want to advertise a few recent papers:

Galactic echoes

Rimpei Chiba[1,2]★, Jupiter Ding[3,4], Chris Hamilton[5], Matthew W. Kunz[4,6] and Scott Tremaine[5]

Extreme Heating of Minor Ions in Imbalanced Solar-wind Turbulence

Michael F. Zhang[1,2], Matthew W. Kunz[1,2], Jonathan Squire[3], and Kristopher G. Klein[4]

Tearing-mediated Reconnection in Magnetohydrodynamic Poorly Ionized Plasmas. I. Onset and Linear Evolution

Elizabeth A. Tolman[1,2], Matthew W. Kunz[3], James M. Stone[1], and Lev Arzamasskiy[1]

Global Simulations of Gravitational Instability in Protostellar Disks with Full Radiation Transport. I. Stochastic Fragmentation with Optical-depth-dependent Rate and Universal Fragment Mass

Wenrui Xu (许文睿)[1], Yan-Fei Jiang (姜燕飞)[1], Matthew W. Kunz[2,3], and James M. Stone[4]

Self-Similar Cosmic-Ray Transport in High-Resolution Magnetohydrodynamic Turbulence

Philipp Kempski,[1] Drummond B. Fielding,[2,3] Eliot Quataert,[1] Robert J. Ewart,[1] Philipp Grete,[4] Matthew W. Kunz,[1,5] Alexander A. Philippov,[6] and James Stone[7]

want to advertise a few recent papers:

Thermodynamics and collisionality in firehose-susceptible high-β plasmas

Archie F. A. Bott[1,2]†, Matthew W. Kunz[1,3], Eliot Quataert[1], Jonathan Squire[4], and Lev Arzamasskiy[5]

Collisionless conduction in a high-beta plasma: a collision operator for whistler turbulence

Evan L. Yerger[1,2,3,†], Matthew W. Kunz[1,2], Archie F.A. Bott[1,4] and Anatoly Spitkovsky[1]

Efficient micromirror confinement of sub-teraelectronvolt cosmic rays in galaxy clusters

Received: 2 November 2023

Accepted: 8 November 2024

Patrick Reichherzer[1,2], Archie F. A. Bott[1,3], Robert J. Ewart[1,4], Gianluca Gregori[1,5], Philipp Kempski[6], Matthew W. Kunz[6,7] & Alexander A. Schekochihin[1,8]

The vertical shear instability in poorly ionized, magnetized protoplanetary discs

Henrik N. Latter[1★] and Matthew W. Kunz[2,3]

but will focus on these:

On hydromagnetic wave interactions in collisionless, high-β plasmas

S. Majeski [1,2,†] and M.W. Kunz [1,2]

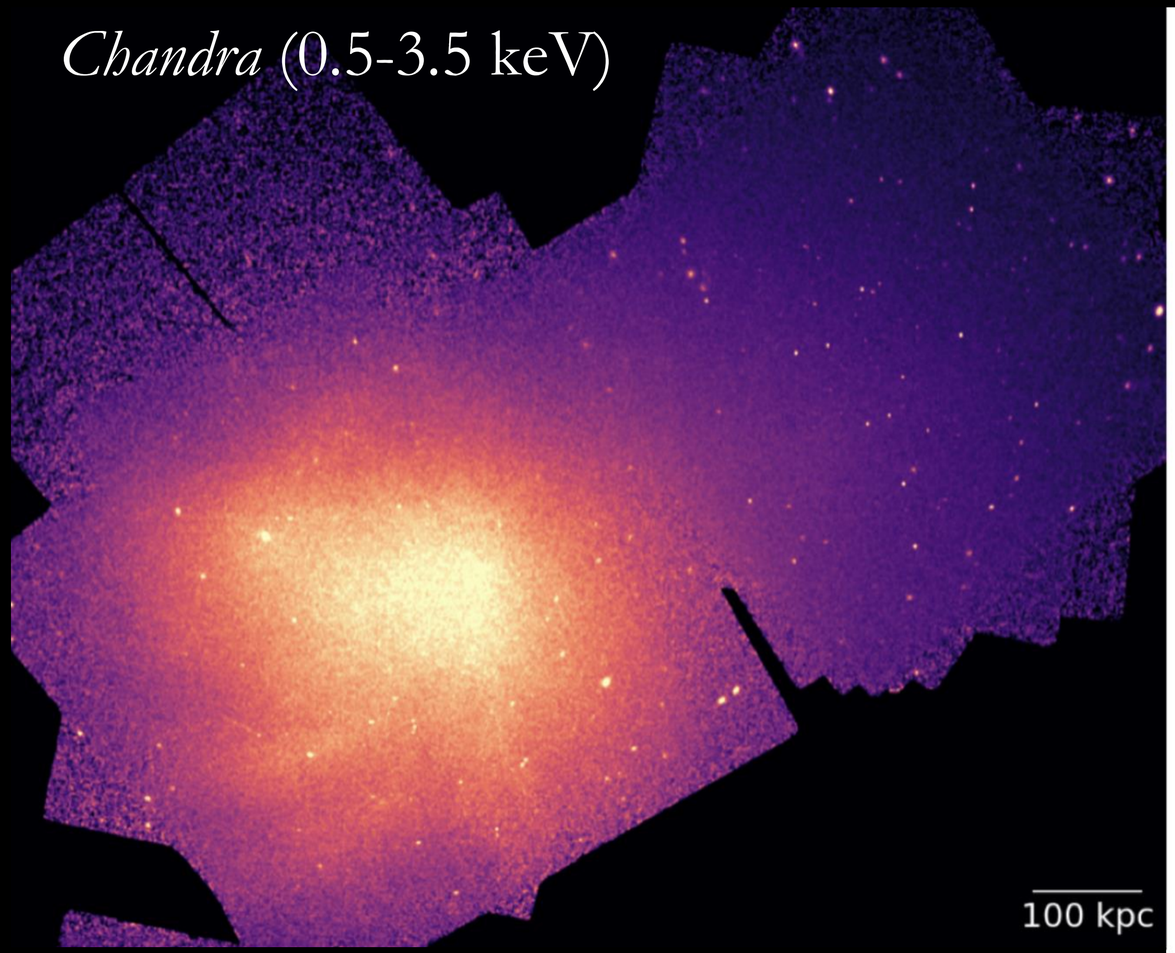
Self-organization in collisionless, high-β turbulence

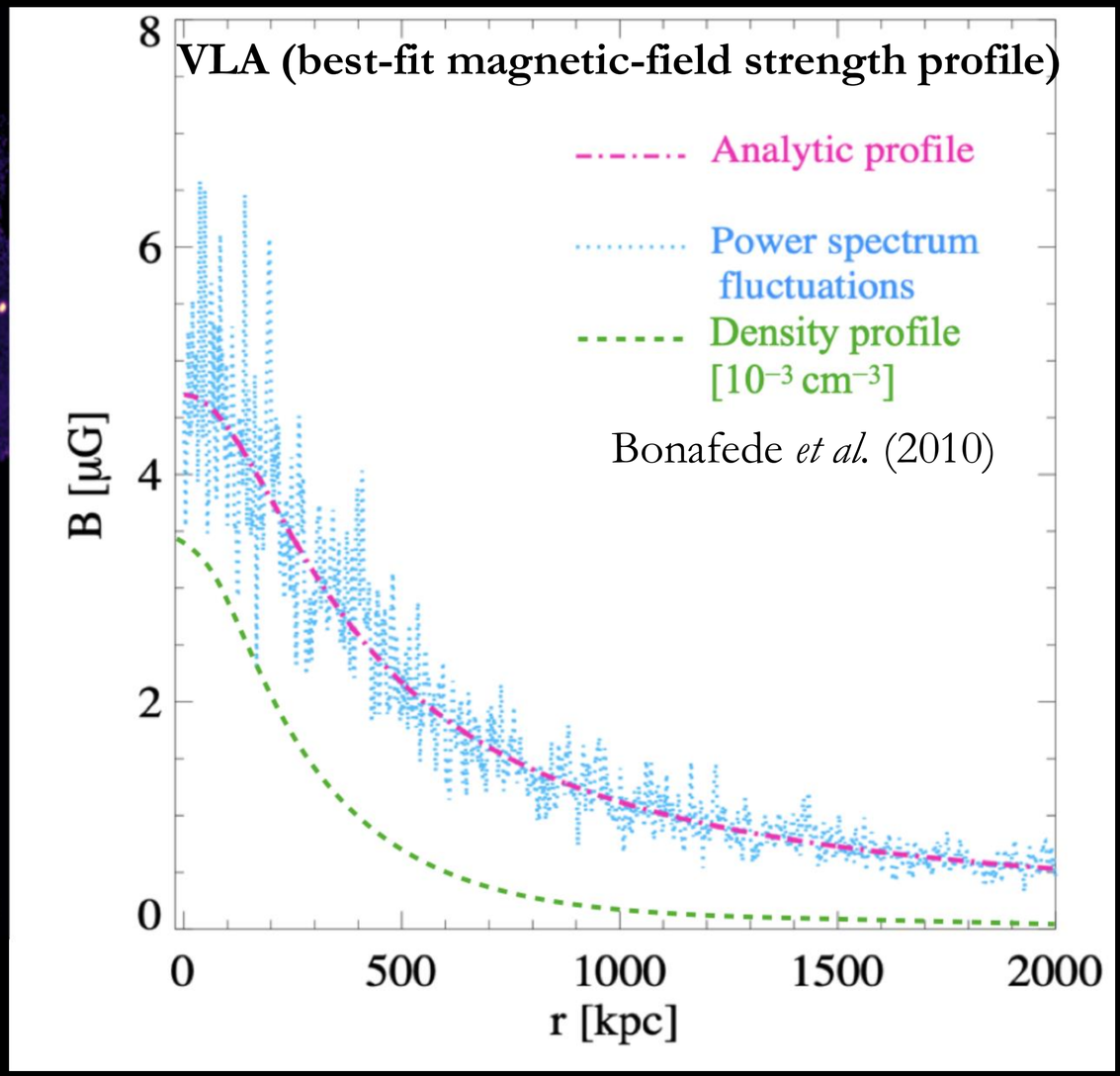
S. Majeski [1,2,†], M.W. Kunz [1,2] and J. Squire [3]

On turbulence and heating in galaxy clusters

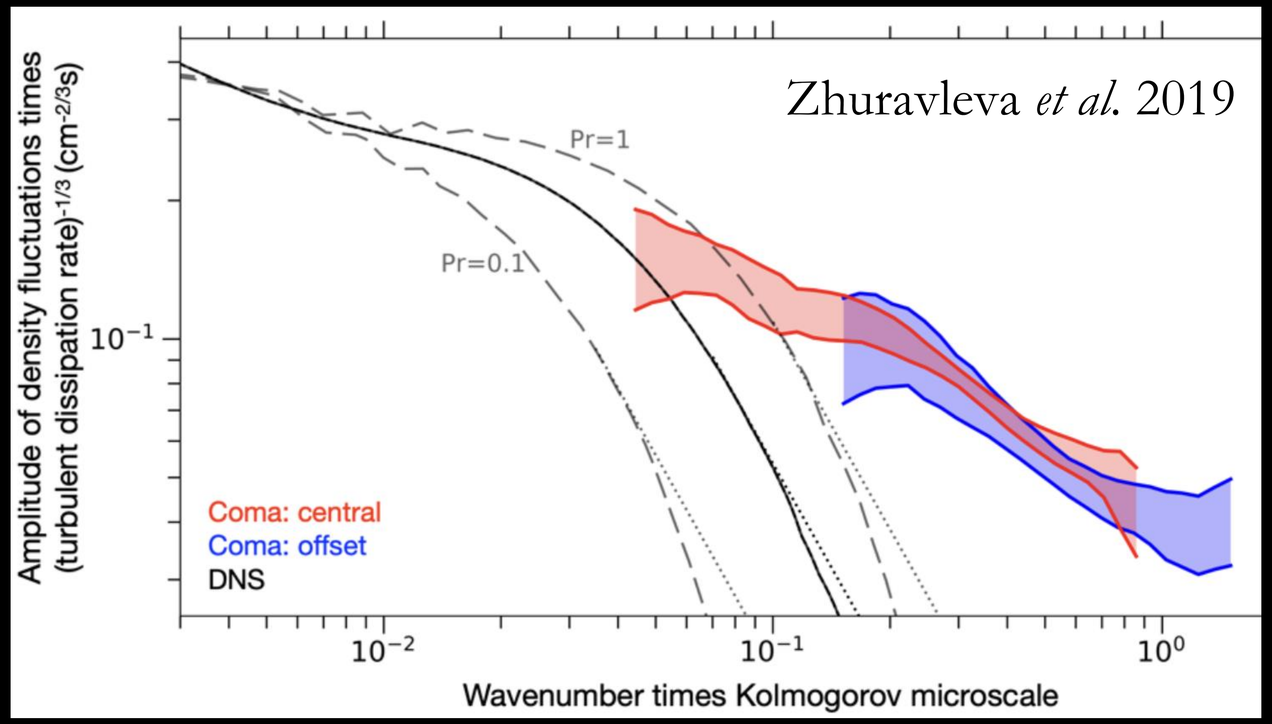
S. Majeski[a,b,1], M. W. Kunz[a,b], J. Squire[c], and A. A. Schekochihin[d,e]

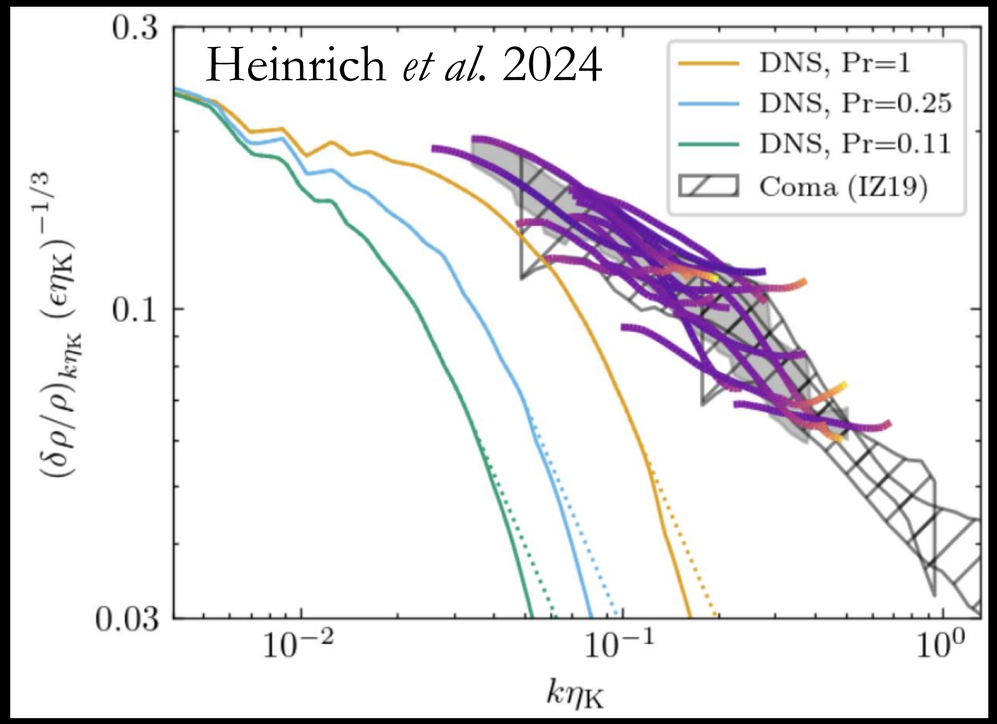
Coma cluster (~100 Mpc away; ~8 keV)



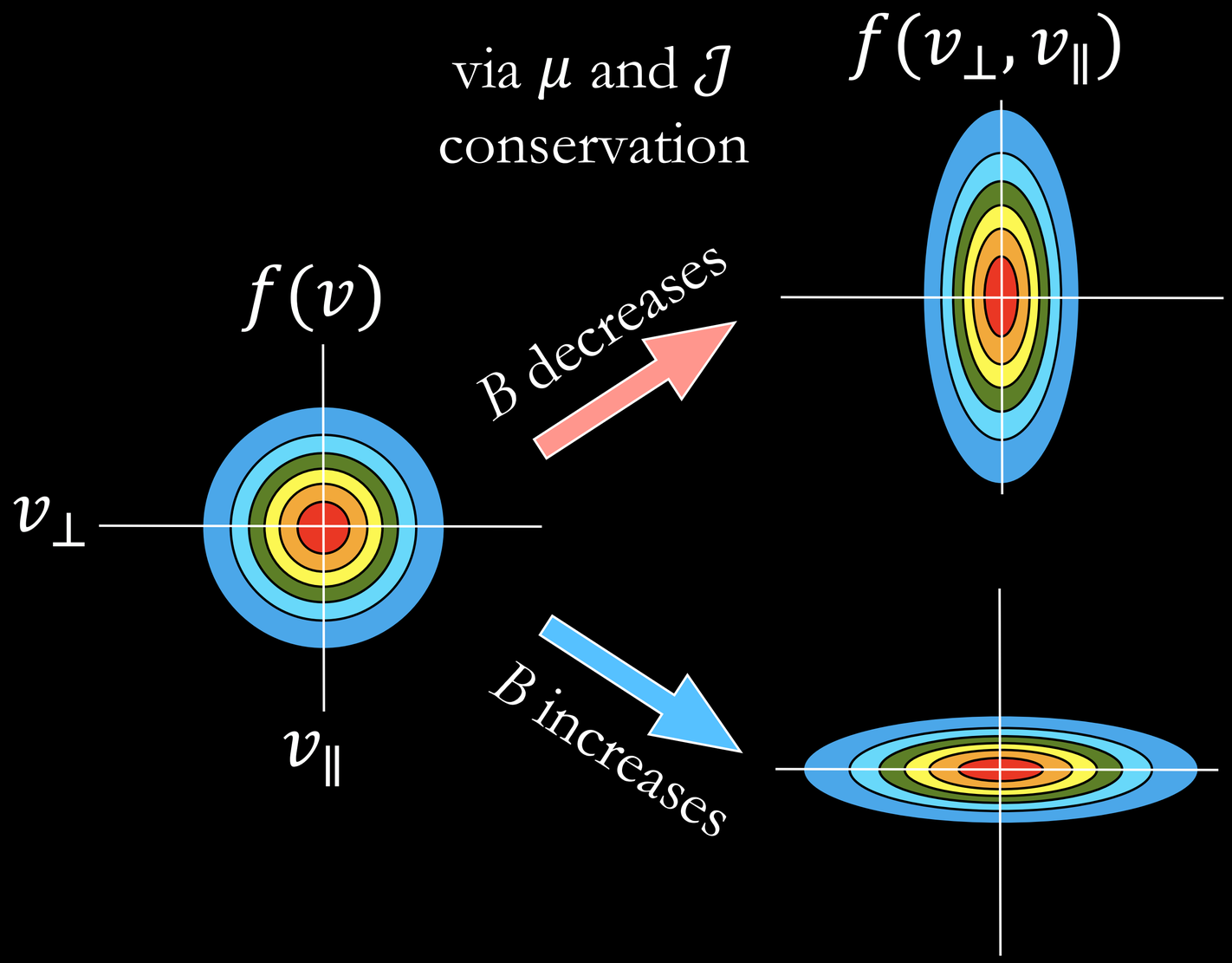


X-ray observations of galaxy clusters can't seem to find viscous scale…





viscosity inferred from X-ray obs of density fluc's from Bremsstrahlung emission in 17 different clusters is **significantly smaller than Spitzer (collisional) value**



pressure anisotropy

can be driven **globally**
(e.g., expansion of solar wind, compression during accretion, differential rotation in disks)

or

can be generated ***in situ***
by **fluctuations**
(e.g., waves, turbulence, contracting current sheets)

via μ and $\mathcal{J}$ conservation

$f(v_\perp, v_\parallel)$

$f(v)$

$v_\perp$

$v_\parallel$

$\mathcal{B}$ decreases

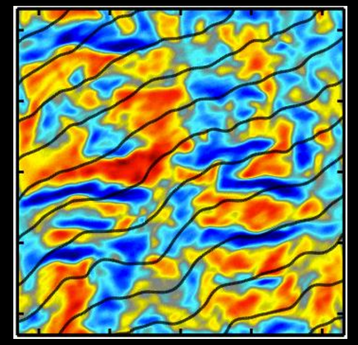
$\mathcal{B}$ increases

$$\frac{p_\parallel - p_\perp}{p} \gtrsim \frac{2}{\beta}$$

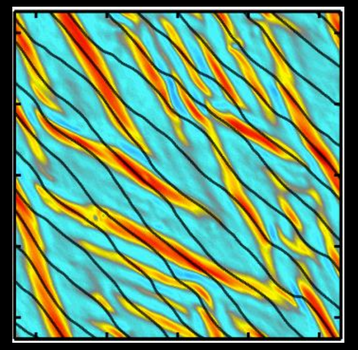
firehose instability

$$\frac{p_\perp - p_\parallel}{p} \gtrsim \frac{1}{\beta}$$

mirror instability



Kunz, Stone & Schekochihin 2014



also, Hellinger+, Riquelme+, Sironi+, Ley+…

we've shown $\nu_{\rm eff} \sim \beta/\tau_{\rm dyn}$ many times now from tracked particles (e.g., Bott+ 2024)

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{p_\perp - p_\parallel}{p} \sim \frac{\mathrm{d}}{\mathrm{d}t}\ln\frac{B^3}{n^2} - \nu\frac{p_\perp - p_\parallel}{p}$$

adiabatic invariance

collisional regulation

$$mn\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = -\boldsymbol{\nabla}\left(p_\perp + \frac{B^2}{8\pi}\right) + \boldsymbol{\nabla}\cdot\left[\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}\left(\frac{B^2}{4\pi} + p_\perp - p_\parallel\right)\right]$$

competes with magnetic tension:

$$\Delta \doteq \frac{p_\perp - p_\parallel}{p} \sim \frac{1}{\beta}\,?$$

Example: Intracluster Medium of Galaxy Clusters

$\sim 10^{14-15}\ \mathrm{M}_\odot$ in ~ 1 Mpc

$\sim 10^{2-3}$ galaxies

ICM:

$\beta \sim 10^2 - 10^4$

$L \gtrsim 100$ kpc

$\lambda_{\mathrm{mfp}} \sim 1 - 10$ kpc

$\rho_{\mathrm{i}} \sim 1$ npc

(size of Jupiter)

$L \sim 100$ kpc

$\lambda_{\rm mfp} \sim$ few kpc

$\rho_{\rm i} \sim 1$ npc

$+$

$\dfrac{U}{v_{\rm th,i}} \sim 0.1 - 0.3$

Braginskii estimate of pressure anisotropy:

$$\frac{p_\perp - p_\parallel}{p} \sim \frac{u}{v_{\rm th,i}} \frac{\lambda_{\rm mfp,c}}{L} \sim 10^{-2}$$

compare to

$$\frac{1}{\beta} \sim 10^{-2}$$

KE, ME, Δp all in approx. equipartition

(i) pressure anisotropy is ***dynamically important***

(ii) bulk ICM likely ***polluted with microscale B fluctuations***, which scatter ions and thereby provide an anomalous ***effective collisionality***

"Magneto-immutability" – self-organization to avoid Δp stress

(Squire *et al.* 2019; Kempski *et al.* 2019; Arzamasskiy, Kunz, Squire *et al.* 2022; Squire, Kunz *et al.* 2023; Majeski, Kunz & Squire 2024 ← develops theory)

recall the force equation:

$$mn\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t} = -\boldsymbol{\nabla}\left(p_\perp + \frac{B^2}{8\pi}\right) + \boldsymbol{\nabla}\cdot\left[\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}\left(\frac{B^2}{4\pi} + p_\perp - p_{\parallel}\right)\right]$$

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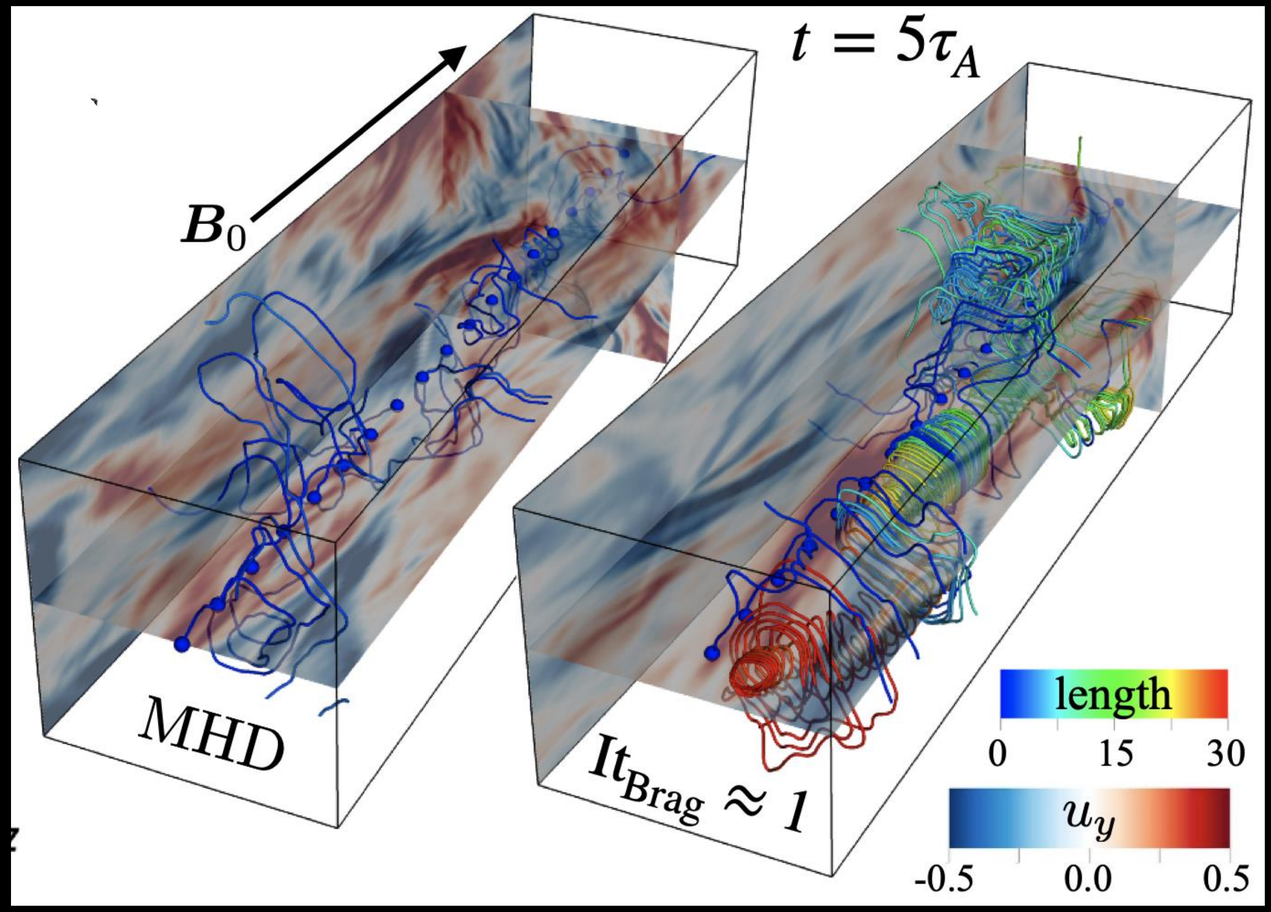
$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{p_\perp - p_\parallel}{p} \sim \frac{\mathrm{d}\ln B}{\mathrm{d}t} \sim \hat{b}\hat{b} : \nabla u$$

control Δp by adjusting this angle to minimize changes in B

velocity streamlines from Braginskii turb sim:



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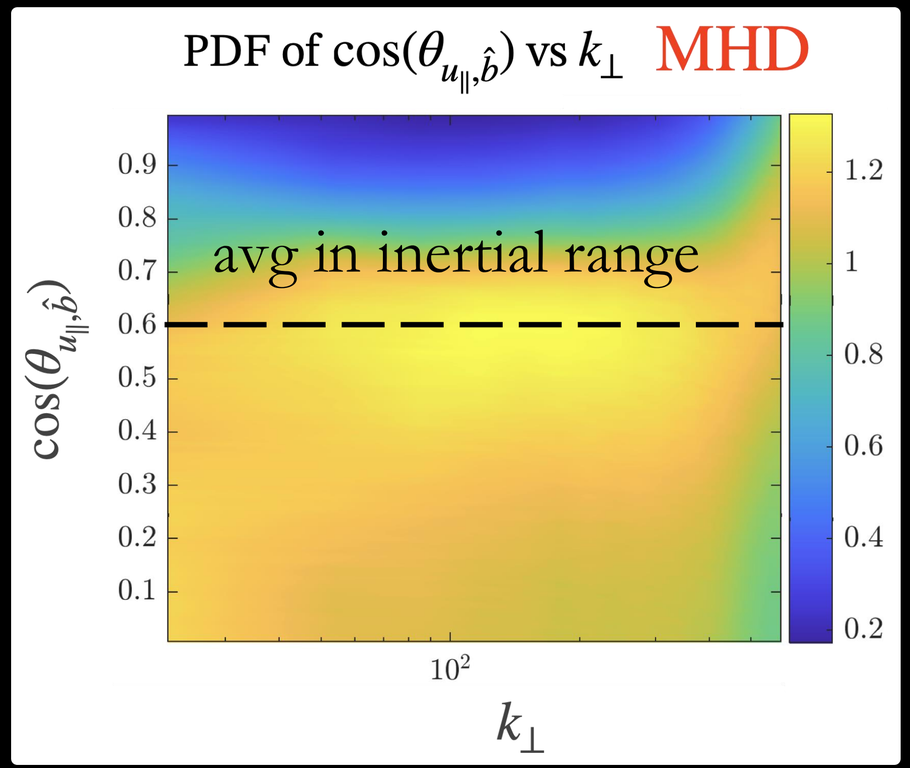
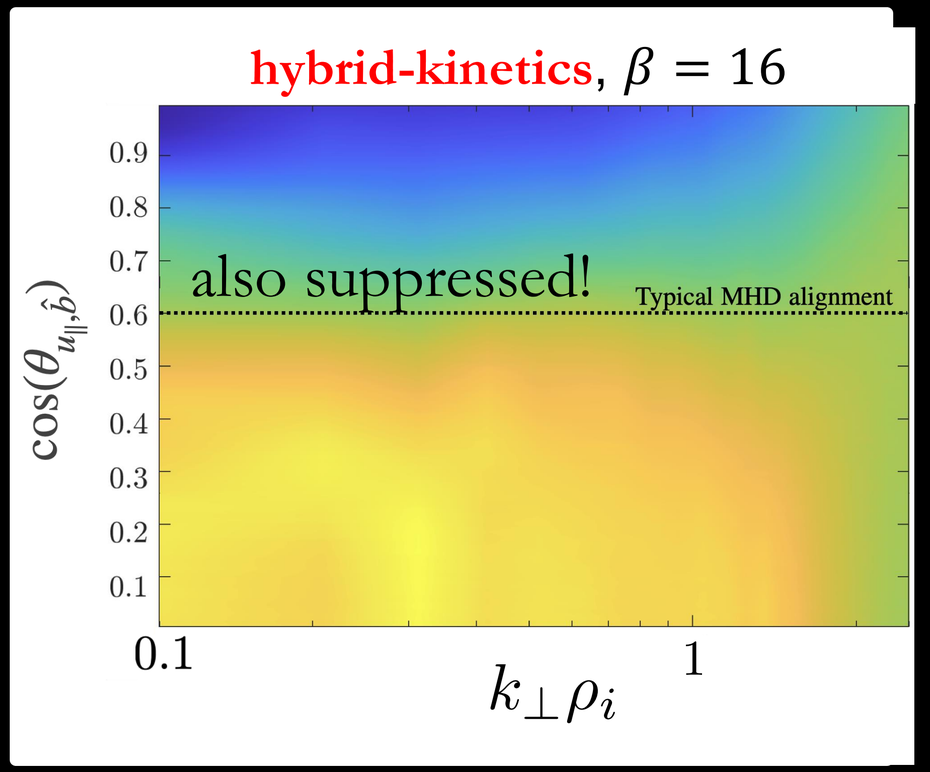




- viscous damping (→ heating) important near outer scale, damps ~1/2 of cascade energy
- the remainder self-organizes into a robust, nearly conservative GS95-like cascade to small scales

incompressibility:

large pressure force opposes any flow with $\boldsymbol{\nabla}\cdot\boldsymbol{u}\neq 0$ that attempts to change p.

p tied to ρ

$$\rho\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t}=-\boldsymbol{\nabla}p+\ldots$$

$$\frac{\mathrm{d}\ln p}{\mathrm{d}t}=-\gamma\boldsymbol{\nabla}\cdot\boldsymbol{u}$$

magneto-immutability:

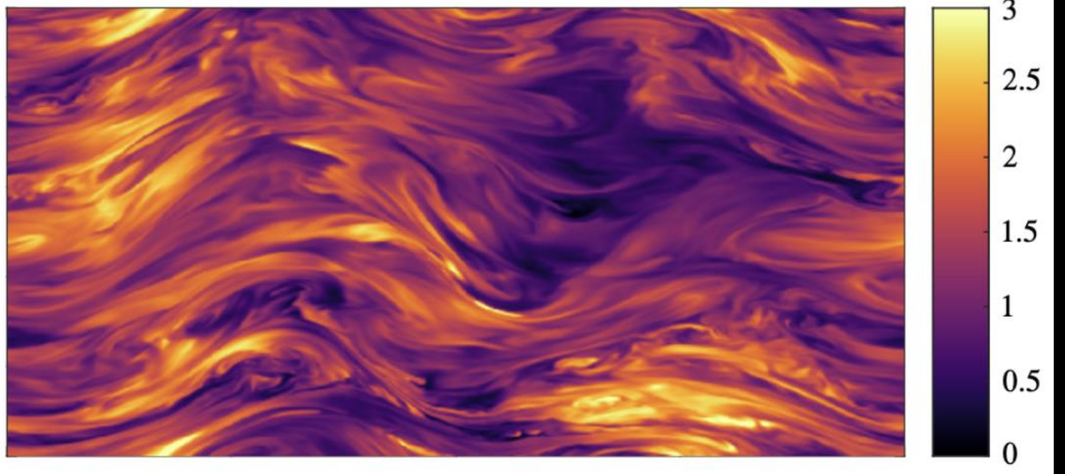
large viscous force opposes any flow with $\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}:\boldsymbol{\nabla}\boldsymbol{u}\neq 0$ that attempts to change Δp.

Δp tied to B

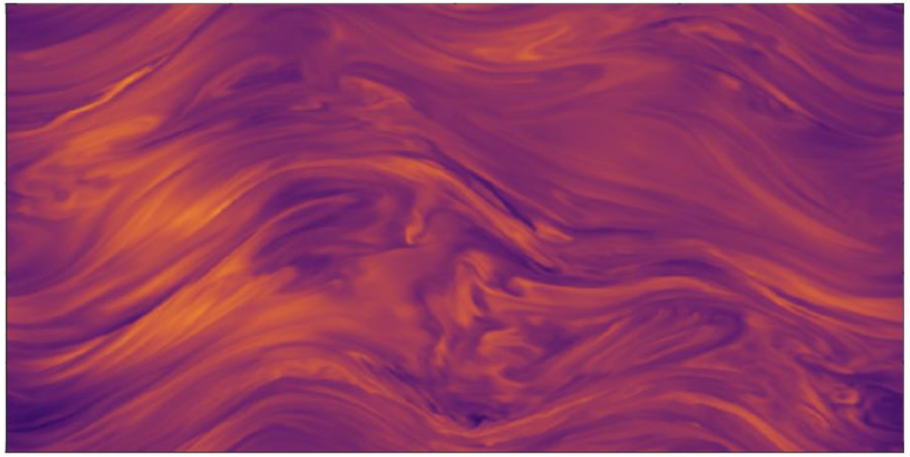
$$\rho\frac{\mathrm{d}\boldsymbol{u}}{\mathrm{d}t}=\boldsymbol{\nabla}\cdot(\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}\Delta p)+\ldots$$

$$\frac{\mathrm{d}\ln B}{\mathrm{d}t}=(\hat{\boldsymbol{b}}\hat{\boldsymbol{b}}-\mathsf{I}):\boldsymbol{\nabla}\boldsymbol{u}$$

B^2 in MHD



B^2 in CGL-MHD



another way to think about magneto-immutability:

approximate conservation of $\mu \propto T_\perp / B$

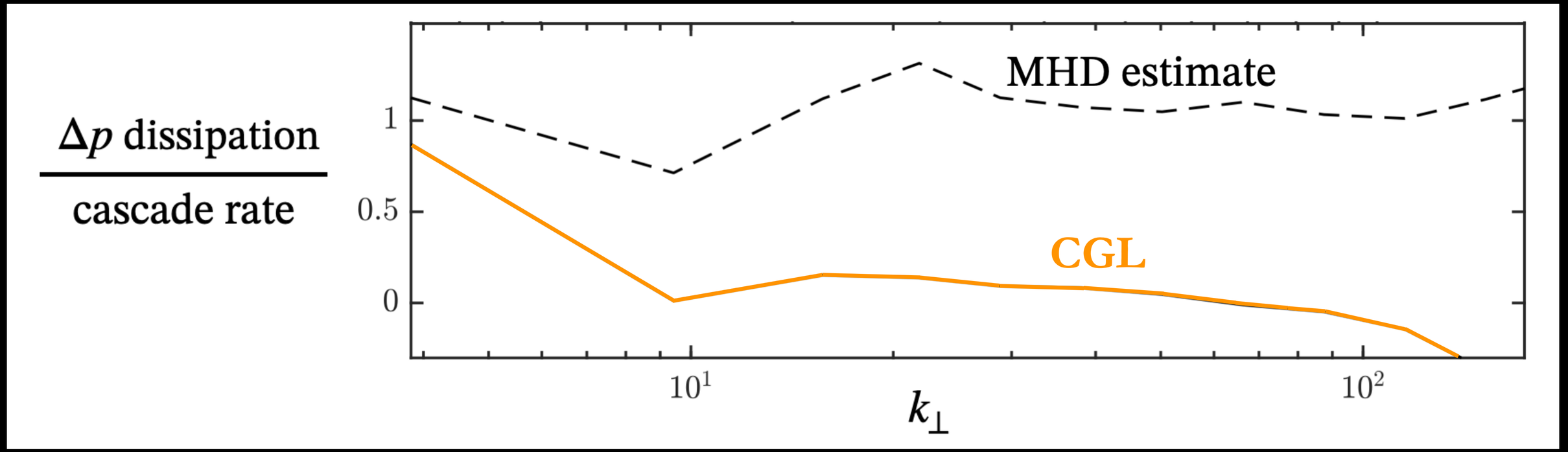
+

perpendicular pressure balance ($k_\parallel \ll k_\perp$)

$\Longrightarrow$ δB^2 must be minimized

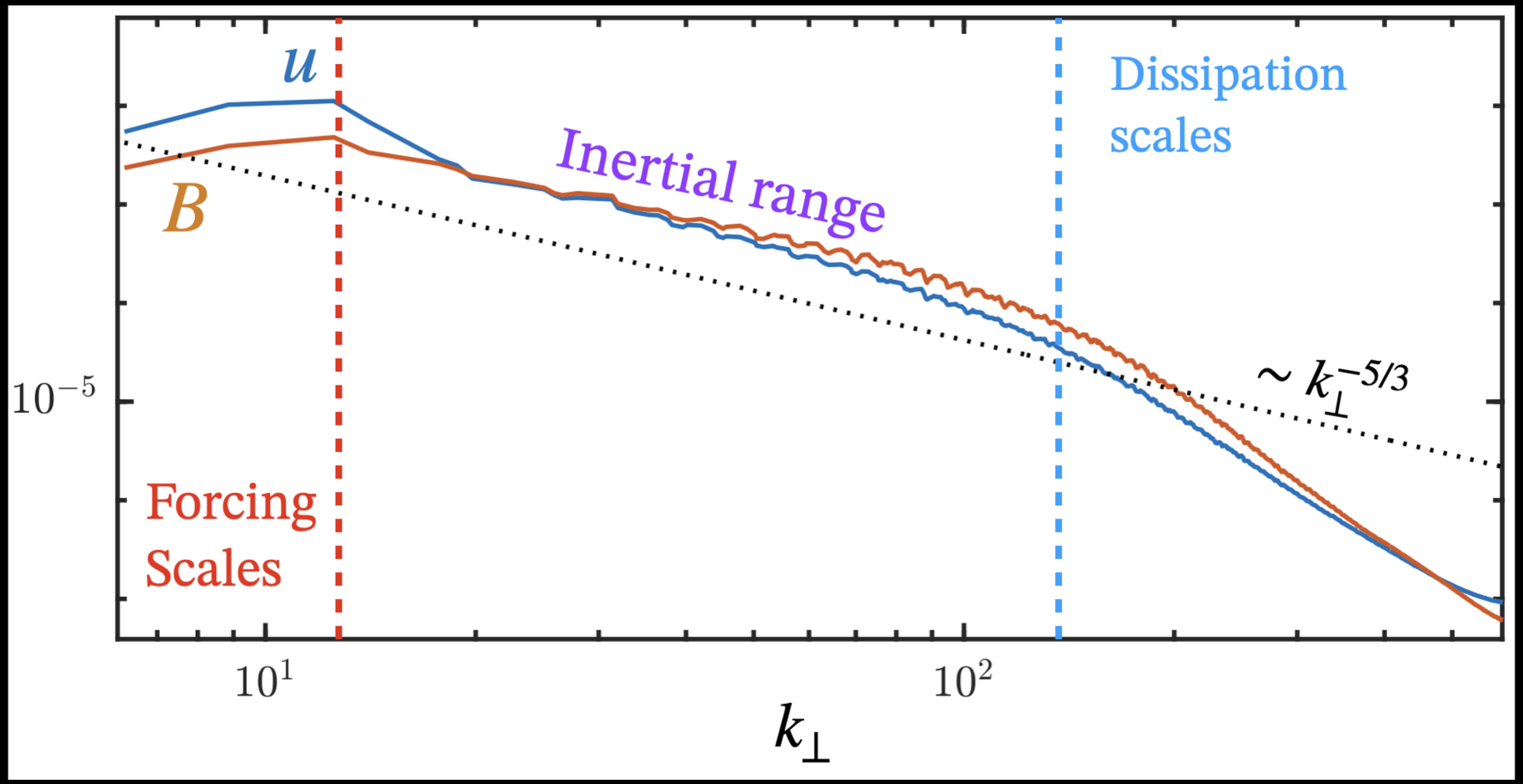
Use $\beta = 10$ MHD turbulence to estimate Δp effects as if they were active:

then turn those effects on and evolve to steady state:



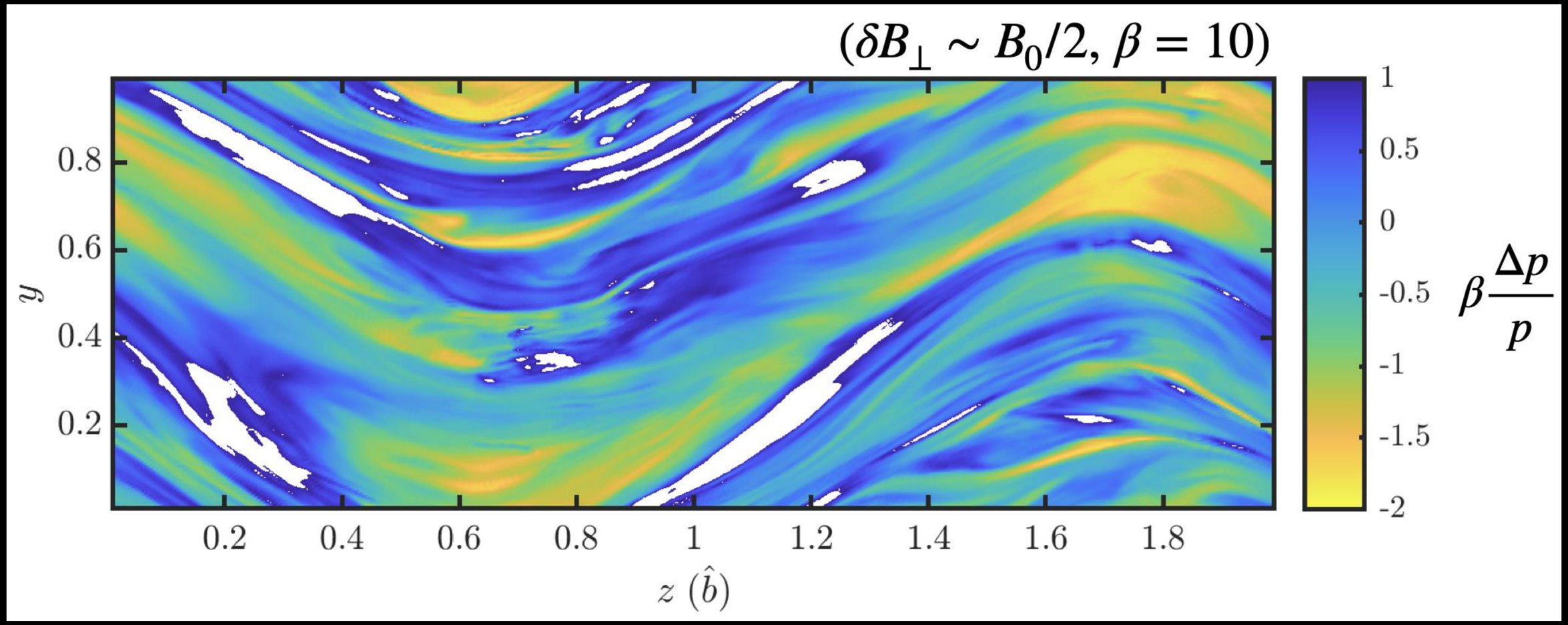
inertial-range turbulence self-organizes to avoid viscous dissipation!

the result is a robust, critically balanced cascade of Alfvénic fluctuations…



Majeski, Kunz & Squire 2024

…with relatively little of the plasma (~10%) unstable to firehose/mirror



(white parts are kinetically unstable)

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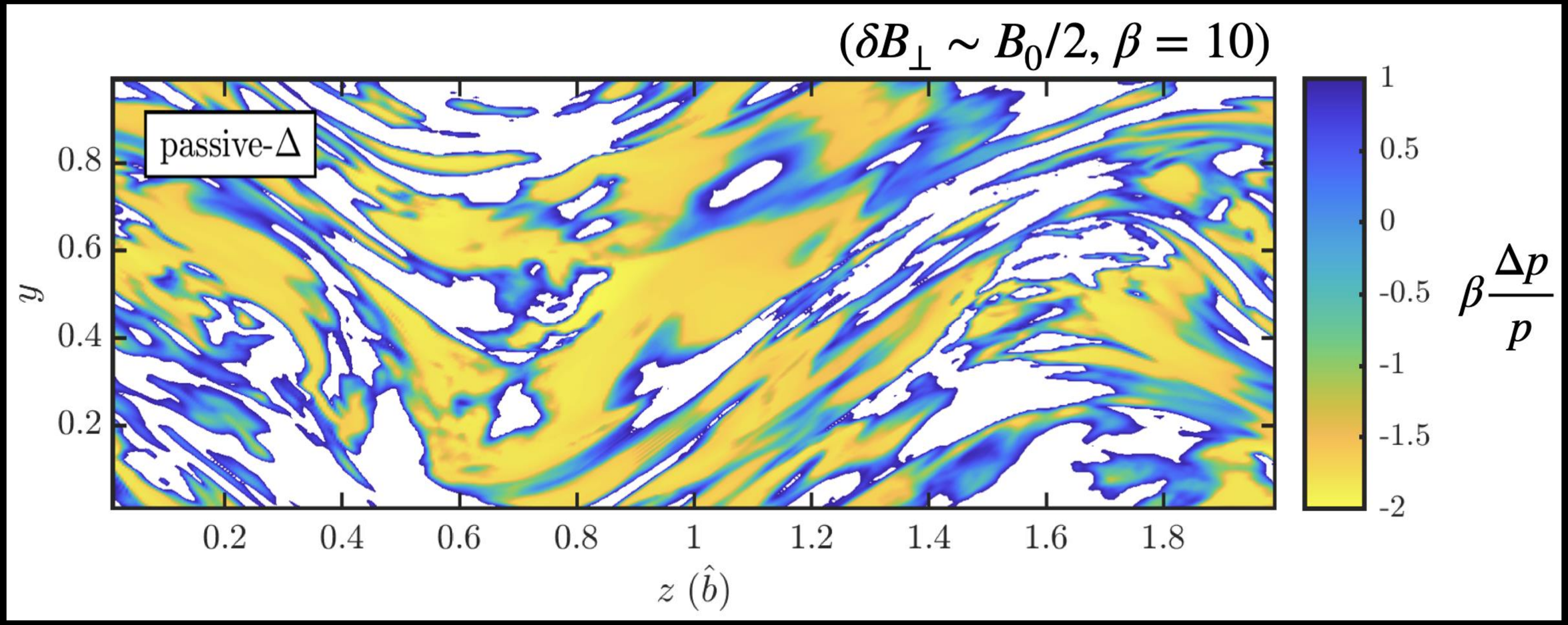

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Majeski, Kunz & Squire 2024

can obtain theory for magneto-immutable turbulence assuming:

$\beta \gg 1$, critical balance, approximate μ conservation

$$\epsilon \sim \frac{1}{\beta} \sim \frac{k_\parallel}{k_\perp} \sim \frac{u_\perp}{v_\mathrm{A}} \sim \frac{u_\parallel}{v_\mathrm{A}} \sim \frac{\delta B_\perp}{B_0} \sim \frac{\delta B_\parallel}{B_0} \sim \frac{\delta T_\perp}{T_0} \sim \frac{\delta T_\parallel}{T_0} \ll 1$$

$$\omega \sim k_\parallel v_\mathrm{A}$$

(see Majeski, Kunz & Squire 2024 for details)

can obtain theory for magneto-immutable turbulence assuming:

$\beta \gg 1$, critical balance, approximate μ conservation

$$\boldsymbol{\nabla}_\perp \cdot \boldsymbol{u}_\perp = \boldsymbol{\nabla}_\perp \cdot \delta\boldsymbol{B}_\perp = 0,$$

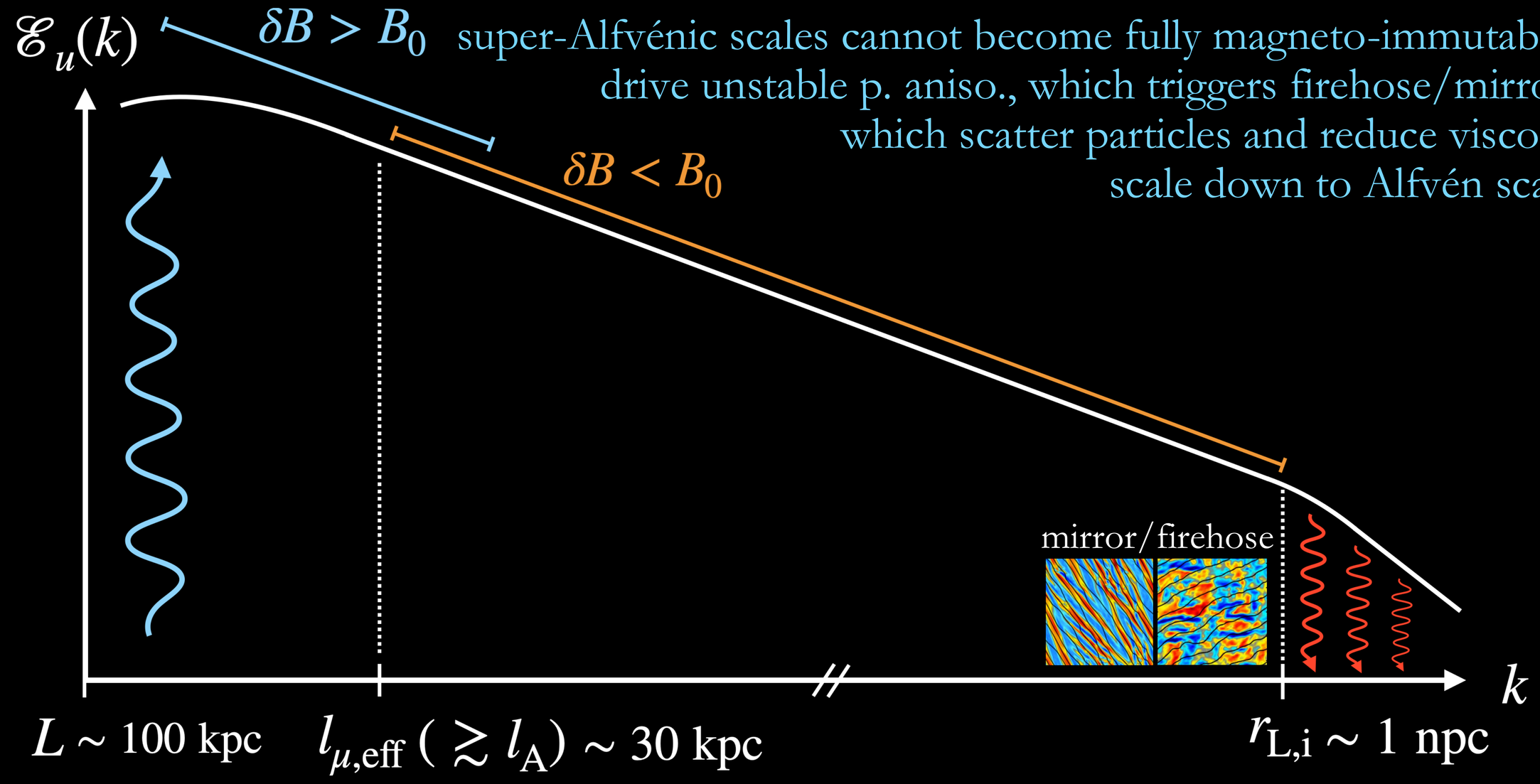
$$\frac{\mathrm{d}\delta\boldsymbol{B}_\perp}{\mathrm{d}t} = B_0 \hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla}_\perp \boldsymbol{u}_\perp,$$

$$\rho_0 \frac{\mathrm{d}\boldsymbol{u}_\perp}{\mathrm{d}t} = -\boldsymbol{\nabla}_\perp P_\mathrm{total} + \left(1 + \frac{\beta}{2}\frac{\Delta p}{p_0}\right)\left(\frac{B_0\hat{\boldsymbol{z}} + \delta\boldsymbol{B}_\perp}{4\pi}\right) \cdot \boldsymbol{\nabla}\delta\boldsymbol{B}_\perp,$$

$$\boxed{\frac{\mathrm{d}\Delta p}{\mathrm{d}t} = \frac{\mathrm{d}\delta B_\parallel}{\mathrm{d}t} = \hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla} u_\parallel = \hat{\boldsymbol{b}} \cdot \boldsymbol{\nabla}\Delta p = 0}$$

(see Majeski, Kunz & Squire 2024 for details)

motivates a theory of ICM turbulence:



($l_{\mu,\mathrm{Coulomb}} \sim 300$ kpc; Coma)

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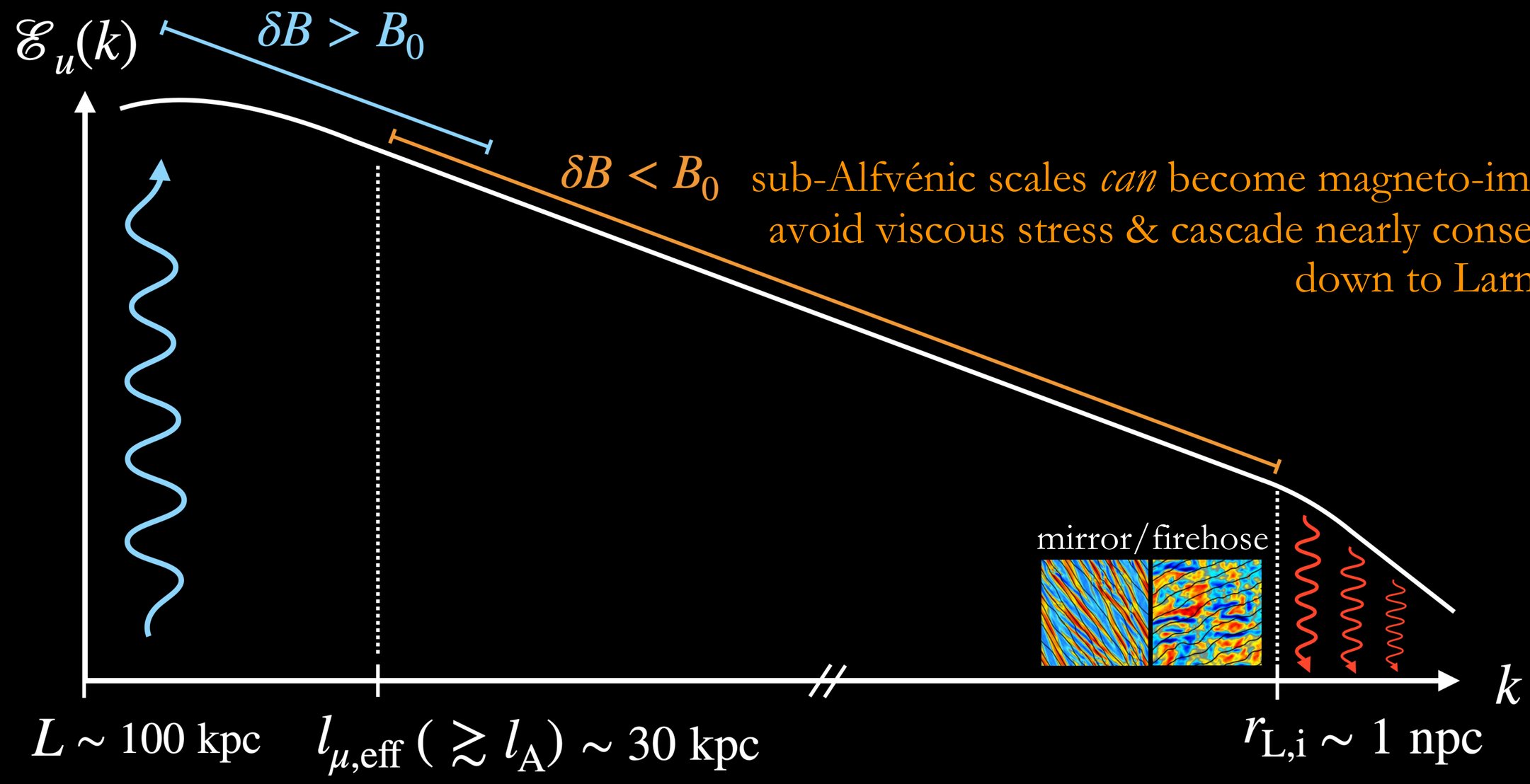


($l_{\mu,\mathrm{Coulomb}} \sim 300$ kpc; Coma)

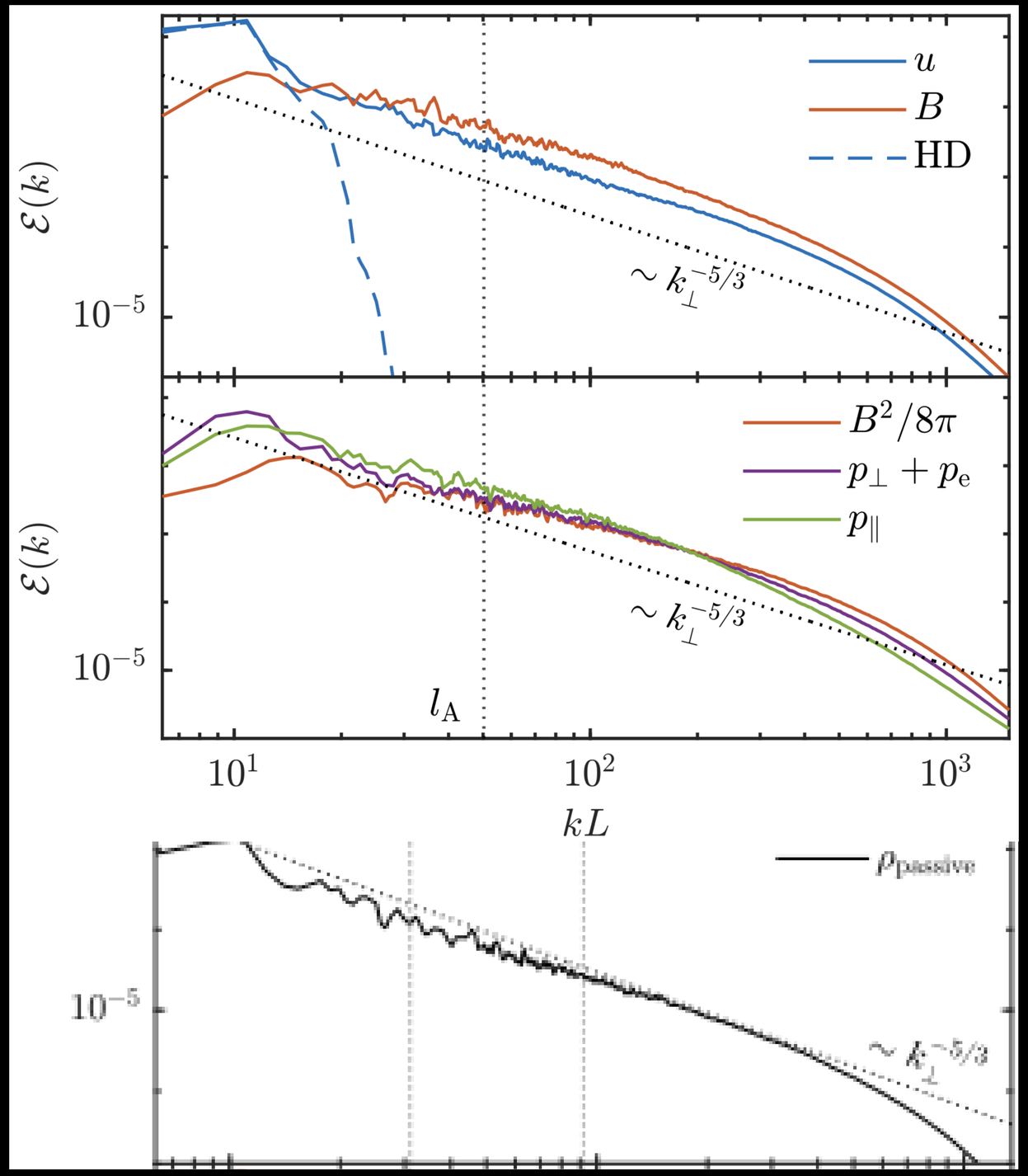
1056^3 CGL-LF-MHD simulation w/

finite (weak) Coulomb collisionality

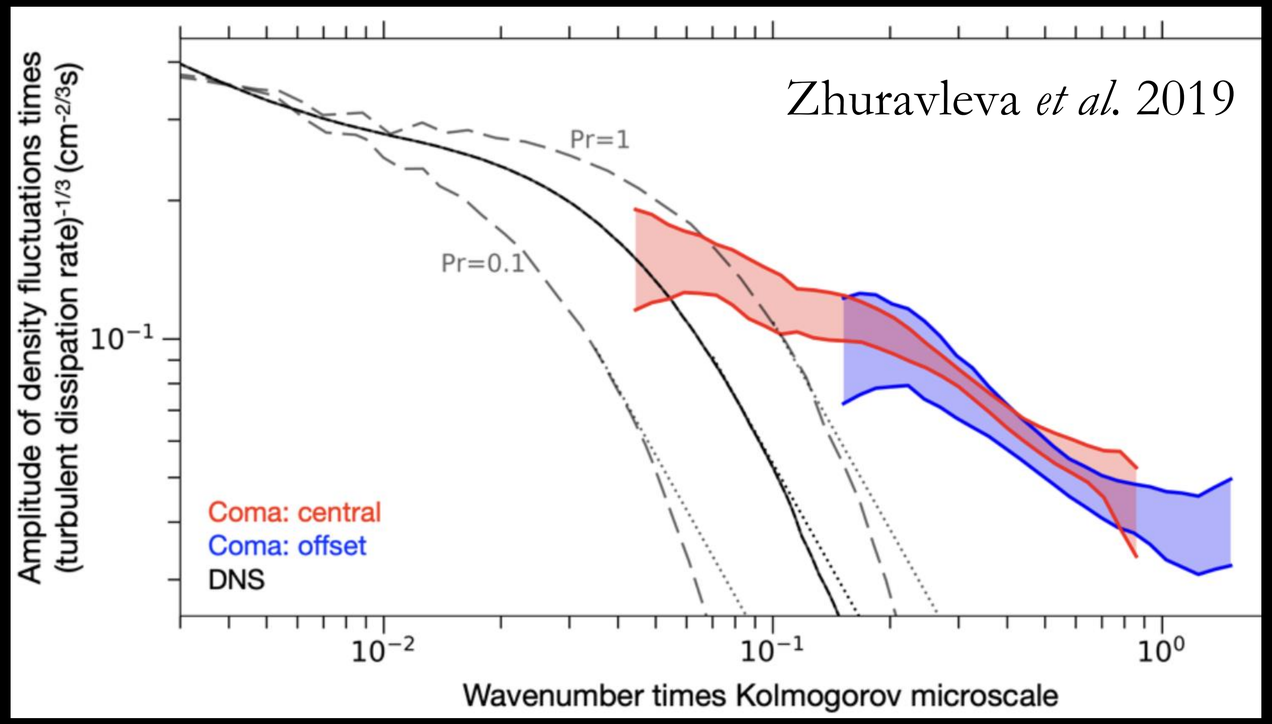
instability collisionality at "correct" rate

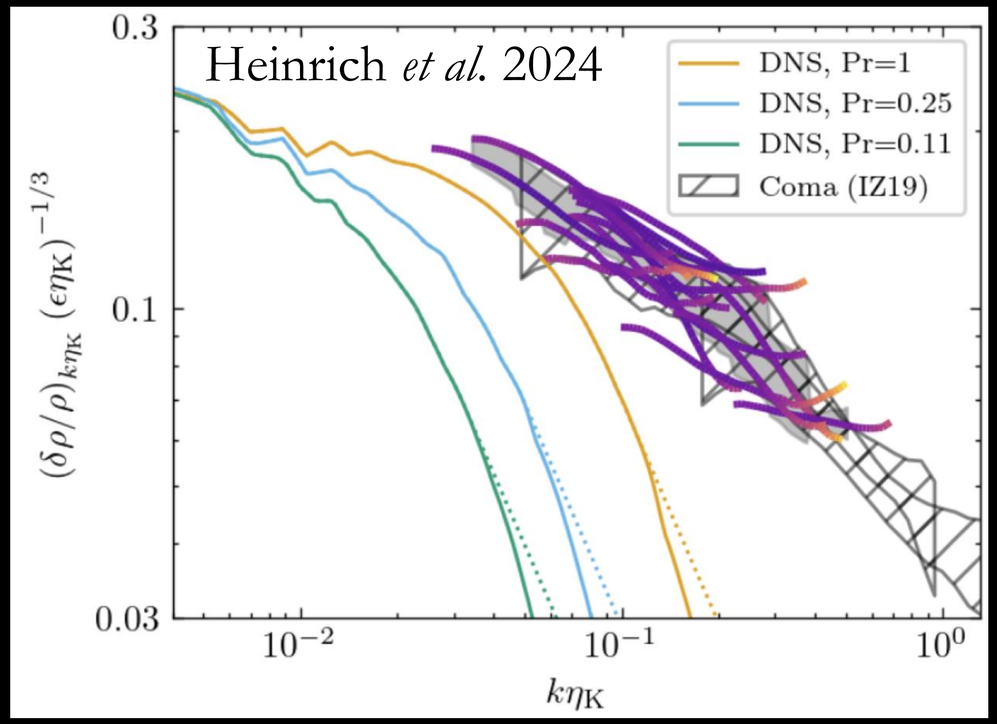
passive scalar (e.g., density)

cascades down to Alfvén scale and then keeps going down to grid



X-ray observations of galaxy clusters can't seem to find viscous scale…





viscosity inferred from X-ray obs of density fluc's from Bremsstrahlung emission in 17 different clusters is **significantly smaller than Spitzer (collisional) value**