Stretching, Mixing, and Tearing:

High-Resolution Simulations of Magnetic-Field Amplification in a Turbulent Plasma

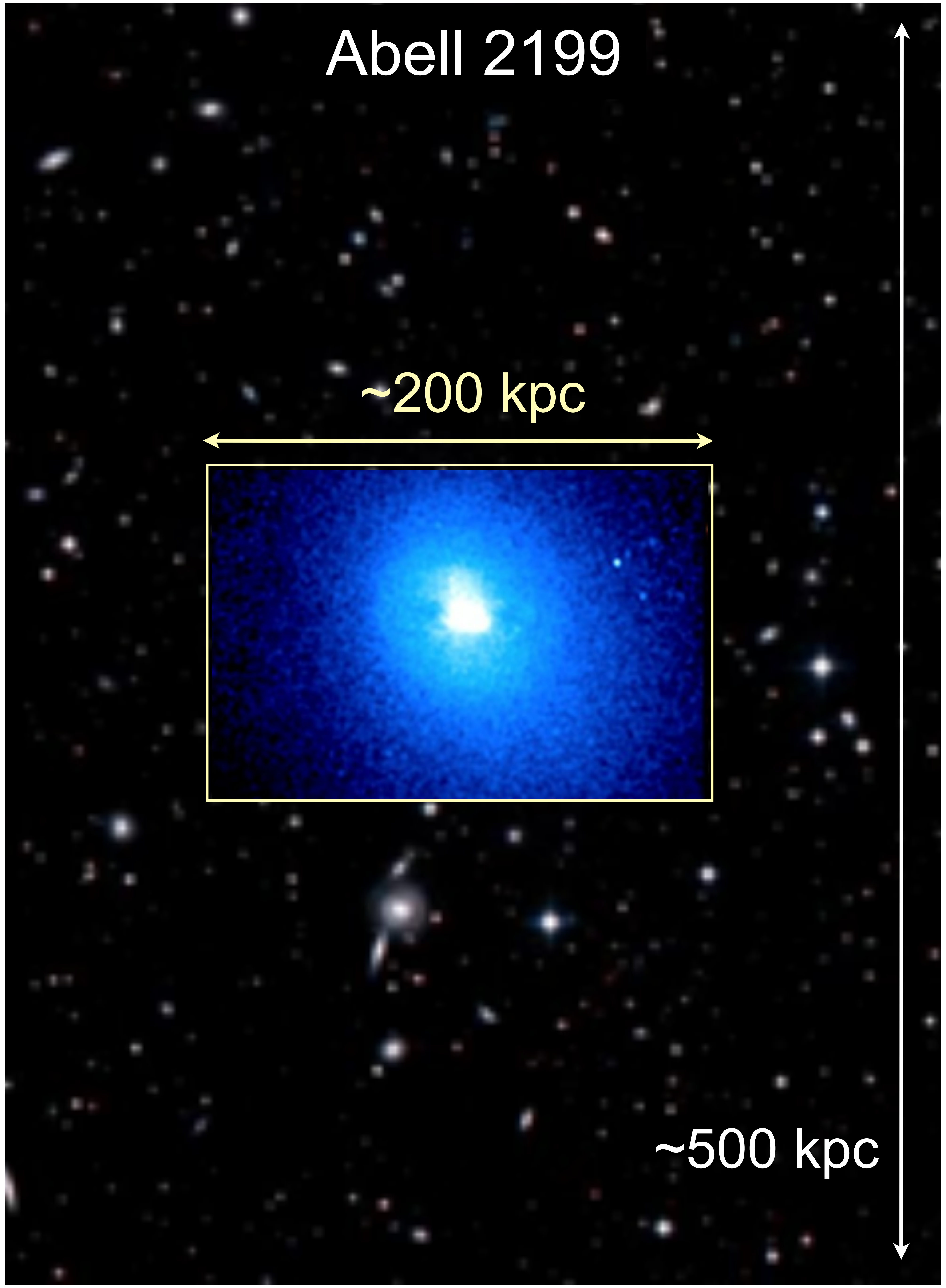
NSF

FRONTERA

Matthew Kunz

PRINCETON UNIVERSITY

with Alisa Galishnikova & Alex Schekochihin



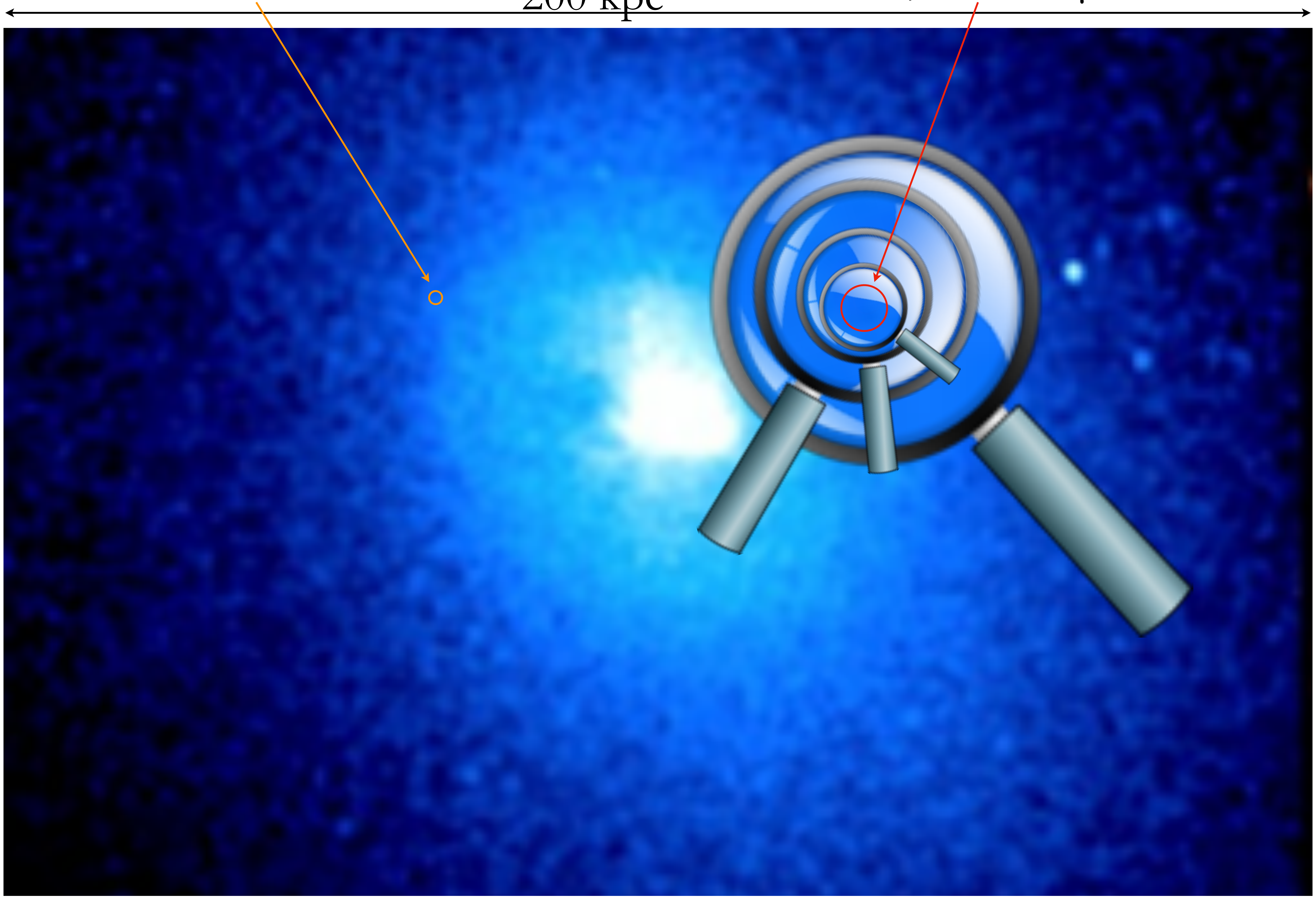
Galaxy Clusters: ~10^{14-15} $M_\odot$ in ~1 Mpc

intracluster medium (ICM)

14 % thermal plasma

$T \sim 1 - 10$ keV

$n \sim 10^{-4} - 10^{-1}$ cm^{-3}



ion Larmor orbit
if $B \sim 10^{-18}$ G

200 kpc

ion Larmor orbit
now, with $B \sim \mu$G

How to make ~μG intracluster magnetic fields in a cosmologically short time?

$$\rho_i \sim \left(\frac{T}{1\ \mathrm{keV}}\right)^{1/2}\left(\frac{B}{10^{-18}\ \mathrm{G}}\right)^{-1}\ \mathrm{kpc} \qquad \beta = \frac{nT}{B^2/8\pi} \sim 10^{26}$$

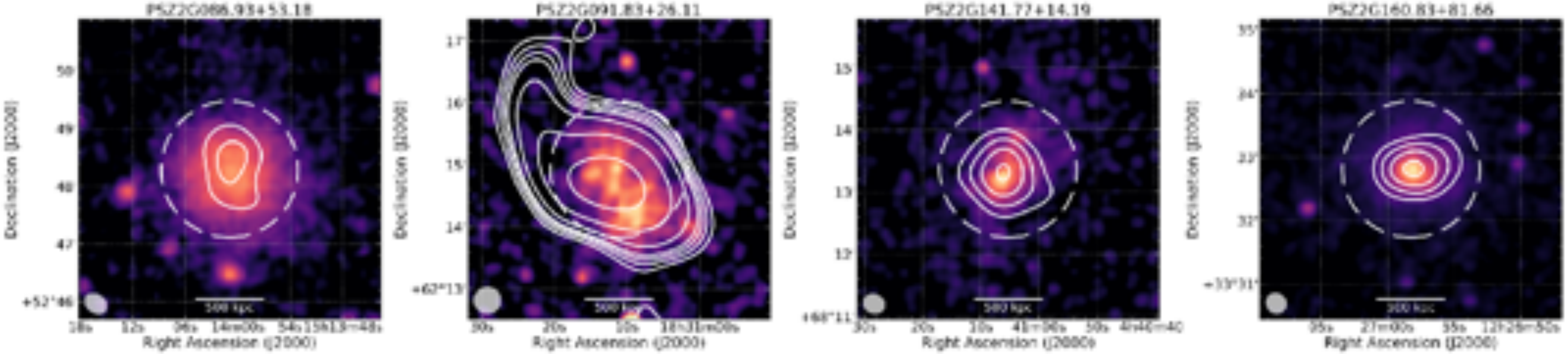
$$\Big\Downarrow\ ?$$

$$\rho_i \sim \left(\frac{T}{1\ \mathrm{keV}}\right)^{1/2}\left(\frac{B}{10^{-6}\ \mathrm{G}}\right)^{-1}\ \mathrm{npc} \qquad \beta = \frac{nT}{B^2/8\pi} \sim 10^{2}$$

(~ size of Jupiter)

Di Gennaro *et al.* (2020, *Nature*):

"The high radio luminosities indicate that these clusters
[detected by LOFAR via diffuse radio emission at $z \sim 0.7$]
have similar magnetic field strengths to those in nearby clusters,
and suggest that magnetic field amplification is fast
during the first phases of cluster formation."

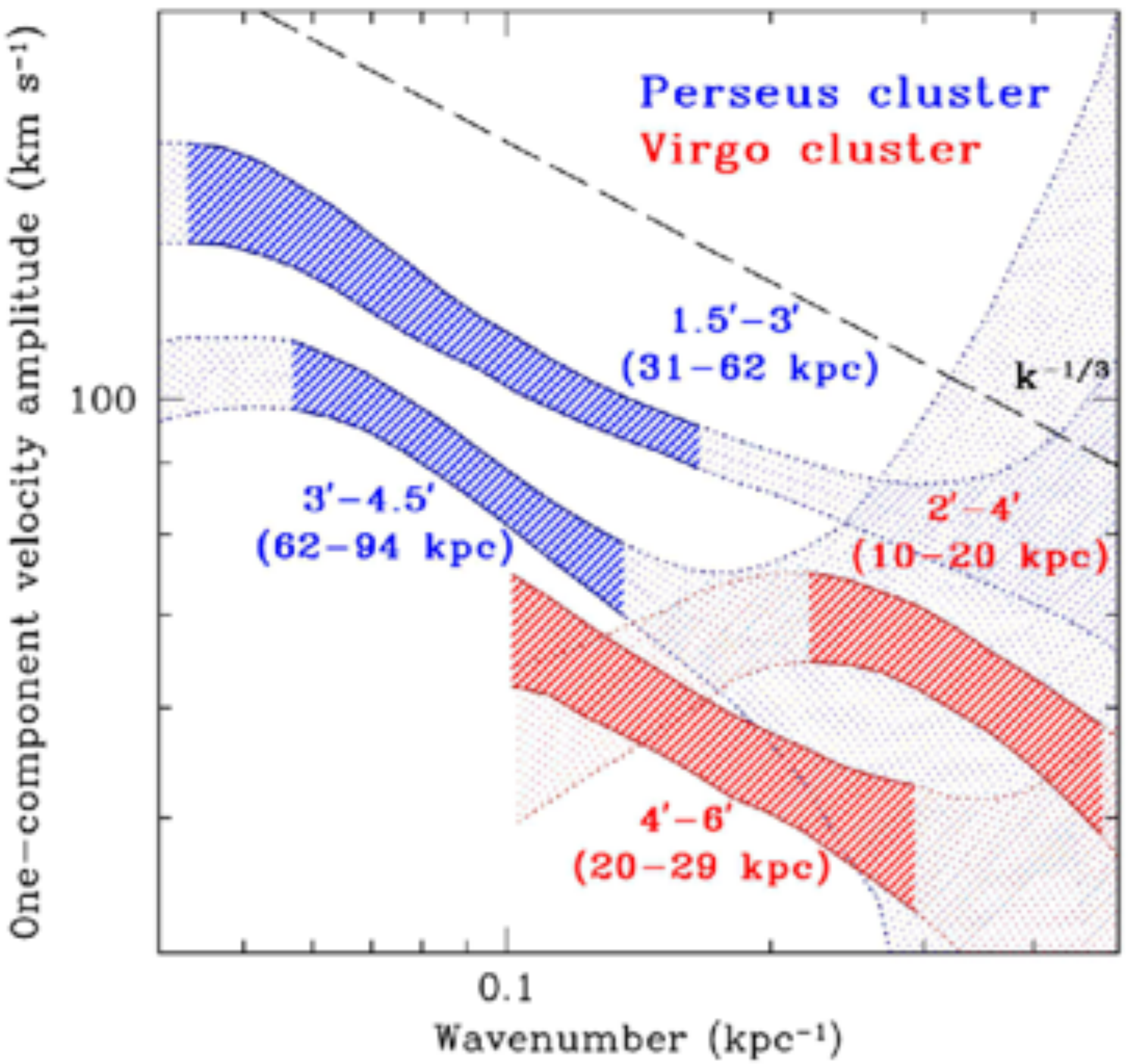


Hints from $z = 0$:

Hitomi, before its
premature death (2016):
$u = 164 \pm 10$ km/s
in Perseus at ~50 kpc

typical B from
rotation measures
↓

$$v_\mathrm{A} = 77 \left(\frac{B}{5\ \mu\mathrm{G}}\right) \left(\frac{n}{0.02\ \mathrm{cm}^{-3}}\right)^{-1/2}\ \mathrm{kpc}$$



Zhuravleva *et al.* 2014, Nature

likely not a coincidence that $M_\mathrm{A} \sim$ few

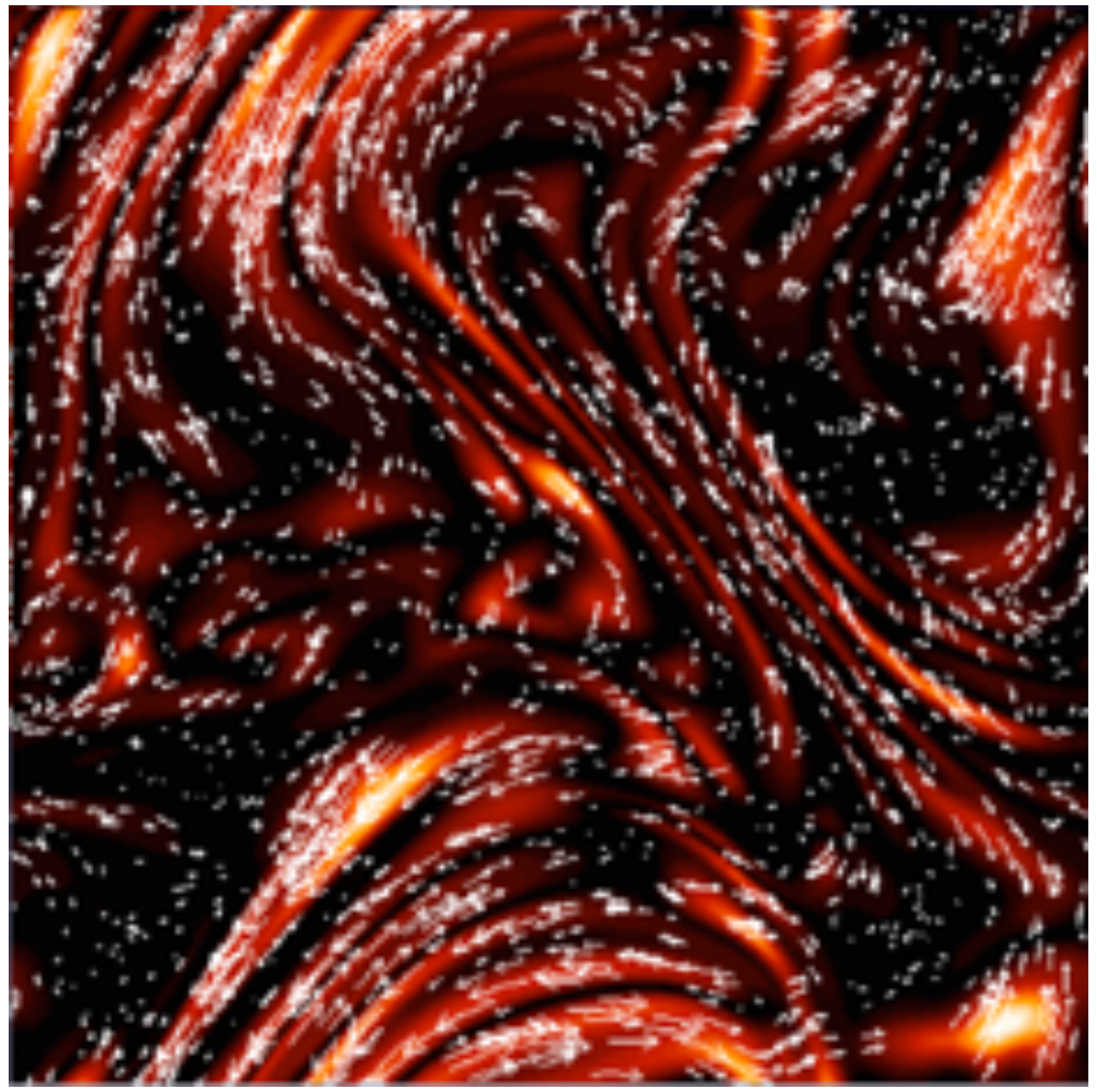
($B \propto n^{1/2}$ inferred in Coma: Bonafede *et al.* 2010) it is then natural to attribute intracluster magnetic field to the **fluctuation ("turbulent") dynamo**

(Batchelor 1950; Kazantsev 1967; Zel'dovich et al. 1984; Childress & Gilbert 1995),

whereby a succession of random velocity shears stretches the field and leads on the average to its growth to dynamical strengths.

$$\frac{\mathrm{d}\ln B}{\mathrm{d}t} = \hat{\boldsymbol{b}}\hat{\boldsymbol{b}}\boldsymbol{:}\nabla\boldsymbol{u}$$

magnetic energy grows in a 3D, smooth, chaotic velocity field



B from Re ~ 1, Pm ≫ 1
Schekochihin *et al.* (2004)

What makes fluctuation dynamo computationally expensive?

1. Zel'dovich 1957: No dynamo can be maintained by a planar flow

→ intrinsically **three-dimensional**

2. Depends sensitively on the material properties of the plasma

→ intrinsically **multi-scale**

MHD fluctuation dynamo basics:

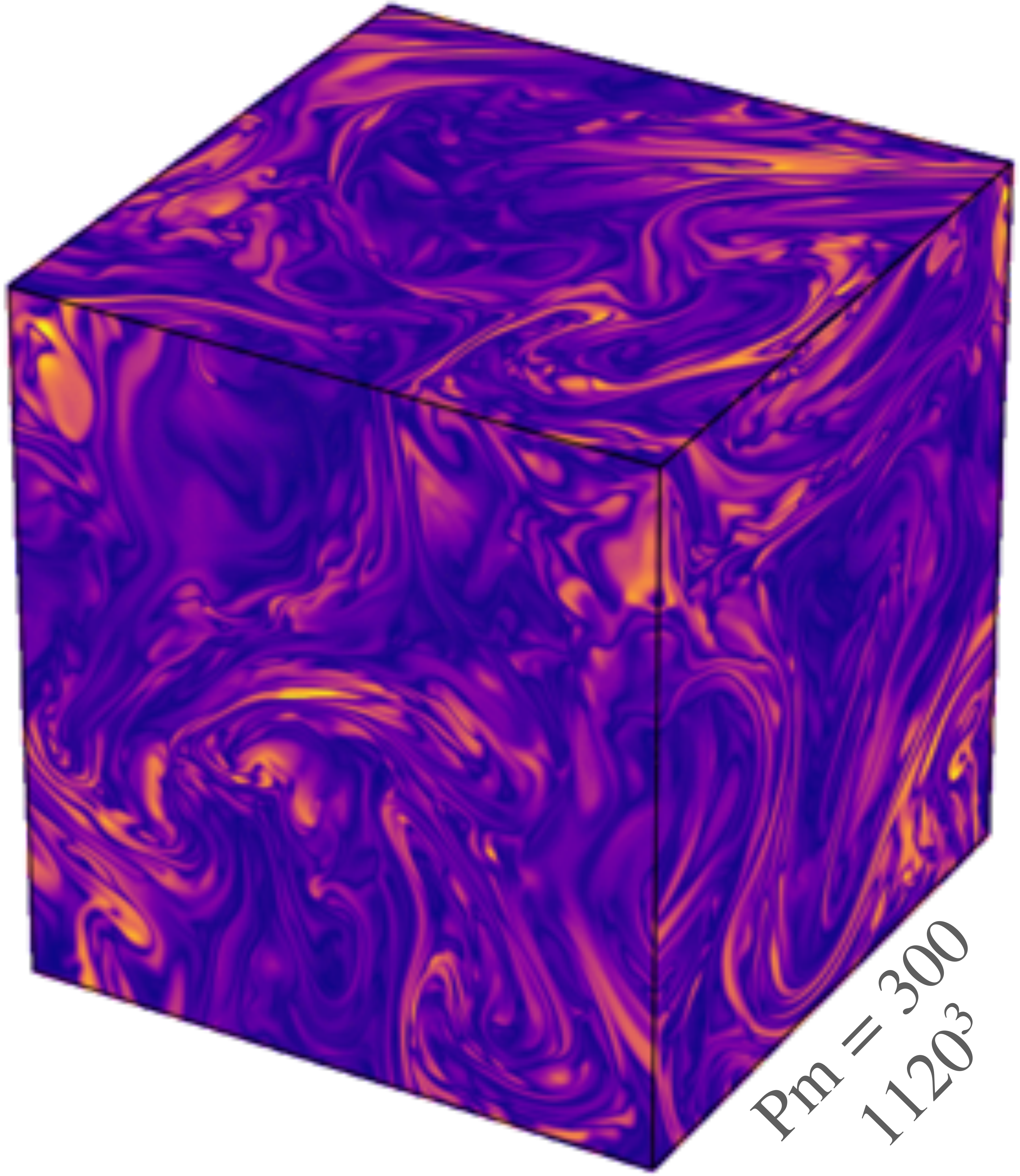
$\mathrm{Pm} = \dfrac{\nu}{\eta}$ matters: stretching vs diffusion

(most astrophysical plasmas have $\mathrm{Pm} \gtrsim 1$)

magnetic field folded and amplified exponentially by viscous-scale eddies in "**kinematic phase**"

until field is strong enough to back-react on plasma motions via Lorentz force in "**nonlinear phase**"

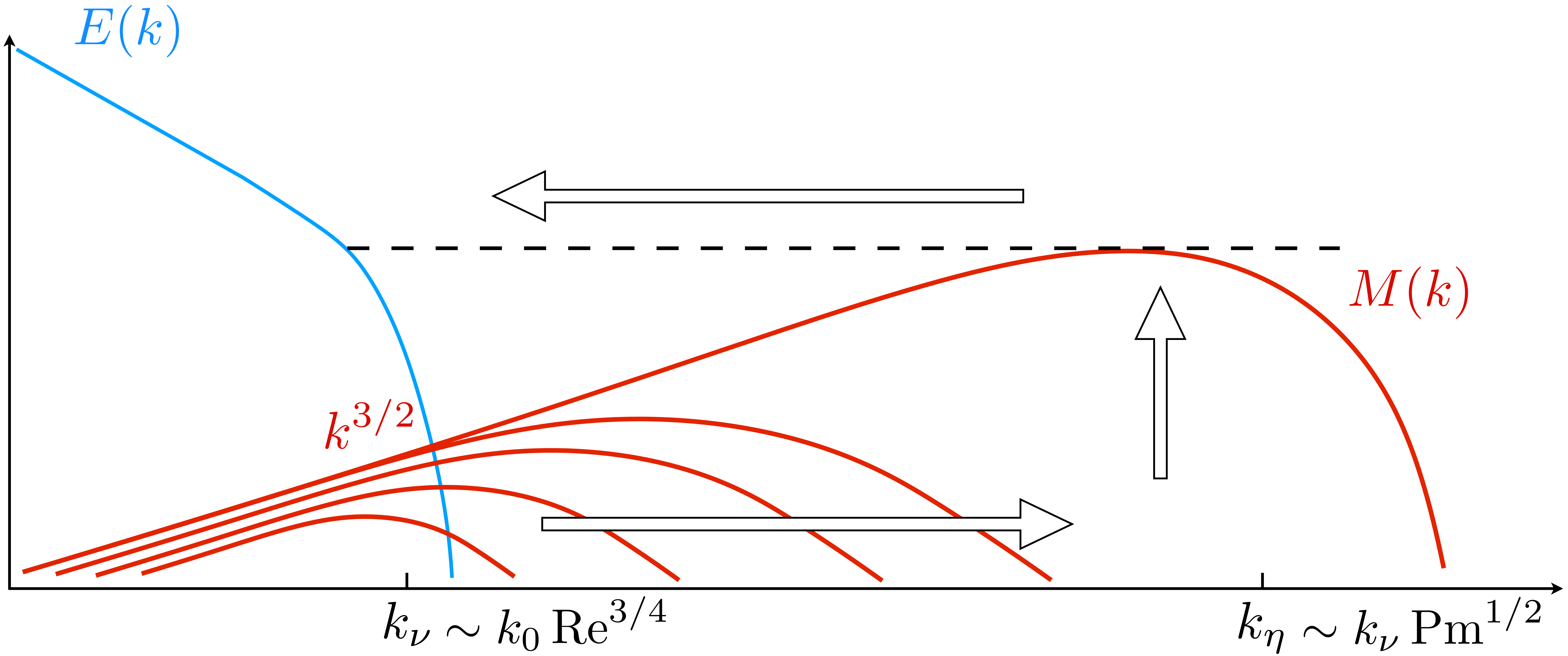
eventually, $\langle B^2 \rangle \sim \langle u^2 \rangle$ in "**saturated state**"



$\mathrm{Pm} = 300$

1120^3

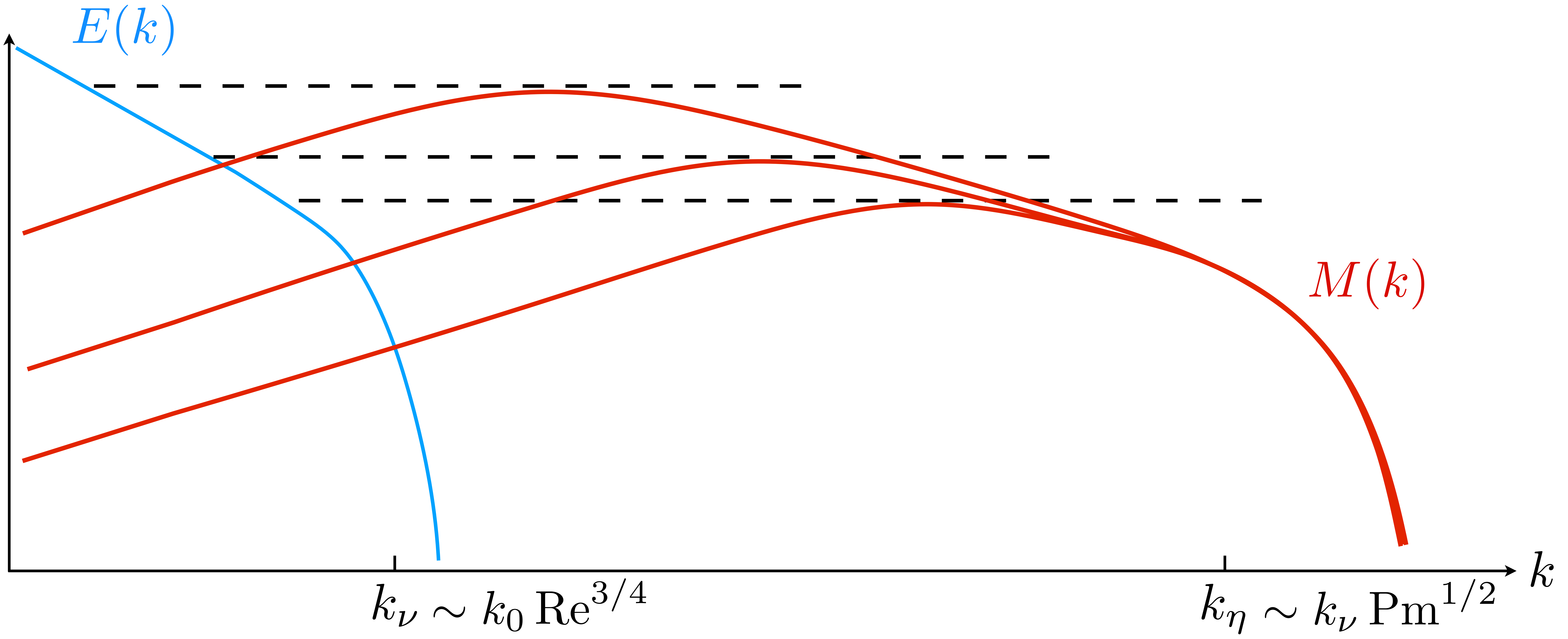
stir incompressible, subsonic turbulence at box scale…



$$\mathrm{Re} = \frac{UL}{\nu}$$

$\mathrm{Pm} \doteq \text{viscosity}/\text{resistivity} = \mathrm{Rm}/\mathrm{Re}$

stir incompressible, subsonic turbulence at box scale…



$$\mathrm{Re} = \frac{UL}{\nu}$$

$\mathrm{Pm} \doteq \mathrm{viscosity/resistivity} = \mathrm{Rm/Re}$

Can the plasma be treated as a fluid?

Yes

magnetohydrodynamics (MHD)
specify $\mathrm{Re} = UL/\nu$, $\mathrm{Rm} = UL/\eta$

Athena++
Eulerian, conservative,
finite-volume Godunov code
(Stone *et al.* 2020, ApJS)

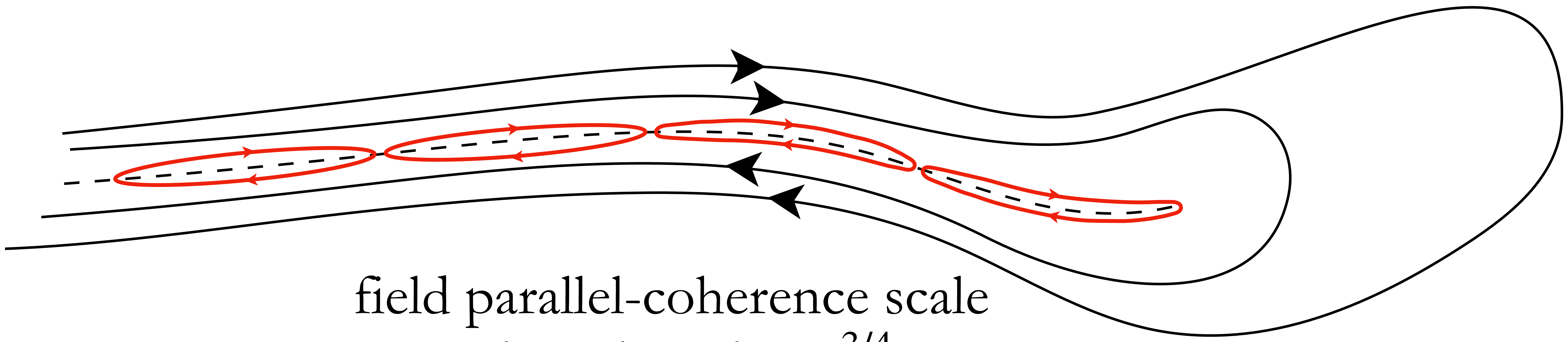
No

kinetics
specify L/ρ_i, m_i/m_e

Pegasus++
hybrid-kinetic ($m_i/m_e \rightarrow \infty$),
particle-in-cell (PIC) code
(Kunz *et al.* 2014, JCoPh;
Arzamasskiy *et al.*, in prep)

both use "task list" approach to overlap communication and computation;
both exploit AVX512 heavily (lots of effort put into optimization); both in C++;
we use large memory nodes on Frontera for data analysis

(new) theoretical expectations for MHD dynamo at $\mathrm{Rm} \gg 1$



field-reversal scale

$k_{BxJ} \sim k_\eta \sim k_0 \, \mathrm{Rm}^{1/2} \gg k_0$

field parallel-coherence scale

$k_\parallel \sim k_\nu \sim k_0 \, \mathrm{Re}^{3/4}$

When $\mathrm{Pm} \gg 1$, $\mathrm{Rm} \gg 1$, magnetic folds may be viewed as thin, elongated **current sheets**.

Such current sheets are **unstable to “tearing”** (reconnection), which should place a lower bound on $k_{B\times J}$

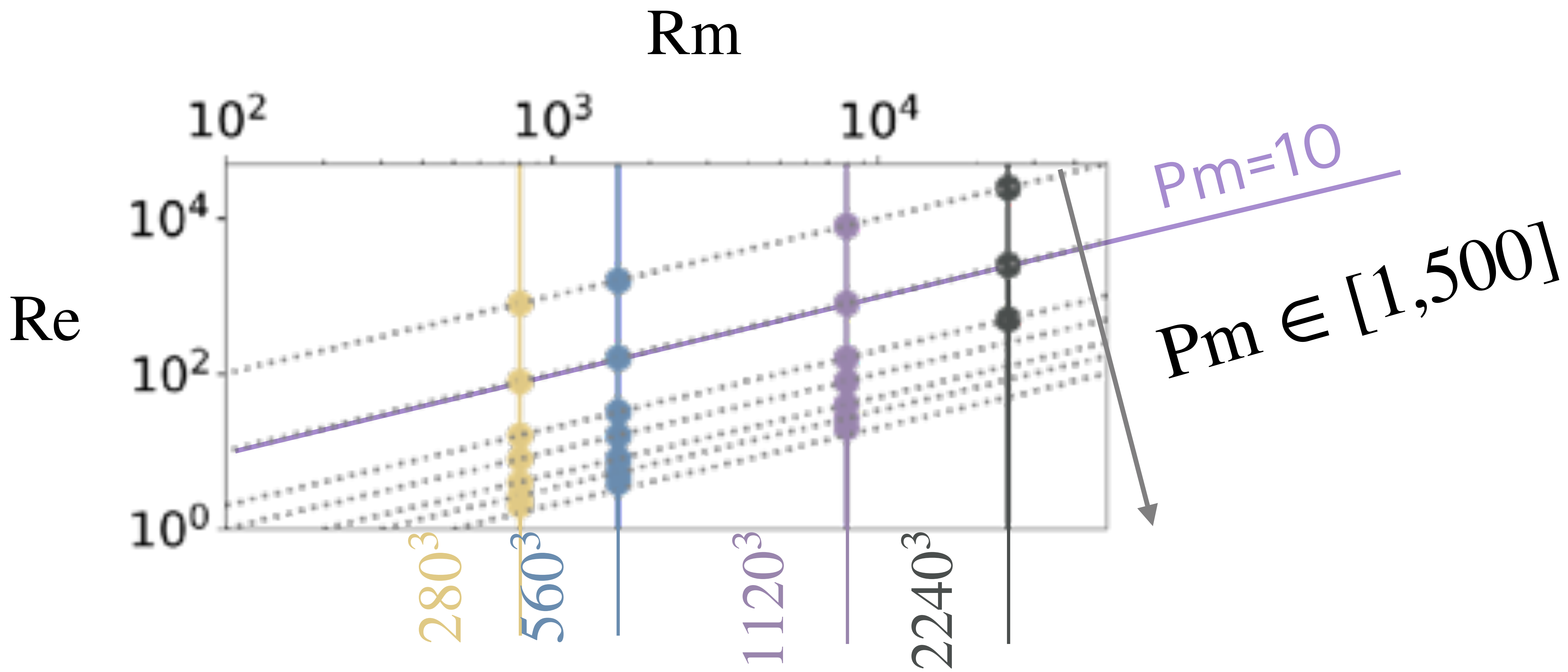
Simple theory for tearing disruption of folds: timescale for disruption $\lesssim$ lifetime of magnetic fold ?

implies **tearing scale** $k_\mathrm{t} \sim k_0 \, \mathrm{Rm}^{1/3} (1 + \mathrm{Pm})^{1/6} < k_\eta$ in the nonlinear phase and saturated state

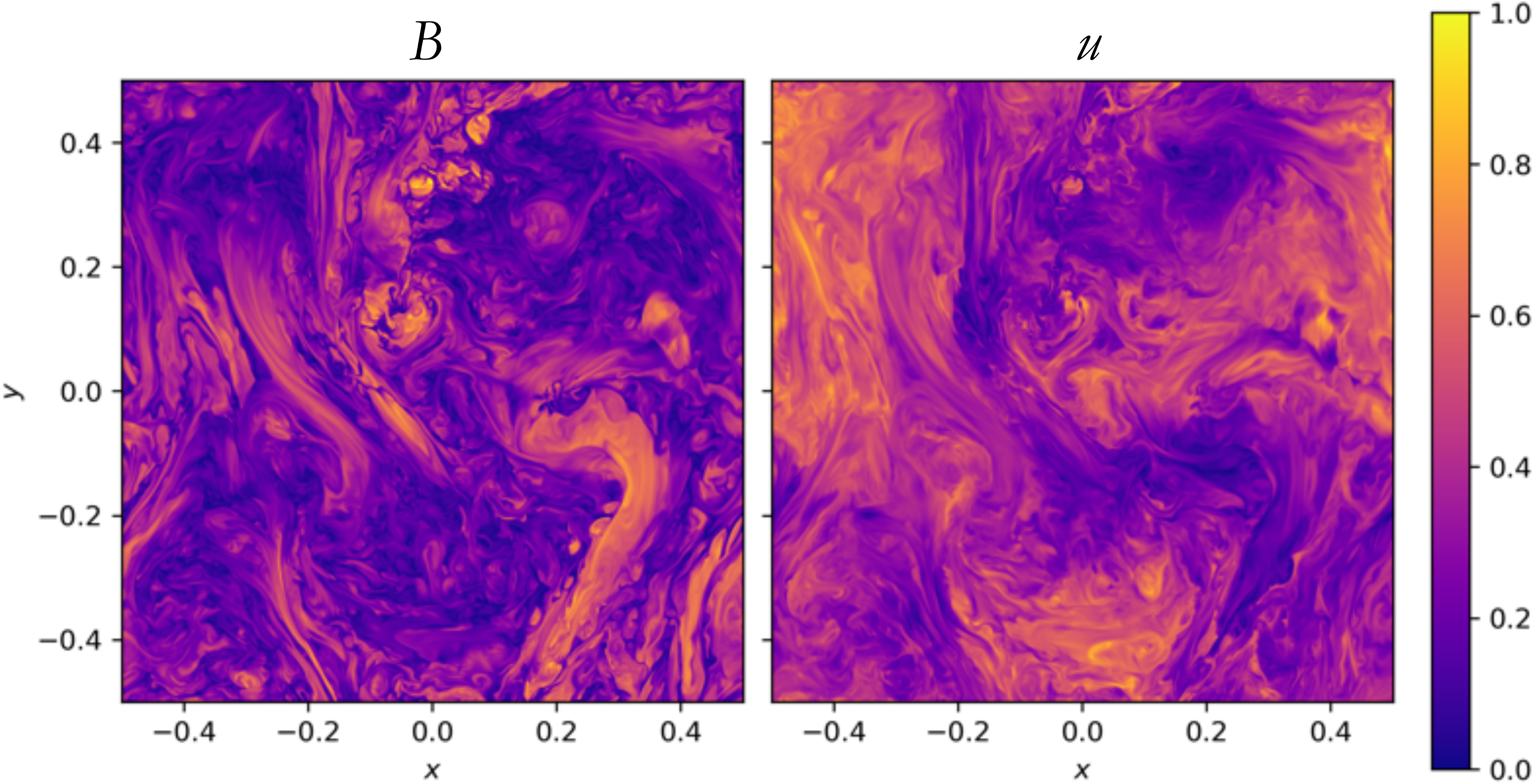
→ should see change in magnetic-field geometry at large enough Rm

Performing large parameter study of Pm $\gtrsim$ 1 MHD dynamo up to highest resolutions

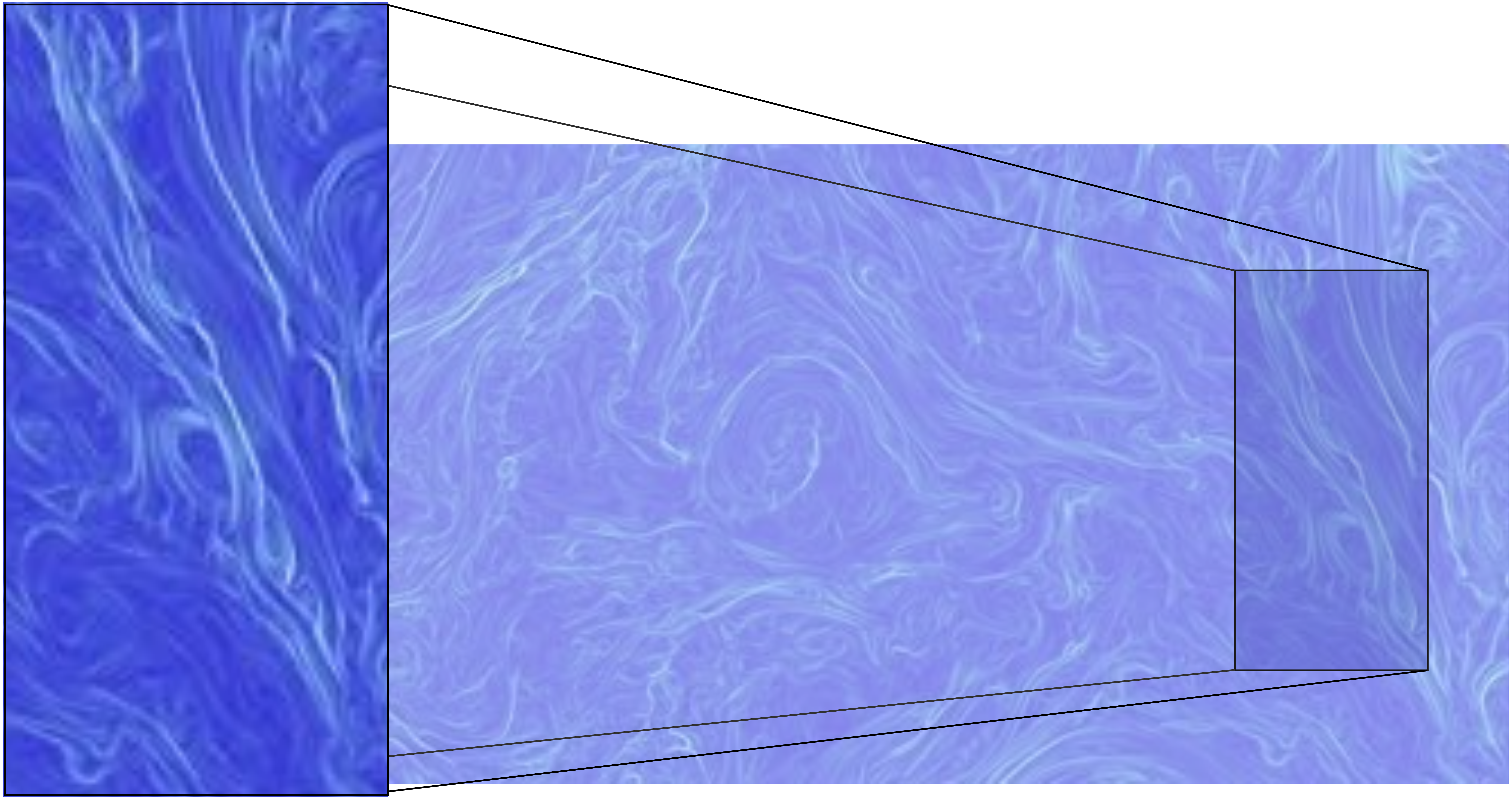
(~700k SUs so far)



at 2240^3, Pm = 10

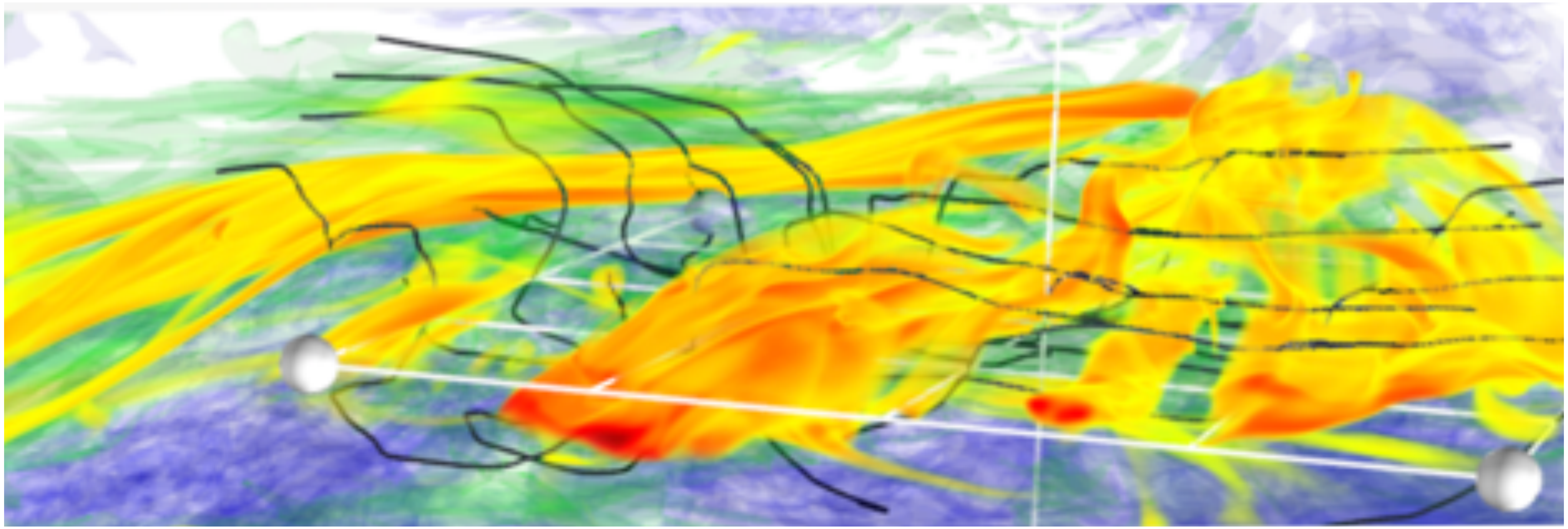


$|\boldsymbol{J}|$ at 2240^3, Pm = 10



at 2240^3, $\mathrm{Pm} = 10$

visual evidence for tearing of magnetic folds and "plasmoids"

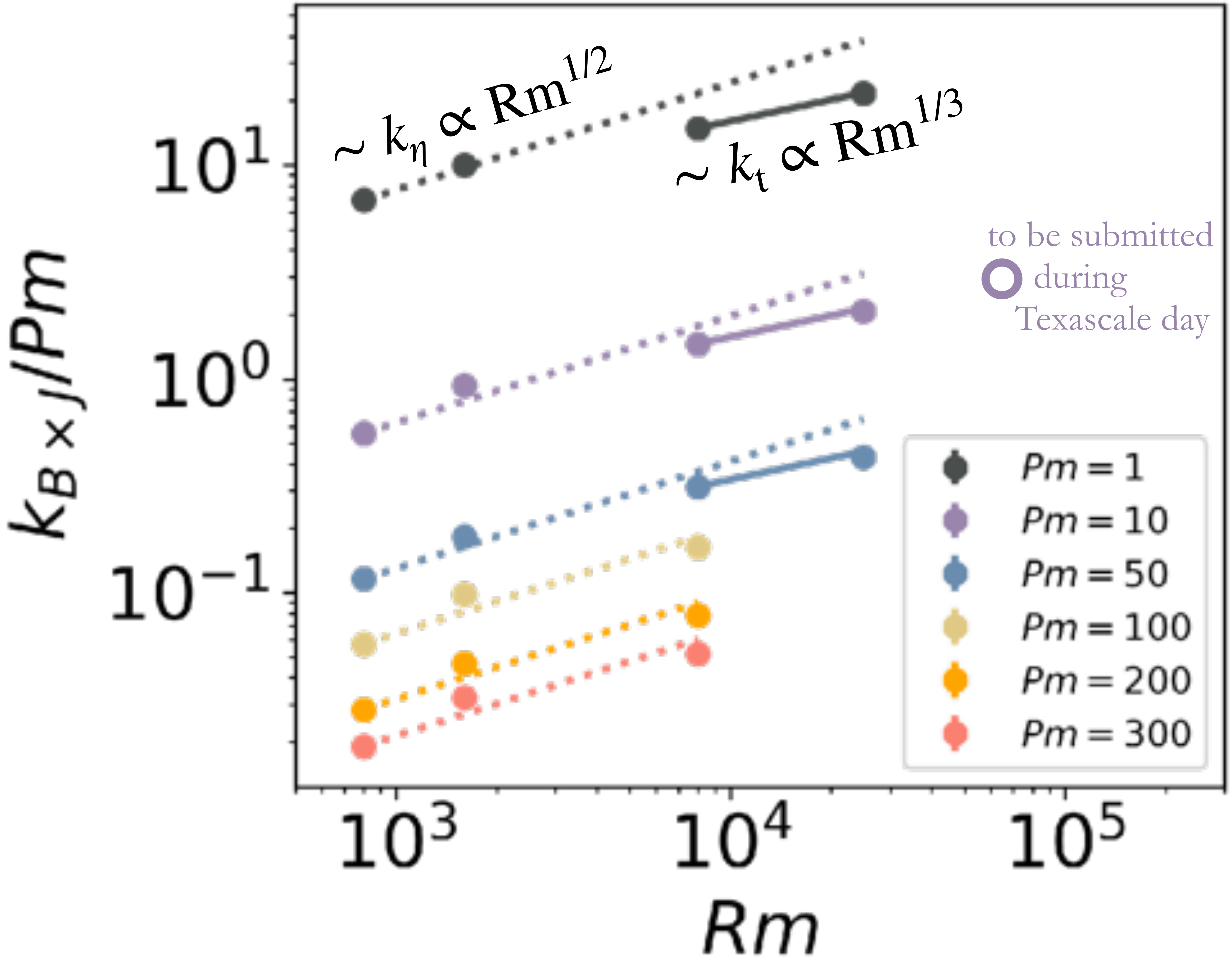


— magnetic-field lines 🟧 field strength

field-reversal scale shifts
from $\sim k_\eta \propto \mathrm{Rm}^{1/2}$ at smaller Rm
to $\sim k_\mathrm{t} \propto \mathrm{Rm}^{1/3}$ at larger Rm,
as predicted

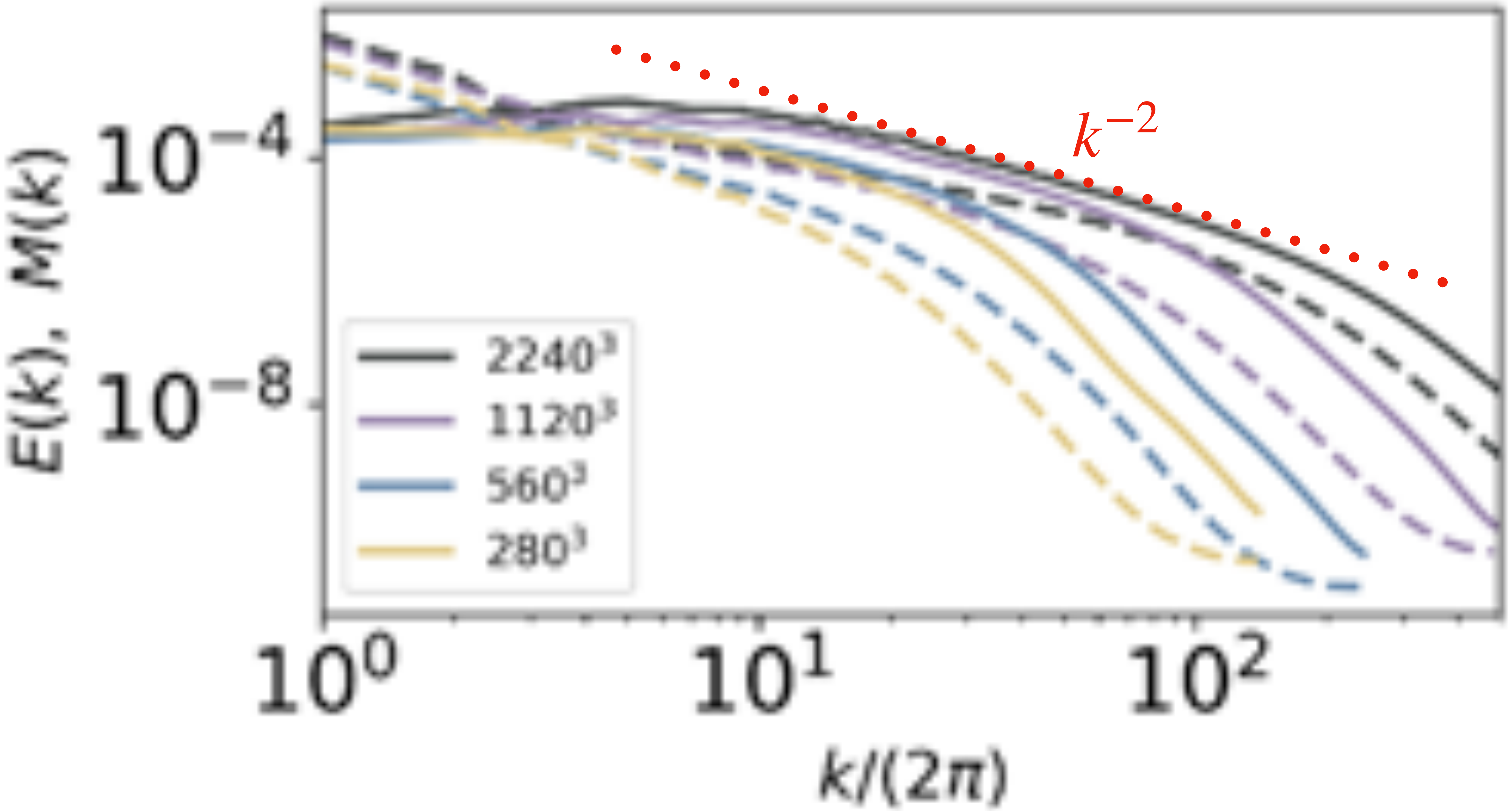
(…for small enough Pm;
fluid cannot be too viscous,
or else tearing modes suffer)

field-reversal scale

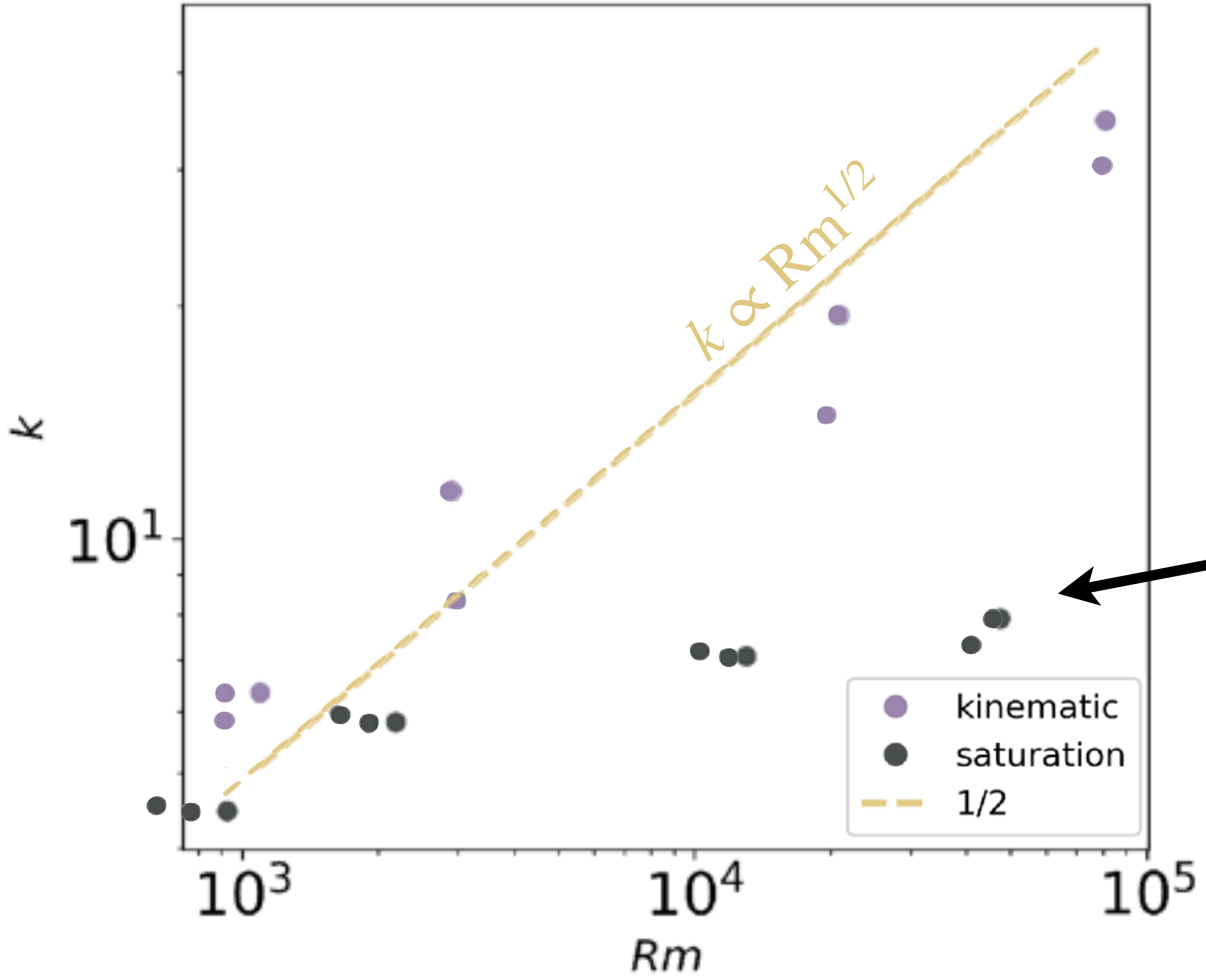


to be submitted
○ during
Texascale day

beneath tearing scale at large Rm,
we observe magnetic spectrum
$M(k) \sim k^{-2}$, as predicted

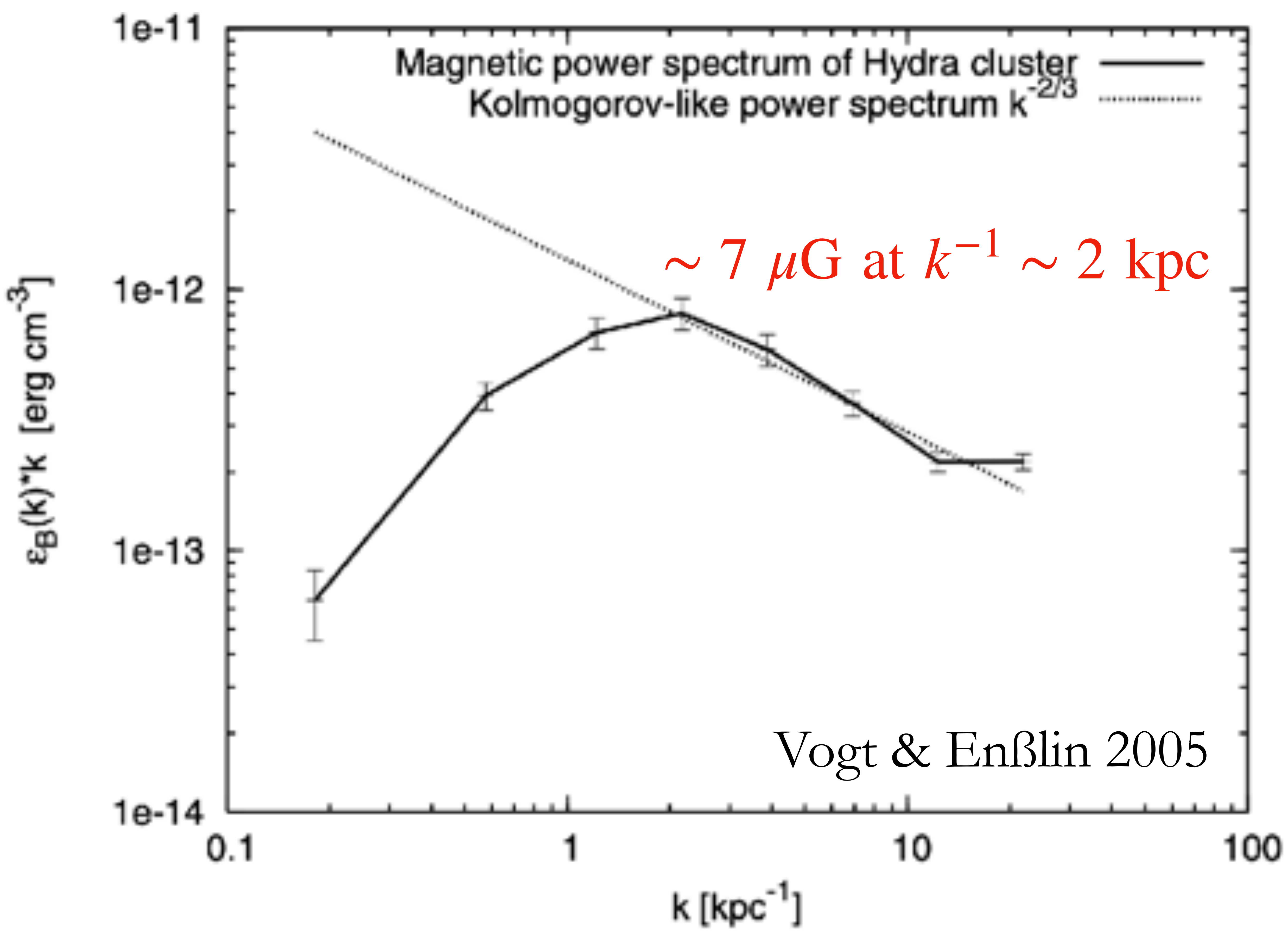


energy containing scale



energy-containing scale
of magnetic field in
saturated state is
independent of **Rm**
at large **Rm**,
within a factor of a few
of driving scale

last point is interesting because (i) not established by prior work at lower res,
question of large-scale coherence from
fluctuation ("small-scale") dynamo is an old one;
(ii) comports with observations (but need more)



$\sim 7\ \mu$G at $k^{-1} \sim 2$ kpc

Vogt & Enßlin 2005

some take-aways on **MHD fluctuation dynamo**

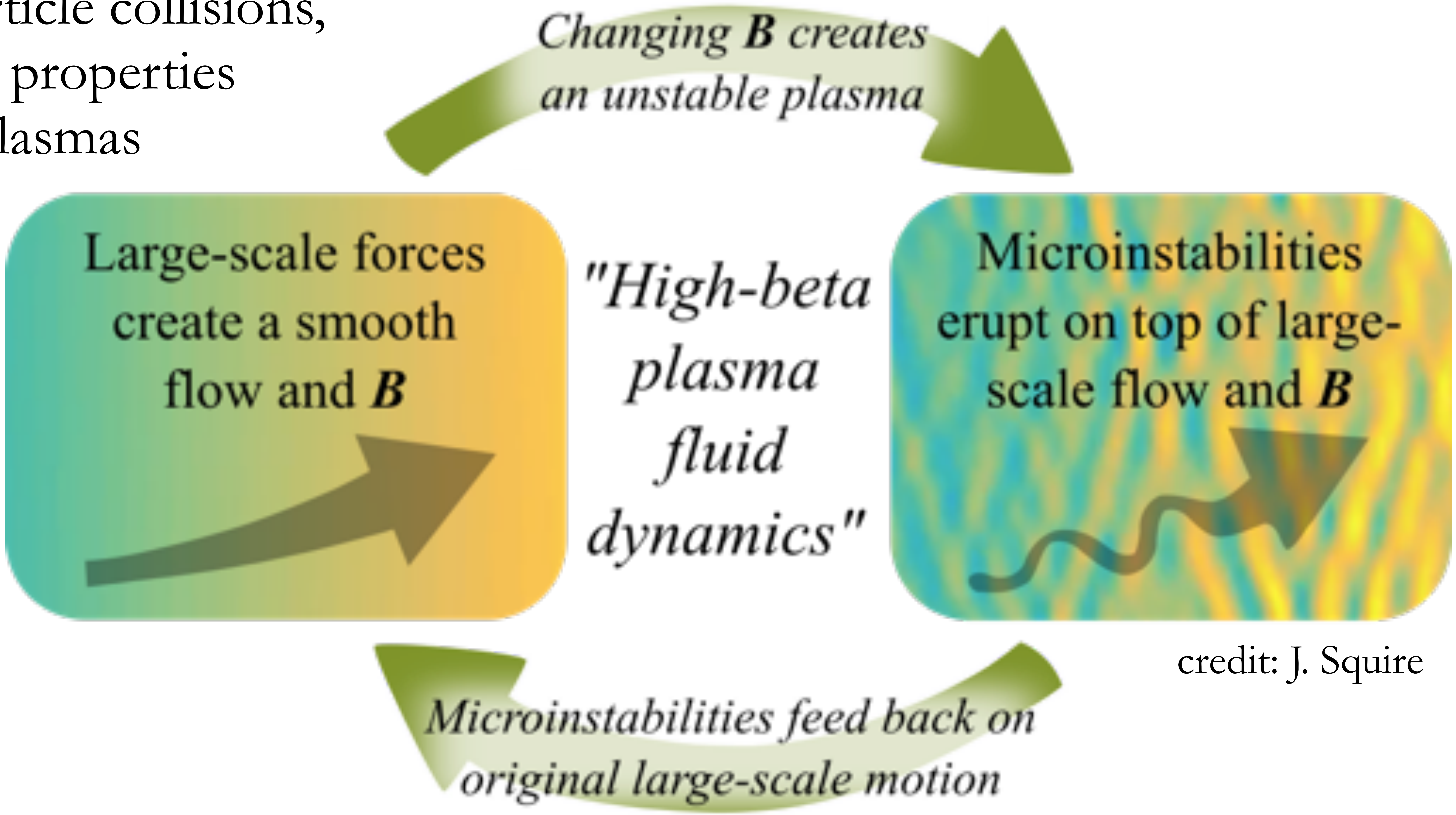
- Very large simulations of $\mathrm{Pm} \gtrsim 1$ MHD fluctuation dynamo, made possible with Frontera time (will be doing one more next weekend)
- At high resolution and not too much viscosity, magnetic folds break up via tearing instability (new) (visual evidence + quantitative agreement with our theory)
- In saturated state, magnetic energy resides at large scales, independent of Rm (new)

being written up now for submission to *Phys. Rev. X*
(Galishnikova, Kunz & Schekochihin)

beautiful set of data that will be used in further research
at Princeton and which we aim to make publicly available

new frontier of **plasma dynamo**

kinetic Larmor-scale instabilities,
rather than particle-particle collisions,
determine material properties
of high-beta plasmas



*Changing **B** creates an unstable plasma*

Large-scale forces create a smooth flow and ***B***

"High-beta plasma fluid dynamics"

Microinstabilities erupt on top of large-scale flow and ***B***

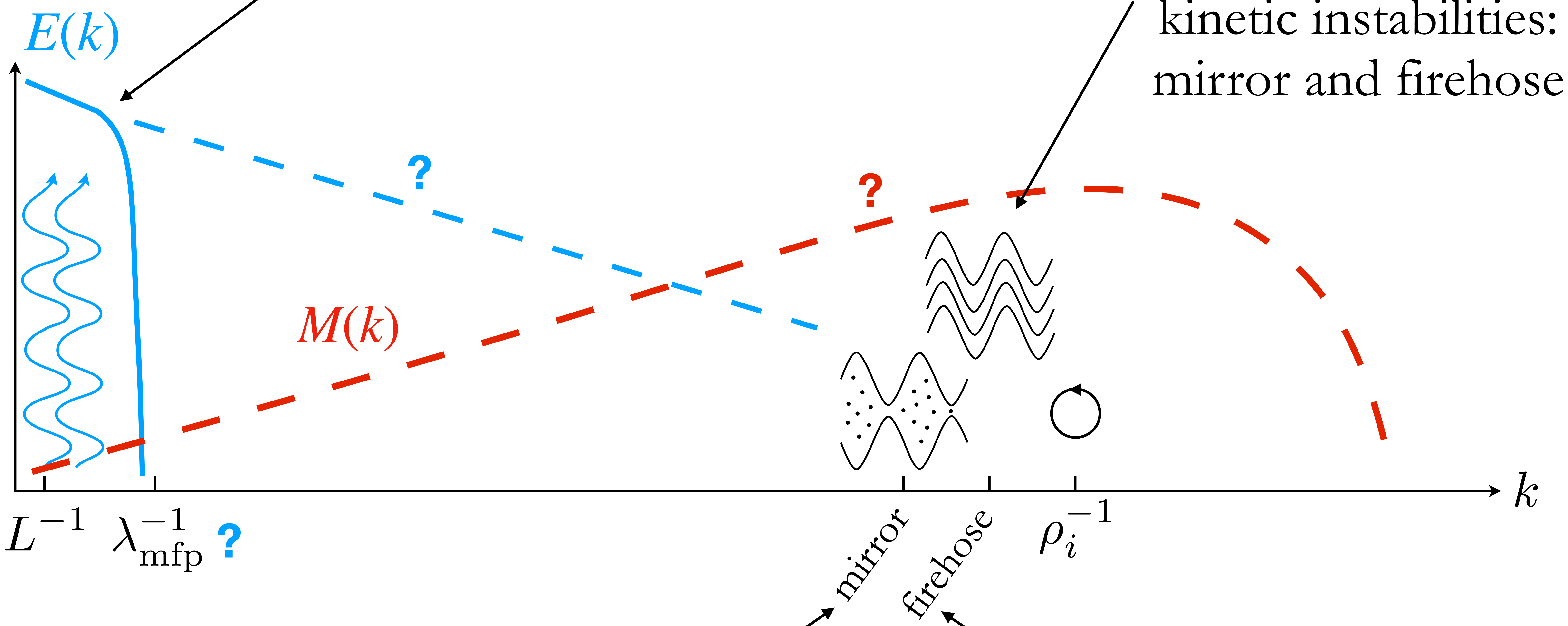
Microinstabilities feed back on original large-scale motion

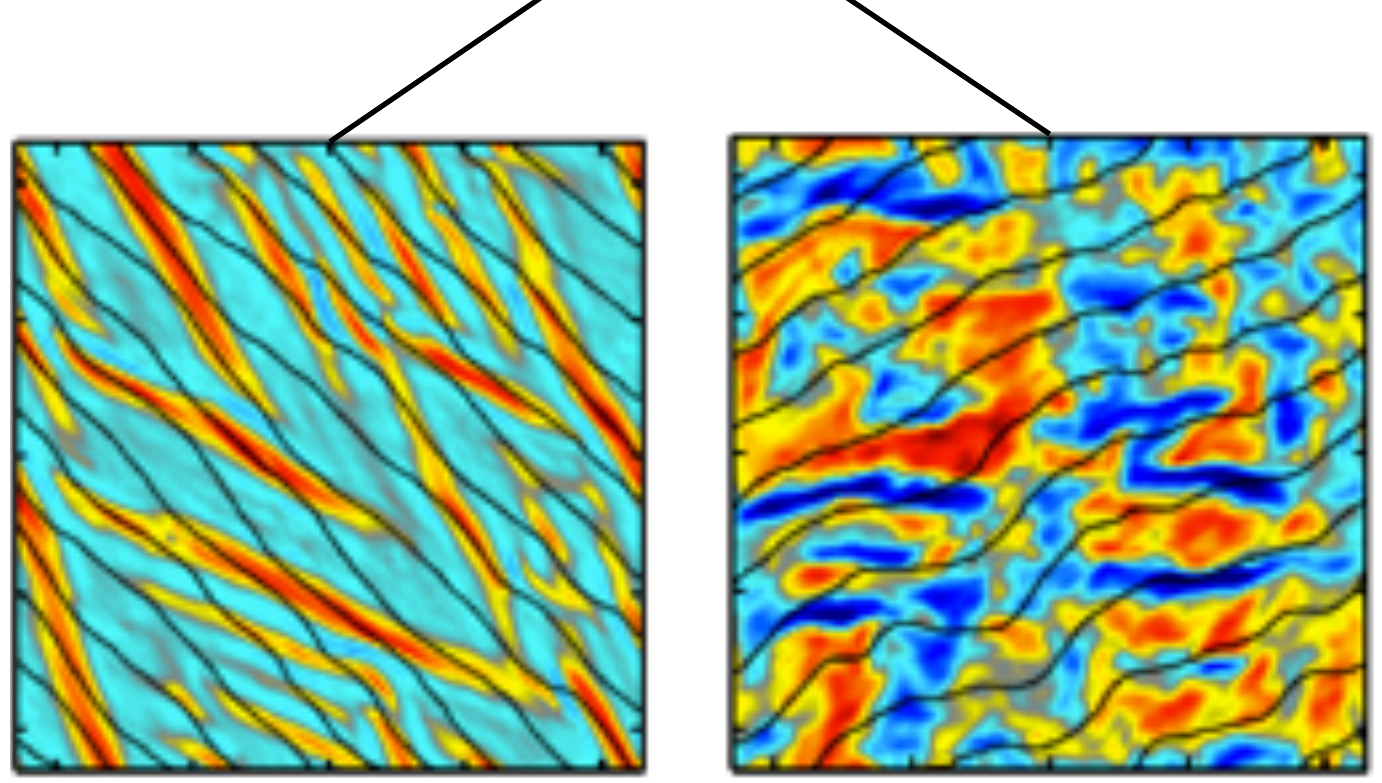
credit: J. Squire

fastest stretching motions at parallel-viscous scale

(recall $\mathrm{d}\ln B/\mathrm{d}t = \hat{\boldsymbol{b}}\hat{\boldsymbol{b}}\boldsymbol{:}\boldsymbol{\nabla}\boldsymbol{u}$)

parallel-viscous scale set by
effective scattering rate of
kinetic instabilities:
mirror and firehose

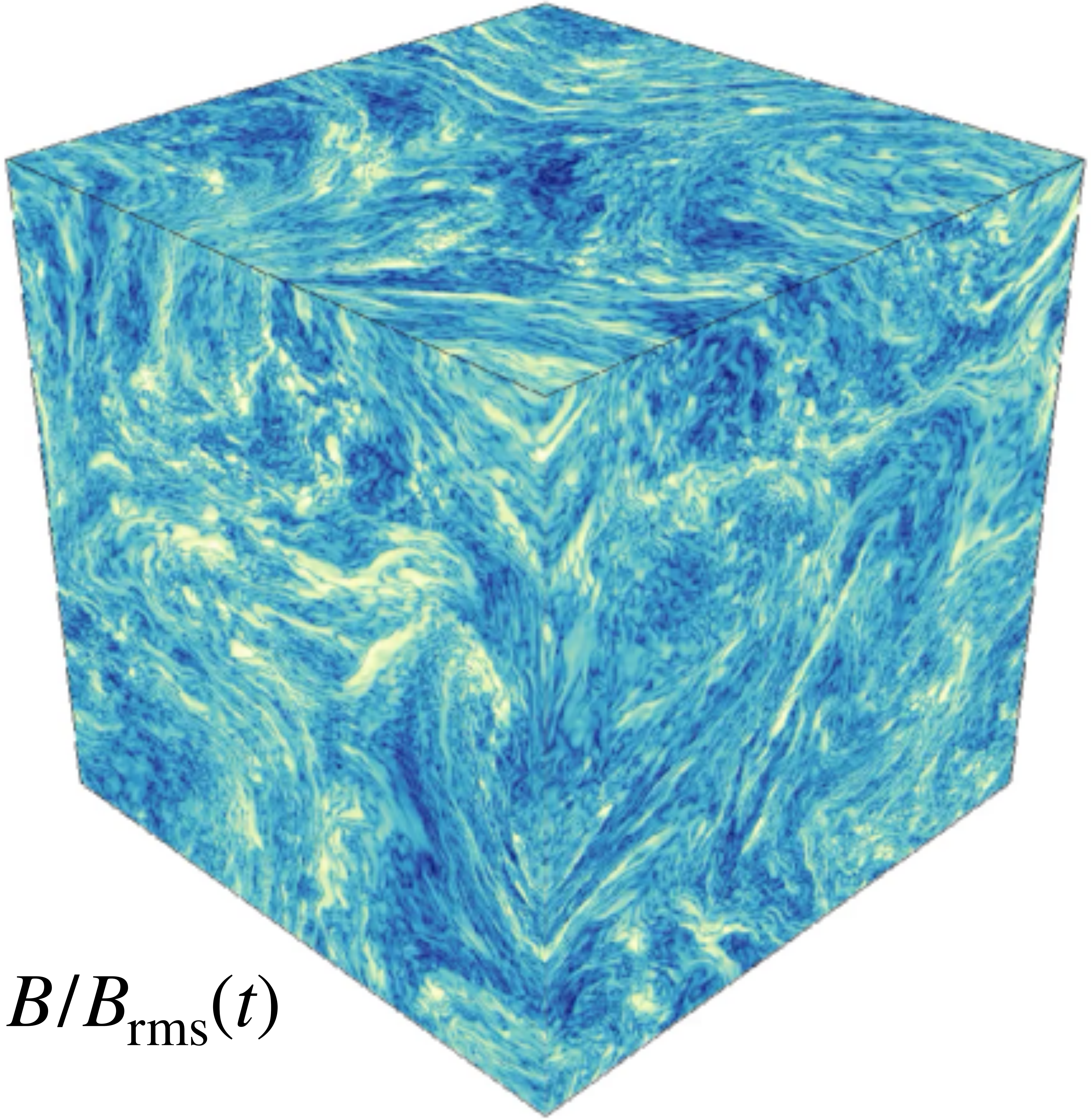



Kunz, Stone & Schekochihin 2014, PRL

these regulate departures
from local thermodynamic
equilibrium, i.e., they
set plasma viscosity

We began a program of **Pegasus** simulations of plasma dynamo

Denis St-Onge & Kunz, 2018 *ApJL*



$B/B_{\rm rms}(t)$

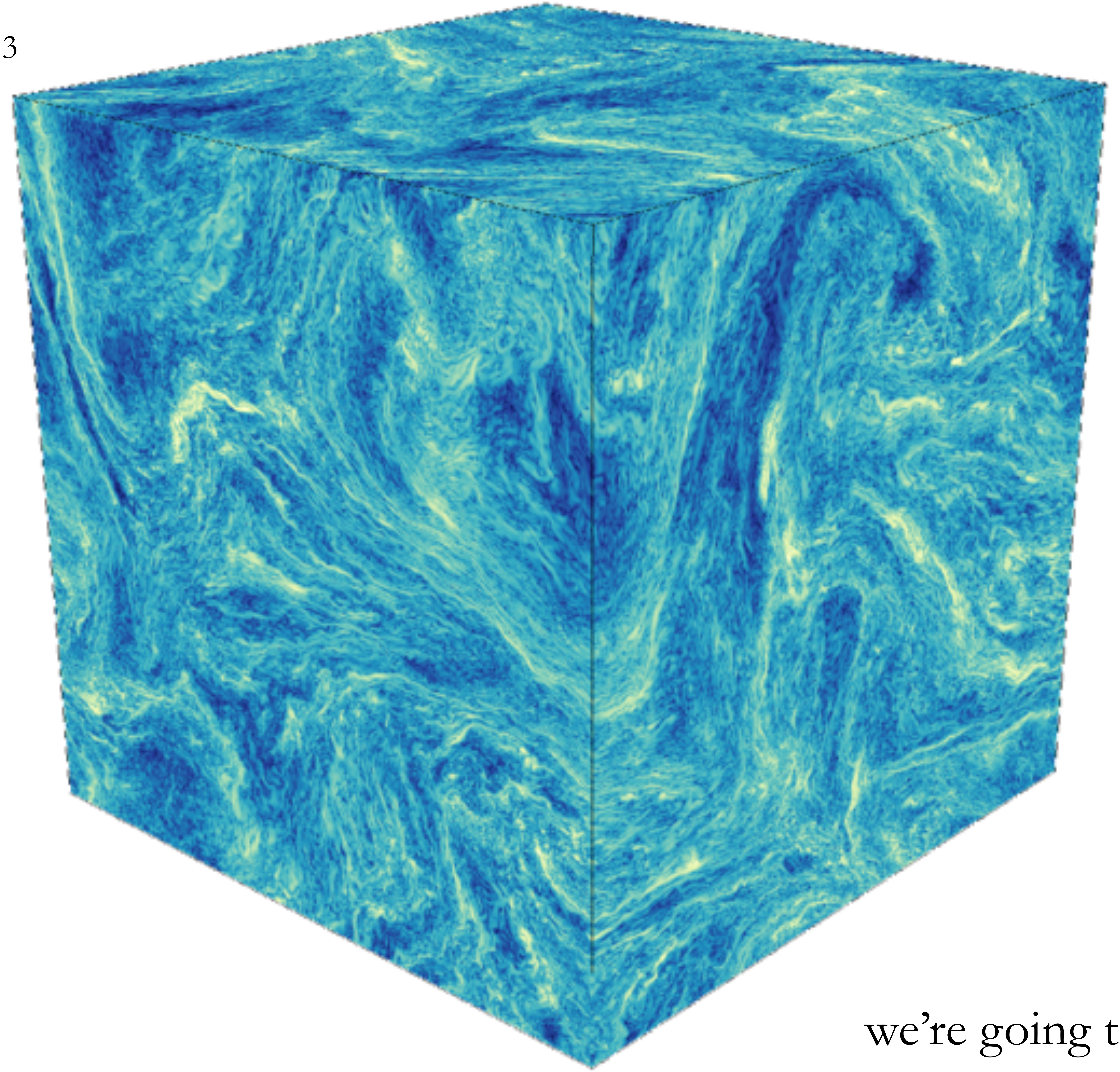
$\sim 10^{11-12}$ particles

simulations are memory intensive:
node count not dictated by want of short run time,
but rather how many particles can fit on a node.
These are necessarily wide jobs.

computational time dominated by pushing particles
and depositing their phase-space density on grid.
Vectorized push and deposit are a must. Data alignment.
Explicit SIMD via OpenMP directives. Loop fission.
Upshot: Excellent scaling (~97%) out to 1,000s of nodes

62 bytes per particle: ~ 10 – 100 TB restart dumps
Grid data is not as large, and is treated differently.
Efficient parallel I/O is crucial. Folder management.

at 1008^3



B

we're going to $\sim 2000^3$ on Frontera…

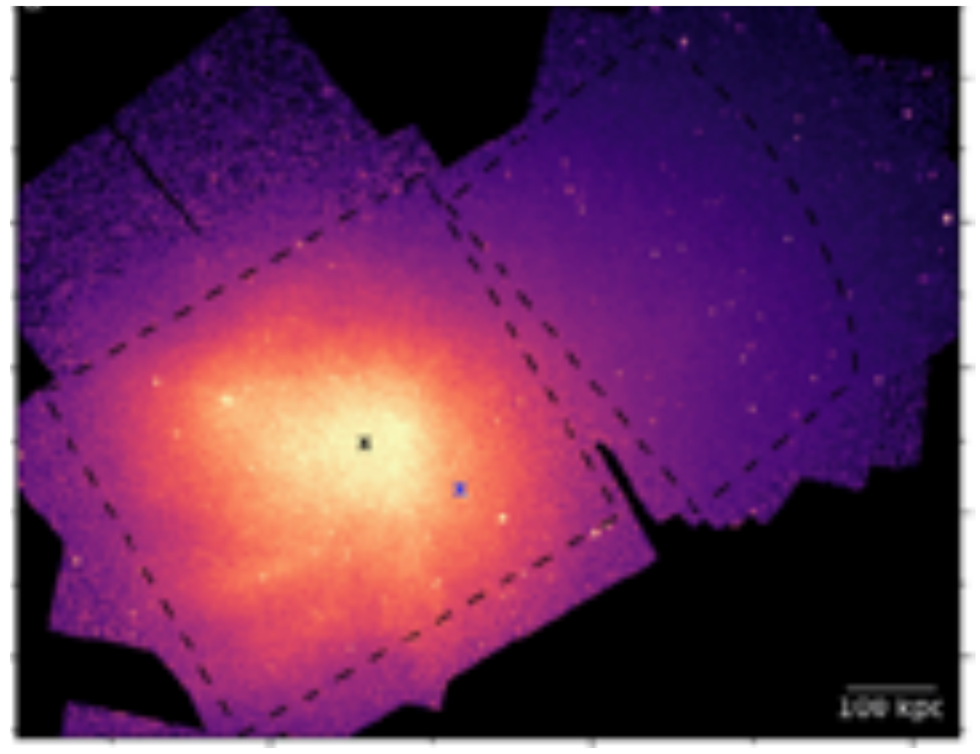
…the reason being that we predict a phase of explosive-in-time growth of B

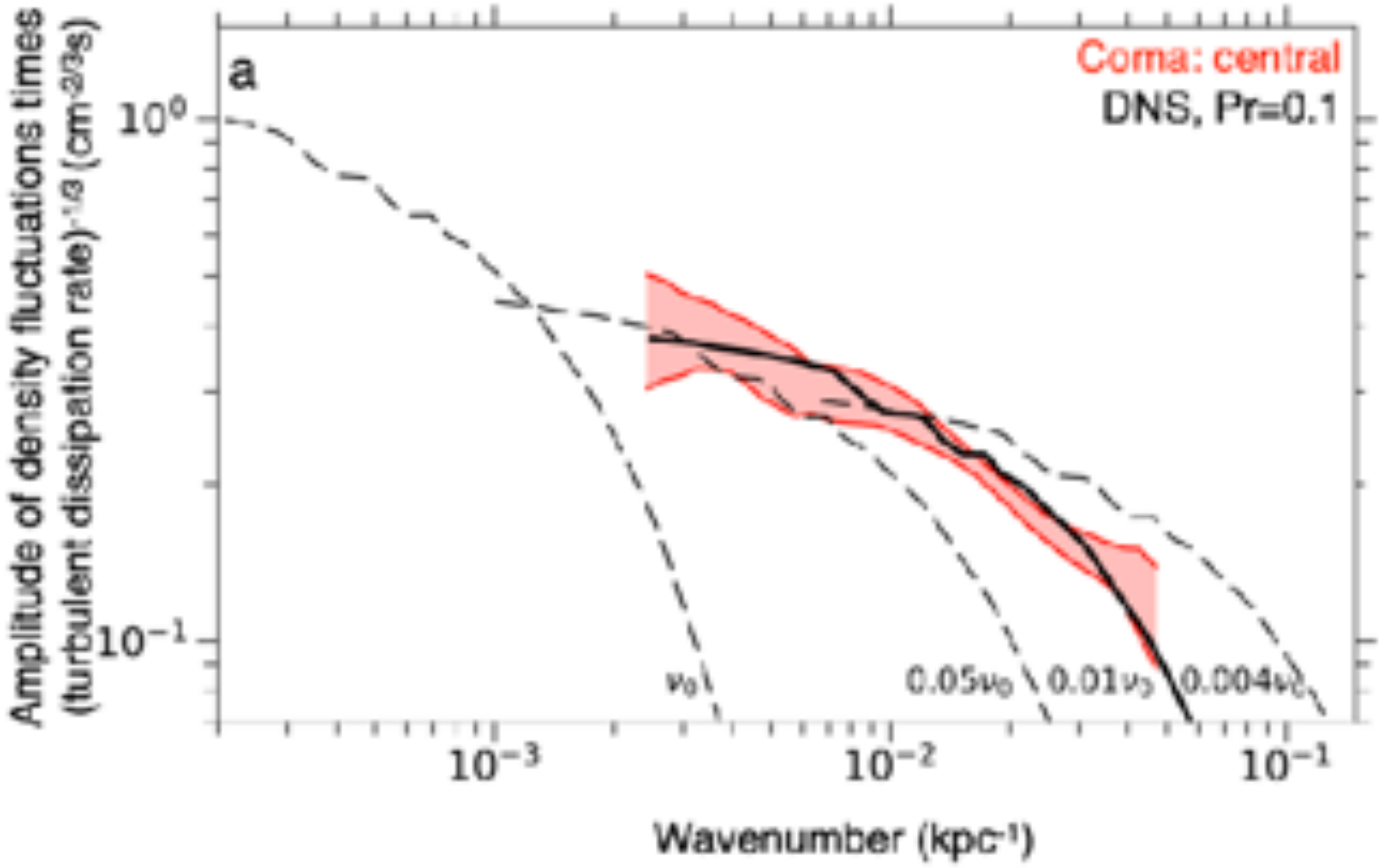
In brief, kinetic instabilities endow the plasma with a B-dependent viscosity, which implies Re $\gg$ 1 when $B \sim 1$ nG → very short turnover time → very fast dynamo

Theory worked out for this. Predicts ~nG fields in cosmologically short time. Also…

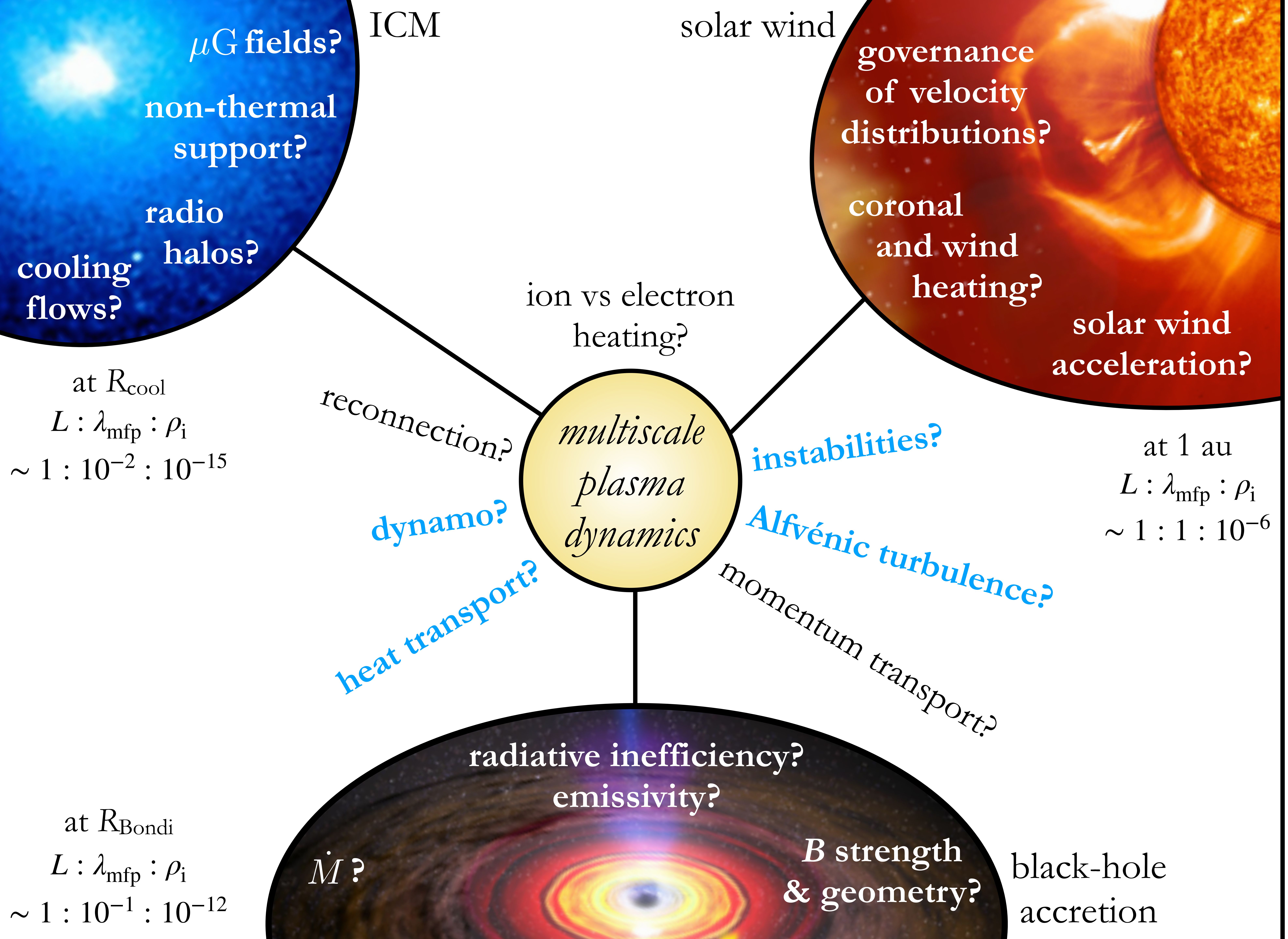
$$\mathrm{Re}_{\|,\mathrm{eff}} \sim 10^3 \left(\frac{M}{0.3}\right)^4 \left(\frac{n}{10^{-3}\ \mathrm{cm}^{-3}}\right)^2 \left(\frac{T}{10^8\ \mathrm{K}}\right)^2 \left(\frac{B}{1\ \mu\mathrm{G}}\right)^{-4}$$

such a viscosity comports with obs’d turbulence spectrum in Coma cluster





Zhuravleva *et al.* (2019, *Nature*) claims that
viscosity is ~0.01 Spitzer ;
consistent with prediction
if $B \sim 1\ \mu$G, which matches
Bonafede *et al.* (2010) estimate
based on RM maps of Coma



ICM

μG fields?

non-thermal support?

radio halos?

cooling flows?

at $R_{\rm cool}$
$L : \lambda_{\rm mfp} : \rho_{\rm i}$
$\sim 1 : 10^{-2} : 10^{-15}$

solar wind

governance of velocity distributions?

coronal and wind heating?

solar wind acceleration?

at 1 au
$L : \lambda_{\rm mfp} : \rho_{\rm i}$
$\sim 1 : 1 : 10^{-6}$

multiscale plasma dynamics

ion vs electron heating?

reconnection?

dynamo?

heat transport?

instabilities?

Alfvénic turbulence?

momentum transport?

black-hole accretion

radiative inefficiency?

emissivity?

$\dot{M}$?

B strength & geometry?

at $R_{\rm Bondi}$
$L : \lambda_{\rm mfp} : \rho_{\rm i}$
$\sim 1 : 10^{-1} : 10^{-12}$

common theme:
unknown material properties of magnetized, collisionless, high-beta plasma

effective…
…collisionality?
…viscosity?
…conductivity?
…resistivity?

cause and effect of wave-particle interactions?

how does microphysics talk to macrophysics?

supported by NSF, NASA, DOE

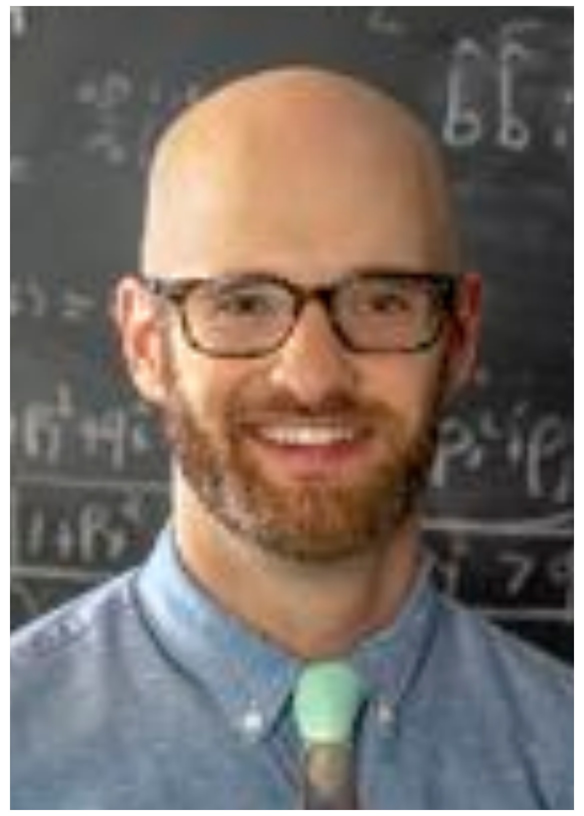
now being addressed using Frontera time

My research group, collaborators, and I are extremely grateful for time on Frontera. We wouldn't be able to do frontier research on astrophysical plasmas without it.

Thank you.


Alisa Galishnikova


Alex Schekochihin


Denis St-Onge


Lev Arzamasskiy


Archie Bott


Eliot Quataert


Evan Yerger

CAREER AST1944972

AST20010

NNX17AK63G

DE-AC02-09CH11466
DE-SC0019047