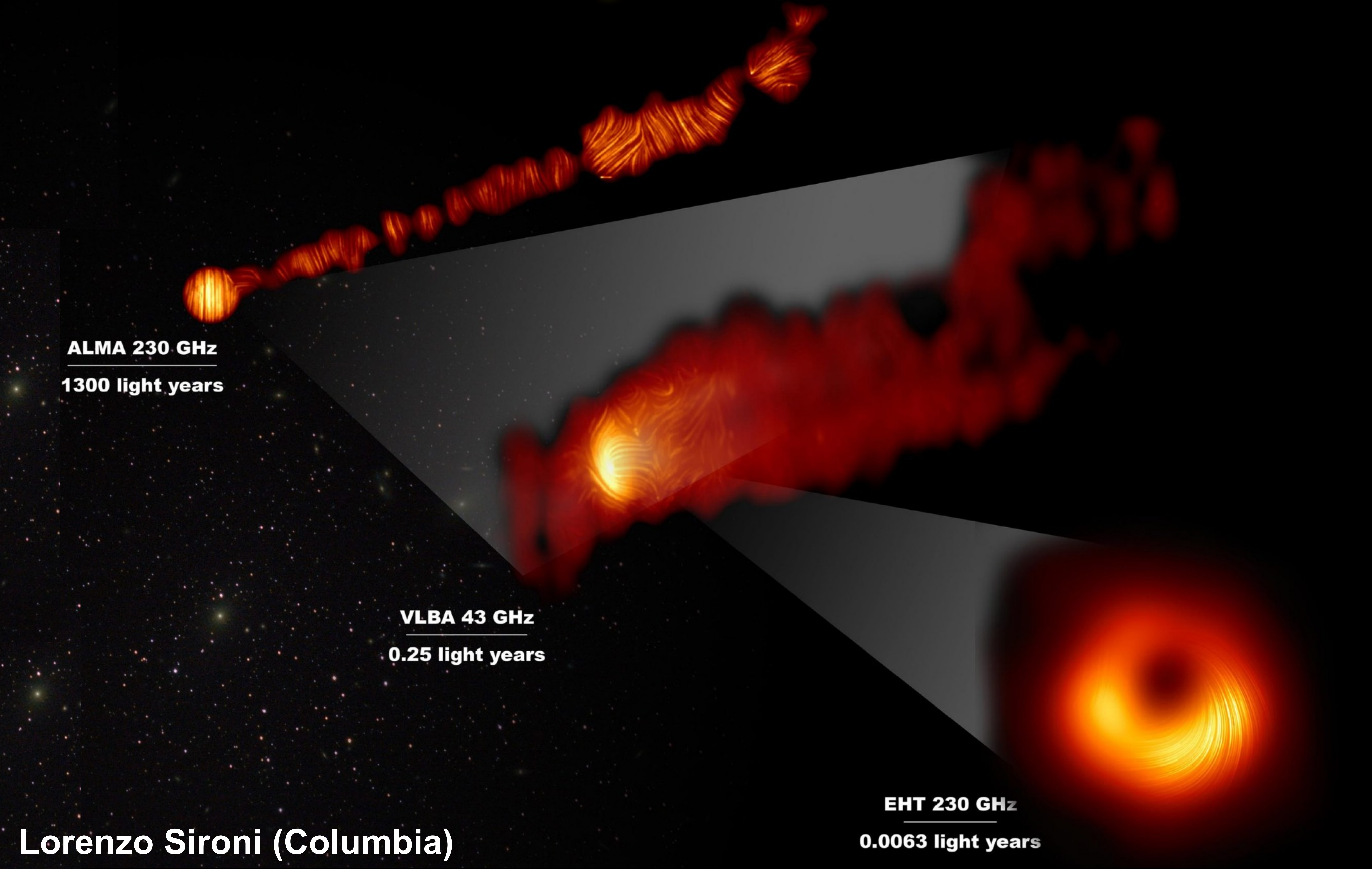
# Reconnection-powered emission





Lorenzo Sironi (Columbia)

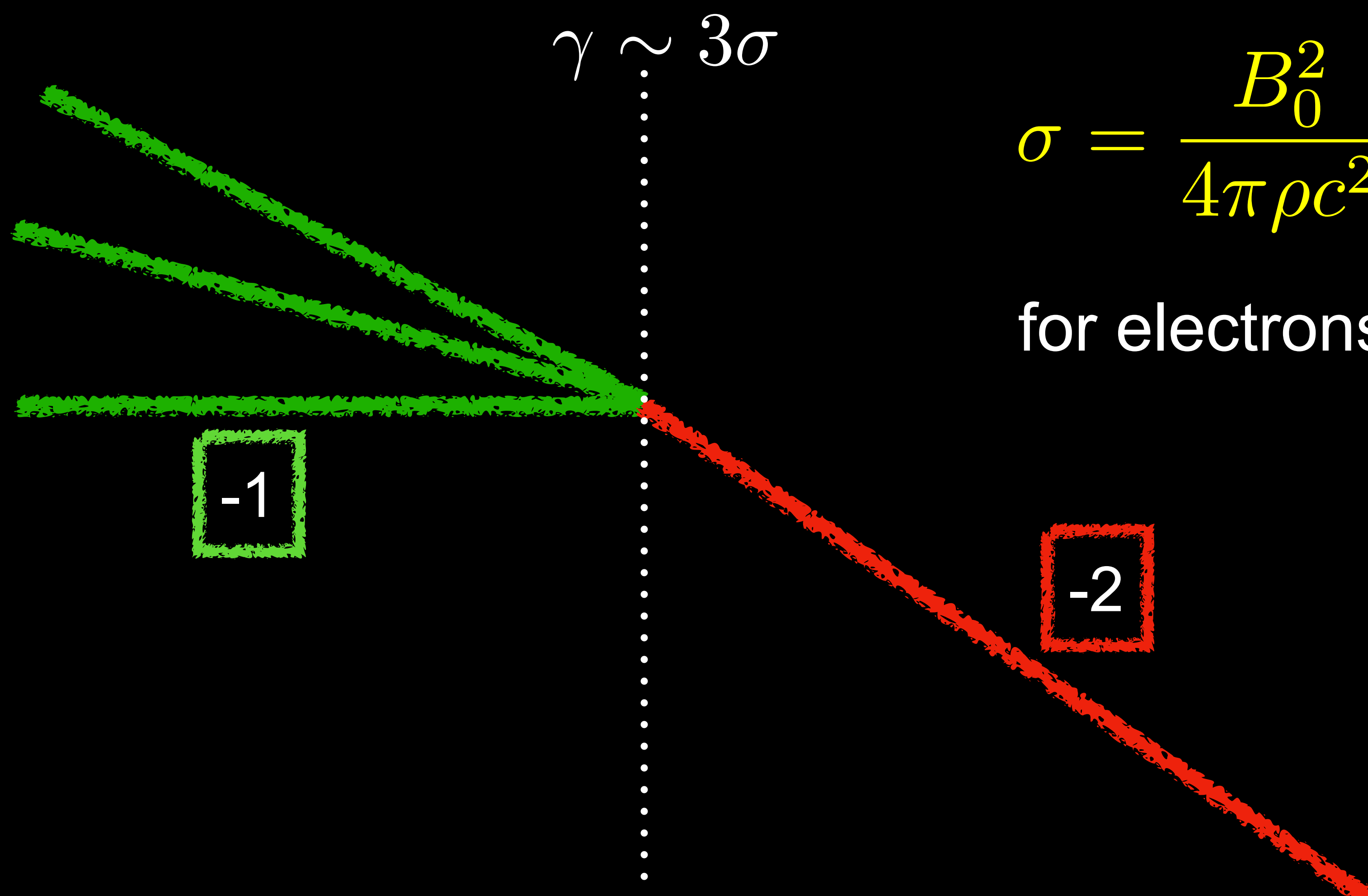

*Foundations of CR Astrophysics, Varenna 2022*

# Overarching summary

Relativistic reconnection can:

- efficiently dissipate magnetic energy (at rate ~ 0.1 c).
- produce non-thermal particles with hard power-law slopes.

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




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

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

# Outline

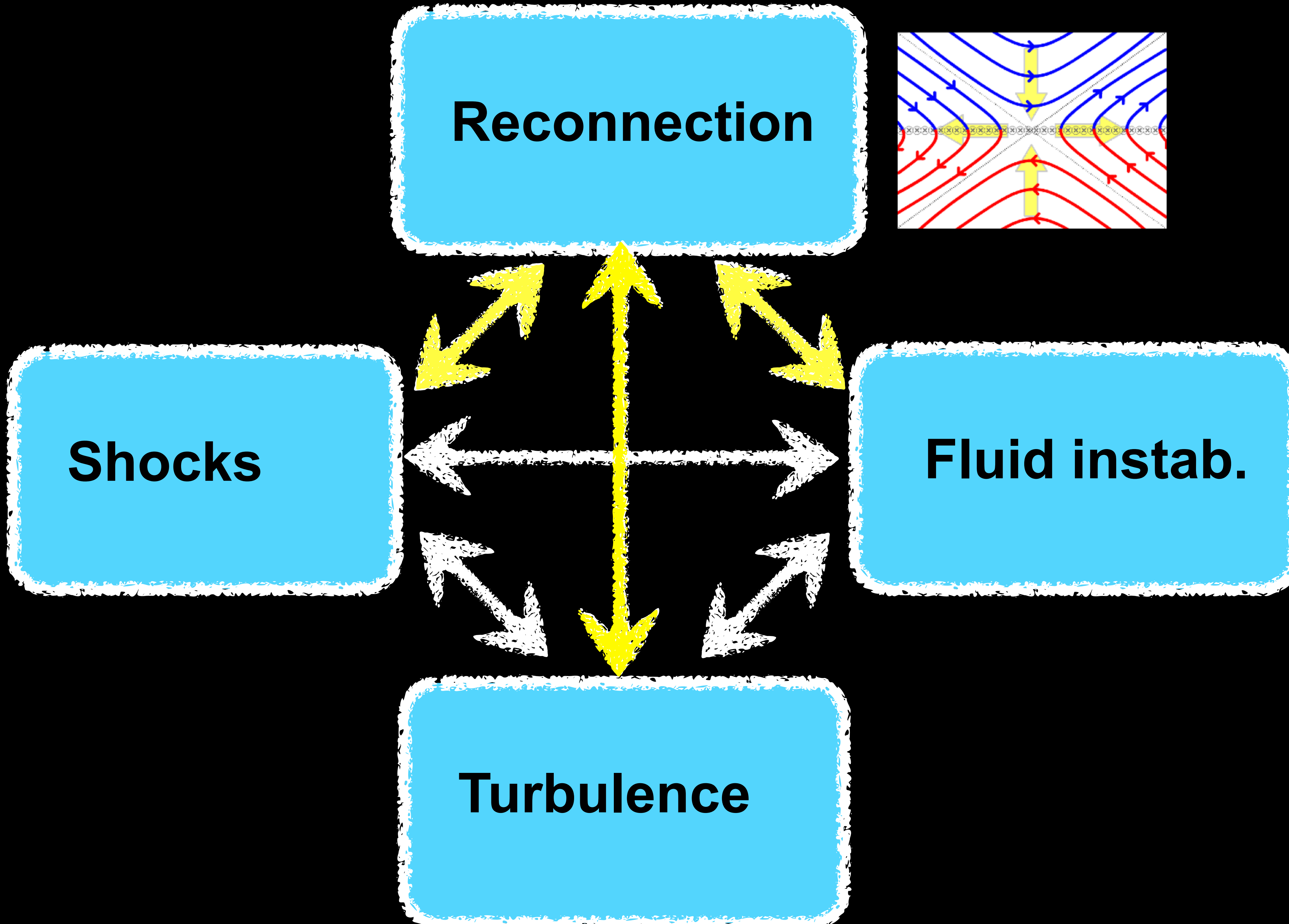
for a recent review, https://www.nature.com/articles/s42254-021-00419-x

What is magnetic reconnection?

- The Sweet-Parker model of magnetic reconnection.
- The regime of relativistic reconnection.
- The physics of particle acceleration in relativistic reconnection.

What can magnetic reconnection do?

- Where/How do reconnection layers form?
- Reconnection-powered particle acceleration and emission.



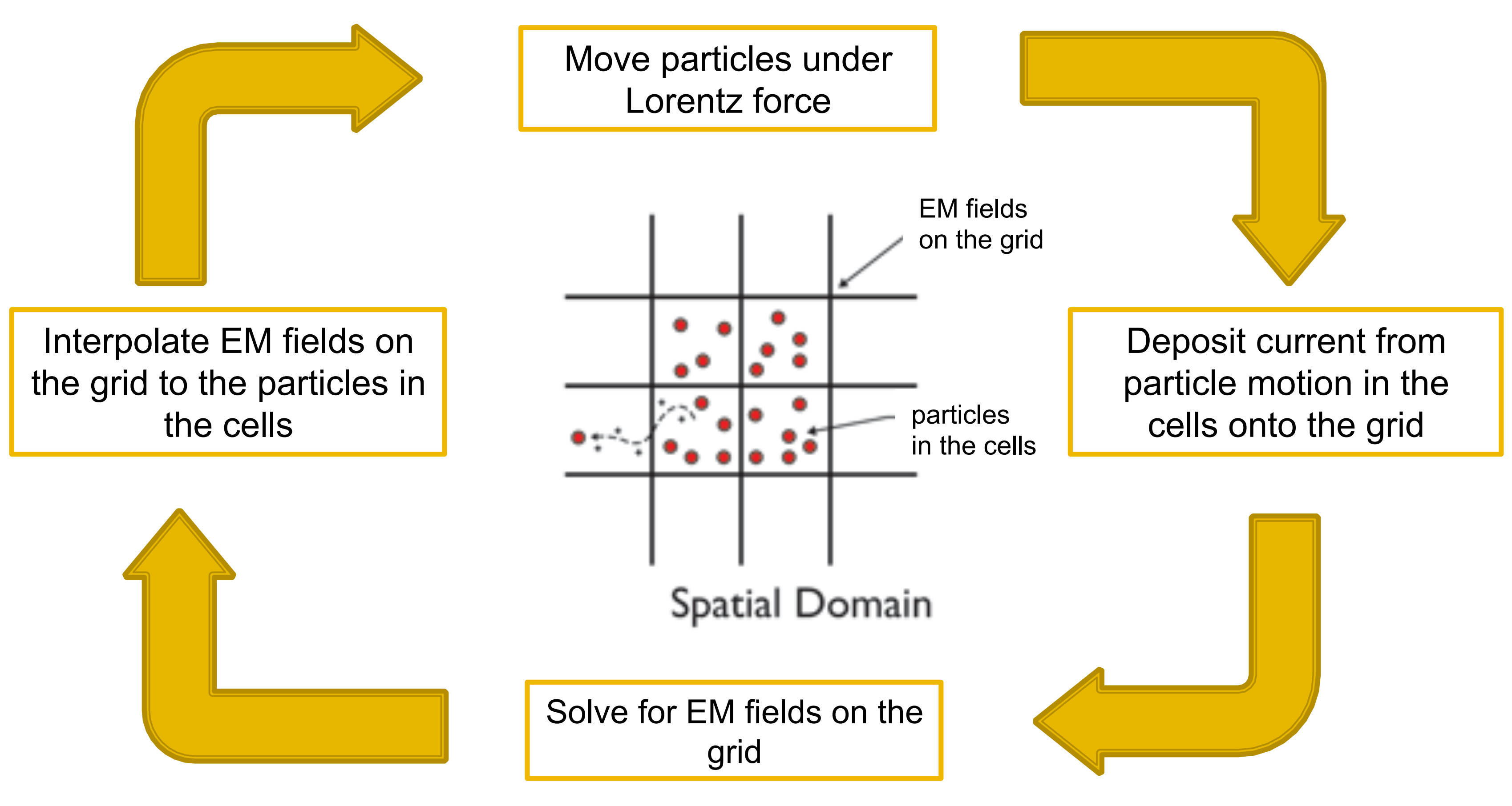

Magnetically-dominated
(aka “relativistic”):

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

# The PIC method

## Particle-in-Cell (PIC) method:

It is the most fundamental way 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 ($c/\omega_p$) and time ($1/\omega_p$) scales are:

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

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

# Shock-driven reconnection in spider pulsars

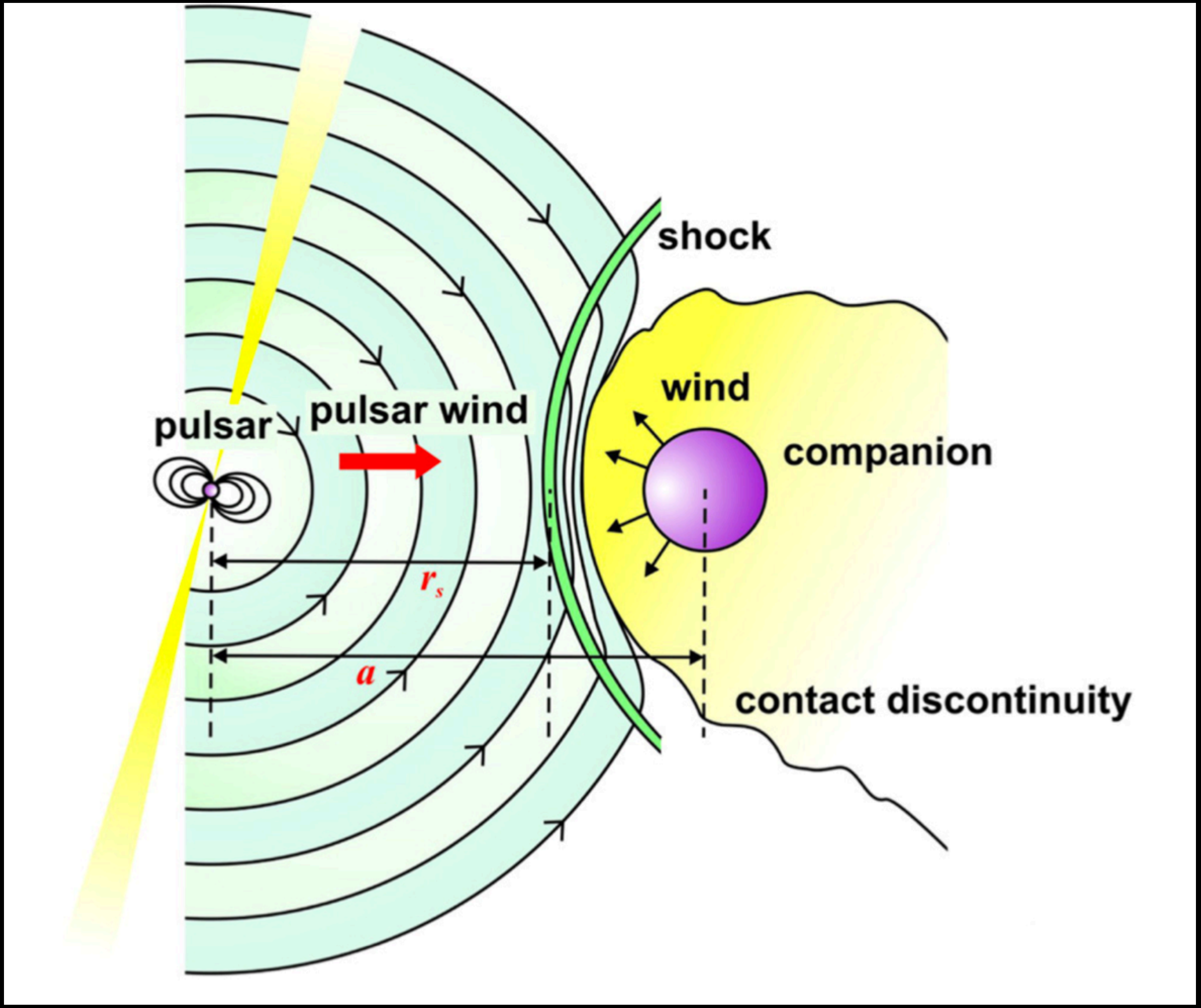
Reconnection ⟷ Shocks


with J. Cortes

Cortes & LS 2022, arXiv:2203.00023

# What are spider pulsars?

- Millisecond pulsars in tight binary orbits with a degenerate (black widows) or non-degenerate (redbacks) companion.
- The pulsar wind evaporates (devours) the companion.



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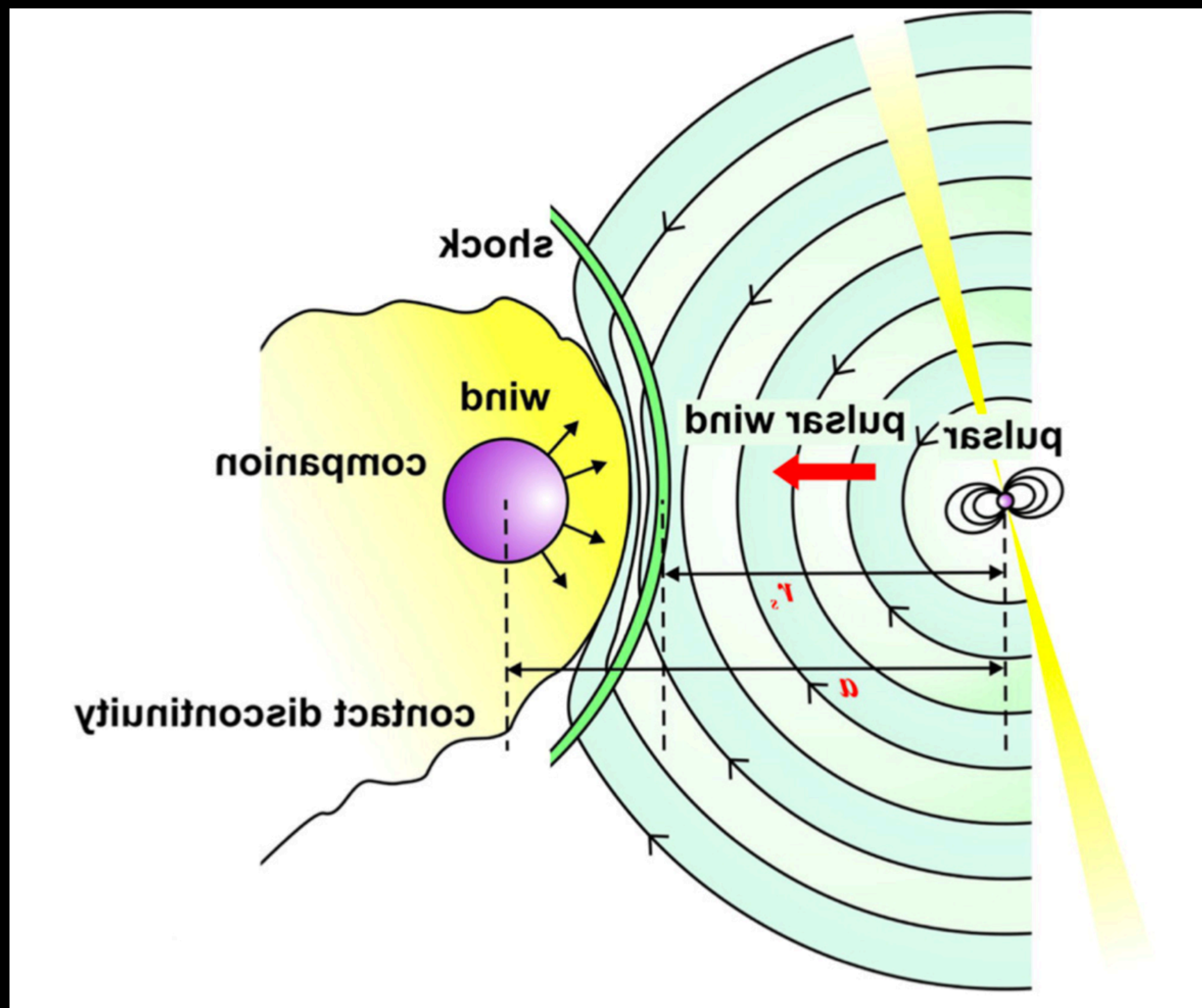
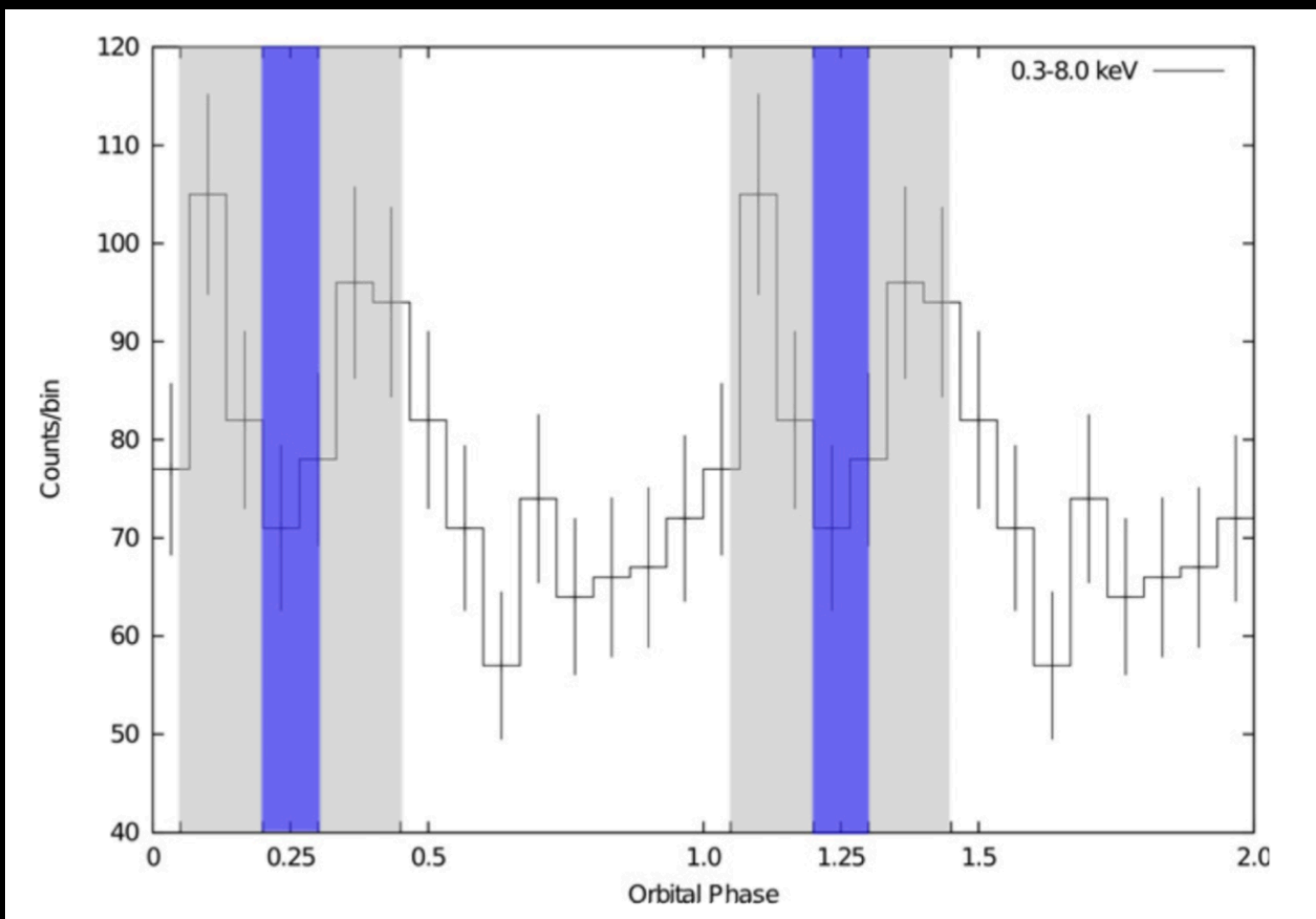
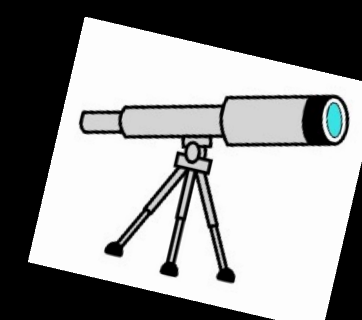


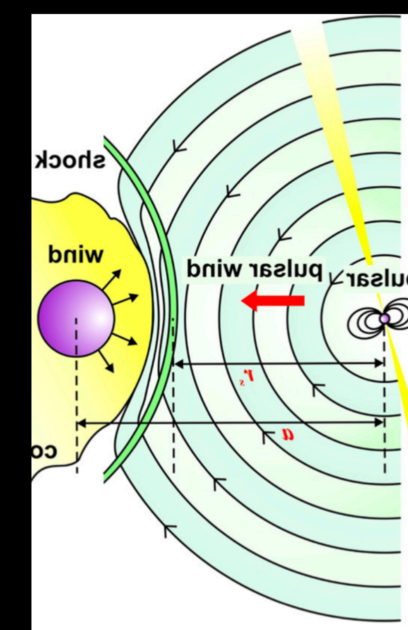
# Spectra and lightcurves

- The X-ray spectrum is hard, requiring an electron spectrum with hard slope.

$$\frac{dn}{d\gamma} \propto \gamma^{-p} \qquad p = -d\log N/d\log\gamma \approx 1-2.$$





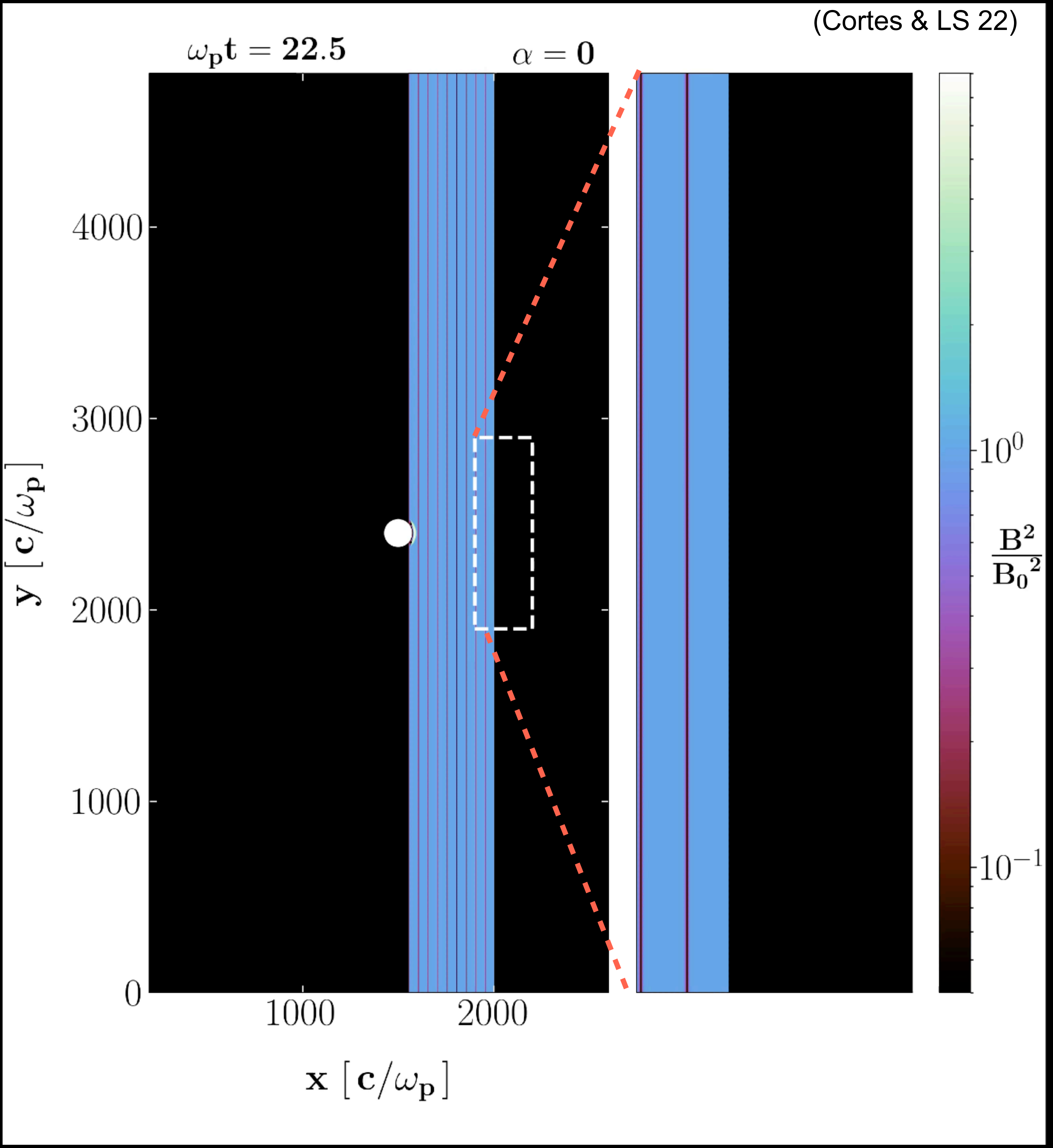

- The X-ray lightcurve has two peaks, just before and after the pulsar eclipse.

# Flow dynamics from a global PIC sim

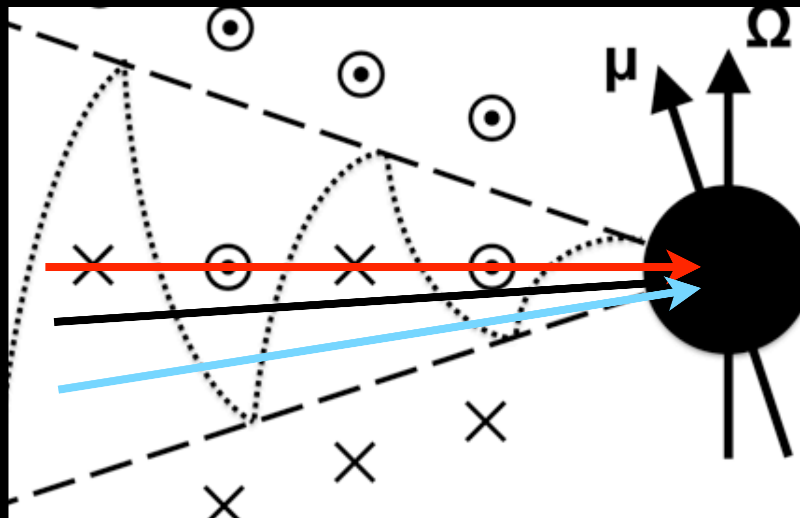
- The pulsar wind is terminated at a relativistic shock that wraps around the companion.

- Shock-driven reconnection dissipates the magnetic stripes.

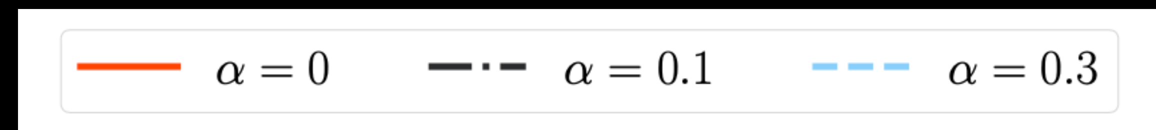
σ=10

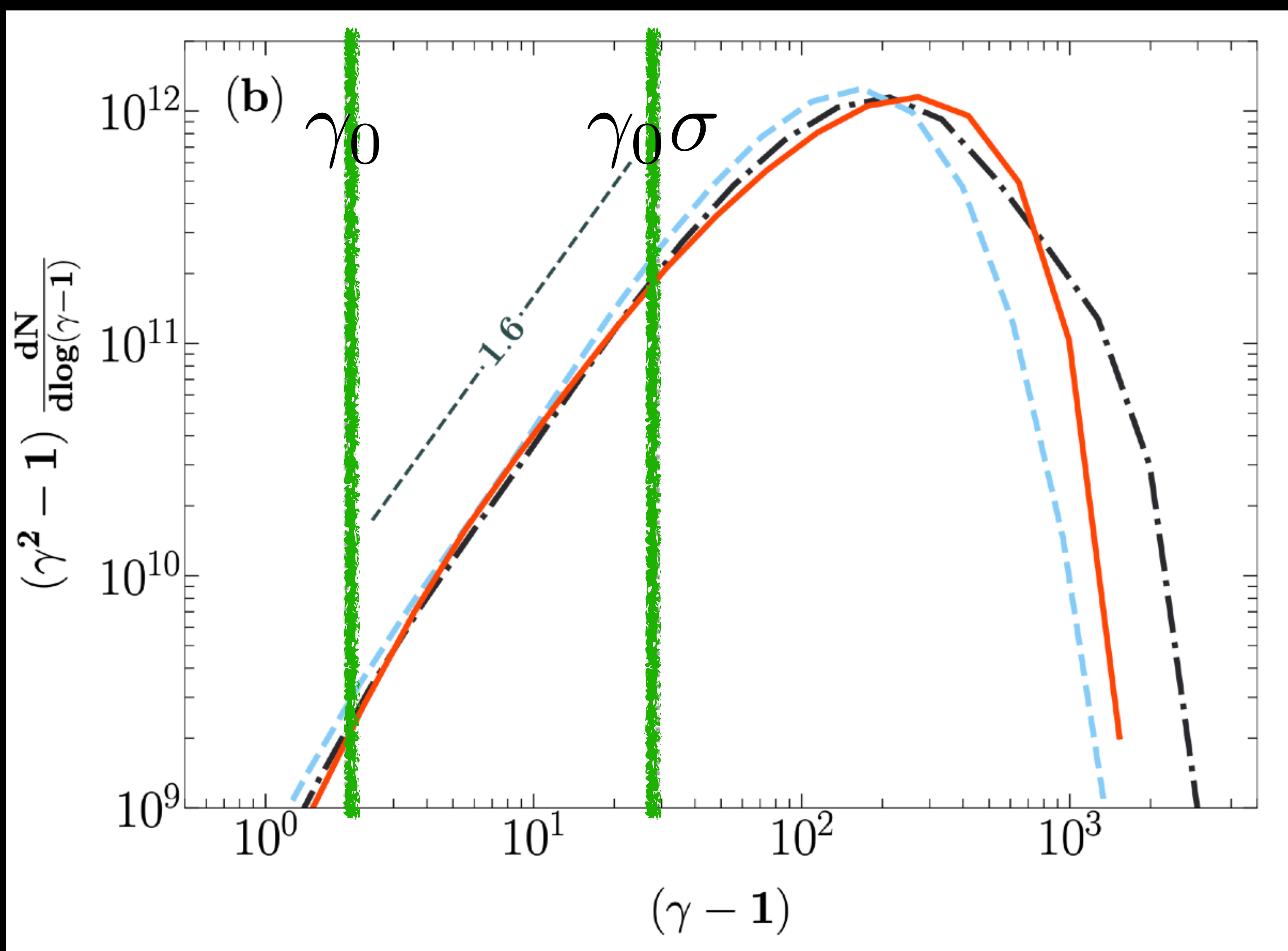


# Particle spectrum




We explore the whole range of latitudes where the wind is striped ($\alpha$ from 0 to 1)



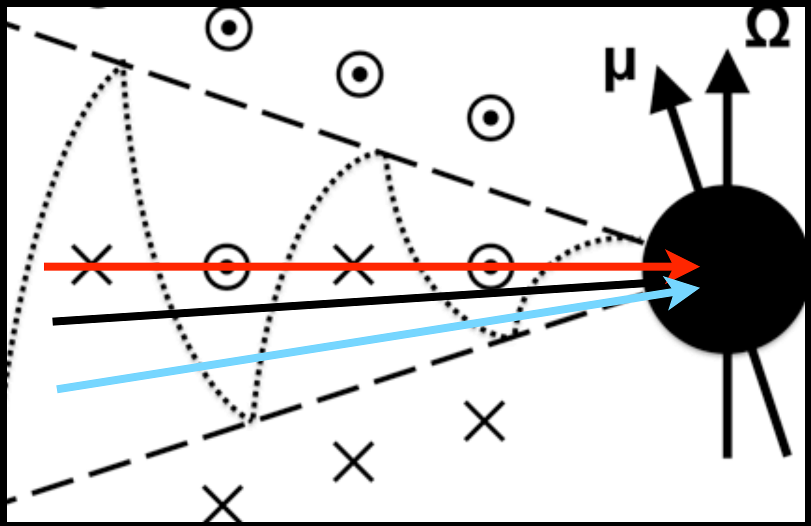




- The particle spectrum is hard, with *p~1.4*, in the range

$$\gamma_0 \lesssim \gamma \lesssim \gamma_0 \sigma$$

as a result of shock-driven reconnection.

# Synchrotron spectrum

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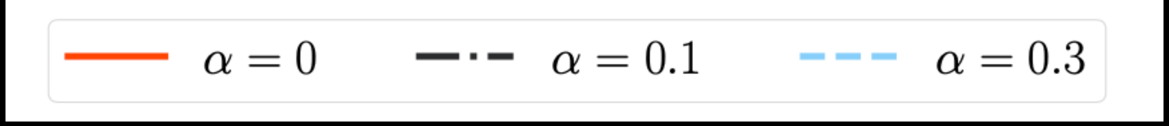
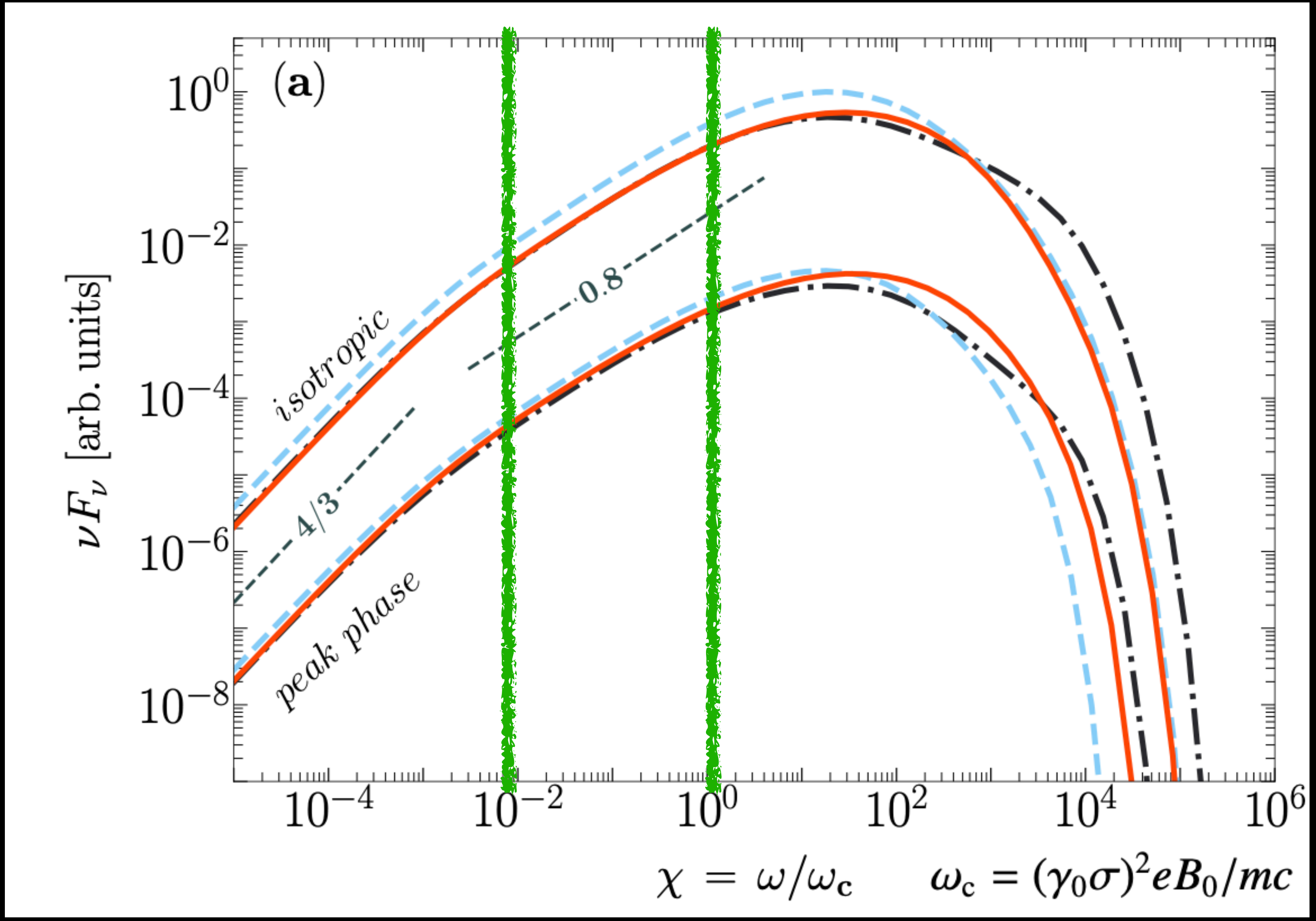
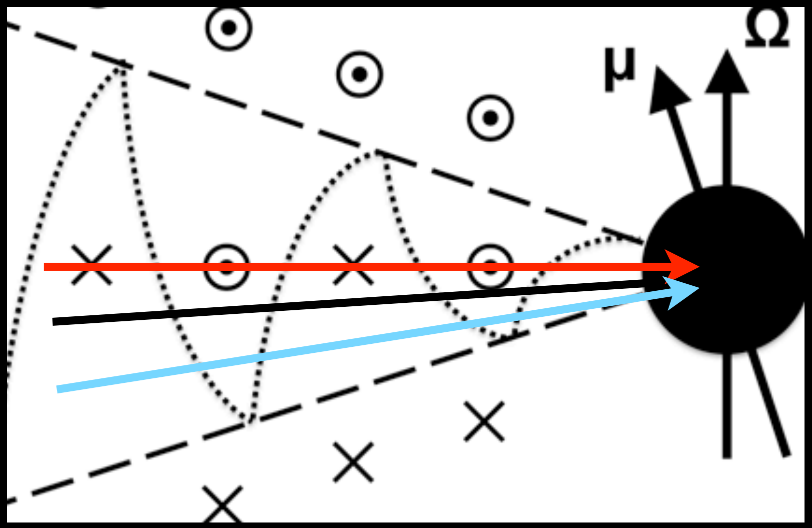


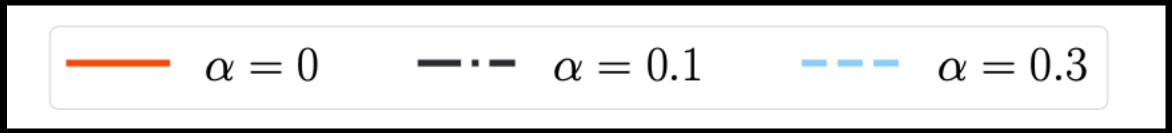



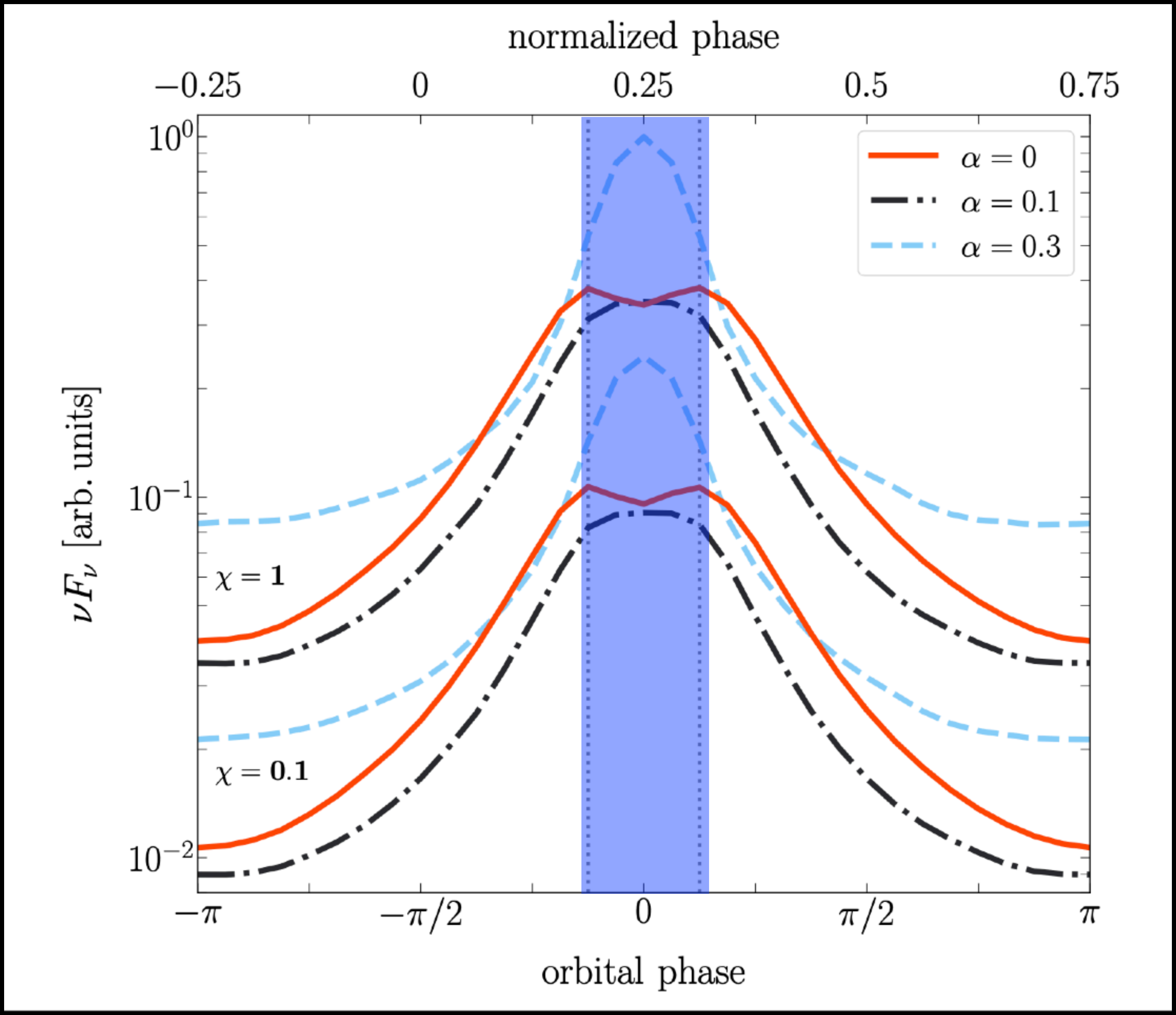

- In the corresponding frequency range, the synchrotron spectrum is hard, with a slope consistent with X-ray observations.

# Lightcurve

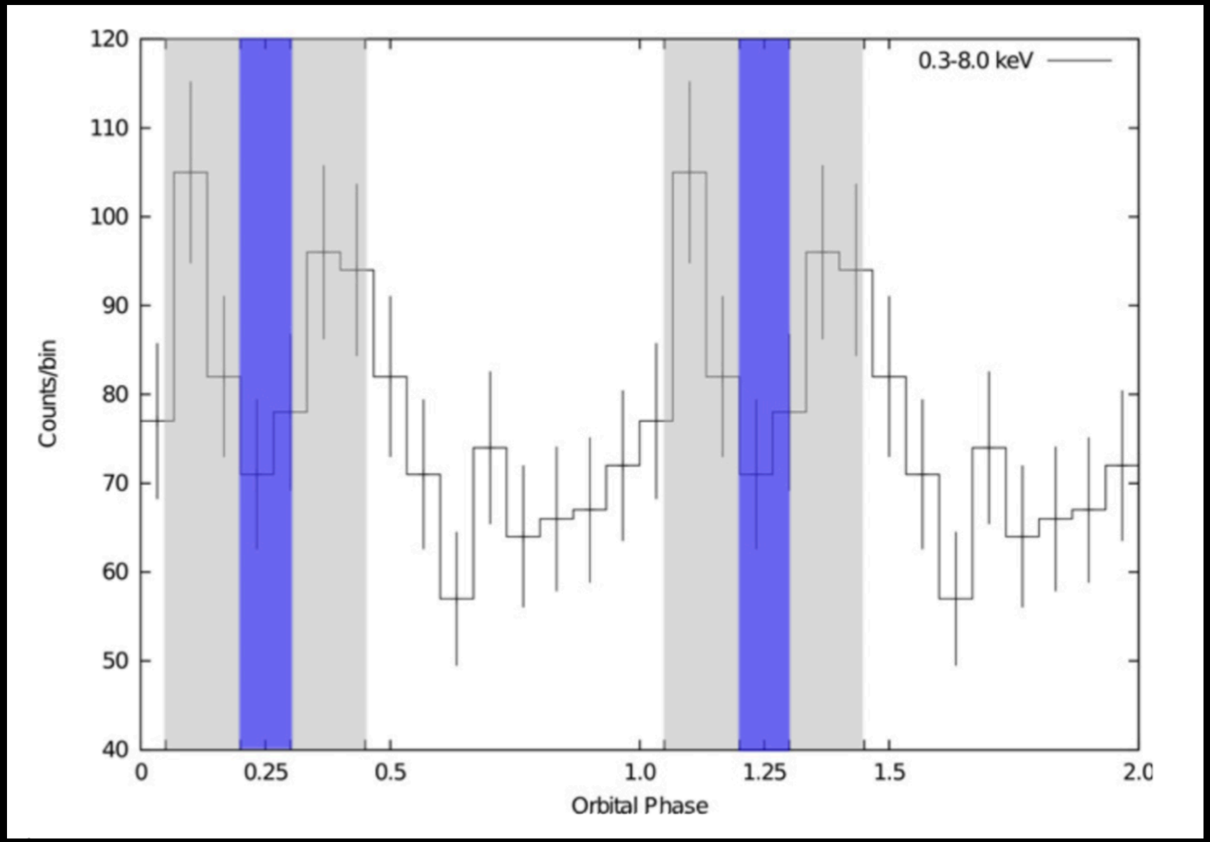



We explore the whole range of latitudes where the wind is striped (α from 0 to 1)



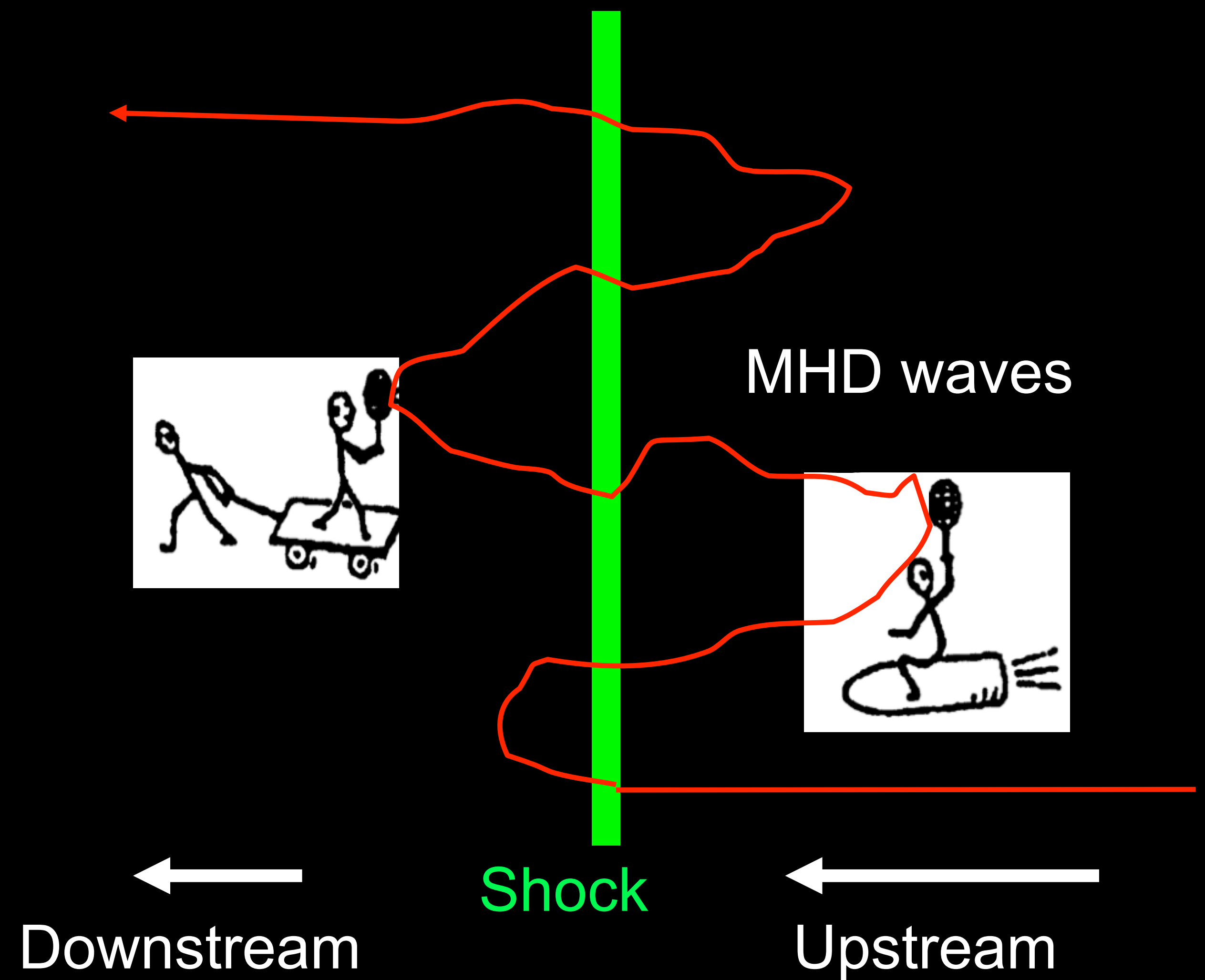




- For α~0, the lightcurve shows two peaks, just before and after the pulsar eclipse.

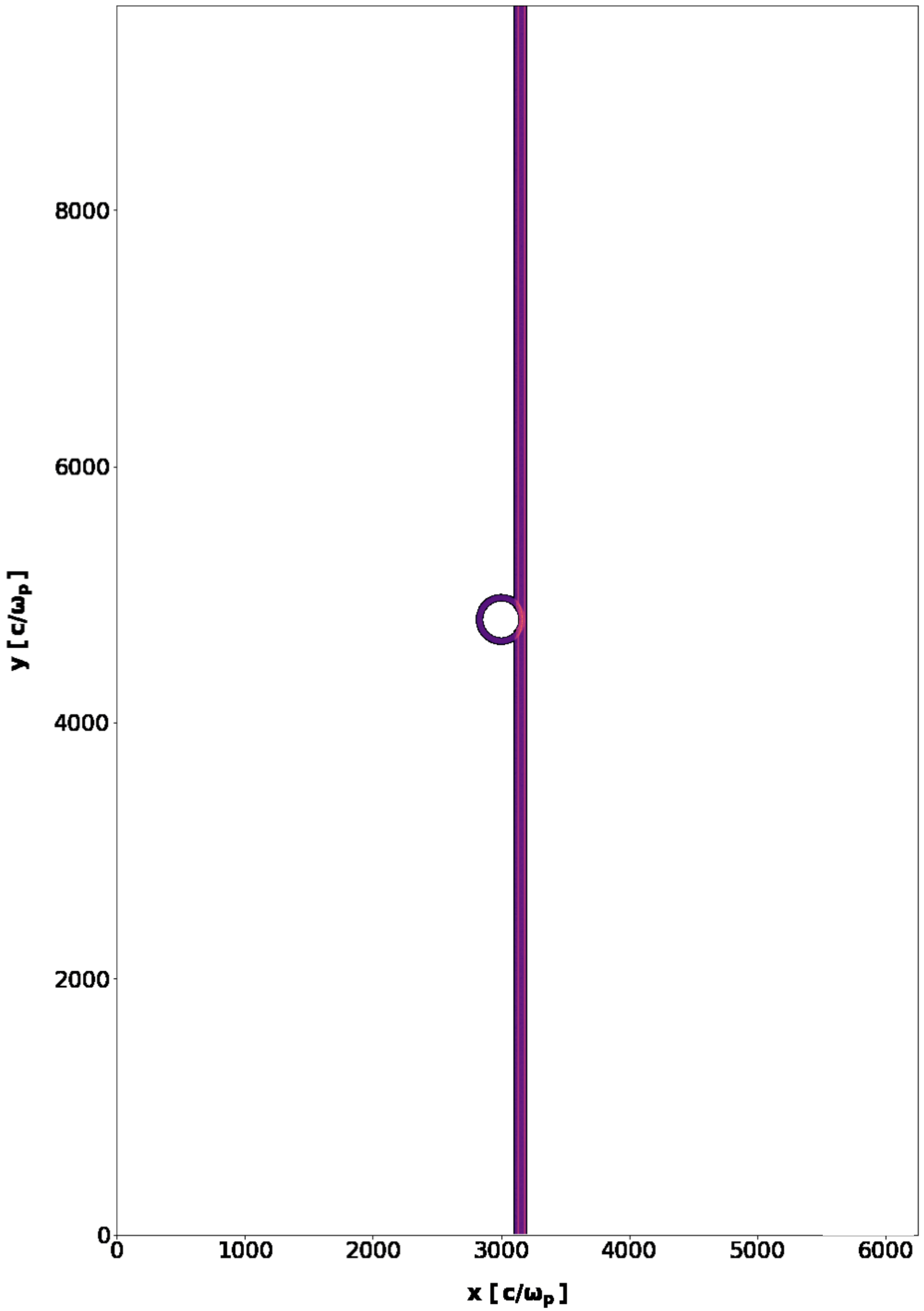


# Fermi acceleration

• For $\alpha$~0, particles accelerated by shock-driven reconnection can be injected in the good old Fermi process at the termination shock.



# Fermi acceleration



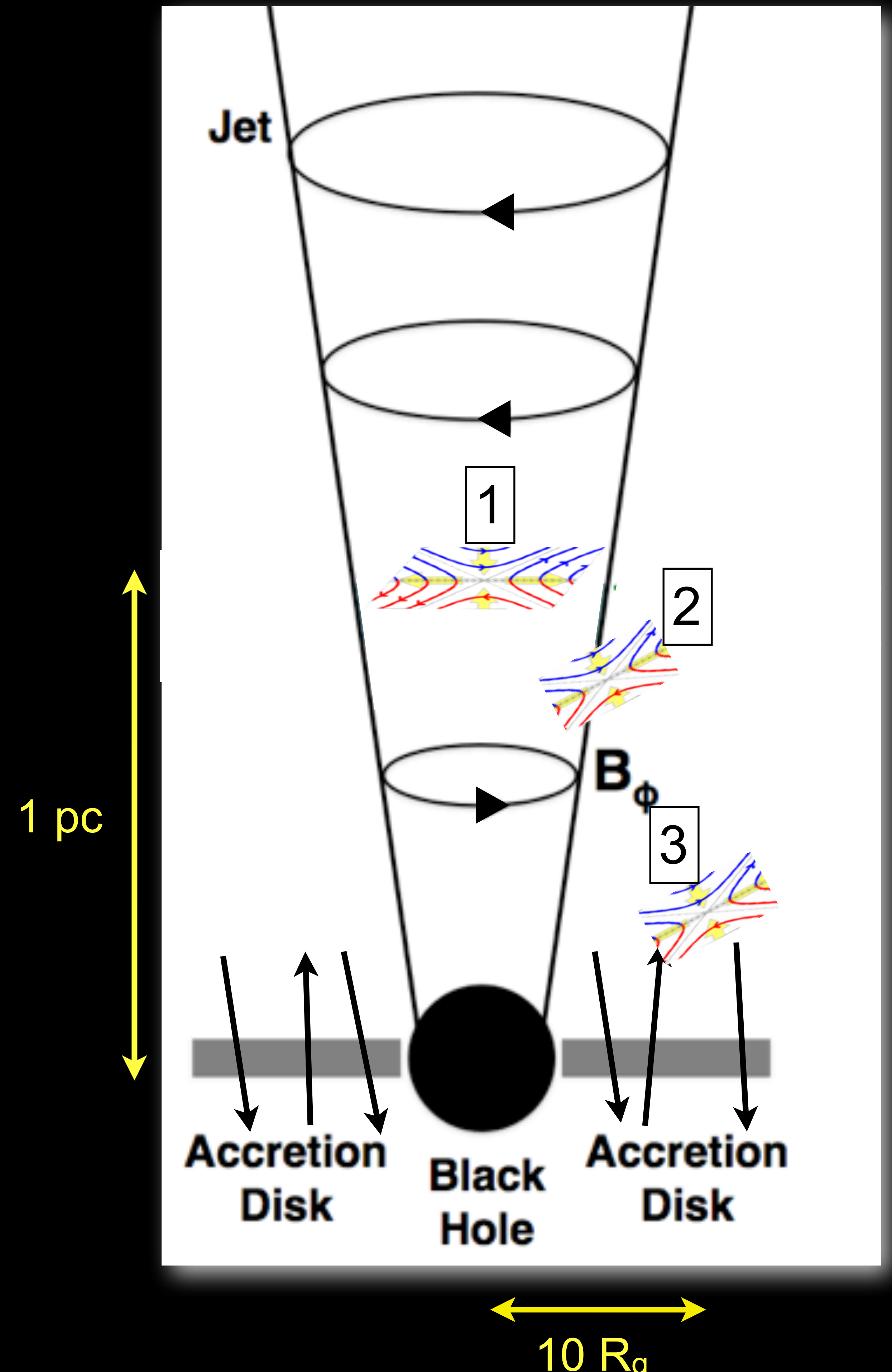

- For $\alpha \sim 0$, particles accelerated by shock-driven reconnection can be injected in the *Fermi process* at the termination shock.

# Overarching summary

Relativistic reconnection can:

- efficiently dissipate magnetic energy (at rate ~ 0.1 c).
- produce non-thermal particles with hard power-law slopes.
- serve as injection process for subsequent (non-reconnection) acceleration: e.g., Fermi acceleration at shocks, stochastic acceleration in turbulence, shear acceleration at jet boundaries.
- imprint strong pitch-angle anisotropy.
- produce trans-relativistic bulk motions.

# Reconnection-powered emission in jets and black hole coronae




(1) Blazars and AGN jets.

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

(2) Boundary layers of relativistic jets.

- Can reconnection explain the limb-brightened appearance of AGN jets?

(3) 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

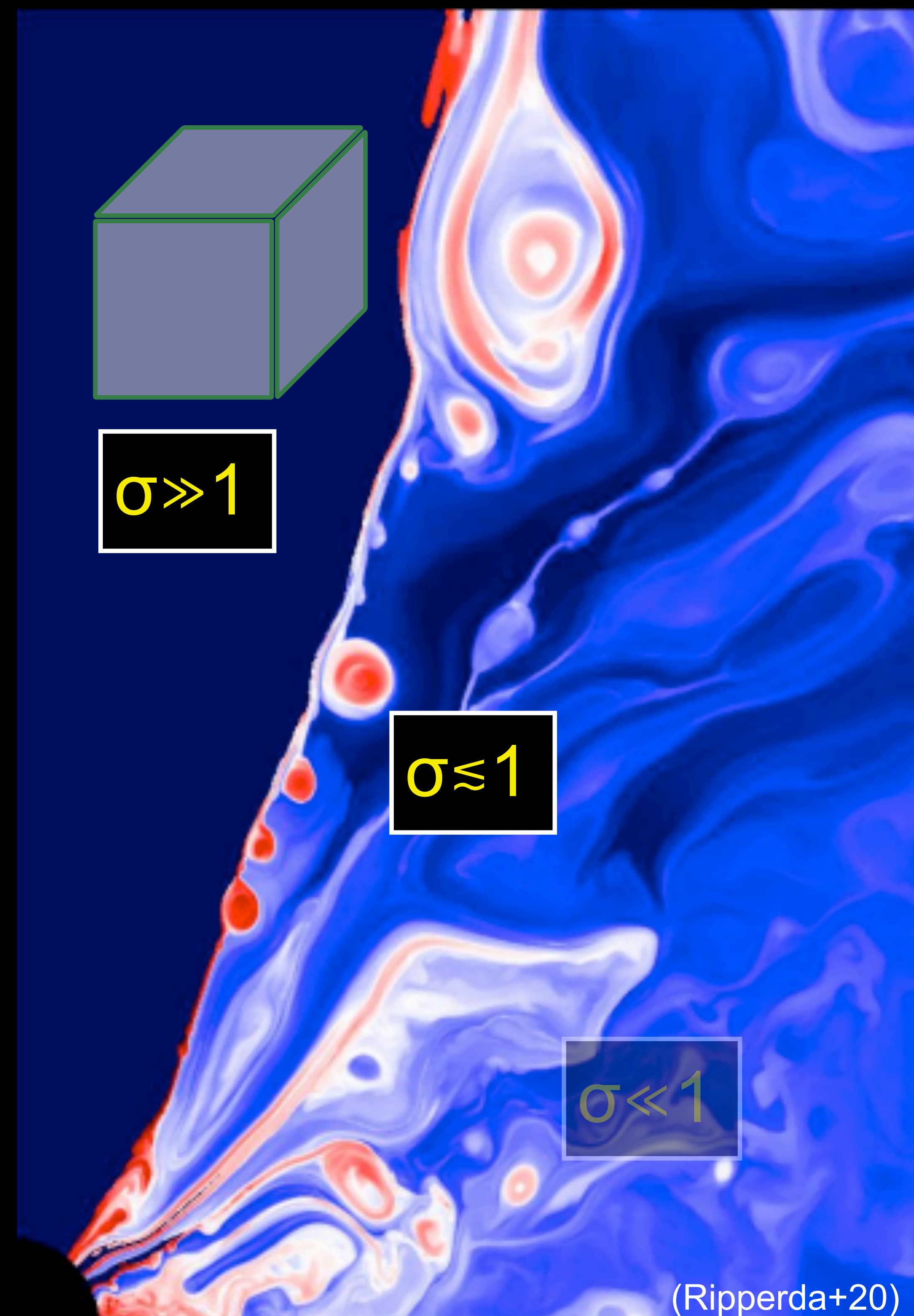
Reconnection ↔ Turbulence

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

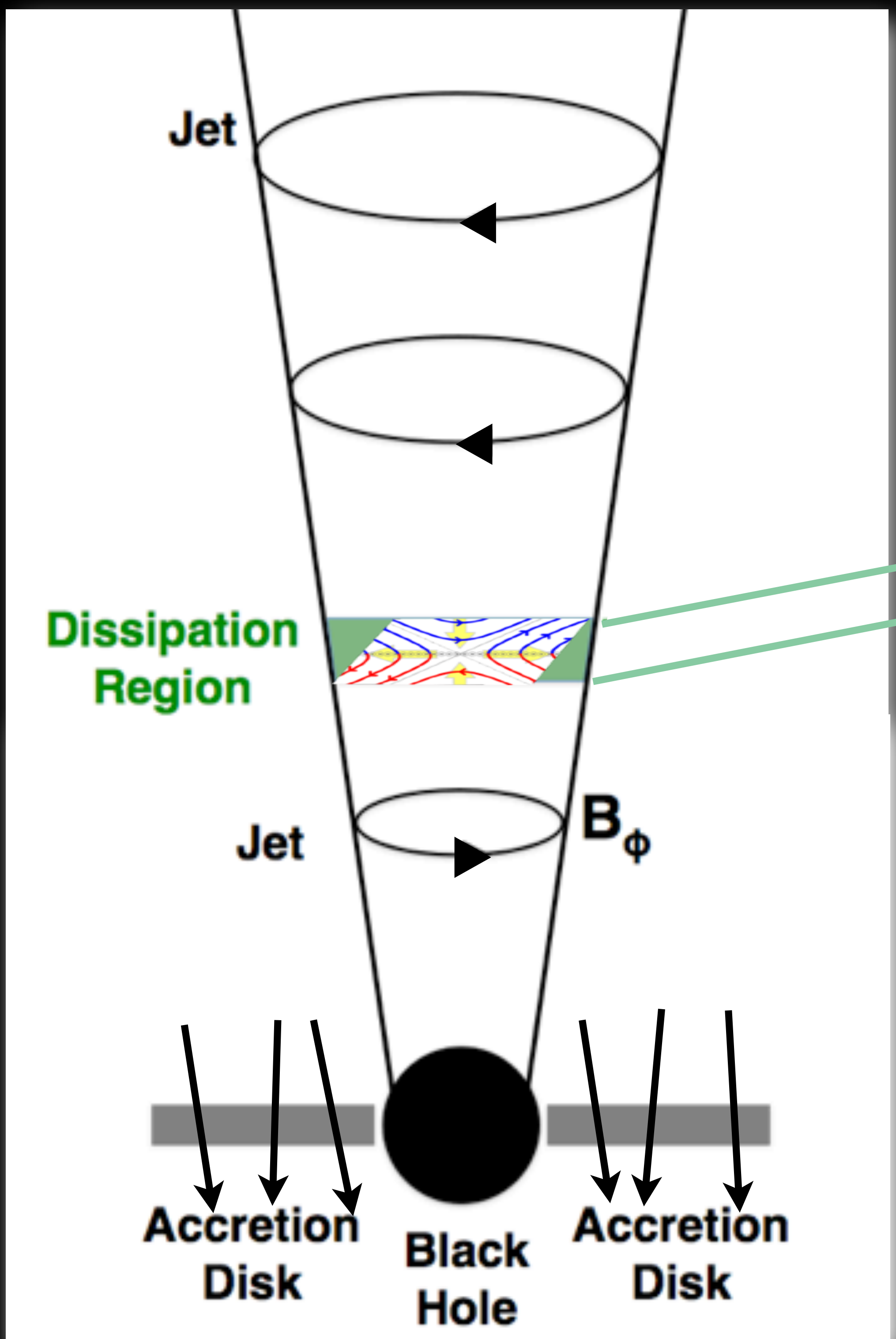
Comisso & LS 2018, PRL, 121, 255101

Comisso & LS 2019, ApJ, 886, 122

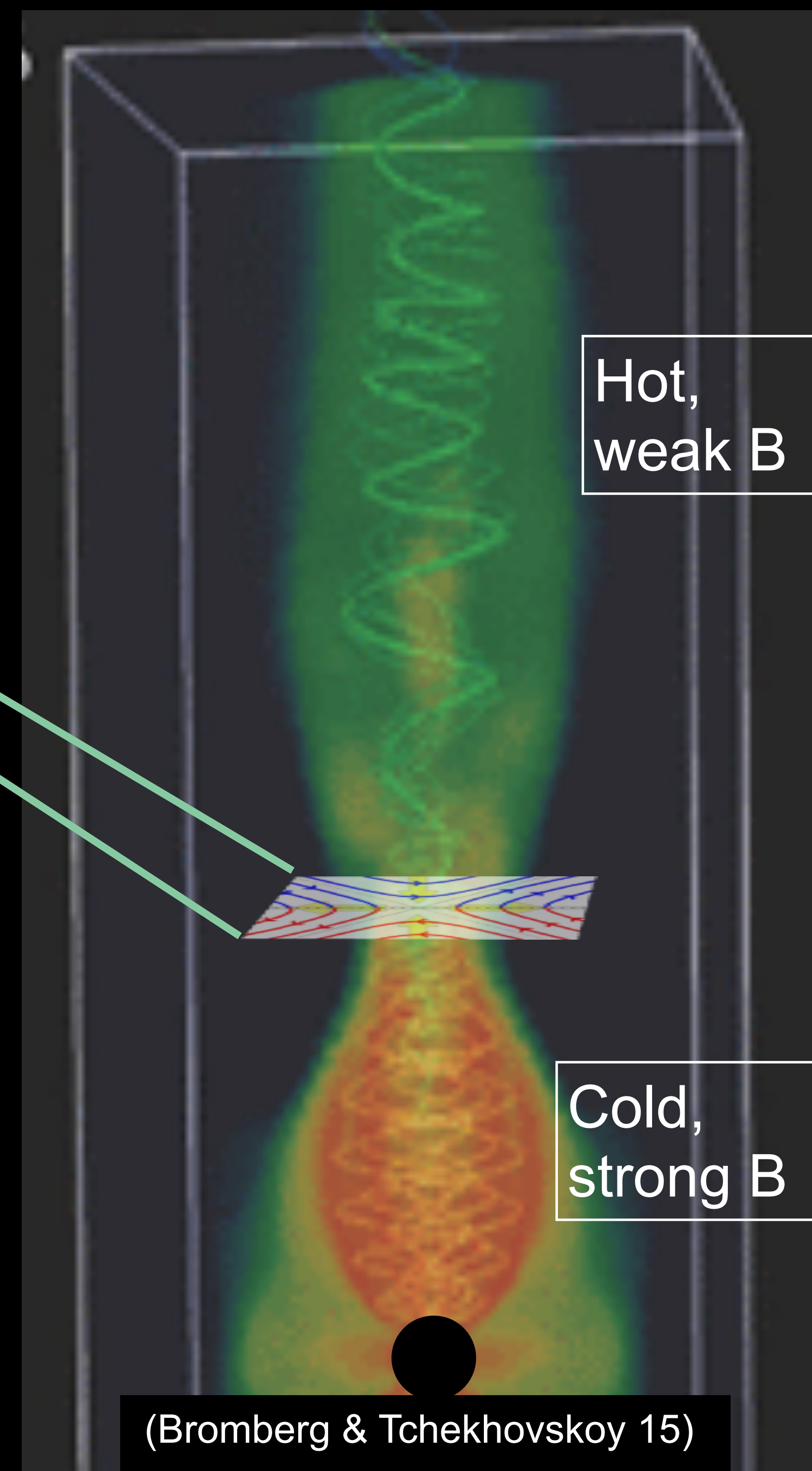
Sobacchi, Nattila & LS 2021, MNRAS, 503, 688



# Why does reconnection occur?

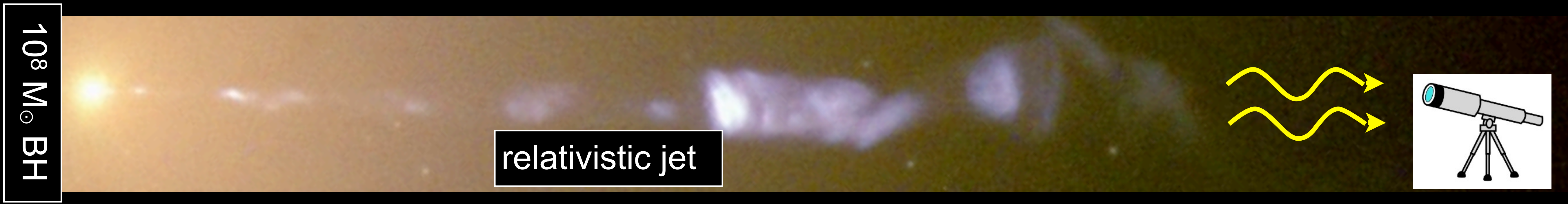


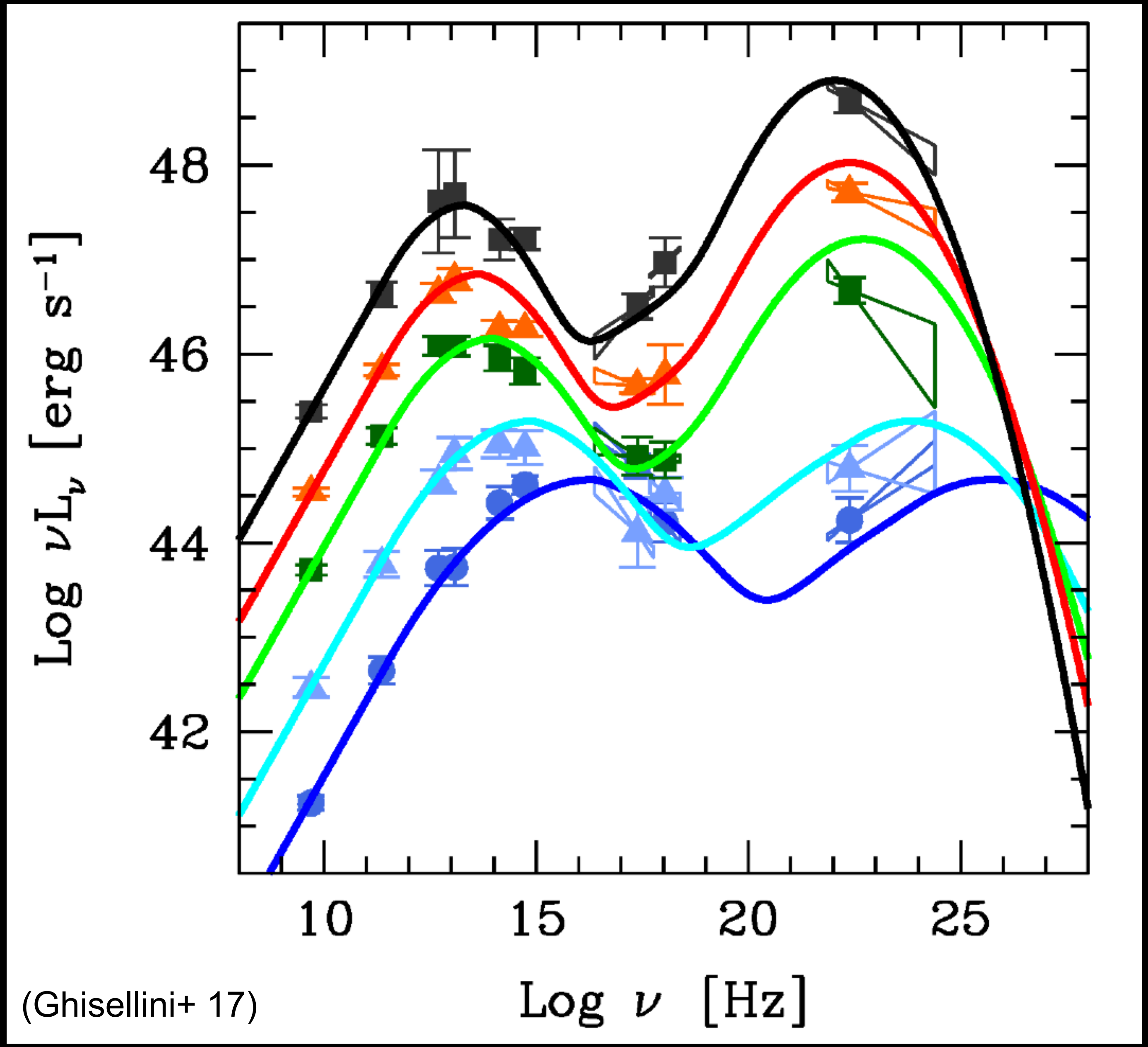

M87



# Blazar jets

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



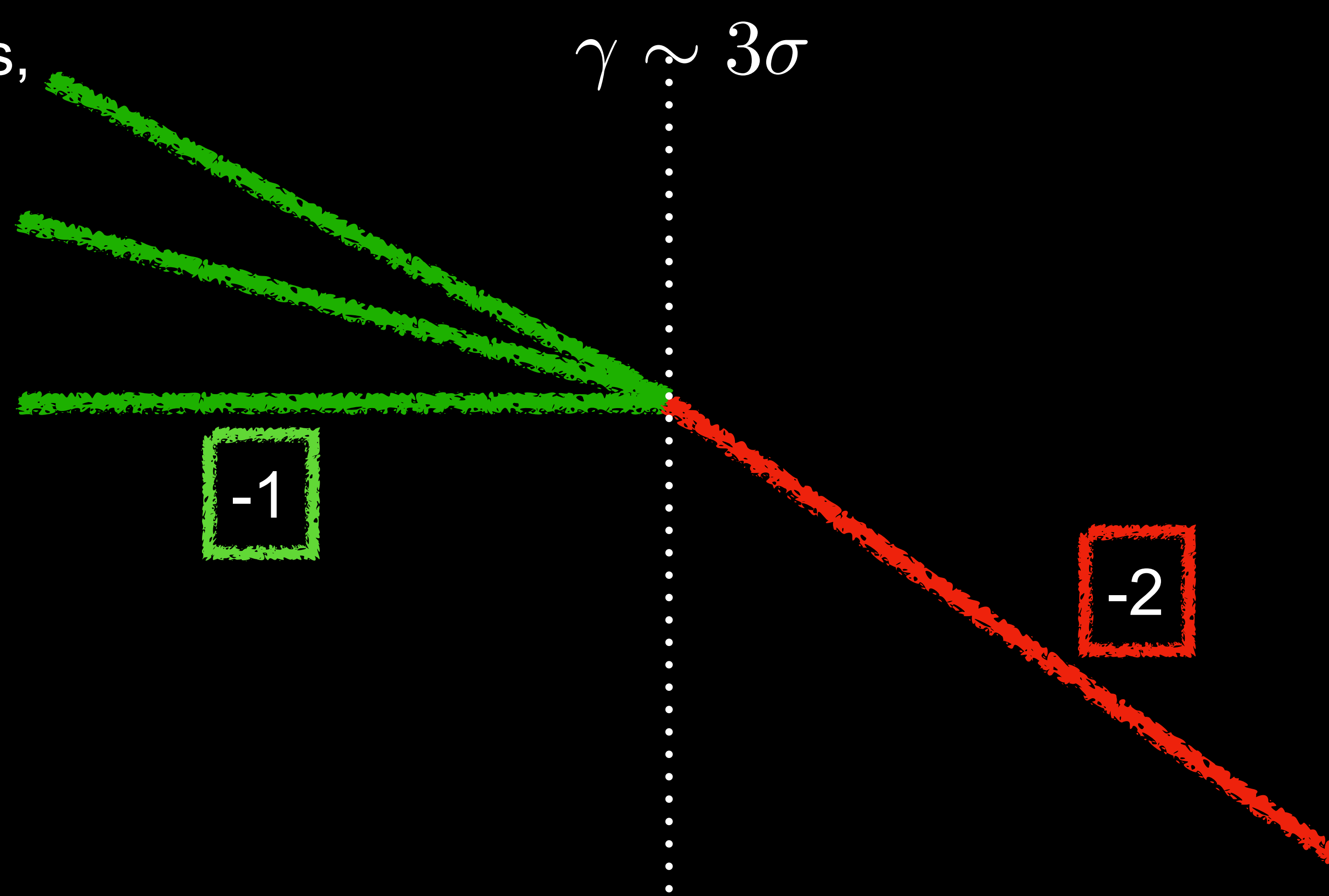

- broadband spectrum, from radio to γ-rays (and even TeV energies)
- low-energy synchrotron + high-energy inverse Compton (IC)
- high degree of radio and optical polarization

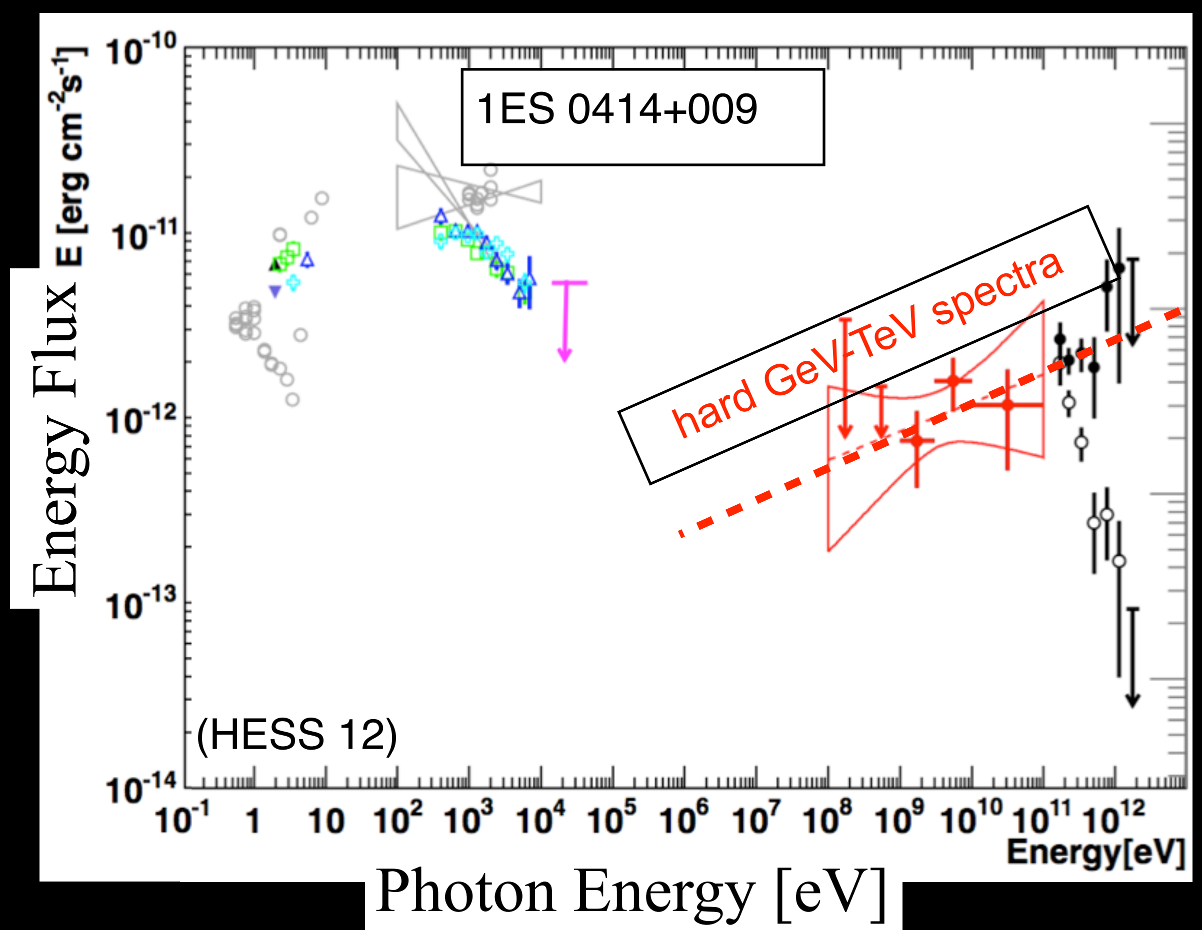
# Blazar emission

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

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

$$p \lesssim 2$$



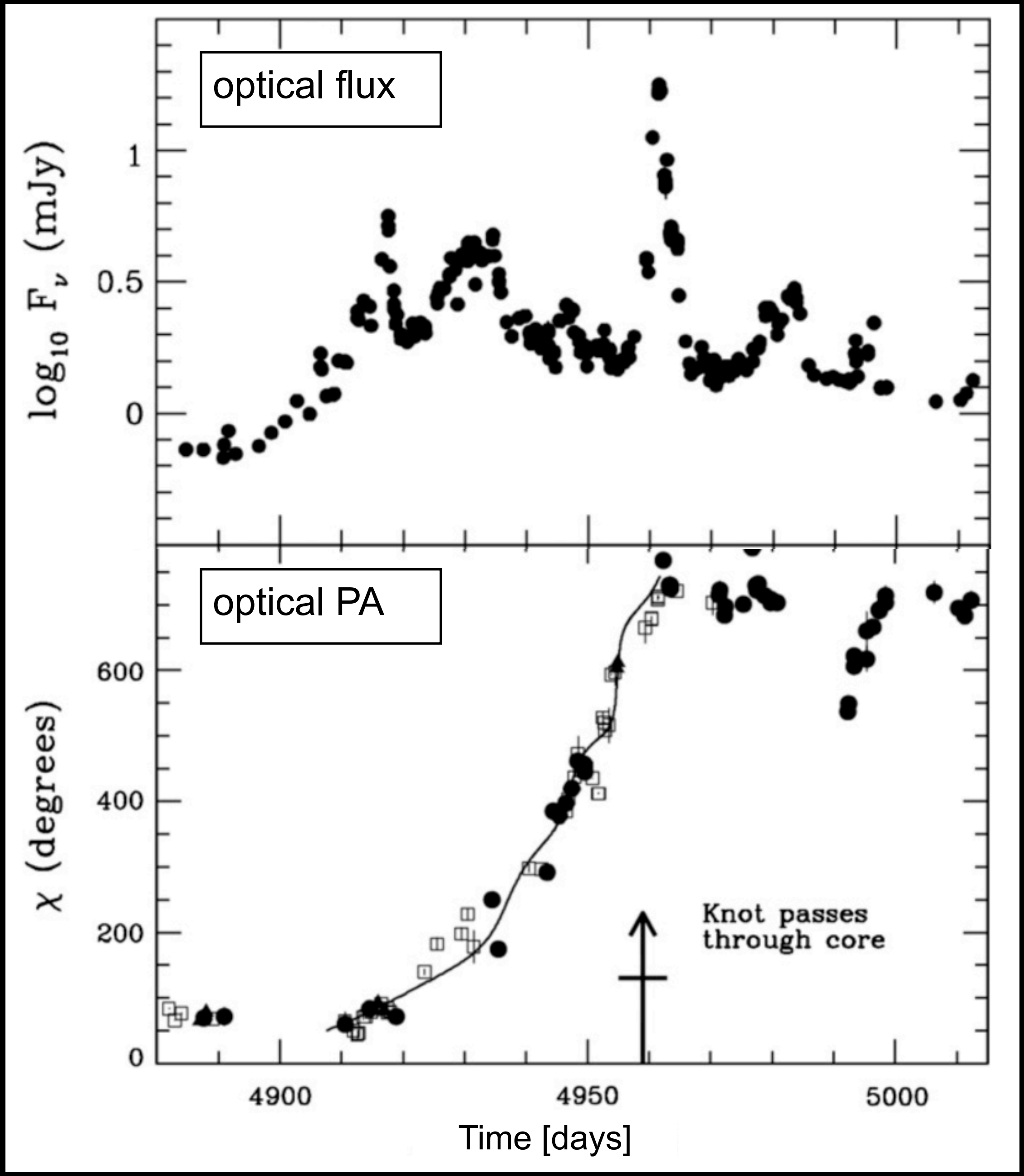




At $\gamma \lesssim 3\sigma$ injection in reconnection leads to σ-dependent slopes, as hard as *p=1*.

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

# Blazar emission

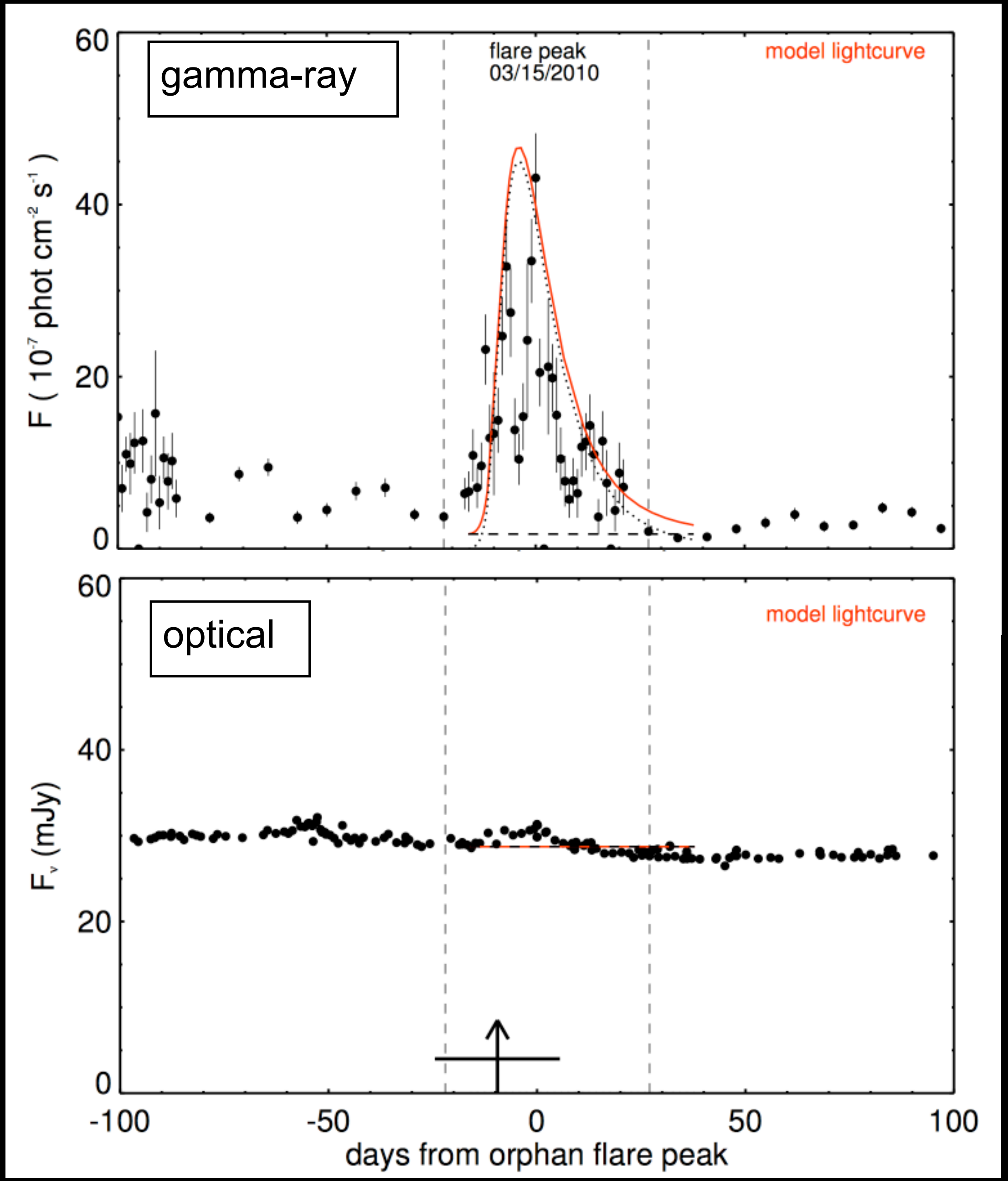
(B) optical polarization rotations




(Marscher+2010)

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

(C) "orphan" gamma-ray flares




(MacDonald+2017)

Gamma-ray flares with no optical counterpart.

## (C) “orphan” gamma-ray flares

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



Comisso & LS 2018, PRL, 121, 255101

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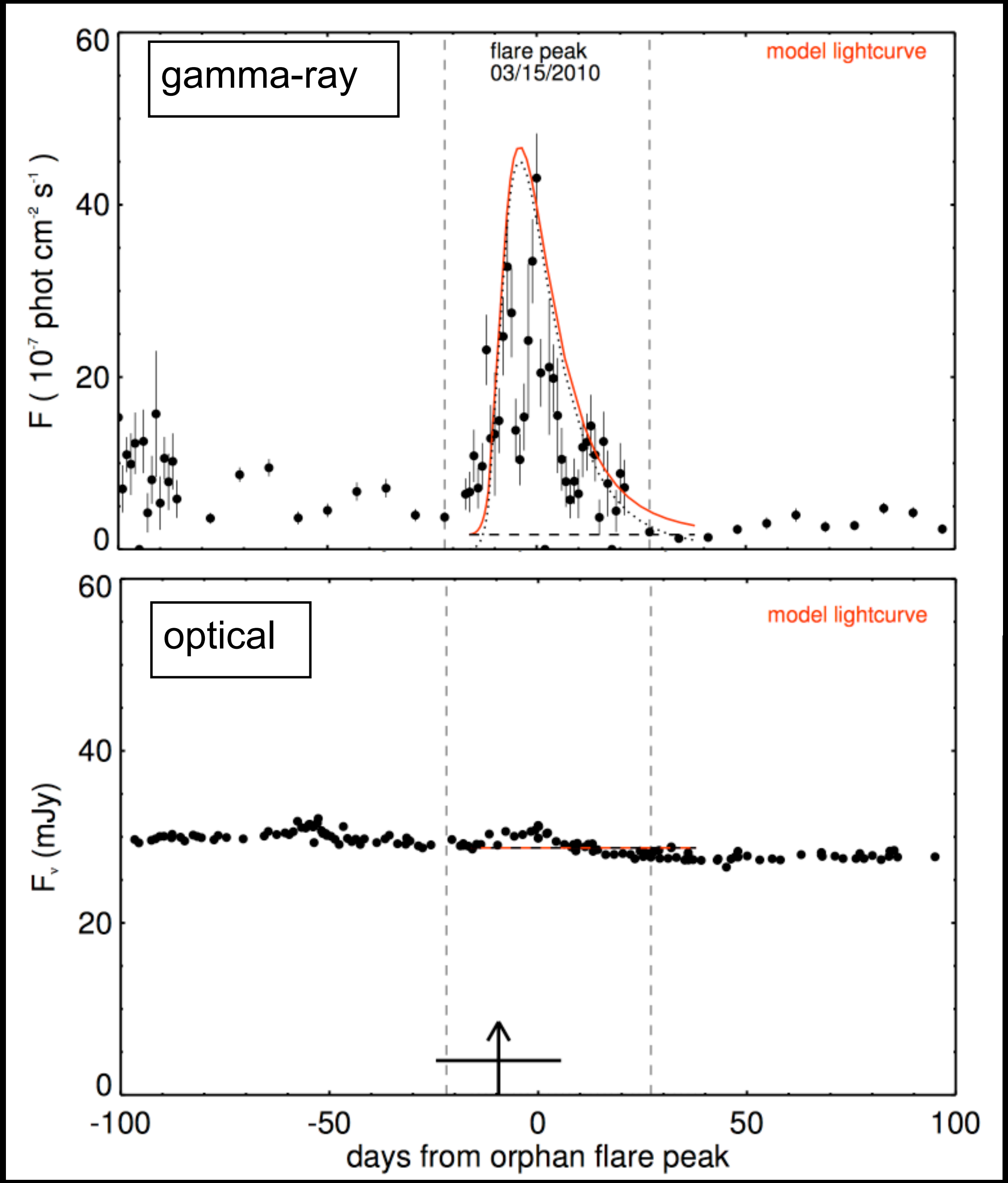
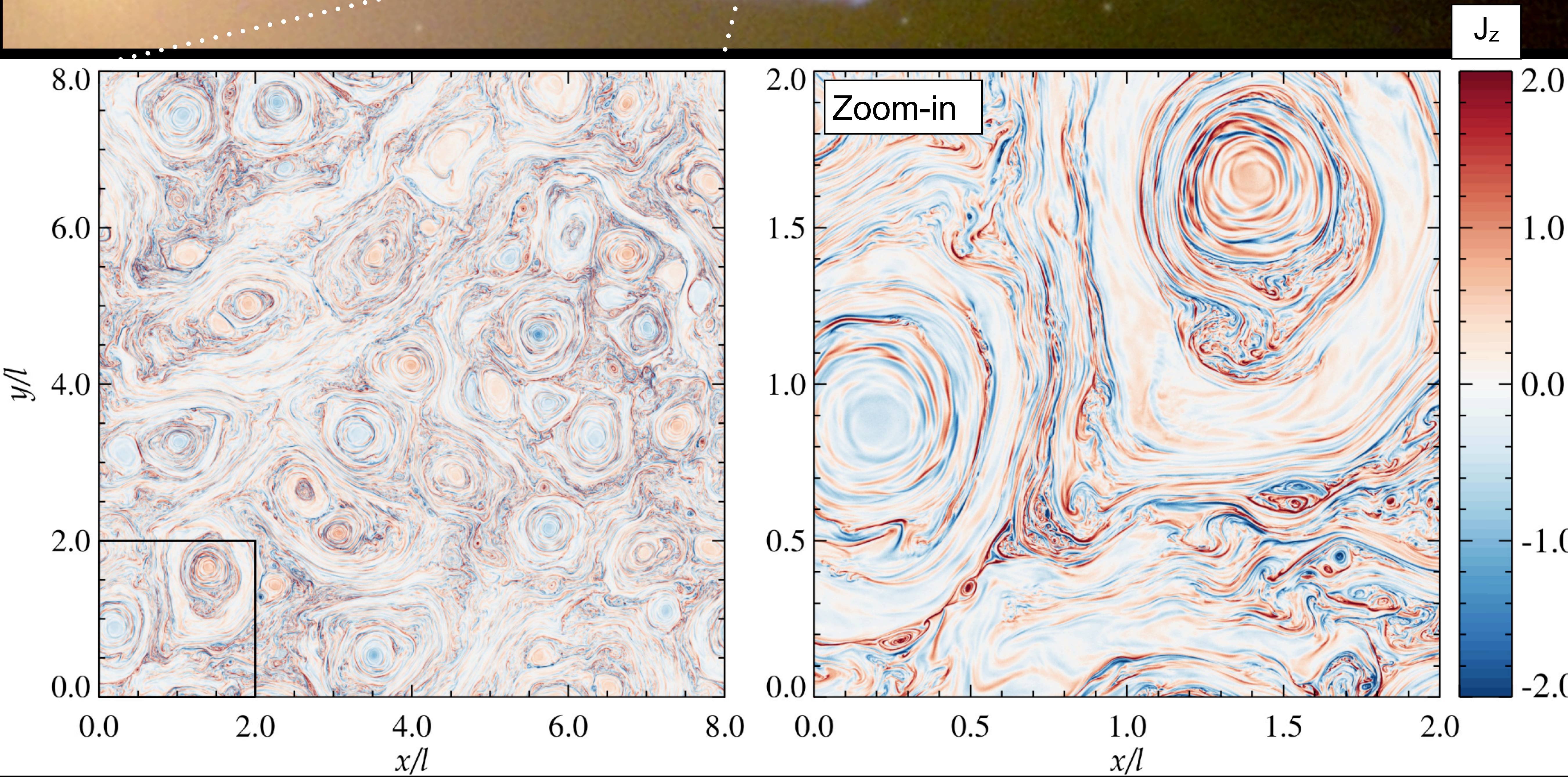



(MacDonald+2017)

Gamma-ray flares with no optical counterpart.

# Reconnection within turbulence

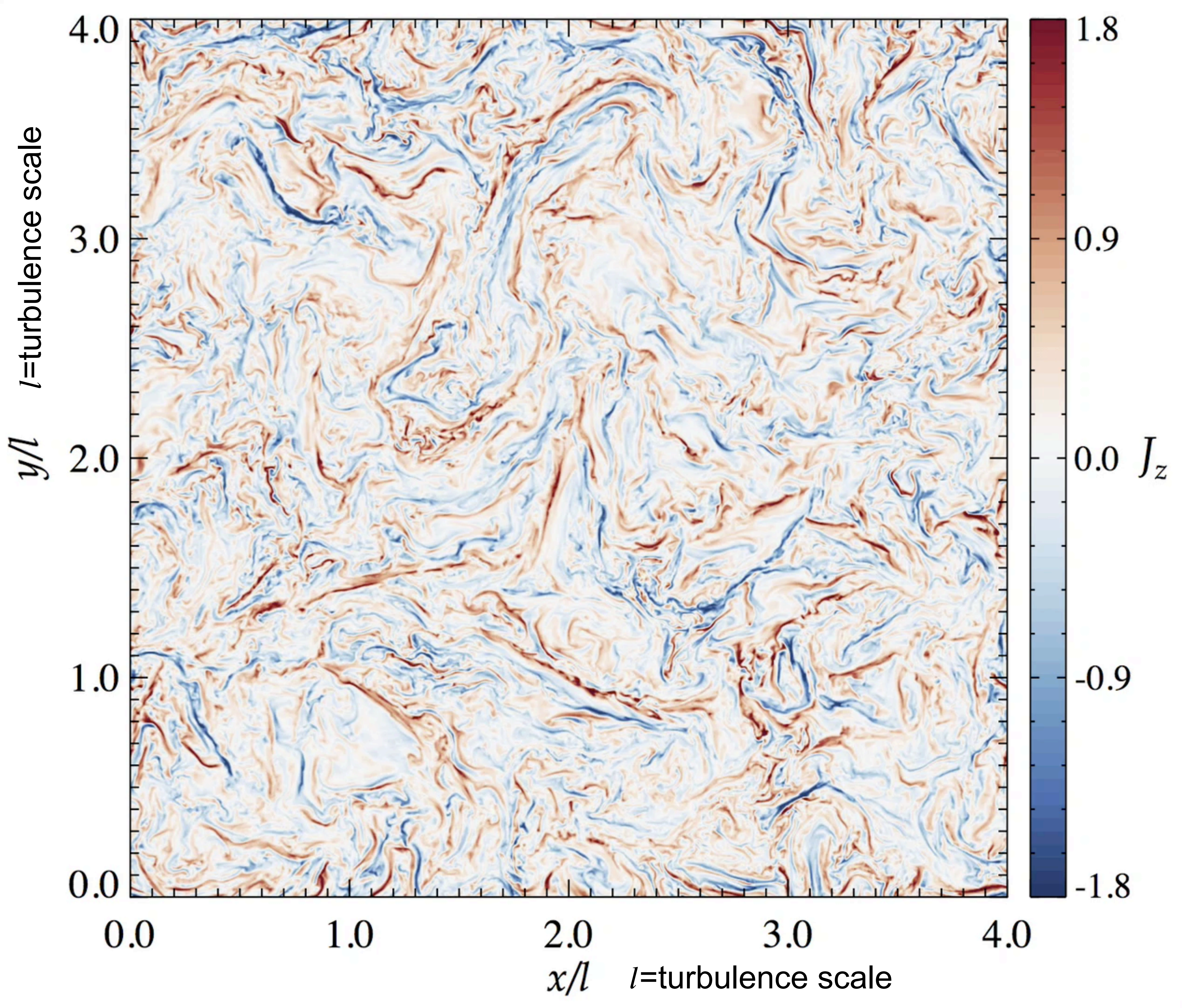
Reconnection is a natural by-product of magnetically-dominated turbulence




$l$=turbulence outer scale

(Comisso & LS 18,19)

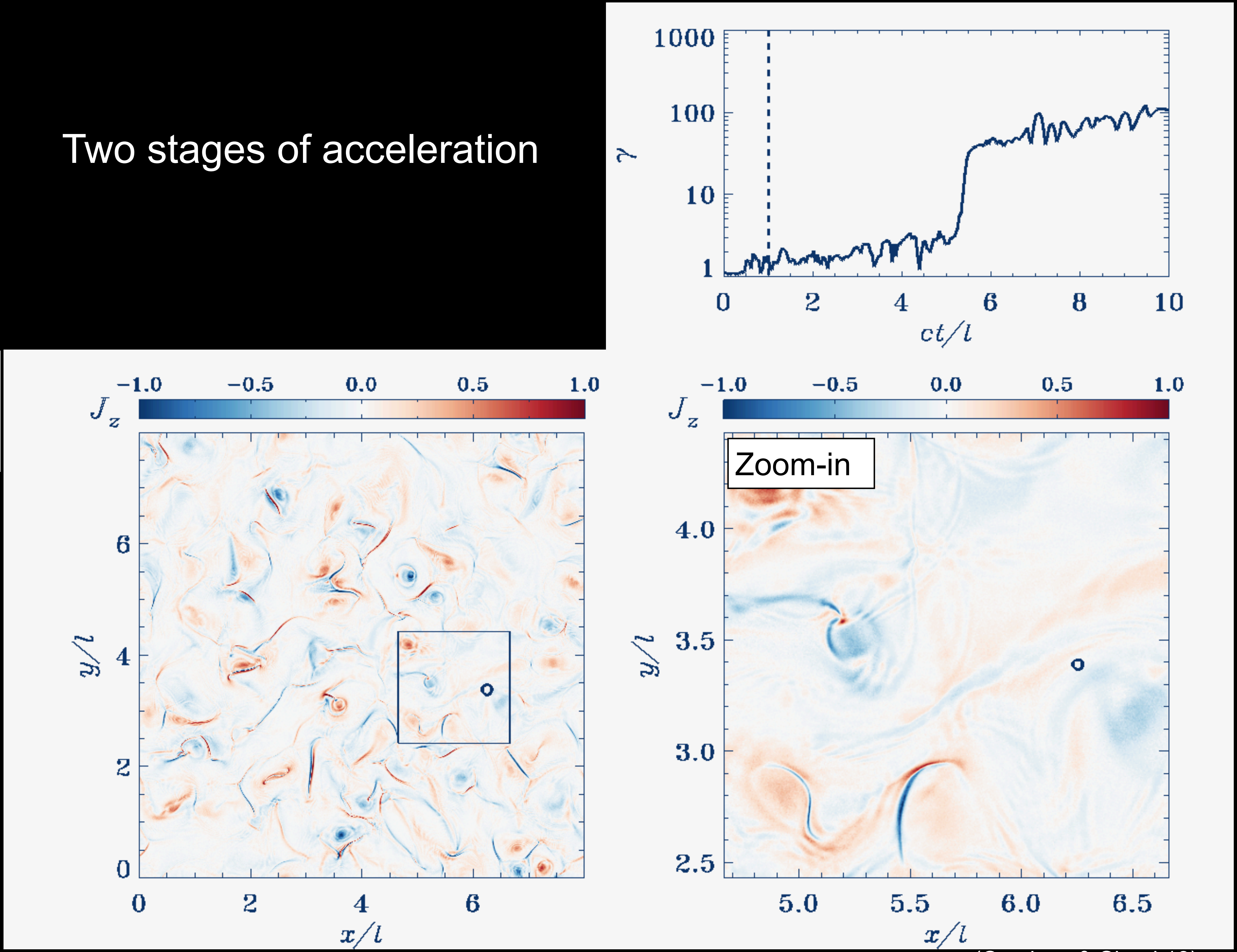
# Fly-through $J_z$ along z direction



# A representative high-energy particle

Two stages of acceleration

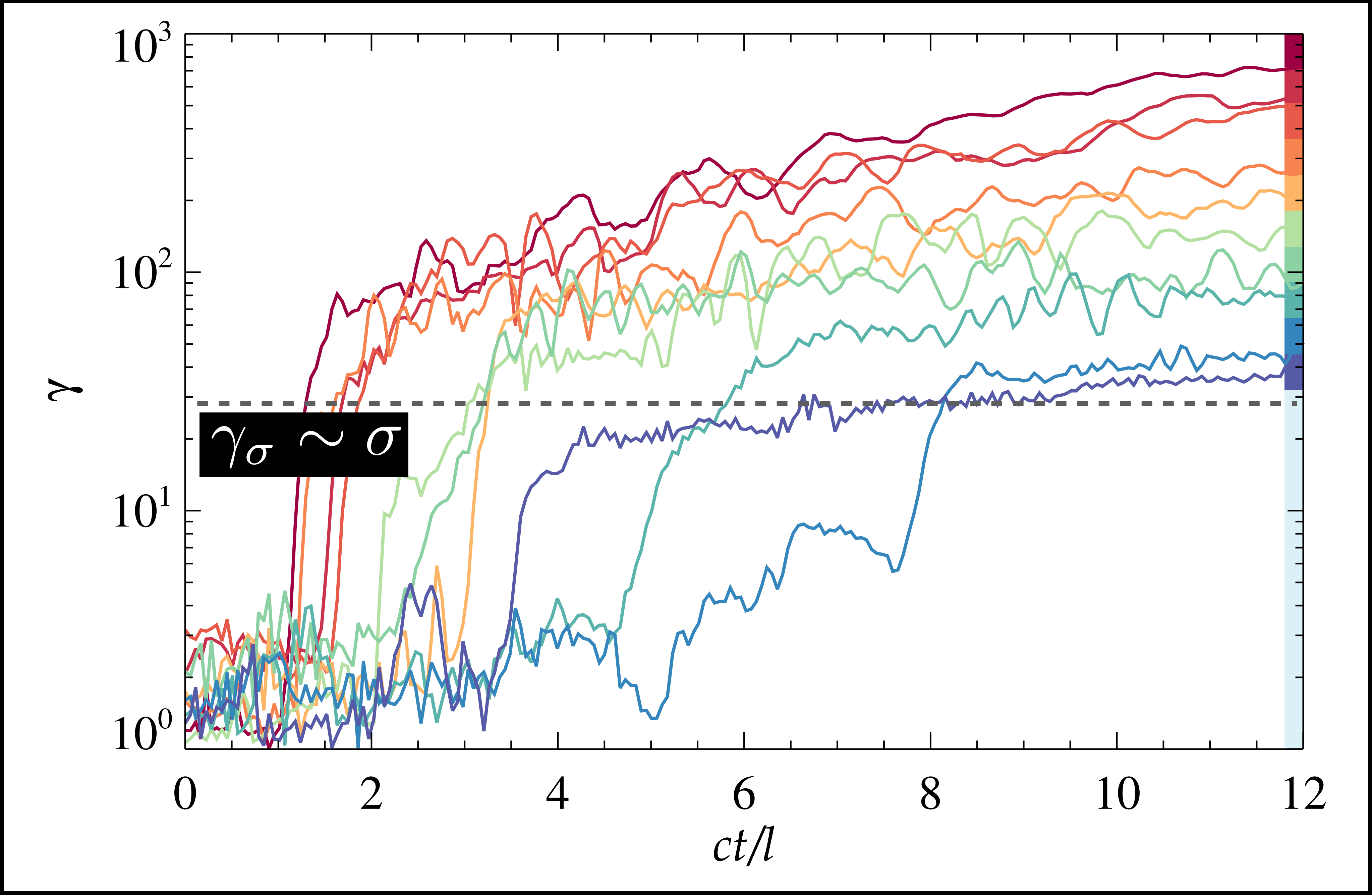
2D
no cooling




(Comisso & Sironi 18)

# Particle acceleration: a two-stage process

3D
no cooling

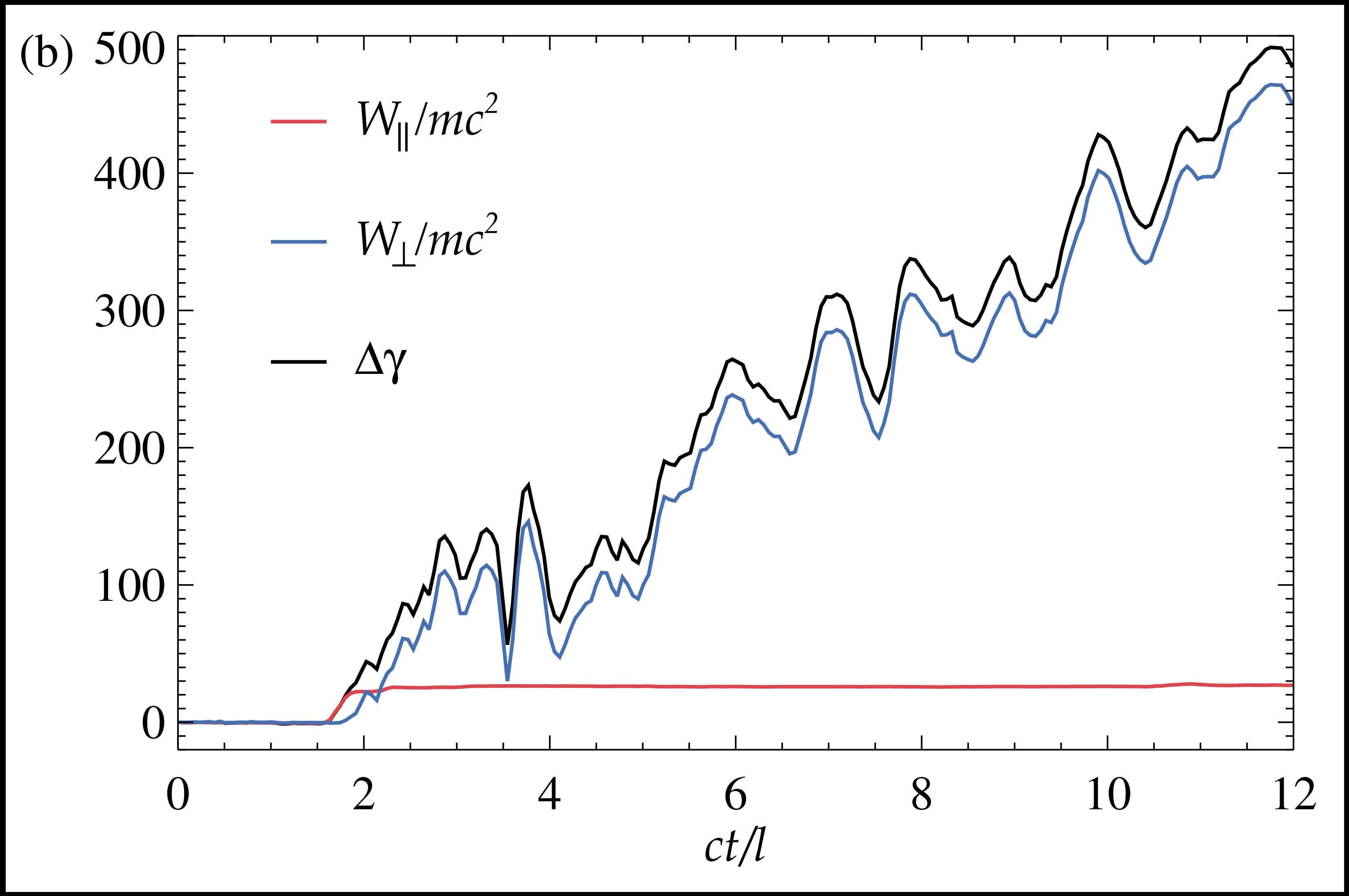



(Comisso & LS 19)

- 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.

# The two stages of acceleration

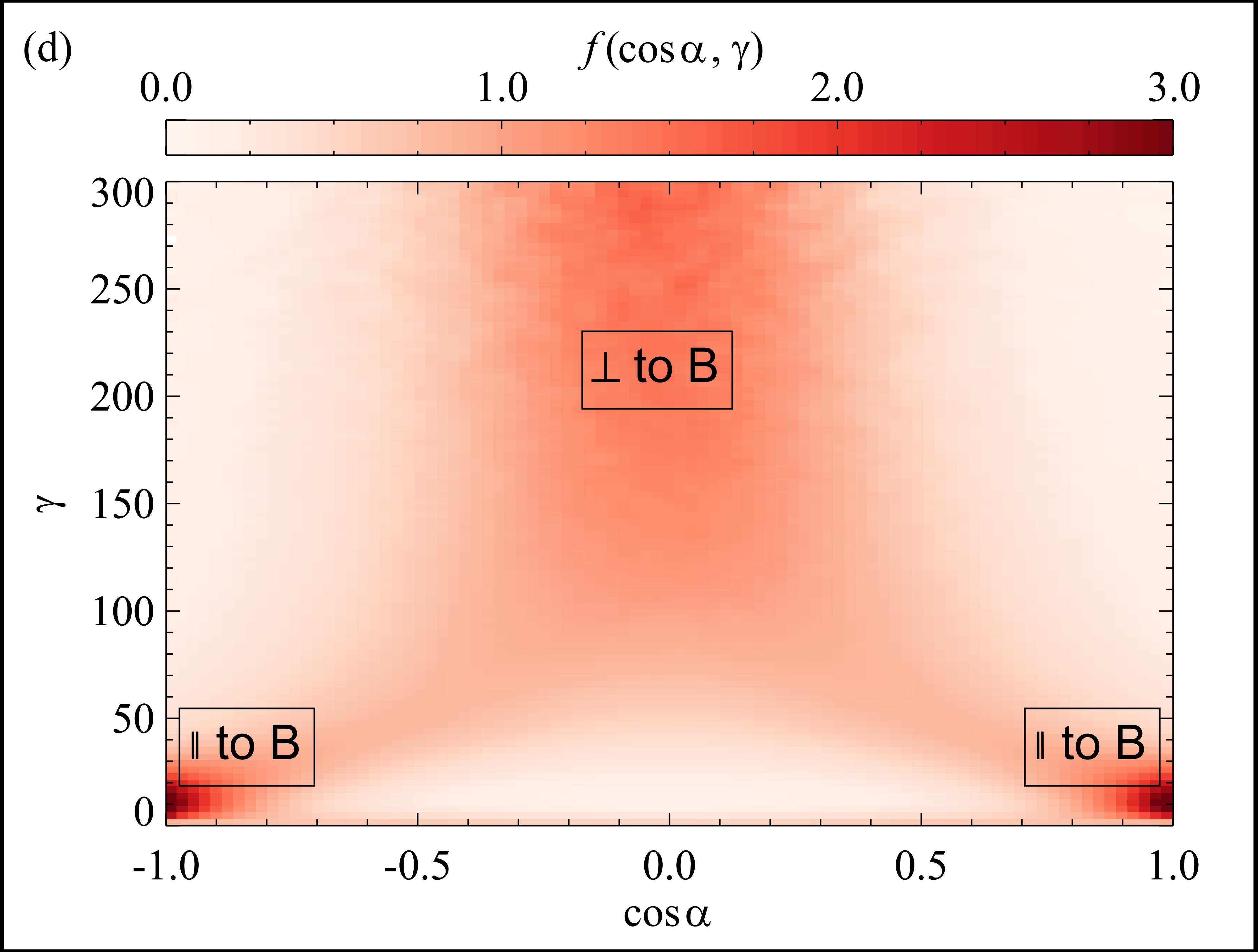
Work by parallel and perp E field: $W_{\parallel,\perp}(t) = q\int_0^t \boldsymbol{E}_{\parallel,\perp}(t')\cdot\boldsymbol{v}(t')\,dt'$




(Comisso & LS 19; Wong+19)

- Injection by $\boldsymbol{E}_{\parallel}$ in reconnection layers.
- Then, acceleration by $\boldsymbol{E}_{\perp}$ via scattering off turbulent fluctuations.

# Particle anisotropy




$$\cos\alpha = \frac{\boldsymbol{v} \cdot \boldsymbol{B}}{|\boldsymbol{v}|\,|\boldsymbol{B}|}$$

(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.

# IC cooling in blazar jets

We parameterize IC cooling losses via a critical Lorentz factor $\gamma_{cr}$ (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. $\gamma_{\rm cool} \sim 0.01 - 0.1\gamma_\sigma$

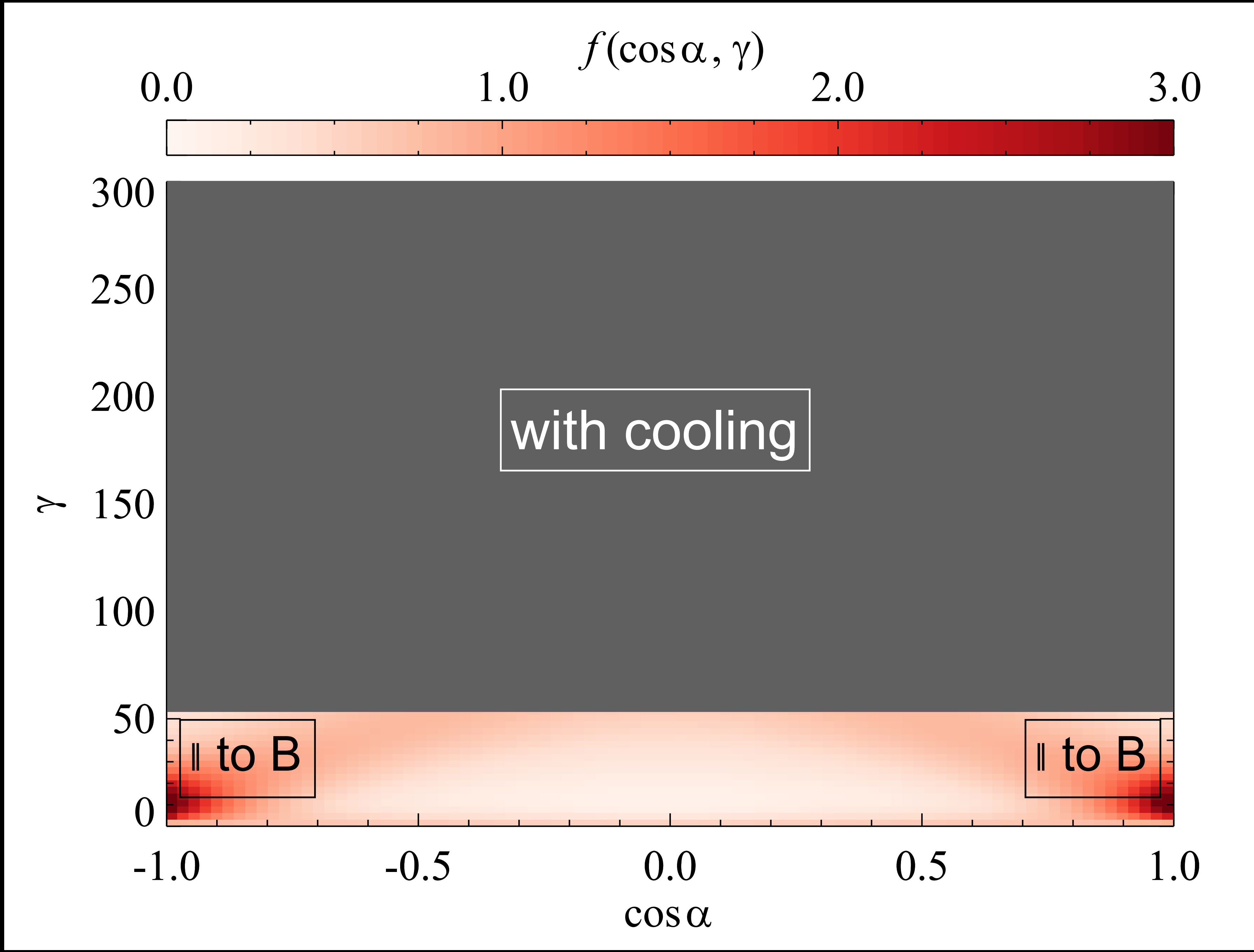
**In our simulations**

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 $\gamma_\sigma$ is unaffected by cooling since $t_{inj} \ll t_{cool}$

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

# Particle anisotropy

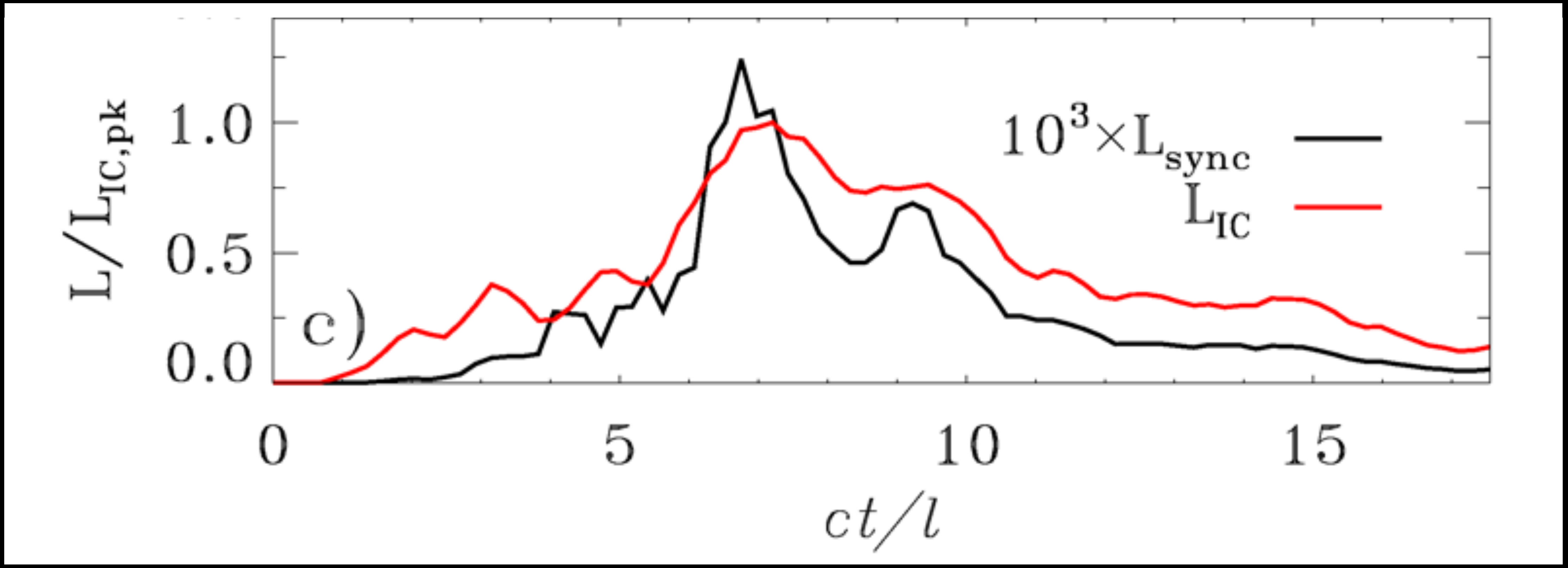



(Comisso & LS 19)

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

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

# Overarching summary

Relativistic reconnection can:

- efficiently dissipate magnetic energy (at rate ~ 0.1 c).
- produce non-thermal particles with hard power-law slopes.
- serve as injection process for subsequent (non-reconnection) acceleration:

e.g., Fermi acceleration at shocks, stochastic acceleration in turbulence, shear acceleration at jet boundaries.

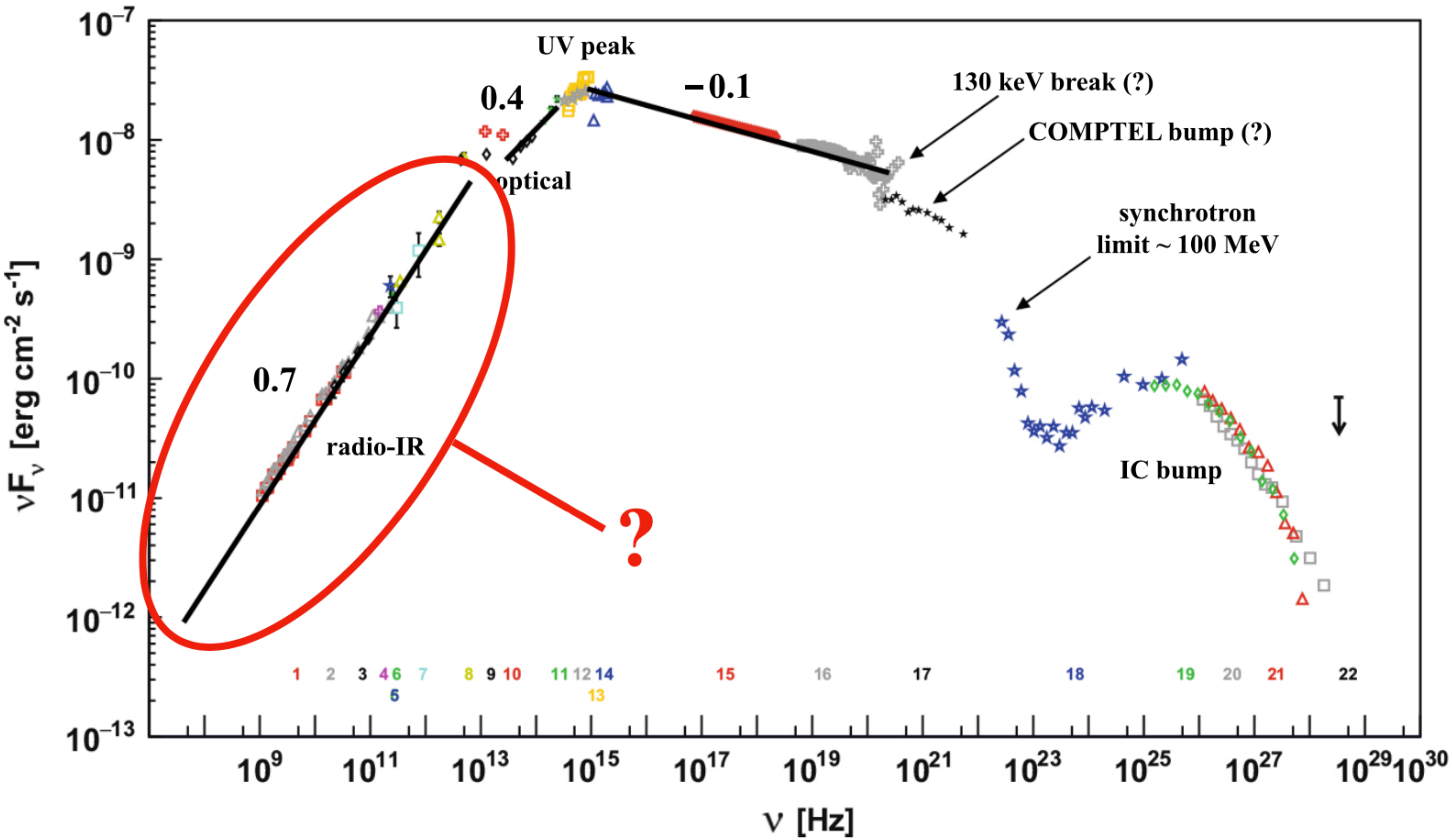
- imprint strong pitch-angle anisotropy.
- produce trans-relativistic bulk motions.

- A system with high-sigma reconnection has field B and size L. What is the max energy of a synchrotron photon in this system? Account for the effect of the particle anisotropy.

- A striped pulsar wind has magnetic field B and wavelength $\lambda$. What is the minimum energy that shock-driven reconnection should provide, so that particles can be injected into Fermi acceleration?

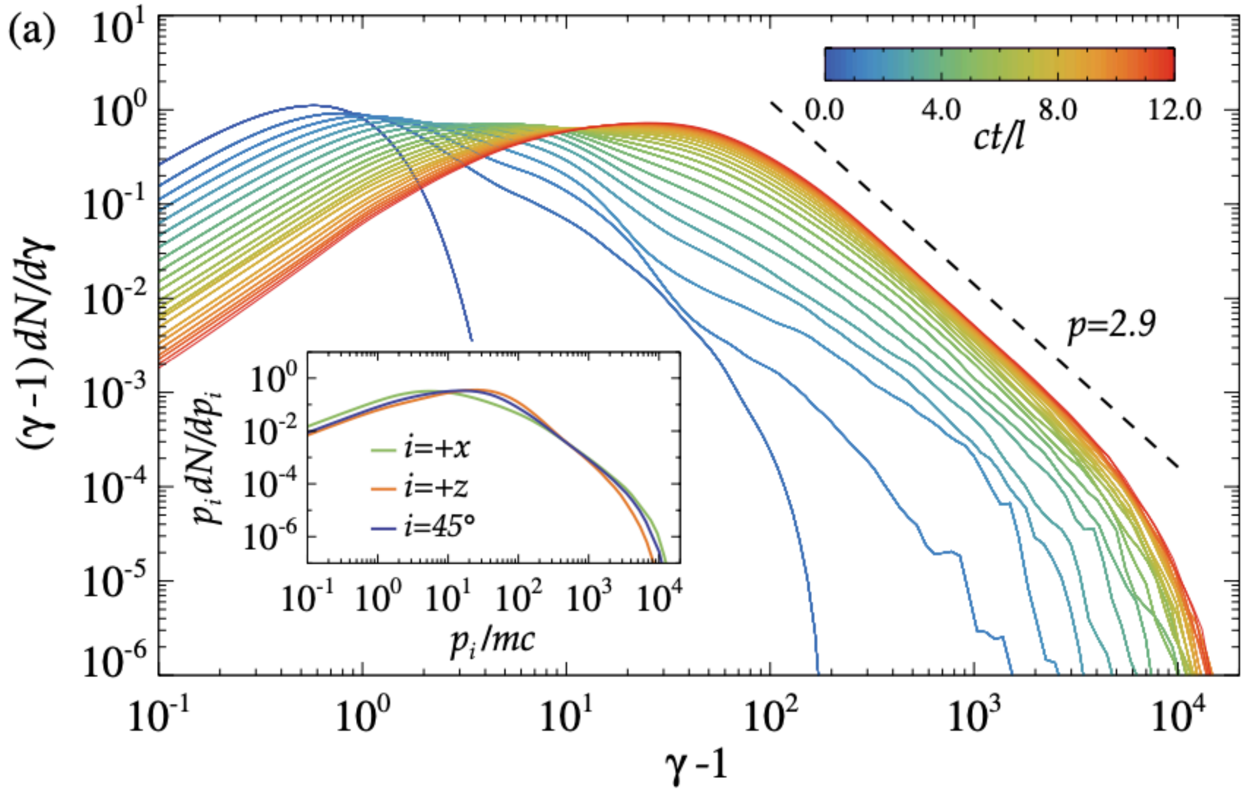
- Propose an alternative explanation for orphan flares in blazars.

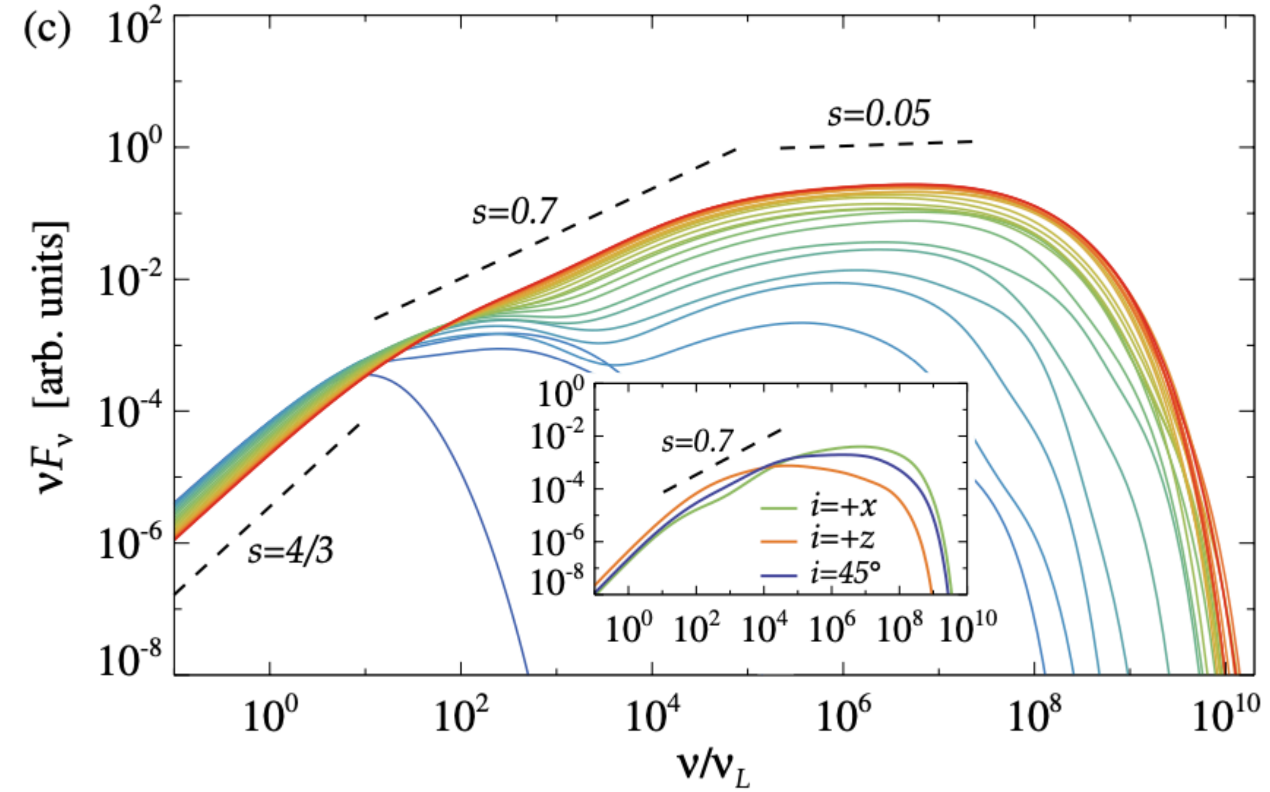
# The Crab Nebula radio spectrum




Zanin 2017, Lyutikov *et al.* 2019

# The role of pitch angle anisotropy




- Low frequencies: $\nu F_\nu \propto \nu^{4/3}$

- High frequencies: $\nu F_\nu \propto \nu^{(3-p)/2}$

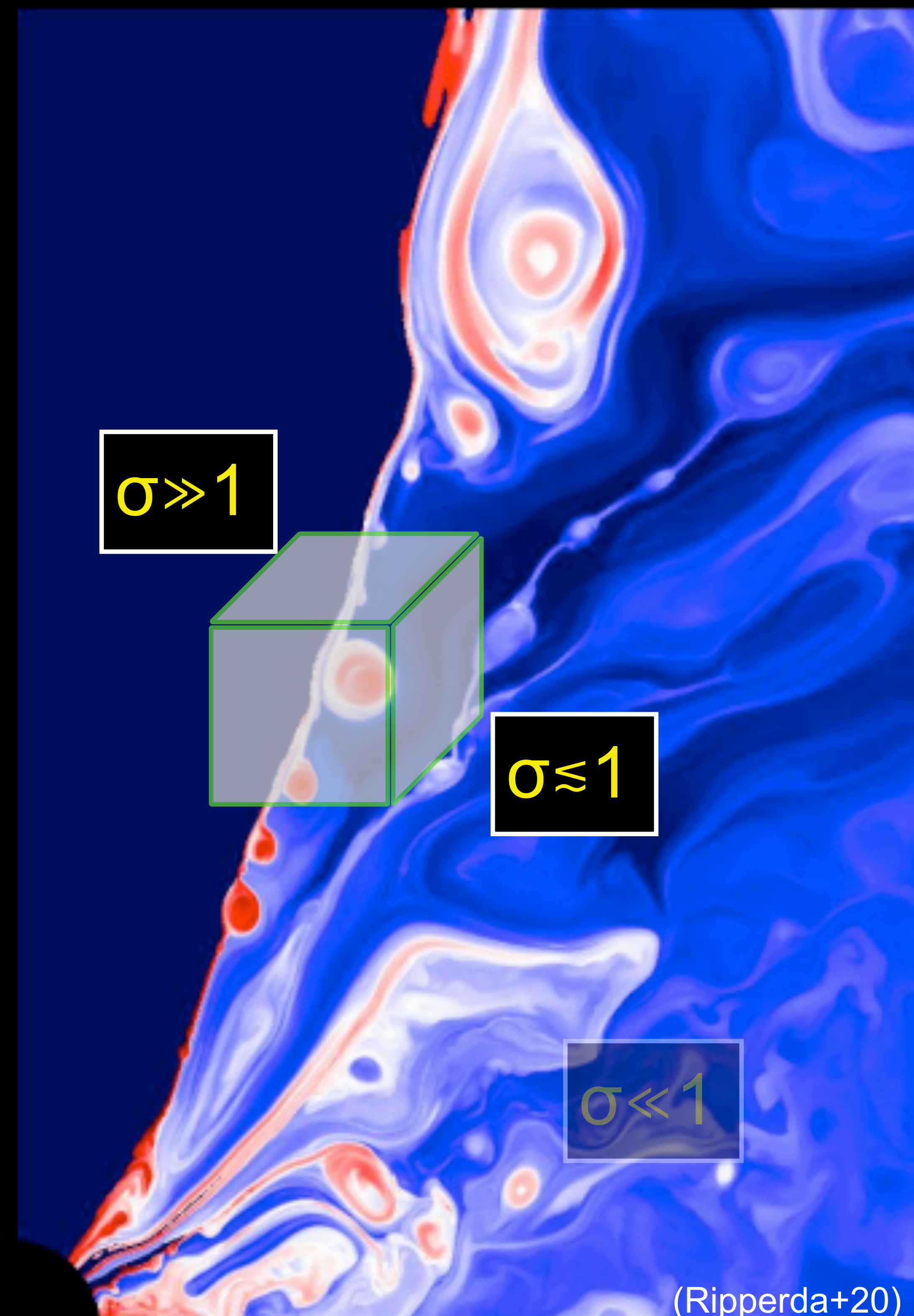
Comisso, Sobacchi, Sironi 2020

# 2. KH-driven relativistic reconnection at jet boundaries

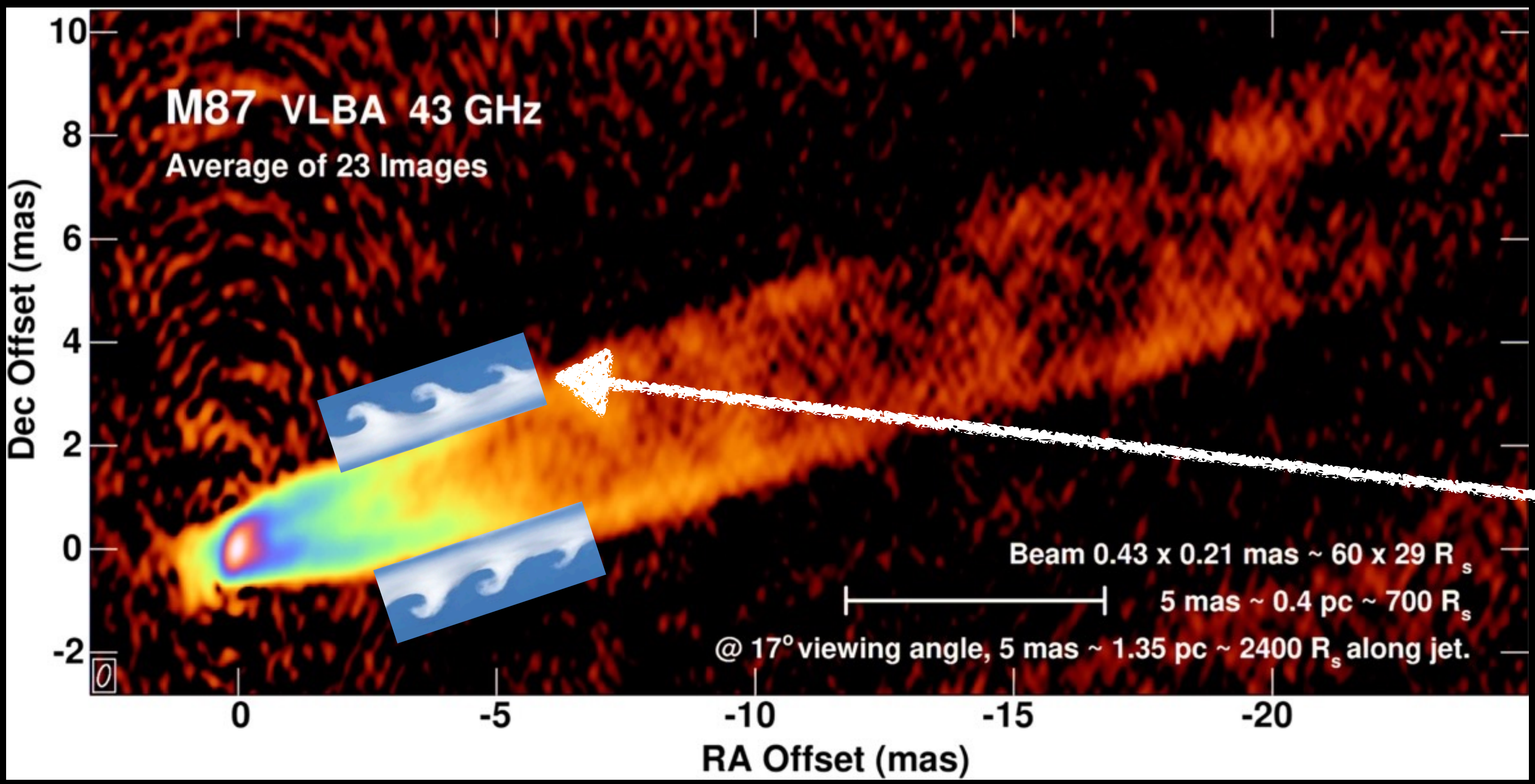
**Reconnection** ⟷ **Fluid instab.**

with M. Rowan and R. Narayan

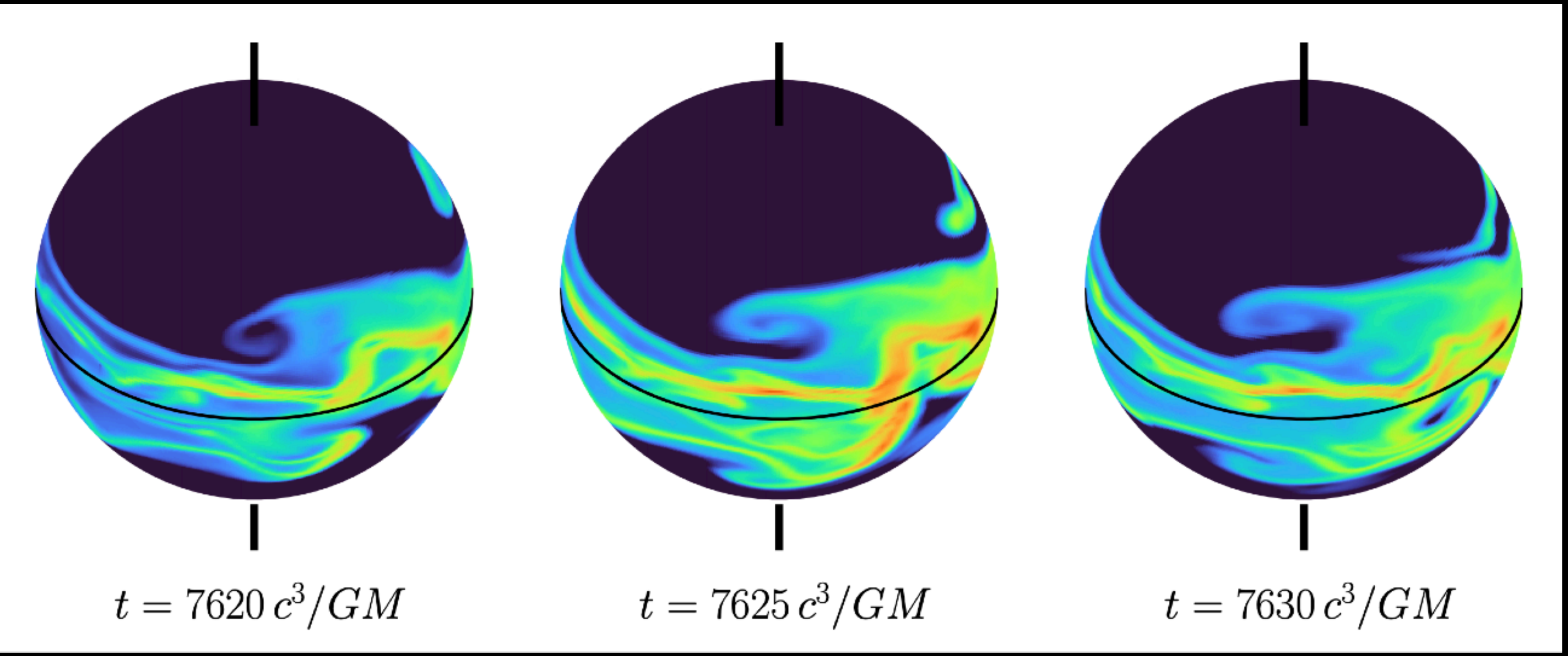
LS et al. 2021, ApJL, 907, L44



# The boundary of M87 jet




Kelvin-Helmholtz (KH) instability at the jet boundary

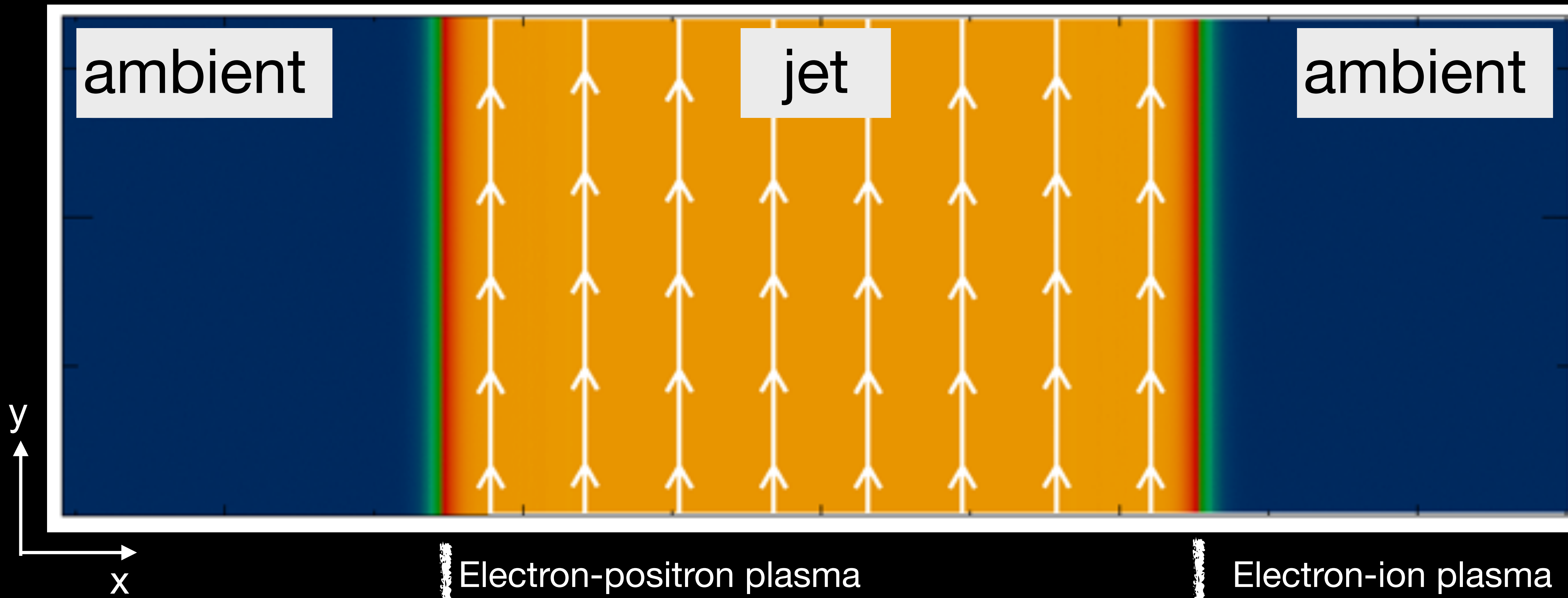



(Wong+21; see also Chatterjee+19)

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

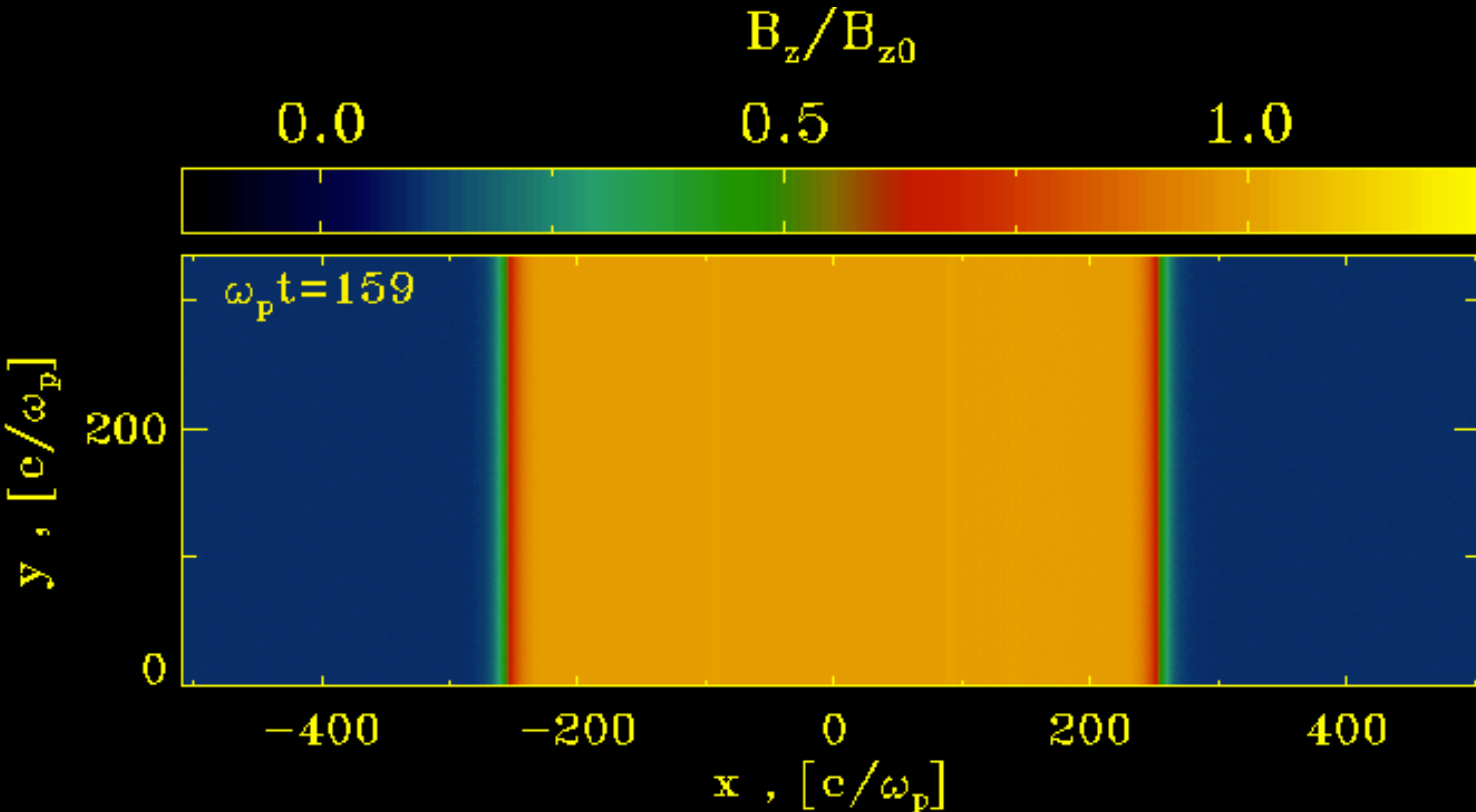
# The jet / ambient system

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) $\sigma_{\mathrm{j},y} = B_{\mathrm{j},y}^2/(4\pi n_0 m_{\mathrm{e}} c^2) = 6.7$ | Plasma-pressure dominated, weak $B_z$ |
| Field obliquity $\theta = 75^\circ$ | |

# Kelvin-Helmholtz (KH) instability

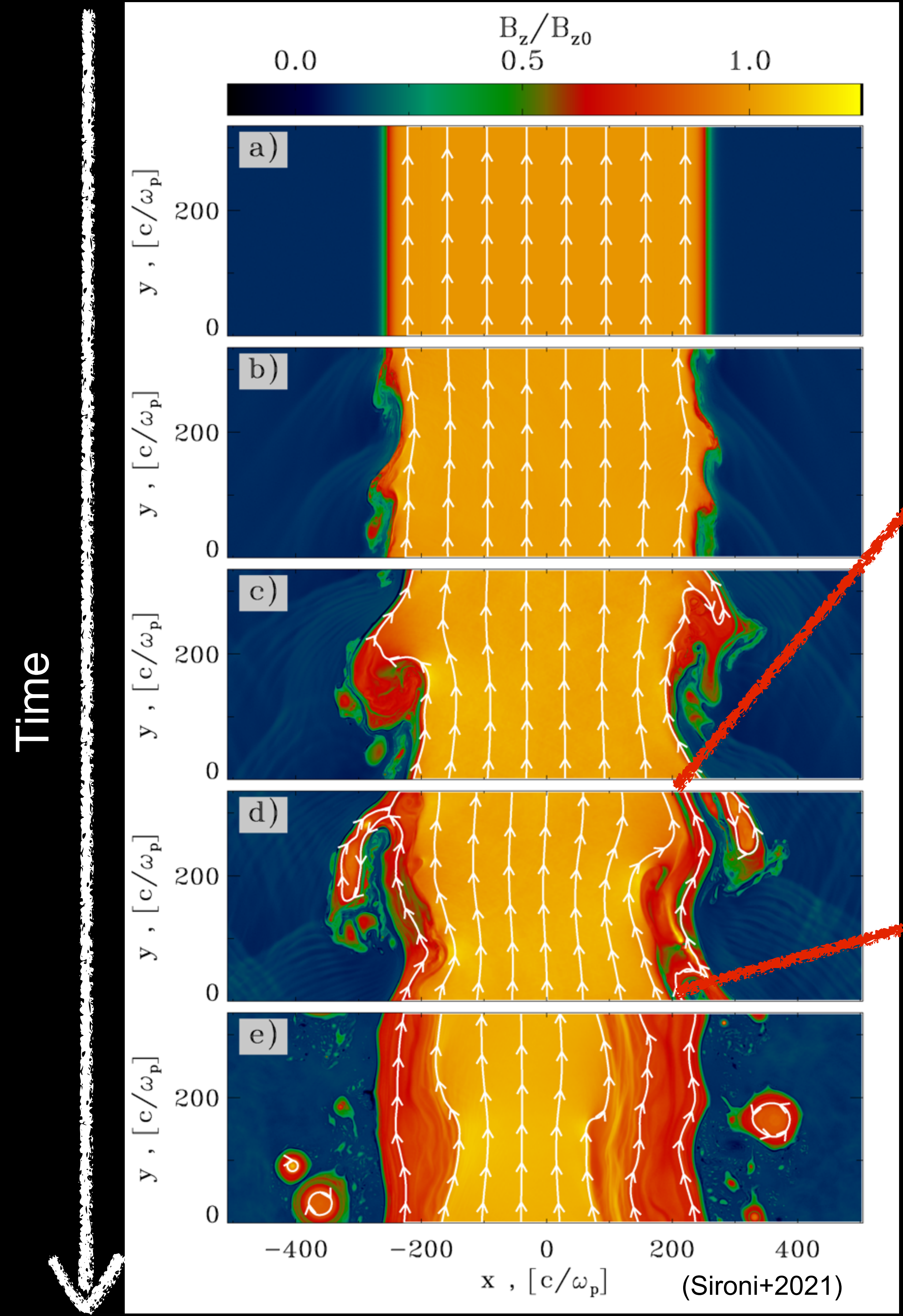


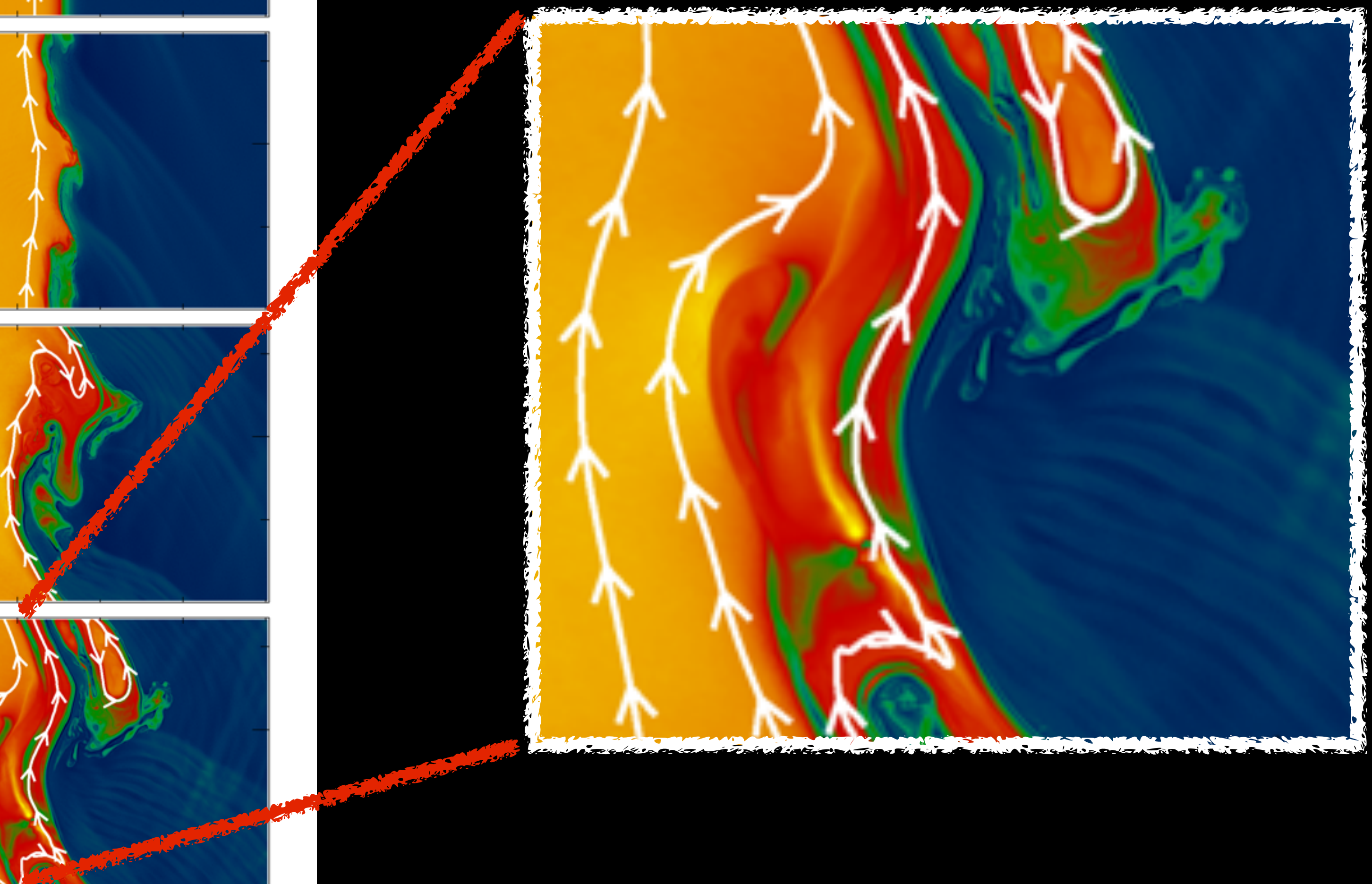

(Sironi+21)

- For realistic jet and ambient plasma conditions, the interface is KH unstable.

- The KH growth rate matches well with MHD expectations
  [which confirms that we start from ~ MHD-scale initial conditions]

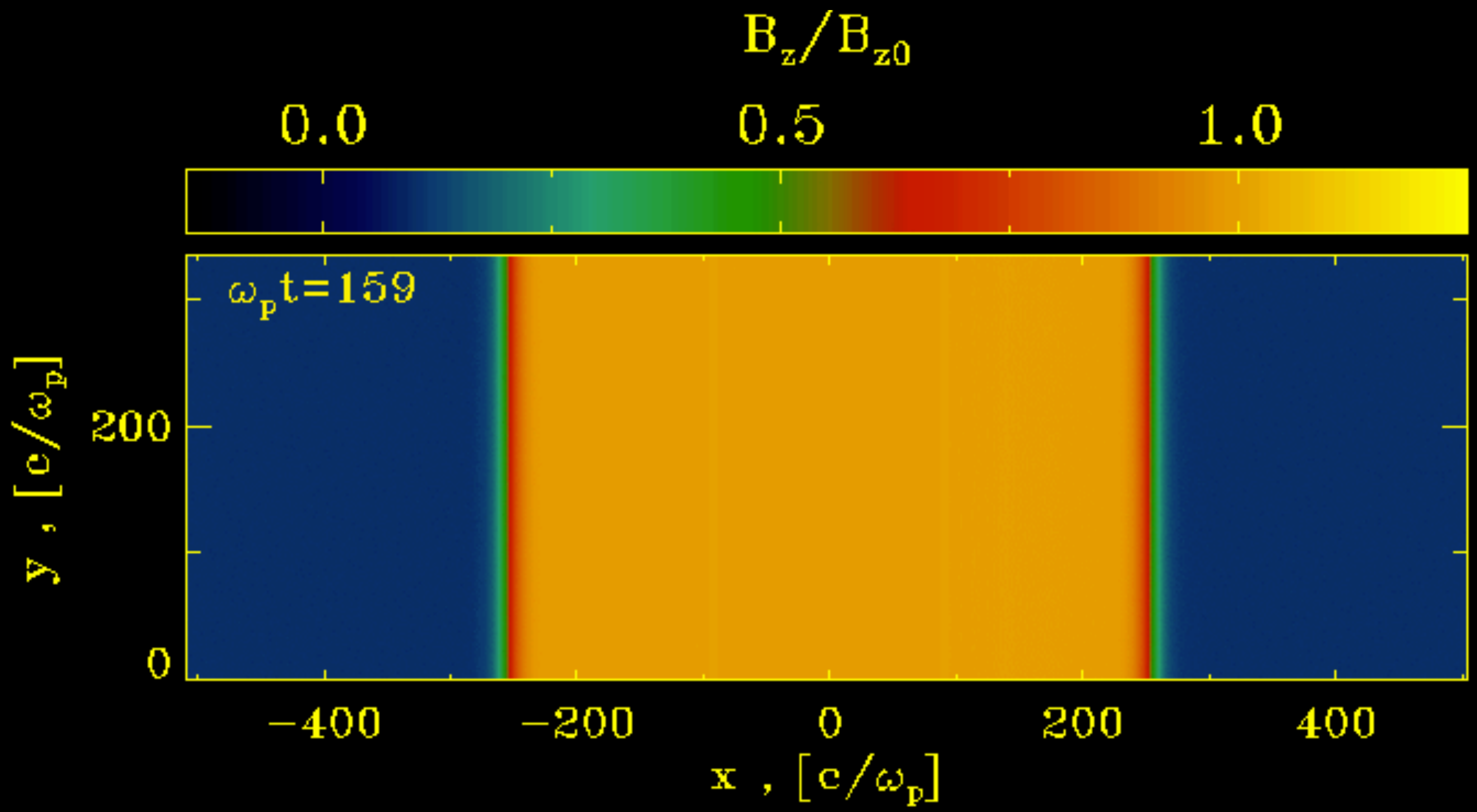
# KH → reconnection



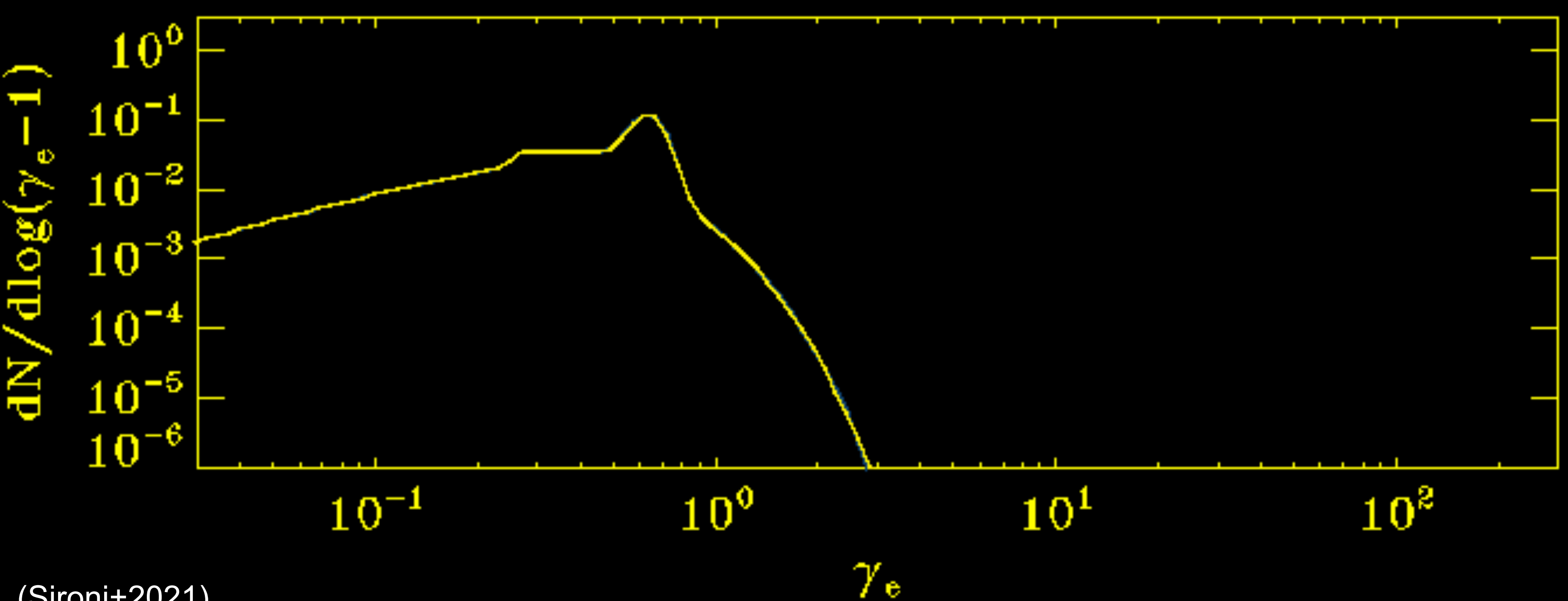



Magnetic reconnection is a natural by-product of the nonlinear KH evolution.

# KH → reconnection → particle acceleration



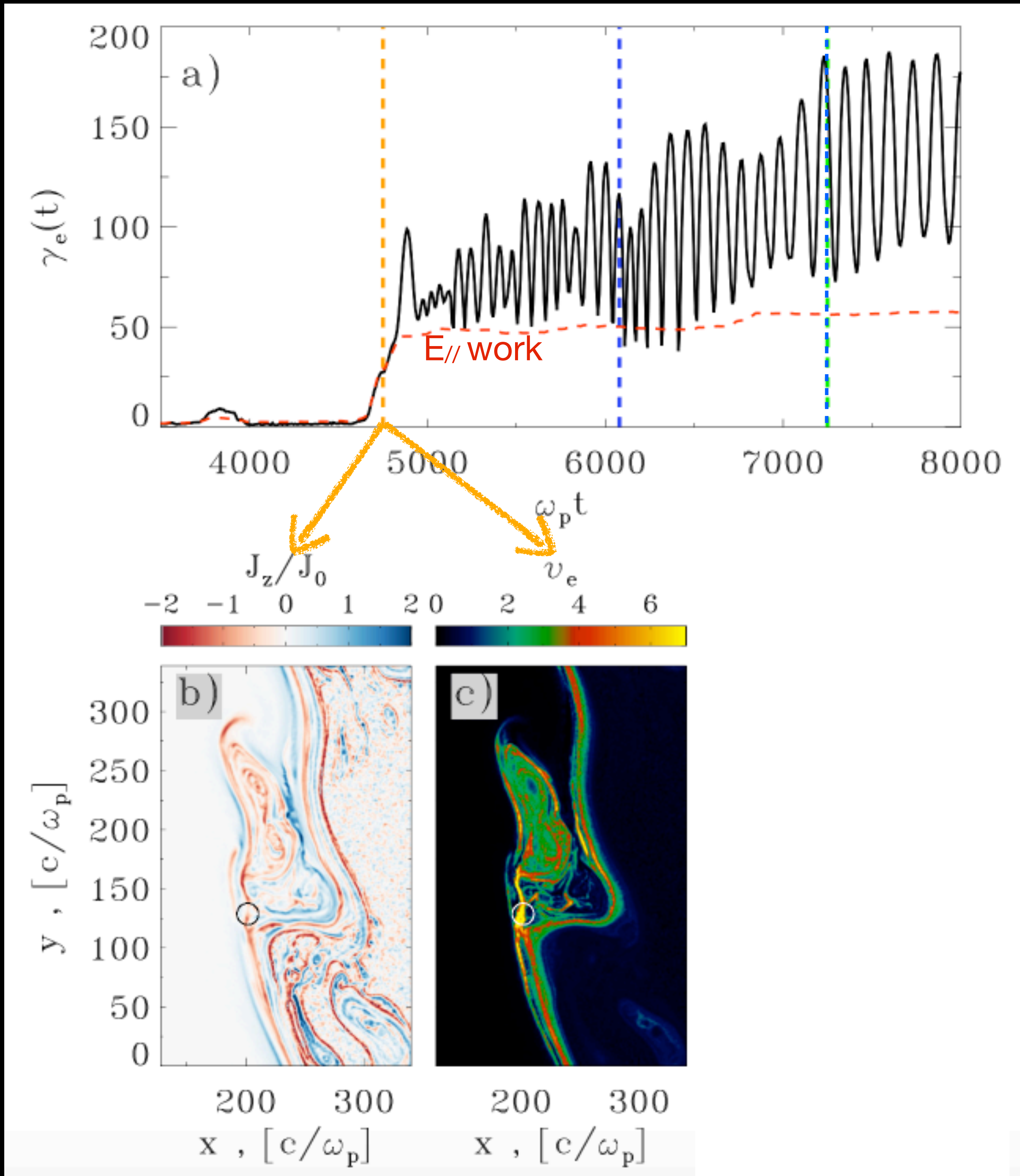

KH-driven reconnection leads to efficient acceleration of jet particles.




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

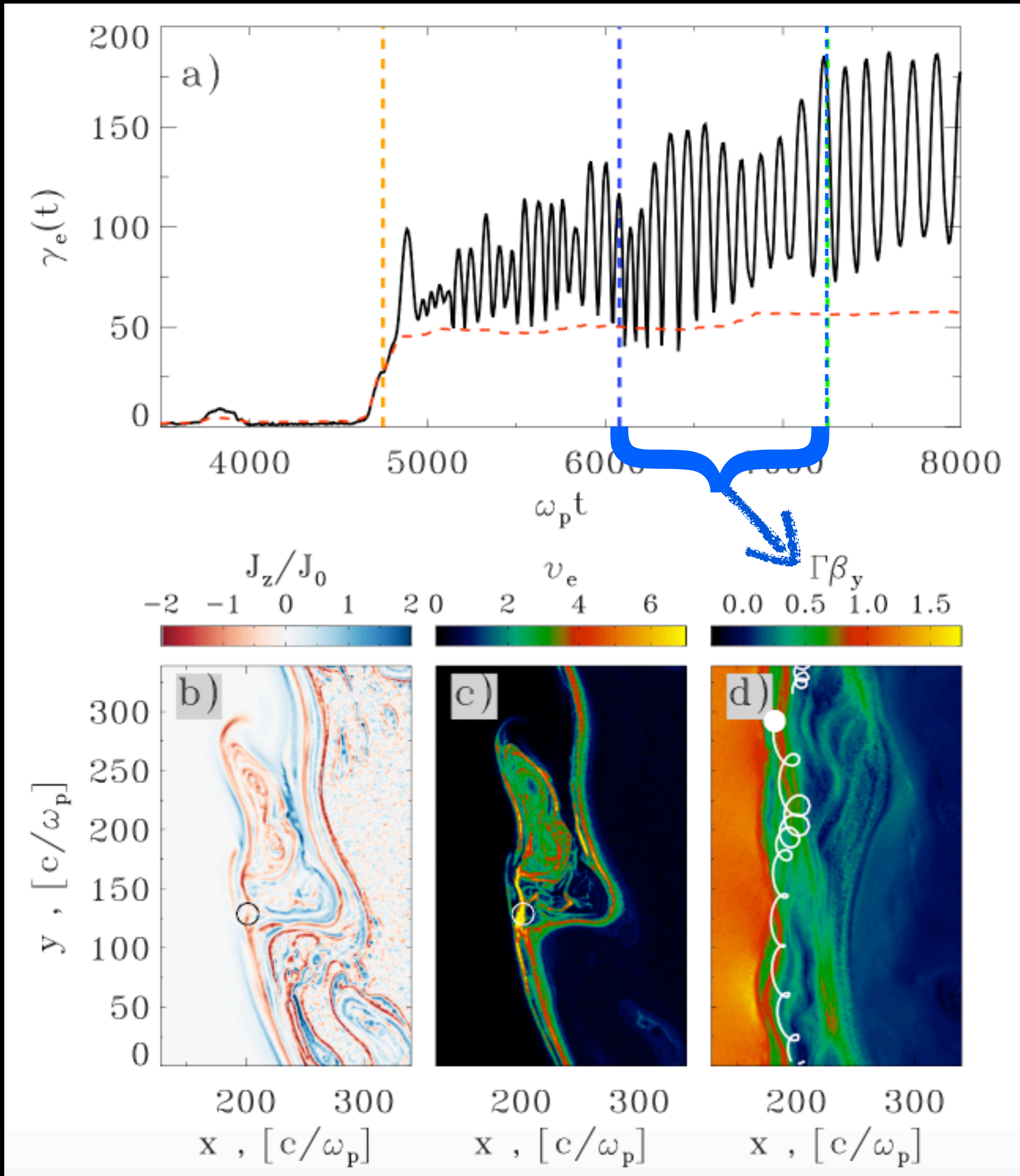
(Sironi+2021)

# The acceleration mechanism



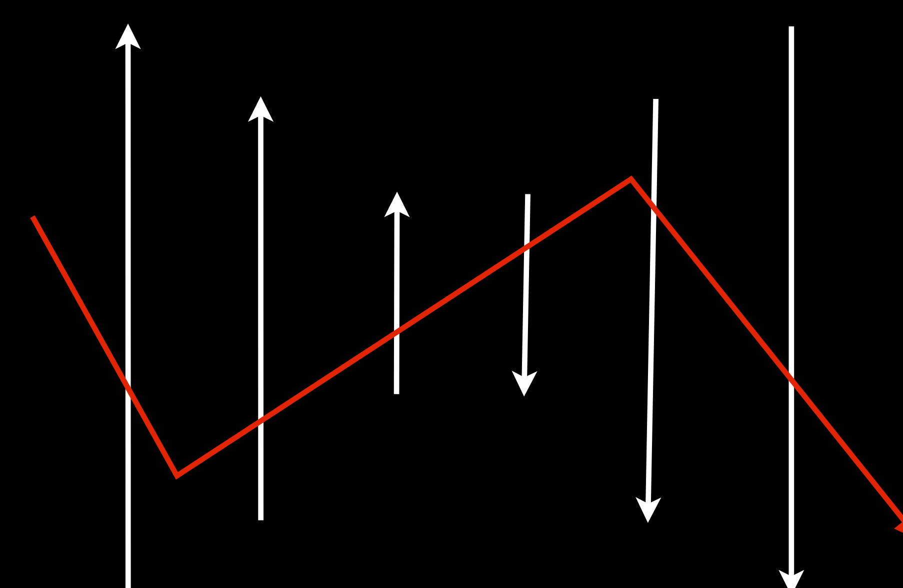

(1) The early acceleration stages (injection) are powered by $E_{//}$ at reconnection layers.

# The acceleration mechanism




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

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



# Overarching summary

<u>Relativistic reconnection can:</u>

- efficiently dissipate magnetic energy (at rate ~ 0.1 c).
- produce non-thermal particles with hard power-law slopes.
- serve as injection process for subsequent (non-reconnection) acceleration:

e.g., Fermi acceleration at shocks, stochastic acceleration in turbulence, shear acceleration at jet boundaries.

- imprint strong pitch-angle anisotropy.
- produce trans-relativistic bulk motions.

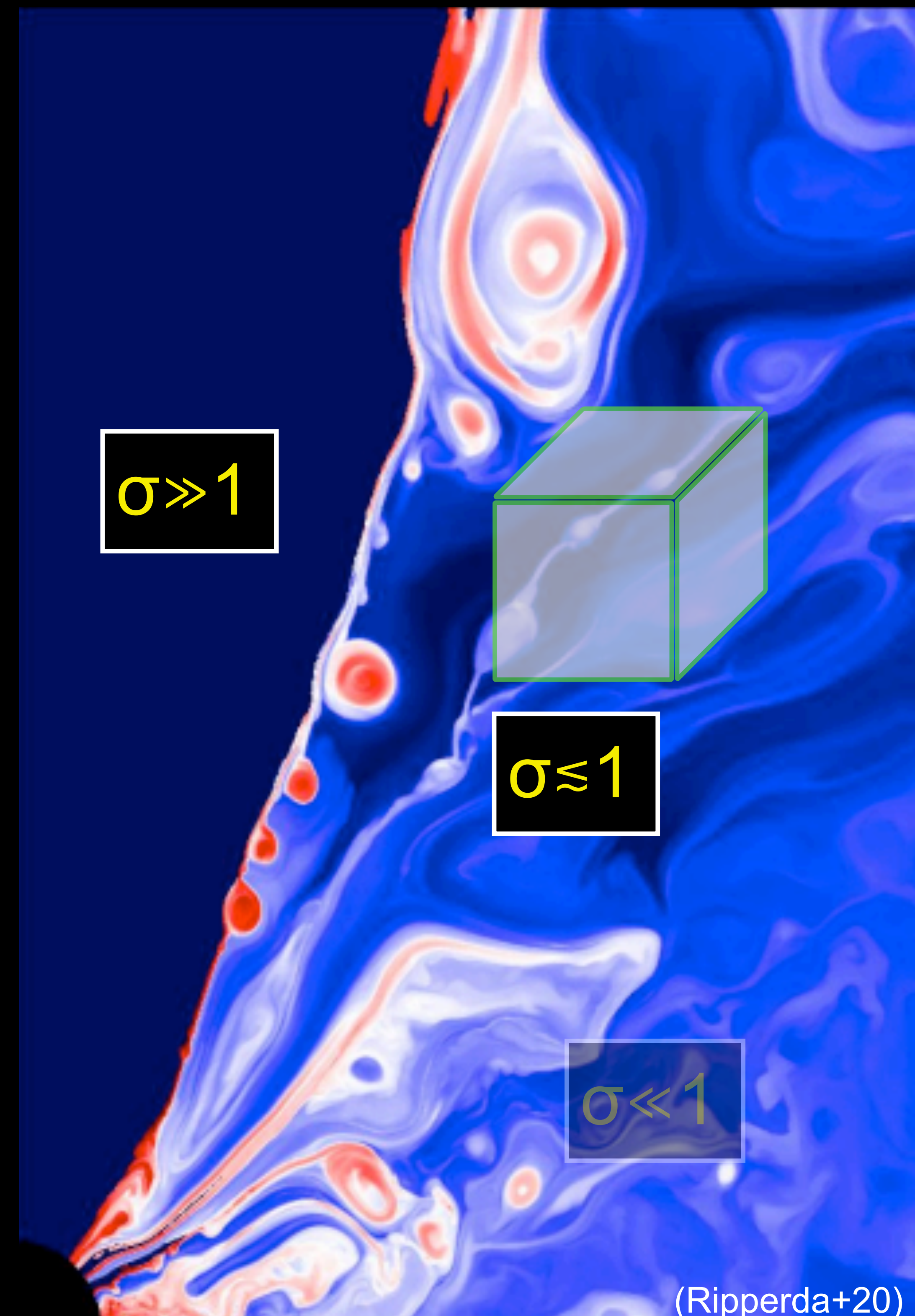
# 3. Radiative relativistic reconnection in black hole X-ray coronae

with N. Sridhar and A. Beloborodov

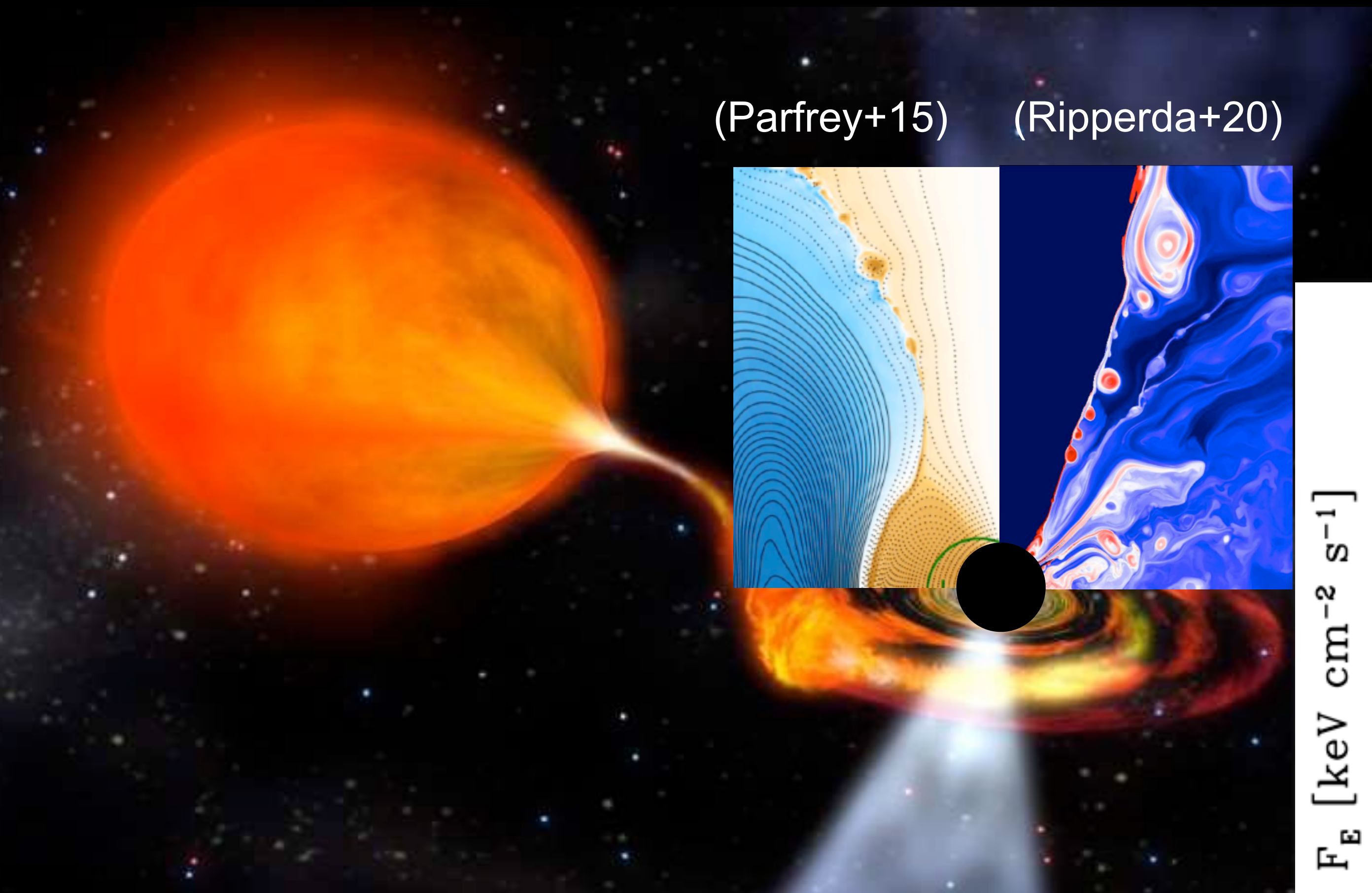
Sridhar, LS et al. 2022, arXiv:2203.02856

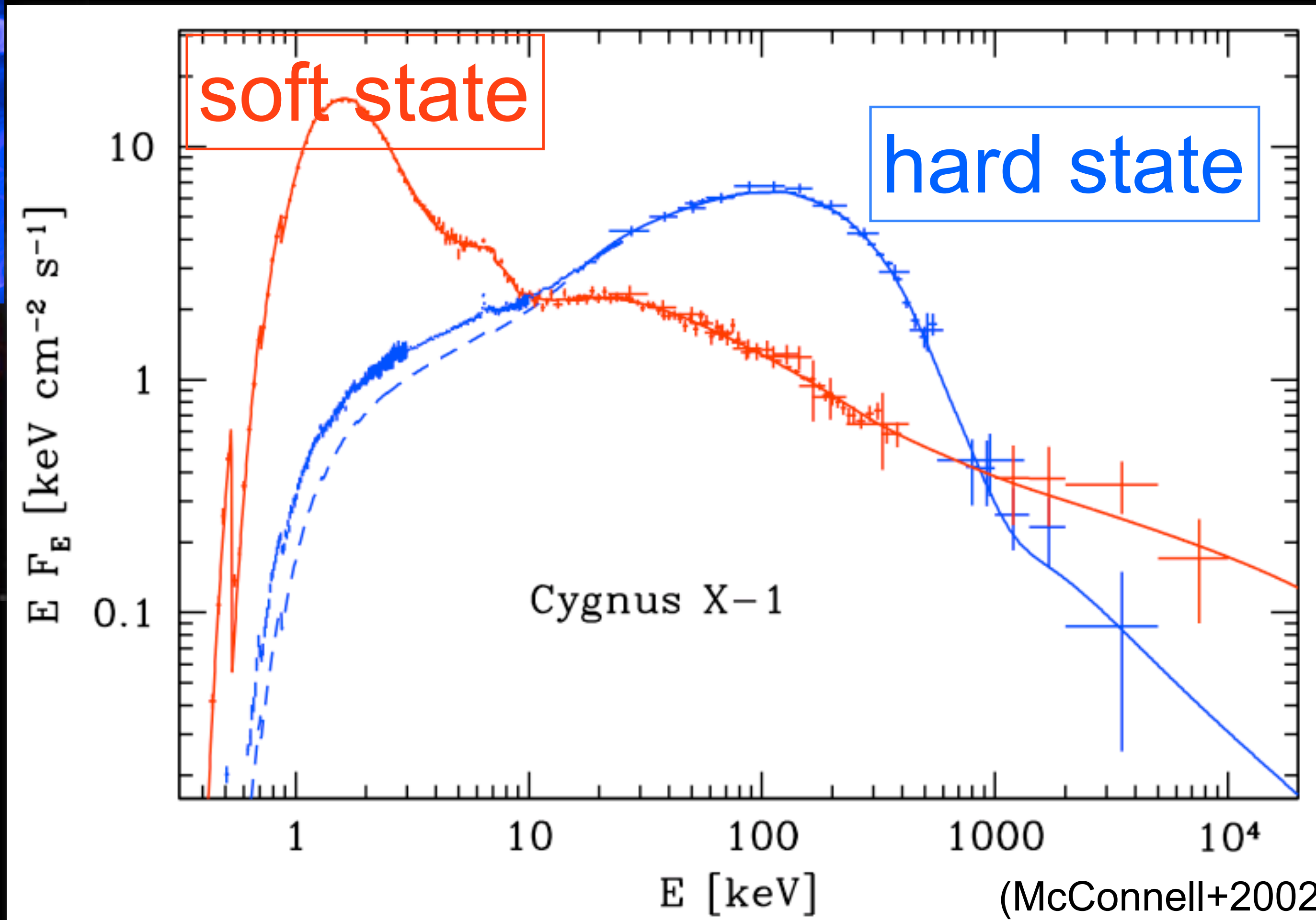
Sridhar, LS et al. 2021, MNRAS, 507, 5625

LS & Beloborodov 2020, ApJ, 899, 52



# The hard state of X-ray binaries



(McConnell+2002)

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

But: how can the electrons stay hot?

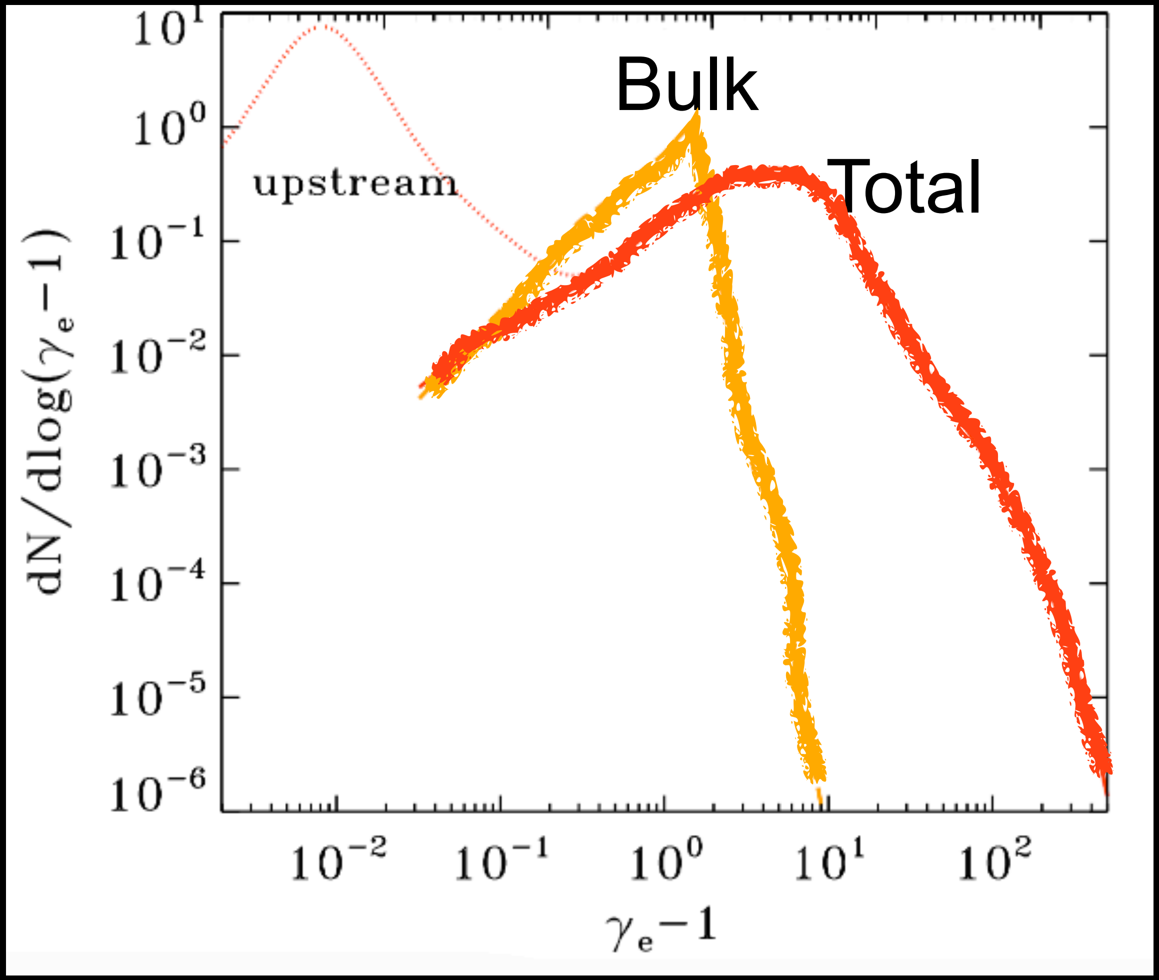
# Radiative reconnection

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

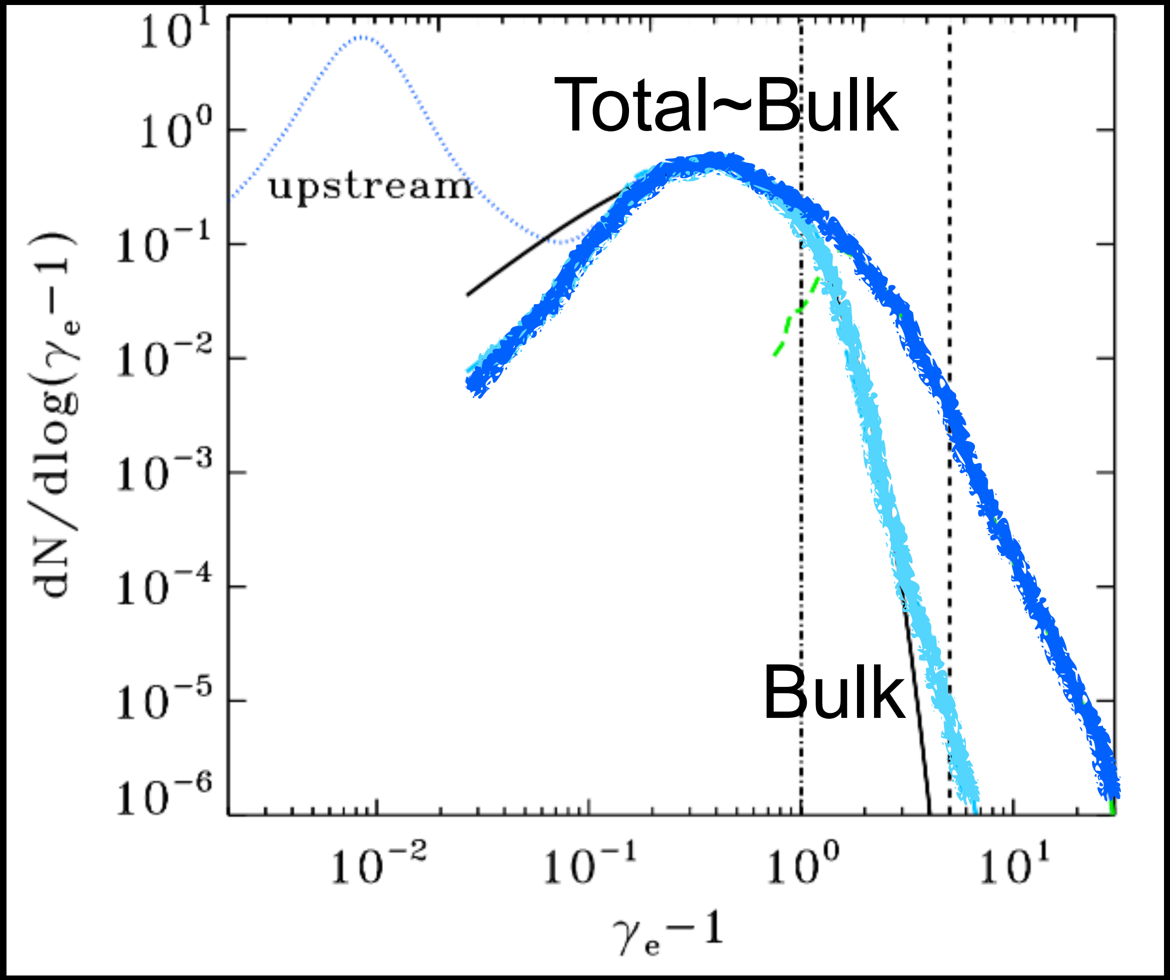
$$eE_{\rm rec} = \frac{4}{3}\sigma_{\rm T}\gamma_{\rm cr}^2 U_{\rm rad}$$

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

$\gamma_{cr}=\infty$ [uncooled]



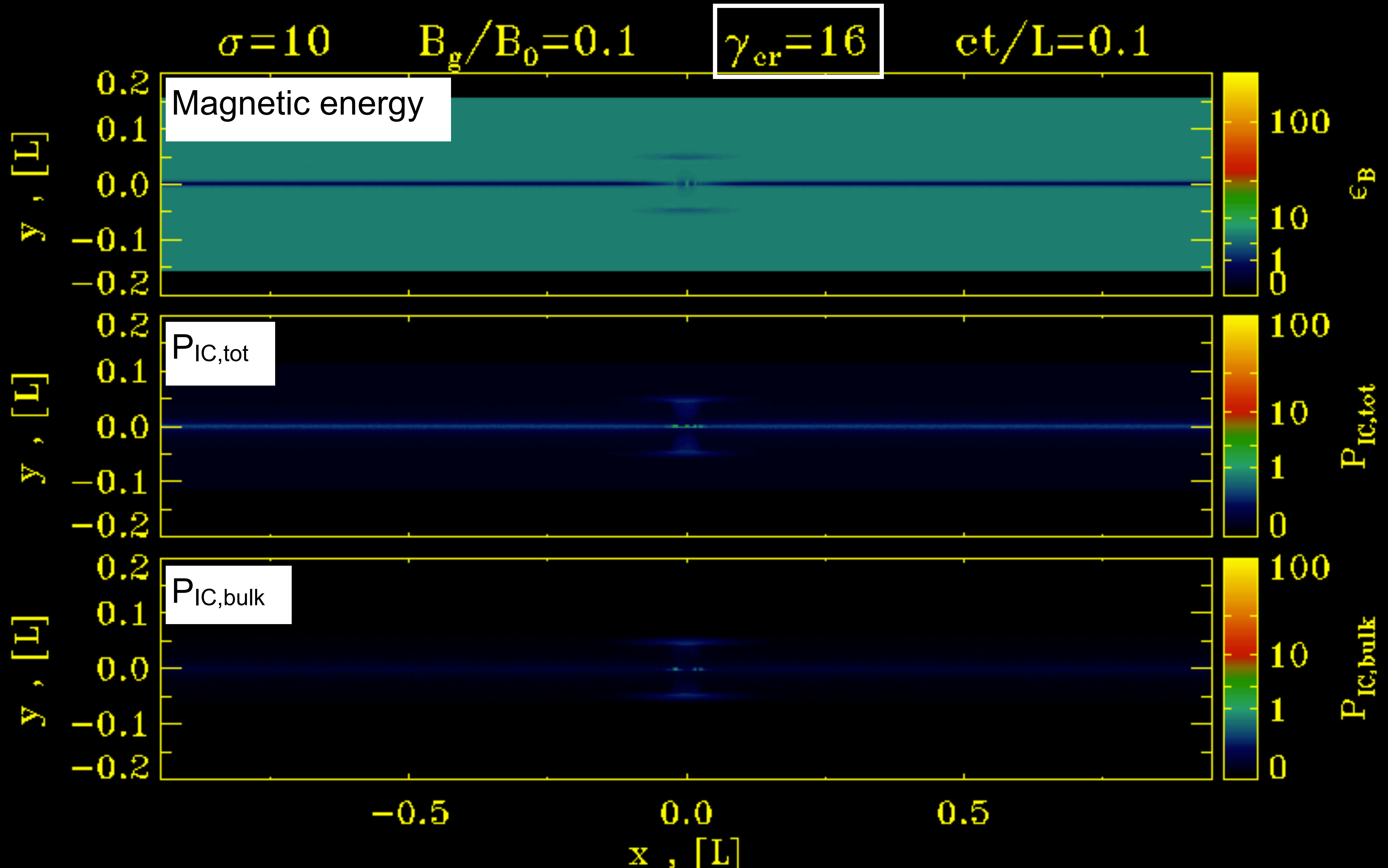

$\gamma_{cr}=16$




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

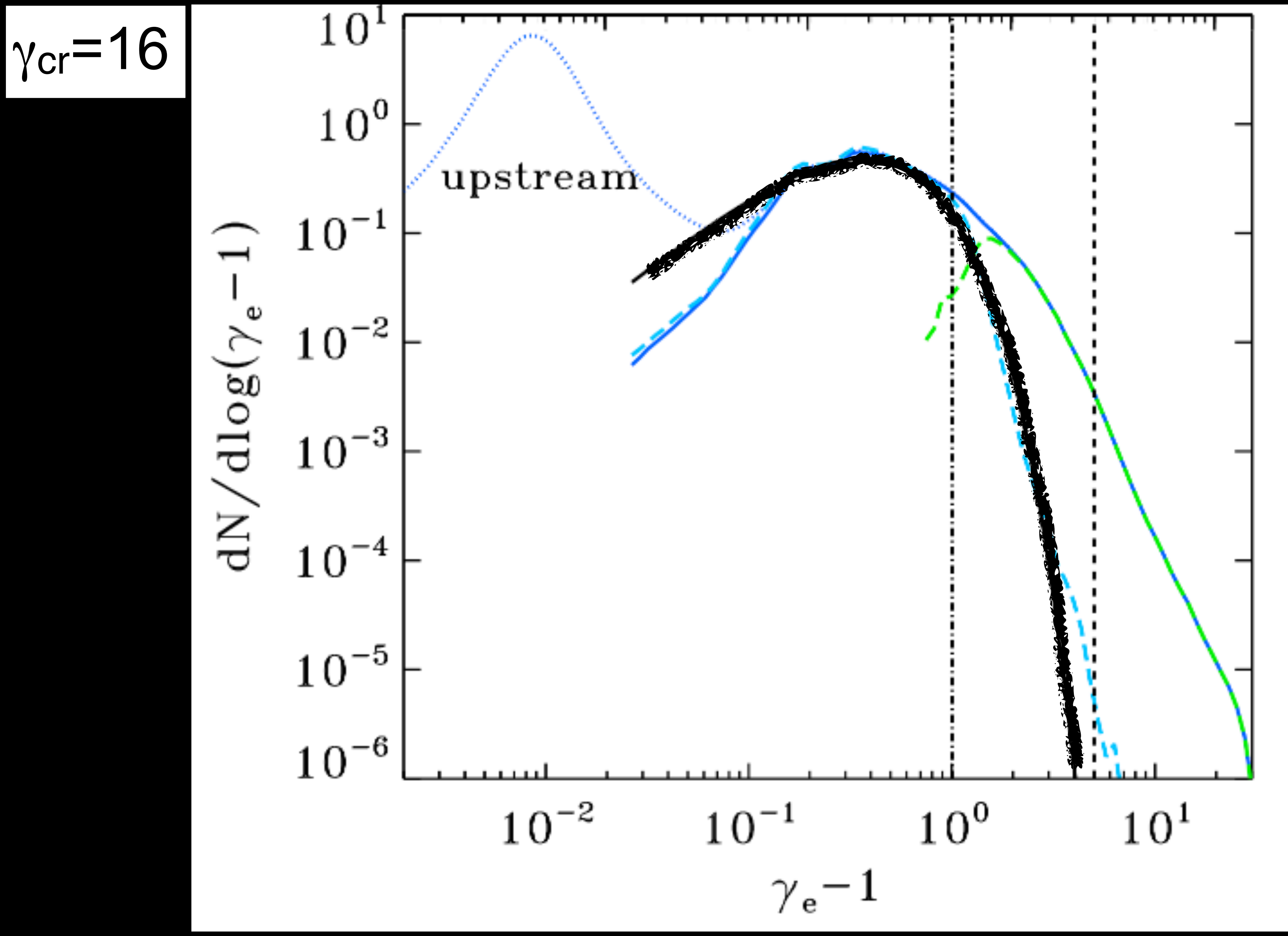
- Strong IC cooling suppresses particle acceleration.
- For strong cooling, the particle spectrum is dominated by plasmoid bulk motions.

# The radiative plasmoid chain




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

# Particle energy spectrum

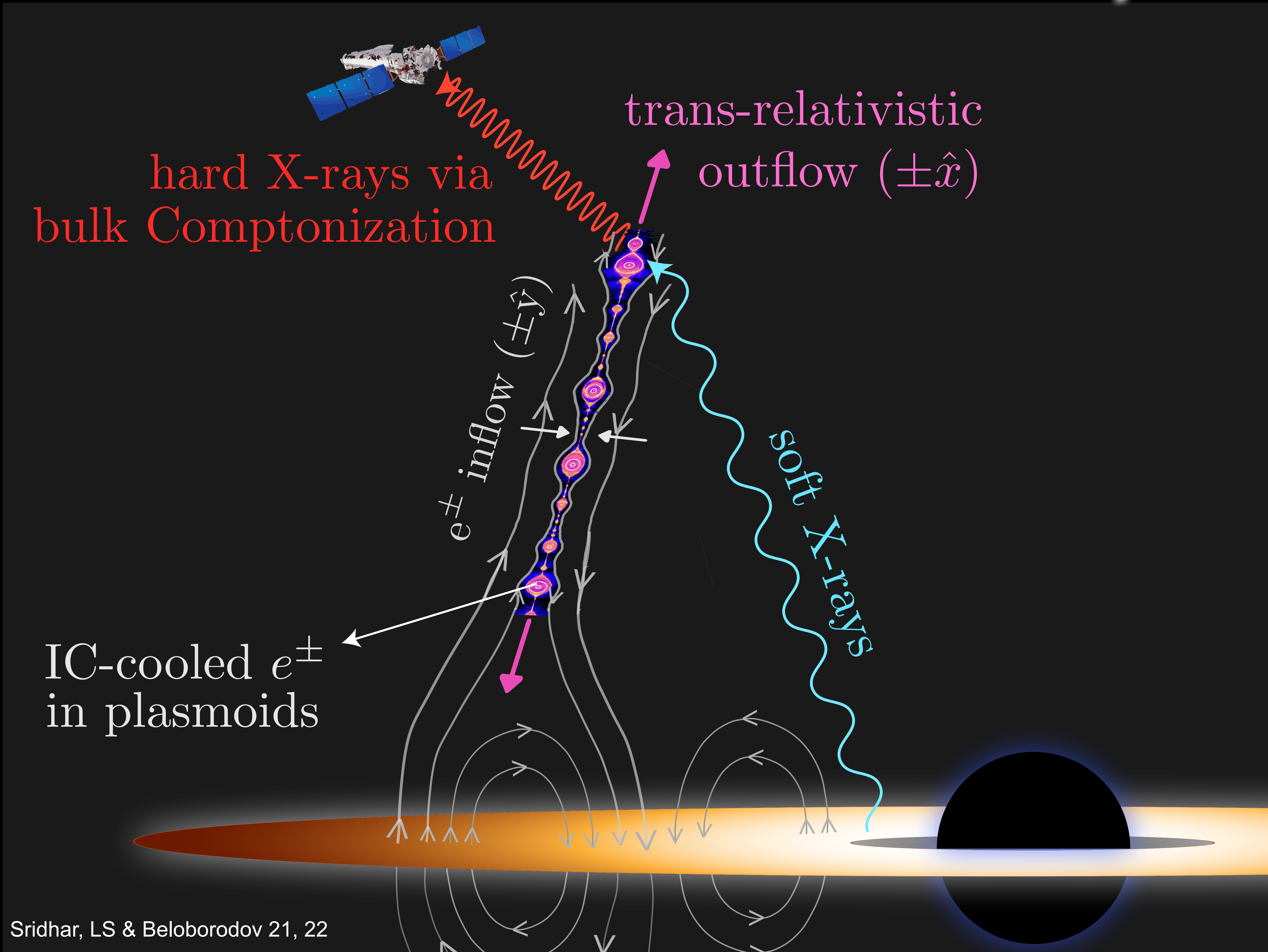



(LS & Beloborodov 20; Sridhar, LS & Beloborodov 21, 22)

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

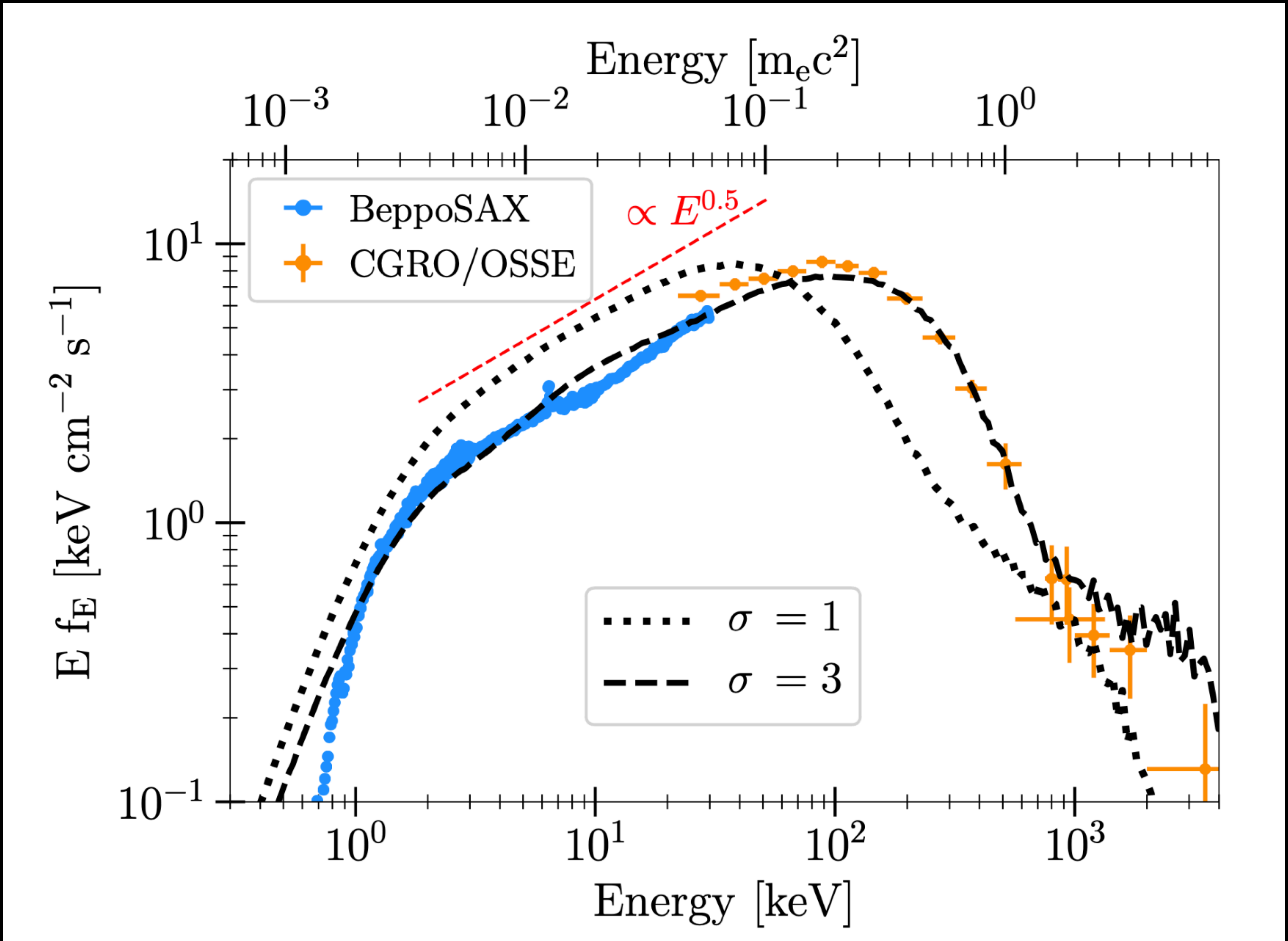
→ Bulk Comptonization in the plasmoid chain mimics thermal Comptonization

# A reconnection model for hard X-rays




Sridhar, LS & Beloborodov 21, 22

# X-ray photon spectrum




(Sridhar, LS & Beloborodov 21, 22)

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