MAGNETO-IMMUTABLE TURBULENCE IN WEAKLY COLLISIONAL PLASMAS

KITP plasmas — September 2019

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ALONG WITH: E. Quataert, A. Schekochihin, M. Kunz, P. Kempskii

QUESTION:

WHAT GOVERNS THE LARGE-SCALE DYNAMICS OF THE INTRA-CLUSTER-MEDIUM PLASMA?

PLASMA PARAMETERS

e.g., Rosin et al. 2010, Hydra A
Zhuravleva et al. 2014

Dynamically weak field

Subsonic turbulence

$$\beta = \frac{P_{\mathrm{thermal}}}{P_B} \approx 100$$

$$\mathscr{M} \approx 0.3$$

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GENERAL APPLICATION TO:

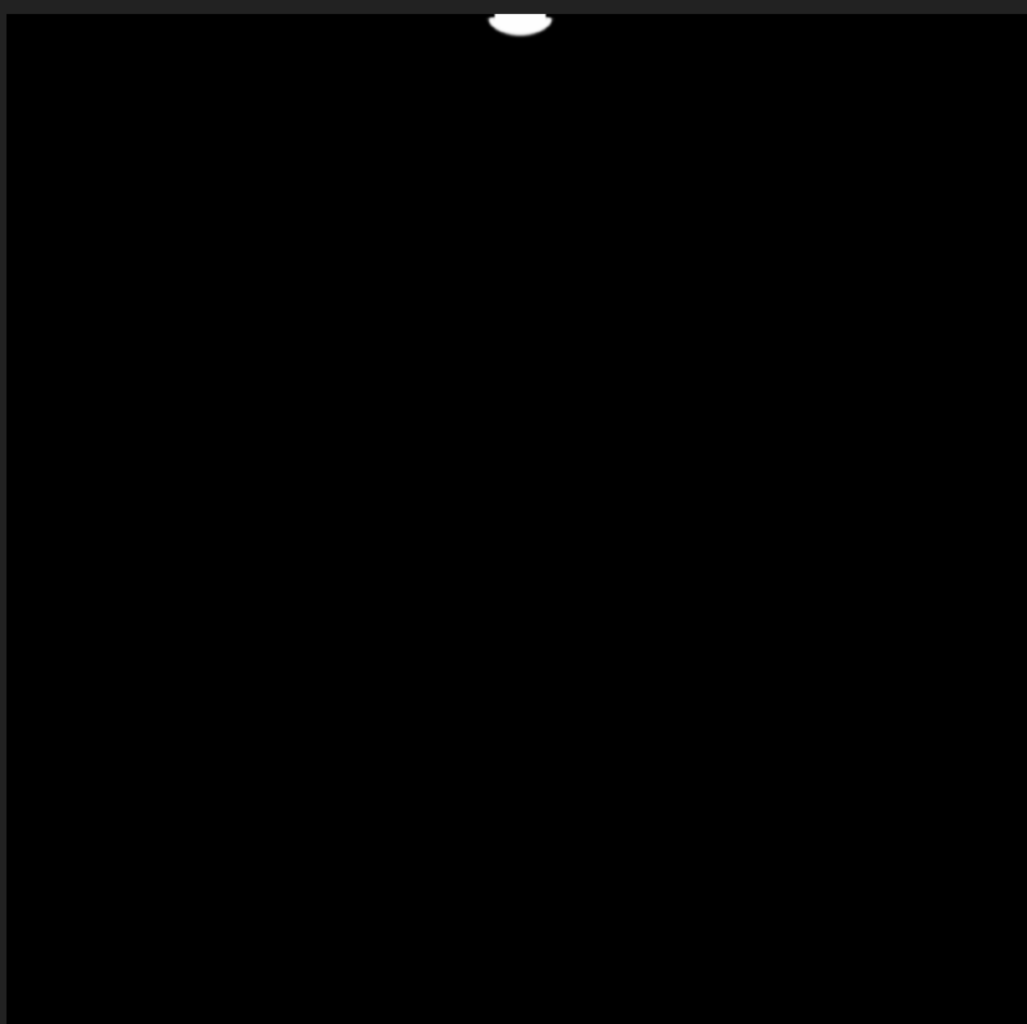
black-hole accretion, solar wind, hot ionized medium, high-z halos?

HOW DOES THIS PLASMA BEHAVE?

Is it well described by normal (magneto)hydrodynamics?

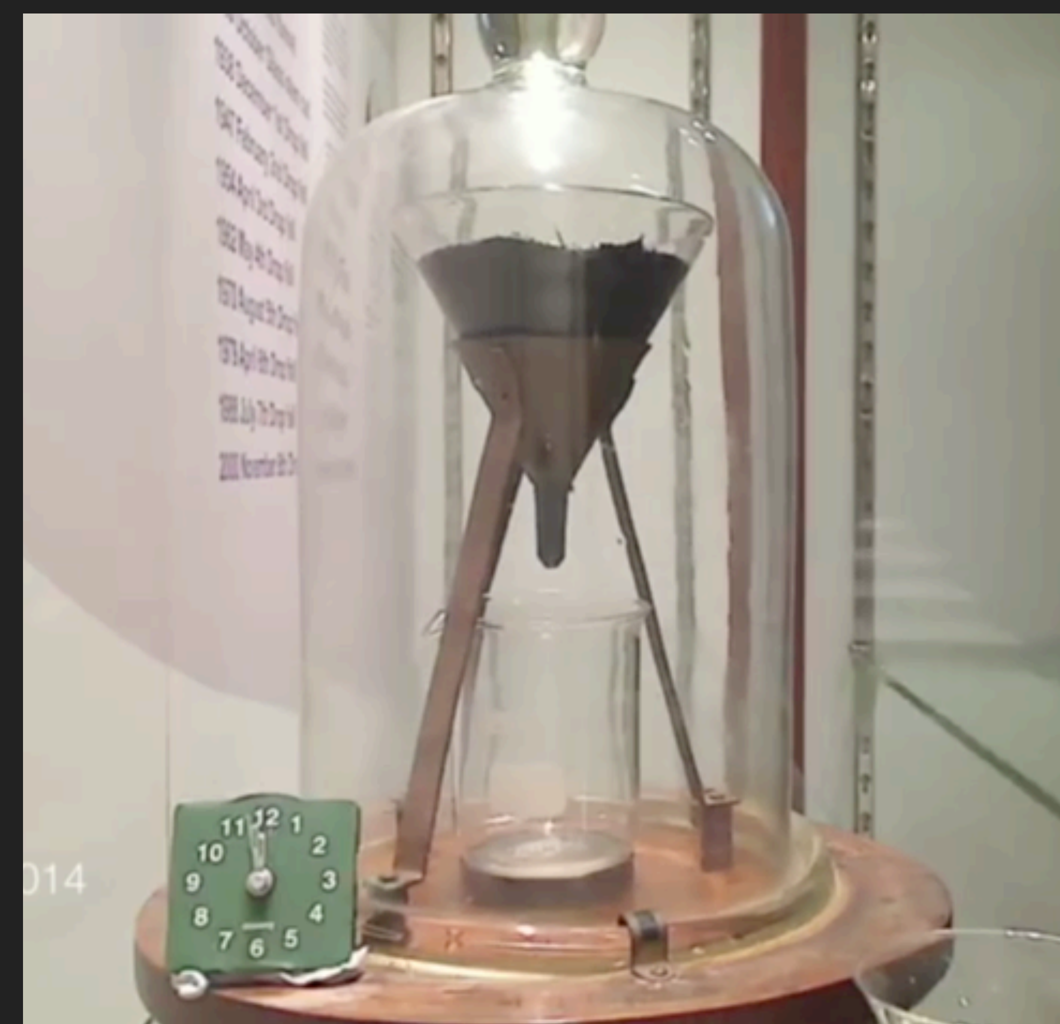
$$D_t\boldsymbol{u} = -\rho^{-1}\nabla P + \rho^{-1}\boldsymbol{J}\times\boldsymbol{B} + \ldots ?$$

What determines its viscosity, resistivity, heat transport etc.? $\mathrm{Re} = 60$?



Credit: Universität Duisburg-Essen

vs.



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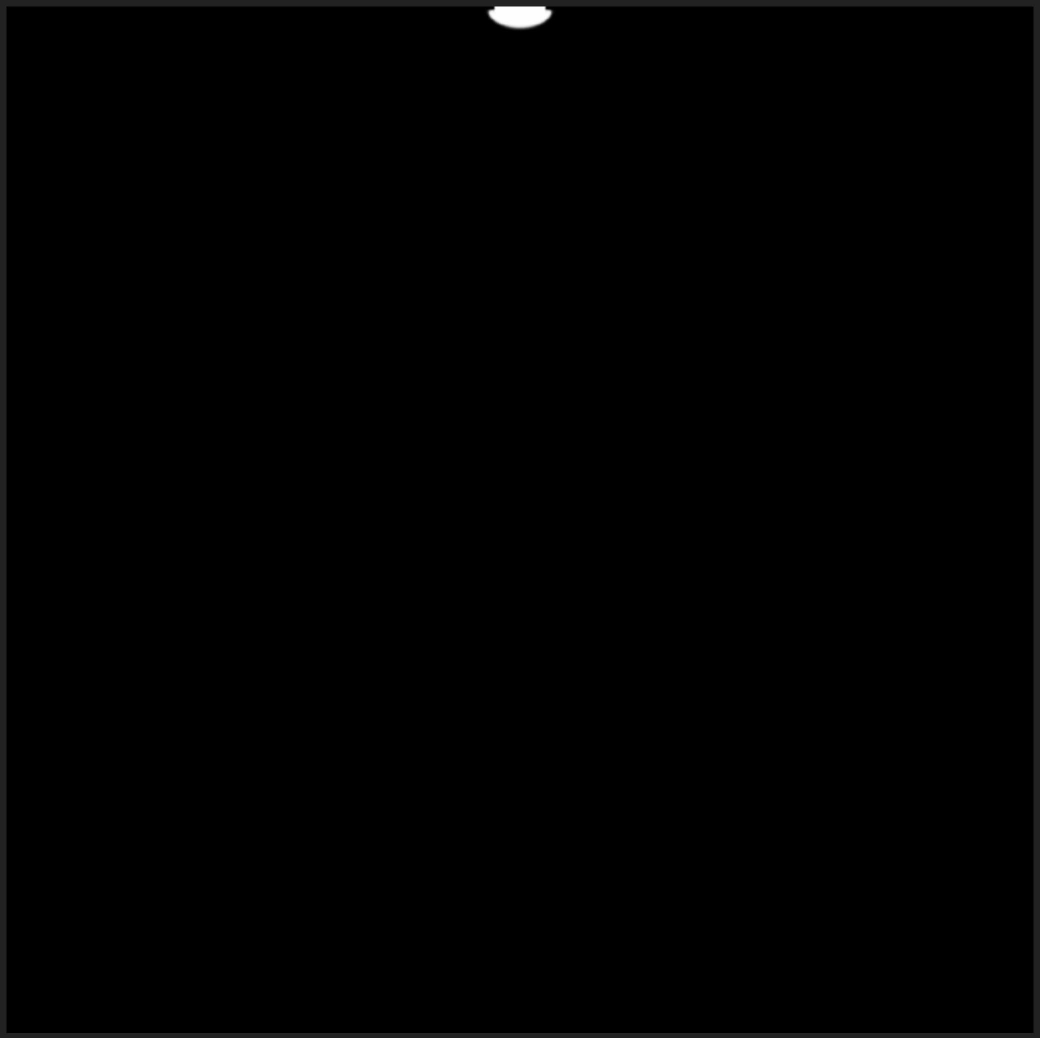

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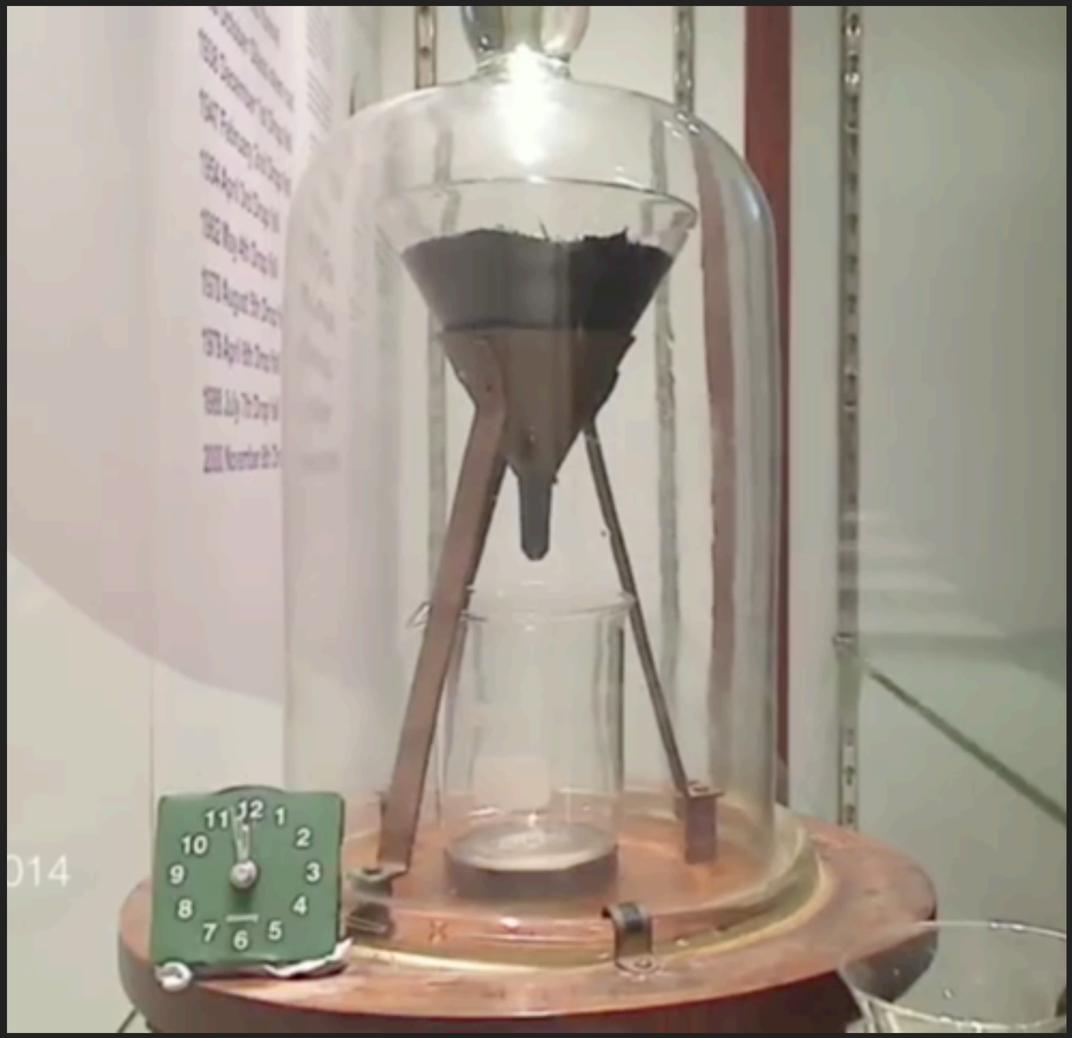

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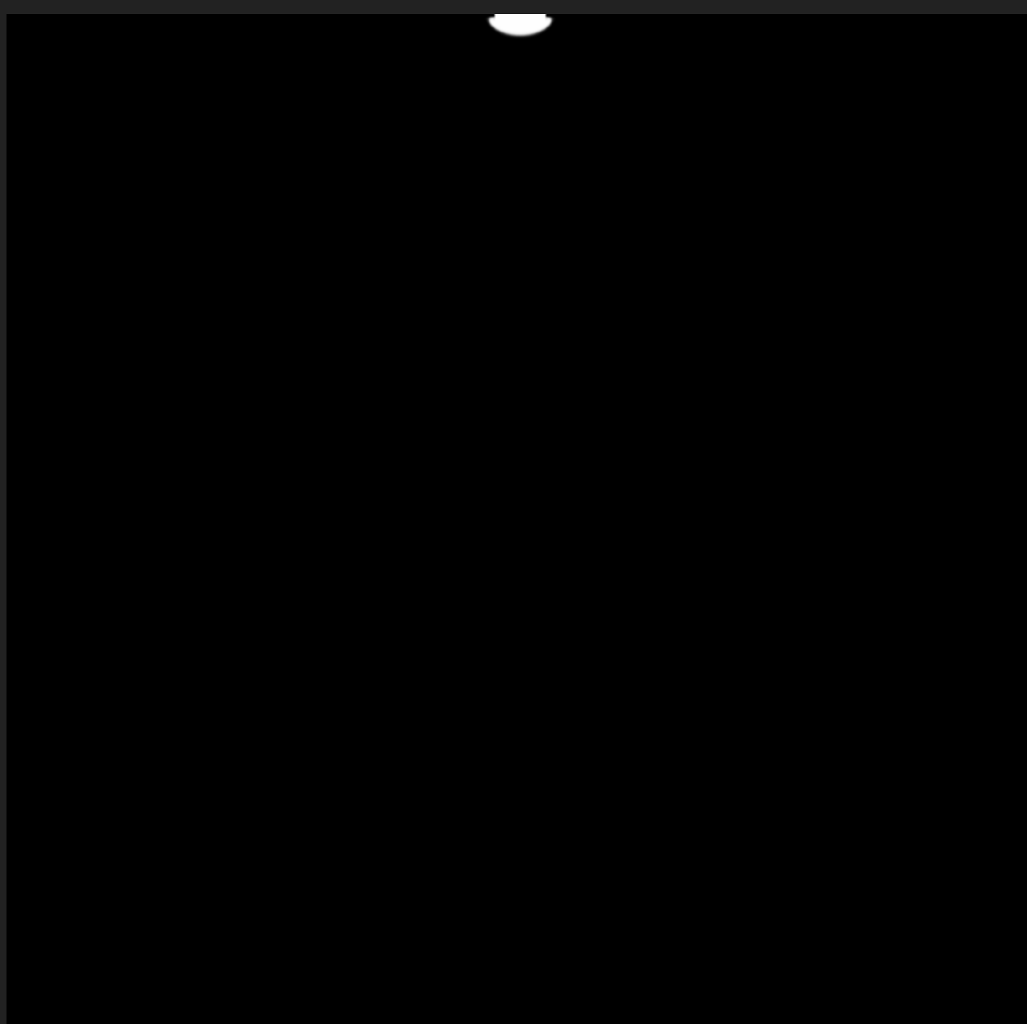

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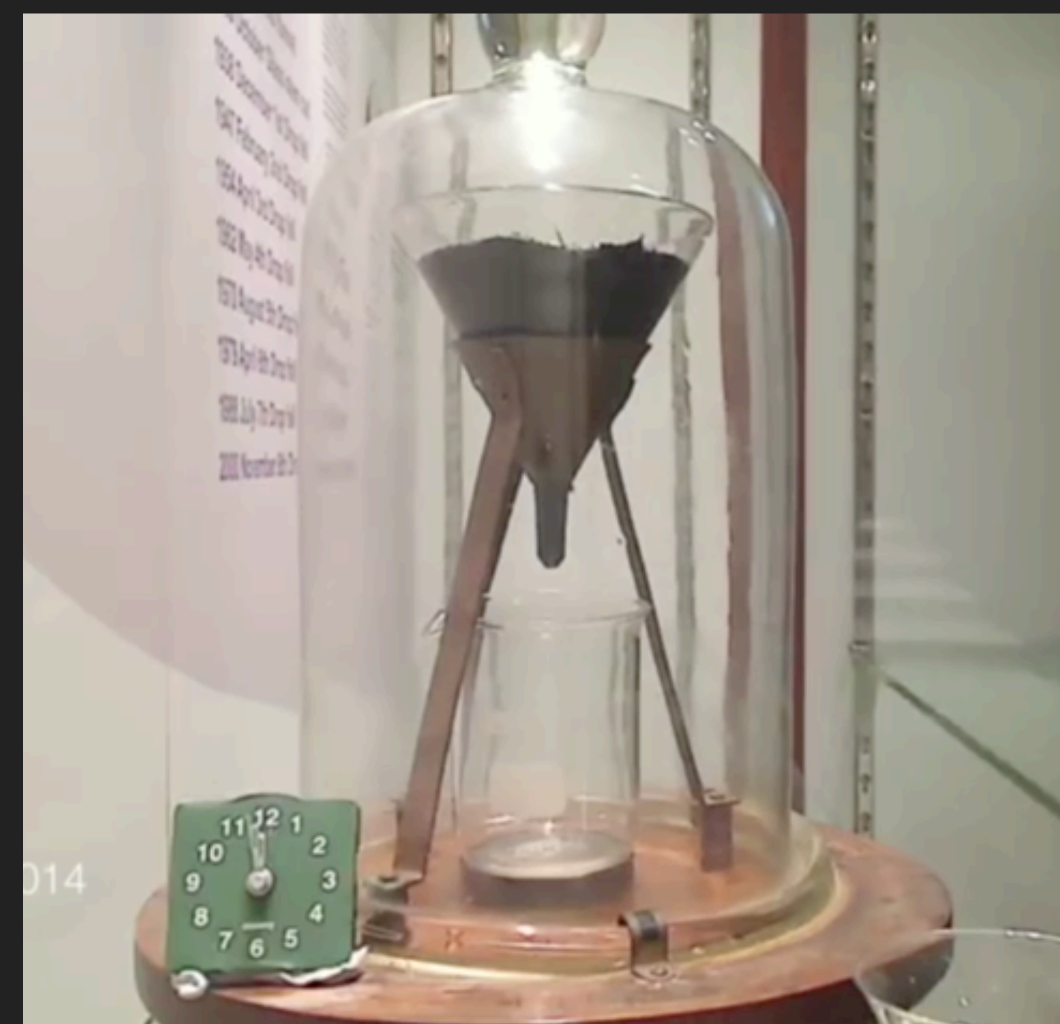

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OUTLINE – MAGNETO-IMMUTABLILITY

Focus on fluid-scale effects, not the kinetic micro-physics

- The dynamical effect of pressure anisotropy
  - Generation of pressure anisotropy
  - A simple prediction — shear-Alfvén wave interruption
  - How the plasma avoids this — magneto-immutability
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DIFFERENCE COMPARED TO MHD

- Context: Kulsrud's kinetic MHD

Expand kinetic equation in $\rho_i/L \ll 1$

Obtain MHD-like equation, with $p_\perp, p_\parallel$ obtained from drift kinetic equation

$$P = \begin{pmatrix} p_\perp & 0 & 0 \\ 0 & p_\perp & 0 \\ 0 & 0 & p_\parallel \end{pmatrix}$$

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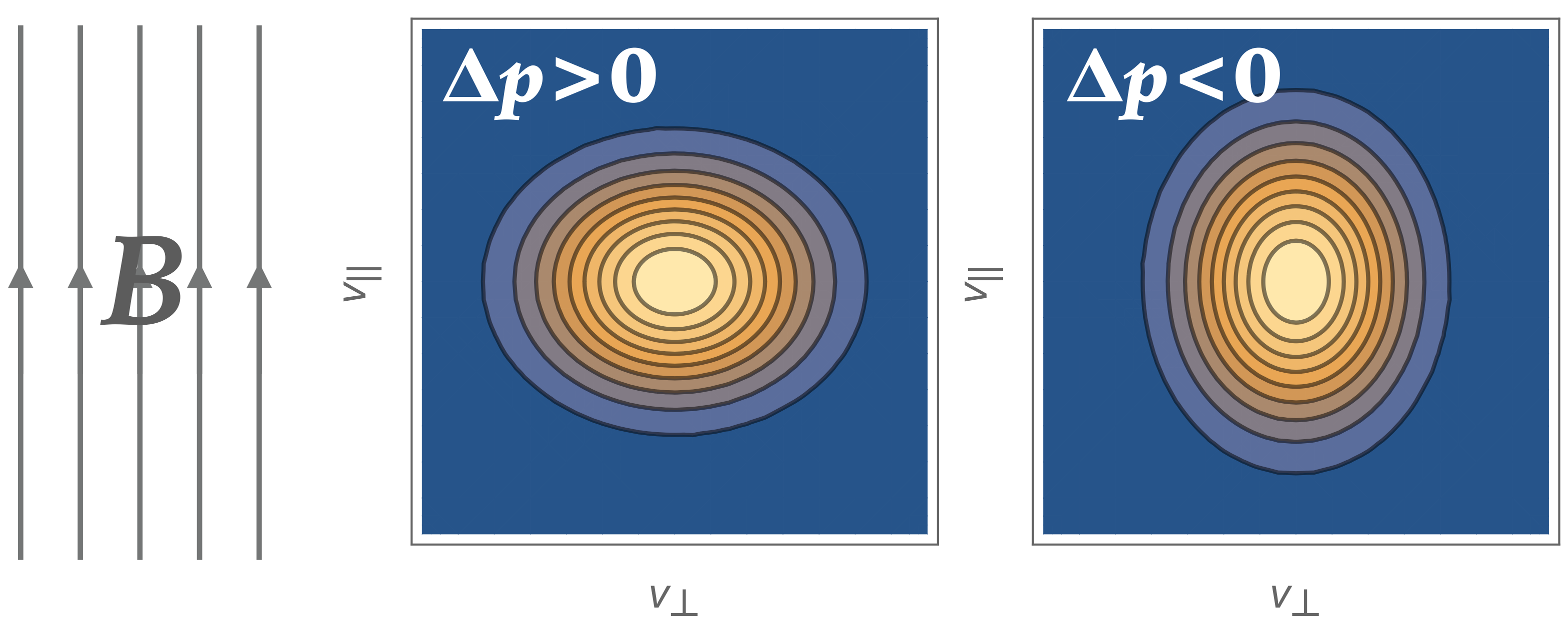
MHD $$D_t \boldsymbol{u} = -\nabla(p + B^2/2) + \nabla \cdot (\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}B^2)$$

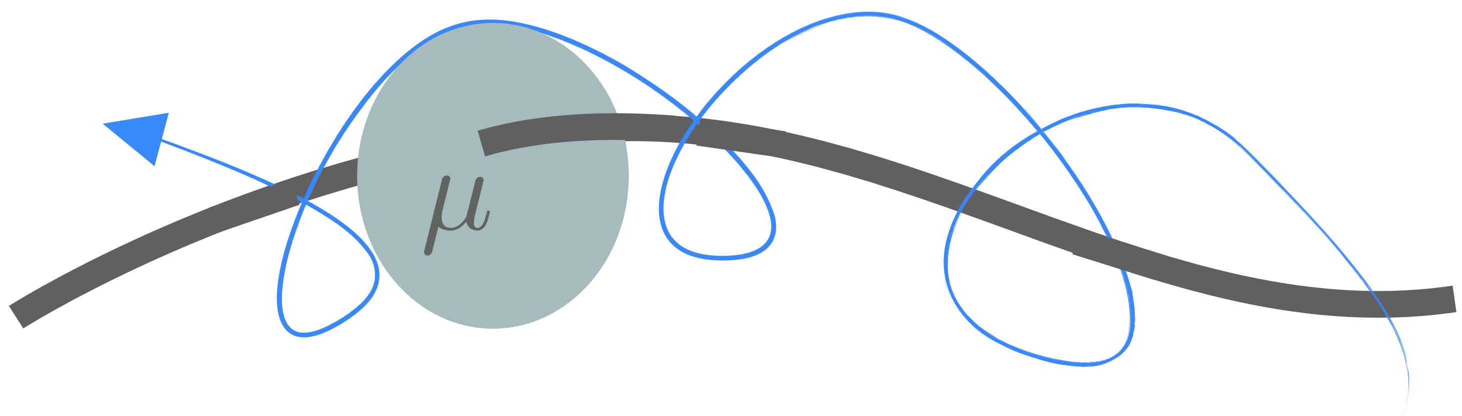
Kinetic MHD $$D_t \boldsymbol{u} = -\nabla(p_\perp + B^2/2) + \nabla \cdot [\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}(B^2 + \Delta p)]$$



$$\Delta p = p_\perp - p_\|$$

- Single particle motion

$$\mu = \frac{mv_\perp^2}{2B} \quad \textit{conserved}$$



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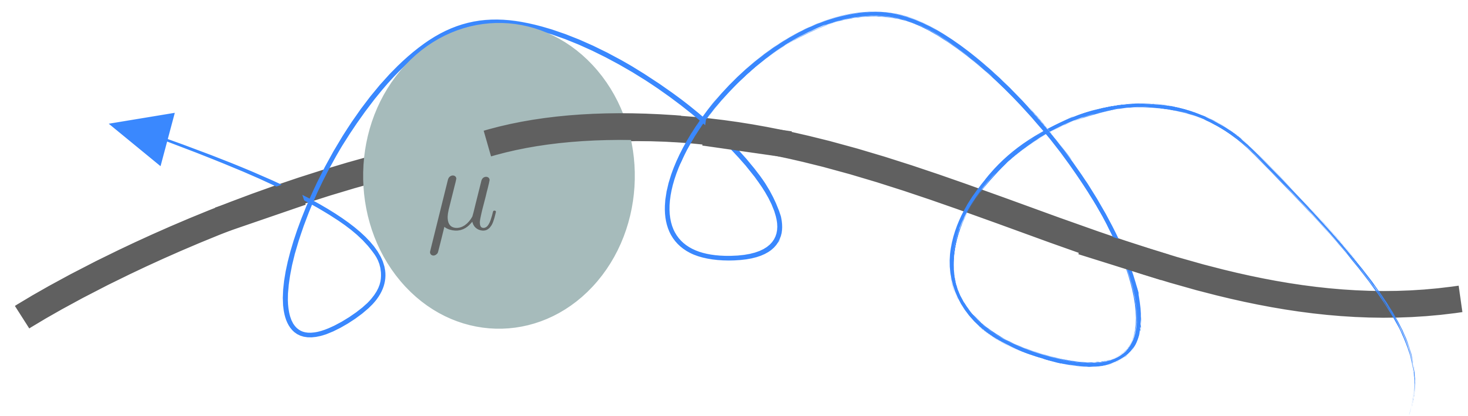
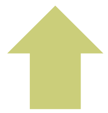


- So, without collisions $|B|$ 

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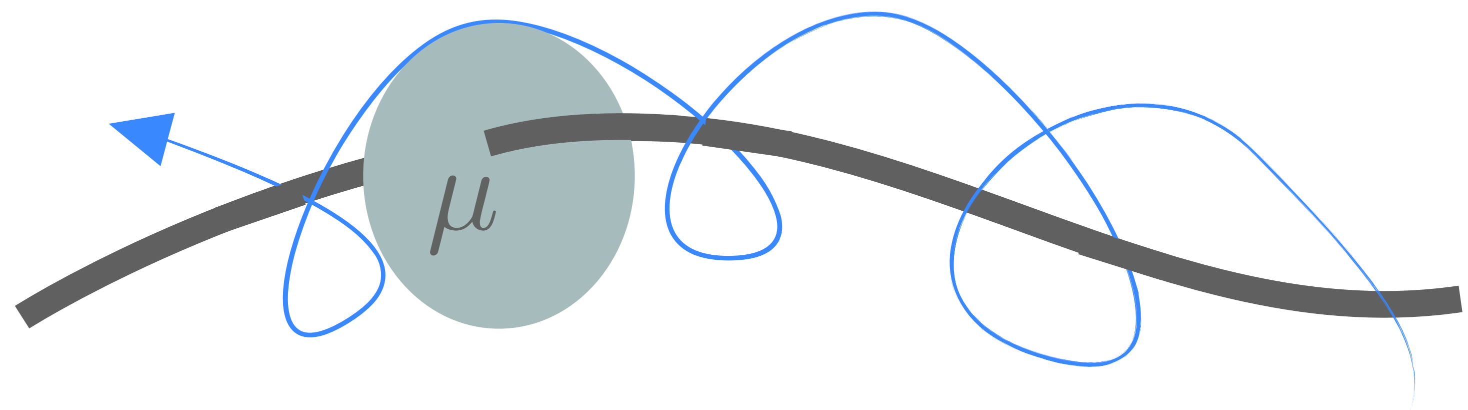

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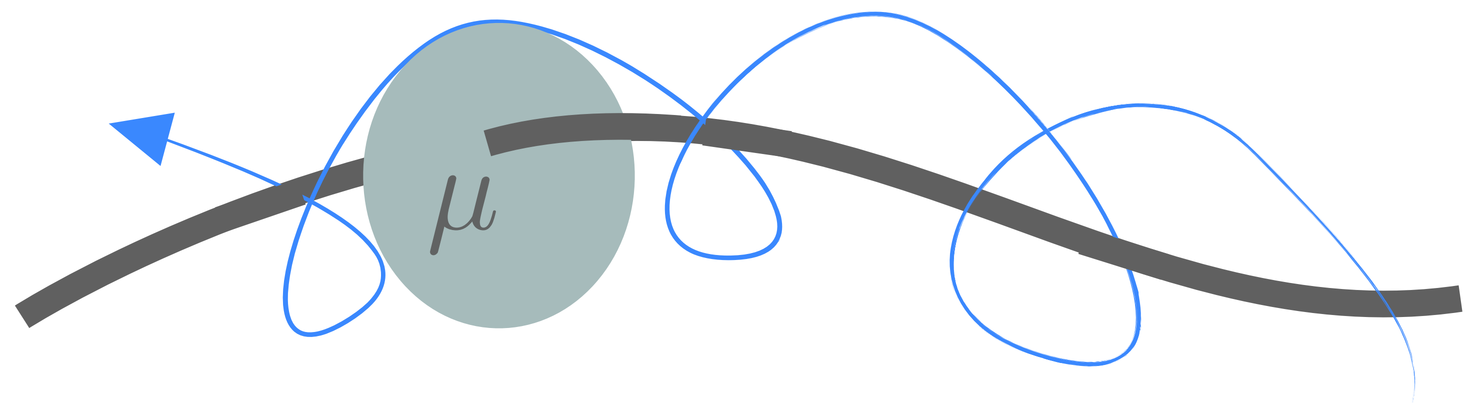

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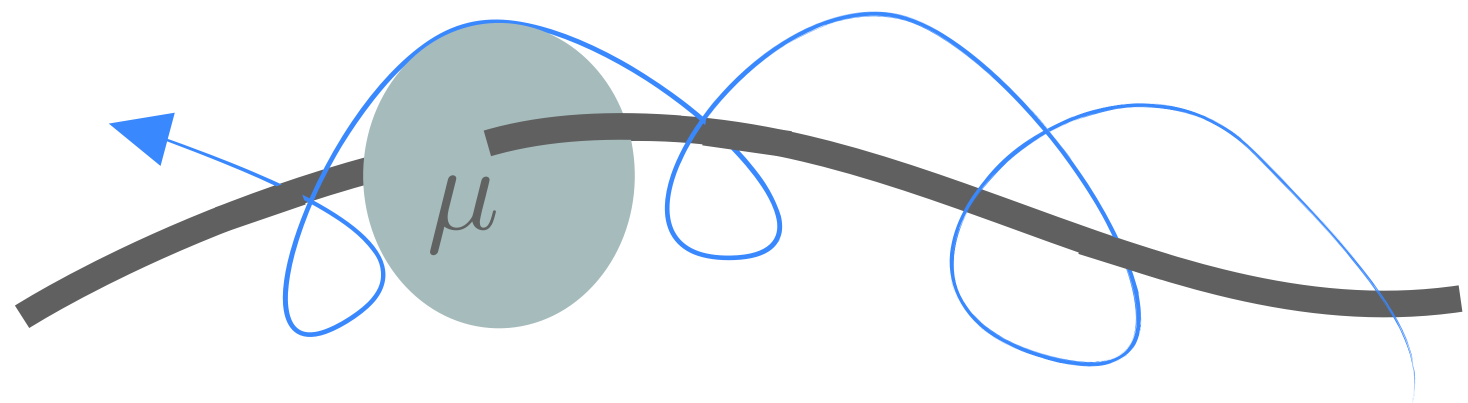

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$$\frac{d\Delta p}{dt} = 3p_0 \frac{1}{B}\frac{dB}{dt} - (3p_{\|} - p_\perp)\frac{1}{\rho}\frac{d\rho}{dt} + \nabla \cdot [\hat{\boldsymbol{b}}(q_\perp - q_{\|})] - 3q_\perp \nabla \cdot \hat{\boldsymbol{b}} - 3\nu_c \Delta p$$

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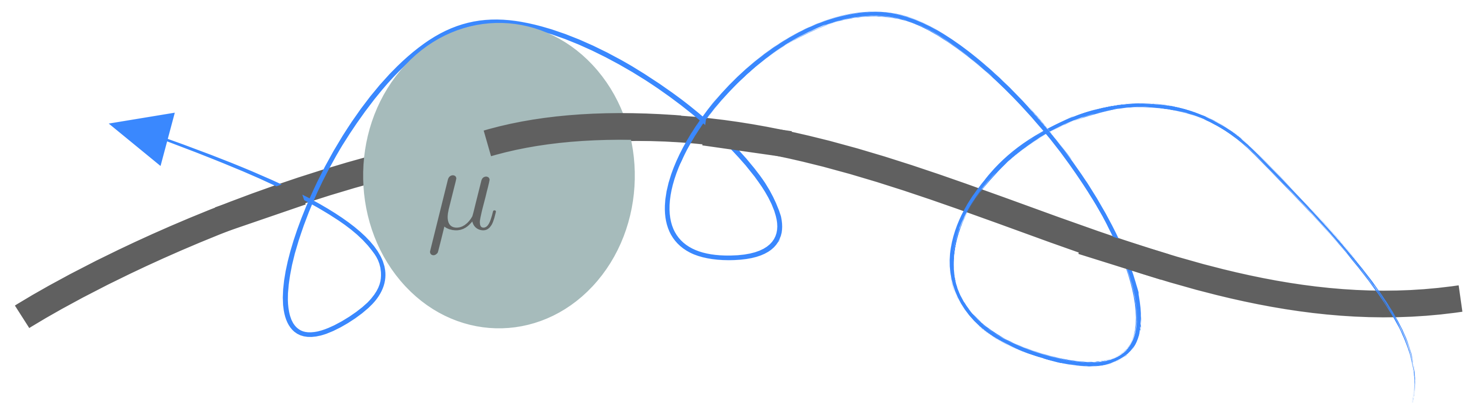

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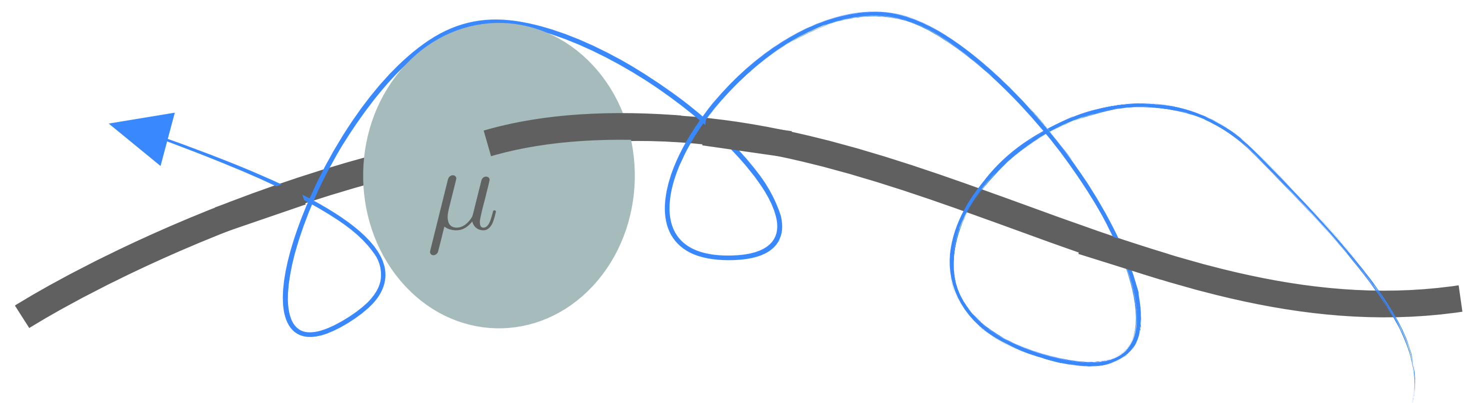

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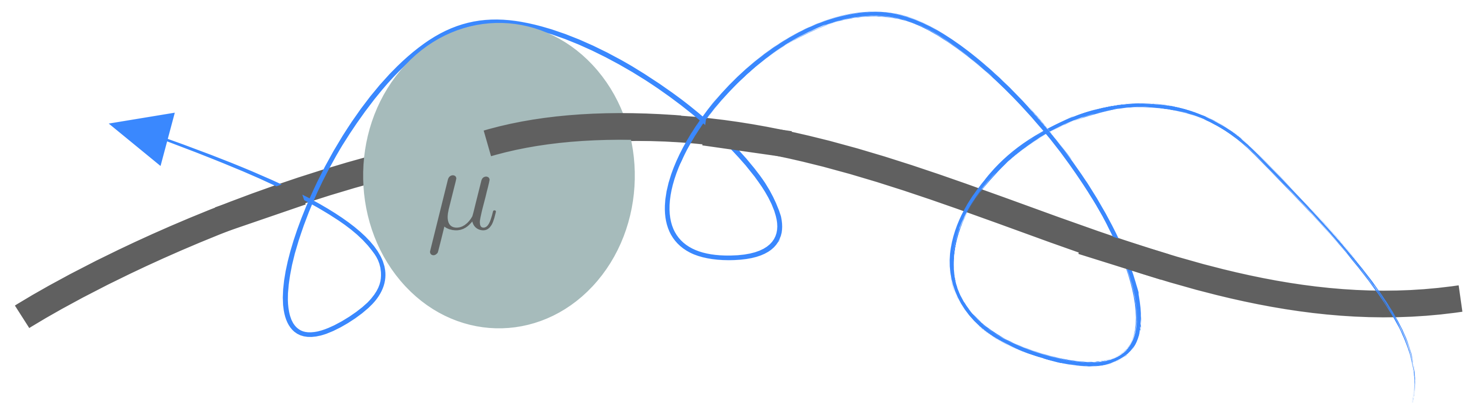

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Braginskii MHD $\Delta p \approx \frac{p_0}{\nu_c} \hat{\boldsymbol{b}}\hat{\boldsymbol{b}} : \nabla \boldsymbol{u}$ $(\nu_{\mathrm{Brag}} \approx p_0/\nu_c)$

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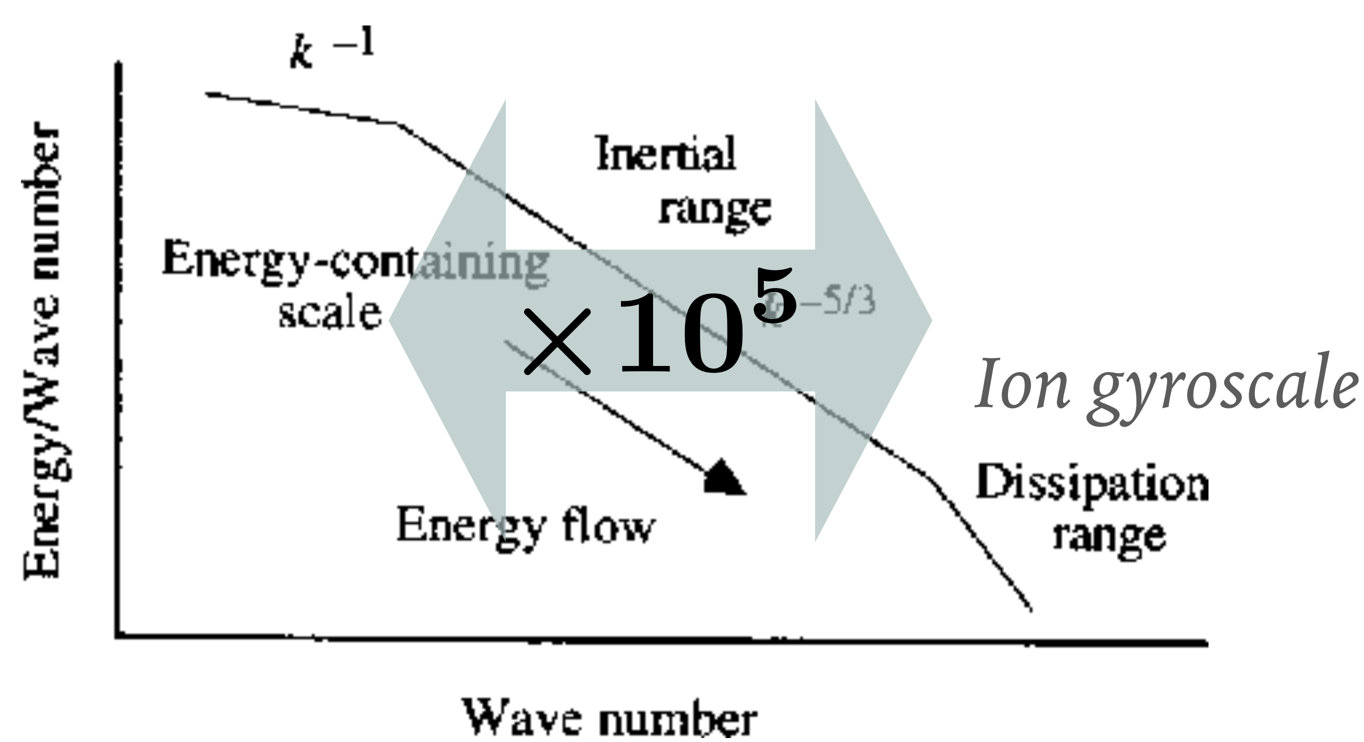
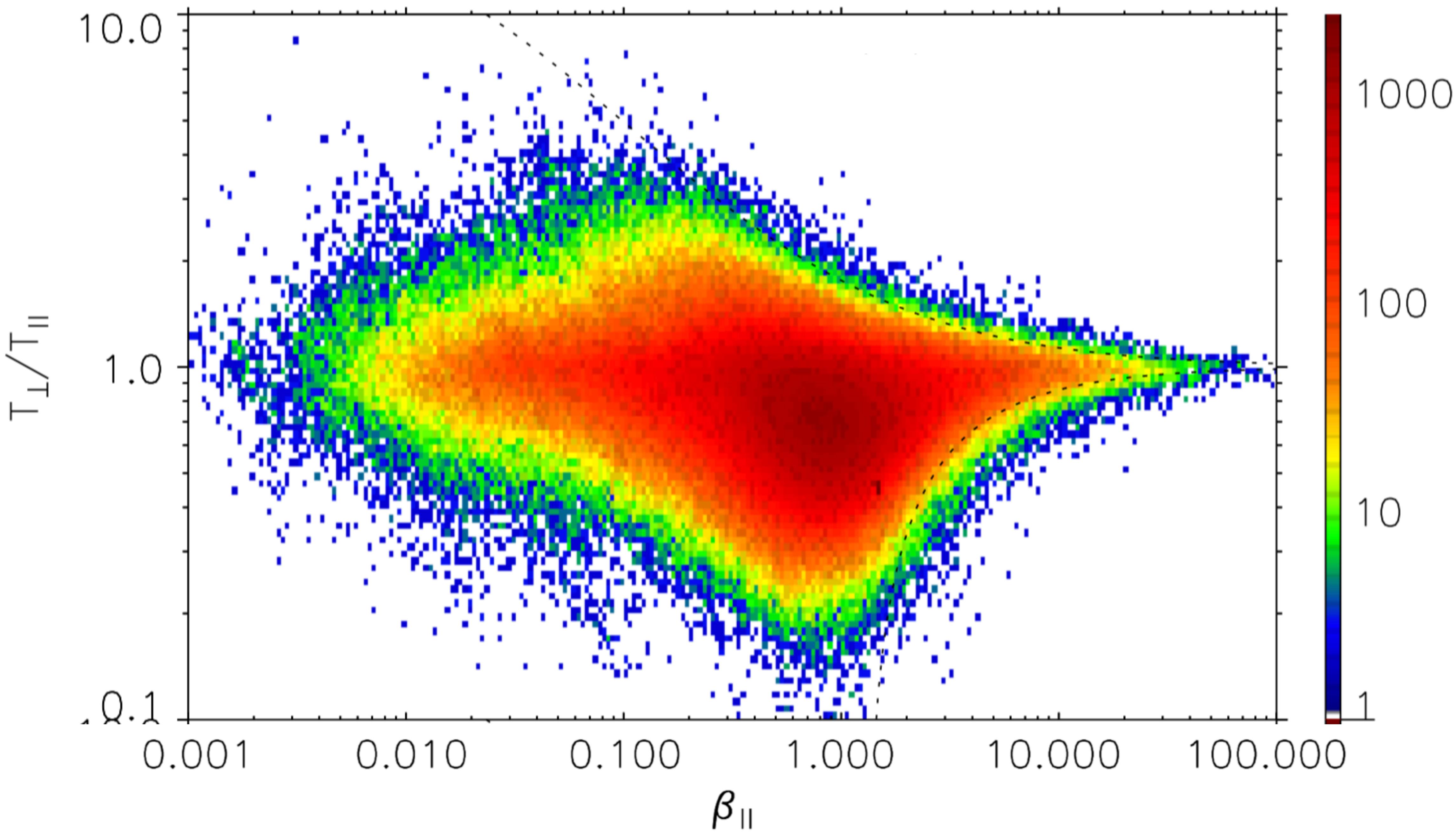
*Momentum stress due to Δp ~ β*magnetic pressure*

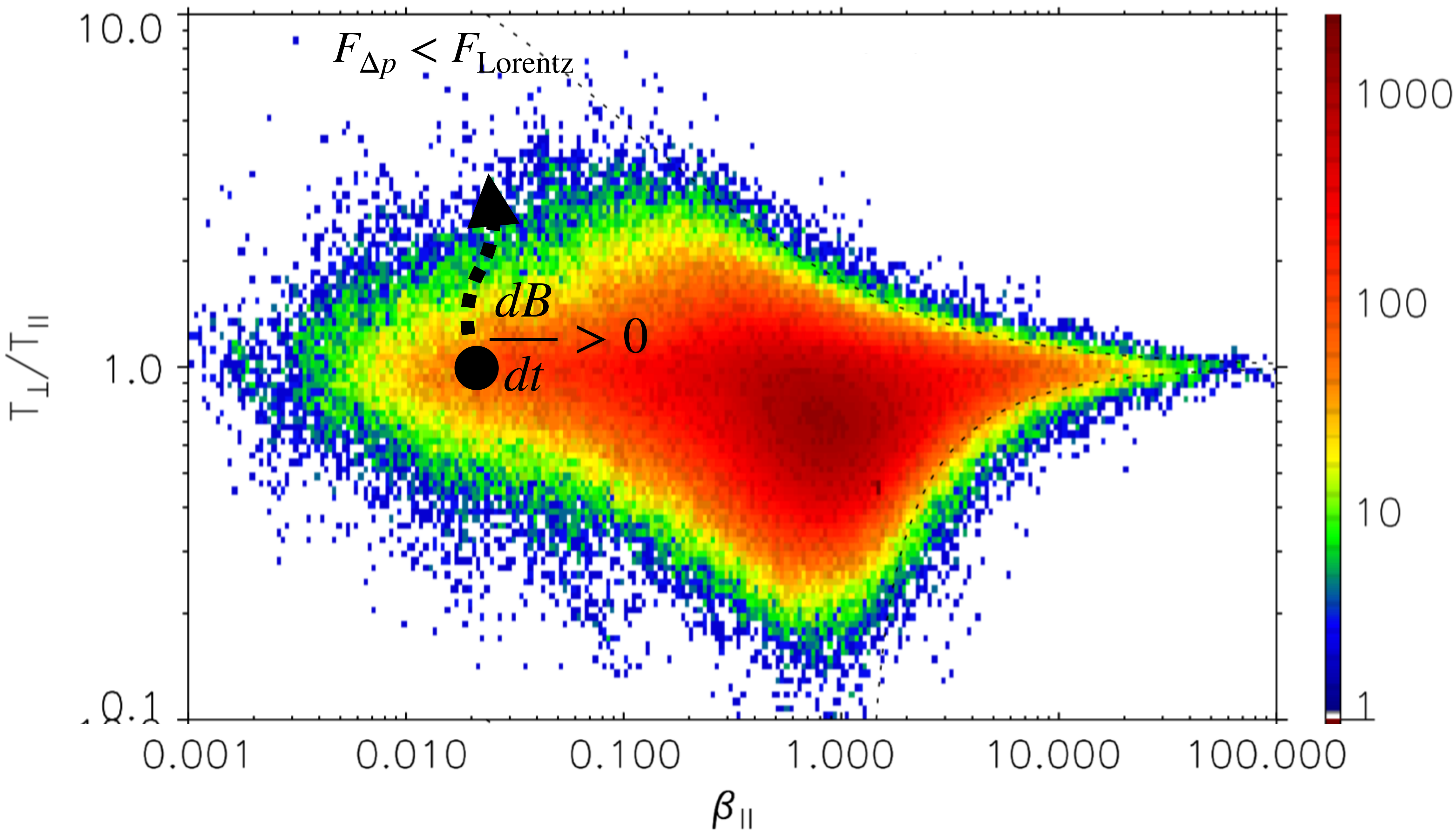
MHD completely wrong?

Even though
$L \ggg \rho_i$





Bale et al. 2009



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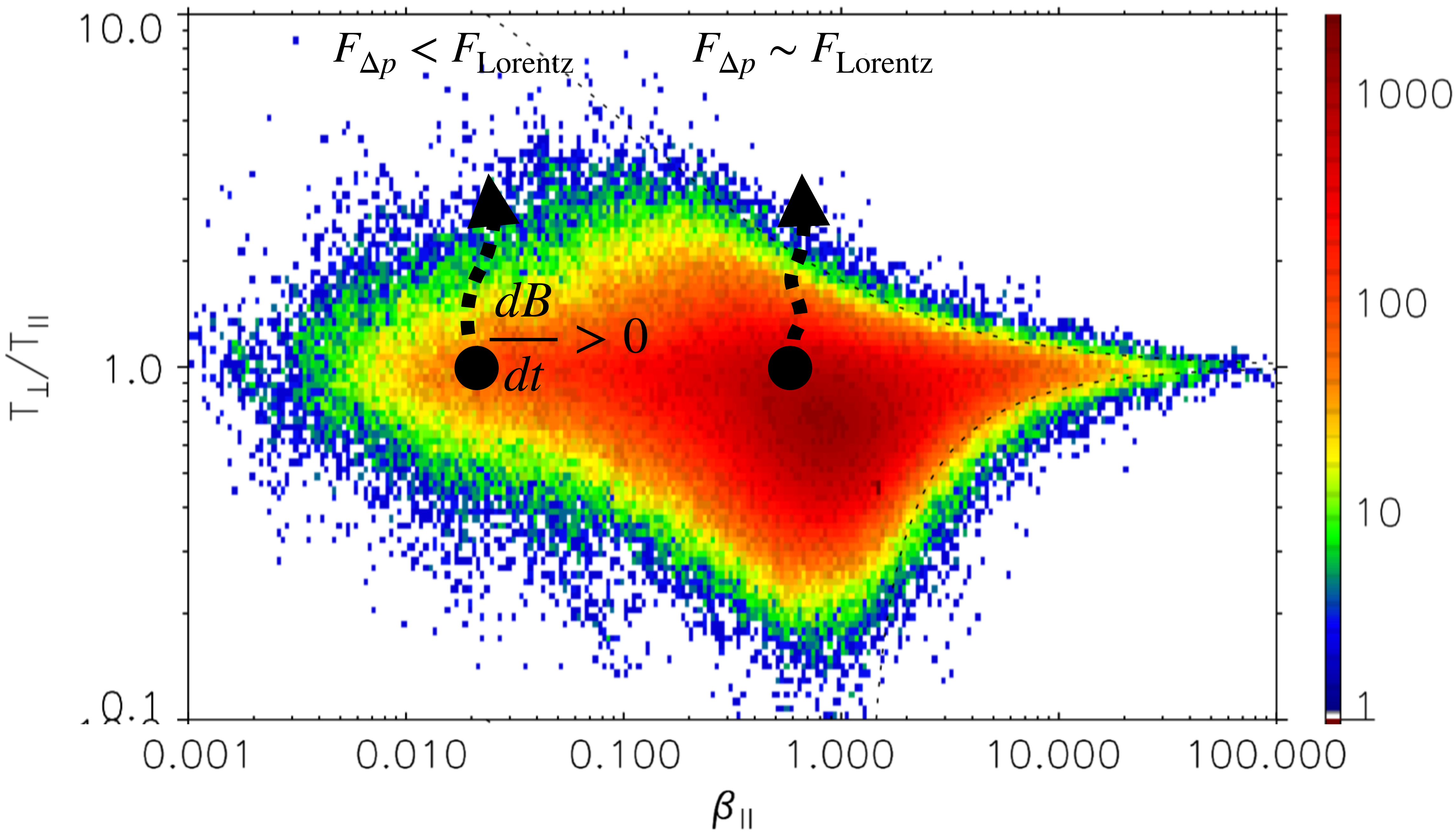

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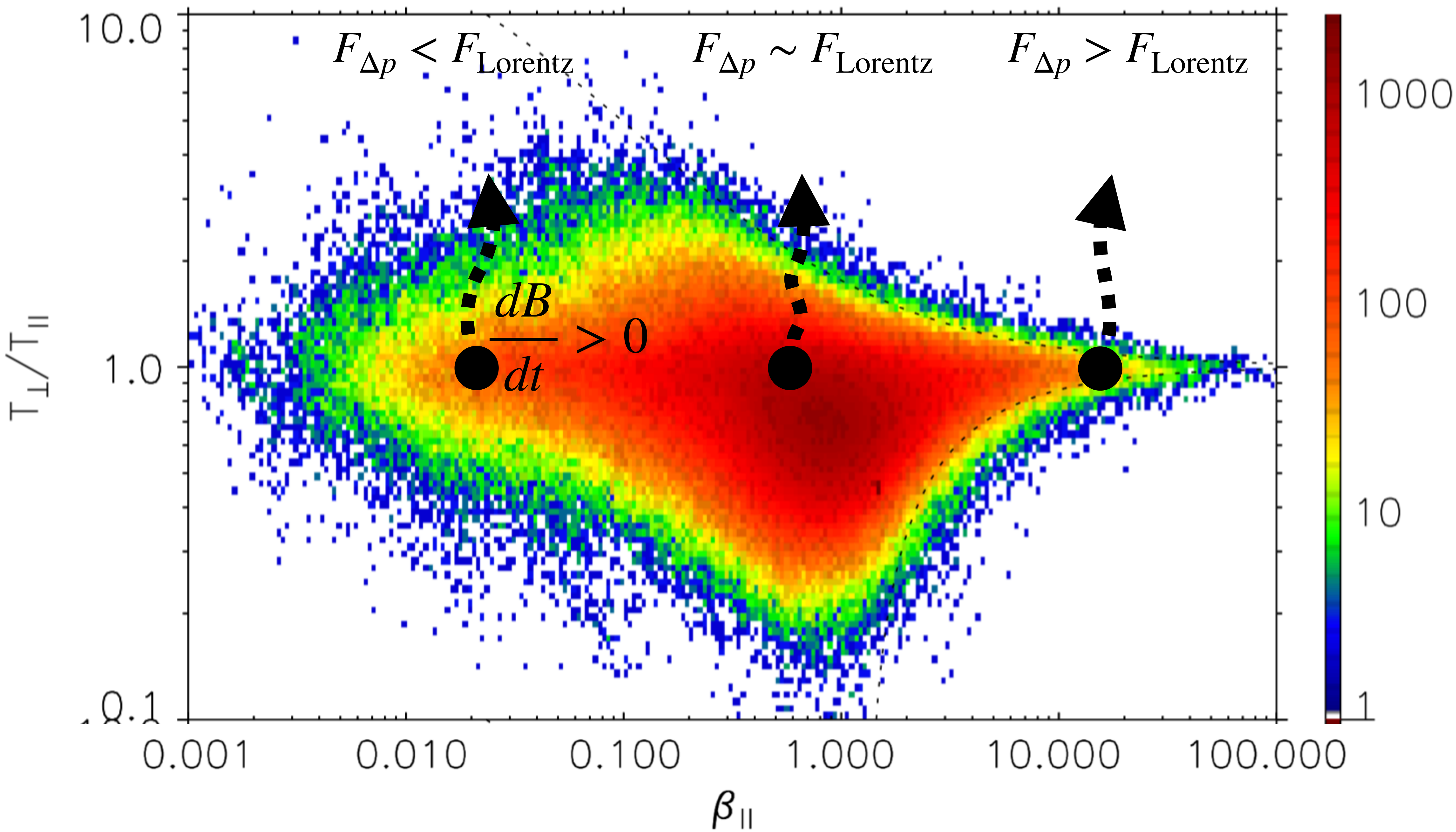

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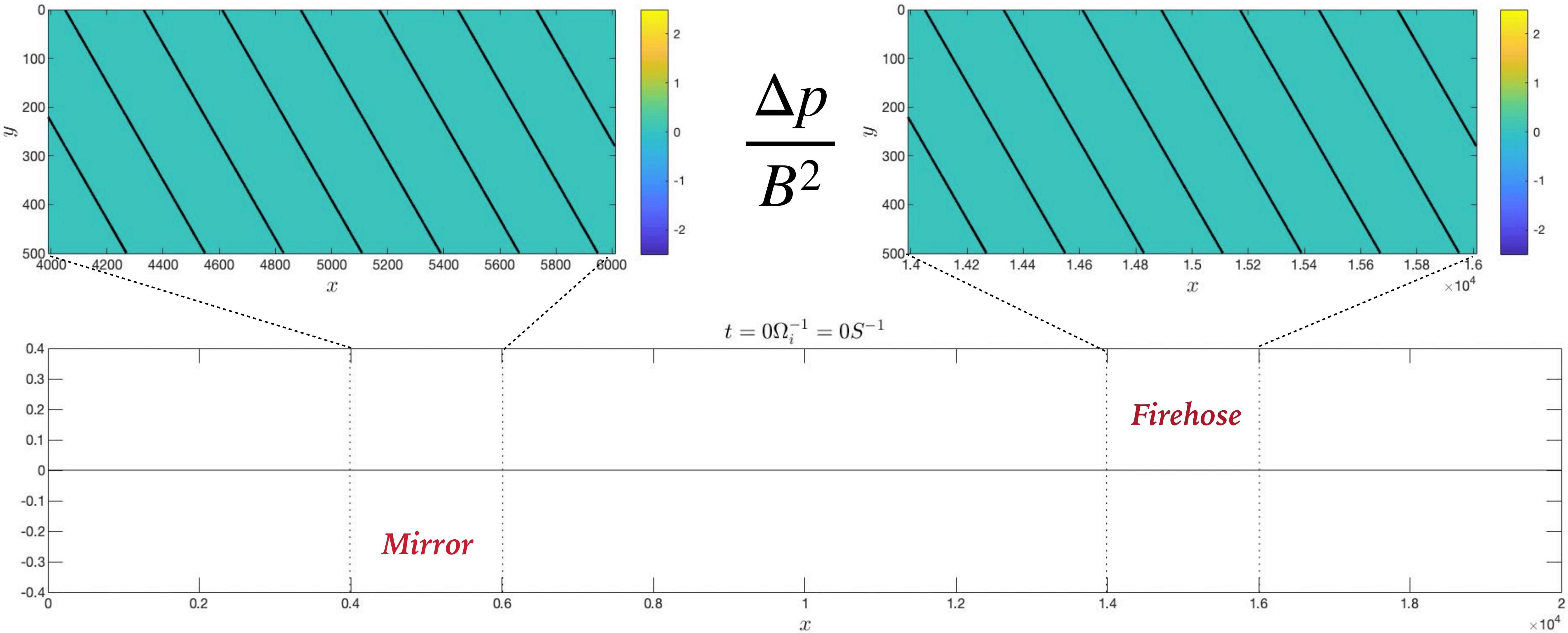
KINETIC MICRO-INSTABILITIES

- The plasma responds at $F_{\Delta p} \sim F_{\mathrm{Lorentz}}$ (when $|\Delta p|/p \sim \beta^{-1}$) by generating micro-instabilities (firehose, mirror)
- These help regulate the growth of $|\Delta p|$



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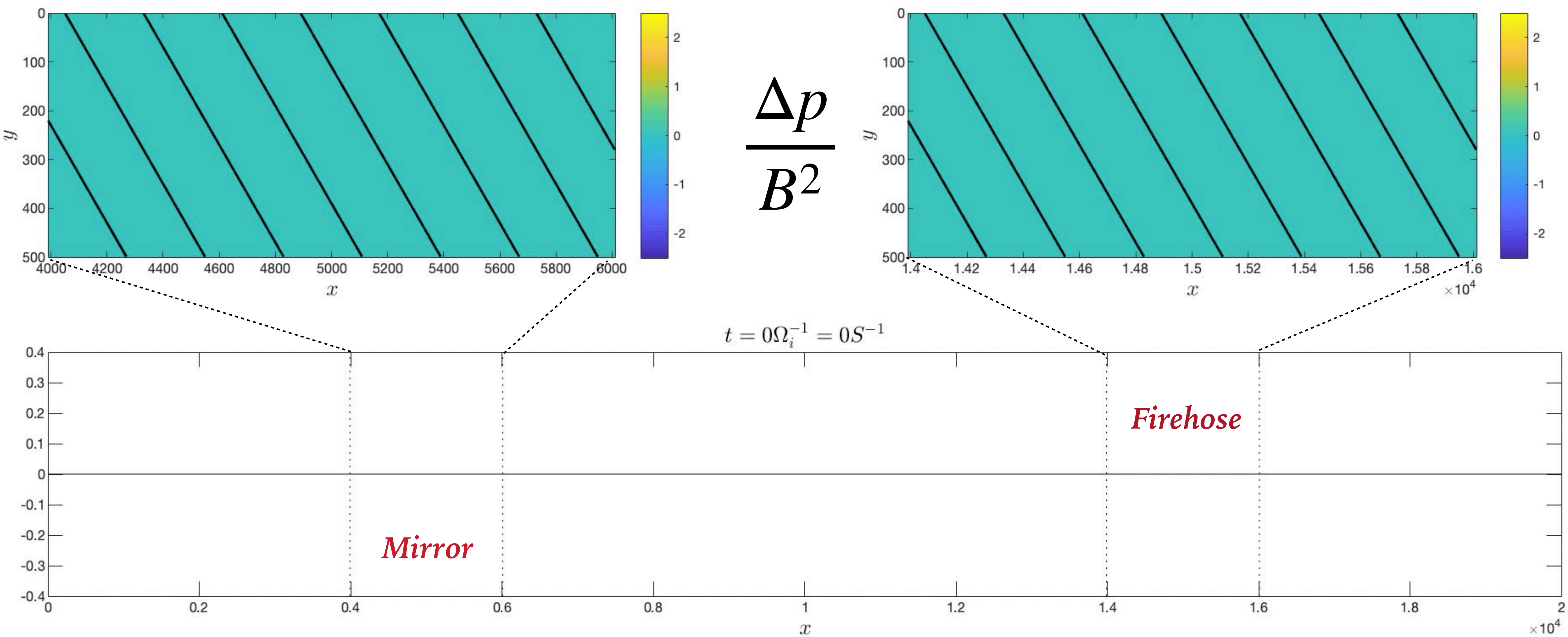

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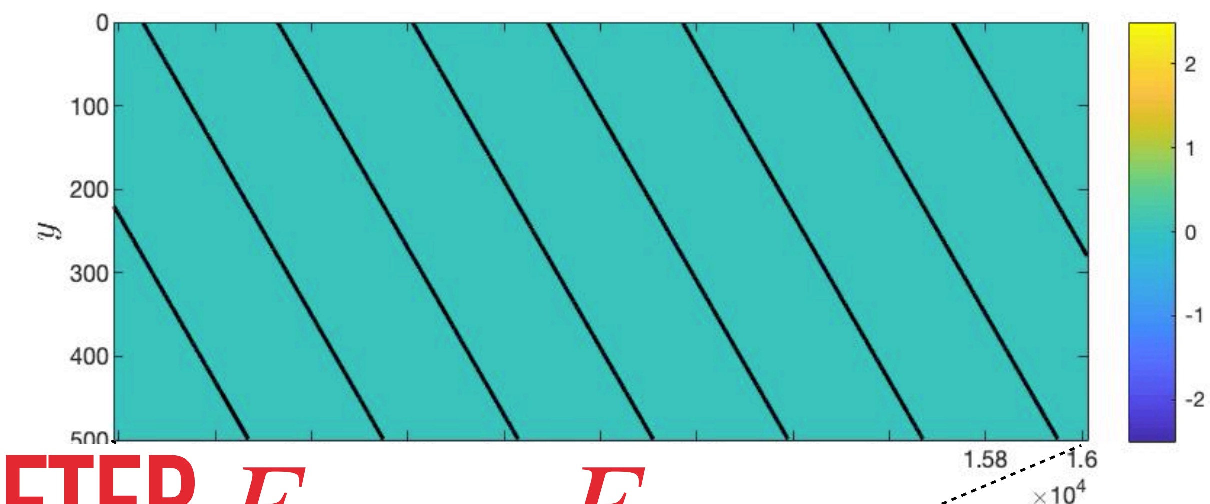
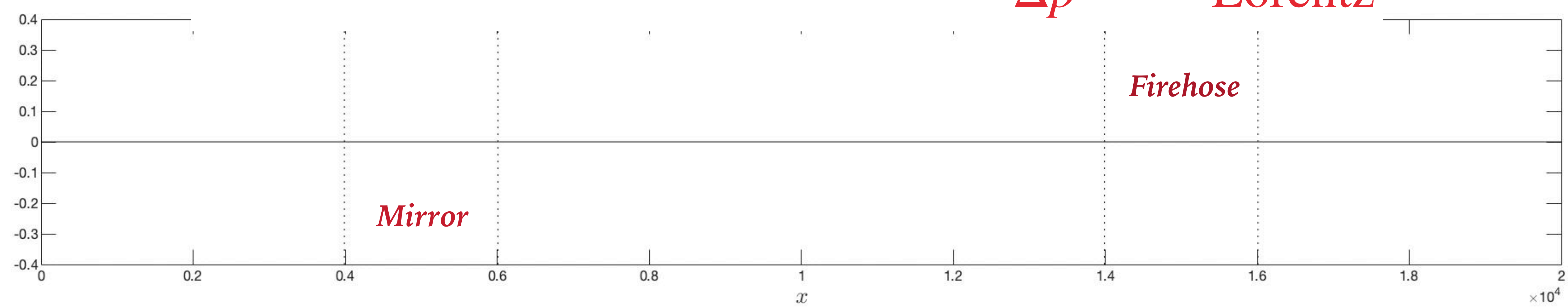
$$\frac{\Delta p}{B^2}$$



FEEDBACK OCCURS ONLY AFTER $F_{\Delta p} \sim F_{\text{Lorentz}}$



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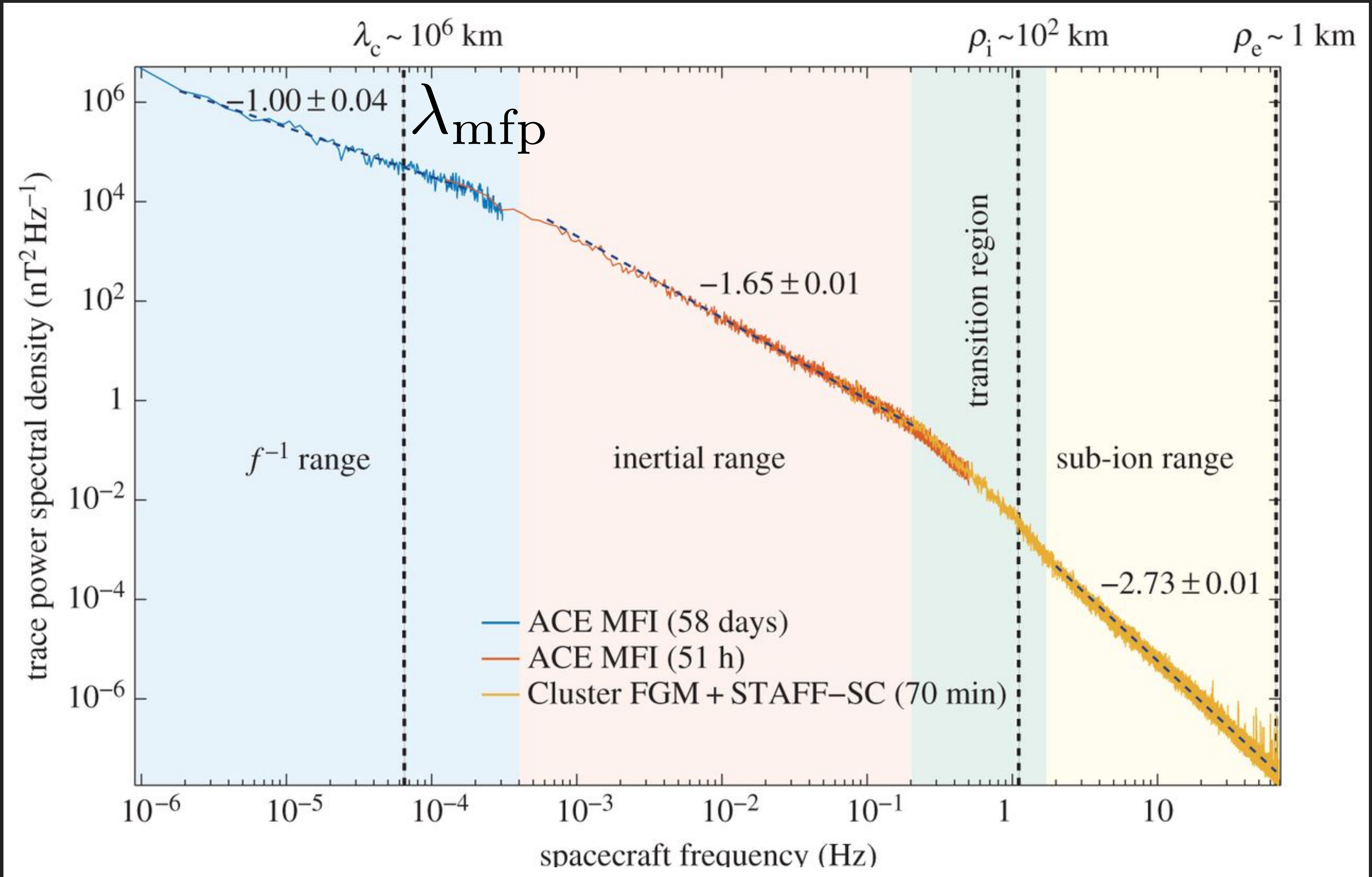
Schekochihin et al. 2009

Because of shear-Alfvén waves

TURBULENCE IS LIKE MHD, EVEN FOR $l \ll \lambda_{\rm mfp}$

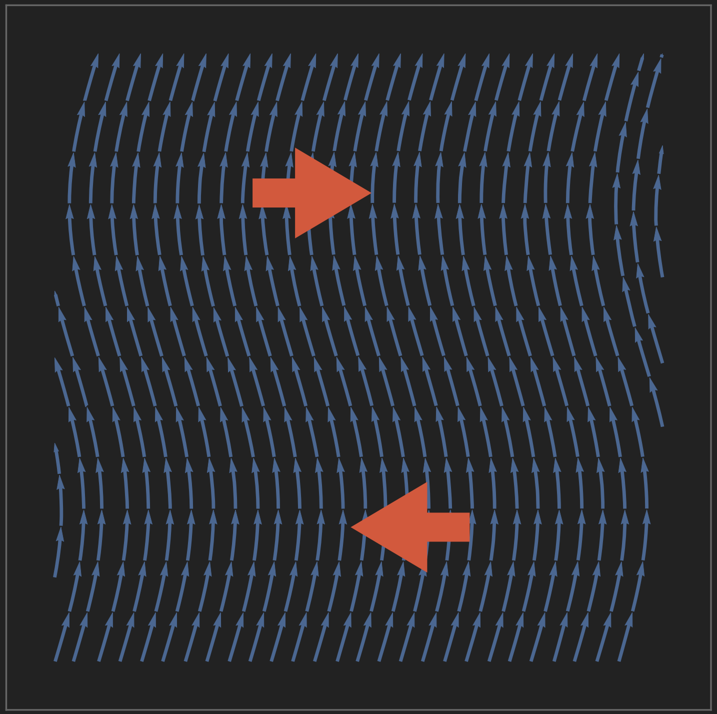


Kiyani et al. 2015

ALFVÉN-WAVE INTERRUPTION

In a linearly polarized wave

$$\frac{dB}{dt} < 0$$



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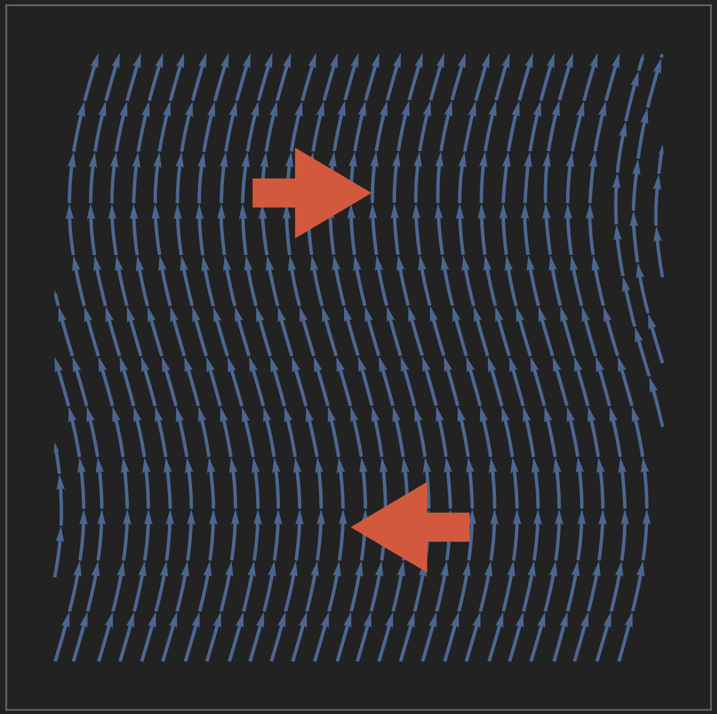

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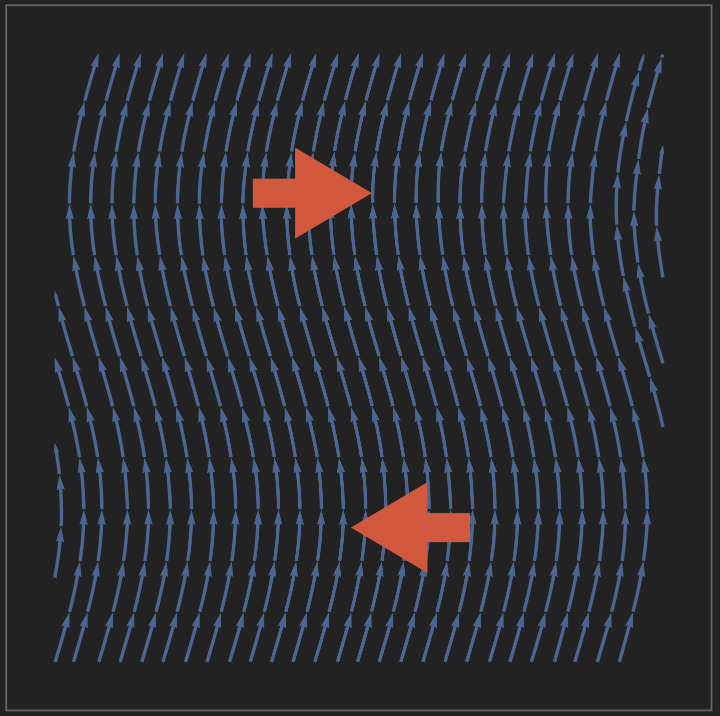

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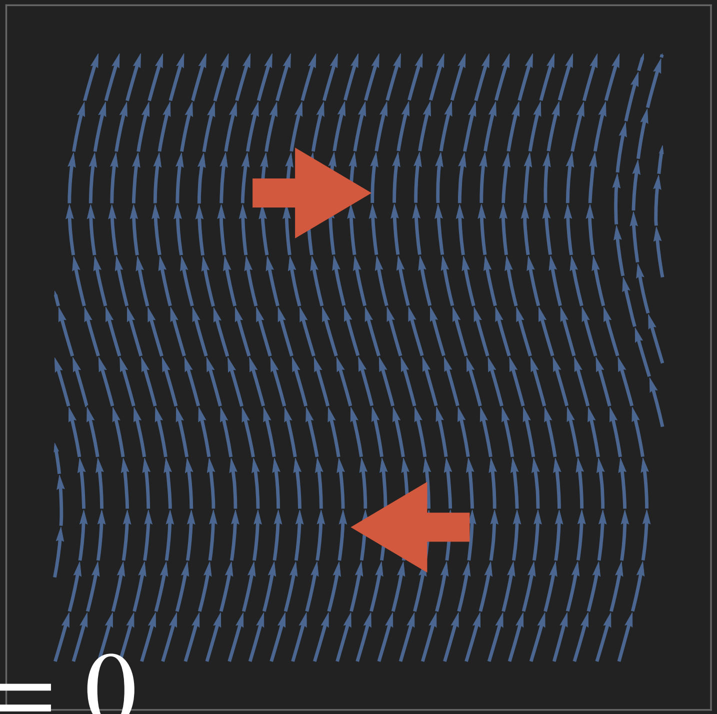

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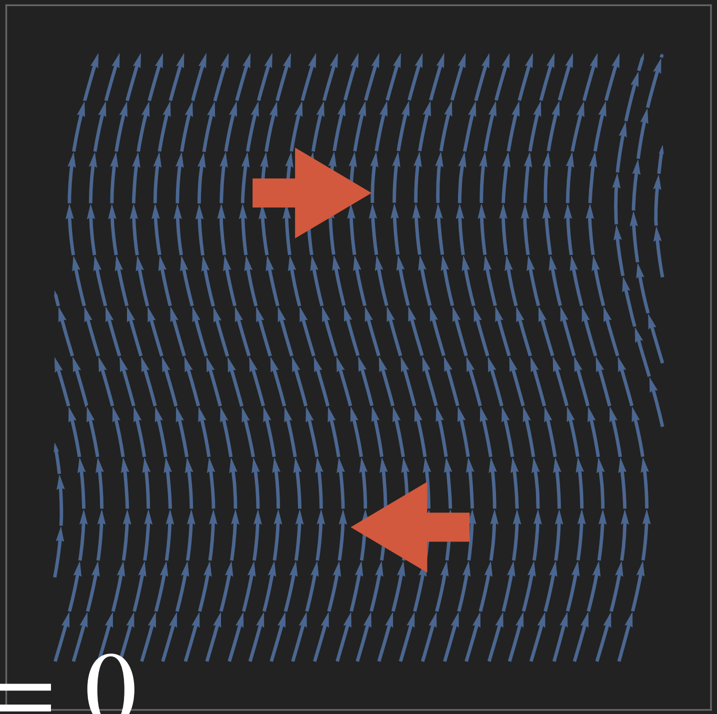

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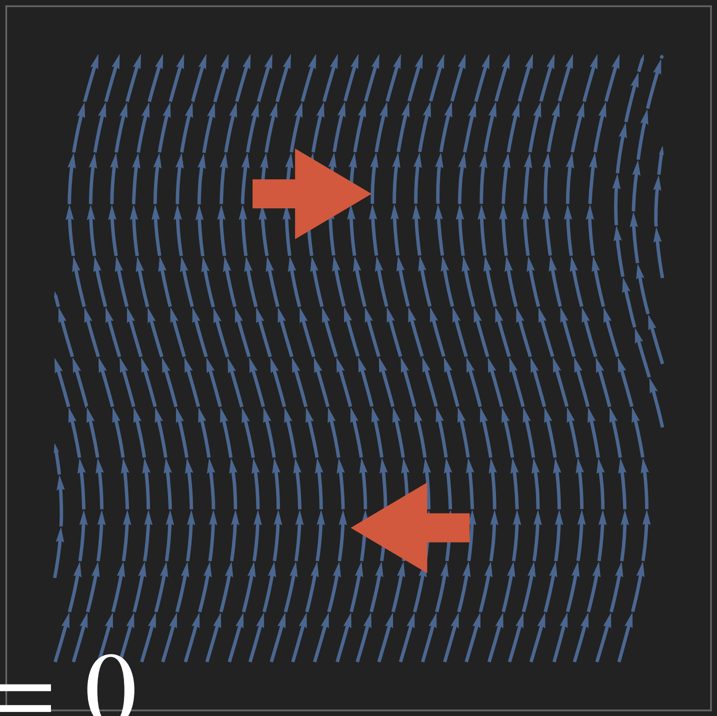

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This occurs if $\frac{\delta B_\perp}{B_0} \gtrsim \sqrt{\frac{\omega_A}{\nu_c}}\beta^{-1/2}$ *or* $\frac{\delta B_\perp}{B} \gtrsim \beta^{-1/2}$

Squire+ ApJL 2016
Squire+ NJP 2017

ALFVÉN-WAVE INTERRUPTION

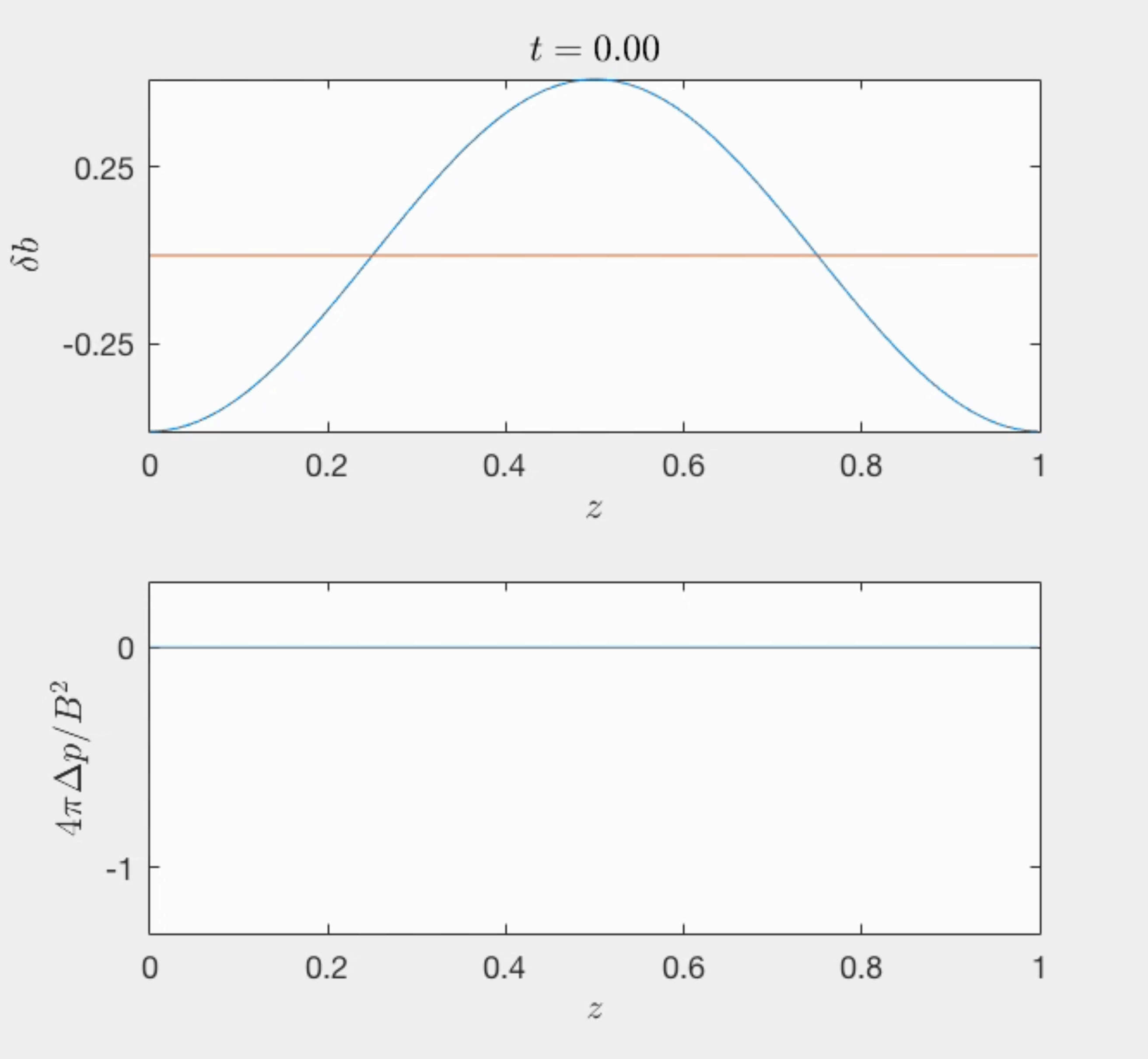
- Details depend on regime

- In Braginskii MHD,

$$\Delta p \approx \frac{p_0}{\nu_c} \hat{b}\hat{b} : \nabla \boldsymbol{u}$$

wave decays over timescale

$$t_{\rm decay} > \tau_A$$



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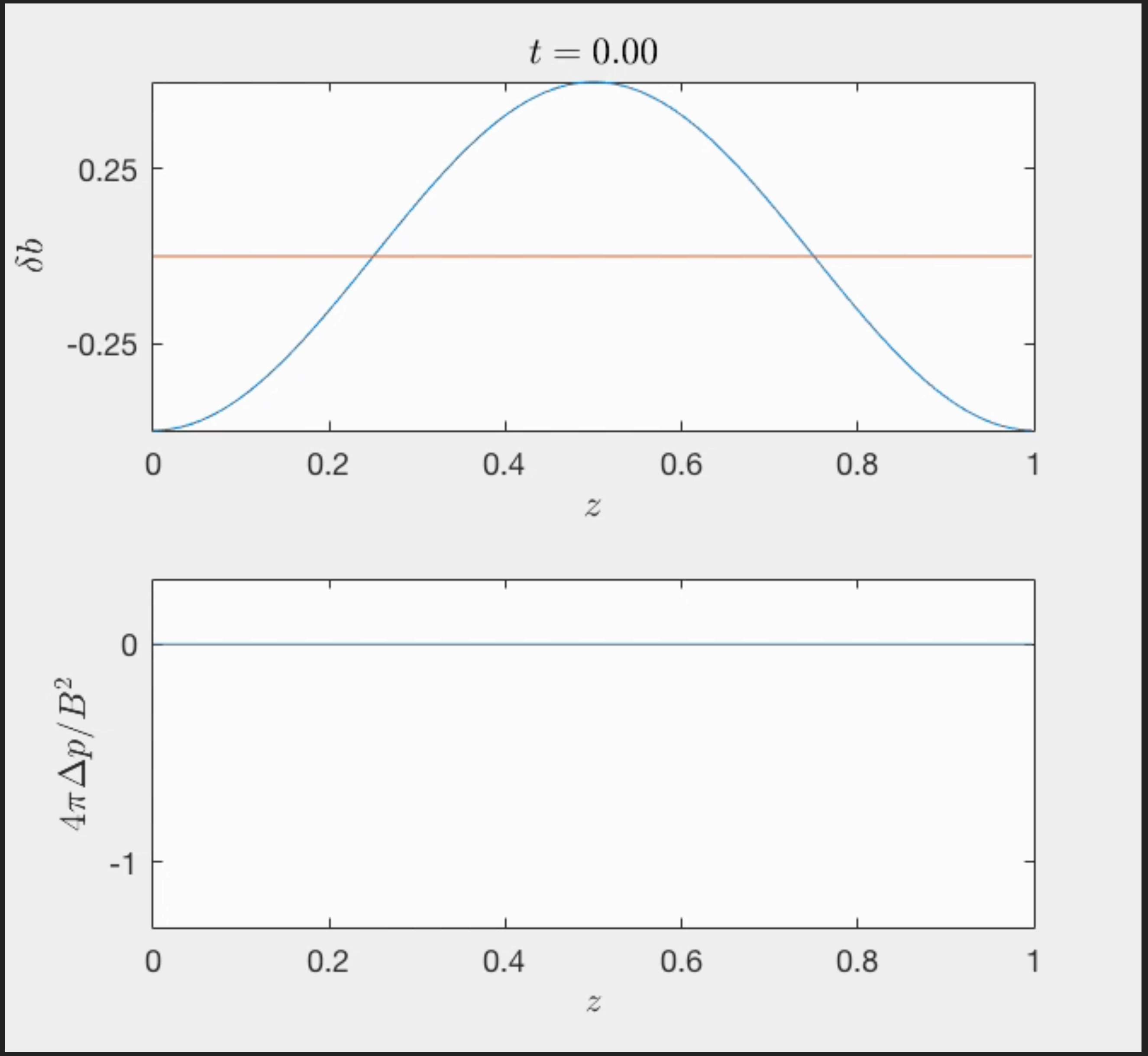

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Is turbulence damped in a weakly collisional plasma with

$$\frac{\delta B_\perp}{B_0} \gtrsim \sqrt{\frac{\omega_A}{\nu_c}}\beta^{-1/2} \ ?$$

Squire+ JPP 2019

MAGNETO-IMMUTABILITY

- Due to $F_{\Delta p}$, plasma organizes itself to avoid motions that generate large $\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}:\nabla\boldsymbol{u}$ and Δp

- $\Delta p \approx \dfrac{p_0}{\nu_c}\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}:\nabla\boldsymbol{u} \approx \dfrac{p_0}{\nu_c}\dfrac{1}{B}\dfrac{dB}{dt}$ (from $\dfrac{1}{B}\dfrac{DB}{Dt} \approx \hat{\boldsymbol{b}}\hat{\boldsymbol{b}}:\nabla\boldsymbol{u}$)
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We call this effect

"Magneto-immutability"

INCOMPRESSIBILITY AND MAGNETO-IMMUTABILITY

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$$D_t \boldsymbol{u} = -\nabla p + \dots$$

drives flows away from large p

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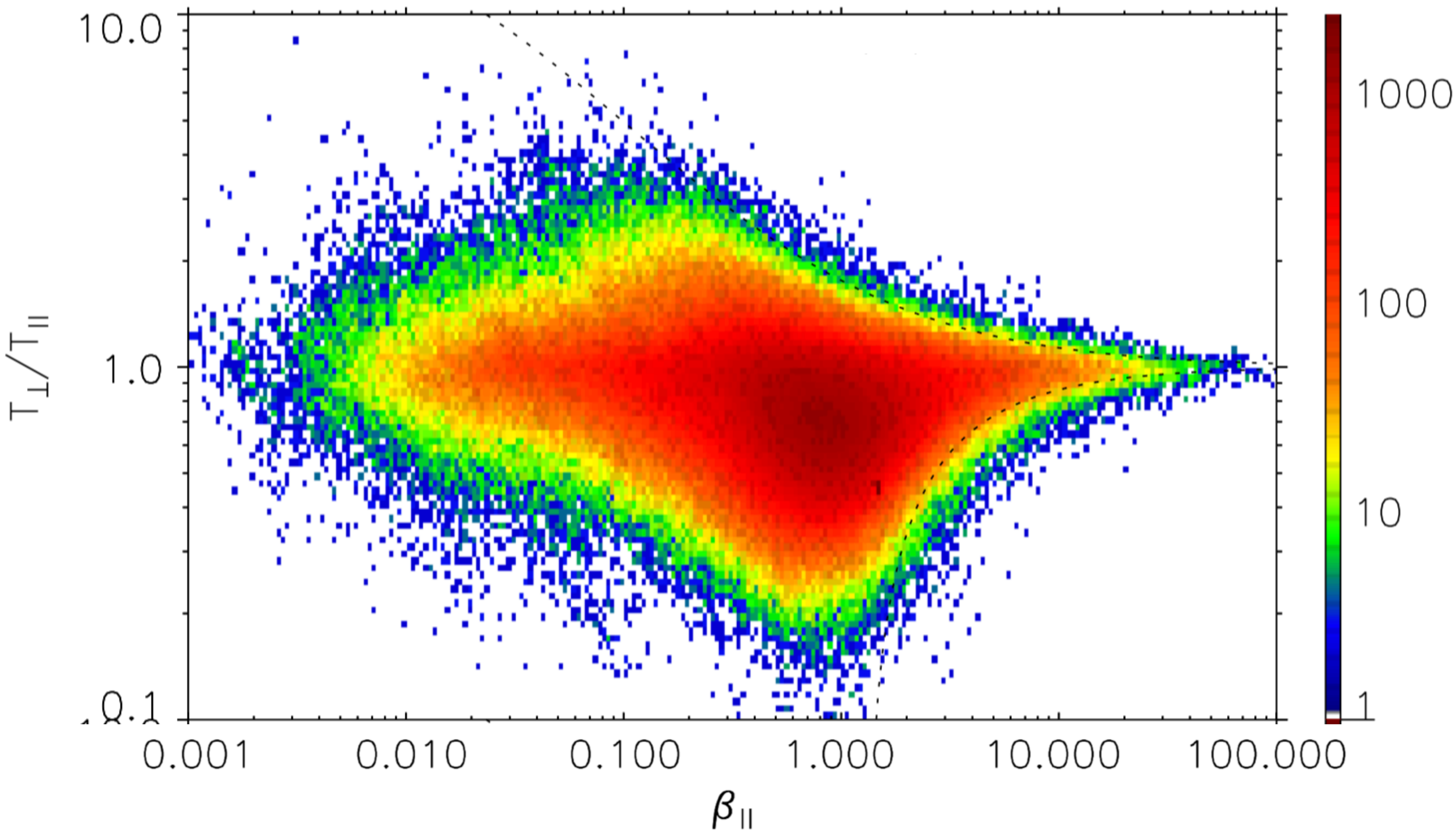
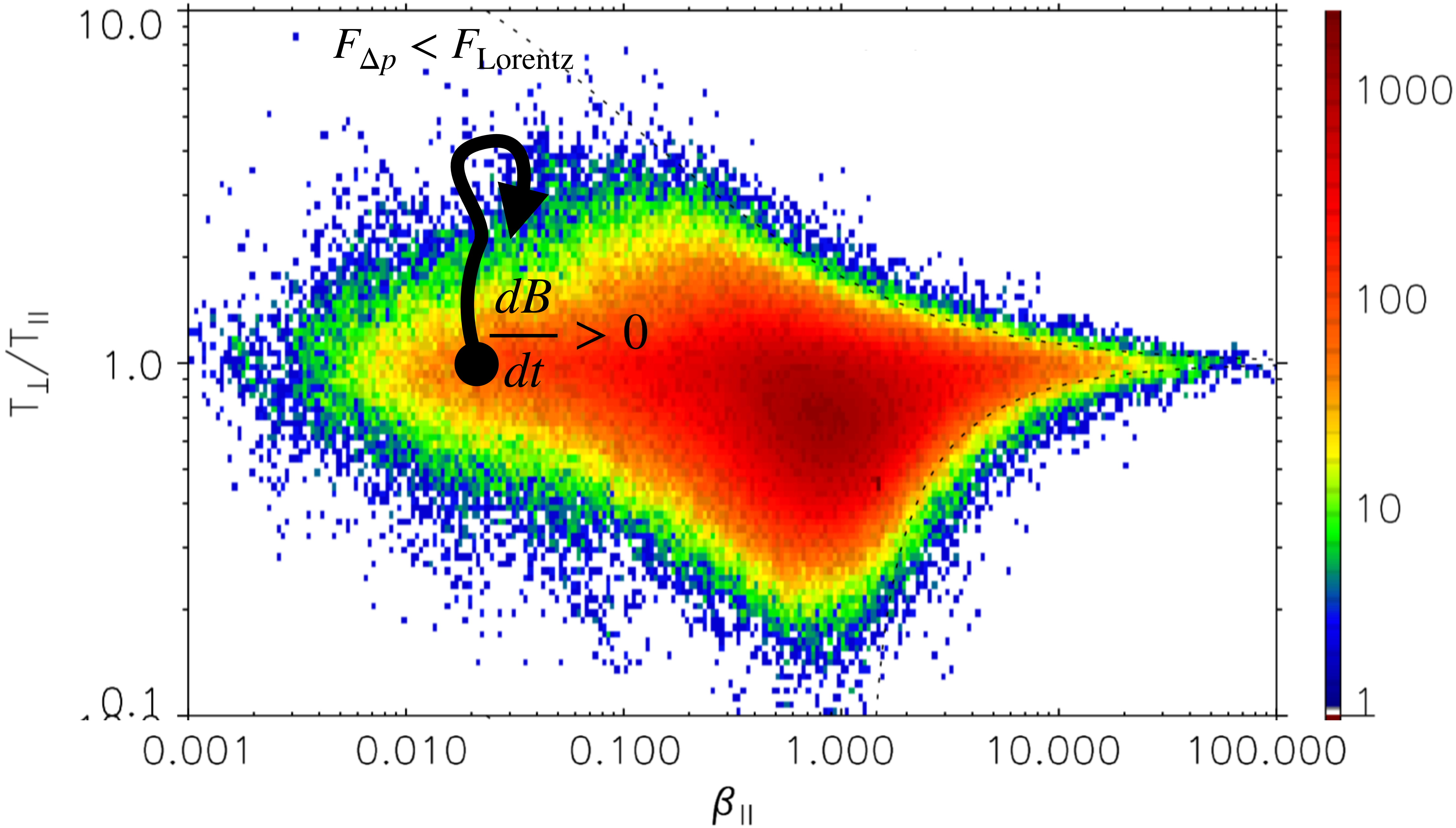
“Magneto-immutable”



Bale et al. 2009



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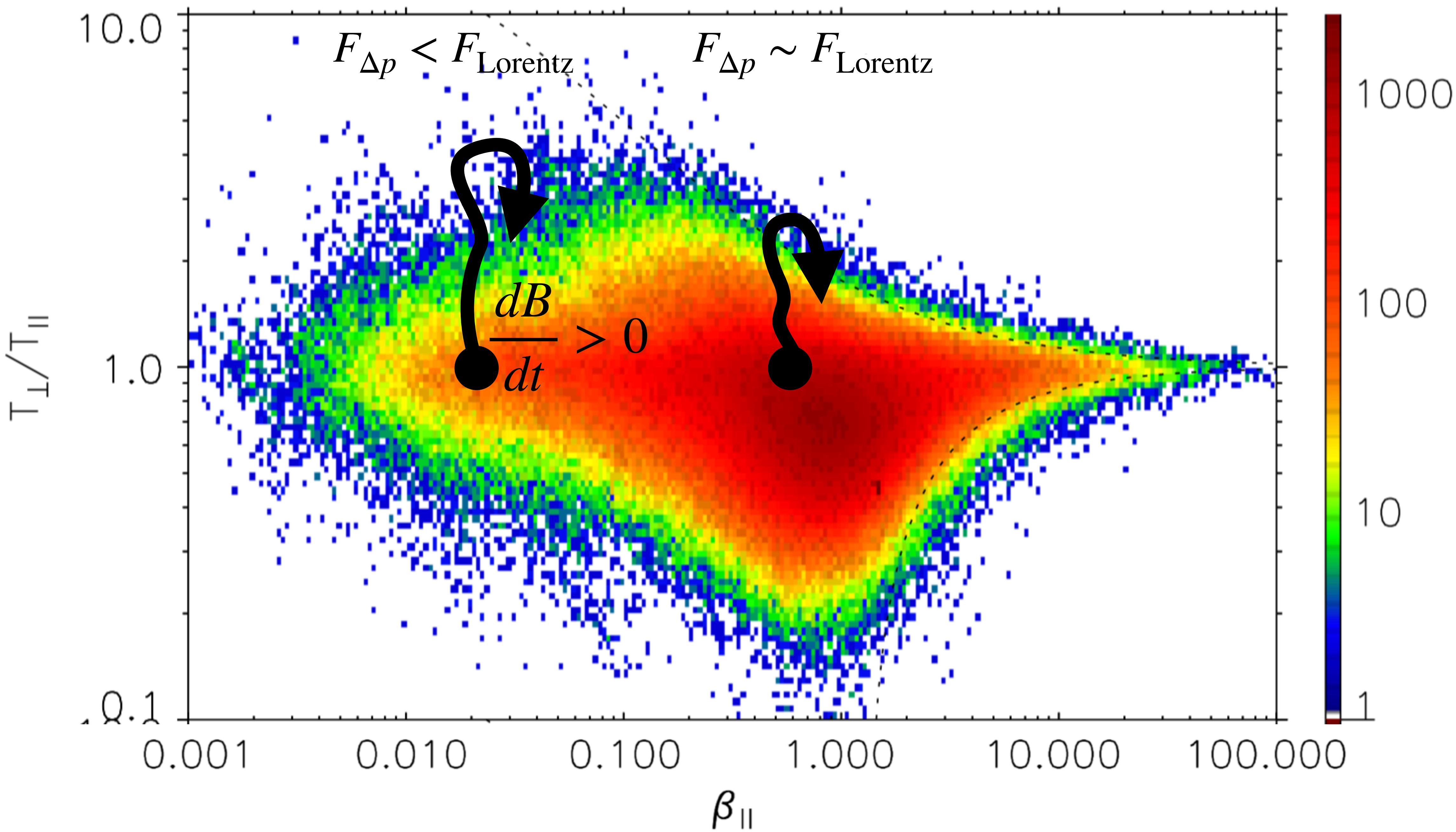

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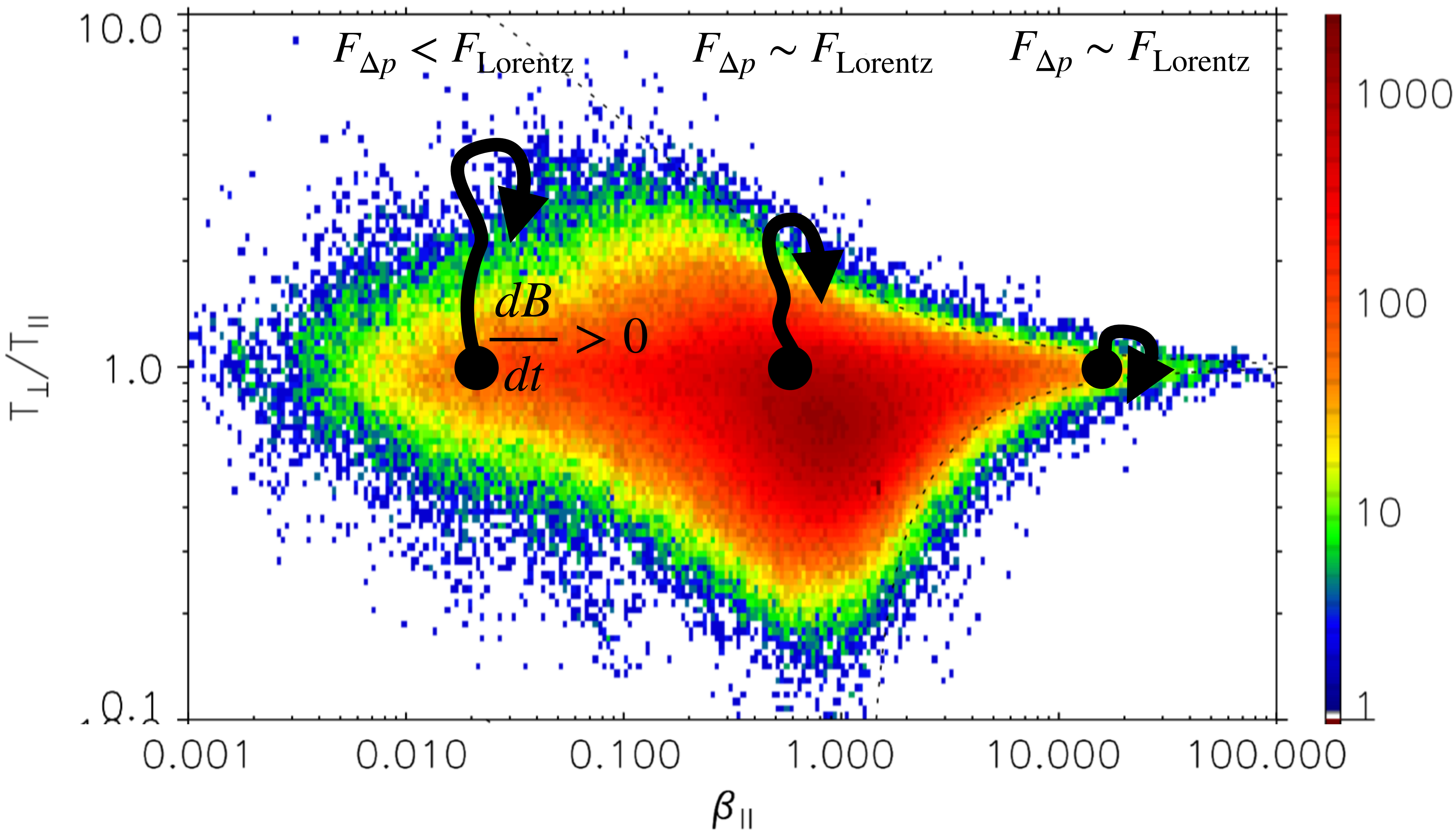

Bale et al. 2009

OUTLINE – MAGNETO-IMMUTABLILITY

Focus on fluid-scale effects, not the kinetic micro-physics

- The dynamical effect of pressure anisotropy
  - Generation of pressure anisotropy
  - A simple prediction — shear-Alfvén wave interruption
  - How the plasma avoids this — magneto-immutability
- Simulations (Braginskii MHD)
  - Driven Alfvénic turbulence
  - The MRI

SIMULATIONS — ALFVENIC TURBULENCE

- Standard, driven, critically balanced MHD turbulence with $\frac{\delta B_\perp}{B_0} \gtrsim \sqrt{\frac{\omega_A}{\nu_c}}\beta^{-1/2}$ (large Braginskii viscosity, $\mathrm{It}_{\mathrm{Brag}} \lesssim 1$).
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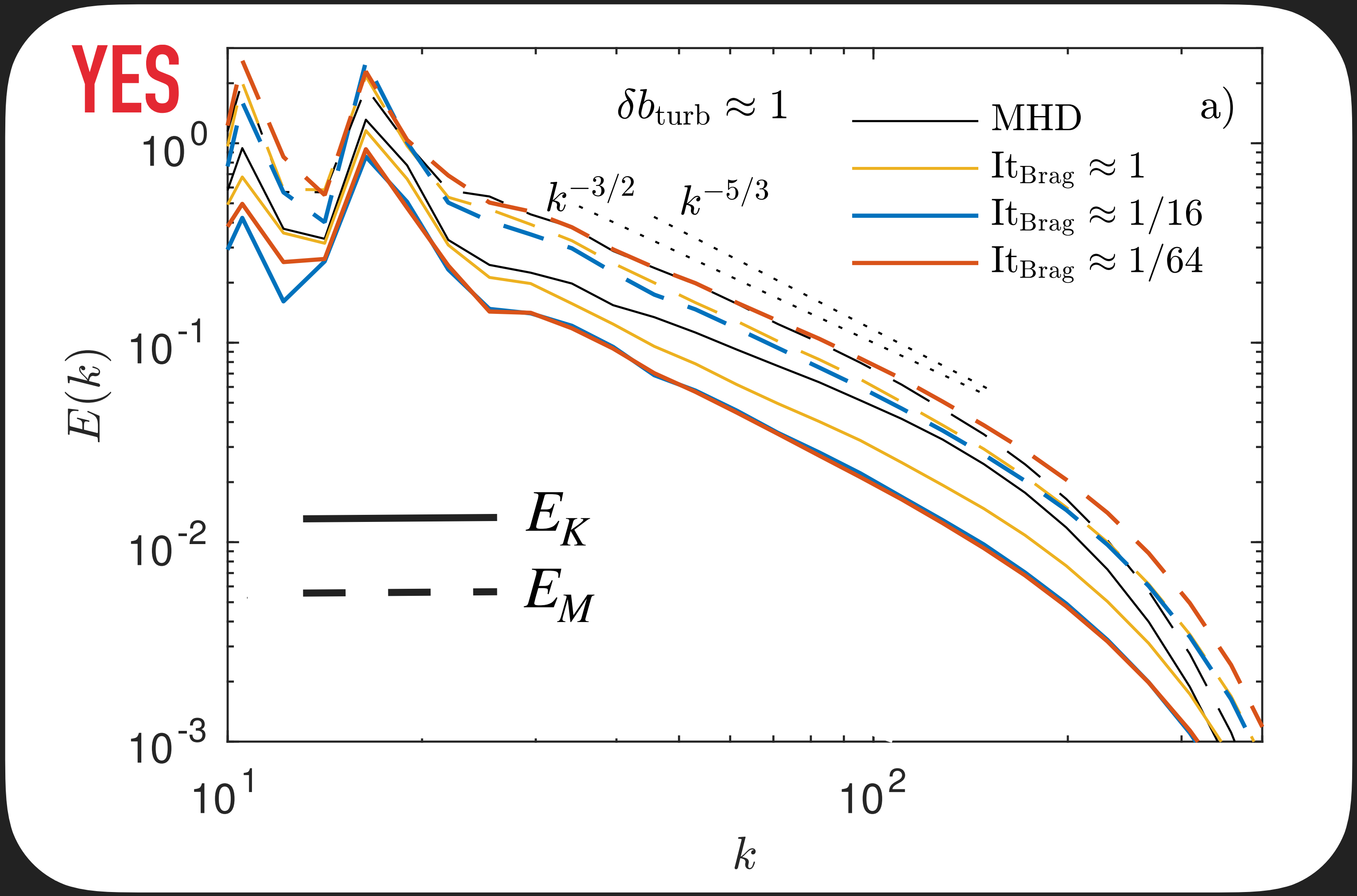
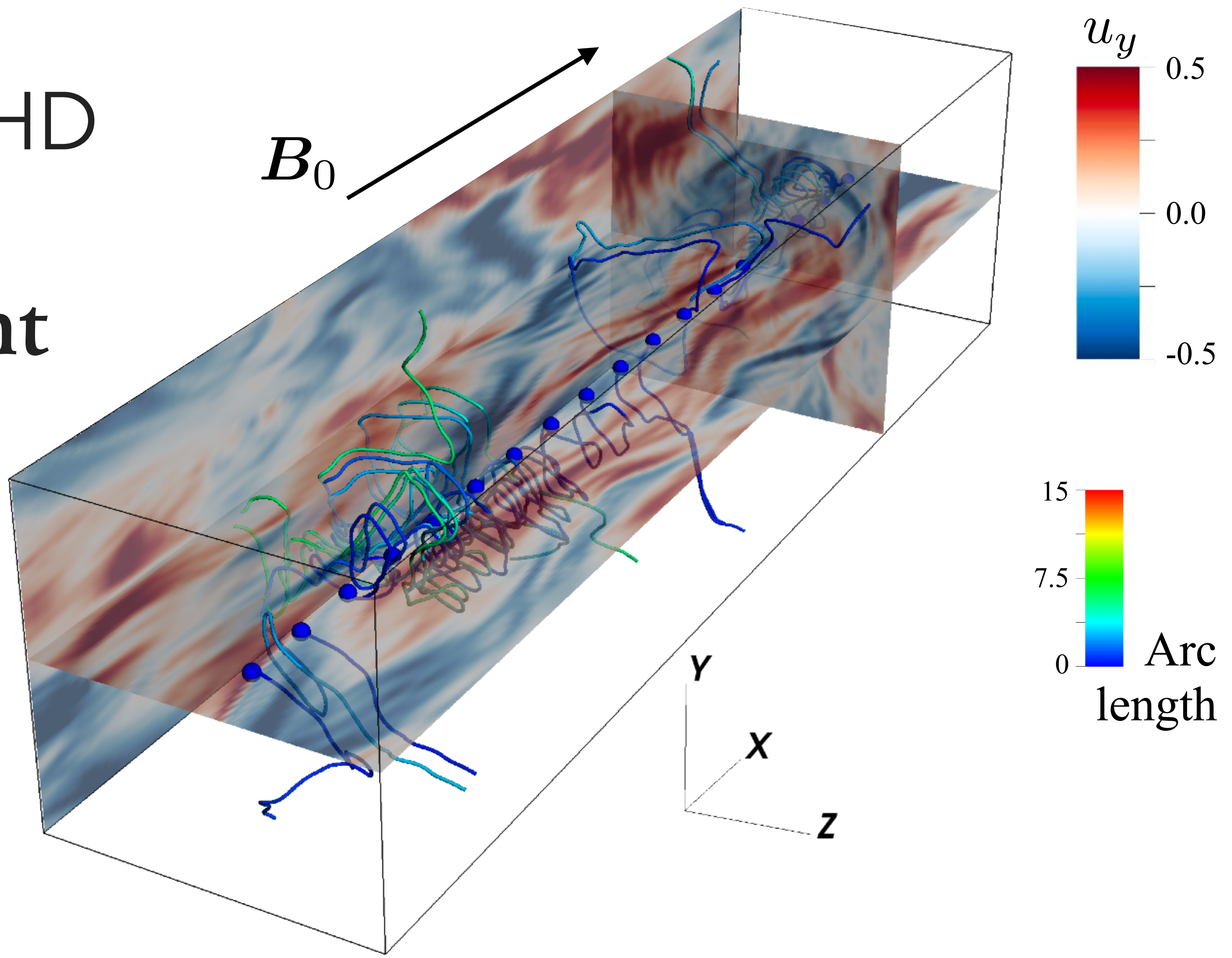


But the fluid motions themselves are quite different

MHD

Fully turbulent

$t = 4\tau_A$



Squire+ JPP 2019

Nonlinear analogue to circularly polarized wave

Magneto-immutable

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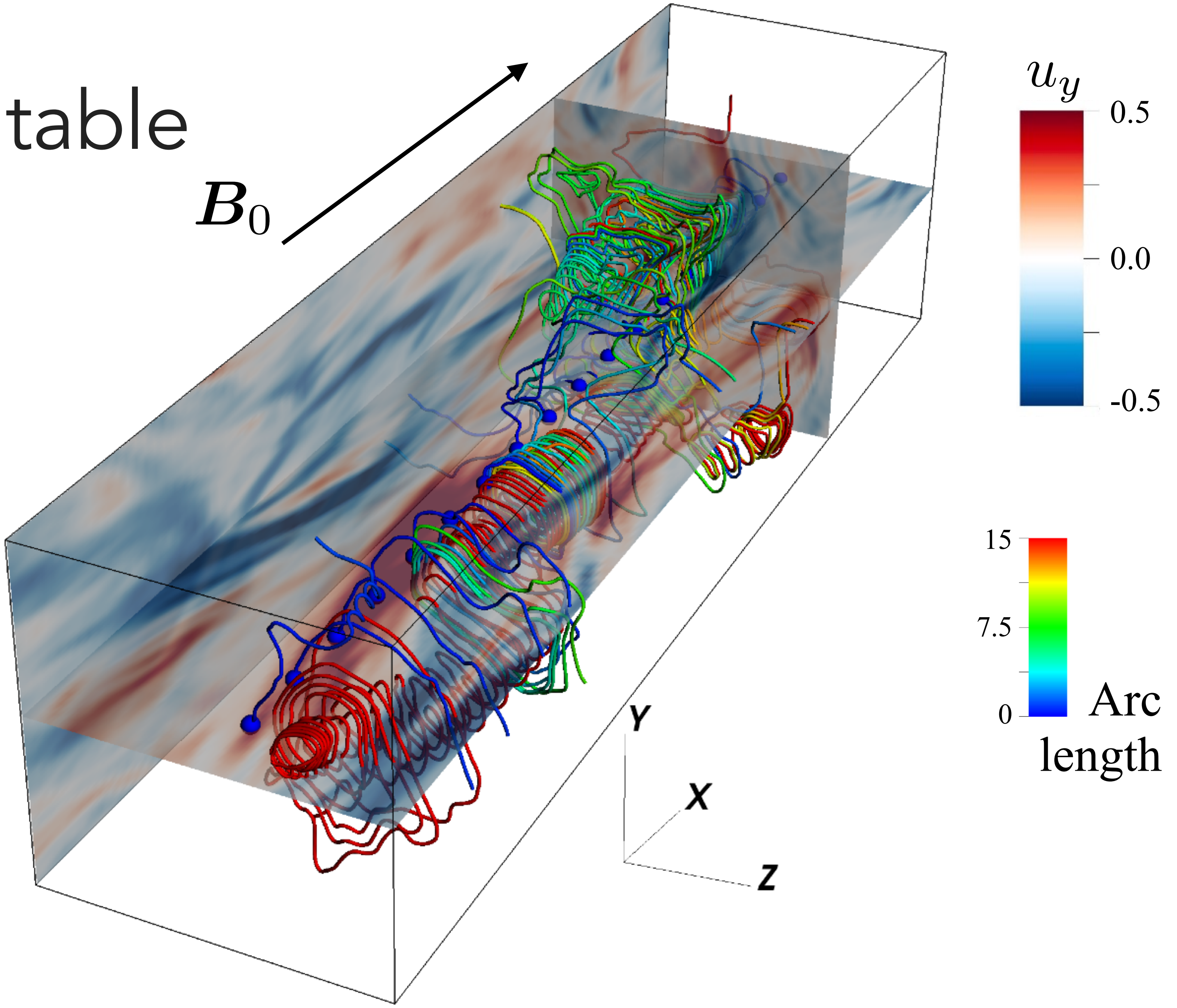

- Low-mach-number flows minimize $\nabla \cdot \boldsymbol{u}$
- Similarly, magneto-immutable flows minimize $\hat{\boldsymbol{b}}\hat{\boldsymbol{b}} : \nabla \boldsymbol{u}$

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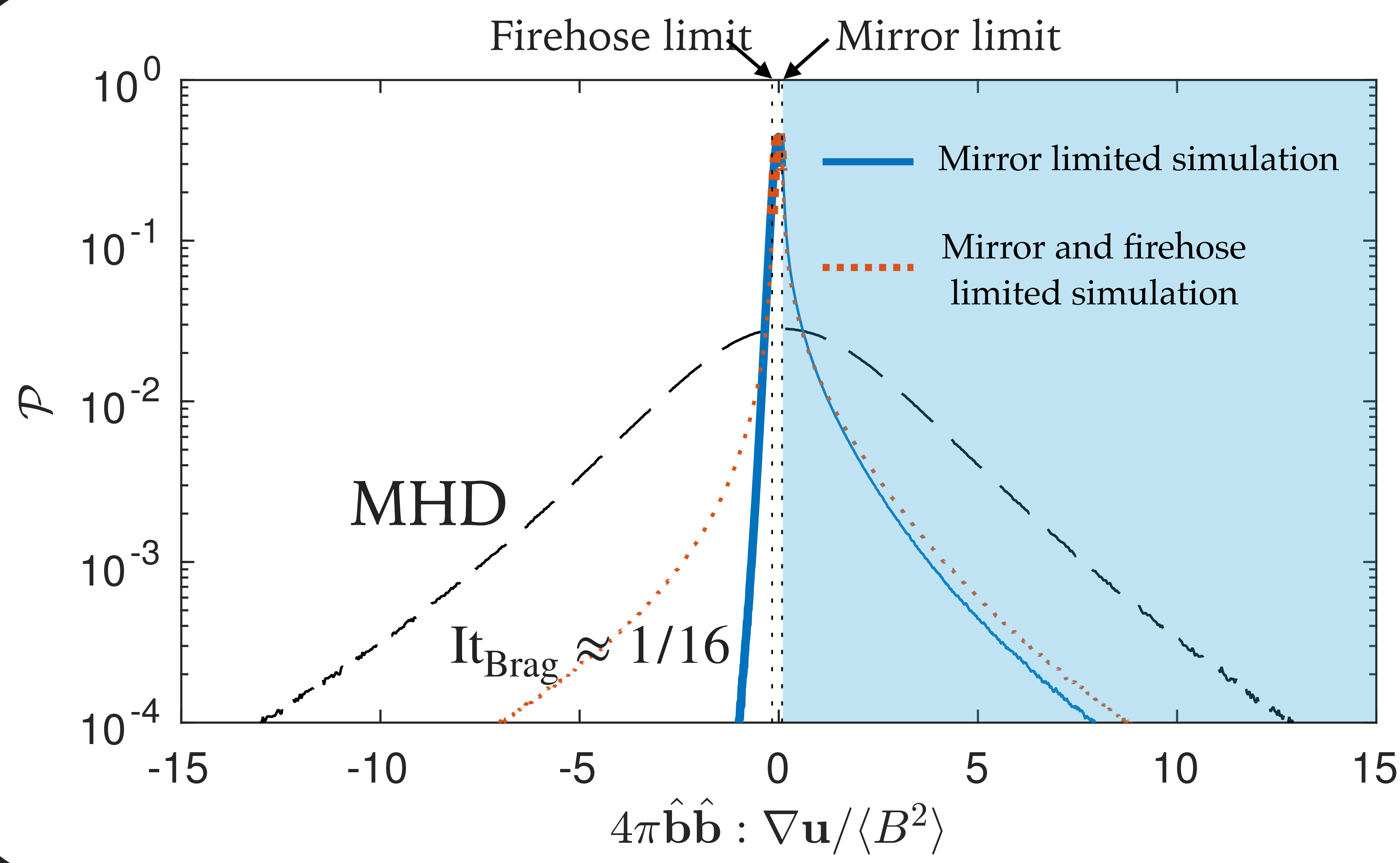

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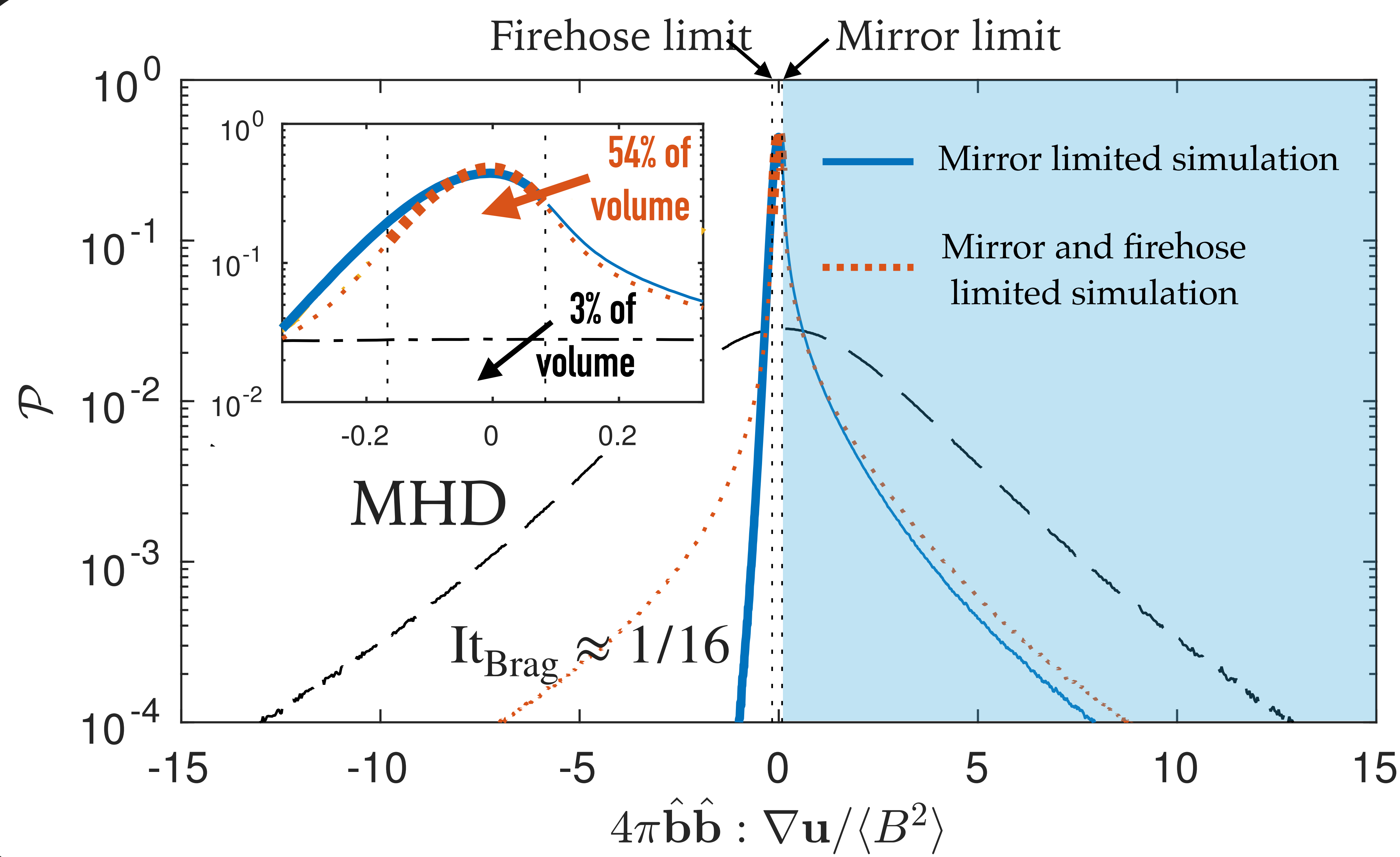

Kempski+ MNRAS 2019

MRI

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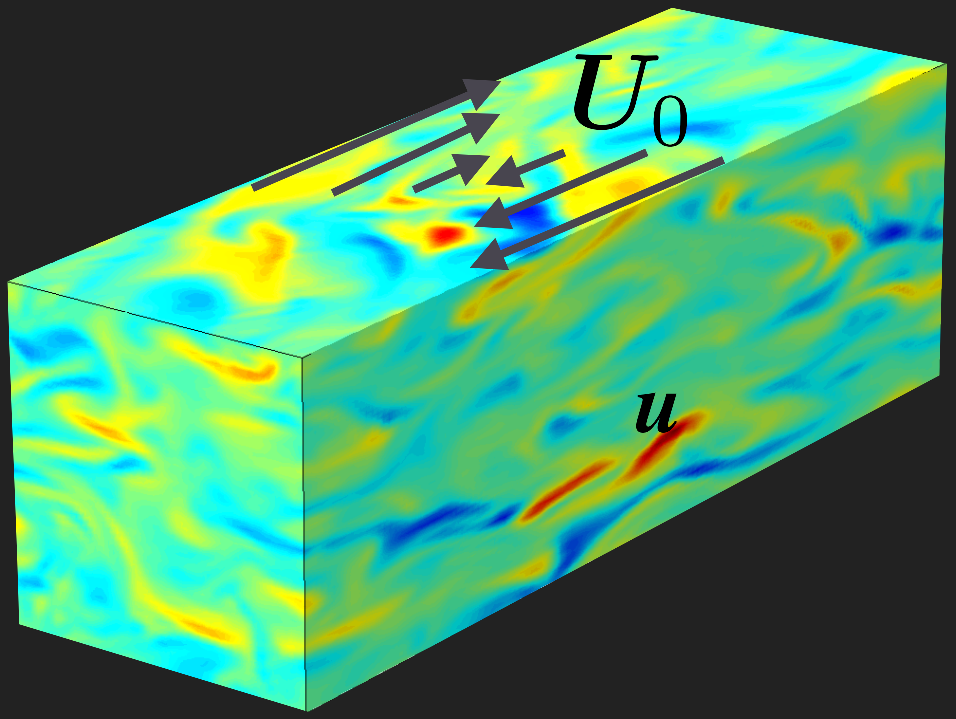

Kempski+ MNRAS 2019

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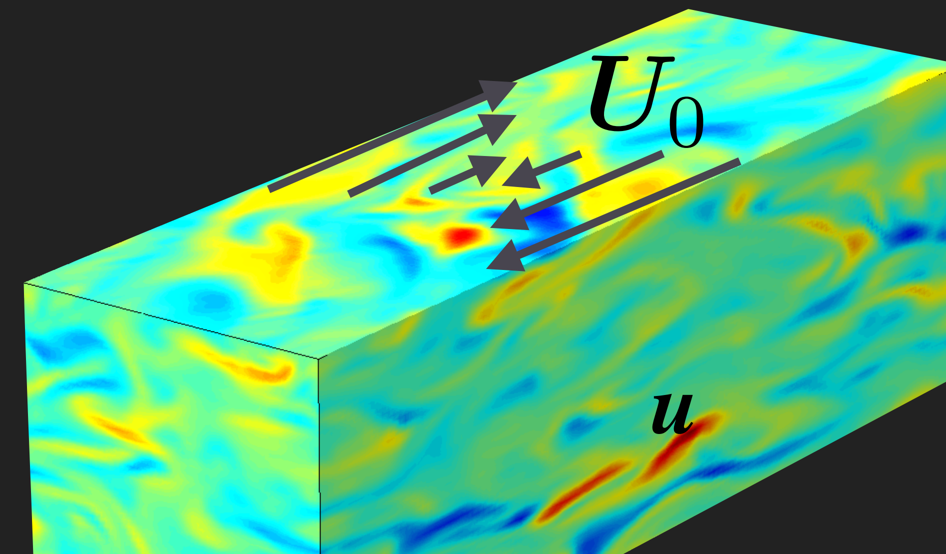

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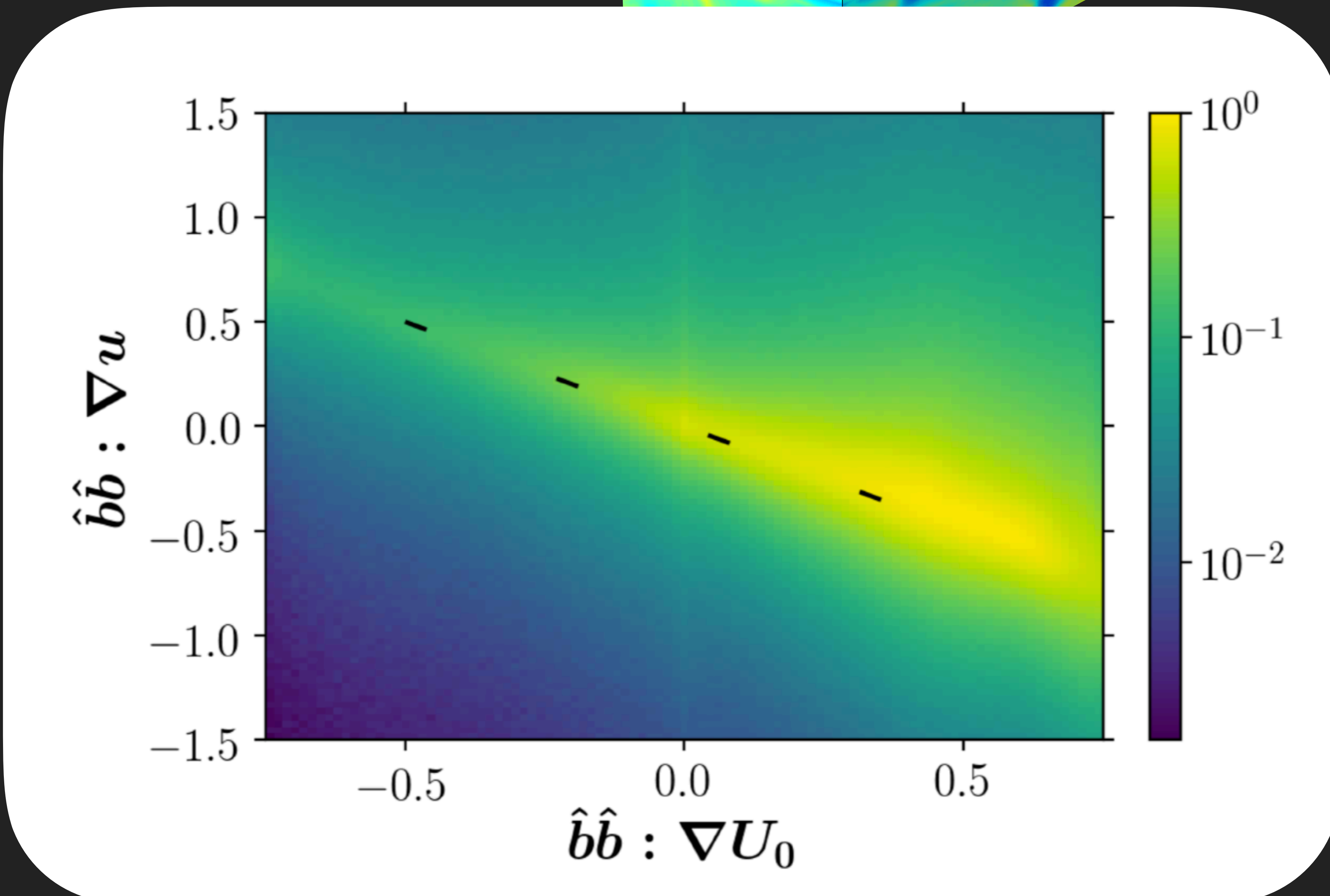
- The turbulence minimizes the ***total*** Δp by cancelling $\hat{\boldsymbol{b}}\hat{\boldsymbol{b}} : \nabla \boldsymbol{U}_0$ with $\hat{\boldsymbol{b}}\hat{\boldsymbol{b}} : \nabla \boldsymbol{u}$



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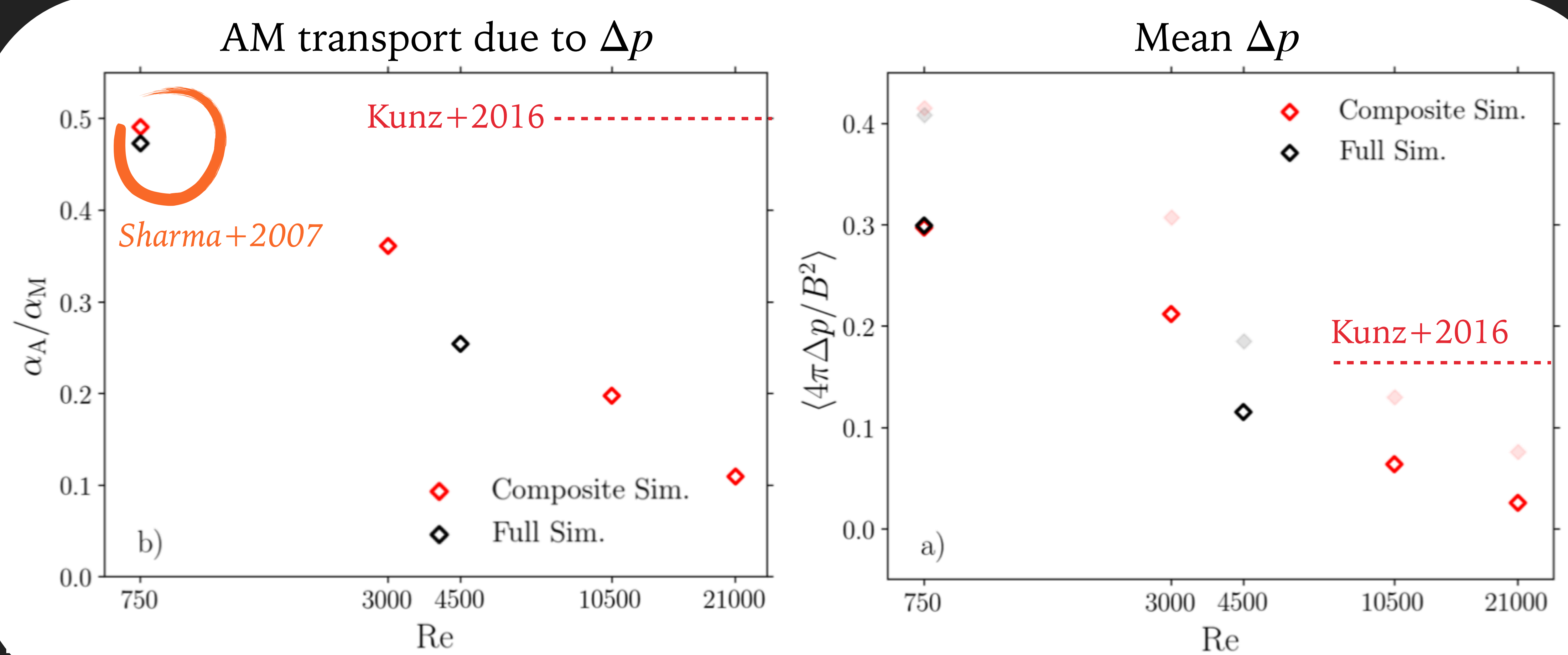
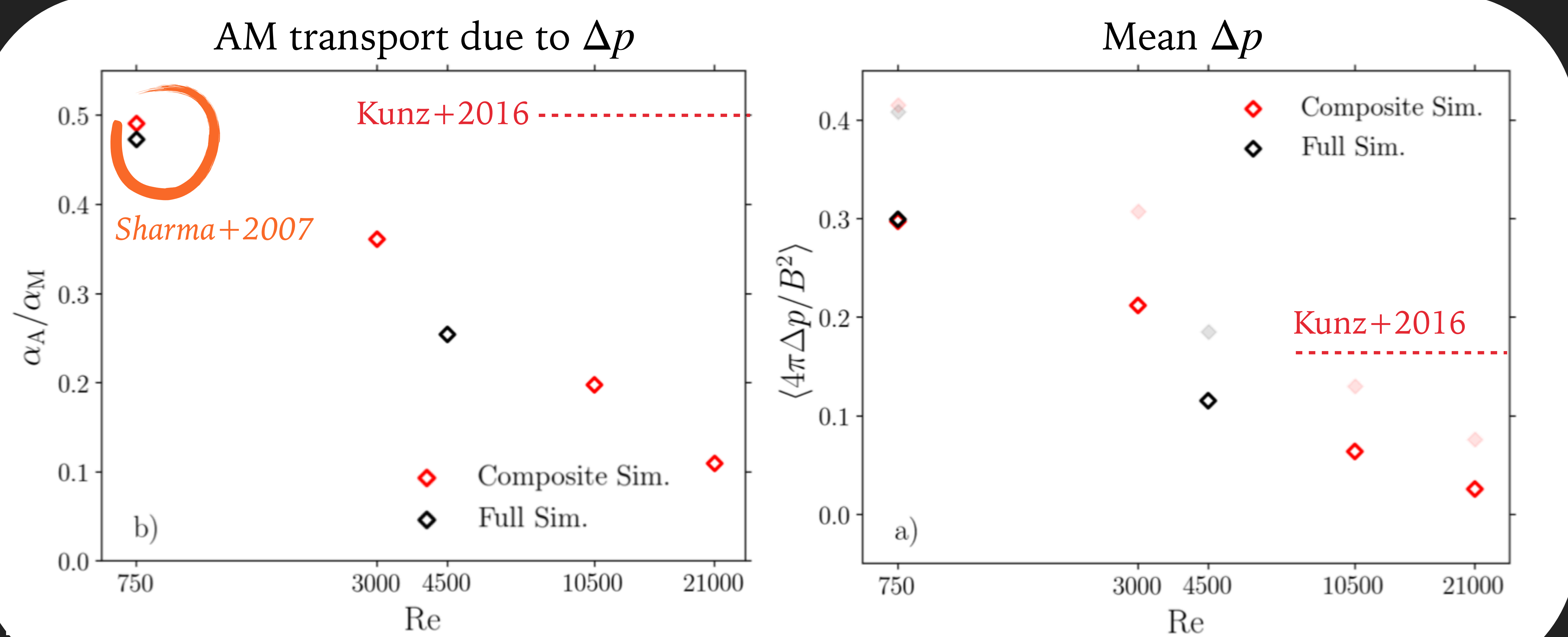


Relation to kinetics (Kunz+ 2016, Hoshino 2015) remains unclear

- Turbulence becomes ***more similar*** to MHD as isotropic Re increases



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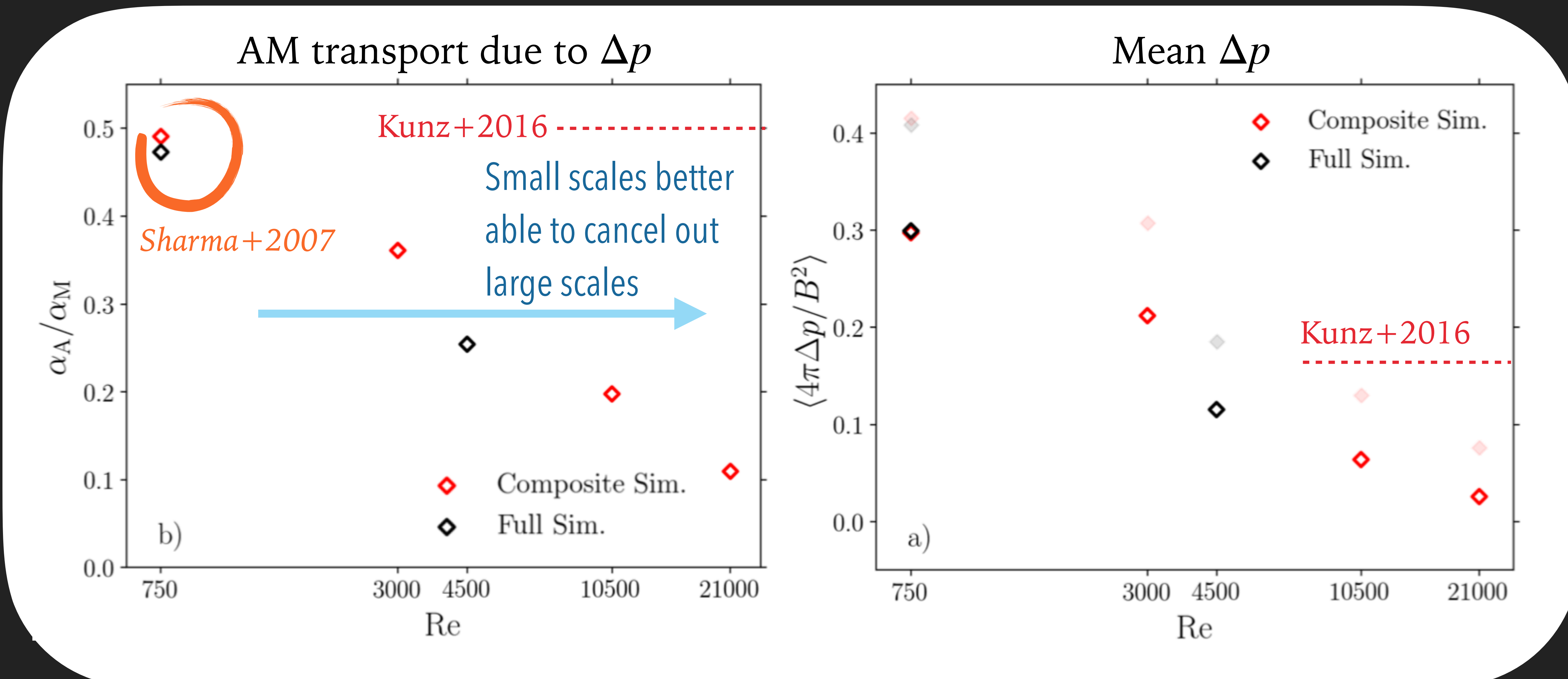

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Squire+ JPP 2019
Kempski+ MNRAS 2019

CONCLUSIONS

- The dynamical feedback of Δp on flow occurs around the same point that mirror/firehose are excited
- This feedback tends to reduce Δp, and consequently, variations in $|\boldsymbol{B}|$

  we call this ***magneto-immutability***

- Braginskii MHD simulations show that "magneto-immutable" turbulence is very similar to MHD, despite minimizing $\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}:\nabla \boldsymbol{u}$
- More work needed to understand collisionless regime