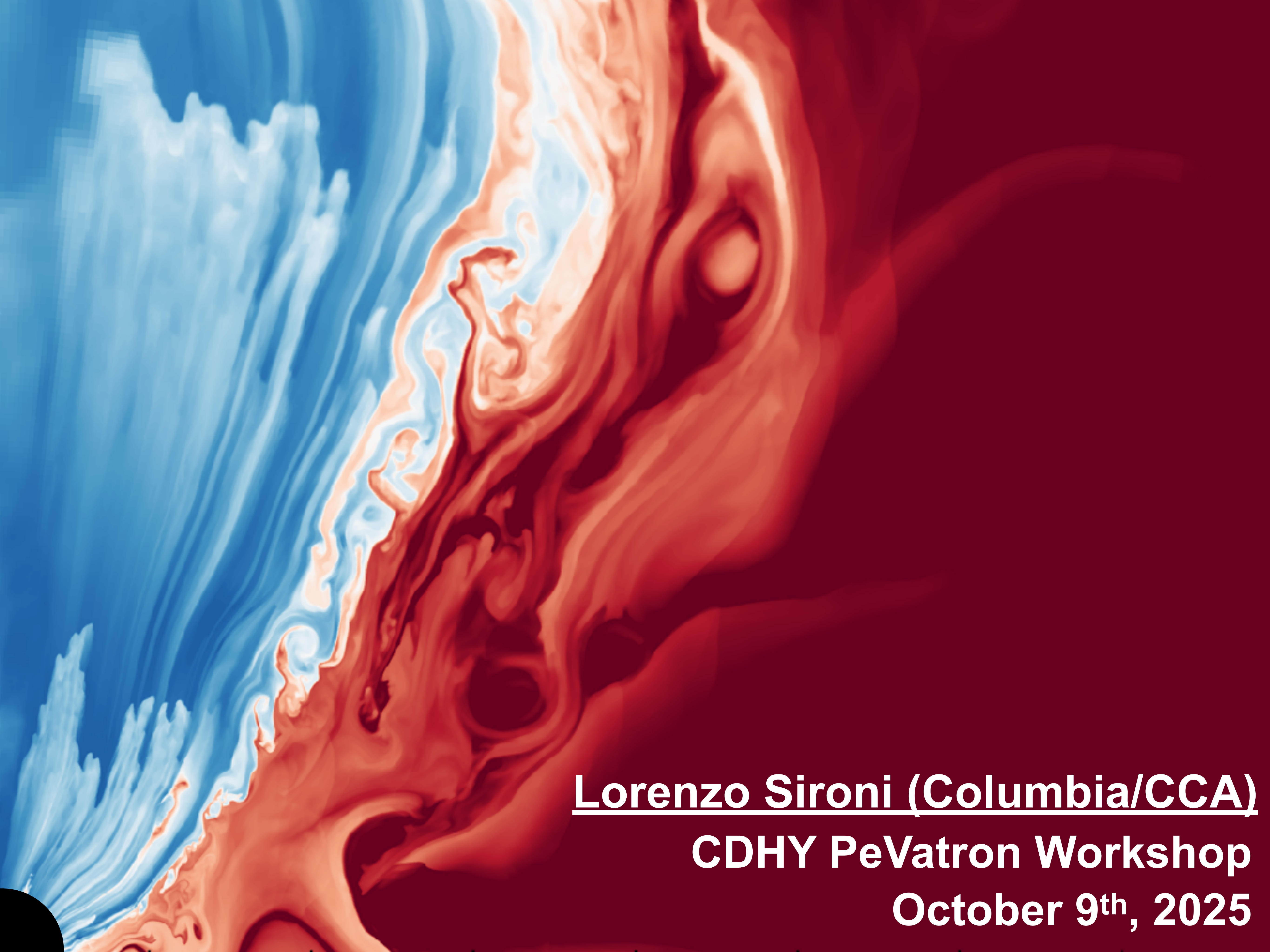


Lorenzo Sironi (Columbia/CCA)

CDHY PeVatron Workshop

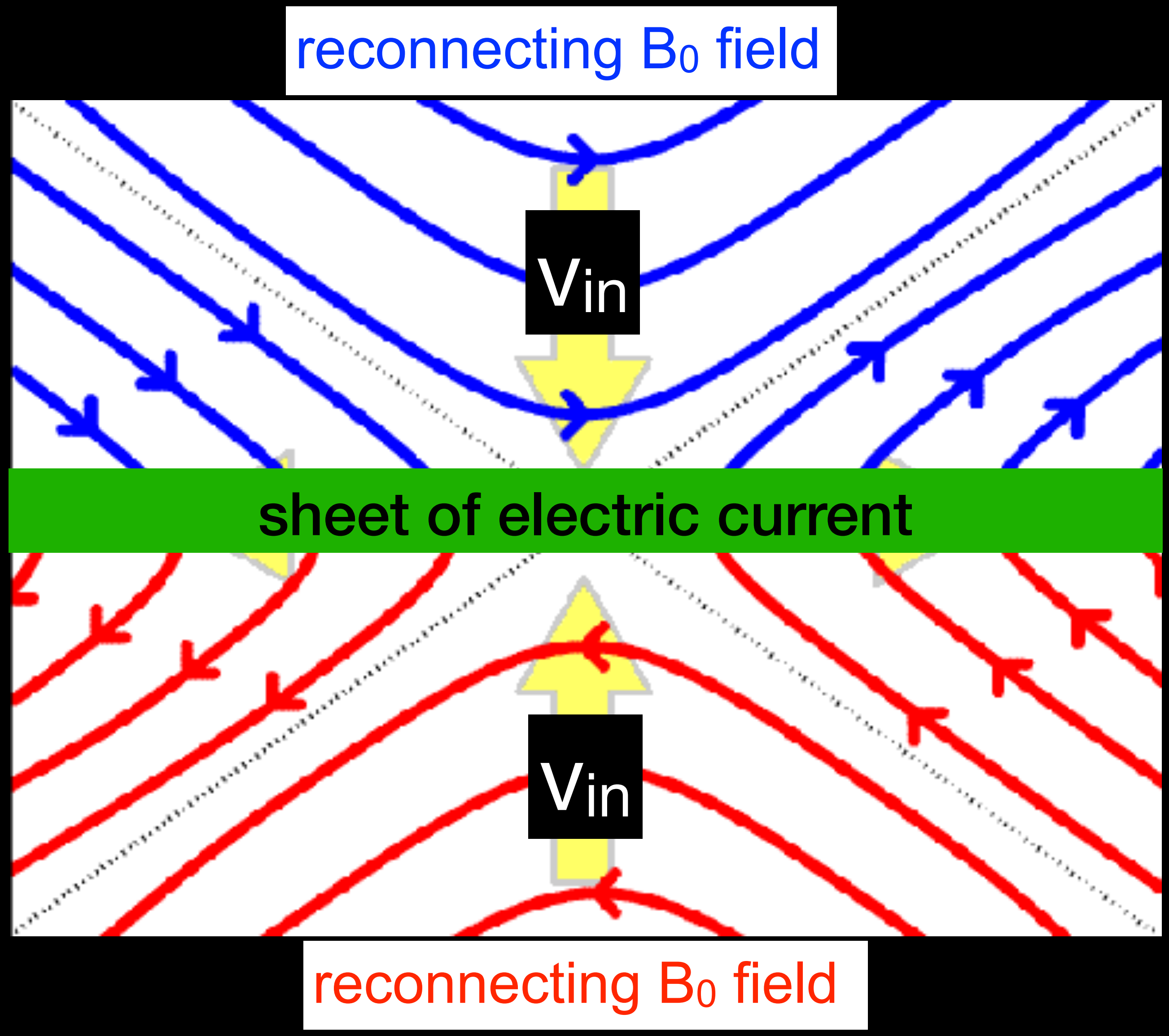
October 9th, 2025

Relativistic, collisionless reconnection

for a recent ARAA review: Sironi, Uzdensky & Giannios, arXiv:2506.02101
with vital contributions from Hakobyan, Cerutti, Willingale, Ji

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

$$v_A \sim c$$



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

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

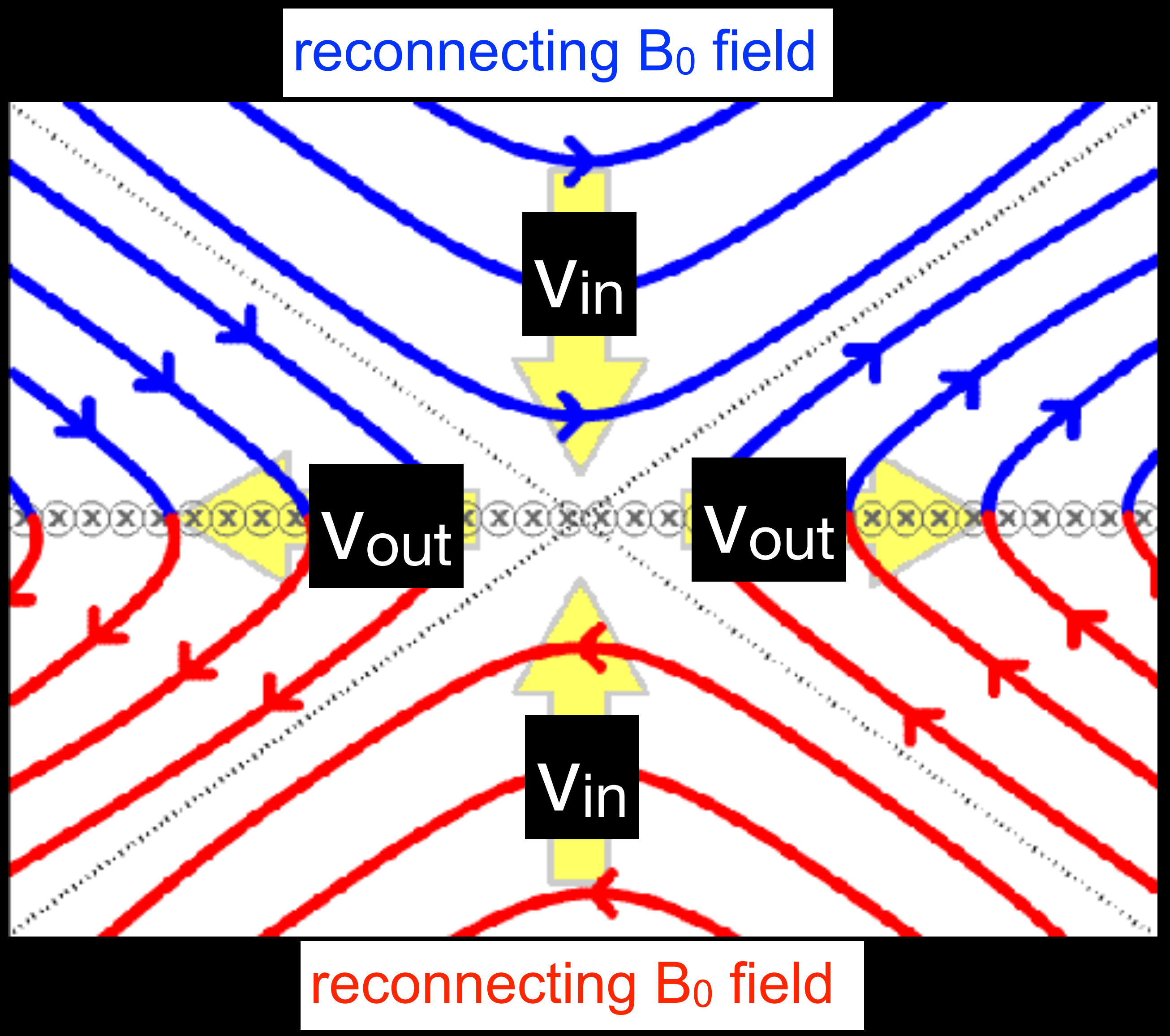
The energy census in reconnection

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

with vital contributions from Hakobyan, Cerutti, Willingale, Ji

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

$$v_A \sim c$$



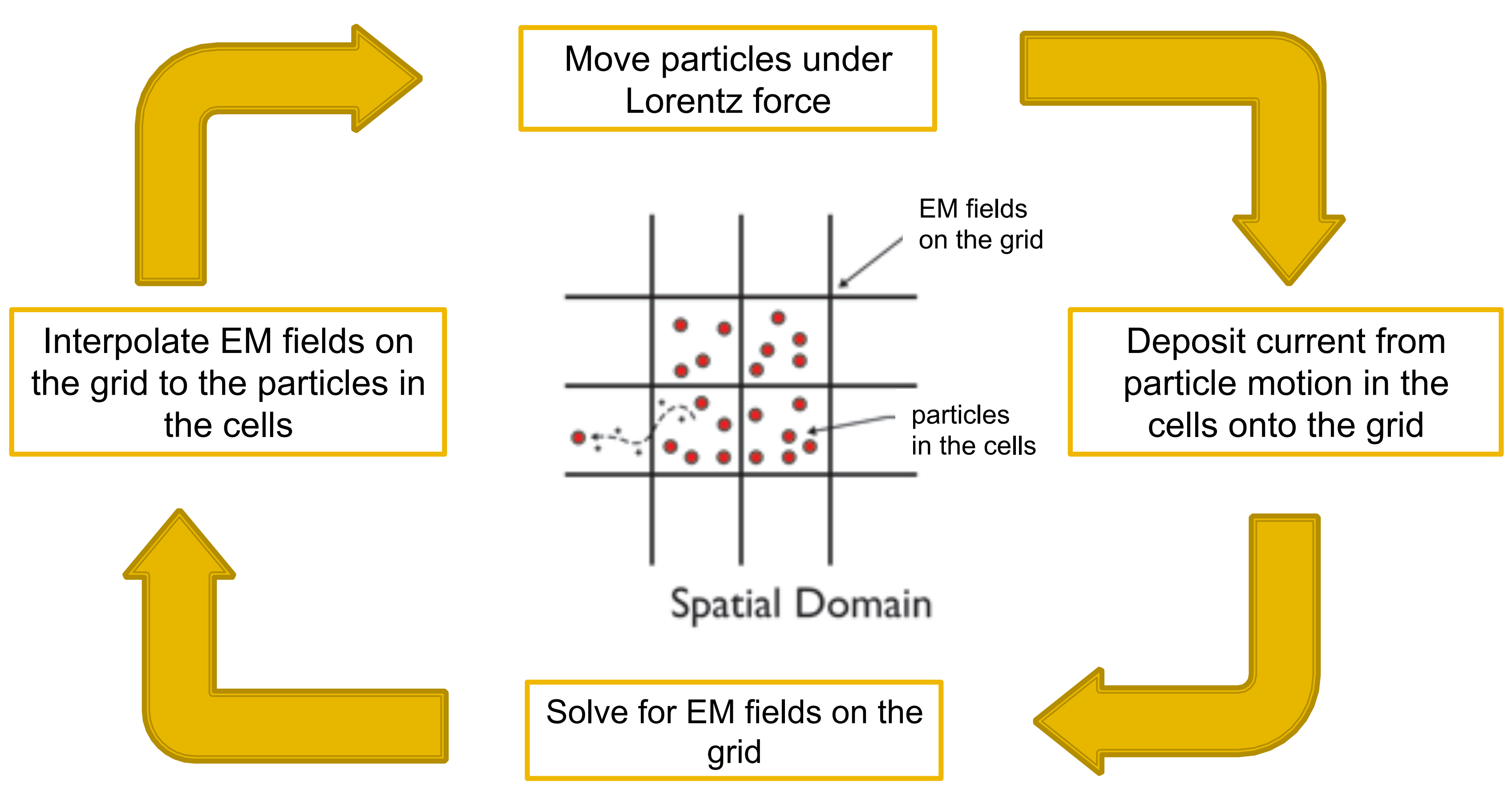
The dissipated *B*-field energy results in:

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

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 resolved by PIC simulations are much smaller than *astronomical* scales.

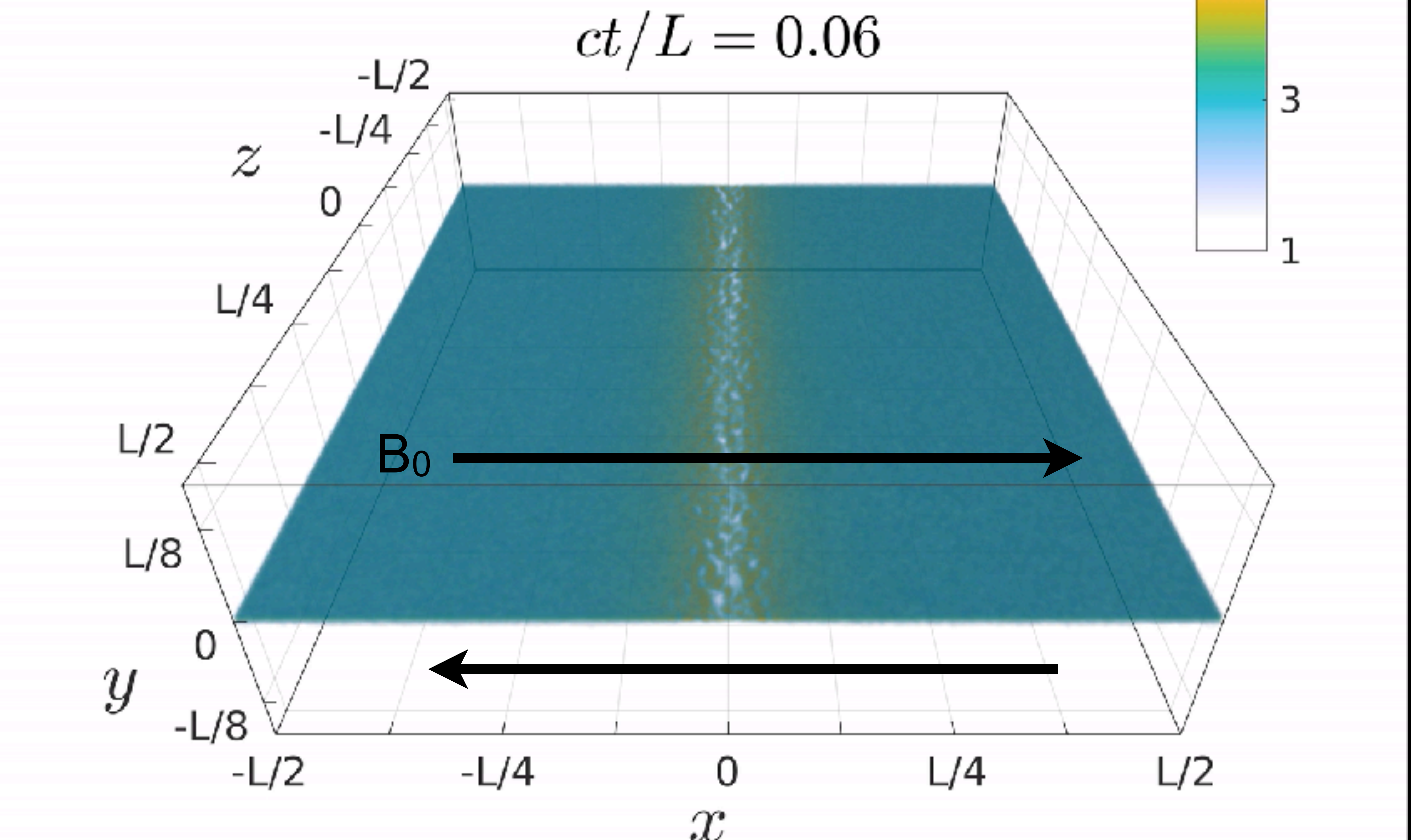
Typical length (c/ω_p) and time ($1/\omega_p$) scales are:

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

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

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

What can relativistic reconnection do?

- B-field energy → bulk motions, heat, non-thermal acceleration.

- Power the multi-wavelength and multi-messenger signatures of high-energy astro sources, including BH coronae.

Reconnection in BH coronae

Gupta, Sridhar & LS 2024, MNRAS, 527, 6065

Groselj, Hakobyan et al. 2024, PRL, 132, 085202

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

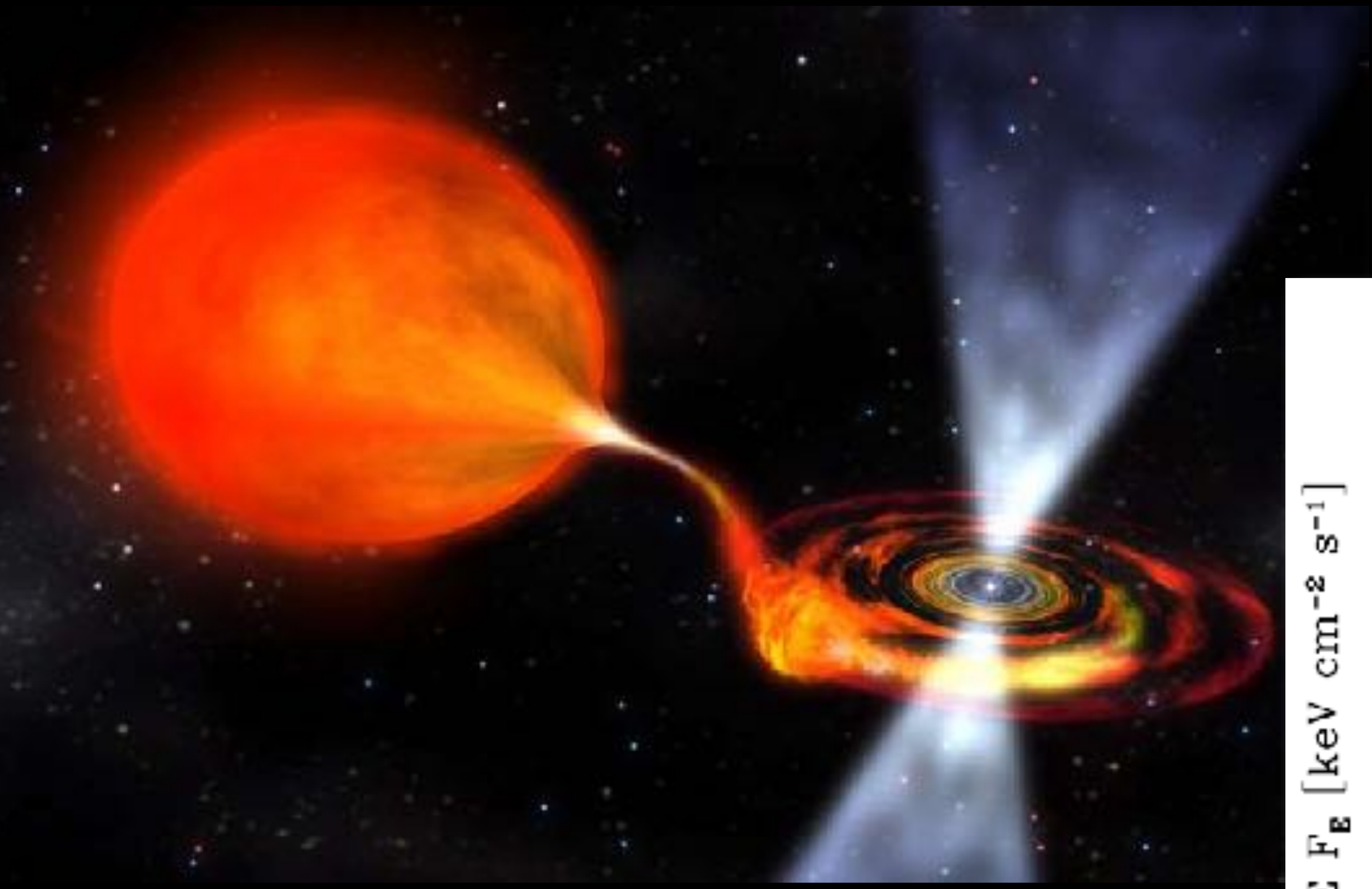
D. Groselj

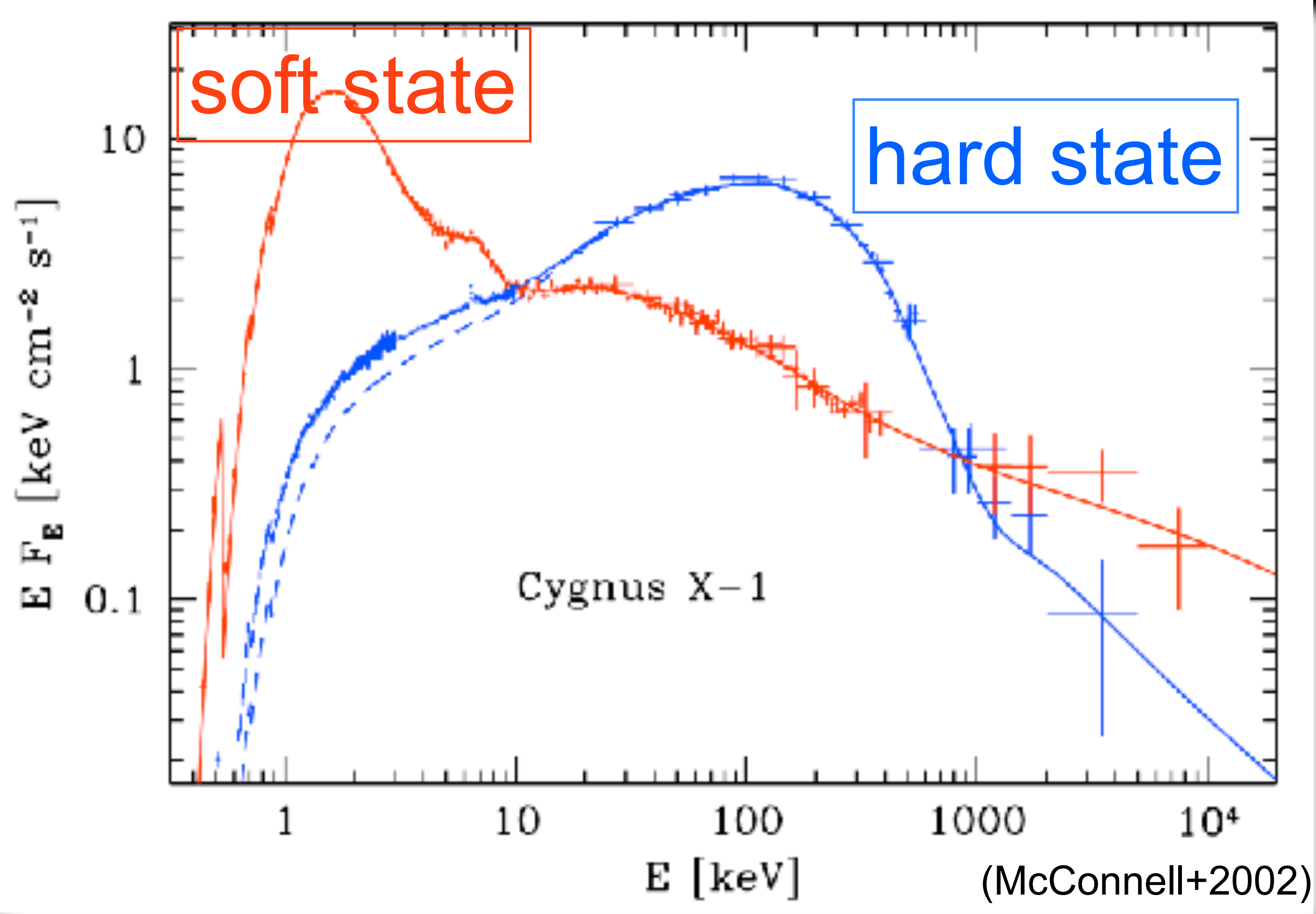
H. Hakobyan

A. Philippov

A. Beloborodov

The hard state of X-ray binaries



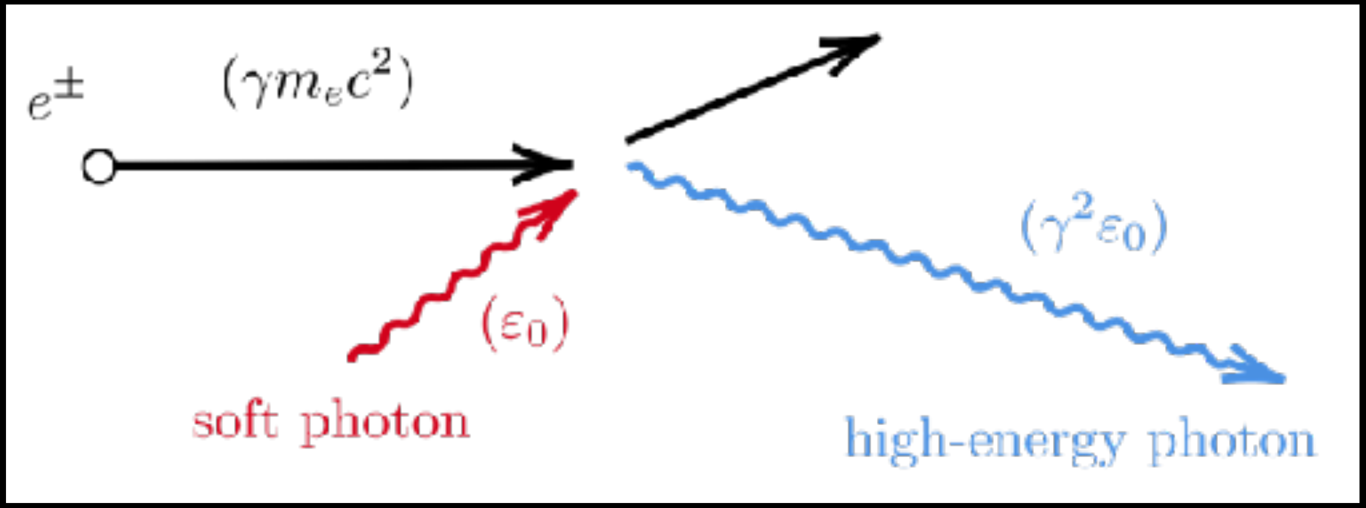


Soft state: thermal emission from the BH accretion disk.

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 ($\tau_T \sim 1$).

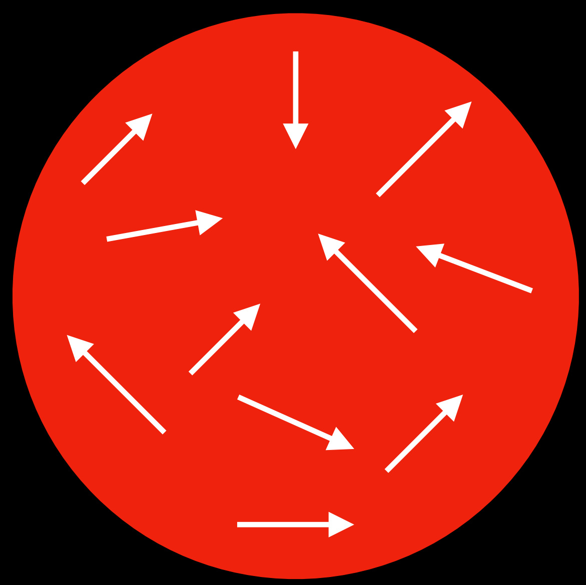


Can the emitting electrons in BH coronae stay hot?

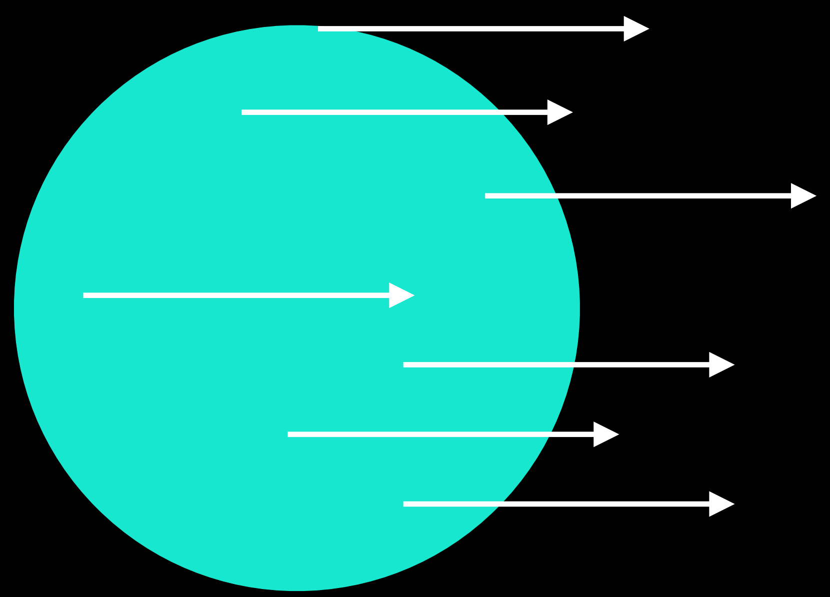
Internal vs bulk motions

Can the emitting electrons in BH coronae stay hot?

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



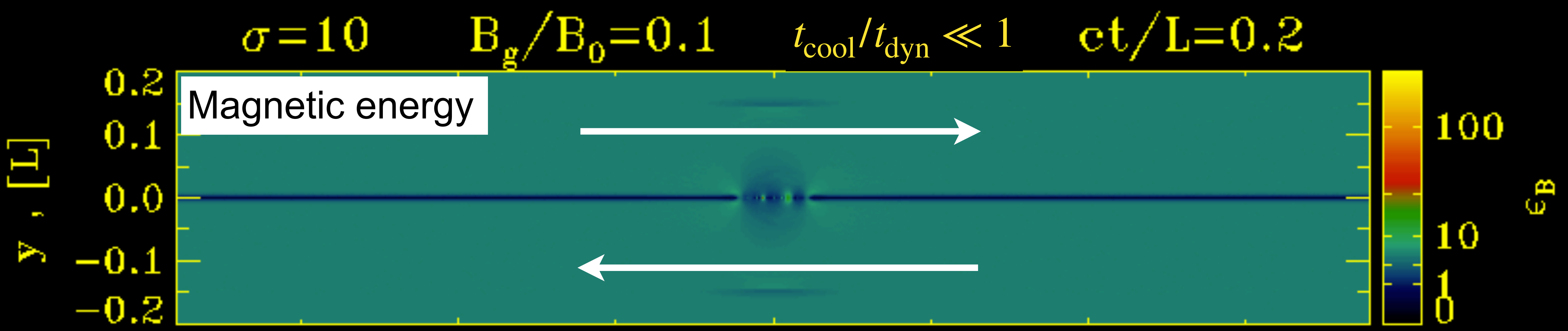
Internal motions (random)



Bulk motions (ordered)

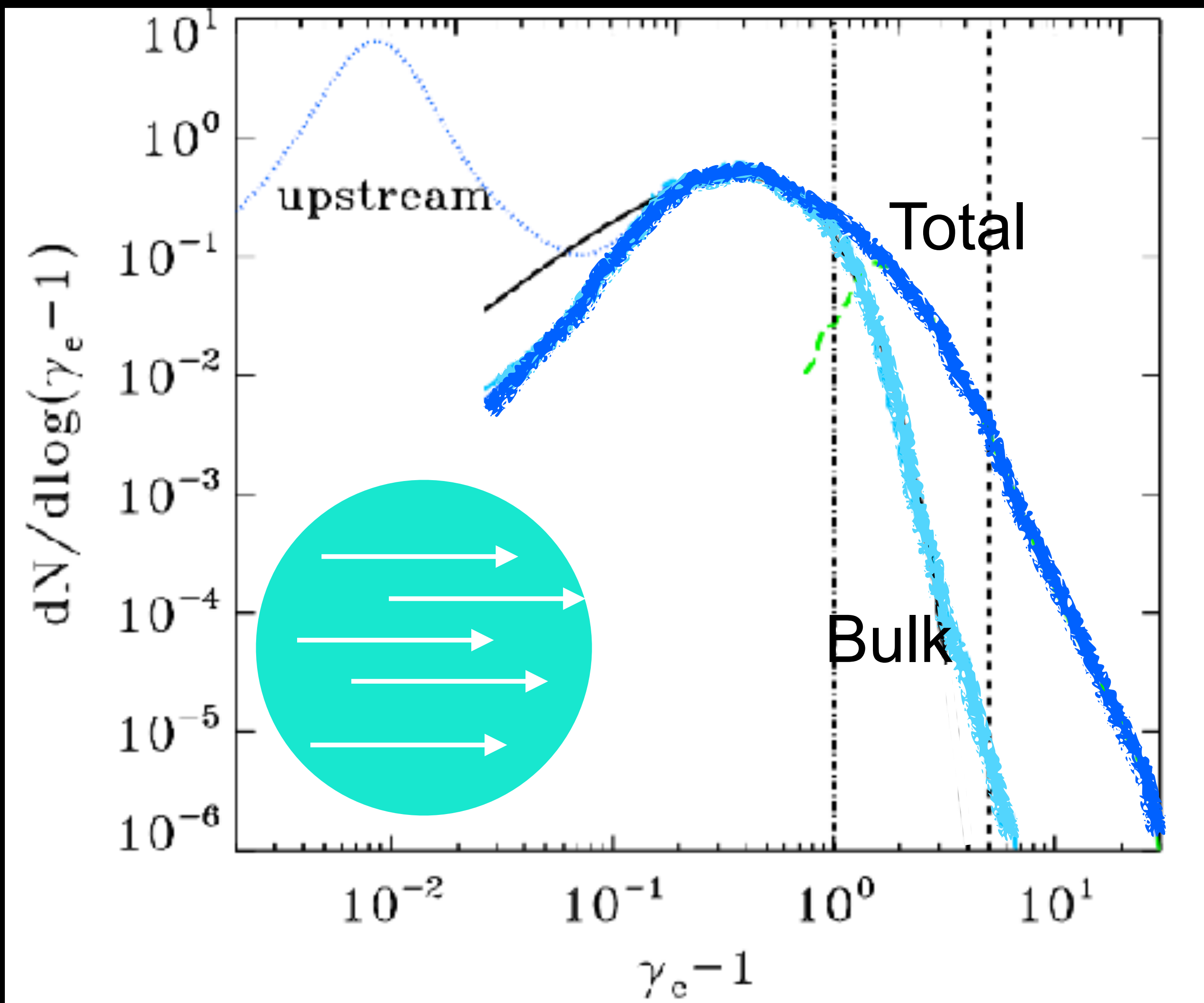
What provides ordered/bulk motions for Comptonization?

What provides the bulk motions?

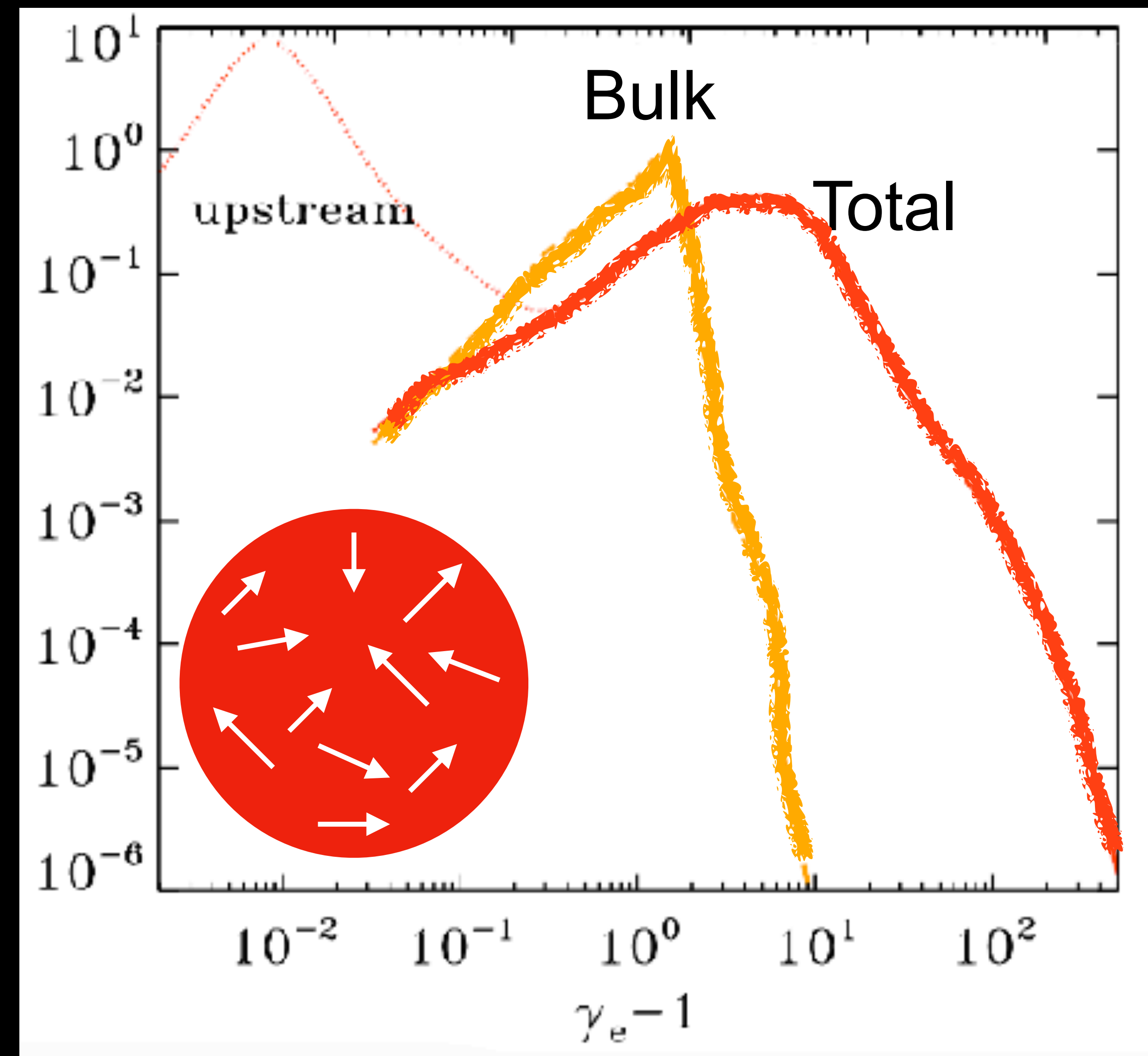


Internal vs bulk motions

Fast cooling



Slow/no cooling

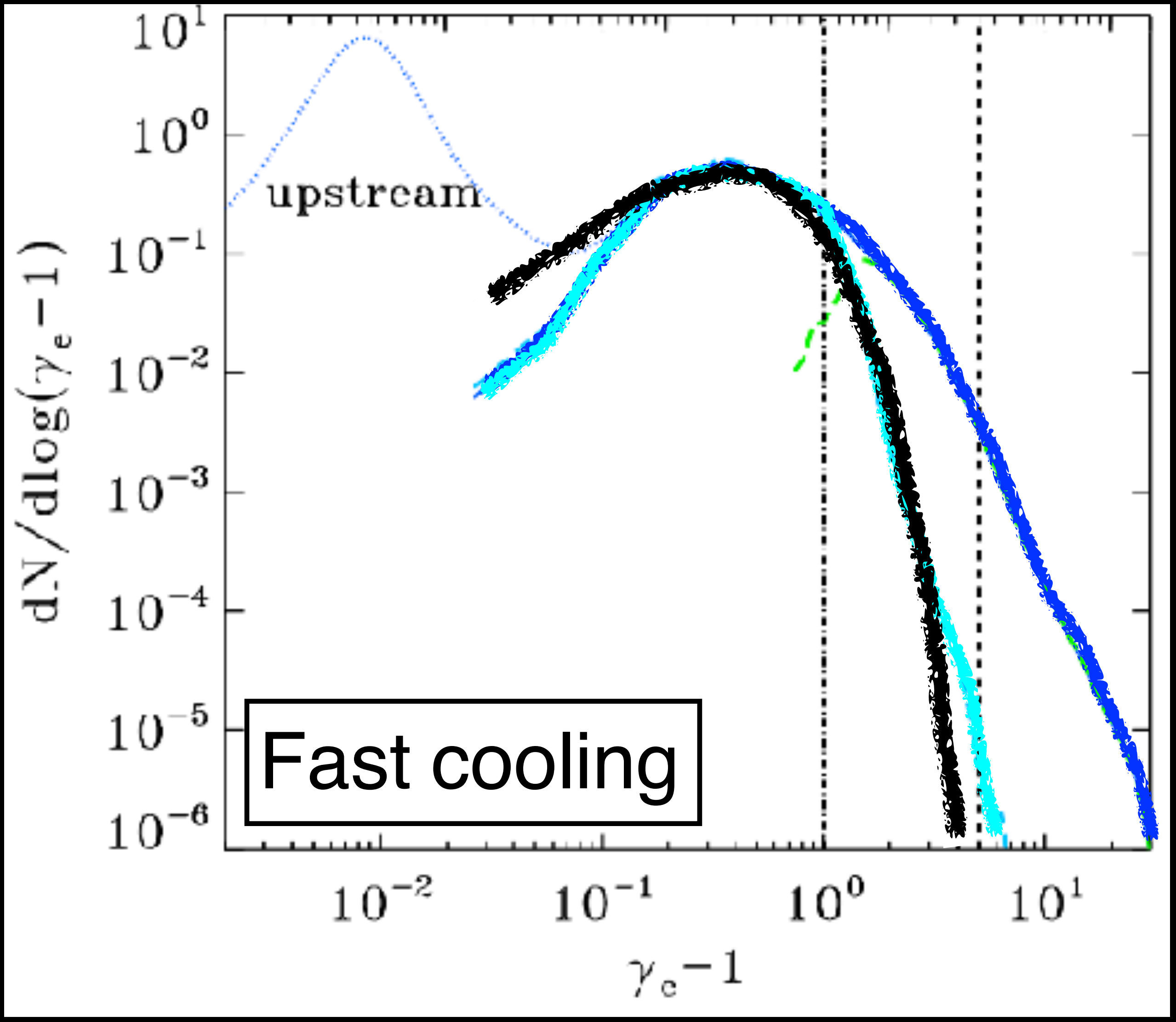


(LS & Beloborodov 20; Sridhar, LS & Beloborodov 21, 23)

- In BH coronae, strong cooling suppresses internal motions.
- For strong cooling, the particle spectrum is dominated by <u>bulk</u> motions.

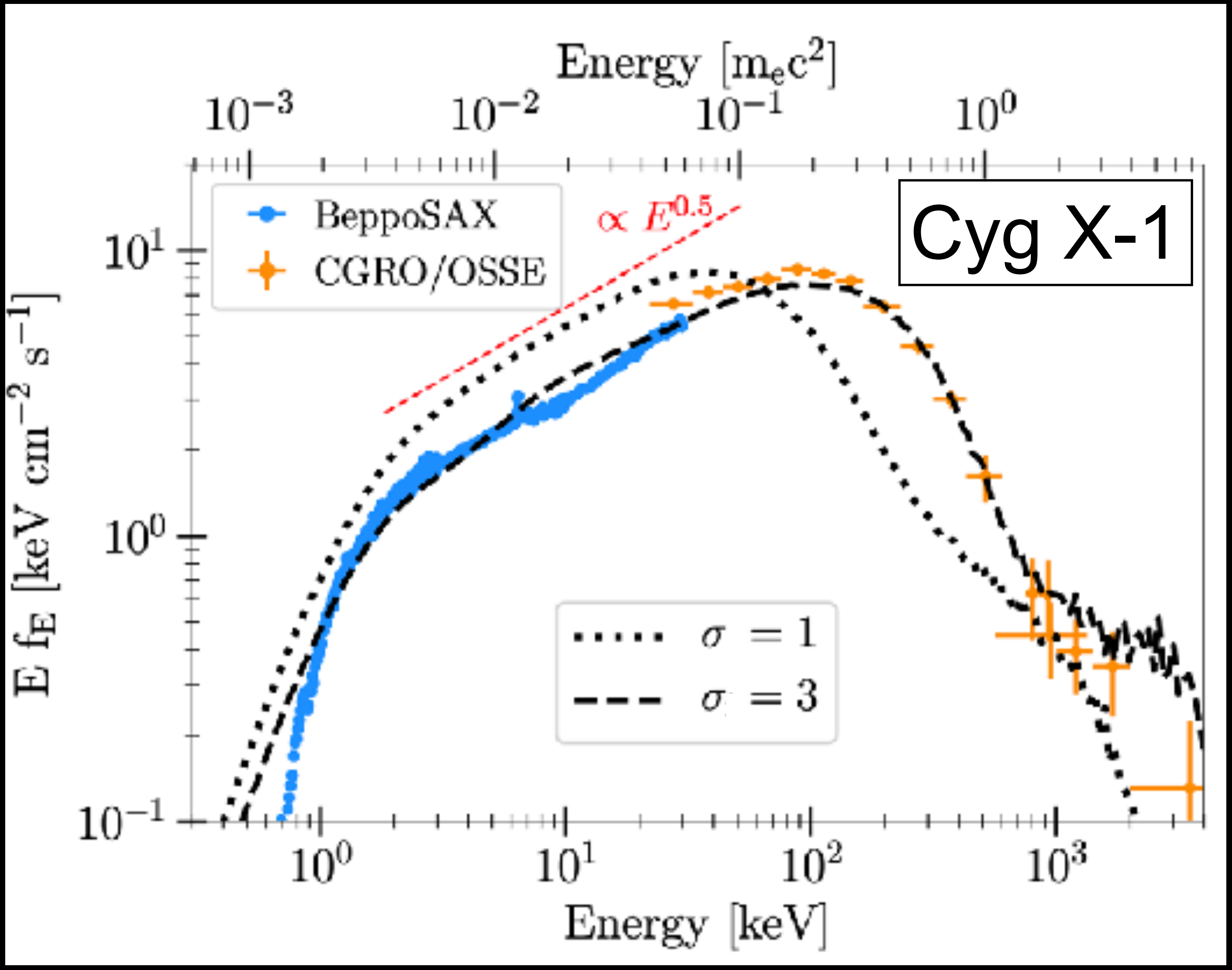
Plasmoid chain Comptonization

Particles



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

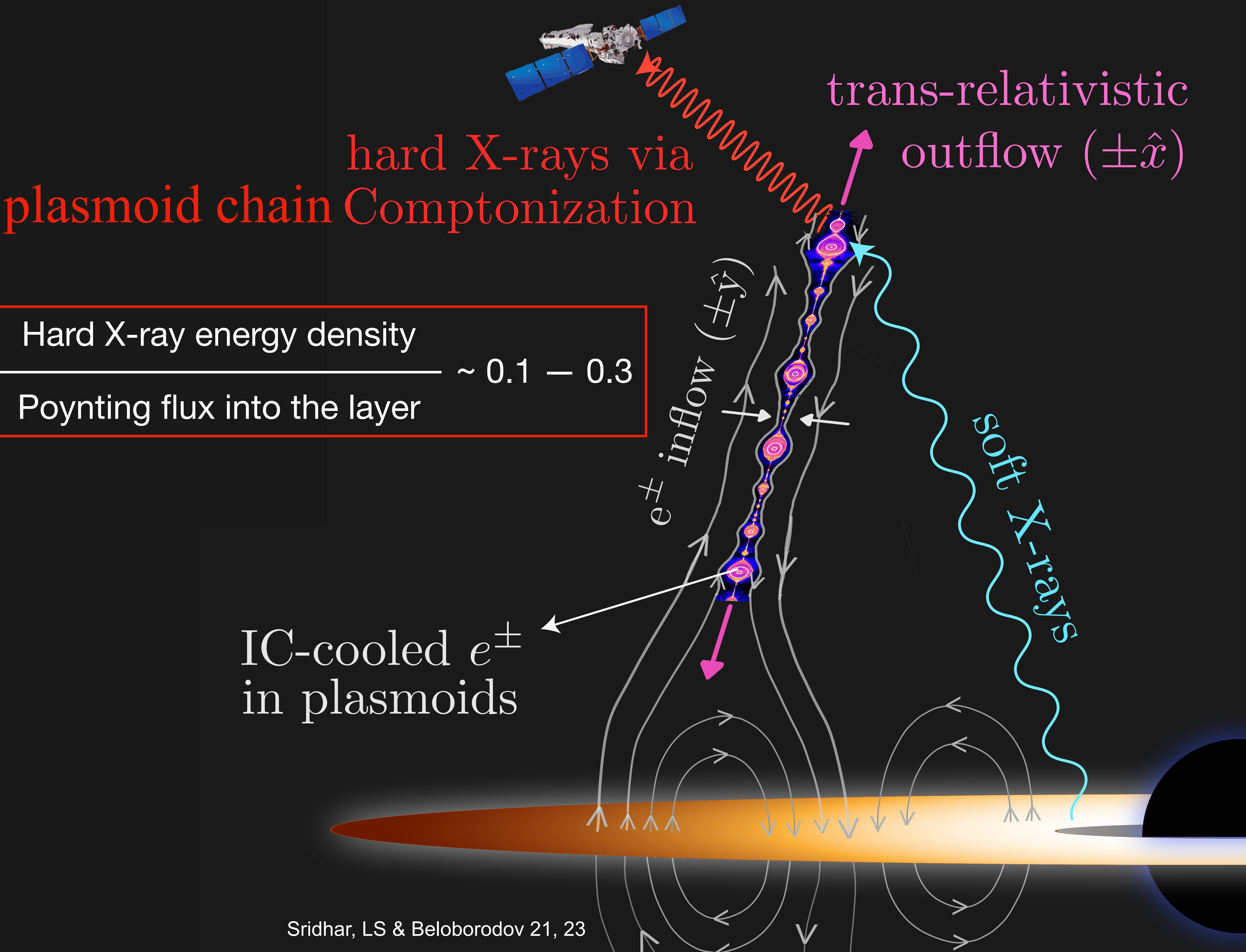
Photons



(Sridhar, LS & Beloborodov 21, 23)

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

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



$$\frac{\text{Hard X-ray energy density}}{\text{Poynting flux into the layer}} \sim 0.1 - 0.3$$

Sridhar, LS & Beloborodov 21, 23

What can relativistic reconnection do?

- B-field energy → bulk motions, heat, non-thermal acceleration.

- Power the multi-wavelength and multi-messenger signatures of high-energy astro sources, including BH coronae.

Particle acceleration in relativistic reconnection

Gupta, Sridhar & LS 2025, MNRAS, 538, 49

Zhang, LS & Giannios 2023, ApJL, 956, L36

LS 2022, PRL, 128, 145102

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

S. Gupta

H. Zhang

M. Petropoulou

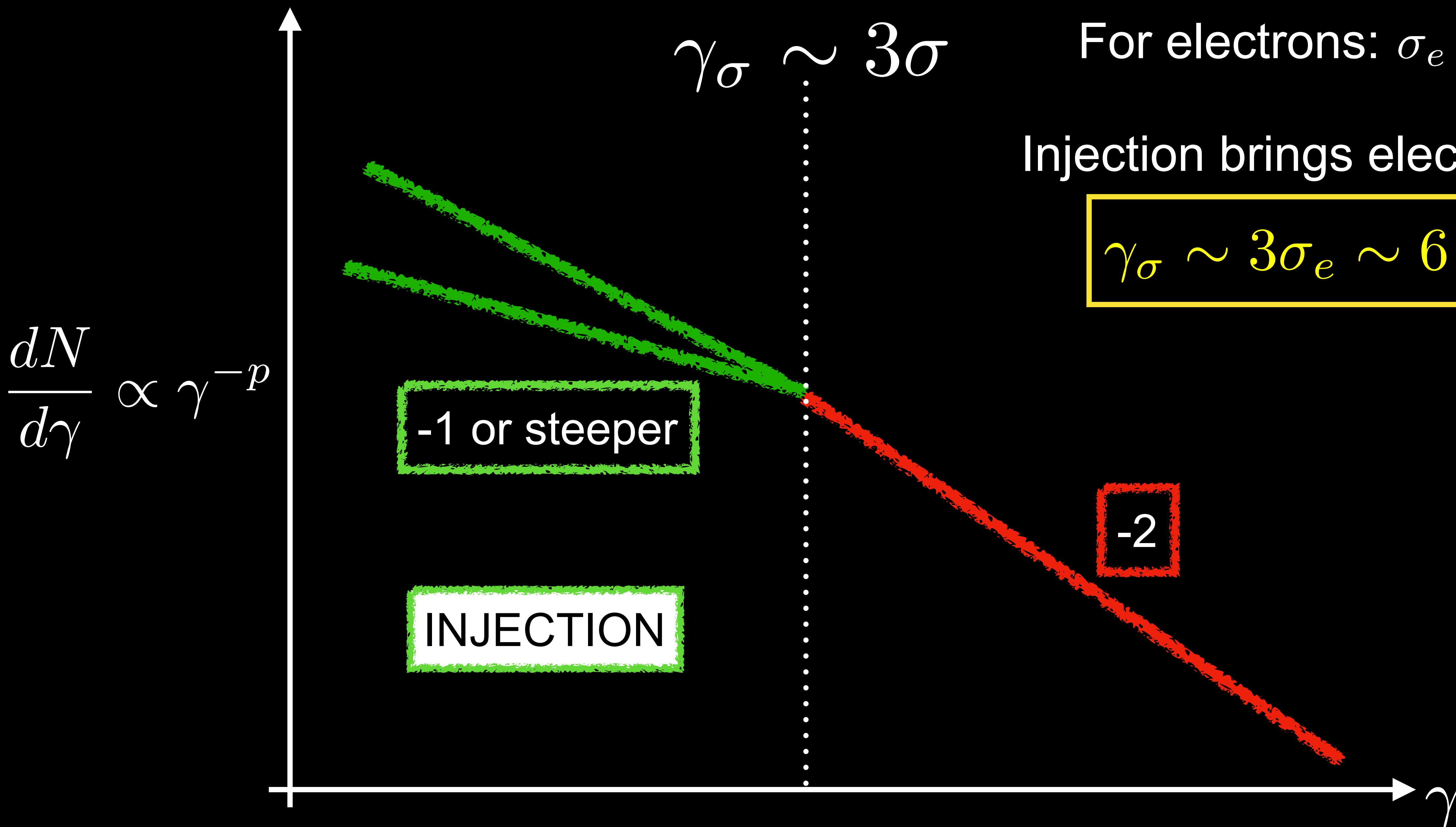
D. Giannios

Reconnection makes broken power laws

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

Injection brings electrons up to

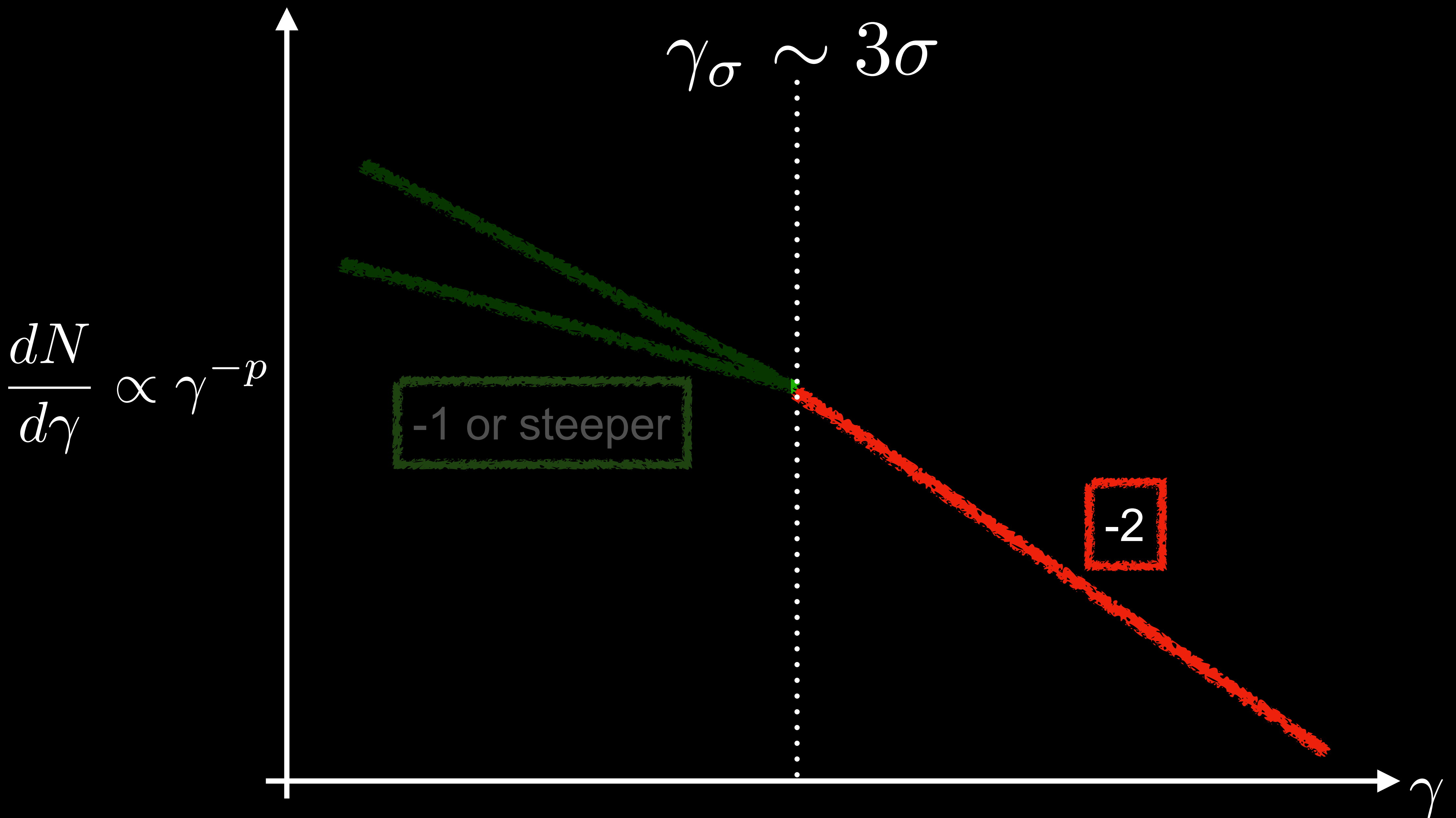
$$\gamma_\sigma \sim 3\sigma_e \sim 6\times 10^3\sigma$$



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 ~ σ-independent slope of *p*~2.

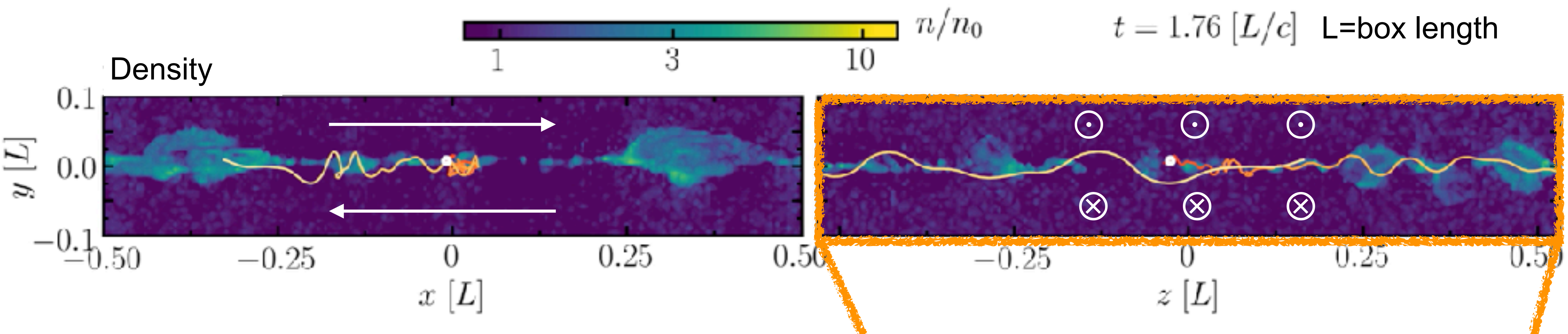
Reconnection makes broken power laws

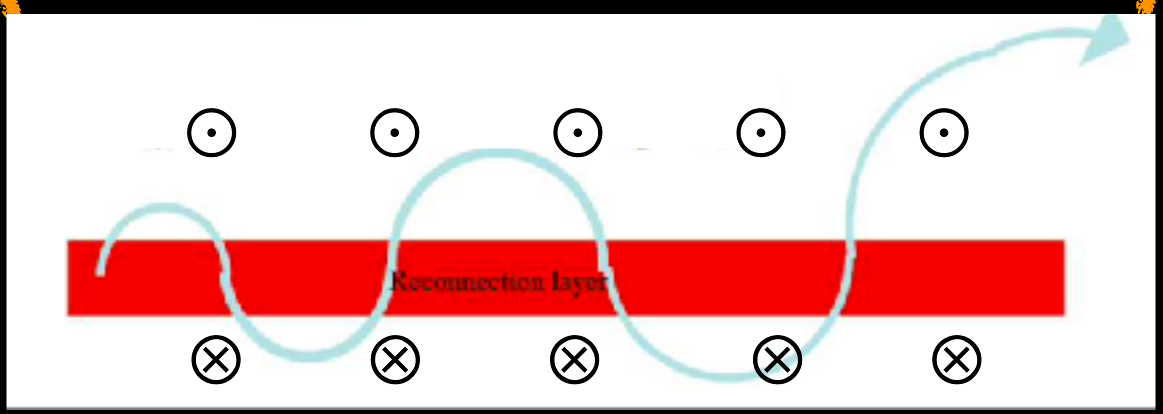


At $\gamma \lesssim 3\sigma$ "injection" in reconnection leads to σ-dependent slopes, with $p \gtrsim 1$.

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

Particle acceleration to the highest energies

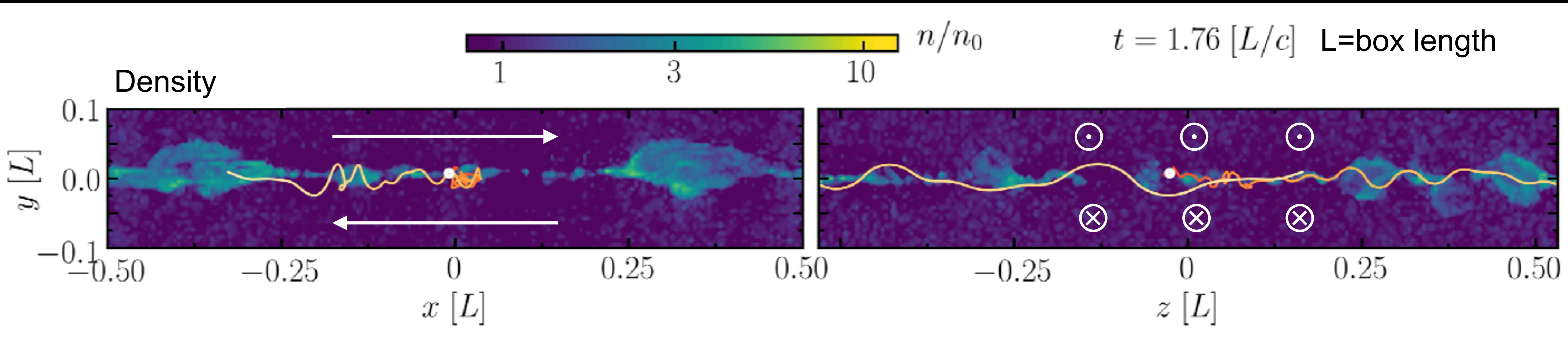




(Lazarian +12)

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

Particle acceleration to the highest energies

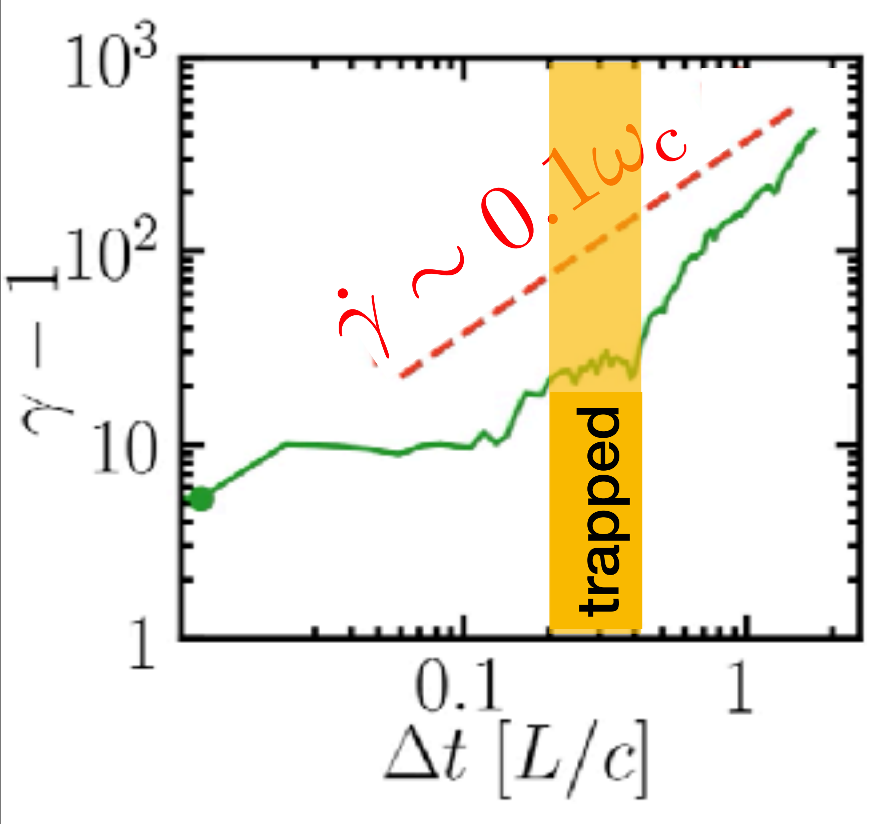


- In 3D, lucky particles escape from the reconnected plasma and swim “freestyle” around the reconnection layer.

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

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

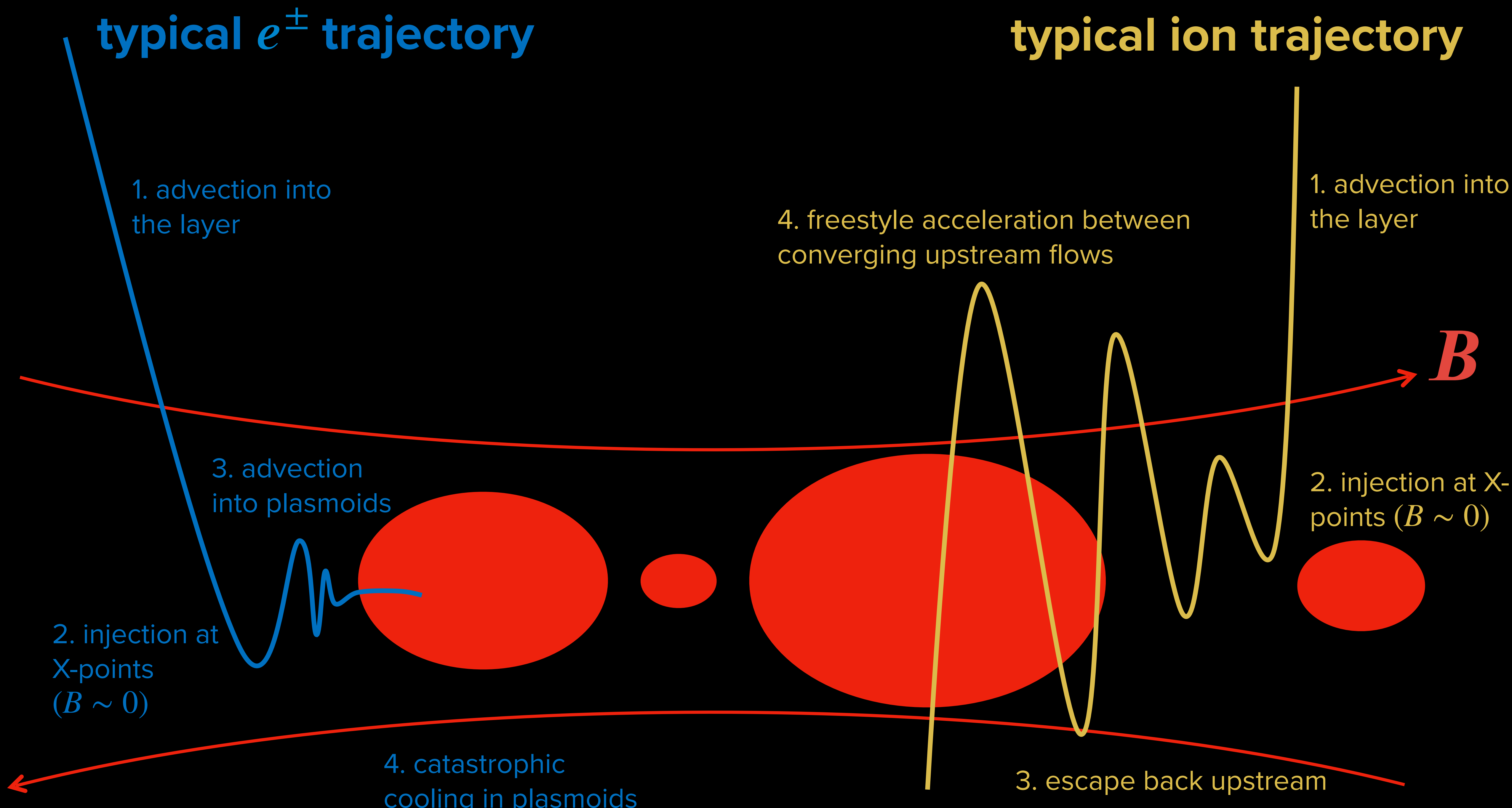
$$\sim 0.1 e B_0 c$$



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

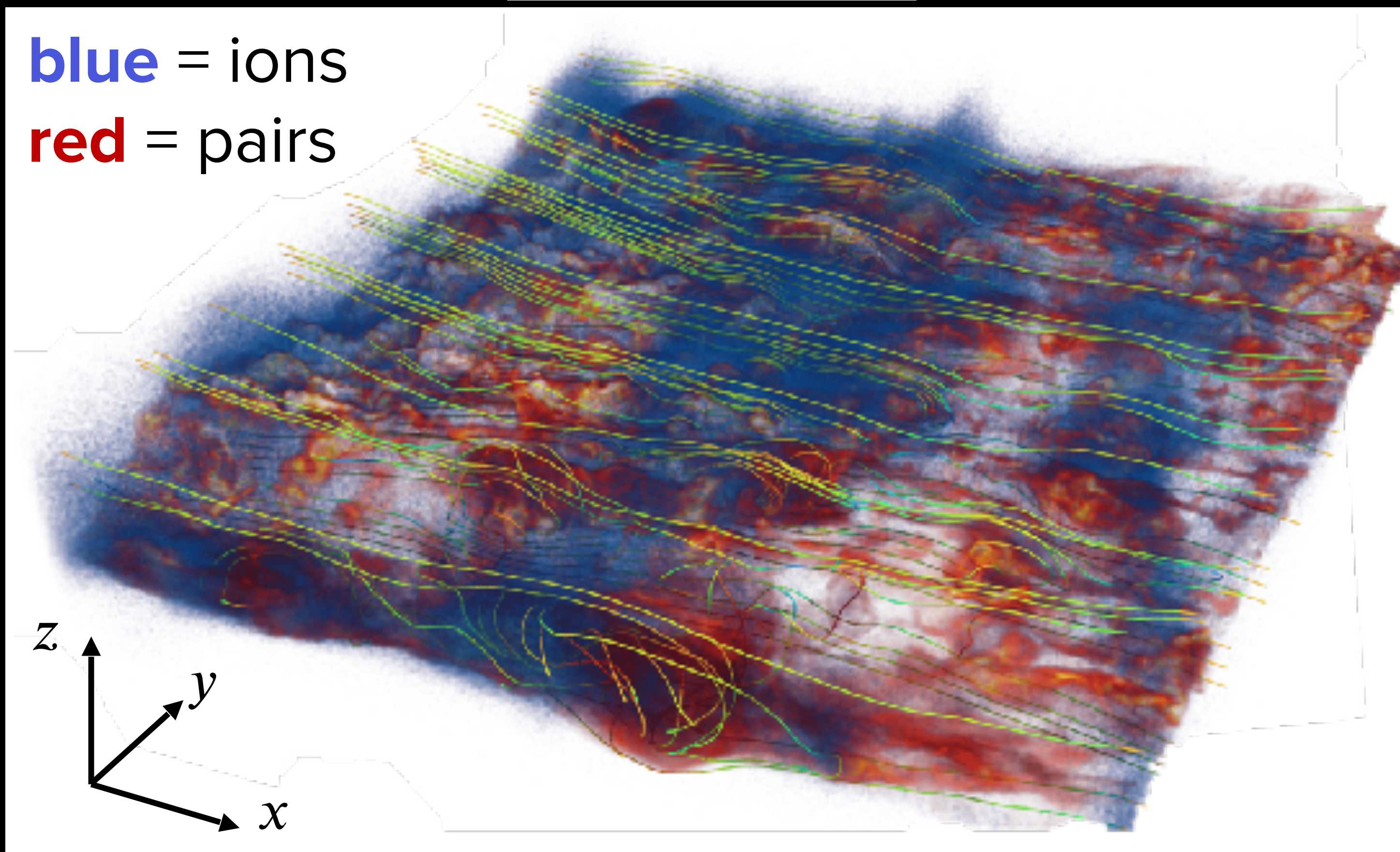
Pair-ion relativistic reconnection

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

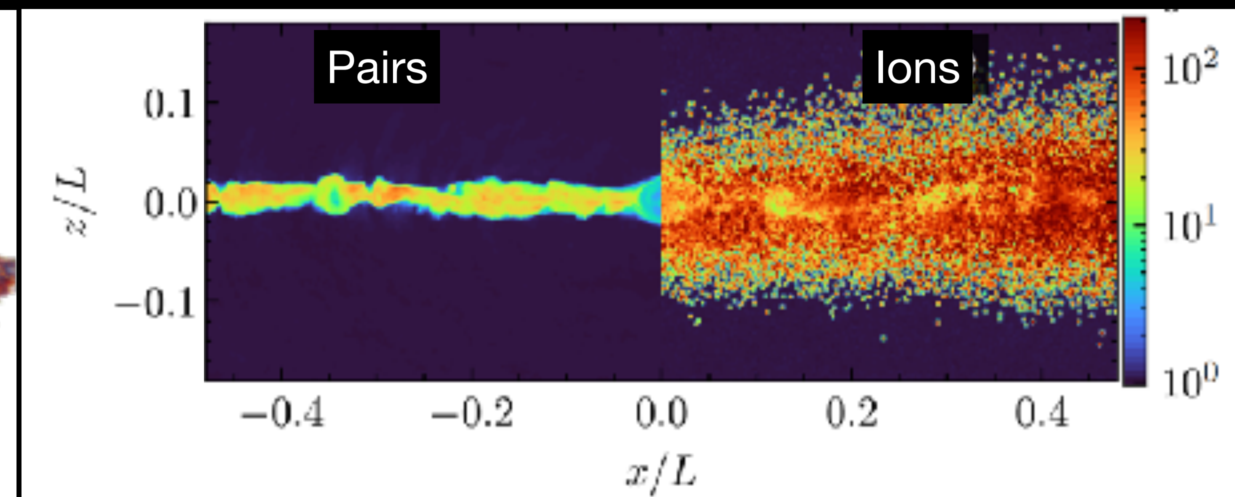


Pairs and ions decouple

$\gamma_{\rm rad}^{\pm}/\sigma \approx 0.15$



Average Lorentz factor

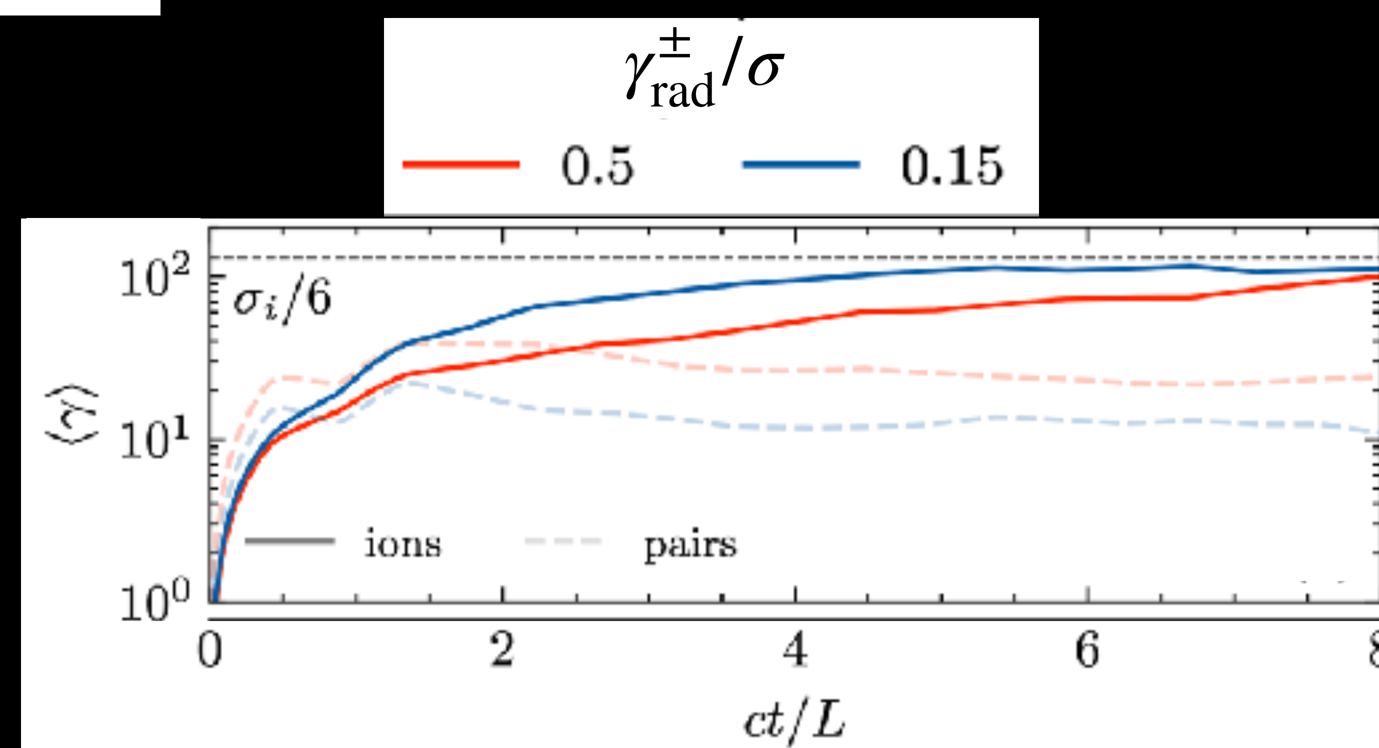


(Hakobyan+ 25)

- The dynamics of pairs and ions are nearly decoupled.

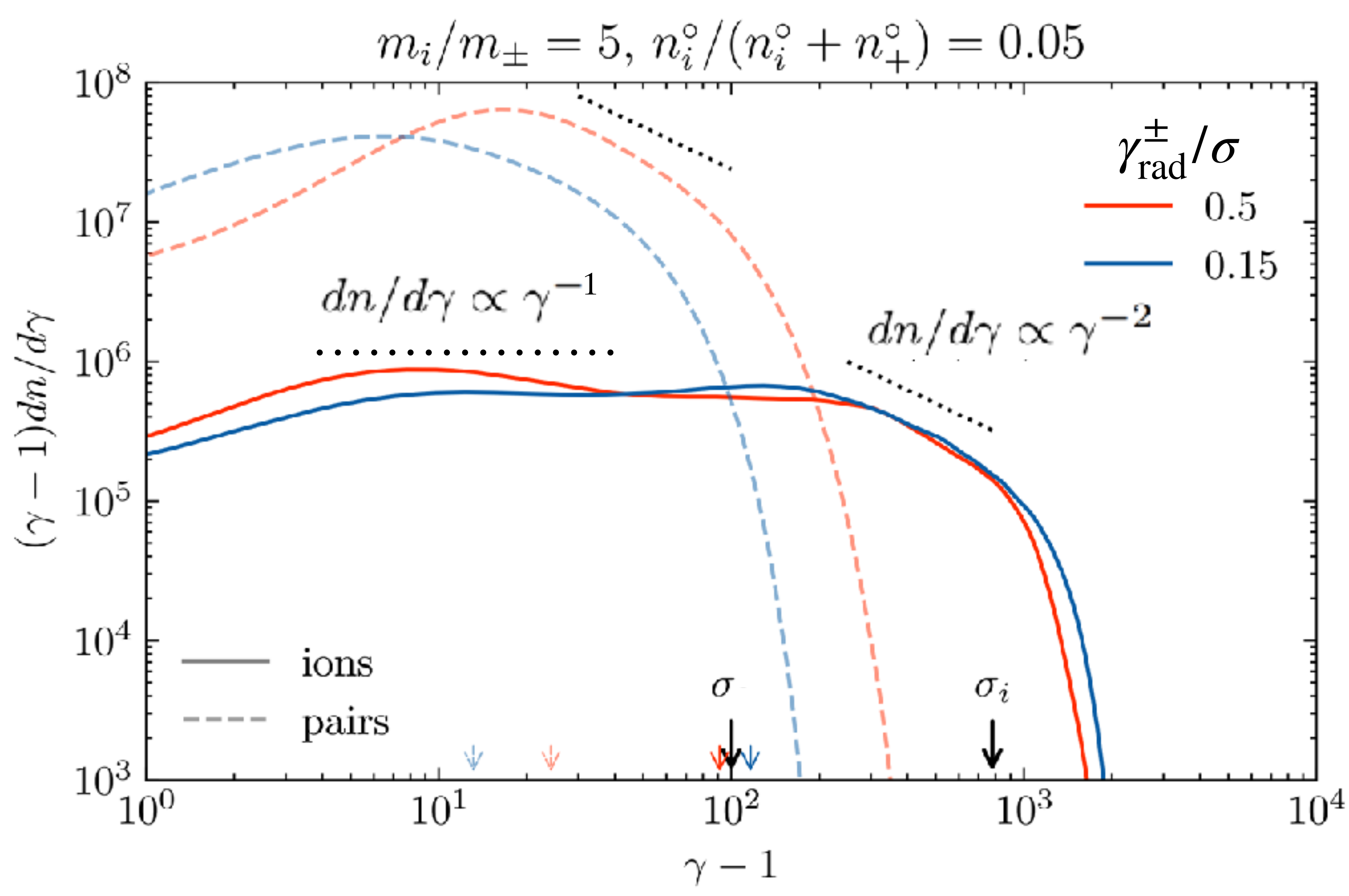
- The ion average Lorentz factor approaches equipartition:

$$\langle \gamma_i \rangle \sim 0.2\, \sigma_i = 0.2\, \frac{B_0^2/4\pi}{n_i m_i c^2}$$



Particle spectrum in pair-ion reconnection

The ion average Lorentz factor approaches equipartition: $\langle\gamma_i\rangle \sim 0.2\,\sigma_i = 0.2\,\frac{B_0^2/4\pi}{n_i m_i c^2}$



(Hakobyan+ 25)

The ion spectrum is a broken power law:

- The low-energy slope -1, the high-energy slope is -2
- The break Lorentz factor is $\sim \langle\gamma_i\rangle \sim 0.2\,\sigma_i$

What can relativistic reconnection do?

- B-field energy → bulk motions, heat, non-thermal acceleration.

- Power the multi-wavelength and multi-messenger signatures of high-energy astro sources, including BH coronae:

  (1) GeV flares from M87* magnetosphere

  (2) TeV neutrinos from luminous BH coronae

GeV flares from M87* magnetosphere

Hakobyan, Levinson, LS et al. 2025, arXiv:2507.14002

H. Hakobyan

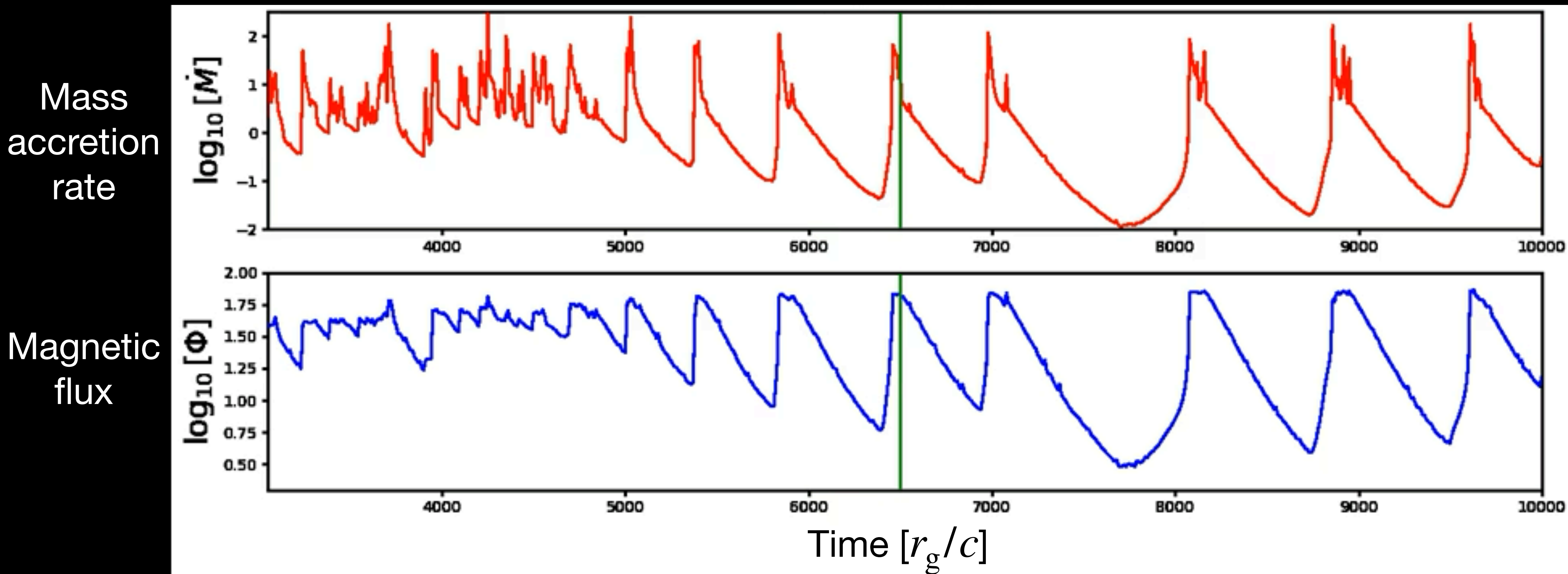
A. Levinson

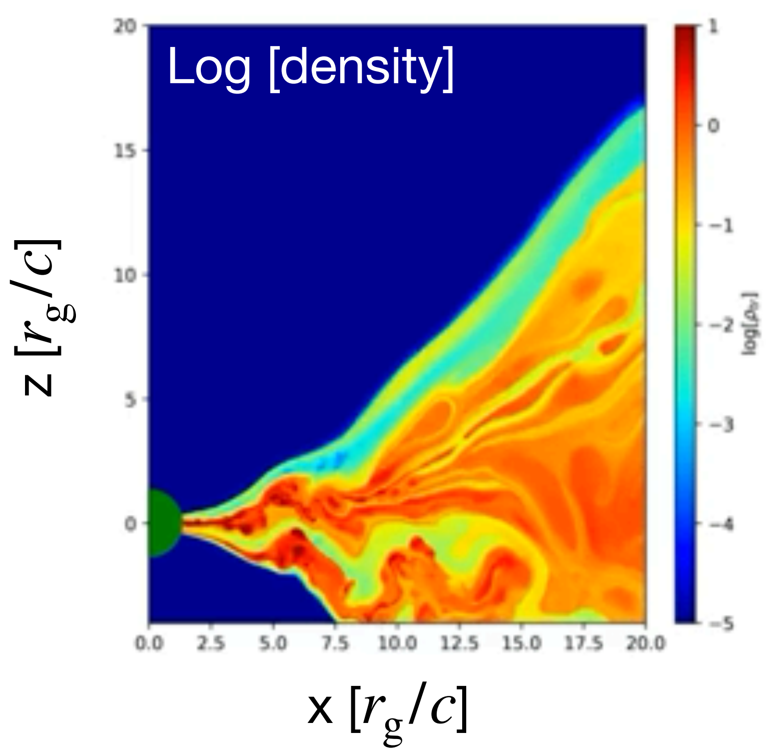
A. Philippov

B. Ripperda

Reconnection in BH magnetospheres

Reconnection layer in the magnetically-arrested (MAD) state





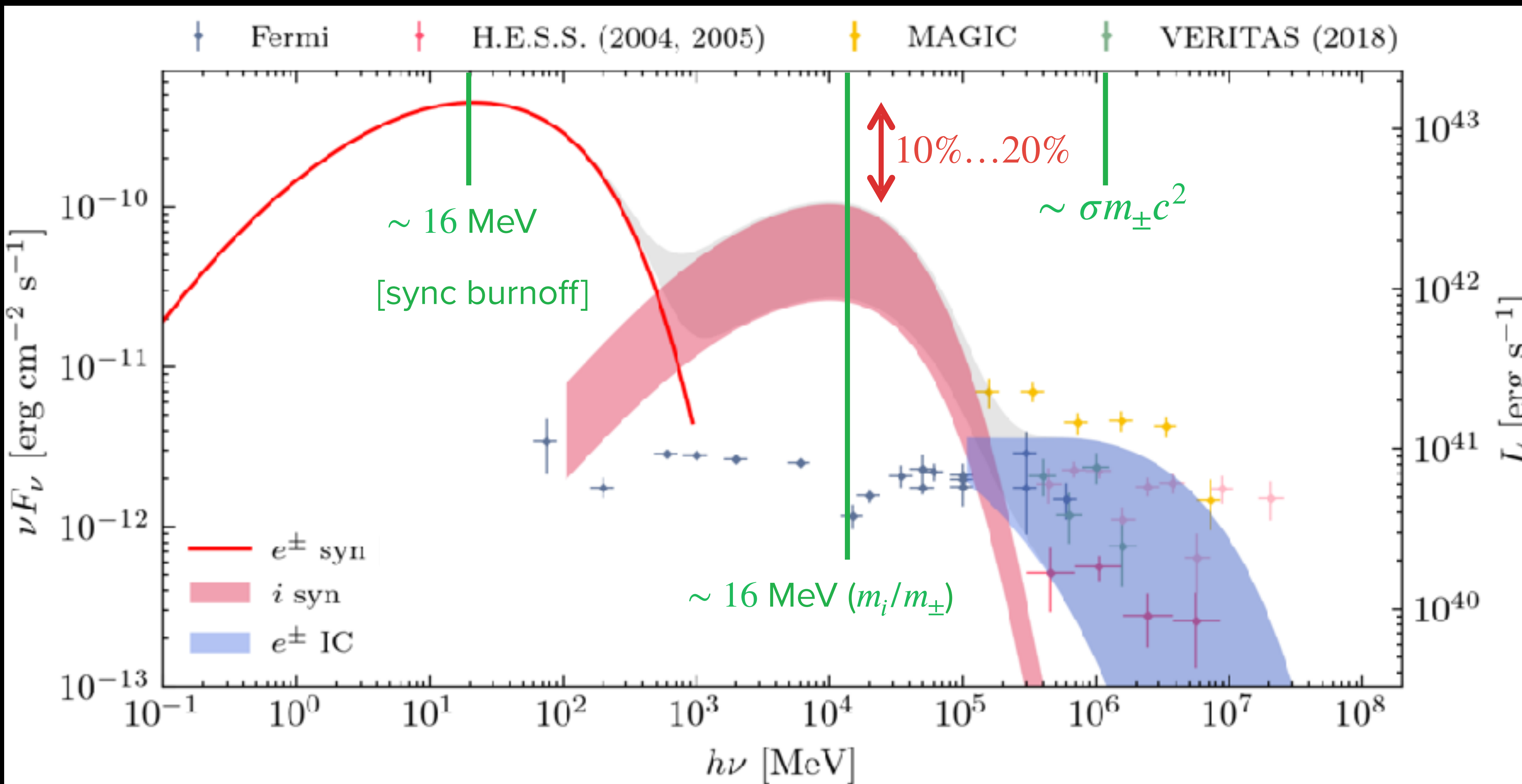
A reconnection layer forms near the equatorial plane during flux eruption events

(Chow, LS et al, in prep)

GeV flares from M87* magnetosphere

In M87* magnetosphere:
- $\sigma \sim 10^8$, depends on B_0 and $n_\pm$
- $\gamma_{\rm rad}^{\pm} \sim 10^7$, depends on B_0 alone

$\rightarrow \gamma_{\rm rad}^{\pm}/\sigma \ll 1$



- $e^\pm$-synchrotron of strongly cooled pairs (with $\gamma_\pm \sim \gamma_{\rm rad}^{\pm}$) $\rightarrow$ MeV
- synchrotron emission of protons near $\gamma_i \sim \gamma_{\rm rad}^{i}$ $\rightarrow$ GeV
- inverse-Compton scattering of $\leq$ eV photons on $e^\pm$ (with $\gamma_\pm \sim \sigma$) $\rightarrow$ TeV

TeV neutrinos from luminous BH coronae

Karavola et al. 2025, JCAP, 4, 75

Fiorillo et al. 2024, ApJL, 961, L14

D. Karavola

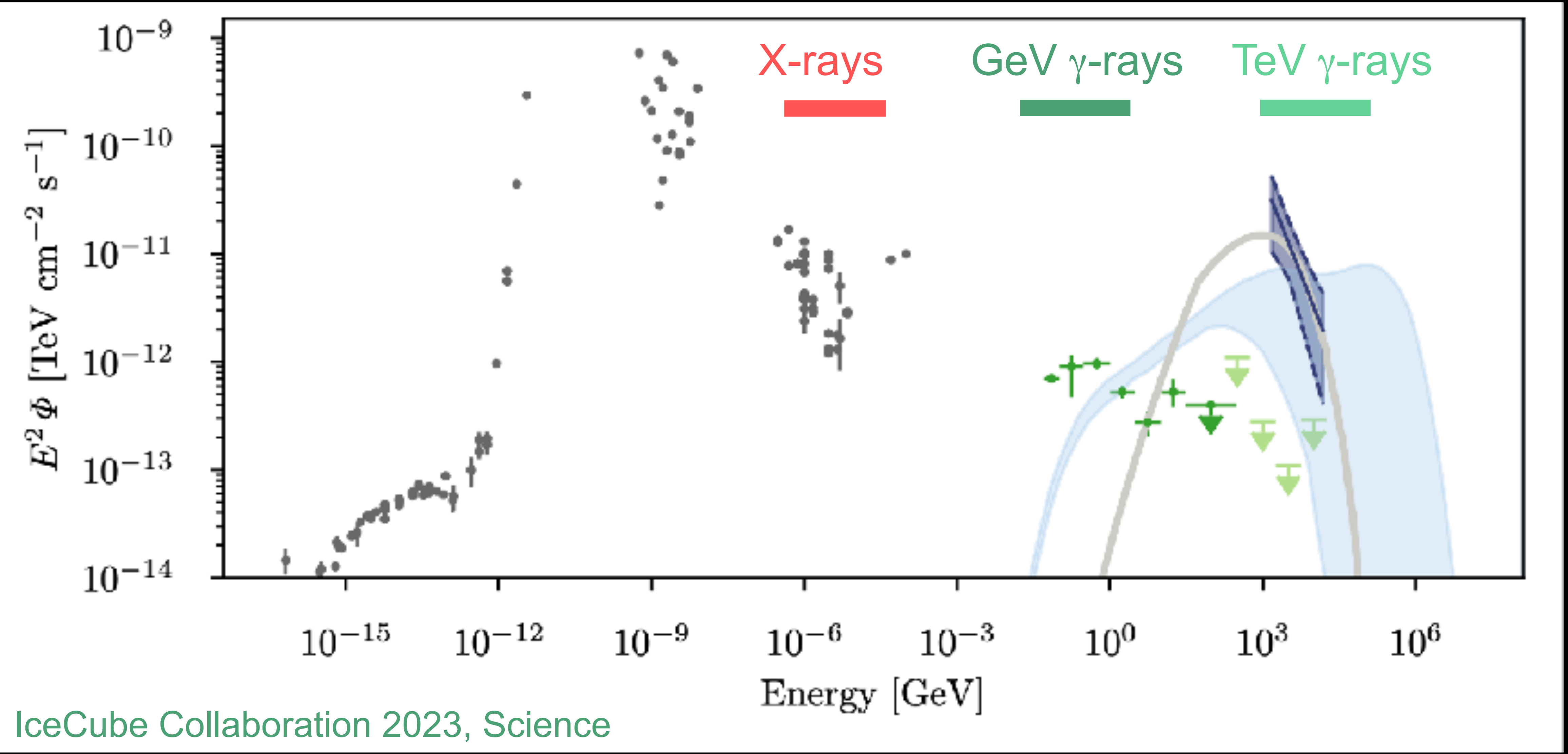
D. Fiorillo

M. Petropoulou

L. Comisso

E. Peretti

Multi-messenger observations



- $L_\nu \sim (0.8 - 4) \times 10^{42}$ ergs/s [all flavor]
- $E_{\nu,\mathrm{pk}} \sim$ TeV
- Spectrum above the peak: $dN_\nu/dE_\nu \propto E_\nu^{-3}$

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

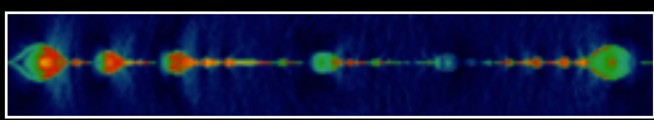
A reconnection-based coronal model

EM flux into the reconnection layer

~ 0.1 efficiency

Relativistic proton energy density

Radiative efficiency ~ 0.1 for plasmoid chain Comptonization

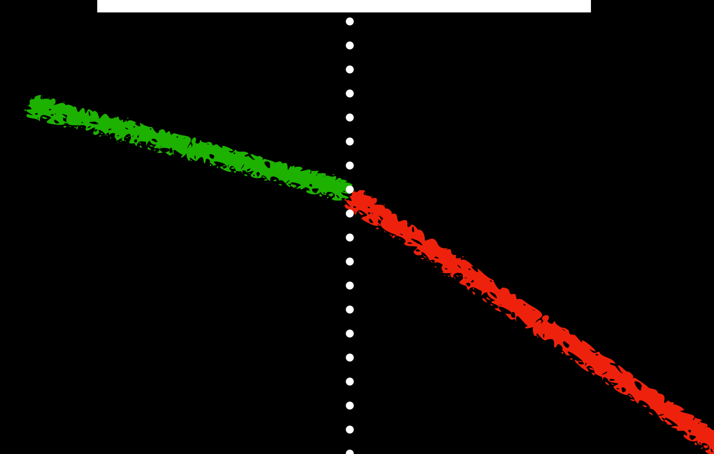


Comptonized X-ray flux

p-γ interactions

Neutrino spectrum

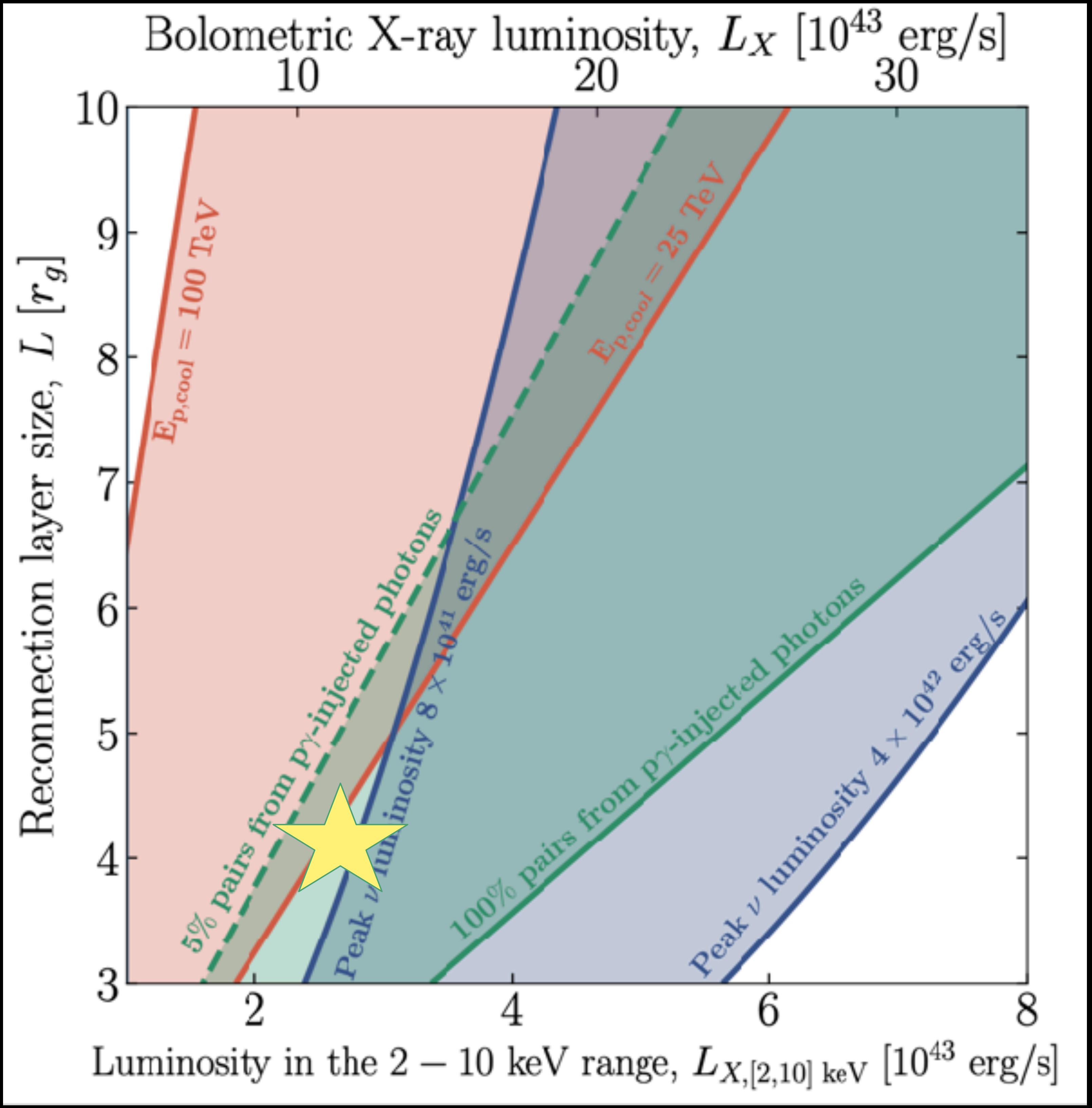
Proton spectrum



Thomson depth ~ 1

Pair density

A tightly constrained system



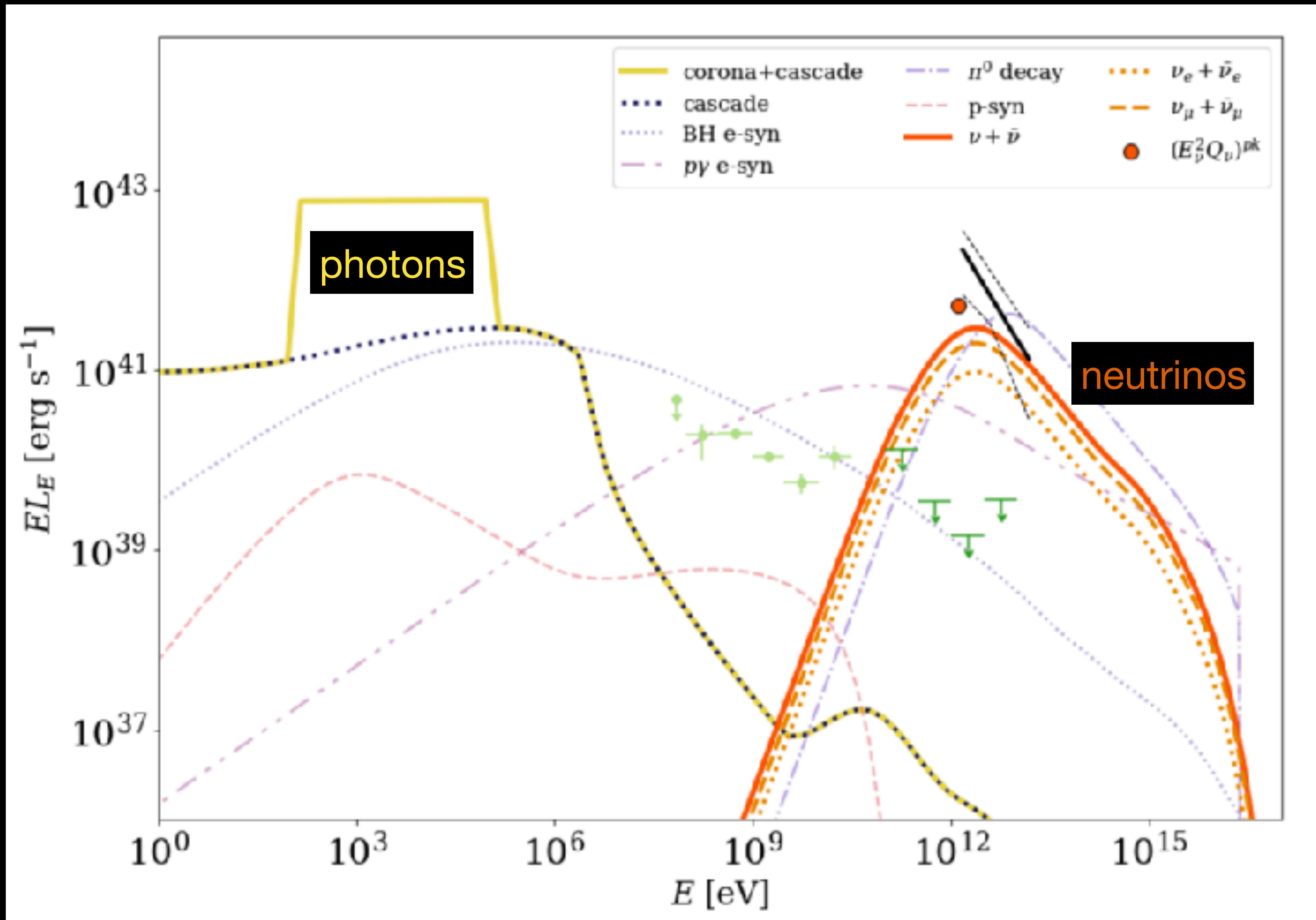
(Fiorillo et al 24)

We find:

- Compact corona: L~ few r_g
- Highly magnetized corona with pair-to-proton ratio $\gg 1$ and

$\sigma_e \sim 10^2\,; \sigma_p \sim 10^5$

Neutrino and photon spectra



(Fiorillo et al 24)

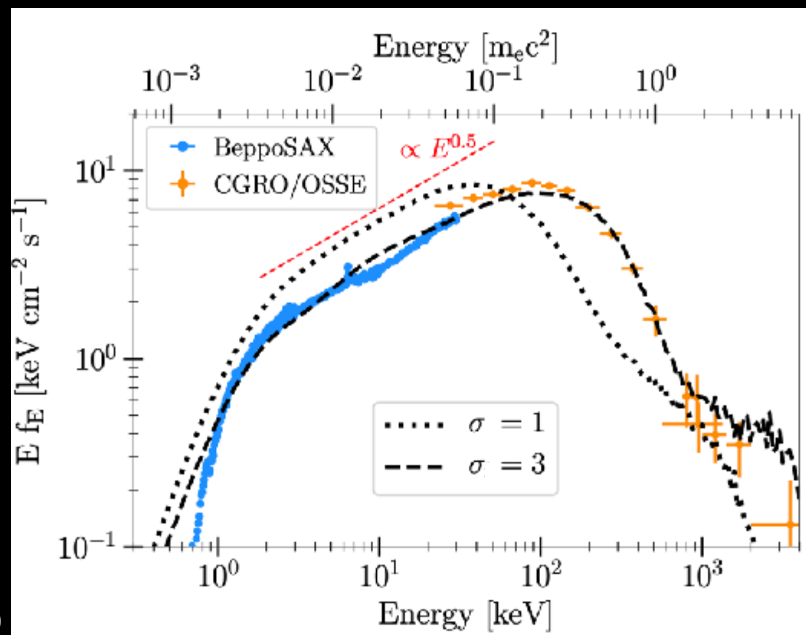
- The neutrino spectrum requires a post-break proton spectrum $dN/d\gamma \propto \gamma^{-3}$
- GeV-TeV photons of hadronic origin are absorbed locally.

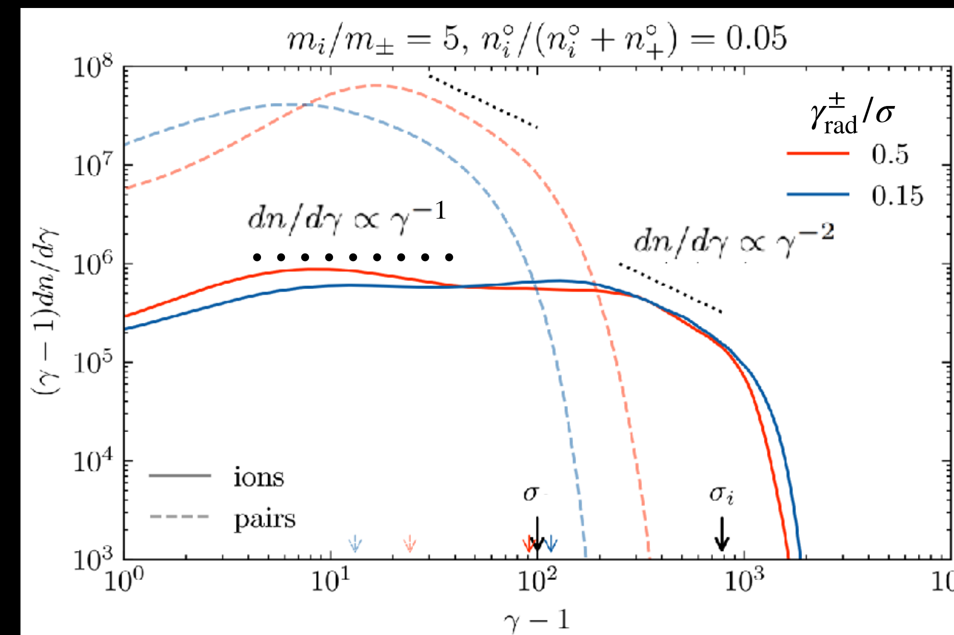
They cascade to MeV energies and result in pairs that naturally account for $\tau_T \sim 1$

What can relativistic reconnection do?

- B-field energy → bulk motions, ~~heat~~, non-thermal acceleration.

(Sridhar+ 23)





(Hakobyan+ 25)

- Power the multi-wavelength and multi-messenger signatures of high-energy astro sources, including BH coronae:

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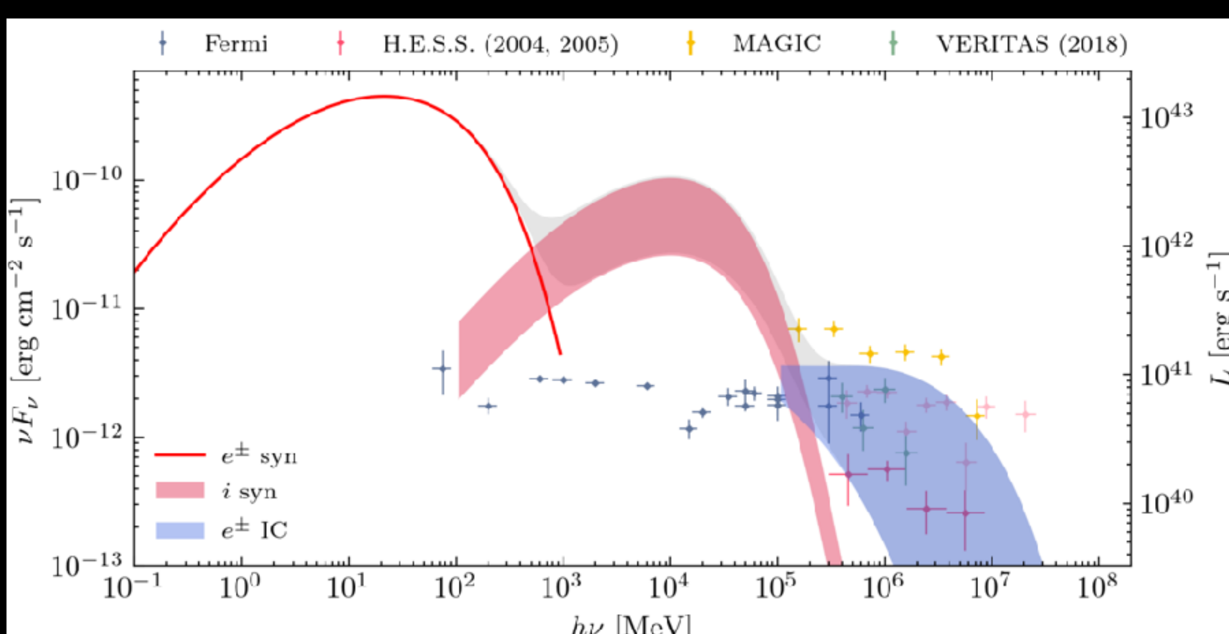
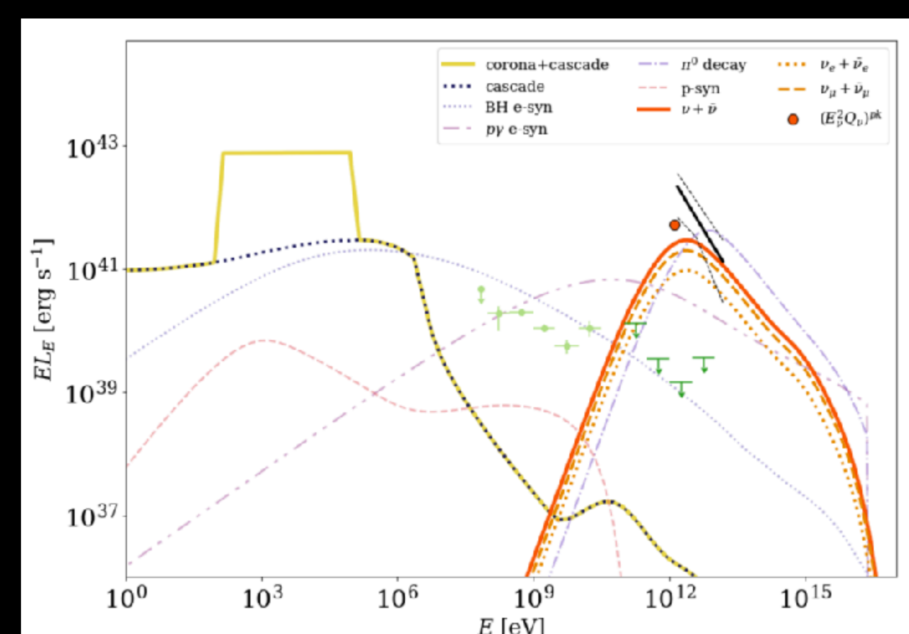
(2) TeV neutrinos from luminous BHs





(Hakobyan+ 25)

(Fiorillo+ 24)