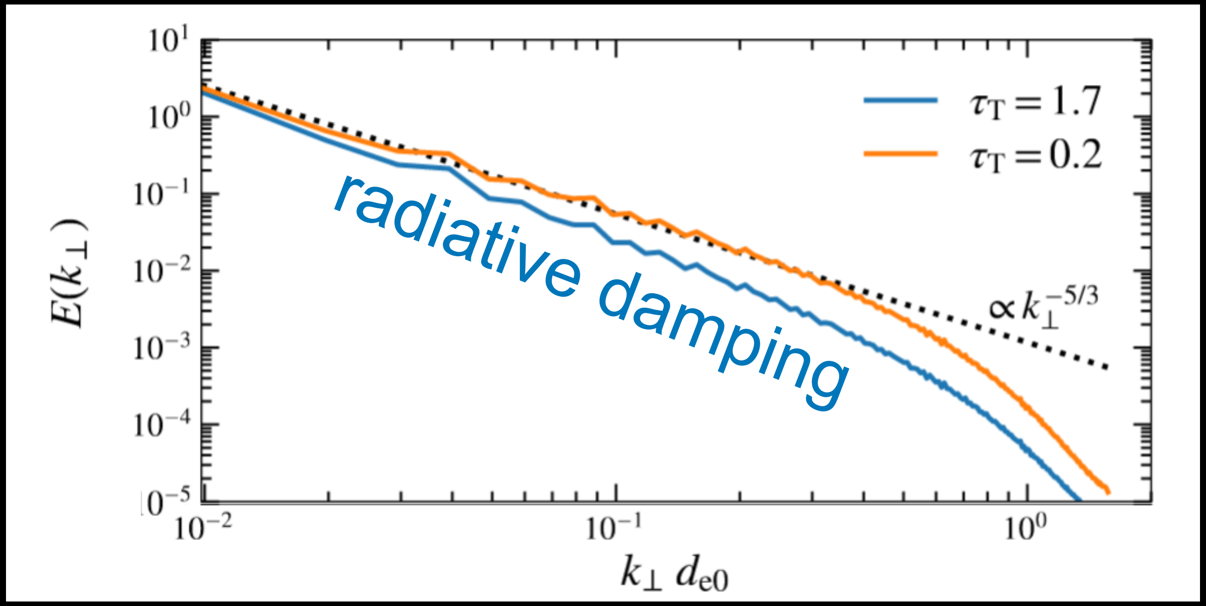
Electric current



Photon energy density

(Groselj+ 23; using TRISTAN-MP v2.0, Hakobyan+)

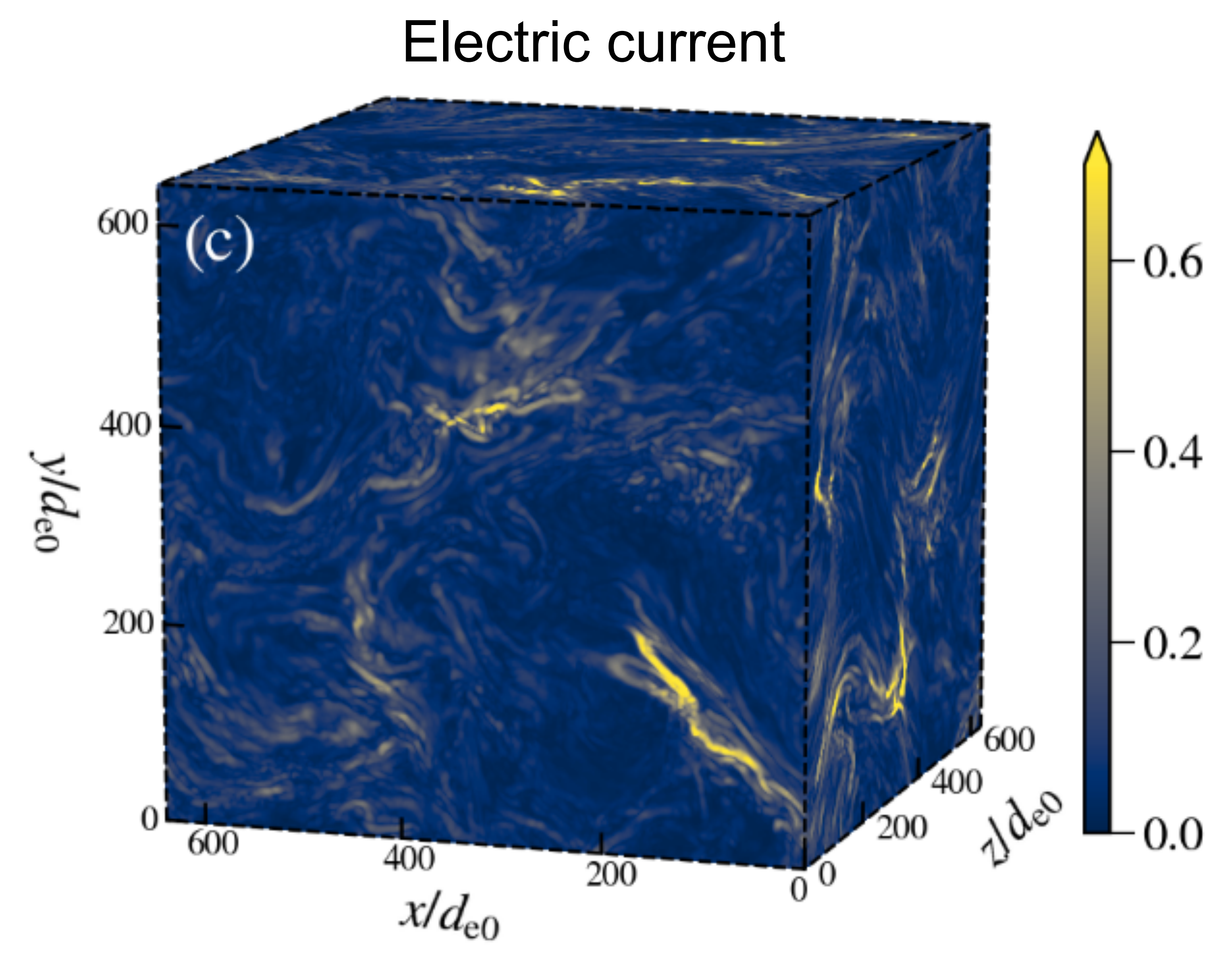
Option 2: turbulence



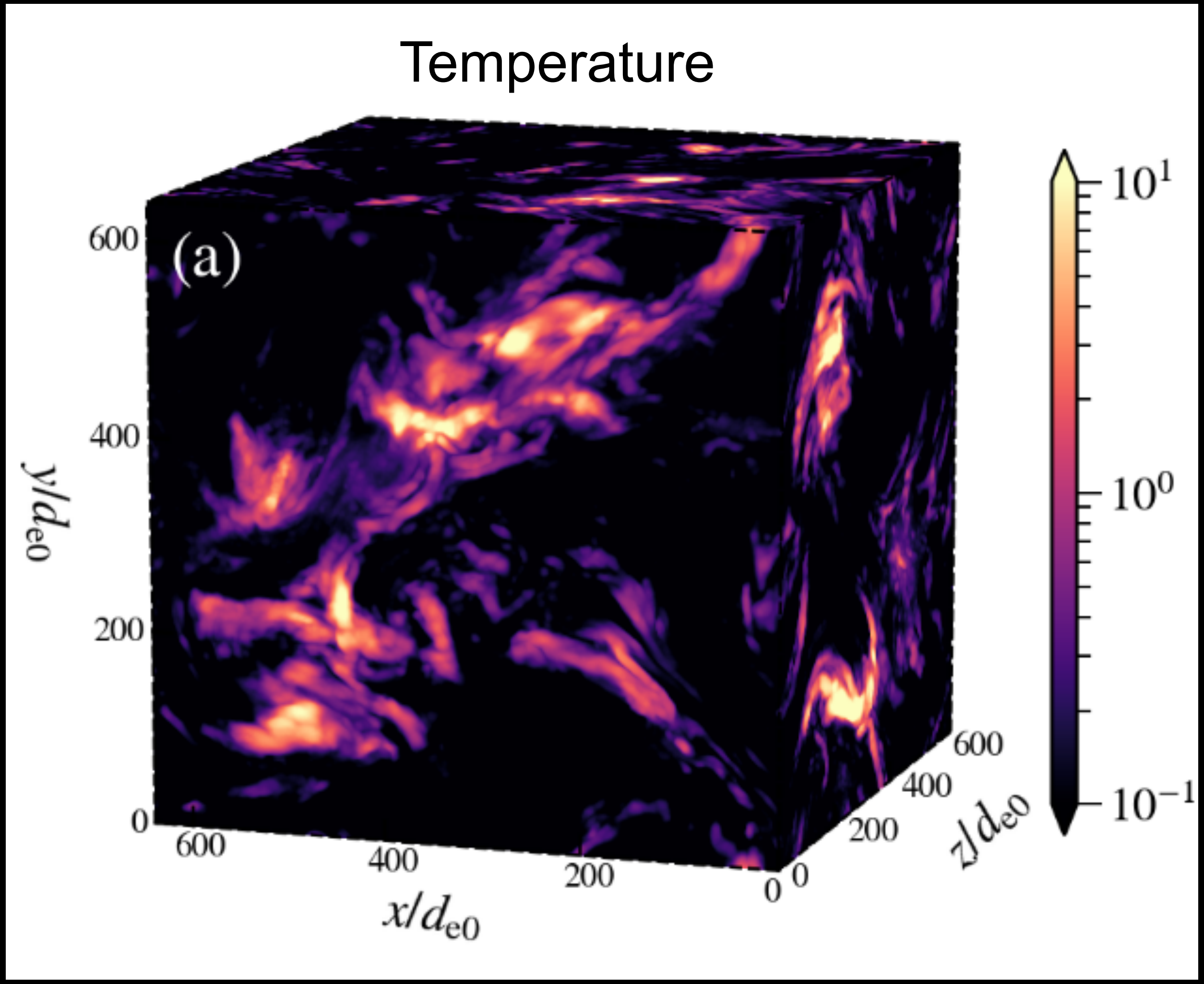
- Most of the turbulent energy converts to photon energy via bulk Comptonization, before the cascade reaches the plasma microscales.

- The rest is dissipated as heat in “hot spots”.

Electric current



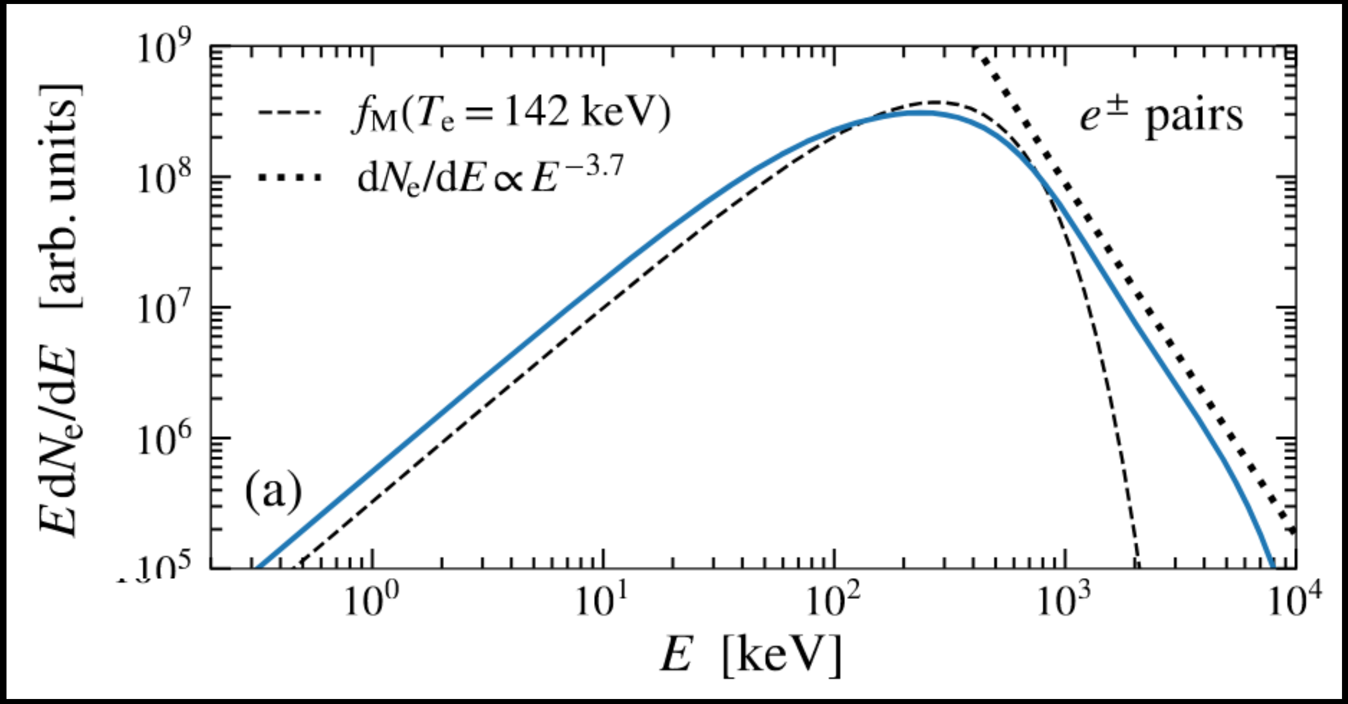
Temperature



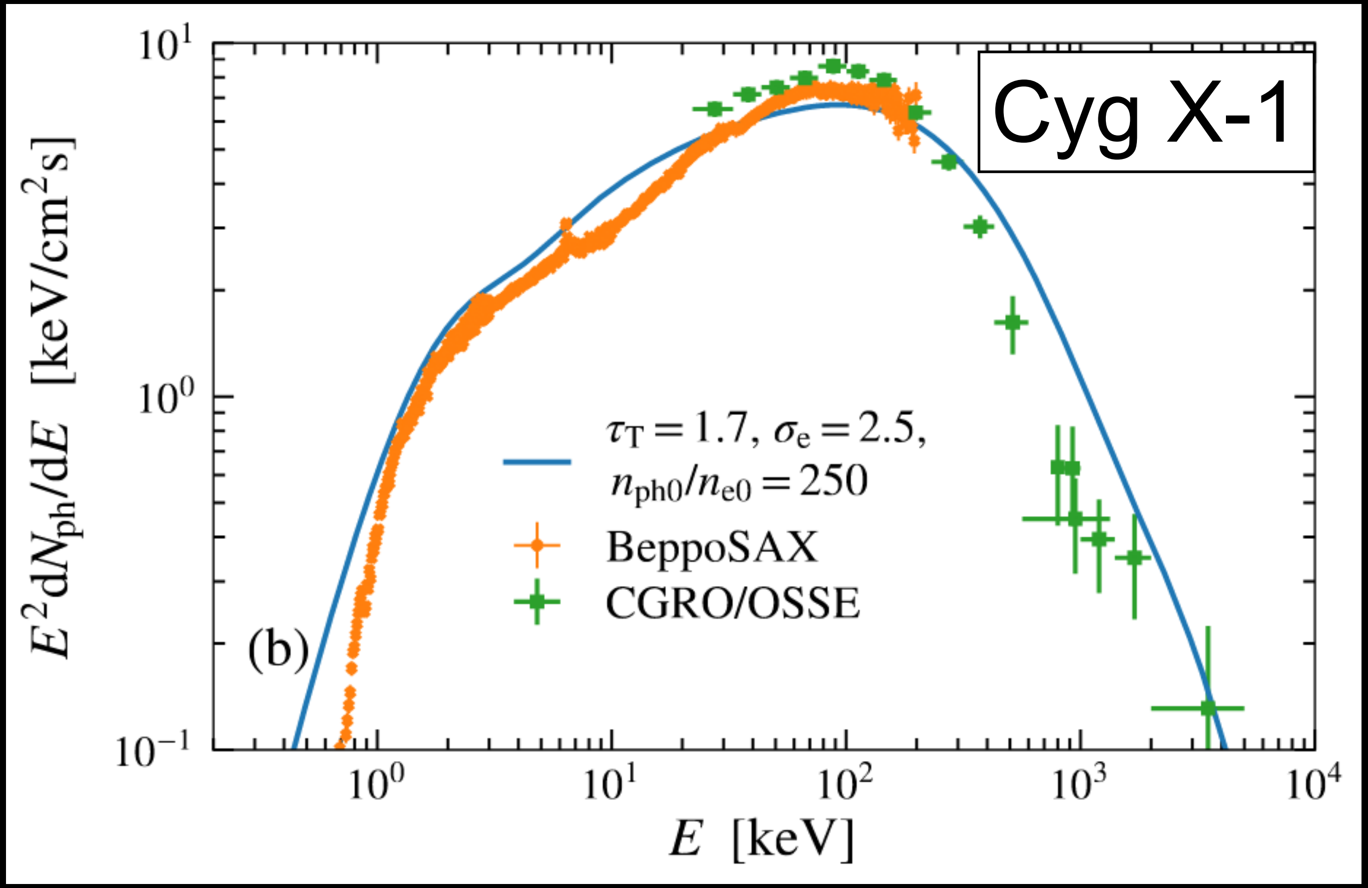
(Groselj+ 23; using TRISTAN-MP v2.0, Hakobyan+)

Option 2: turbulence

Particles



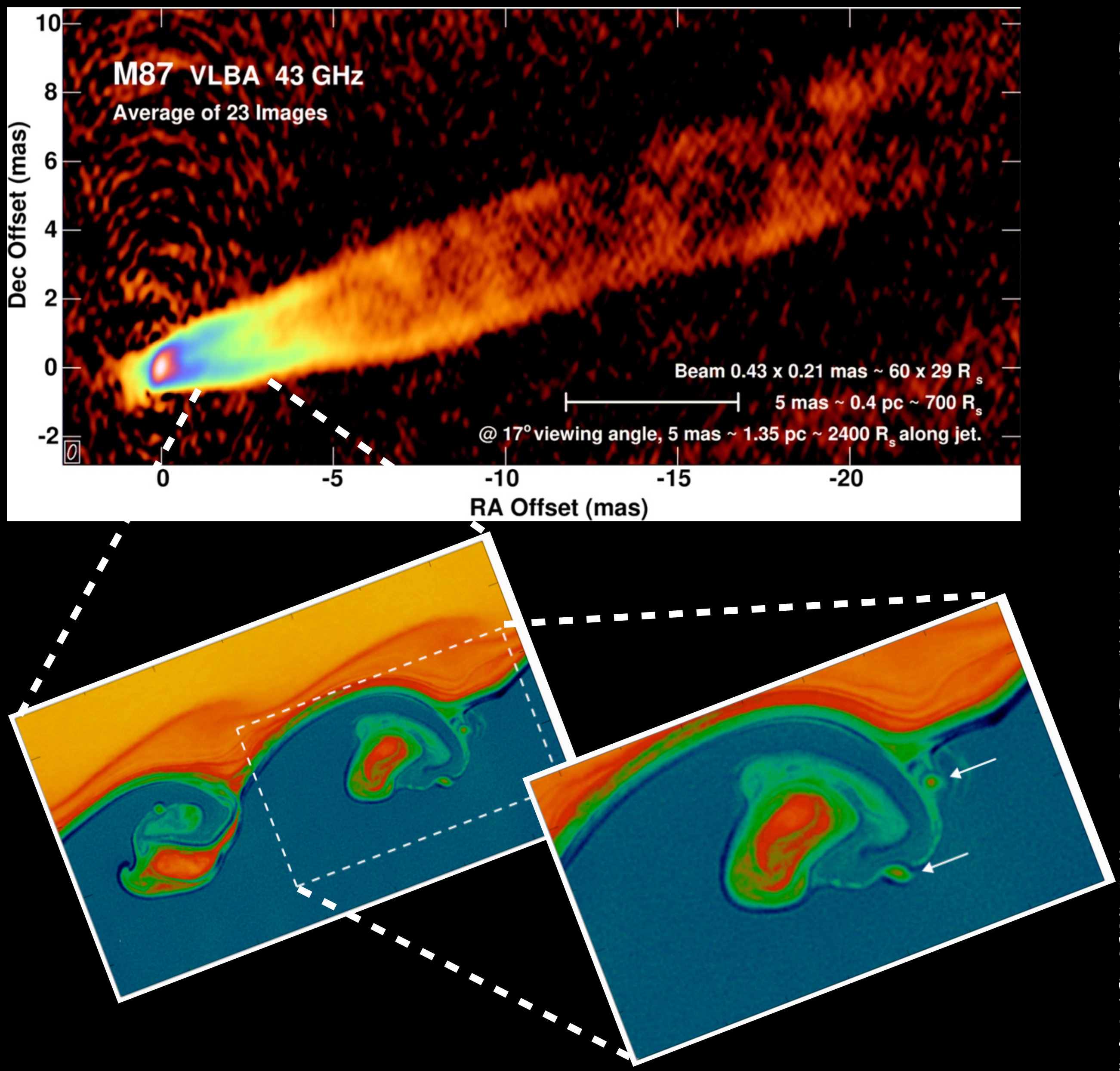
Photons



- The particle energy spectrum resembles a Maxwellian with T~100 keV

- For optical depth ~ 1 and σ ~ few, our photon spectrum matches the observations.
- The MeV tail may require including self-consistent pair production.

Reconnection at jet boundaries



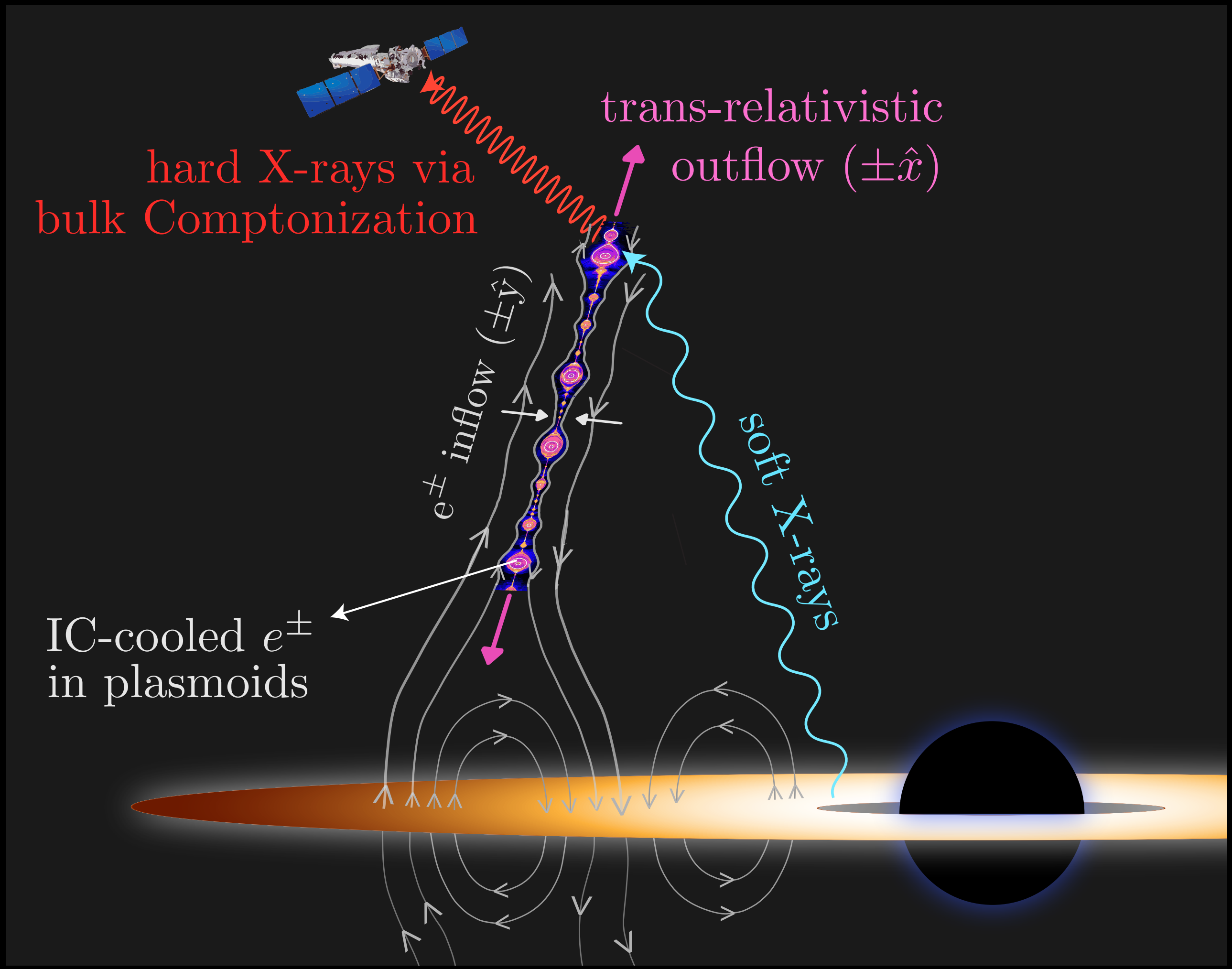
KH instability at jet boundaries

→ relativistic reconnection

→ particle injection

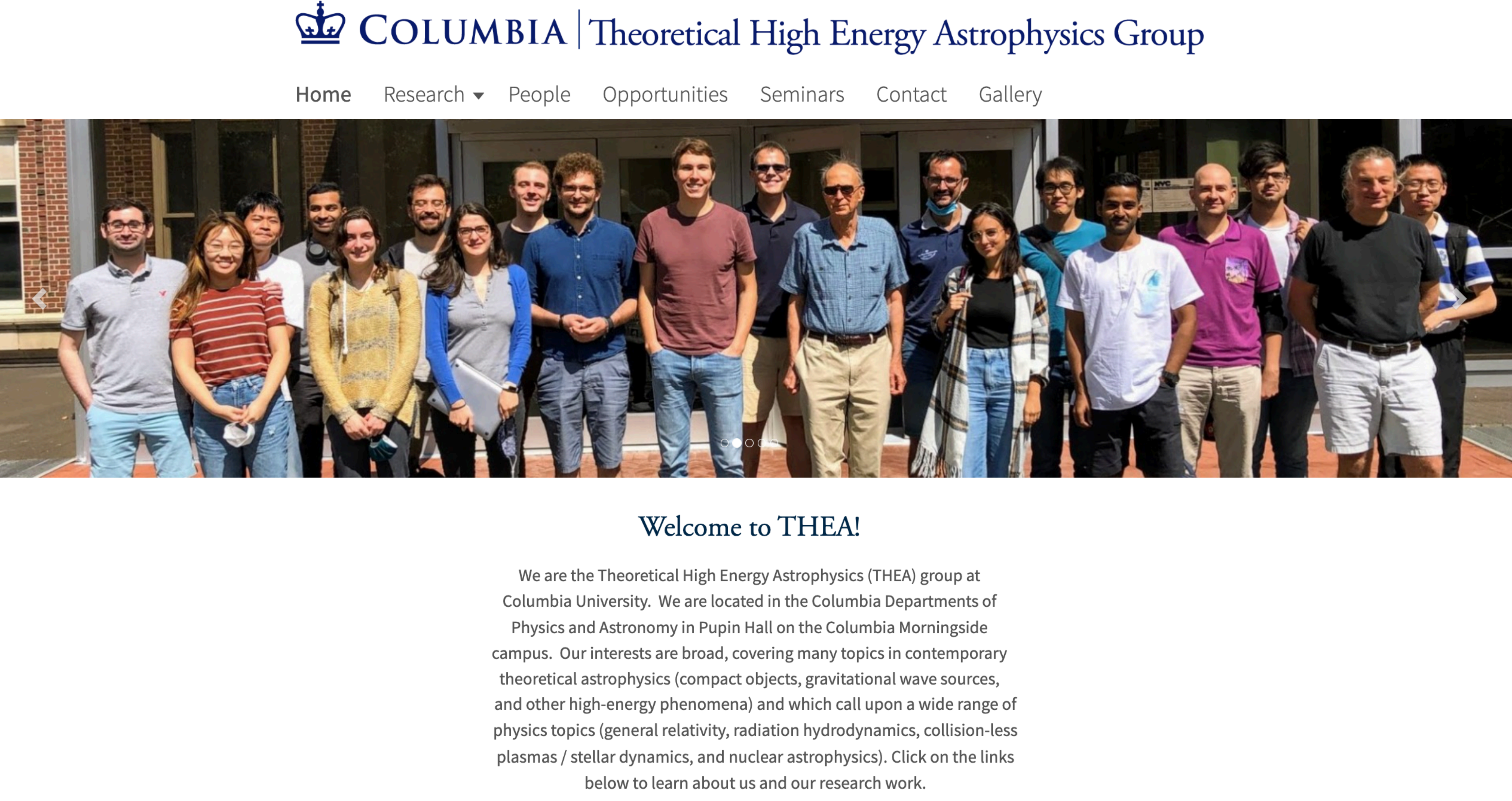
→ shear-driven acceleration

Reconnection in BH coronae



- σ ~ few reconnection (cold trans-rel plasmoids) or turbulence.
- bulk Comptonization with effective temperature ~ 100 keV.
- hard state spectra of X-ray binaries.

https://thea.astro.columbia.edu/



Welcome to THEA!

We are the Theoretical High Energy Astrophysics (THEA) group at Columbia University. We are located in the Columbia Departments of Physics and Astronomy in Pupin Hall on the Columbia Morningside campus. Our interests are broad, covering many topics in contemporary theoretical astrophysics (compact objects, gravitational wave sources, and other high-energy phenomena) and which call upon a wide range of physics topics (general relativity, radiation hydrodynamics, collision-less plasmas / stellar dynamics, and nuclear astrophysics). Click on the links below to learn about us and our research work.