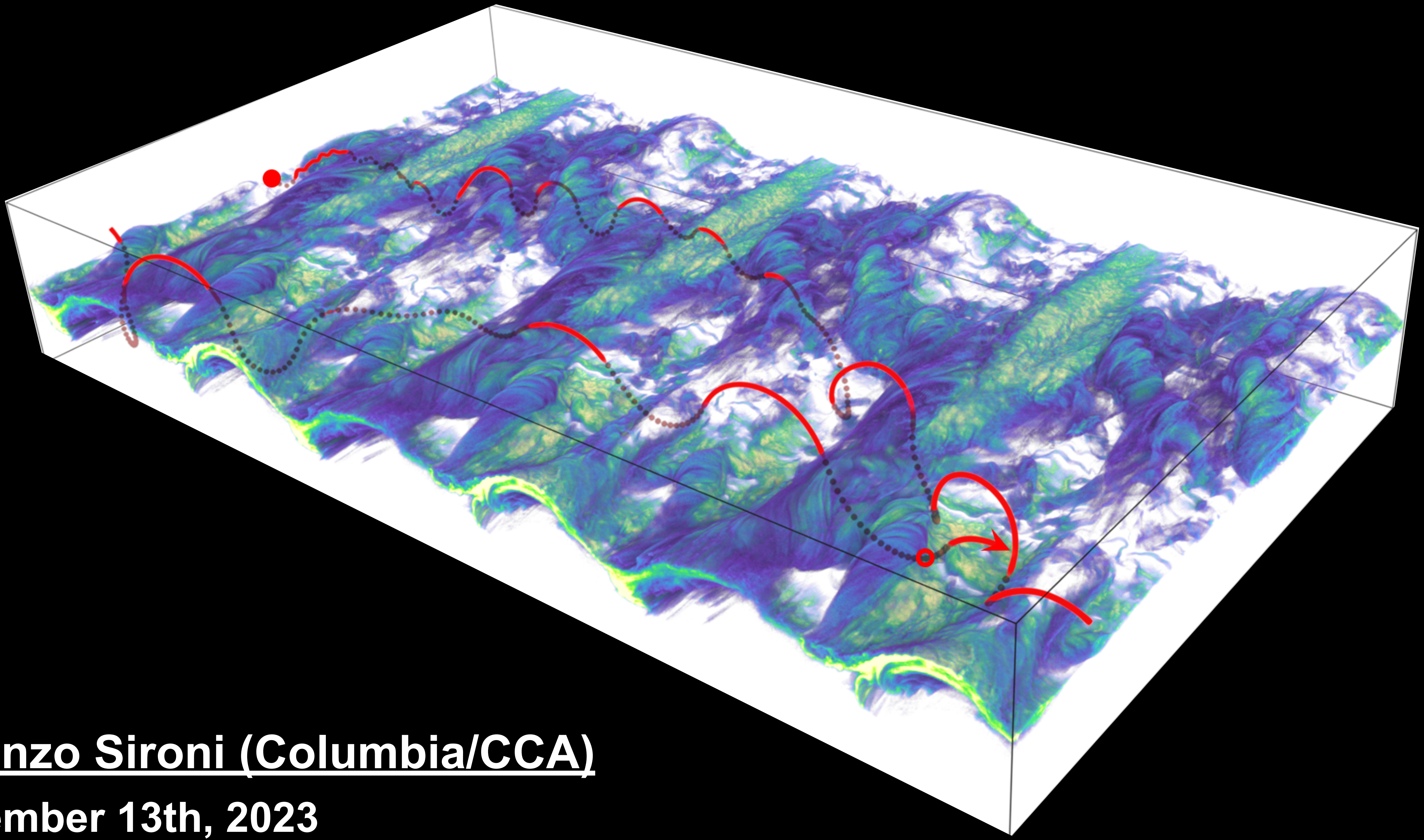
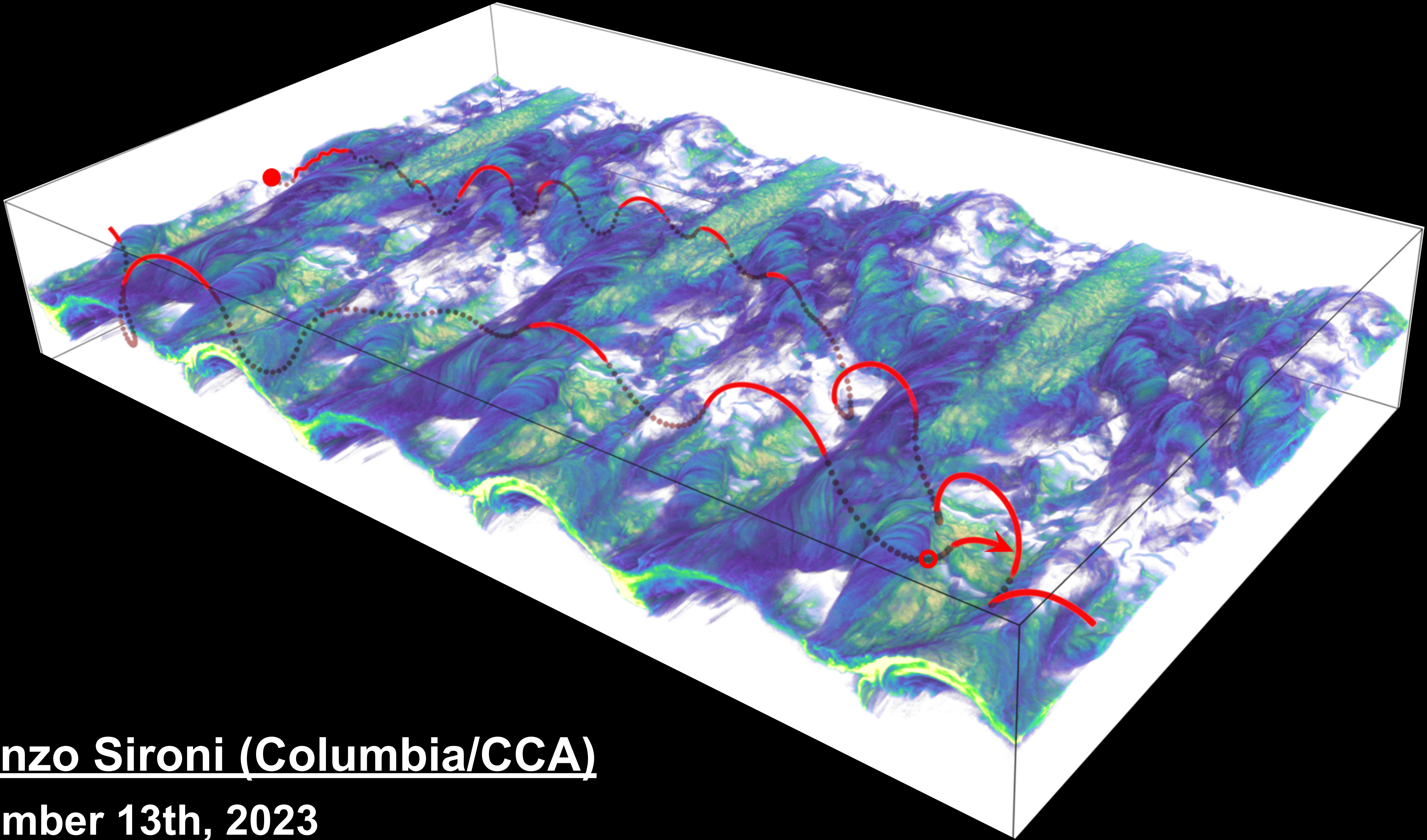
Particle acceleration in BH jets and coronae



Lorenzo Sironi (Columbia/CCA)

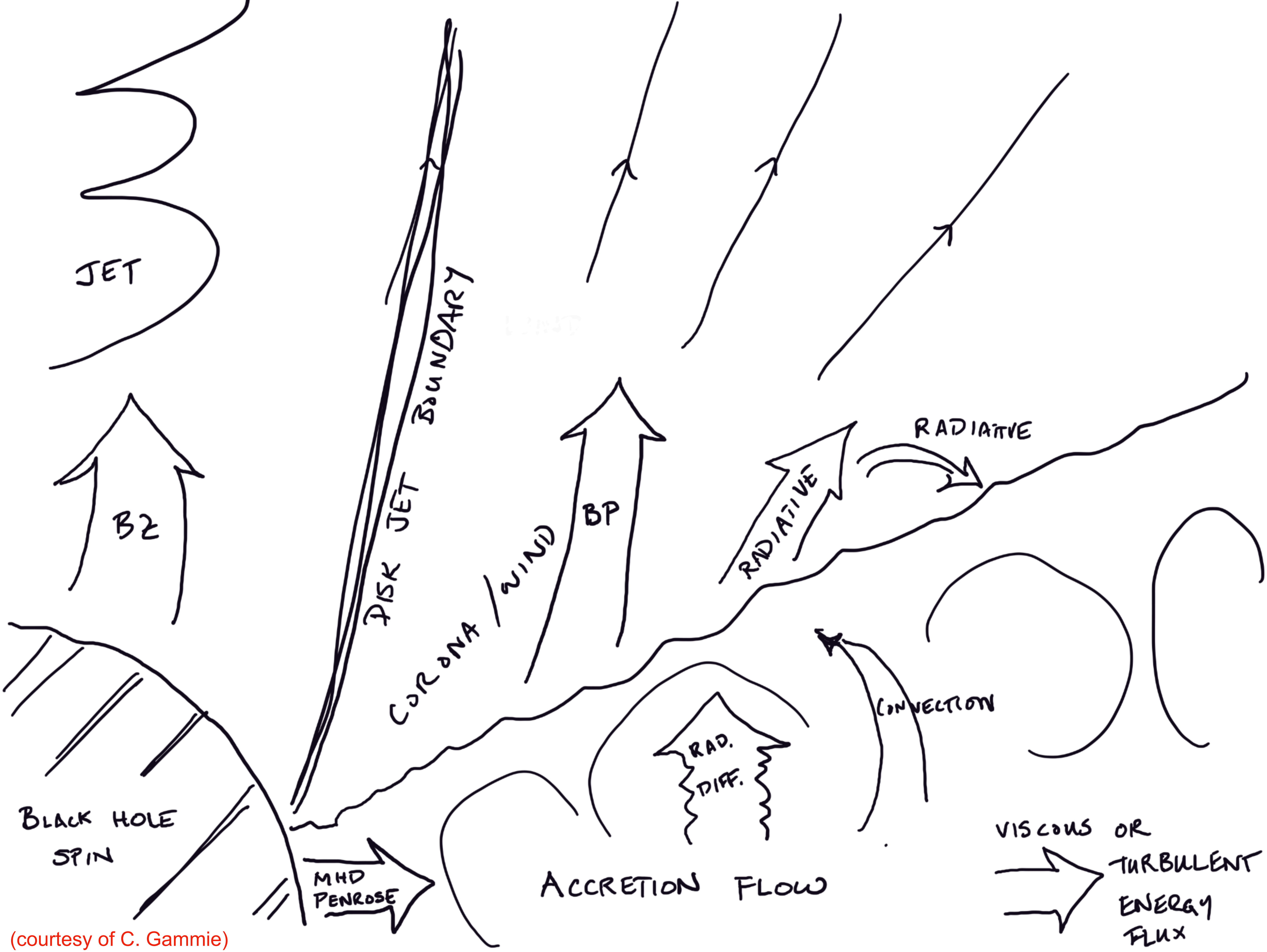
November 13th, 2023

[Some aspects of] particle acceleration in BH jets and coronae

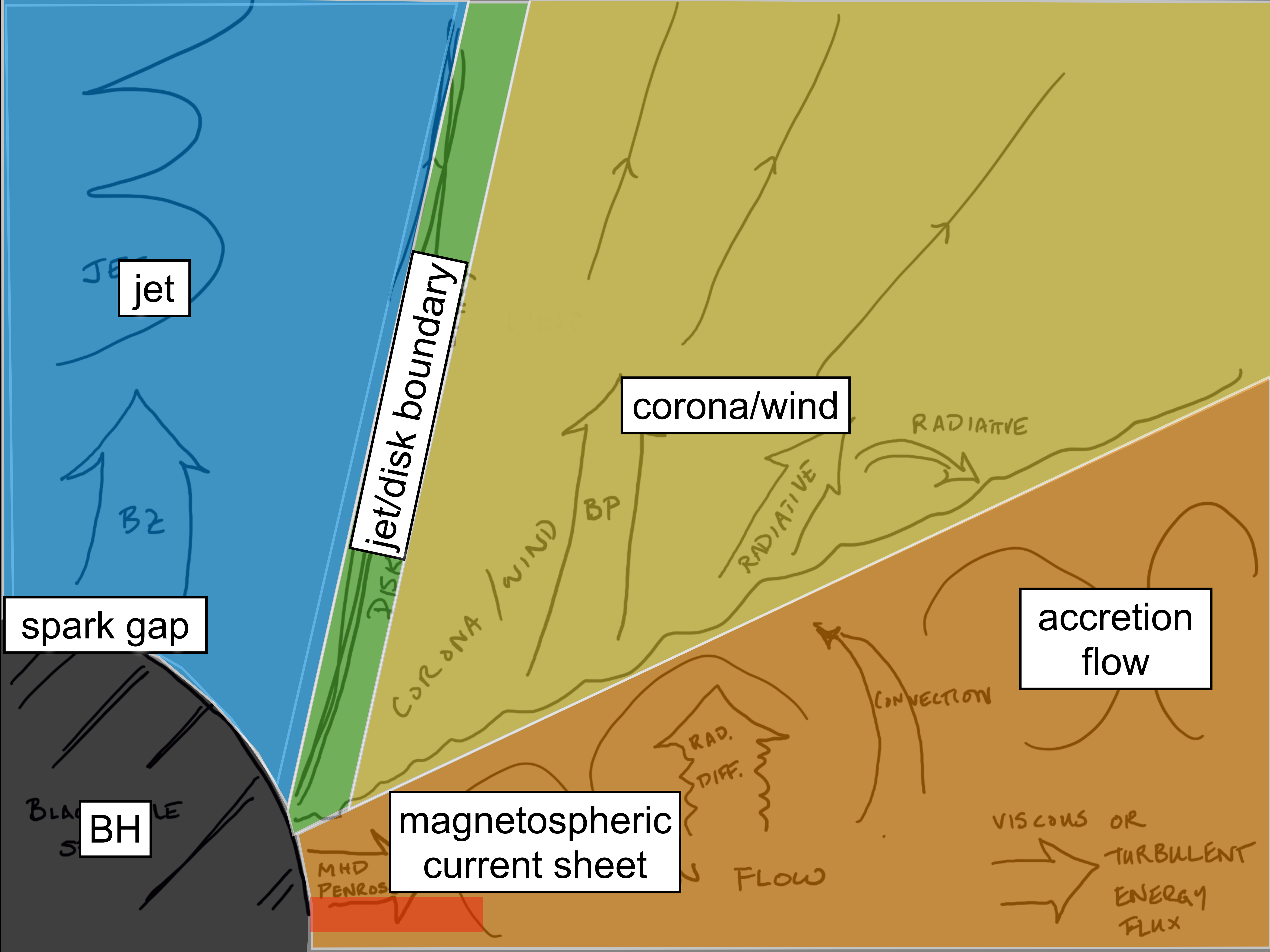


Lorenzo Sironi (Columbia/CCA)

November 13th, 2023



(courtesy of C. Gammie)



jet

jet/disk boundary

corona/wind

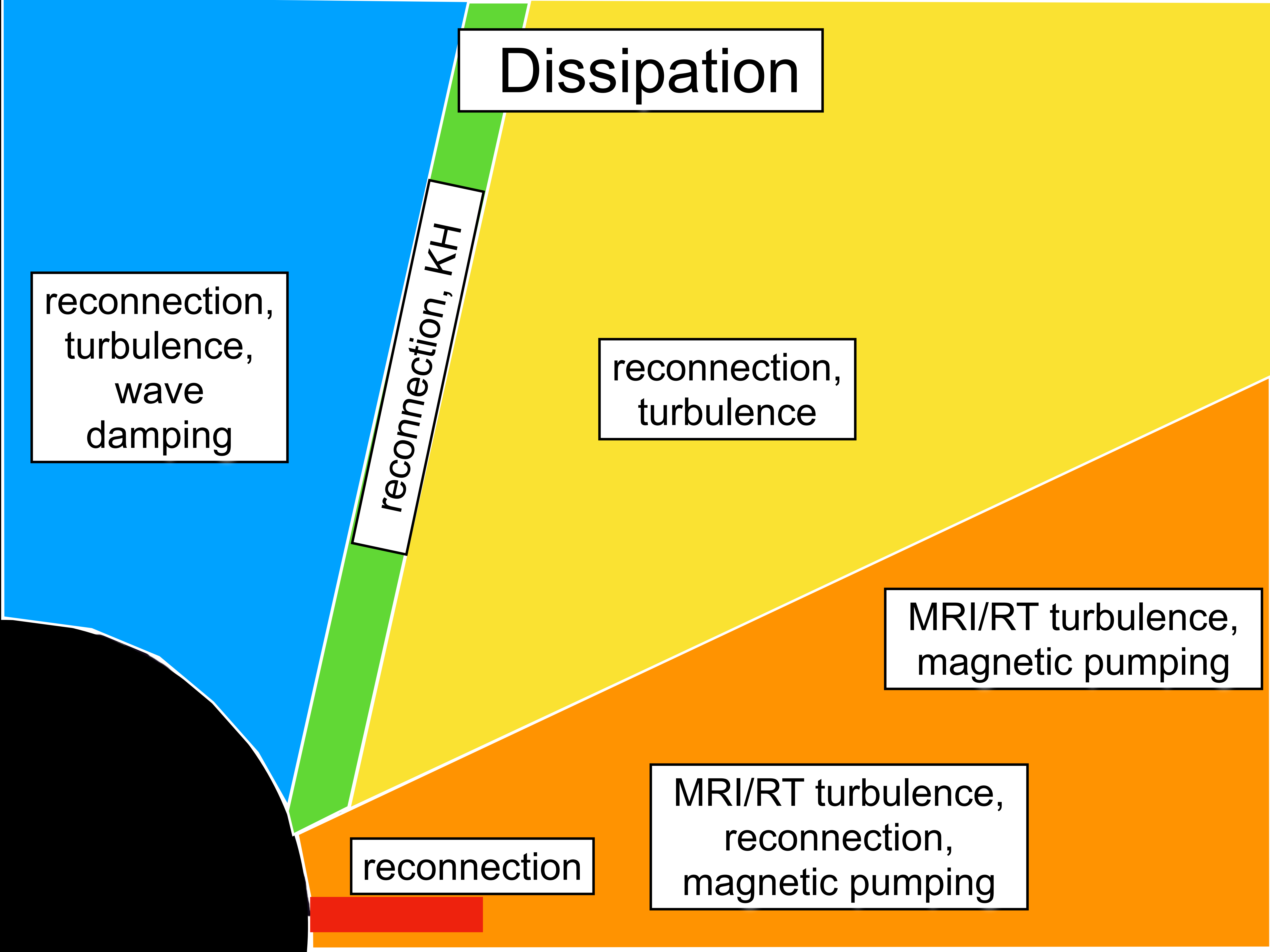
spark gap

accretion flow

BH

magnetospheric current sheet

Dissipation



reconnection, turbulence, wave damping

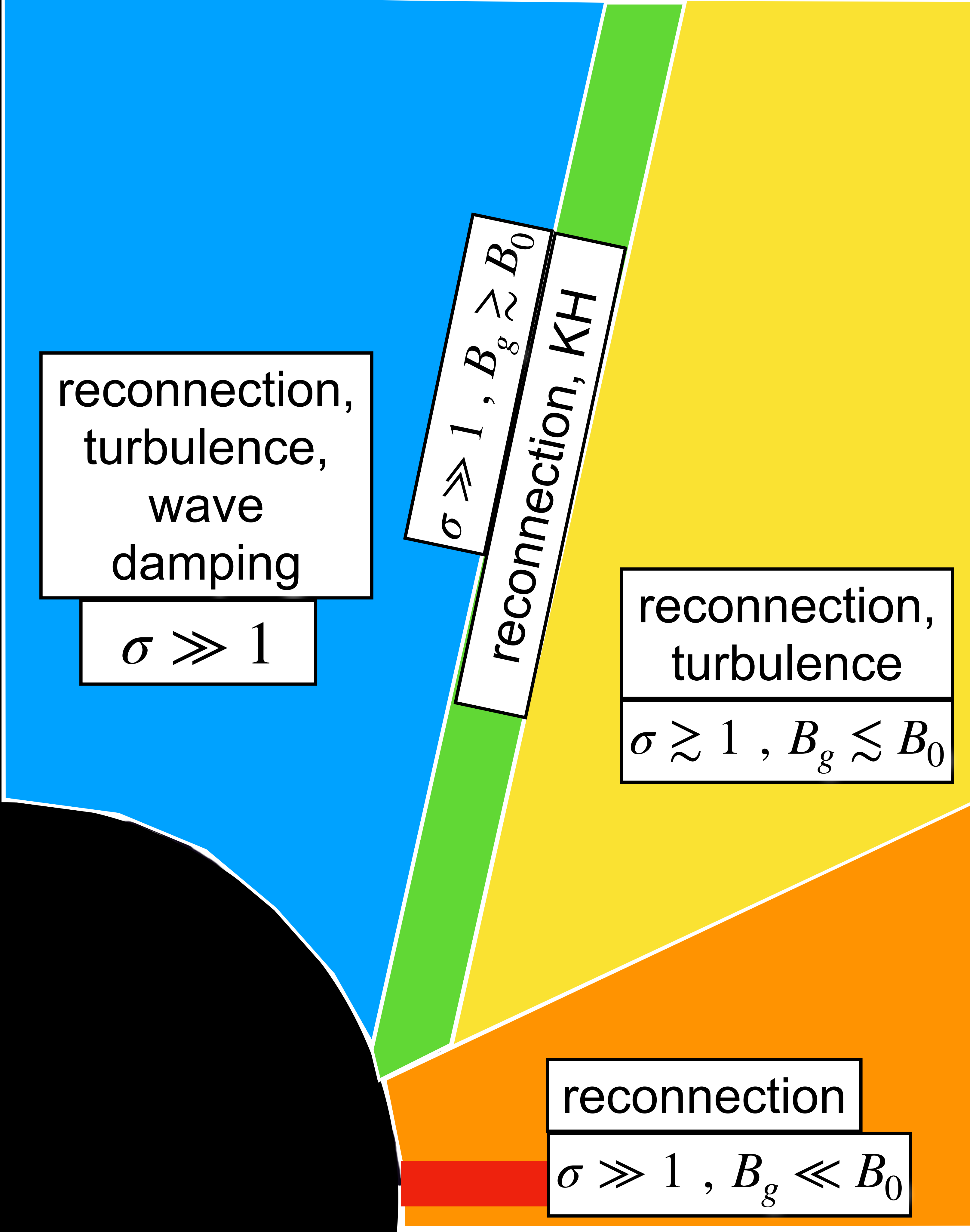
reconnection, KH

reconnection, turbulence

MRI/RT turbulence, magnetic pumping

reconnection

MRI/RT turbulence, reconnection, magnetic pumping



reconnection, turbulence, wave damping

$\sigma \gg 1$

$\sigma \gg 1$, $B_g \gtrsim B_0$

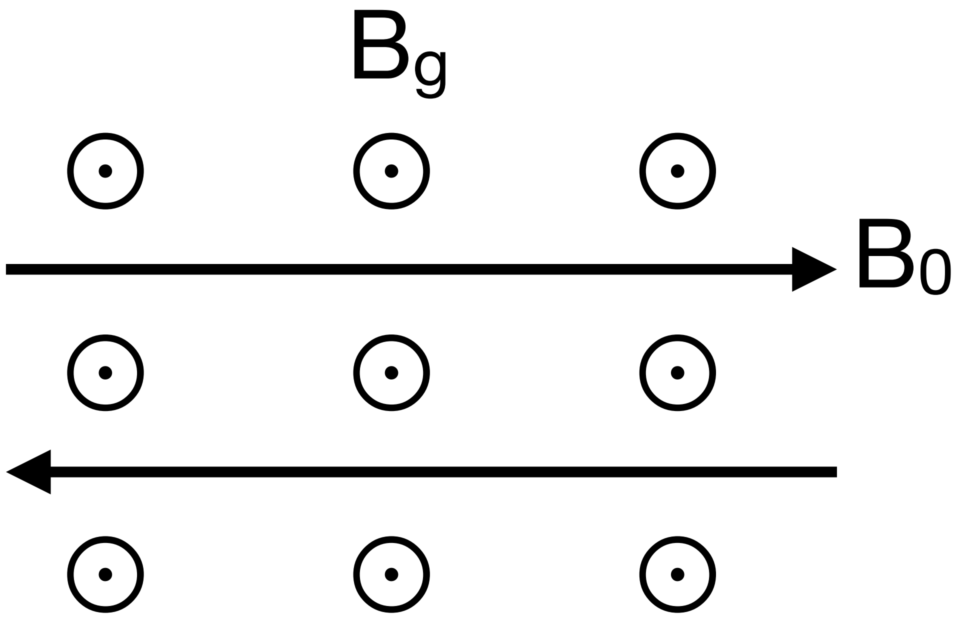
reconnection, KH

reconnection, turbulence

$\sigma \gtrsim 1$, $B_g \lesssim B_0$

reconnection

$\sigma \gg 1$, $B_g \ll B_0$



Key parameters:

- magnetization

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

- “guide” field B_g

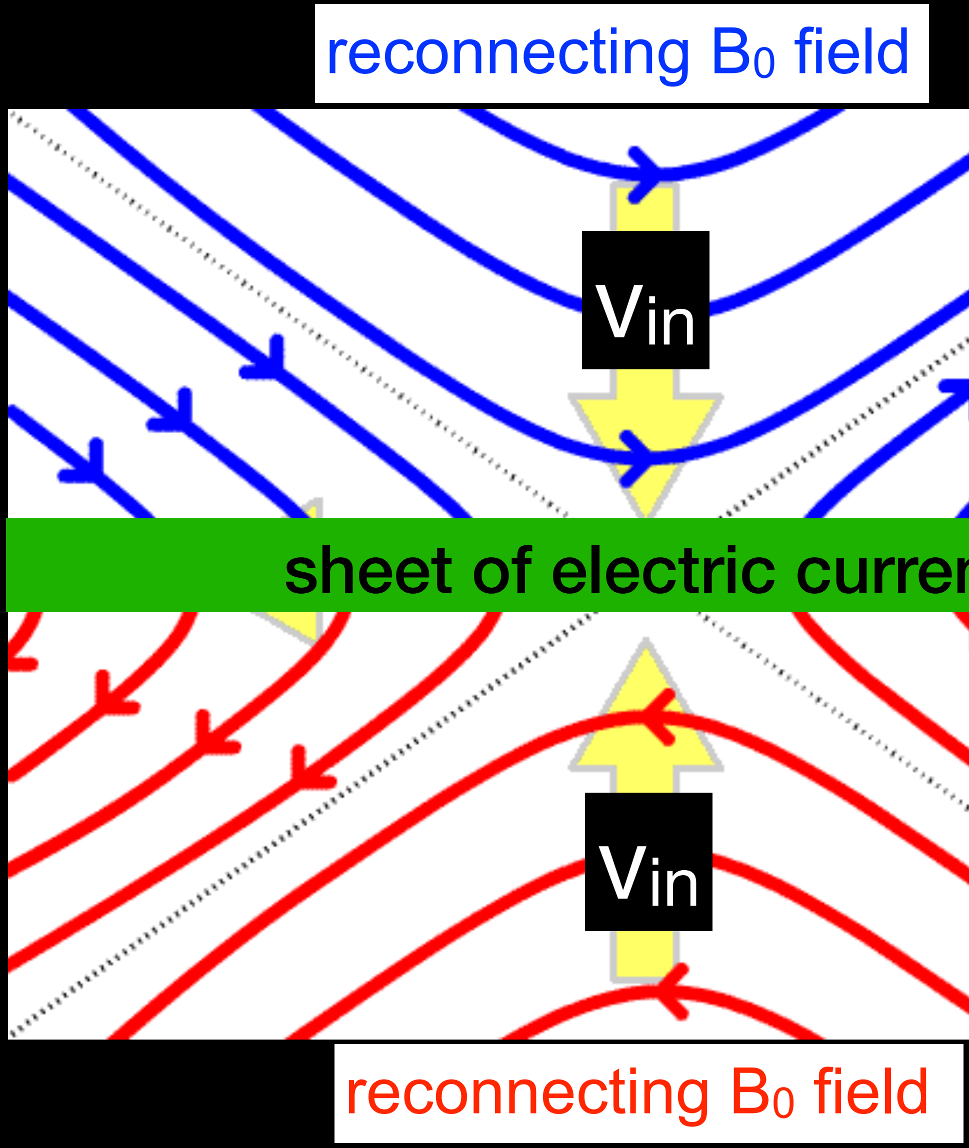
  (out-of-plane).

- $\beta = P_{\text{gas}}/P_B \ll 1.$

Relativistic reconnection

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

$$v_A \sim c$$



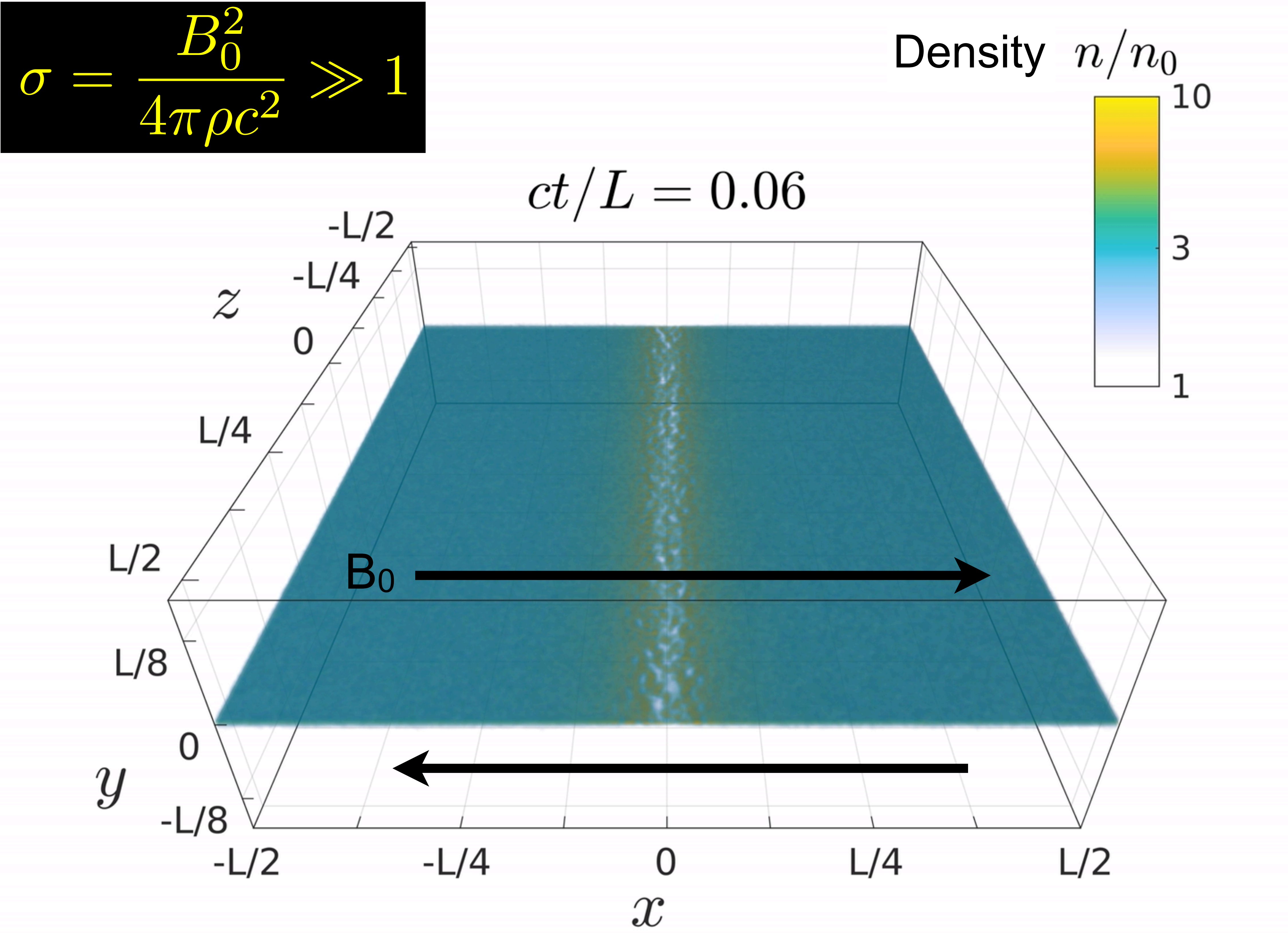
- The plasma flows into the reconnection region with $\frac{v_{\rm in}}{v_A} = \frac{E_{\rm rec}}{B_0} \sim 0.1$

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

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

3D 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, ApJL, 956, L36

LS 2022, PRL, 128, 145102

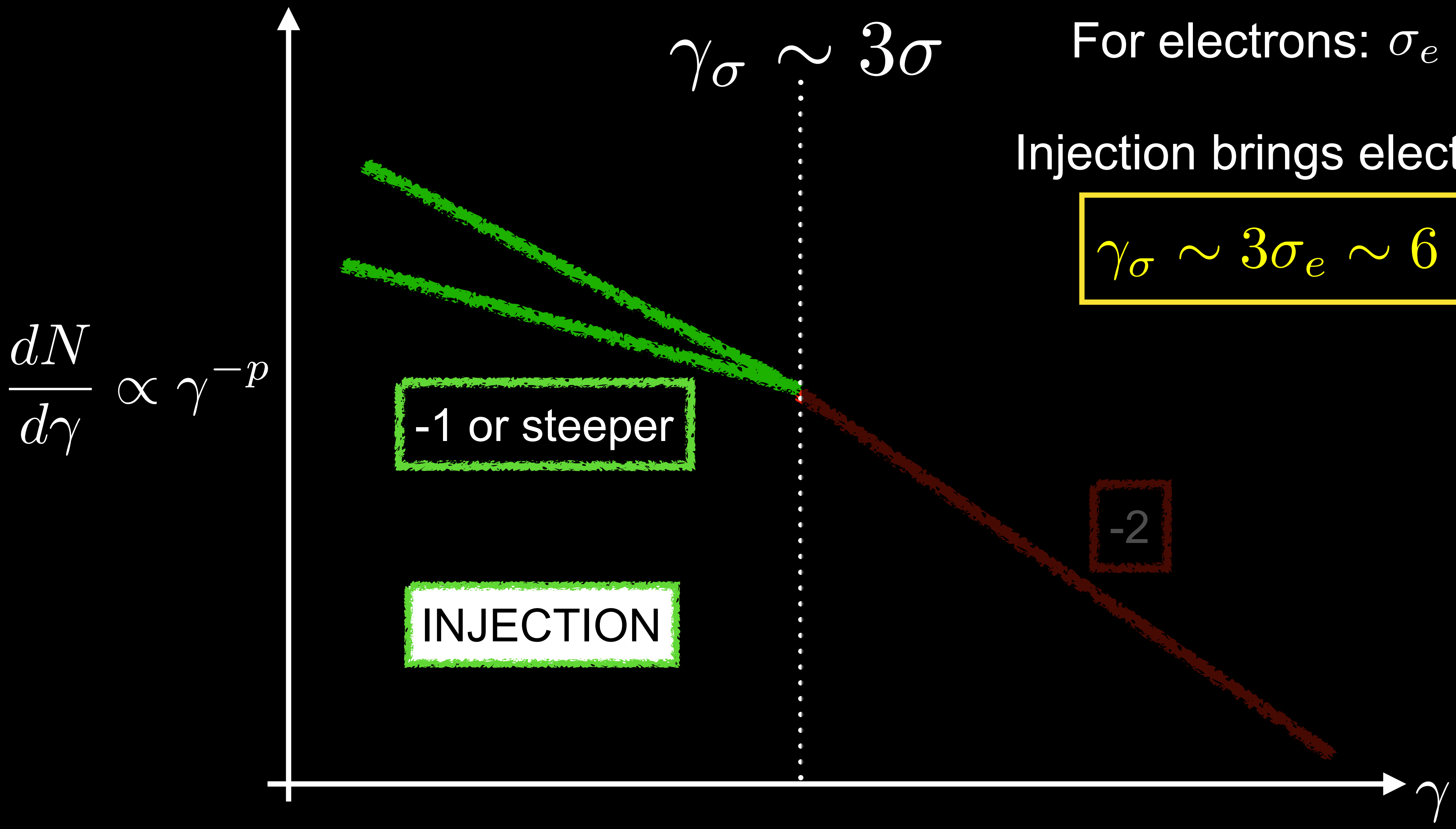
Zhang, LS & Giannios 2021, ApJ, 922, 261

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 $p \gtrsim 1$.

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

Particle injection: from $\gamma \sim 1$ to $\gamma \sim 3\sigma$

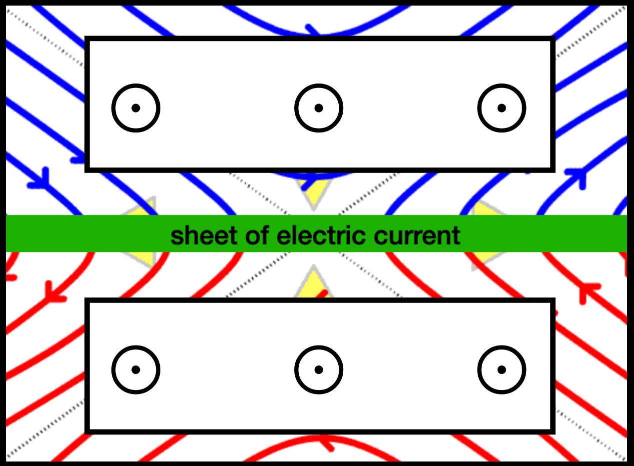
Particles are injected if they interact with non-ideal fields $\mathbf{E} \neq -\frac{\mathbf{v}}{c} \times \mathbf{B}$

$$\boxed{E > B}$$

for weak $\boxed{B_g}$

$$\boxed{E_{\parallel} = \mathbf{E} \cdot \mathbf{B}/B}$$

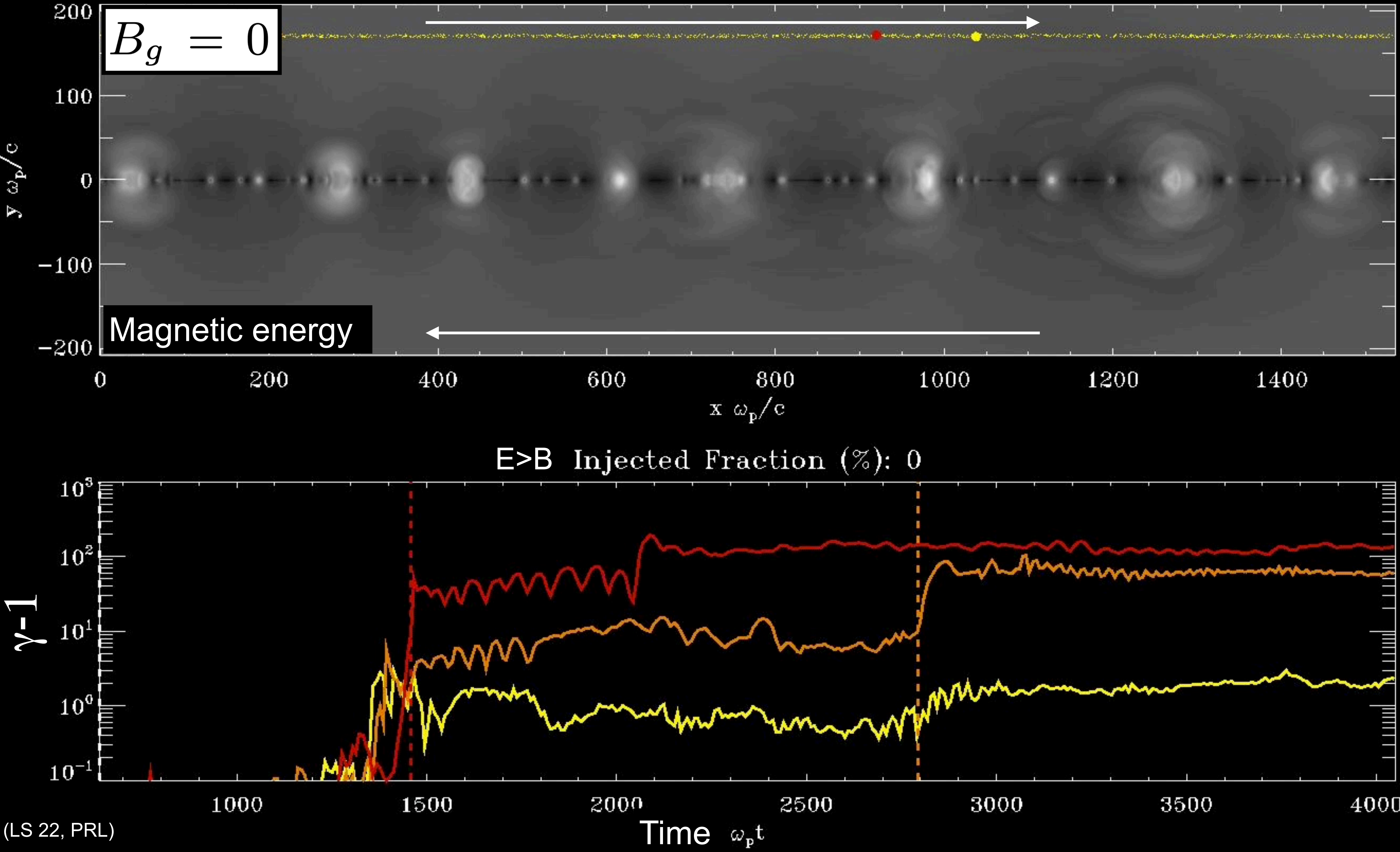
for strong $\boxed{B_g}$



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

Non-ideal fields are essential for injection

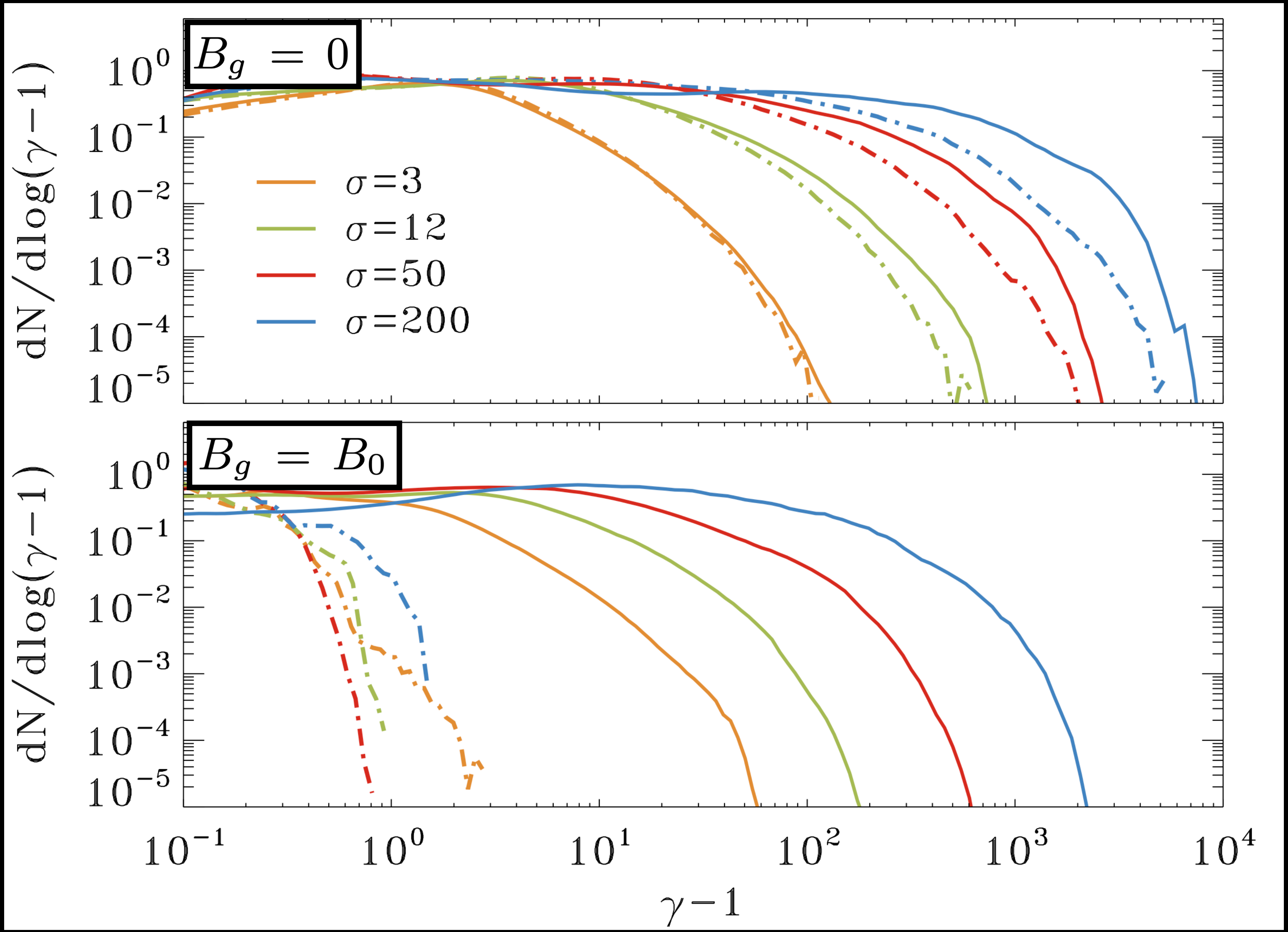
Particles are injected if they interact with <u>non-ideal fields</u> $\mathbf{E} \neq -\frac{\mathbf{v}}{c} \times \mathbf{B}$



(LS 22, PRL)

How to kill particle injection?

Testparticles: like regular particles, but they do not contribute to the current.



Solid: regular particles

Dot-dashed: testparticles whose energy is kept <u>fixed</u> while in E>B regions.

Solid: regular particles

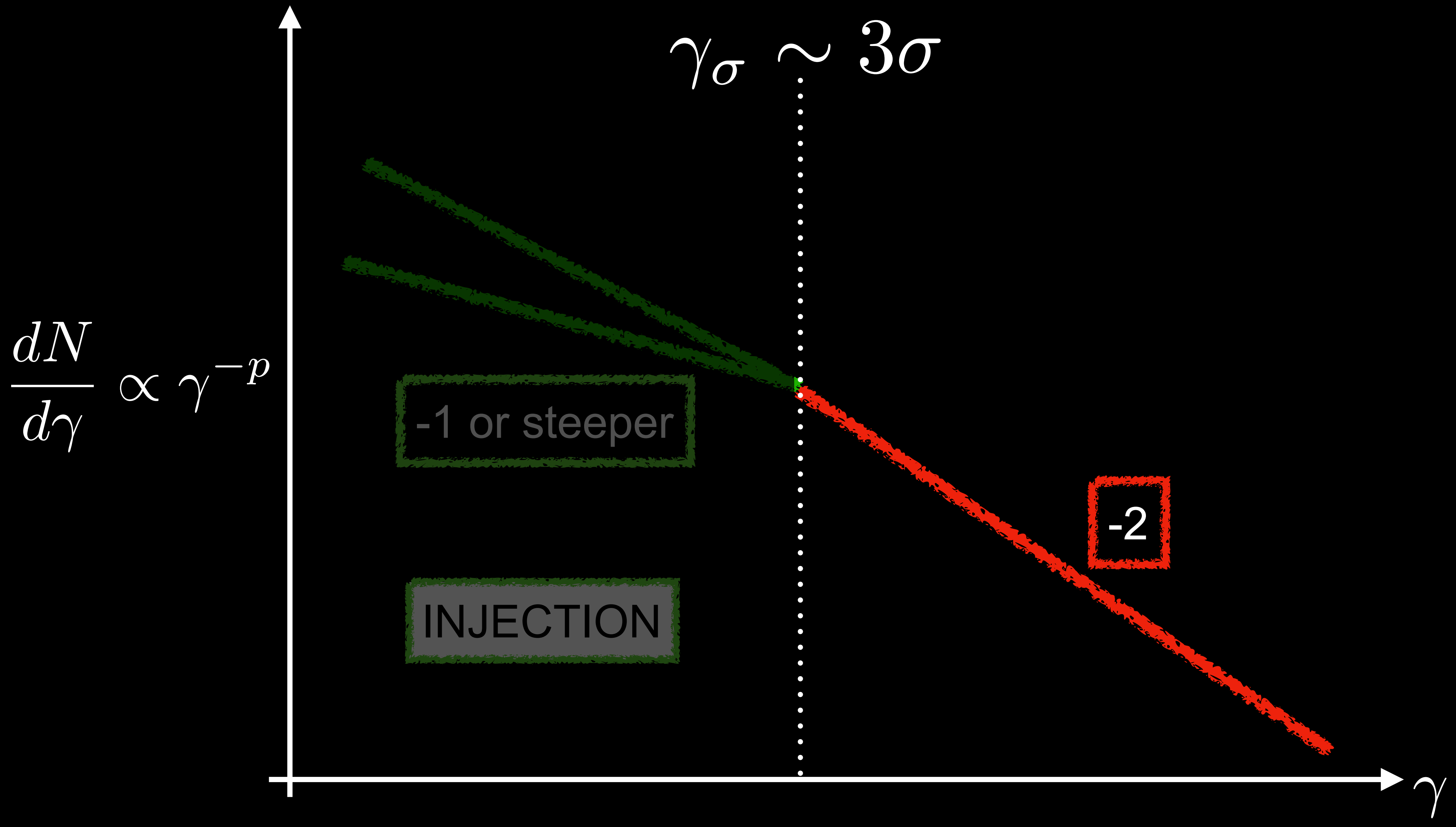
Dot-dashed: testparticles evolved without $E_{//}$

$$E_\parallel = \mathbf{E}\cdot\mathbf{B}/B$$

(LS 22, PRL)

⇒ Injection by non-ideal fields is a <u>necessary prerequisite</u> for further acceleration.

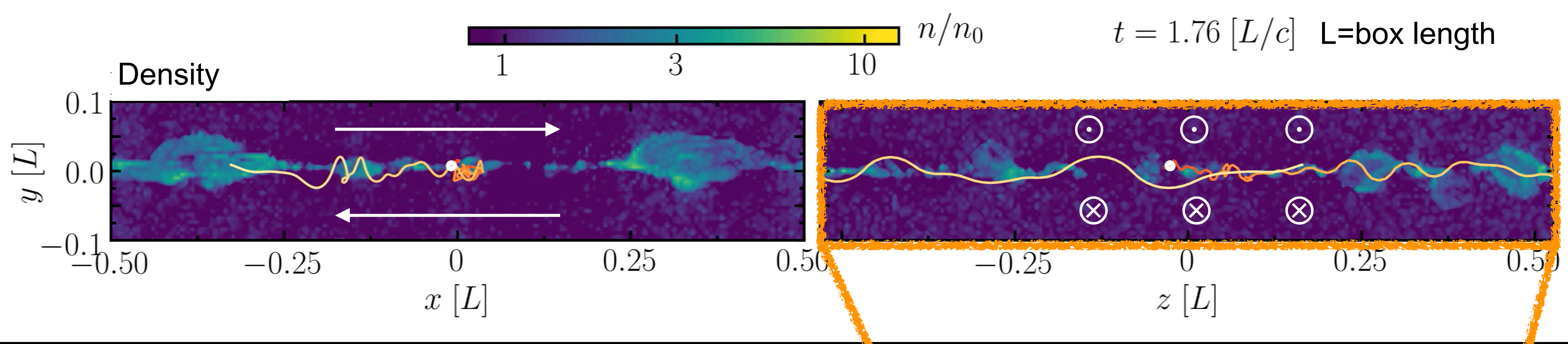
Reconnection makes broken power laws

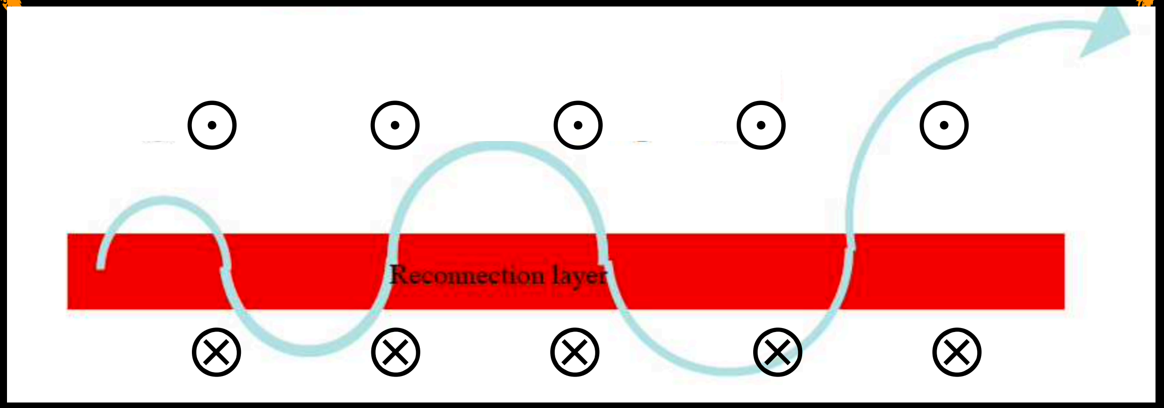


At $\gamma \lesssim 3\sigma$ “injection” in reconnection leads to σ-dependent slopes, with *p*≳*1*.

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

Particle acceleration to the highest energies

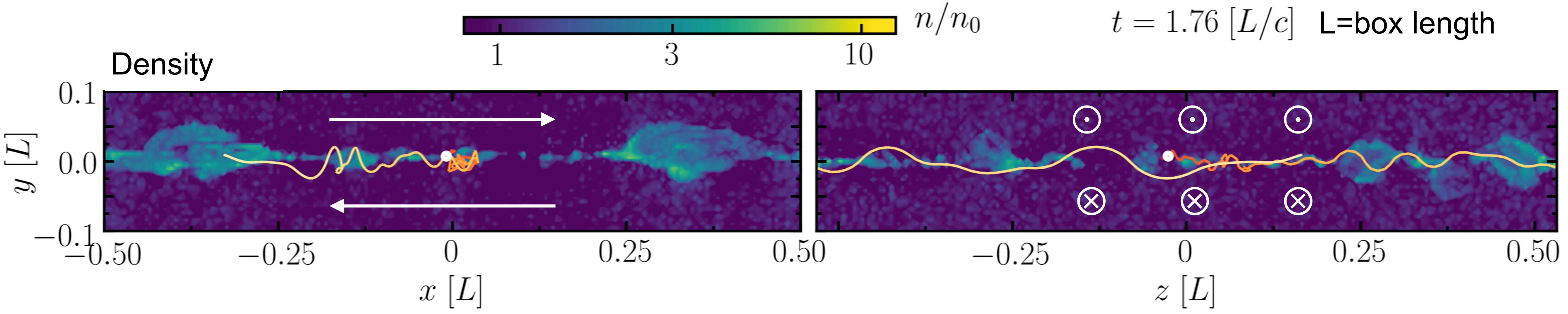




(Lazarian +12)

- In 3D, lucky particles escape from the reconnected plasma and swim “freestyle” around the reconnection layer.

Particle acceleration to the highest energies

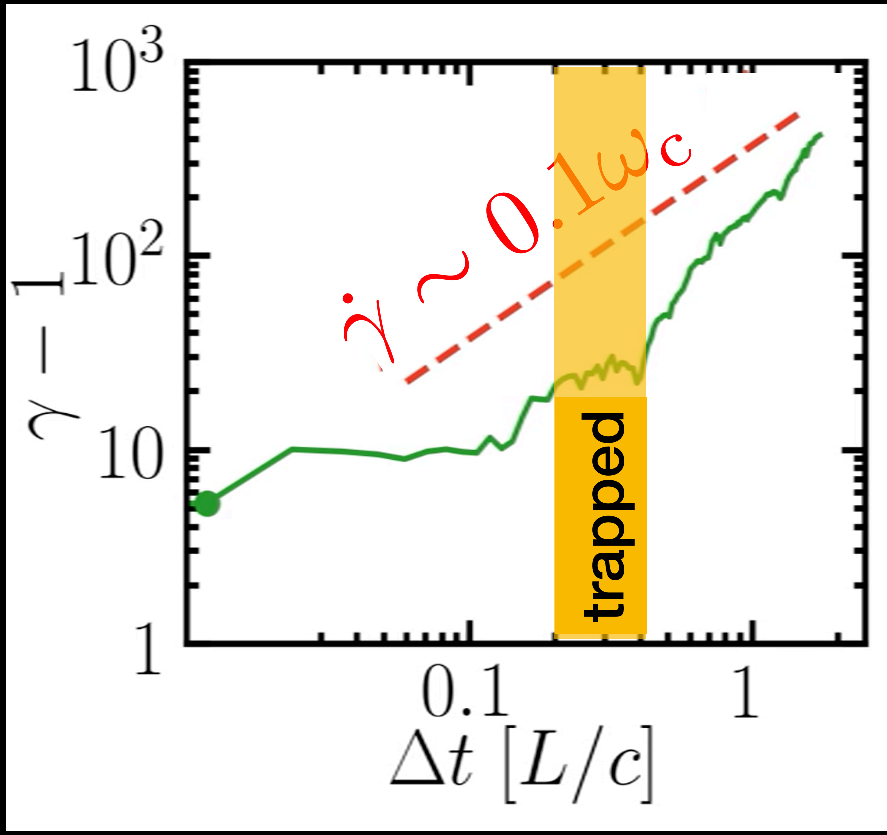


- In 3D, lucky particles escape from the reconnected plasma and swim “freestyle” around the reconnection layer.

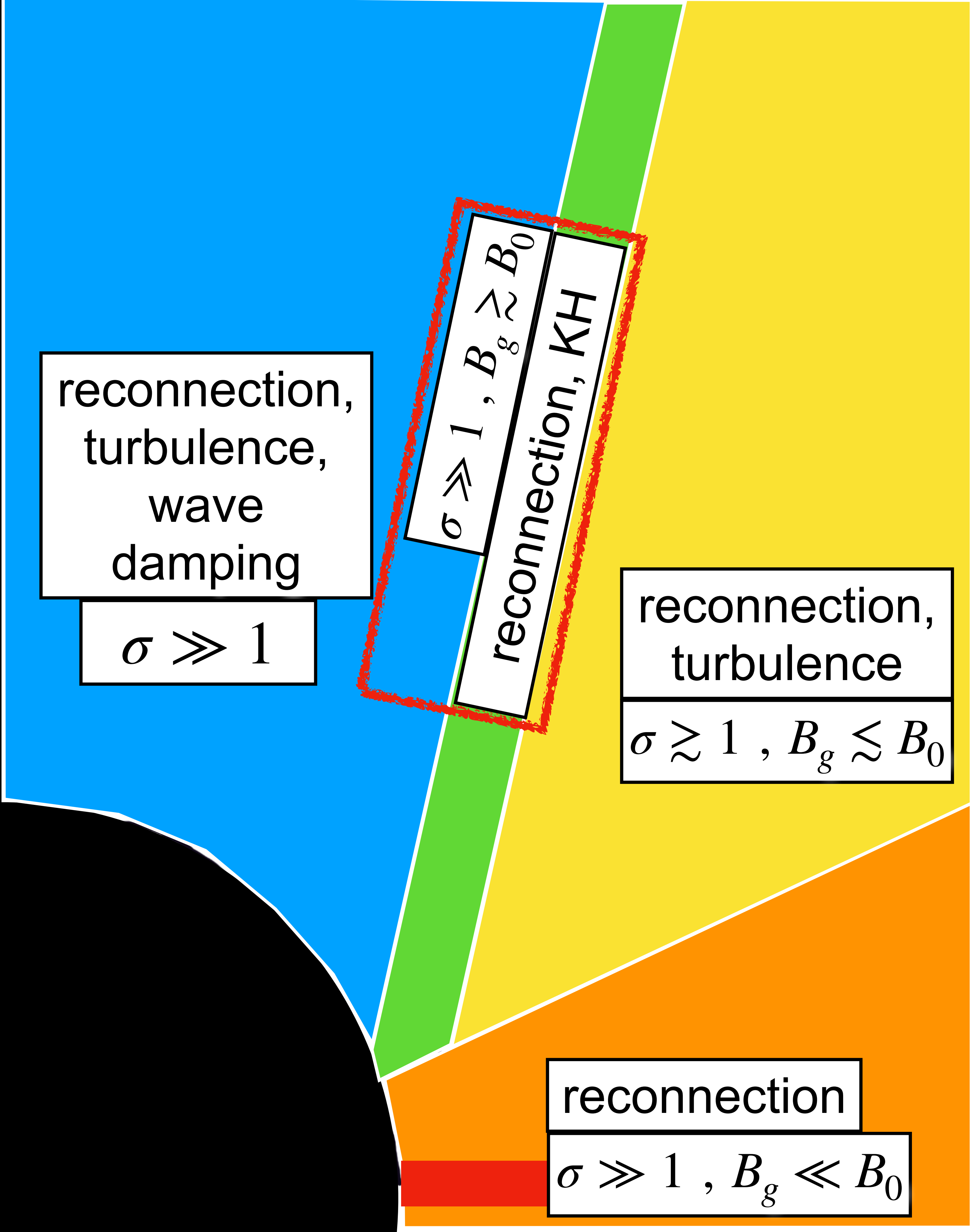
- They get accelerated linearly in time by the large-scale ideal electric field in the inflow region.

- The energy gain rate approaches $\sim eE_{\mathrm{rec}}c$

$$\sim 0.1eB_0c$$



(Zhang, LS, Giannios 21, 23; Chernoglazov+ 23)



reconnection, turbulence, wave damping

$\sigma \gg 1$

$\sigma \gg 1\ ,\ B_g \gtrsim B_0$

reconnection, KH

reconnection, turbulence

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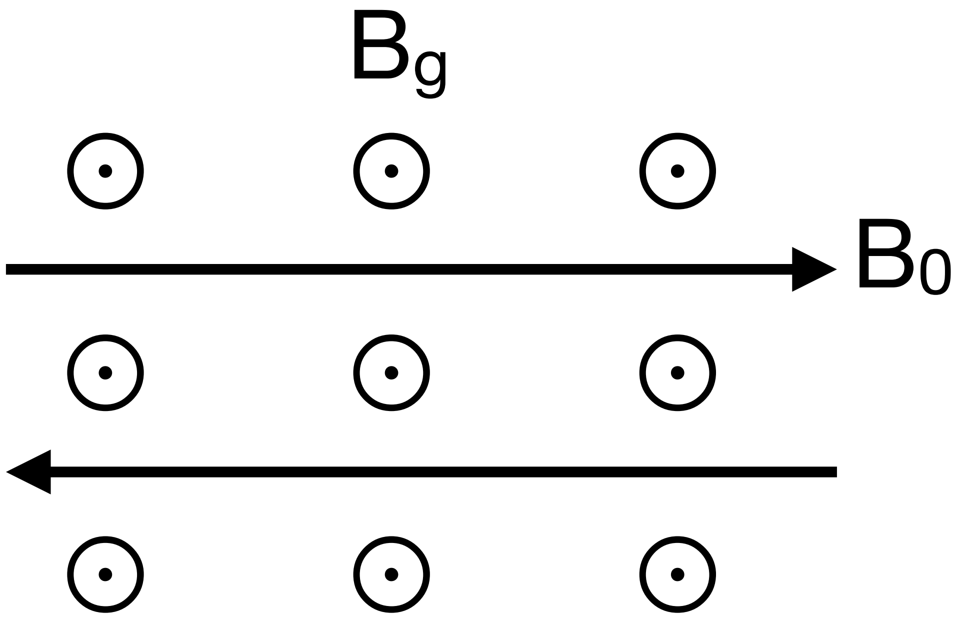
reconnection

$\sigma \gg 1\ ,\ B_g \ll B_0$



Key parameters:

- magnetization

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

- “guide” field B_g (out-of-plane).
- $\beta = P_{gas}/P_B \ll 1.$

Reconnection at jet boundaries

Davelaar et al. 2023, ApJL submitted, arXiv:2309.07963

Chow, Rowan, LS et al. 2023, MNRAS, 524, 90

Chow, Davelaar, Rowan & LS 2023, ApJL, 951, L23

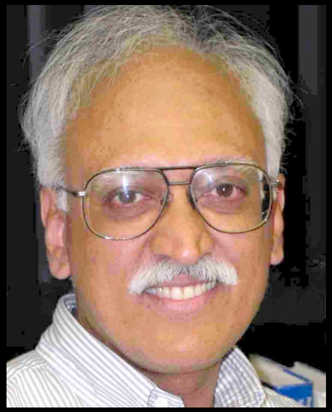
LS, Rowan & Narayan 2021, ApJL, 907, L44

A. Chow

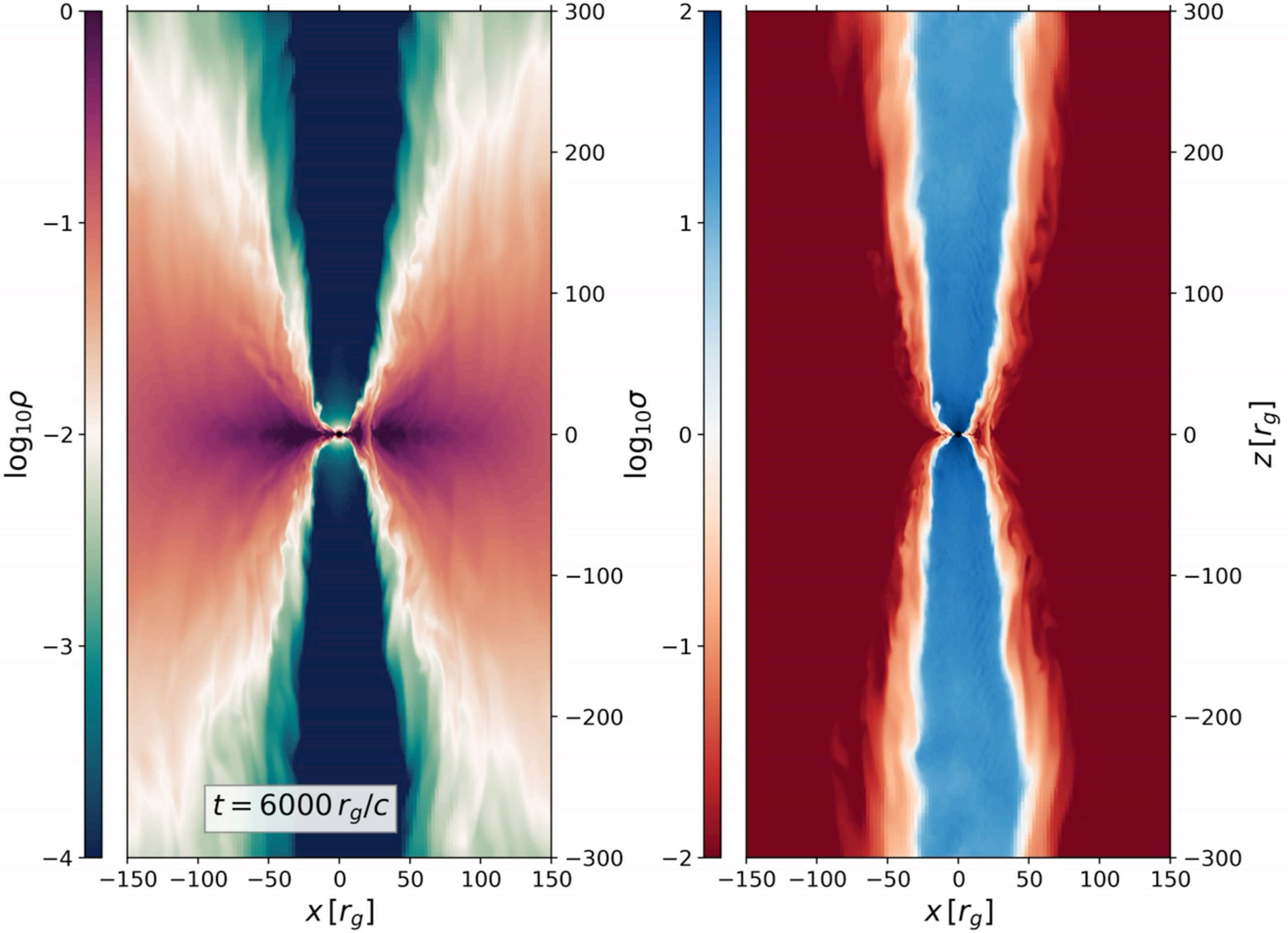
M. Rowan

J. Davelaar

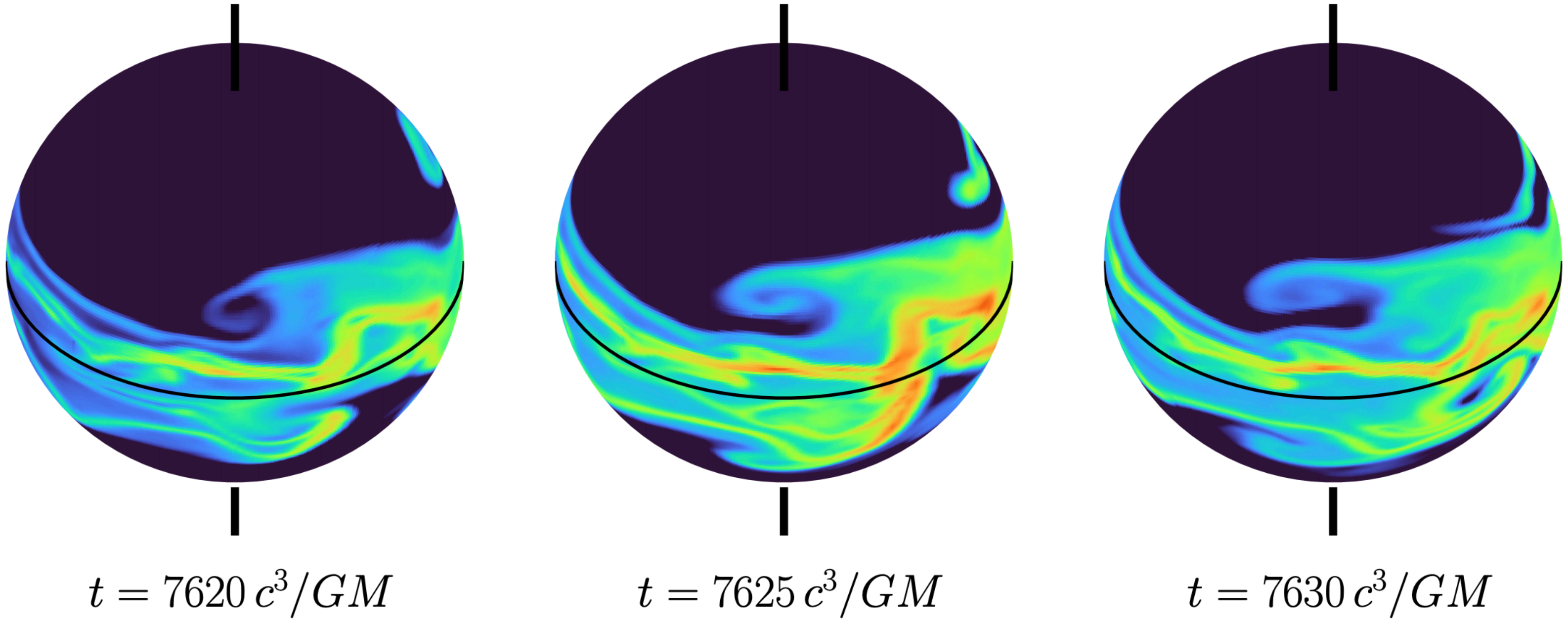
R. Narayan



Kelvin-Helmholtz (KH)-like vortices at the jet boundary

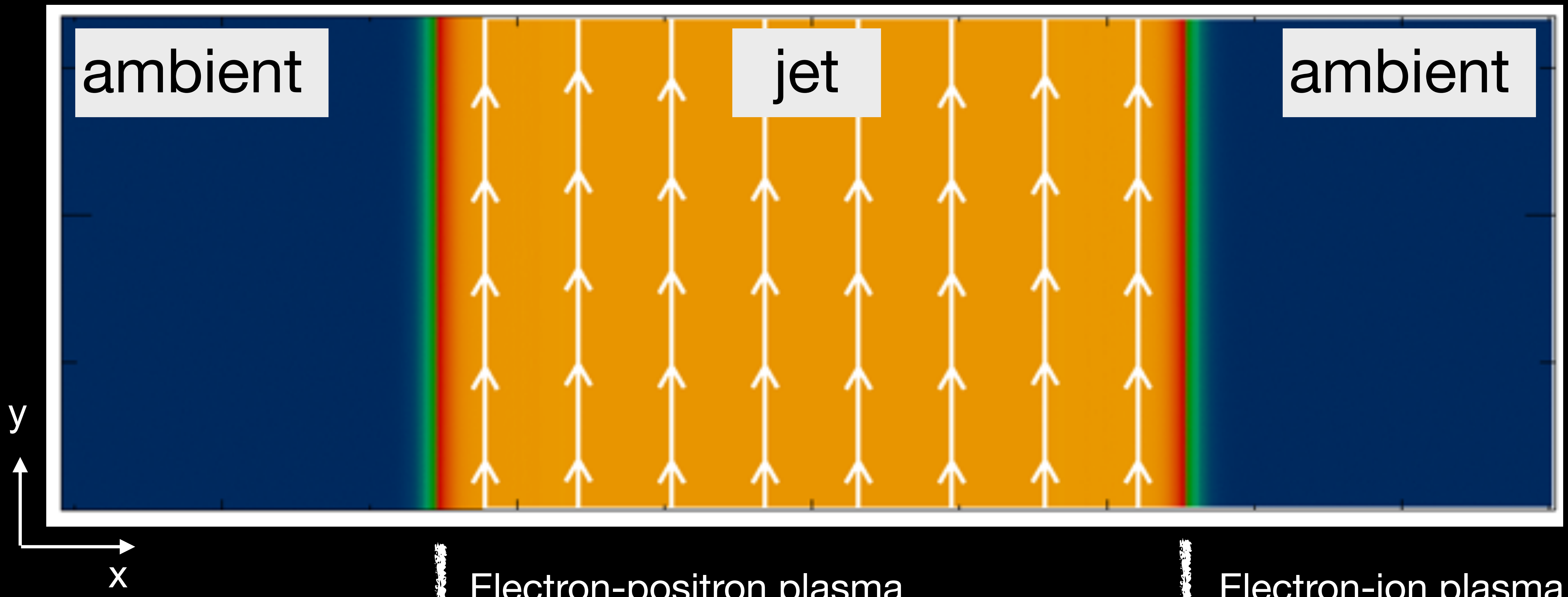


(Davelaar+ 23)


$t = 7620\, c^3/GM$ $t = 7625\, c^3/GM$ $t = 7630\, c^3/GM$

(Wong+ 21)

Local PIC setup



Electron-positron plasma

Ultra-relativistic bulk motion

Strong B_y (poloidal) and B_z (toroidal)

$$\sigma_{\mathrm{j},y} = B^2_{\mathrm{j},y}/(4\pi n_0 m_\mathrm{e} c^2) = 6.7$$

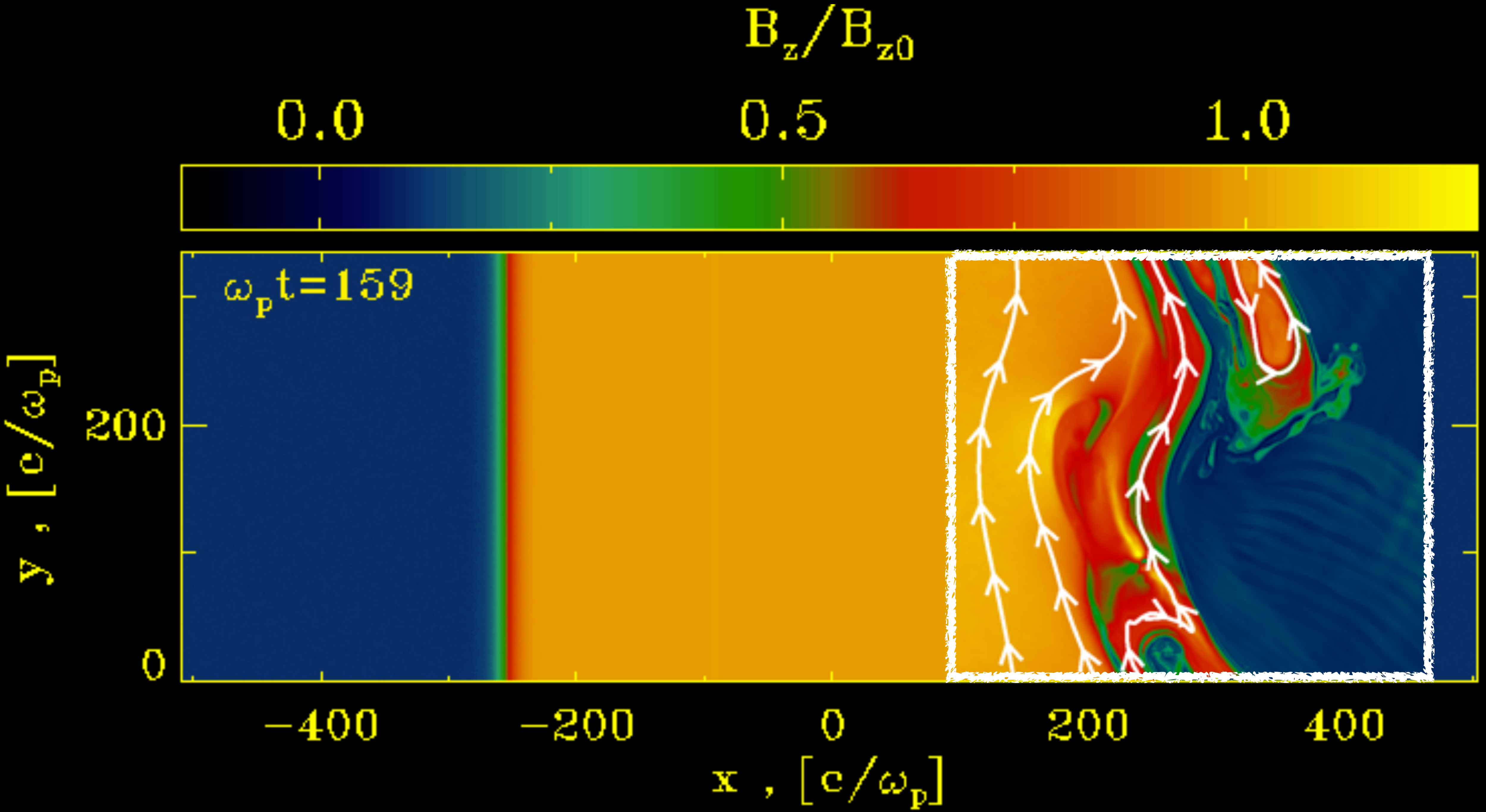
Field obliquity $\theta = 75^\circ$

Electron-ion plasma

Stationary

Plasma-pressure dominated, weak B_z

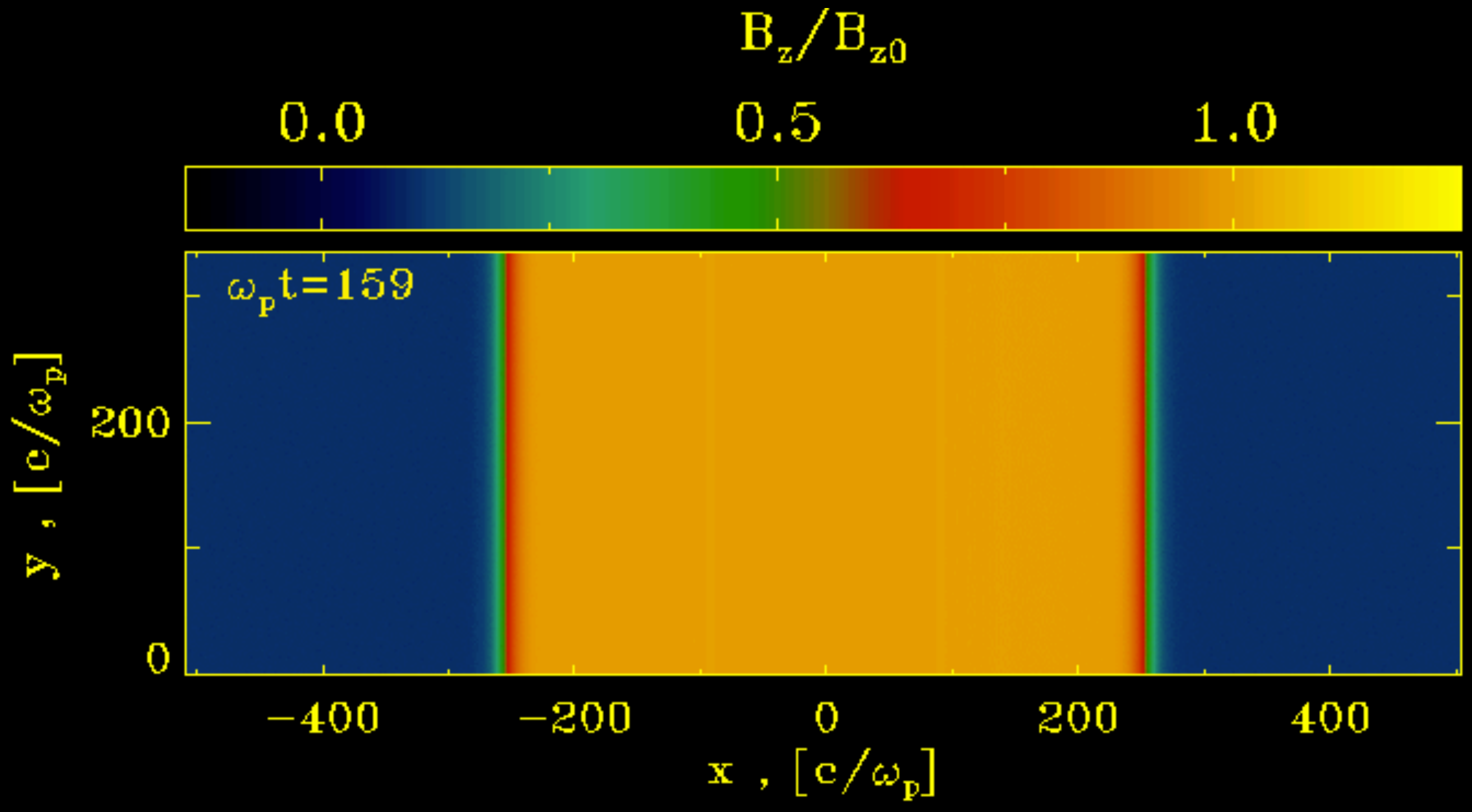
Kelvin-Helmholtz (KH) instability



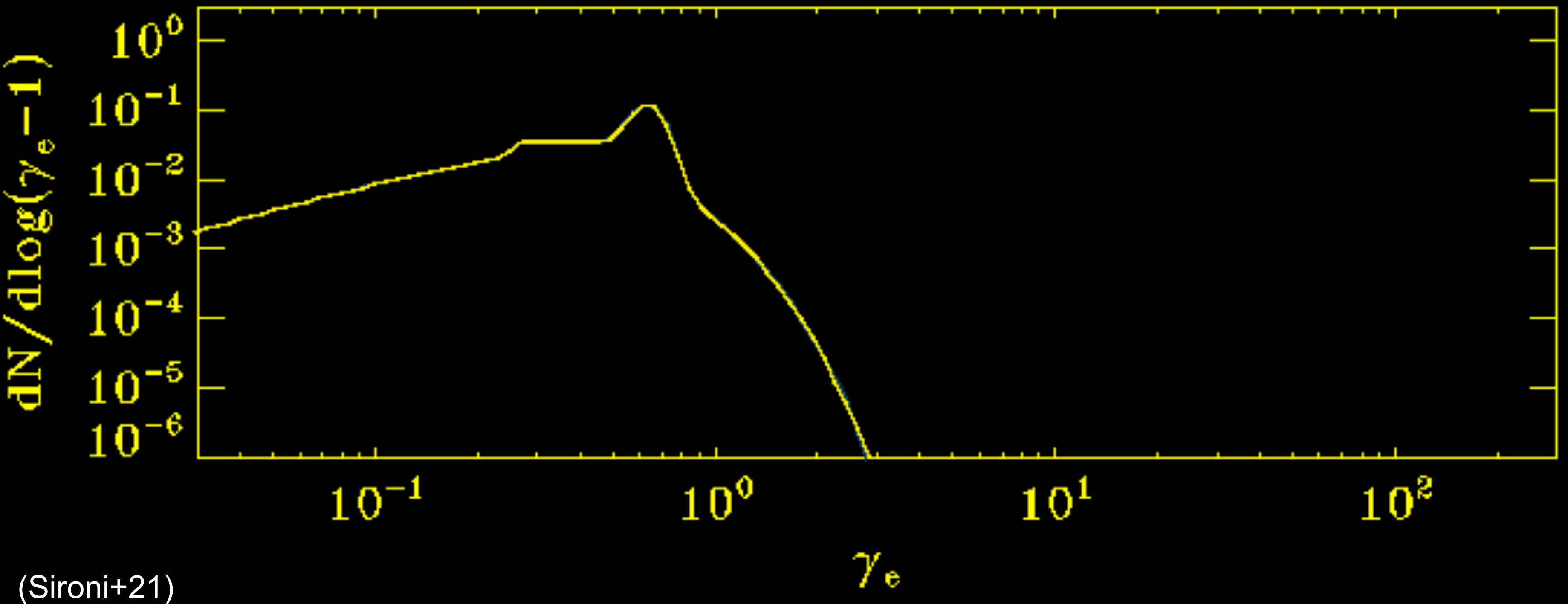
(Sironi+21)

- The linear and non-linear evolution is the same in PIC and resistive MHD (Chow+22).
- Reconnection is a natural by-product of the nonlinear KH evolution.
- Post reconnection, the jet boundary has trans-rel velocities and $\beta = P_{\rm gas}/P_B \sim 1$

KH → reconnection → particle acceleration



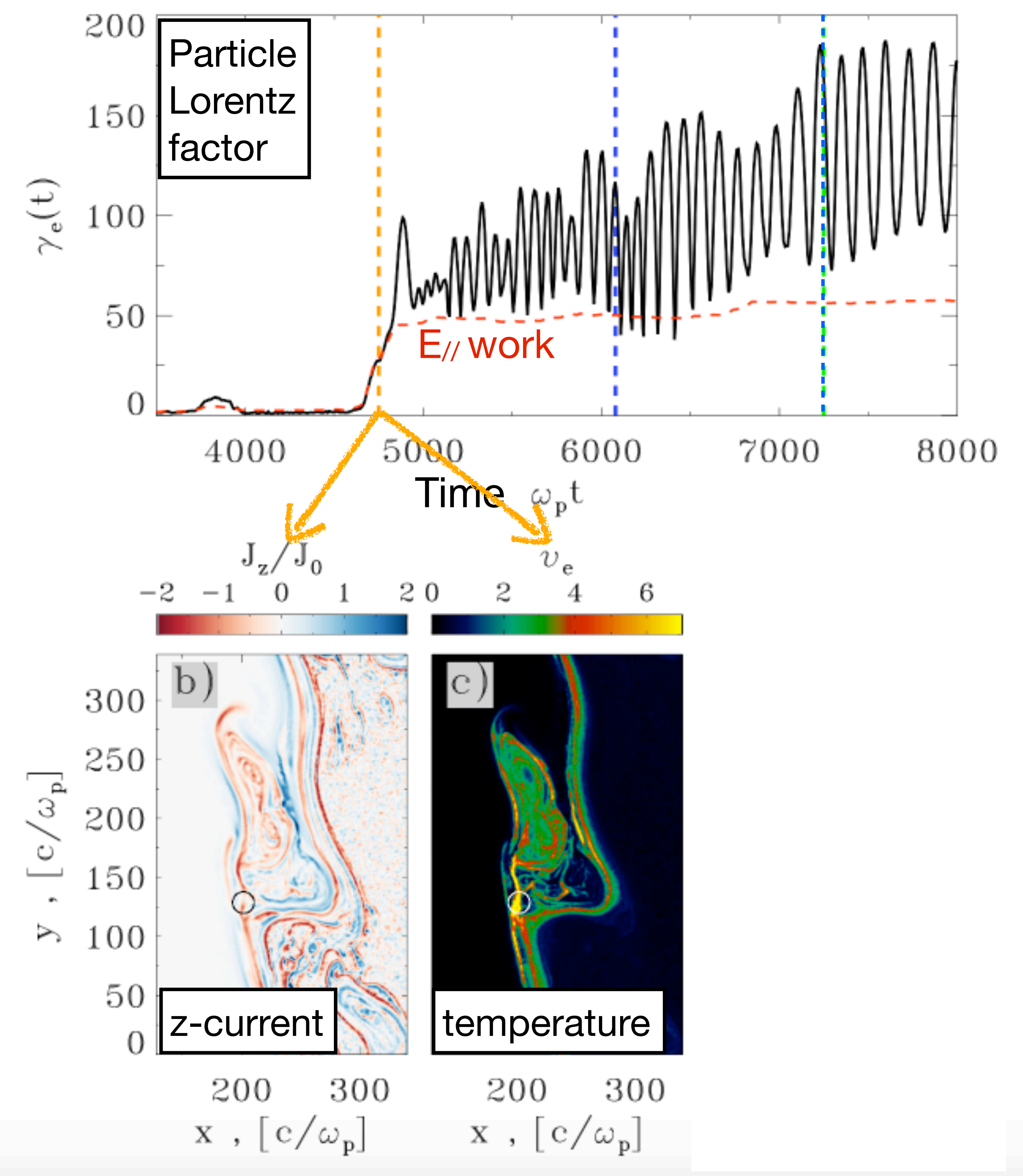
KH-driven reconnection leads to efficient particle acceleration.



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

(Sironi+21)

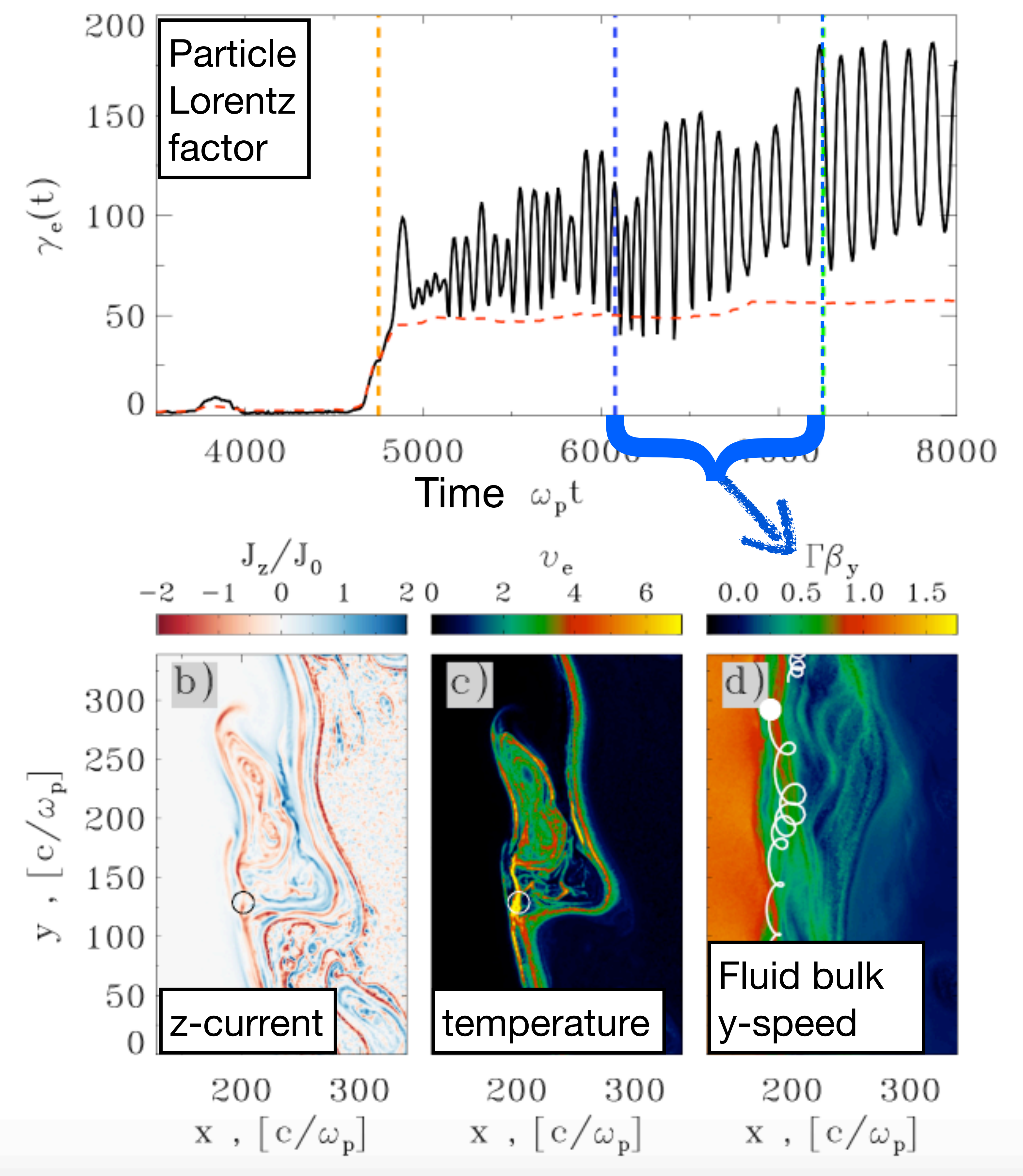
Two-stage particle acceleration



(1) The early acceleration stages (injection) up to $\gamma \sim \sigma$ are powered by $E_{//}$ at reconnection layers.

$$E_\parallel = \mathbf{E} \cdot \mathbf{B}/B$$

Two-stage particle acceleration



(1) The early acceleration stages (injection) up to $\gamma \sim \sigma$ are powered by $E_{//}$ at reconnection layers.

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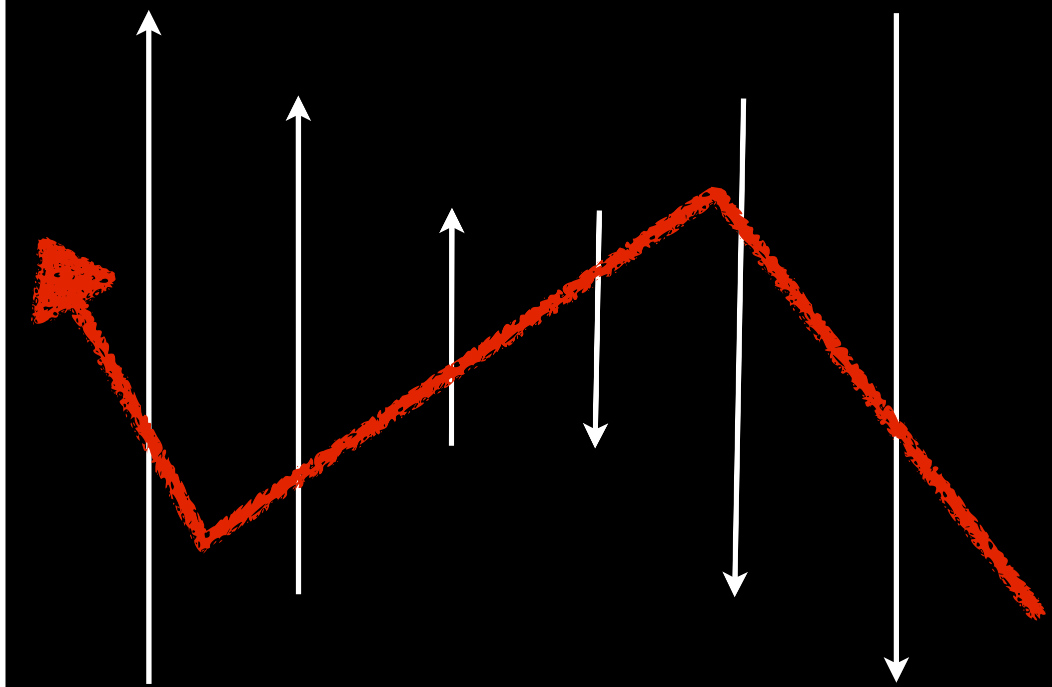
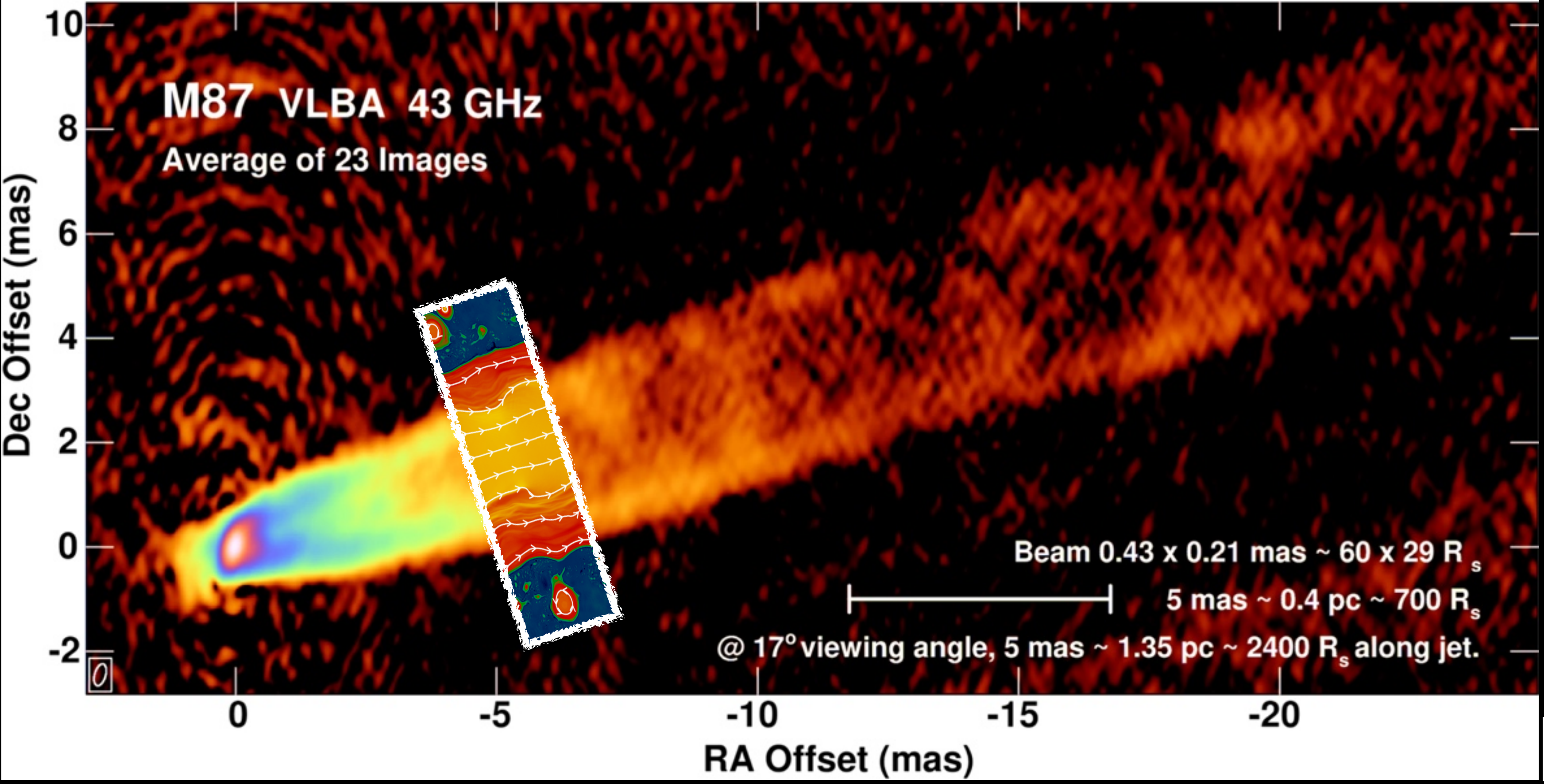
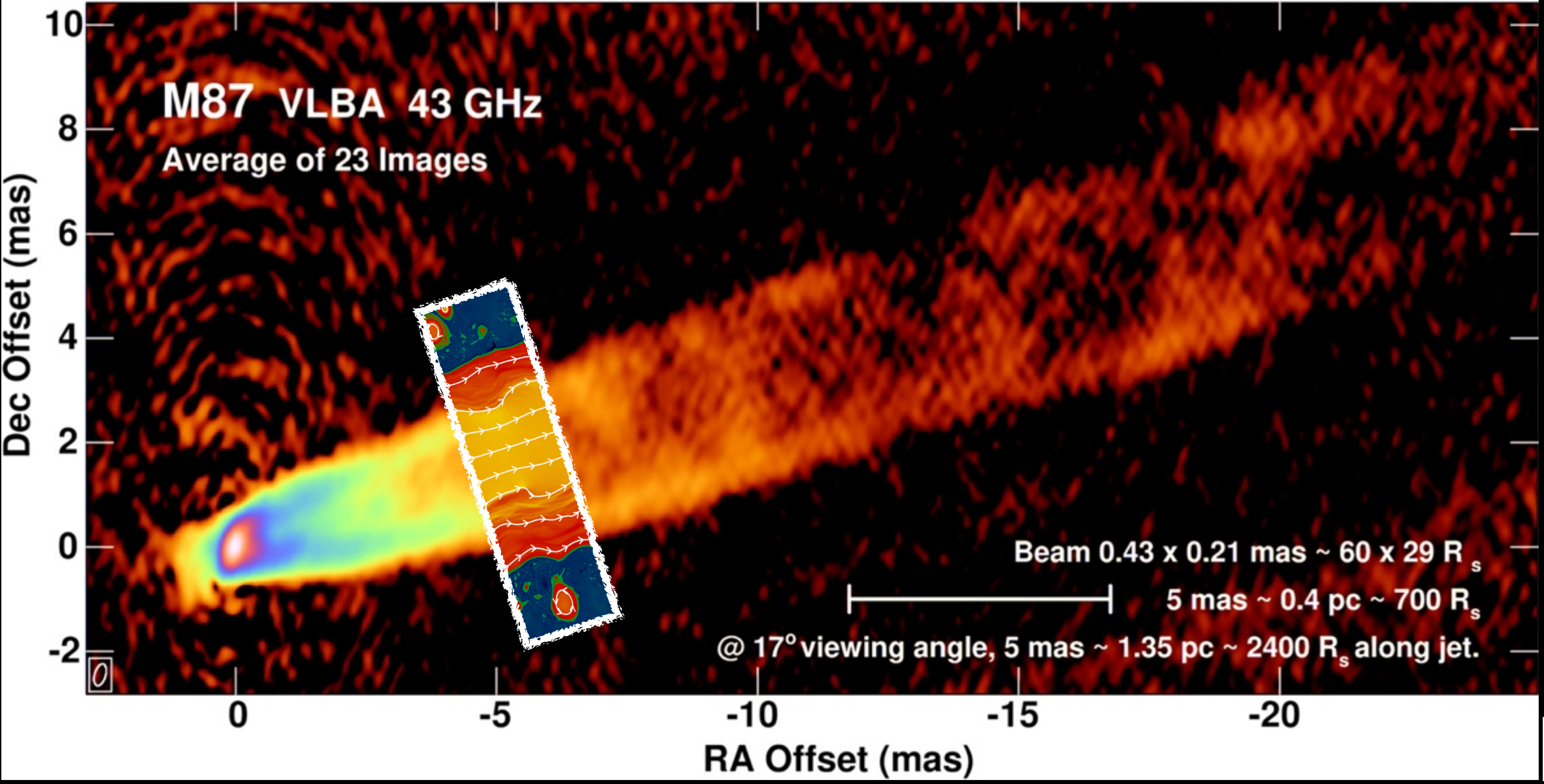
(2) Reconnection-accelerated particles then experience shear-driven acceleration.





Walker+2018

Particle acceleration via KH-driven reconnection can explain the jet limb brightening.



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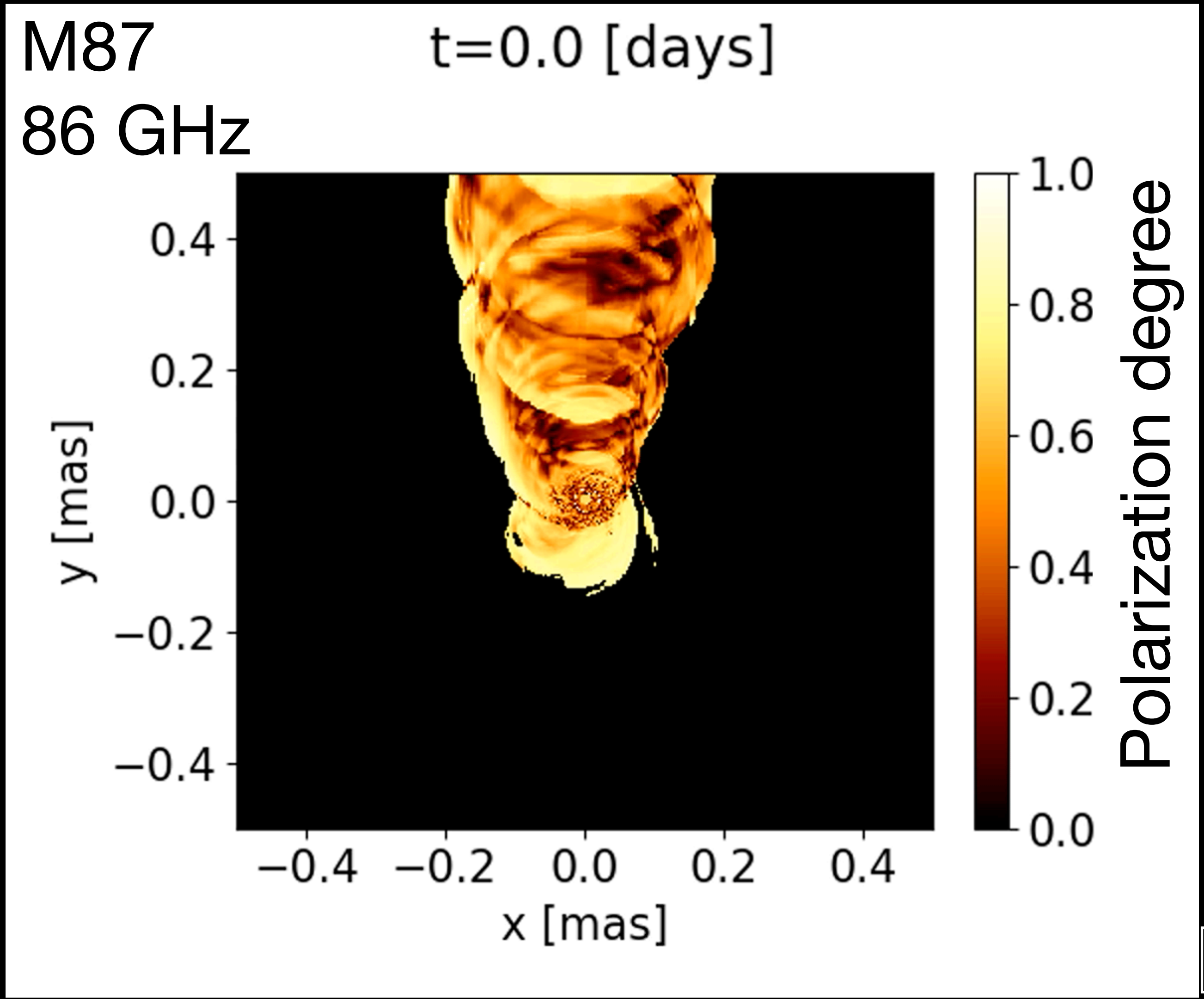
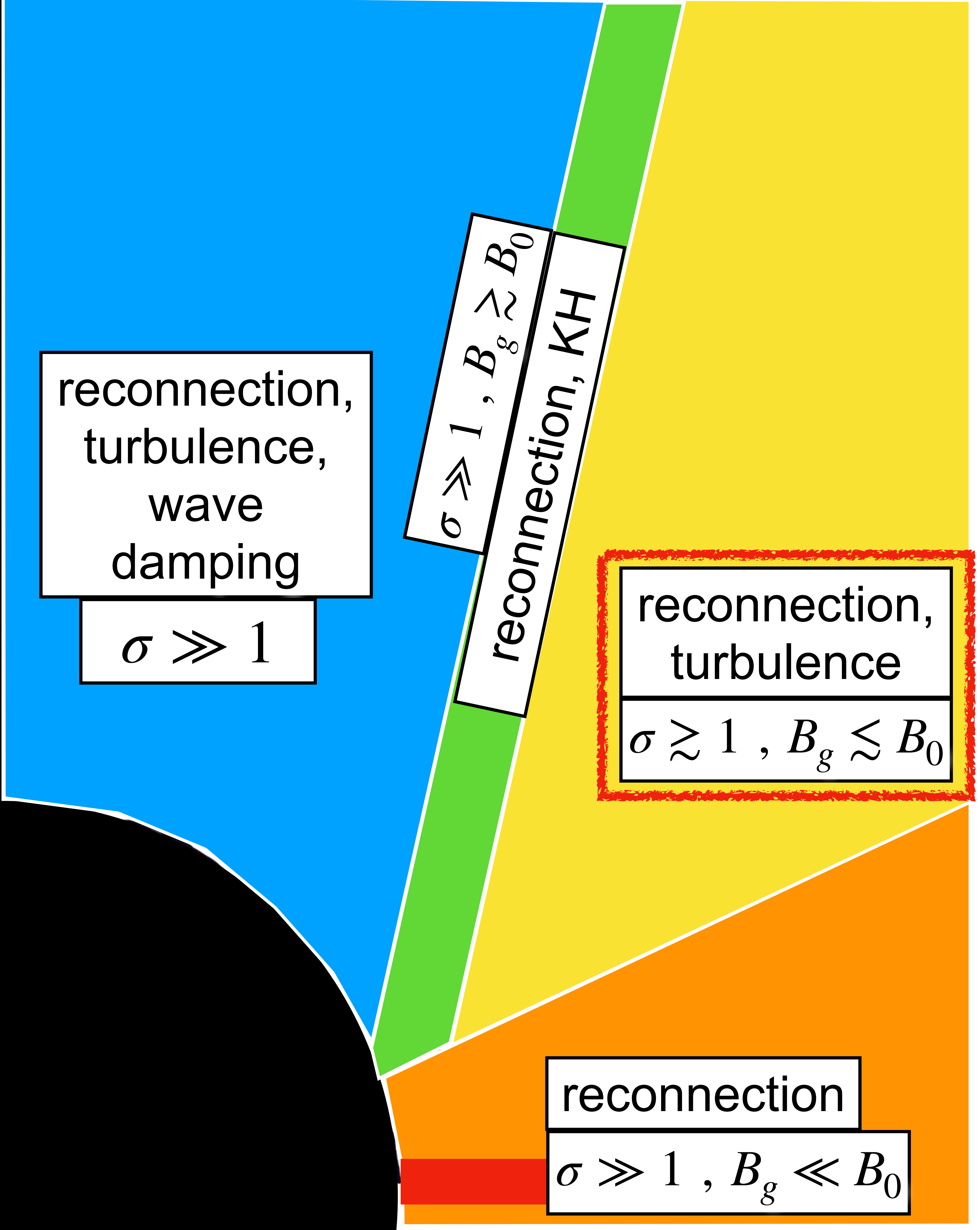


KH-like rolls-ups lead to Stokes vectors with variable orientations, along a given ray.

↓

Lower polarization degree than for a laminar jet boundary.

Davelaar+23



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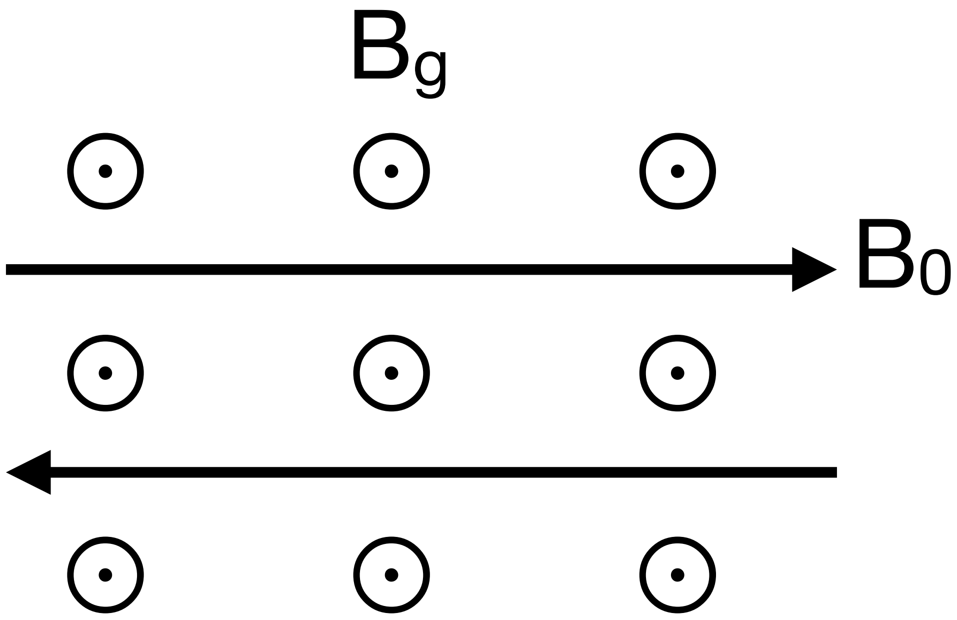

Key parameters:

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- $\beta = P_{\rm gas}/P_B \ll 1.$

Reconnection & turbulence in BH X-ray coronae

Gupta, Sridhar & LS 2023, MNRAS submitted, arXiv:2310.04233

Groselj, Hakobyan et al. 2023, PRL submitted, arXiv:2301.11327

Sridhar, LS et al. 2023, MNRAS, 518, 1301

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

LS & Beloborodov 2020, ApJ, 899, 52

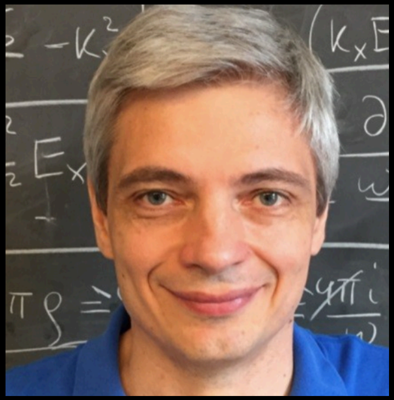

N. Sridhar


S. Gupta

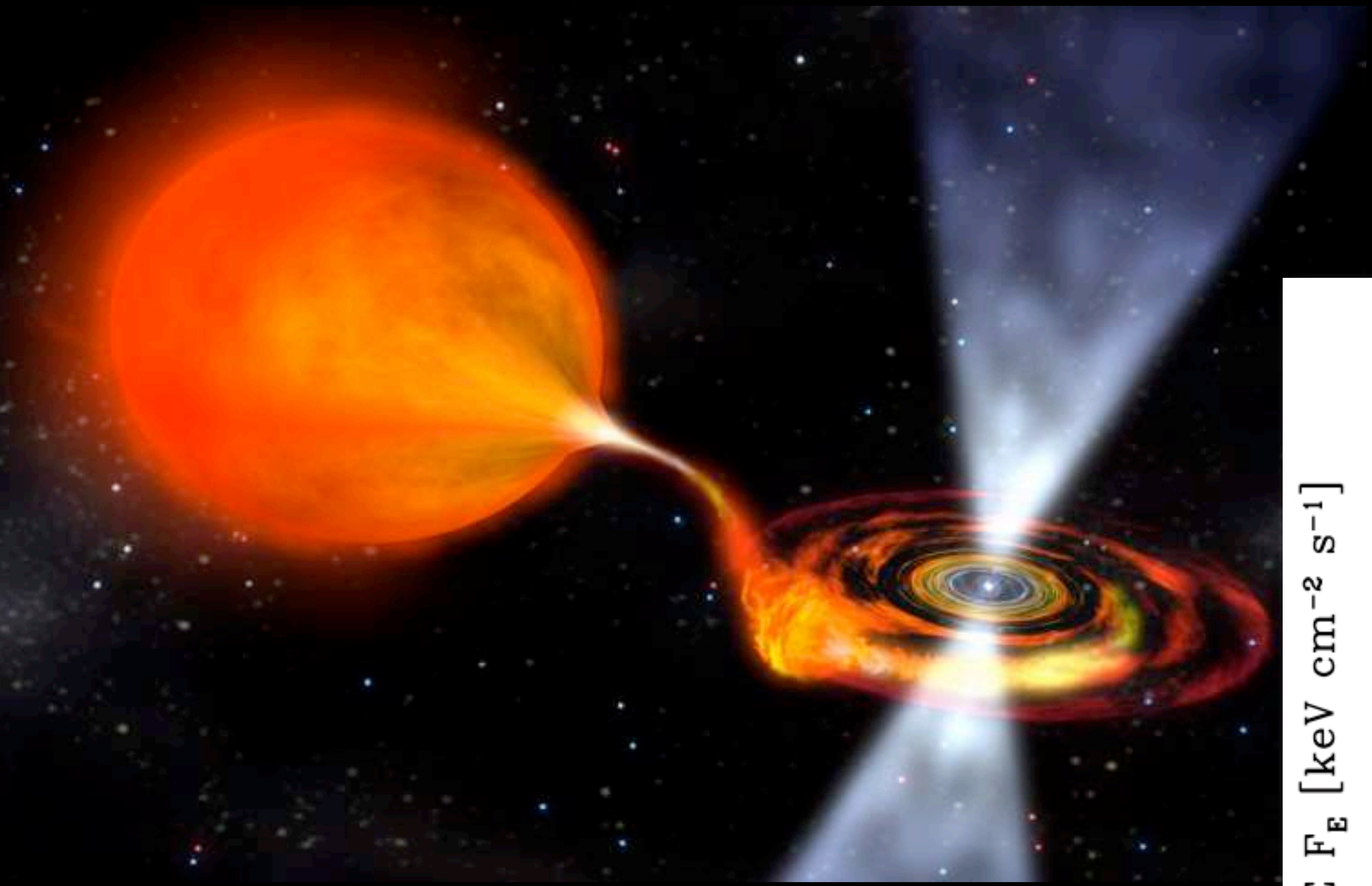

D. Groselj

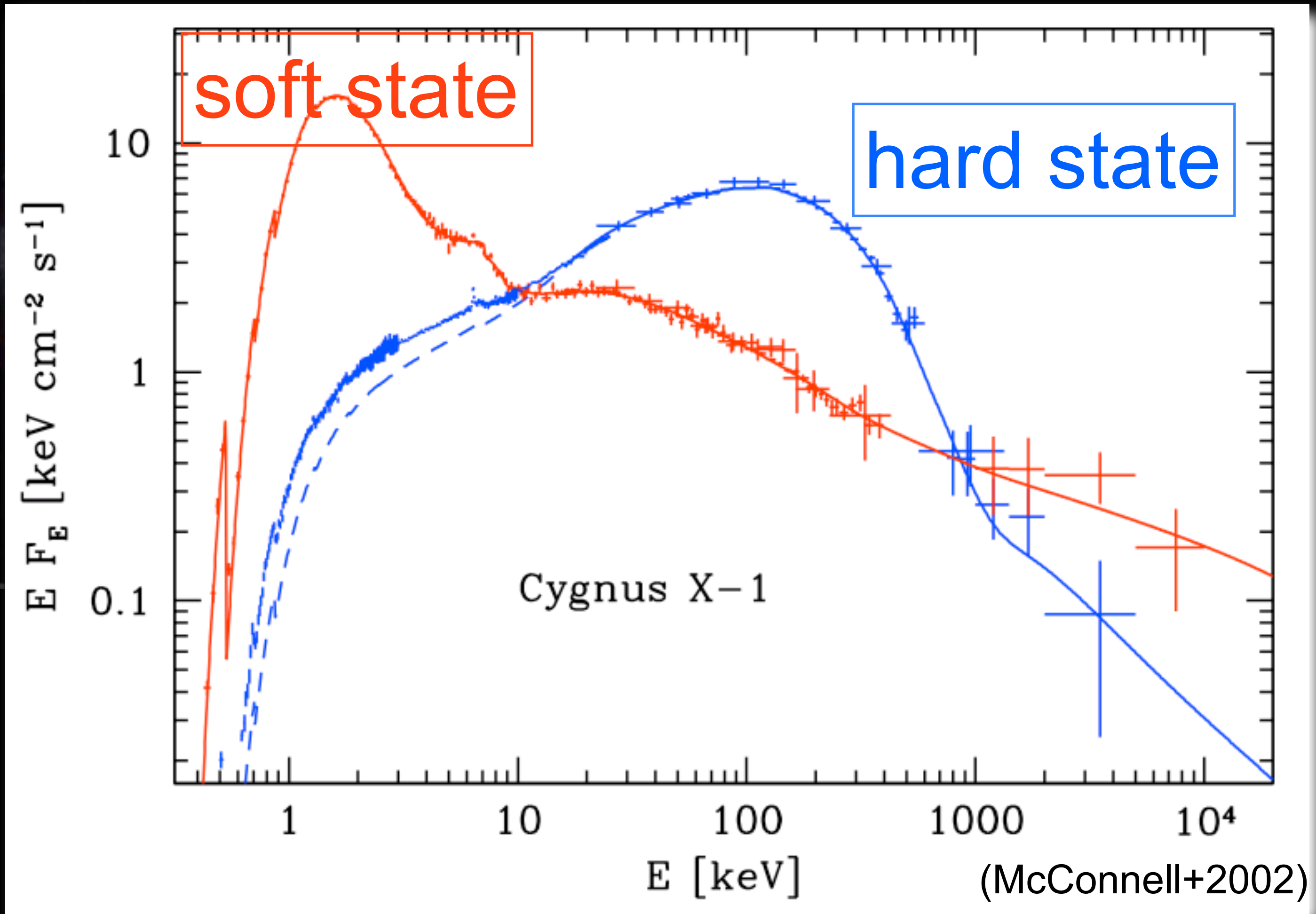

H. Hakobyan


A. Philippov


A. Beloborodov

The hard state of X-ray binaries





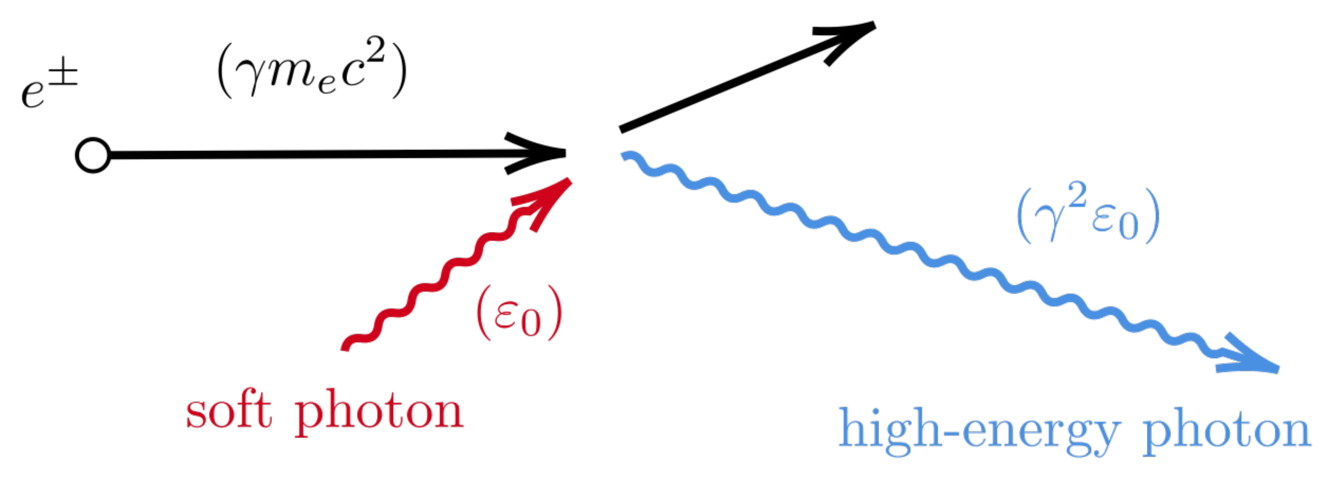
(McConnell+2002)

Soft state: thermal emission from the BH accretion disk.

Hard state: soft disk photons are scattered to higher energies by “coronal” electrons.

The standard model

Hard state: interpreted as thermal Comptonization by "coronal" plasma with electron temperature ~100 keV and moderate optical depth ($\tau_T \sim 1$).

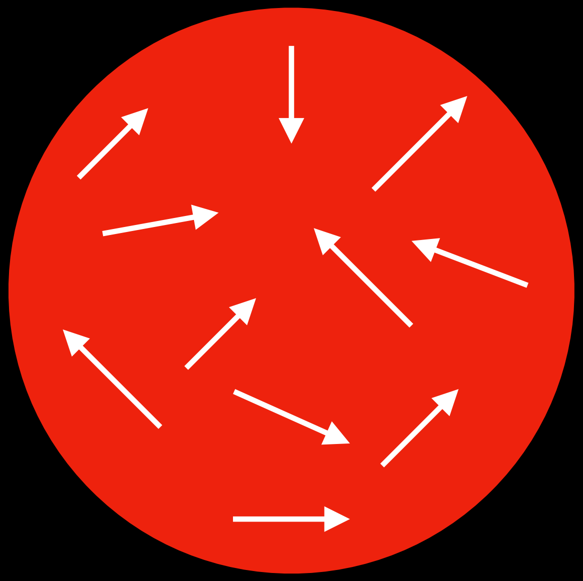


Can the emitting electrons in BH coronae stay hot?
If not, what provides Comptonization?

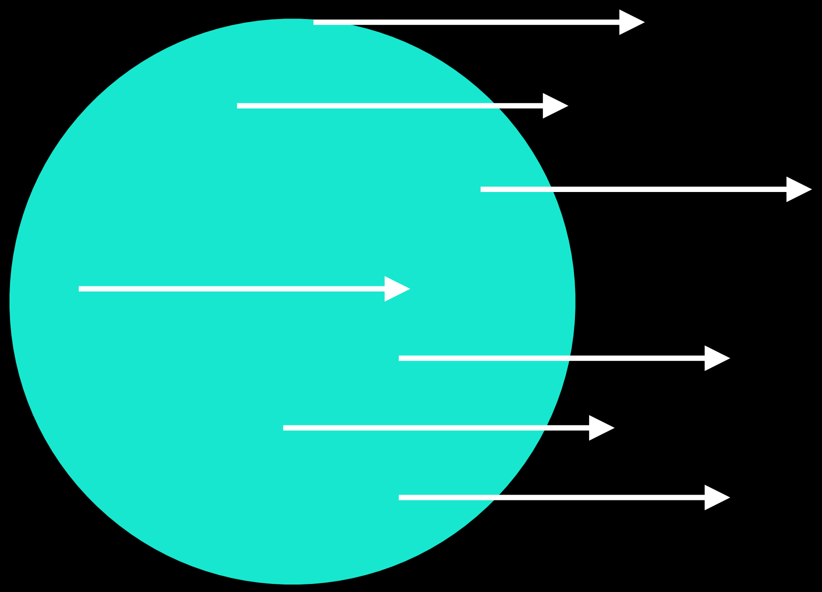
Internal vs bulk motions

Can the emitting electrons in BH coronae stay hot?

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



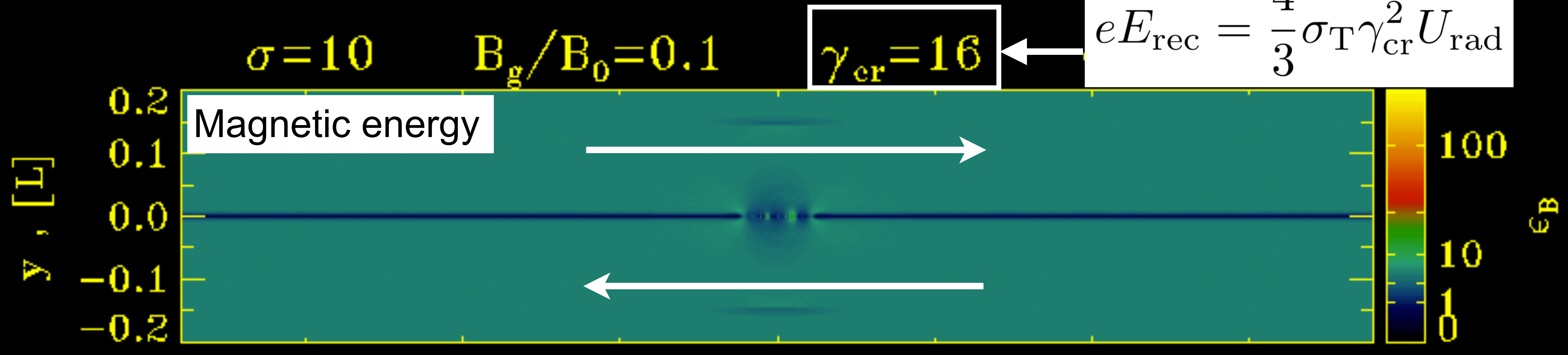
Internal motions (random)



Bulk motions (ordered)

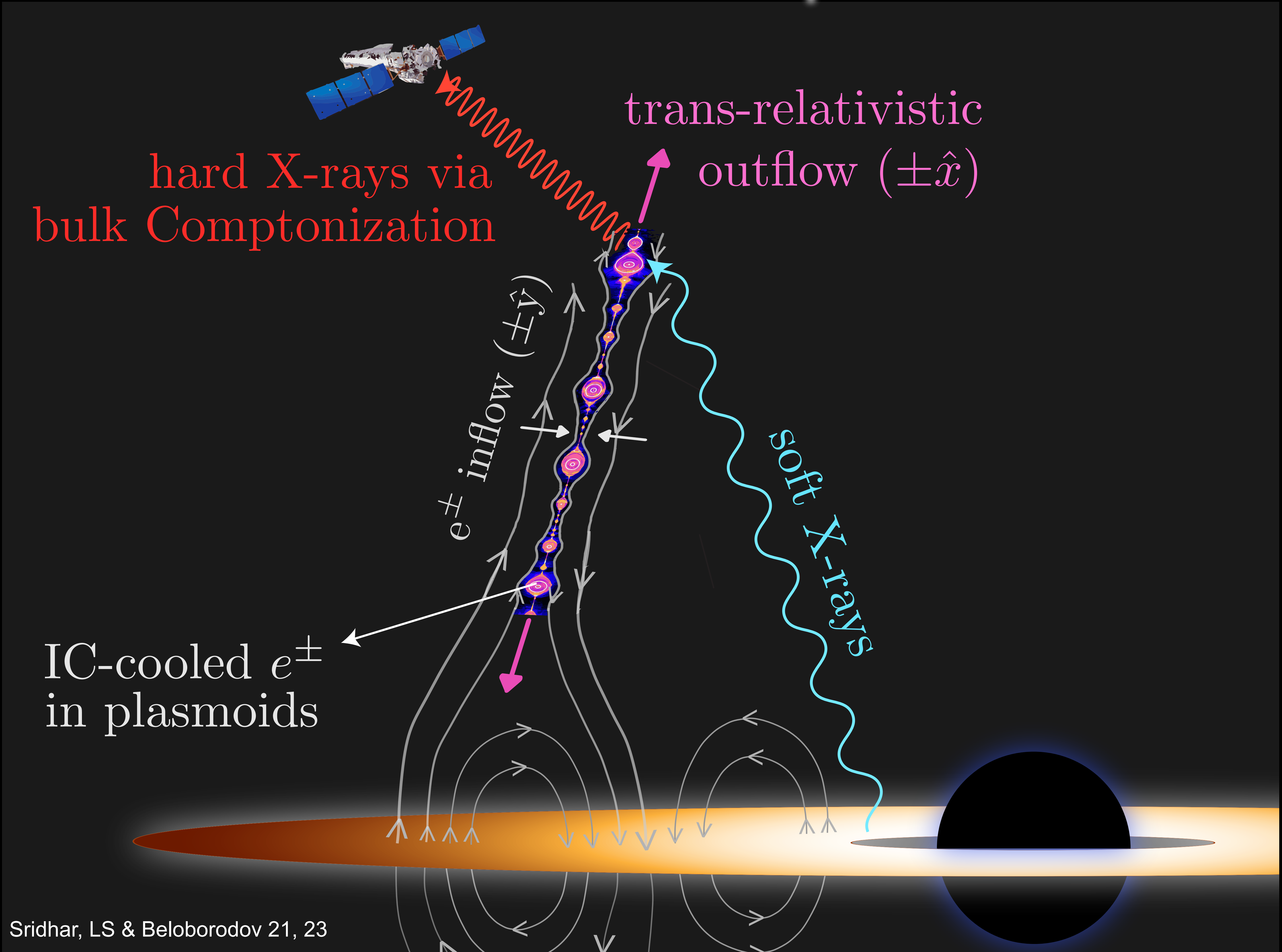
What provides ordered/bulk motions for Comptonization?

Option 1: reconnection



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

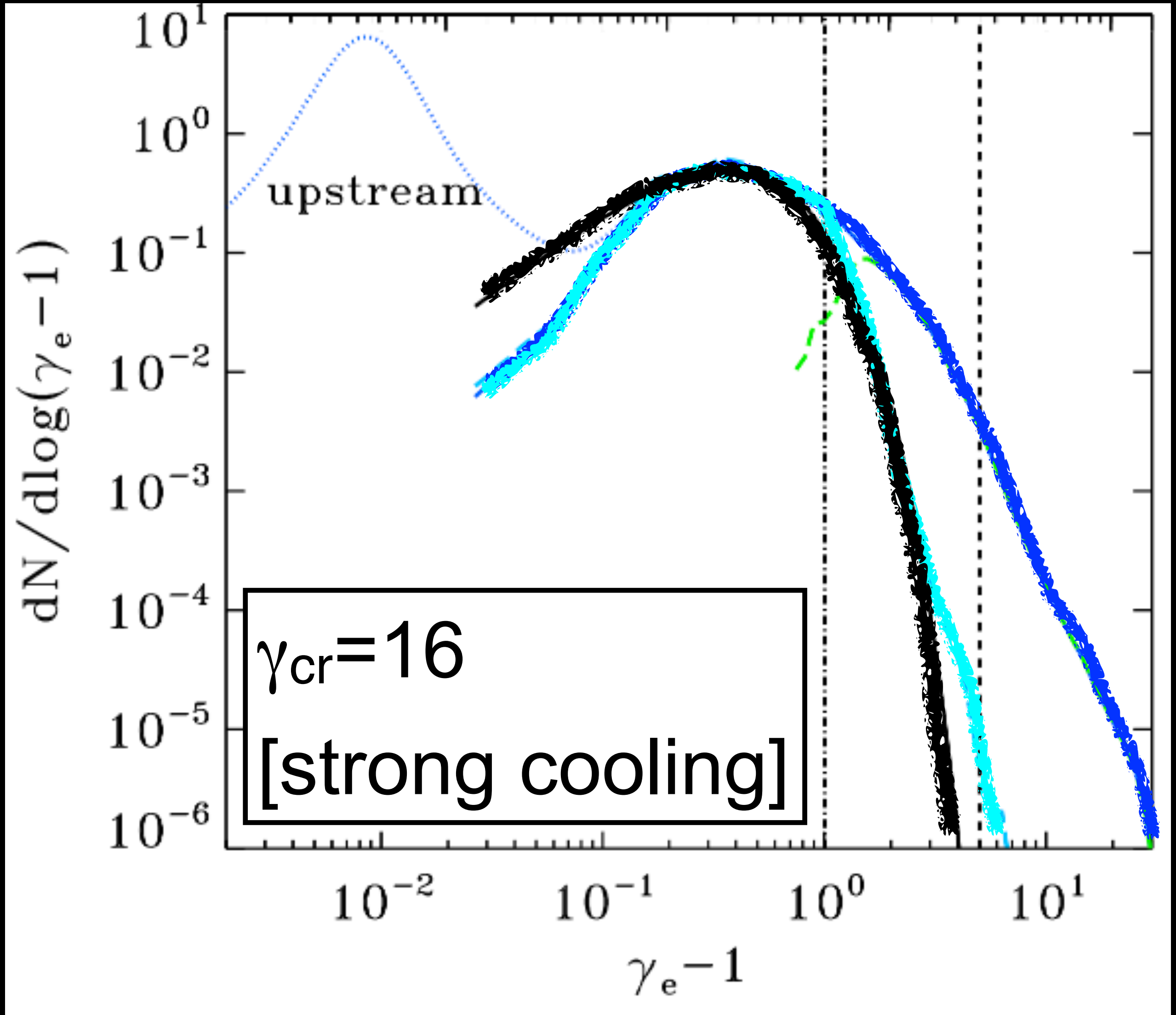
Plasmoid chain Comptonization



Sridhar, LS & Beloborodov 21, 23

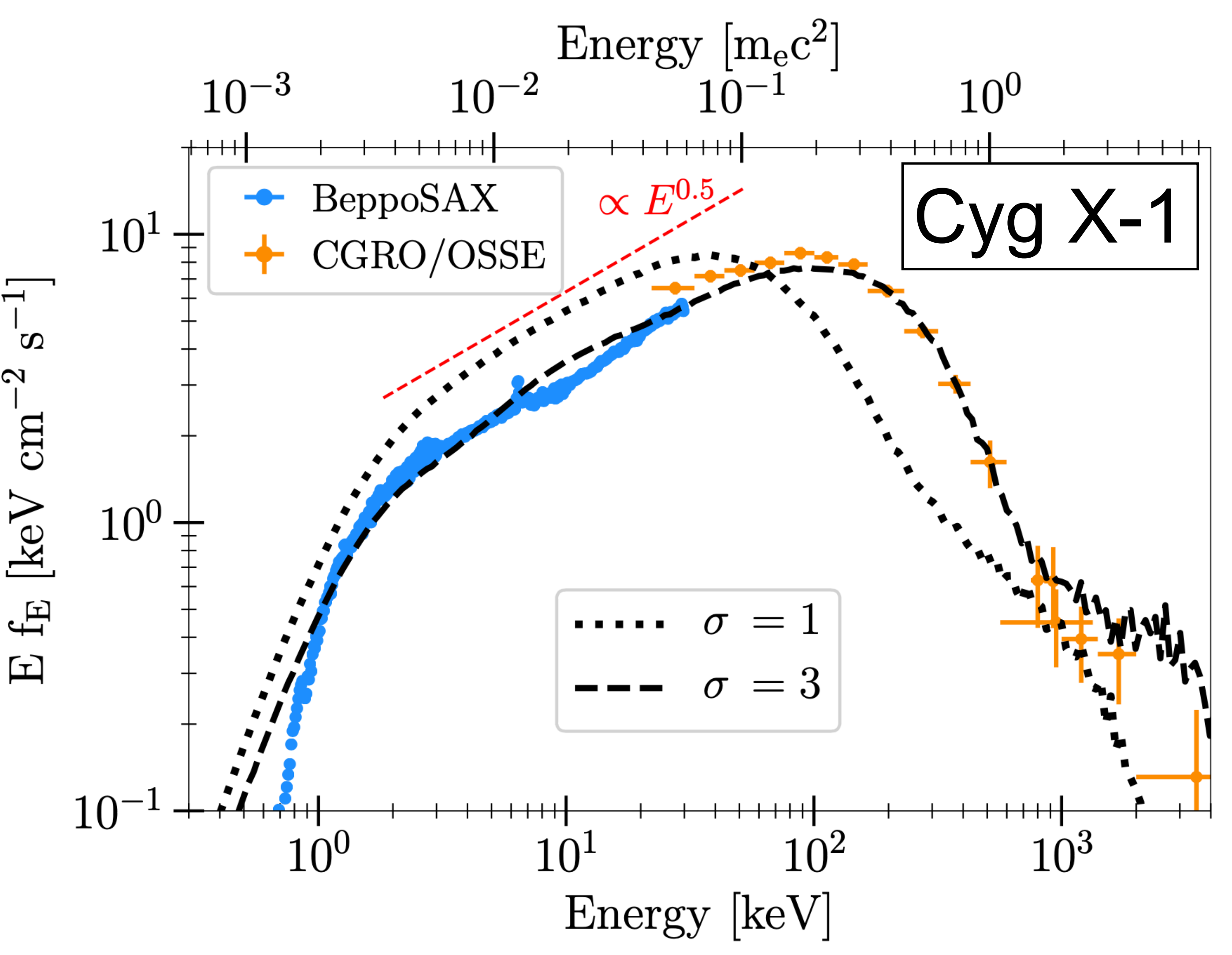
Plasmoid chain Comptonization

Particles



(LS & Beloborodov 20; Sridhar, LS & Beloborodov 21, 23)

Photons



(Sridhar, LS & Beloborodov 21, 23)

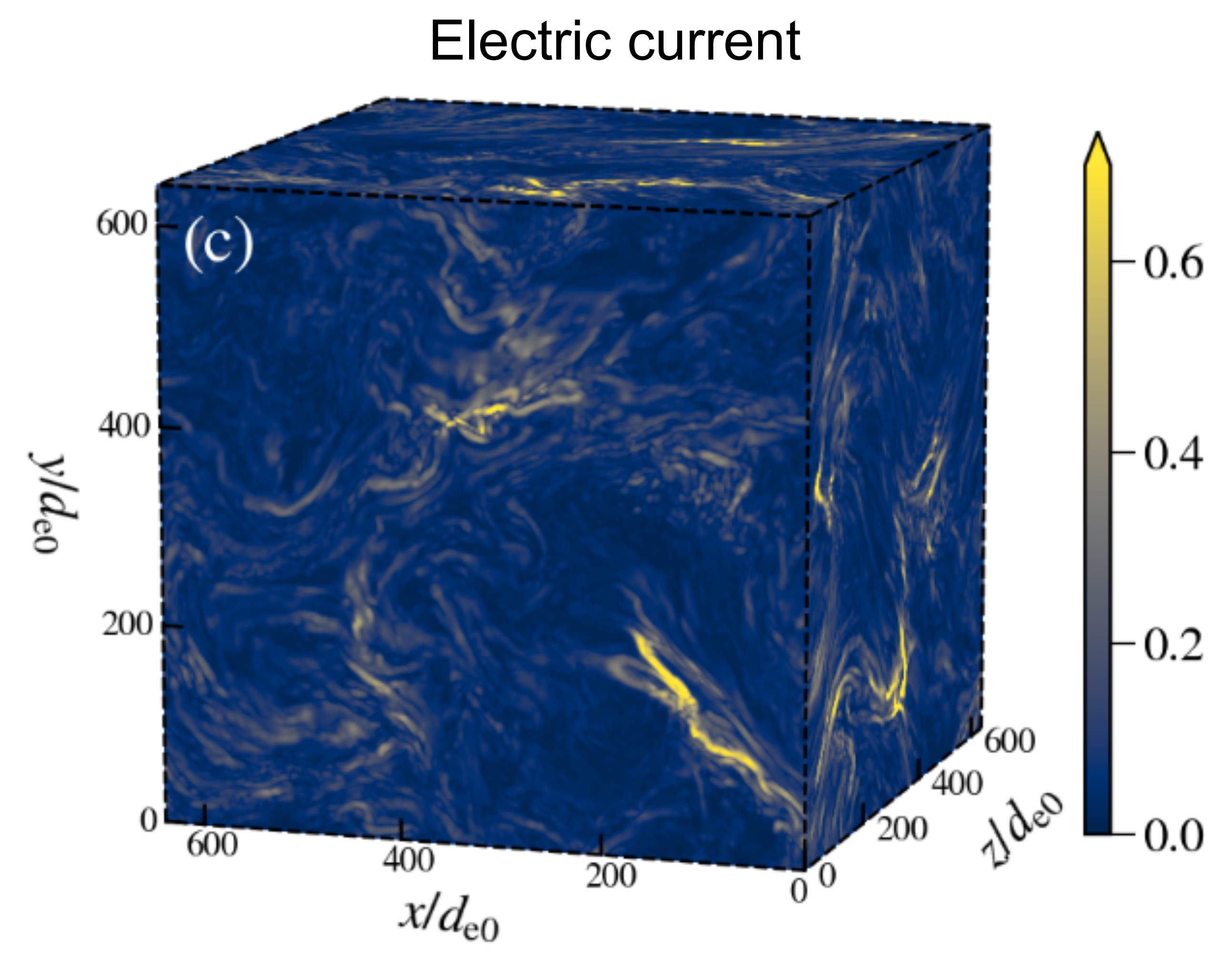
- The particle <u>bulk</u> energy spectrum resembles a <u>Maxwellian</u> with T_{eff}~100 keV

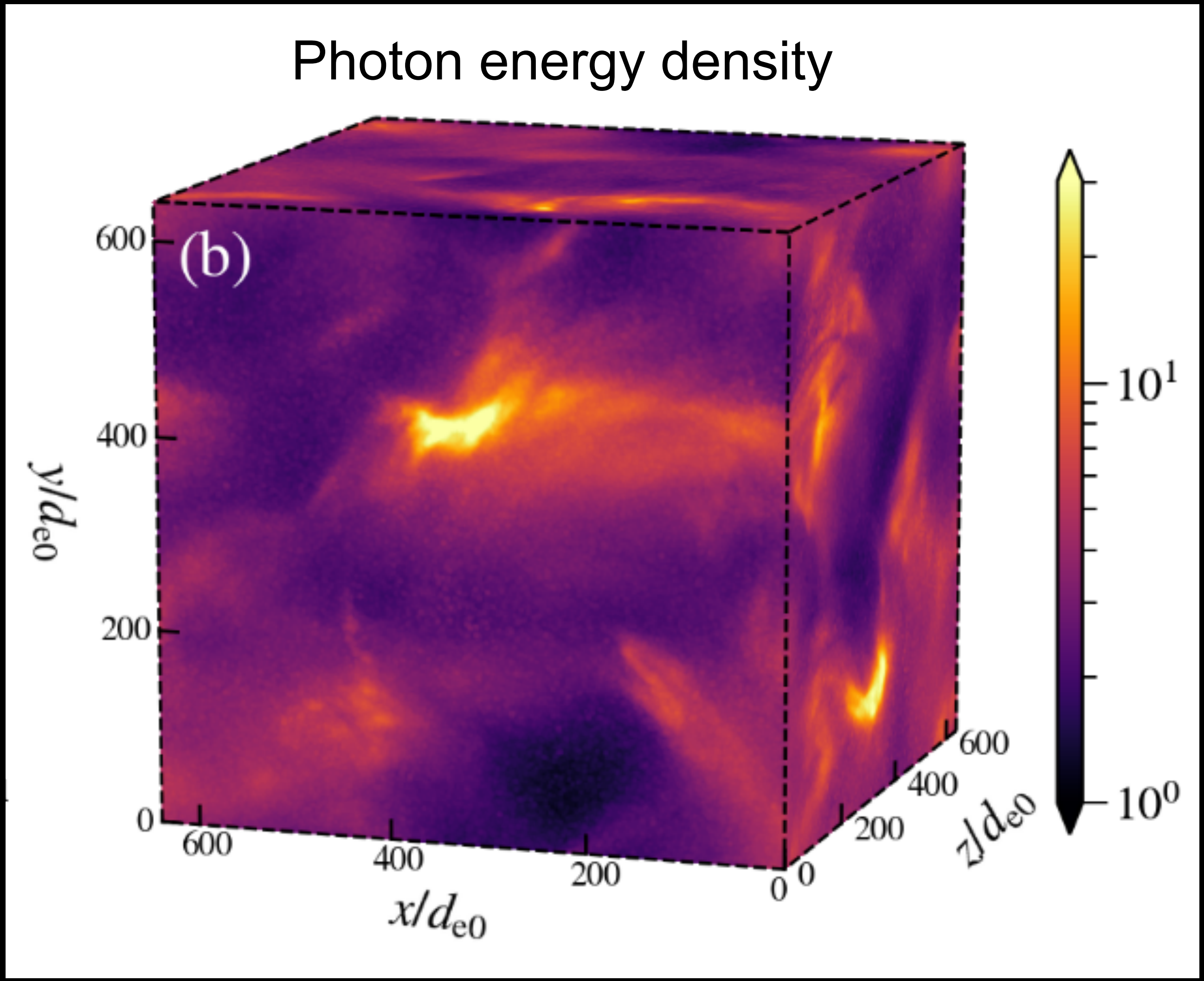
- For optical depth ~ 1 and σ ~ few, our photon spectrum matches the observations.

Option 2: turbulence

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

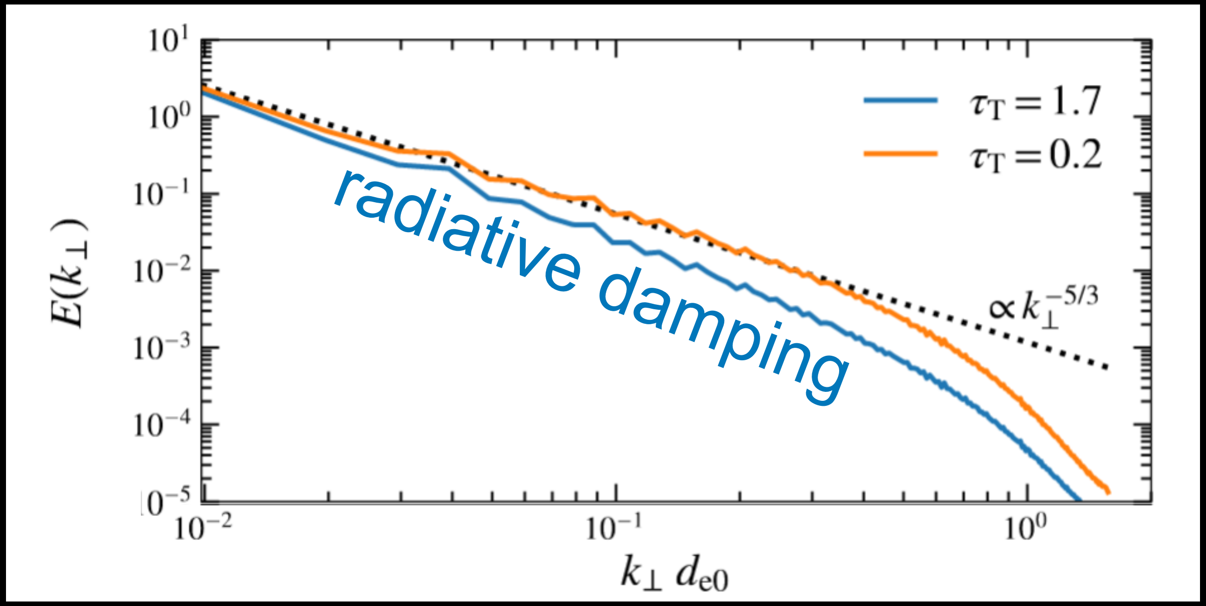
- Injection of soft seed photons from a thermal bath at ~ 1 keV
- Photon escape
- Spatially-resolved Compton scattering with full Klein-Nishina cross-section (Monte-Carlo method)


Electric current


Photon energy density

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

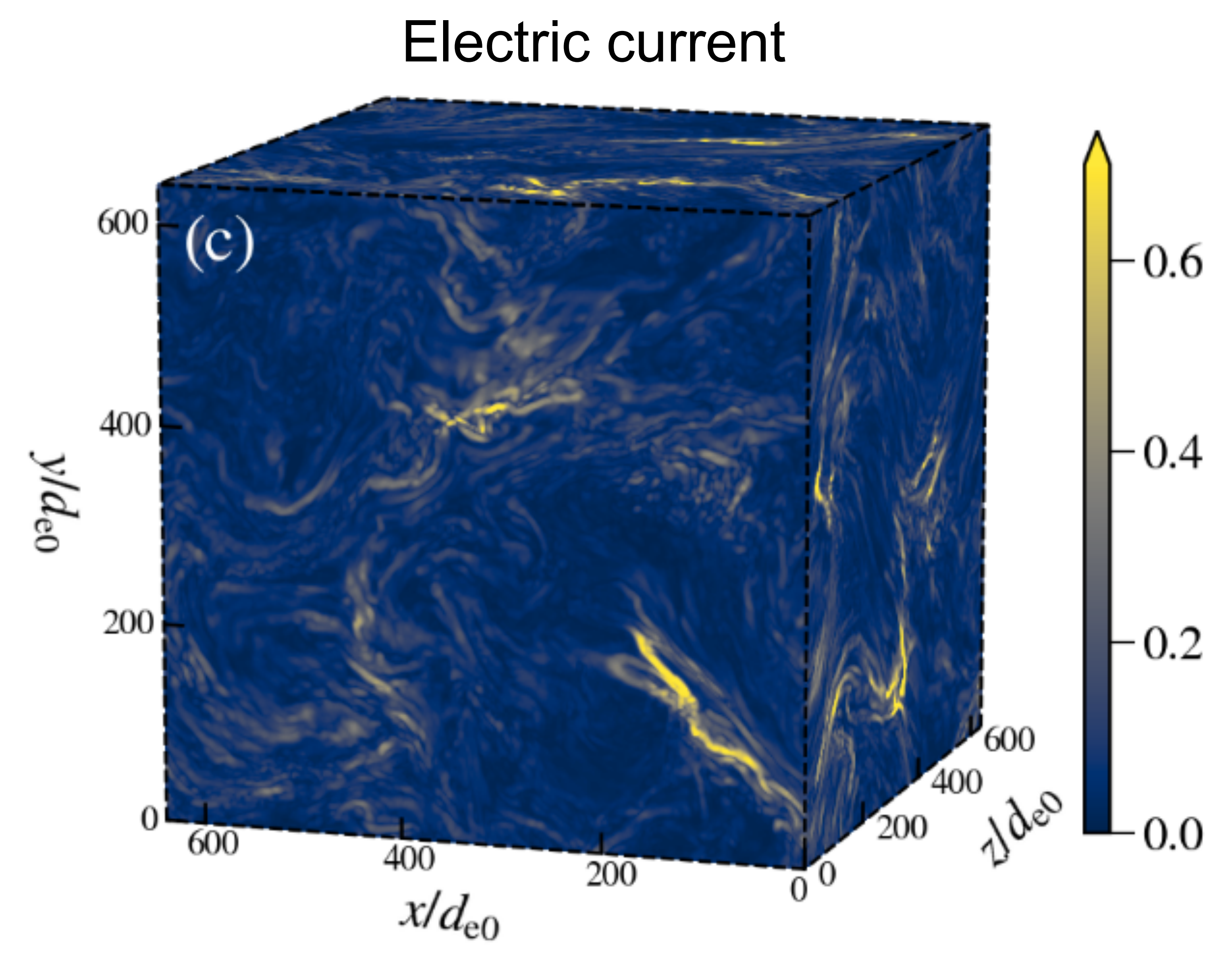
Turbulent Comptonization

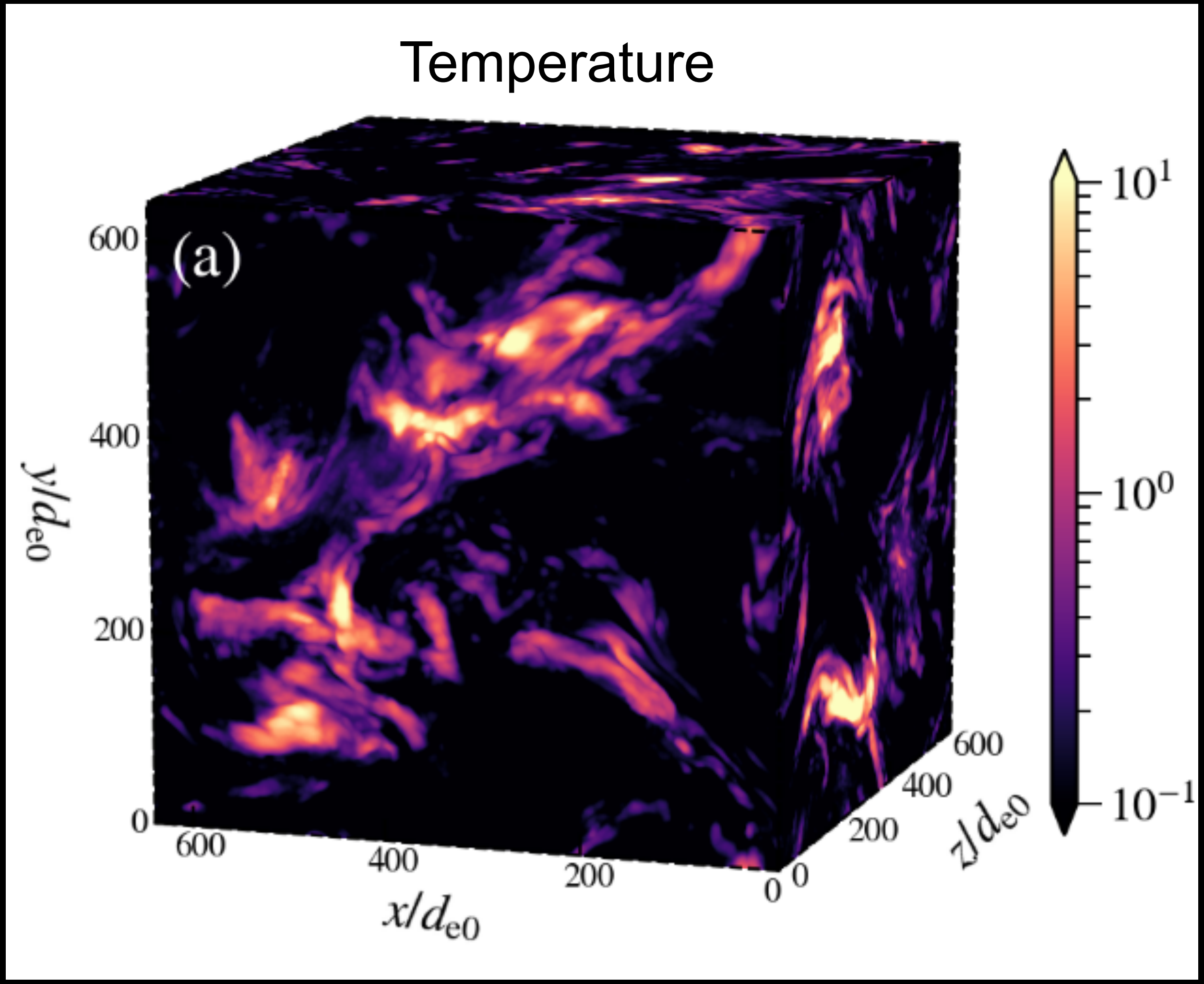


radiative damping

- 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”.

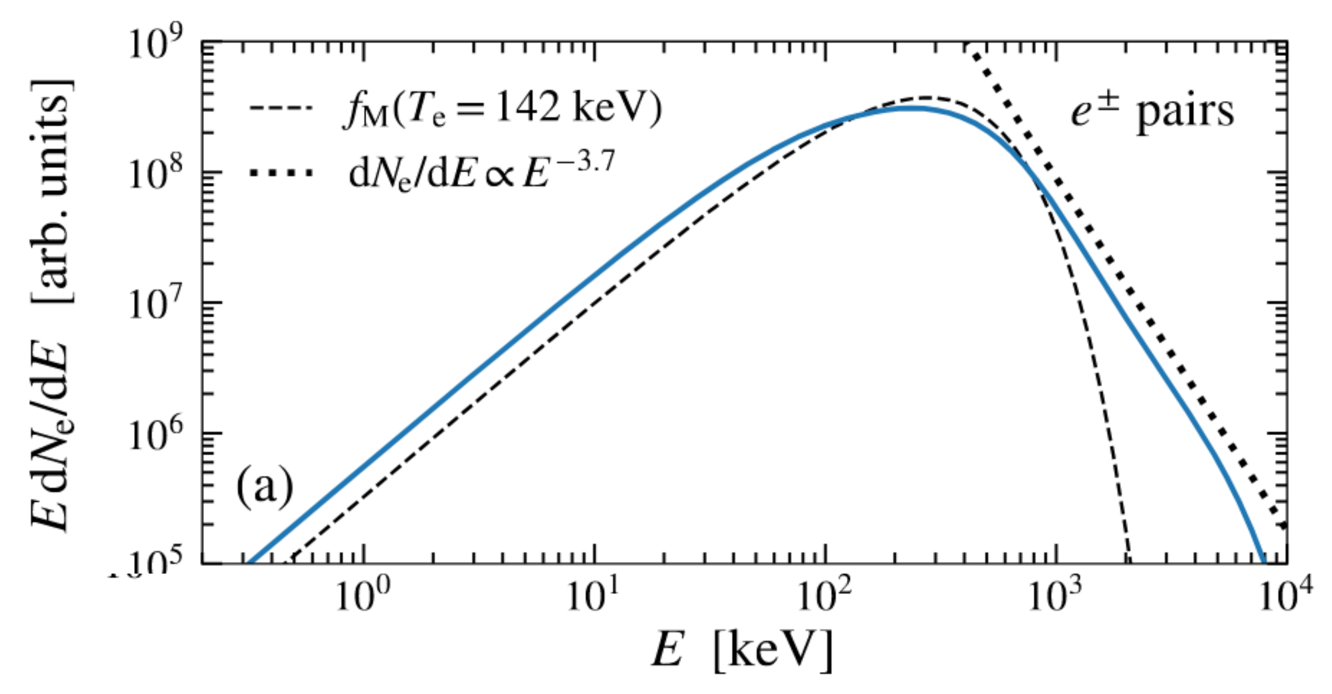

Electric current


Temperature

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

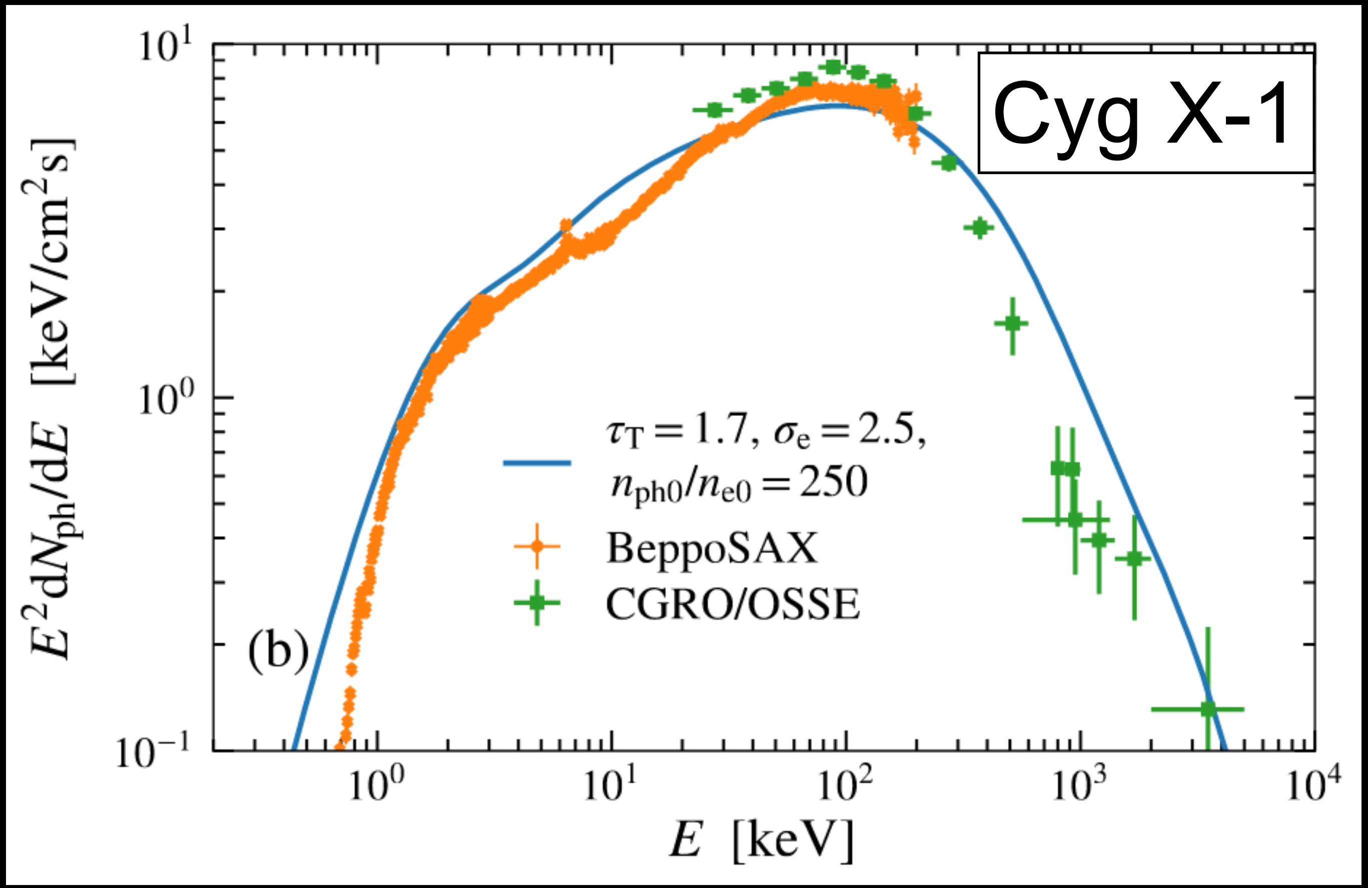
Turbulent Comptonization

Particles



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

Photons



- The particle energy spectrum is dominated by bulk motions, yet it resembles a Maxwellian with $T_{\rm eff}$ ~100 keV

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

- The MeV tail requires including self-consistent pair production.

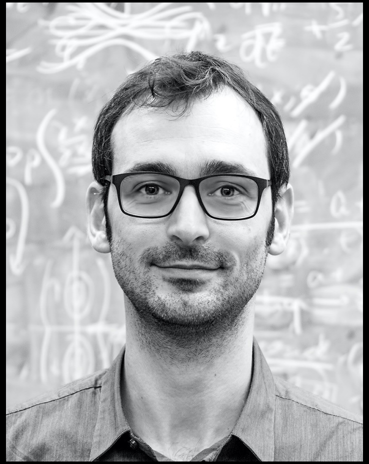
Neutrinos from BH coronae

Fiorillo et al. 2023, ApJL submitted, arXiv:2310.18254

D. Fiorillo

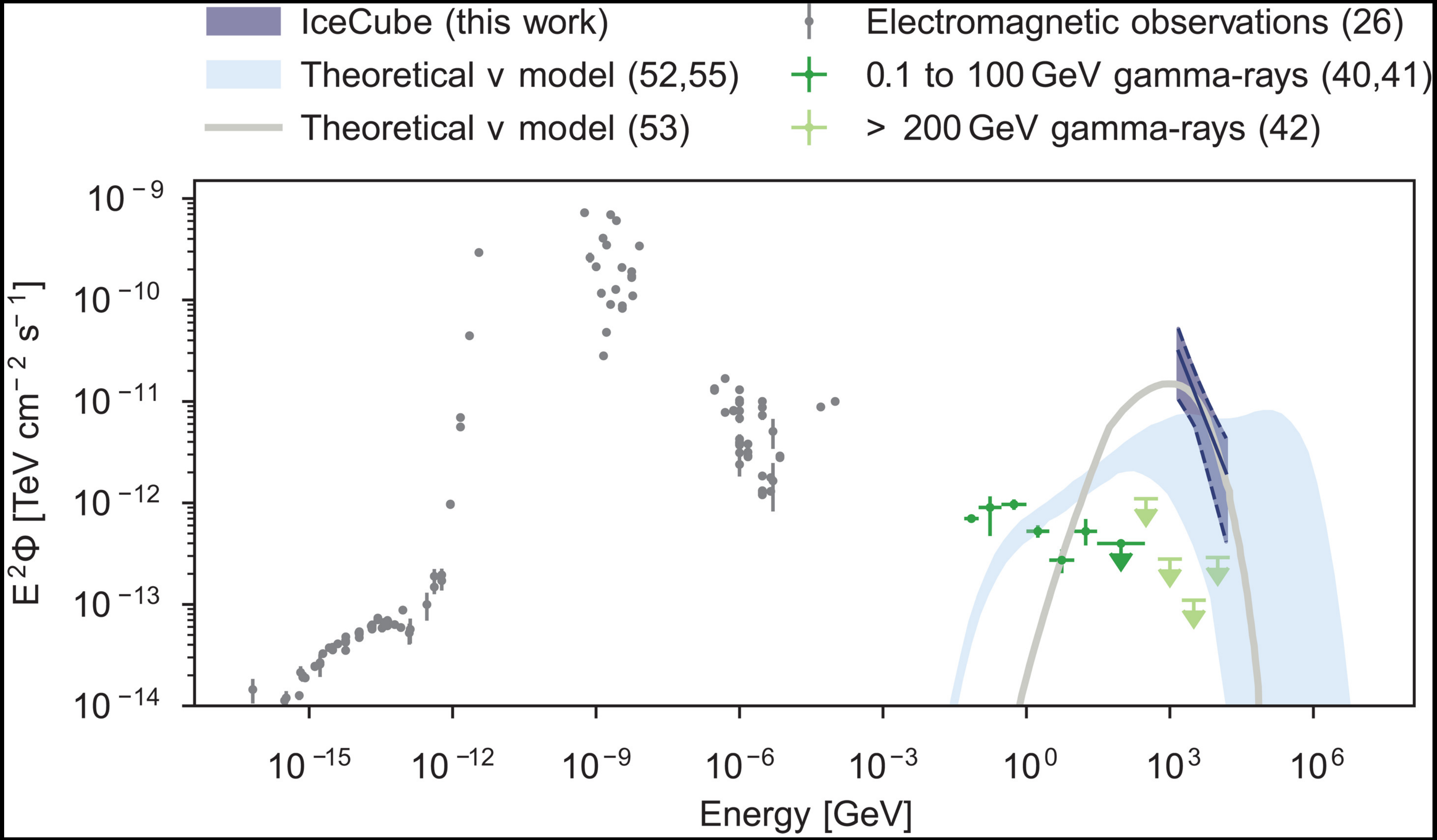
M. Petropoulou

L. Comisso



E. Peretti

Neutrinos from BH coronae



From coronal X-ray emission to local plasma properties:

- $\tau_T \sim 1 \rightarrow$ electron number density n_e
- X-ray luminosity, if powered by B-field dissipation → B-field strength

What is the mechanism of proton acceleration?

Reconnection? (Fiorillo+ 23, arXiv:2310.18254) [see also K. Murase’s talk]

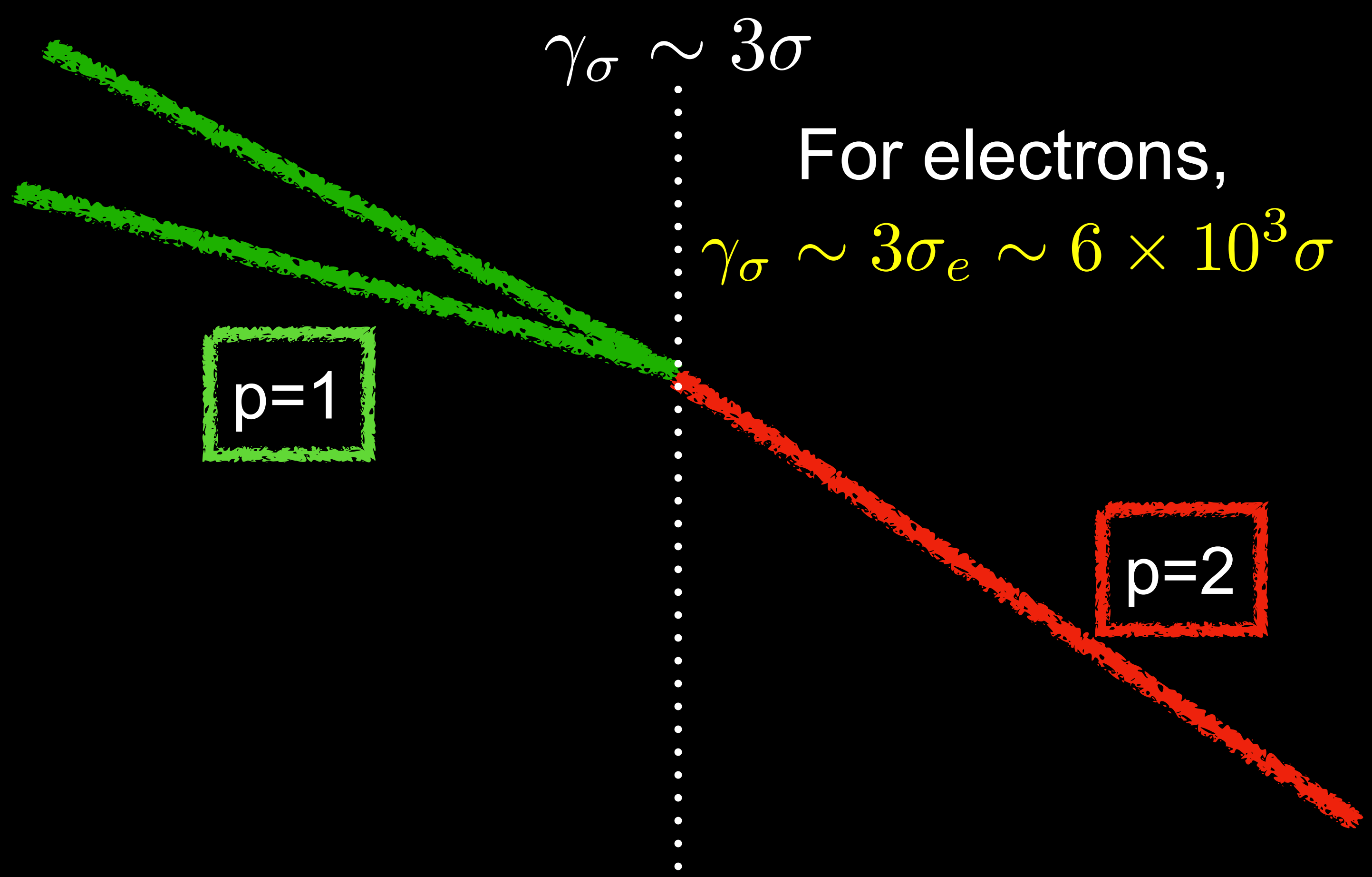
Two-stage acceleration in reconnection

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

- Further acceleration beyond injection ($\gamma \gtrsim 3\sigma$) leads to ~ σ-*independent* slopes, with *p~2* if B_g=0.

[steeper for stronger guide fields, see Werner & Uzdensky 2017]

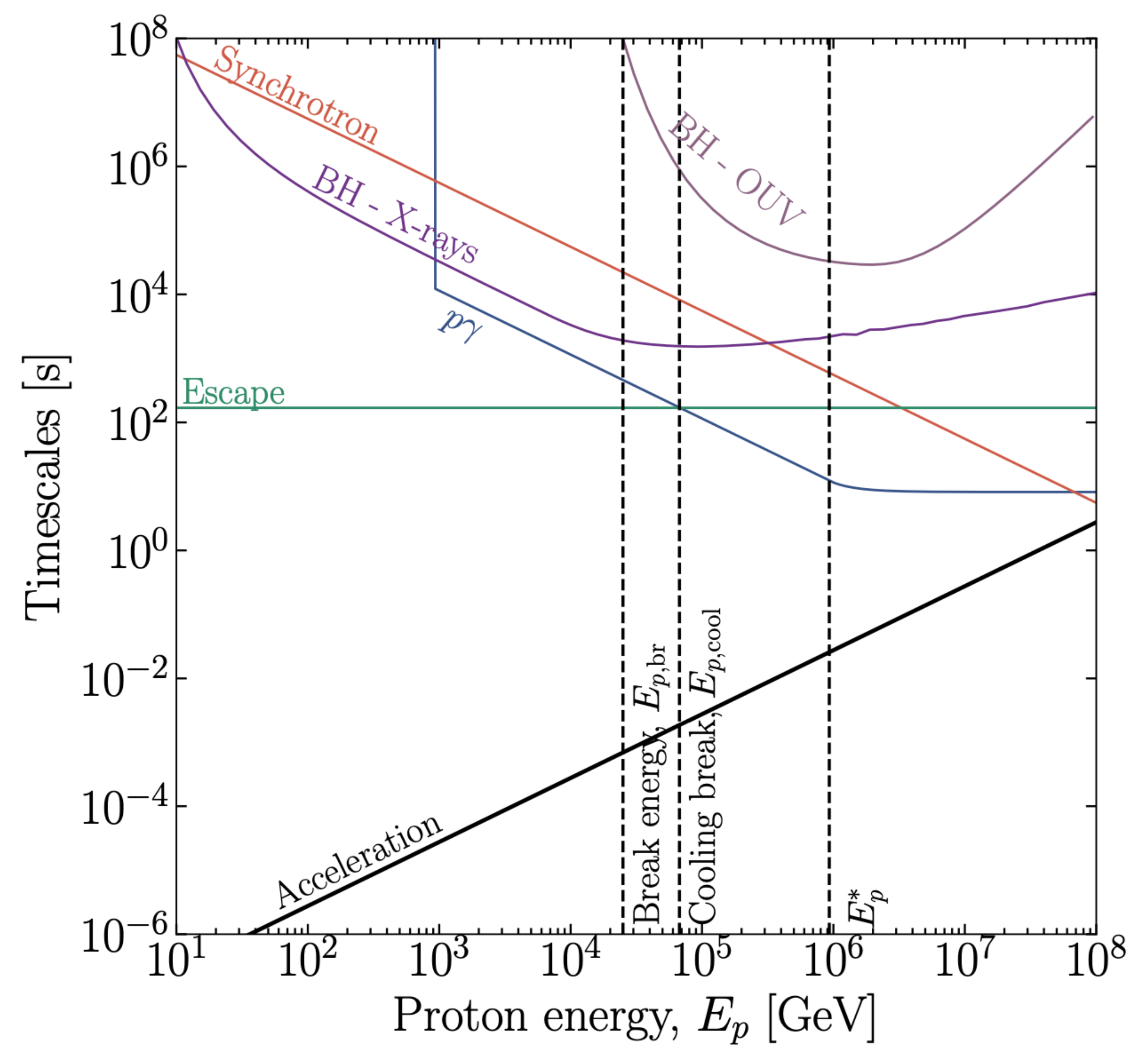
$$\frac{dN}{d\gamma} \propto \gamma^{-p}$$



For electrons,

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

Hierarchy of time / energy scales



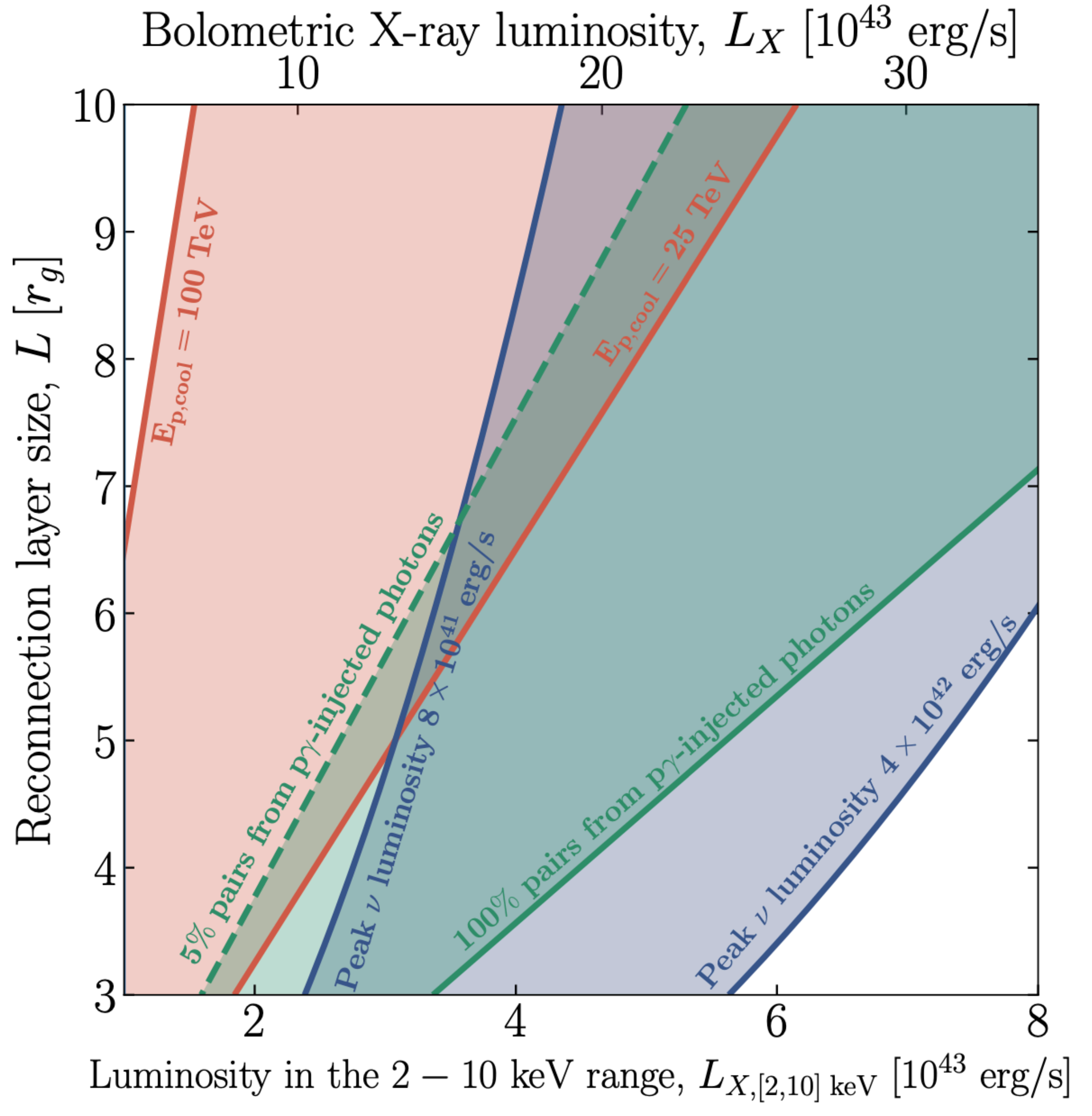
- $E_{p,br}$: break of proton spectrum, inferred from peak of ν spectrum.
- $E_{p,cool}$: pγ cooling time = escape time from the reconnection layer.
- E_p^* : change of photo-hadronic efficiency (dependent on the lower cutoff of the X-ray spectrum).
- $E_{p,rad}$: pγ cooling time = acceleration time.

$$\boxed{E_{p,\mathrm{br}} \lesssim E_{p,\mathrm{cool}} < E_p^* < E_{p,\mathrm{rad}}}$$

A tightly constrained system

Assumptions:

- Hard X-ray emission and proton energization come from B-field dissipation.
- Proton energy density is O(0.1) fraction of the magnetic energy density.

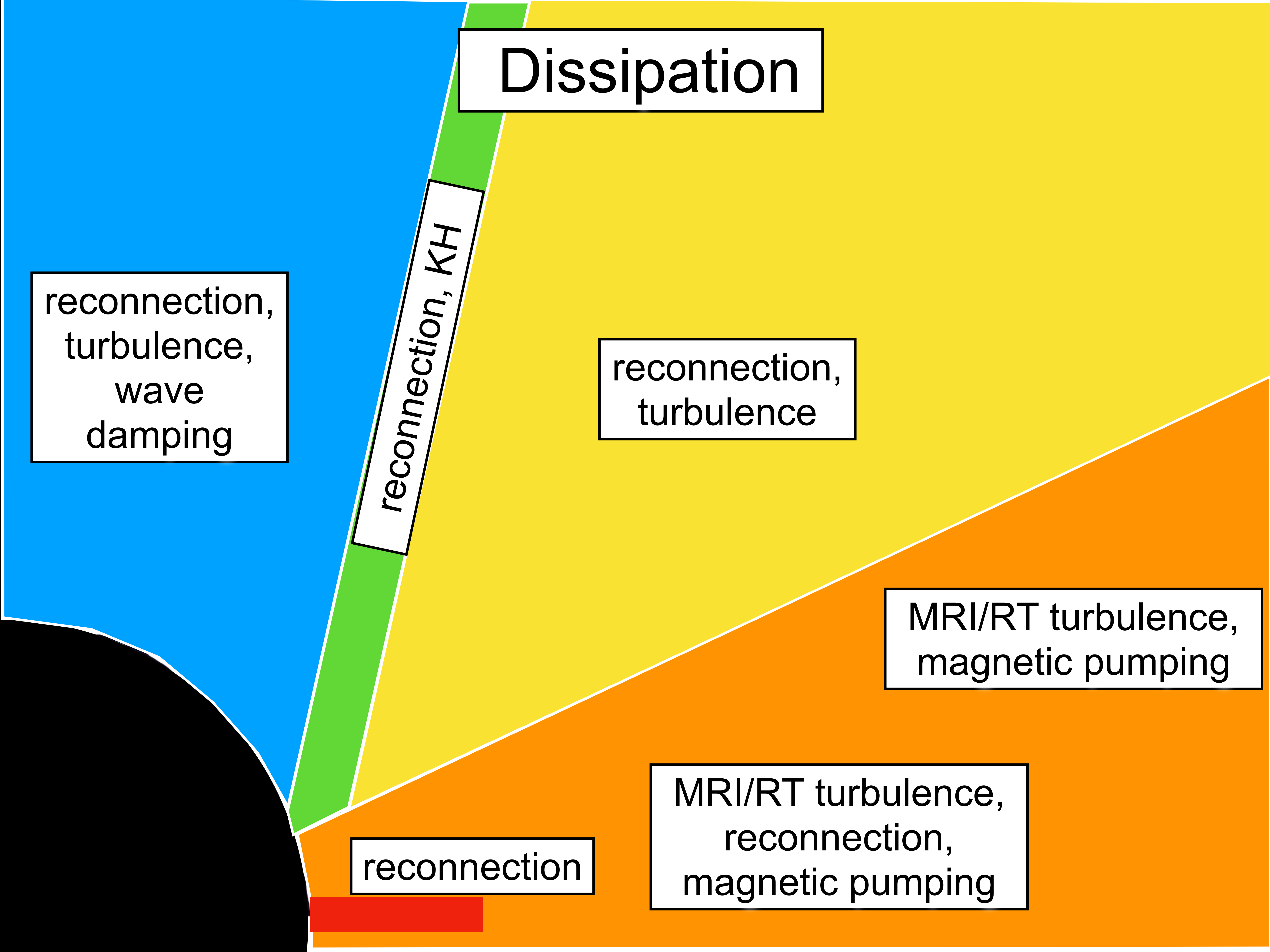


Constraints:

- $L_\nu \sim (0.8 - 4) \times 10^{42}$ ergs/s
- $L_X \sim 3^{+3}_{-2} \times 10^{43}$ ergs/s
- $E_{\mathrm{p,cool}} \sim E_{\mathrm{p,br}}$ (proton calorimeter)

Results:

- Compact corona: L~ few r_g
- Pairs from the proton-initiated cascade may account for most of the leptons required by $\tau_T \sim 1$.



Dissipation

reconnection,
turbulence,
wave
damping

reconnection, KH

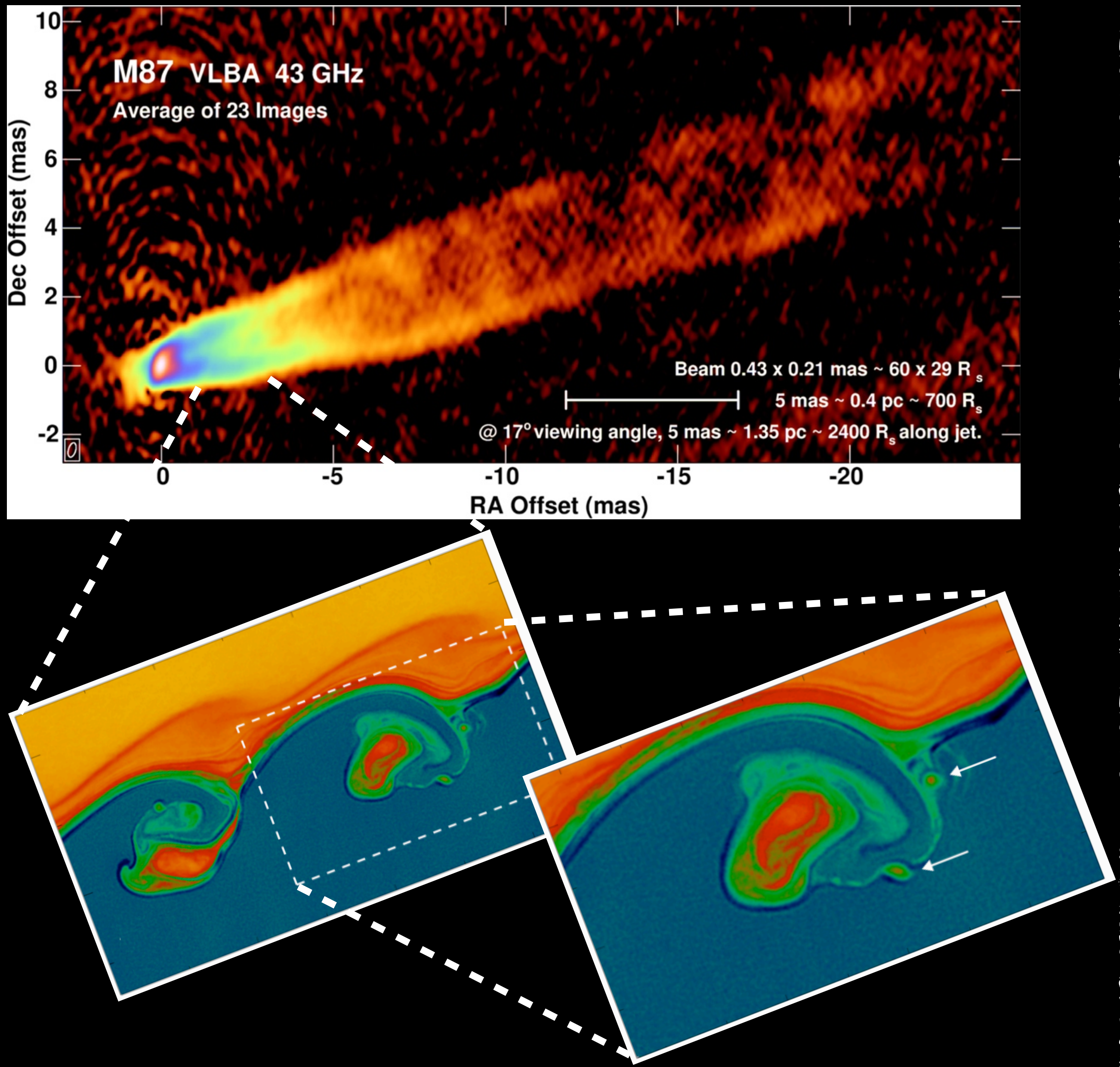
reconnection,
turbulence

MRI/RT turbulence,
magnetic pumping

reconnection

MRI/RT turbulence,
reconnection,
magnetic pumping

Reconnection at jet boundaries



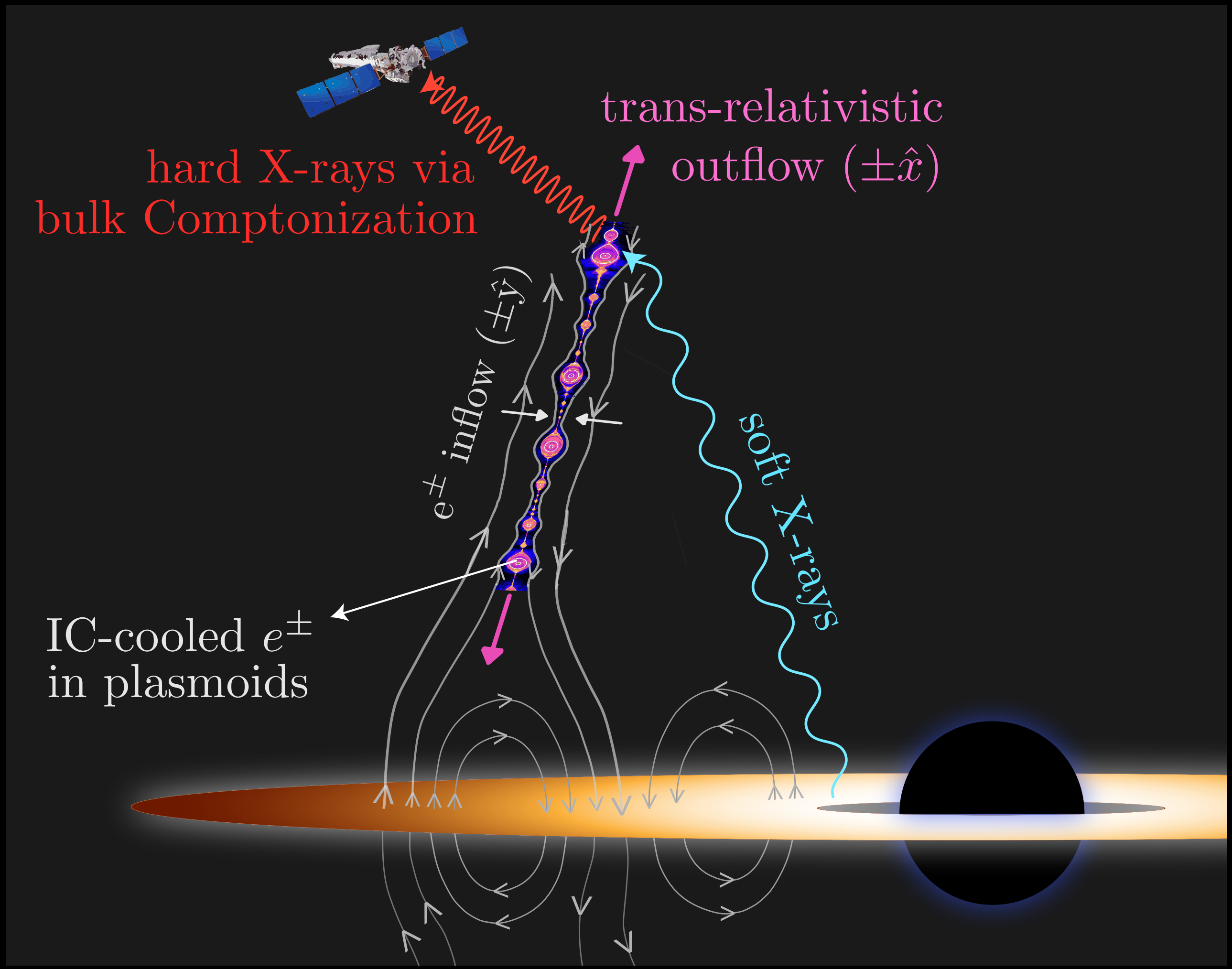
KH-like vortices at jet boundaries:

→ relativistic reconnection

→ particle injection

→ shear-driven acceleration

Reconnection in BH coronae



Relativistic reconnection / turbulence in BH coronae:

- Bulk Comptonization with effective temperature ~ 100 keV.
- hard state spectra of X-ray binaries.
- a source of neutrinos?