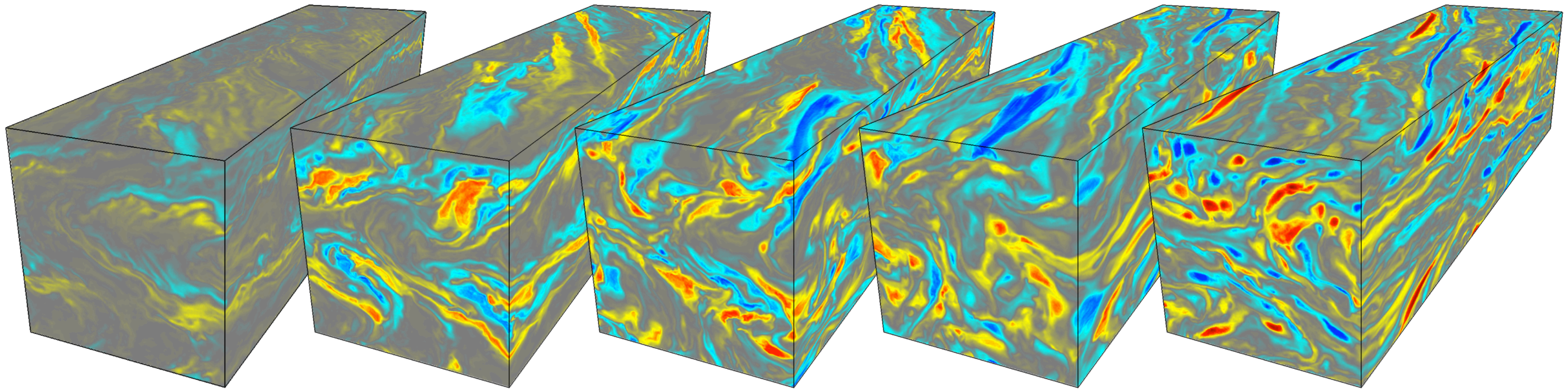
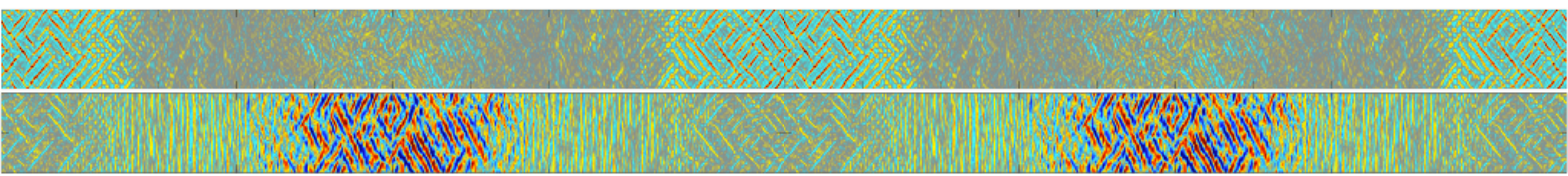


Troubling (and not-so-troubling) aspects of waves, turbulence, and reconnection in high-β, collisionless plasmas

or, just how small can v/c get and I still be allowed to talk?

Matthew Kunz

PRINCETON UNIVERSITY



(waves) Jono Squire, Eliot Quataert, Alex Schekochihin
(turbulence) Denis St-Onge, Eliot Quataert, Jim Stone
(reconnection) Andy Alt

Many space (and, supposedly, astrophysical) plasmas are pressure-anisotropic…

…because they are strongly magnetized, weakly collisional

solar wind:

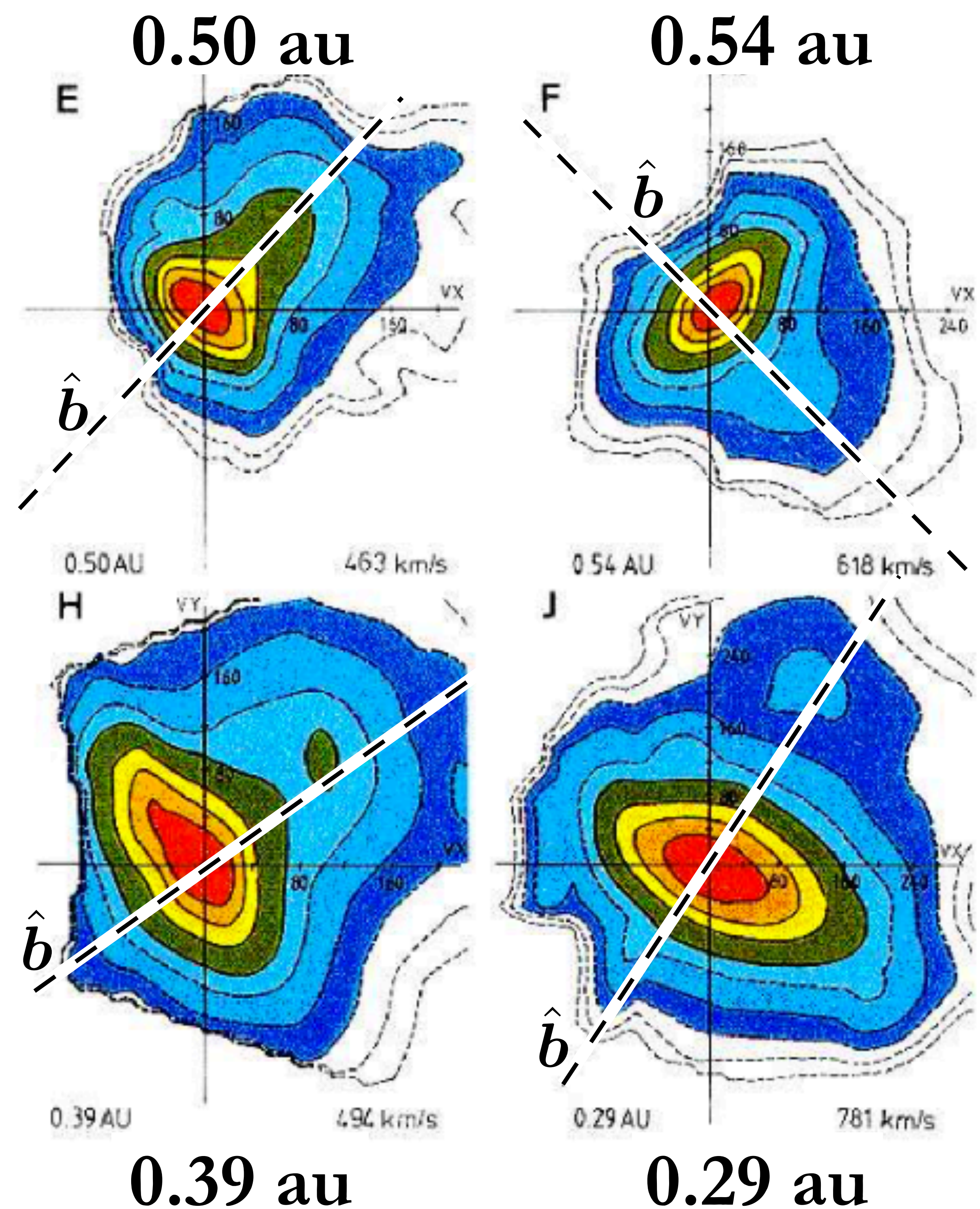
$\rho_i \sim 10^{-6}$ au

$\lambda_{\rm mfp} \sim 1$ au

intracluster medium:

$\rho_i \sim 10^{-9}$ pc

$\lambda_{\rm mfp} \sim 10$ kpc

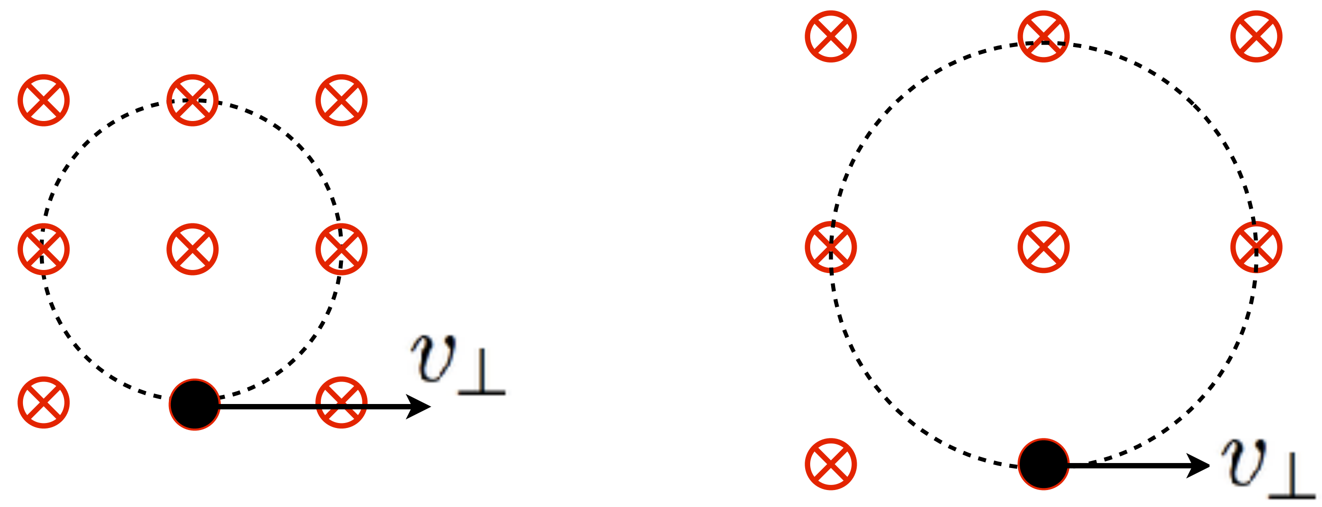


Marsch (2006)

B introduces periodic motion, which leads to adiabatic invariants… $\frac{\mathrm{d}}{\mathrm{d}t}\oint \boldsymbol{p}\cdot \mathrm{d}\boldsymbol{q} \simeq 0$

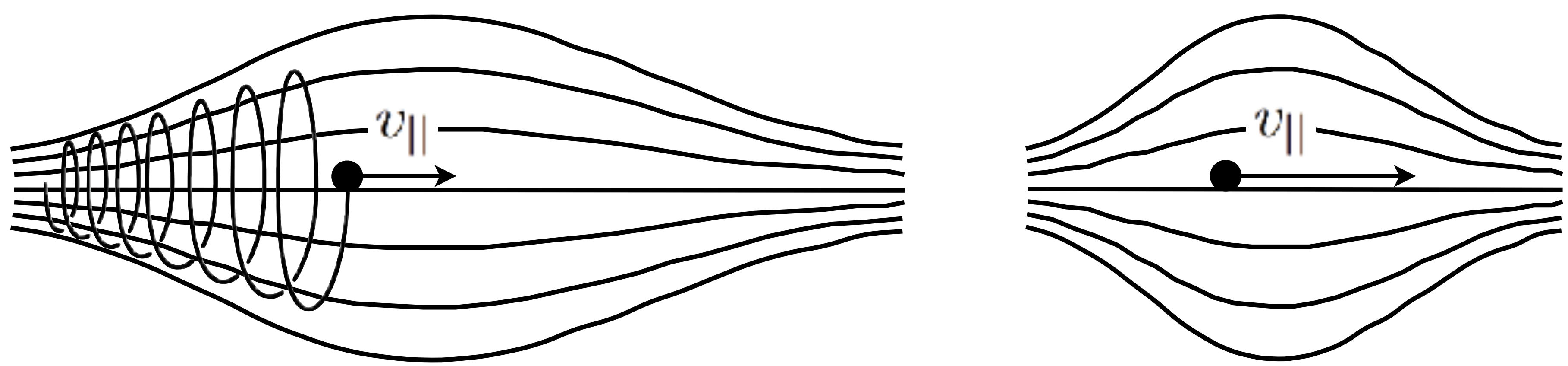
$$\mu = \frac{mv_\perp^2}{2B}$$

Kruskal (1958)



$$J = \oint \mathrm{d}\ell_{\mathrm{B}}\, mv_{\|}$$

Northrop & Teller (1960)



averaging over particles gives

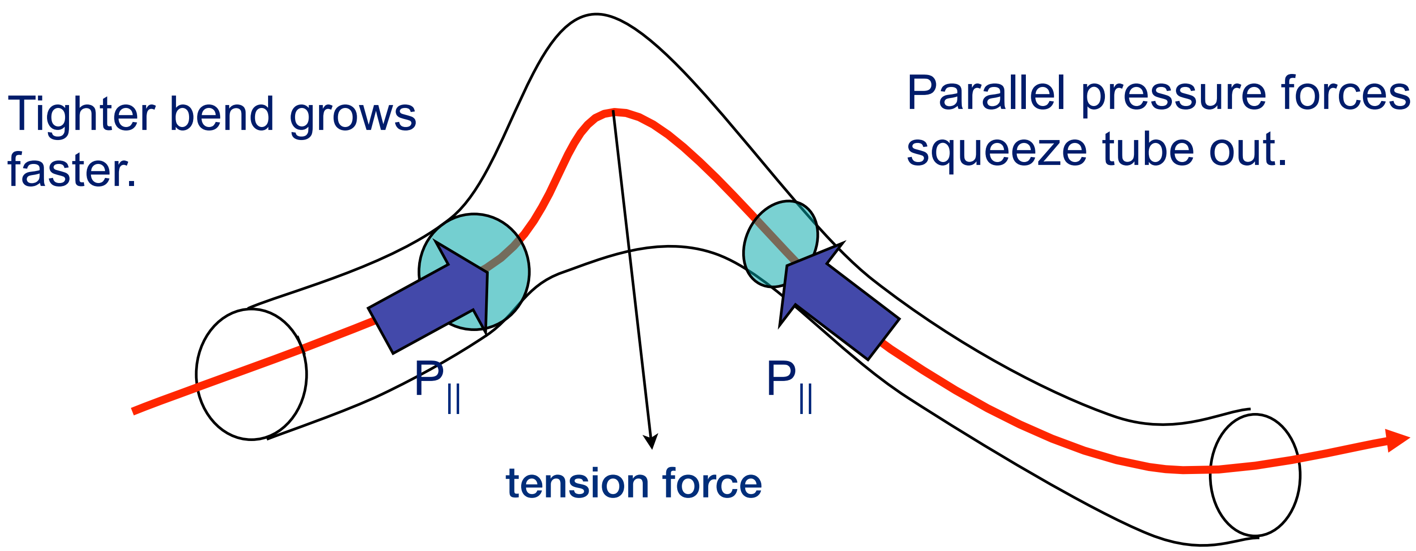
Chew, Goldberger & Low (1956)

$$\frac{P_\perp}{\rho B} \sim \text{const} \qquad \frac{P_{\|} B^2}{\rho^3} \sim \text{const}$$

…when you try to propagate an Alfvén wave in a pressure-anisotropic plasma

firehose instability

$$p_{||} - p_{\perp} \gtrsim \frac{B^2}{4\pi}$$

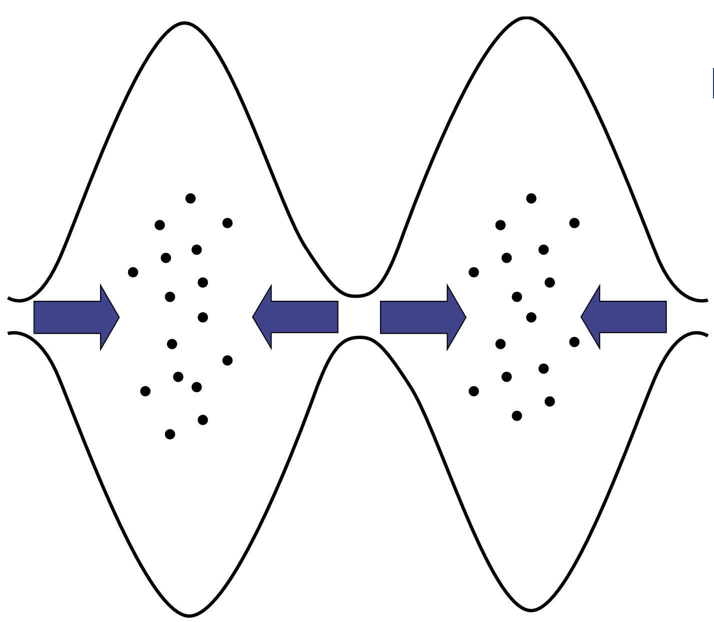


Rosenbluth 1956
Parker 1958

…when you try to Barnes-damp a slow mode in a pressure-anisotropic plasma

mirror instability

$$p_{\perp} - p_{||} \gtrsim \frac{B^2}{8\pi}$$

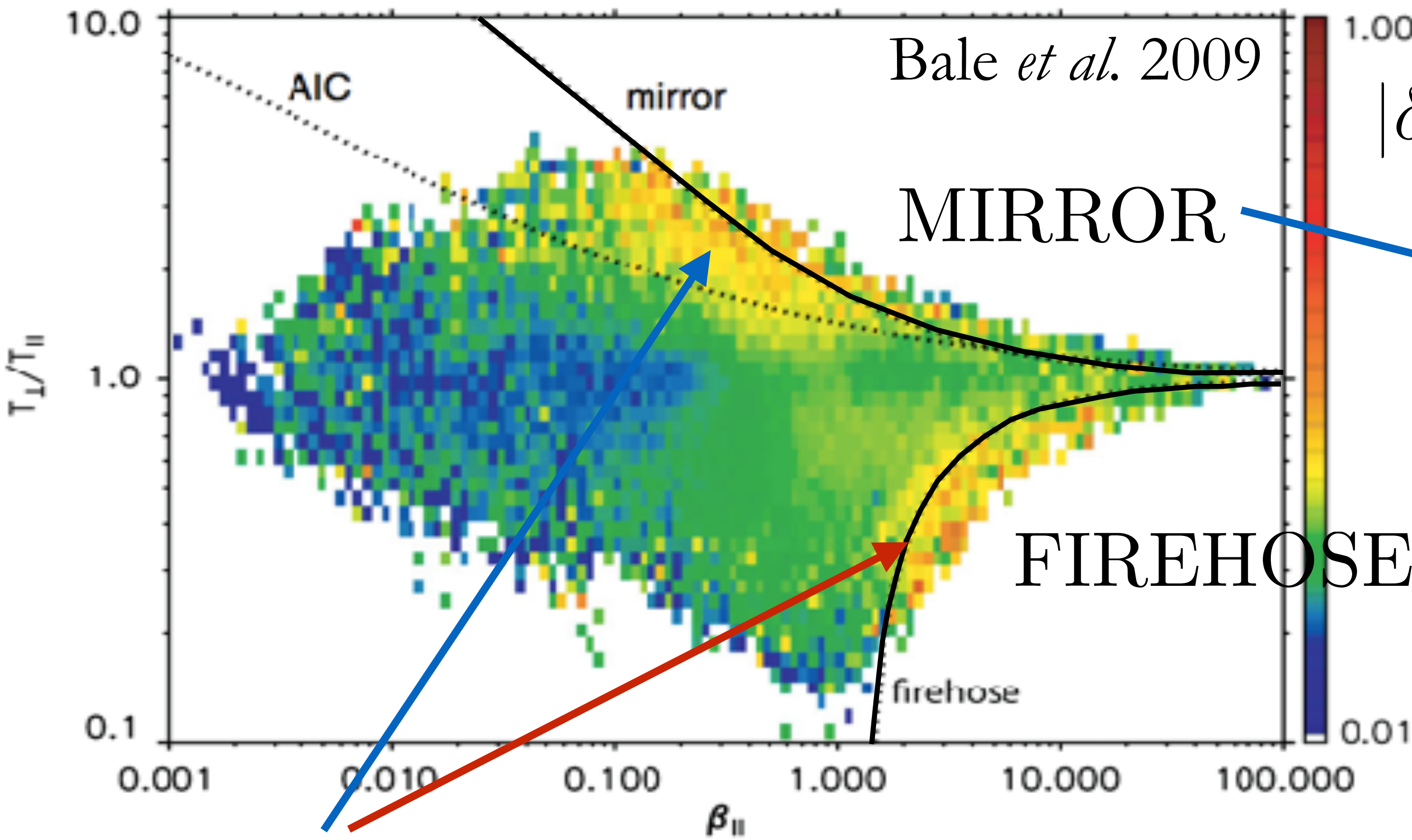


Perpendicular pressure forces blow out field lines.

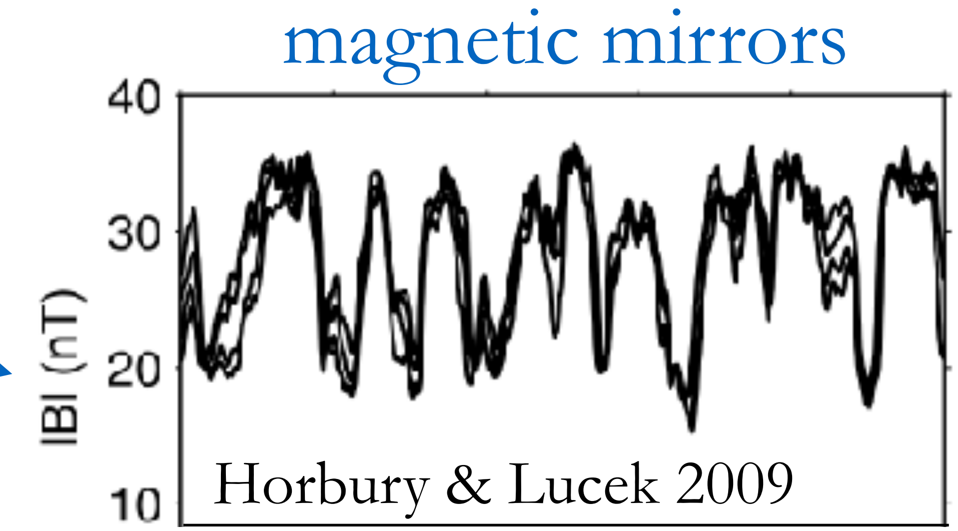
$$-\hat{\boldsymbol{b}}\,(p_{\perp} - p_{||})\nabla_{||}\delta B_{||}$$

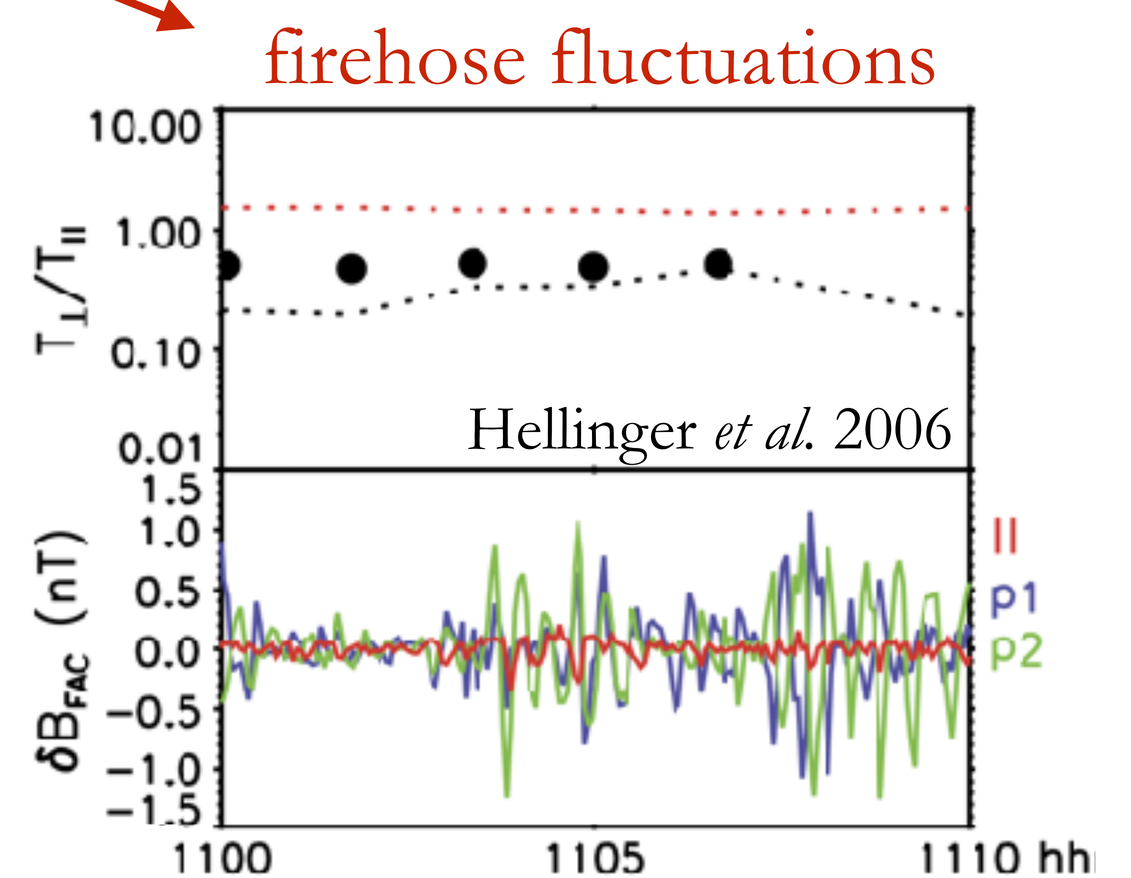
Rudakov and Sagdeev 1961
Southwood & Kivelson 1993

Pressure anisotropy is limited in solar wind: $\left|\frac{P_\perp}{P_\parallel} - 1\right| \lesssim \frac{1}{\beta}$

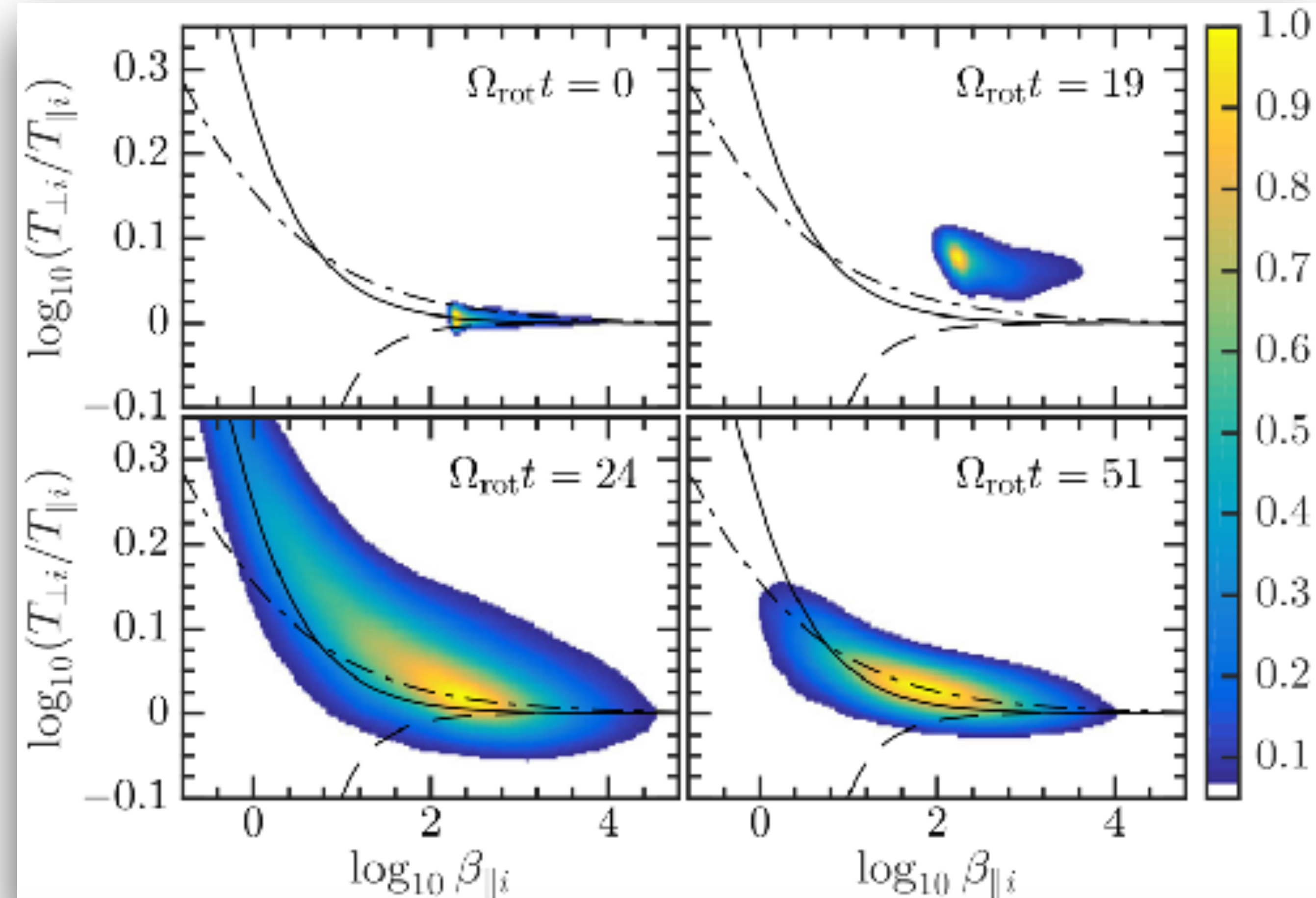


magnetic fluctuations are enhanced near stability thresholds



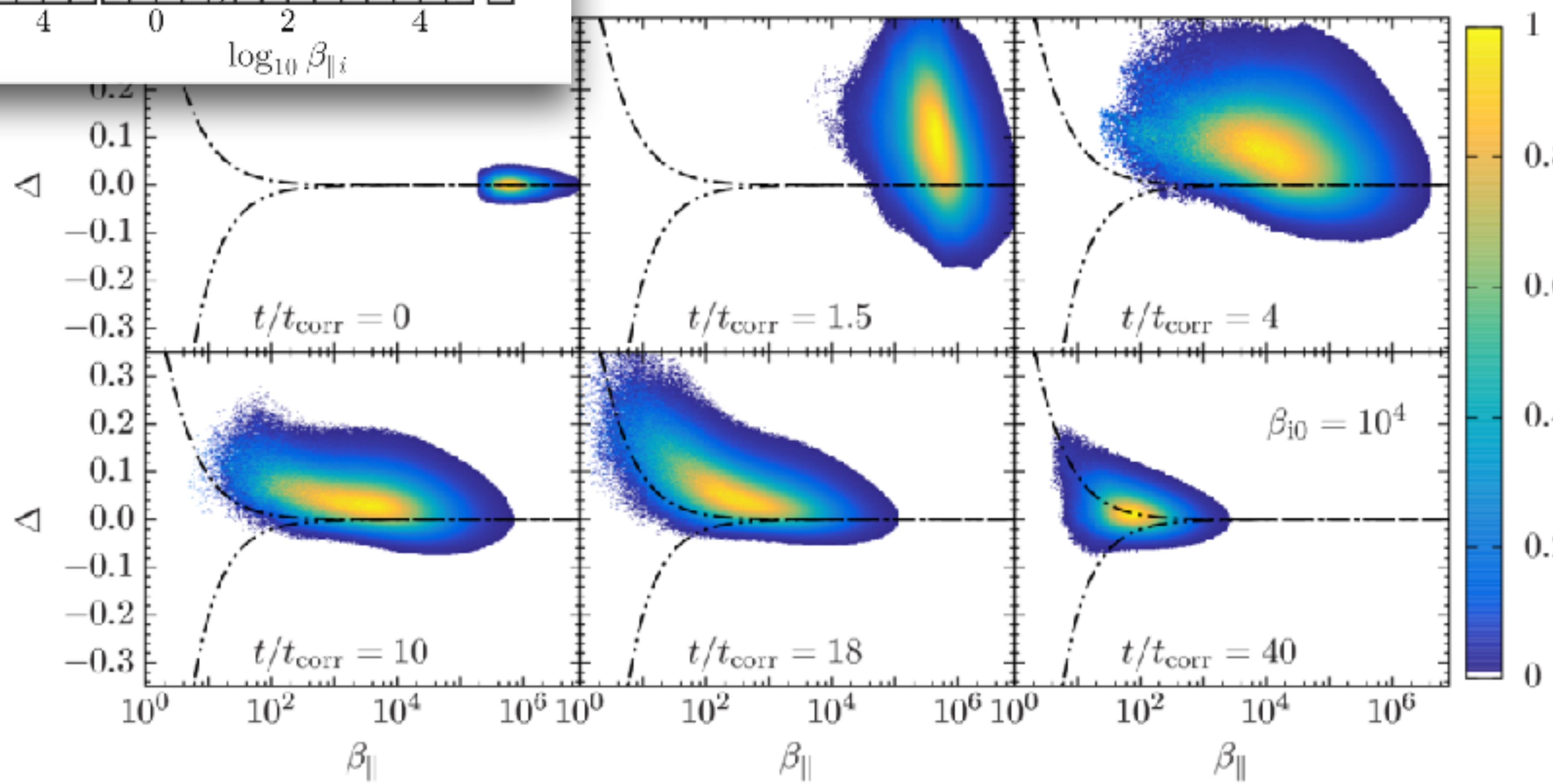


…and in kinetic simulations of turbulence



kinetic magnetorotational turbulence
(Kunz, Stone & Quataert, 2016 PRL)

turbulent dynamo in a collisionless plasma
(St-Onge & Kunz, 2018 submitted)



How is marginal firehose/mirror stability achieved?

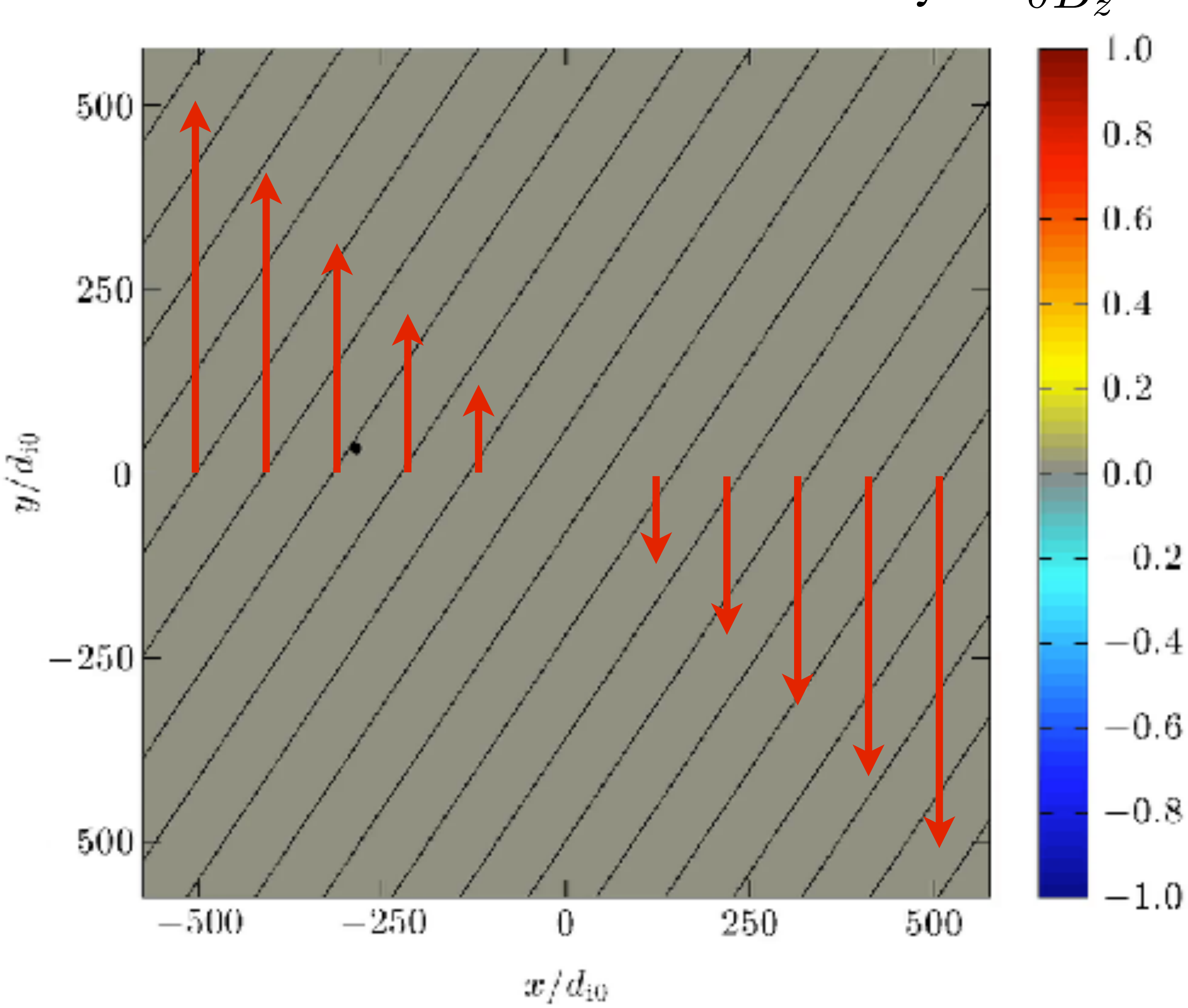
and

How does this impact the macroscopic evolution?

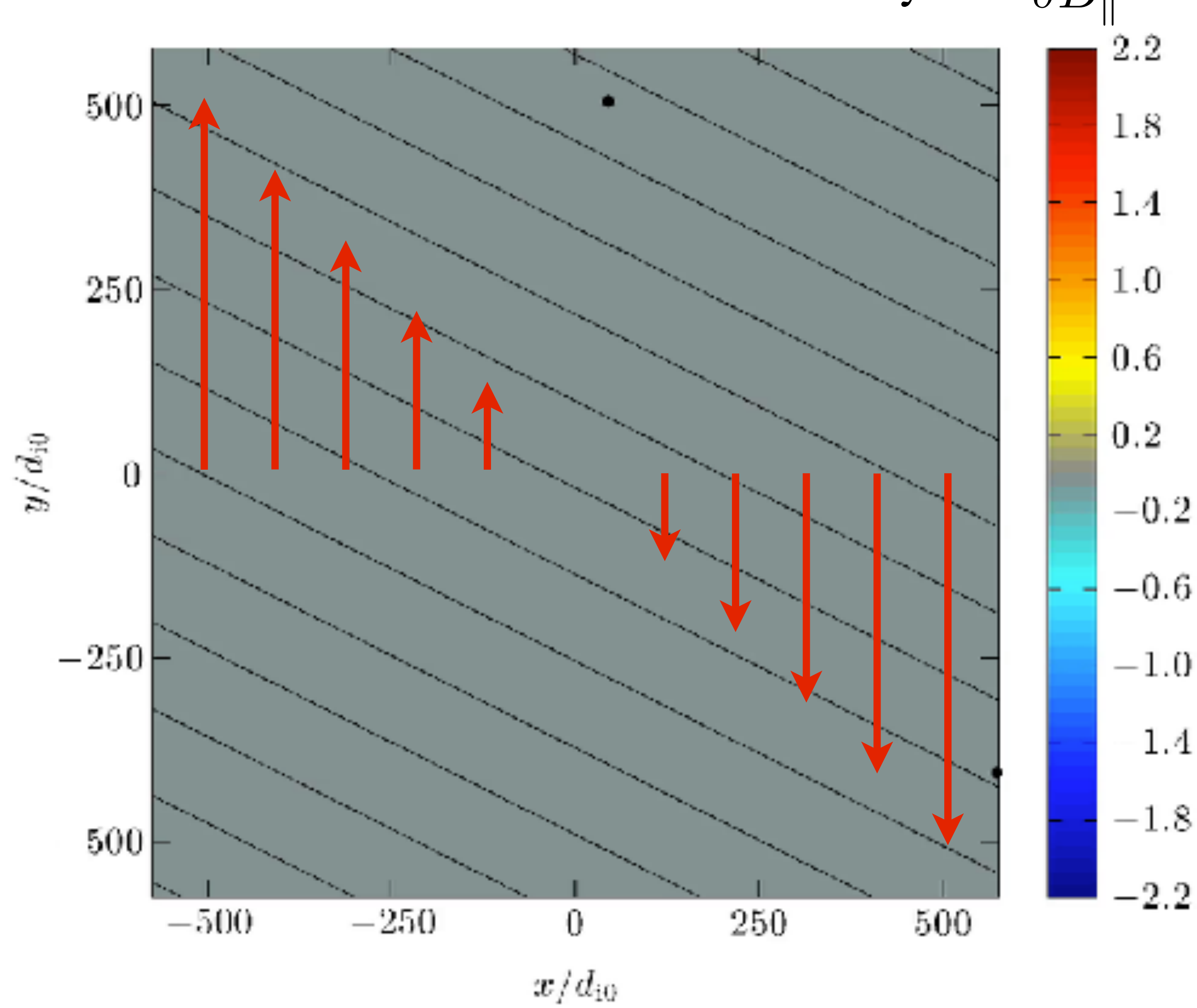
firehose and **mirror** instabilities studied with shear-driven pressure anisotropy

Kunz, Schekochihin & Stone (2014), *Phys. Rev. Lett.*

driven firehose instability



driven mirror instability



see also Riquelme *et al.* (2015); Melville, Schekochihin & Kunz (2016) and Hellinger and Trávníček (2015); Sironi and Narayan (2015); Hellinger (2017)

firehose and **mirror** instabilities studied with shear-driven pressure anisotropy

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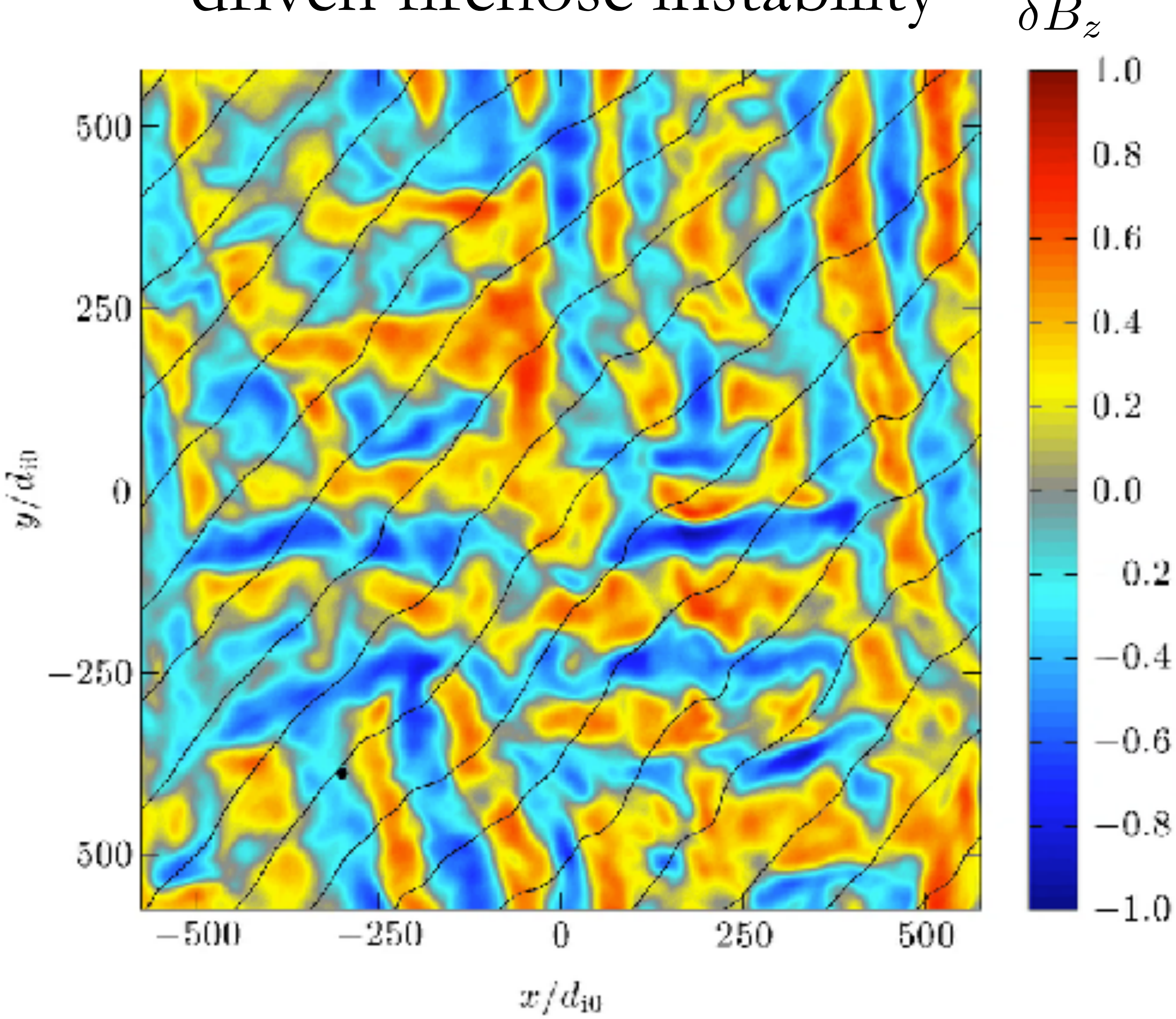
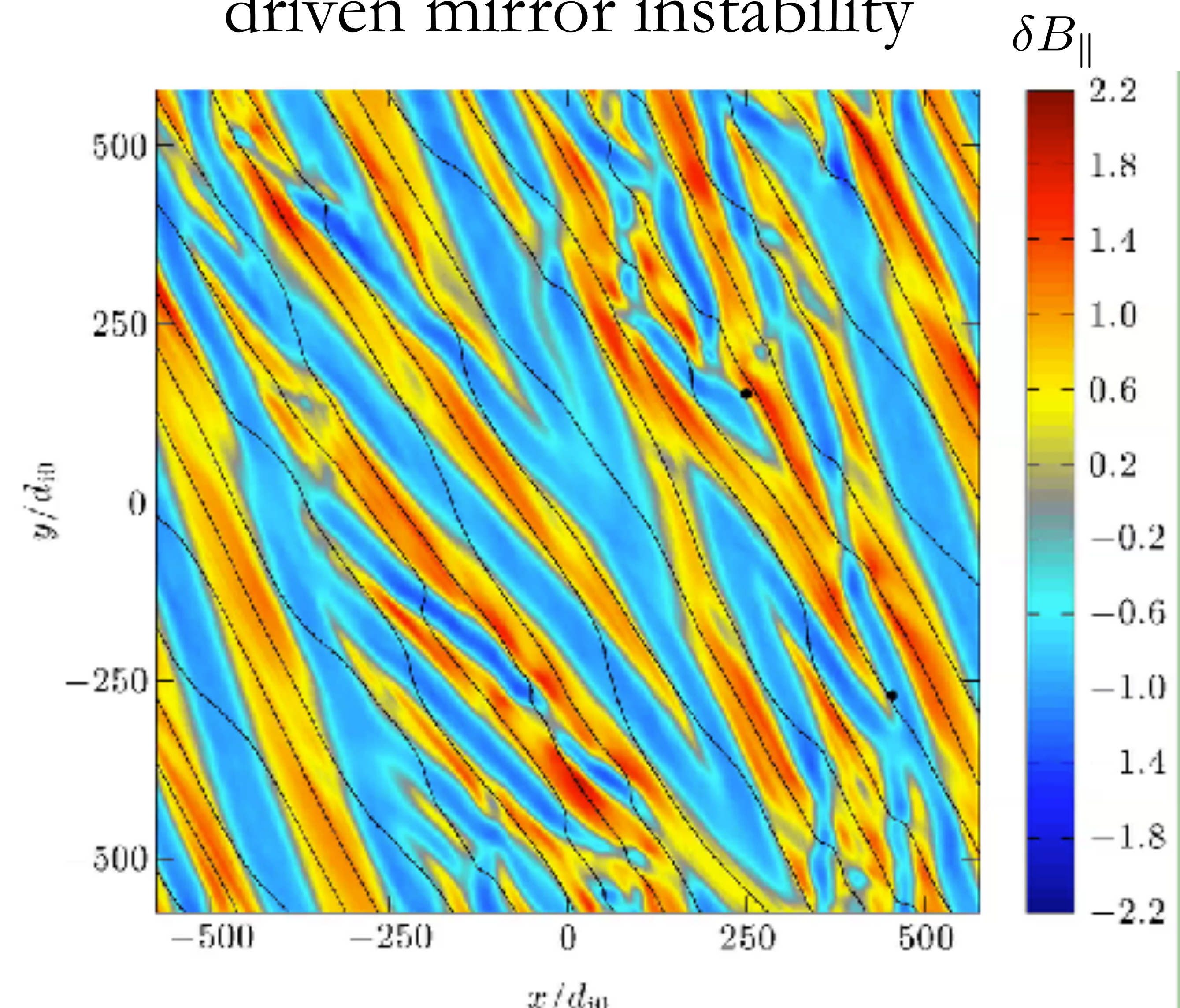


driven mirror instability



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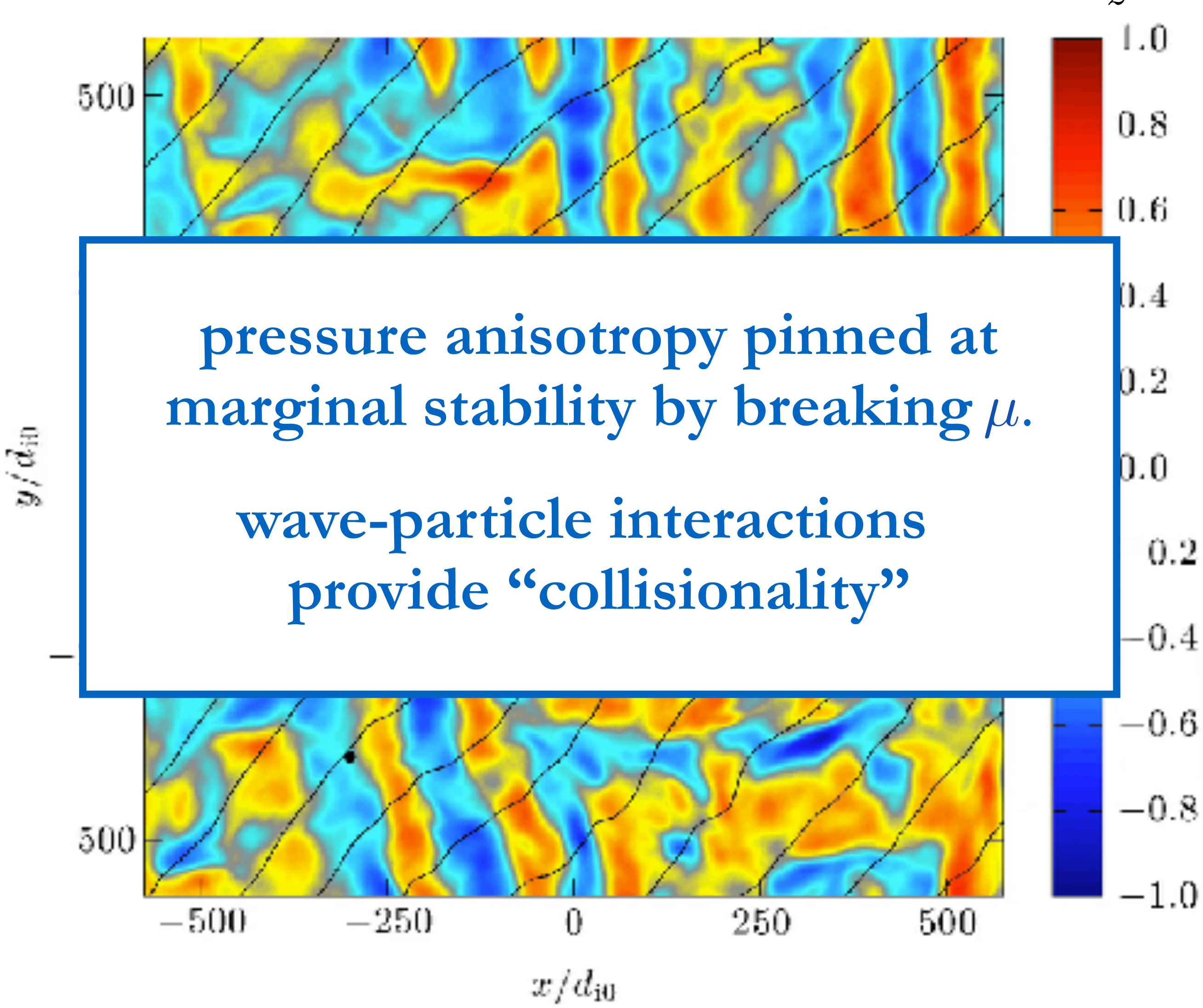
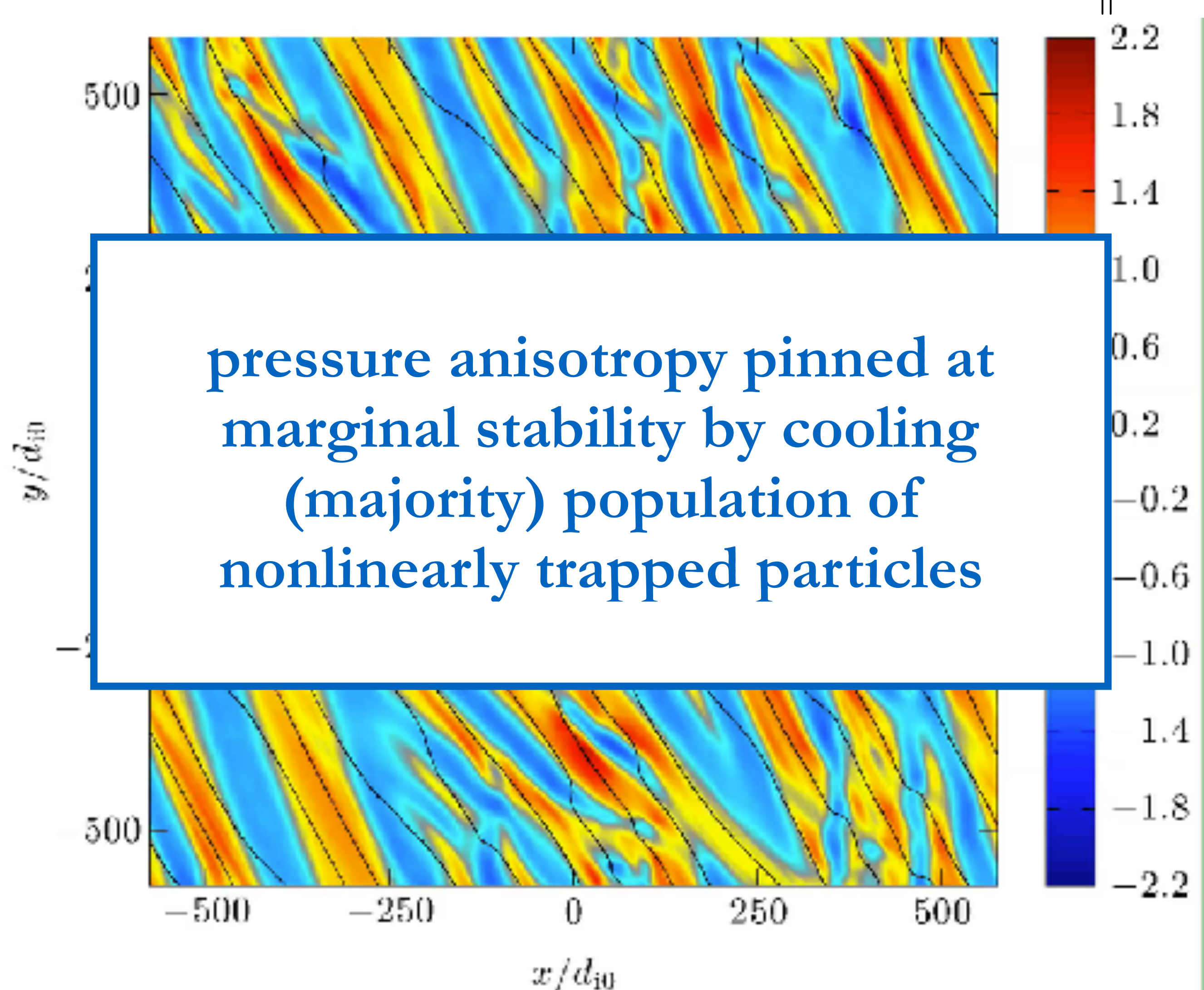


pressure anisotropy pinned at marginal stability by breaking μ.

wave-particle interactions provide "collisionality"

driven mirror instability

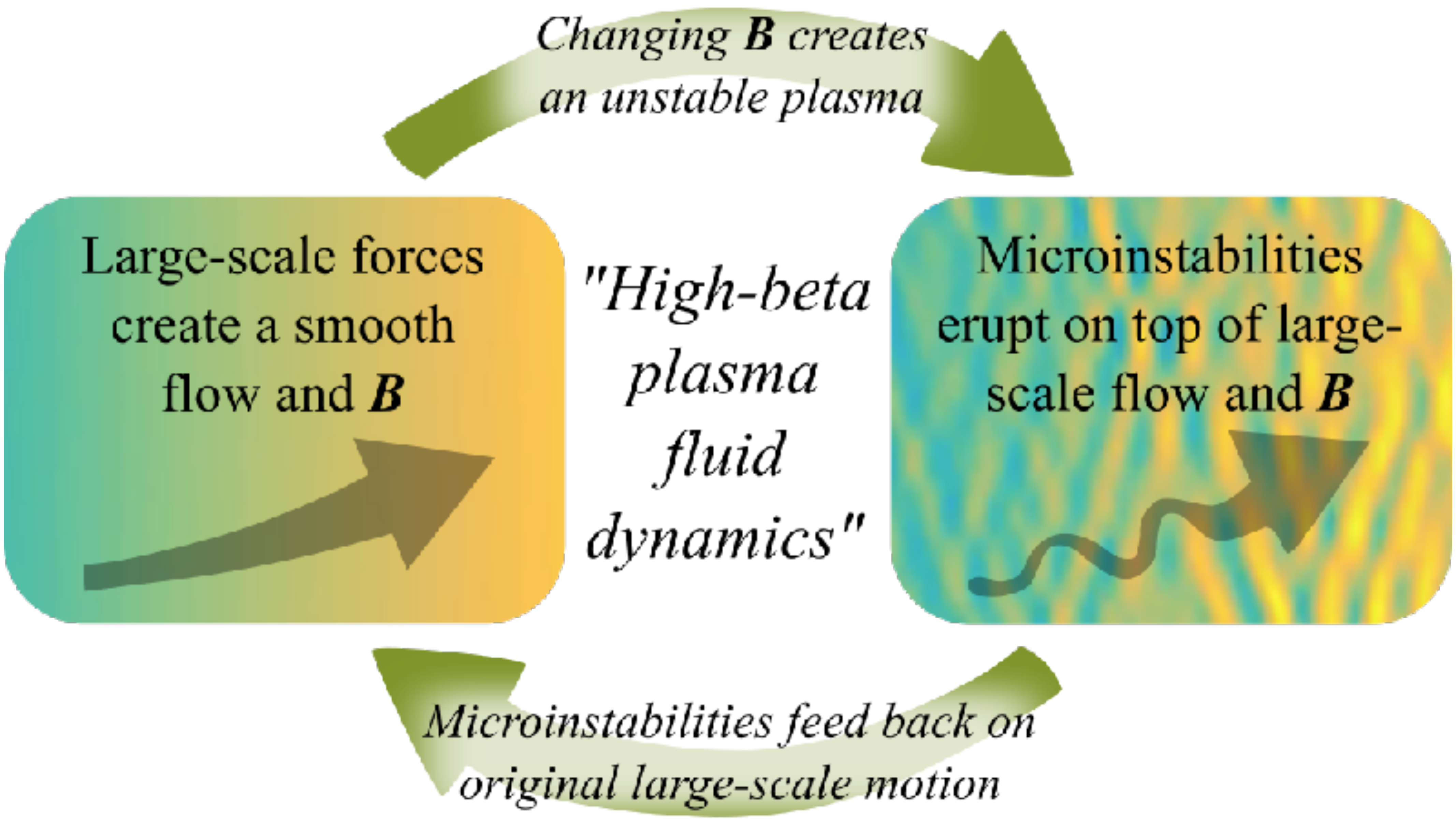


pressure anisotropy pinned at marginal stability by cooling (majority) population of nonlinearly trapped particles

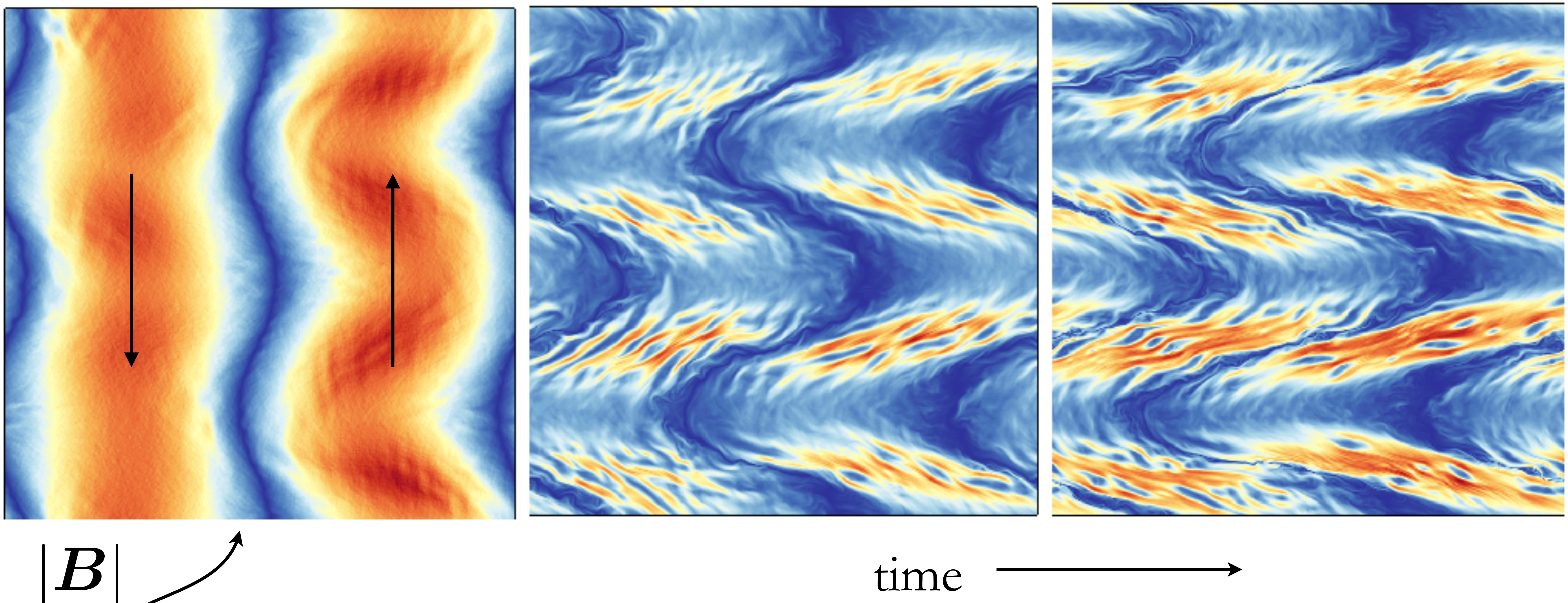
see also Riquelme *et al.* (2015); Melville, Schekochihin & Kunz (2016) and Hellinger and Trávníček (2015); Sironi and Narayan (2015); Hellinger (2017)

key idea:

these kinetic instabilities restore
fluid-like behavior to collisionless systems
by limiting departures from
local thermodynamic equilibrium



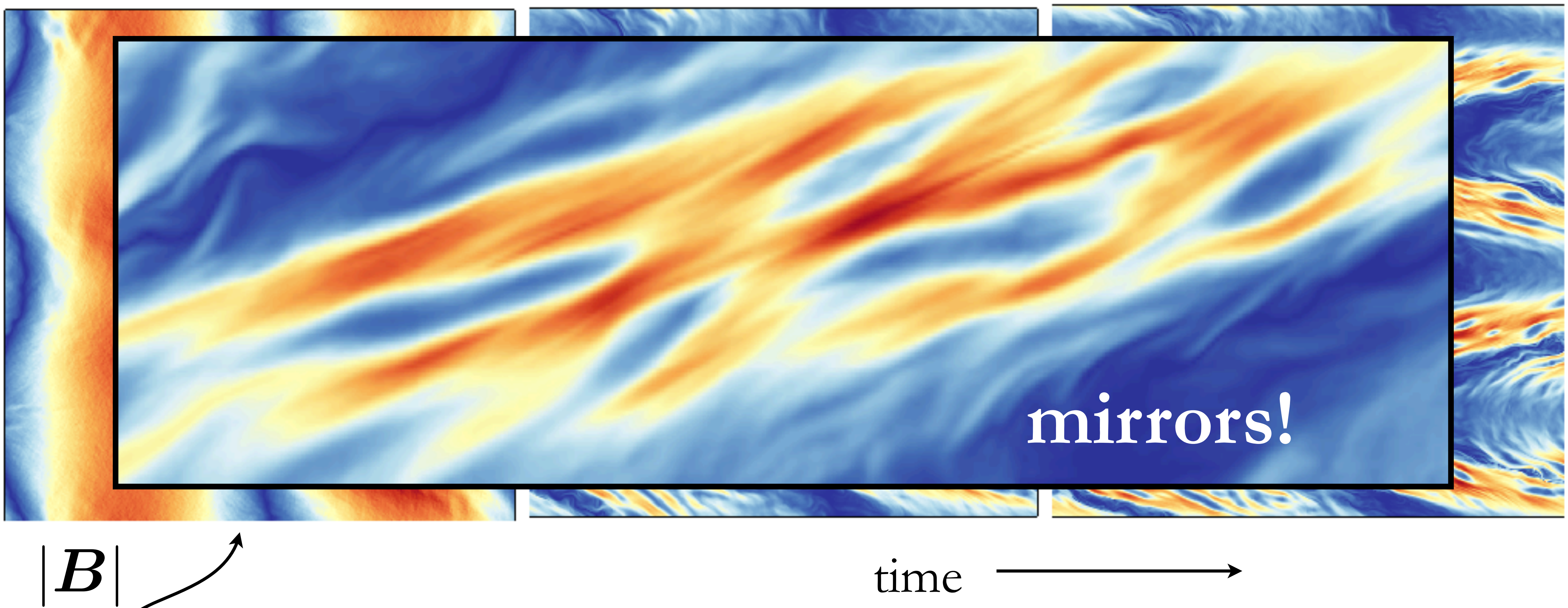
impact on macroscopic evolution, example: MRI turbulence



demonstration of MRI “channel modes” in collisionless plasma

new feature: MRI adiabatically drives pressure anisotropy, which triggers kinetic instabilities that regulate it

see Riquelme *et al.* (2012) and Hoshino (2013) for more on kinetic MRI in 2D impact on macroscopic evolution, example: MRI turbulence



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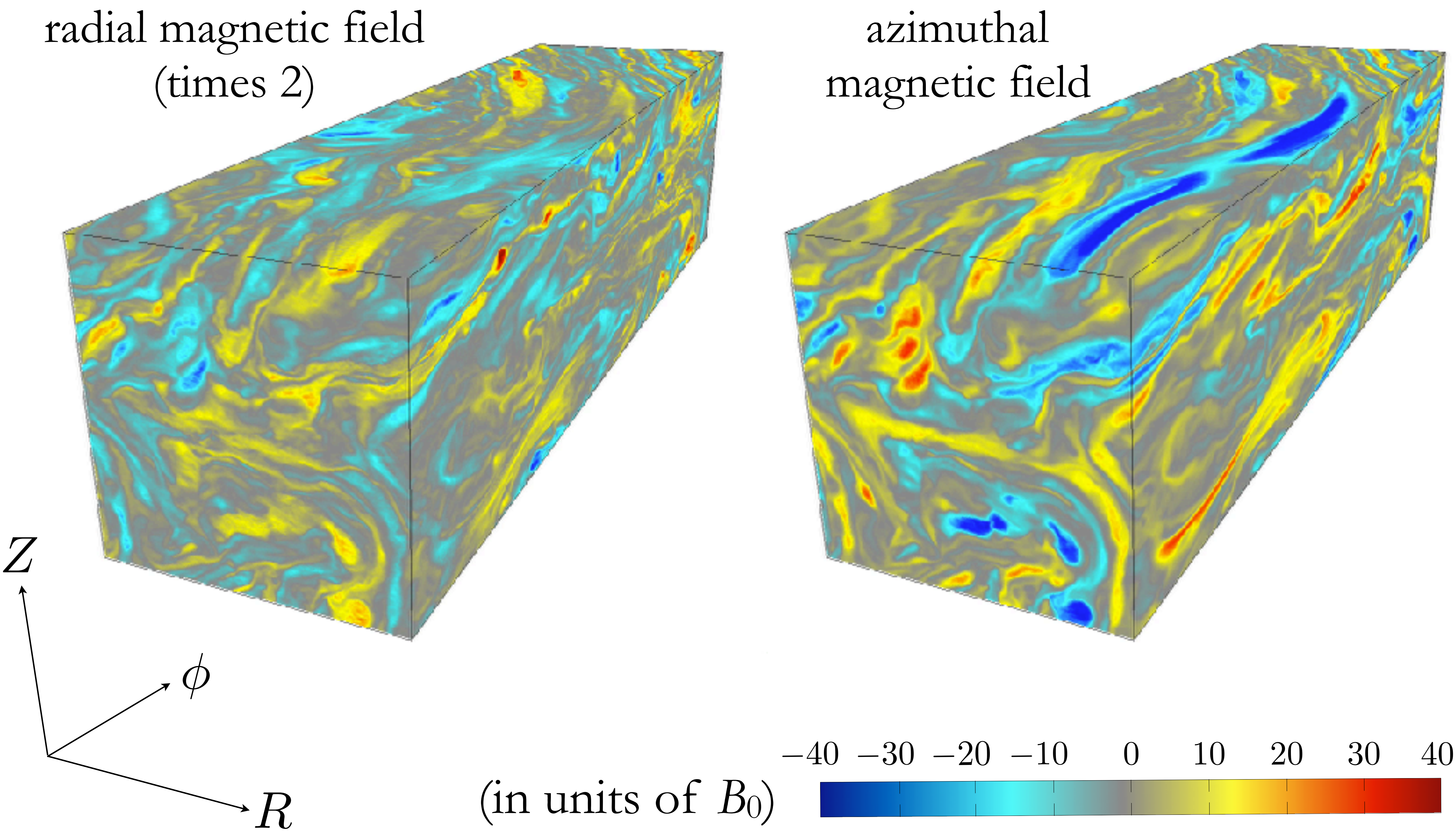

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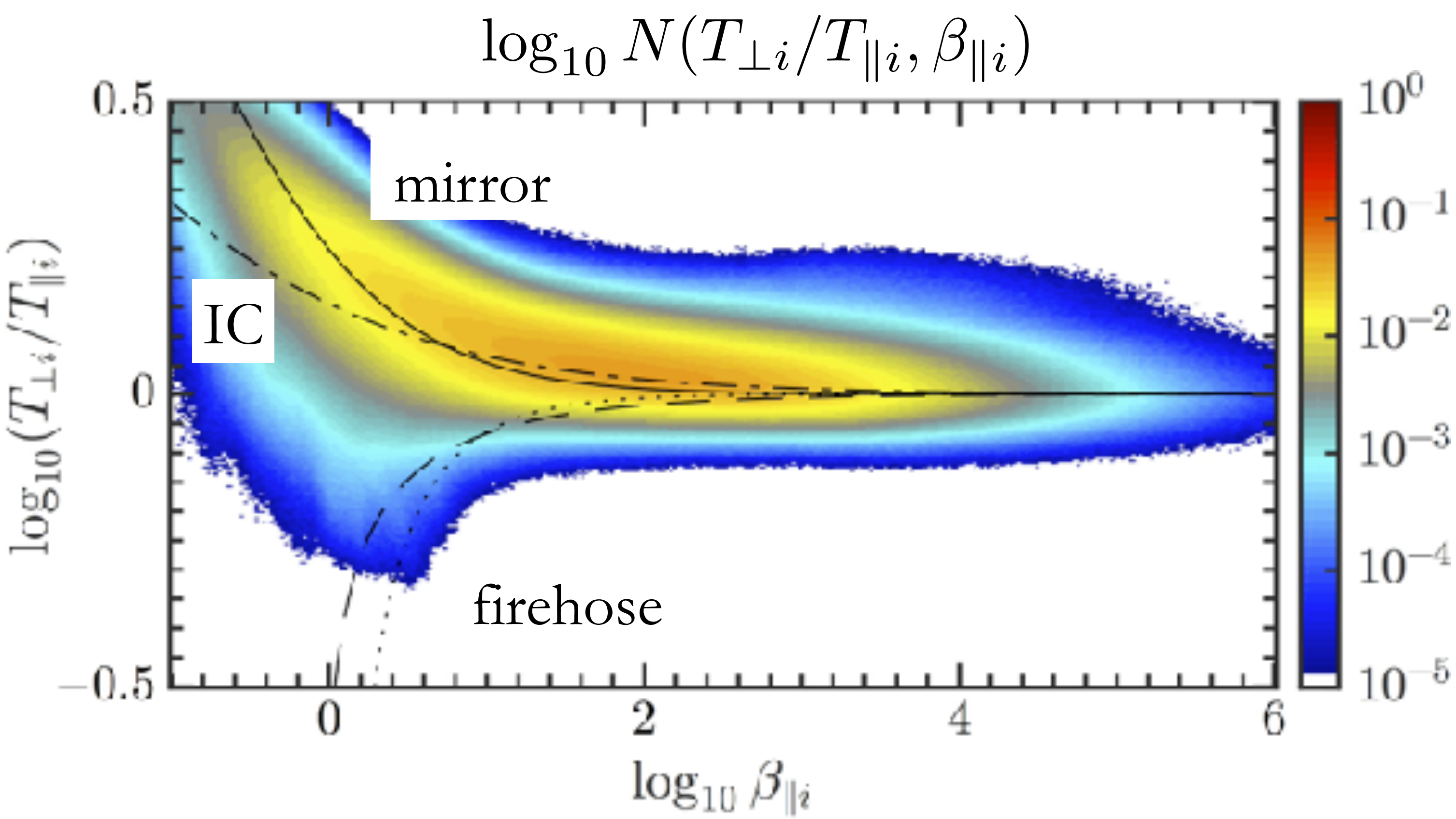
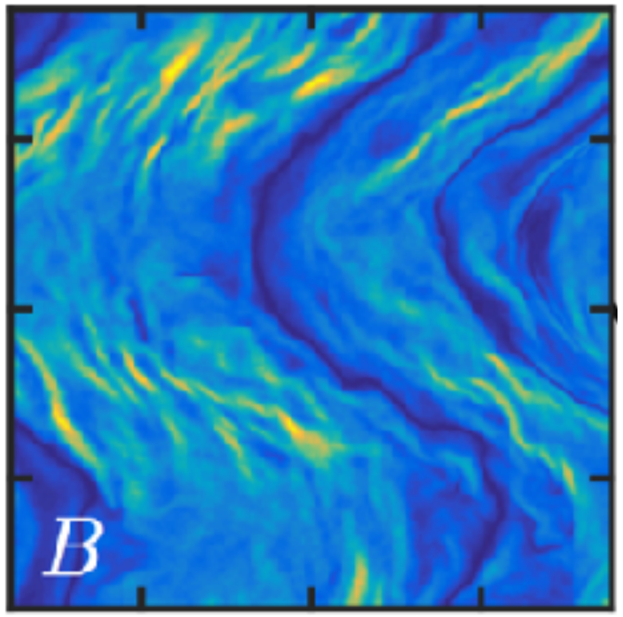
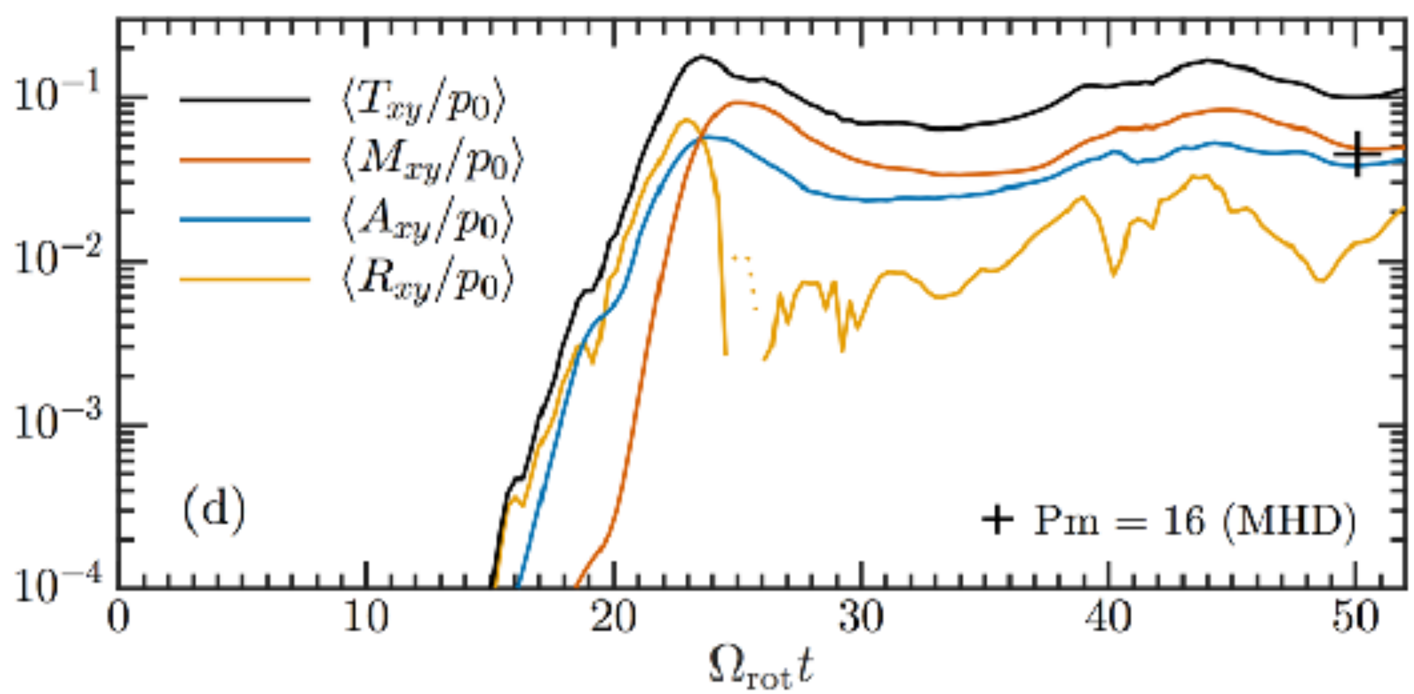


mirrors on MRI channel:



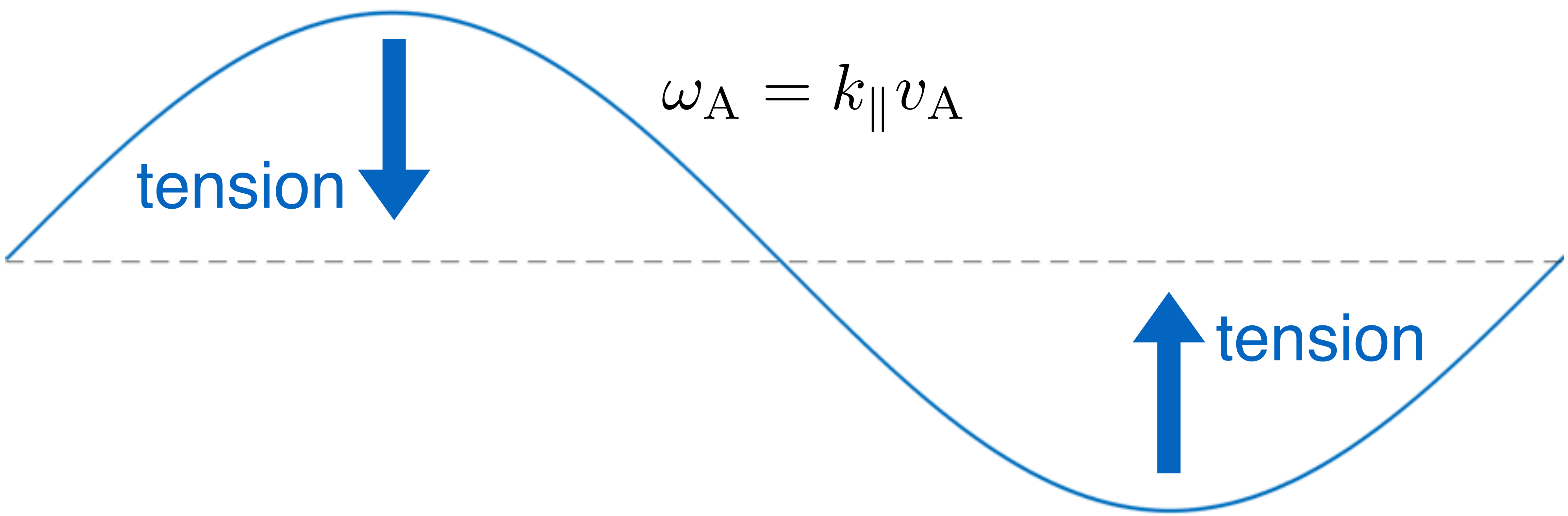


direct connection between plasma microphysics and macroscale dynamics

Let's take a step back…

(following Squire *et al*. 2016, ApJL)

Consider a standing, shear-Alfvén wave:



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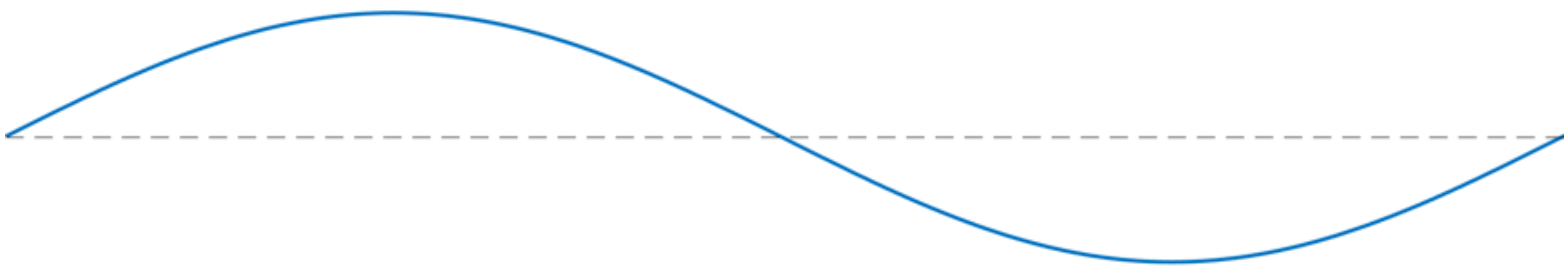


Let's take a step back…

(following Squire *et al*. 2016, ApJL)

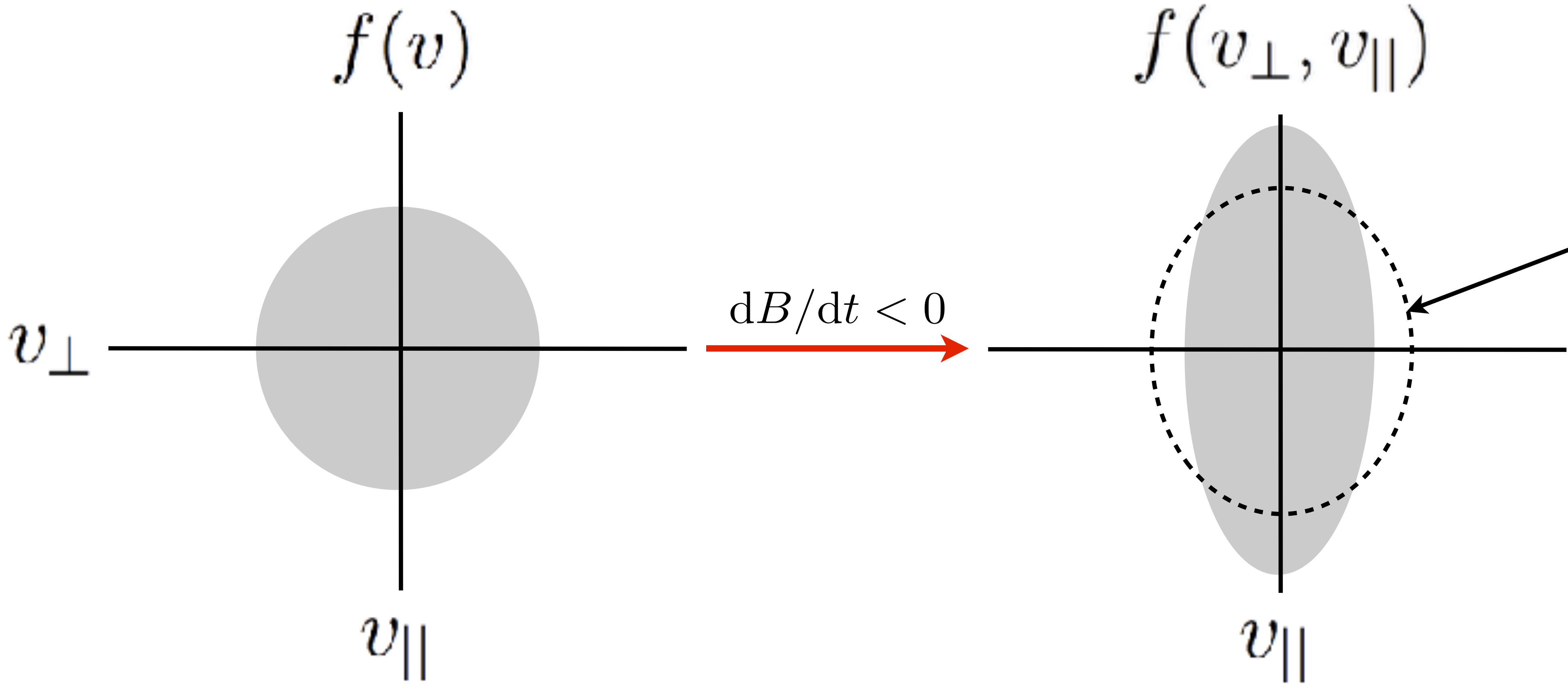
Consider a standing, shear-Alfvén wave:

Let's take a step back…

(following Squire *et al*. 2016, ApJL)

Consider a standing, shear-Alfvén wave:

Now, how much pressure anisotropy was driven by this decrease in field strength?



$$\boxed{p_{||} - p_\perp \gtrsim \frac{B^2}{4\pi}}$$

Answer: $$\frac{P_\perp}{P_{||}} - 1 \simeq -\frac{3}{4}\left|\frac{\delta B_\perp}{B_0}\right|^2$$

If $\left|\frac{\delta B_\perp}{B_0}\right| \gtrsim \frac{1}{\sqrt{\beta}}$, plasma goes firehose unstable.

Note that these can have $\delta B_\perp / B_0 \ll 1$!

What happens at this wave-amplitude threshold?

1. Wave is "interrupted" and can't oscillate/propagate.

$$\nabla \cdot \left[\hat{\boldsymbol{b}}\hat{\boldsymbol{b}} \left(\frac{B^2}{4\pi} + P_\perp - P_\| \right) \right]$$

magnetic tension

nullified if this is $-B^2/4\pi$

Alfvén wave nonlinearly removes its own restoring force.

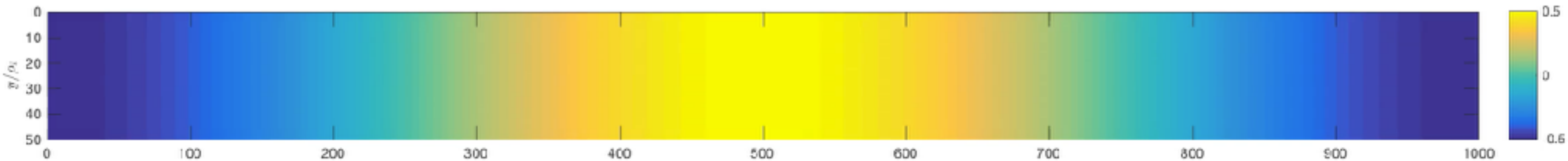
2. Plasma is unstable to a sea of ion-Larmor-scale fluctuations, which trap and scatter particles and viscously decay the wave.

(similar to what occurs in the exhaust of reconnection sites, e.g., Drake *et al.* 2006; Schoeffler, Drake & Swisdak 2011)

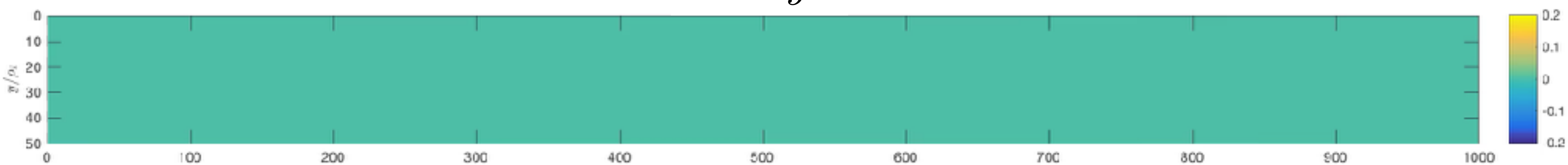
linearly polarized, standing Alfvén wave

$\boldsymbol{B}_0 = B_0\hat{\boldsymbol{x}}$

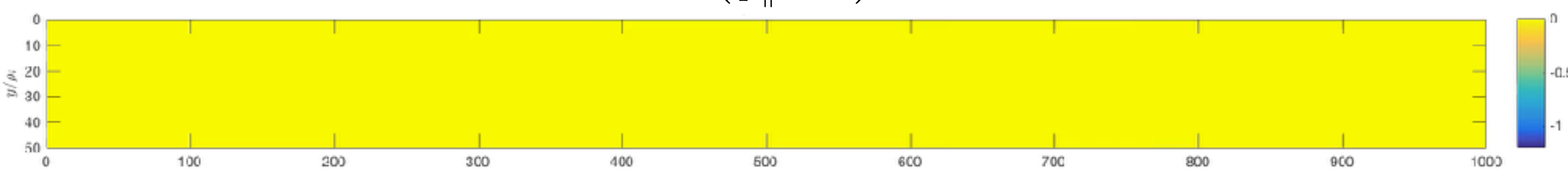
δB_z



δB_y



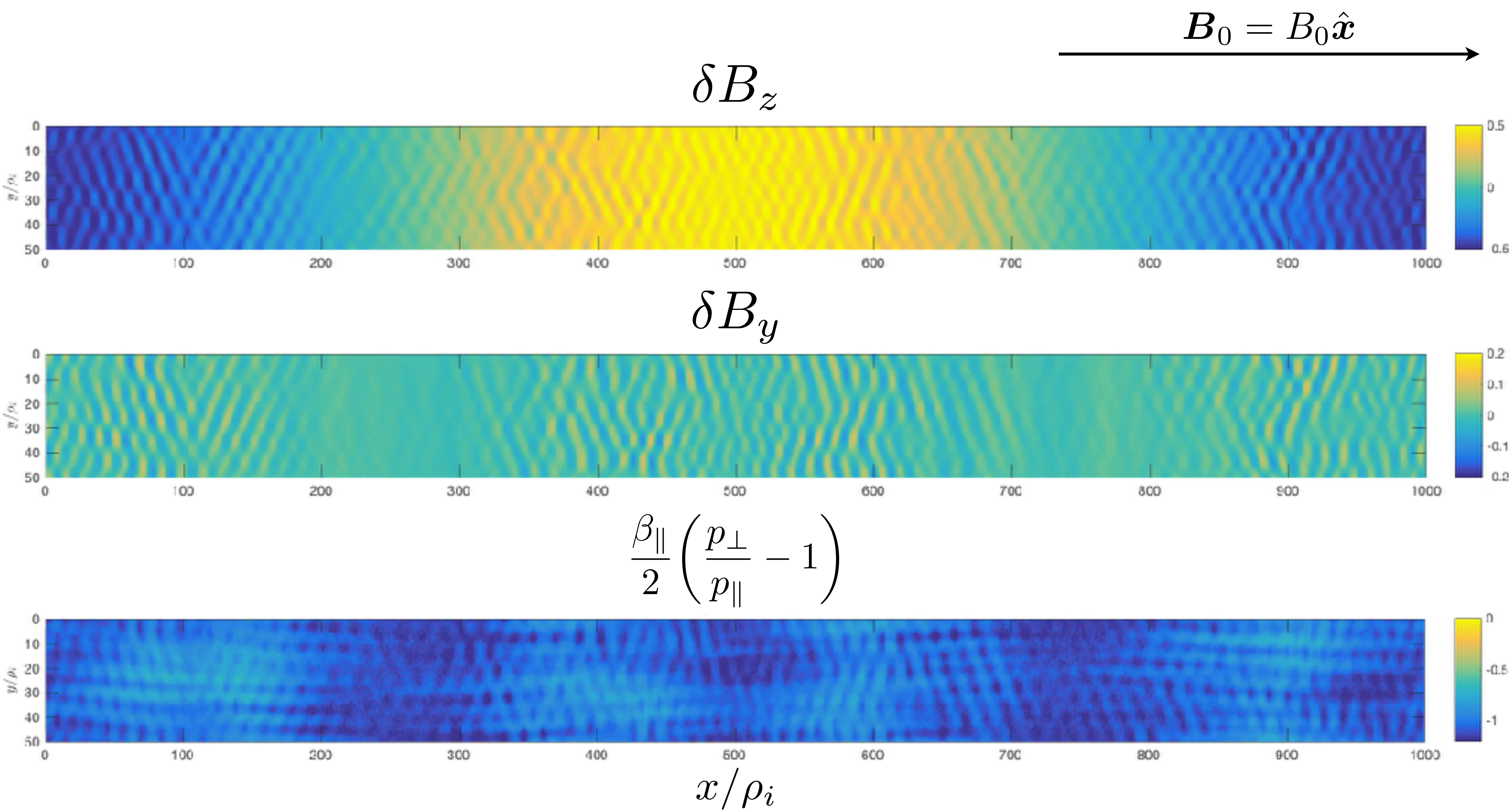
$$\frac{\beta_{\parallel}}{2}\left(\frac{p_{\perp}}{p_{\parallel}} - 1\right)$$



x/ρ_i

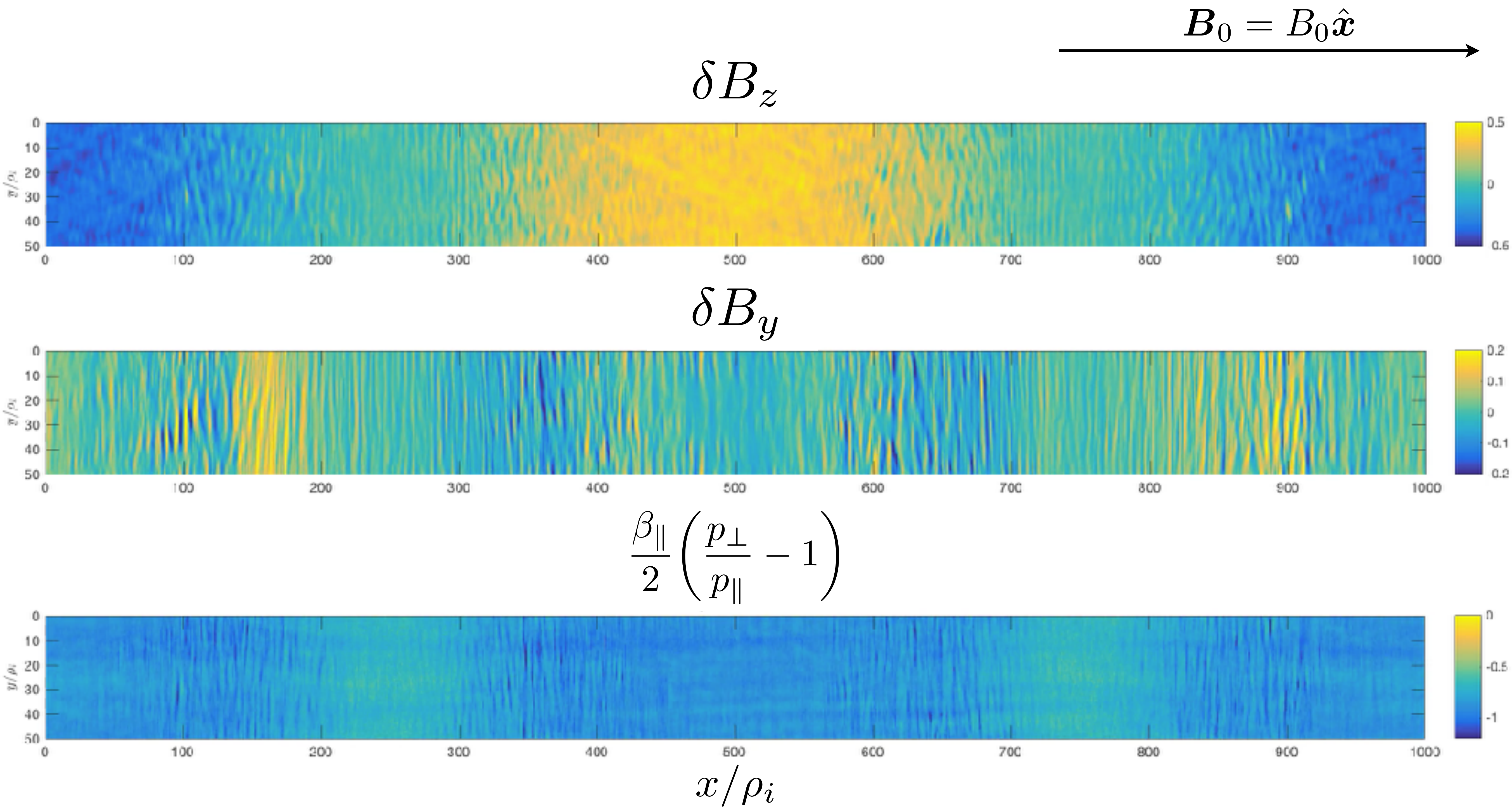
Squire, Kunz, Quataert & Schekochihin (2017), *Phys. Rev. Lett.*

linearly polarized, standing Alfvén wave



Squire, Kunz, Quataert & Schekochihin (2017), *Phys. Rev. Lett.*

linearly polarized, standing Alfvén wave



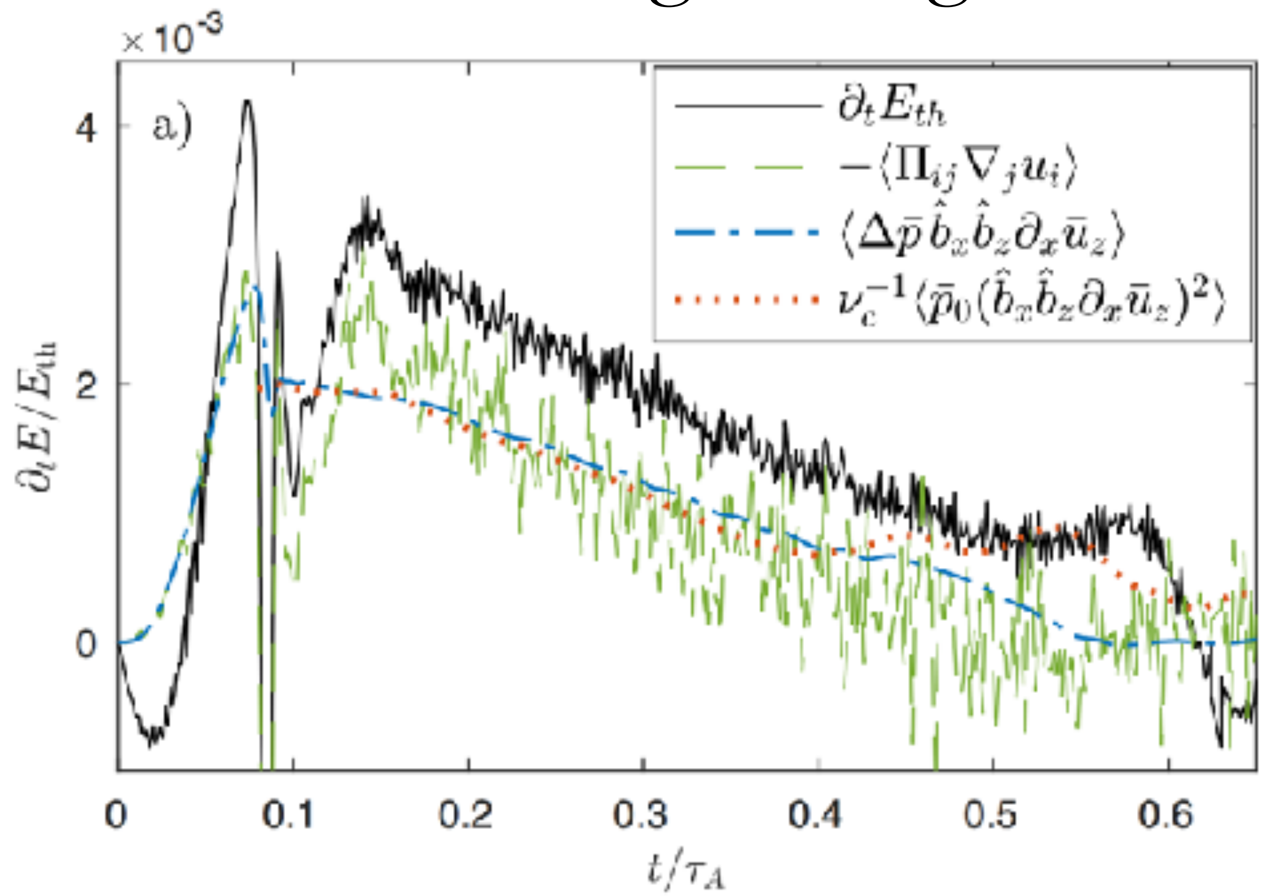
Squire, Kunz, Quataert & Schekochihin (2017), *Phys. Rev. Lett.*

Conclusion:

linearly polarized Alfvén waves cannot be sustained with amplitudes $\delta B_\perp / B_0 \gtrsim \beta^{-1/2}$.

(some evidence for this in the solar wind… ask if you want to see)

Measured ion viscous heating is Braginskii-like (of practical use)



What about compressive fluctuations?

In a magnetized, weakly collisional plasma: $\omega^2 = k^2 a^2 - \mathrm{i}\omega k^2 \mu$

But for (small) viscous losses (and steepening), sound waves propagate just fine

In a magnetized, collisionless plasma: $\frac{\omega}{k v_{\mathrm{thi}}} Z\left(\frac{\omega}{k v_{\mathrm{thi}}}\right) = -\left(1 + \frac{T_{\mathrm{i}}}{T_{\mathrm{e}}}\right)$

solving this… $\frac{\gamma}{|\omega|} \sim -1 \;\text{ if }\; T_{\mathrm{i}} \sim T_{\mathrm{e}}$

A. Schekochihin: *"[in a collisionless hot plasma] no one will hear you scream"*

well, not necessarily…

what if compressive fluctuations drives pressure anisotropy,
which excites mirror/firehose, which makes the plasma act "MHD-like"

[redacted]

Implications, Predictions, and Wild Speculation

In a high-β low-collisionality plasma…

- Firehose and mirror instabilities regulate the pressure anisotropy, and thus set the effective plasma viscosity (important for dynamo, MRI, waves)
- There should be a β-dependent maximum amplitude for different polarizations of Alfvén waves (testable prediction in SW)
- Compressive fluctuations with amplitudes above a β-dependent threshold should live longer than they would otherwise (MHD SW?)
- Direct energy transfer from macroscales to microscale fluctuations and thermal energy, w/o customary scale-by-scale cascade ($\mathrm{Re}_{\mathrm{eff}} \sim 1$?)
- Modern theories of Alfvén-wave turbulence (e.g., GS95) most likely don't apply at sufficiently high β. New theory of turbulence needs to be developed…

[redacted]

[redacted]