MHD Turbulence in Partially Ionized Gas and the Astrophysical Applications

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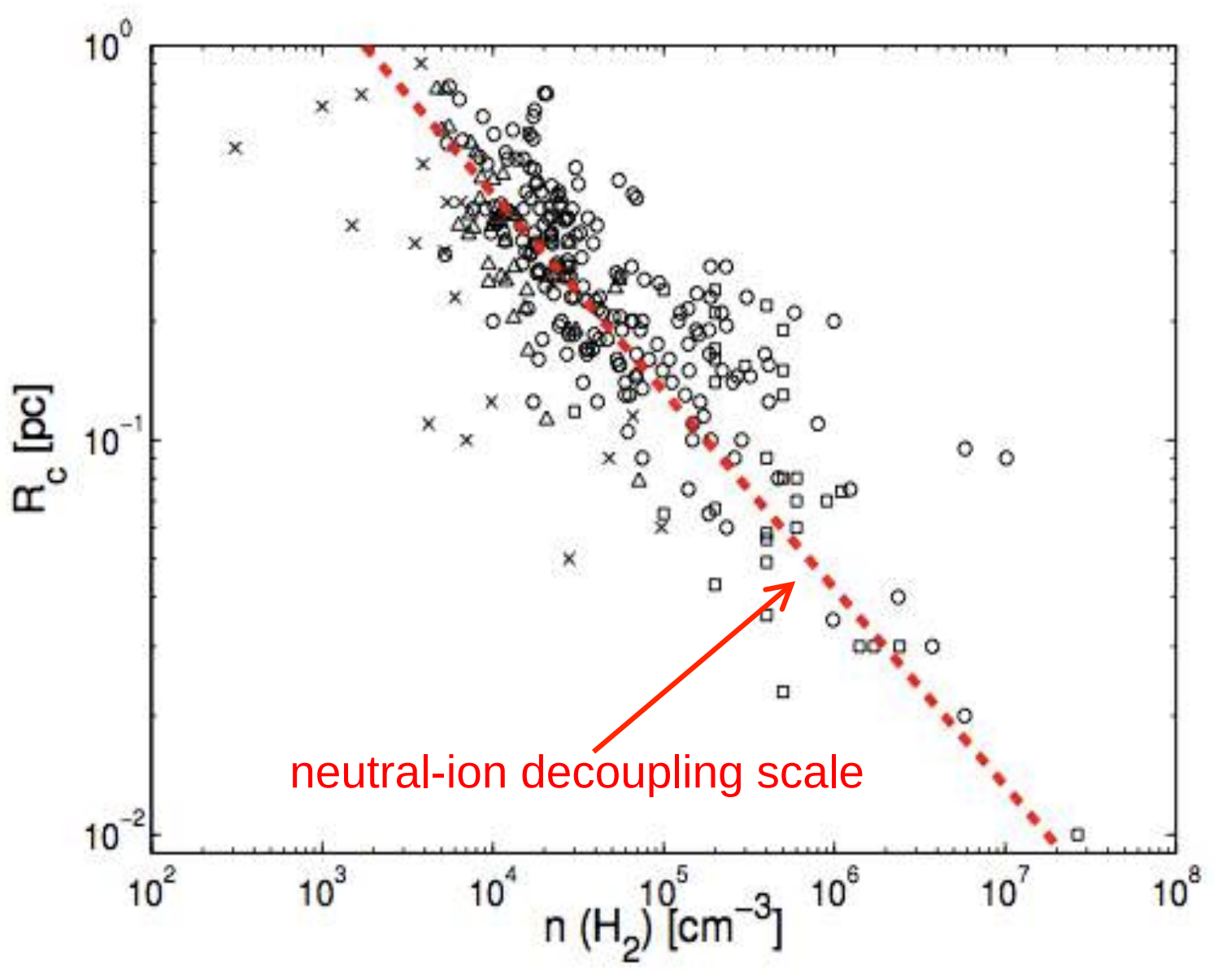
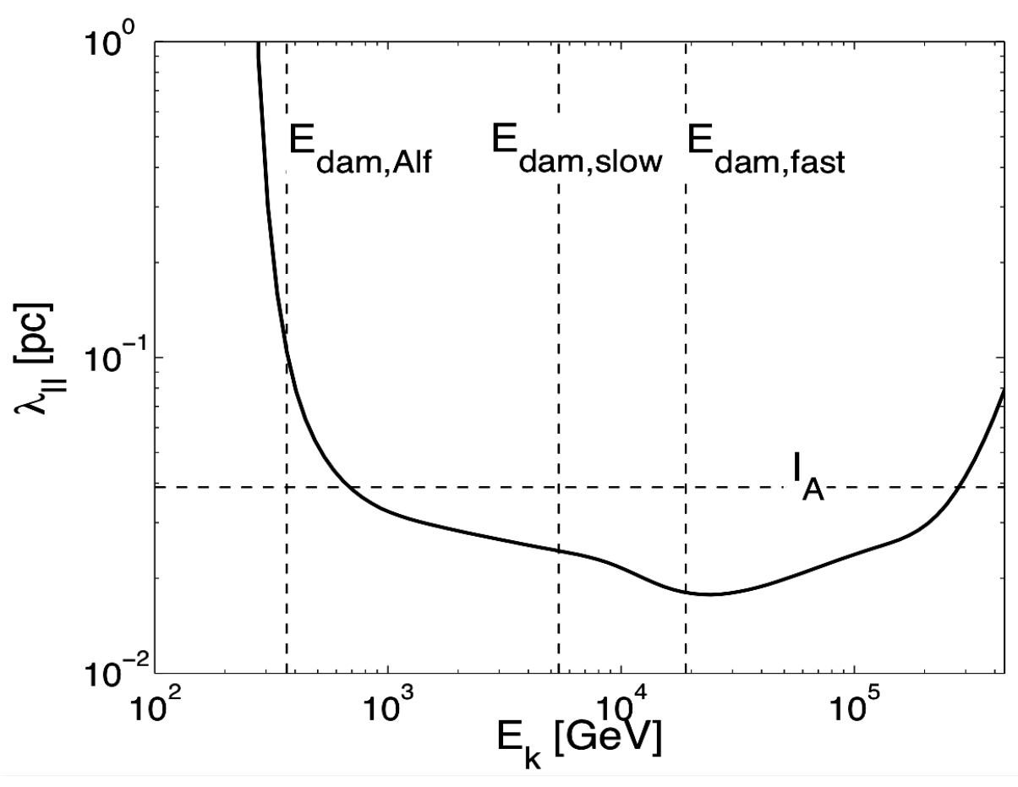
Application I: formation of filaments and cores in molecular clouds (MCs)

- ✧ Both magnetic field and turbulence are influential in fragmenting molecular clouds.
- ✧ Under the consideration of turbulent energy cascade, the formation of filaments and cores is tightly correlated.
- ✧ Filaments form from a joint effect of the collapse along magnetic field lines and contraction across field lines which is enhanced by *turbulence anisotropy* and *reconnection diffusion.*
- ✧ The fragmentation scale of nascent cores is characterized by the neutral-ion decoupling scales of Alfven and fast modes, where a localized isotropic collapse is triggered due to the evacuation of magnetic support.



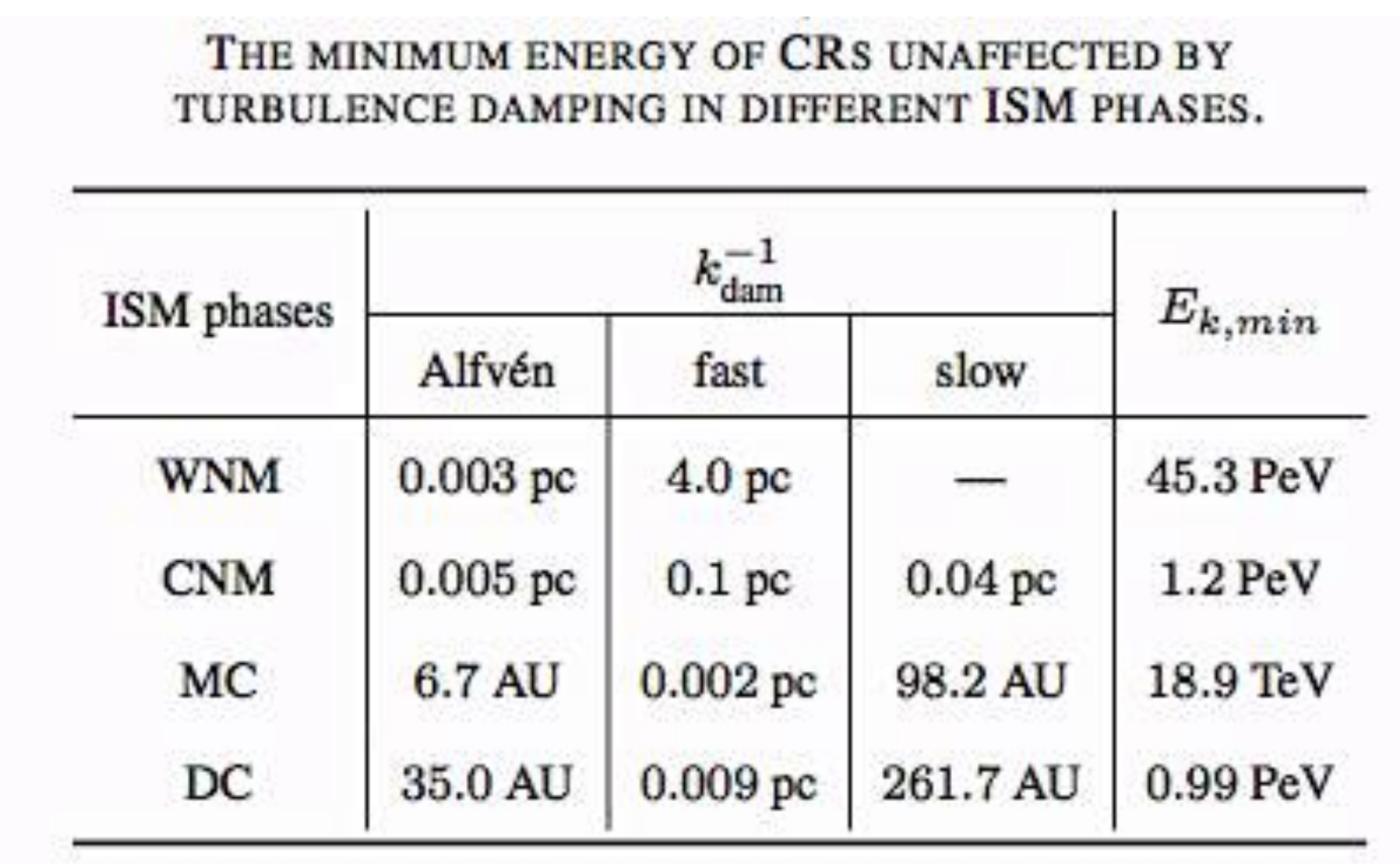
Direct comparison between neutral-ion decoupling scales and sizes of 286 infrared dark cloud cores shows a good consistency over a wide range of densities and core sizes.

Application II: propagation of cosmic rays (CRs)



Parallel mean free path of CRs vs. energies

- The scattering frequency of both transit-time damping (TTD) and gyroresonance (GR) with fast modes decrease with CR energy. GR with Alfven modes increases with energy.
- Turbulence is damped out at a large scale where turbulence anisotropy is weak. Hence Alfven modes can be more efficient than fast modes in GR scattering of high-energy CRs.



THE MINIMUM ENERGY OF CRS UNAFFECTED BY TURBULENCE DAMPING IN DIFFERENT ISM PHASES.

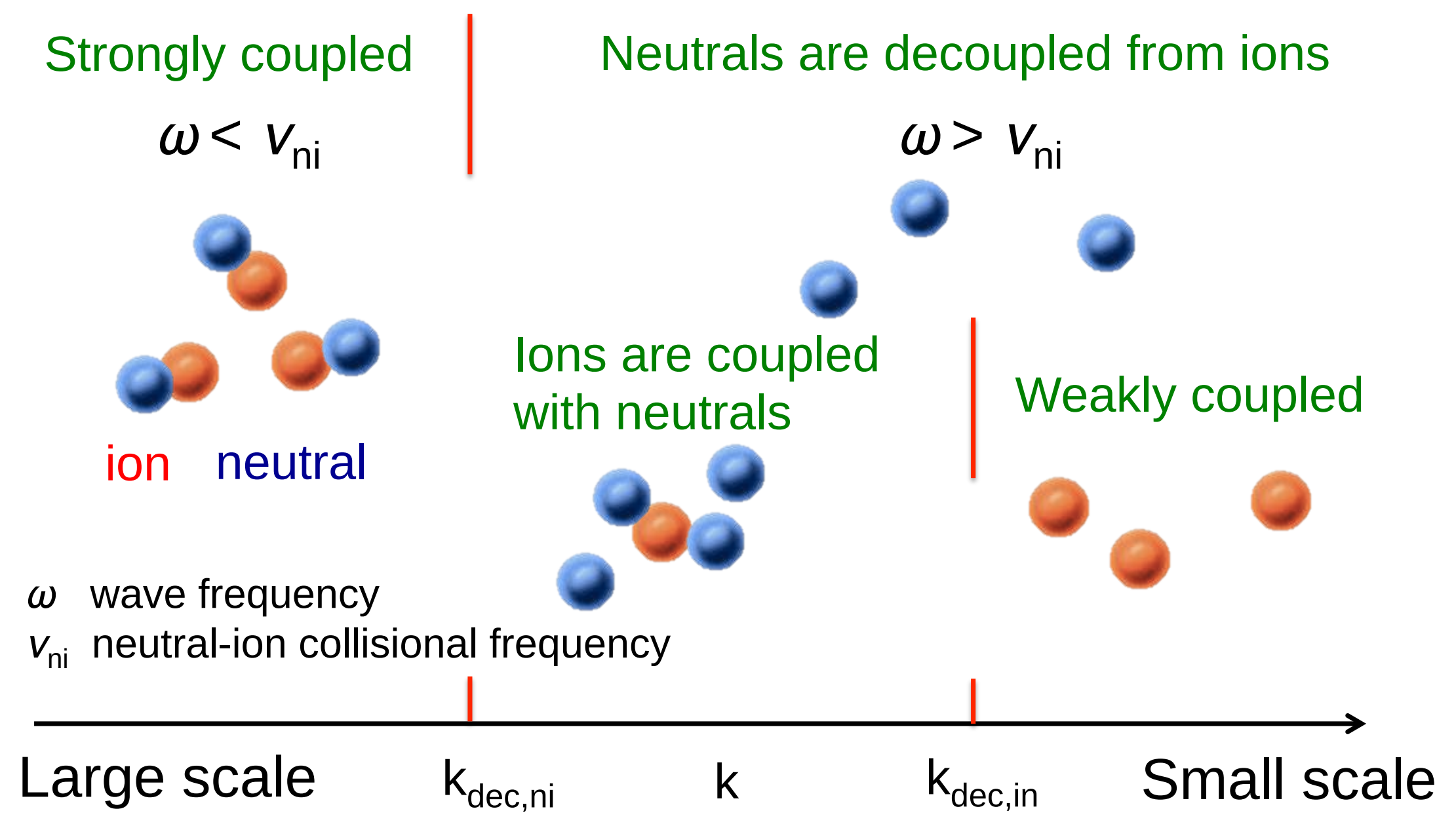
ISM phases	k_{dam}^{-1}			$E_{k,min}$
	Alfvén	fast	slow	
WNM	0.003 pc	4.0 pc	—	45.3 PeV
CNM	0.005 pc	0.1 pc	0.04 pc	1.2 PeV
MC	6.7 AU	0.002 pc	98.2 AU	18.9 TeV
DC	35.0 AU	0.009 pc	261.7 AU	0.99 PeV

Turbulence damping significantly affects CR scattering when their energies are below the boundary energies given in above table.

MHD turbulence in partially ionized gas

Introduction

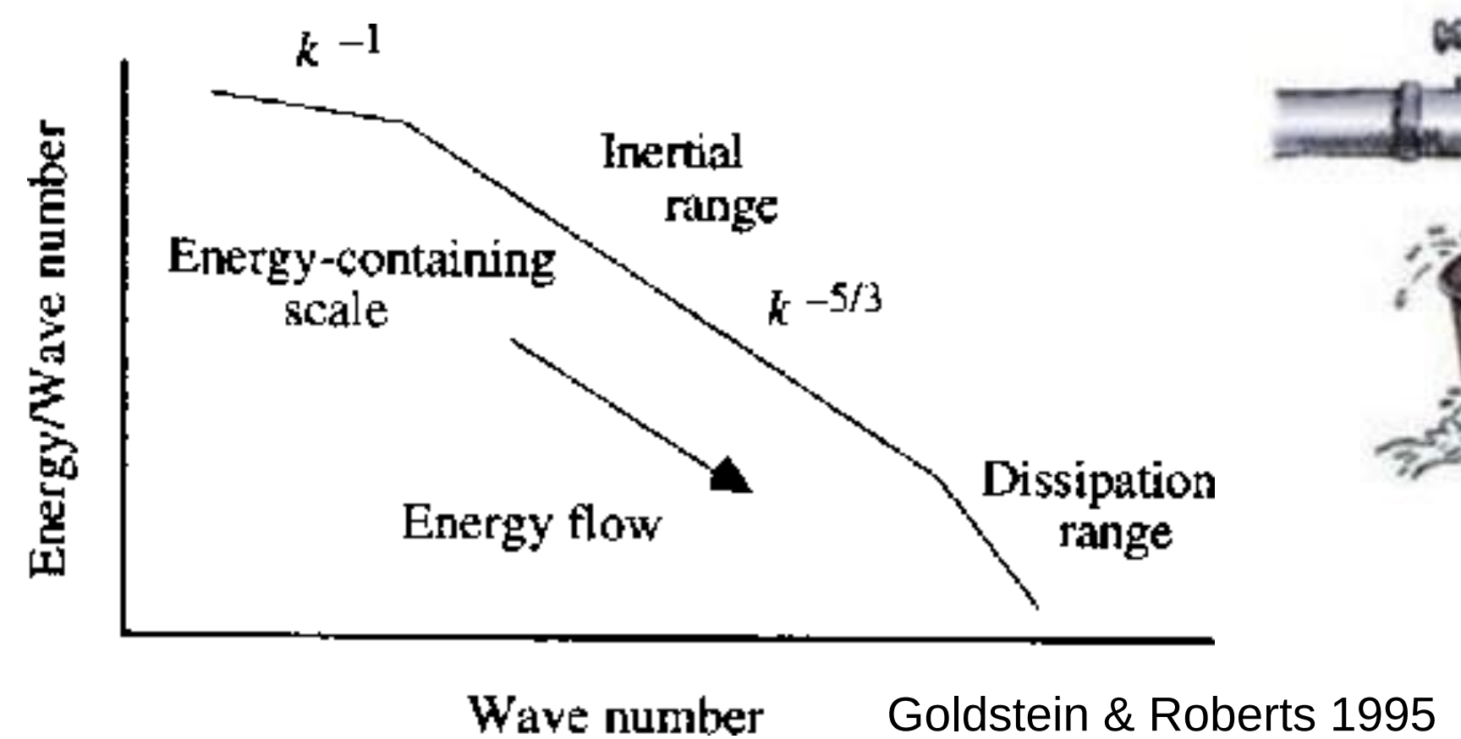
The interstellar medium is turbulent and magnetized, and contains substantial fractions of neutral particles. The presence of neutrals affects the plasma dynamics indirectly, mediated by the friction between ions and neutrals. The theory of magnetohydrodynamic (MHD) turbulence in partially ionized gas should be constructed under the consideration of collisional damping effect. The output of this theory has a wide range of astrophysical applications, from star formation to cosmic ray propagation.



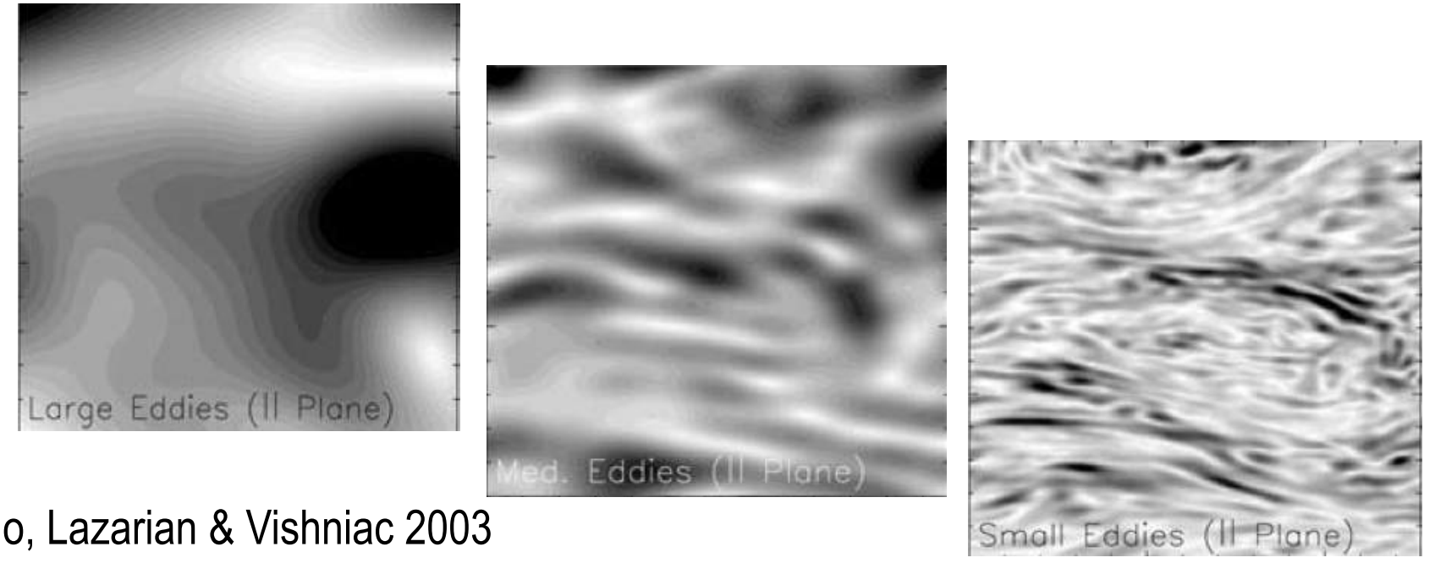
Coupling state between neutrals and ions vs. scales

● *Turbulence cascade and scaling*

Turbulent energy cascades down from large to small scales at the eddy turnover rate.



Goldstein & Roberts 1995



Cho, Lazarian & Vishniac 2003

Anisotropy of MHD turbulence increases with decreasing scales.

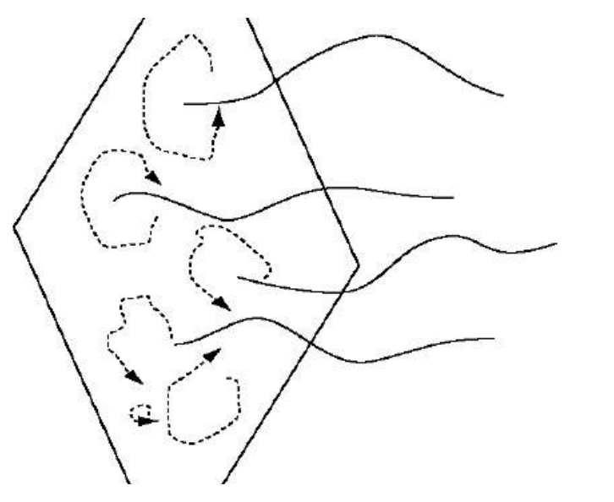
● *Turbulence damping*

1. Derive the dispersion relations from basic MHD equations by linear stability analysis.

2. Analytically solve the dispersion relations in strongly and weakly coupled regimes.
The propagation and dissipation of MHD waves strongly depend on the coupling state between neutrals and ions.

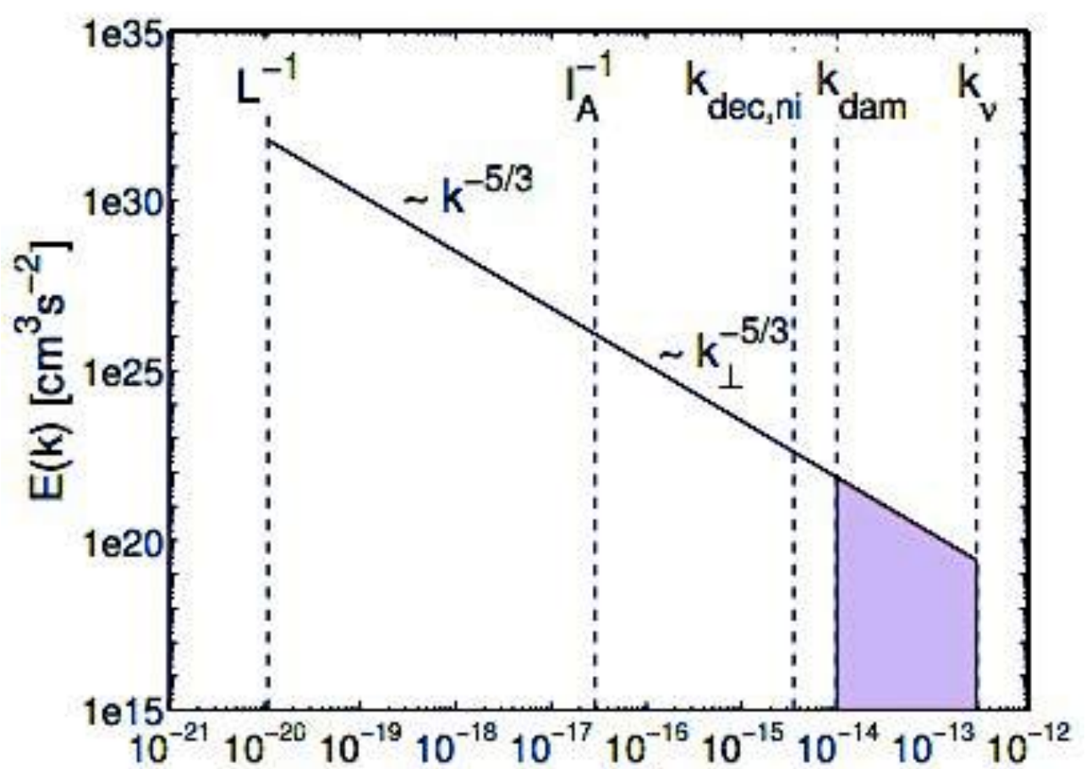
3. The imaginary part of wave frequency is negative, and represents the exponential damping rate of MHD waves.

4. At the damping scale where energy cascade rate is exceeded by energy damping rate, turbulence cascade is cut off.



Turbulence damping is connected with wave damping by the **critical balance** between the eddy-like motions $\perp \vec{B}$ and wave-like motions // $\vec{B}$ of MHD turbulence.

Application III: different linewidths of coexistent neutrals and ions



(Xu, Lazarian & Yan 2015)

Turbulent energy spectra of neutrals and ions have different damping scales

- ➢ Neutral-ion linewidth difference (LD) can be explained by differential damping of the Alfvenic turbulence in ions and hydrodynamic turbulence in neutrals.
- ➢ Quantitative descriptions of LD and its dependence on magnetic field strength vary in different turbulent regimes.
- ➢ We proposed new methods of measuring magnetic fields from LD, which require additional procedure for identifying turbulence regime from more observational inputs to ensure reliable magnetic field estimates.

Application IV: small-scale dynamo in partially ionized gas

Small-scale dynamo converts the turbulent kinetic energy into magnetic energy. Its efficiency depends on the neutral-ion coupling degree, i.e., ionization fraction.

Evolution regimes of magnetic energy
in partially ionized gas with different ionization fractions

Low ionization fraction

Diffusion-free	Viscous	Damping	Nonlinear
$e^{2\gamma t}$	$e^{\gamma t/3}$	t^2	t

Intermediate ionization fraction

Diffusion-free	Viscous	Nonlinear
$e^{2\gamma t}$	$e^{\gamma t/3}$	t

High ionization fraction

Diffusion-free	Nonlinear
$e^{2\gamma t}$	t

Remarks

A proper treatment of MHD turbulence is the essence of this investigation. MHD turbulence theory has been remarkably advanced since Goldreich & Sridhar (1995), with its many intrinsic features including scale-dependent anisotropy, fast magnetic reconnection revealed and confirmed via highly-resolved 3D numerical simulations.

On the established ground of MHD turbulence in fully ionized gas, we construct the MHD turbulence theory in partially ionized gas by fully examining the damping process in the presence of neutrals.

This study can be applied broadly to different branches of astrophysics and reform our understanding of many fundamental interstellar processes.

Relevant publications

Xu, S., Lazarian, A., & Yan, H. 2015, ApJ, 810, 44
Xu, S., Yan, H., & Lazarian, A. 2015, arXiv: 1506.05585
Xu, S., & Yan, H. 2013, ApJ, 779,140

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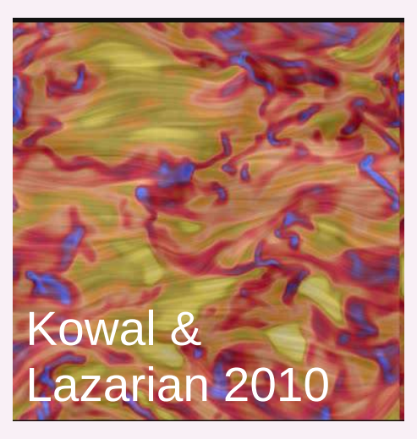

Kowal & Lazarian 2010