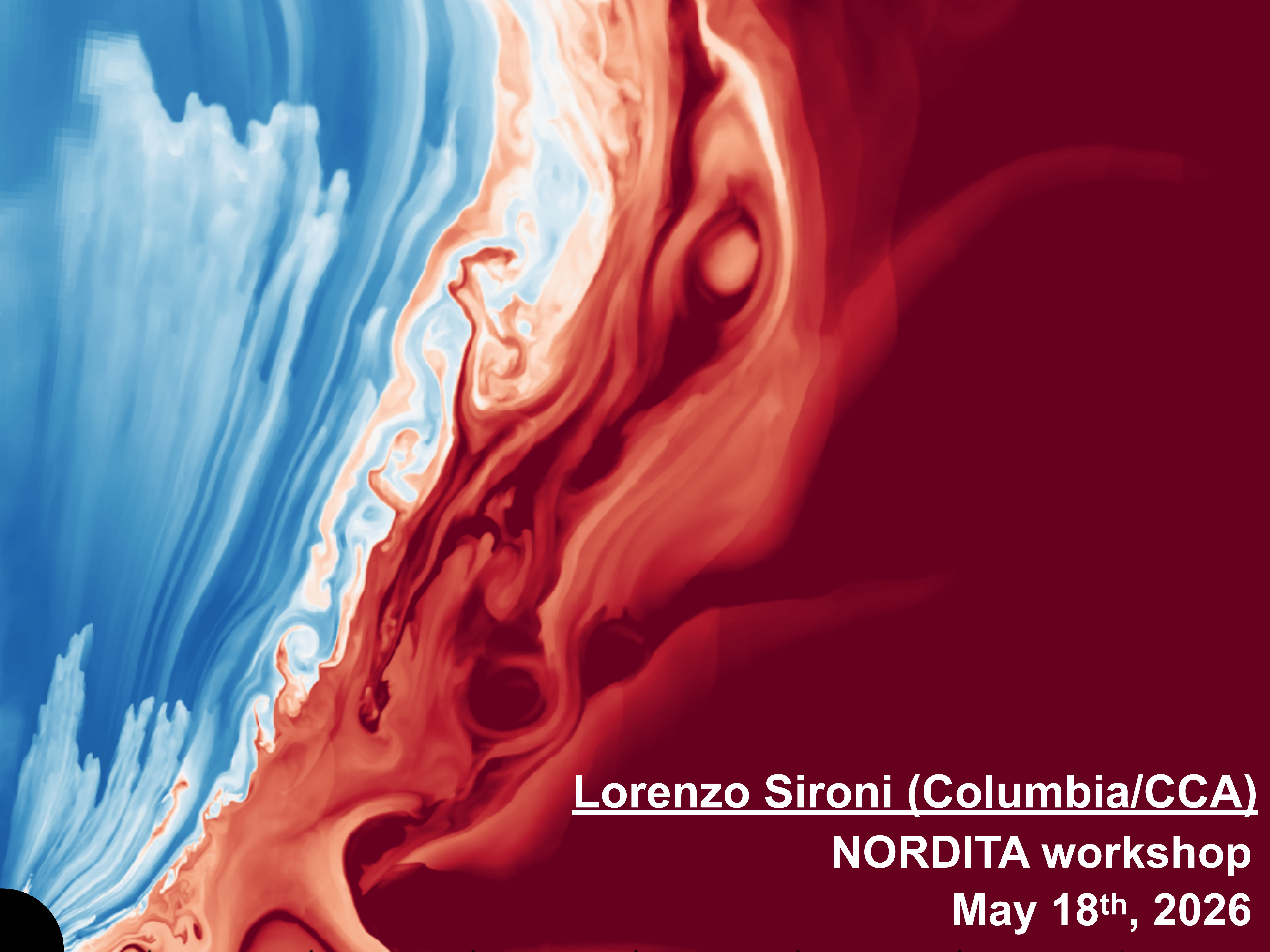


Lorenzo Sironi (Columbia/CCA)

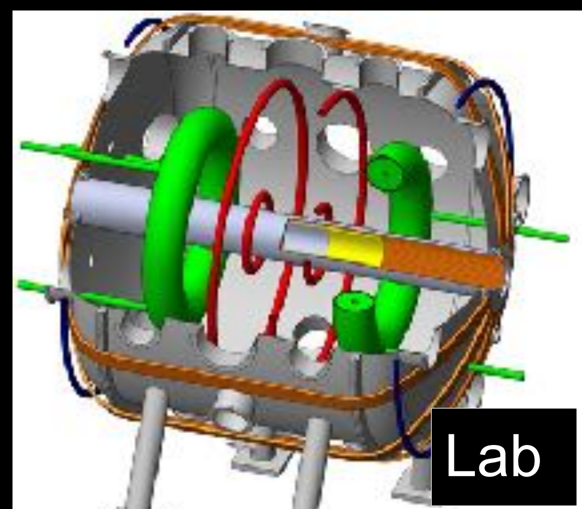
NORDITA workshop

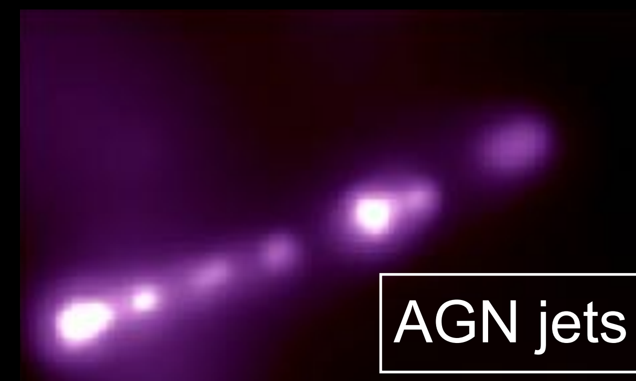
May 18th, 2026

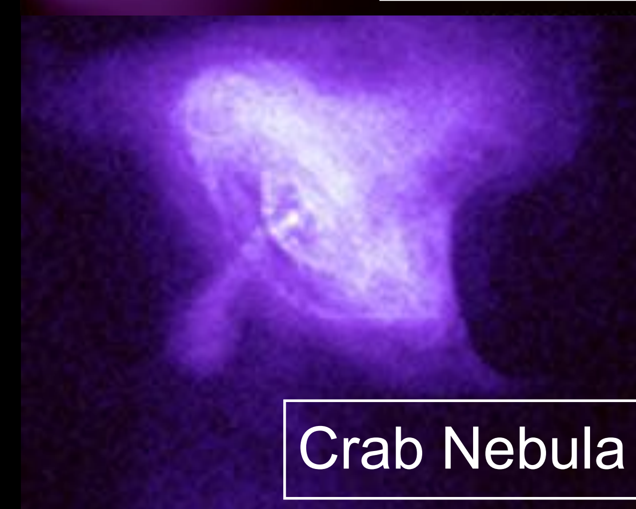
Reconnection in high-energy astro

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

σ≪1 σ≫1







Magnetically-dominated / relativistic: $\sigma = \frac{B_0^2}{4\pi\rho c^2} \gg 1$ or $v_A \sim c$

Collisionless relativistic reconnection [RR]

for a recent ARAA review: Sironi, Uzdensky & Giannios, arXiv:2506.02101

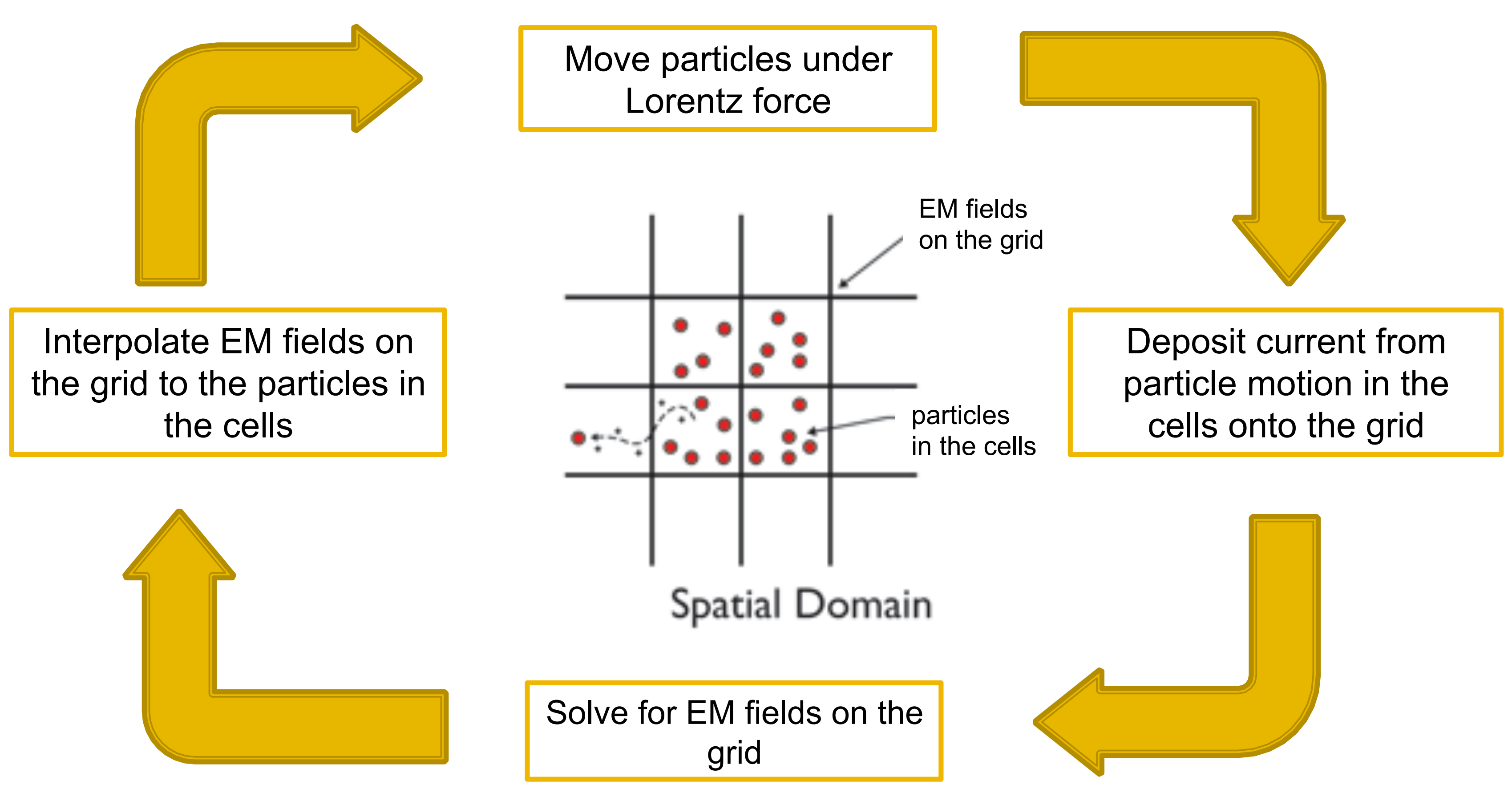

with vital contributions from H. Hakobyan, B. Cerutti, L. Willingale, H. Ji




The PIC method

Particle-in-Cell (PIC) method:

It is the most fundamental way of capturing the interplay of charged particles and electromagnetic fields.



[credit: Xinyi Guo]

The computational challenge:

The *microscopic* scales of PIC simulations are much smaller than *astronomical* scales.

Typical plasma length (c/ω_p) and time ($1/\omega_p$) scales are:

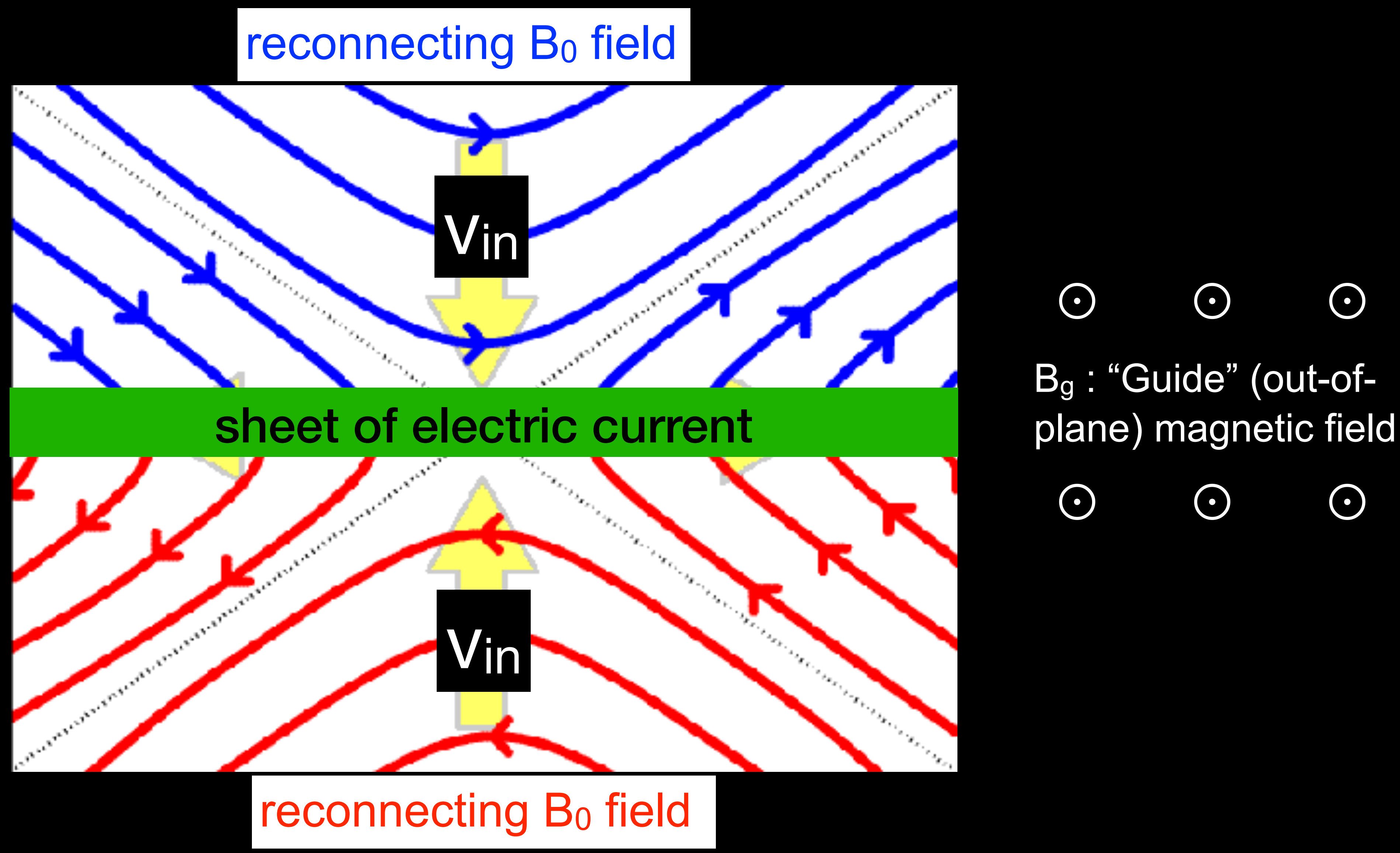
$$\frac{c}{\omega_p} \simeq 5.5 \times 10^5 \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{cm} \qquad \frac{1}{\omega_p} \simeq 1.8 \times 10^{-5} \left(\frac{n}{1\,\mathrm{cm}^{-3}}\right)^{-1/2} \mathrm{s}$$

$$\omega_p = \omega_{pe} \quad ; \quad \omega_{pi} = \omega_{pe}\sqrt{m_e/m_i}$$

The dissipation rate in RR

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

$$v_A \sim c$$



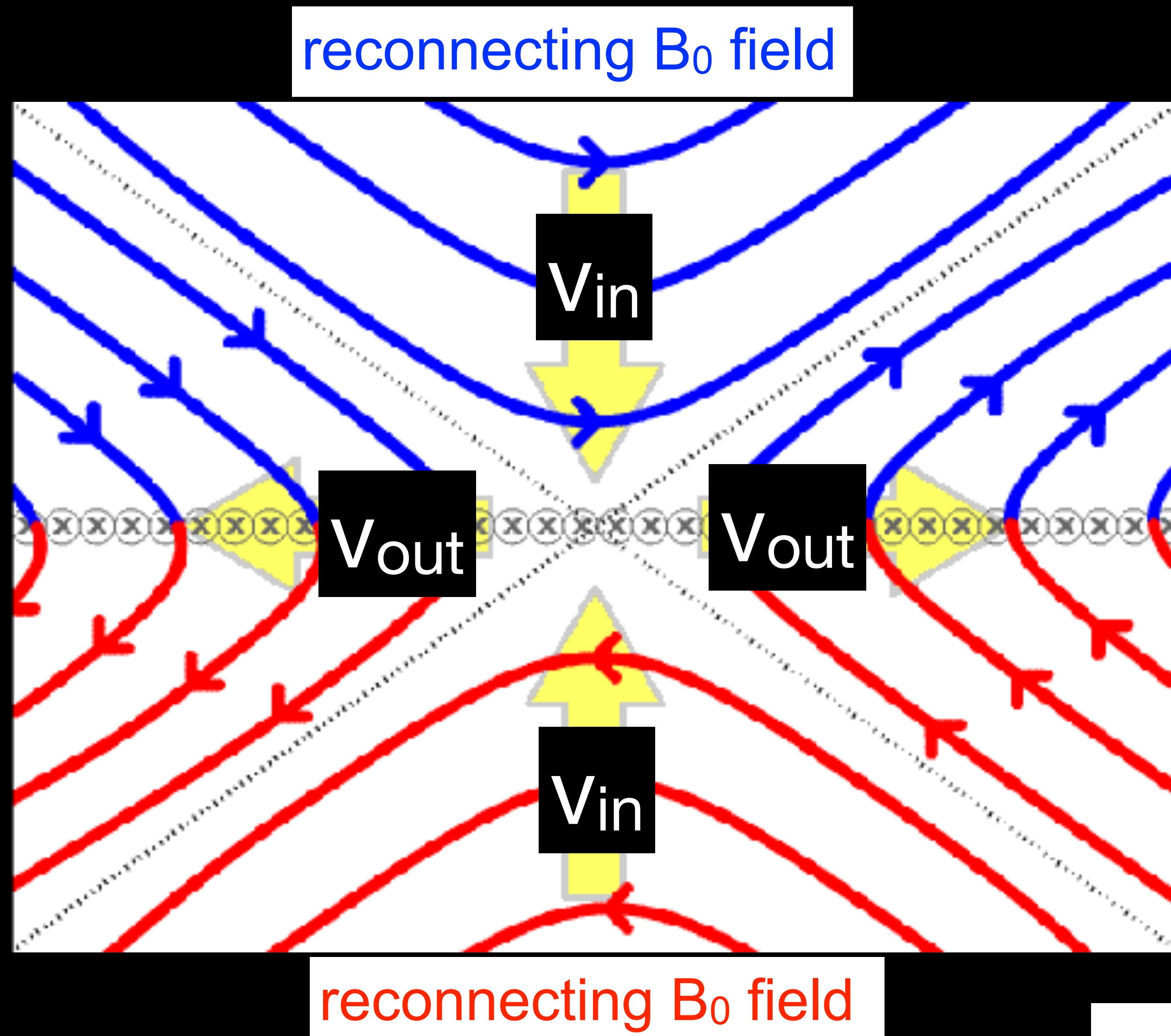
- The plasma flows into the reconnection region with $v_{\rm in} \sim 0.1 v_A \sim 0.1c$

→ RR can efficiently dissipate the *B*-field energy (at rate ~ 0.1 c).

The energy census in RR

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

$$v_A \sim c$$



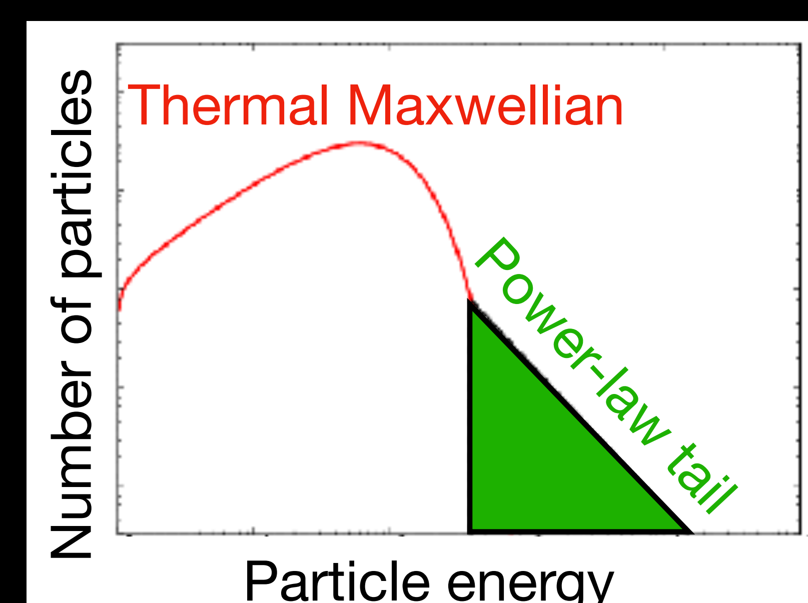
⊙ ⊙ ⊙

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

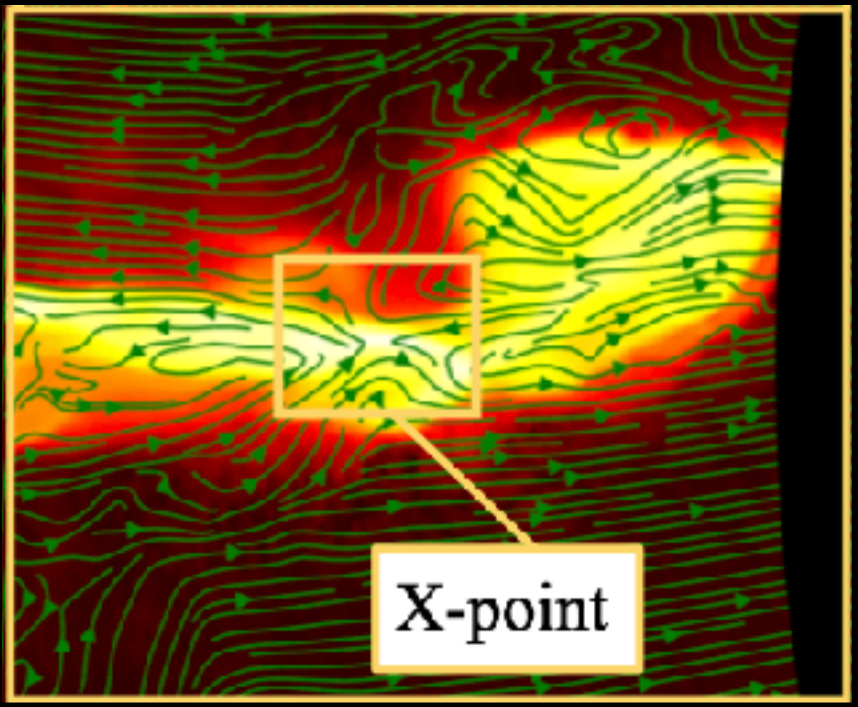
⊙ ⊙ ⊙

The dissipated *B*-field energy results in:

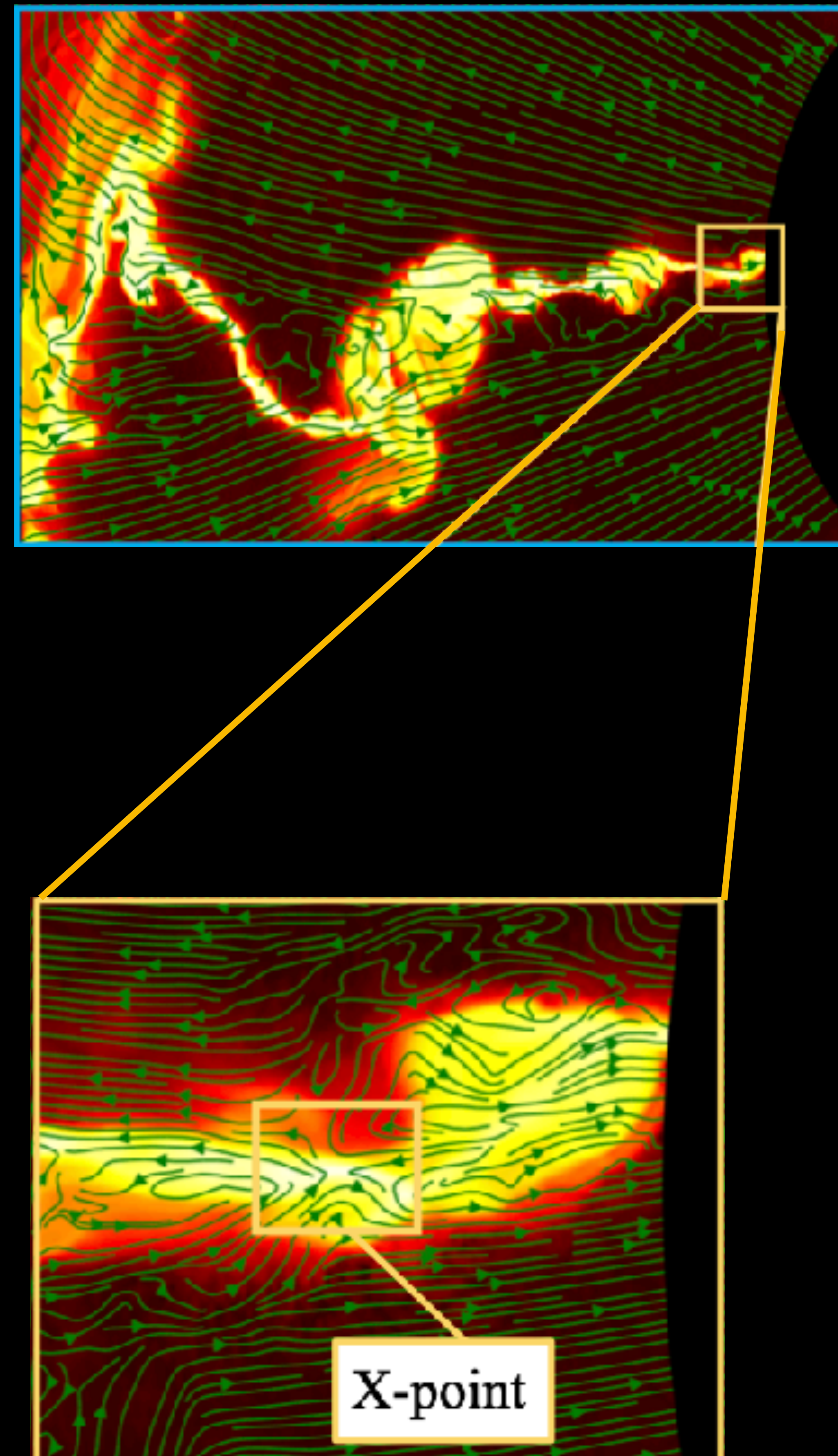
- bulk motions of the outflowing plasma
- non-thermal particles, accelerated via $E \sim (v_{\rm in}/c)\, B_0 \sim 0.1\, B_0$

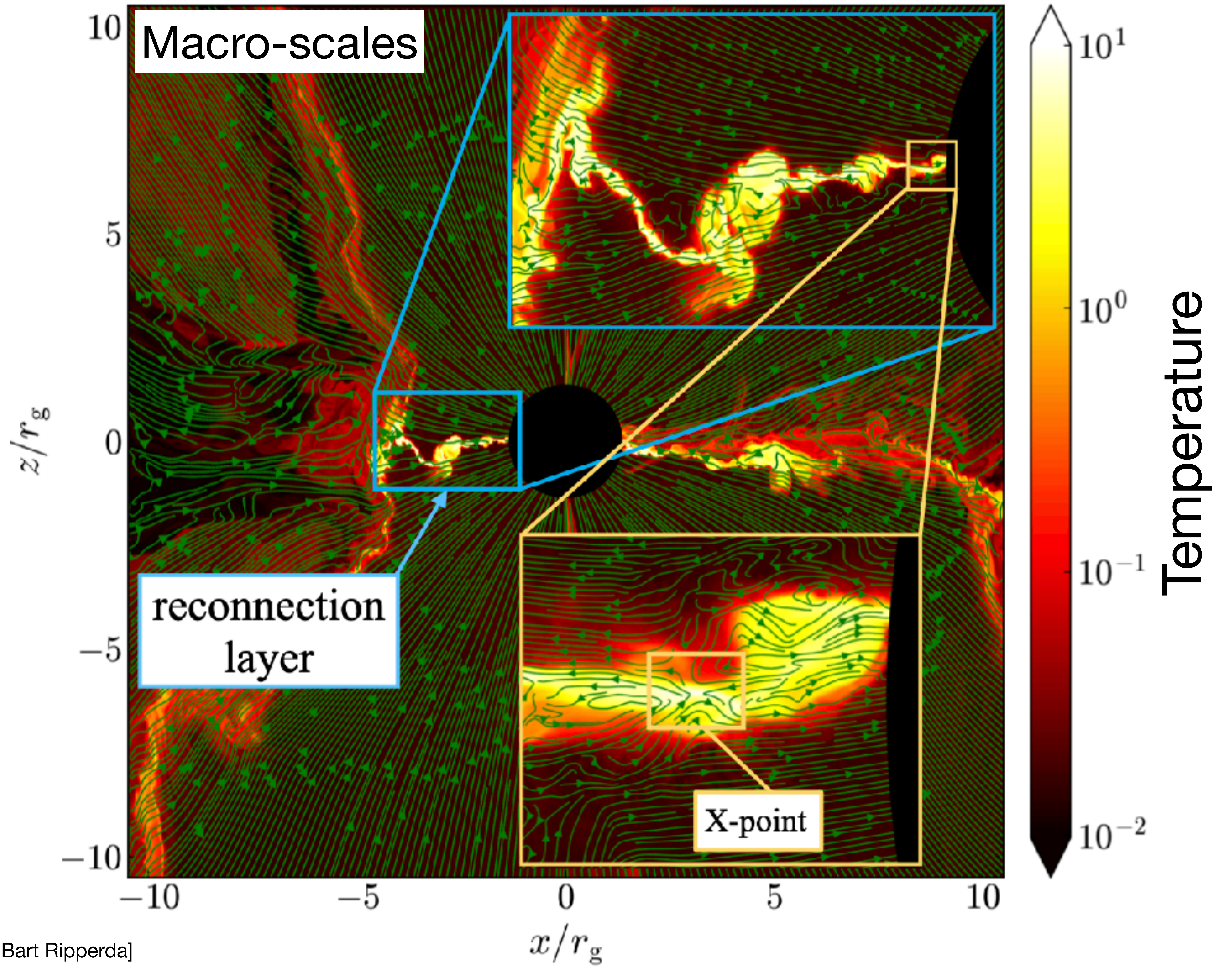


Micro-scales



Meso-scales





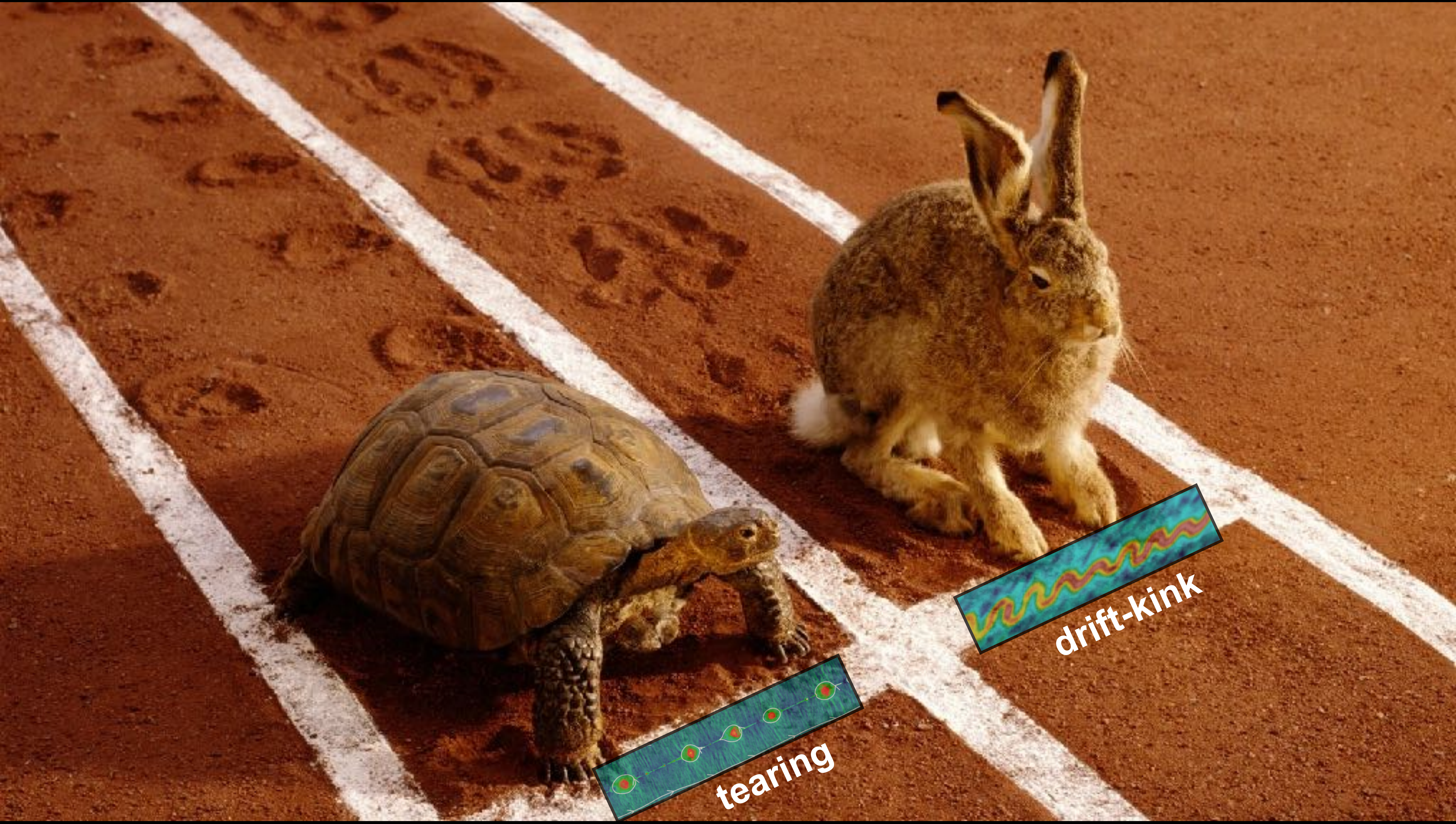
[credit: Bart Ripperda]

Micro-scales

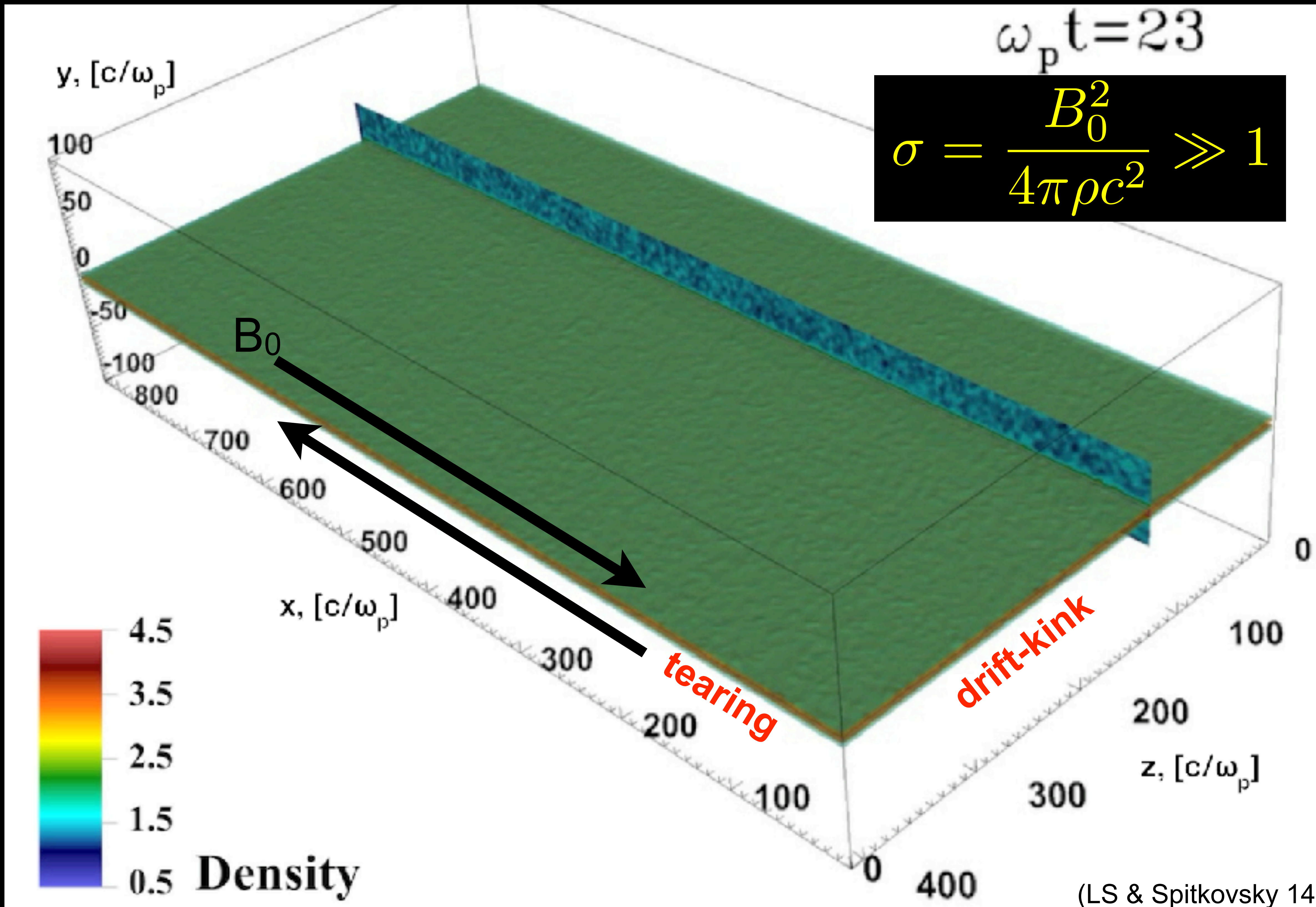
The fluid picture of RR: a slew of instabilities

	2D	3D
primary		

The tortoise and the hare



The tearing mode wins the race



(LS & Spitkovsky 14)

The late-time evolution is dominated by tearing and flux-rope-kink modes

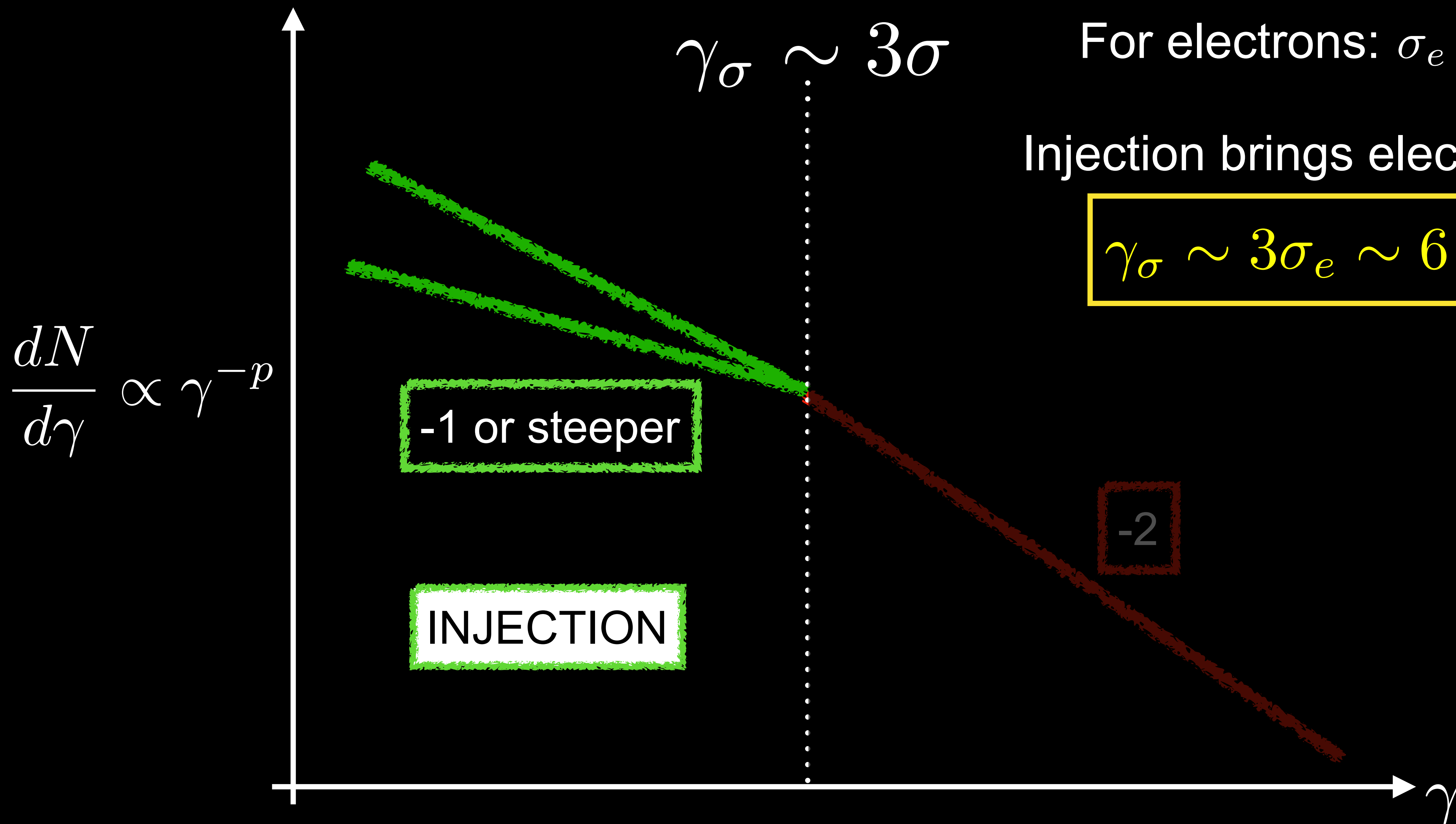
Nonthermal particle acceleration in RR

Reconnection makes broken power laws

For electrons: $\sigma_e = \dfrac{B_0^2}{4\pi\rho_e c^2}$

Injection brings electrons up to

$$\gamma_\sigma \sim 3\sigma_e \sim 6\times10^3\sigma$$



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 ~ σ-independent slope of *p*~2.

Particle injection: from $\gamma\sim1$ to $\gamma\sim3\sigma$

In ideal MHD, the electric field is *always* $\mathbf{E} = -\frac{\mathbf{v}}{c} \times \mathbf{B}$

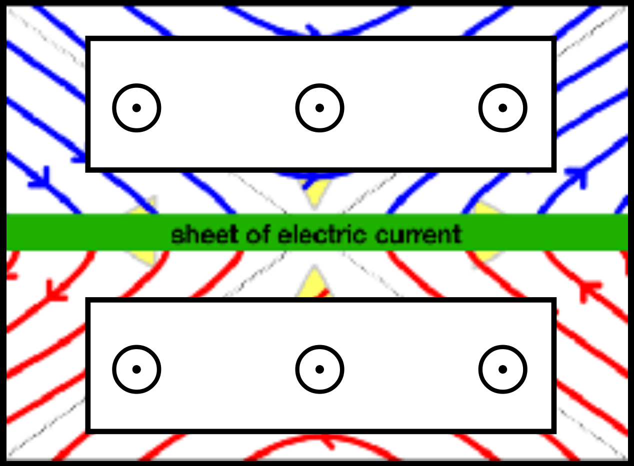
Particles are injected if they interact with non-ideal fields $\mathbf{E} \neq -\frac{\mathbf{v}}{c} \times \mathbf{B}$

$E > B$

for $B_g/B_0 \lesssim 0.1$

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

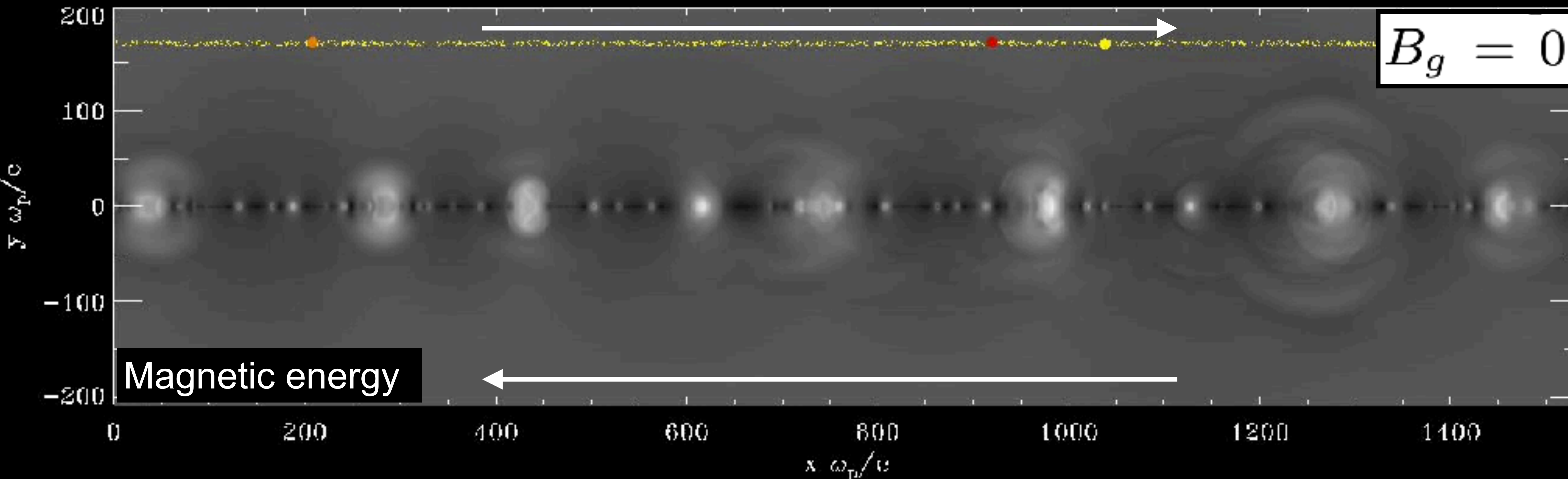
for $B_g/B_0 \gtrsim 0.1$

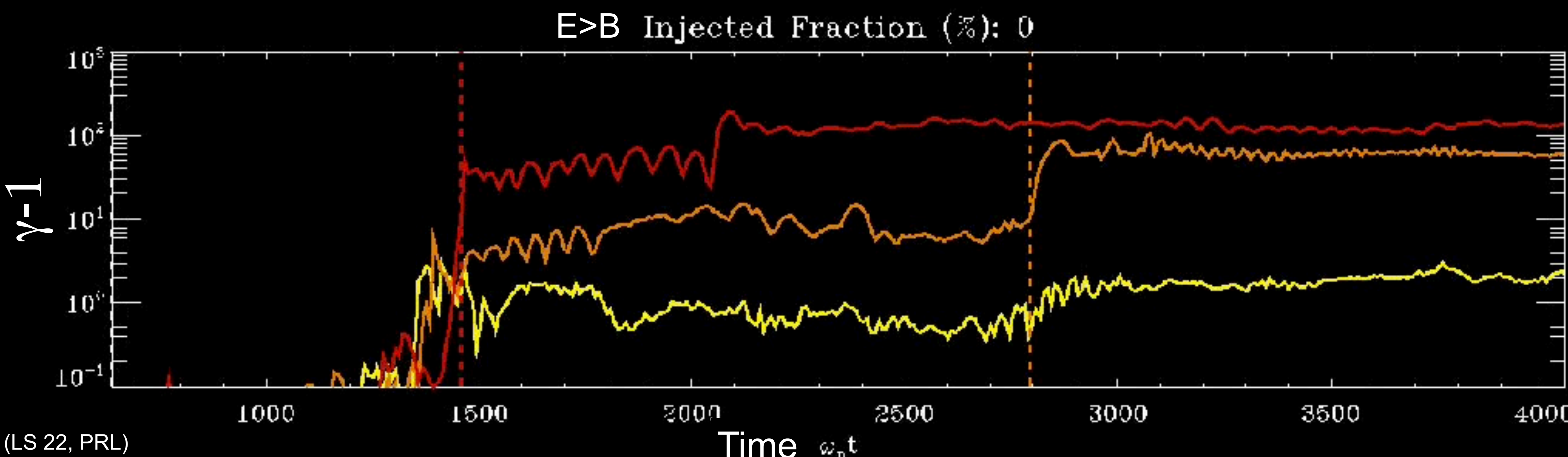


B_g : “Guide” (out-of-plane) magnetic field

Particle injection: from γ~1 to γ~3σ

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



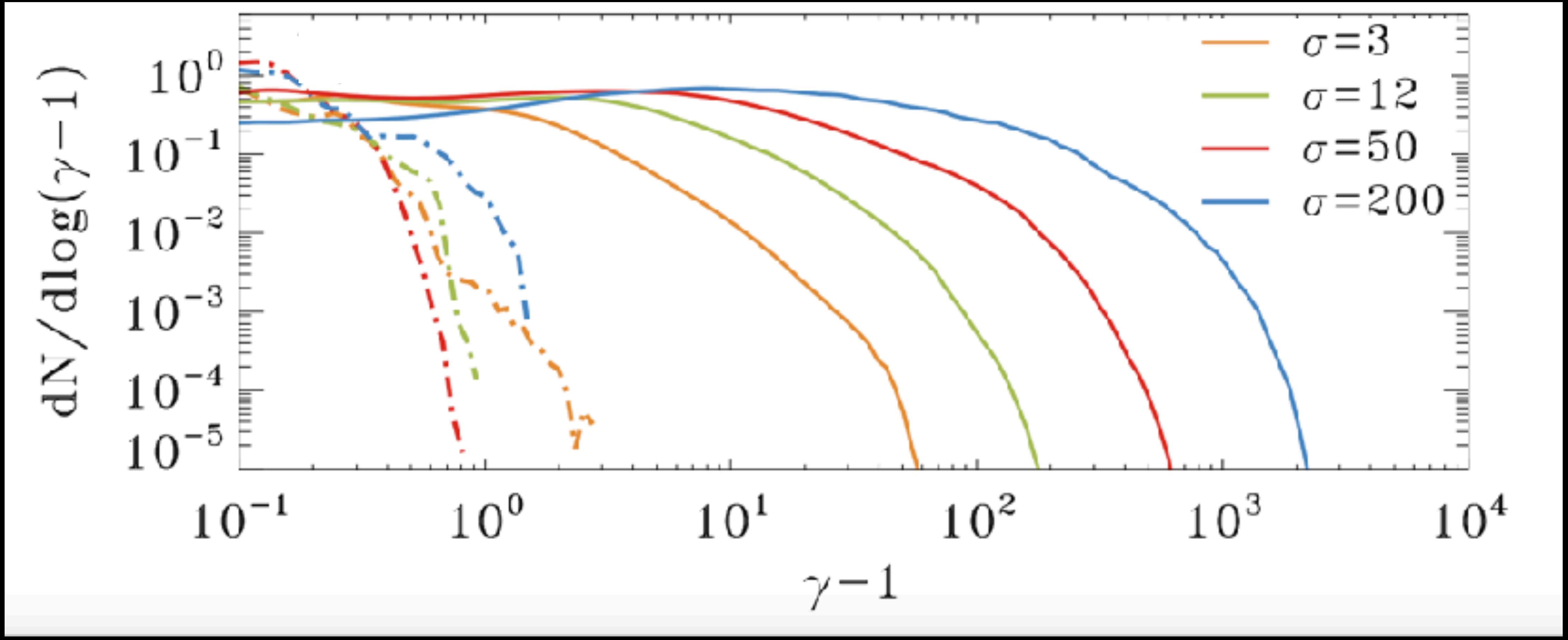


(LS 22, PRL)

How to (artificially) inhibit particle injection?

Test-particles: evolved like regular particles, but they do not contribute to the current.

$B_g = B_0$



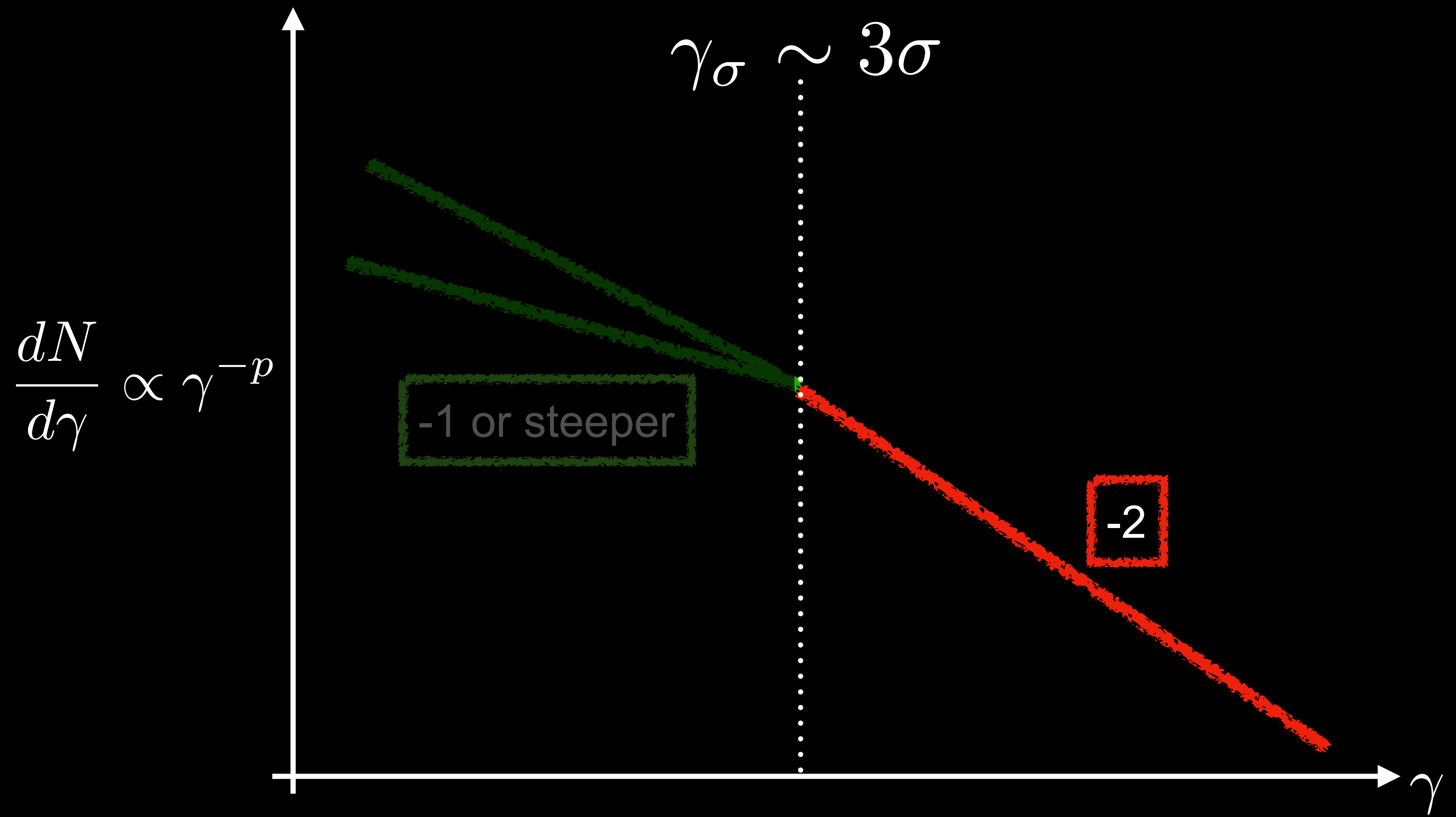
(LS 22, PRL; French+23, 25)

Solid: spectrum of *regular particles*.

Dot-dashed: spectrum of *testparticles* evolved without $E_{\|} = \mathbf{E} \cdot \mathbf{B}/B$

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

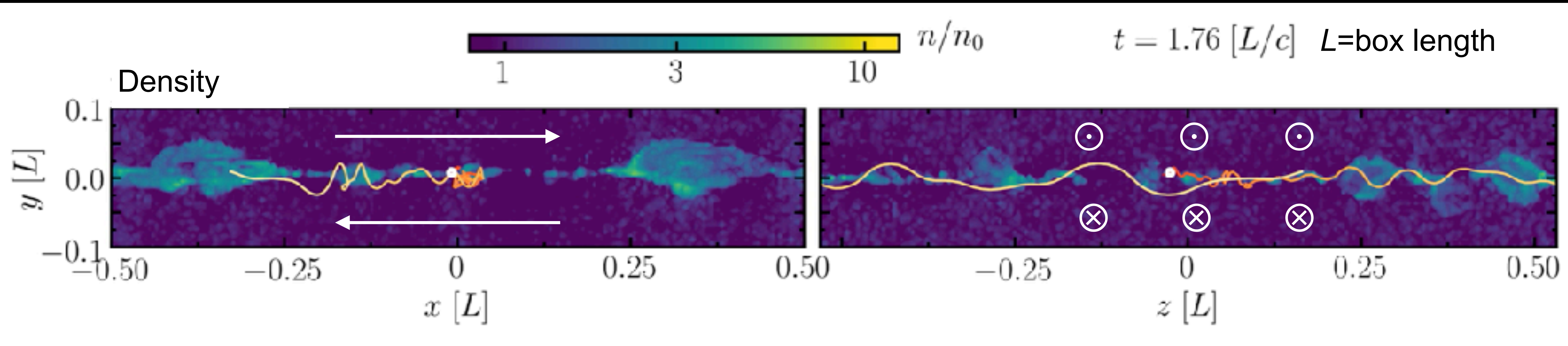
Reconnection makes broken power laws



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

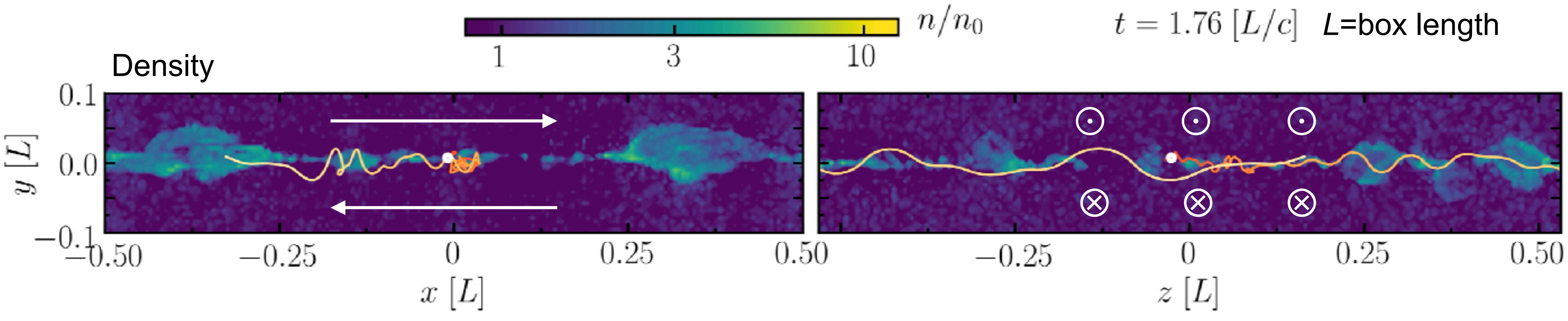
At $\gamma \gtrsim 3\sigma$ 3D reconnection leads to a ~ σ-independent slope of $p \sim 2$.

Particle acceleration to $\gamma \gg 3\sigma$



- In 3D, some particles escape *out of* the reconnected plasma and swim “freestyle” around the reconnection layer.

Particle acceleration to $\gamma \gg 3\sigma$

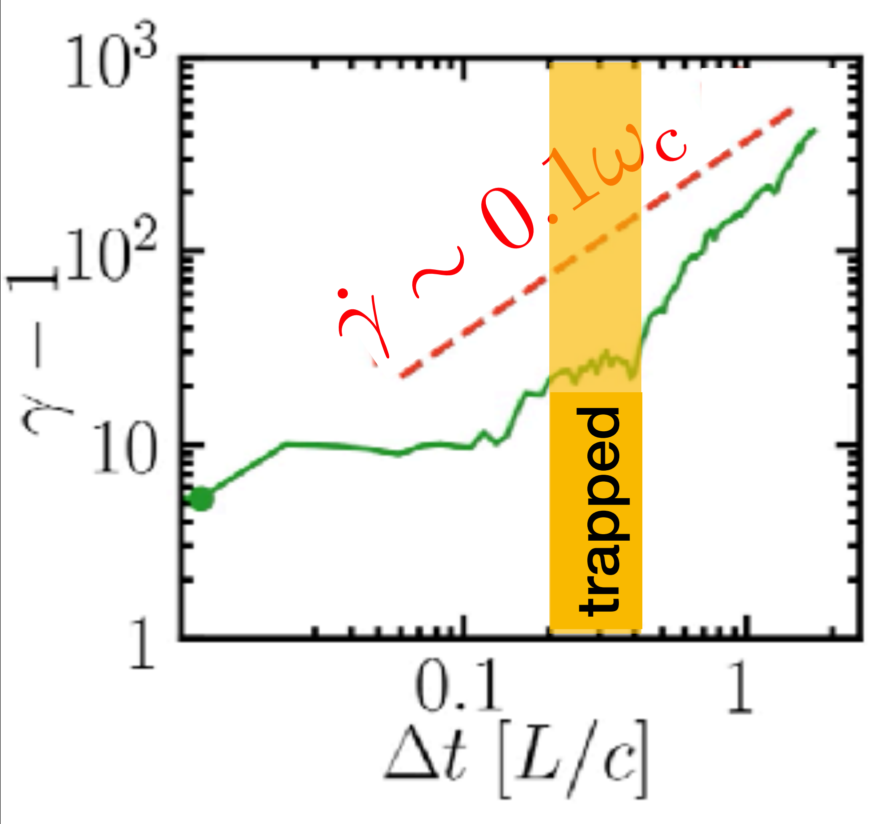


- In 3D, some particles escape *out of* the reconnected plasma and swim "freestyle" around the reconnection layer.

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

- The energy gain rate approaches $\sim eE\,c$

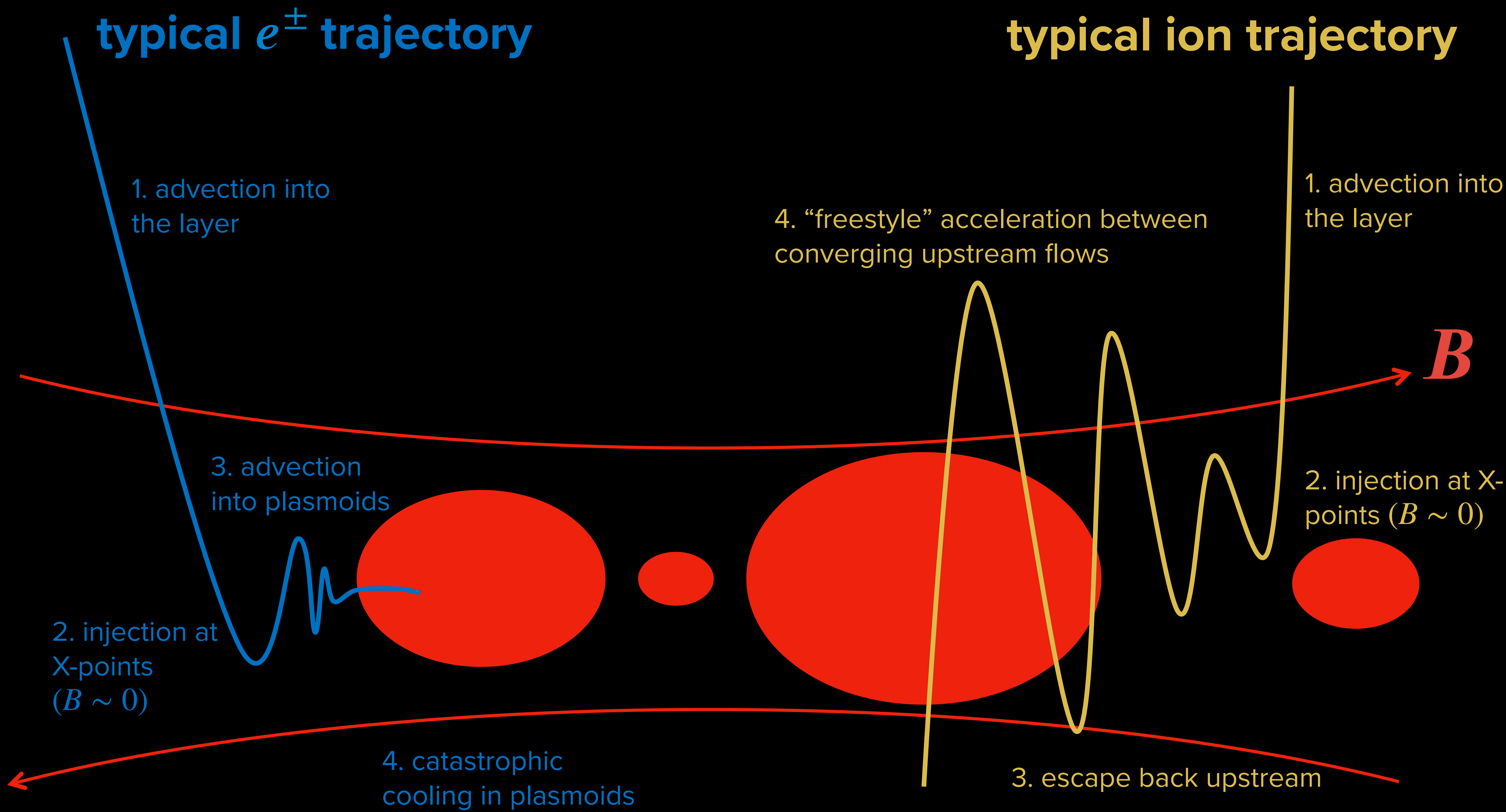
$$\sim 0.1 e B_0 c$$



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

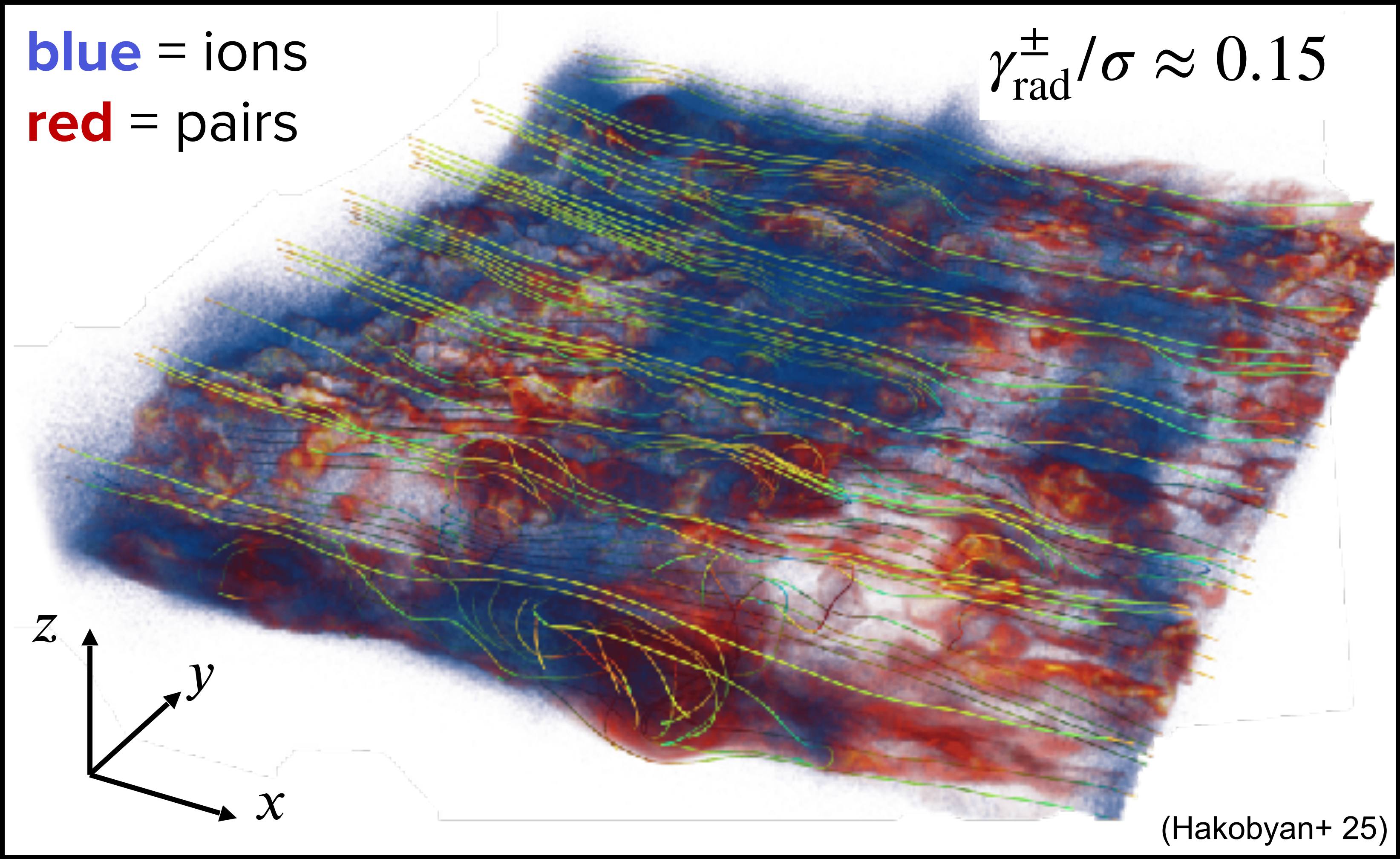
Pair-ion relativistic reconnection

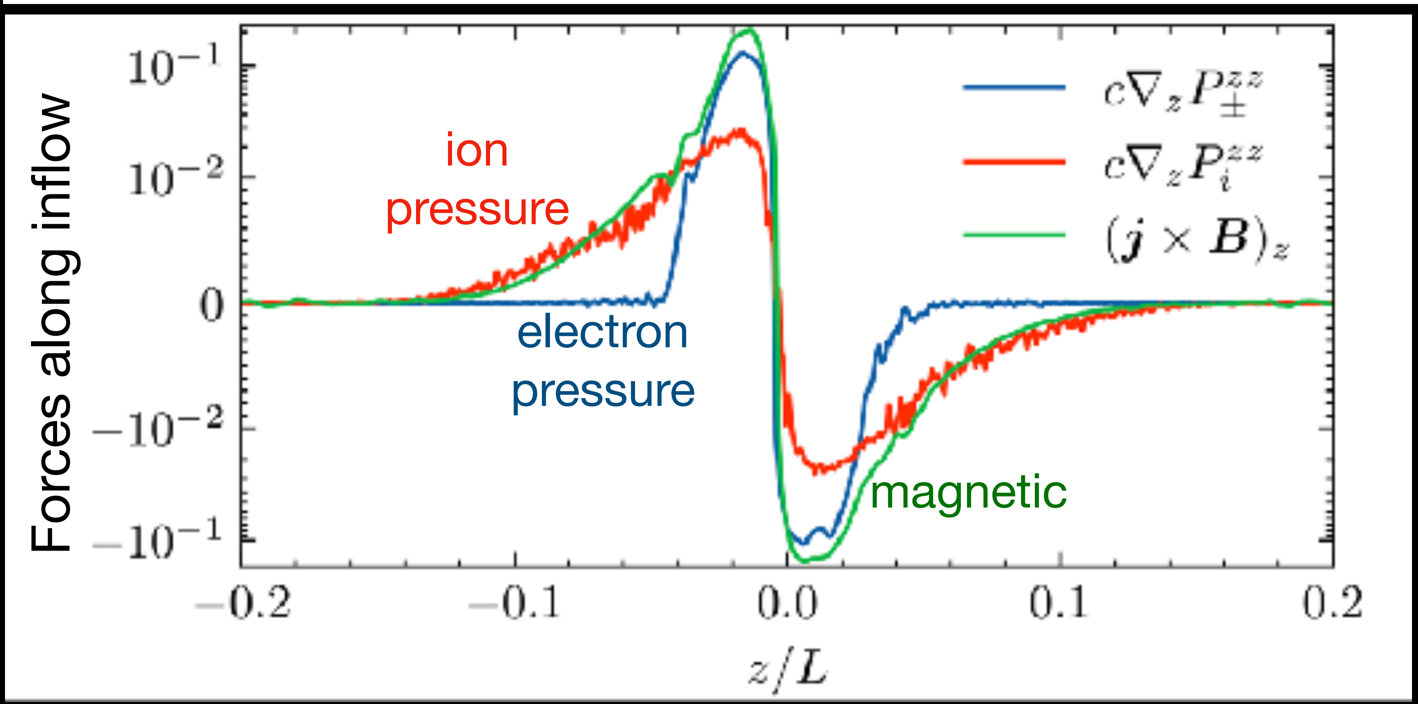
- Pairs dominate in number and rest mass. They are strongly cooled ($\gamma_{\rm rad}^{\pm}/\sigma \ll 1$).
- Ions are not subject to cooling.



Pairs and ions decouple

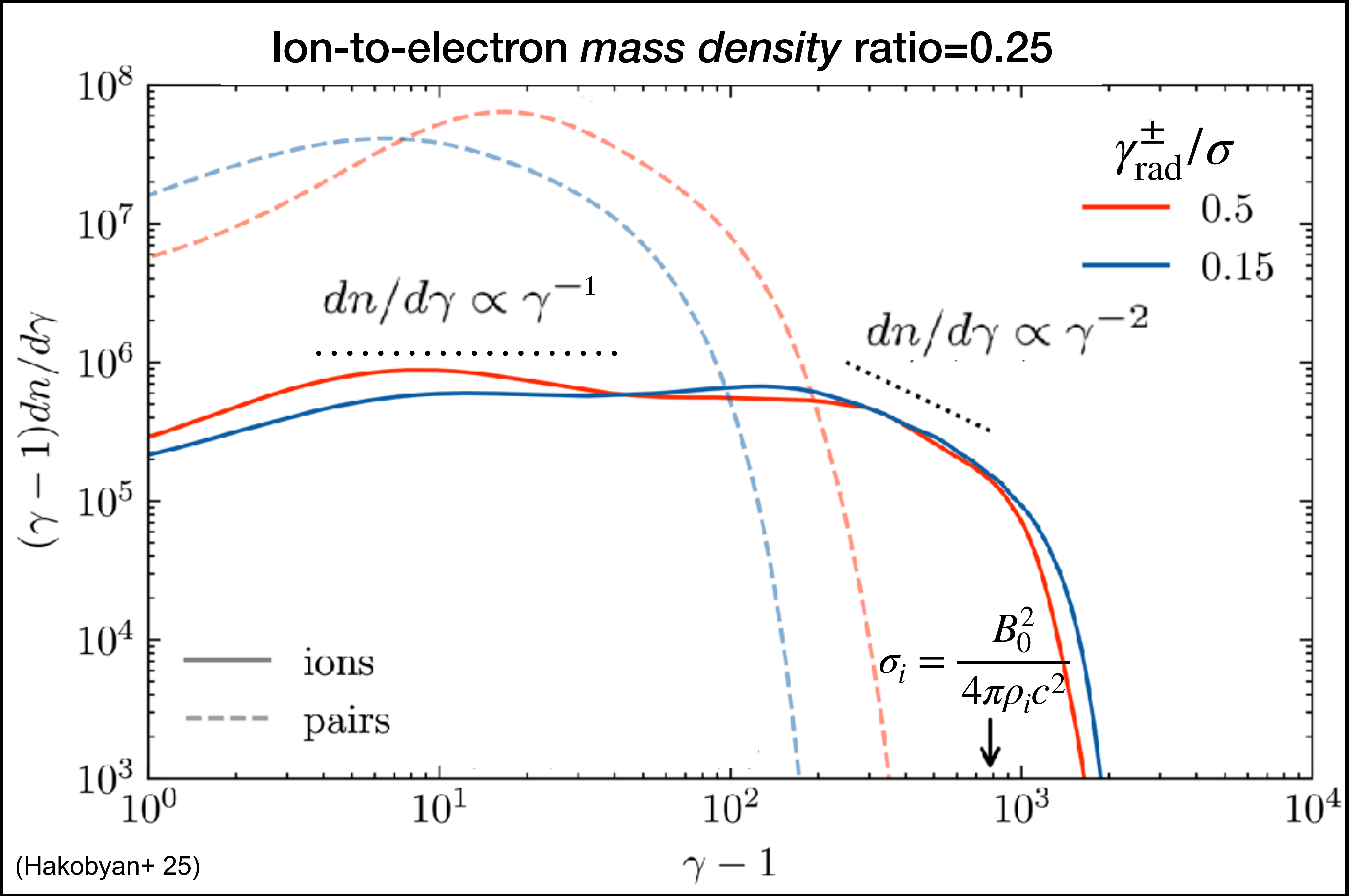
Ion-to-electron *mass density* ratio=0.25





- Pairs and ions are decoupled.
- Far from the midplane, magnetic stresses are in force balance with *ion* pressure gradients.

The ion spectrum in pair-ion reconnection

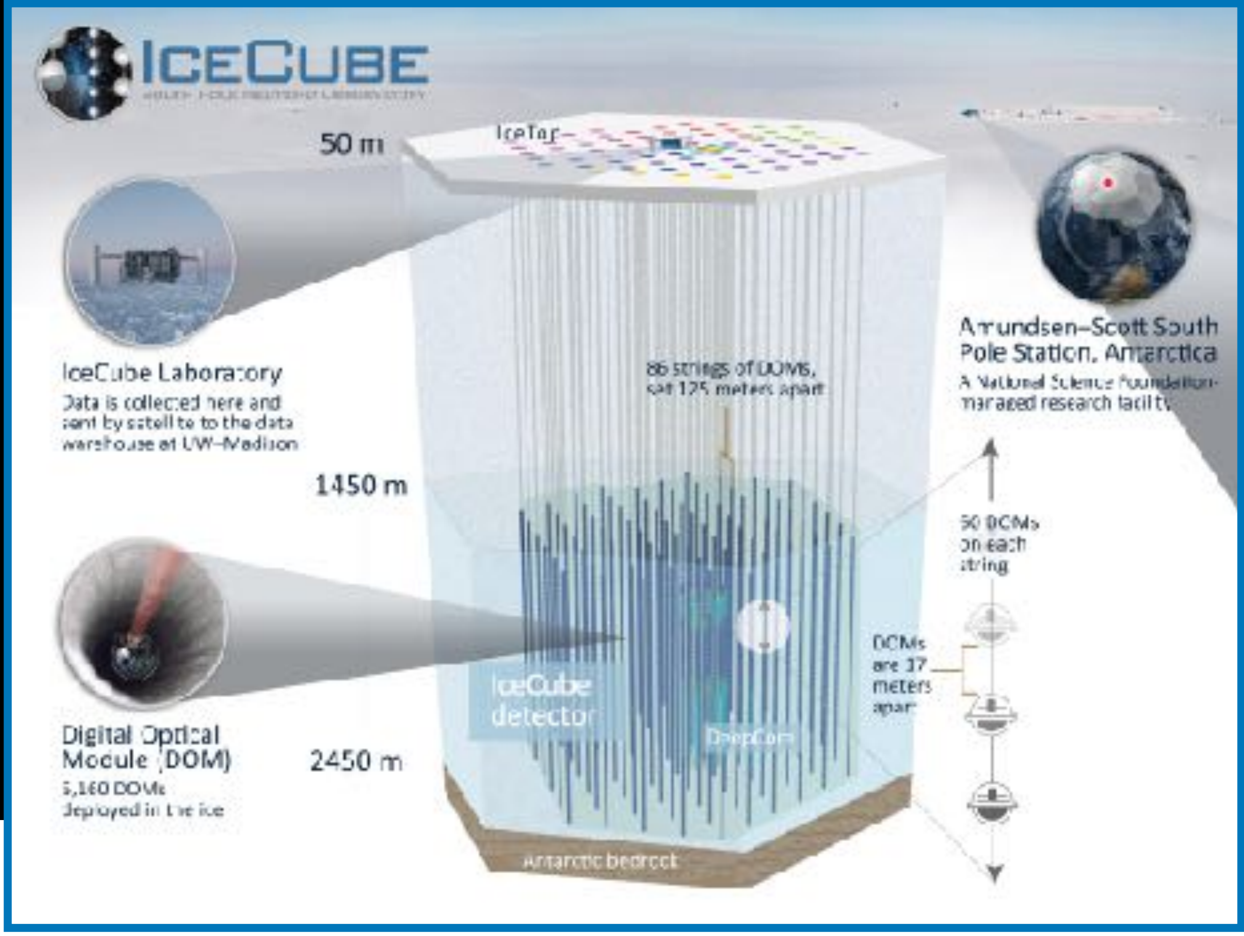


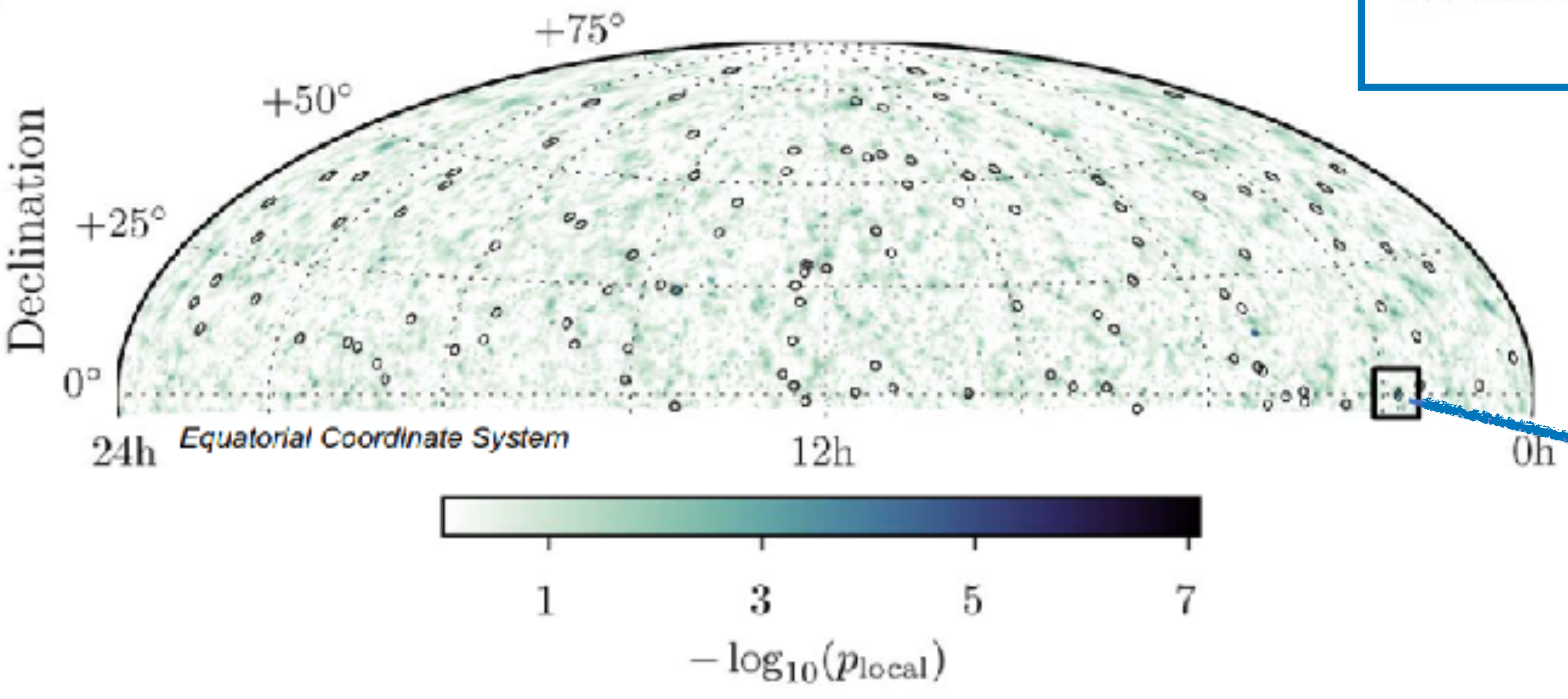
The ion spectrum is a broken power law:

- The low-energy slope is -1, the high-energy slope is -2.
- The break Lorentz factor is $\sim 0.2\,\sigma_i \rightarrow$ near-equipartition with magnetic energy

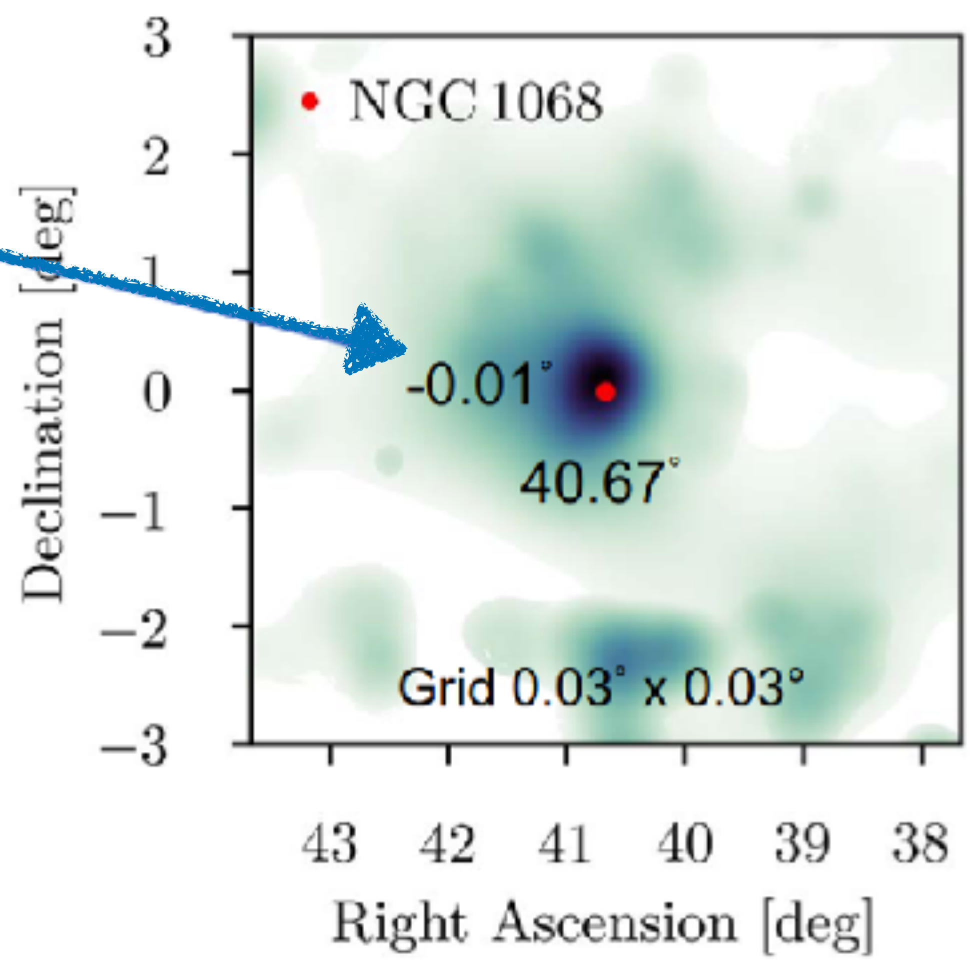
Proton acceleration in RR: implications for TeV neutrinos

A “hot spot” in the *IceCube* neutrino sky



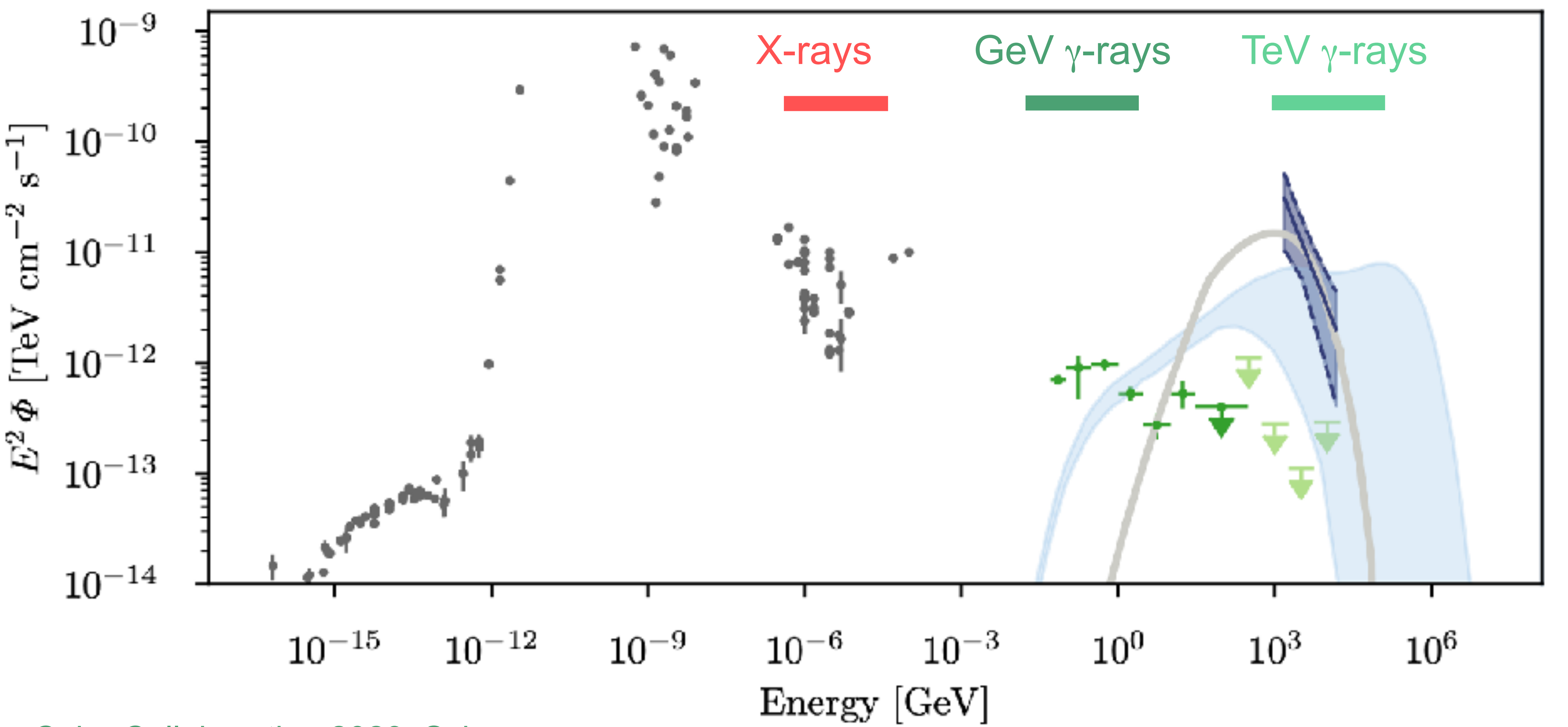


[IceCube Collab. 2023, Science]



Astrophysical neutrinos from the Seyfert galaxy NGC 1068.

Multi-messenger observations

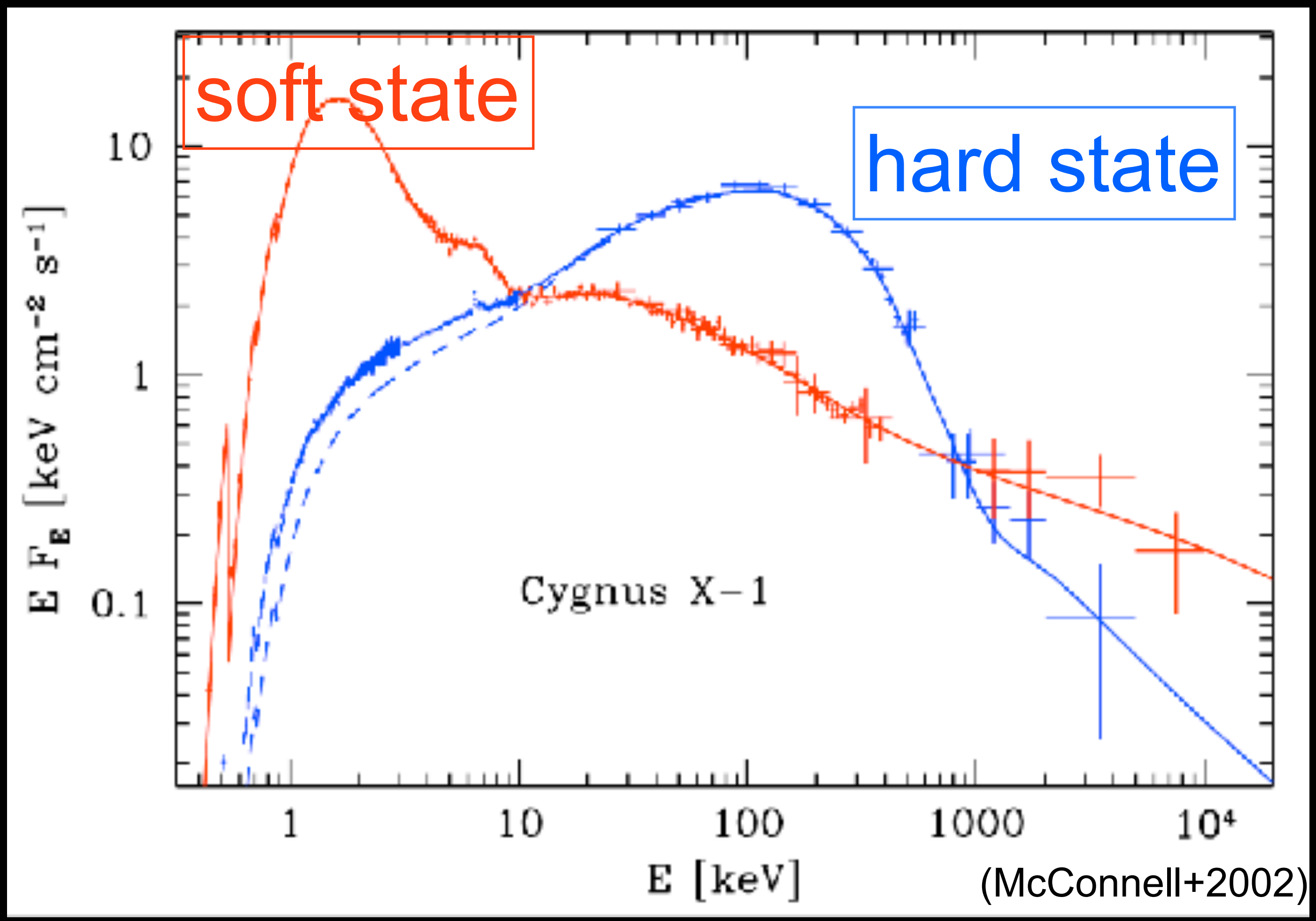


IceCube Collaboration 2023, Science

- $L_\nu \sim (0.8 - 4) \times 10^{42}$ ergs/s [all flavor]
- $E_{\nu,\mathrm{pk}} \sim$ TeV

- $L_X \sim 3^{+3}_{-2} \times 10^{43}$ ergs/s [2-10 keV] of “coronal” origin
- GeV and TeV luminosity $\ll L_\nu$

What/Where is the black hole (BH) corona?

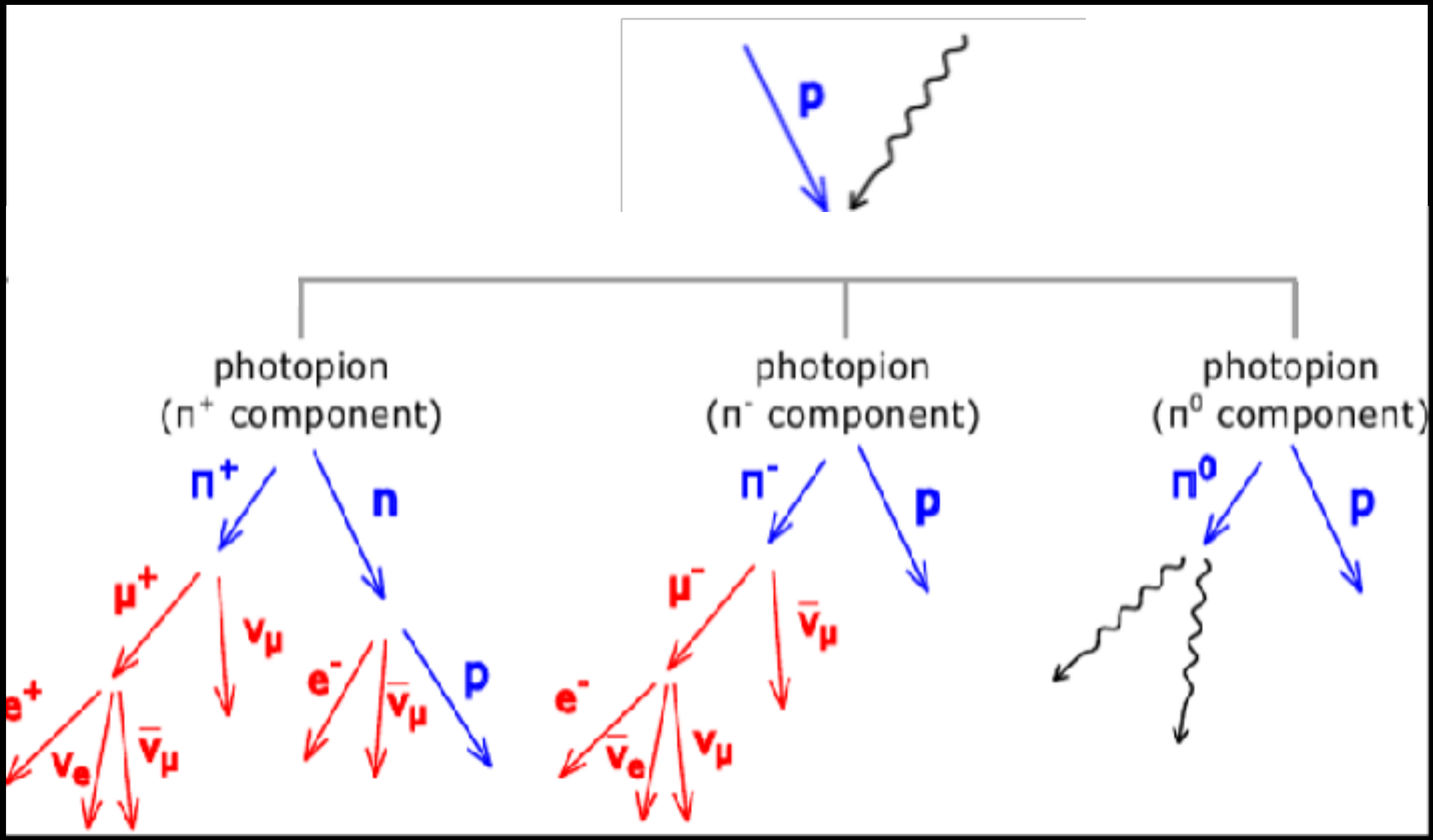


Soft state: thermal emission from the BH accretion disk.

Hard state: soft disk photons are scattered to higher energies by “coronal” electrons with temperature ~ 100 keV.

Neutrino production

High-energy neutrinos require high-energy protons.



The hadronic production of neutrinos should give comparable <u>neutrino</u> and <u>gamma-ray</u> luminosities.

A reconnection-based coronal model

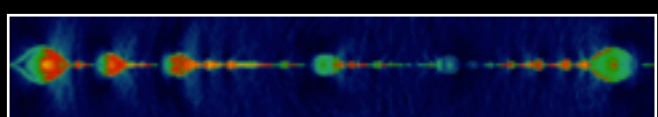
EM flux into the reconnection layer

~ 0.1 efficiency [PIC]

Relativistic proton energy density

+

Radiative efficiency ~ 0.1 [PIC]

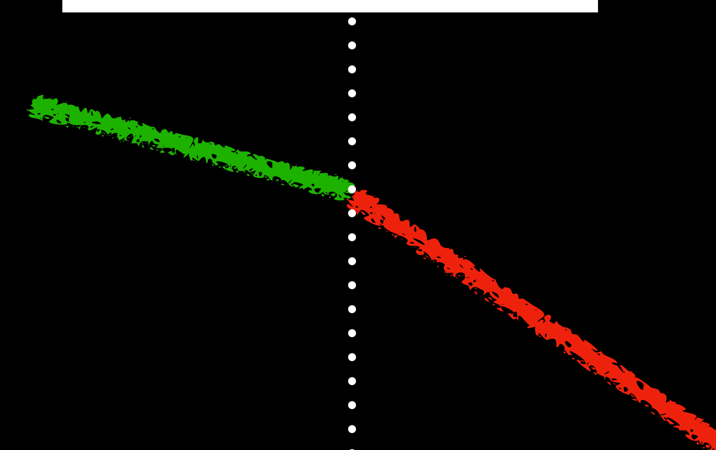


Hard X-ray flux

p-γ interactions

Neutrino spectrum

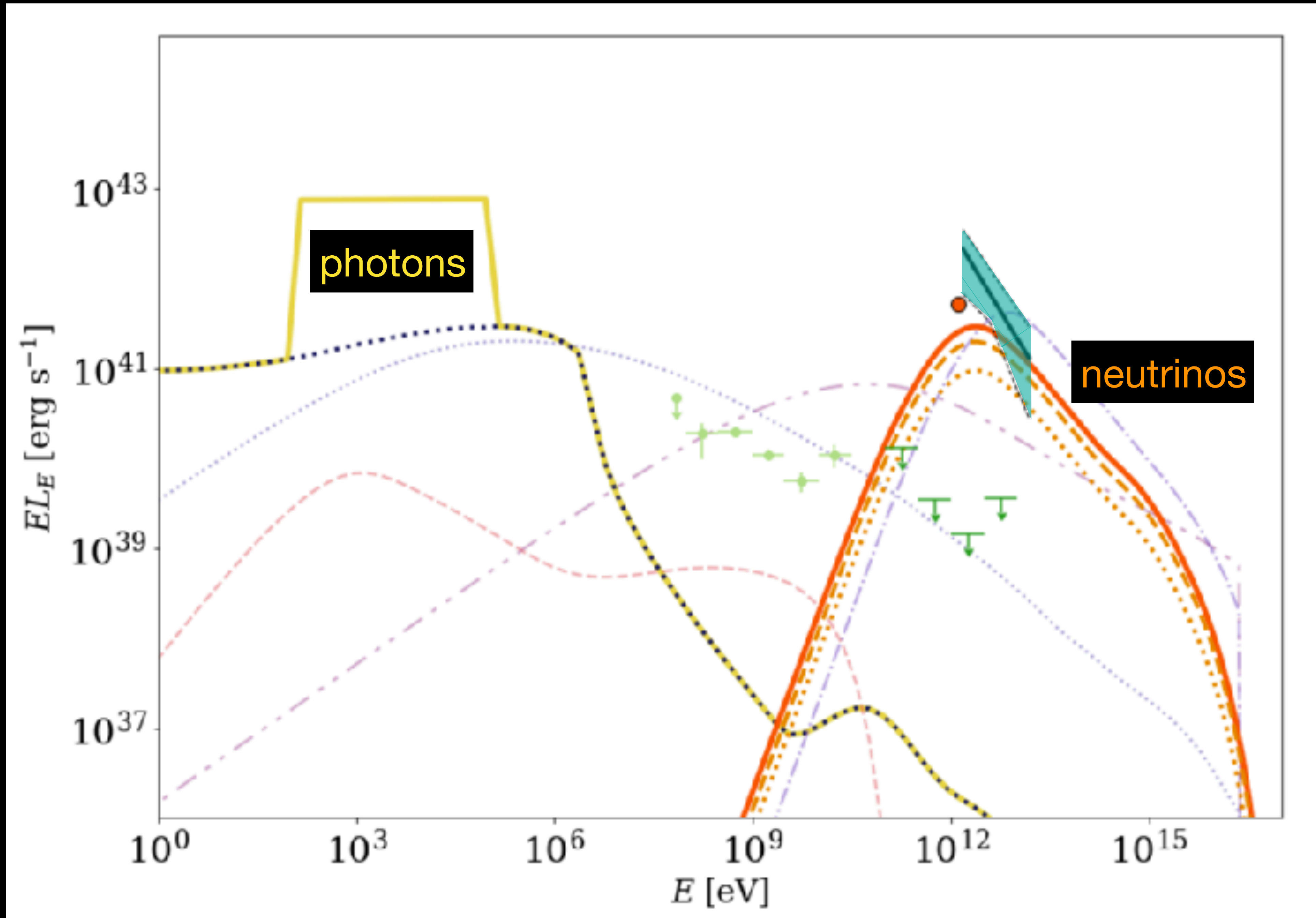
Proton energy spectrum



Thomson depth ~ 1

Pair density

Neutrino and photon spectra



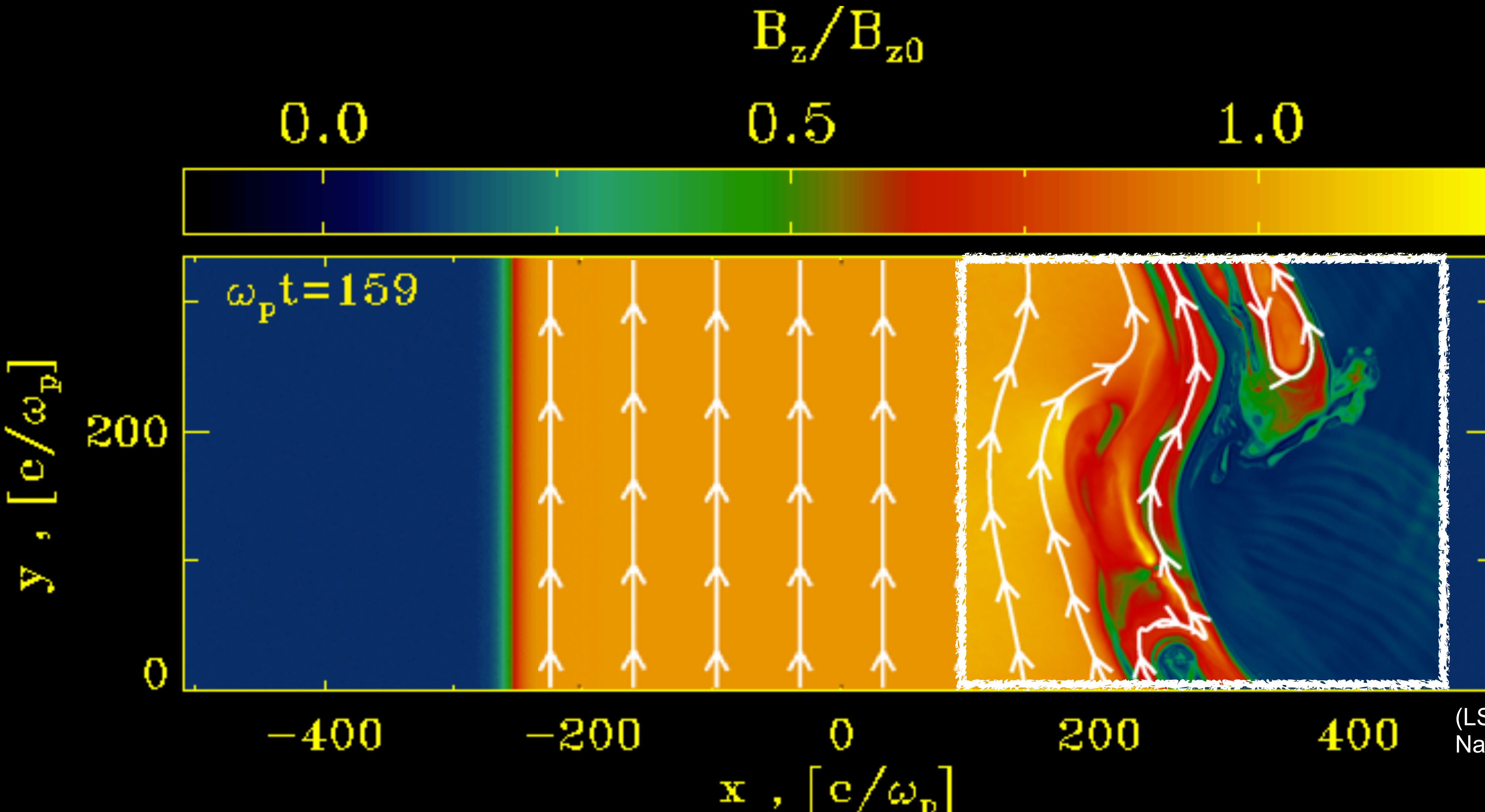
(Fiorillo+ 24, Karavola+ 25)

- The neutrino-producing "corona" is compact (~ few r_g) and pair-dominated.
- GeV-TeV photons of hadronic origin are absorbed locally.

They cascade to MeV energies and result in pairs that naturally account for $\tau_T \sim 1$

Meso-scales

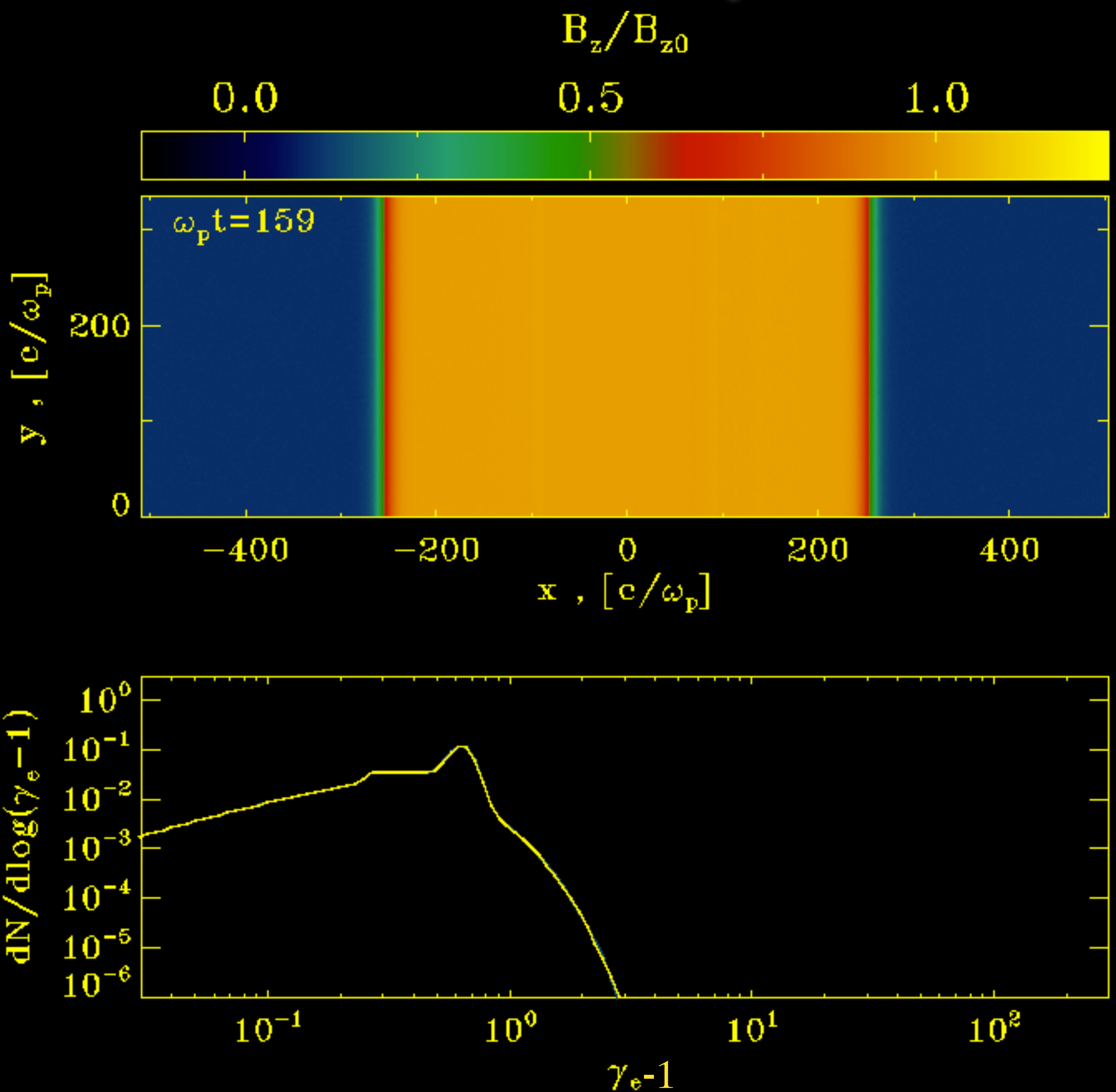
RR as by-product of MHD instabilities



(LS, Rowan & Narayan 21)

RR (with $B_g/B_0 \sim 1$) is a by-product of nonlinear Kelvin-Helmholtz (KH) vortices.

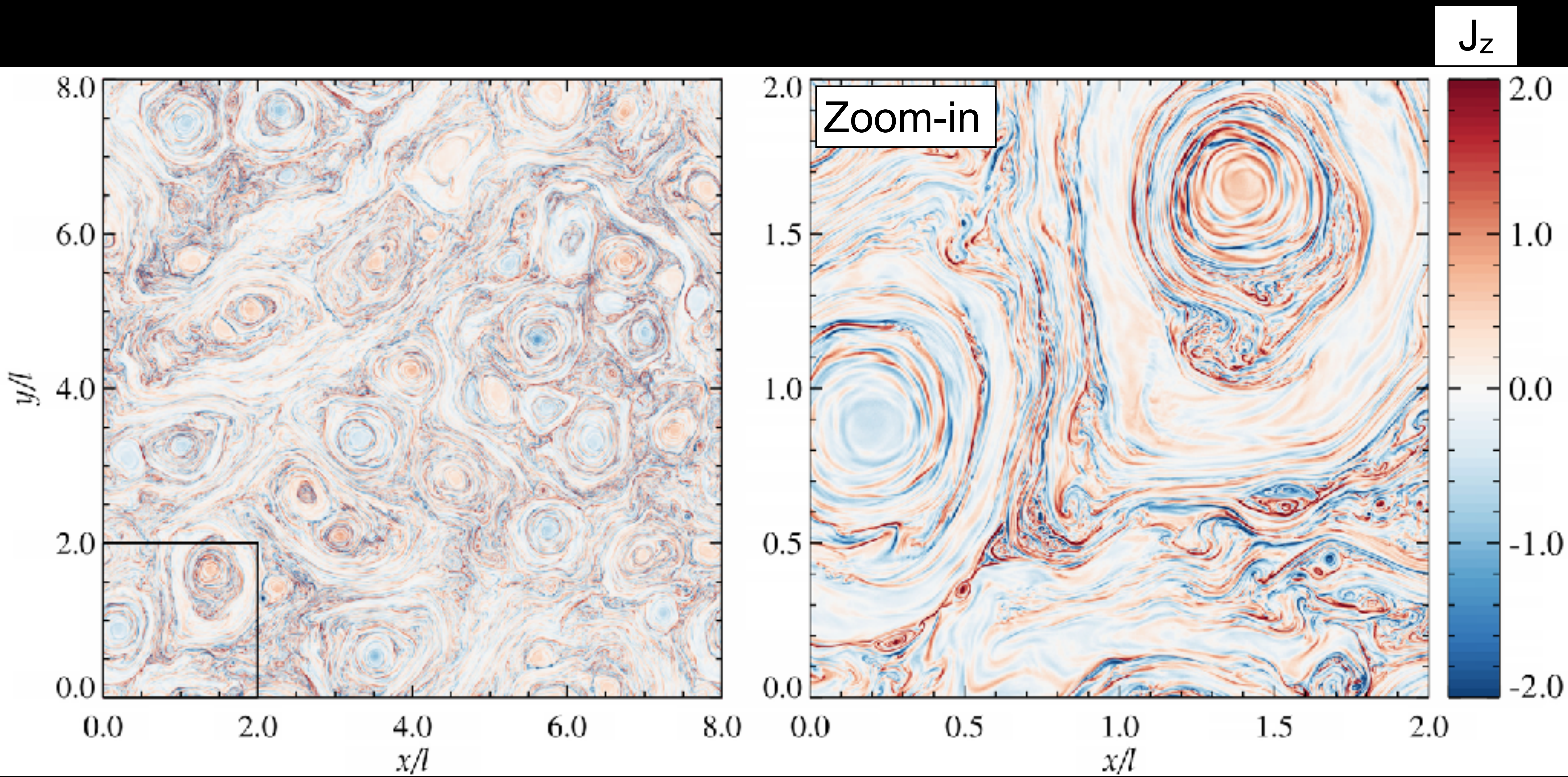
KH → RR → particle acceleration



KH-driven RR leads to efficient particle acceleration.

(LS, Rowan & Narayan 21)

RR as by-product of magnetized turbulence



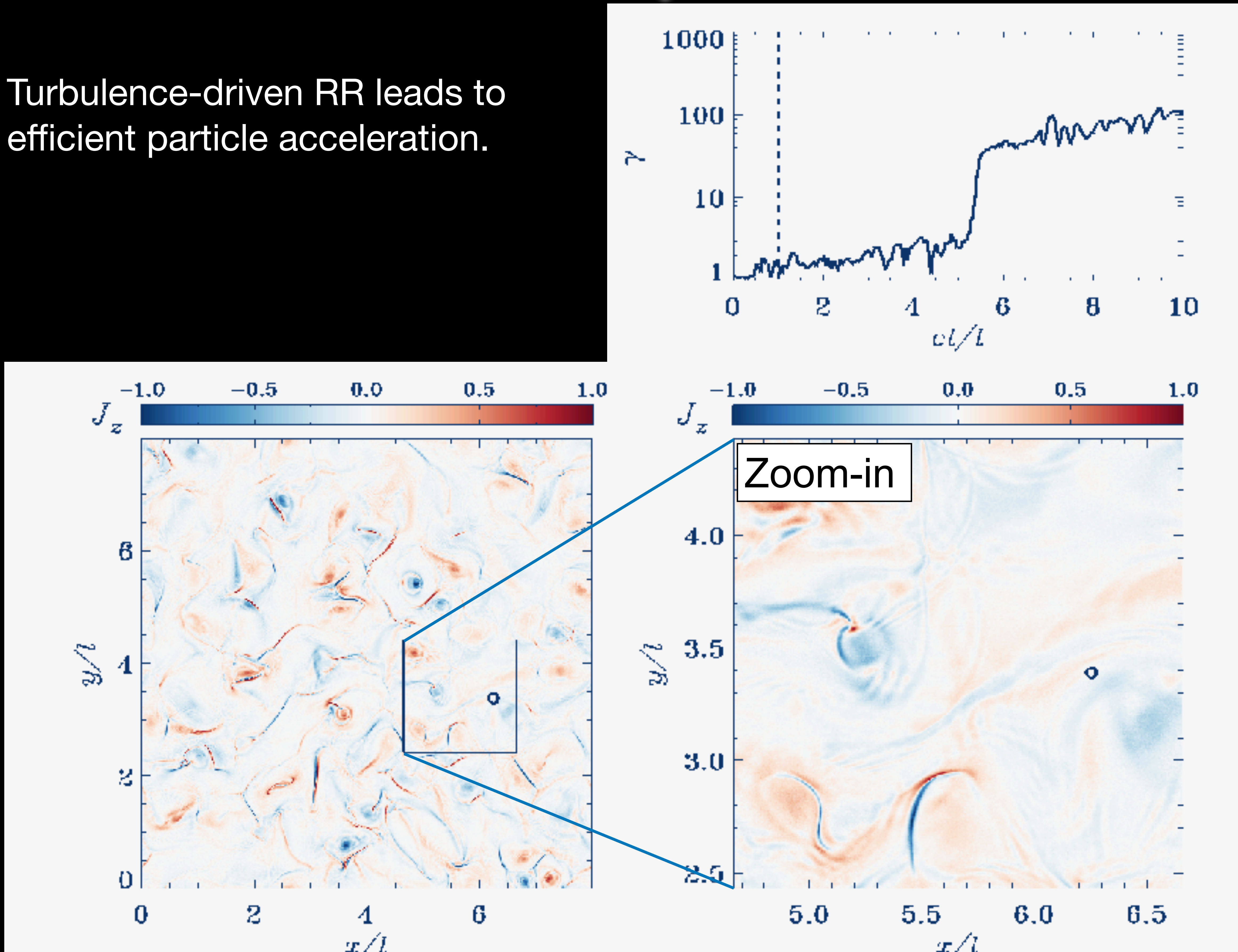
l=turbulence outer scale

(Comisso & LS 18,19, 21)

RR (with $B_g/B_0 \sim 1$) is a by-product of magnetically-dominated turbulence

Turbulence → RR → particle acceleration

Turbulence-driven RR leads to efficient particle acceleration.



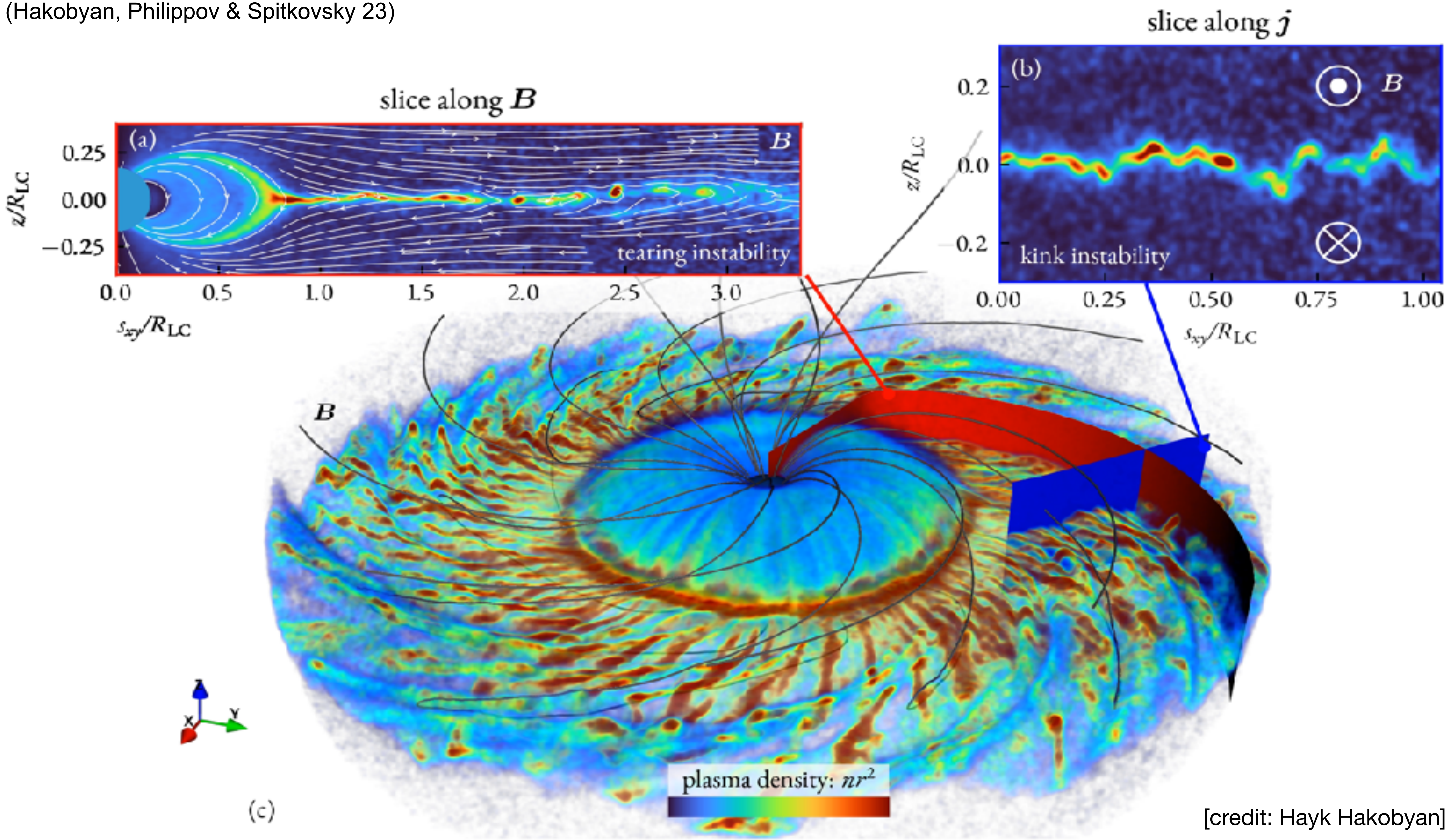
(Comisso & Sironi 18, 19, 21)

Macro-scales

Global PIC simulations of pulsars

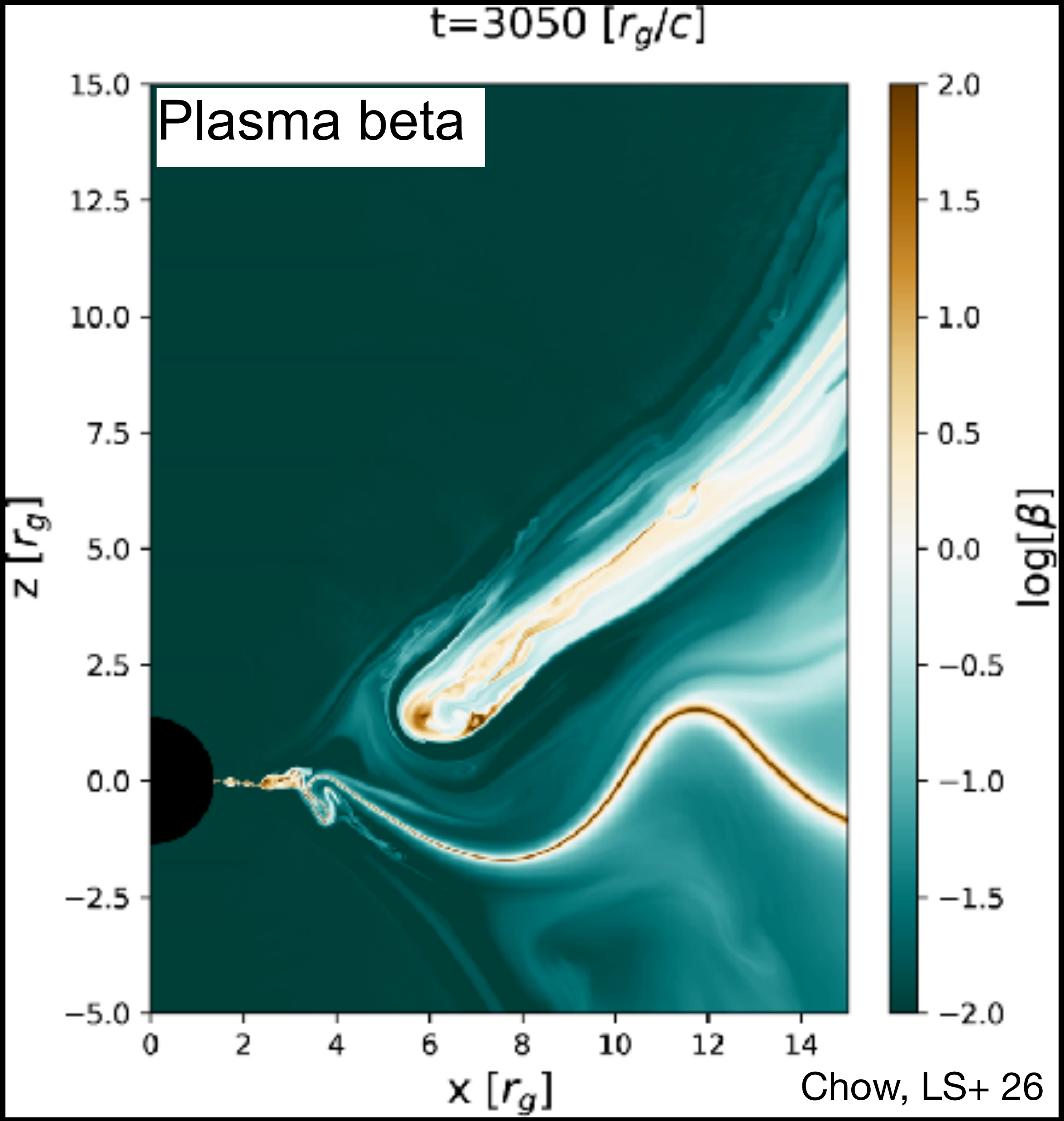
Field-aligned currents flowing from the polar caps to infinity
return back toward the pulsar along an equatorial current sheet.

(Hakobyan, Philippov & Spitkovsky 23)



[credit: Hayk Hakobyan]

MHD is often employed for the global evolution of *collisionless* systems.



collisional MHD

$$v_{\rm in} \sim 0.01 v_A$$

collisional, relativistic Ohm's law:

$$\Gamma_f \left[\boldsymbol{E} + \frac{\boldsymbol{v}_f}{c} \times \boldsymbol{B} - \frac{(\boldsymbol{E}\cdot\boldsymbol{v}_f)\boldsymbol{v}_f}{c^2} \right] = \eta(\boldsymbol{J} - \rho_e \boldsymbol{v}_f)$$

collisionless kinetics

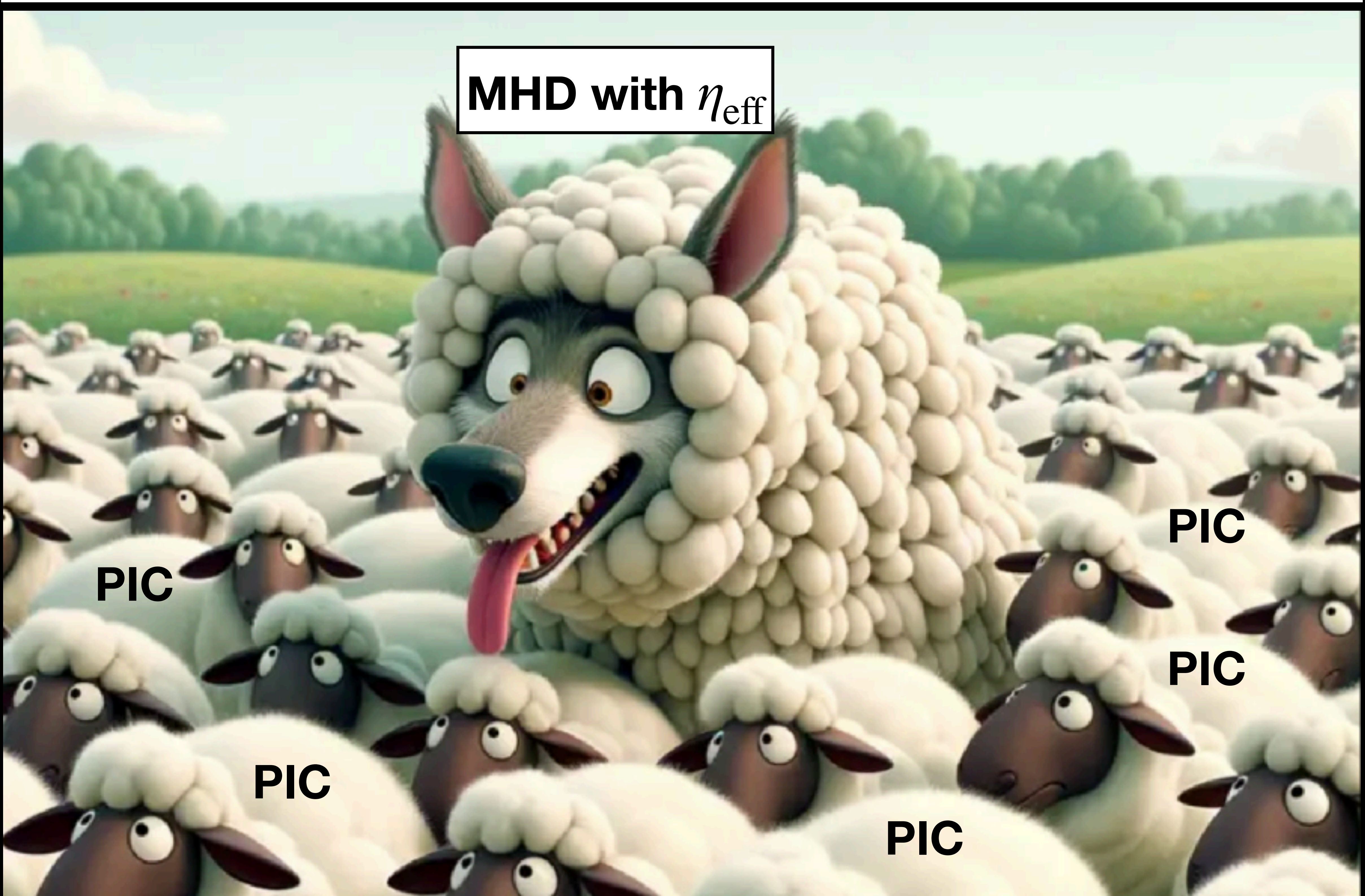
$$v_{\rm in} \sim 0.1 v_A$$

collisionless, relativistic Ohm's law:

$$\boldsymbol{E} + \frac{\langle \boldsymbol{v}_s \rangle}{c} \times \boldsymbol{B} = \frac{\nabla \cdot \boldsymbol{P}_s}{q_s n_s} + \frac{m_s}{q_s} \left[\frac{\partial \langle \boldsymbol{u}_s \rangle}{\partial t} + (\langle \boldsymbol{v}_s \rangle \cdot \nabla) \langle \boldsymbol{u}_s \rangle \right]$$

Effective resistivity

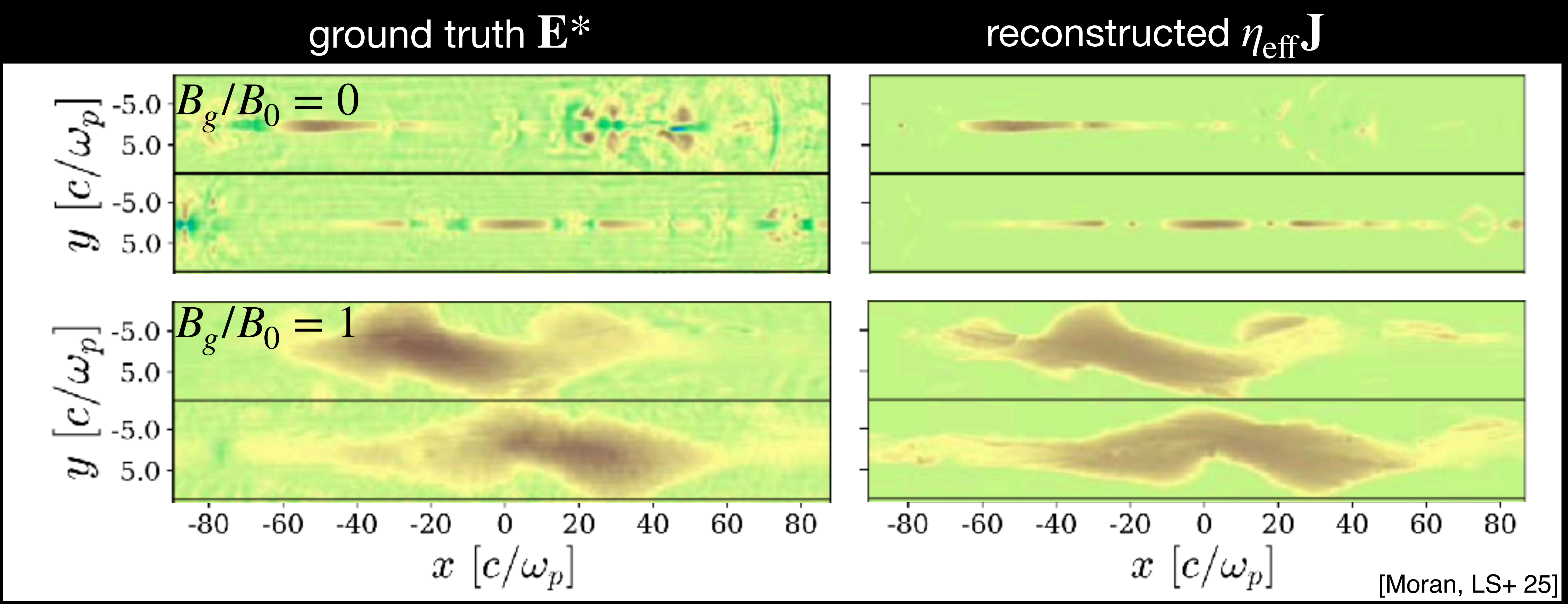
Strategy: derive from PIC simulations some effective resistivity η_{eff} that reproduces in MHD the *collisionless* reconnection rate.



Effective resistivity from PIC

- Ohm's law: the non-ideal electric field is $\mathbf{E}^* = \mathbf{E} + \mathbf{v}/c \times \mathbf{B} = \eta_{\rm eff}\mathbf{J}$
- At X-points, postulate that the current is charge-starved: $J = enc$

$$\Rightarrow \quad \eta_{\rm eff} = \frac{E^*}{enc}$$



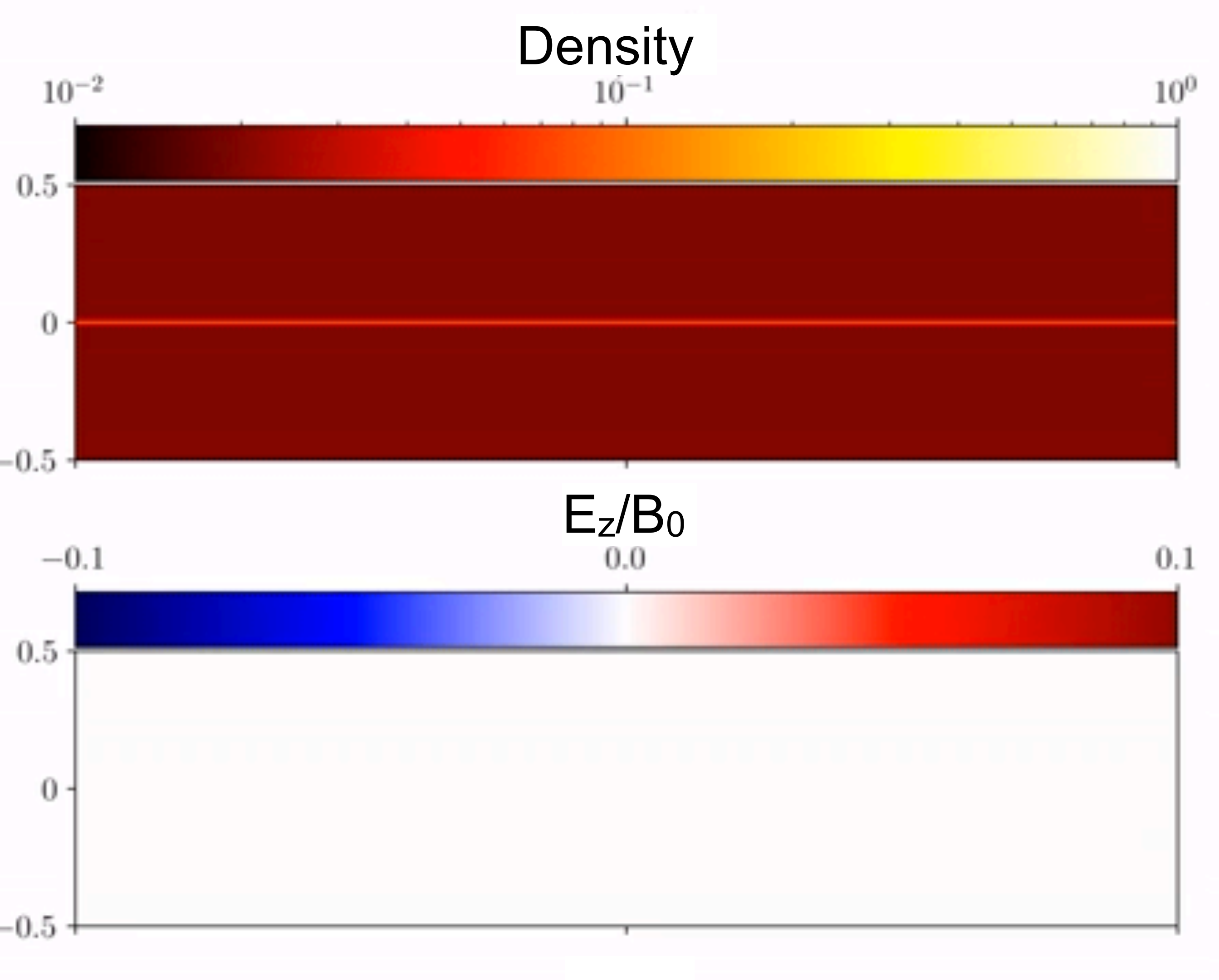
[Moran, LS+ 25]

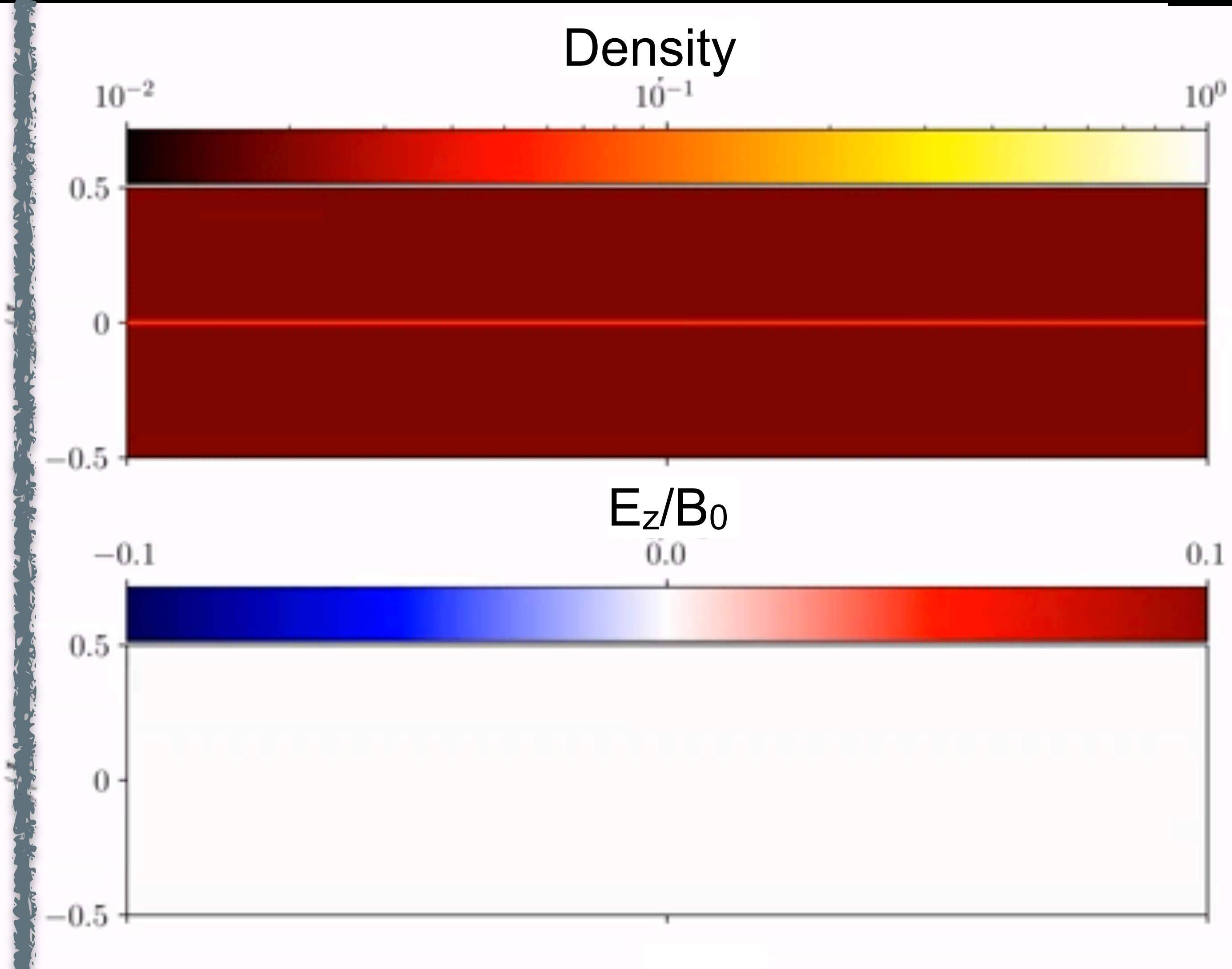
This effective resistivity is coordinate-agnostic, and holds for any B_g/B_0.

Effective resistivity in MHD: local Harris

Uniform resistivity

PIC-motivated resistivity $\eta_{\text{eff}} = \dfrac{E^*}{enc}$

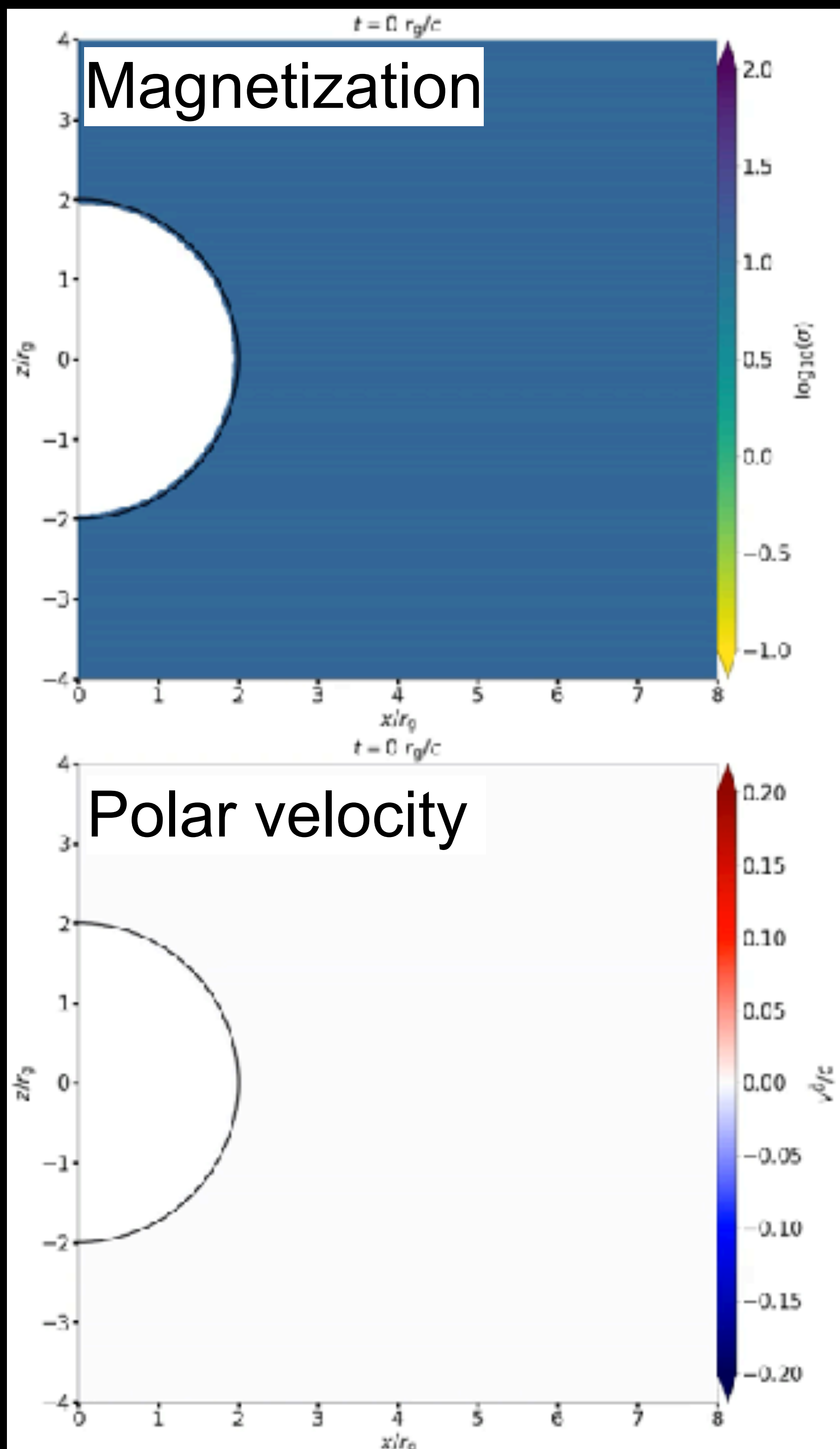




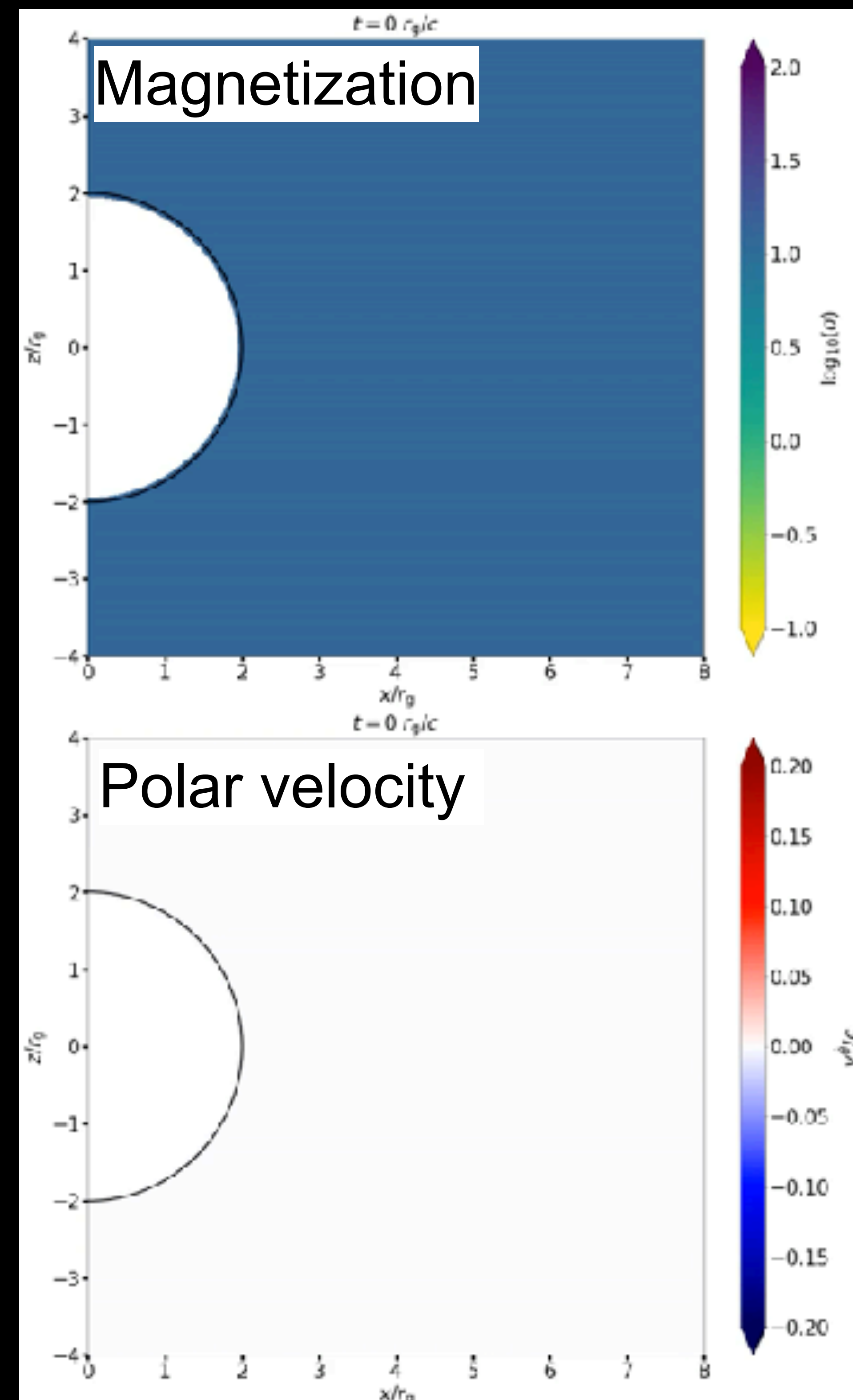
[Ripperda+ 26; Bugli+ 25]

Effective resistivity in GRMHD: global balding

Uniform resistivity



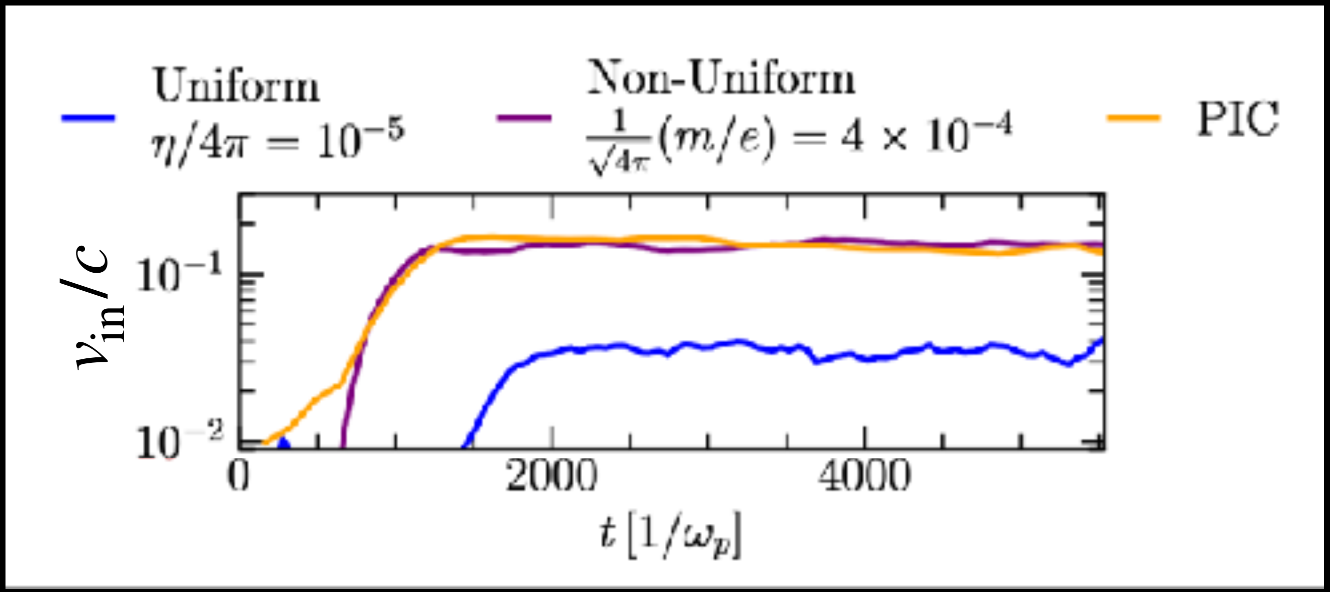
PIC-motivated resistivity $\eta_{\rm eff} = \frac{E^*}{enc}$



[Ripperda+ 26]

Effective resistivity in MHD

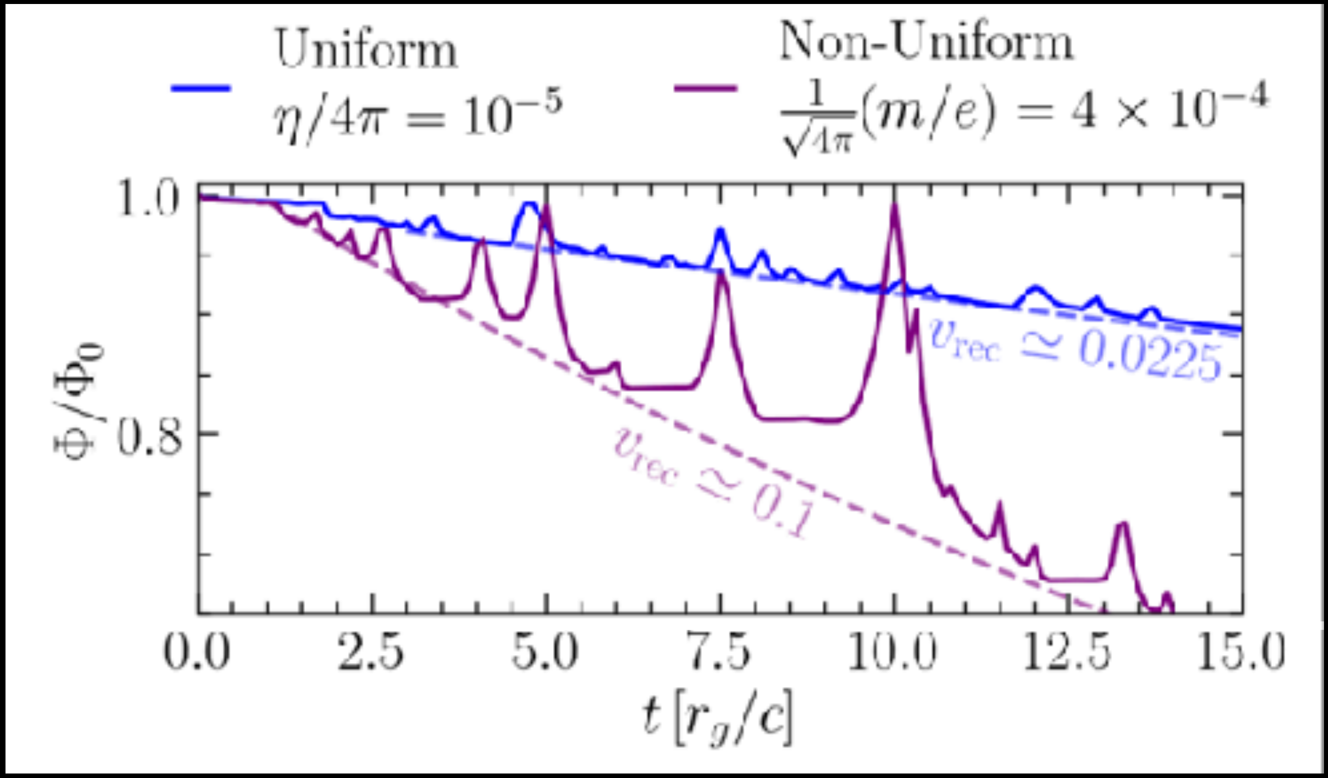
Local test: Harris



[Ripperda+ 26]

- MHD with PIC-motivated resistivity reproduces the "ground truth" PIC reconnection rate.

Global test: BH balding

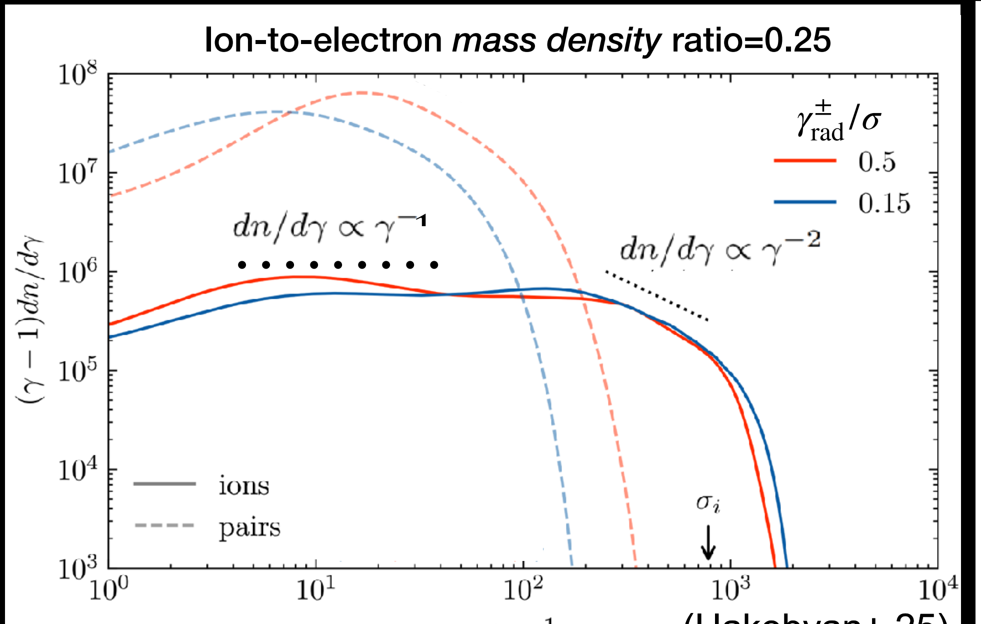


[Ripperda+ 26]

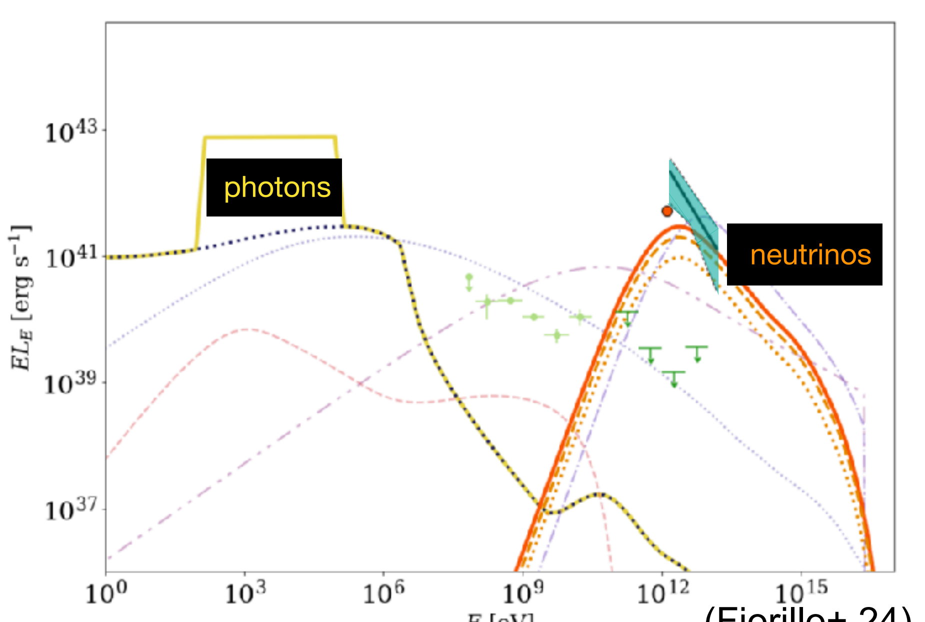
- GRMHD with PIC-motivated resistivity reproduces the "ground truth" GRPIC flux balding rate (Bransgrove+ 21).

Relativistic reconnection [RR]

- Micro-scales: RR powers high-energy emission and ultra-relativistic particles (cosmic rays and neutrinos).

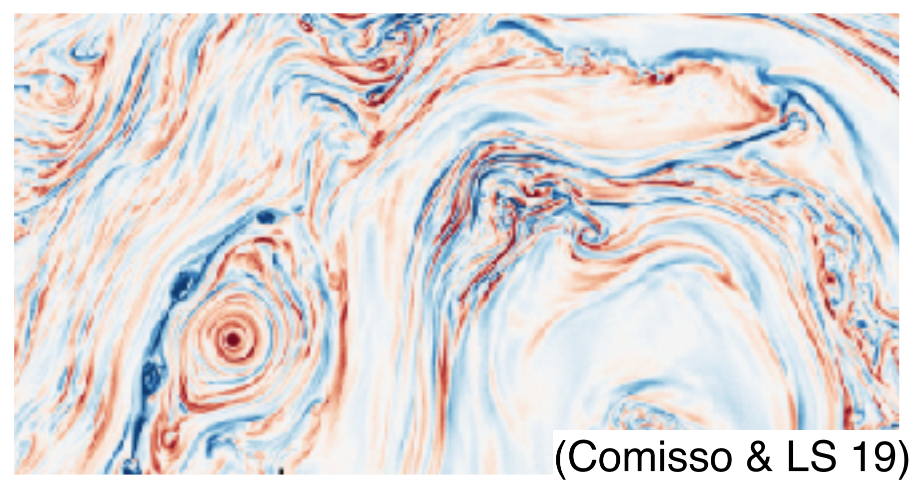


(Hakobyan+ 25)

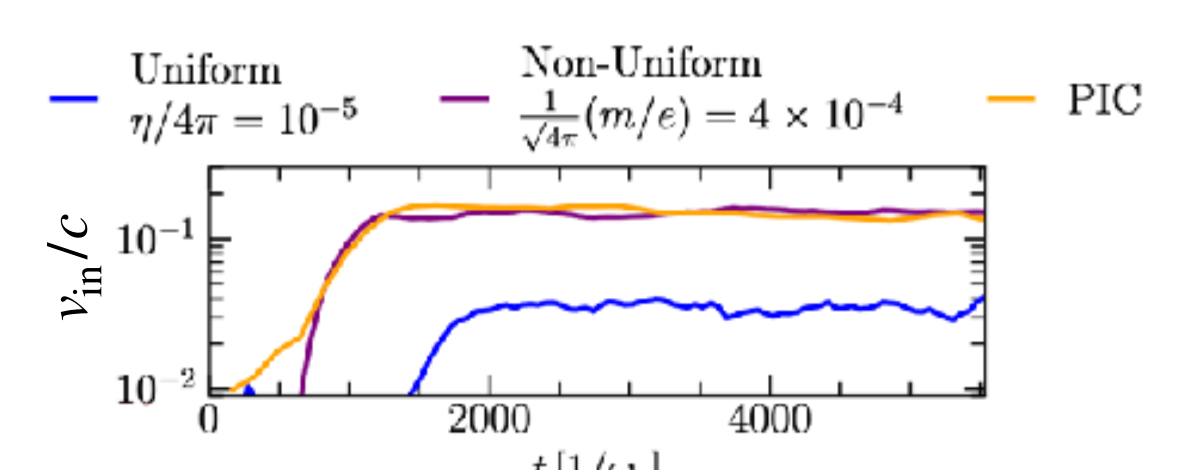


(Fiorillo+ 24)

- Meso-scales: MHD instabilities and turbulence self-consistently produce RR layers, where particles are first accelerated.


(Comisso & LS 19)

- Macro-scales: PIC-based effective resistivity allows to perform global (GR)MHD simulations with the correct *collisionless* reconnection rate.



(Ripperda+ 26)