Magnetized supersonic turbulence sustained by a fluctuation dynamo

66th annual APS-DPP meeting

James Beattie

Postdoc. research associate / fellow
Princeton / CITA

In collaboration: Amitava Bhattacharjee (Princeton), Christoph Federrath (ANU), Ralf Klessen (UH) & Salvatore Cielo (LRZ)

Objectives

1. Present the energy spectra (maybe just kinetic) from the world's largest supersonic MHD turbulence simulation.

2. *(Time-permitting)* some ideas / insights into dynamical turbulent dynamo saturation.

Beattie+*(2024). Magnetized compressible turbulence with a fluctuation dynamo and Reynolds numbers over a million* arXiv:2405.16626

Beattie+(submitted, *Nature Astronomy*). The spectrum of magnetized turbulence in the interstellar medium

James Beattie. Magnetic reconnection in a turbulent fluid. Iterative LIC.

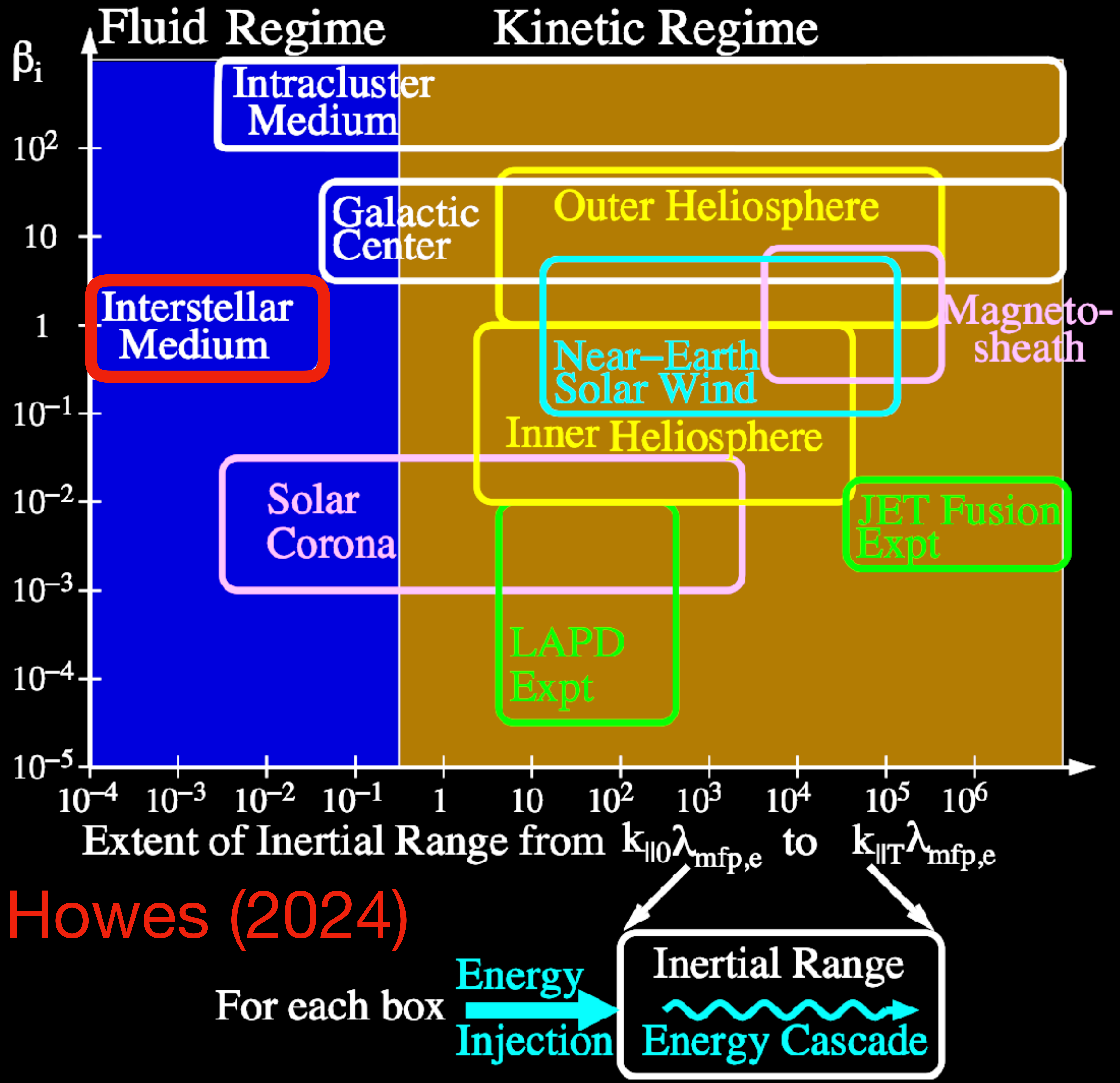
Krumholz & McKee (2005); Federrath & Klessen (2012); Tritsis+(2016); Xu & Lazarian (2016); Soler & Hennebelle (2017); Squire & Hopkins (2017); Mocz & Burkhart (2018), Burkhart & Mocz (2018); Heyer+(2012); Tritsis+(2018); Hu+(2019); Heyer+(2020); Krumholz+(2020); Beattie & Federrath (2020); Beattie+(2020); Körtgen & Soler (2020); Skalidis & Tassis (2020); Federrath+(2021); Bukhart (2021); Barreto-Mota+(2021); Hopkins+(2022); Beattie+(2022); Fielding+(2022); Sampson+ (2022); Kriel+(2022); Galishnikova+(2022); Beattie+(2023)

- ~ 20% Milkyway ISM plasma is molecular hydrogen, organised into MCs (low-volume filling ~ 1-2%).
- Cold, $T \sim 10\,K$, approximately isothermal, c_s is low.
- $\langle u \rangle^{1/2}/c_s \sim 10$, supersonic (compressible), $\mathrm{Re} \sim 10^9$, turbulent motions.
- $\ell_0 \sim 10\,\mathrm{pc} \implies t_0 = \ell_0/\left\langle u^2 \right\rangle^{1/2} \sim \mathcal{O}(\mathrm{Myr})$
- $n \sim 10^3 - 10^{7+}$, huge density contrasts.
- Threaded by dynamically important magnetic fields: $\mathcal{M}_A \sim 1 - 2$

W3/W4/W5 MCs and star forming region complex.

Krumholz & McKee (2005); Federrath & Klessen (2012); Trit
Mocz & Burkhart (2018), Burkhart & Mocz (2018); Heyer+(2
(2020); Beattie+(2020); Körtgen & Soler (2020); Ska
Hopkins+(2022); Beattie+(2022); Fielding+(202

- ~ 20% Milkyway ISM plasma i (low-volume filling ~ 1-2%).
- Cold, $T \sim 10\,K$, approximatel
- $\langle u \rangle^{1/2}/c_s \sim 10$, supersonic (c
- $\ell_0 \sim 10\,\mathrm{pc} \implies t_0 = \ell_0/\langle u$
- $n \sim 10^3 - 10^{7+}$, huge density
- Threaded by dynamically impo



Howes (2024)

W3/W4/W5 MCs and star forming region complex.
ESA/Herschel/NASA/JPL-Caltech CC BY-SA 3.0 IGO

$10{,}080^3$ magnetized supersonic turbulence simulation

Beattie, Federrath, Klessen, Cielo & Bhattacharjee

1. **What is the scaling of the energy cascade in compressible MHD turbulence with no net b flux?**
2. **How are the characteristic scales organised in the compressible interstellar medium turbulence?**
3. **What are the saturation physics of the turbulent dynamo?**

PI of a 100million core-hour project on superMUC-NG

ILES of compressible MHD turbulence

Turbulence: $\sigma_V / c_s \approx 4,\ \ell_0 = L/2$

Magnetic fields: $B = b_{\mathrm{turb}},\ \mathcal{M}_{\mathrm{A}} \approx 2$

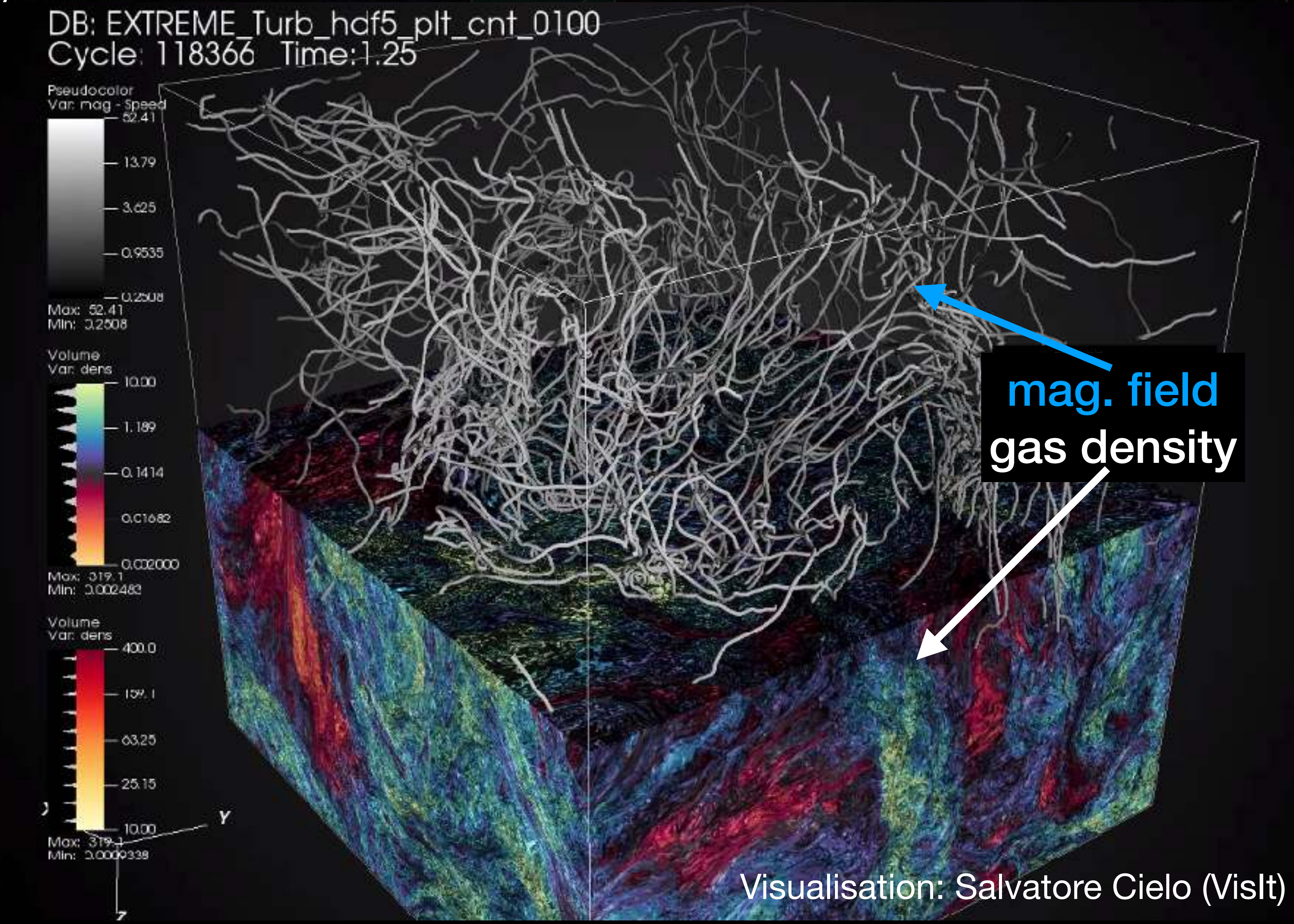
Three experiments for convergence tests:

- **LOW-RES:** $2{,}520^3$ **(0.3Mcore-h, 8,640cores)**
- **MID-RES:** $5{,}040^3$ **(4.0Mcore-h, 34,560cores)**
- **HIGH-RES:** $10{,}080^3$ **(80.0Mcore-h, 148,240cores)**
    - **Resolving 10pc down to ~200au everywhere on the grid**
    - **Factor of 4 higher linear grid resolution than IllustrisTNG**

$3.45\mathrm{PB}$ **in data products**

Broad Code details:

- Highly-modified version of finite volume code *FLASH*, second-order in space approximate Riemann (PPM) solver with framework outlined in Bouchut+2010, tested in *FLASH* in Waagen+2011.
- Ideal (ILES) compressible non-helical, isothermal MHD turbulence with finite correlation time (OU process; Federrath2022).



Visualisation: Salvatore Cielo (VisIt)

Worried about magnetic ICs? Turbulent dynamo takes care of initial magnetic field conditions!

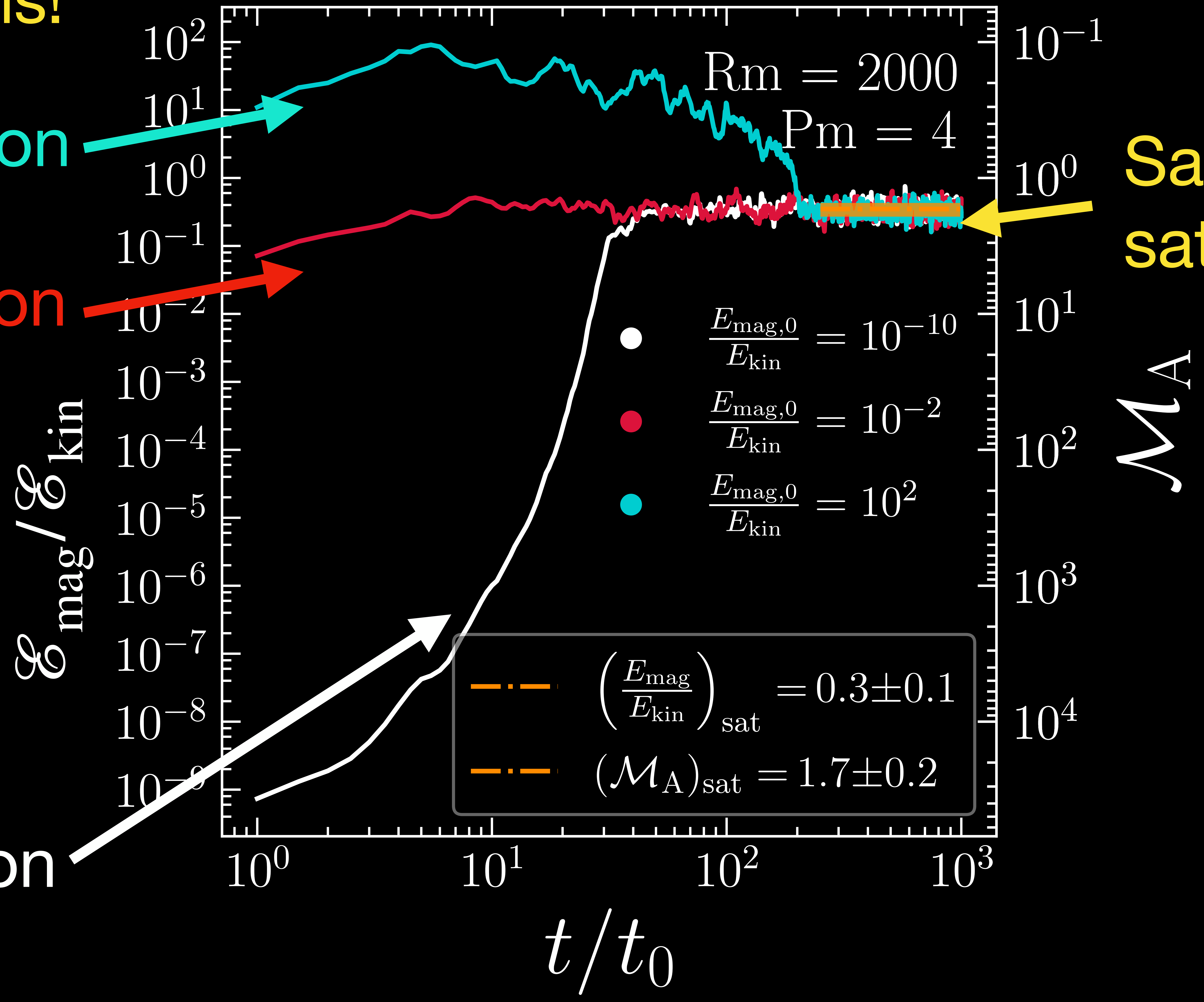
Decay into the saturation

Initialise in the saturation

Grow into the saturation

Same saturation

$$\mathscr{M}_A = \sqrt{\frac{E_{\mathrm{kin}}}{E_{\mathrm{mag}}}}$$

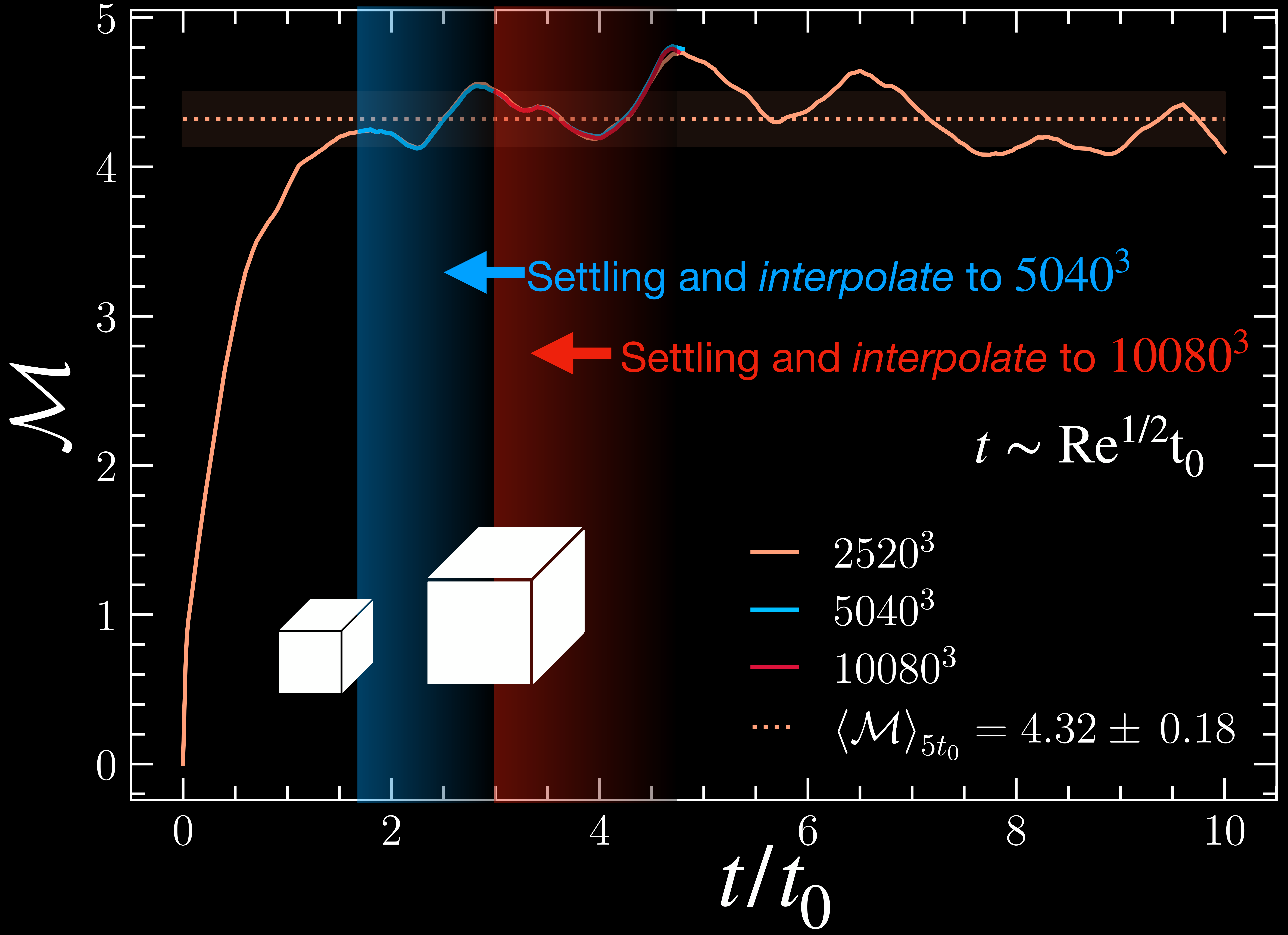


Beattie et al. (2023, MNRAS). *Growth or Decay — I: Universality of the turbulent dynamo saturation*

Volume integral Quantities

$$\mathscr{M} = \left\langle \frac{u^2}{c_s} \right\rangle_{\mathscr{V}}^{1/2}$$

Interpolation to generate ICs for successively higher resolution experiments

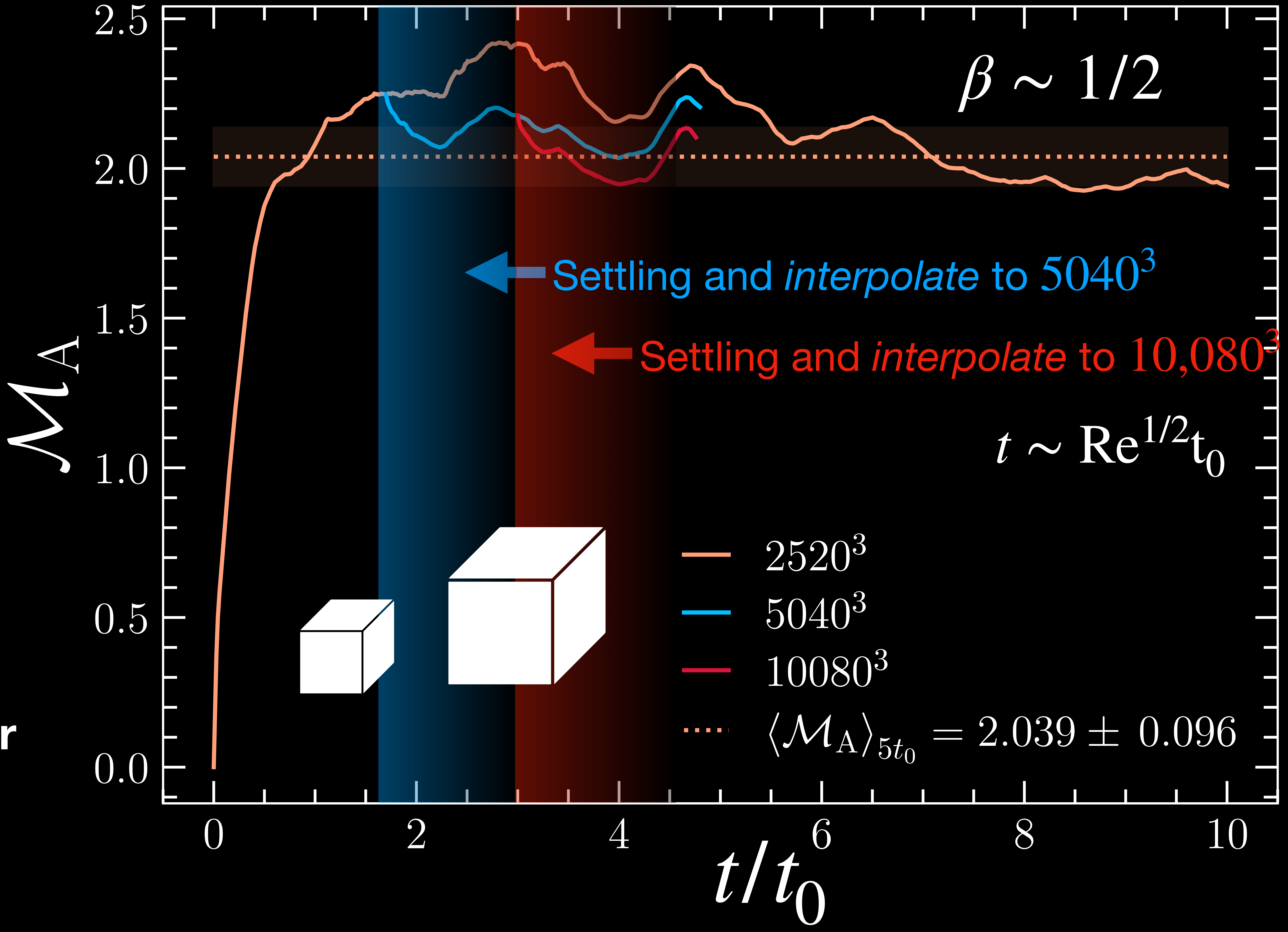


Beattie+(submitted, *Nature Astronomy*). The spectrum of magnetized turbulence in the interstellar medium

Volume integral Quantities

$$\mathscr{M}_A = \sqrt{\frac{E_{\rm kin}}{E_{\rm mag}}}$$

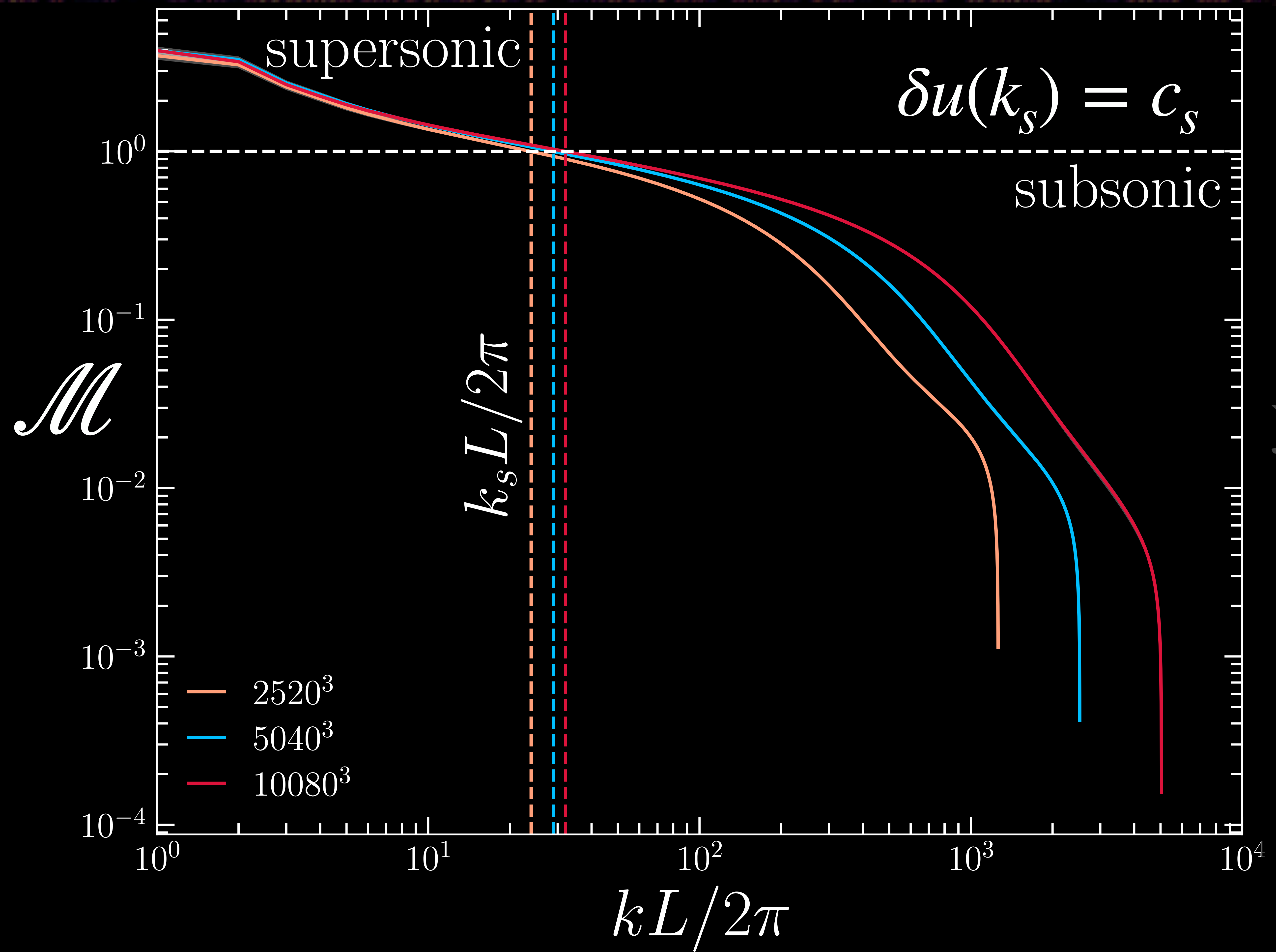
Interpolation to generate ICs for successively higher resolution experiments



Beattie+(submitted, *Nature Astronomy*). The spectrum of magnetized turbulence in the interstellar medium

Beattie+(submitted, *Nature Astronomy*). The spectrum of magnetized turbulence in the interstellar medium

Energy spectrum: two important scales



Turbulent motions are supersonic

$$\delta u(k) > c_s$$

Transition scale

$$\delta u(k_s) = c_s$$

Turbulent motions are subsonic

$$\delta u(k_s) < c_s$$

Sonic scale

Magnetic reconnection in a turbulent plasma (visualisation by J. Beattie).

Energy spectrum: two important scales

Kinetic energy dominates, $\mathscr{E}_{\text{mag}} < \mathscr{E}_{\text{kin}}$

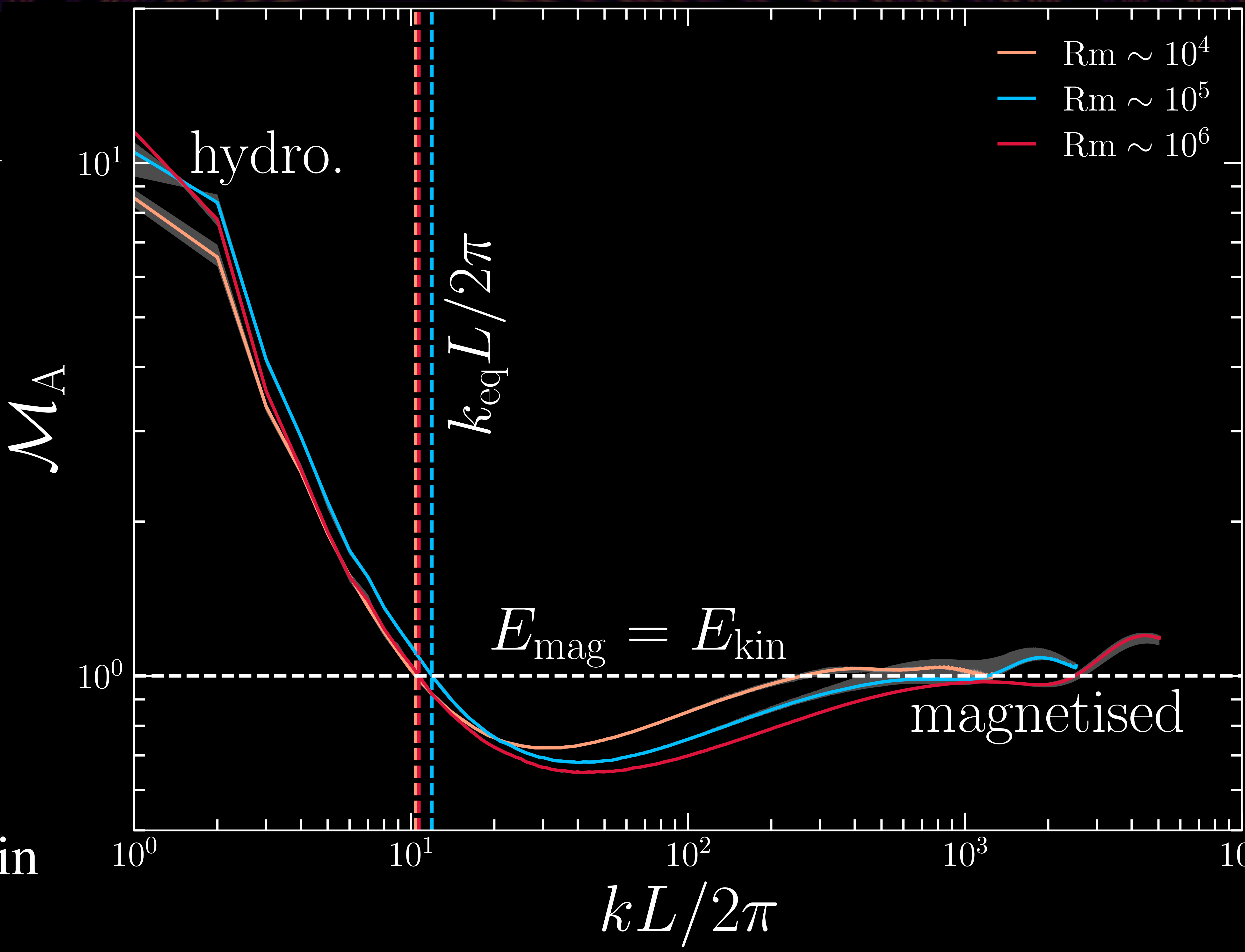
$$\mathscr{M}_A > 1$$

Transition into magnetically dominated turbulence $\mathscr{E}_{\text{mag}} = \mathscr{E}_{\text{kin}}$

$$\mathscr{M}_A = 1$$

Magnetic energy dominates, $\mathscr{E}_{\text{mag}} > \mathscr{E}_{\text{kin}}$

$$\mathscr{M}_A < 1$$



Alfvénic scale

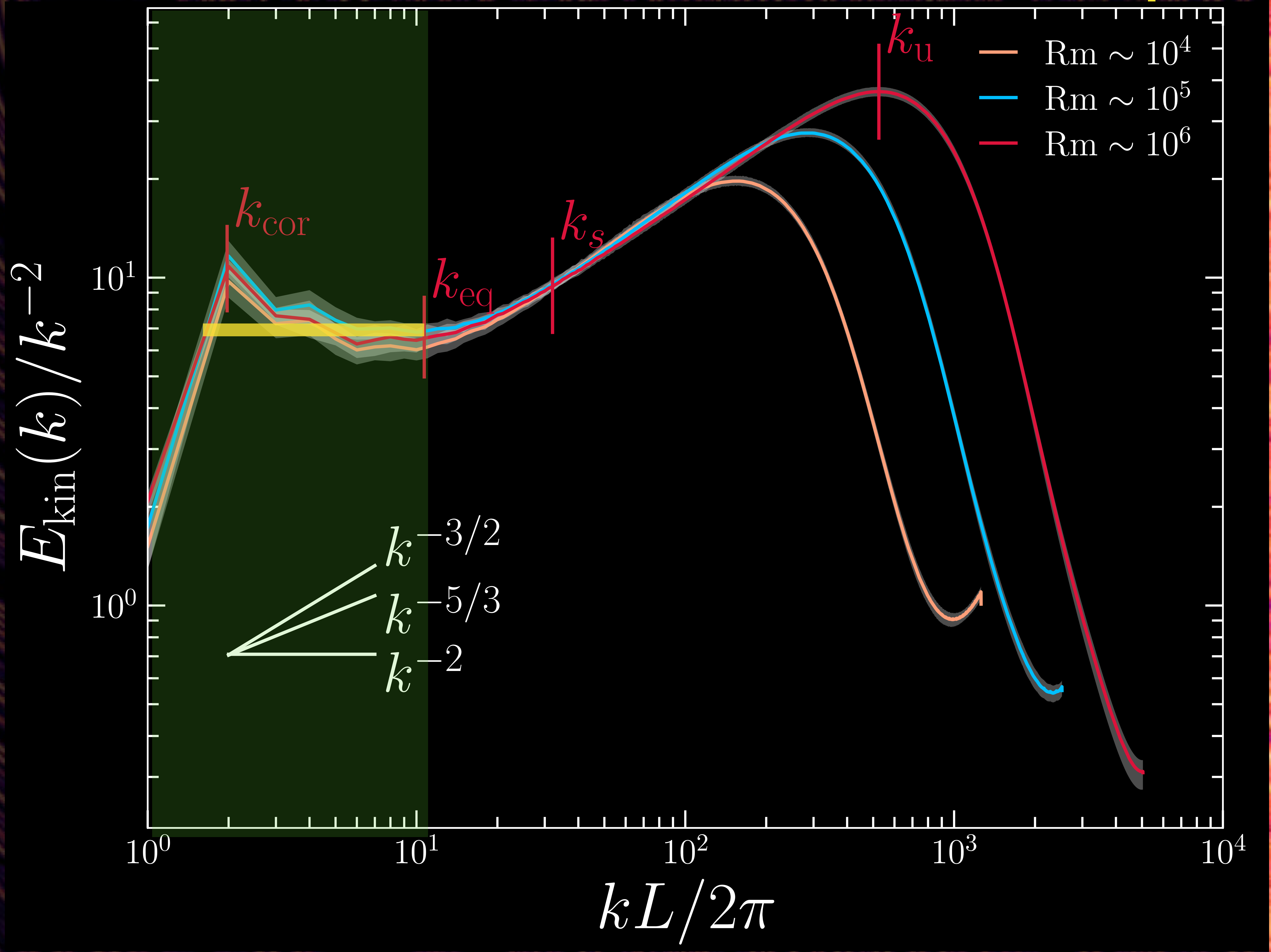
Magnetic reconnection in a turbulent plasma (visualisation by J. Beattie).

The velocity spectrum

Magnetic reconnection in a turbulent plasma (visualisation by J. Beattie).

The supersonic spectrum

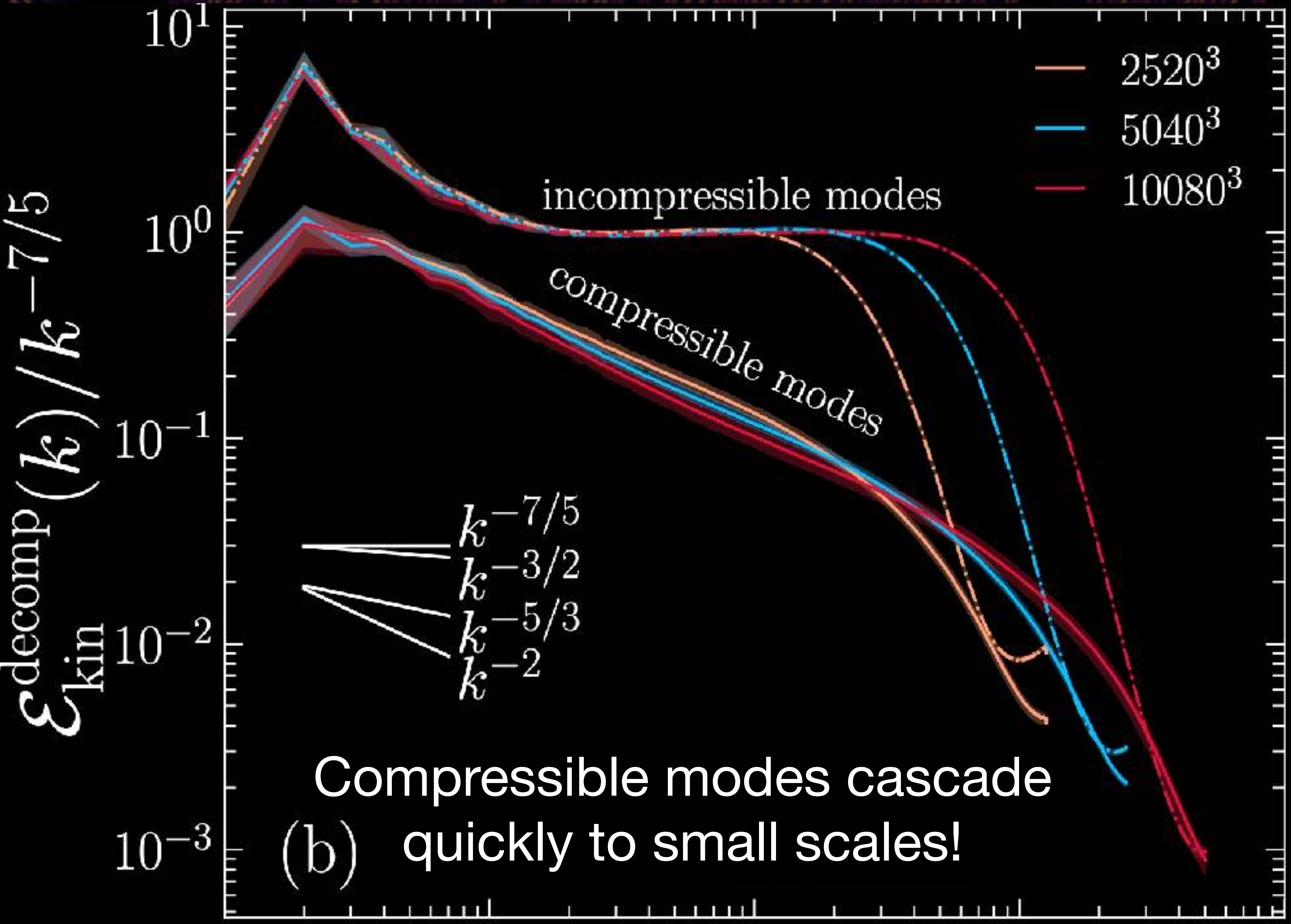
$$\mathcal{E}(k) \sim k^{-2},\ k \leq k_{\mathrm{eq}}$$



Magnetic reconnection in a turbulent plasma (visualisation by J. Beattie).

The supersonic spectrum

$$\mathcal{E}(k) \sim k^{-2},\ k \leq k_{\mathrm{eq}}$$



Magnetic reconnection in a turbulent plasma (visualisation by J. Beattie).

The subsonic spectrum (also ~ incompressible)

$$\mathcal{E}(k) \sim k^{-3/2},\ k > k_{\mathrm{eq}}$$

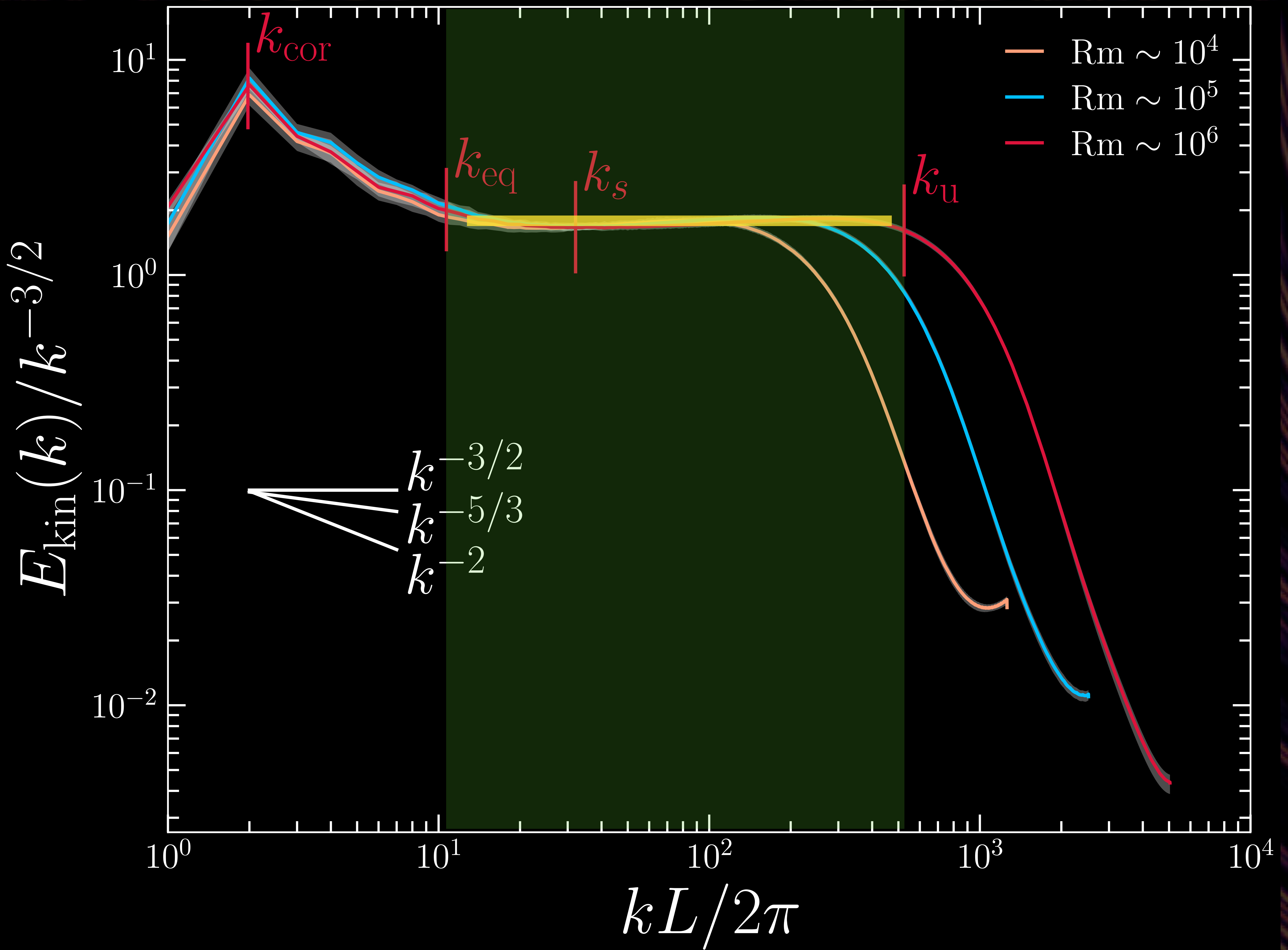
IK-type turbulence (Kolmogorov + b flux)?

Dynamical alignment?

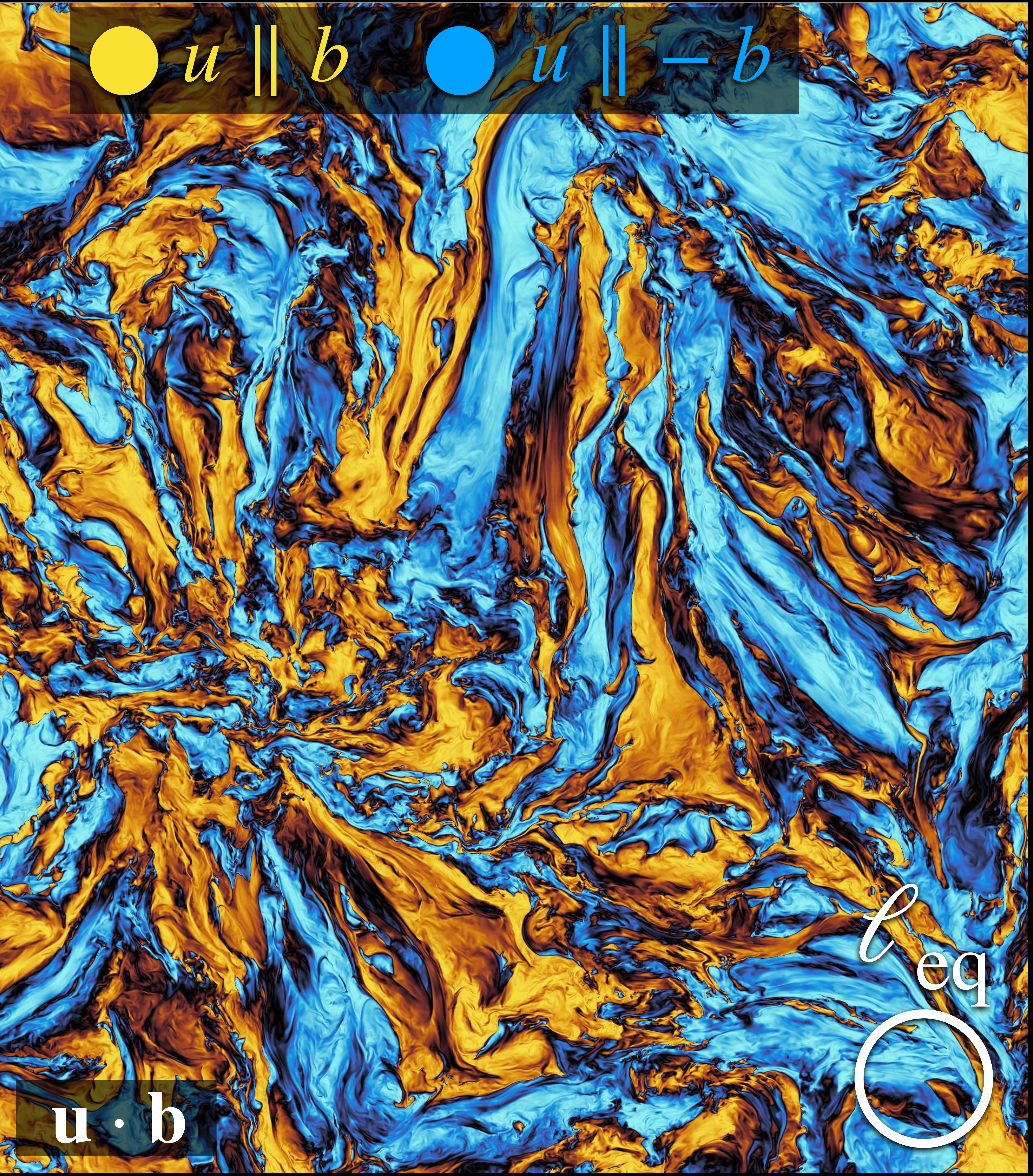
?

In general, we need:

A mechanism for depleting nonlinearities in the turbulence

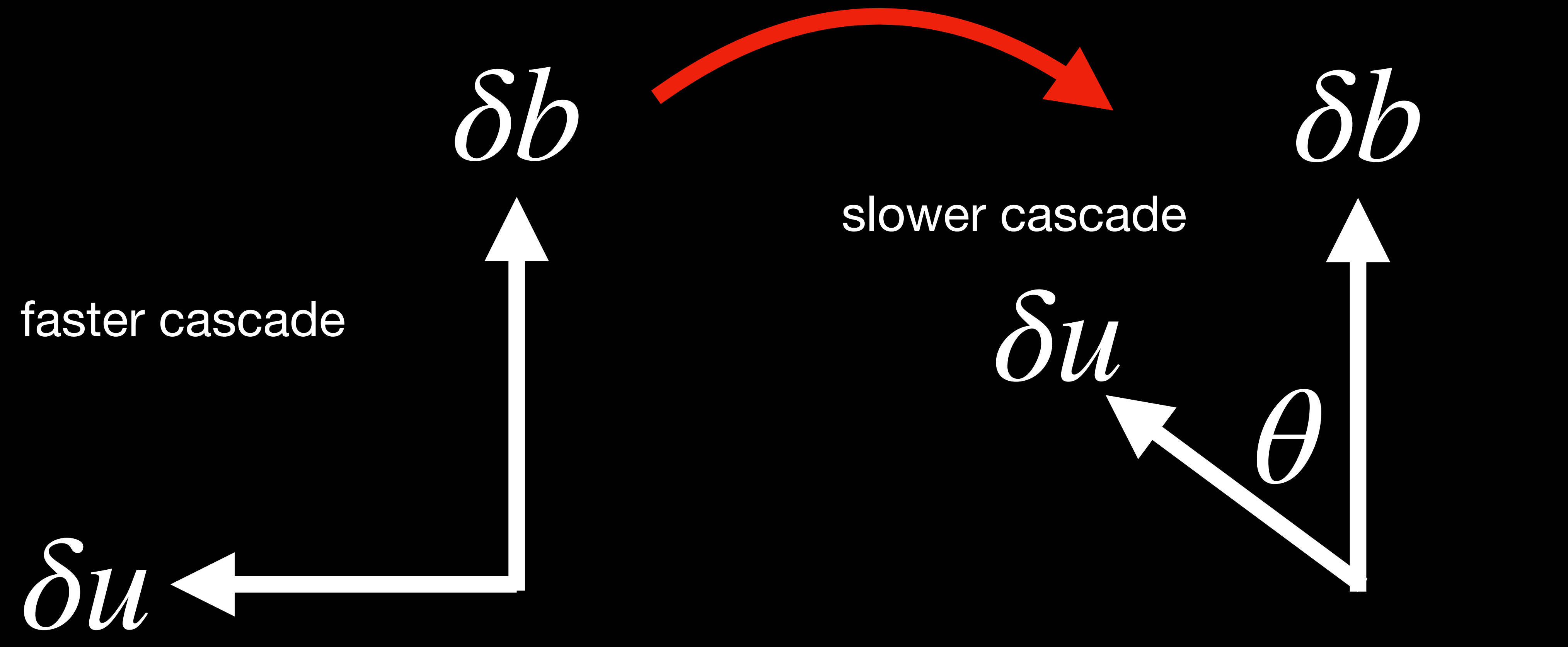


Magnetic reconnection in a turbulent plasma (visualisation by J. Beattie).



Dynamic alignment?

Shearing events between counter-propagating Alfvén waves



$E_{\mathrm{kin}}(k_\perp) \propto k_\perp^{-5/3}$

Goldreich & Shridar (1995)

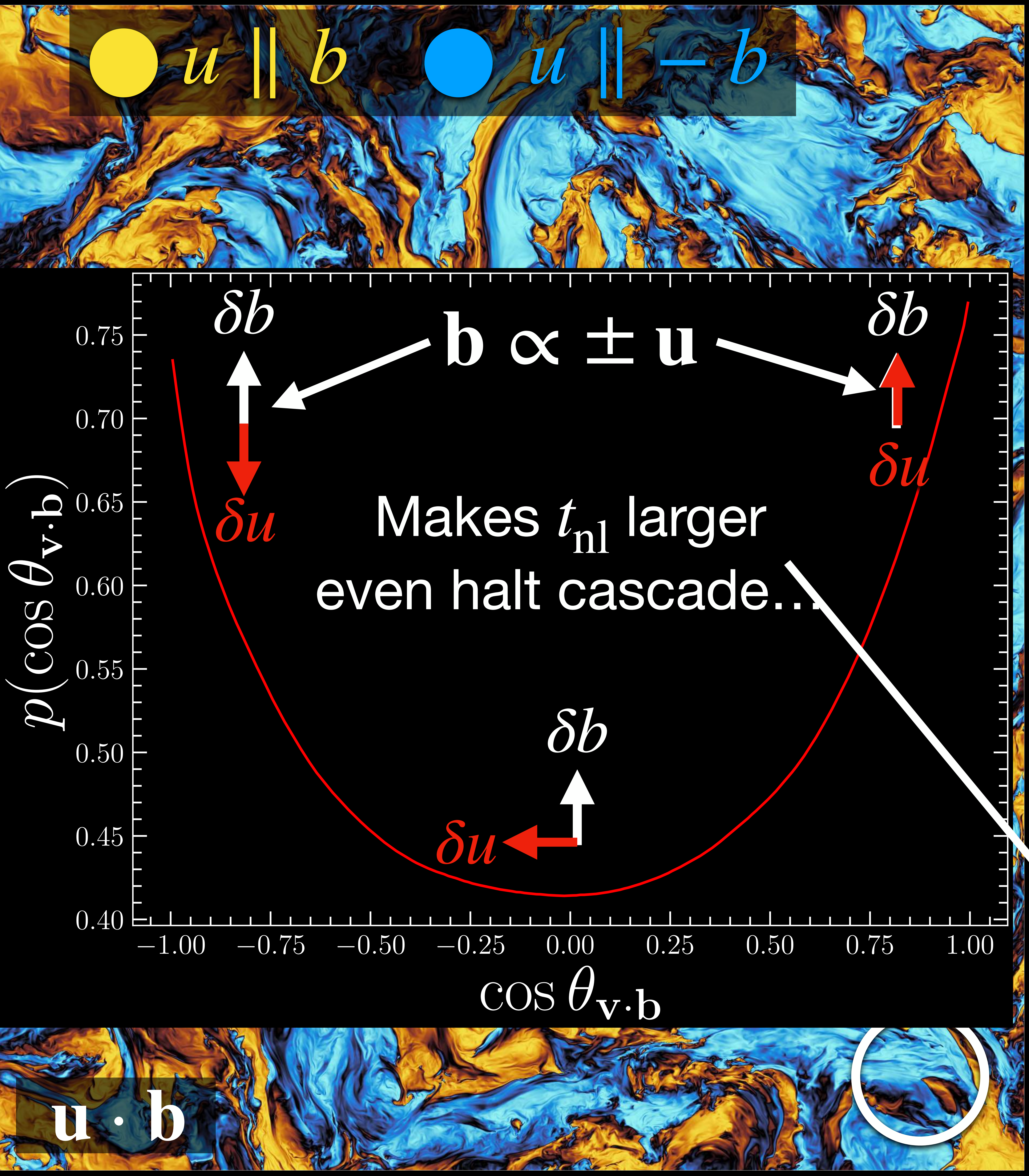
$E_{\mathrm{kin}}(k_\perp) \propto k_\perp^{-3/2}$

Boldyrev (2006)

Modifies the cascade timescale

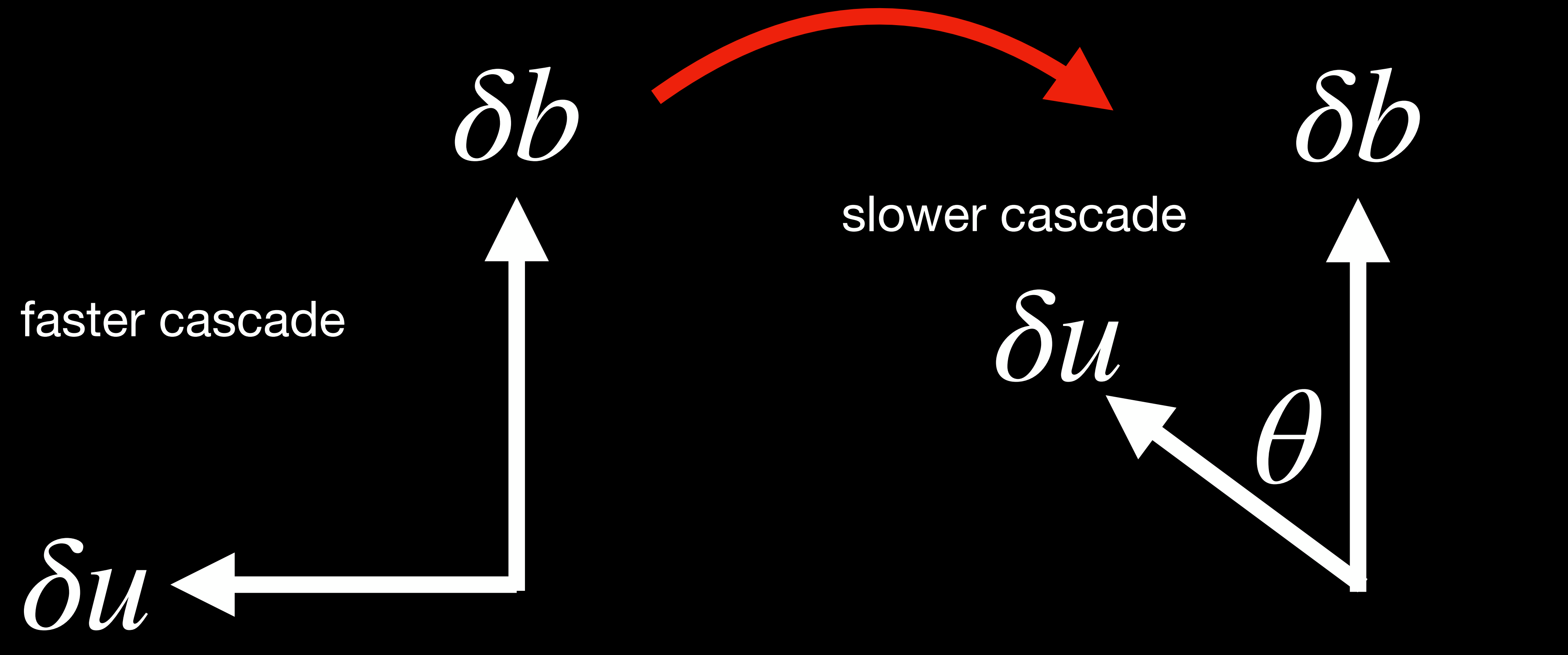
$$t_{\mathrm{nl}} \sim \frac{\ell_\perp}{z^{\mp} \sin \theta_{z^{\mp}}}, \quad z^{\mp} = (u \mp b)$$

Boldyrev (2006)



Dynamic alignment?

Shearing events between counter-propagating Alfvén waves



$E_{\rm kin}(k_\perp) \propto k_\perp^{-5/3}$

Goldreich & Shridar (1995)

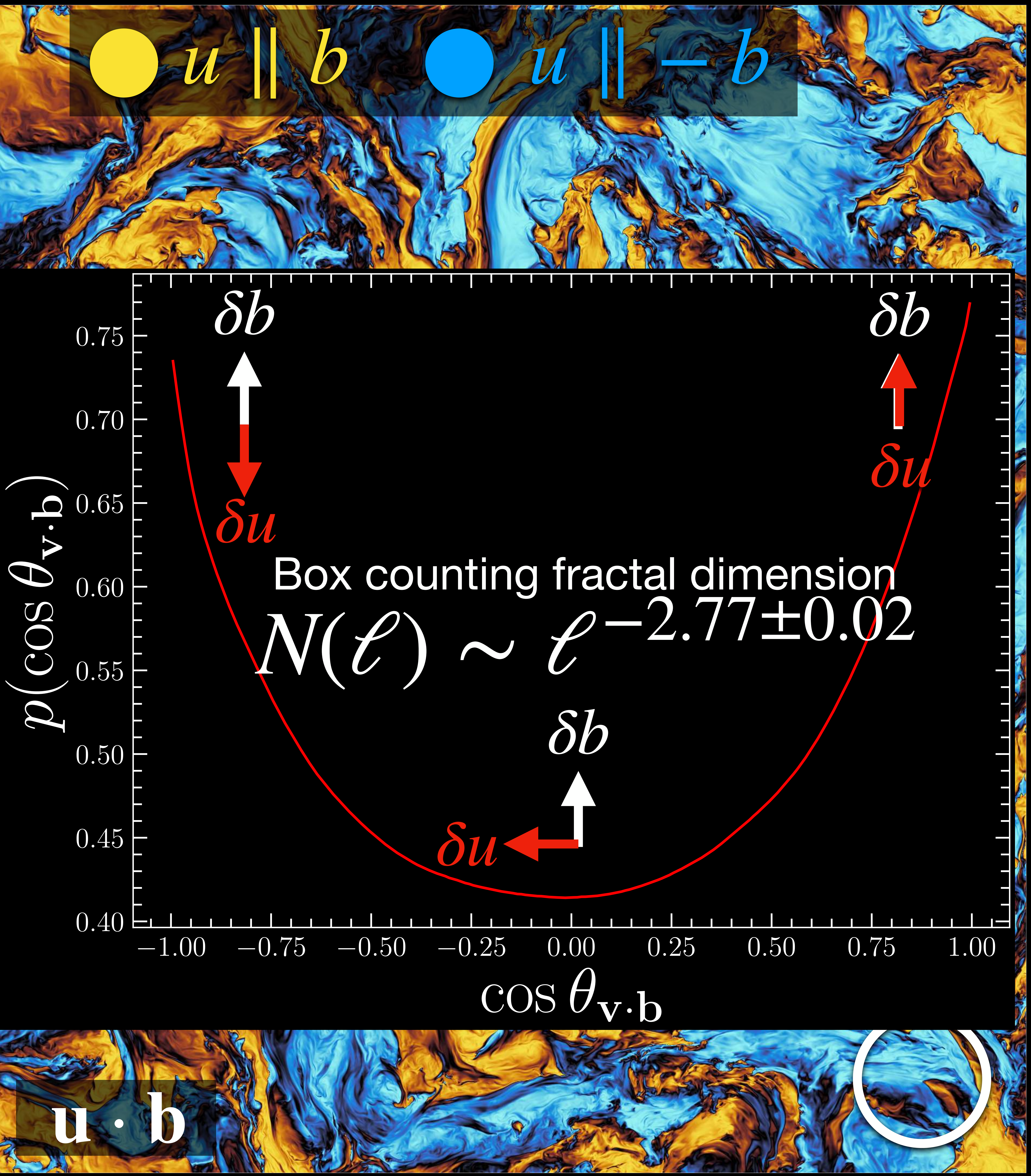
$E_{\rm kin}(k_\perp) \propto k_\perp^{-3/2}$

Boldyrev (2006)

Modifies the cascade timescale

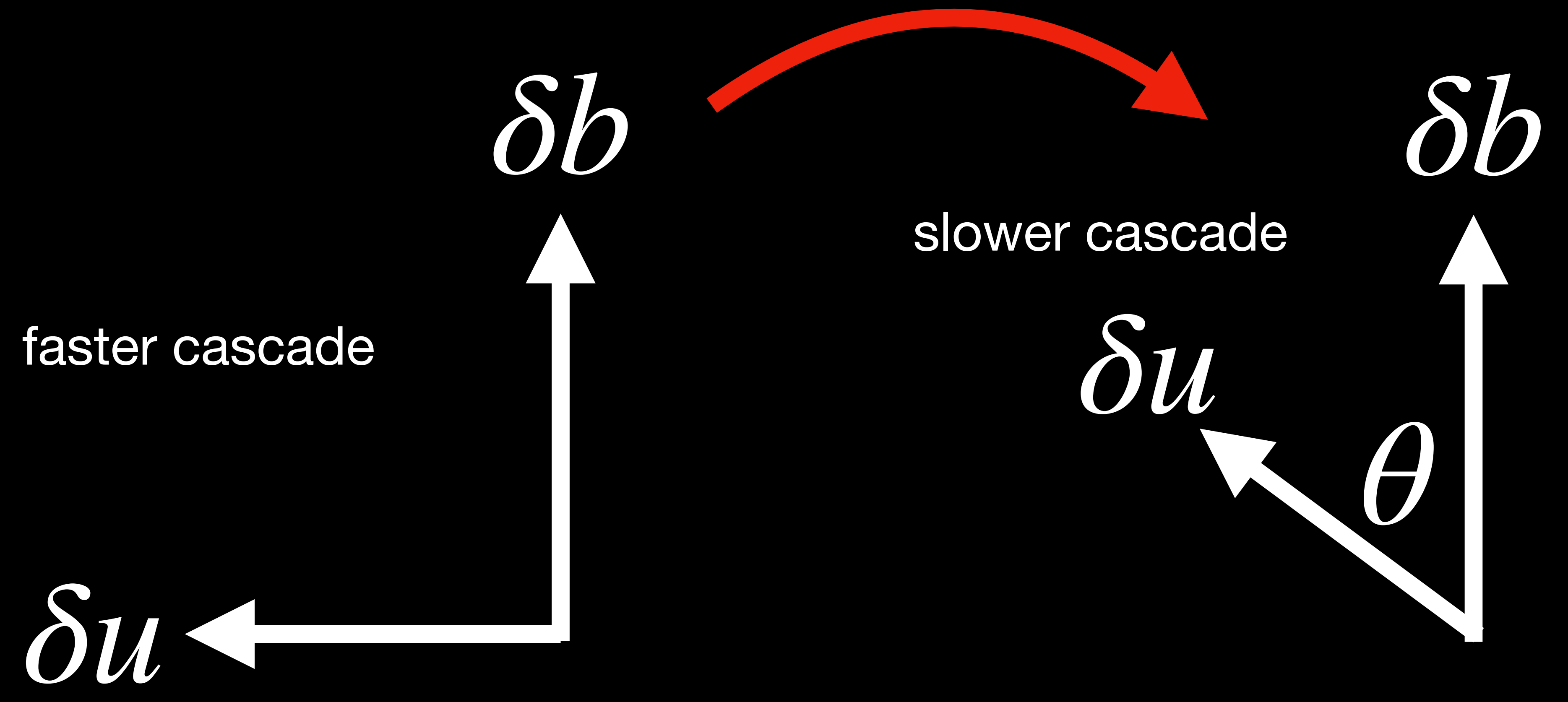
$$t_{\rm nl} \sim \frac{\ell_\perp}{z^{\mp} \sin\theta_{z^{\mp}}}, \quad z^{\mp} = (u \mp b)$$

Boldyrev (2006)



Dynamic alignment?

Shearing events between counter-propagating Alfvén waves



$E_{\text{kin}}(k_\perp) \propto k_\perp^{-5/3}$

Goldreich & Shridar (1995)

$E_{\text{kin}}(k_\perp) \propto k_\perp^{-3/2}$

Boldyrev (2006)

Modifies the cascade timescale

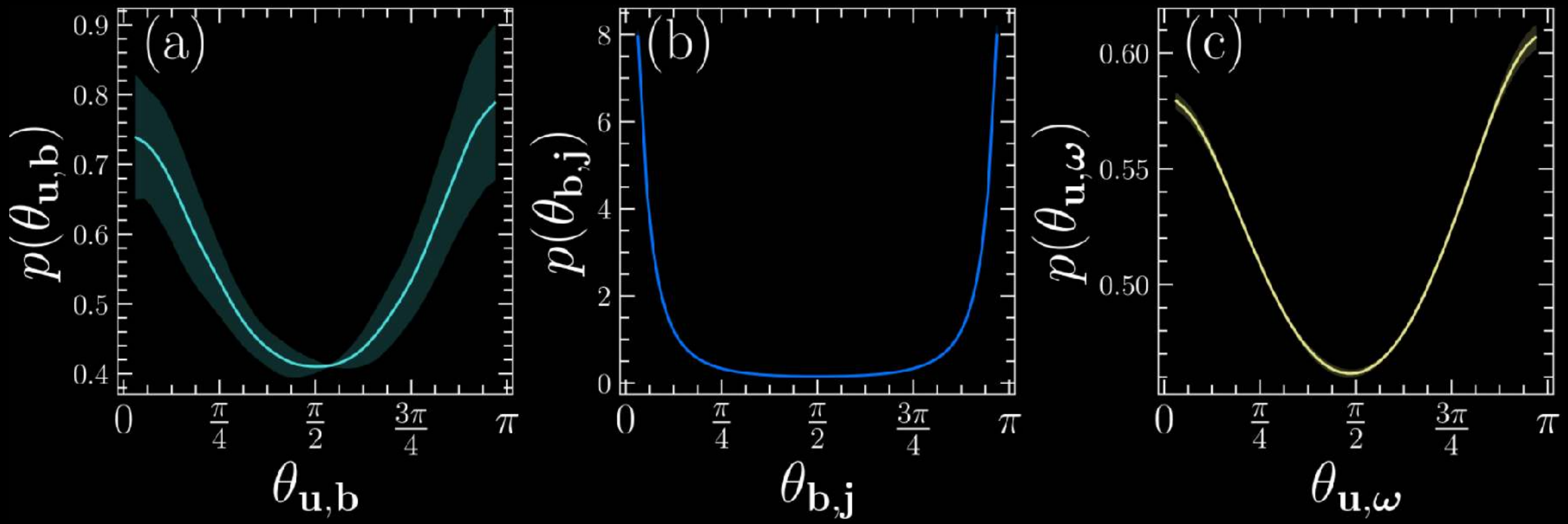
$$t_{\text{nl}} \sim \frac{\ell_\perp}{z^\mp \sin\theta_{z^\mp}}, \quad z^\mp = (u \mp b)$$

Boldyrev (2006)

But even more alignment than just u and b

Searching to weaken the nonlinearities

$$\boldsymbol{\omega} = \nabla \times \mathbf{u}$$

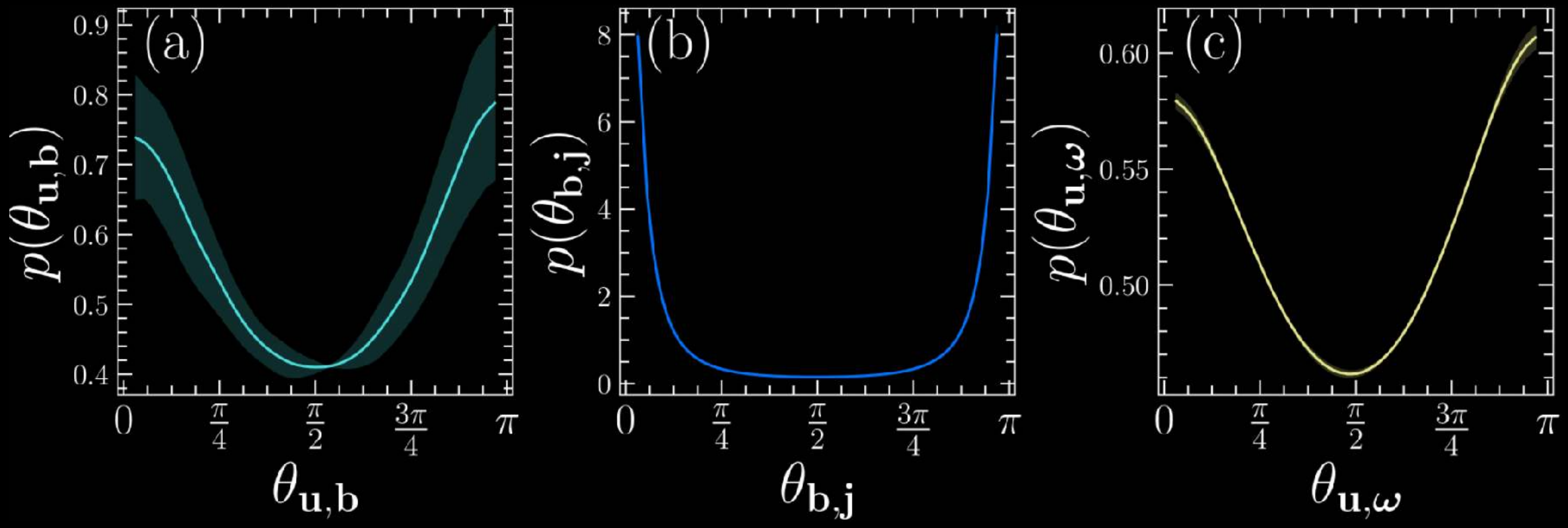


$$\mathbf{u} \propto \mathbf{b} \propto \mathbf{j} \propto \boldsymbol{\omega}$$

Beattie & Bhattacharjee *(in prep.). Scale dependent alignment in compressible magnetohydrodynamic turbulence*

But even more alignment than just u and b

Searching to weaken the nonlinearities

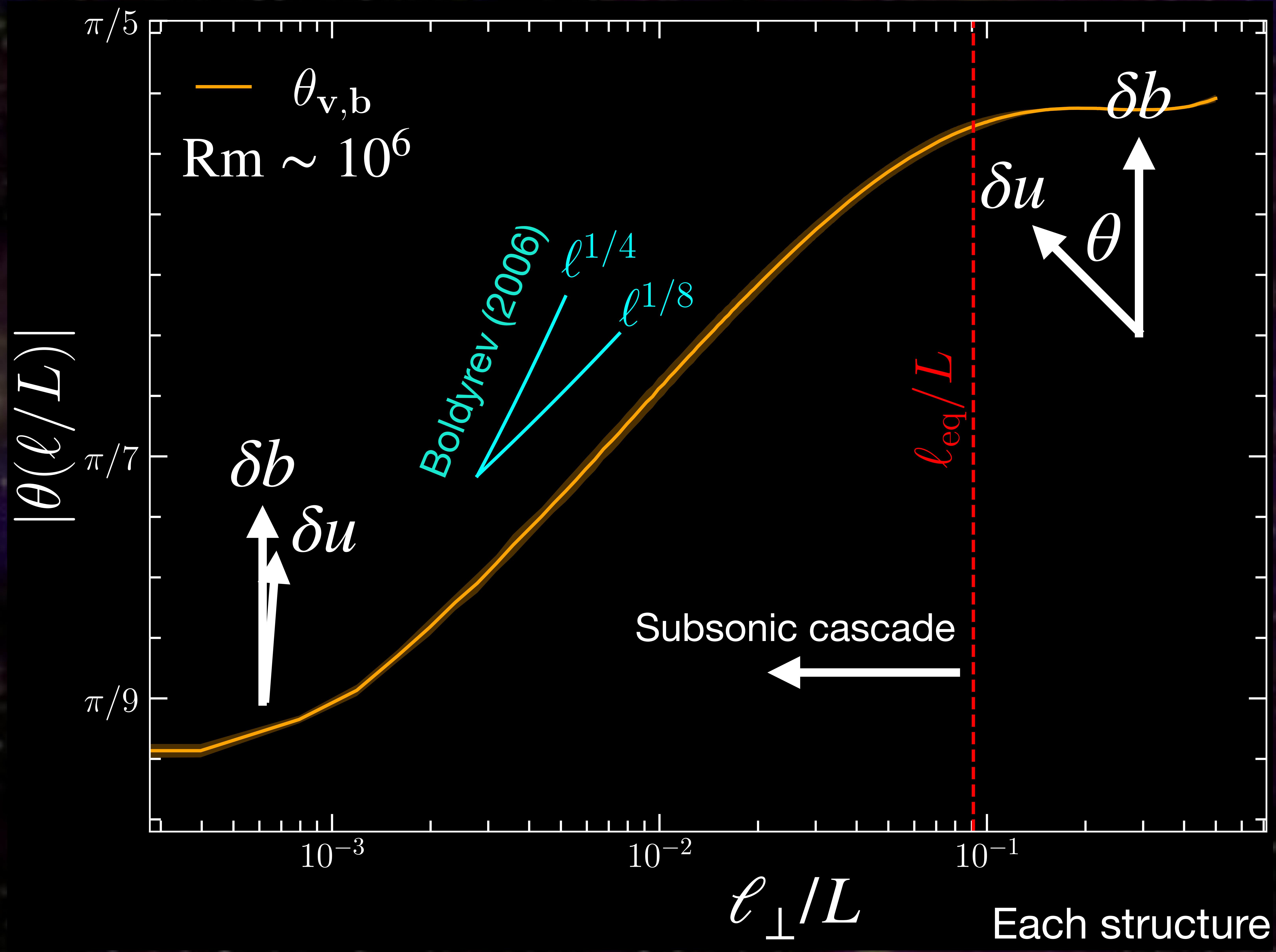


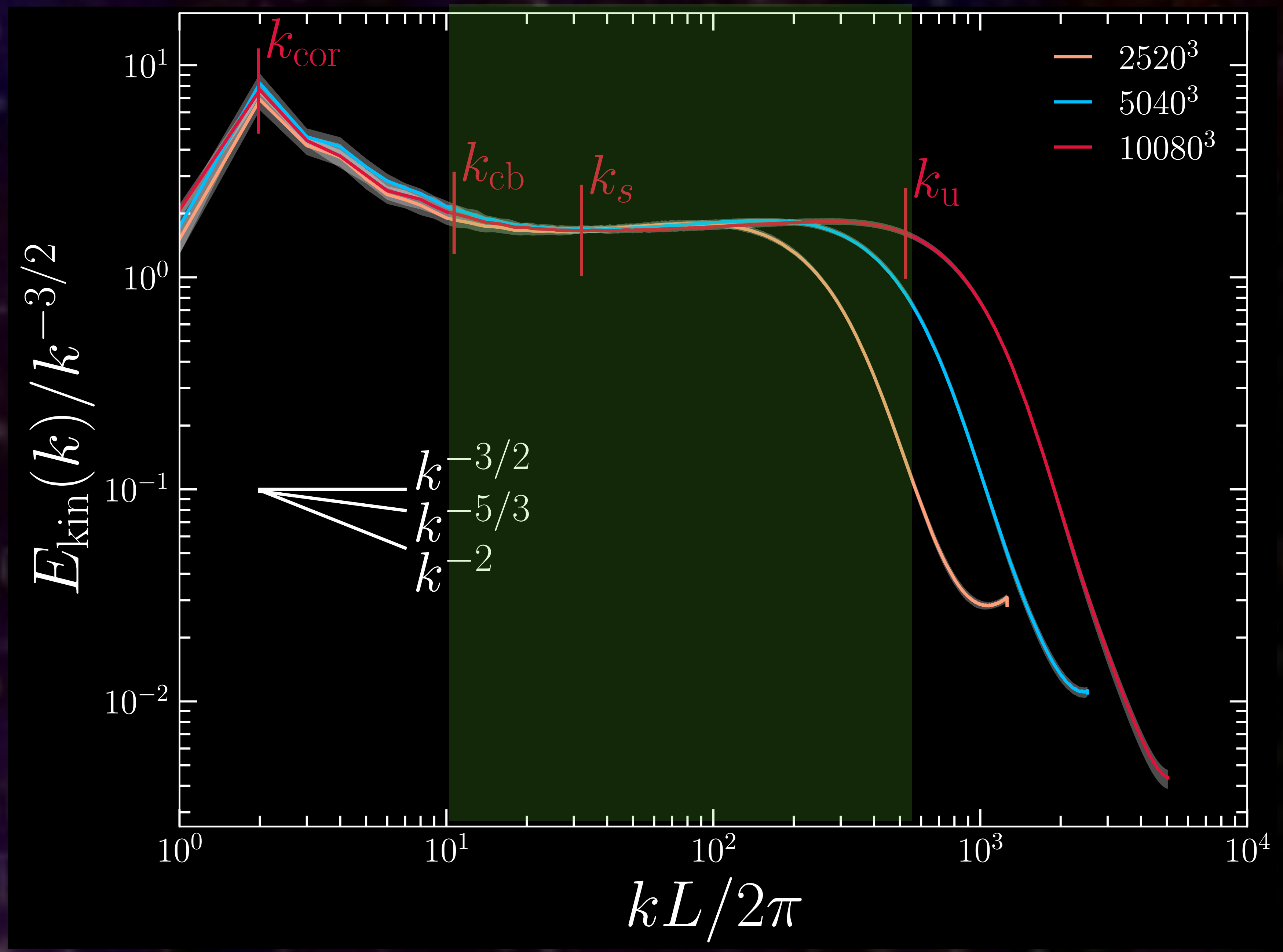
$\nabla \times (\mathbf{u} \times \mathbf{b})$	$\mathbf{j} \times \mathbf{b}$	$\nabla \cdot (\mathbf{u} \otimes \mathbf{u}) \sim \boldsymbol{\omega} \times \mathbf{u}$
Induction	Lorentz force	Reynolds nonlinearity

Beattie & Bhattacharjee *(in prep.). Scale dependent alignment in compressible magnetohydrodynamic turbulence*

Alignment not happening on all scales…

Beattie & Bhattacharjee *(in prep.). Scale dependent alignment in compressible magnetohydrodynamic turbulence*





We find

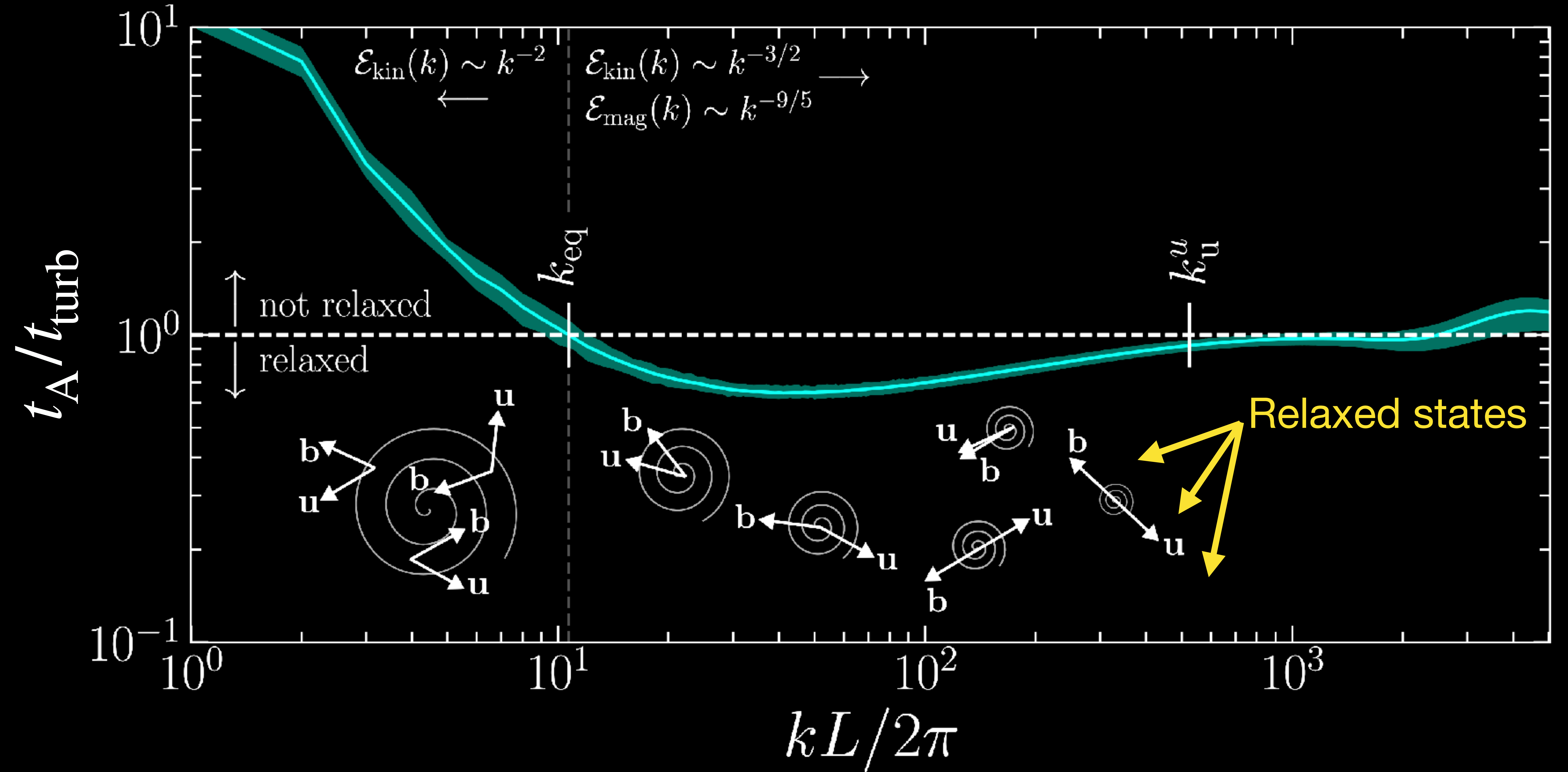
$$\theta(\ell) \sim \ell^{1/8}$$

scale-dependent alignment, but not Boldyrev (2006).

Each structure function costs 100,000 core hours!

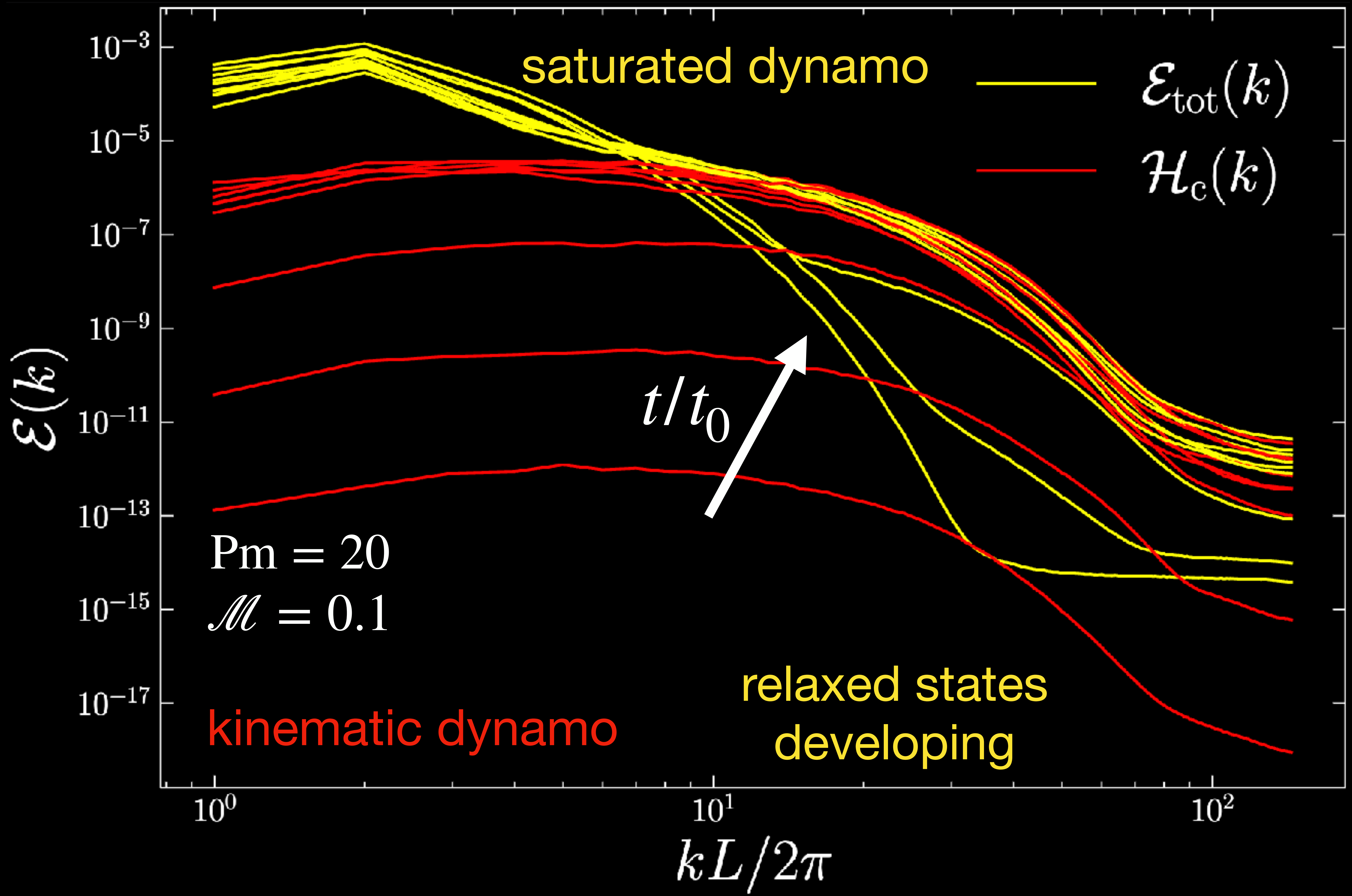
Why? First ingredient — separation of timescales

Can we align faster than the turbulence can perturb magnetic field out of alignment?



Why? Second ingredient — cross helicity spectrum

Can we ~ conserve rugged invariants in space instead of just in time?



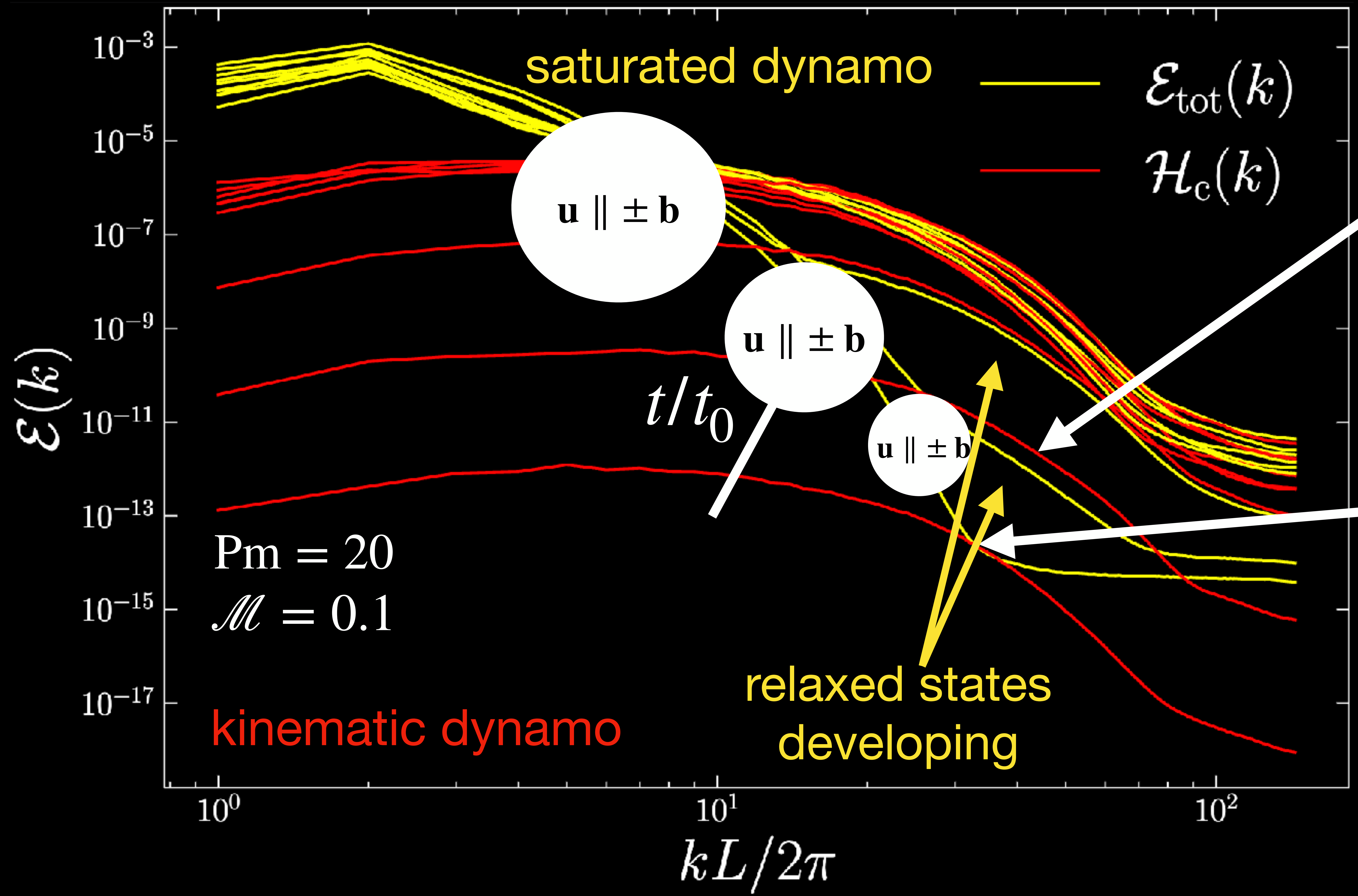
$$\mathscr{H}_c = \mathbf{u} \cdot \mathbf{b}$$

nonlinear dynamo (backreaction kicking in)

$\mathscr{H}_c$ grows $\Longrightarrow$ aligned scales develop where $\mathscr{H}_c > \mathscr{E}_{\rm tot} \Longrightarrow$ induction turns off

Why? Second ingredient — cross helicity spectrum

Can we ~ conserve rugged invariants in space instead of just in time?



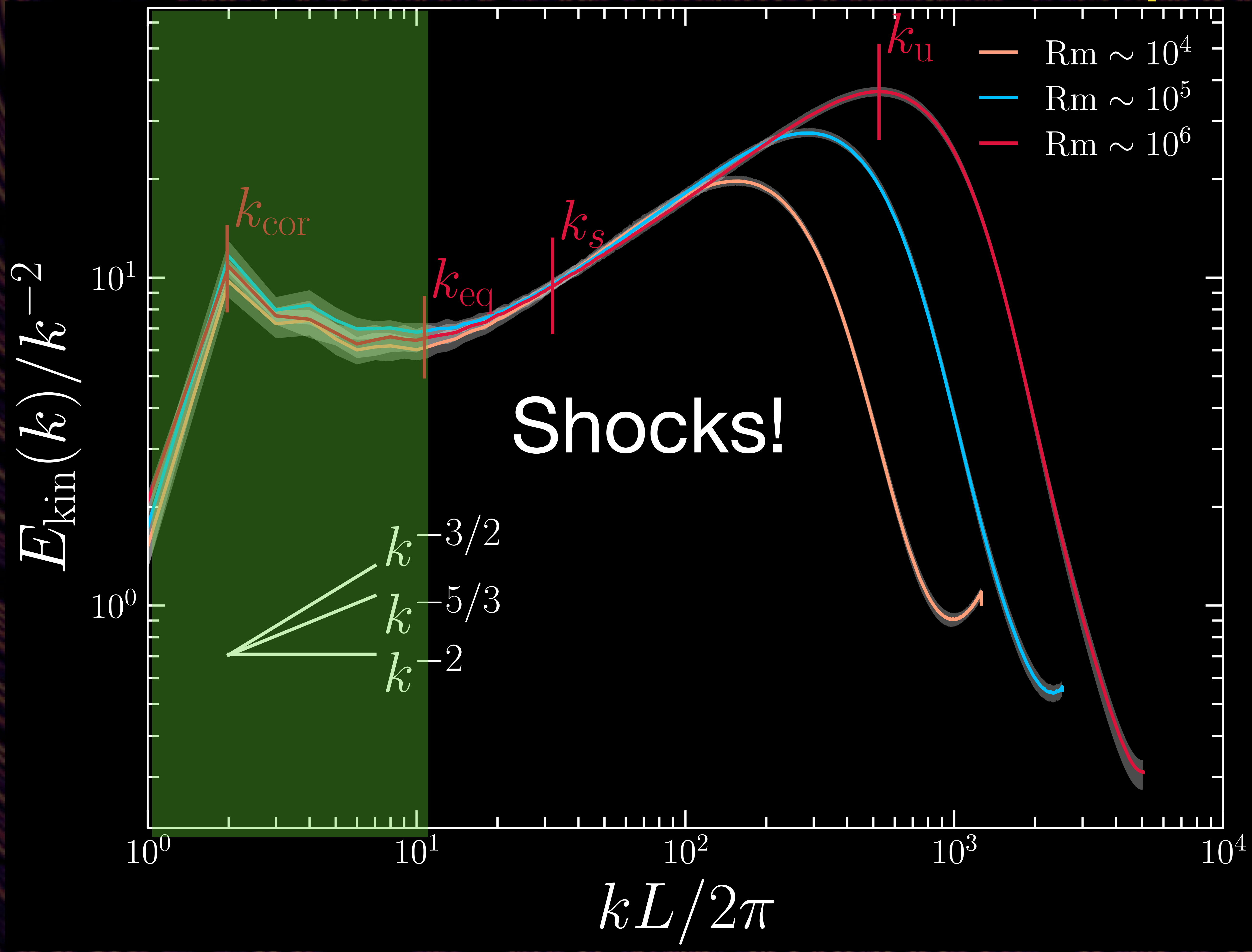
$$\mathscr{H}_c = \mathbf{u} \cdot \mathbf{b}$$

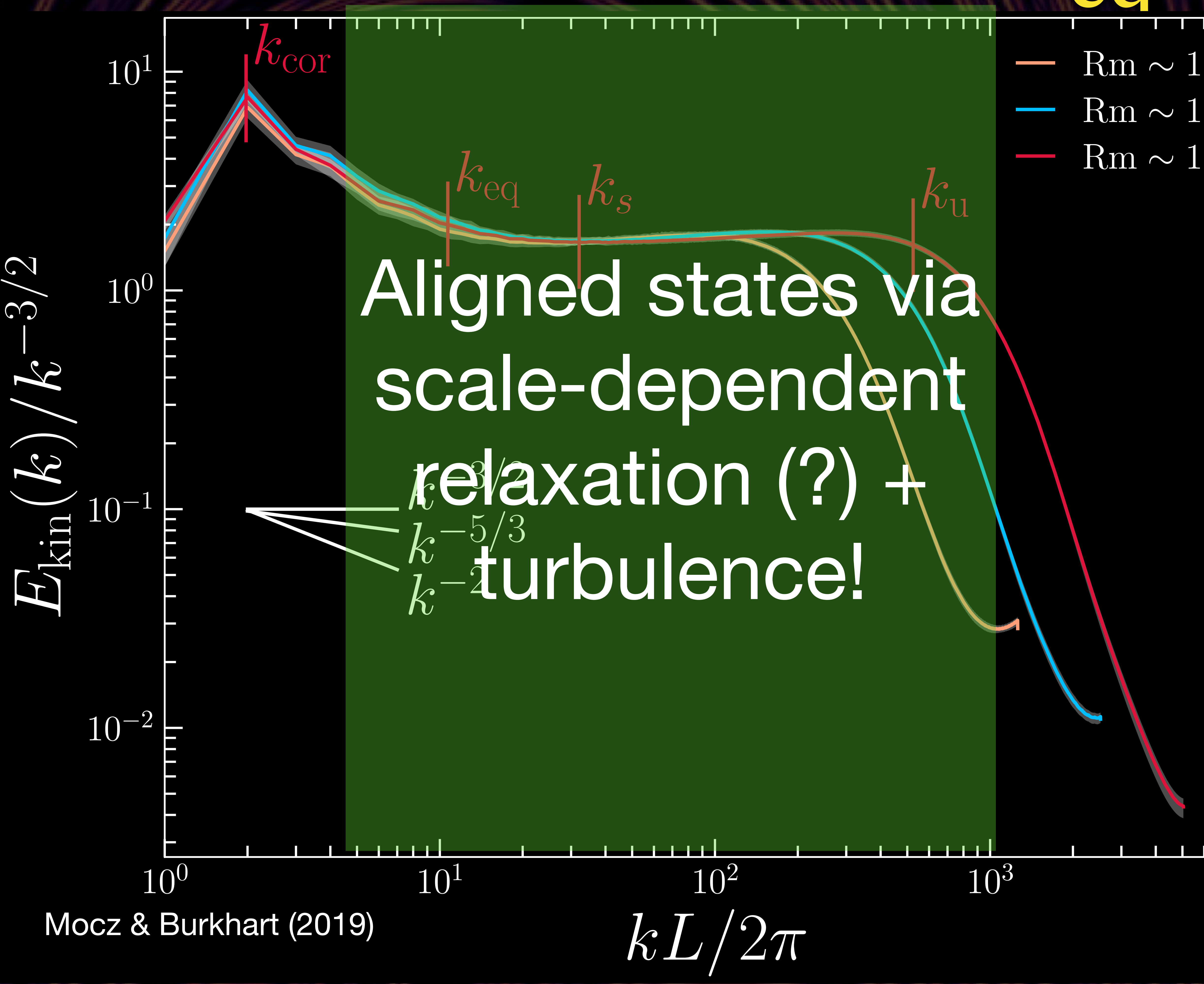
nonlinear dynamo (backreaction kicking in)

$\mathscr{H}_c$ grows $\Longrightarrow$ aligned scales develop where $\mathscr{H}_c > \mathscr{E}_{\rm tot} \Longrightarrow$ induction turns off

Velocity spectrum

$$\mathcal{E}(k) \sim k^{-2},\ k \le k_{\rm eq} \qquad \mathcal{E}(k) \sim k^{-3/2},\ k > k_{\rm eq}$$





Mocz & Burkhart (2019)

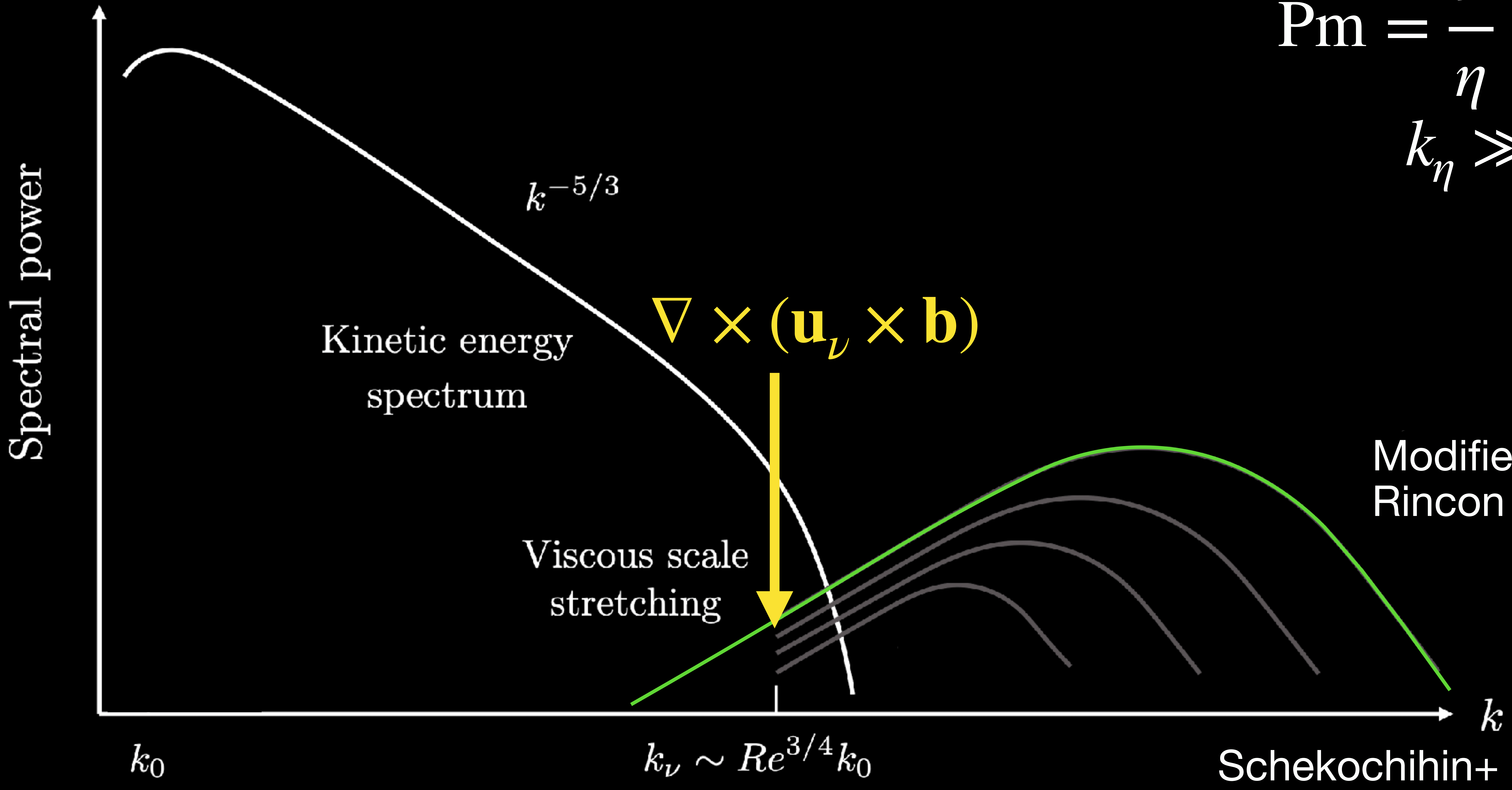
Magnetic reconnection in a turbulent plasma (visualisation by J. Beattie).

The dynamical saturation of the dynamo

Saturation through alignment

$$\mathrm{Pm} = \frac{\nu}{\eta} \gg 1$$

$$k_\eta \gg k_\nu$$

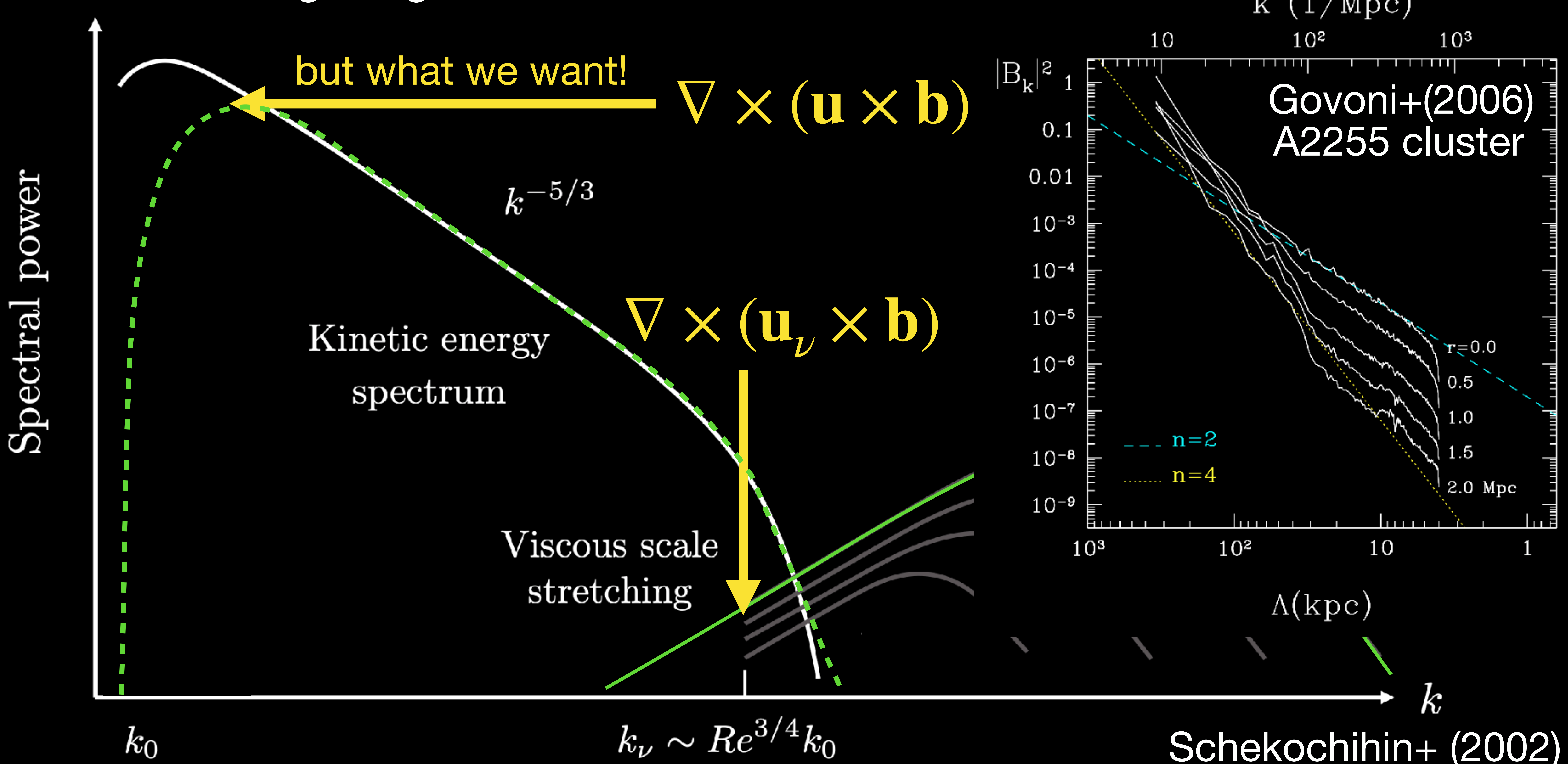


Modified from Rincon (2019)

Schekochihin+ (2002)

The dynamical saturation of the dynamo

Saturation through alignment



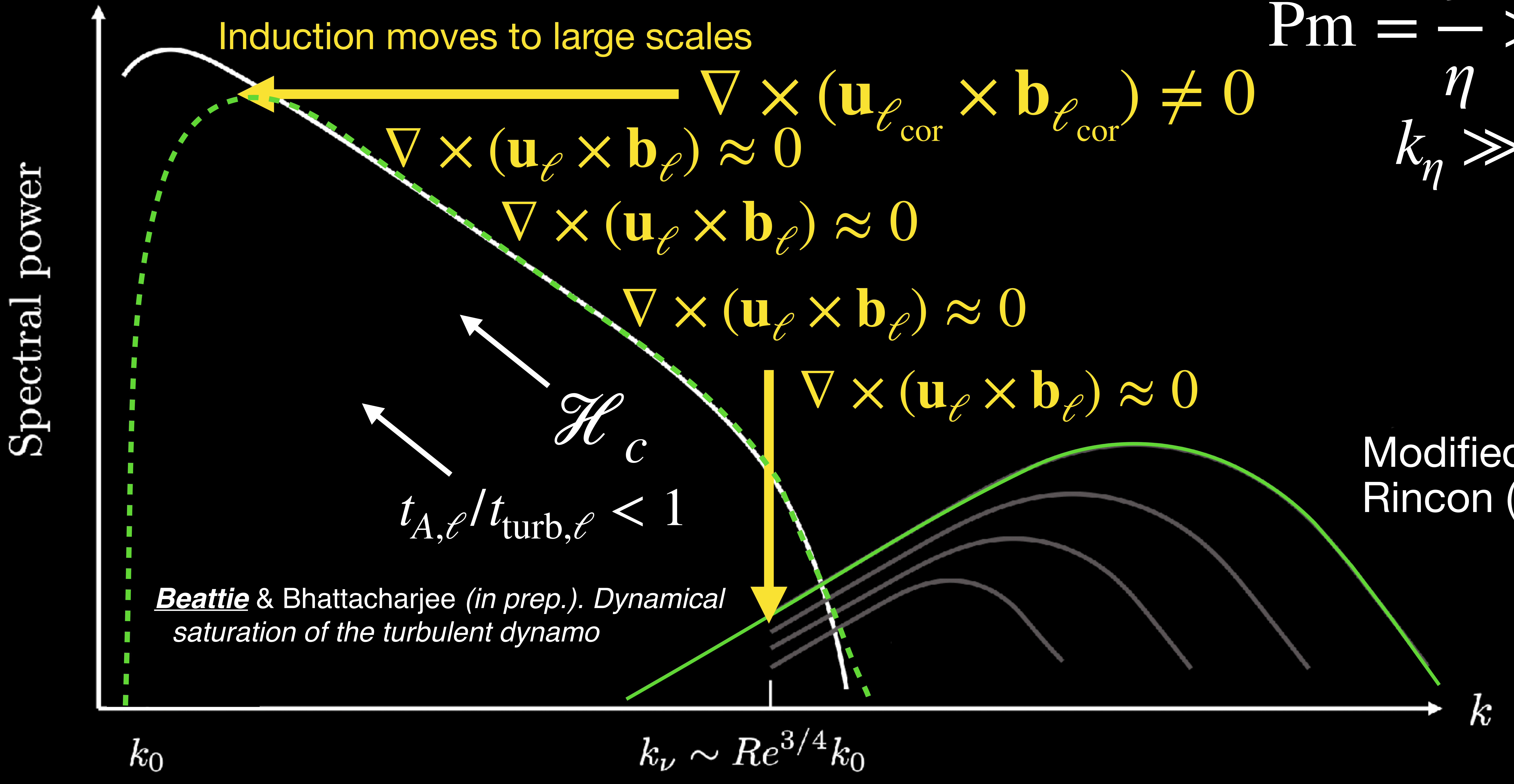
Schekochihin+ (2002)

The dynamical saturation of the dynamo

Saturation through alignment

$$\mathrm{Pm} = \frac{\nu}{\eta} \gg 1$$

$$k_\eta \gg k_\nu$$



Beattie & Bhattacharjee *(in prep.). Dynamical saturation of the turbulent dynamo*

Modified from Rincon (2019)

Inevitability of the turbulent dynamo

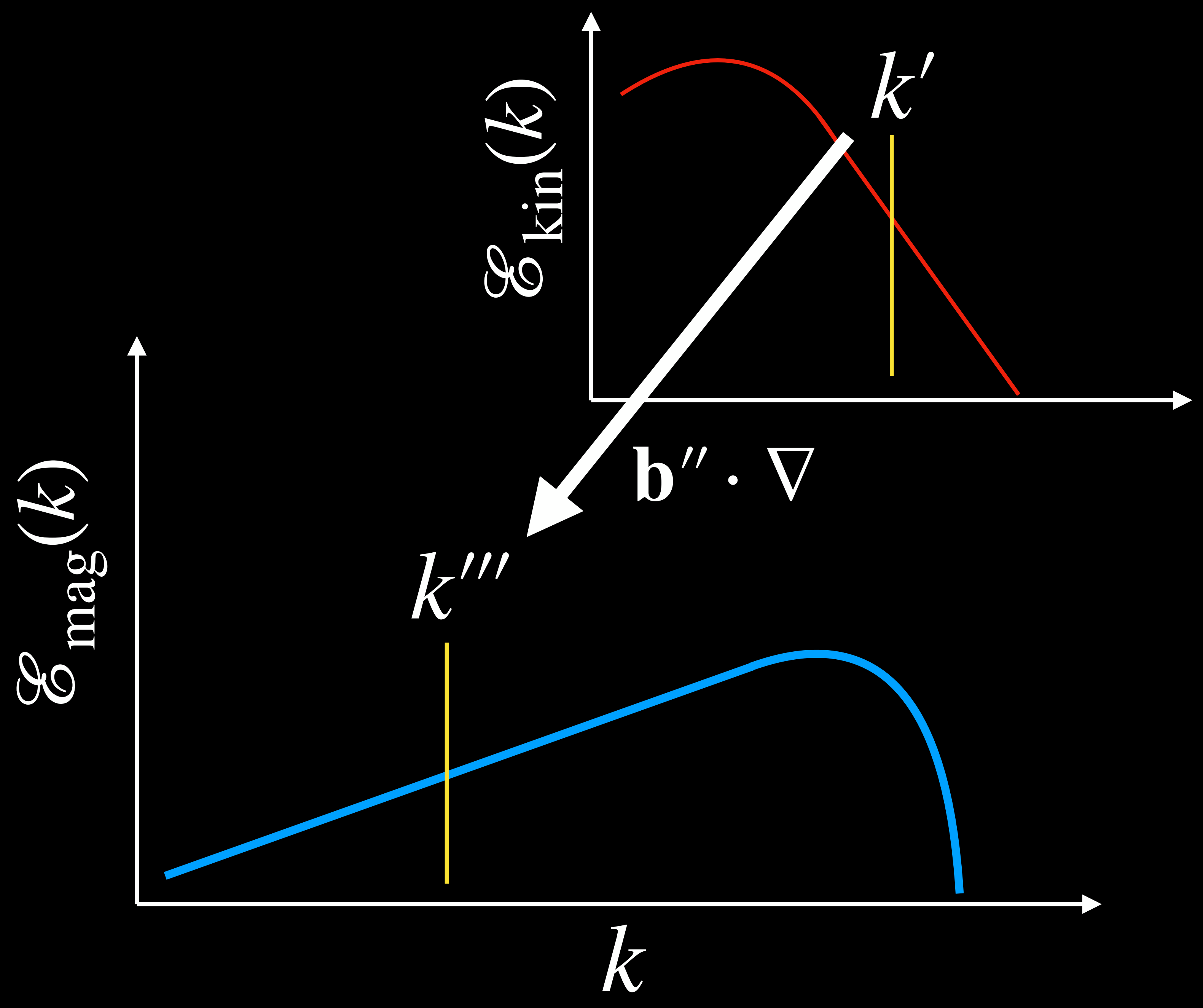
Saturation through alignment

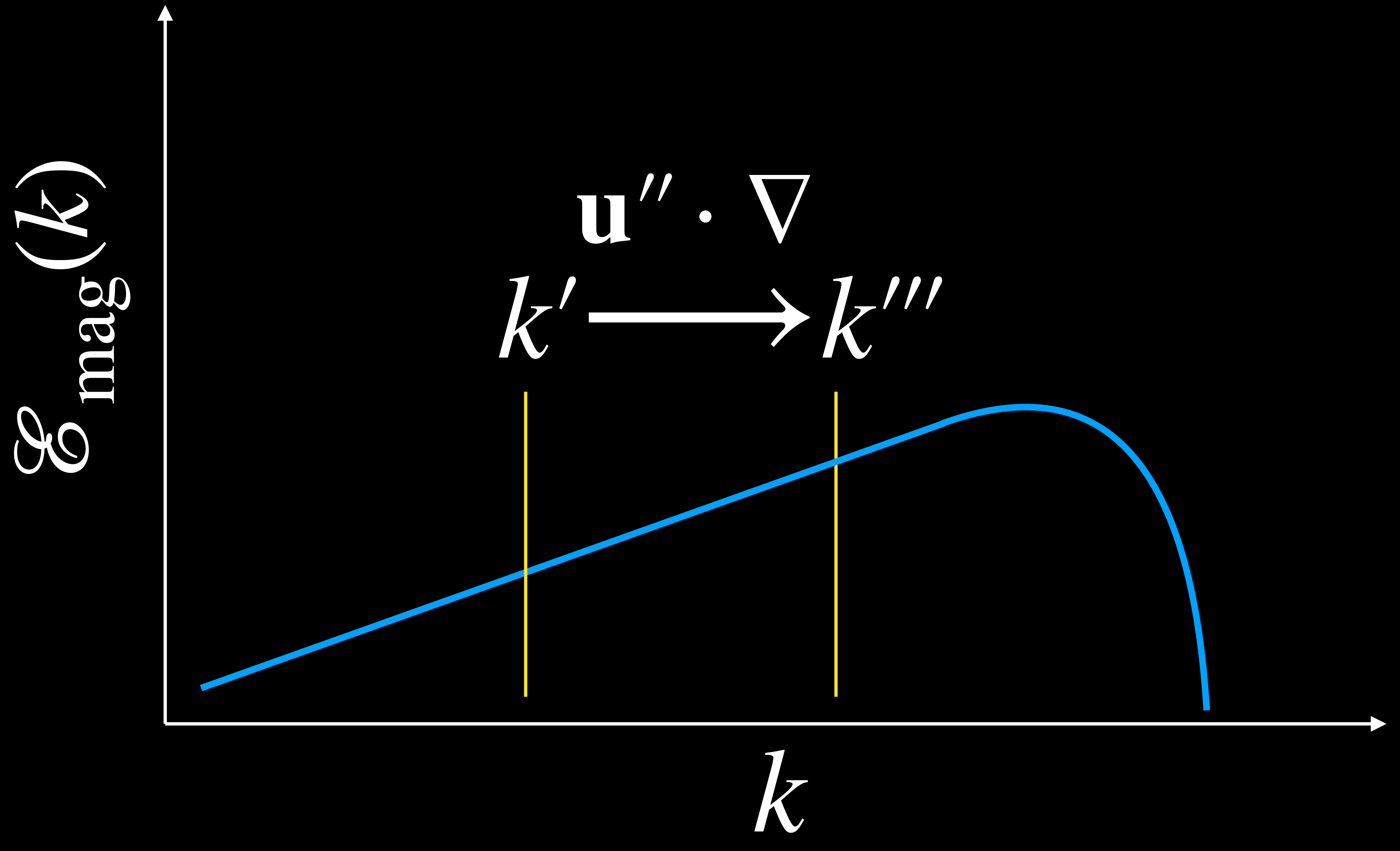
$$\mathbf{k}' \xrightarrow{\mathbf{k}''} \mathbf{k}'''$$

Alignment implies a perfect balance between dynamo and cascade energy fluxes

$$\nabla \times (\mathbf{u}_\ell \times \mathbf{b}_\ell) \approx 0 \implies$$

$$\underbrace{\mathbf{b}''' \otimes \mathbf{b}'' : \nabla \otimes \mathbf{u}'}_{\text{kinetic to magnetic energy transfer}} = \overbrace{\mathbf{b}''' \otimes \mathbf{u}'' : \nabla \otimes \mathbf{b}' + \frac{1}{2}\mathbf{b}' \otimes \mathbf{b}''' : (\nabla \cdot \mathbf{u}'')\mathbb{I}}^{\text{magnetic cascade terms}}$$





Magnetic spectrum in saturated state

***Beattie**+(2024). Magnetized compressible turbulence with a fluctuation dynamo and Reynolds numbers over a million* arXiv:2405.16626

Thanks, questions?

james.beattie@princeton. @astro_magnetism

Carina Nebula, JWST