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Understanding correlations and energy transfer in magnetized turbulence

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and Kris Beckwith (Sandia)

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Motivation

- Compressible, magnetized turbulence is ubiquitous in astrophysics
- Plasma turbulence is also critical to terrestrial problems of interest (e.g., dense plasma focus, plasma opening switch; see Beckwith+ 2019)
- Common problems: huge range of spatial, temporal scales

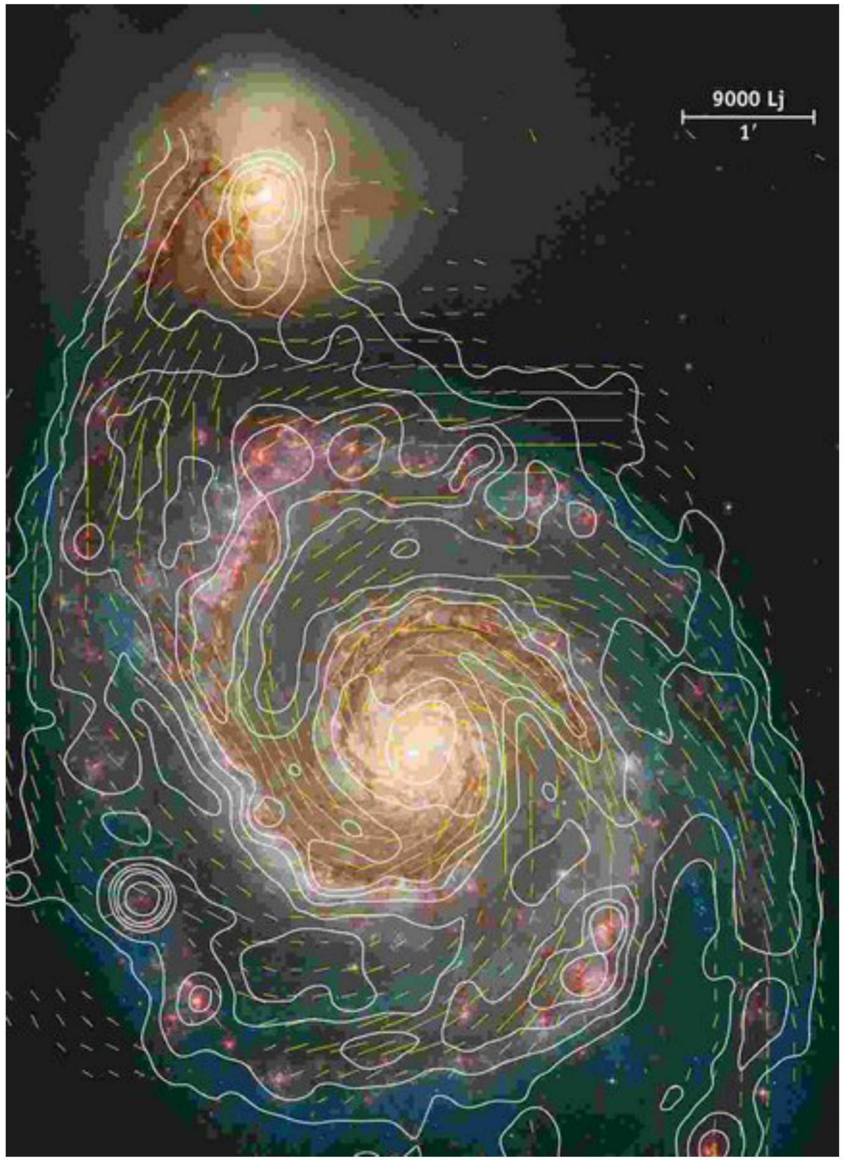


Image: MPIfR / Newcastle University

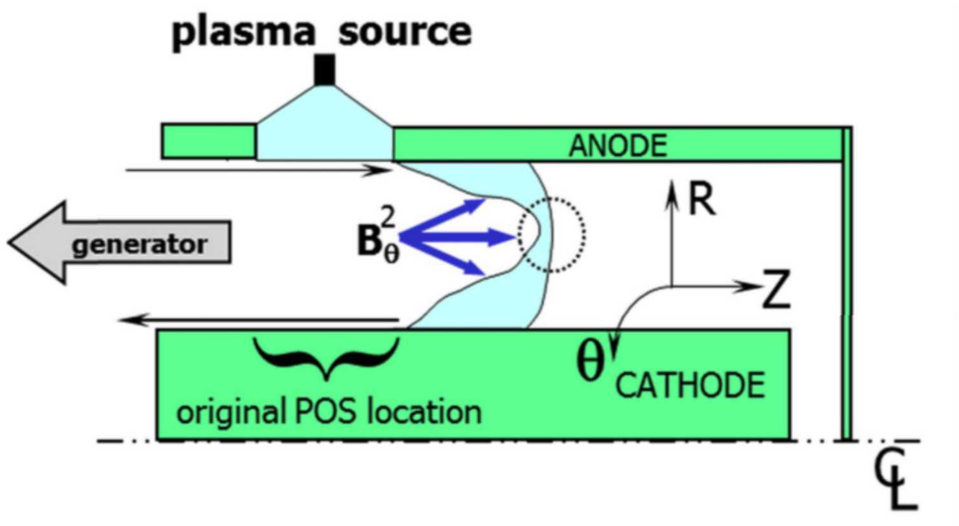
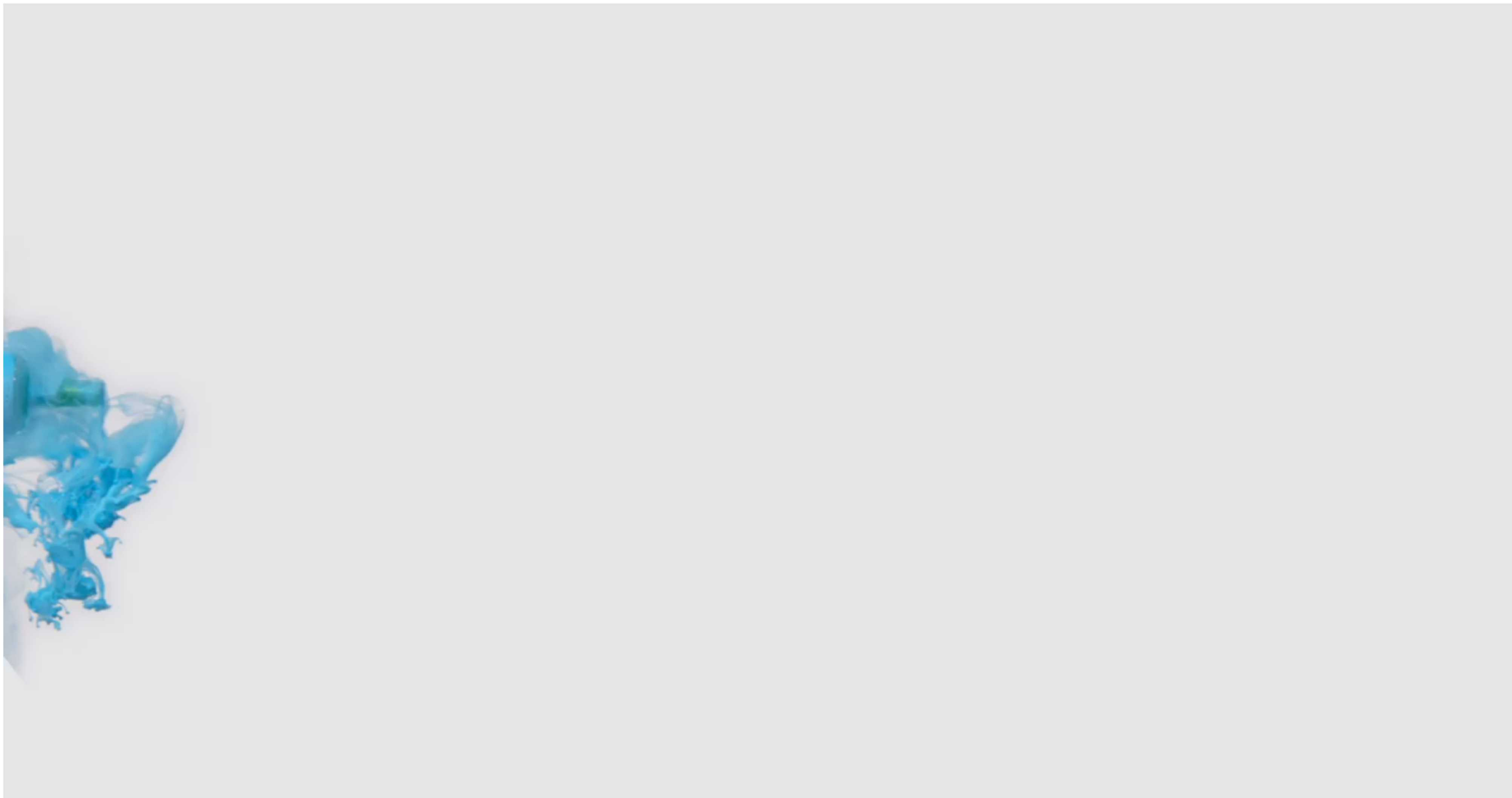


Image: Schumer et al. 2001

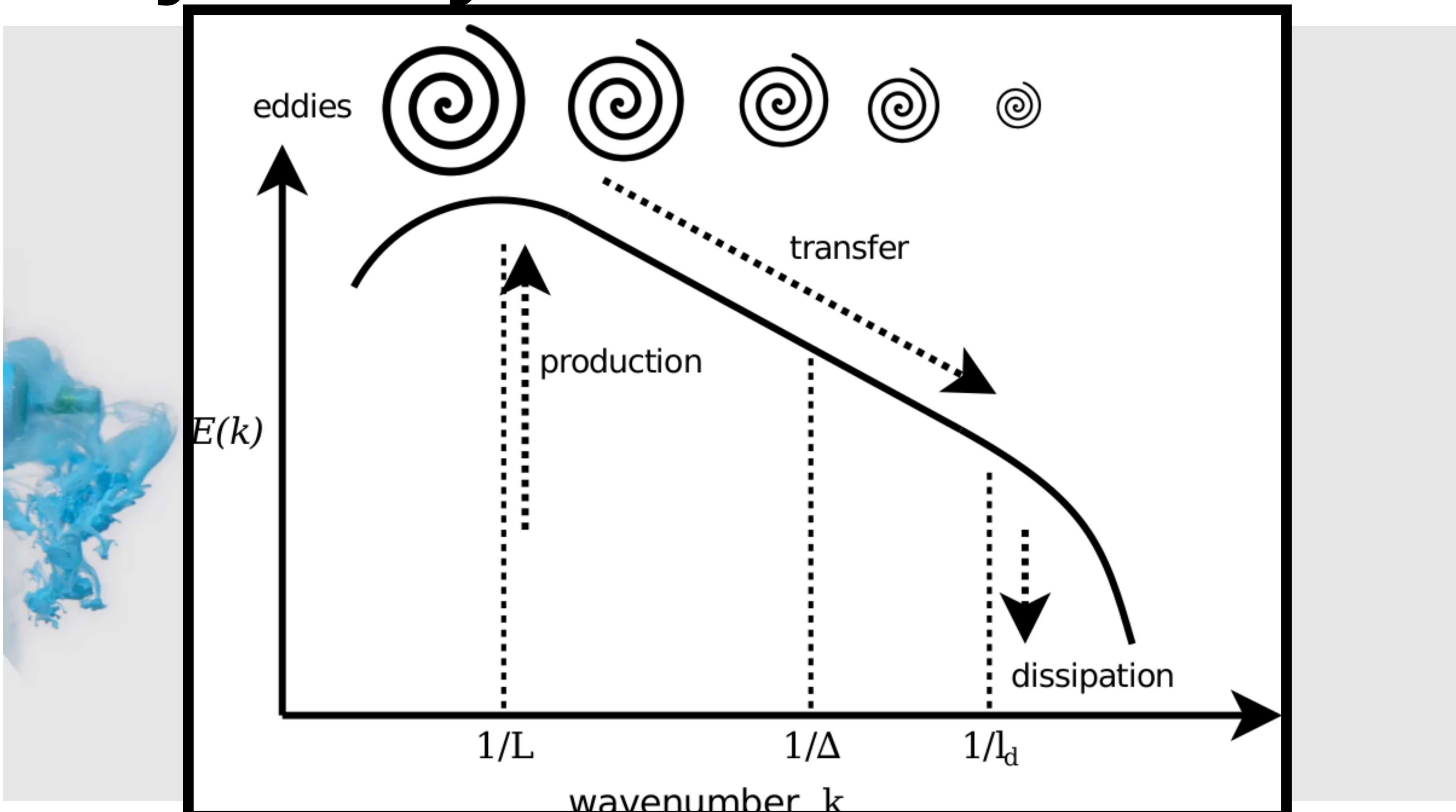
Hydrodynamic turbulence



Re ~ 10^4

Clip from The Slo-Mo Guys, YouTube, 2015

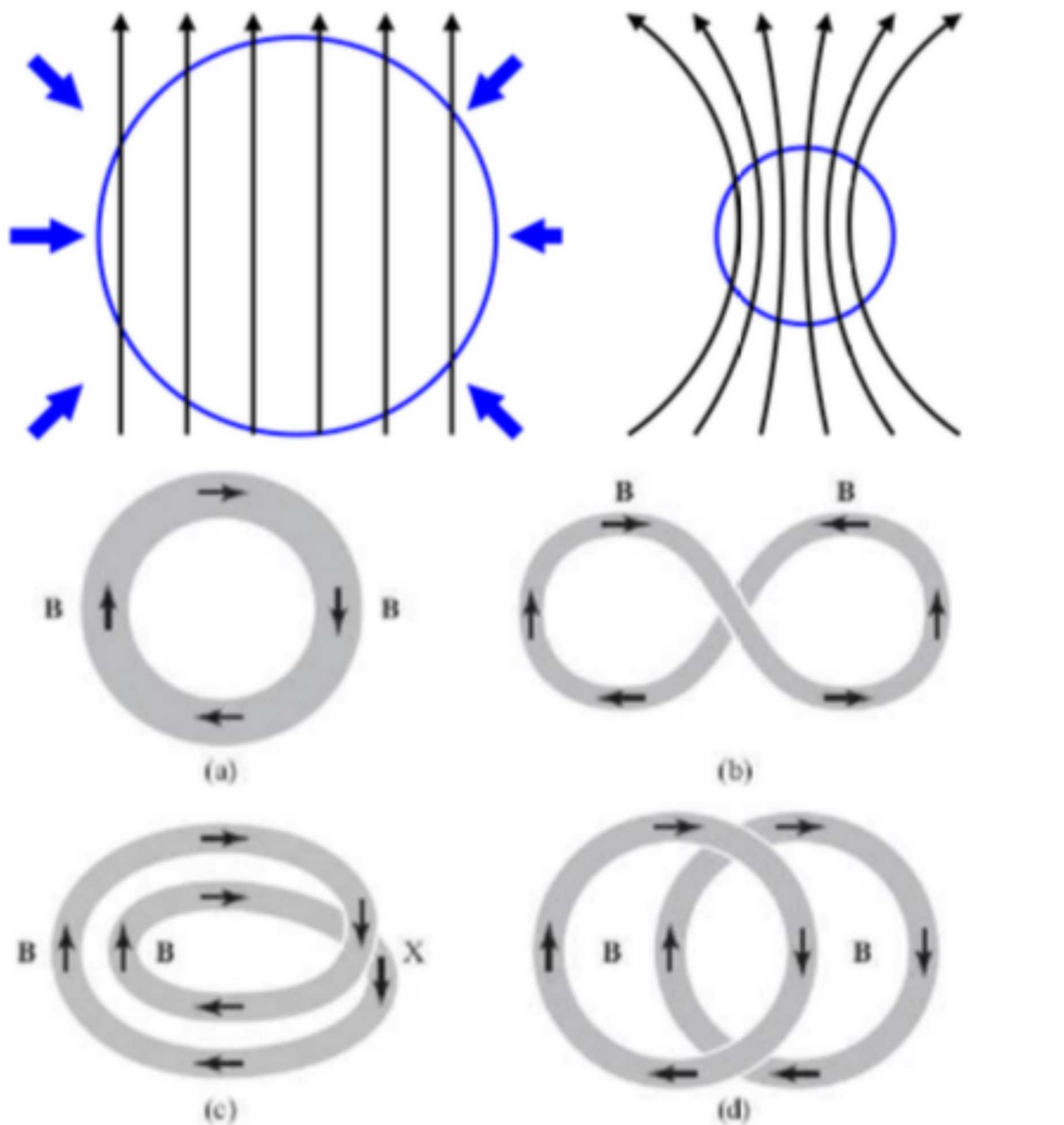
Hydrodynamic turbulence



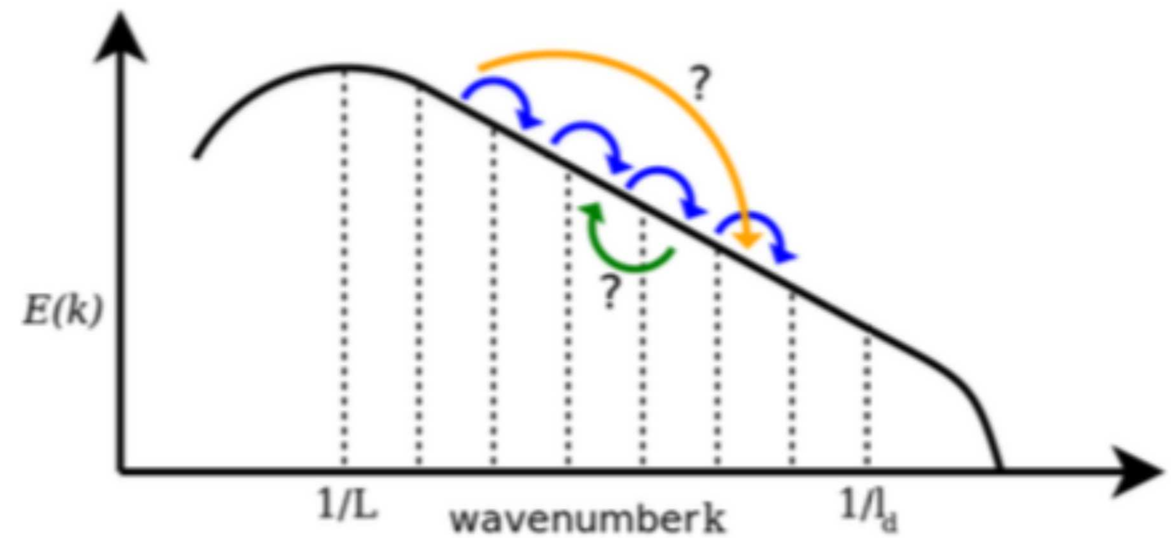
Re ~ 10^4

Clip from The Slo-Mo Guys, YouTube, 2015

Complexities from magnetic fields



[Dynamo image credit: Vainshtein & Zel'dovich '72]

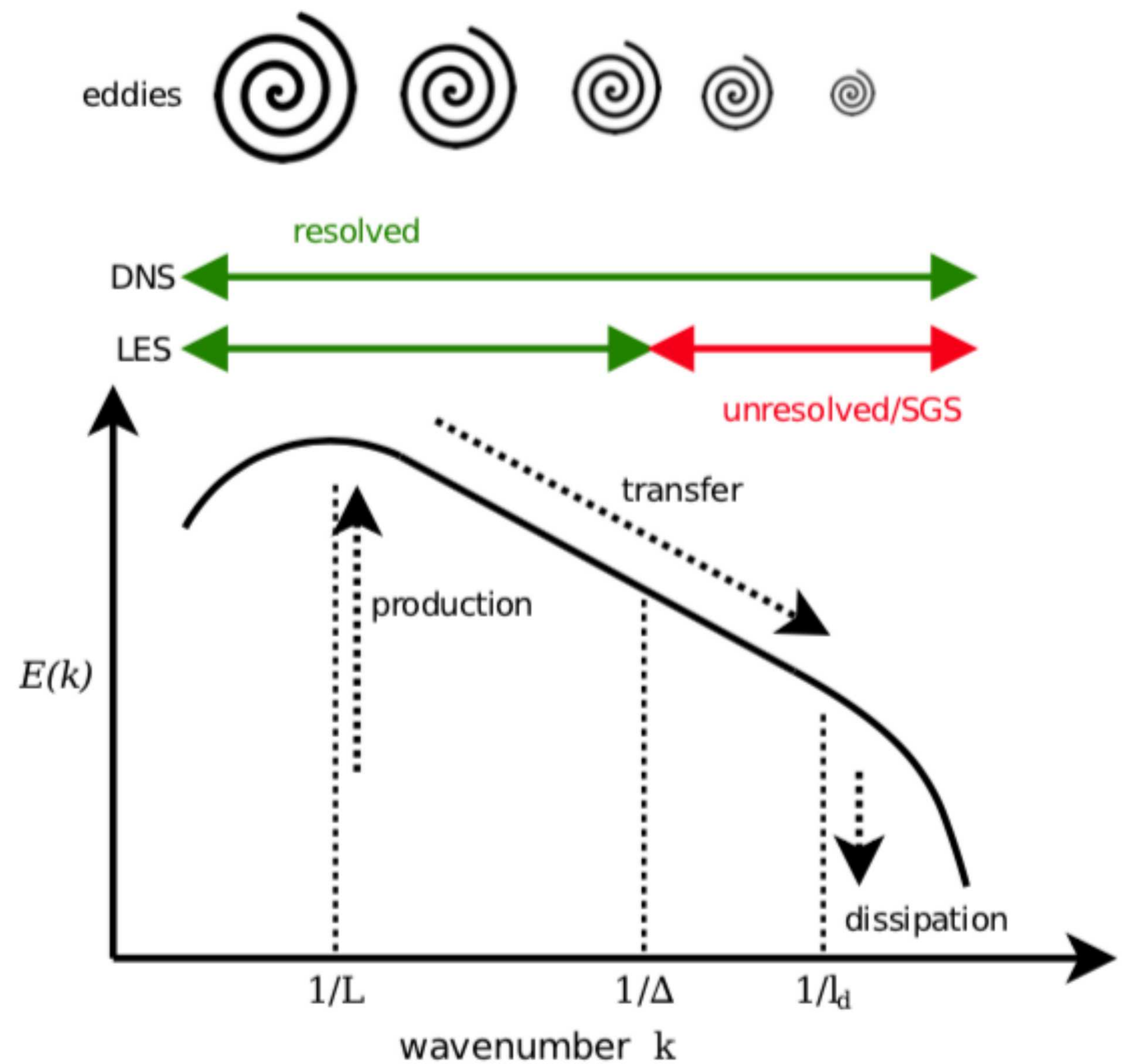


Energy transfer:

- Energy cascade
- Inverse transfer
- Nonlocal transfer

Large eddy simulations

- Challenge: expense of full MHD simulations
- Separation of scales suggests large eddy simulations as possible solution
- Problem: MHD subgrid-scale (SGS) model
- Study energy transfer in idealized setups!



Energy budgets in incompressible MHD

$$E_u(K) = \sum_Q \int - \underbrace{\mathbf{w}^{\mathrm{K}} \cdot (\mathbf{u} \cdot \nabla)\, \mathbf{w}^{\mathrm{Q}}}_{\text{advection (kinetic cascade)}} + \underbrace{\mathbf{w}^{\mathrm{K}} \cdot (\mathbf{v}_{\mathrm{A}} \cdot \nabla)\, \mathbf{B}^{\mathrm{Q}}}_{\text{magnetic tension}} + \cdots \mathrm{d}\mathbf{x}$$

$$E_b(K) = \sum_Q \int - \underbrace{\mathbf{B}^{\mathrm{K}} \cdot (\mathbf{u} \cdot \nabla)\, \mathbf{B}^{\mathrm{Q}}}_{\text{advection (magnetic cascade)}} + \underbrace{\mathbf{B}^{\mathrm{K}} \cdot \nabla \cdot \left(\mathbf{v}_{\mathrm{A}} \otimes \mathbf{w}^{\mathrm{Q}}\right)}_{\text{magnetic tension}} + \cdots \mathrm{d}\mathbf{x}$$

e.g., Verma 2004, Alexakis+ 2005

Energy budgets in compressible MHD

$$E_u(K) = \sum_Q \int - \underbrace{\mathbf{w}^{\mathrm{K}} \cdot (\mathbf{u} \cdot \nabla)\, \mathbf{w}^{\mathrm{Q}}}_{\text{advection (kinetic cascade)}} - \underbrace{\frac{1}{2}\mathbf{w}^{\mathrm{K}} \cdot \mathbf{w}^{\mathrm{Q}} \nabla \cdot \mathbf{u}}_{\text{compression}}$$

$$+ \underbrace{\mathbf{w}^{\mathrm{K}} \cdot (\mathbf{v}_{\mathrm{A}} \cdot \nabla)\, \mathbf{B}^{\mathrm{Q}}}_{\text{magnetic tension}} - \underbrace{\frac{\mathbf{w}^{\mathrm{K}}}{2\sqrt{\rho}} \cdot \nabla \left(\mathbf{B} \cdot \mathbf{B}^{\mathrm{Q}}\right)}_{\text{magnetic pressure}} + \cdots \mathrm{d}\mathbf{x}$$

$$E_b(K) = \sum_Q \int - \underbrace{\mathbf{B}^{\mathrm{K}} \cdot (\mathbf{u} \cdot \nabla)\, \mathbf{B}^{\mathrm{Q}}}_{\text{advection (magnetic cascade)}} - \underbrace{\frac{1}{2}\mathbf{B}^{\mathrm{K}} \cdot \mathbf{B}^{\mathrm{Q}} \nabla \cdot \mathbf{u}}_{\text{compression}}$$

$$+ \underbrace{\mathbf{B}^{\mathrm{K}} \cdot \nabla \cdot \left(\mathbf{v}_{\mathrm{A}} \otimes \mathbf{w}^{\mathrm{Q}}\right)}_{\text{magnetic tension}} - \underbrace{\mathbf{B}^{\mathrm{K}} \cdot \mathbf{B} \nabla \cdot \left(\frac{\mathbf{w}^{\mathrm{Q}}}{2\sqrt{\rho}}\right)}_{\text{magnetic pressure}} + \cdots \mathrm{d}\mathbf{x}$$

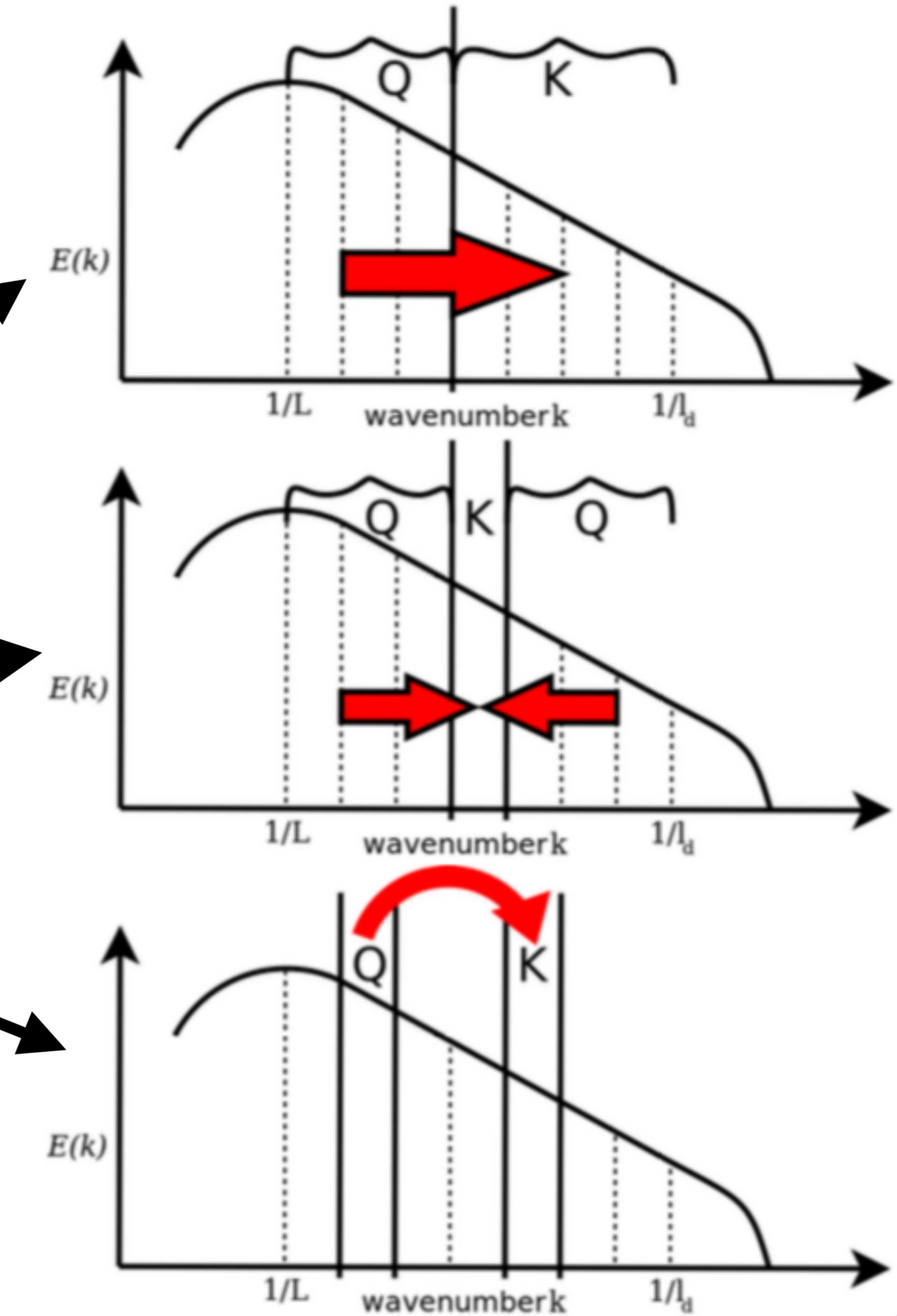
Grete+ 2017, Physics of Plasmas

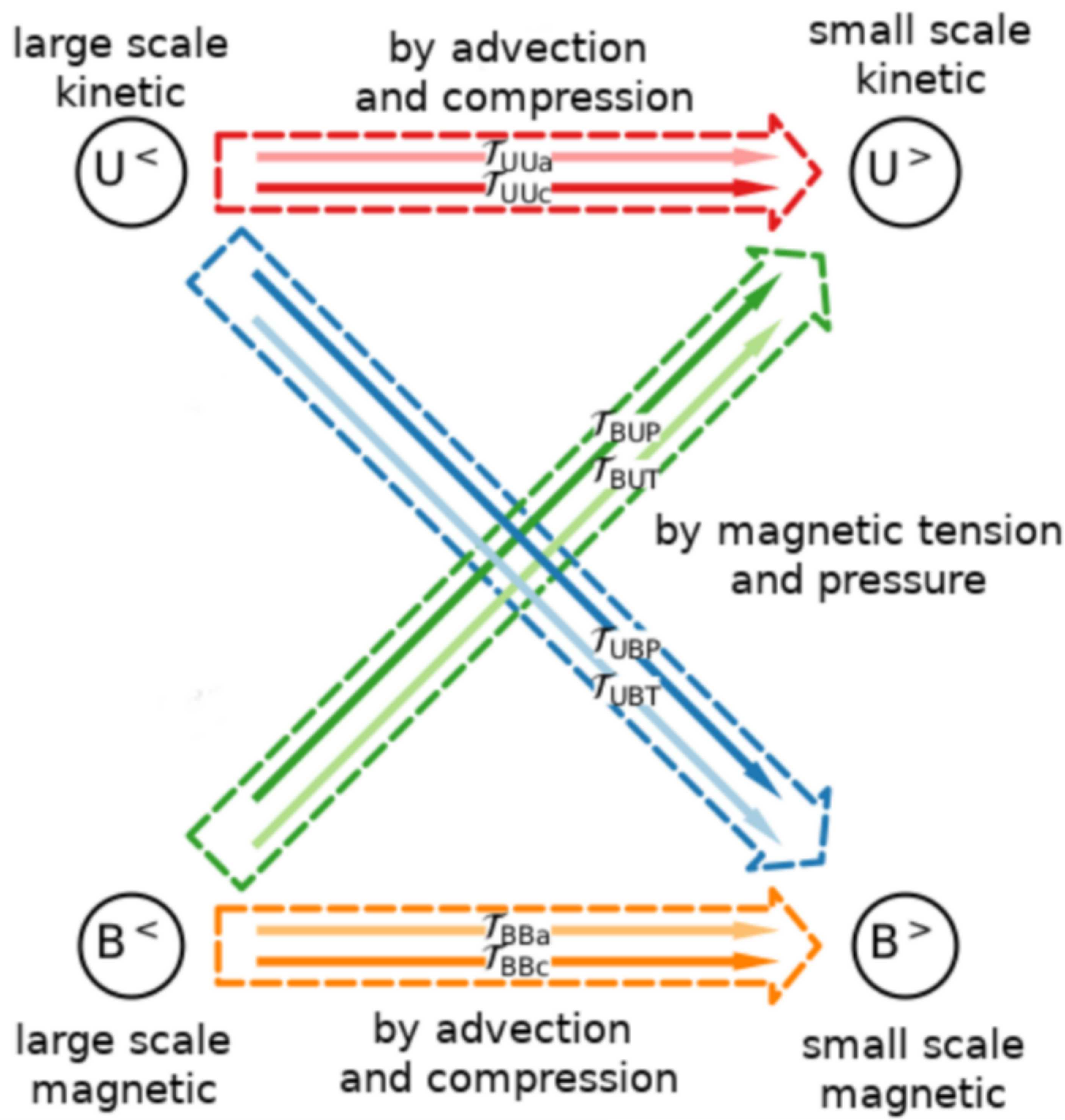
What can we learn from the energy transfer function?

Cross-scale transfer

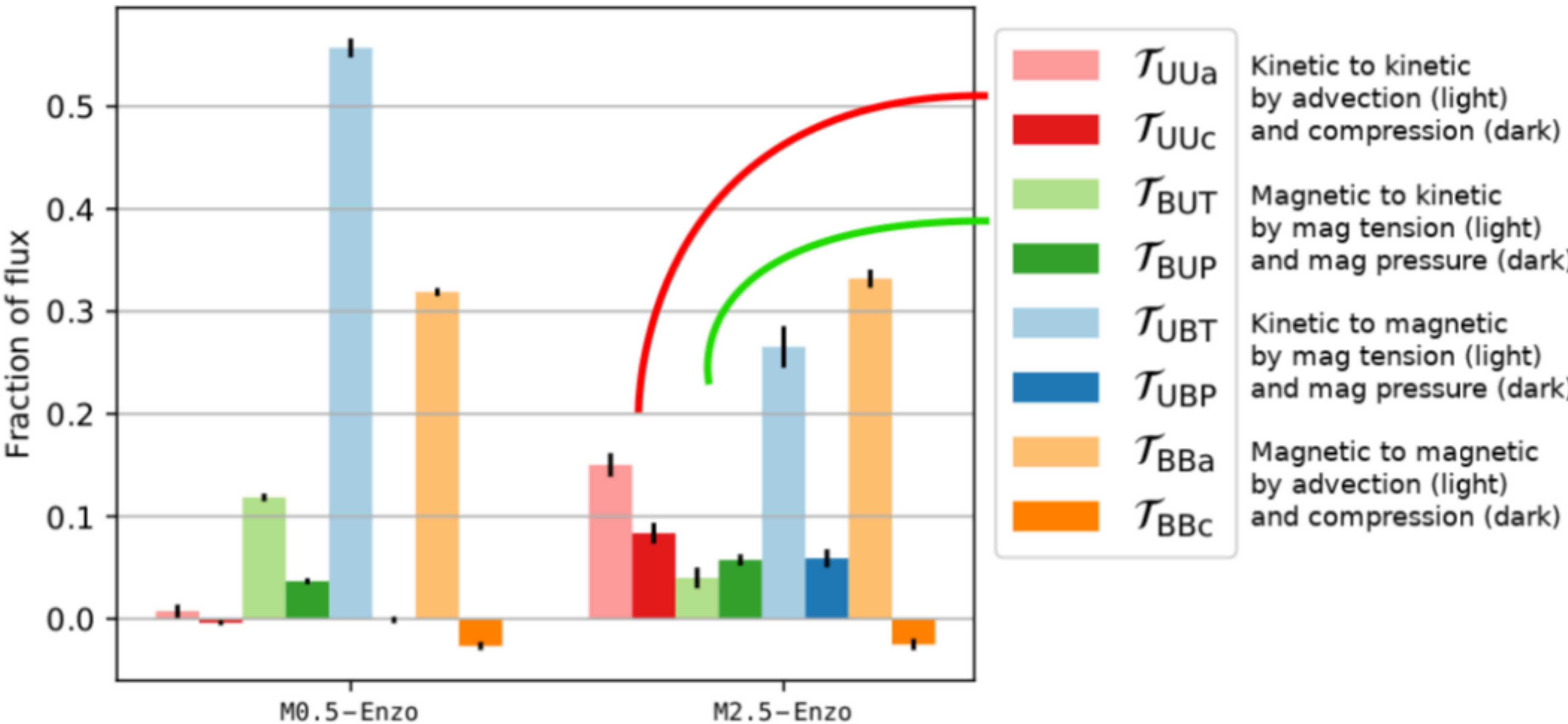
Total transfer

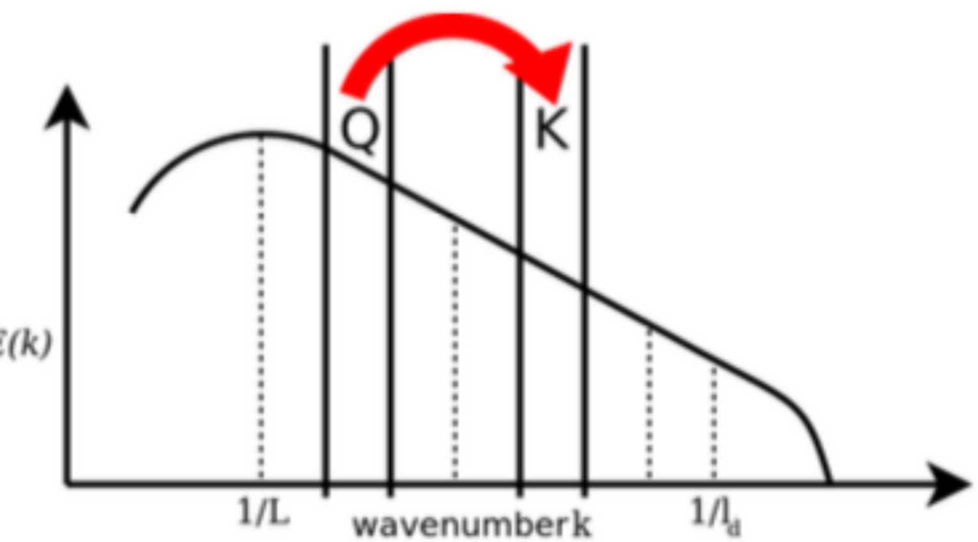
Shell-to-shell transfer

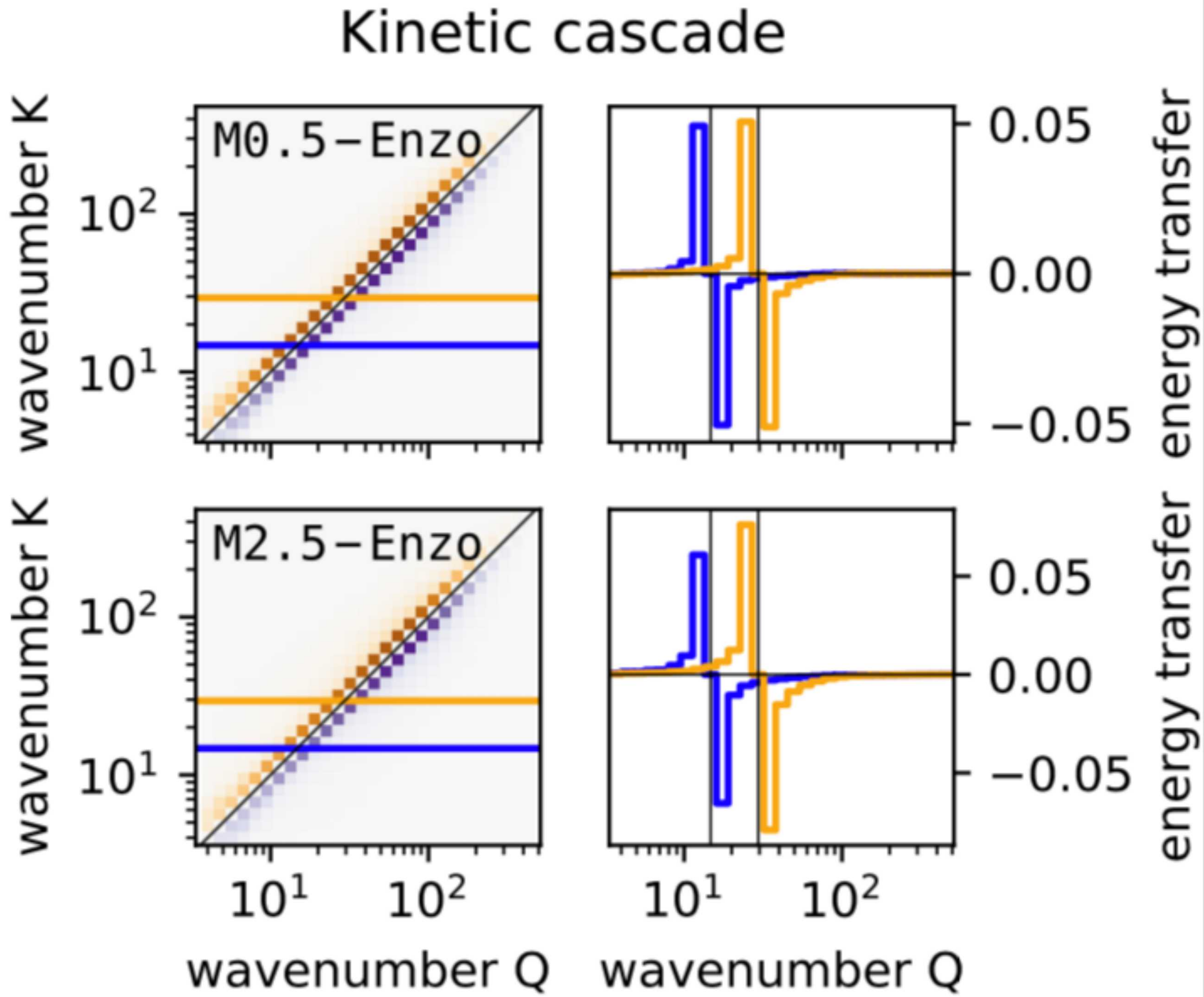



large scale kinetic
by advection and compression
small scale kinetic
$U^<$
$\mathcal{T}_{UUa}$
$\mathcal{T}_{UUc}$
$U^>$
$\mathcal{T}_{BUP}$
$\mathcal{T}_{BUT}$
by magnetic tension and pressure
$\mathcal{T}_{UBP}$
$\mathcal{T}_{UBT}$
$B^<$
$\mathcal{T}_{BBa}$
$\mathcal{T}_{BBc}$
$B^>$
large scale magnetic
by advection and compression
small scale magnetic

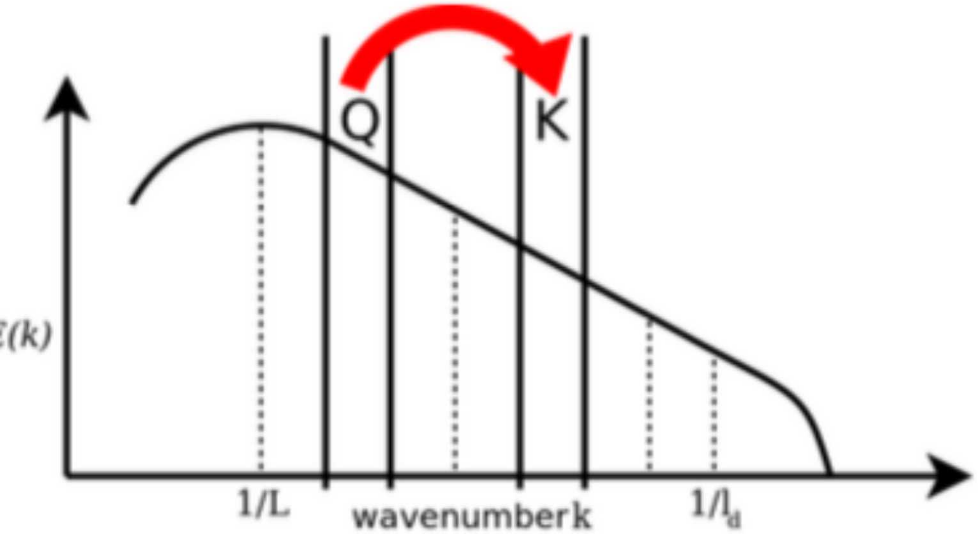
Mean cross-scale flux in the inertial range

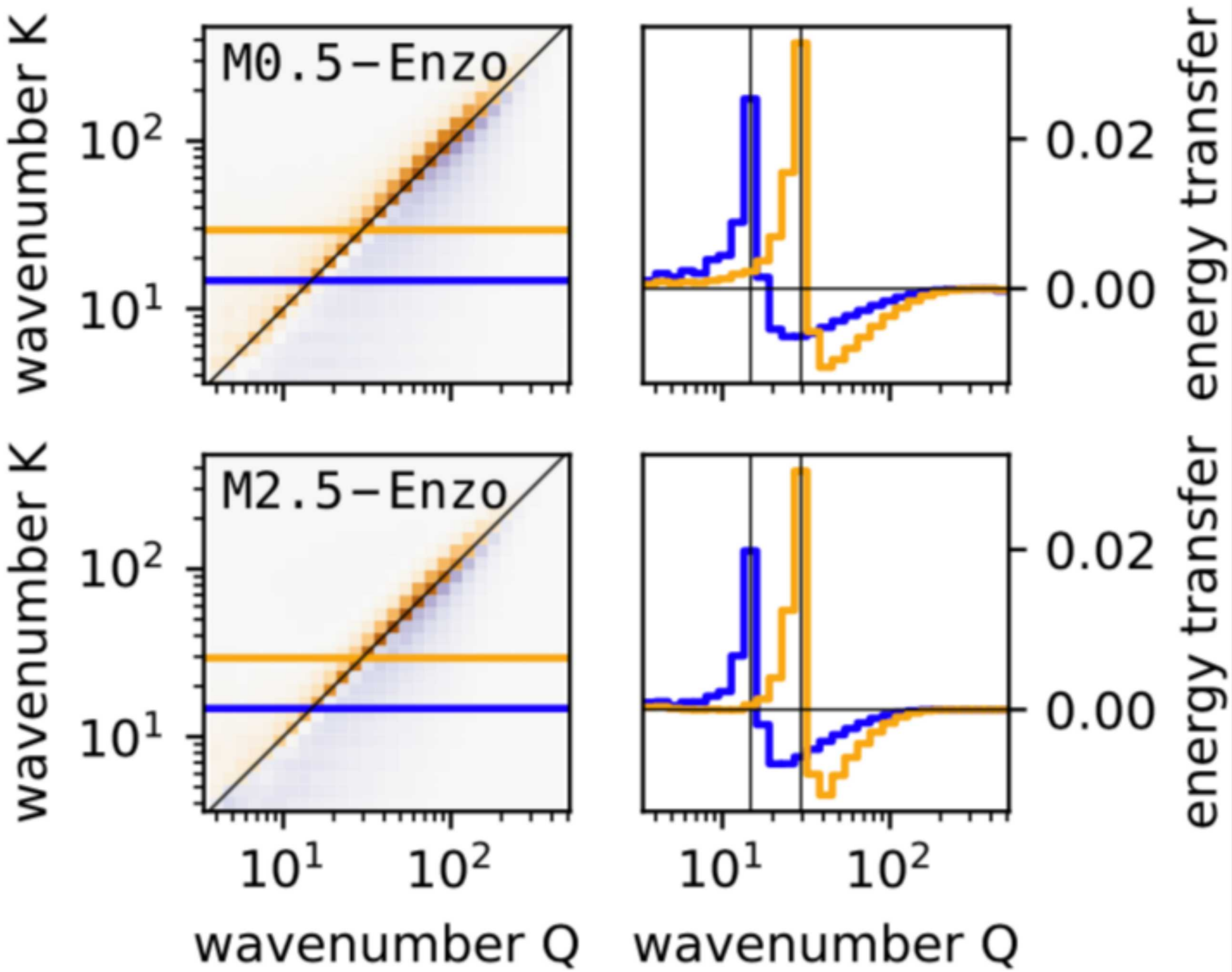



Q
K
(k)
1/L
wavenumberk
1/l_d


Kinetic cascade
M0.5−Enzo
M2.5−Enzo
wavenumber K
wavenumber Q
energy transfer
10^1
10^2
0.05
0.00
−0.05

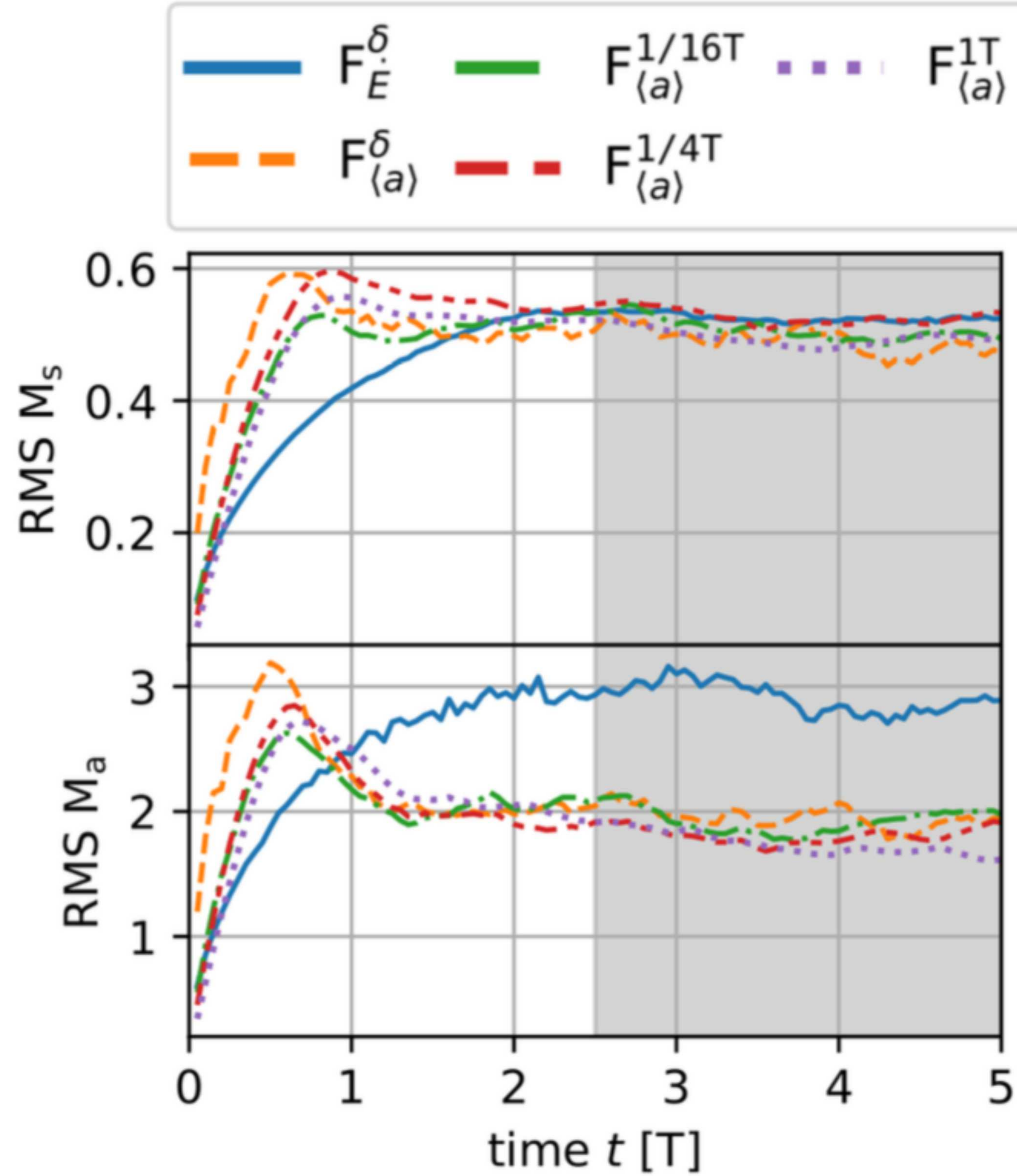
Mag. to kin. by magnetic tension





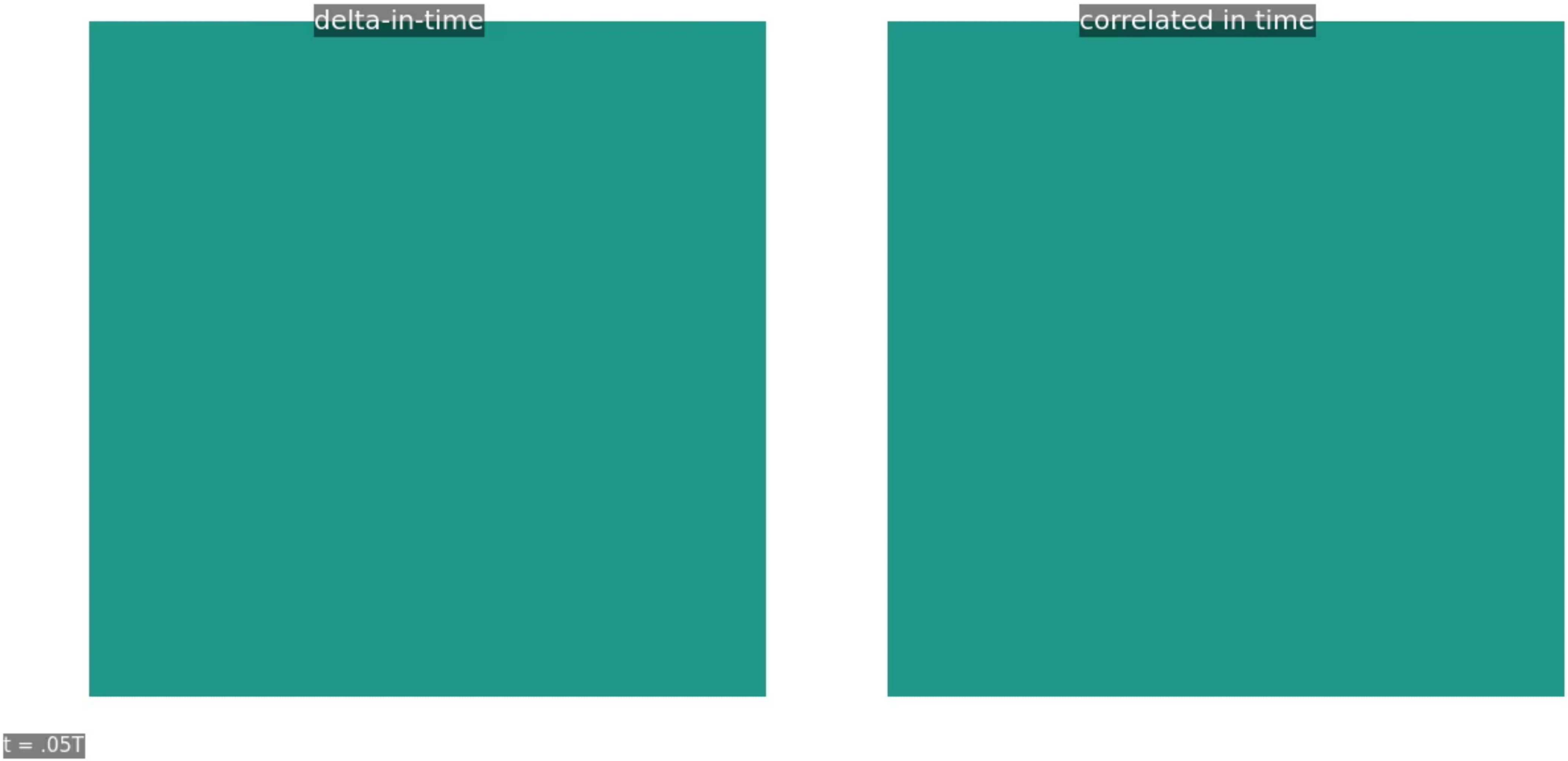
Correlations in isothermal turbulence

- Isothermal, isotropic, homogeneous MHD turbulence
- Subsonic (M_s ~ 0.5), super-Alfvénic
- Solenoidal driving with varying autocorrelation time and normalization.



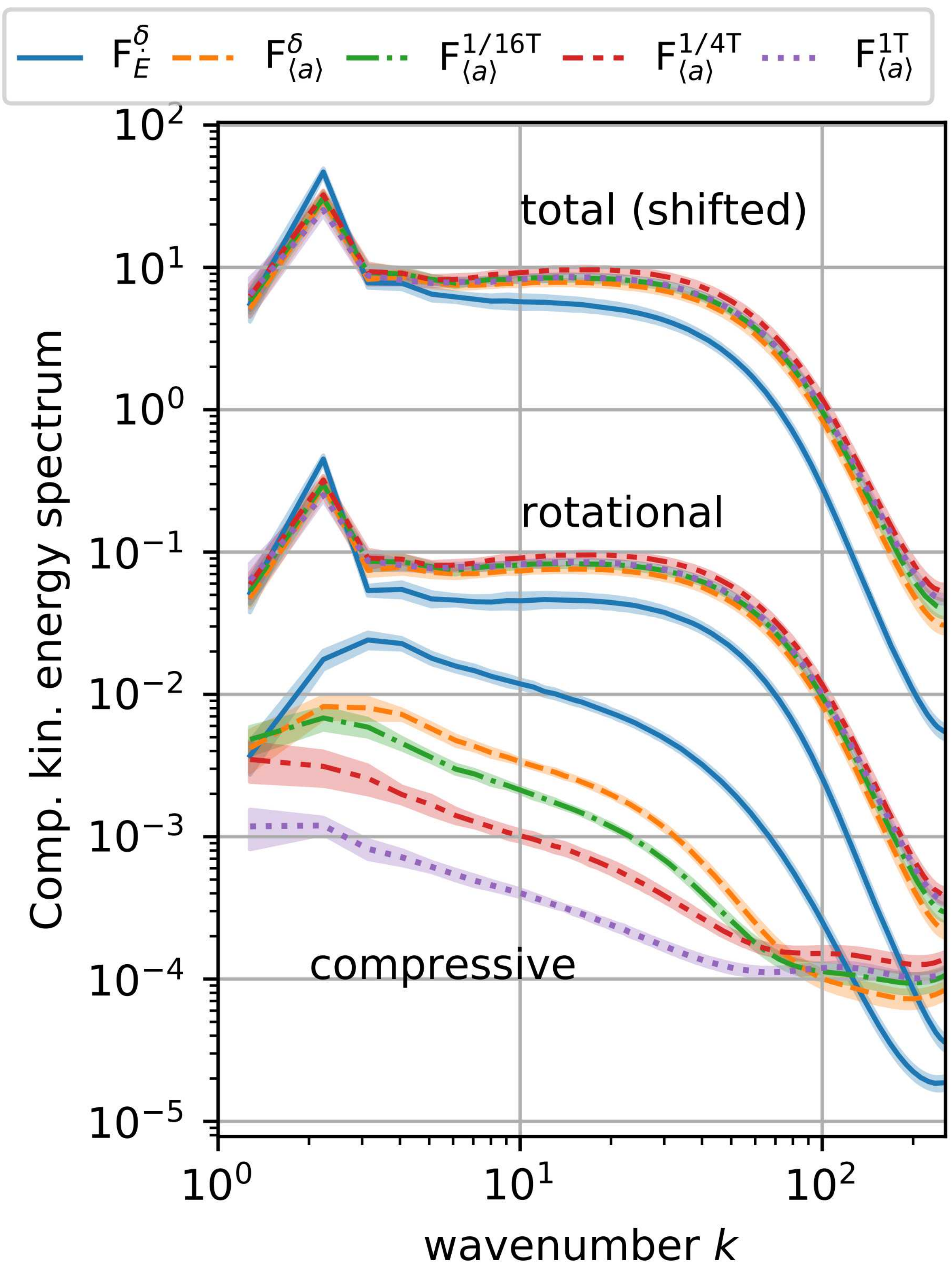
Grete, O'Shea & Beckwith 2018, ApJ Letters

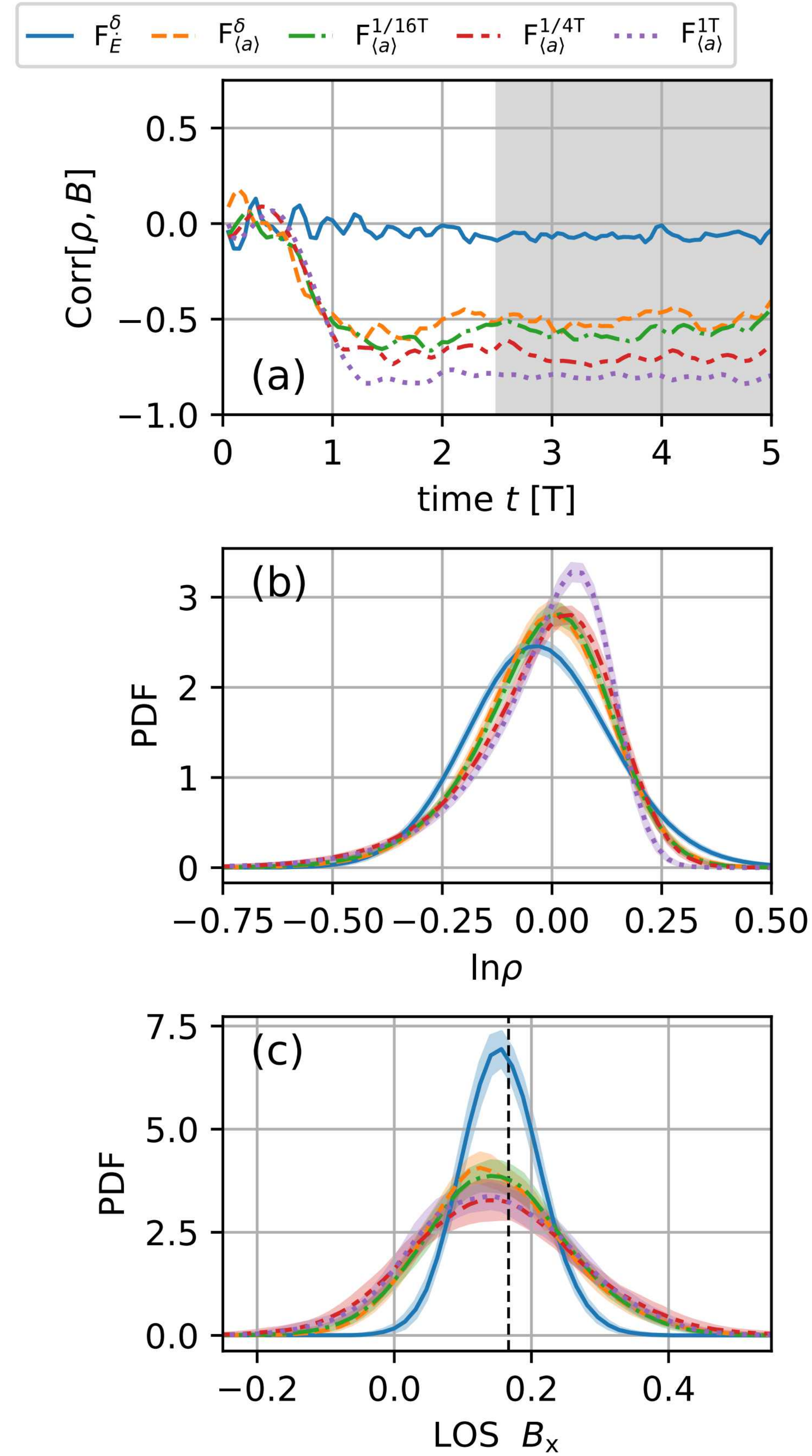
Correlations in isothermal turbulence



Grete, O'Shea & Beckwith 2018, ApJ Letters

Correlations in isothermal turbulence

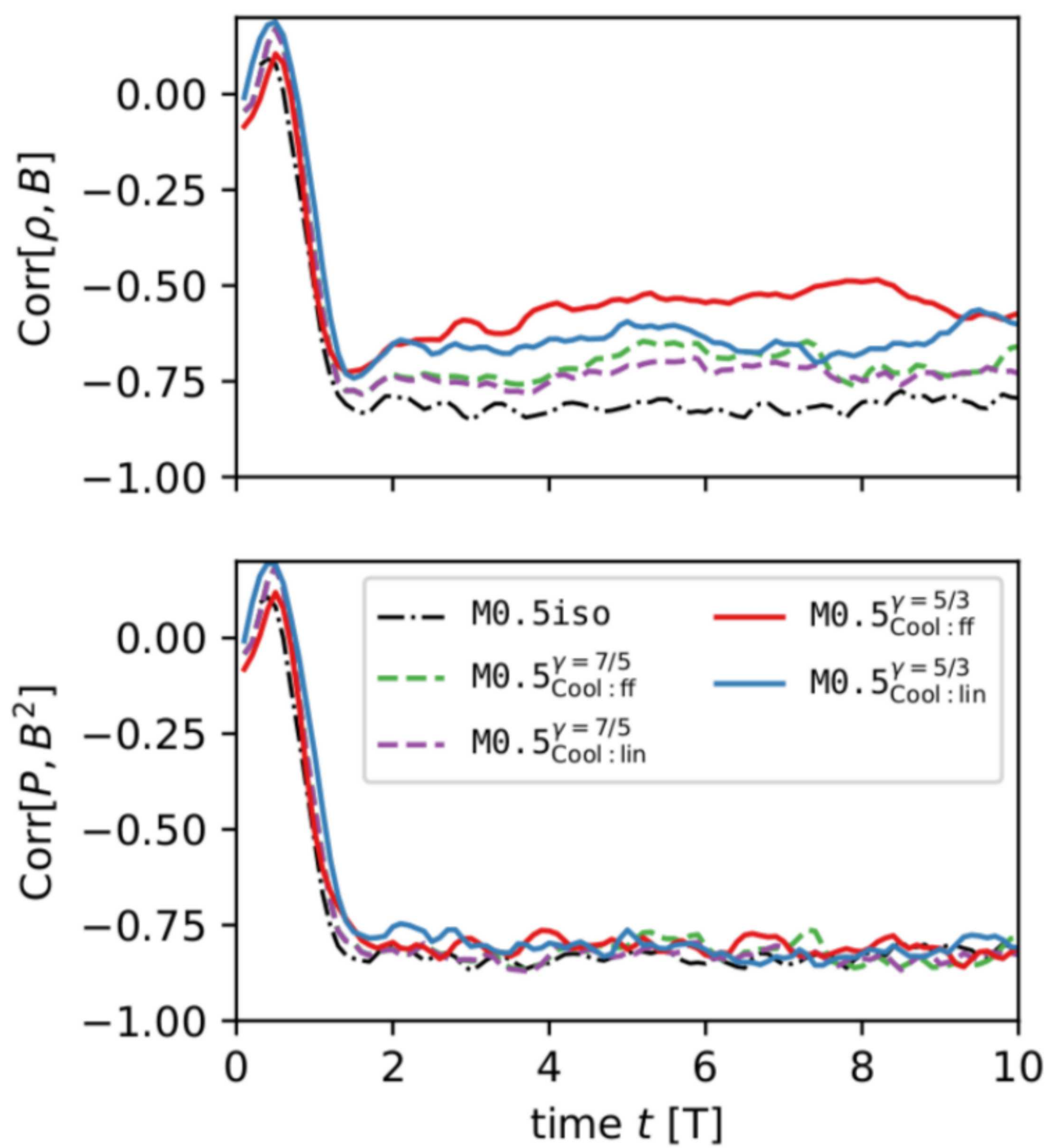




Grete, O'Shea & Beckwith 2018, ApJ Letters

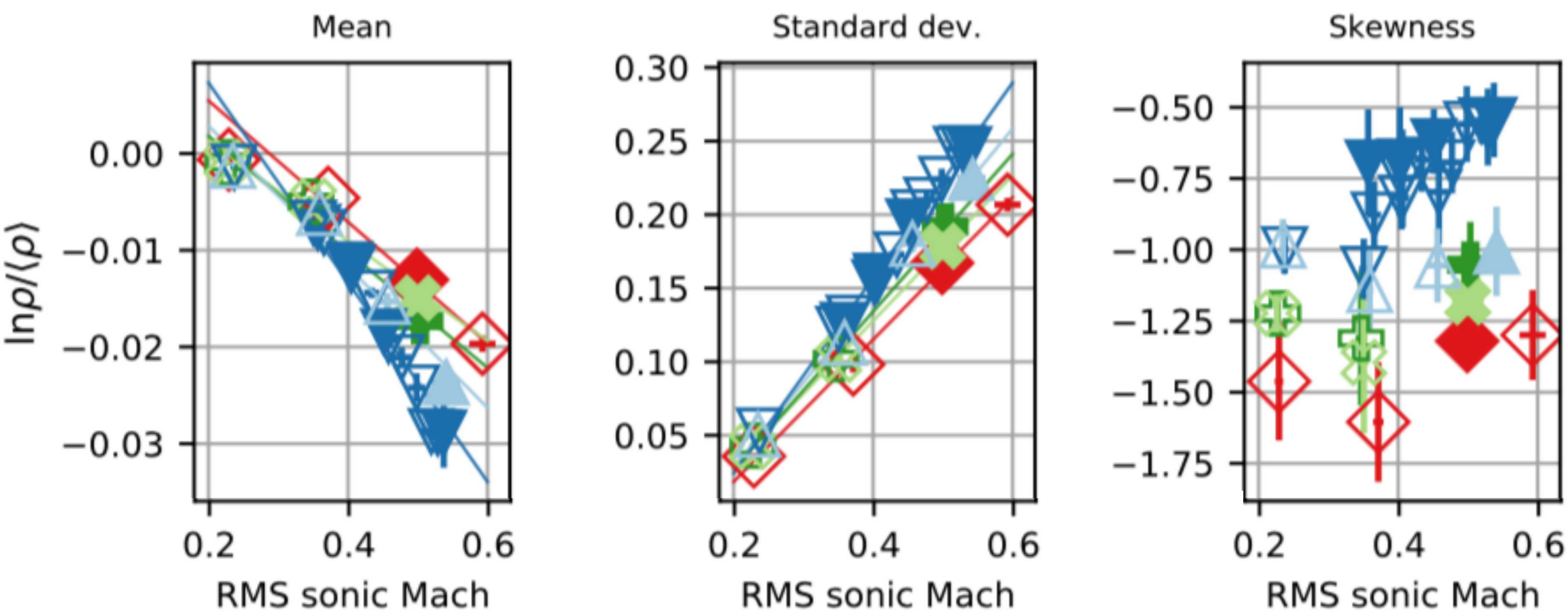
Correlations in adiabatic turbulence

- Subsonic, super-Alfvénic
- EOS: ɣ = 1.0001, 7/5, 5/3
- Cooling:
    - ~Linear: $\mathcal{L} \propto \rho T$
    - ~Free-free: $\mathcal{L} \propto \rho^2 \sqrt{T}$

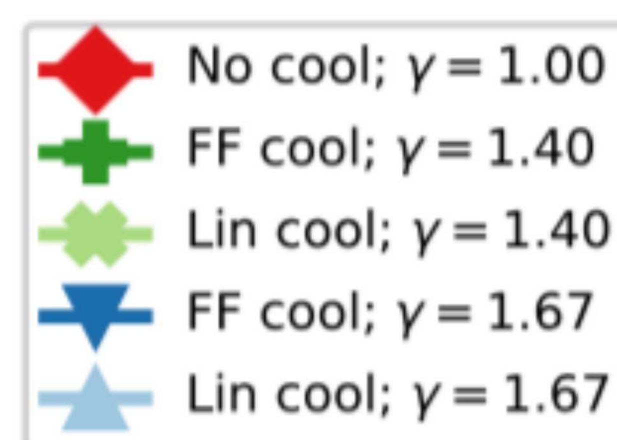


Grete, O'Shea & Beckwith 2019, submitted

Correlations in adiabatic turbulence

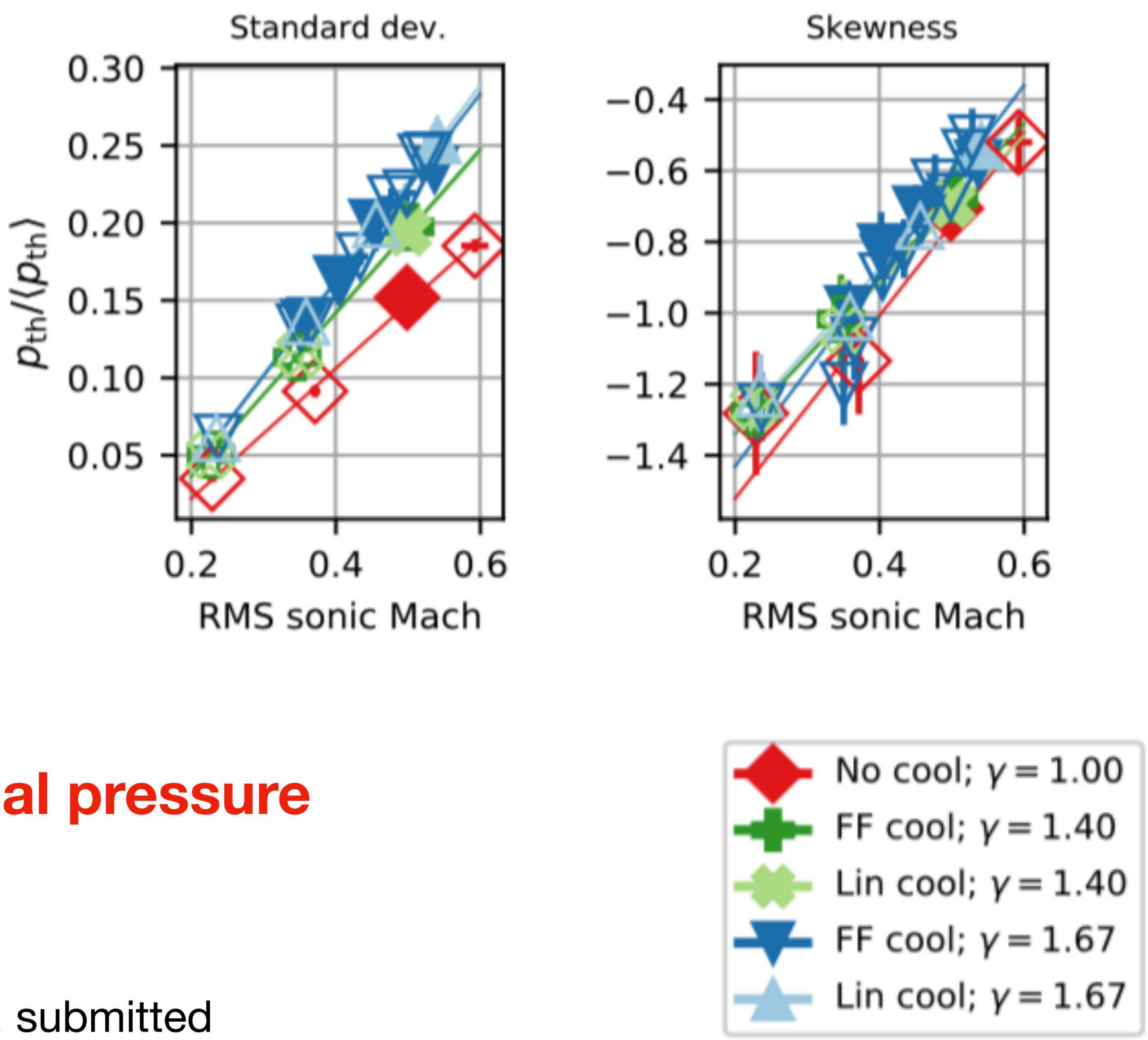


Density



Grete, O’Shea & Beckwith 2019, submitted

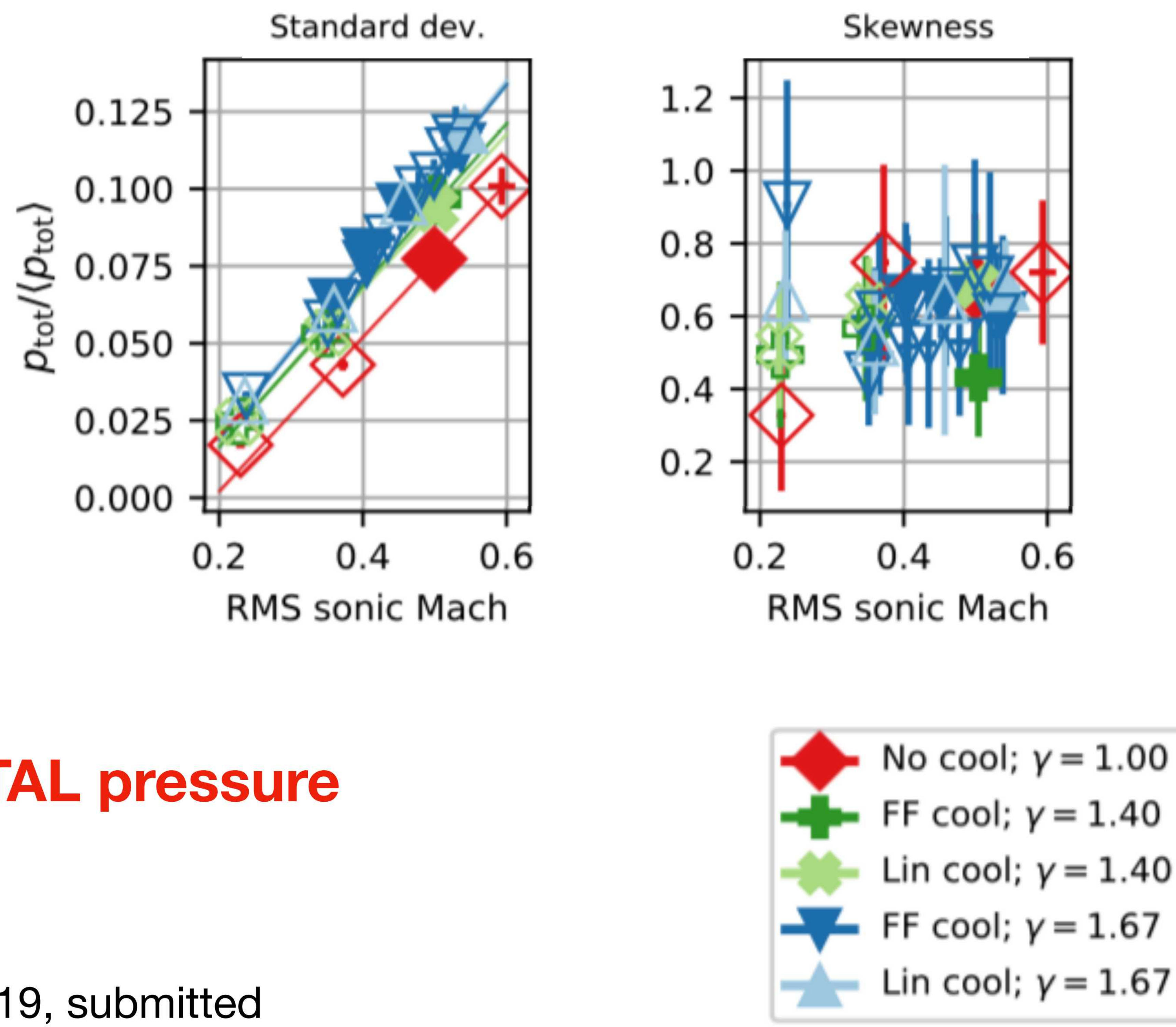
Correlations in adiabatic turbulence



Thermal pressure

Grete, O'Shea & Beckwith 2019, submitted

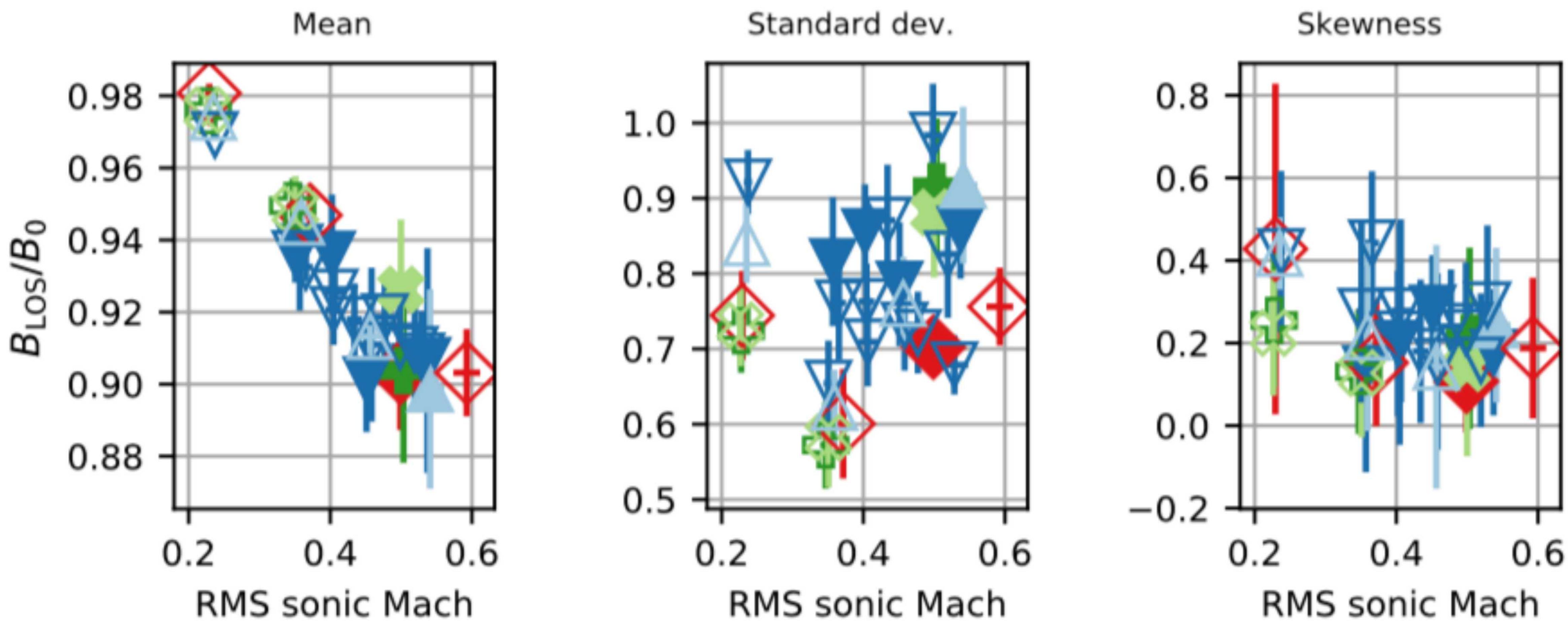
Correlations in adiabatic turbulence



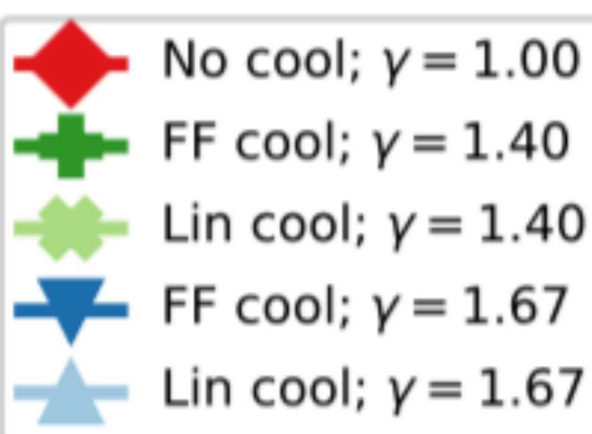
TOTAL pressure

Grete, O’Shea & Beckwith 2019, submitted

Correlations in adiabatic turbulence



Derived line-of-sight magnetic field



Grete, O'Shea & Beckwith 2019, submitted

Future work

- Energy transport in adiabatic turbulence with anisotropic transport (viscosity, conduction)

- Extremely large scale calculations on Summit (with K-Athena, a performance-portable version of Athena++ - Grete, Glines, and O'Shea 2019, submitted)

- Development of MHD subgrid models for application to astrophysical turbulence

Summary

1. Including magnetic fields in turbulence adds channels for energy transport, and thus increases the complexity of analysis.
2. We have developed a **formalism for studying energy transport** in **compressible, magnetized turbulence**, with the goal of developing subgrid-scale (SGS) models for application to a variety of (astro)physical phenomena
3. Statistical properties turbulence are affected by the driving mechanism: longer correlation -> differences in density distribution and density-mag. field correlation -> skewed estimates of magnetic field from Faraday rotation!
4. Examining the effect of varied equations of state shows that many properties have a weak dependence on EOS, but strong dependence on compressibility.

Acnowledgments

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