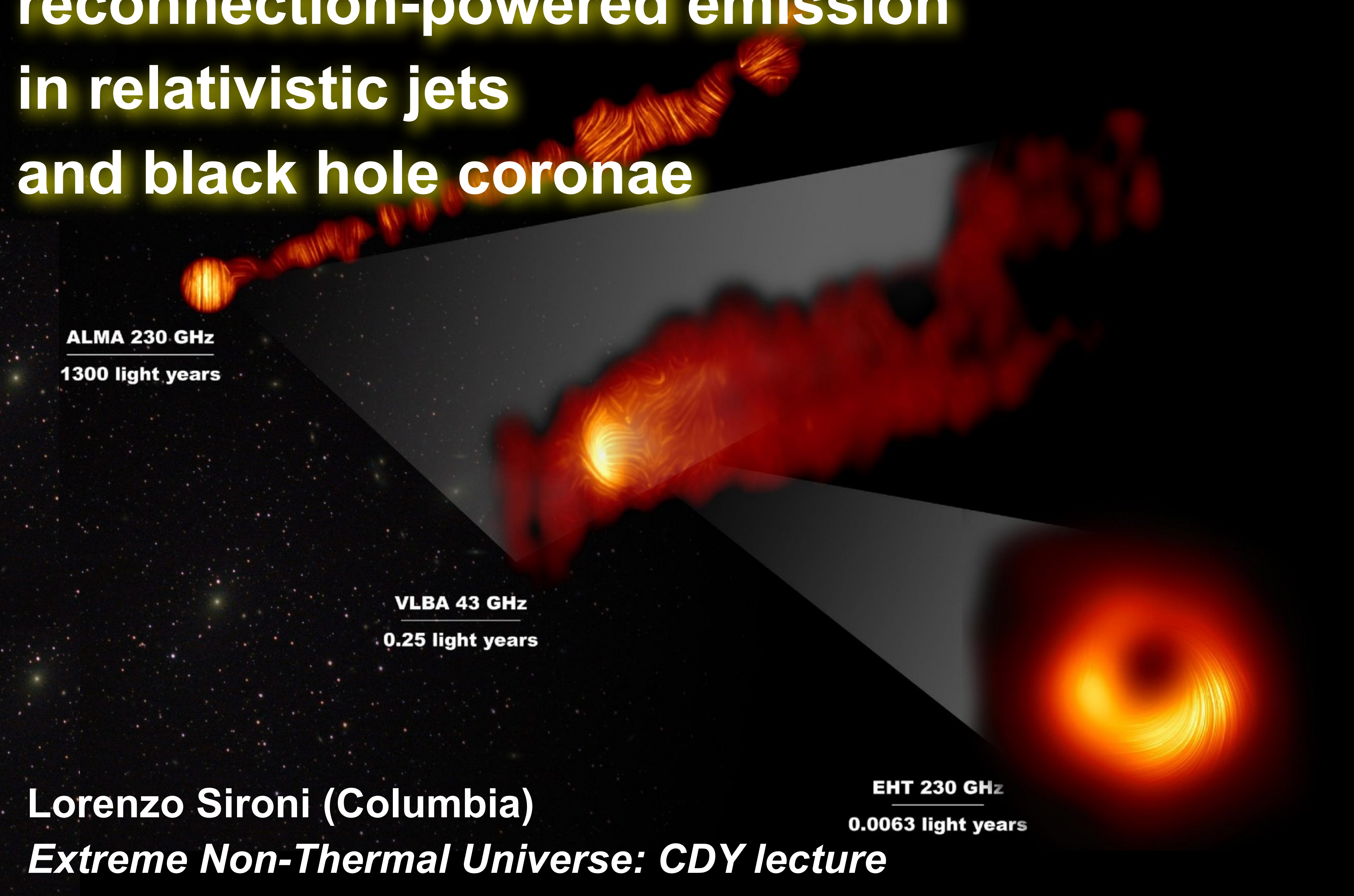
Fast and furious: reconnection-powered emission in relativistic jets and black hole coronae



Lorenzo Sironi (Columbia)

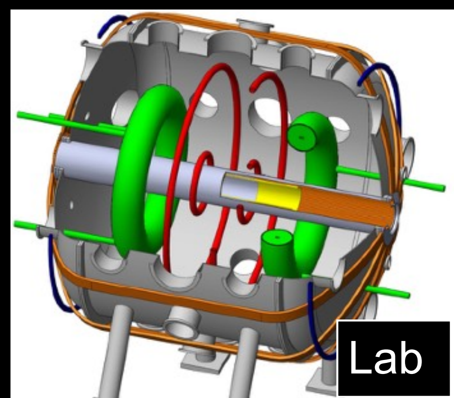
Extreme Non-Thermal Universe: CDY lecture

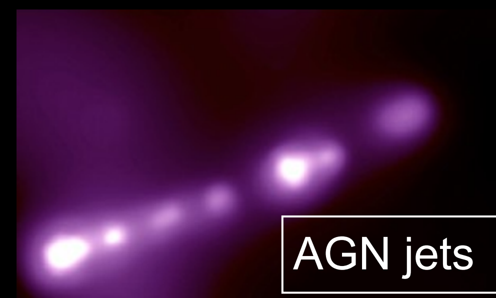
The regime of "relativistic plasmas"

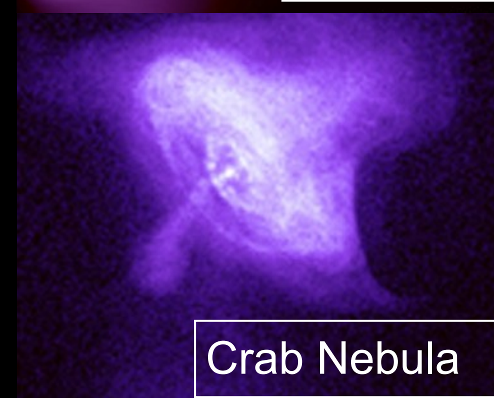
$$\sigma = \frac{B_0^2}{4\pi \rho c^2}$$

σ≪1

σ≫1





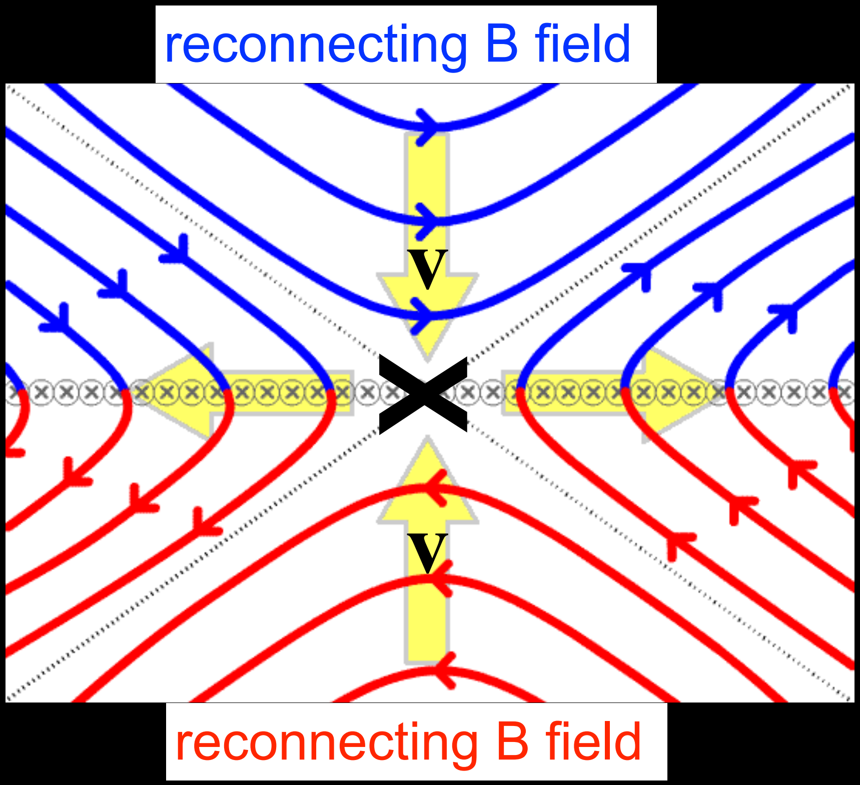


Magnetically-dominated plasmas:

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

High-energy astro sources are our best "laboratories" of relativistic plasma physics

Relativistic reconnection



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

- Reconnection electric field (out-of-plane): $E_{\rm rec} \simeq 0.1 B_0$
- “Guide” (out-of-plane) uniform magnetic field B_g

The physics of particle acceleration in relativistic reconnection

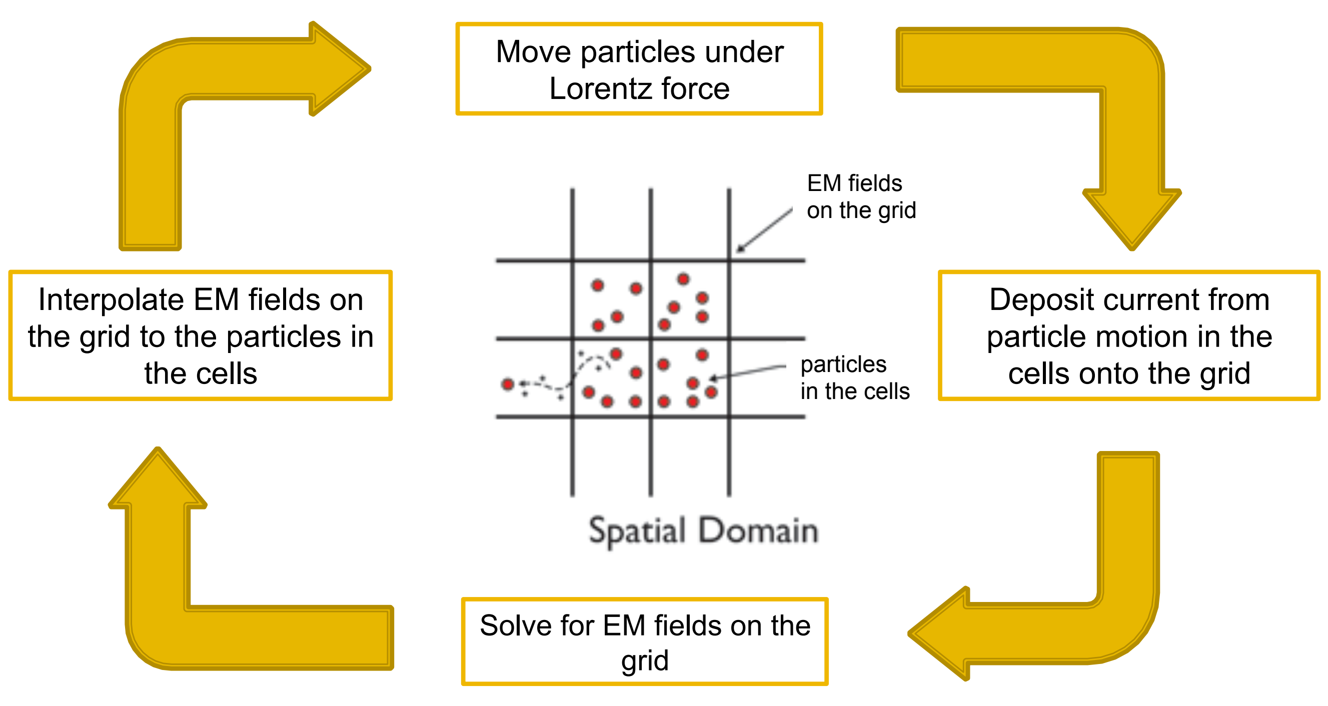
LS 2022, PRL, 128, 145102

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

The PIC method

Particle-in-Cell (PIC) method:

It is the <u>most fundamental way</u> of capturing the interplay of charged particles and e.m. fields.



The computational challenge:

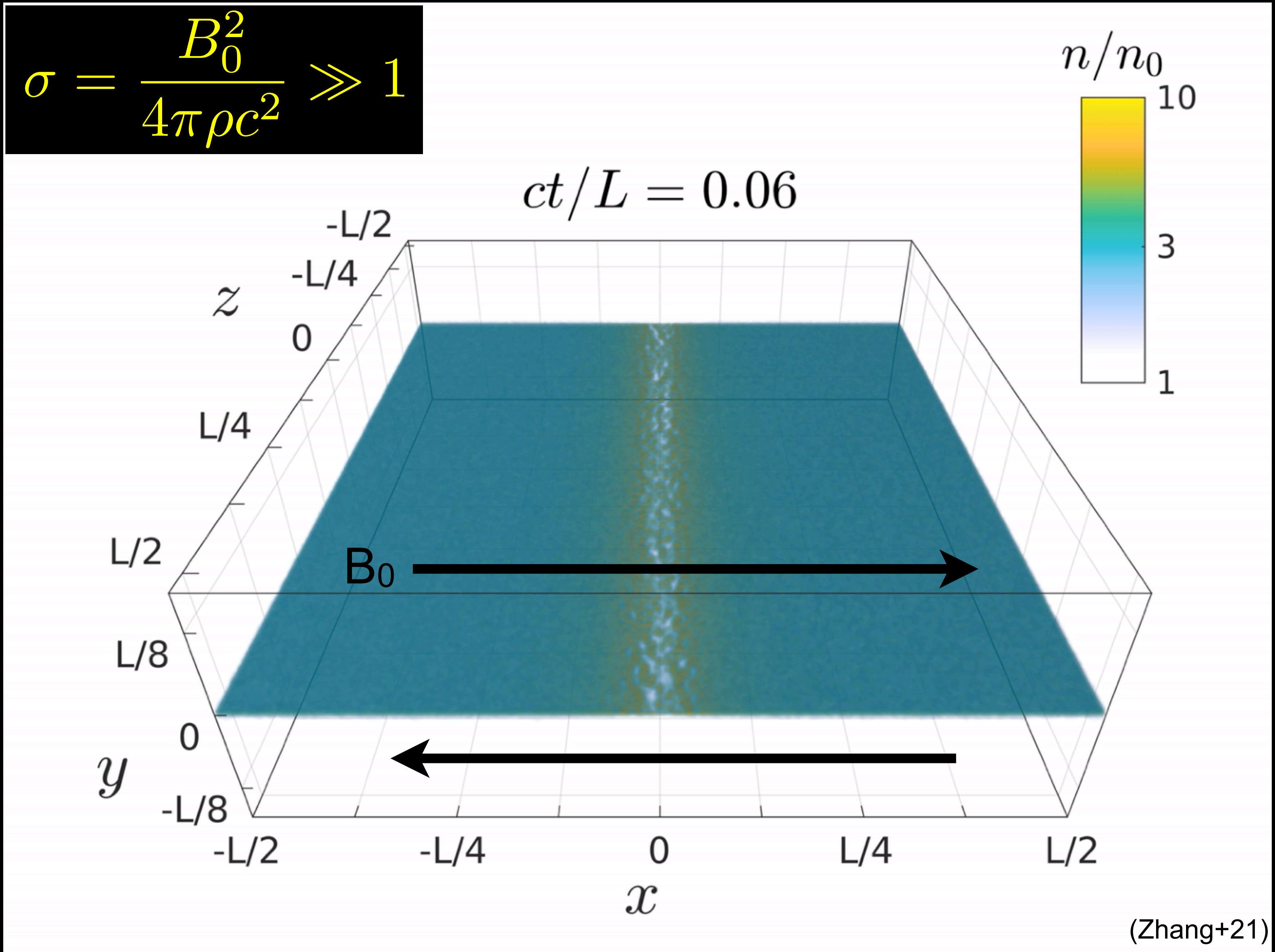
The *microscopic* scales resolved by PIC simulations are much smaller than *astronomical* scales.

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

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

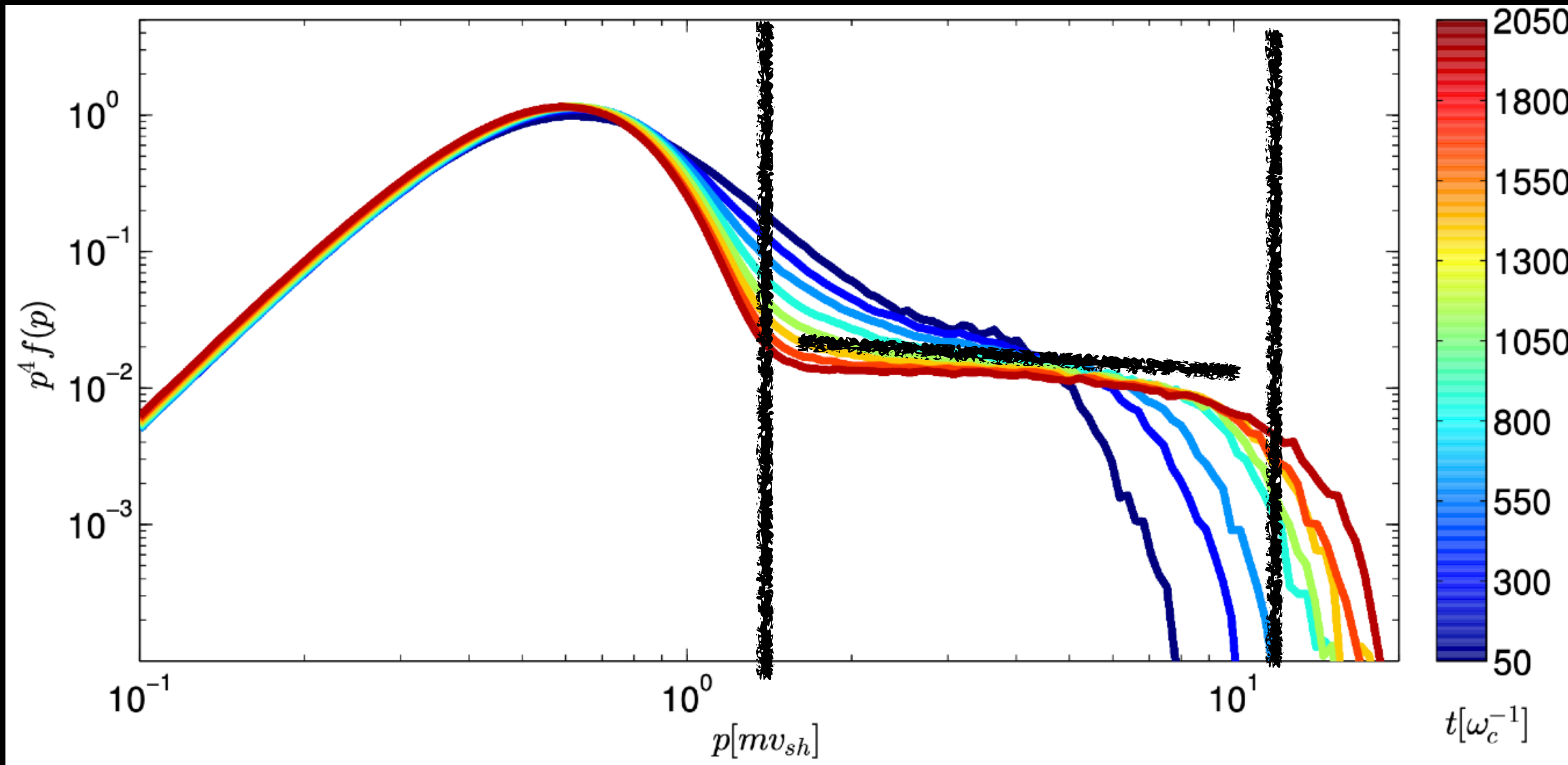
$$\omega_p = \omega_{pe} \quad ; \quad \omega_{pi} = \omega_{pe}\sqrt{m_e/m_i}$$

PIC simulation of σ=10 (relativistic) reconnection



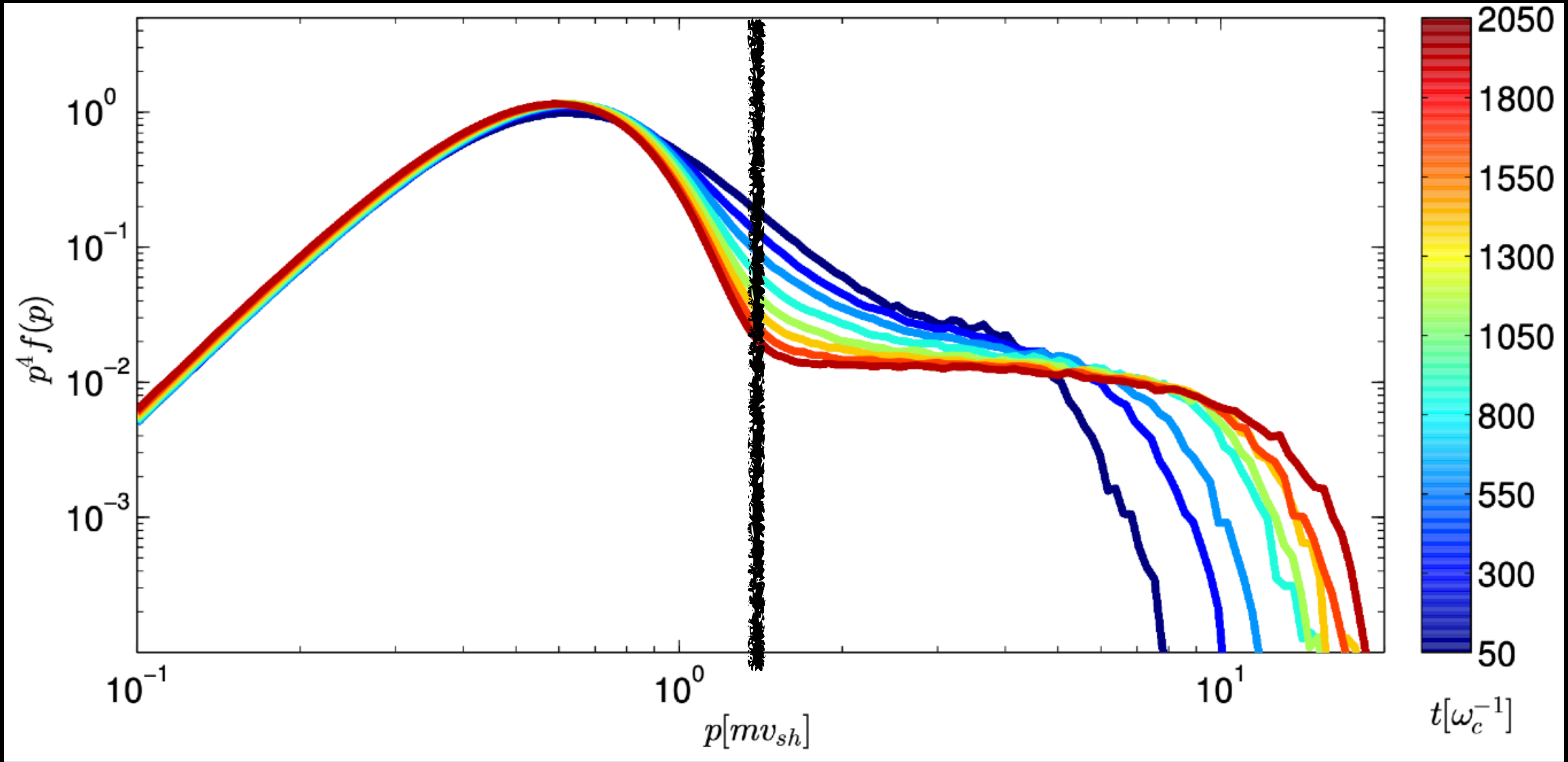
The reconnection layer breaks into a chain of magnetic islands / plasmoids

The three stages of any accelerator



(Caprioli & Spitkovsky 14)

- Injection
- Power-Law Formation
- Maximum Energy (cutoff)



10^0
10^{-1}
10^{-2}
10^{-3}
$p^4 f(p)$
10^{-1}
10^0
10^1
$p[mv_{sh}]$
2050
1800
1550
1300
1050
800
550
300
50
$t[\omega_c^{-1}]$

- Injection

Particle injection

How can the inflowing cold particles be promoted to $\gamma \sim \sigma/2$ and above?

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

They need to be in the right place at the right time!

where they interact with non-ideal fields $\mathbf{E} \neq -\frac{\mathbf{v}}{c} \times \mathbf{B}$

$E > B$ for $B_g/B_0 \lesssim \eta_{\rm rec}$

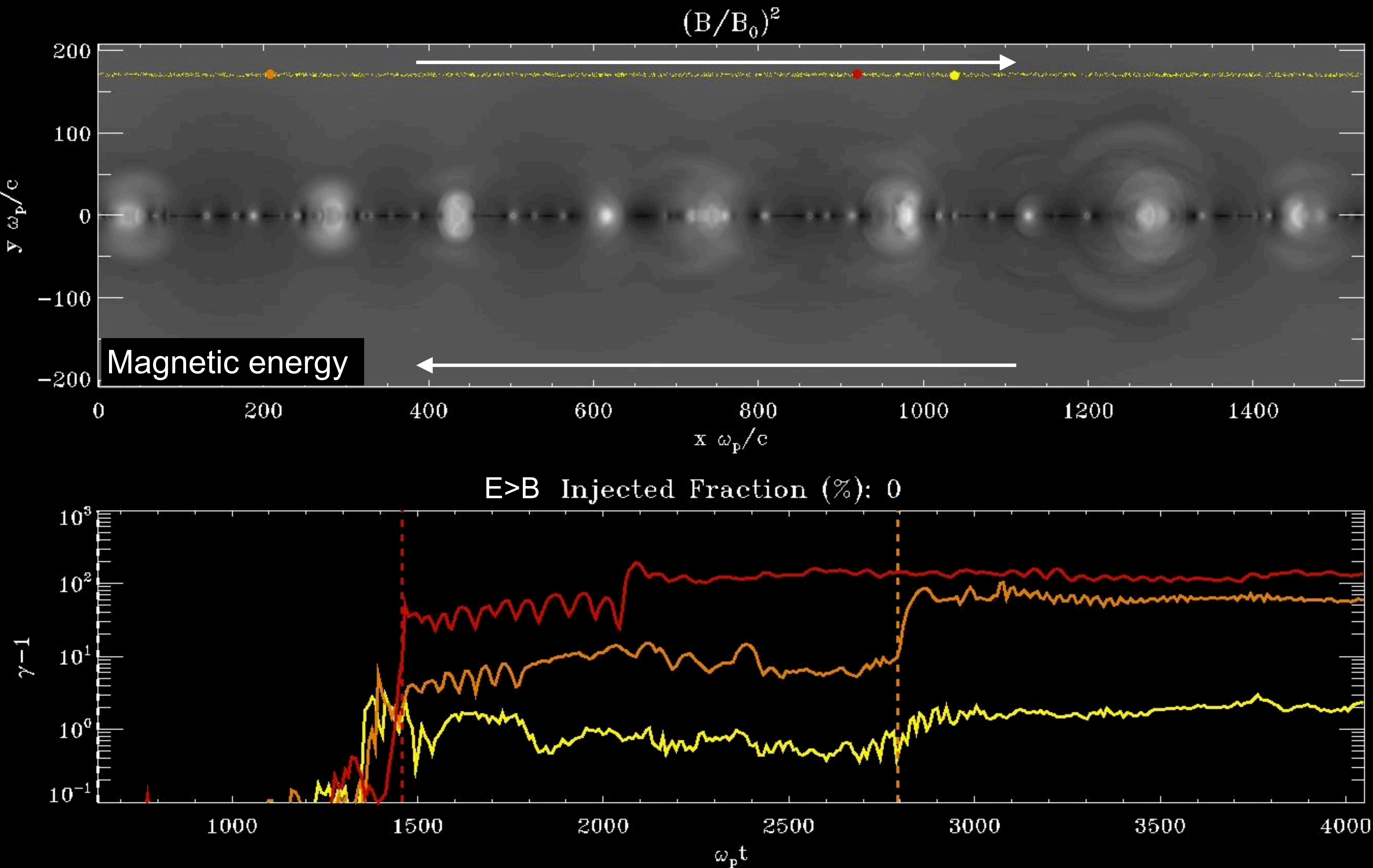
$E_{||}$ for $B_g/B_0 \gtrsim \eta_{\rm rec}$

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

$\eta_{\rm rec} \sim 0.1$ reconnection rate

B_g guide field (along electric current)

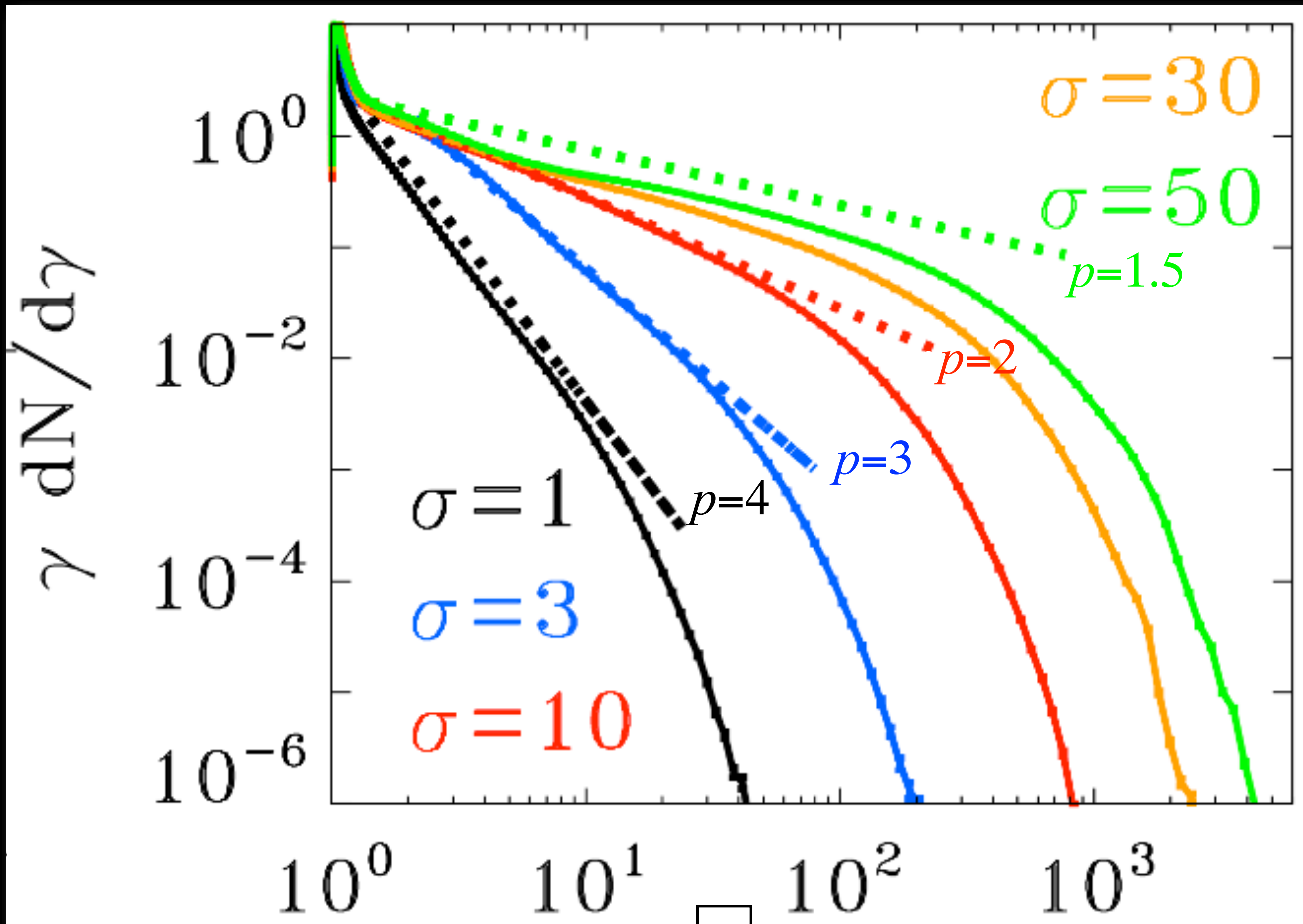
Particle injection



(LS 22, PRL)

The injection stage gives hard spectra

2D and 3D electron-positron



γ

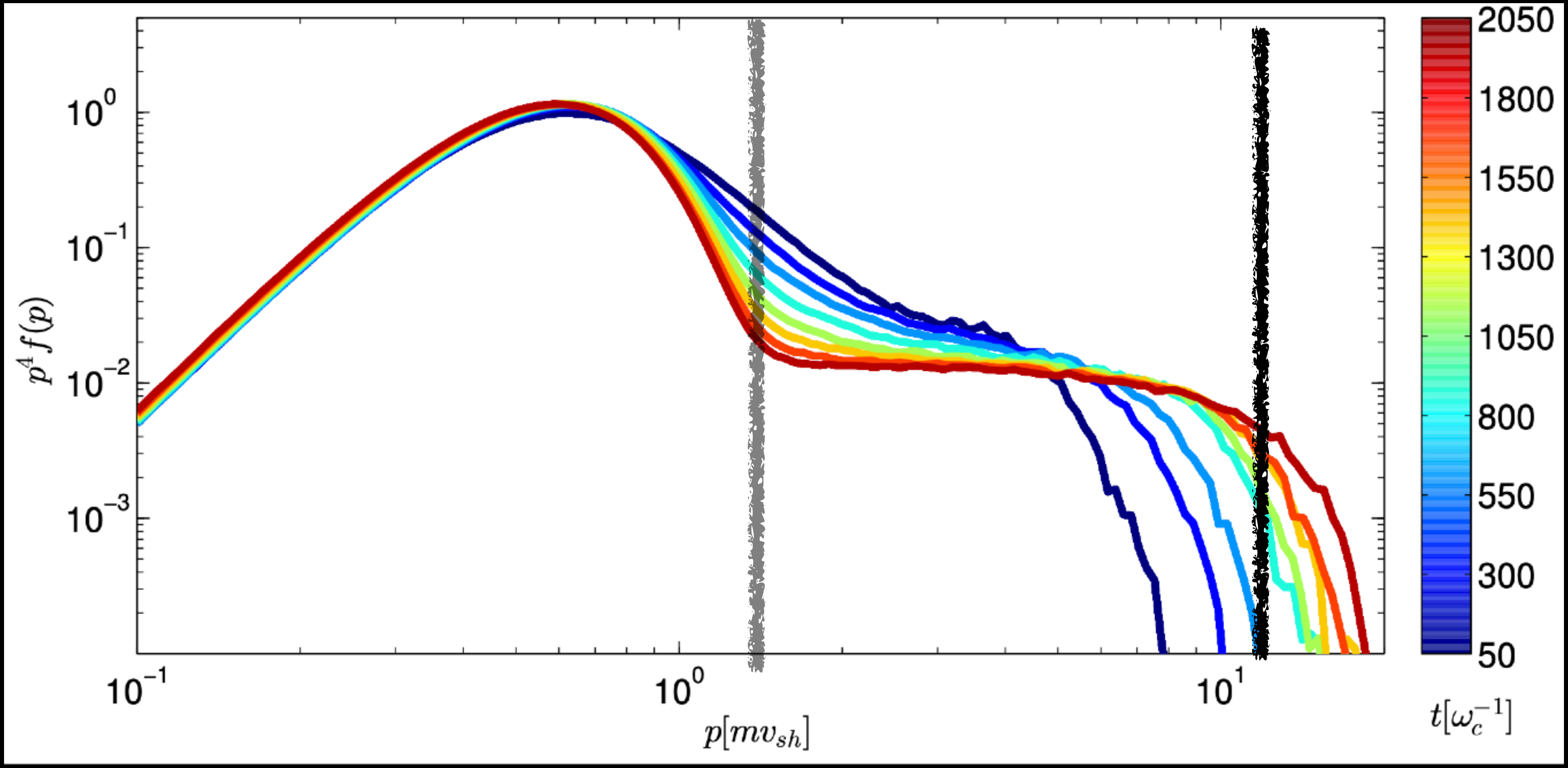
$$\sigma = \frac{B_0^2}{4\pi\rho c^2}$$

(LS & Spitkovsky 14, see also Melzani+14, Guo+14,15, Werner+16,17)

The injection stage produces power laws at $\gamma \lesssim 3\sigma$, with slope as hard as *p=1* for high magnetizations.

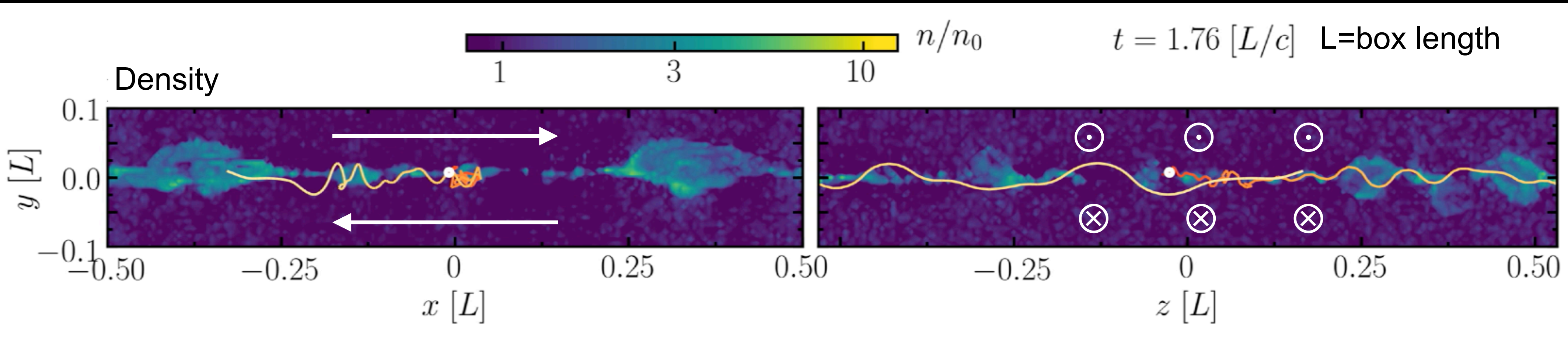
$$\frac{dn}{d\gamma} \propto \gamma^{-p}$$

This holds in electron-positron, electron-proton and electron-positron-proton plasmas.



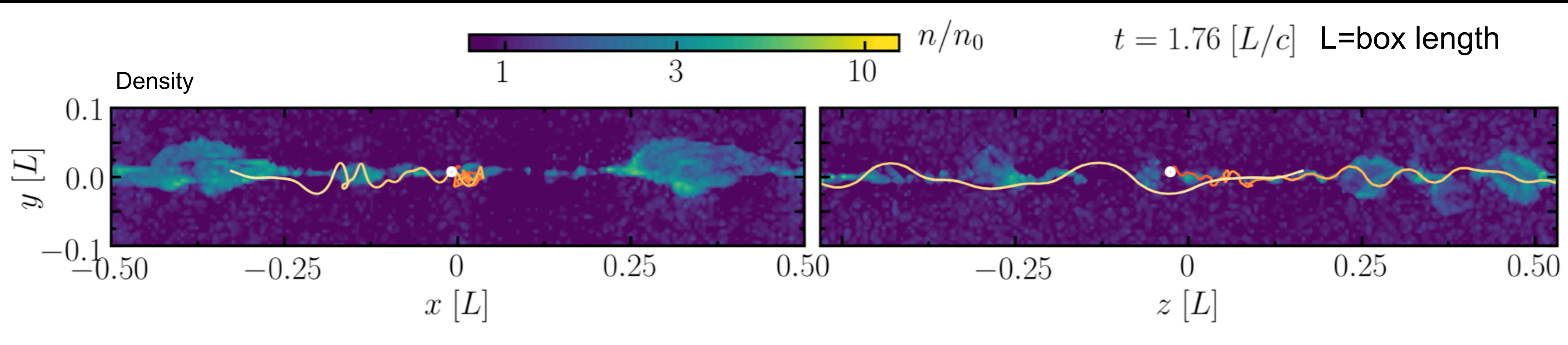
- Injection
- Maximum Energy (cutoff)

The highest energy particles in 3D



• In 3D, lucky particles escape from plasmoids (Dahlin+15) and wiggle “free” around the layer.

The highest energy particles in 3D



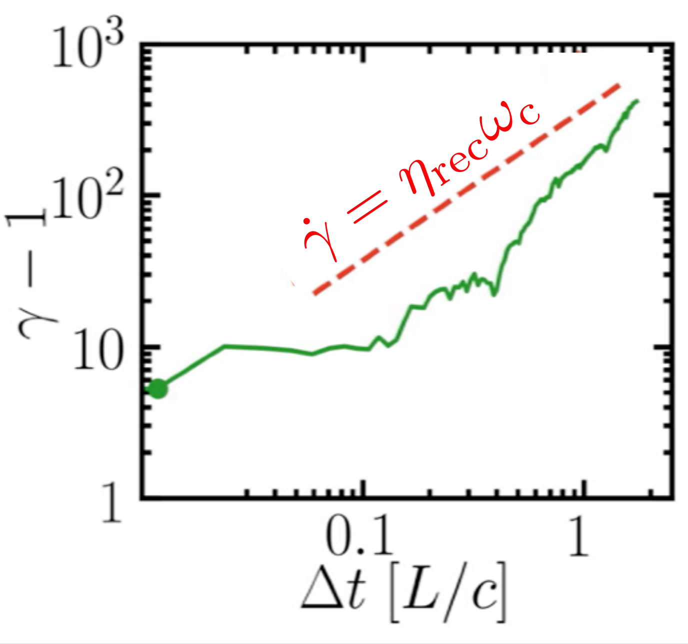
- In 3D, lucky particles escape from plasmoids (Dahlin+15) and wiggle "free" around the layer.

- They get accelerated linearly in time, $\gamma \propto t$, by the large-scale (ideal) electric field in the upstream.

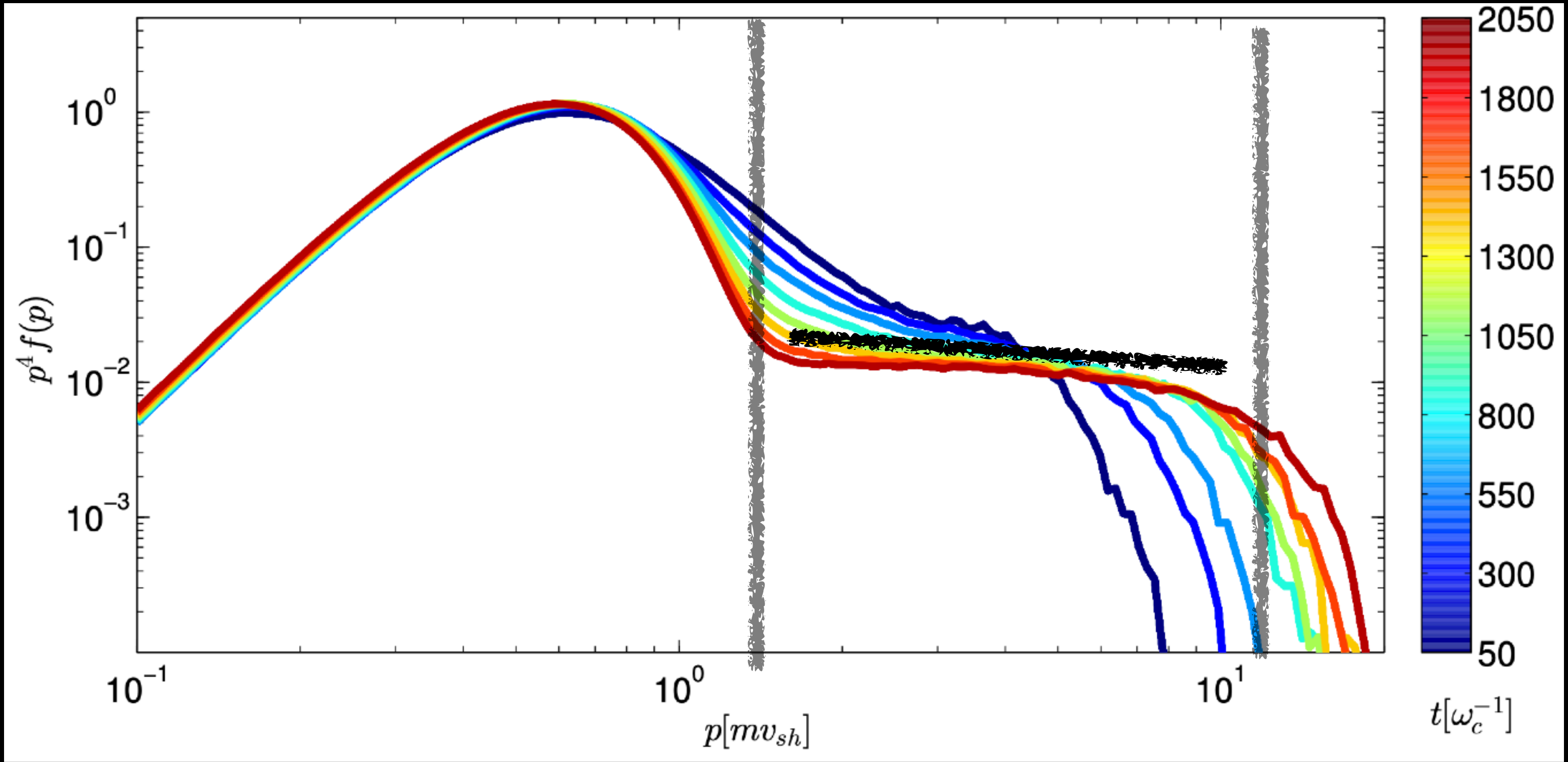
- The energy gain rate approaches $\sim eE_{\rm rec}c$

$$E_{\rm rec} \simeq 0.1 B_0$$

- AGN jets are able to accelerate UHECRs.



(Zhang, LS, Giannios 21)



- Injection
- Power-Law Formation
- Maximum Energy (cutoff)

Theory of power-law formation

- In steady state,

$$\frac{\partial}{\partial\gamma}\left(\frac{\gamma}{t_{\rm acc}}f\right)+\frac{f}{t_{\rm esc}}=Q_0\delta(\gamma-3\sigma)$$

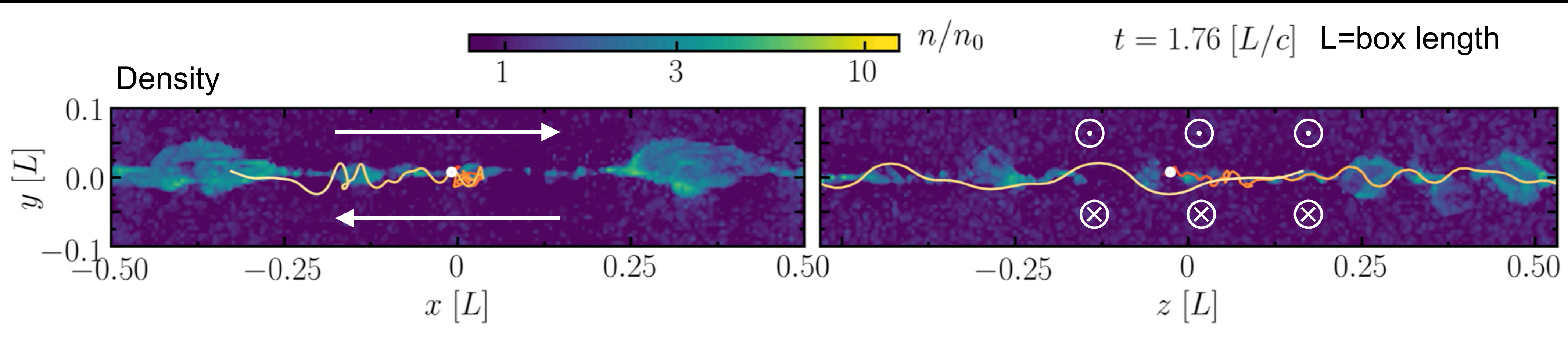
assuming injection at $\gamma = 3\sigma$.

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

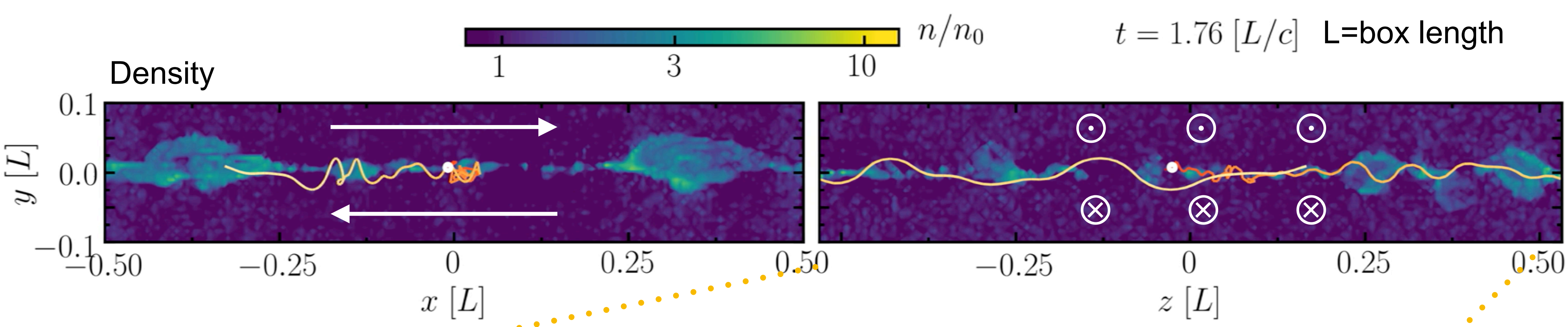
$$f \propto \gamma^{-t_{\rm acc}/t_{\rm esc}}$$

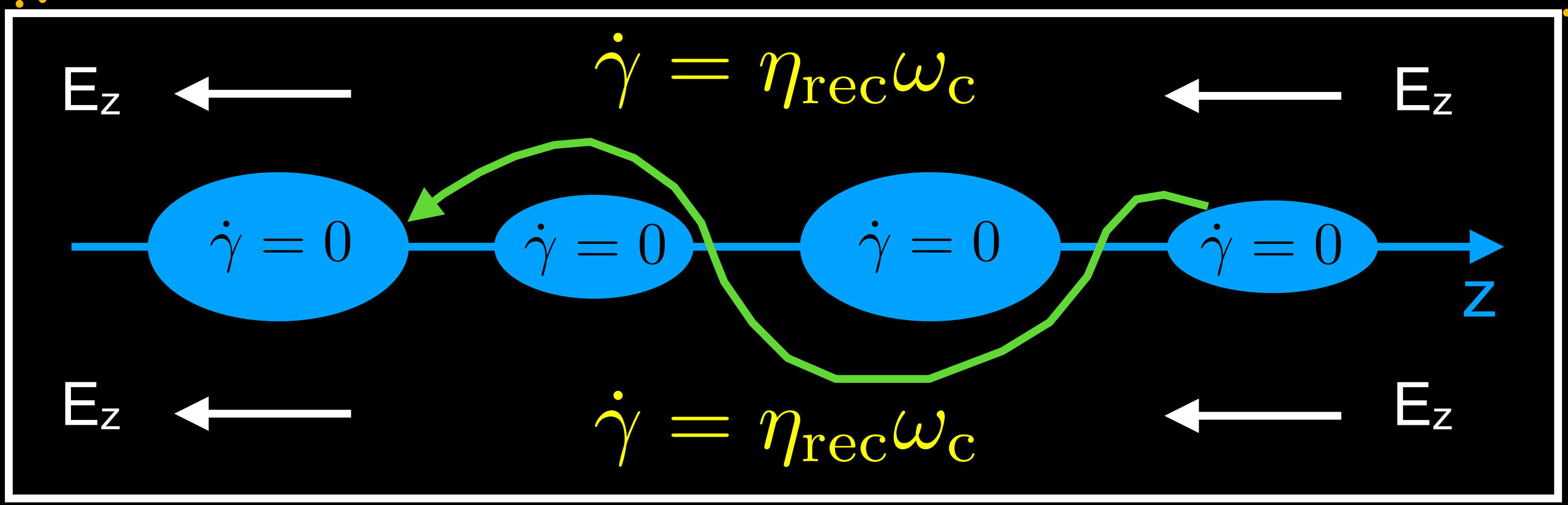
- What is the acceleration time $t_{acc} = \gamma/\dot{\gamma}$?
- What is the escape time t_{esc} ?

A new 3D theory of power-law formation



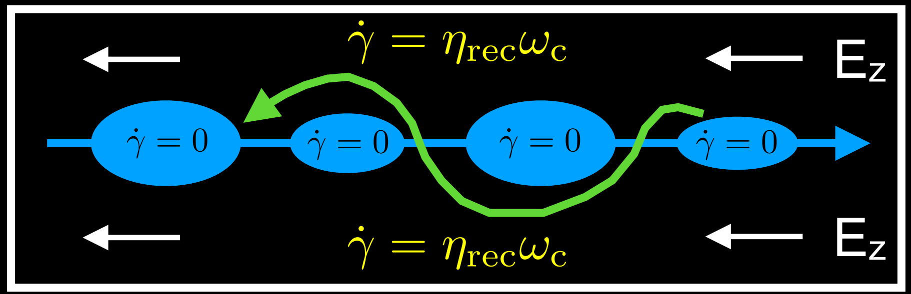
A new 3D theory of power-law formation



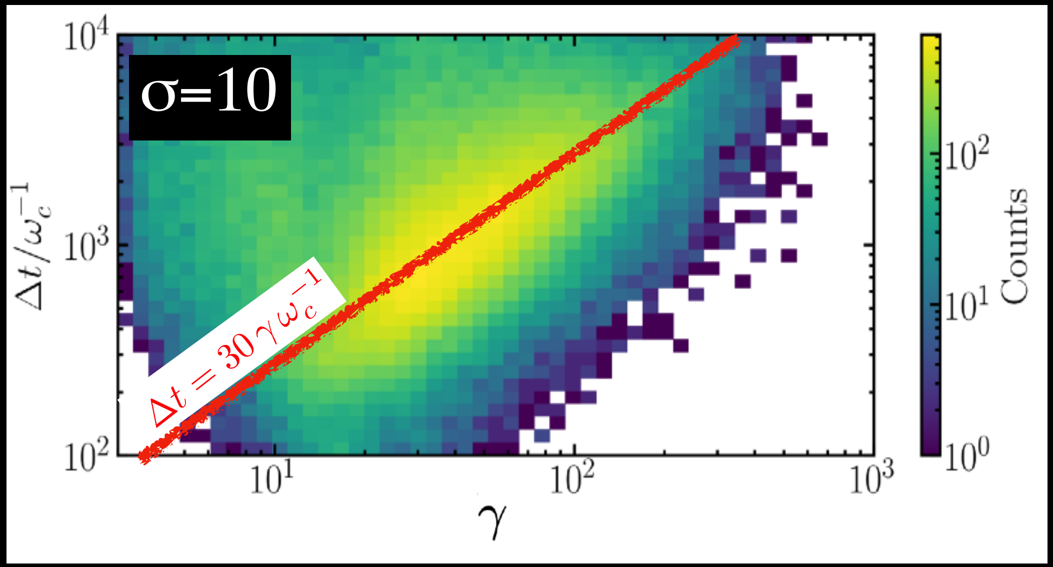


- Active acceleration only in the “free” state while particles are in the upstream.
- Acceleration ceases when particles are captured by plasmoids (escape term).

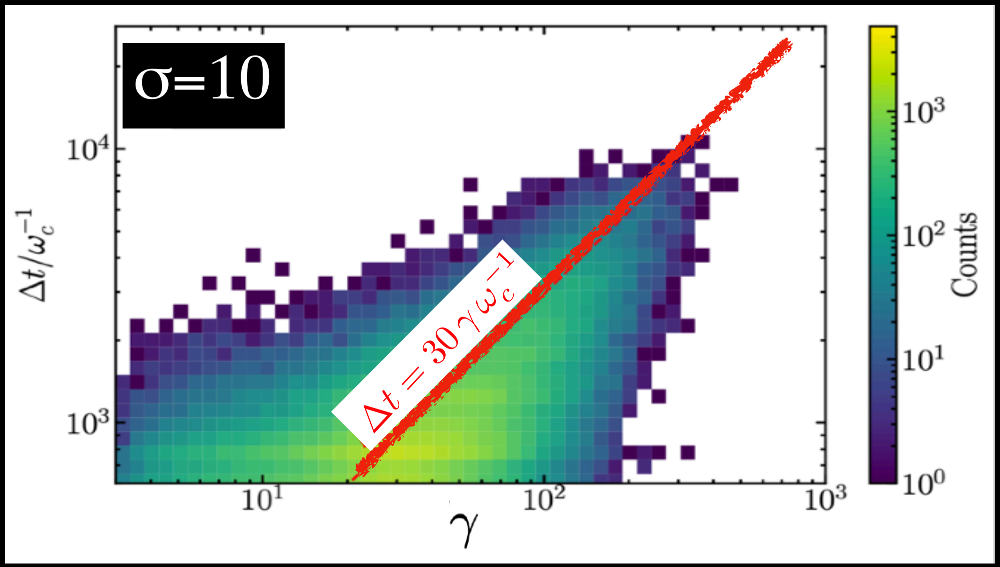
Acceleration and escape times



Acceleration time $t_{acc} = \gamma/\dot{\gamma}$



Escape/trapping time t_{esc}

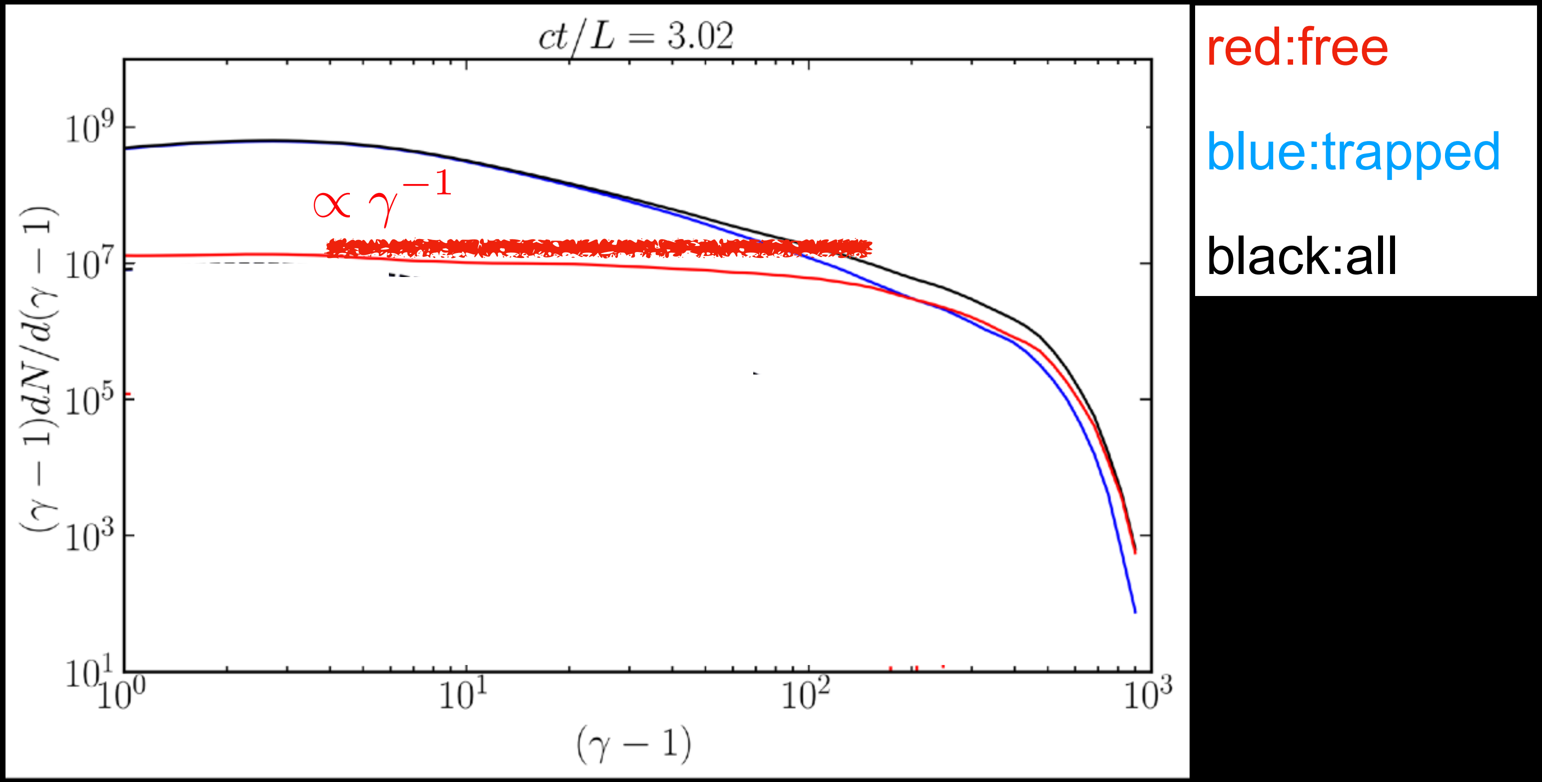


The two timescales are comparable, so

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

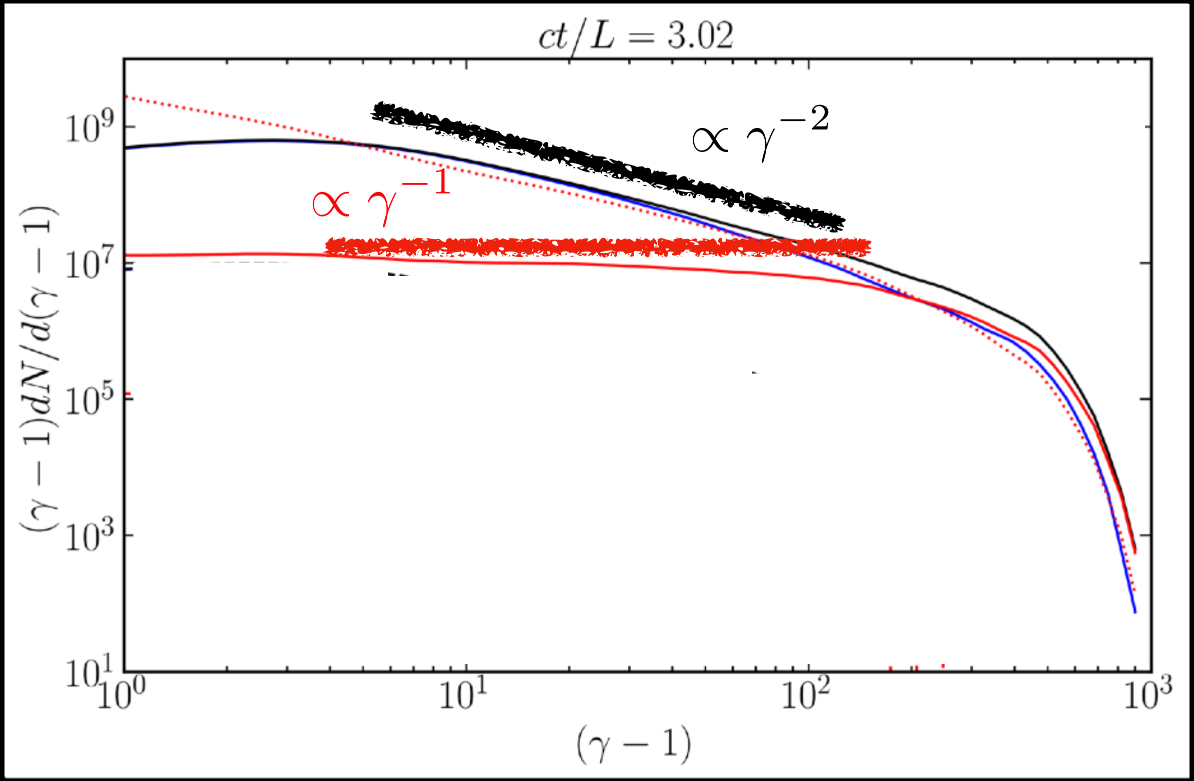
Free vs trapped vs all

σ=10



Free vs trapped vs all

σ=10



red:free

blue:trapped

black:all

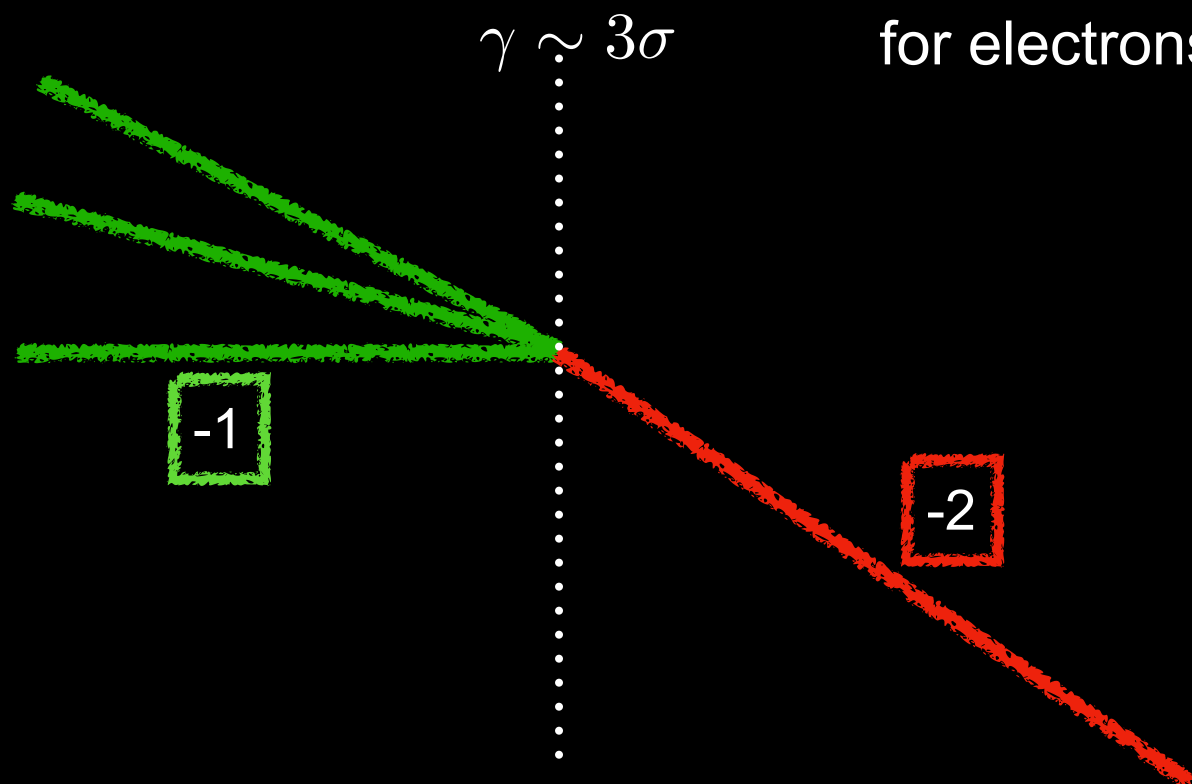
<u>In steady state:</u>

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 (σ-independent) slope of *p*=2.

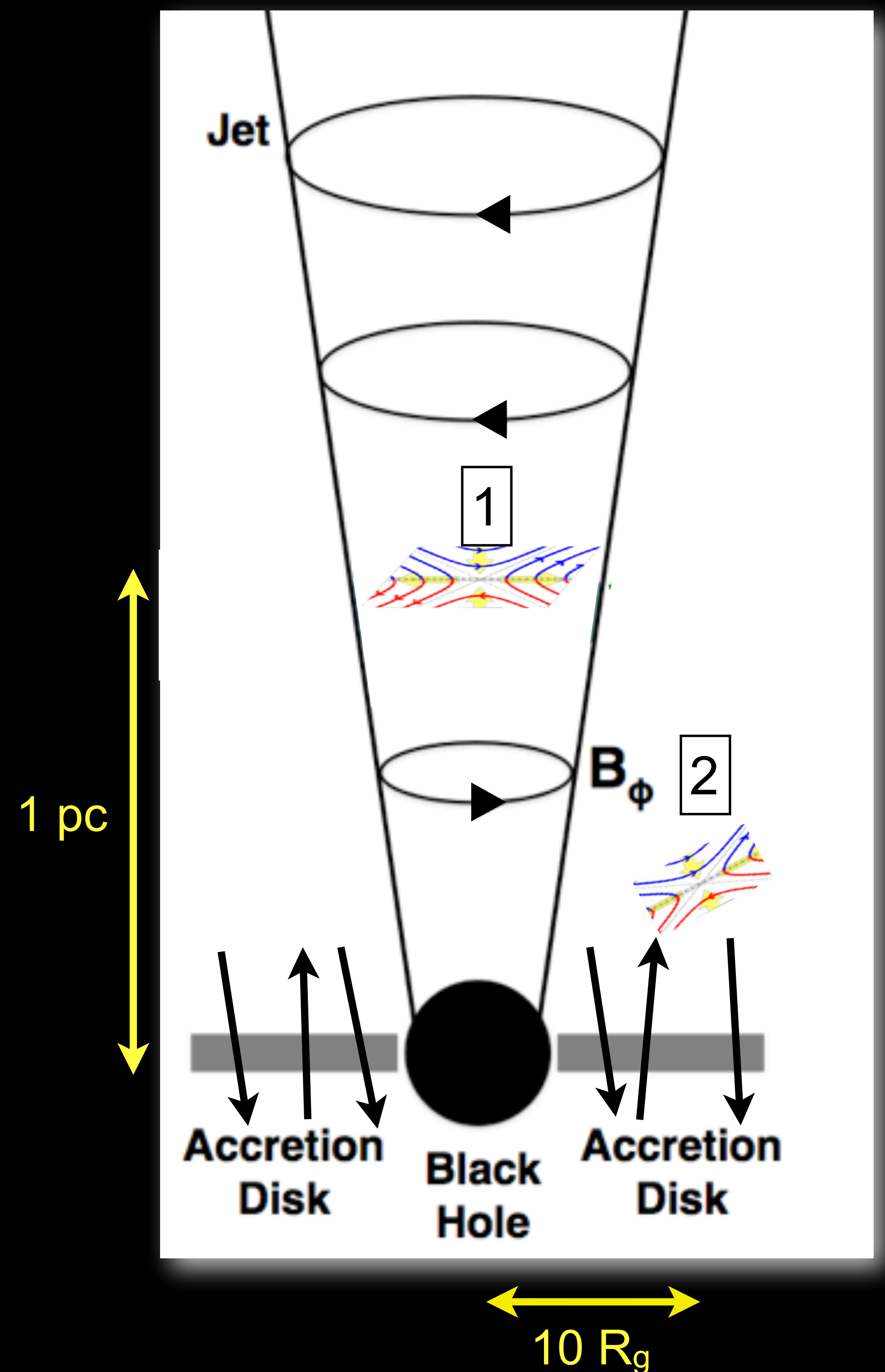
The outcome: a broken power law



for electrons: $\sigma_e = \dfrac{m_p}{m_e}\sigma$

At $\gamma \lesssim 3\sigma$ injection in reconnection leads to σ-dependent slopes, as hard as *p=1*.

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



(1) Blazars and AGN jets.

• Can reconnection explain the multi-wavelength and multi-timescale blazar emission?

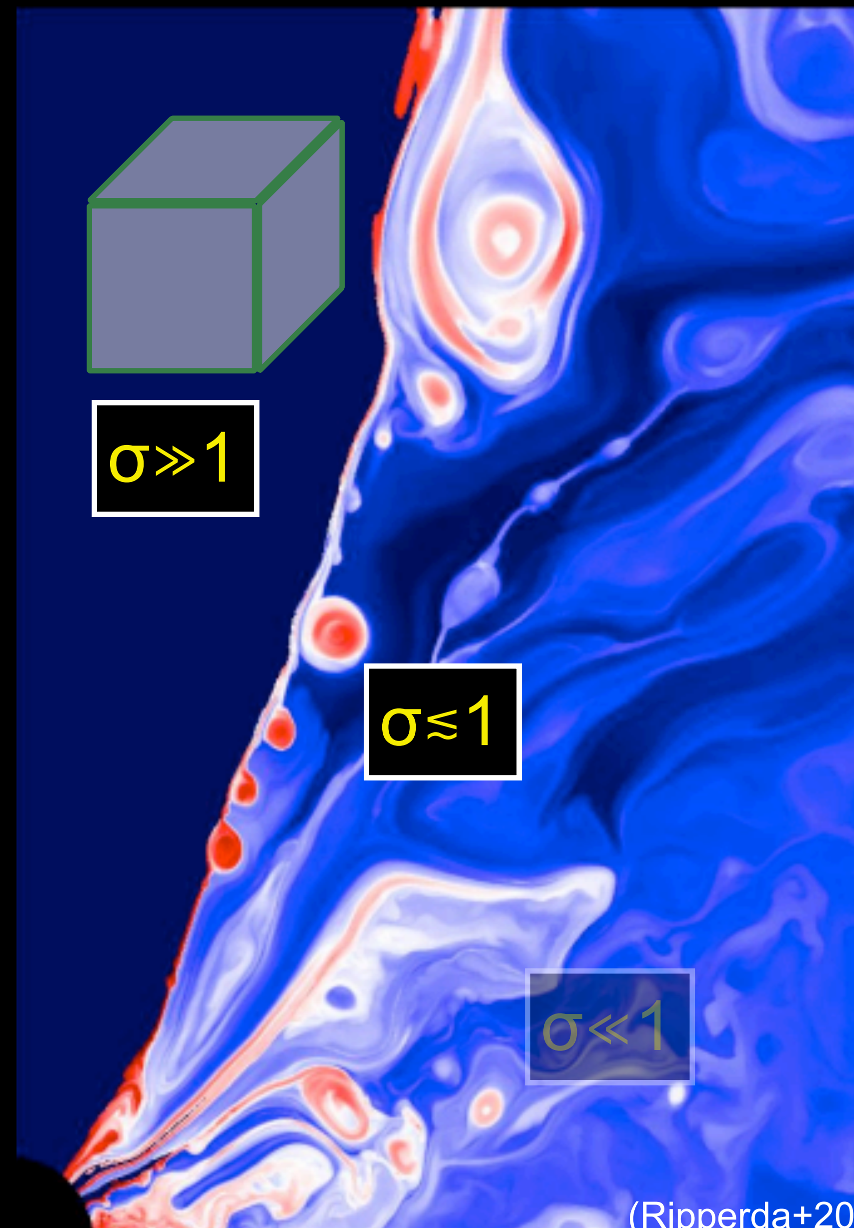
(2) Magnetized coronae of highly accreting BHs in X-ray binaries.

• Can radiative reconnection explain the hard-state X-ray emission?

1. Relativistic reconnection in blazar jets

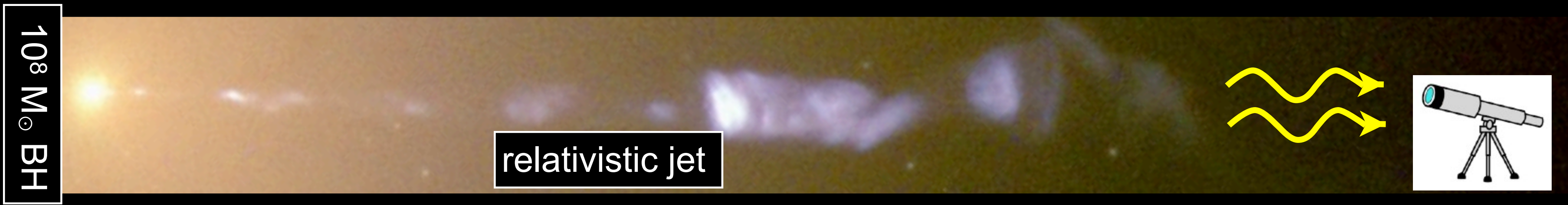
with D. Hosking

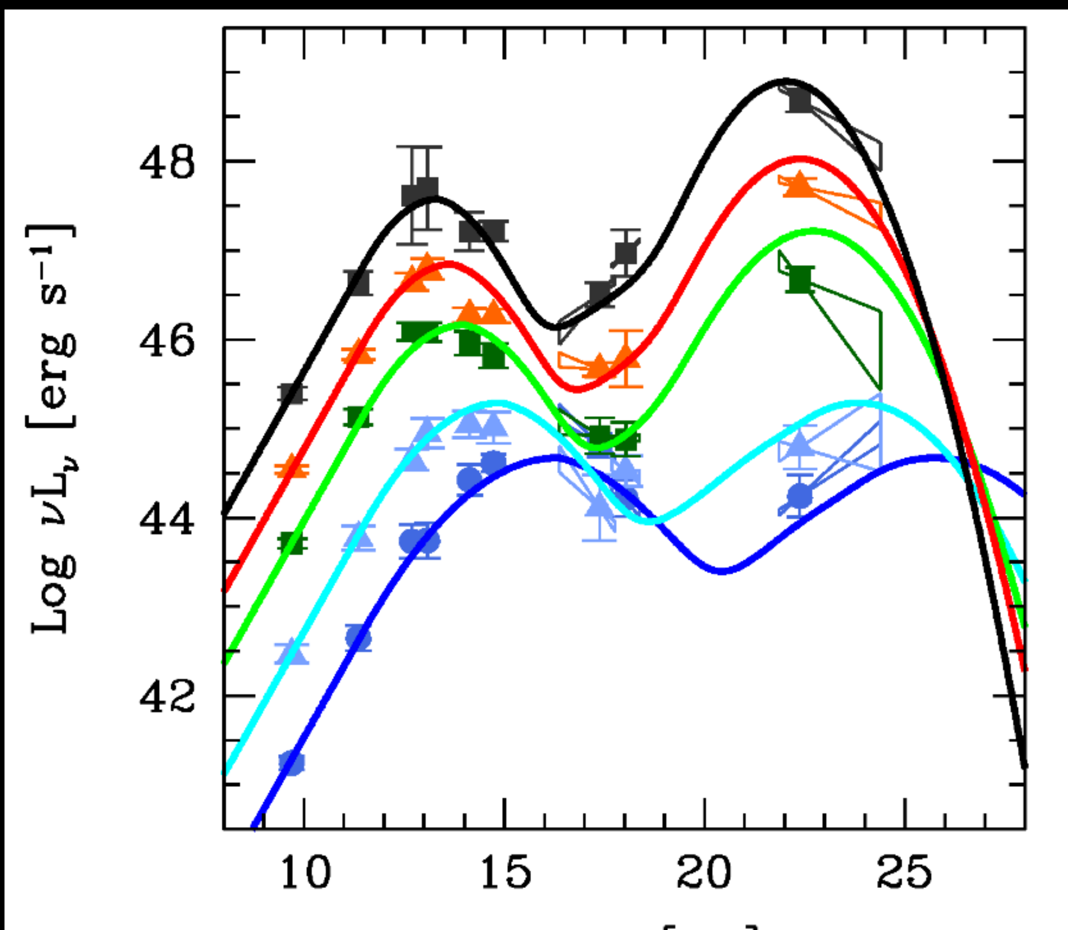
with L. Comisso, E. Sobacchi and J. Nättilä



Blazar jets

Blazars: jets from Active Galactic Nuclei pointing along our line of sight





(Ghisellini+ 17)

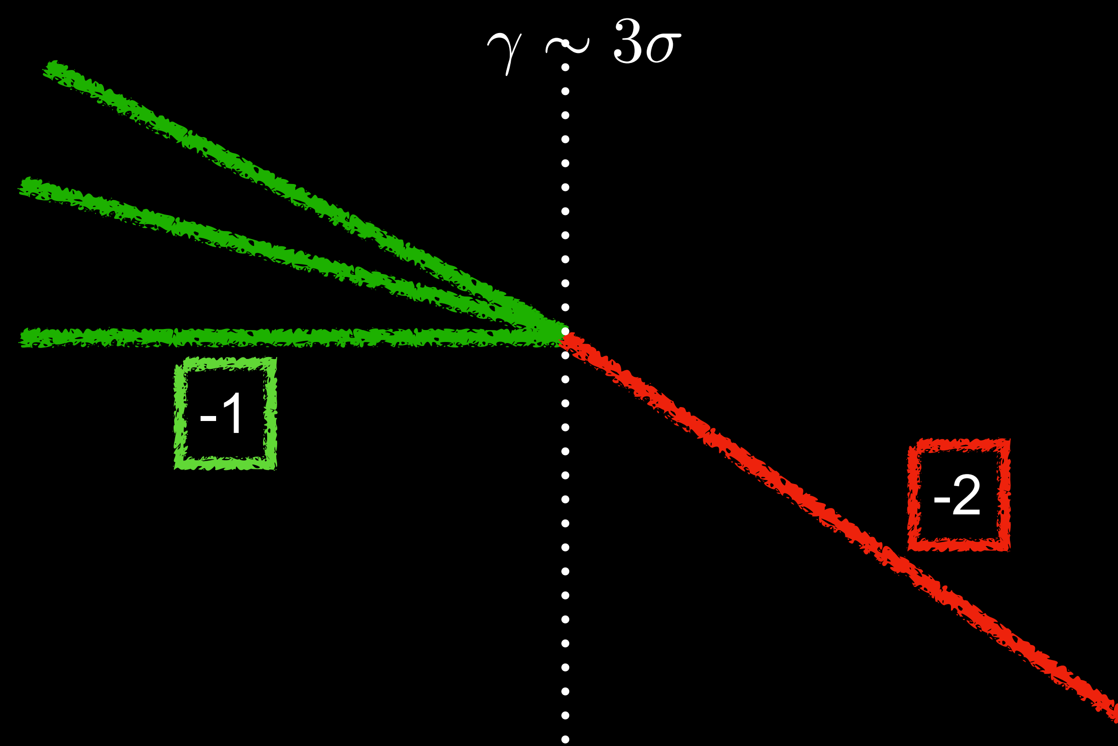
- broadband spectrum, from radio to γ-rays (and even TeV energies)
- low-energy synchrotron + high-energy inverse Compton (IC)
- high degree of radio and optical polarization

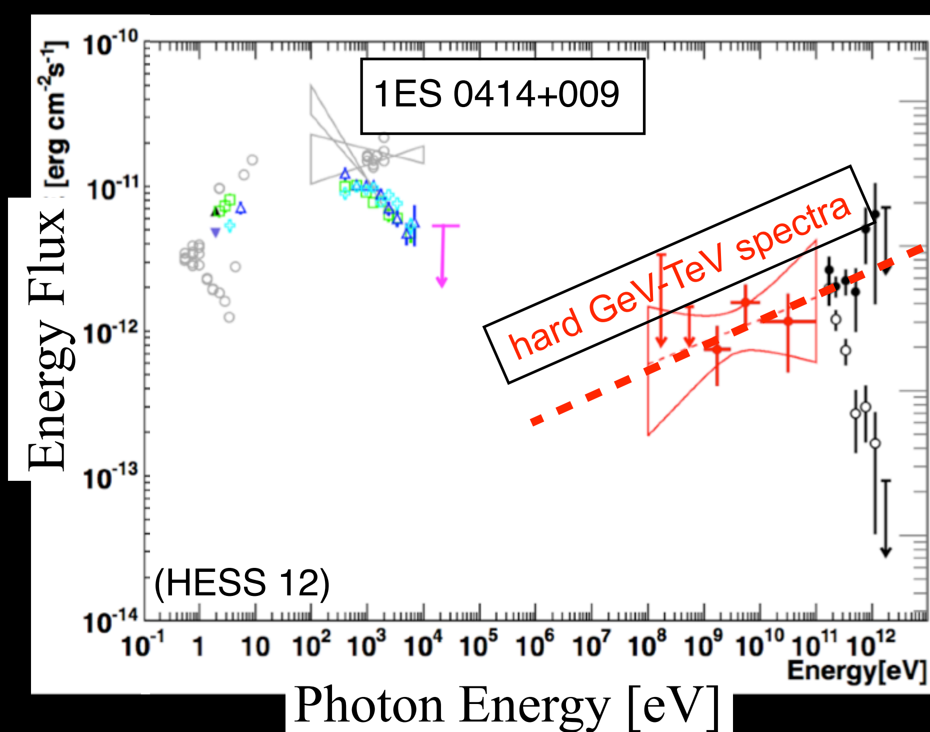
The ABC[D] of blazar emission

(A) power-law spectra of the emitting particles, often with hard slope

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

$$p \lesssim 2$$





At $\gamma \lesssim 3\sigma$ injection in reconnection leads to σ-dependent slopes, as hard as *p=1*.

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

The ABC[D] of blazar emission

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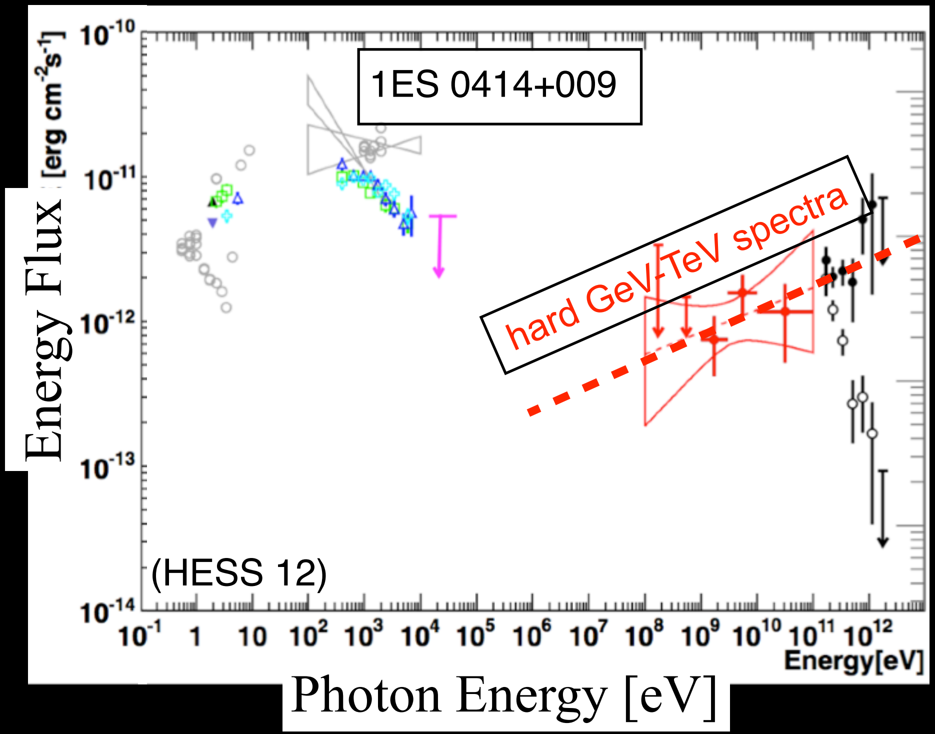
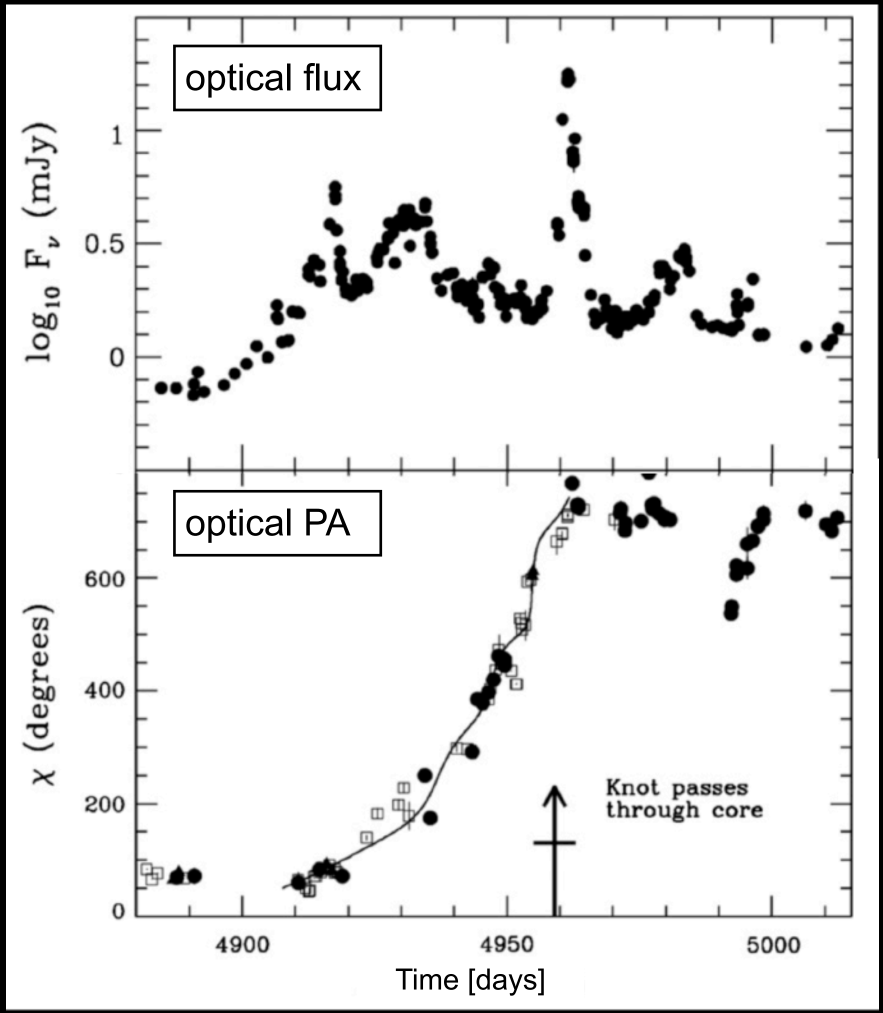


(B) optical polarization rotations

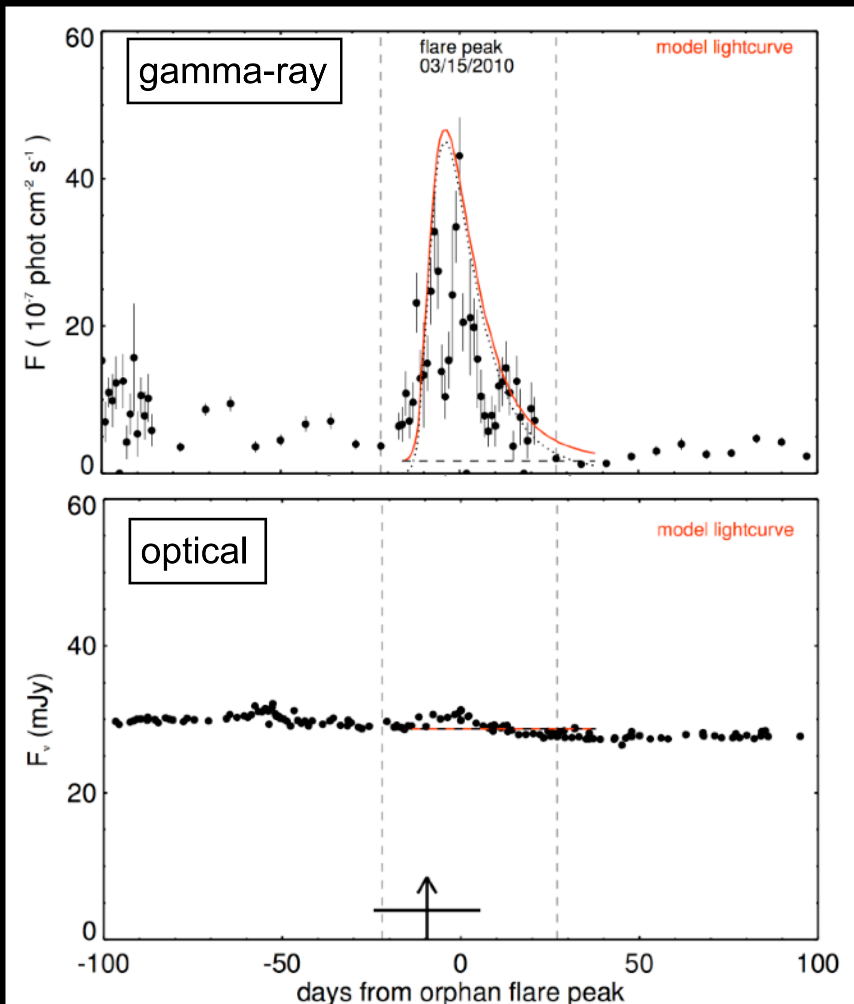


(Marscher+2010)

Large-angle polarization rotations during optical day-long flares.

The ABC[D] of blazar emission

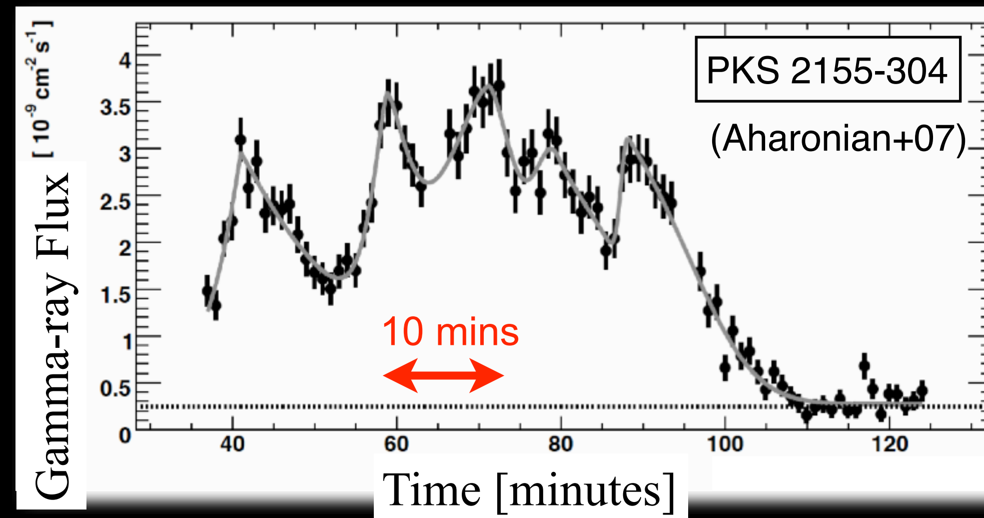
(C) “orphan” gamma-ray flares



(MacDonald+2017)

Gamma-ray flares with no optical counterpart.

(D) ultra-fast time variability

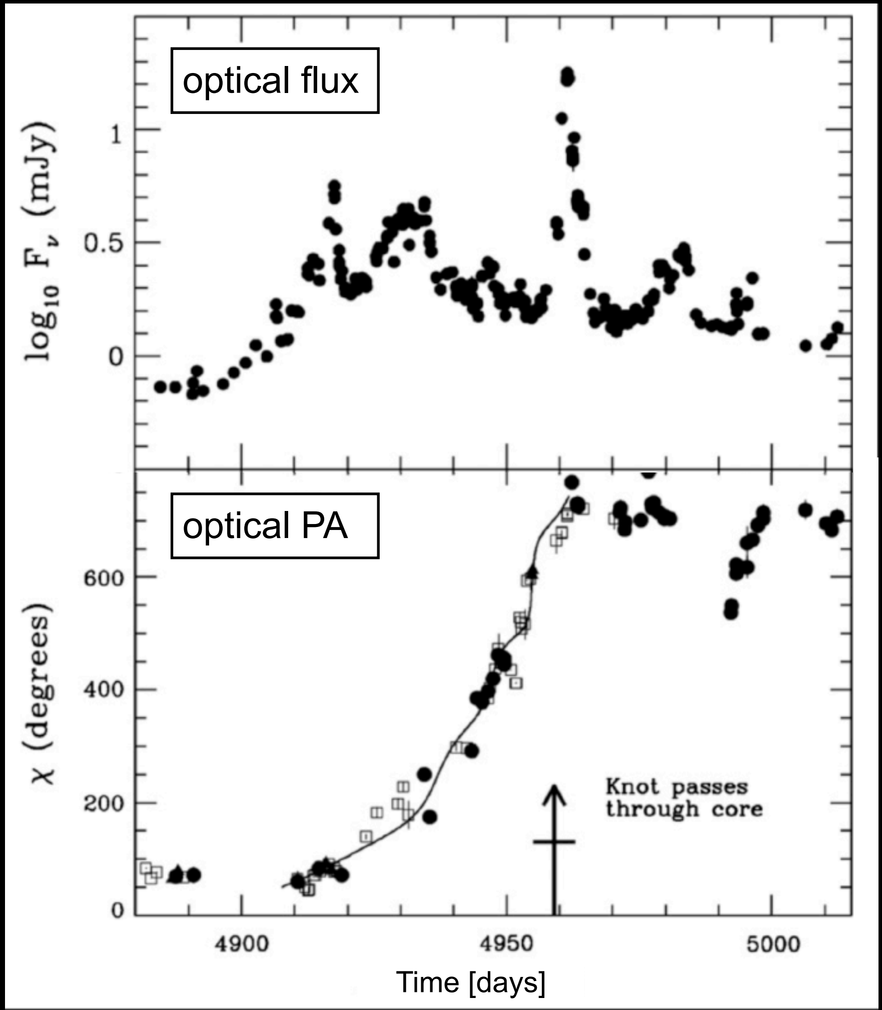


credit: Interstellar

(B) optical polarization rotations

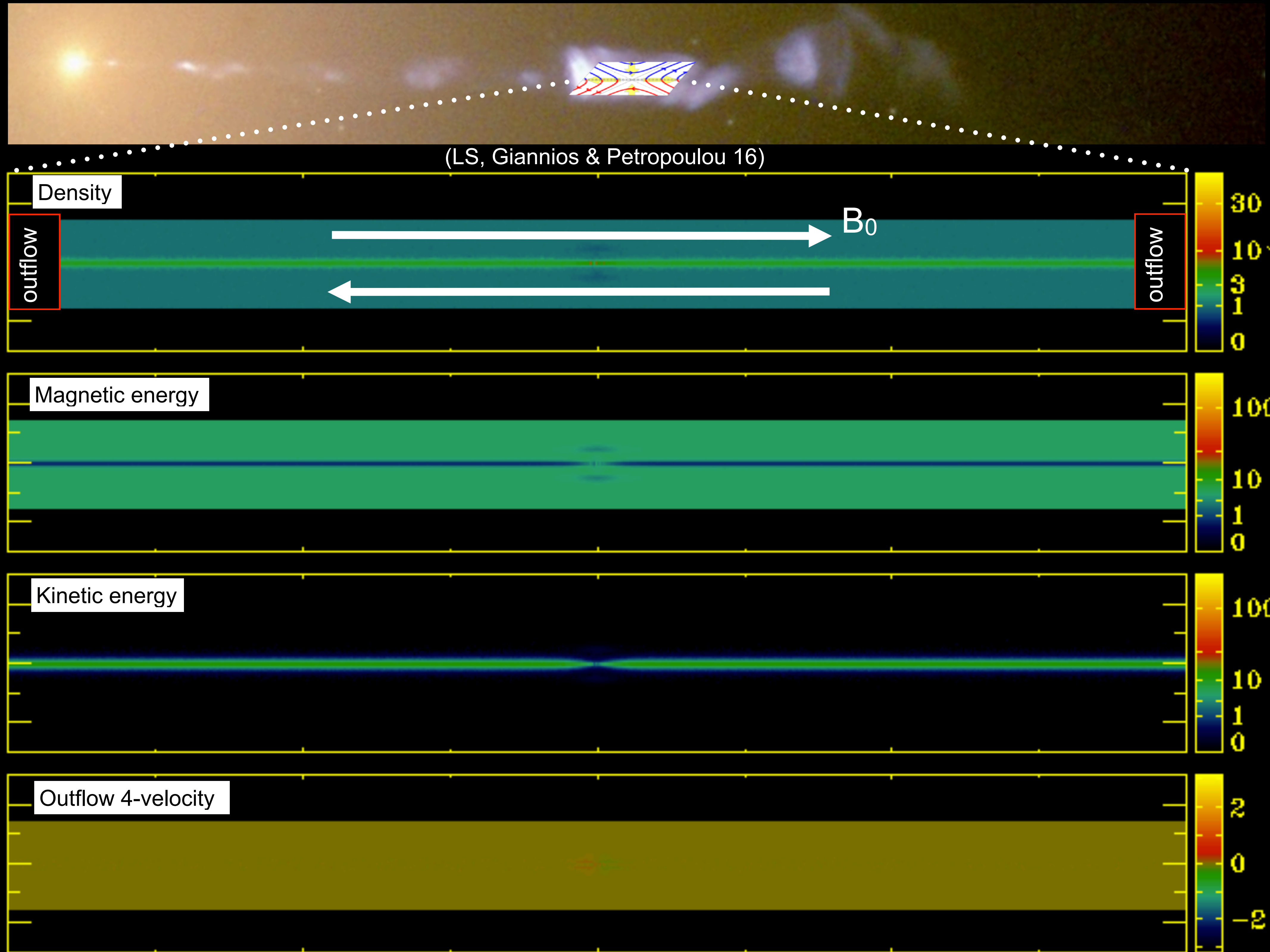
with D. Hosking

Hosking & LS 2020, ApJL, 900, L23

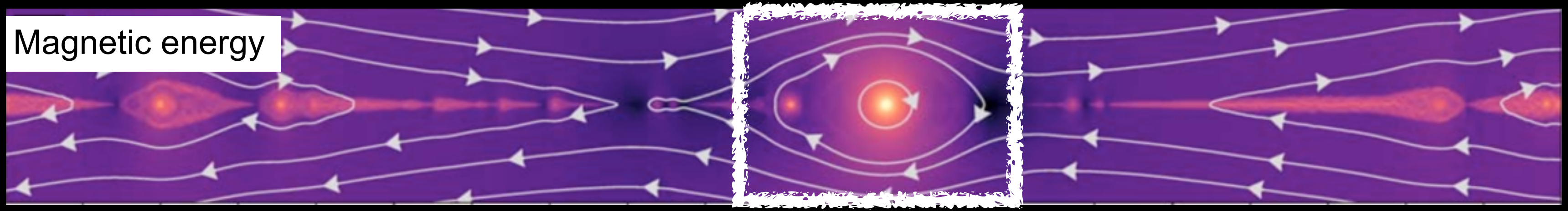


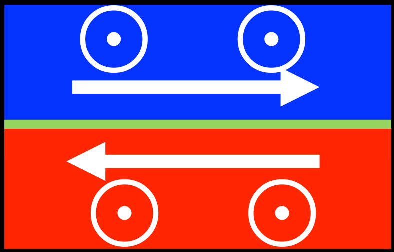
(Marscher+2010)

Large-angle polarization angle (PA) rotations during day-long flares.

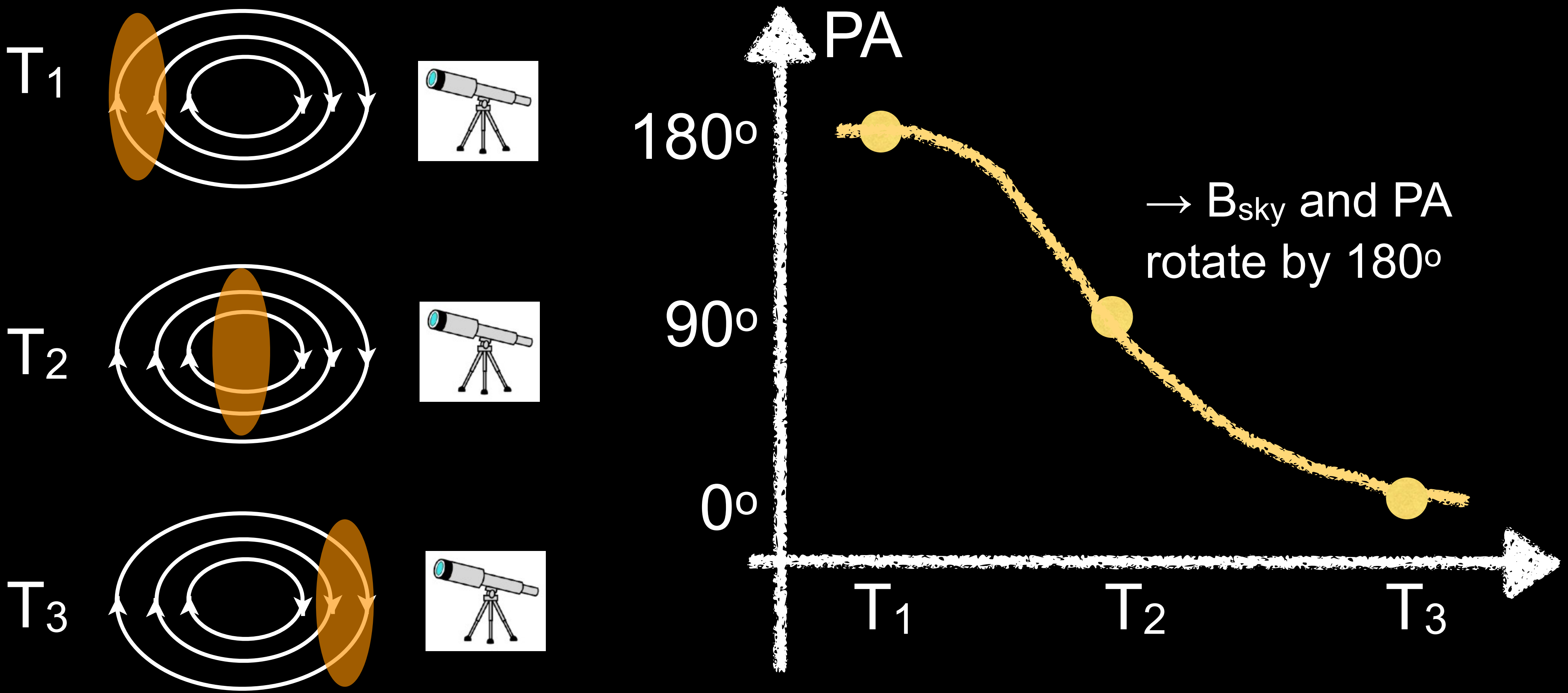

(LS, Giannios & Petropoulou 16)
Density
outflow
outflow
B0
30
10
3
1
0
Magnetic energy
10
1
0
Kinetic energy
10
1
0
Outflow 4-velocity
2
0
−2

A cartoonish model for PA rotations





Weak guide field
$B_g = 0.25\ B_0$



→ B_{sky} and PA rotate by 180°

Synchrotron cooling in blazar jets

We parameterize synchrotron cooling via a critical Lorentz factor γ_{cr} (balancing acceleration with synchrotron losses):

$$eE_{\rm rec} \sim \frac{4}{3}\sigma_{\rm T}\gamma_{\rm cr}^2 \frac{B_0^2}{8\pi}$$

$$E_{\rm rec} = \eta_{\rm rec} B_0 \quad (\eta_{\rm rec} \sim 0.1)$$

In blazar jets

1. $\gamma_\sigma \sim \sigma \sim 10^2 - 10^3$
2. $\gamma_{\rm cr} \gg \gamma_\sigma$
3. $\gamma_{\rm cool} \sim 0.01 - 0.1\gamma_\sigma$

In our simulations

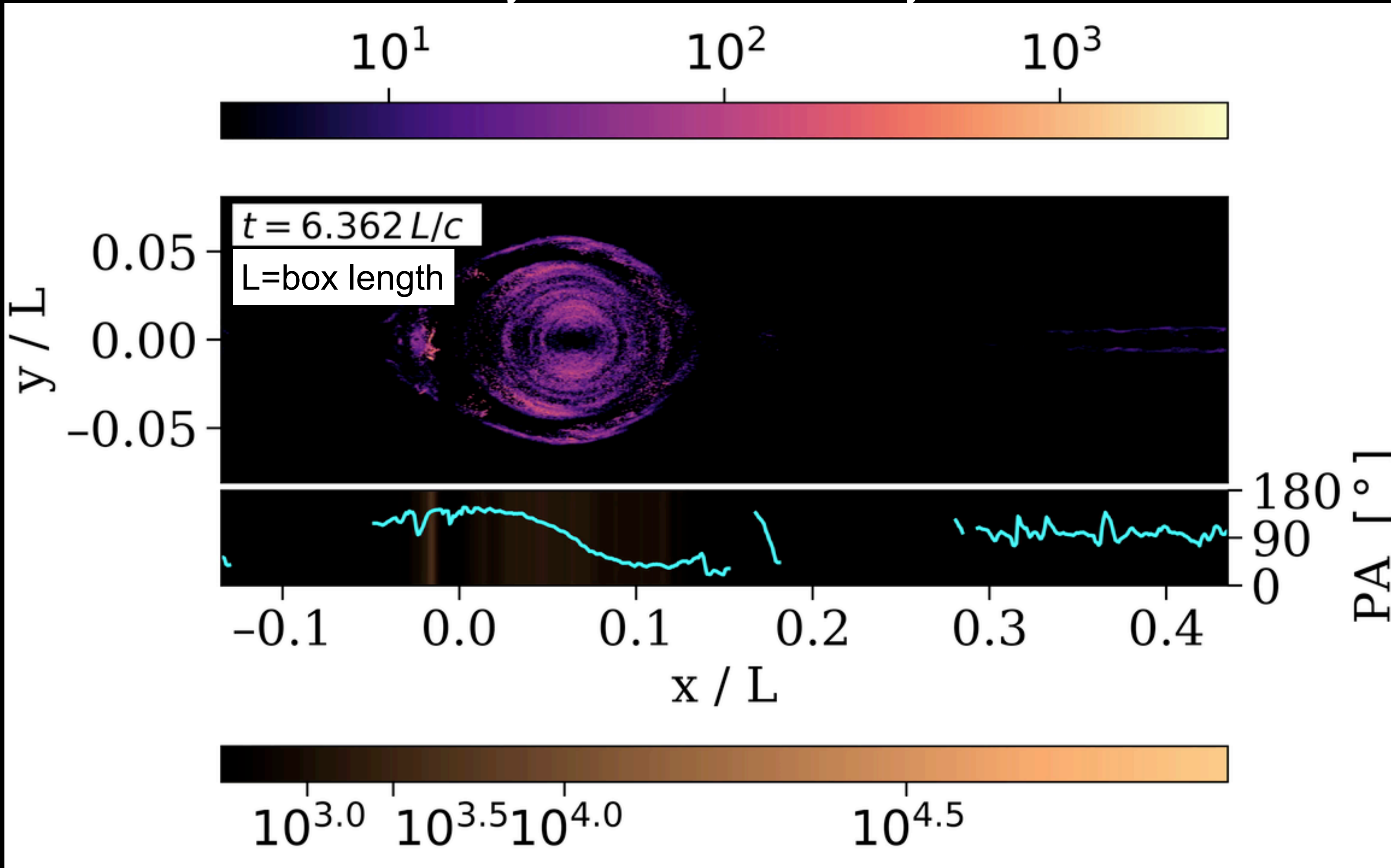
1. $\gamma_\sigma \sim \sigma = 10$
2. $\gamma_{\rm cr} = 40$
3. $\gamma_{\rm cool} \sim 0.1\gamma_\sigma$

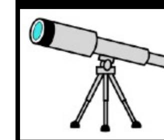
→ cooling time at γ_σ is ~ 0.1 of the dynamical time L/c

→ cooling time at γ_σ is ~ light crossing time of large plasmoids (size ~ 0.1 L)

Plasmoid mergers induce PA rotations

synchrotron emissivity



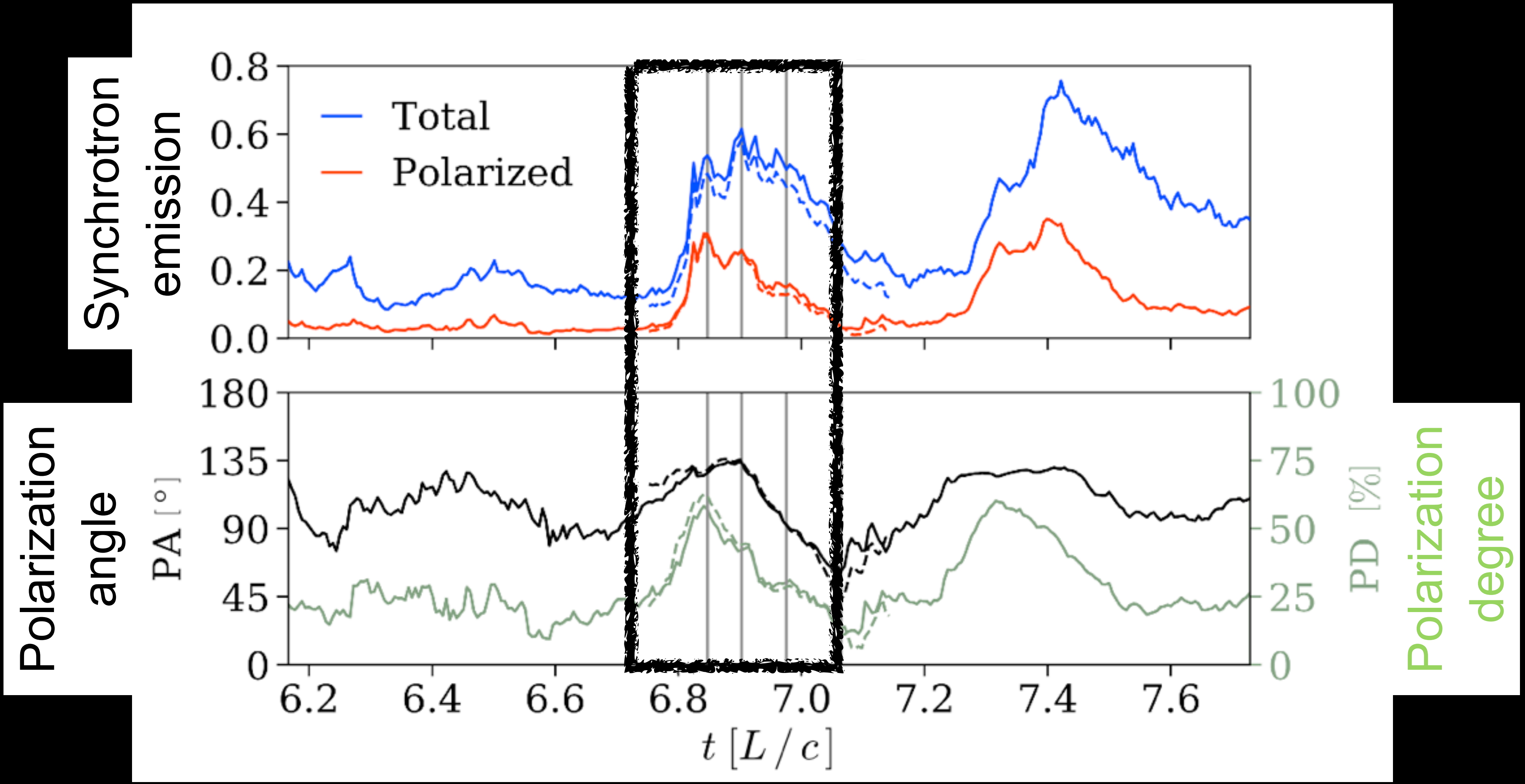


y-integrated synchrotron emissivity

(Hosking & LS 20)

Reconnection can explain PA rotations

- Particles are accelerated at the interface of merging plasmoids → flare
- They stream through the post-merger plasmoid while cooling
→ large-amplitude synchrotron PA rotations



(Hosking & LS 20; see also Zhang+18,20)

(C) "orphan" gamma-ray flares

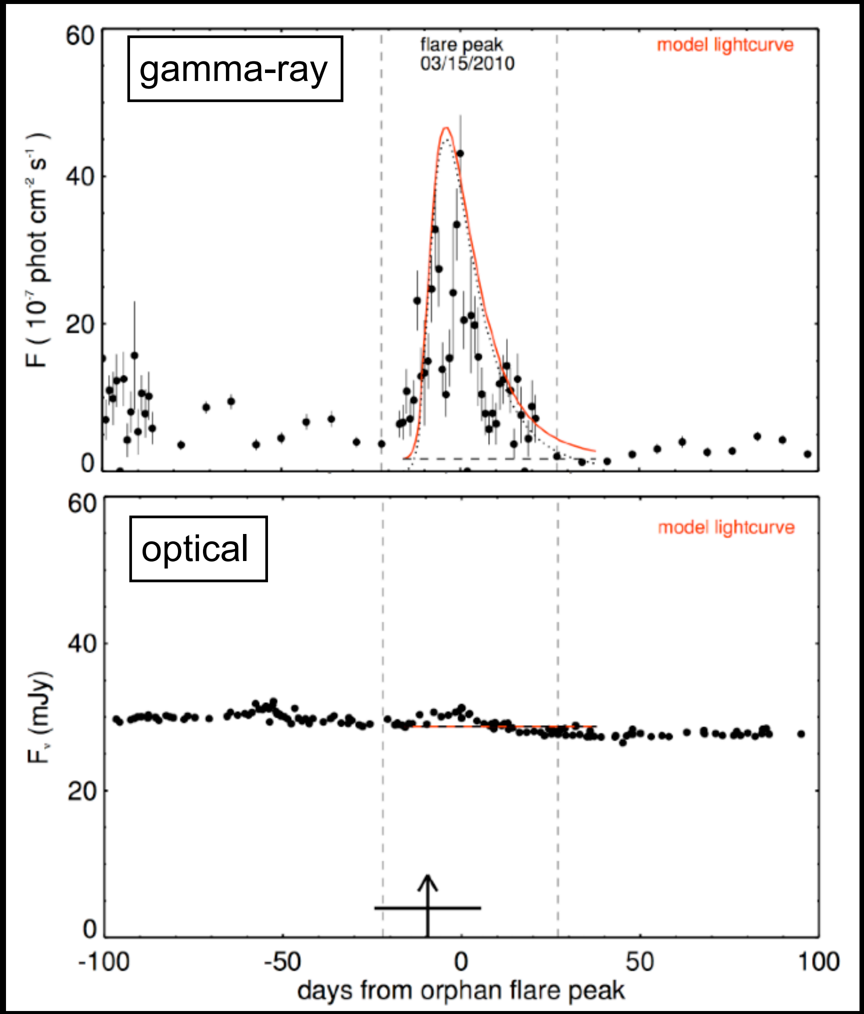
with L. Comisso, E. Sobacchi and J. Nättilä

Comisso & LS 2018, PRL, 121, 255101

Comisso & LS 2019, ApJ, 886, 122

Sobacchi, Nattila & LS 2021, MNRAS, 503, 688

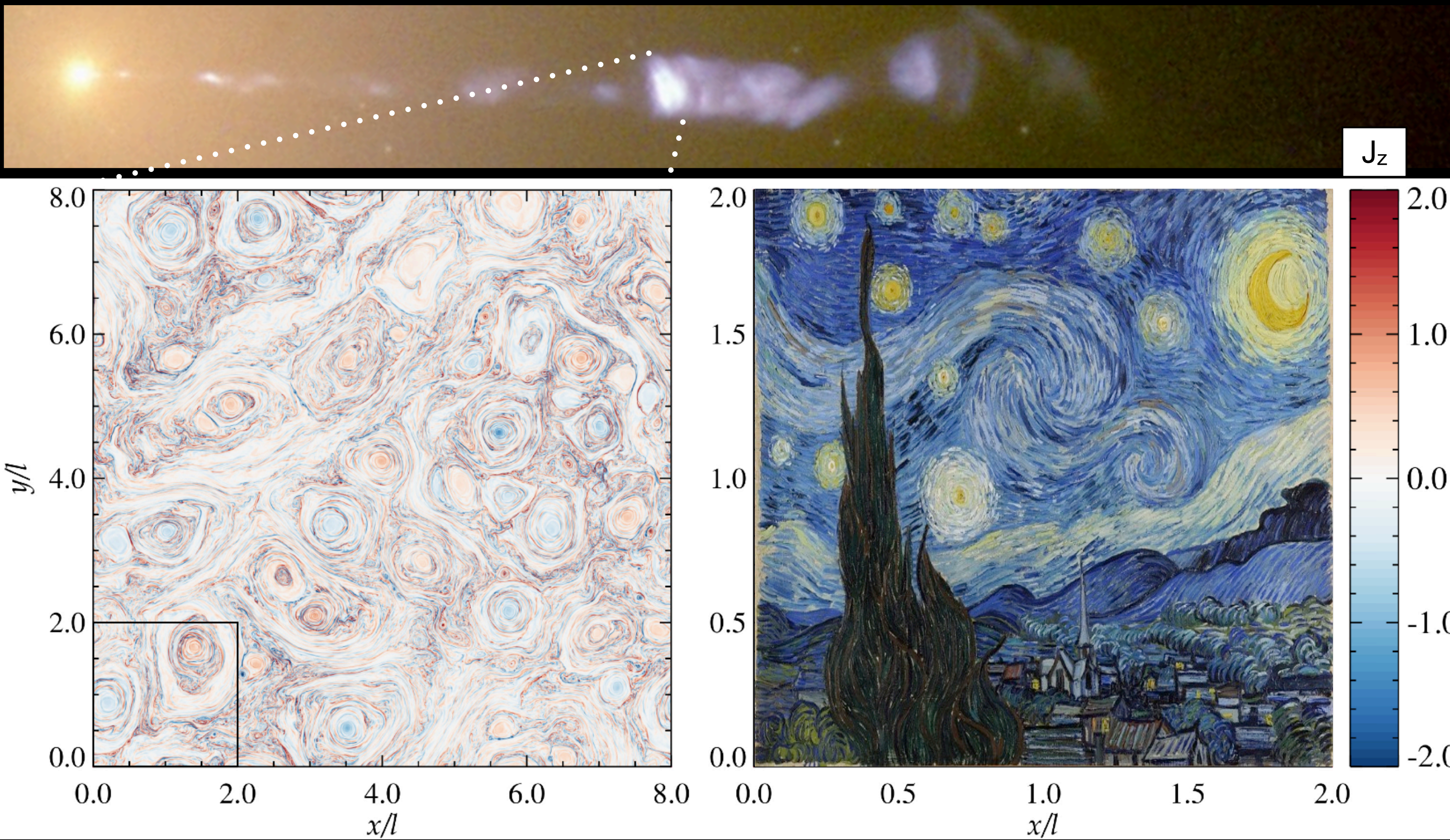


(MacDonald+2017)

Gamma-ray flares with no optical counterpart.

Reconnection within turbulence

Reconnection is a natural by-product of magnetically-dominated turbulence

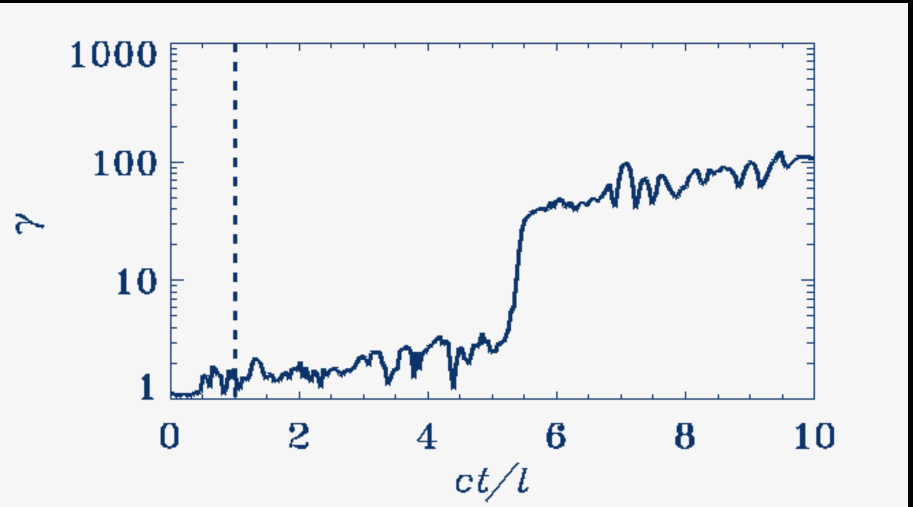


l=turbulence outer scale

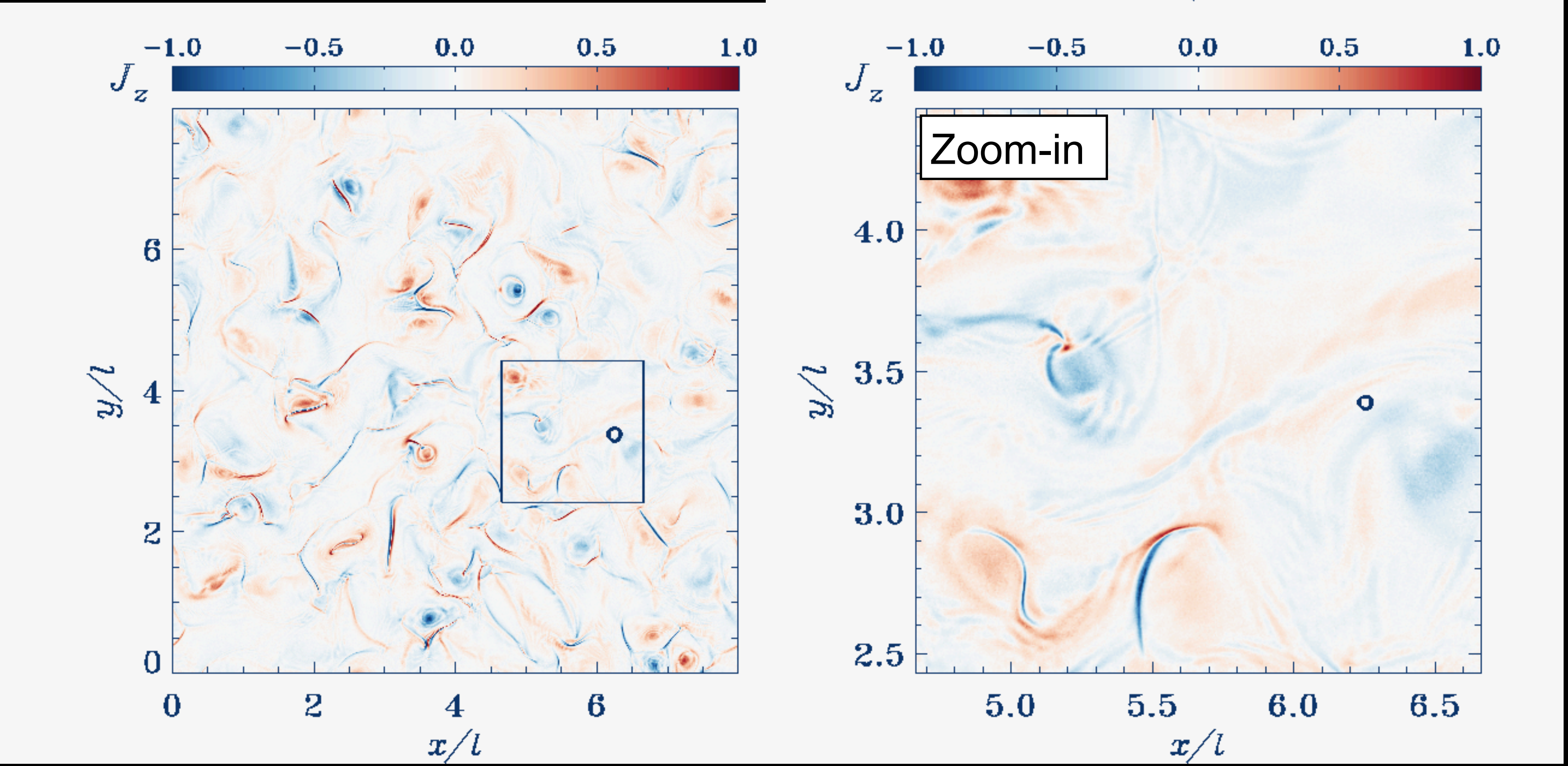
(Comisso & LS 18,19)

A representative high-energy particle

Two stages of acceleration



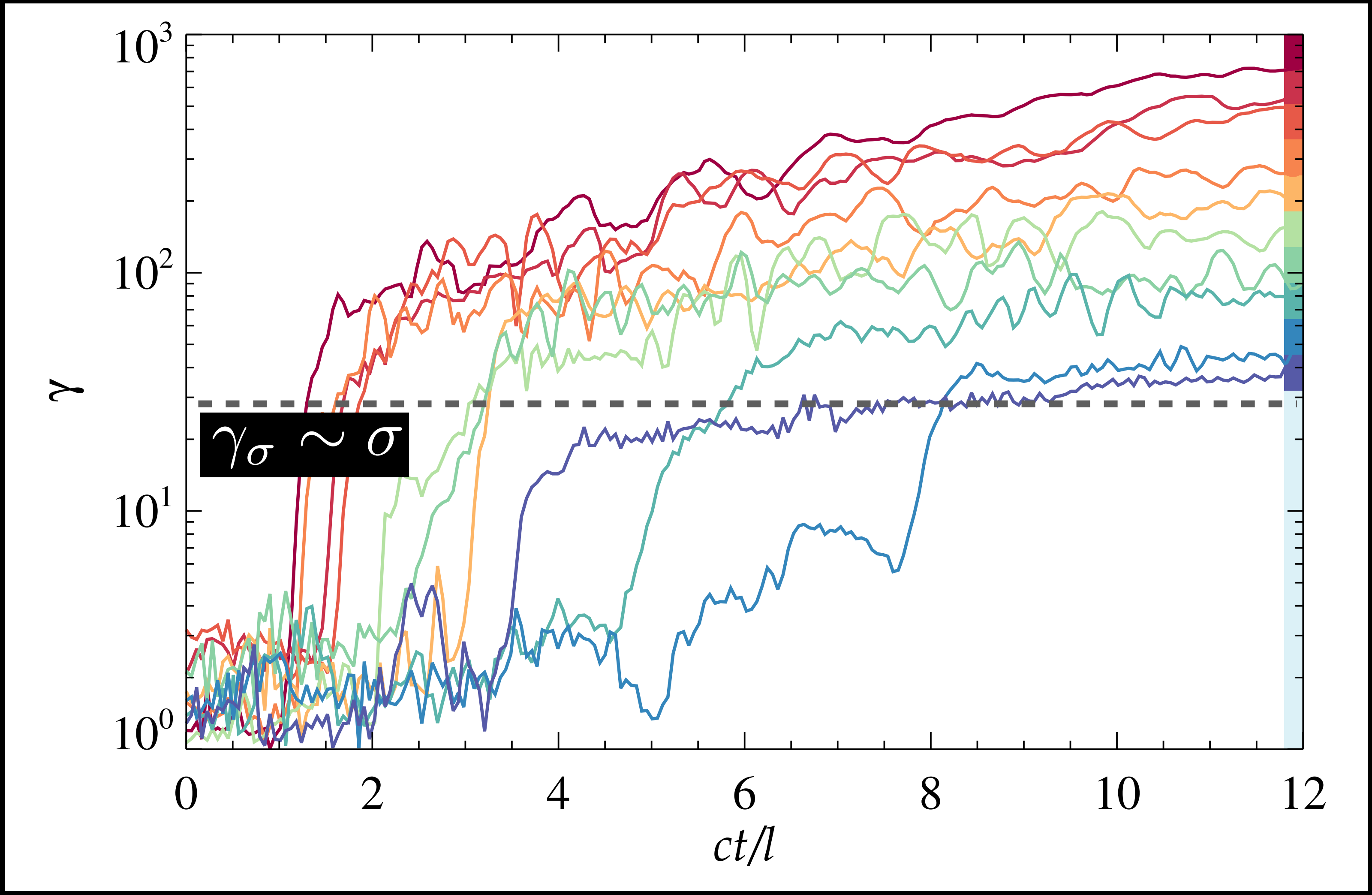
2D
no cooling



(Comisso & Sironi 18)

Particle acceleration: a two-stage process

3D
no cooling



(Comisso & LS 19)

- Particle injection occurs quickly ($t_{\rm inj} \sim 10/\omega_c$), at reconnection layers.
- This is followed by further acceleration (but slower, $t_{\rm scatt} \sim l/c$) by scattering off the turbulent fluctuations.

IC cooling in blazar jets

We parameterize IC cooling losses via a critical Lorentz factor γ_{cr} (balancing acceleration with IC losses):

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

$$E_{\rm rec} = \eta_{\rm rec} B_0 \;\; (\eta_{\rm rec} \sim 0.1)$$

In blazar jets

1. $\gamma_\sigma \sim \sigma \sim 10^2 - 10^3$
2. $\gamma_{\rm cr} \gg \gamma_\sigma$
3. $\gamma_{\rm cool} \sim 0.01 - 0.1\gamma_\sigma$

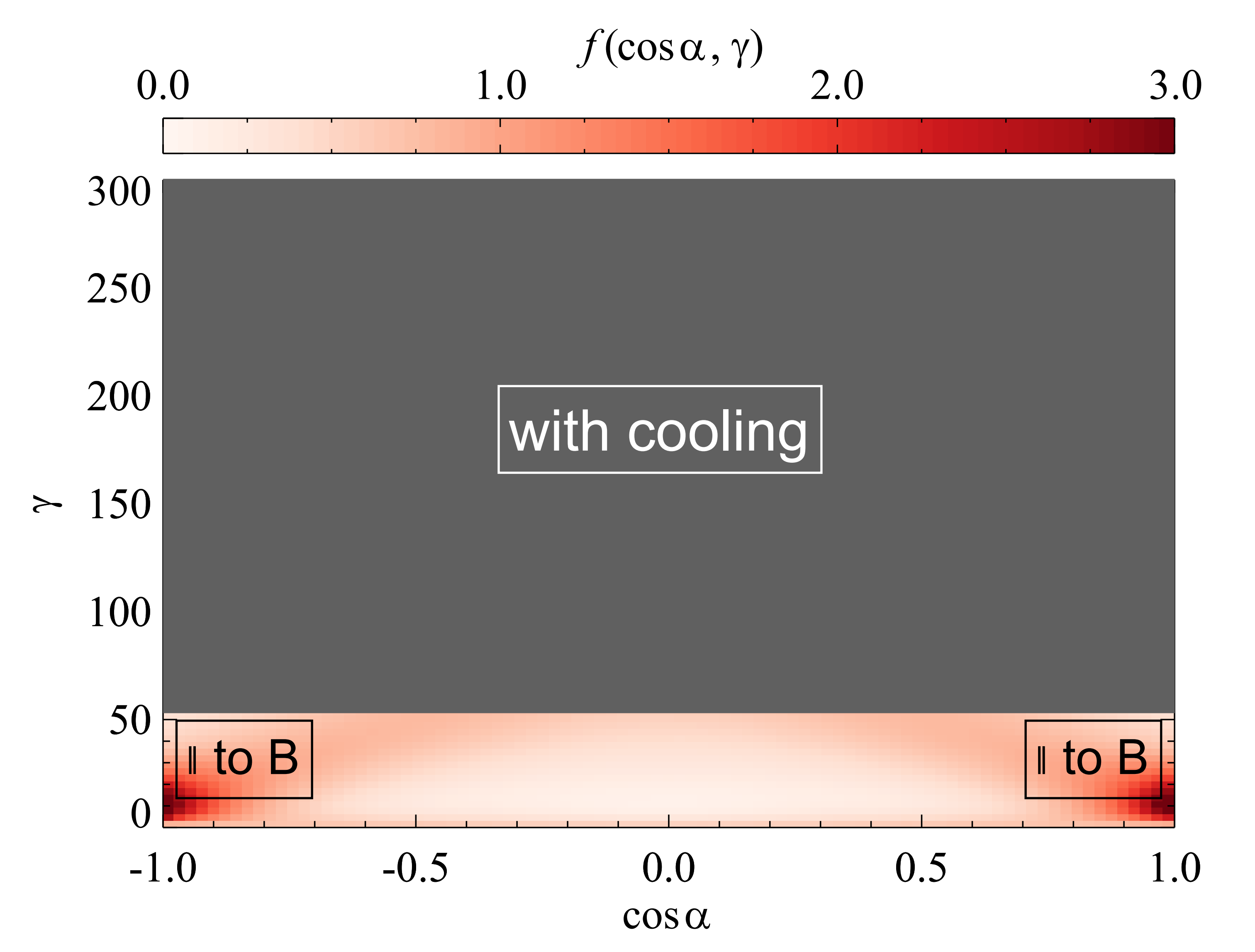
In our simulations

1. $\gamma_\sigma \sim \sigma = 160$
2. $\gamma_{\rm cr} \gtrsim \gamma_\sigma$
3. $\gamma_{\rm cool} \sim 0.01\gamma_\sigma$

→ injection up to γ_σ is unaffected by cooling since $t_{inj} \ll t_{cool}$

→ acceleration to $\gg \gamma_\sigma$ is prohibited by cooling since $t_{scatt} \gg t_{cool}$

Reconnection drives anisotropy

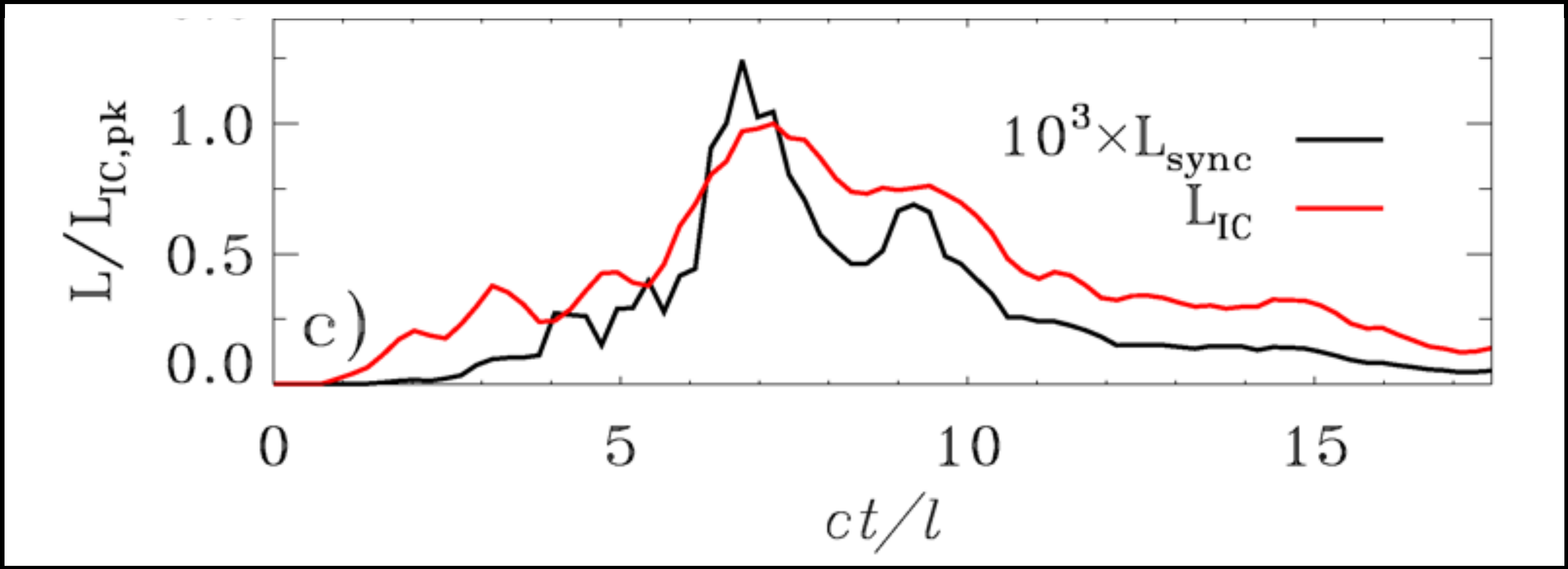


(Comisso & LS 19)

- Lower energy particles (near injection) are mostly aligned with B field.
- Higher energy particles lie mostly in a plane perp to B.

Synchrotron and IC emission

- Small pitch angles suppress the synchrotron emission, $P_{\rm sync} \propto \sin^2 \alpha$

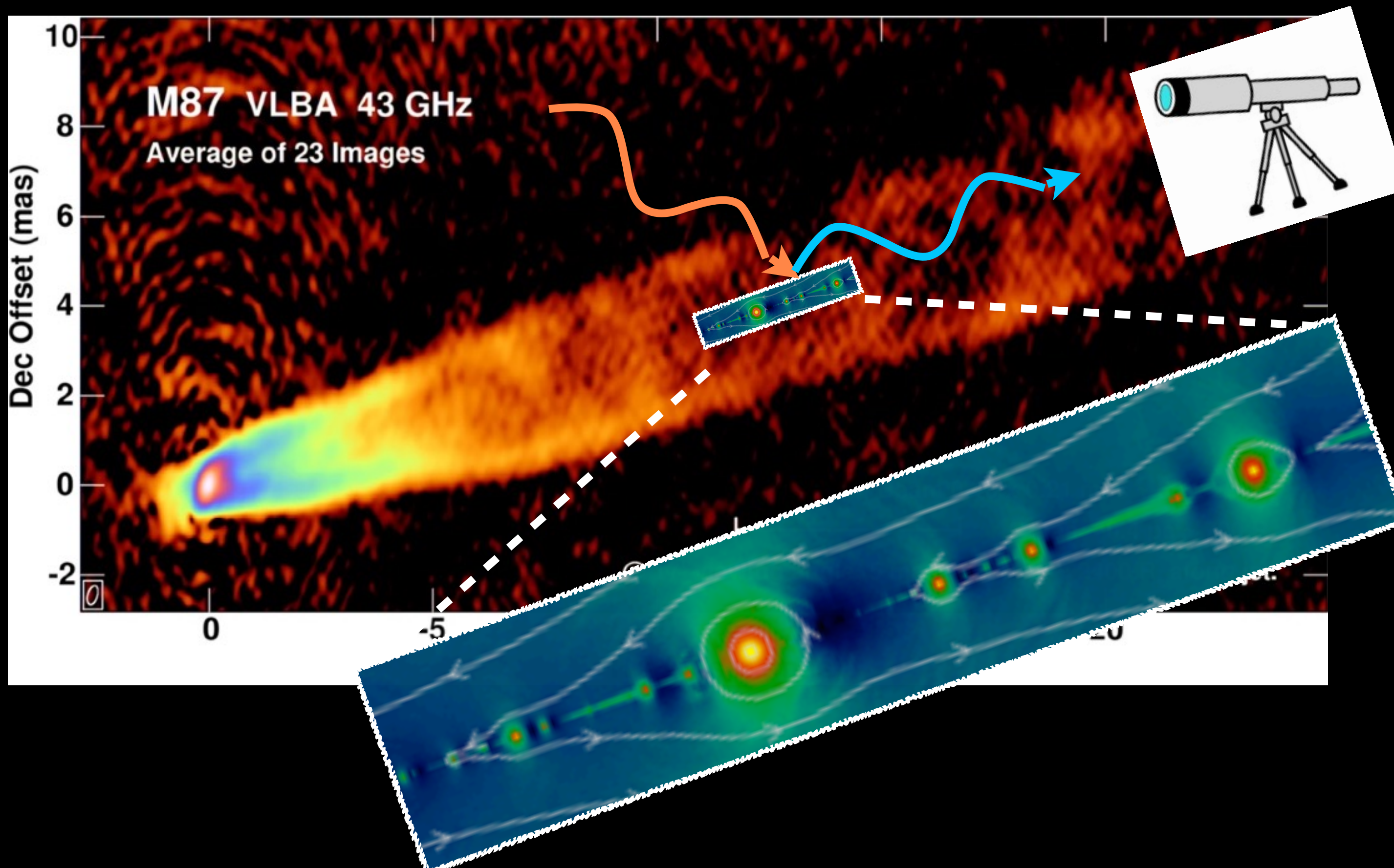


(Sobacchi + 21)

- Even though $U_B/U_{\rm rad}$~1, we find that $L_{\rm sync}/L_{\rm IC}$~10^{-3}.

→ a first-principles explanation for orphan gamma-ray flares!

Summary: reconnection in blazar jets

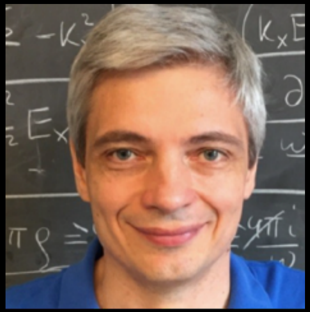


In blazar jets, reconnection can produce:

- non-thermal particles with hard power-law slopes.
- optical flares accompanied by polarization angle rotations.
- “orphan” gamma-ray flares (due to strong pitch angle anisotropy).

2. Radiative relativistic reconnection in black hole X-ray coronae

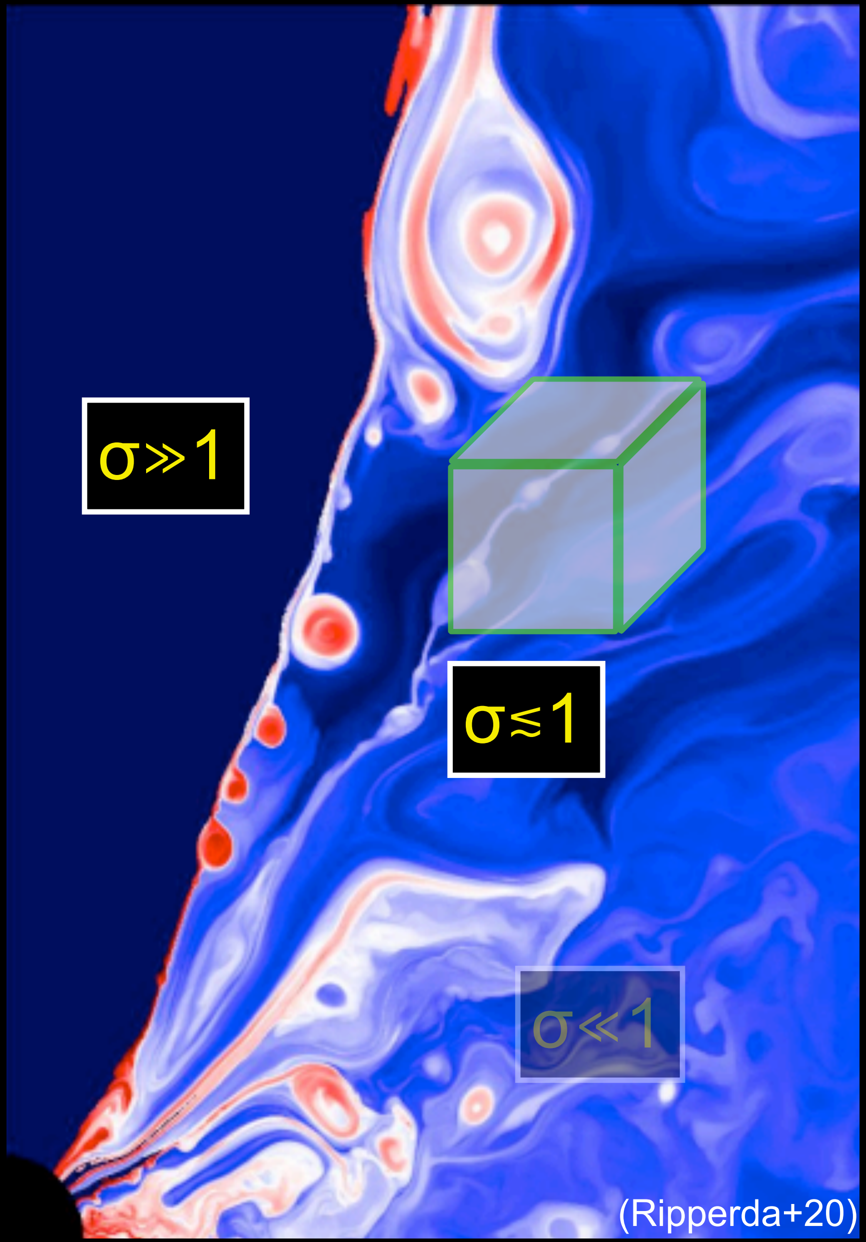
with N. Sridhar and A. Beloborodov



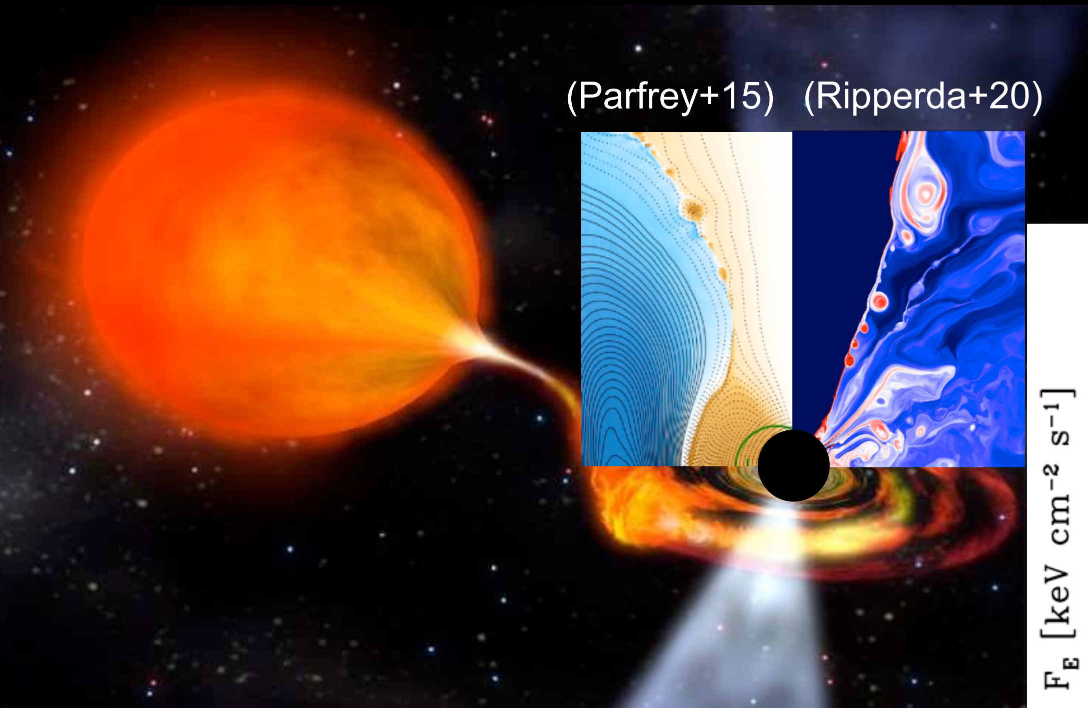
Sridhar, LS et al. 2022, arXiv:2203.02856

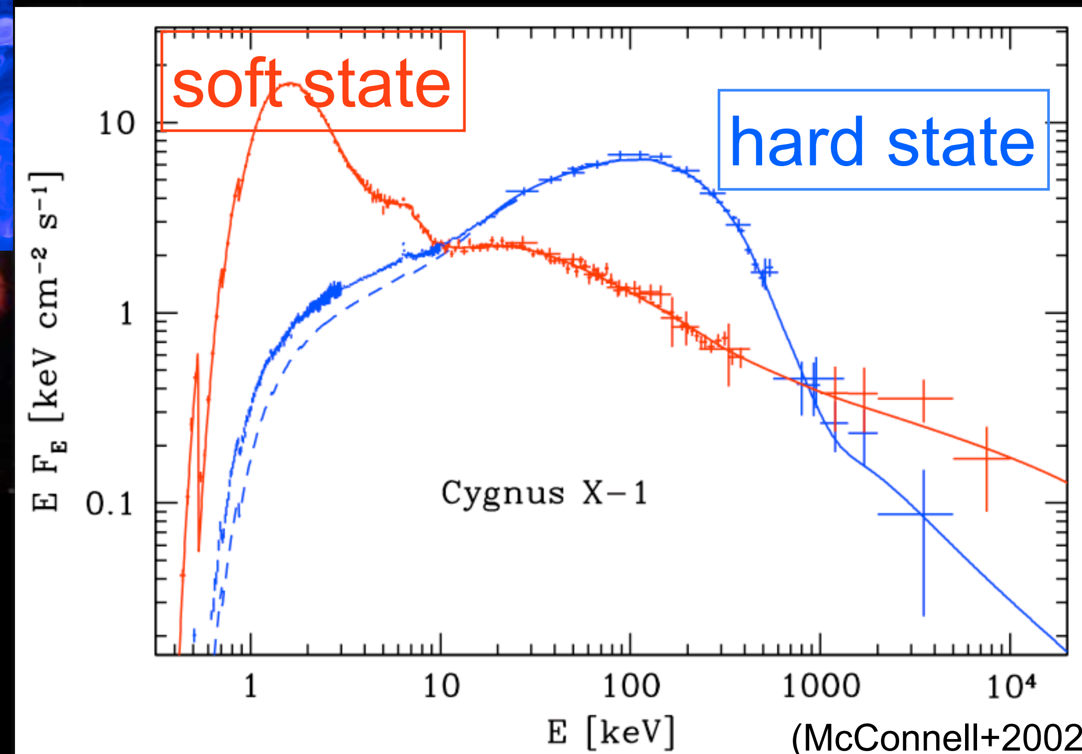
Sridhar, LS et al. 2021, MNRAS, 507, 5625

LS & Beloborodov 2020, ApJ, 899, 52



The hard state of X-ray binaries





Hard state: interpreted as thermal Comptonization by "coronal" plasma with electron temperature ~100 keV.

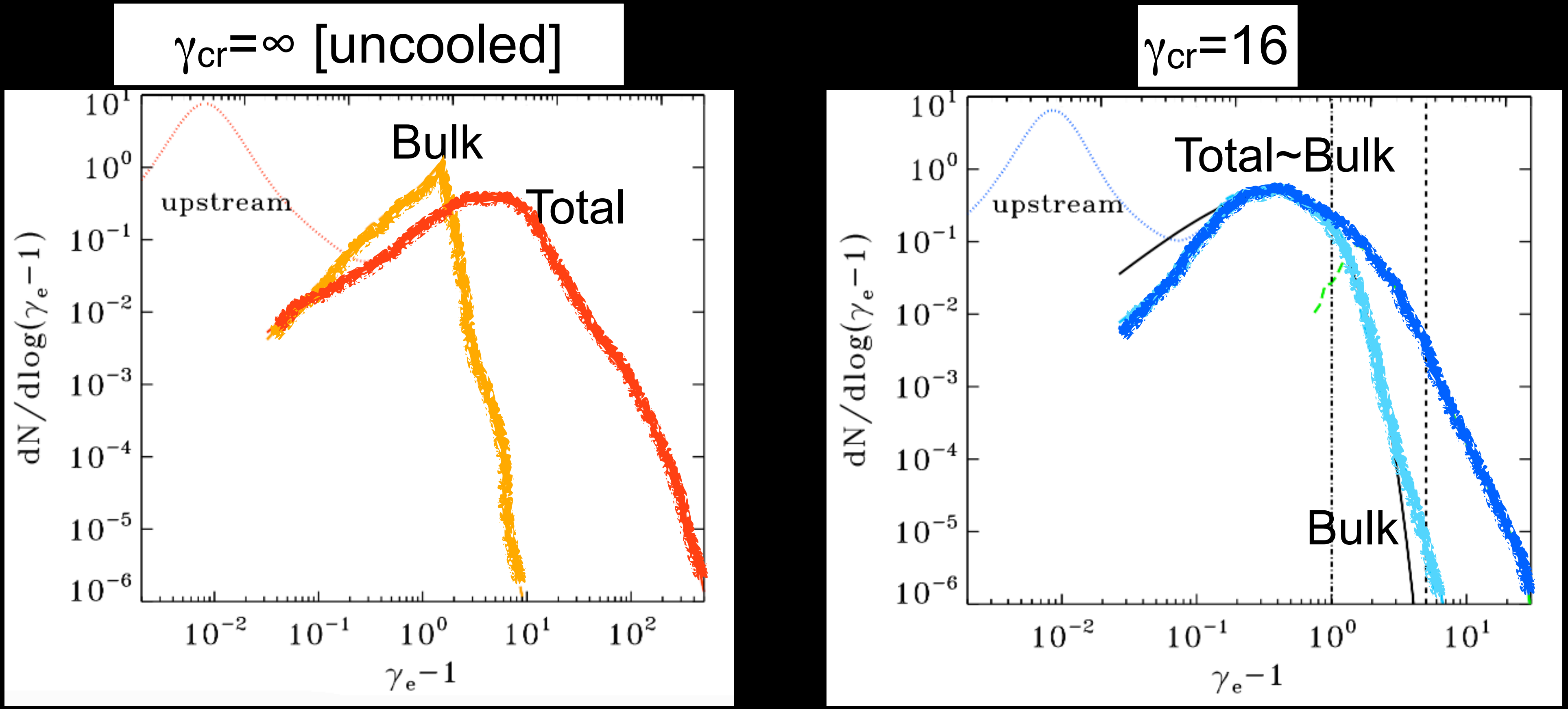
But: how can the electrons stay hot?

Radiative reconnection

We parameterize IC cooling via a critical Lorentz factor γ_{cr} (balancing acceleration with IC losses):

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

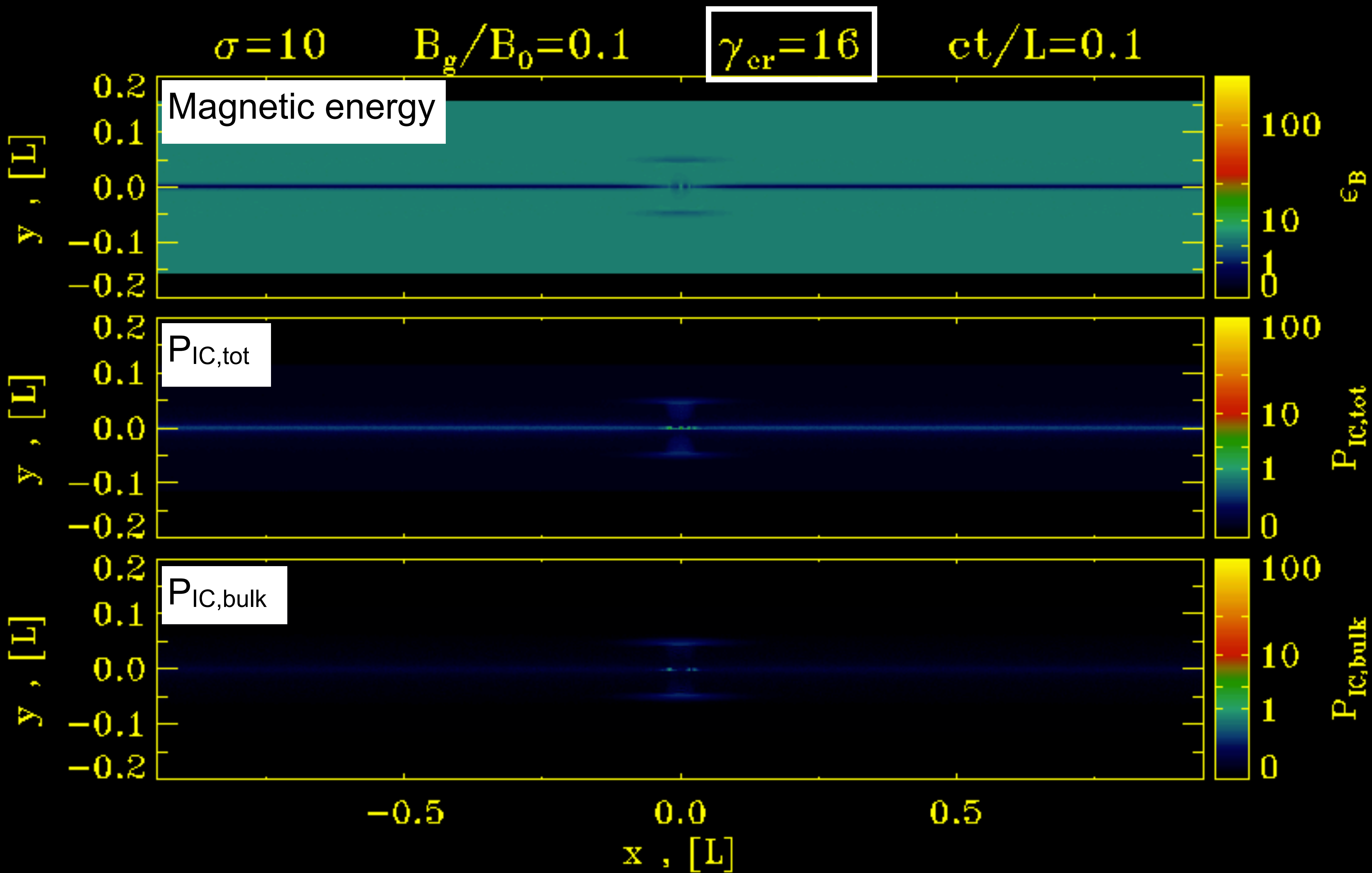
$$E_{\rm rec} \simeq 0.1 B_0$$



(LS & Beloborodov 20; see also Werner+19)

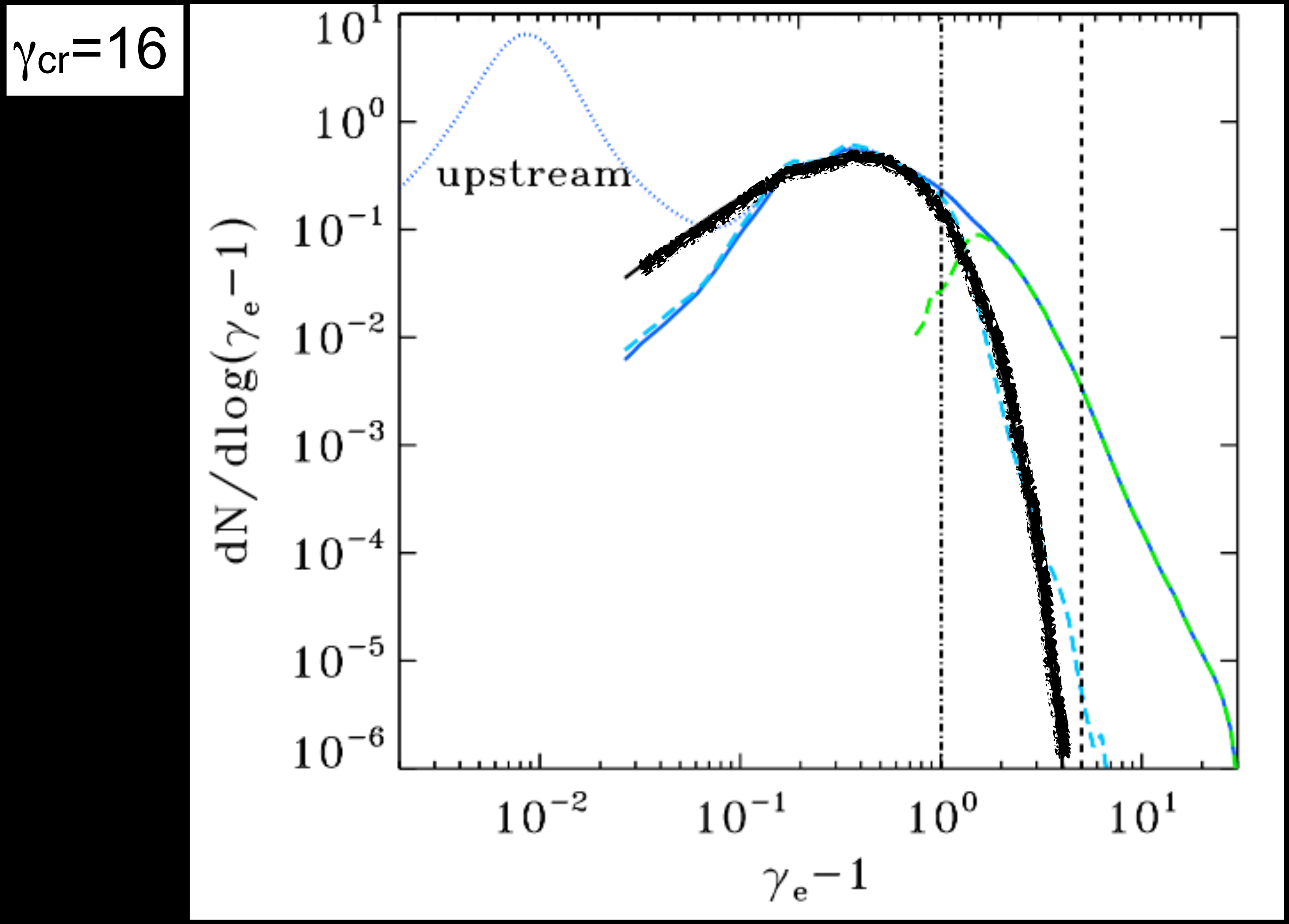
- Strong IC cooling suppresses particle acceleration.
- For strong cooling, the particle spectrum is dominated by plasmoid bulk motions.

The radiative plasmoid chain



The total IC power is dominated by the IC power resulting from trans-rel bulk motions.

Particle energy spectrum

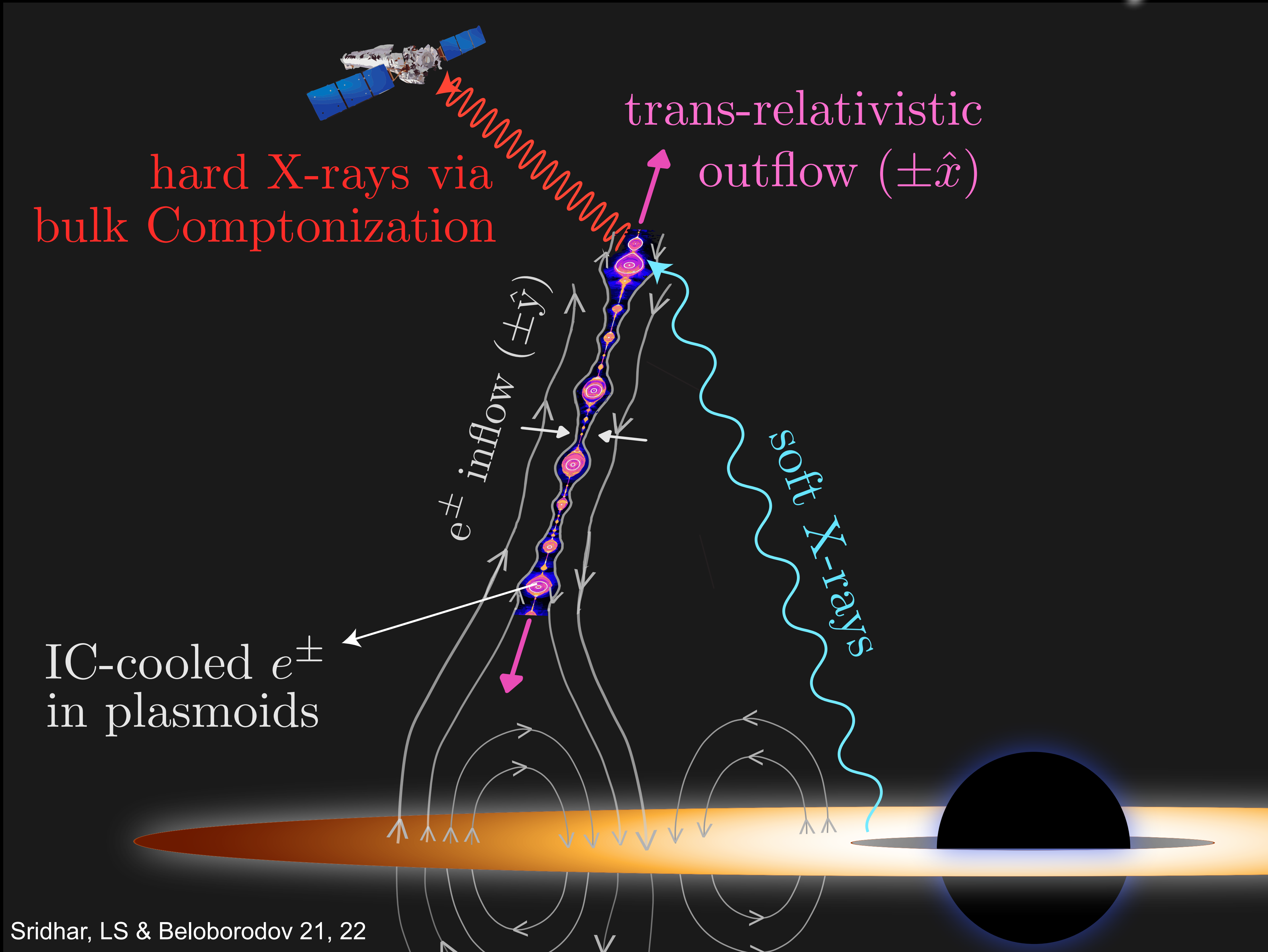


(LS & Beloborodov 20; Sridhar, LS & Beloborodov 21, 22)

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

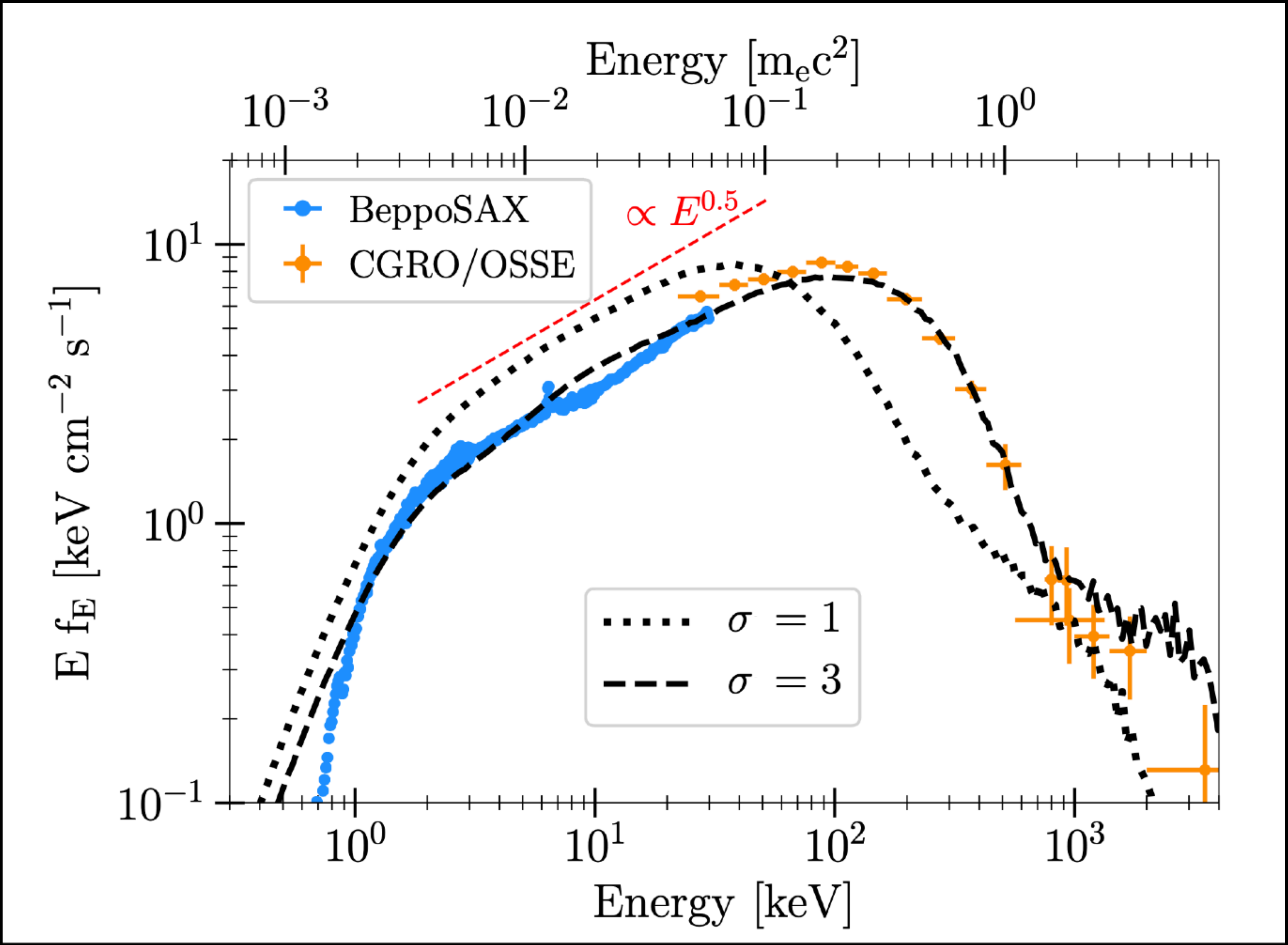
→ <u>Bulk</u> Comptonization in the plasmoid chain mimics <u>thermal</u> Comptonization

A reconnection model for hard X-rays



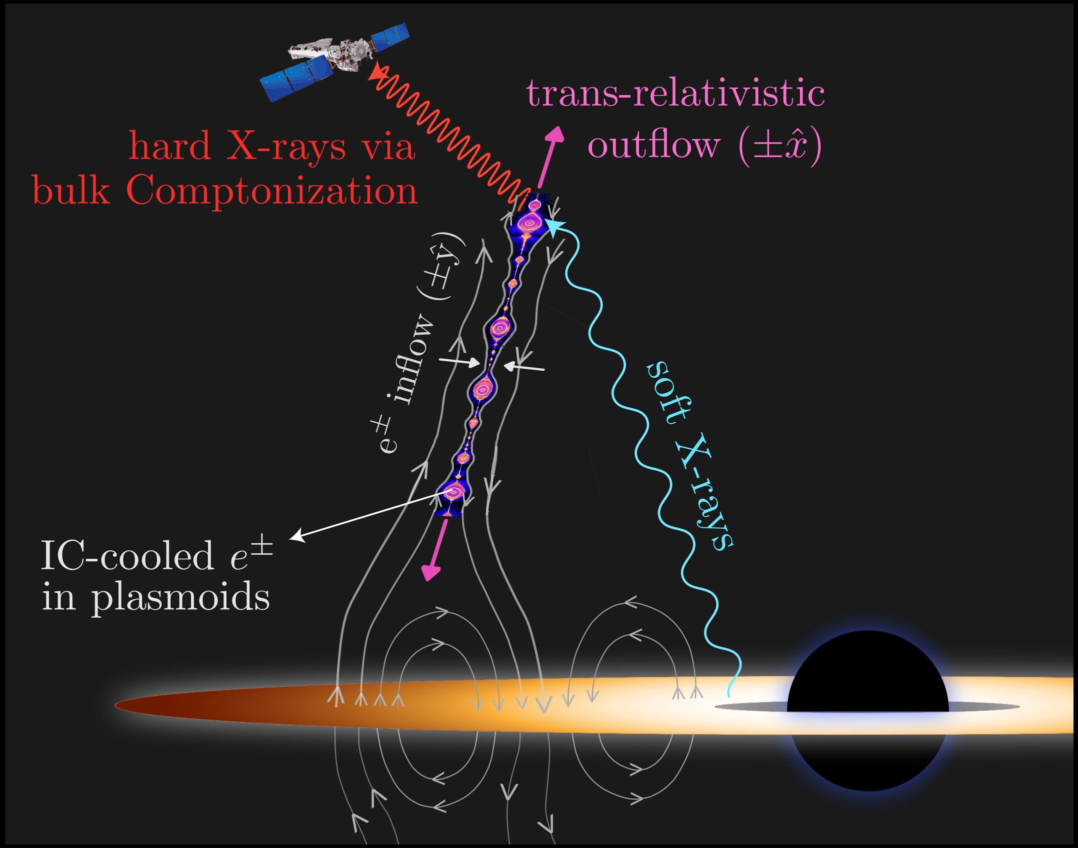
Sridhar, LS & Beloborodov 21, 22

X-ray photon spectrum



(Sridhar, LS & Beloborodov 21, 22)

Summary: reconnection in BH coronae



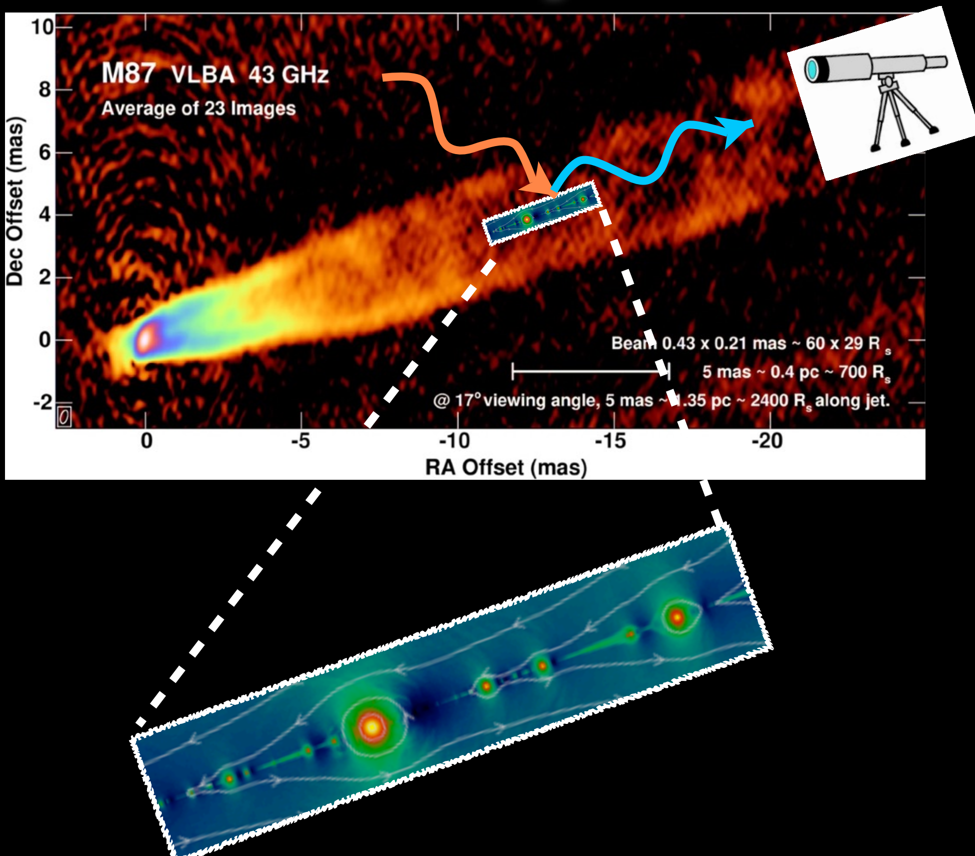
Radiative reconnection in BH coronae:

→ cold plasmoids moving at trans-relativistic speeds

→ plasmoid chain Comptonization with effective temperature ~ 100 keV

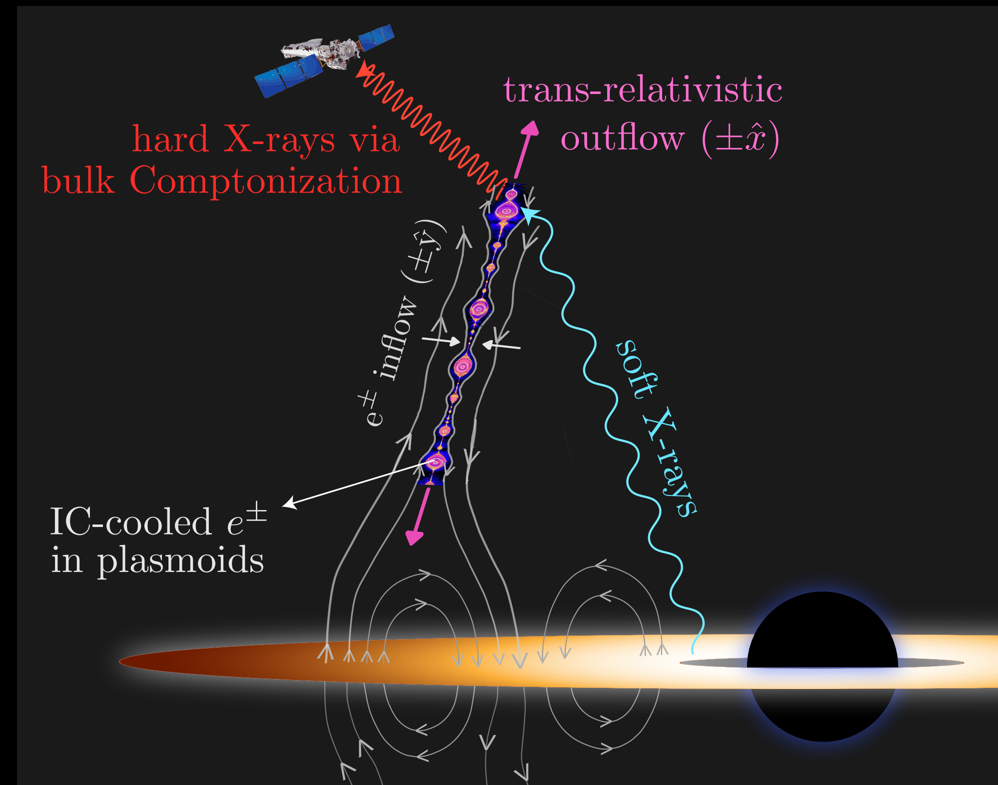
→ hard state spectra of X-ray binaries and AGNs

Relativistic reconnection in blazar jets



- non-thermal particles with hard power-law slopes.
- optical flares accompanied by polarization angle rotations.
- “orphan” gamma-ray flares (due to strong pitch angle anisotropy).

Radiative relativistic reconnection in BH coronae



- cold plasmoids moving at trans-relativistic speeds
- plasmoid chain Comptonization with effective temperature ~ 100 keV
- hard state spectra of X-ray binaries and AGNs

Some open questions

What about fast variability in blazars?

How does reconnection interplay with shocks and turbulence?
How does it interplay with basic fluid-type large-scale instabilities?

Is reconnection the dominant particle accelerator in all magnetized environments?

Is reconnection the source of UHECRs?
What about the good old relativistic shocks?

How is the reconnection physics modified by radiative effects?
(cooling, pair production)

What can we learn from non-relativistic reconnection in lab or solar wind?