As a matter of dynamical range – scale-dependent energy dynamics in MHD turbulence

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in collaboration with
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Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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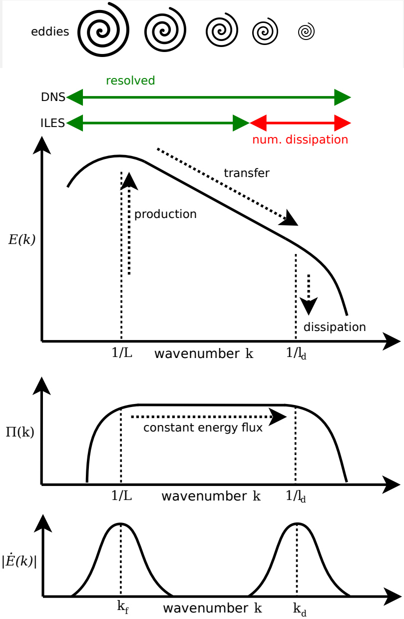
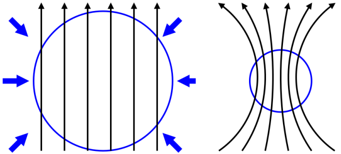
Hydrodynamic turbulence

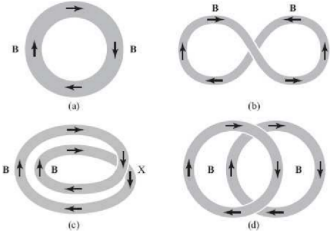
- Basic equations known
- Solutions unknown
- Statistical description for (some) turbulent flows
- Energy cascade from larger to smaller scales ("eddies break up")
- Energy **flux across scales is constant**
- Kolmogorov $-5/3$ **slope**



Video credit: Gabe Weymouth/YouTube

Magnetohydrodynamic (turbulence)

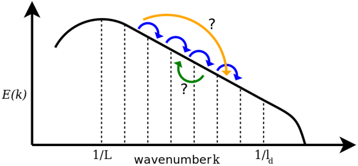




[Dynamo image credit: Vainshtein & Zel'dovich '72]

- "Frozen-in" magnetic field lines
- Magnetic tension
- Magnetic pressure
- Rich interaction between kinetic and magnetic energy budgets

$\Rightarrow$ Study energy transfers

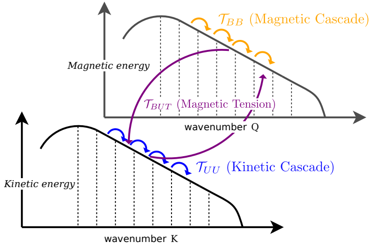


- Energy transfers
  - Energy cascade
  - Inverse transfer
  - Nonlocal transfer

Eddies in motion

[Grete+ Phys. Plasmas 2017]

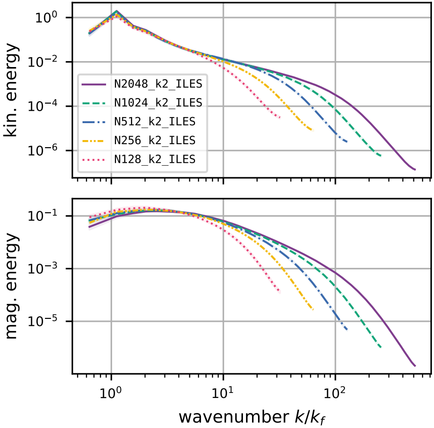
- Driven MHD turbulence (here highlighting rotational motion)
- Study scale-wise energy transfers by various mediators



"Convergence" in numerical simulations

[Grete, O'Shea & Beckwith
to be submitted any day]

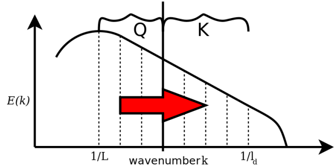
- Reminder:
  - DNS: direct numerical simulation (all scales resolved)
  - ILES: implicit large eddy simulation (large and interm. scales resolved)



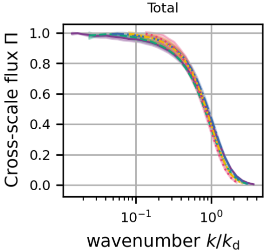
- Typical convergence plot ("identical" simulation with increased res.)
- Subsonic, super-Alfvénic, high β
- NB: Slope in E_{kin} is -4/3 not Kolmogorov -5/3 [Grete+2021]

Cross scale fluxes

[Grete, O'Shea & Beckwith
to be submitted any day]



- Energy flux from all scales larger than k to all smaller scales
- Reminder: constant in hydrodynamics



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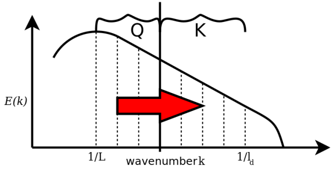

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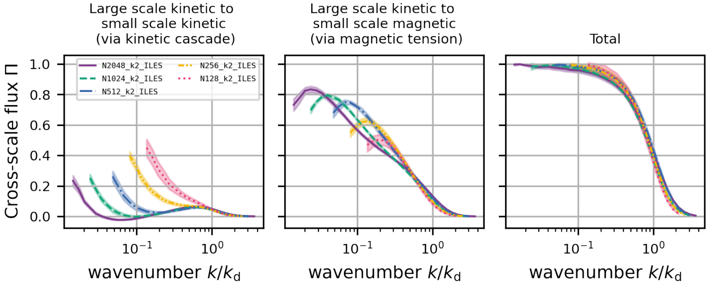
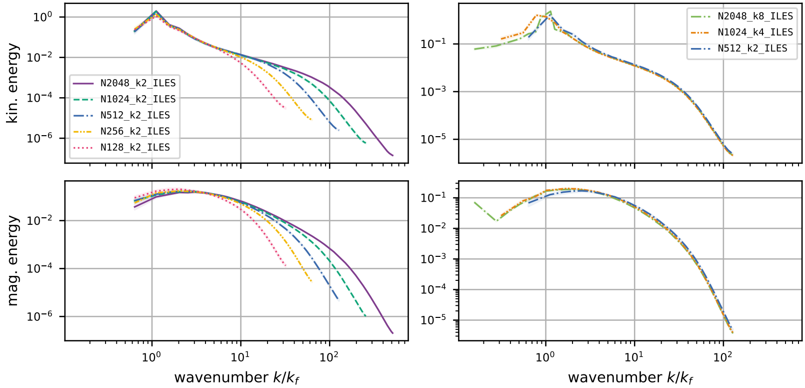


$\Rightarrow$ Individual transfers **not** constant in MHD

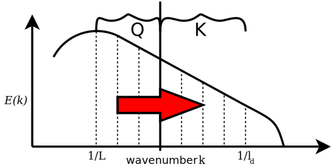
$\Rightarrow$ Individual transfers **vary** with res./dynamical range/Reynolds num.

Comparing simulation with identical "dynamical range"

- Forcing at smaller scales with increasing resolution
- Scale separation between forcing scales and dissipative scales const.



Cross scale fluxes for identical dynamical range



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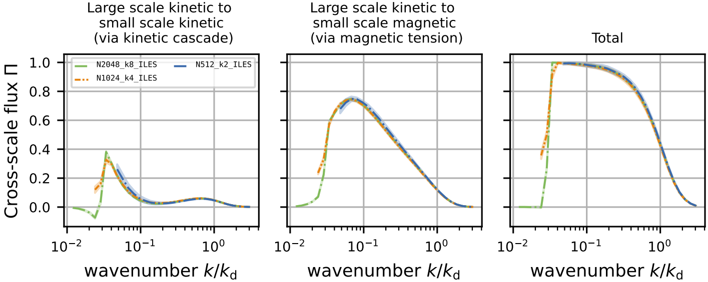

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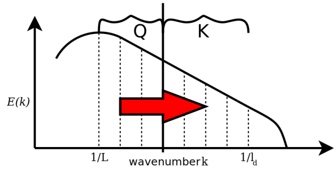

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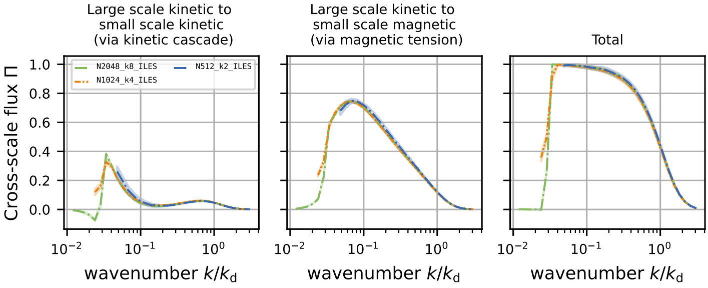
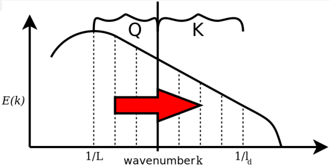


$\Rightarrow$ Individual transfers **not** constant in MHD

Cross scale fluxes for identical dynamical range



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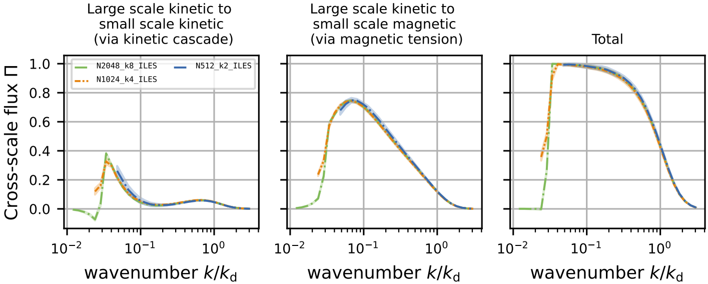
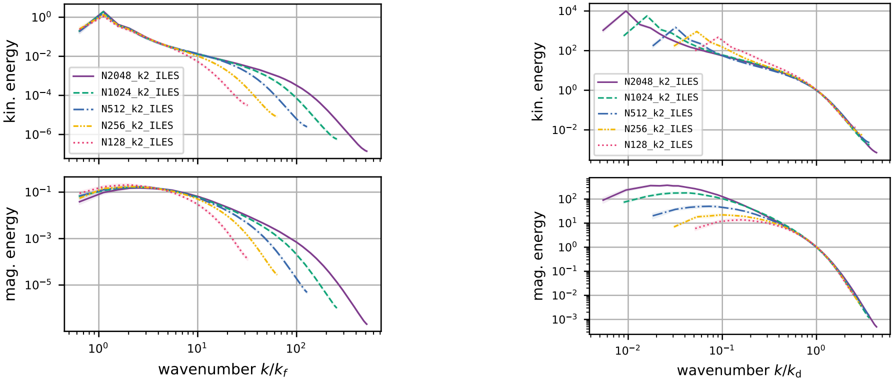


$\Rightarrow$ Individual transfers **not** constant in MHD

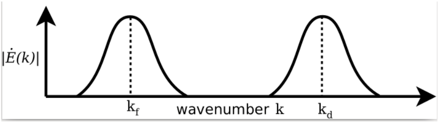
$\Rightarrow$ Individual transfers **const.** for fixed dynamical range

Convergence in numerical simulations (revisited)

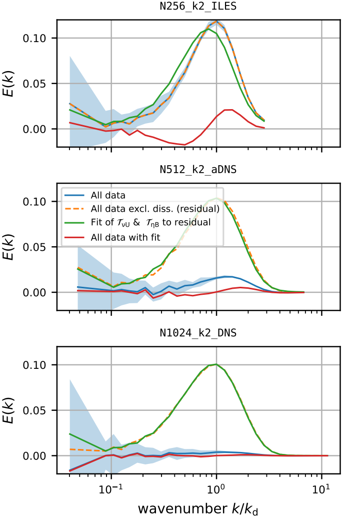


- Same data normalized to
  - forcing/largest scales (left) and dissipative scales (right)
- Dissipative scales are "converged" but overall dynamics are **not**

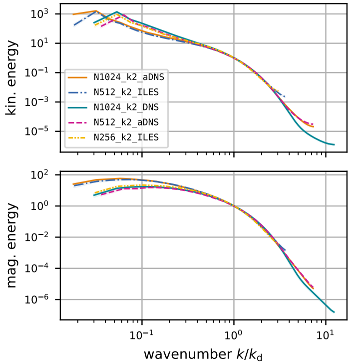
Estimating eff. dissipation in simulations

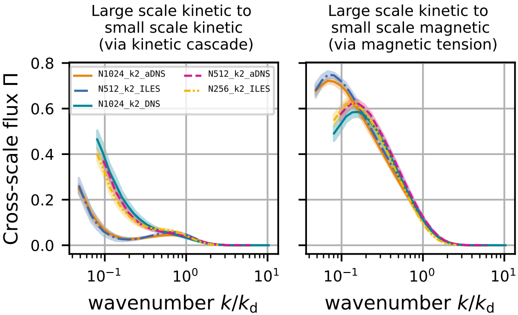


- Rate of change on each scale should be 0
- Residual of $\left|\dot{E}(k)\right|$ is numerical dissipation
- Calc. dissipative losses as if present
- Fit losses to residual to determine coeff.



ILES vs. DNS





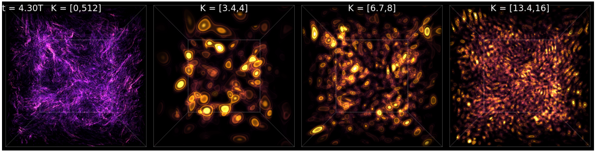
- It's a match!
- Using ILES* is fine for turbulence
  (*) for given set of methods

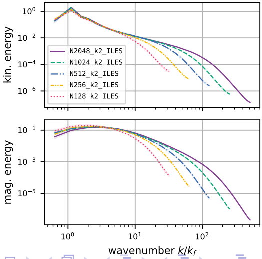
Conclusions, Questions & Outlook I

- Dynamics in MHD are fundamentally different than in HD turbulence
- Convergence may not be what you think it is
- Individual transfers **const.** for fixed dynamical range
- Individual transfer **not** constant in MHD
- "Dynamical range" in astrophysics is significantly larger

$\Rightarrow$ Is there an asymptotic regime (and what does it look like)?

$\Rightarrow$ Are we not resolving MHD turbulence yet even at 2048^3?





Conclusions, Questions & Outlook II

- Exascale supercomputers/codes:

  `Athena++`: (astrophysical) MHD code

\+ `Kokkos`: C++ parallel programming model

\+ `Parthenon` [Grete+ arXiv:2202.12309]

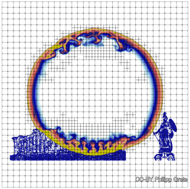
  - Performance portable
    adaptive mesh refinement framework
  - Open collaboration (10+ developers)

= `AthenaPK`

  - Open source MHD physics code
  - Speedup already >10x with AMR
  - AGN, cloud crushing, turbulence...

⇒ Get involved!

(Please contact me directly, if you are interested in the scaling plot that was shown here.)



Third order MHD on Frontier

- 1024^3 on two nodes in 4h
- $16{,}384^3$ in $\approx$ 2 days