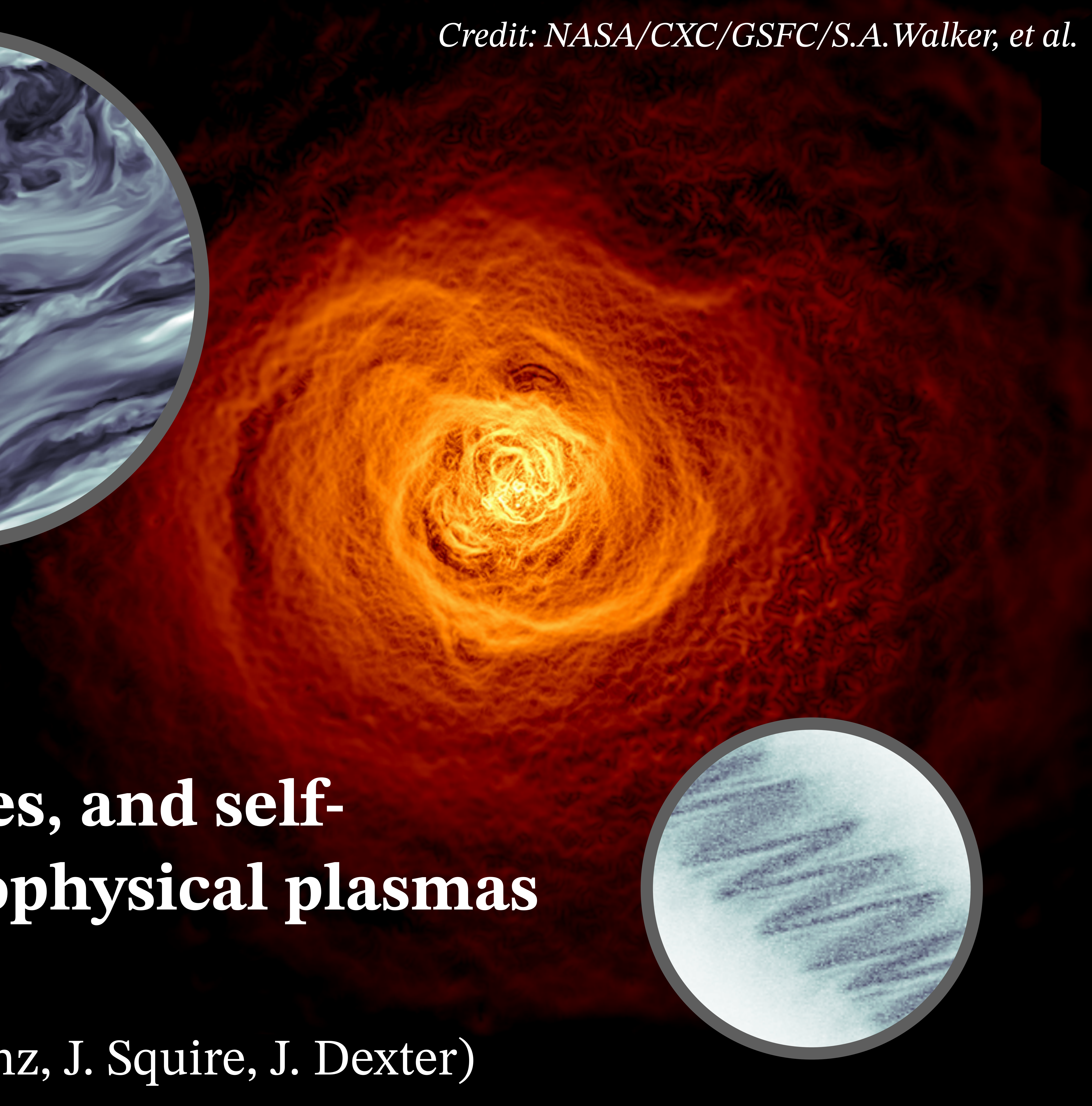
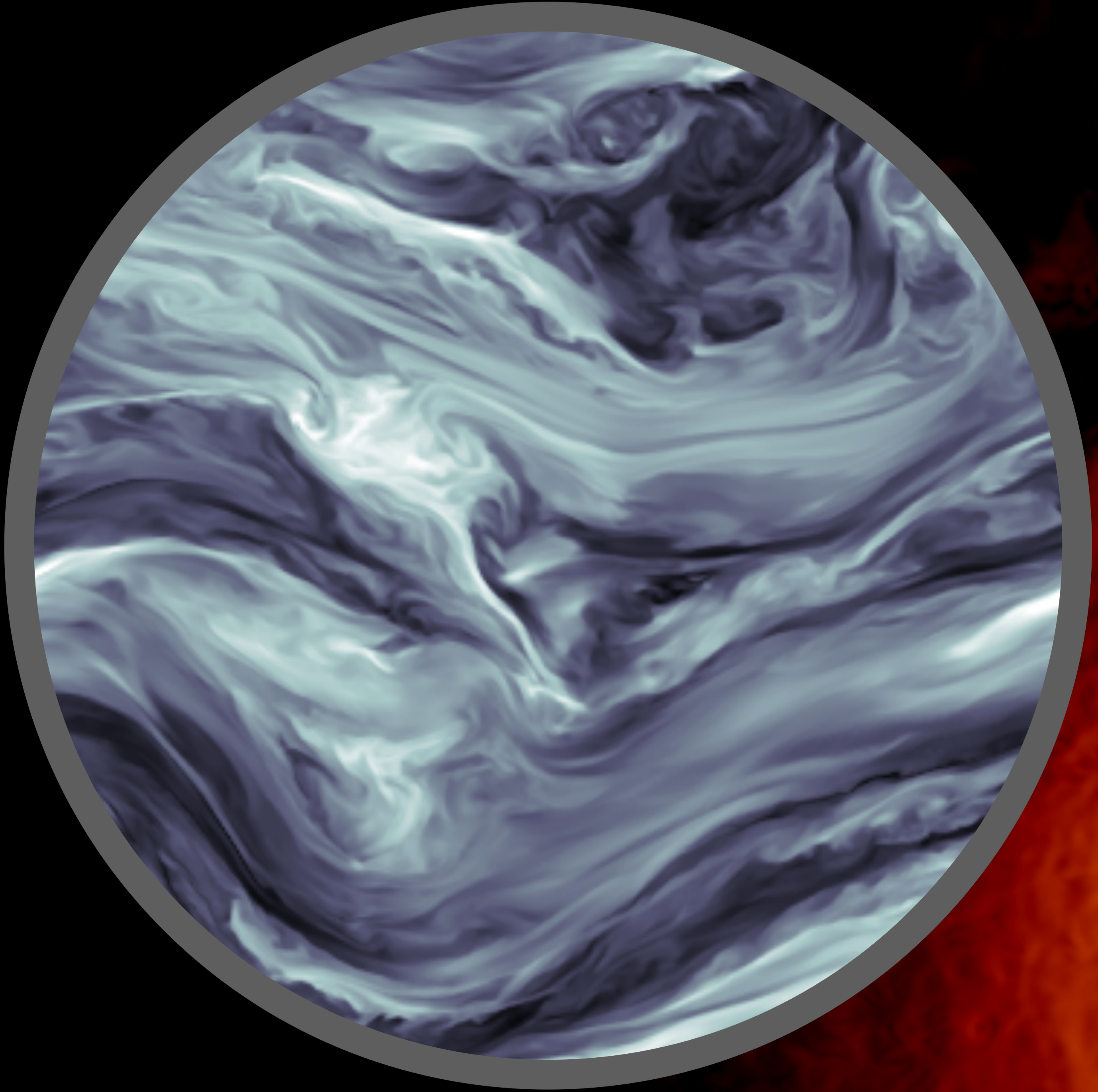
JILA



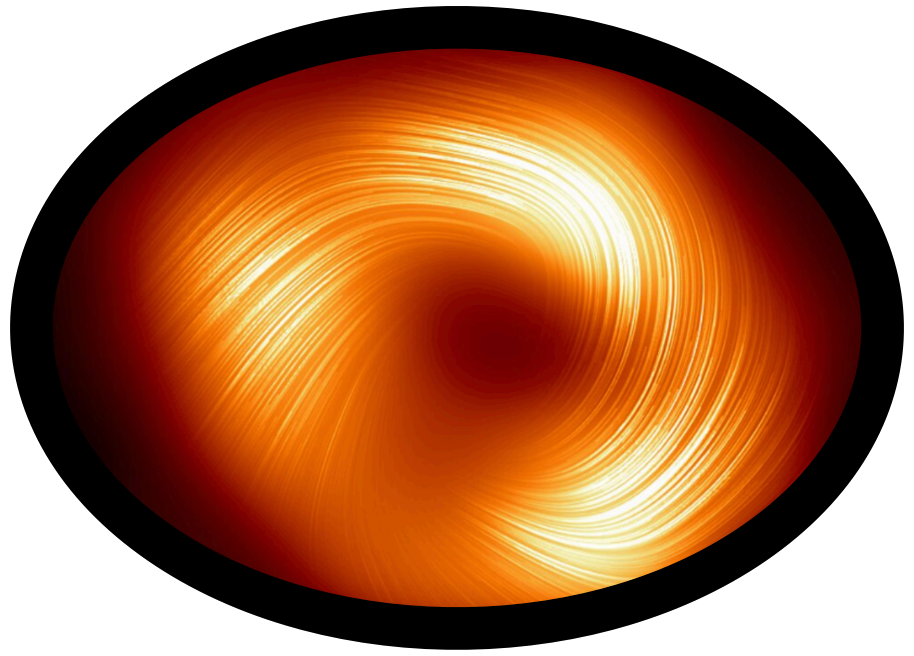


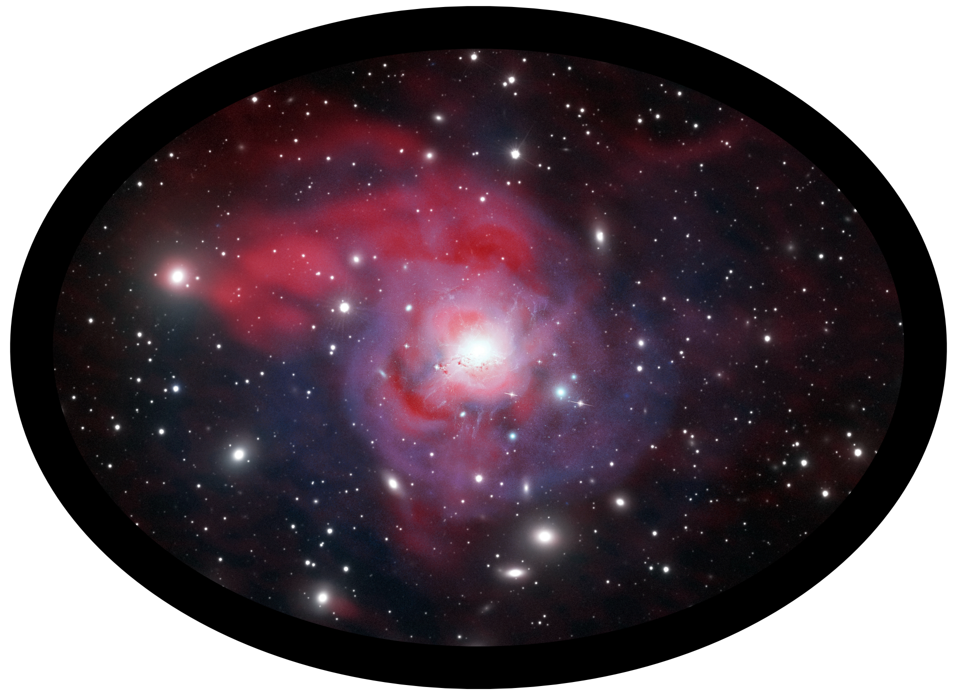
Credit: NASA/CXC/GSFC/S.A.Walker, et al.

Viscosity, micro-instabilities, and self-organization in dilute astrophysical plasmas

Stephen Majeski (Collaborators: M. Kunz, J. Squire, J. Dexter)

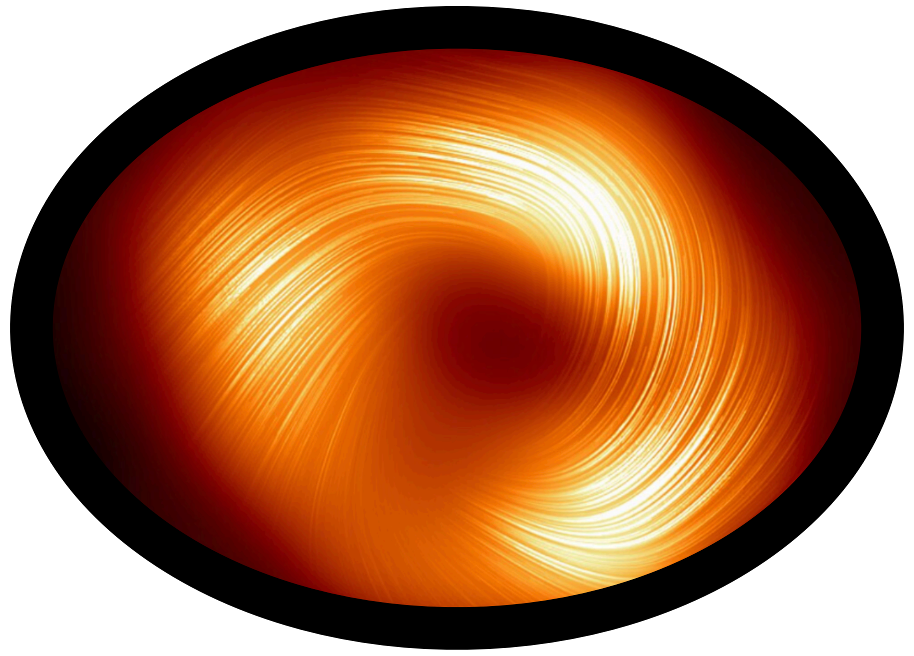
Galactic center accretion flow (GCAF):



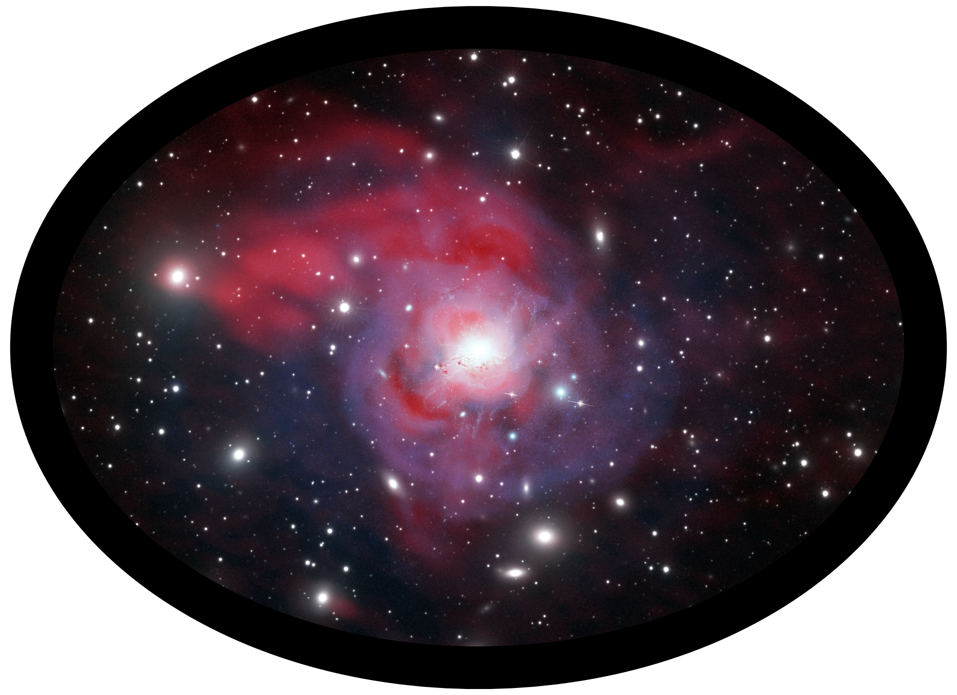


Intracluster media of galaxy clusters (ICM):

Galactic center accretion flow (GCAF):



Thermally dominated ($\beta \gtrsim 1$, up to 100)



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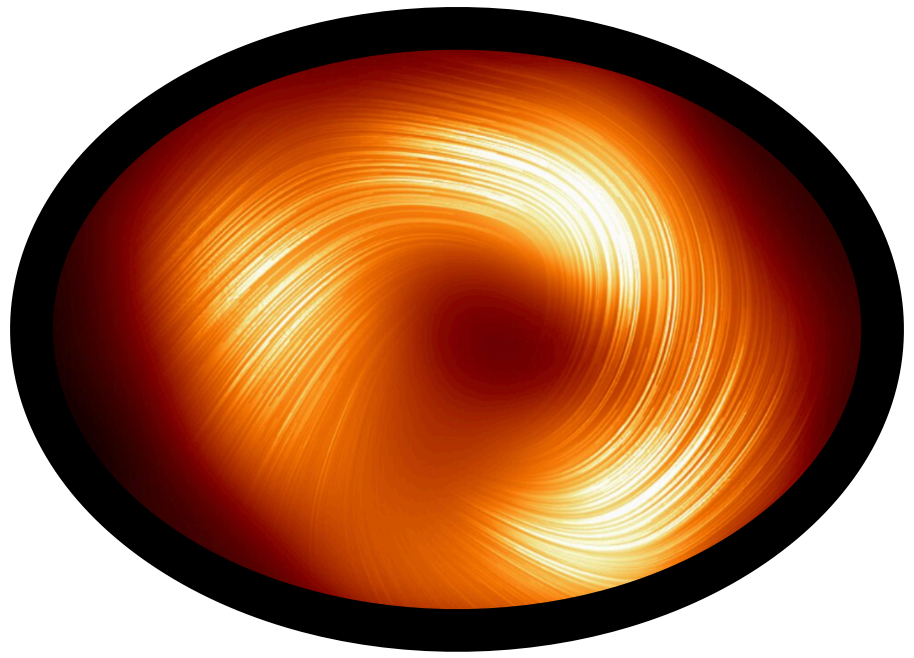
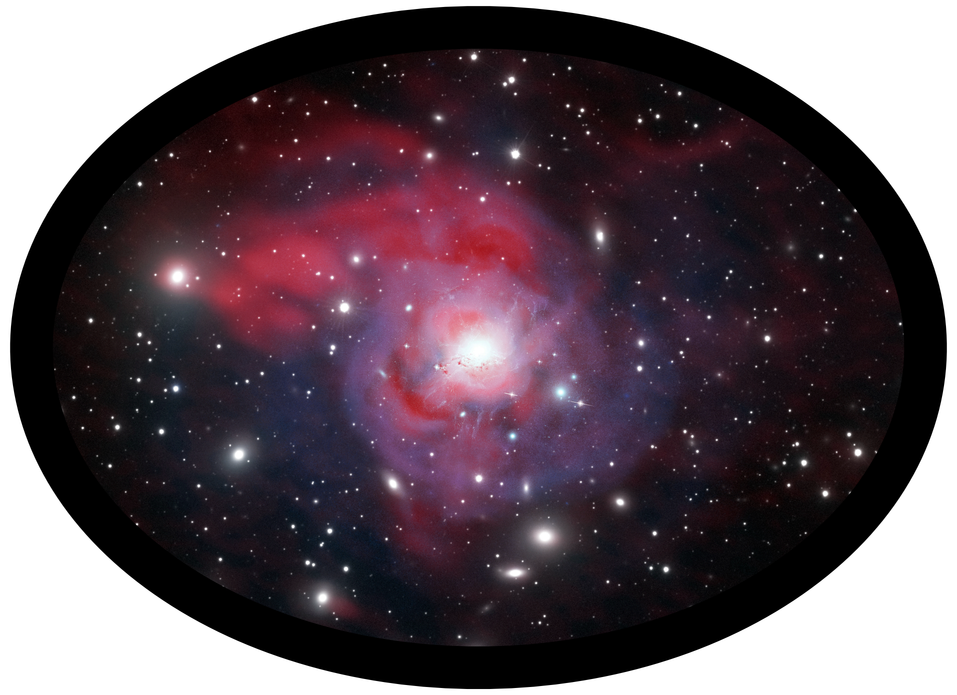


Thermally dominated ($\beta \gtrsim 1$, up to 100)

(Igor relevant?)



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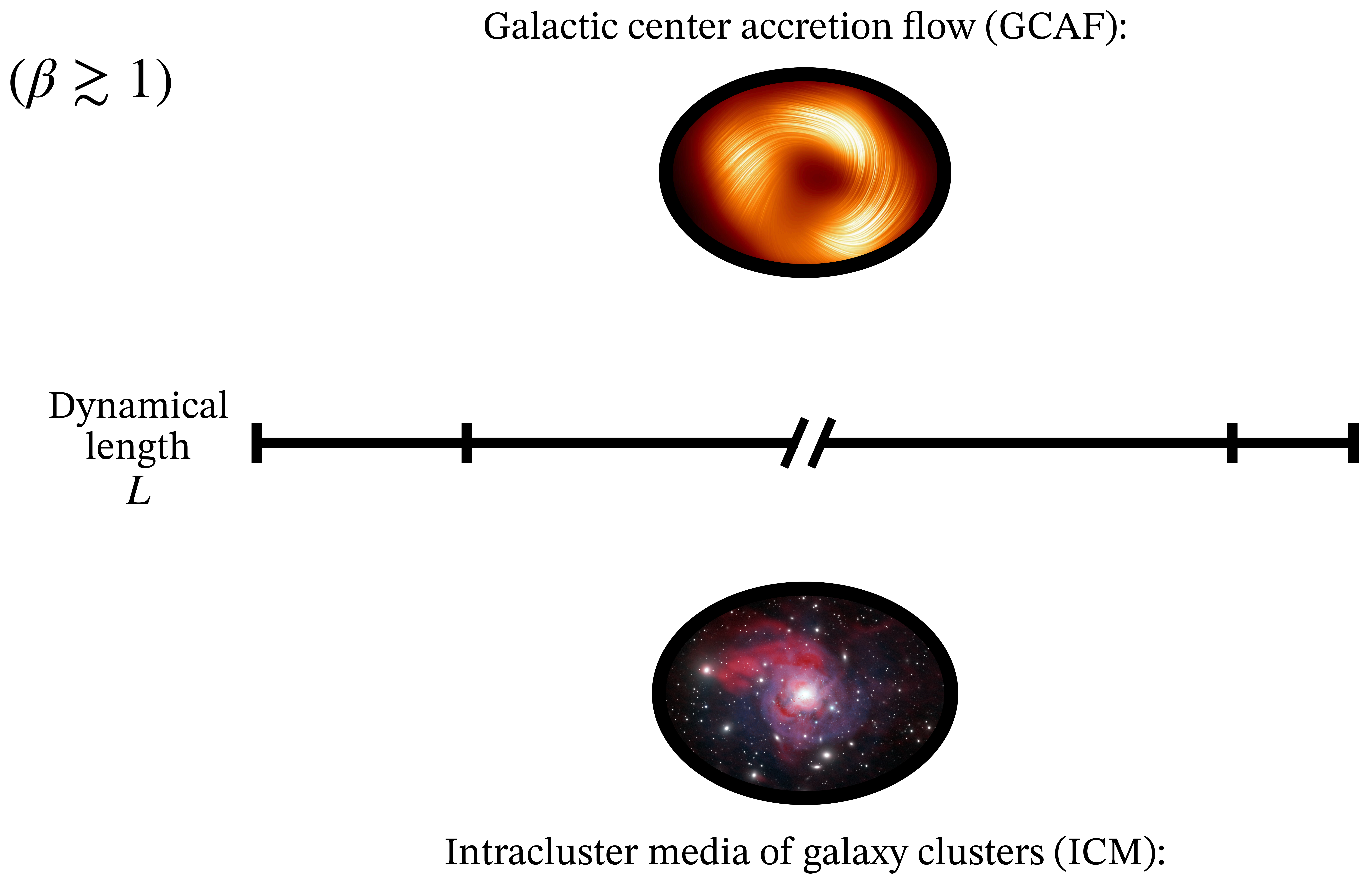
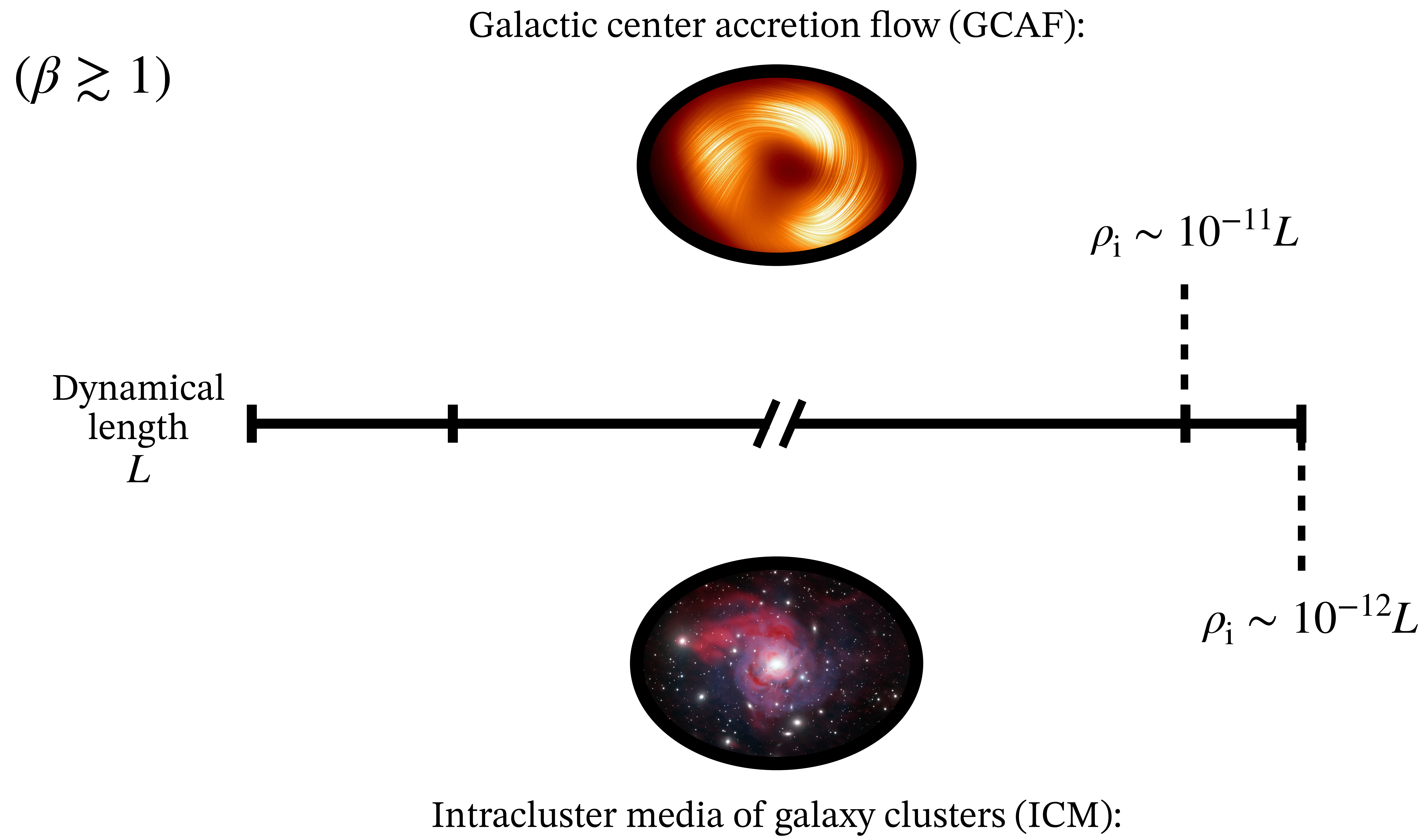

Galactic center accretion flow (GCAF):
($\beta \gtrsim 1$)
Dynamical length L
Intracluster media of galaxy clusters (ICM):



Galactic center accretion flow (GCAF):
($\beta \gtrsim 1$)
$\rho_{\mathrm{i}} \sim 10^{-11}L$
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$\rho_{\mathrm{i}} \sim 10^{-12}L$
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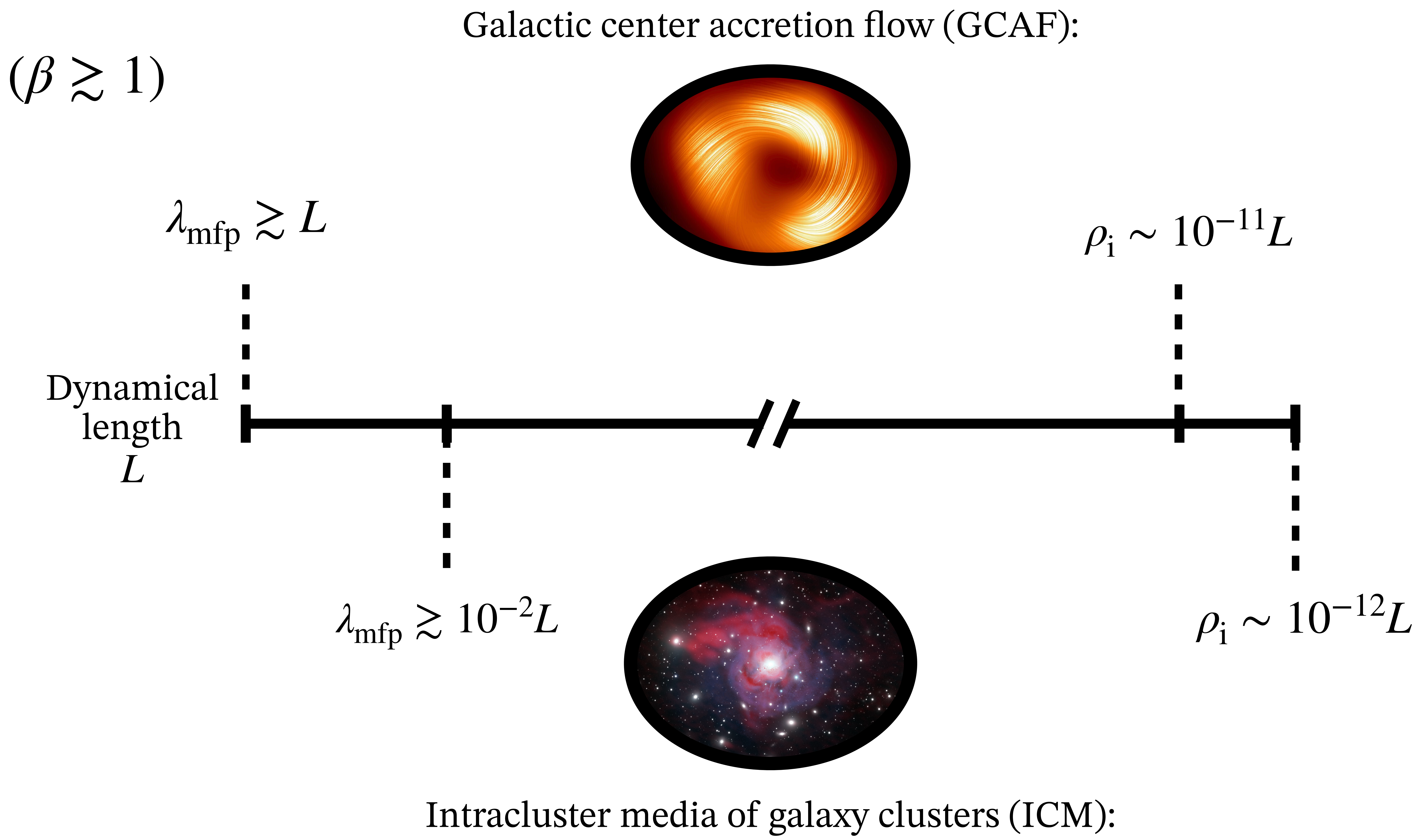
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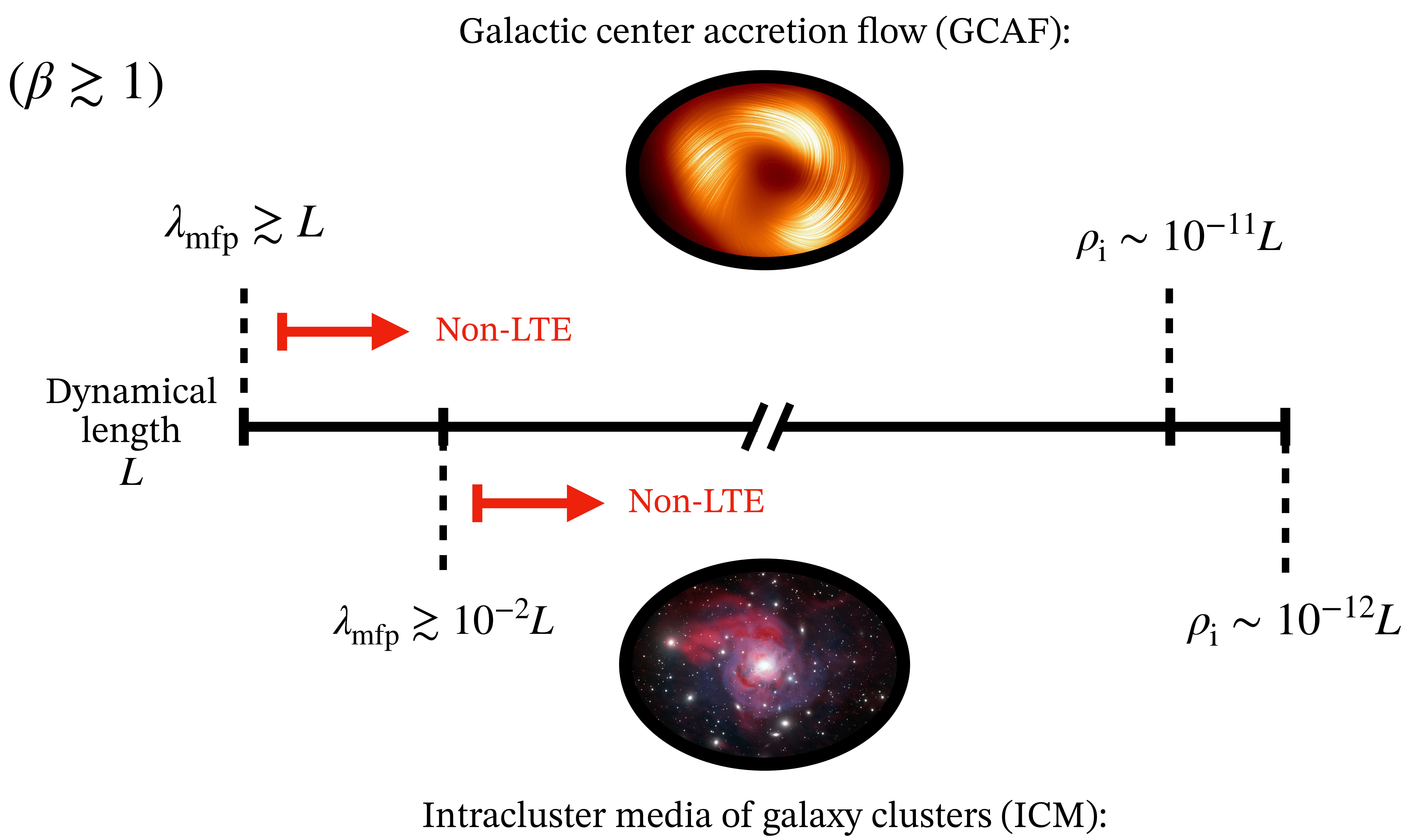

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Non-LTE
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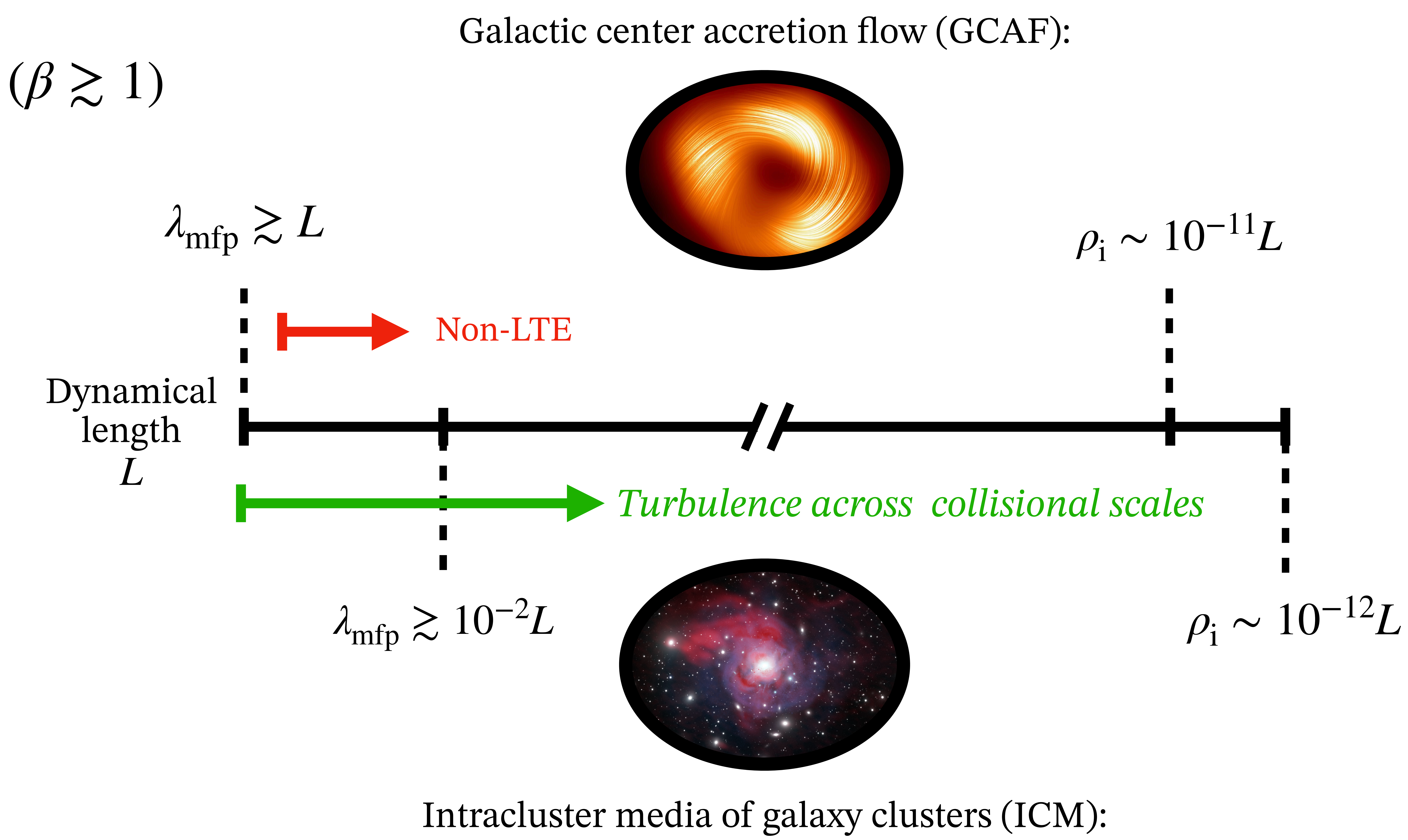
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Dynamical length L
Turbulence across collisional scales
$\lambda_{\rm mfp} \gtrsim 10^{-2}L$
$\rho_{\rm i} \sim 10^{-12}L$
Intracluster media of galaxy clusters (ICM):

The CGL-MHD system:

$$p_\perp \frac{\mathrm{d}}{\mathrm{d}t} \ln\left(\frac{p_\perp}{nB}\right) = \mu \text{ conservation}$$

$$p_\| \frac{\mathrm{d}}{\mathrm{d}t} \ln\left(\frac{p_\| B^2}{n^3}\right) = \mathscr{J}_{||} \text{ conservation}$$

] Double adiabats

The CGL-MHD system:

$$p_\perp \frac{\mathrm{d}}{\mathrm{d}t} \ln\left(\frac{p_\perp}{nB}\right) = -\nabla \cdot (q_\perp \hat{b}) - q_\perp \nabla \cdot \hat{b}$$

$$p_\parallel \frac{\mathrm{d}}{\mathrm{d}t} \ln\left(\frac{p_\parallel B^2}{n^3}\right) = -\nabla \cdot (q_\parallel \hat{b}) + 2 q_\perp \nabla \cdot \hat{b}$$

Double adiabats, with heat fluxes

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Double adiabats, with heat fluxes and collisions

The CGL-MHD system:

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Transition from collisional to collisionless regime

The CGL-MHD system:

$$\frac{\mathrm{d}n}{\mathrm{d}t} + \nabla \cdot (n\vec{u}) = 0, \qquad \frac{\mathrm{d}\overrightarrow{B}}{\mathrm{d}t} = \overrightarrow{B} \cdot \nabla \vec{u} - \overrightarrow{B} \nabla \cdot \vec{u},$$

] Standard MHD induction, continuity

$$p_\perp \frac{\mathrm{d}}{\mathrm{d}t} \ln\left(\frac{p_\perp}{nB}\right) = -\nabla \cdot (q_\perp \hat{b}) - q_\perp \nabla \cdot \hat{b} - \frac{\nu}{3}(p_\perp - p_\parallel),$$

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$$m_{\mathrm{i}}n\frac{\mathrm{d}\vec{u}}{\mathrm{d}t} = -\nabla\left(p_\perp + \frac{B^2}{8\pi}\right) + \frac{\vec{B}\cdot\nabla\vec{B}}{4\pi} + \nabla\cdot\left(\hat{b}\hat{b}\Delta p\right)$$

] Anisotropic pressure tensor

$$\Delta p \equiv p_\perp - p_\parallel$$

$$p_\perp\frac{\mathrm{d}}{\mathrm{d}t}\ln\left(\frac{p_\perp}{nB}\right) = -\nabla\cdot(q_\perp\hat{b}) - q_\perp\nabla\cdot\hat{b} - \frac{\nu}{3}(p_\perp - p_\parallel),$$

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Soon available in AthenaK

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$$\nabla \cdot (\hat{b}\hat{b}\Delta p)$$

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Weakly collisional ($\nu \gg k v_{\rm th,i}$):

$$\Delta p \approx \frac{3p}{\nu}(\hat{b}\hat{b} - I/3) : \nabla \vec{u}$$

(Kevin's "marginally collisional")

(Braginskii 1965)

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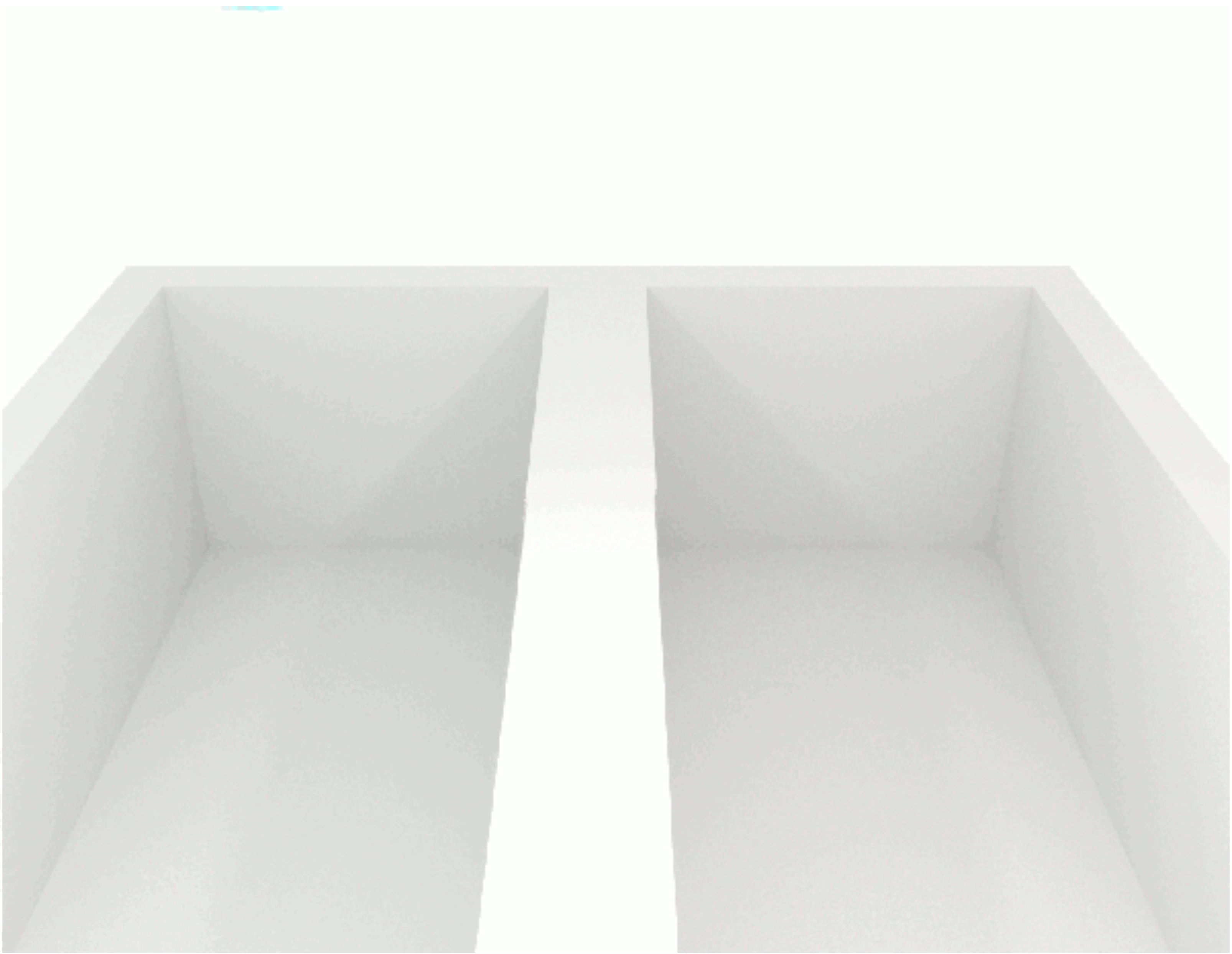
Across $\hat{b}$



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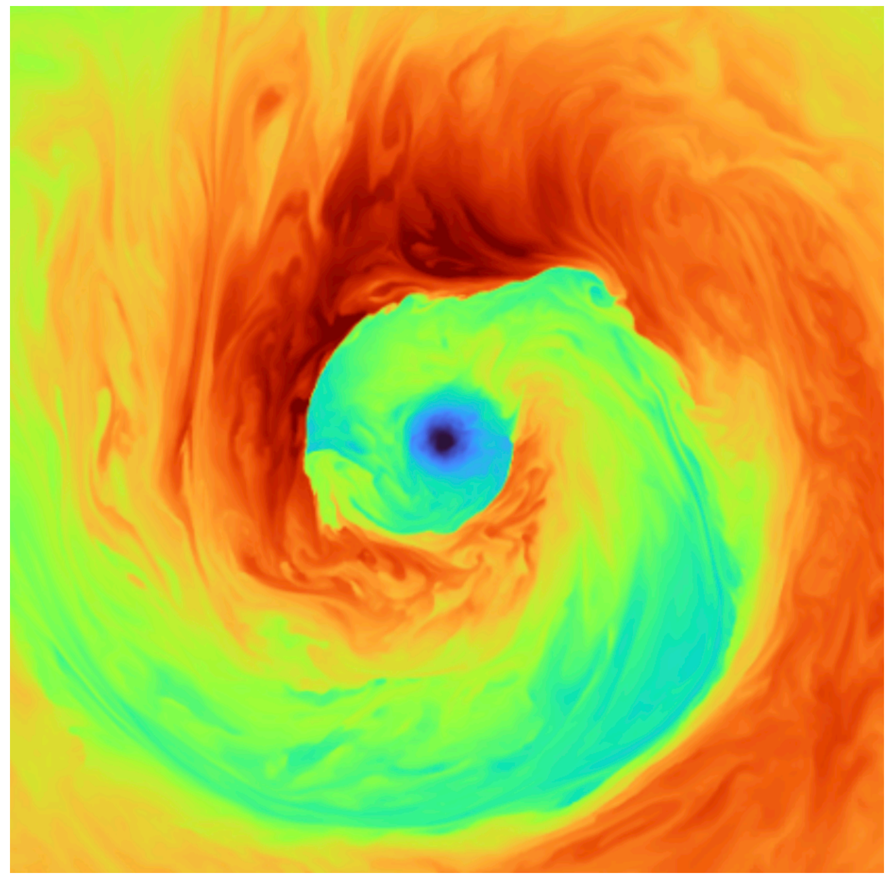
What happens to kinetic energy liberated from…

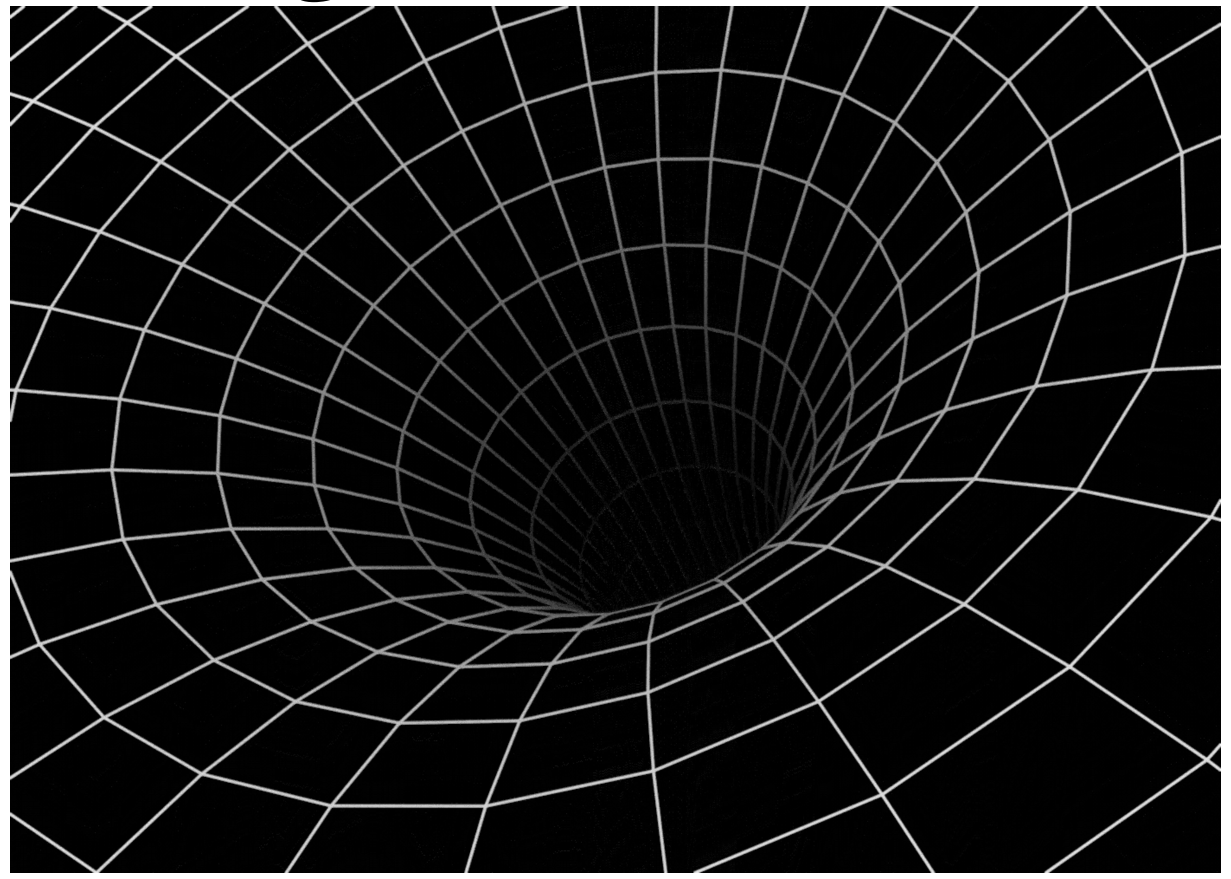
structure formation



ZuHone+ *in prep* (incl. SM)

and

gravitation?



Effective magnetic tension:

$$\frac{\vec{B}\cdot\nabla\vec{B}}{4\pi} + \nabla\cdot\left(\vec{B}\vec{B}\frac{\Delta p}{B^2}\right)$$

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$$\frac{\vec{B} \cdot \nabla \vec{B}}{4\pi} + \nabla \cdot \left(\vec{B}\vec{B} \frac{\Delta p}{B^2} \right) \longrightarrow v_{\mathrm{A,eff}} = v_{\mathrm{A}} \sqrt{1 + \frac{\beta}{2} \frac{\Delta p}{p}}$$

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w/ guide field

*Axel-inspired aside:

$$\boldsymbol{z}^{\pm} = \boldsymbol{u}_{\perp} \pm v_{\mathrm{A,eff}}\frac{\delta\boldsymbol{B}_{\perp}}{B_0}.$$

$$\frac{\partial W^{\pm}_{\mathrm{AW}}}{\partial t} \doteq \frac{\partial}{\partial t}\int \mathrm{d}^3x\,\frac{1}{2}|\boldsymbol{z}^{\pm}|^2 = \mp\int \mathrm{d}^3x\,\frac{P_{\mathrm{total}}}{\rho_0}\frac{\partial v_{\mathrm{A,eff}}}{\partial z}.$$

Cross – helicity $\rightarrow$ $\frac{\partial}{\partial t}\left(W^{+} - W^{-}\right) \neq 0$

Effective magnetic tension:

$\beta \gtrsim 1$

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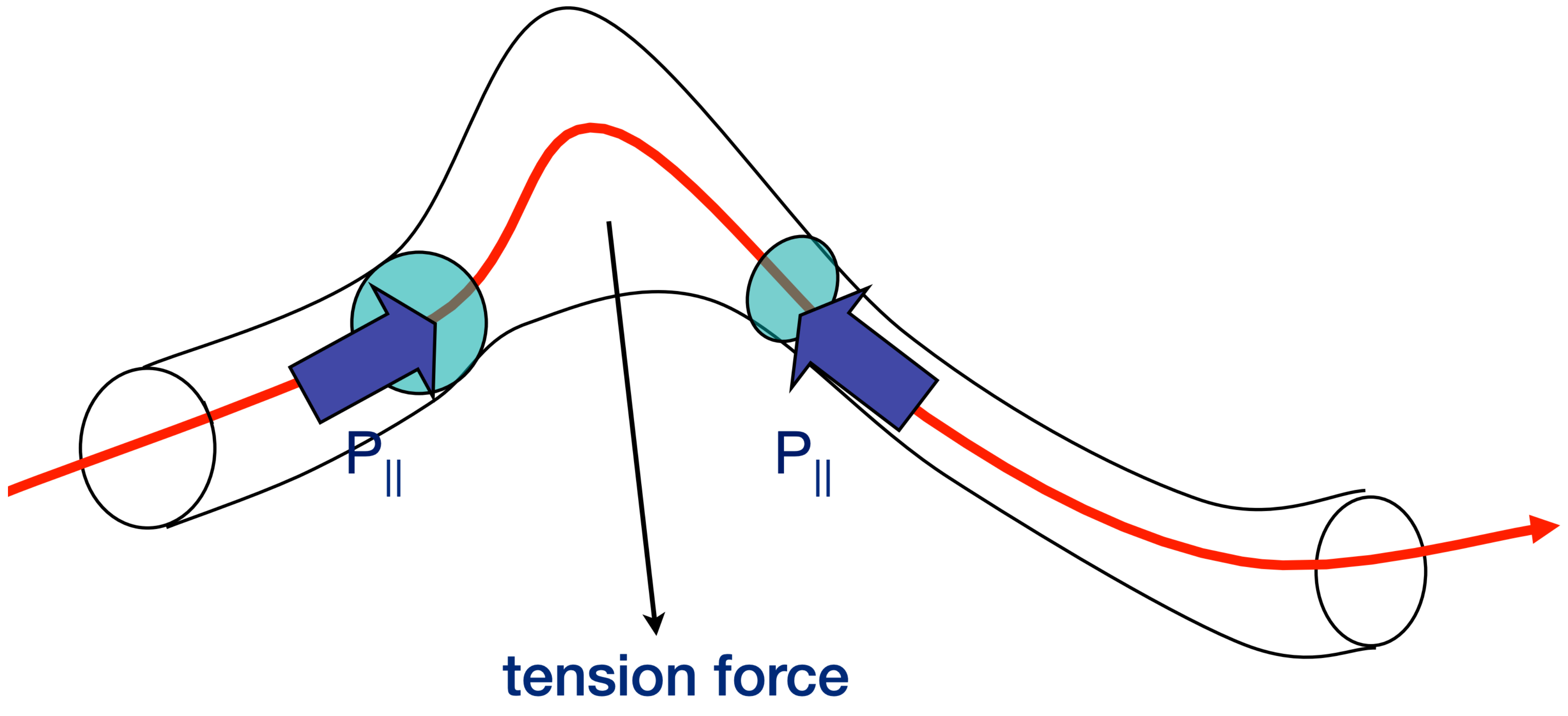
$\beta \gtrsim 1$

Complex when $\frac{\Delta p}{p}\beta \lesssim -2$



Firehose instability (fluid)

Effective magnetic tension:

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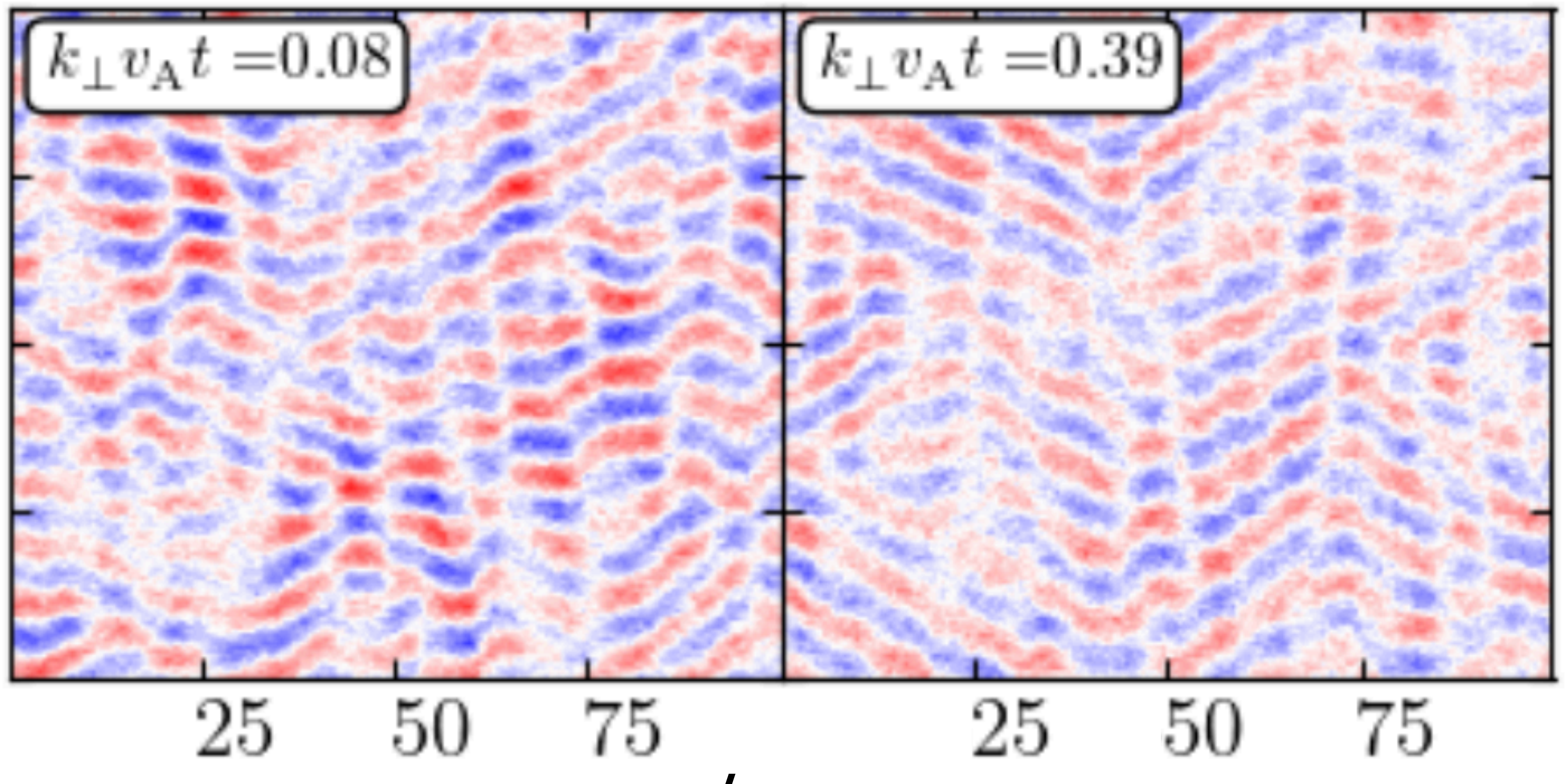
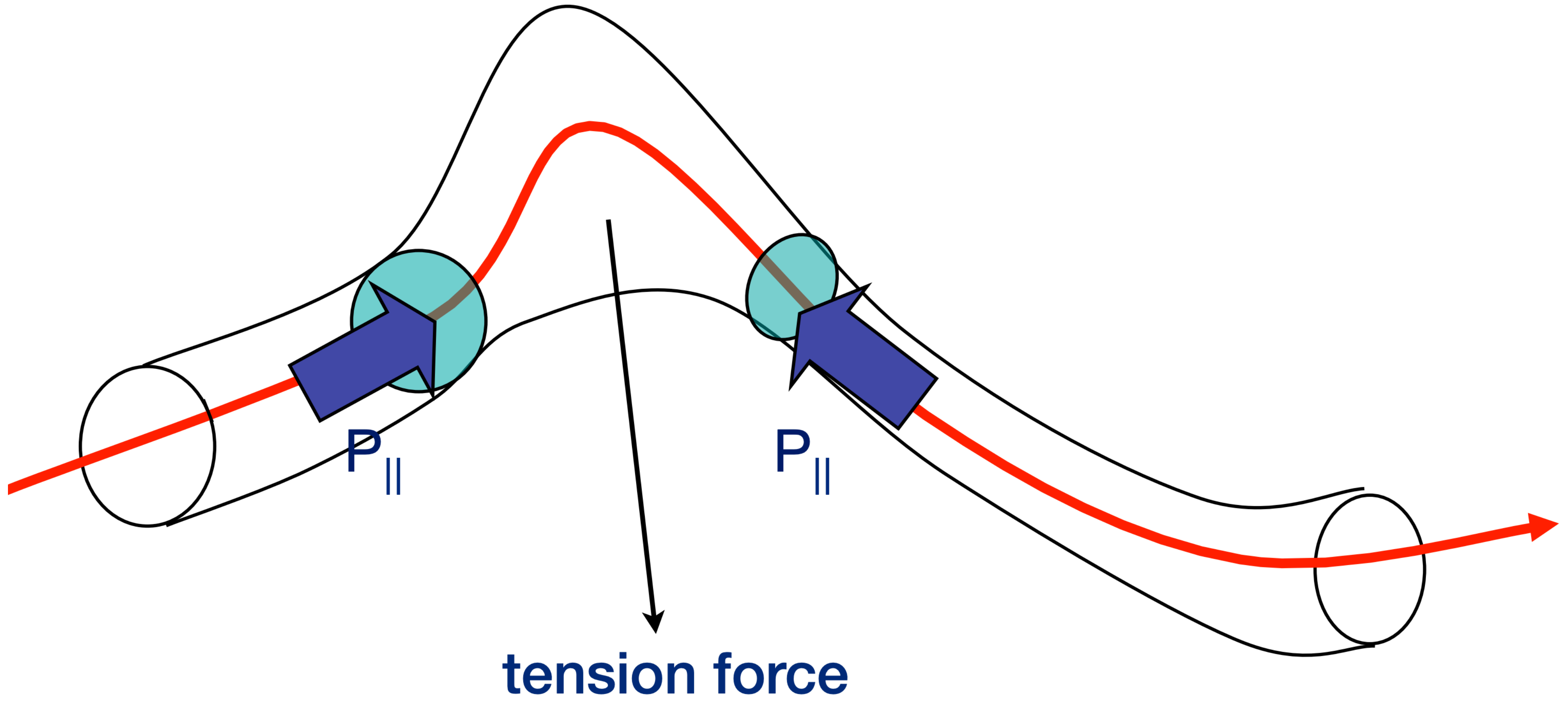
Complex when $\frac{\Delta p}{p} \beta \lesssim -2$

Grow δB at $r_{\mathrm{L,i}}$ scales (known as a **micro**-instability)

$\delta B_{\perp,\mathrm{firehose}}$





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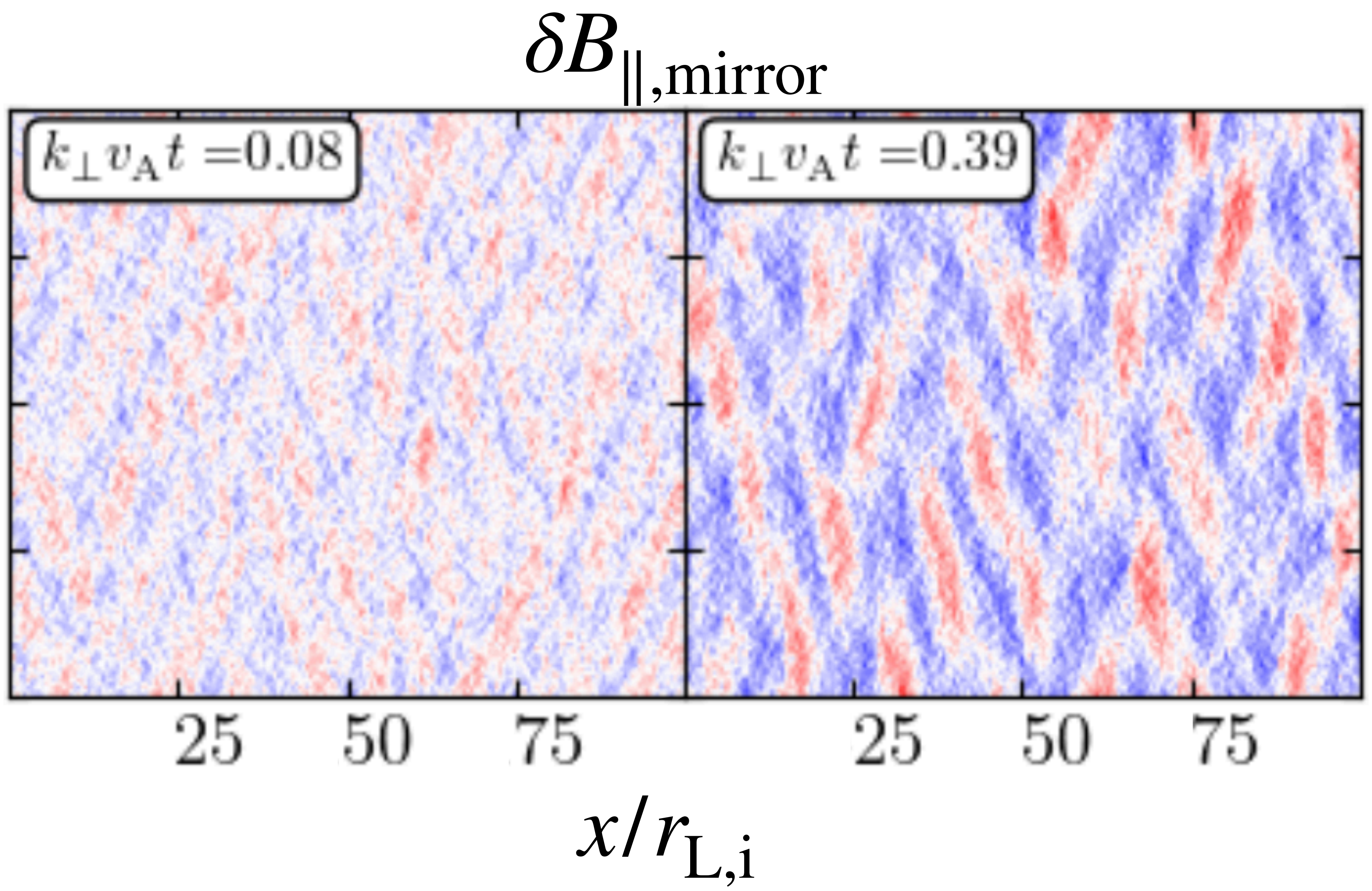
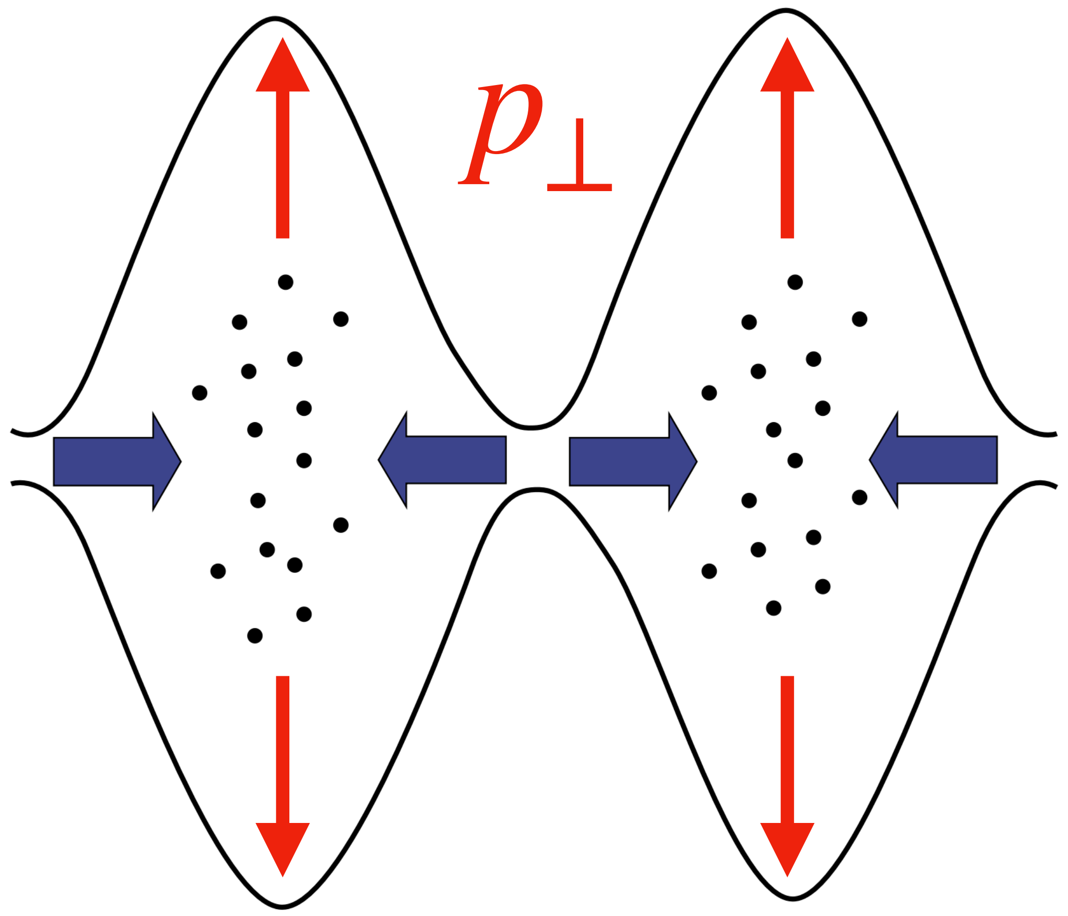
Grow δB at $r_{\mathrm{L,i}}$ scales (known as a **micro**-instability)

Unstable when $\frac{\Delta p}{p}\beta \gtrsim 1$





Mirror instability

($\beta \lesssim 1 \rightarrow$ Alfvén/ion-cyclotron instability)

Macroscopic role of micro-instabilities

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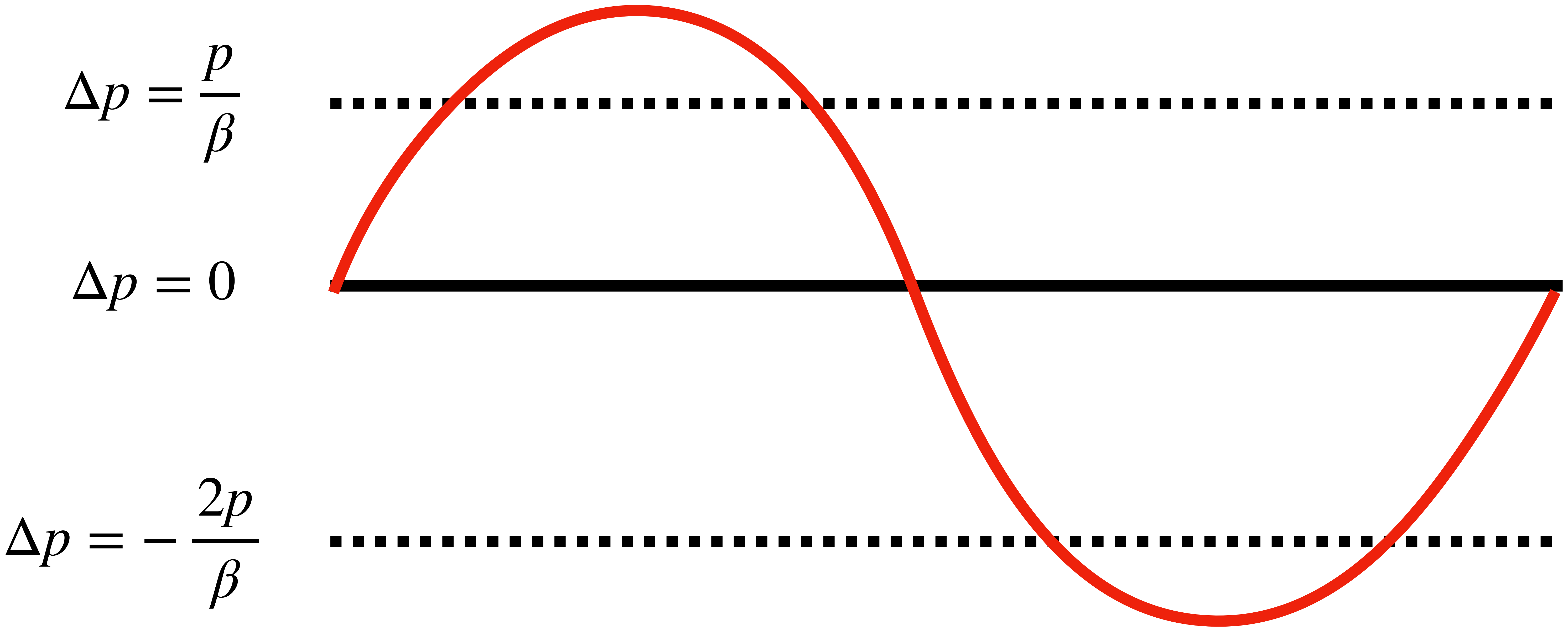
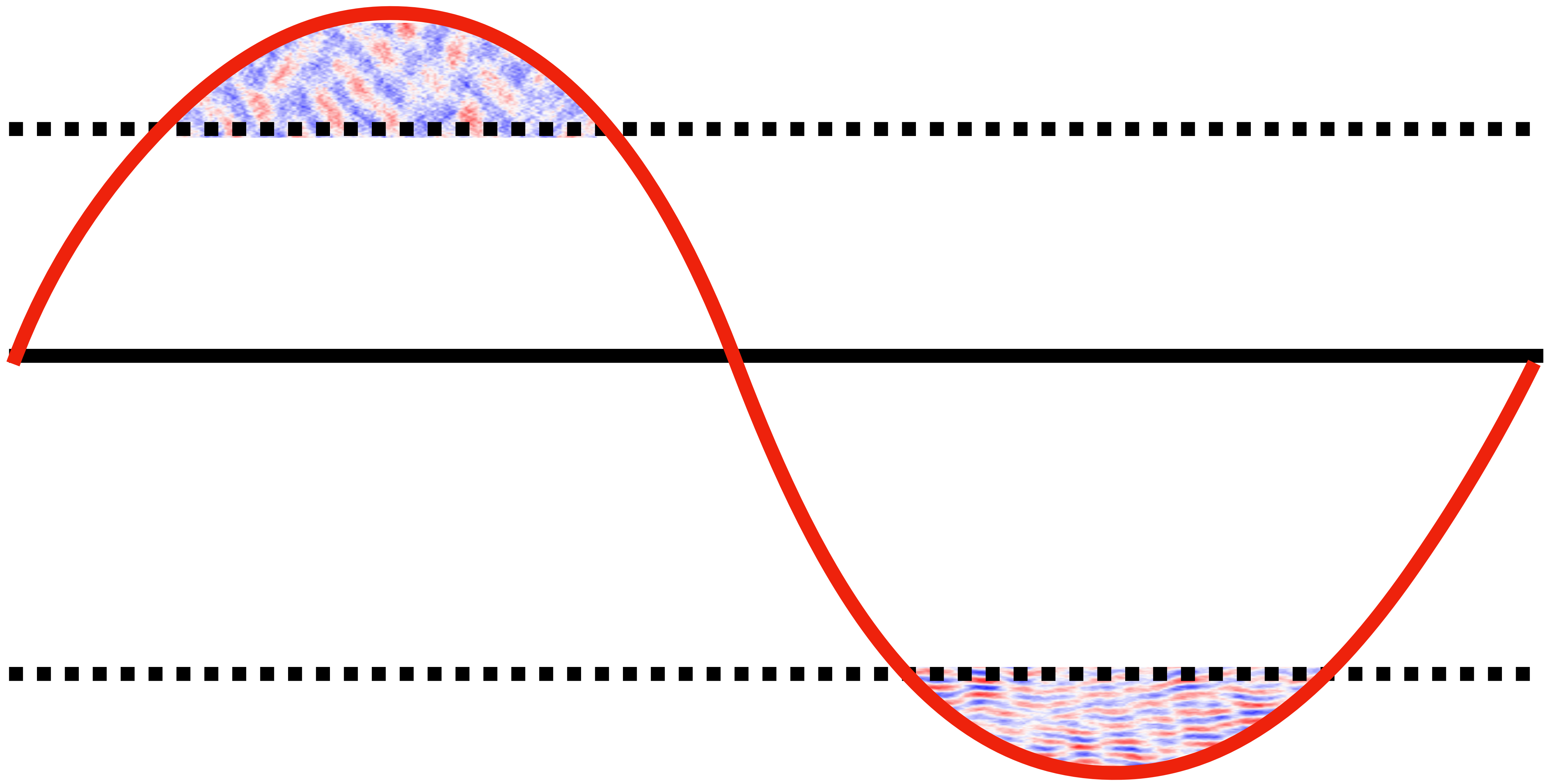


Macroscopic role of micro-instabilities

$$\Delta p = \frac{p}{\beta}$$

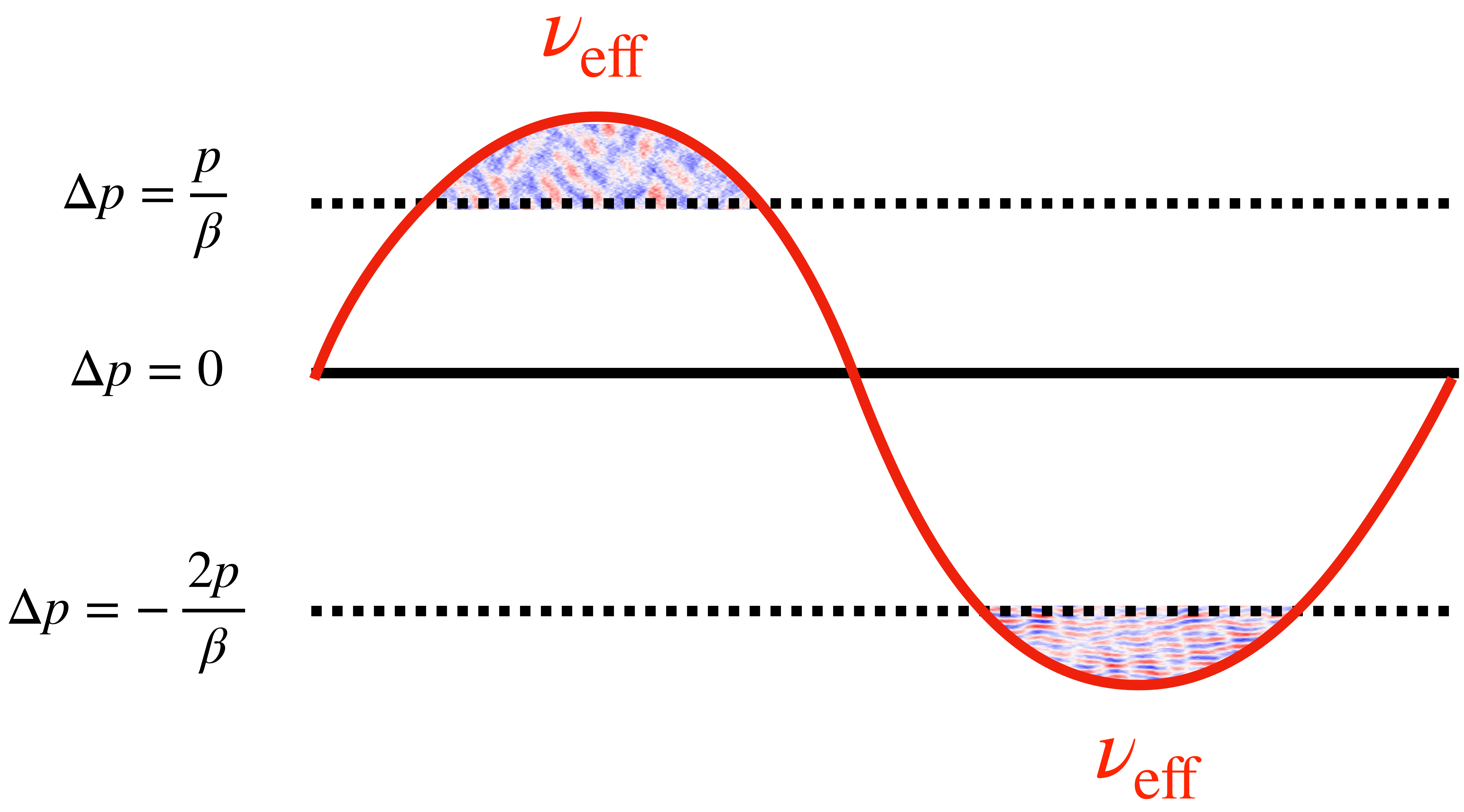
$$\Delta p = 0$$

$$\Delta p = -\frac{2p}{\beta}$$



Macroscopic role of micro-instabilities

*(*or quasilinear for firehose)*



Nonlinear* $k \sim r_{\rm L,i}^{-1}$ fluctuations can break μ, $\mathcal{J}$ conservation

→ Manifests as pitch-angle particle scattering

Kunz+ (2014)

Macroscopic role of micro-instabilities

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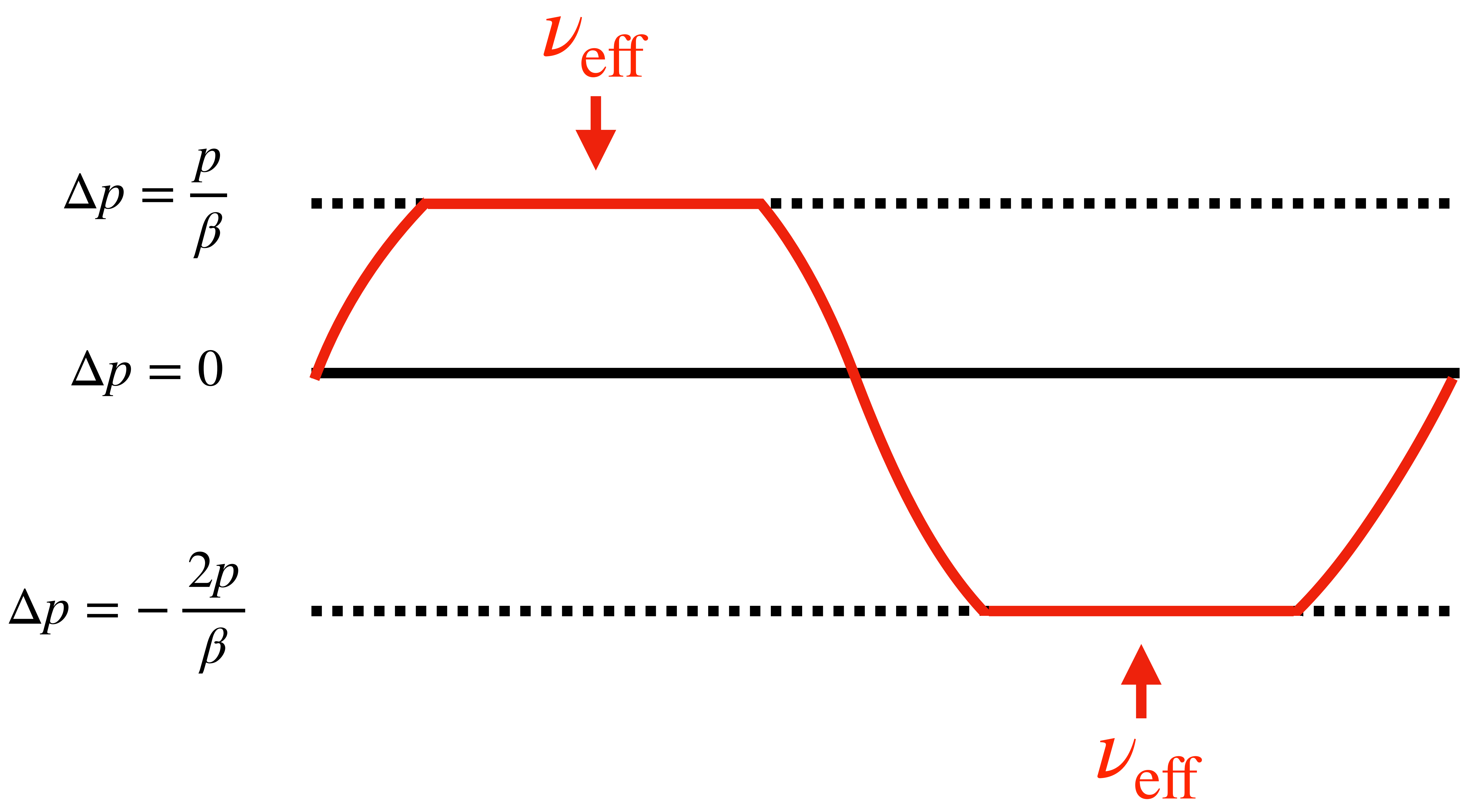

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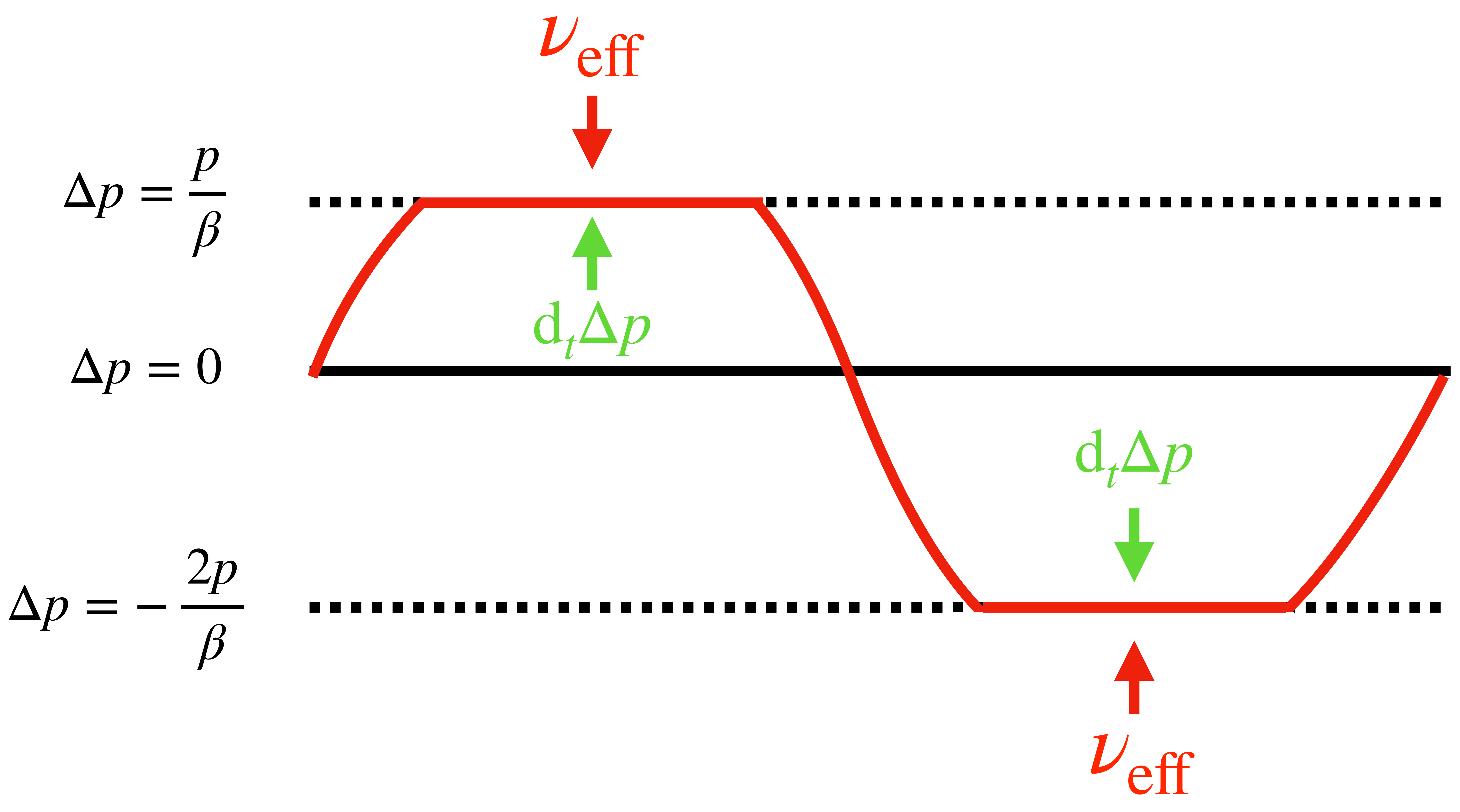


Nonlinear* $k \sim r_{\rm L,i}^{-1}$ fluctuations can break μ, $\mathcal{J}$ conservation

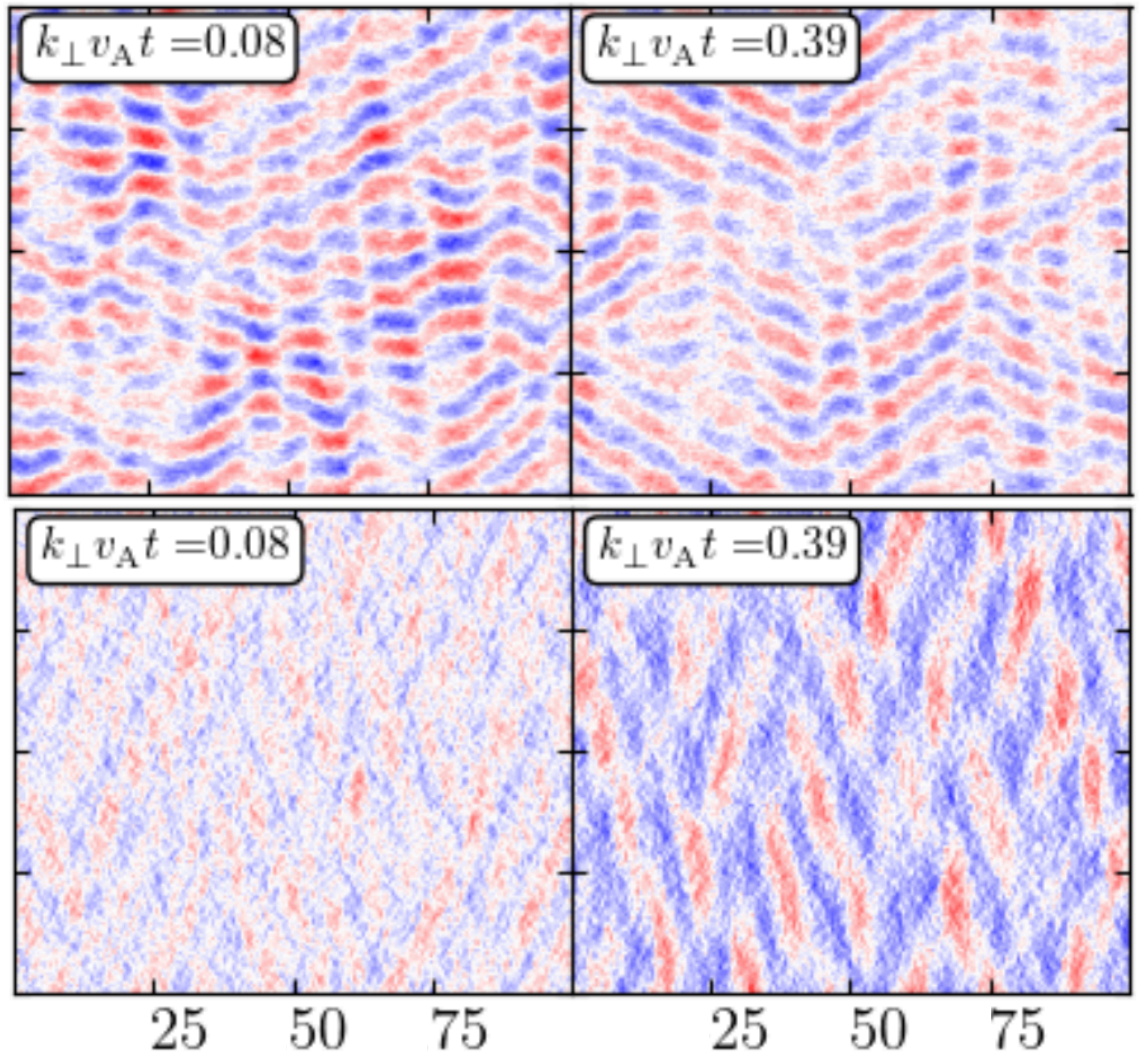
→ Manifests as pitch-angle particle scattering

Marginal stability $\left(-2 \gtrsim \beta \frac{\Delta p}{p} \lesssim 1\right)$ achieved when

$$\nu_{\rm eff} \sim \beta \,|\, 3\hat{b}\hat{b} : \nabla \vec{u} - \nabla \cdot \vec{u} \,|$$

Kunz+ (2014)

$r_{\rm L,i}$ scale δB break μ, $\mathcal{J}_{||}$ conservation

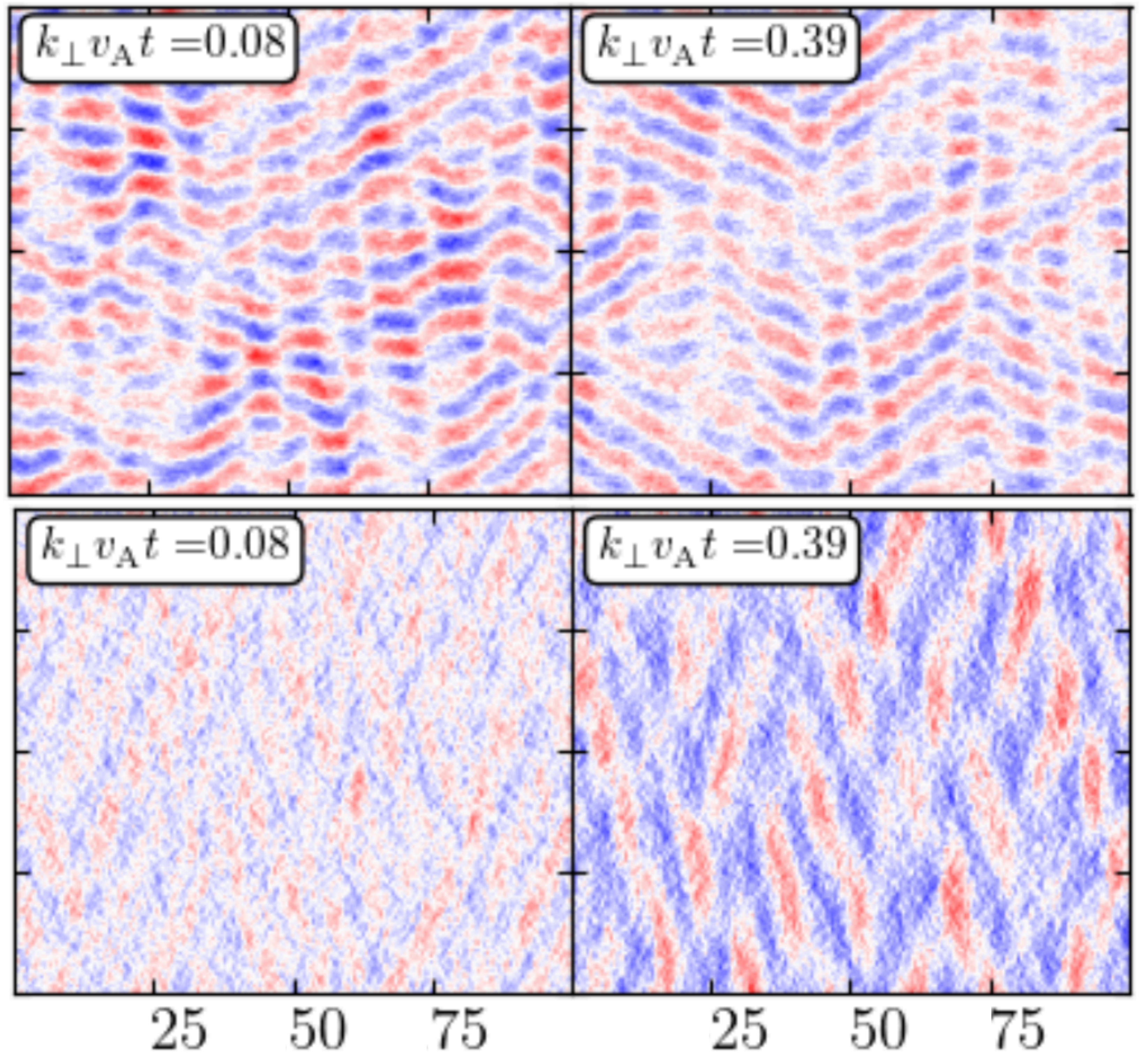


→ $\nu_{\rm eff} \sim \beta | 3\hat{b}\hat{b} : \nabla \vec{u} - \nabla \cdot \vec{u} |$

Kunz+ (2014)

Consequences?

$r_{\mathrm{L,i}}$ scale δB break μ, $\mathcal{J}_{||}$ conservation



$\rightarrow$ $\nu_{\mathrm{eff}} \sim \beta\,|\,3\hat{b}\hat{b} : \nabla\vec{u} - \nabla\cdot\vec{u}\,|$

Kunz+ (2014)

Consequences?

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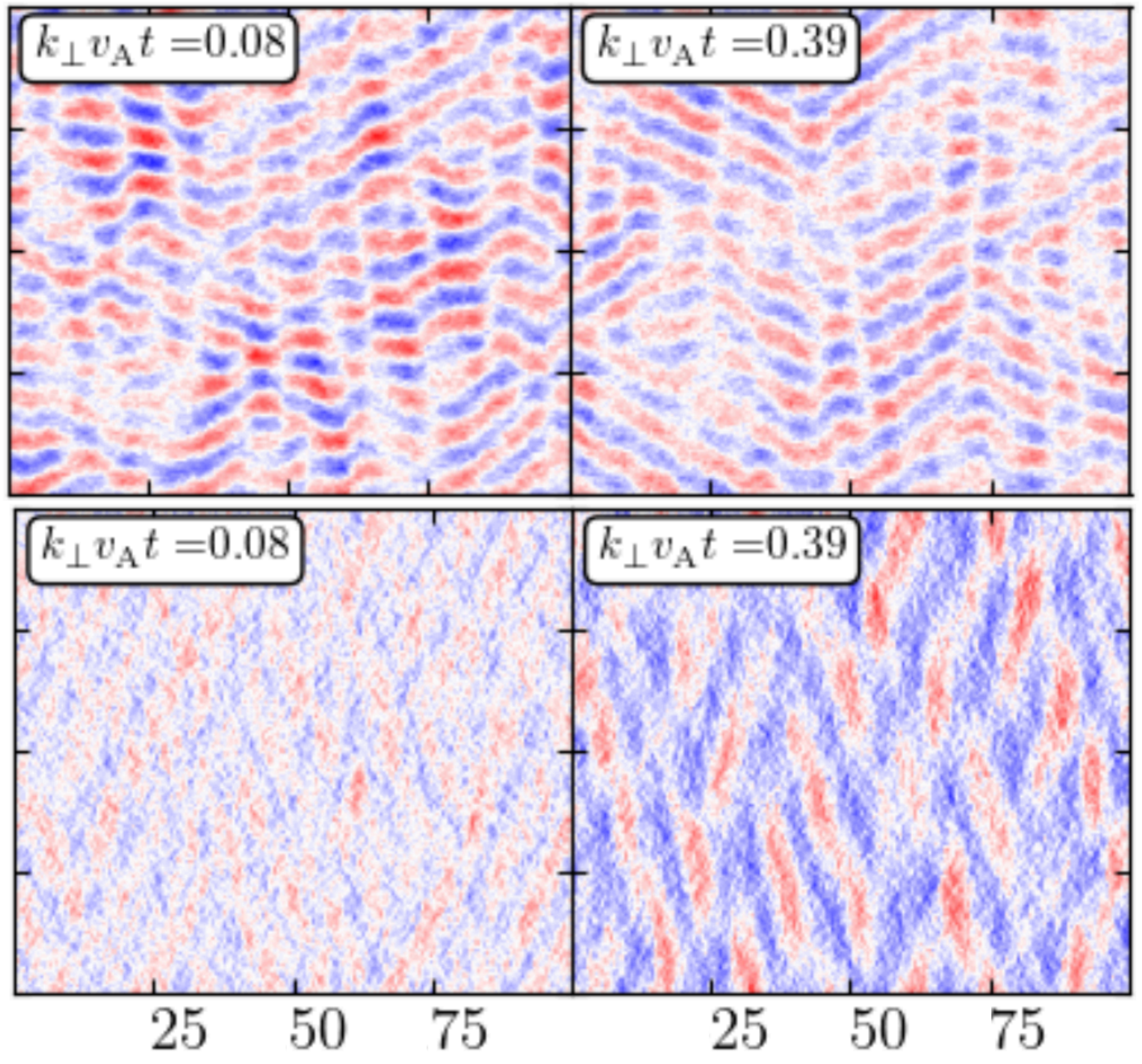
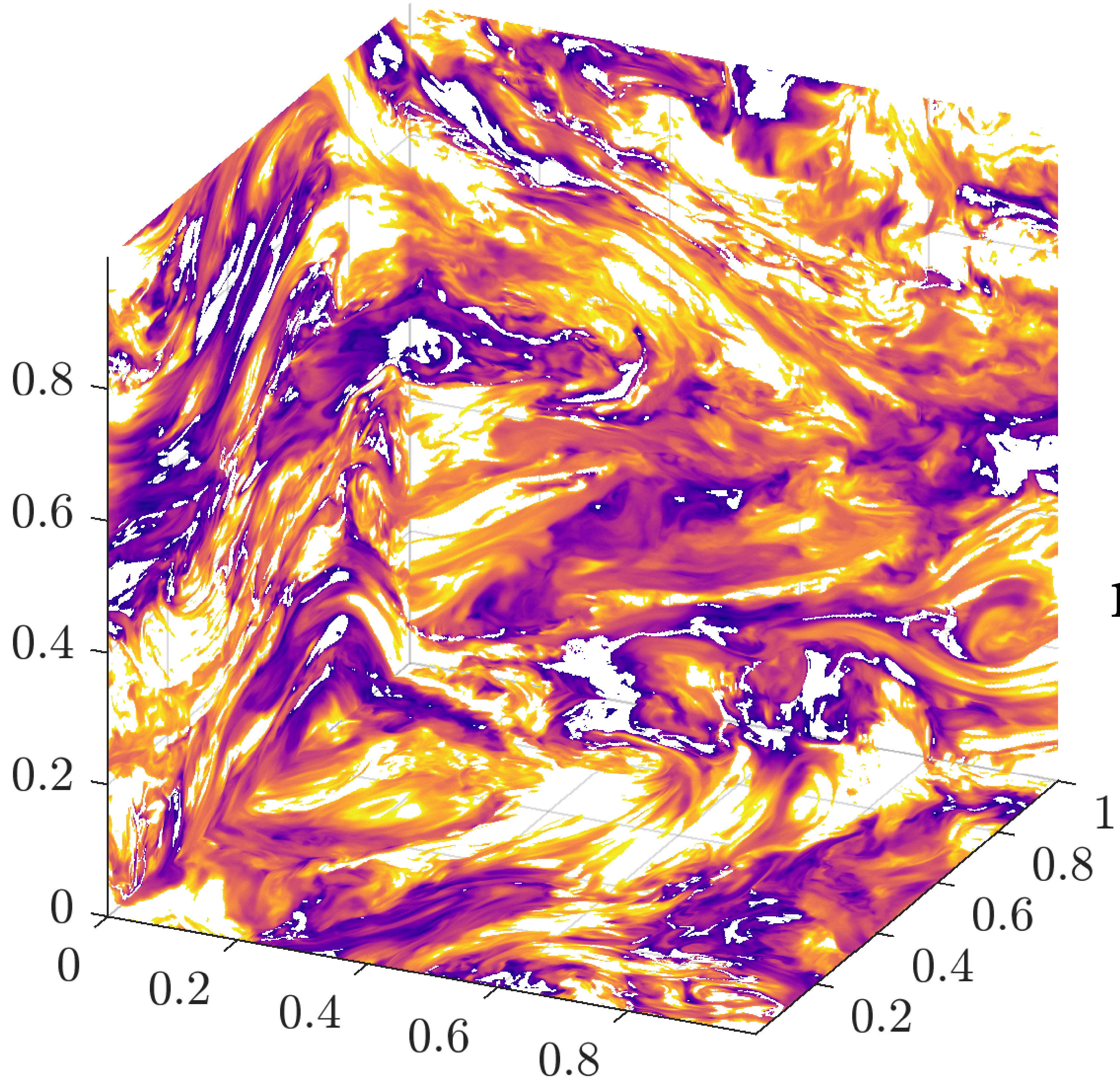


$\rightarrow \; \nu_{\mathrm{eff}} \sim \beta \, | 3\hat{b}\hat{b} : \nabla \vec{u} - \nabla \cdot \vec{u} |$

Kunz+ (2014)

Multi-phase ICM viscosity $\mu_{\mathrm{eff}} \equiv \dfrac{p}{\nu_{\mathrm{eff}}}$

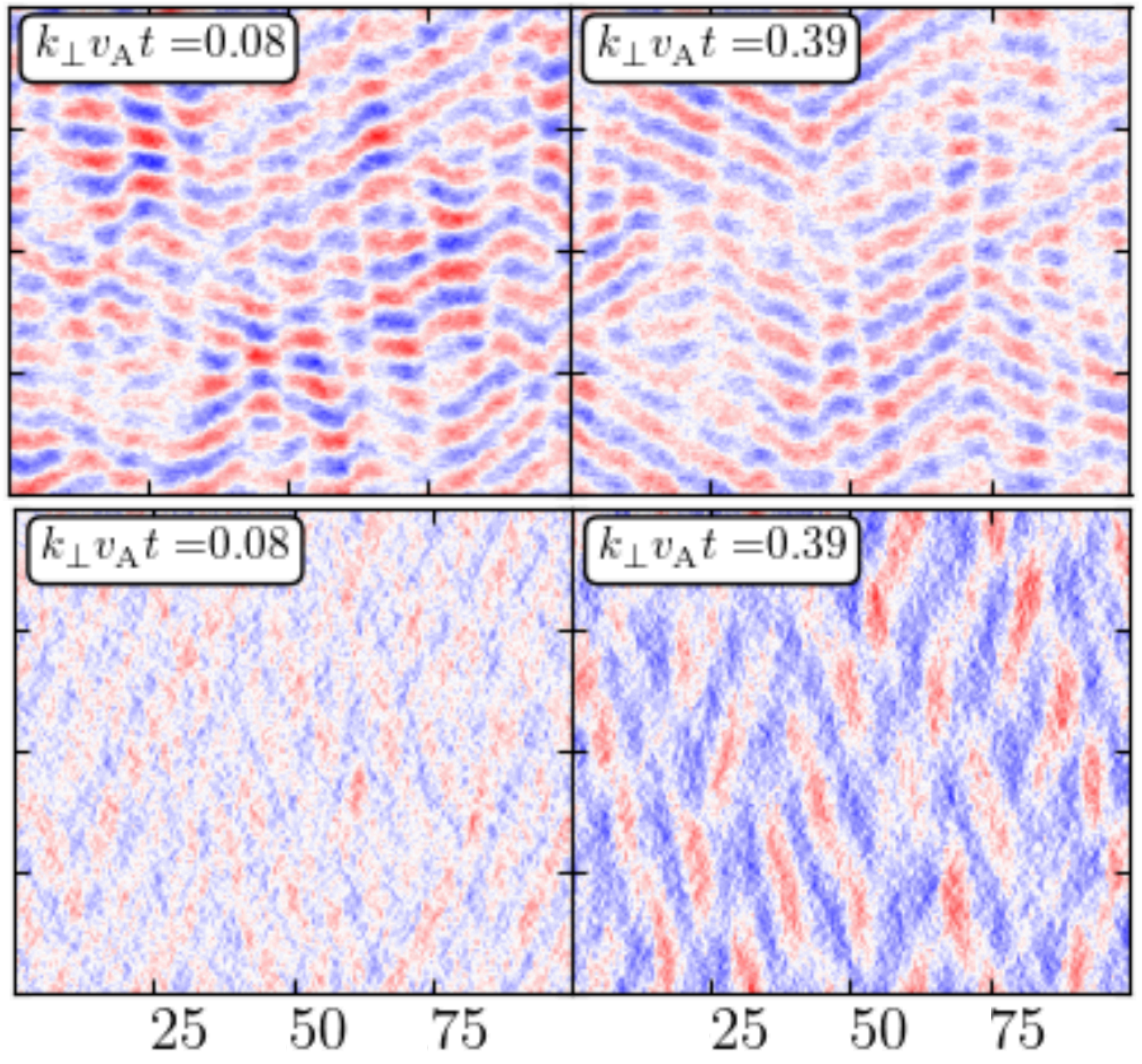


White = micro-unstable

Complex partition of macro- and micro-scale dissipation

S. Majeski+ (in prep. a)

$r_{\mathrm{L,i}}$ scale δB break μ, $\mathcal{J}_{||}$ conservation

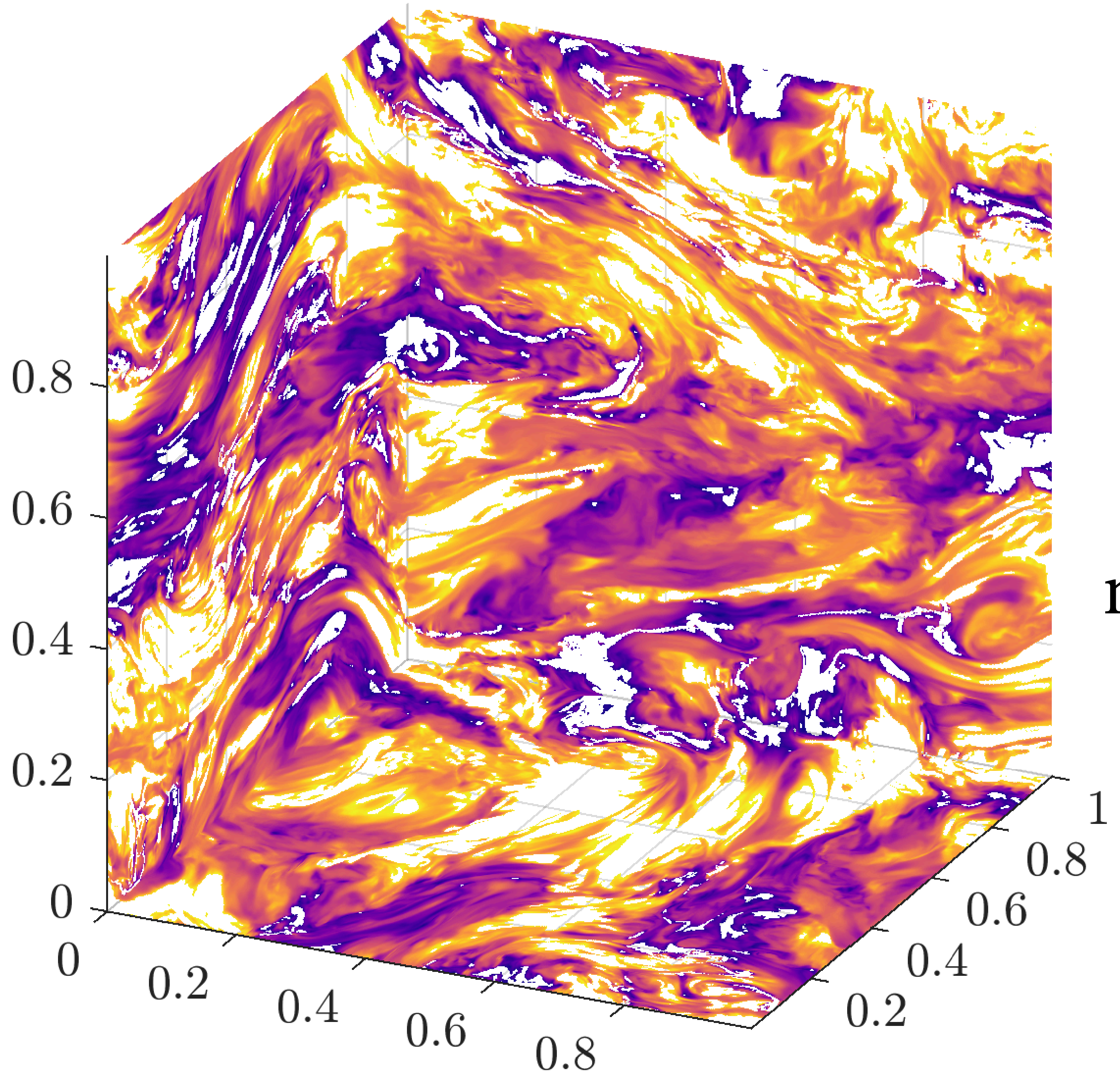


→ $\nu_{\mathrm{eff}} \sim \beta\,|3\hat{b}\hat{b} : \nabla\vec{u} - \nabla\cdot\vec{u}|$

Kunz+ (2014)

Consequences?

Multi-phase ICM viscosity $\mu_{\mathrm{eff}} \equiv \dfrac{p}{\nu_{\mathrm{eff}}}$



White = micro-unstable

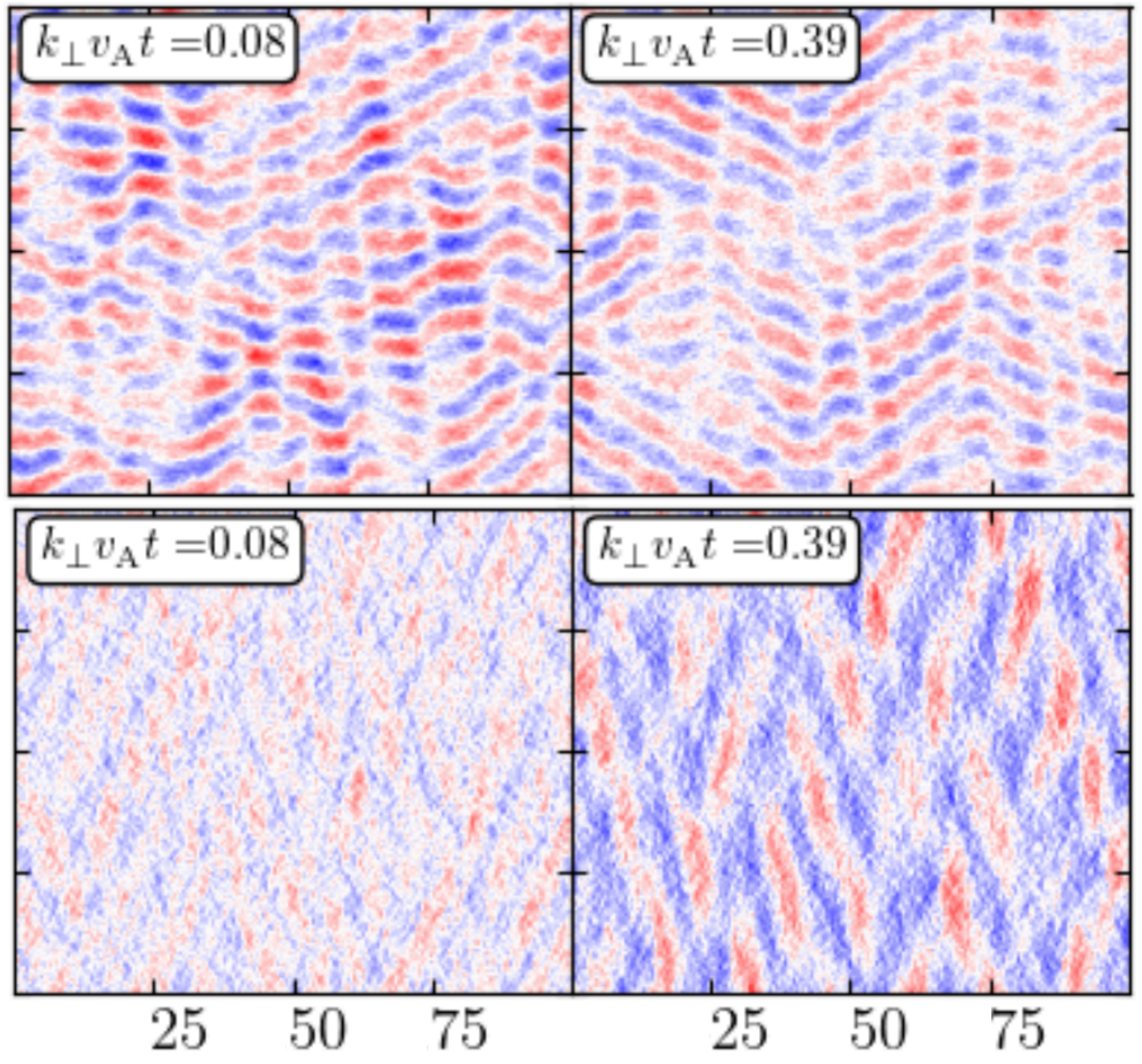
Cascade does not end at viscous scale!

(details available upon reasonable request)

S. Majeski+ (in prep. a)

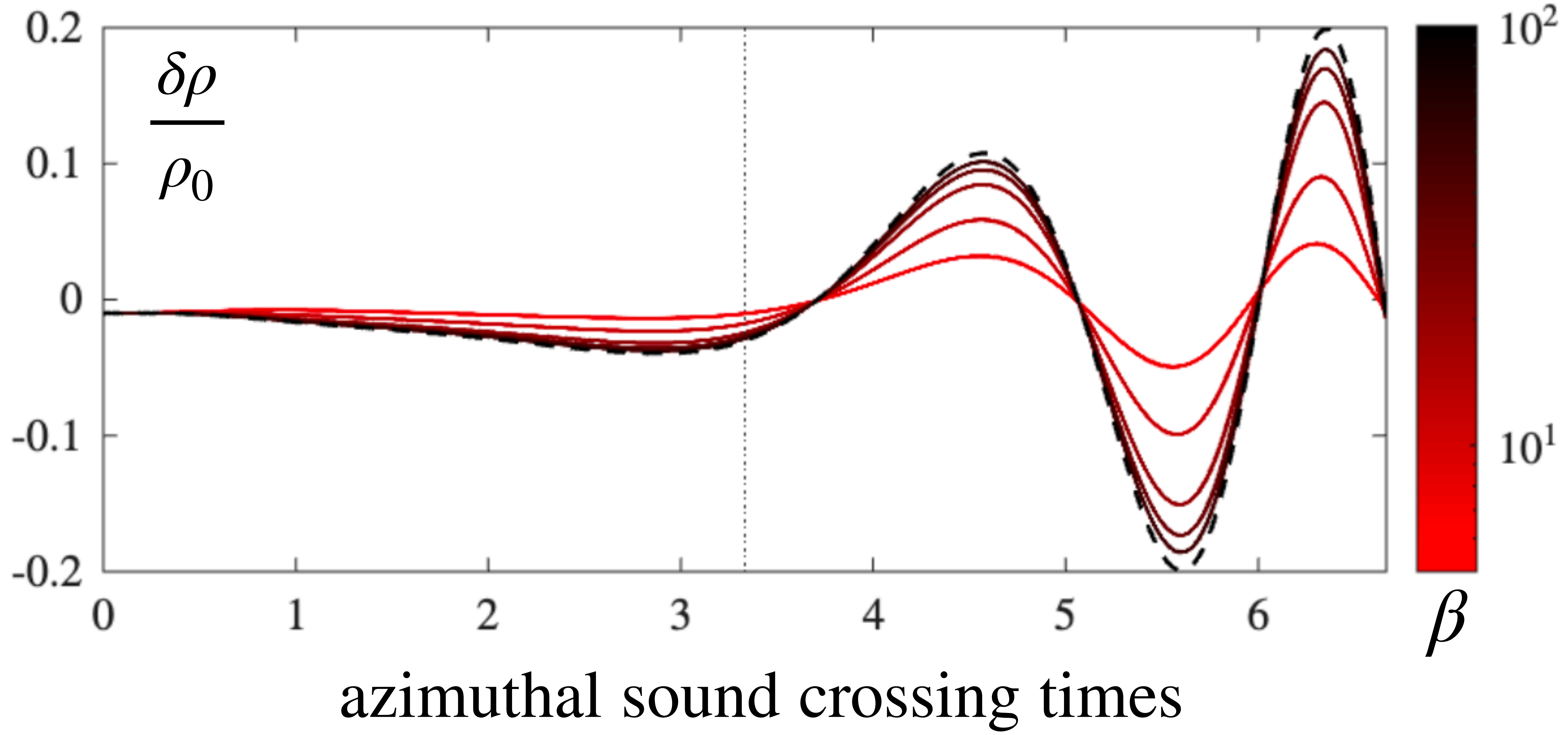
Consequences?

$r_{\mathrm{L,i}}$ scale δB break μ, $\mathcal{J}_{||}$ conservation



$\rightarrow$ $\nu_{\mathrm{eff}} \sim \beta\,|3\hat{b}\hat{b} : \nabla\vec{u} - \nabla\cdot\vec{u}\,|$

μ_{eff} determines the strength of spiral waves that affect variability of the GCAF



Kunz+ (2014)

S. Majeski+ (in prep. b)

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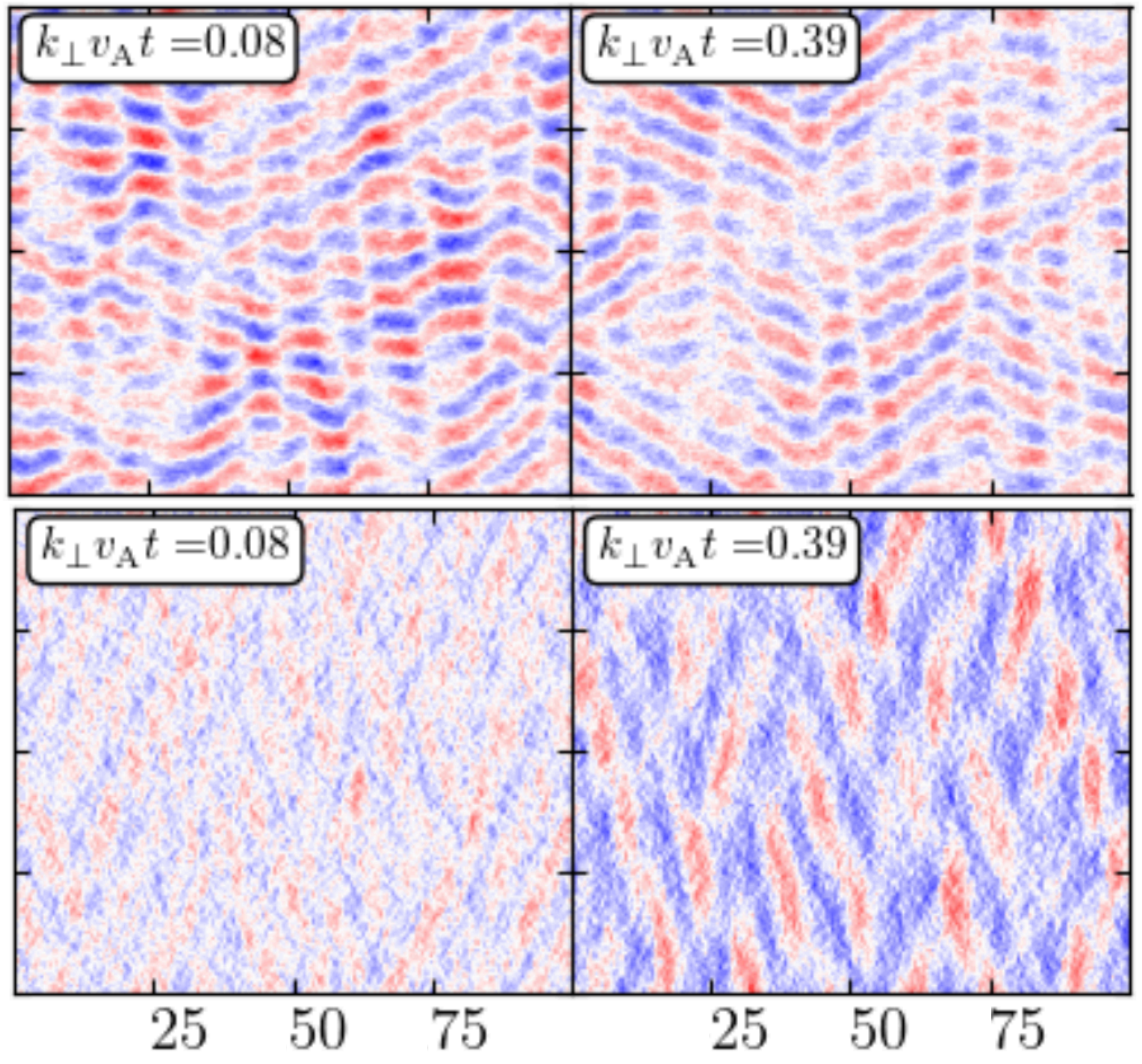
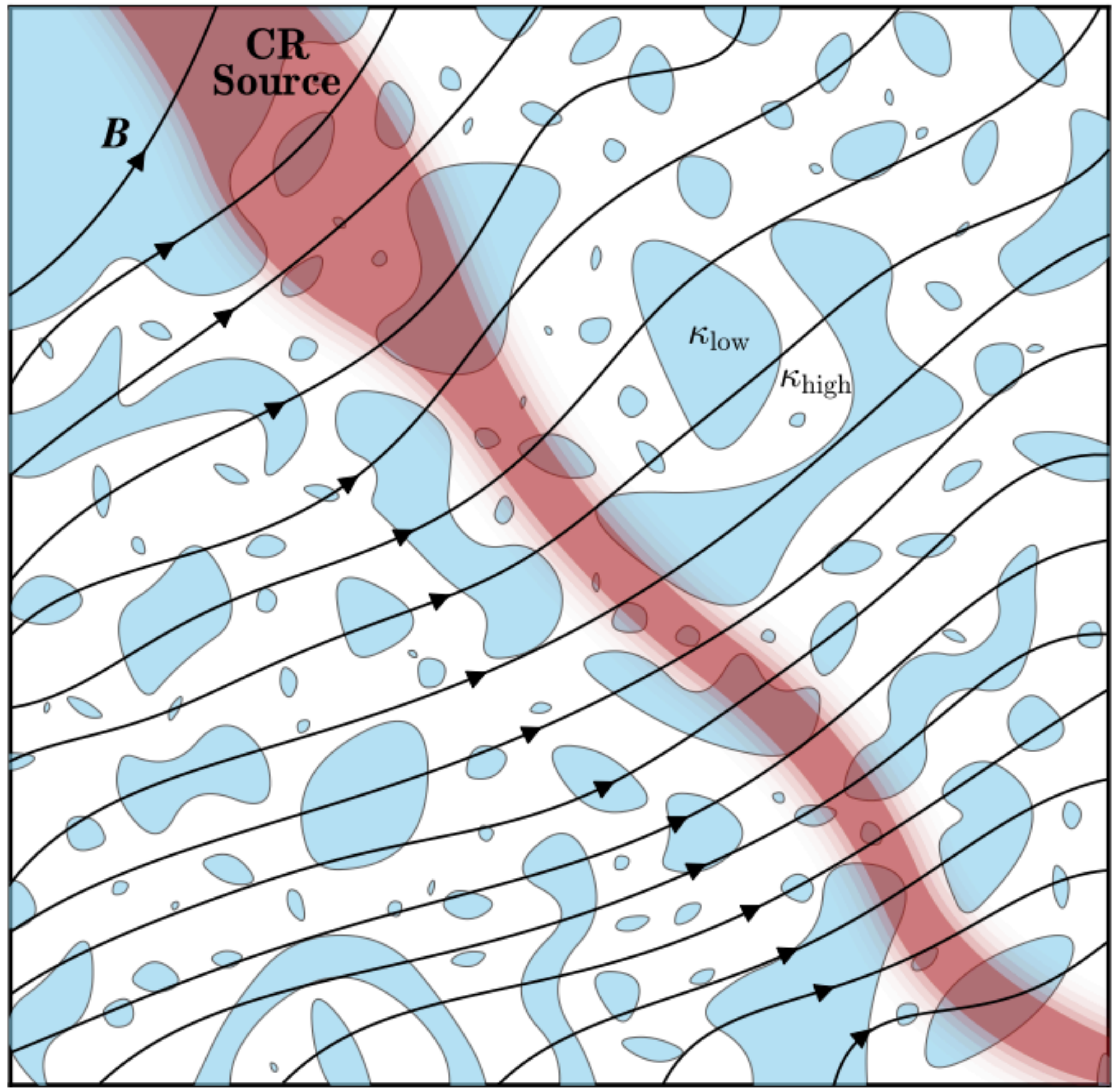




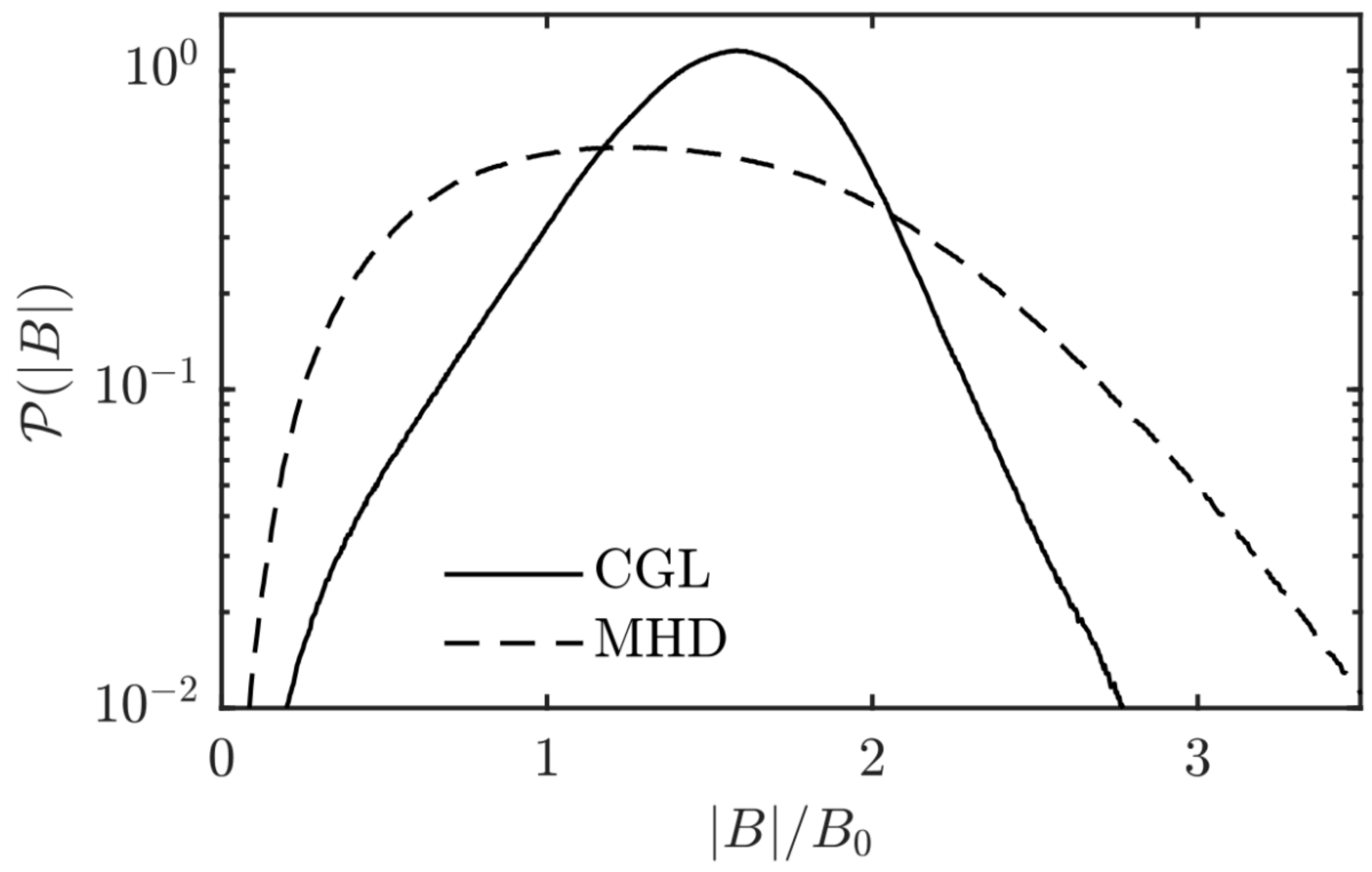
Mirrors *extremely* good at scattering cosmic rays, may dominate their transport (ICM)

$$\rightarrow \quad \nu_{\mathrm{eff}} \sim \beta \,|\, 3\hat{b}\hat{b} : \nabla \vec{u} - \nabla \cdot \vec{u} \,|$$

Ewart+ (2025, incl. SM)
Reichherzer+ (in prep, incl. SM)

Kunz+ (2014)

High-β, weakly collisional turbulence avoids δB:



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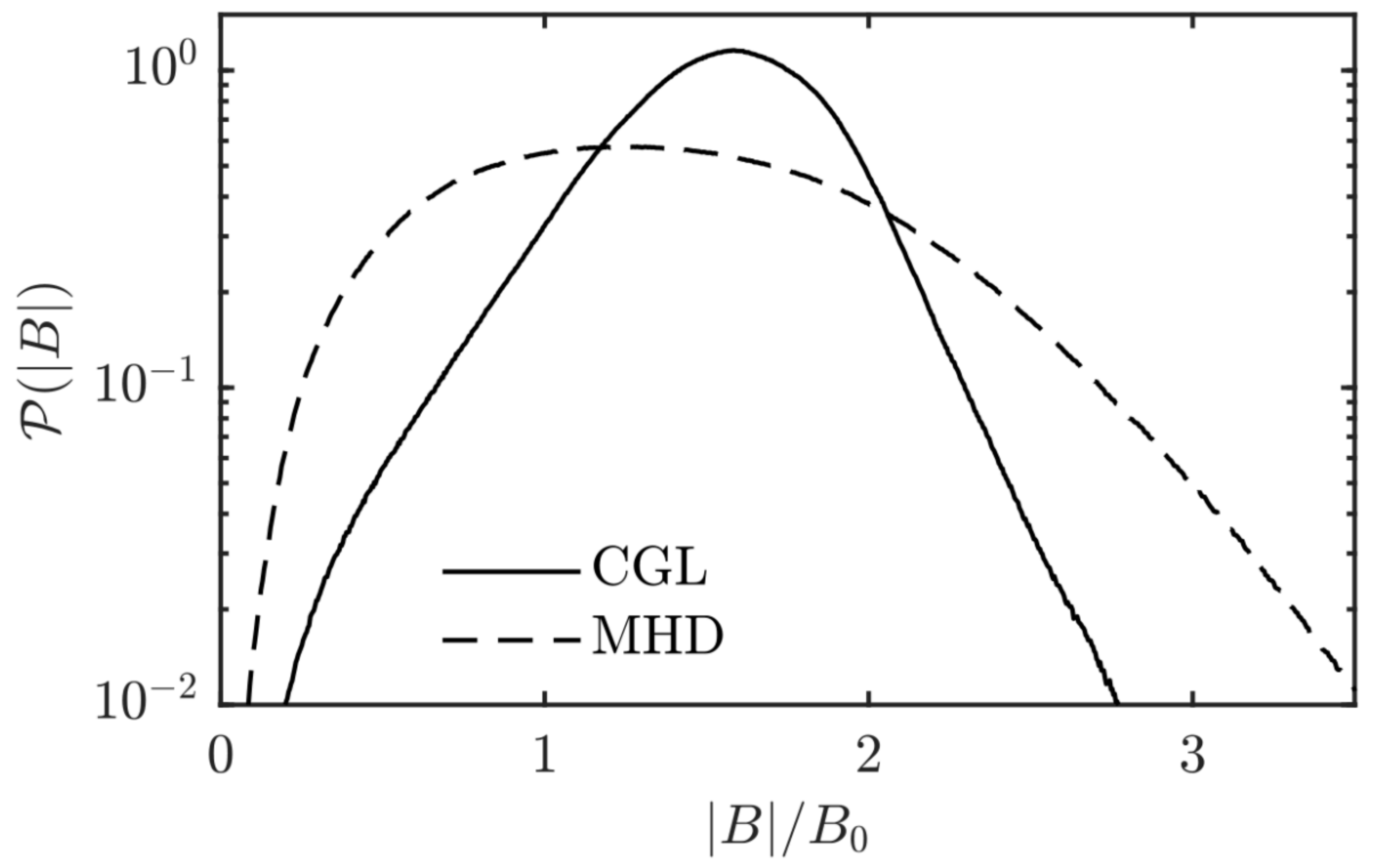

→ suppresses Δp and therefore viscous dissipation

Self-organization: Magneto-immutability

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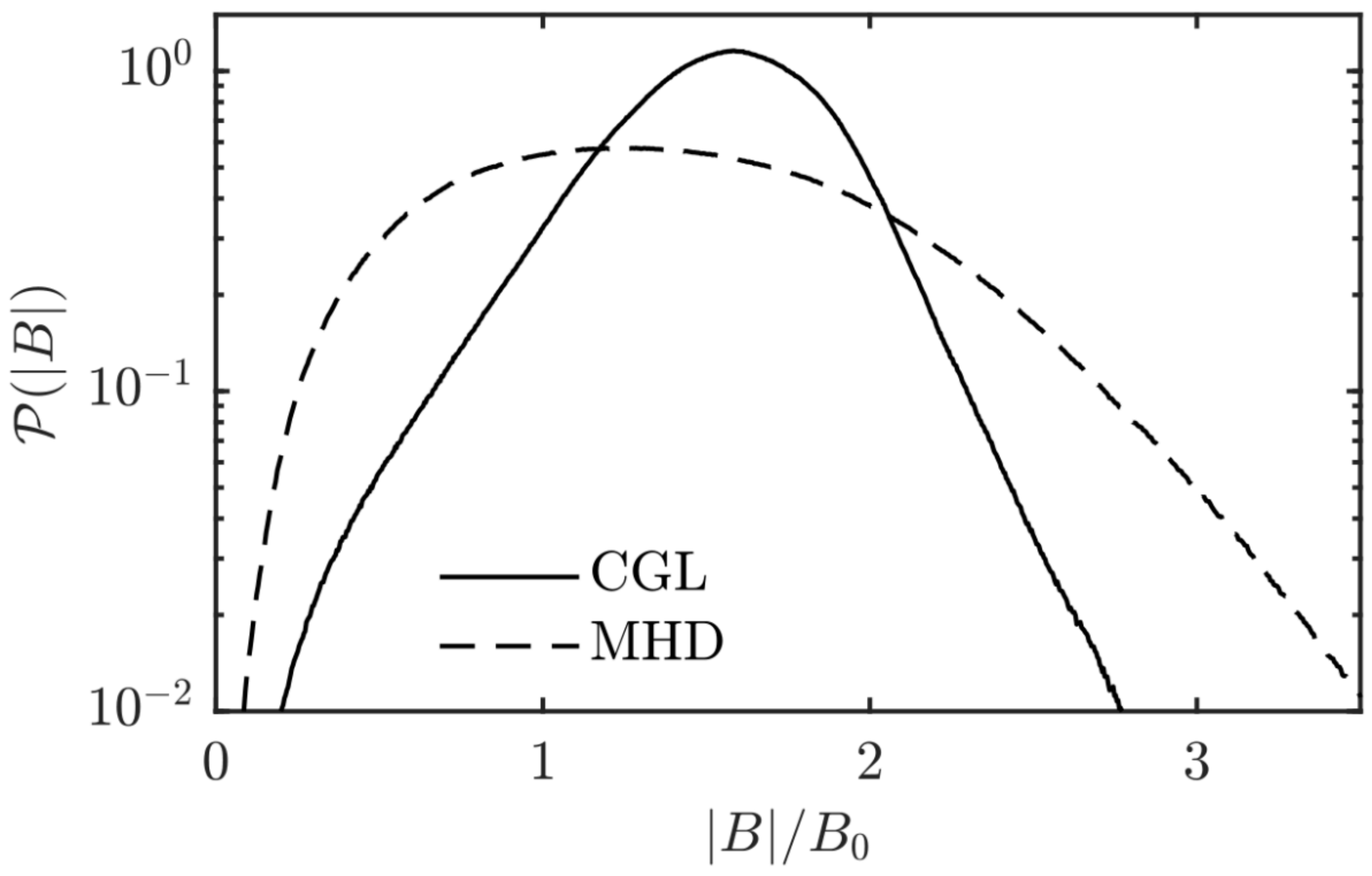
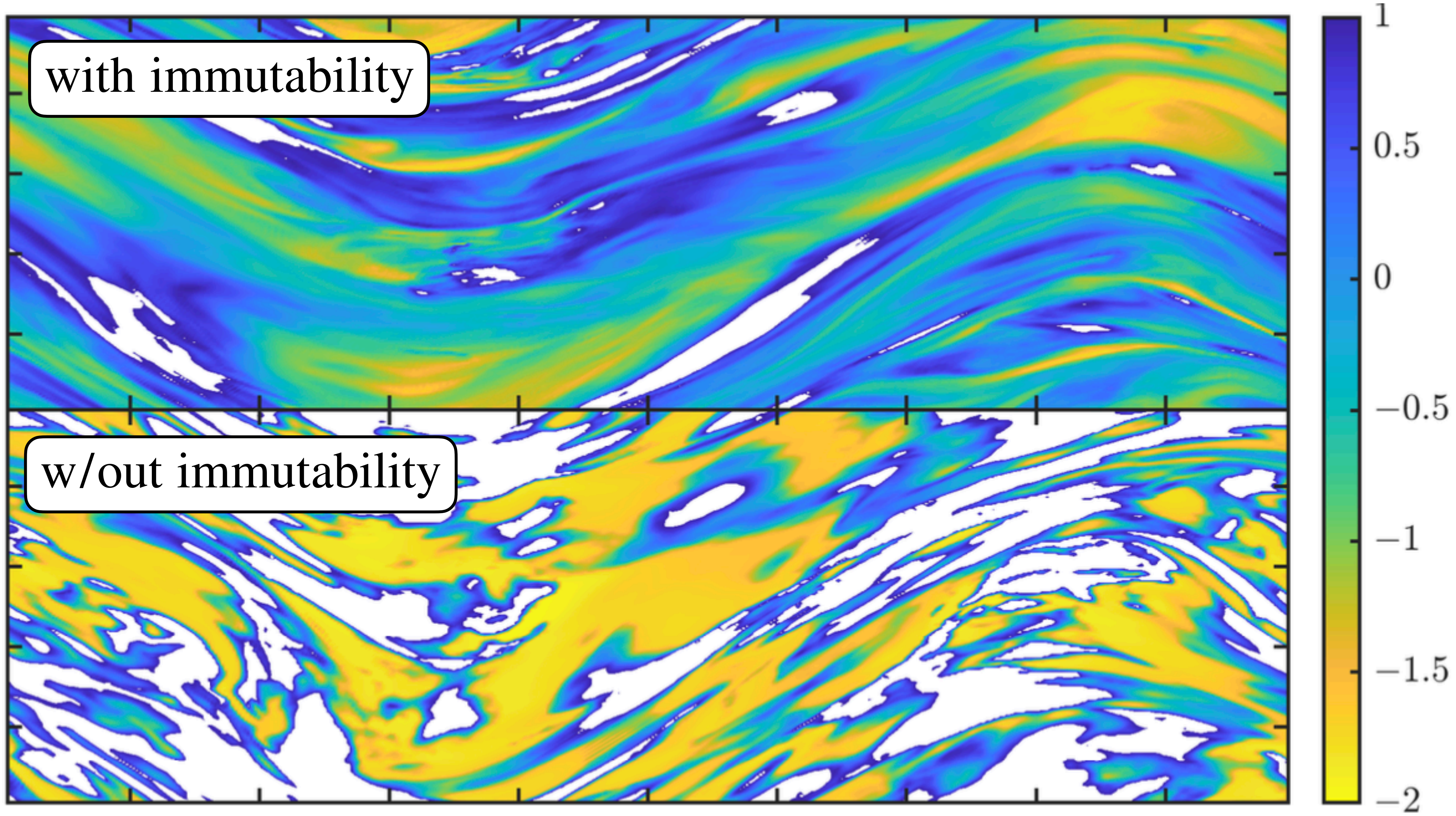


→ suppresses Δp and therefore viscous dissipation

$\Delta\beta$ (unstable regions in white)



→Shown to exist in ICM and magnetorotational turbulence

Squire+ (2019, 2023), Kempski+ (2020), Majeski+ (2024)

Why might you care?

Micro-instabilities known to play a role in the solar wind (see Peter's plenary talk slides!)

➔ *What sets how frequently they are triggered in Alfvénic turbulence?*

➔ *What about magneto-immutable self-organization?*

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Mirror machines can be relatively high-β:

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Some laser-driven experiments probe high-beta, magnetized regime

➔ *Demonstrated role of whistler heat flux instability in regulating electron heat flow (see several works by A.F.A. Bott)*

➔ *Interaction of small- and large-scale dynamics, e.g. turbulence, dynamo…*

Backup Slides

High-β, collisionless turbulence: numerics

CGL-MHD:

$$\rho_{\rm i}/L \lll 1$$

$$p_\perp \frac{\mathrm{d}}{\mathrm{d}t} \ln \frac{p_\perp}{nB} = -\nabla \cdot (q_\perp \hat{b}) - q_\perp \nabla \cdot \hat{b}$$

$$p_\parallel \frac{\mathrm{d}}{\mathrm{d}t} \ln \frac{p_\parallel B^2}{n^3} = -\nabla \cdot (q_\parallel \hat{b}) + 2 q_\perp \nabla \cdot \hat{b}$$

'3+1' Landau-fluid heat fluxes:

$$q_\parallel = -\frac{8 c_{\rm s\parallel}^2}{\sqrt{8\pi} c_{\rm s\parallel} \left| k_\parallel \right|} n \nabla_\parallel \left(\frac{p_\parallel}{n} \right)$$

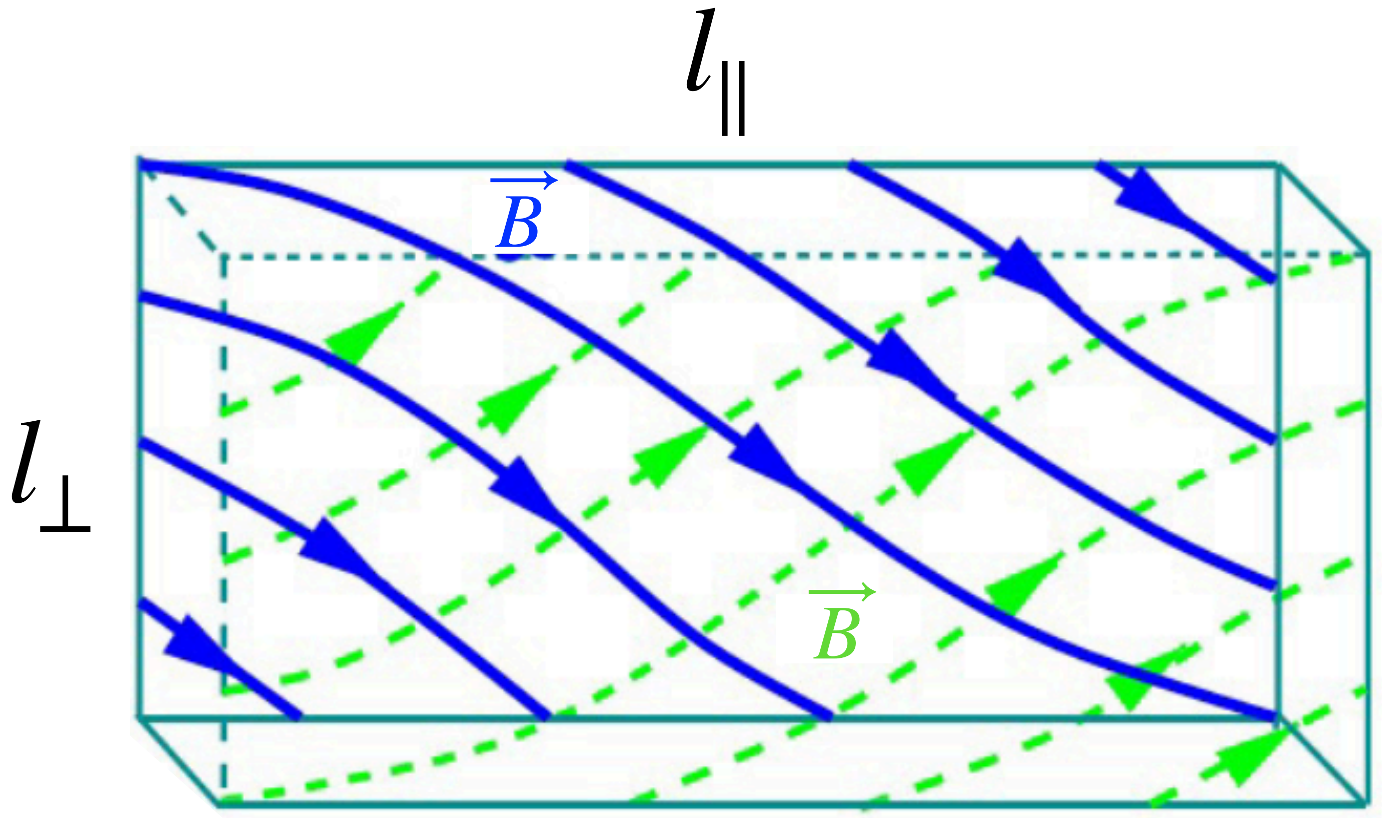
$$q_\perp = -\frac{2 c_{\rm s\parallel}^2}{\sqrt{2\pi} c_{\rm s\parallel} \left| k_\parallel \right|} \left[n \nabla_\parallel \left(\frac{p_\perp}{n} \right) - p_\perp \left(1 - \frac{p_\perp}{p_\parallel} \right) \frac{\nabla_\parallel B}{B} \right]$$

(Snyder+ 1997)

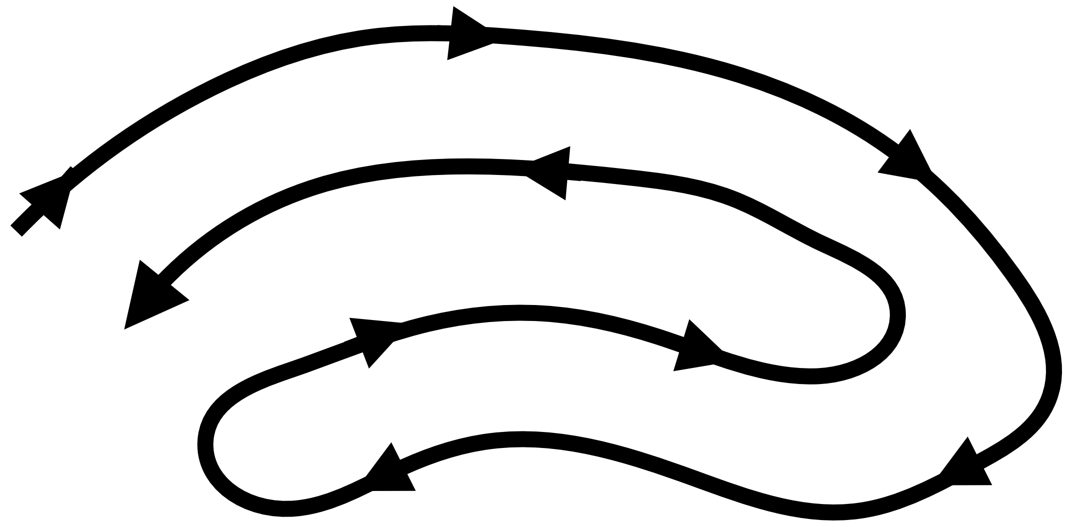
Suppressing $\hat{b}\hat{b} : \nabla \vec{u}$

Suppressing $\hat{b}\hat{b} : \nabla \vec{u}$

Magnetized turbulence and dynamo are anisotropic
($k_\perp \gg k_\parallel$ when $u_l \ll v_A$ — after $l_{\mu,\mathrm{eff}}$)



(Boldyrev '06)


(Schekochihin+ '02)

➔ Isotropic spectrum $\mathscr{E}(k)$ is dominated by $k_\perp$

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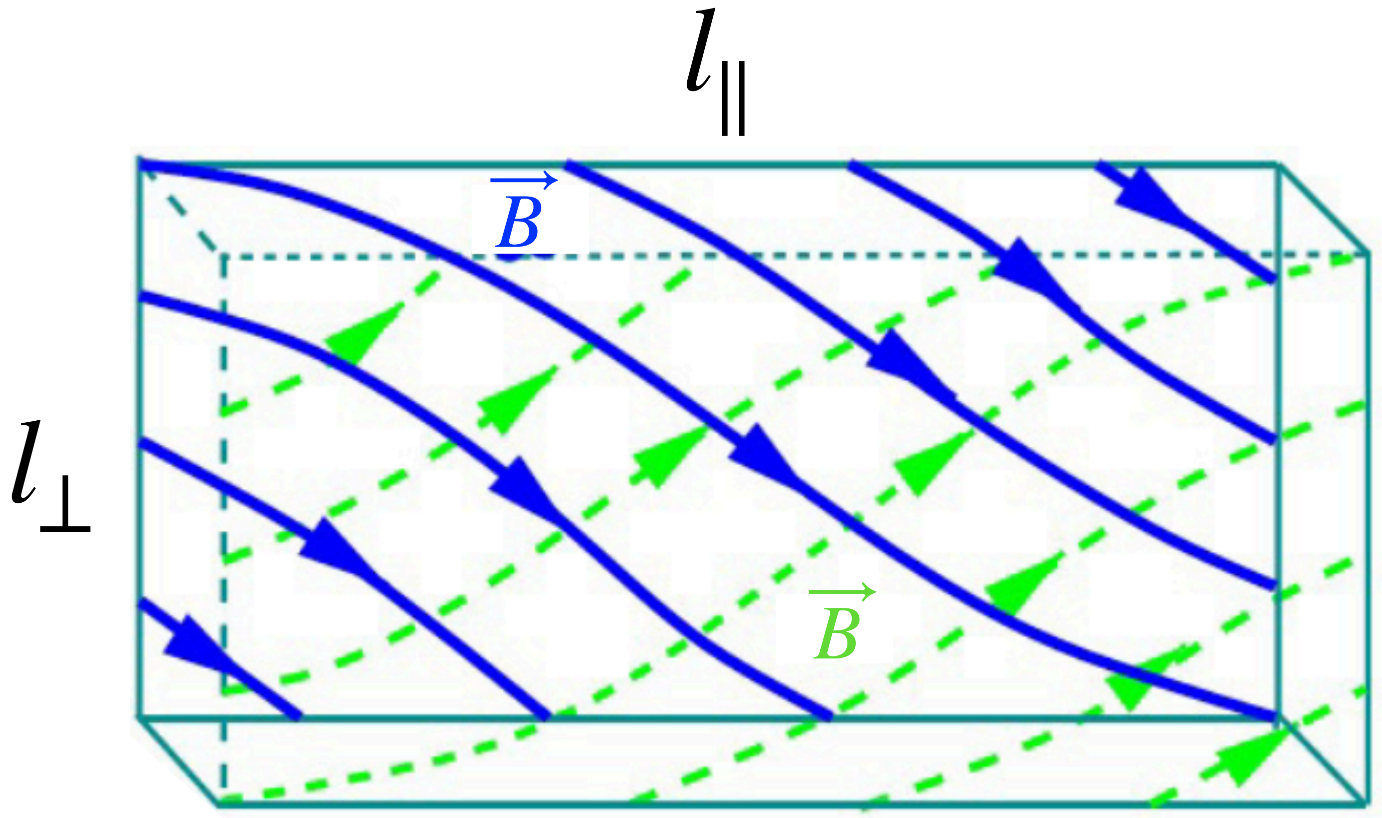

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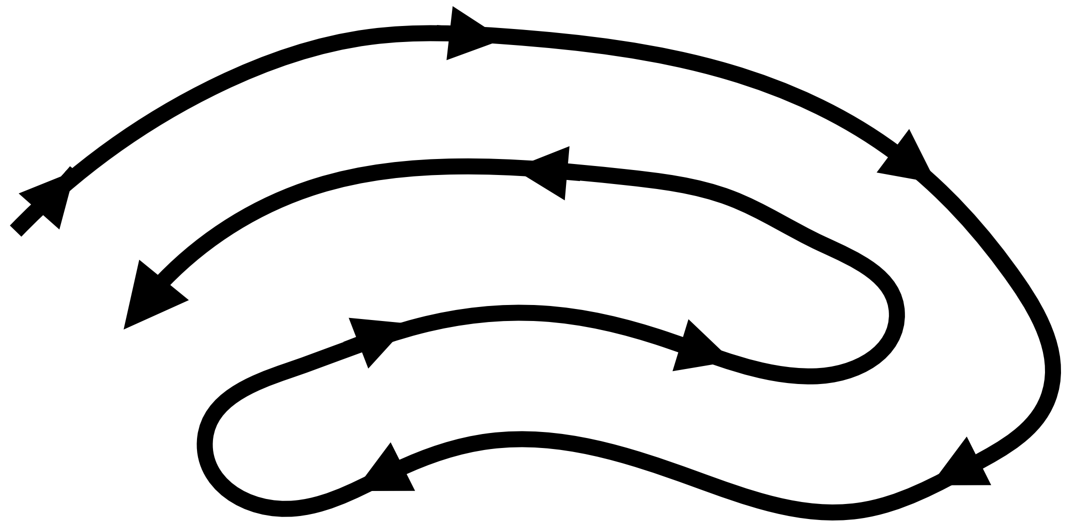
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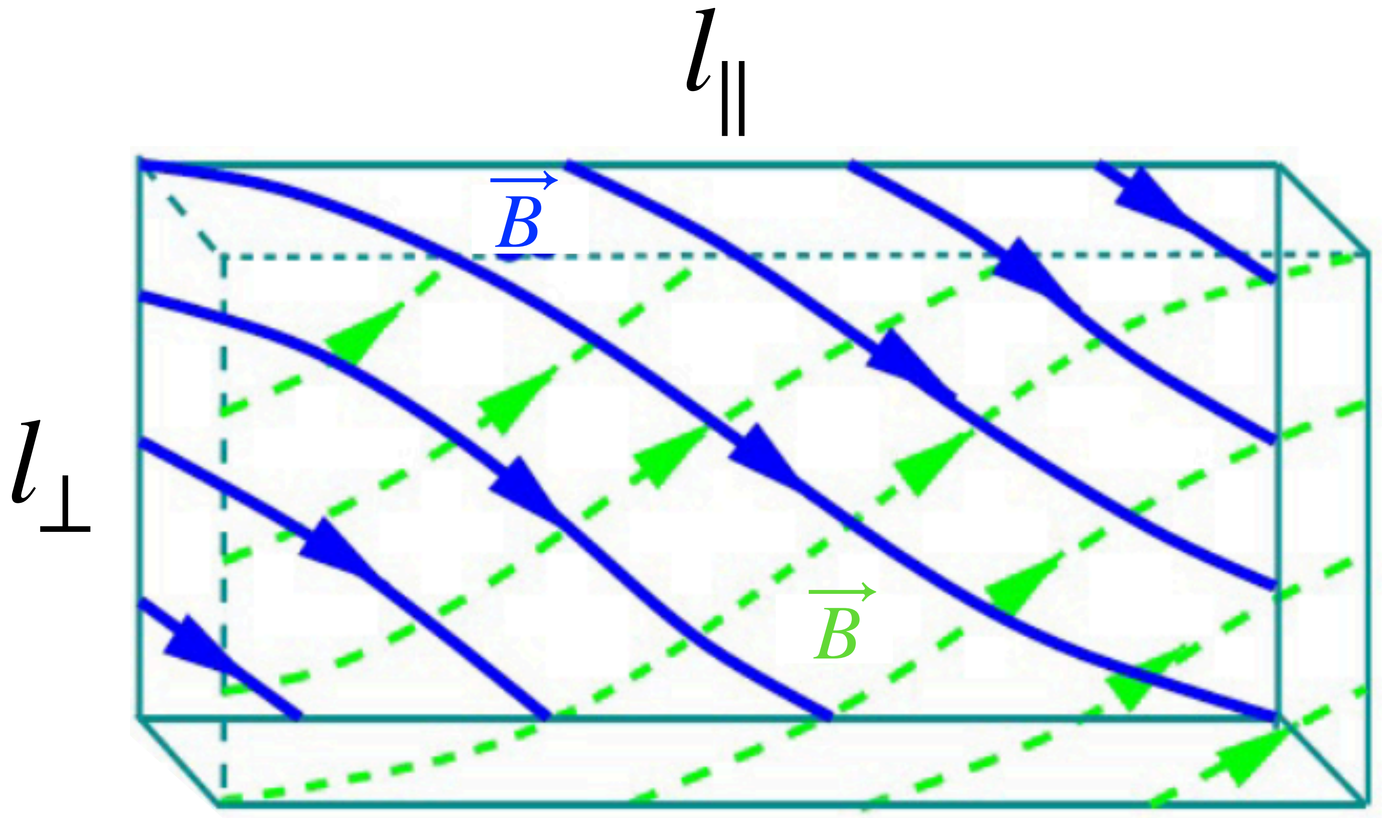

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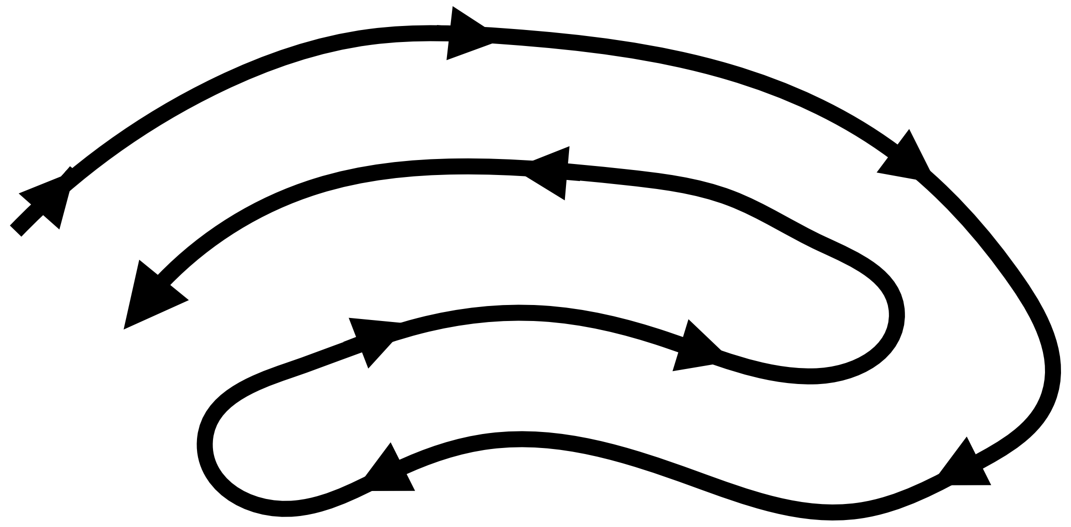
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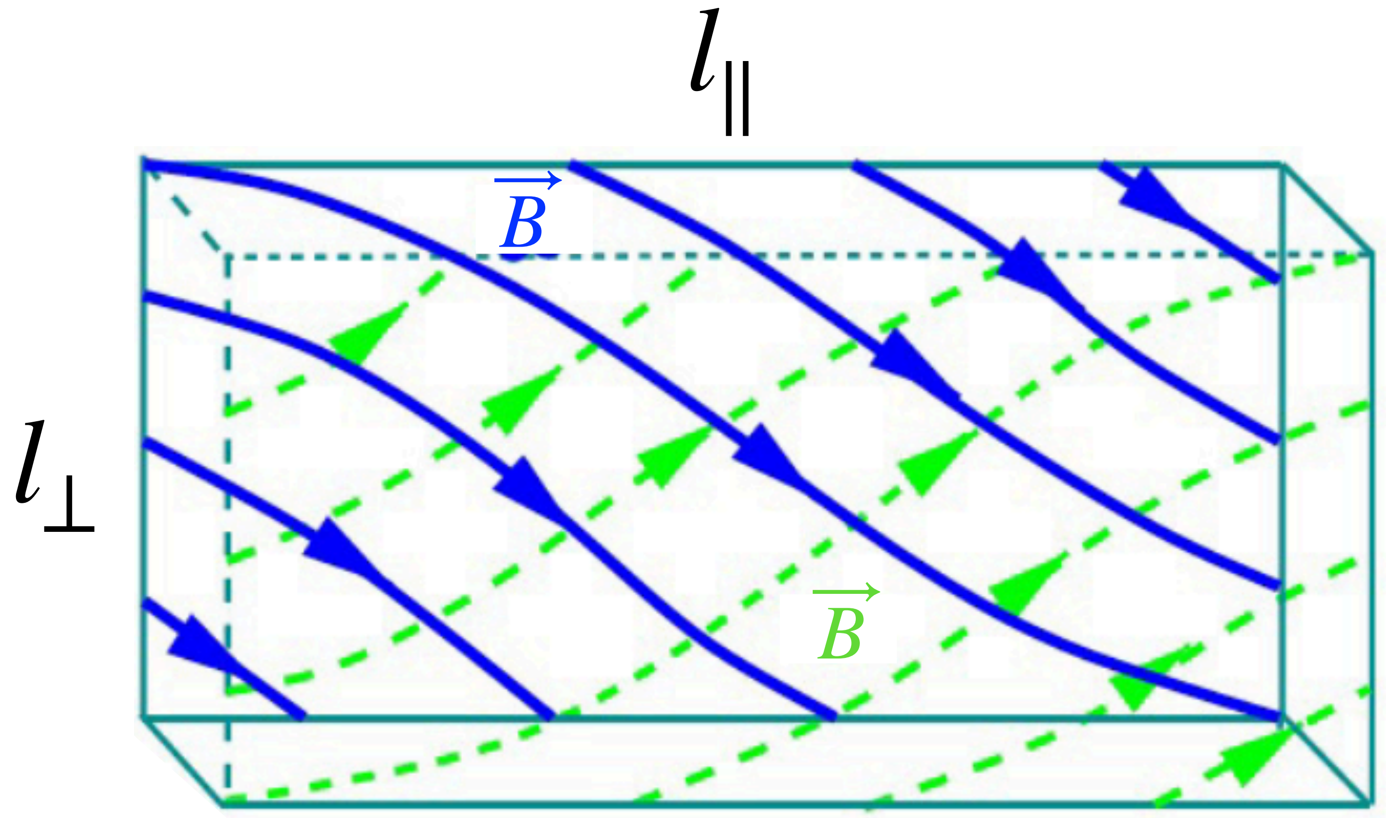

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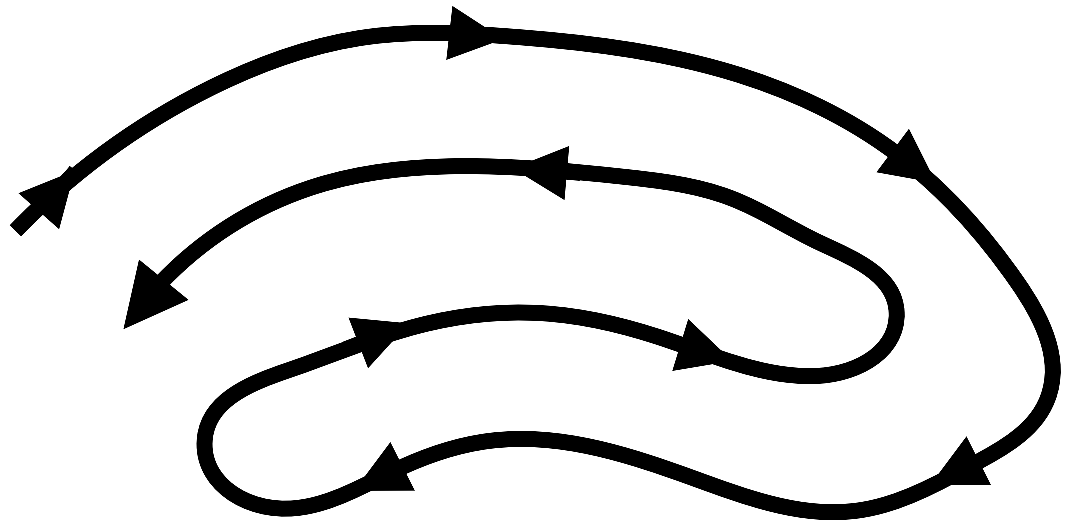

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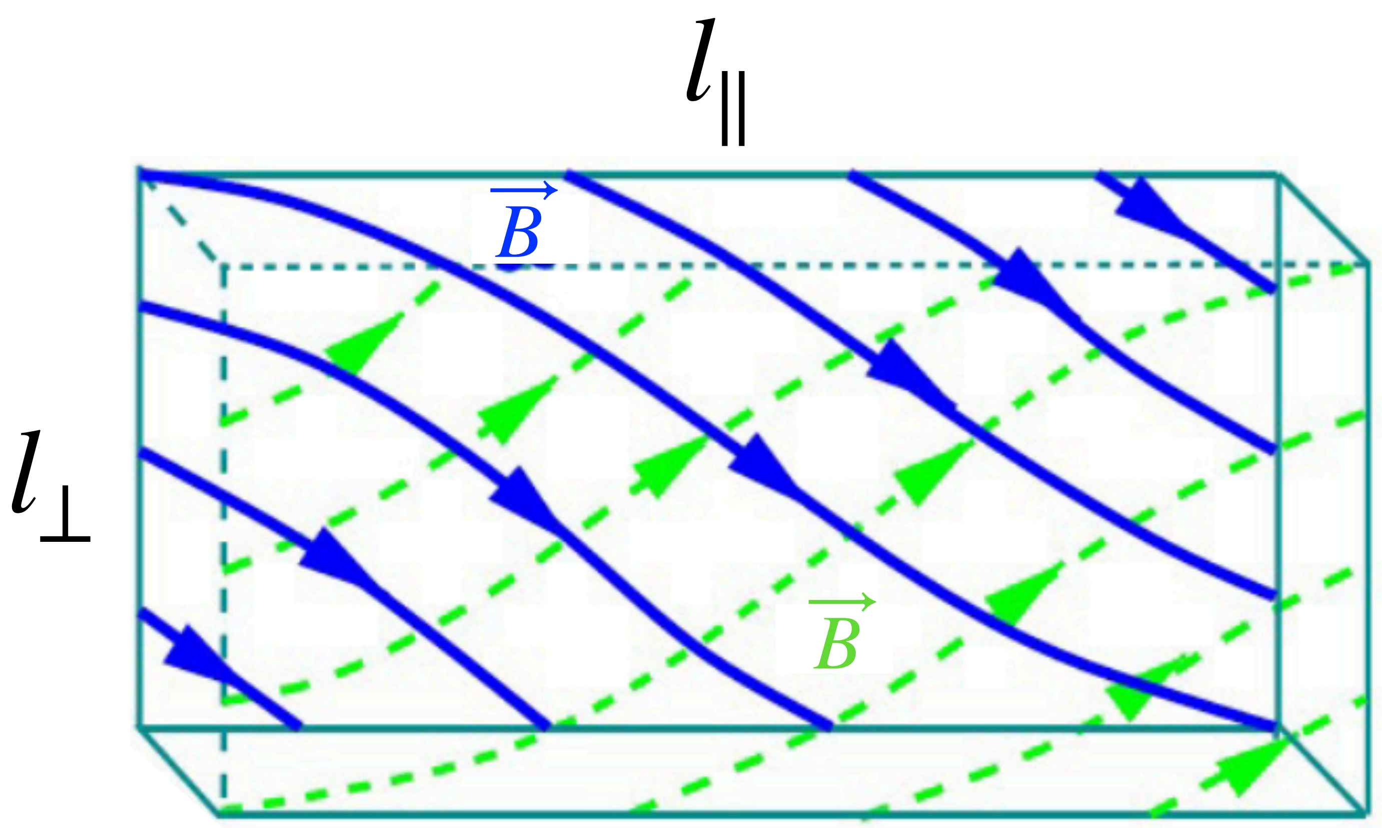

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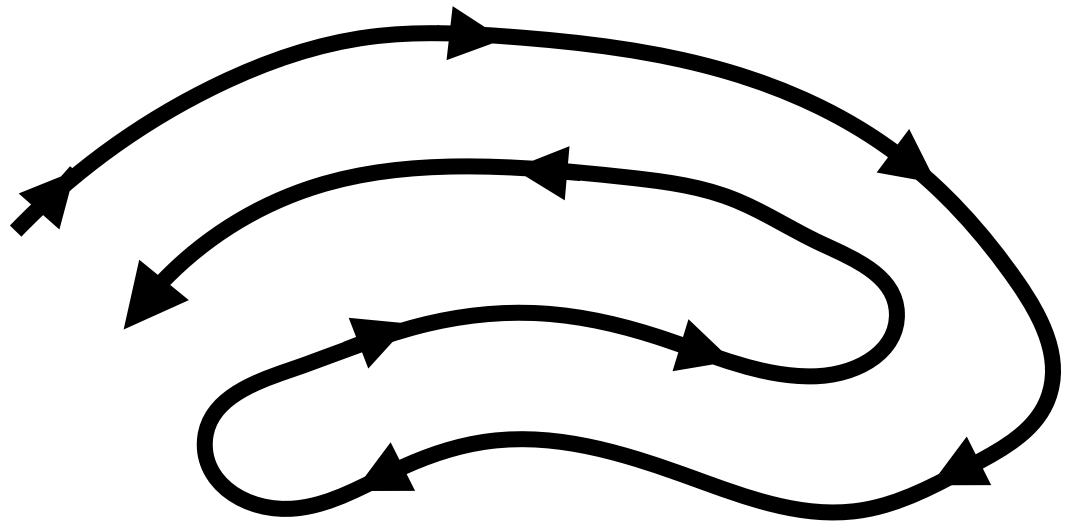

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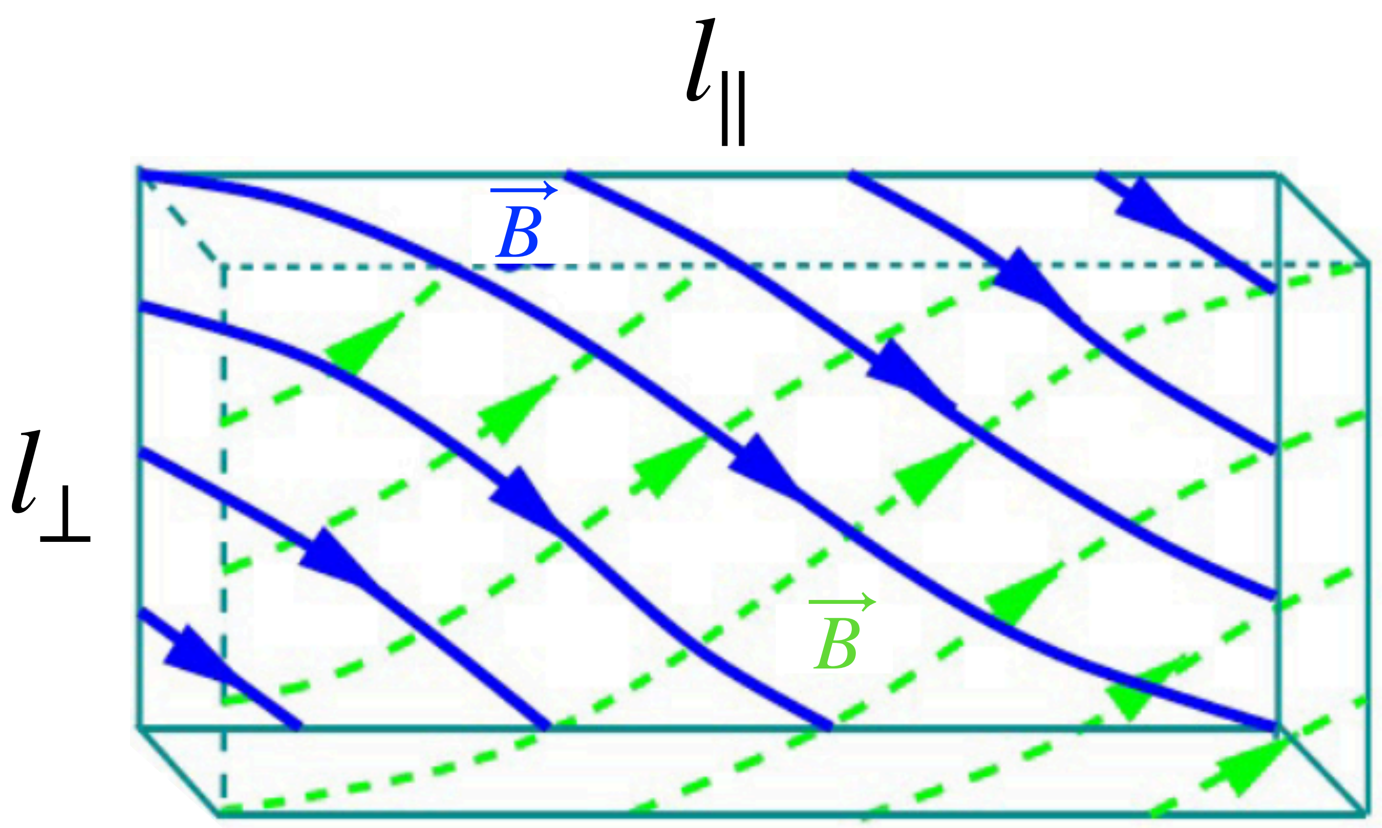

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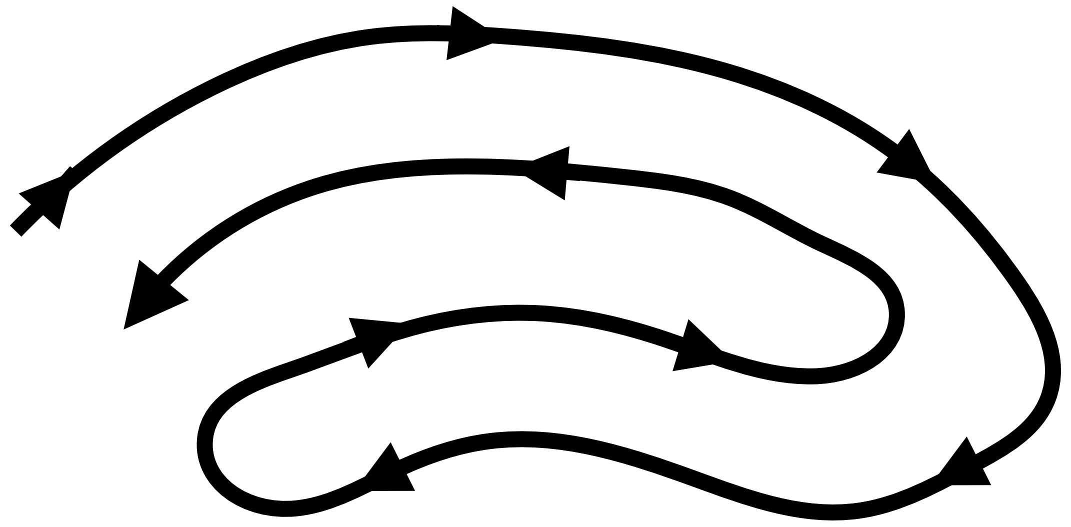

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↓

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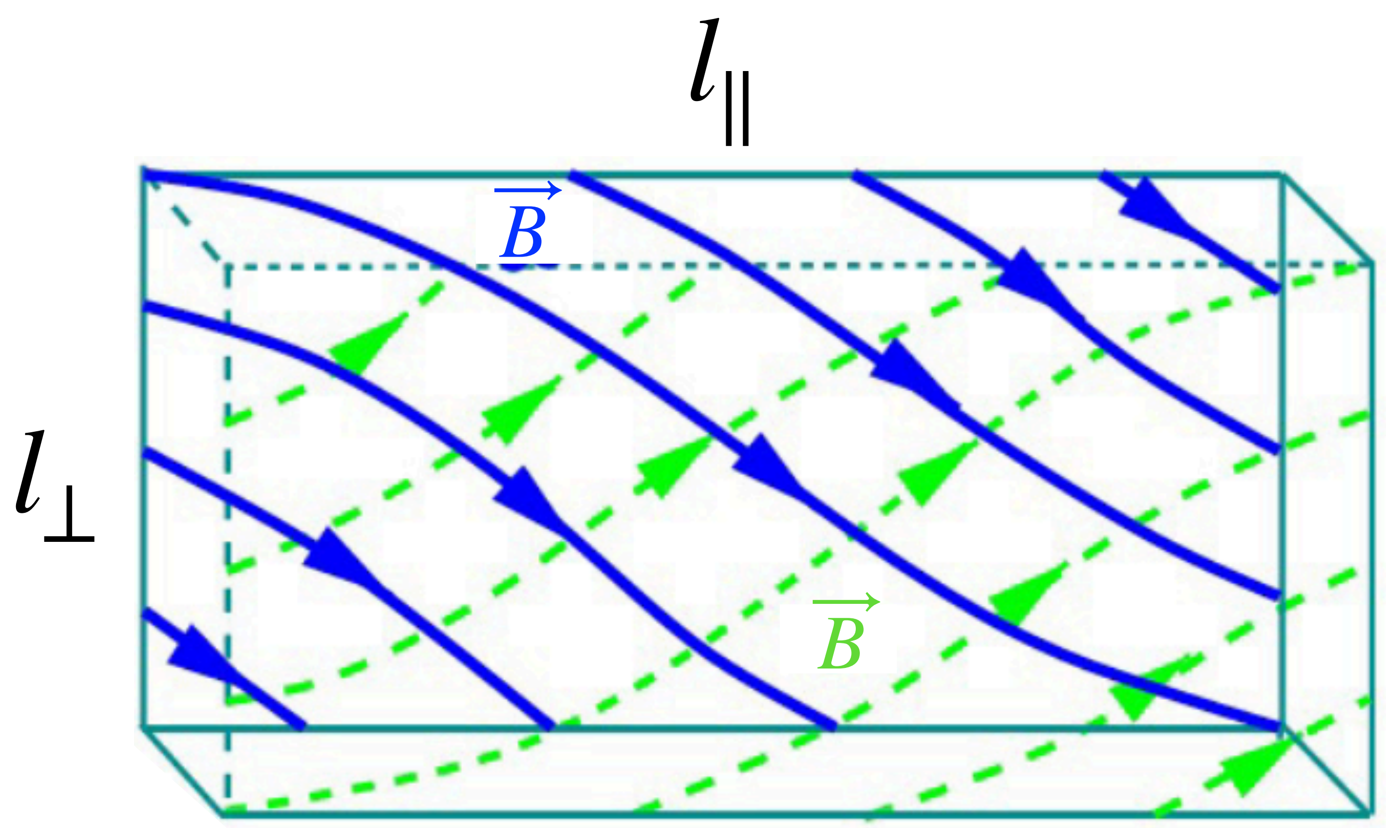

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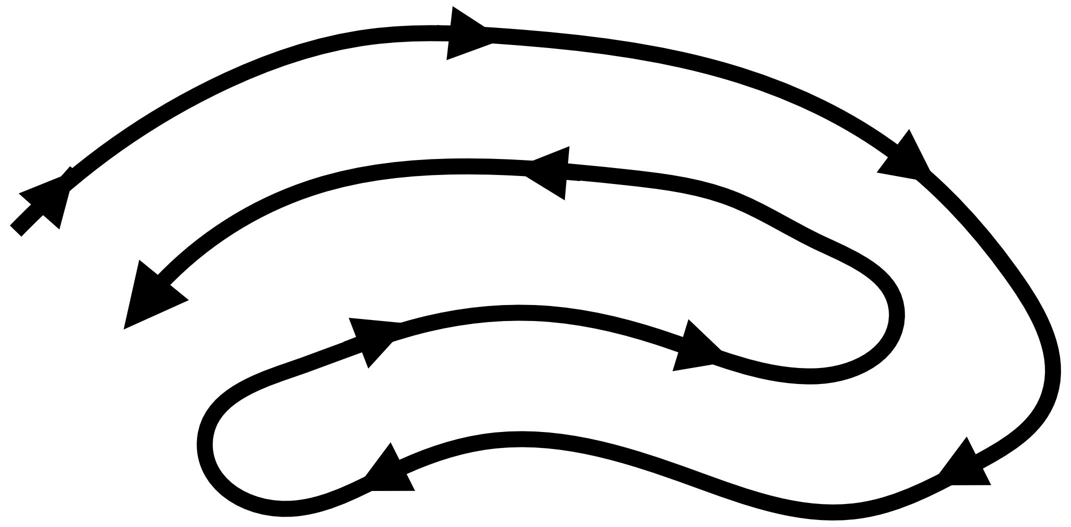

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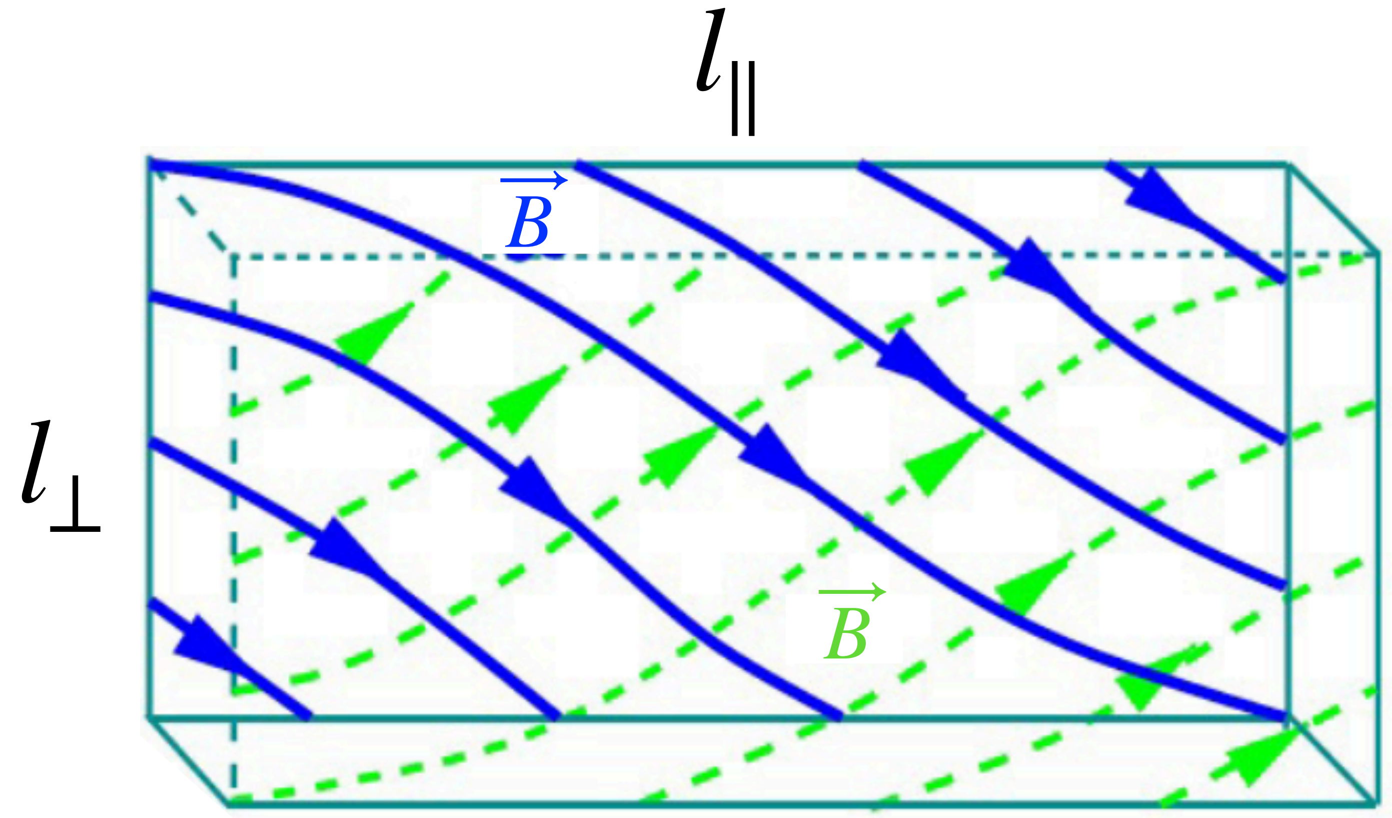

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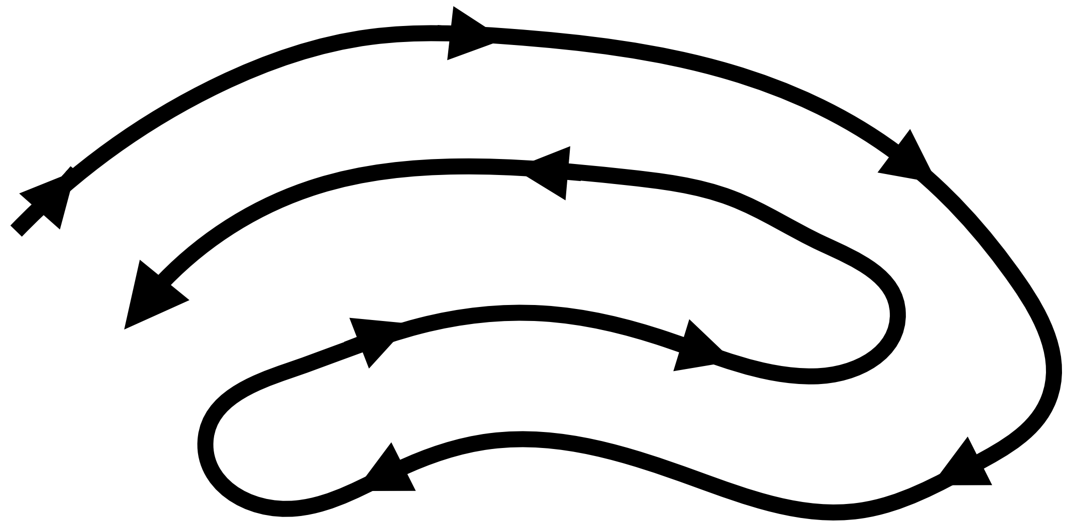
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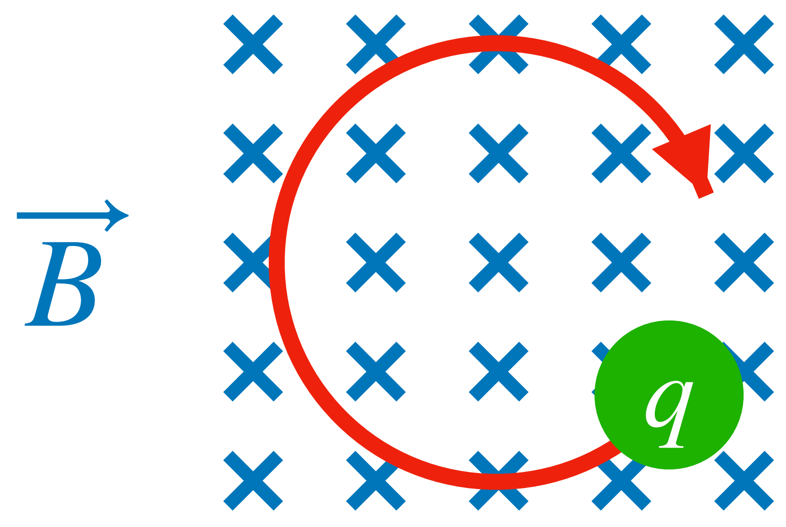

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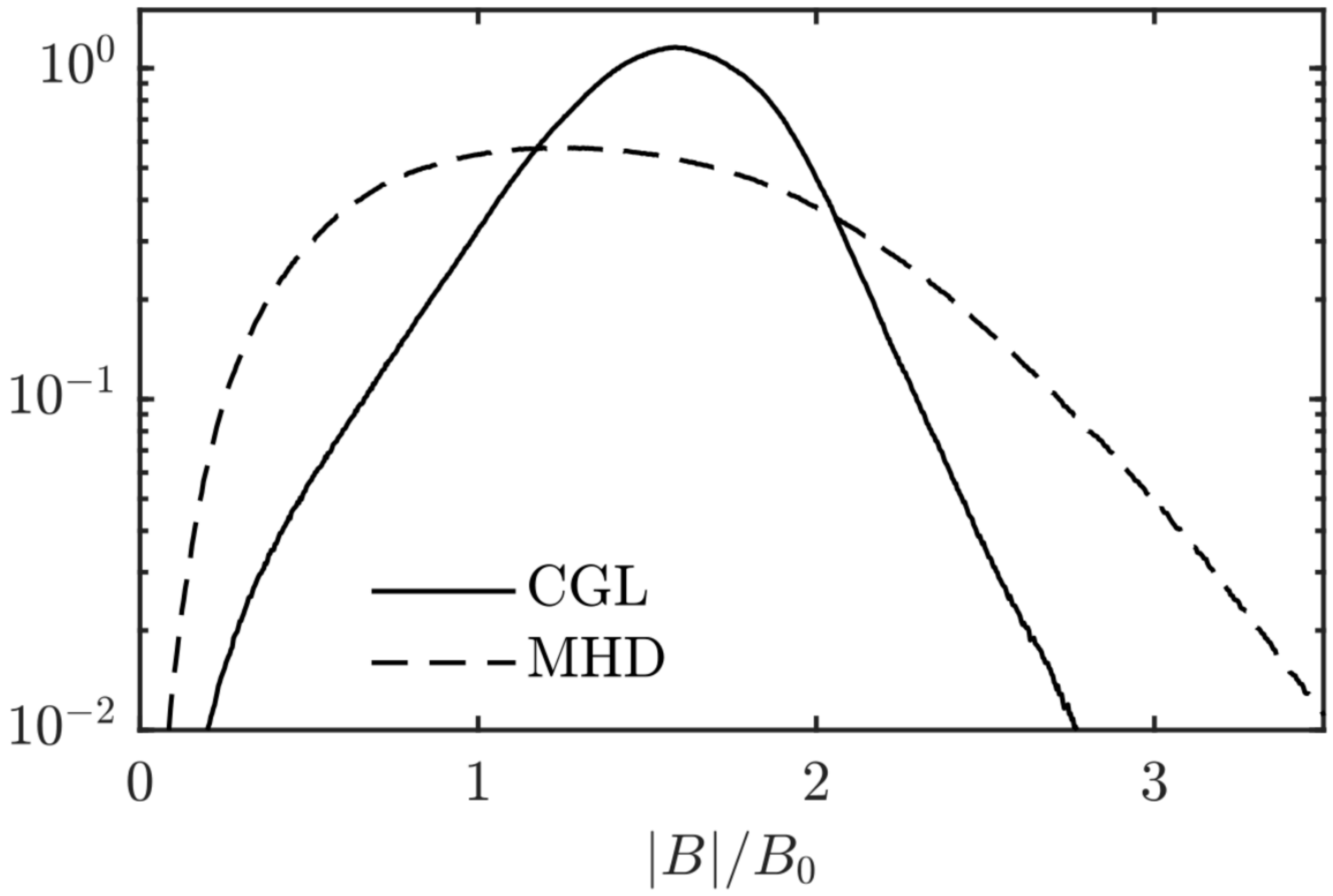
Distribution of values of |B| in ICM-like plasma turbulence:



"Magneto-immutability"
(Squire+ '19, '23, Majeski+ '24)

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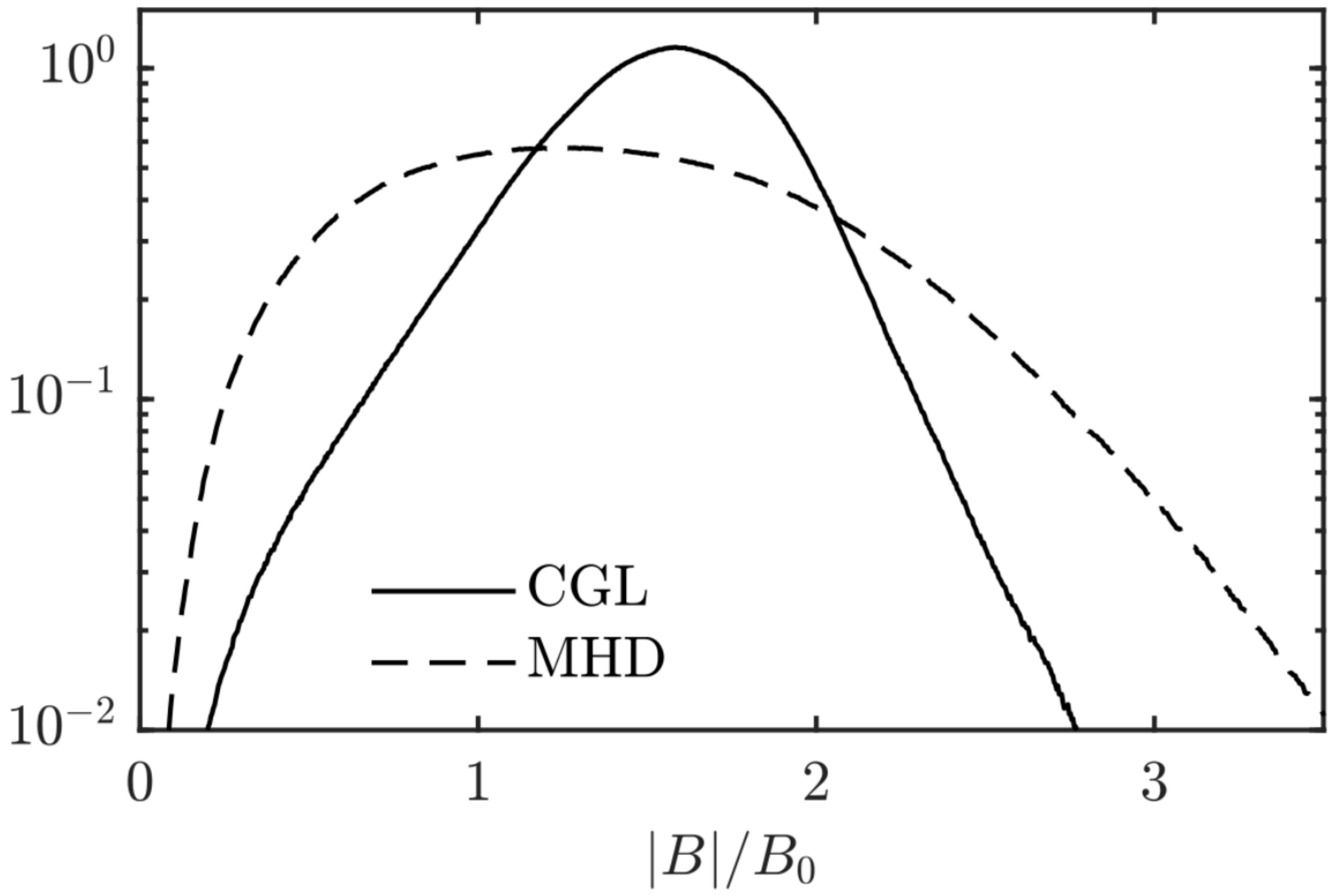

For weakly collisional derivation see Majeski+ 2024 JPP