What astronomers want to know about turbulence

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Astronomy & Physics and Center for Magnetic Self - Organization in Astro and Lab Plasmas

UW Collaboration:
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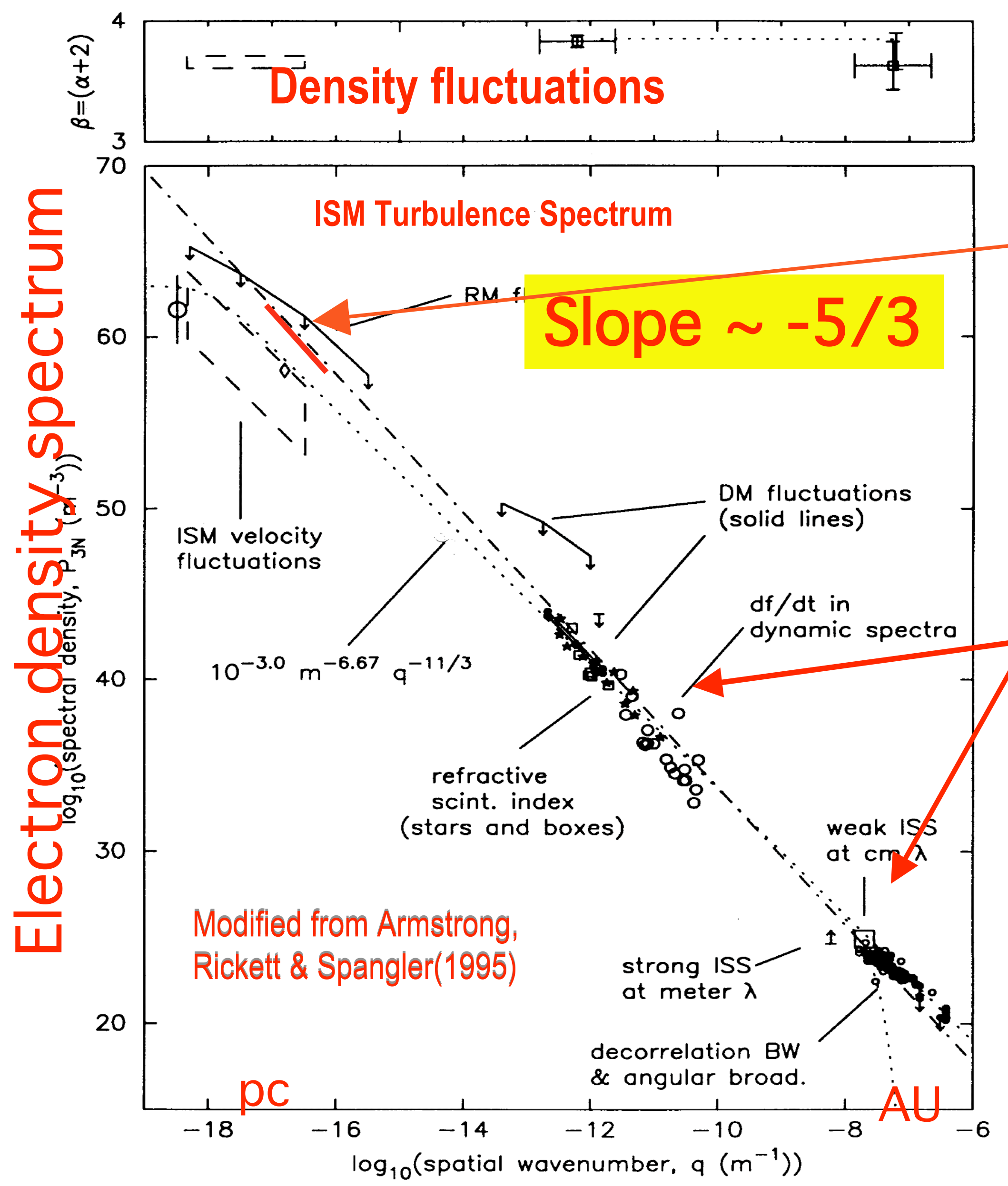
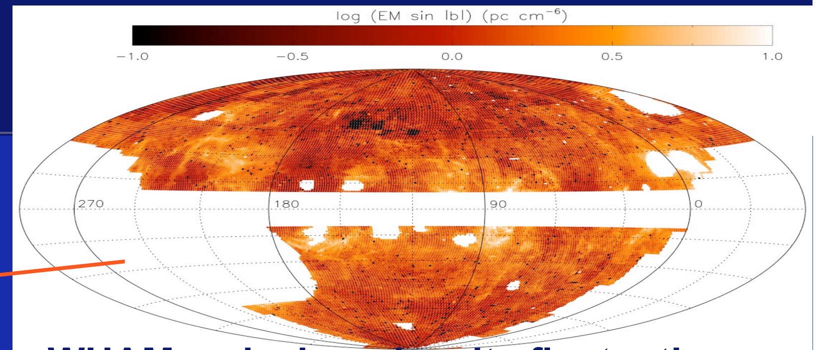
Kowal G.

THE UNIVERSITY of WISCONSIN MADISON

Jayalakshimi Satyendra

ISM observations correspond to Kolmogorov spectrum of density fluctuations.





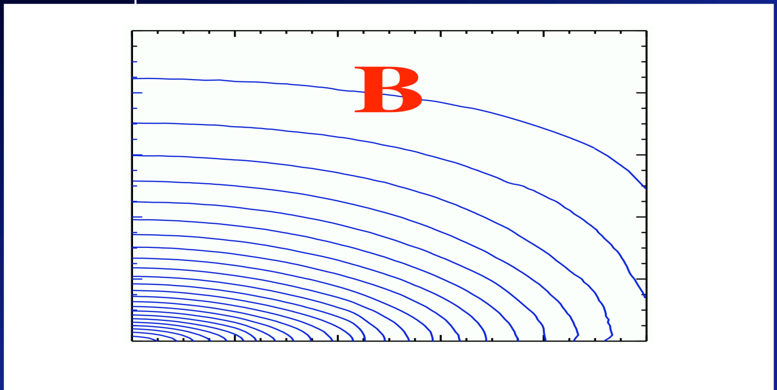
WHAM emission: density fluctuations

Chepurnov & Lazarian 2008

Scincillations and scattering

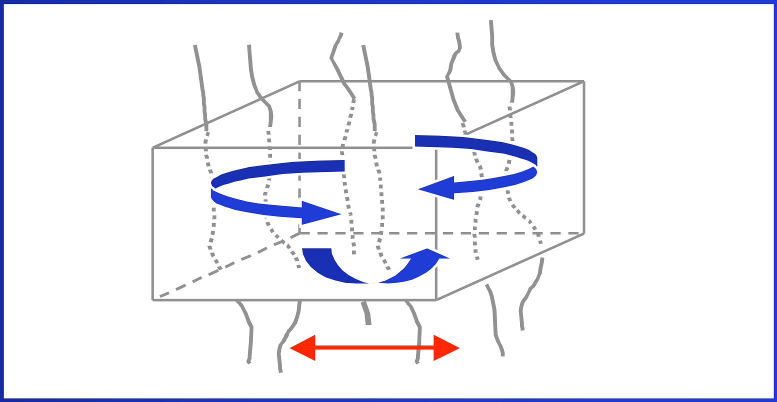
This presentation provides a broad outlook at astrophysical turbulence

Weak, strong, imbalanced regimes



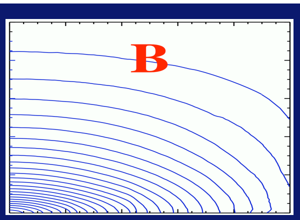
Basic MHD

Partial ionization, collisionless



More Physics

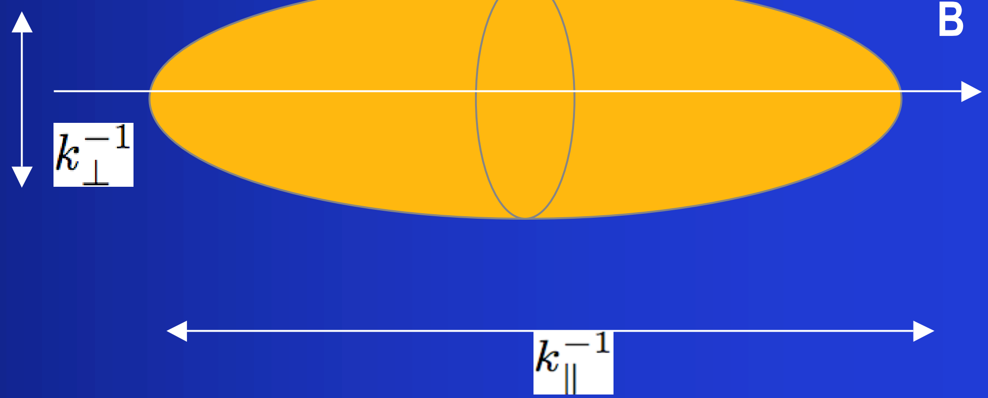
Incompressible MHD turbulence can be weak if $V_L < V_A$, strong for $V_L = V_A$. Weak gets strong at some l<L.



Basic MHD

Turbulent cascade is anisotropic (see Higdon 86, Goldreich & Sridhar 95, 97).

Anisotropic eddy

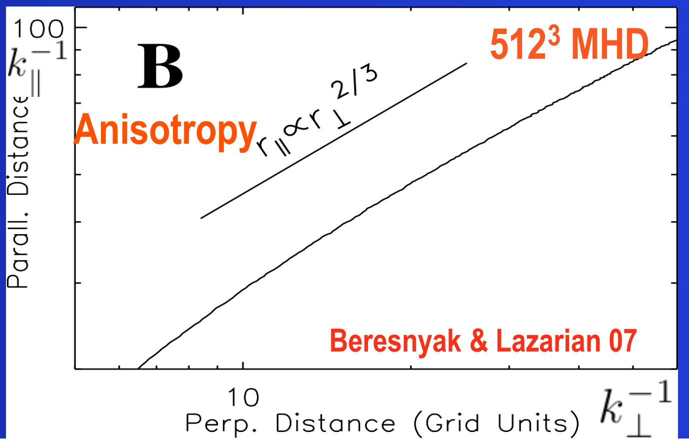


$$\frac{\text{Shearing rate}}{\text{Propagation rate}} = \frac{k_\perp V_k}{k_\parallel V_A}$$

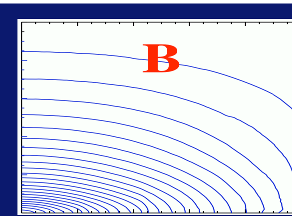
$k_\perp V_k < k_\parallel V_A$ turbulence is weak with spectrum $E(k) \sim k_\perp^{-2}$ and $k_\parallel \sim const$ (see Gaultier et al. 00).

$k_\perp V_k \sim k_\parallel V_A$ turbulence is strong with $E(k) \sim k_\perp^{-5/3}$ and $k_\parallel \sim k_\perp^{2/3}$ (Goldreich & Sridhar 95).

Strong turbulence decays in one wave period.



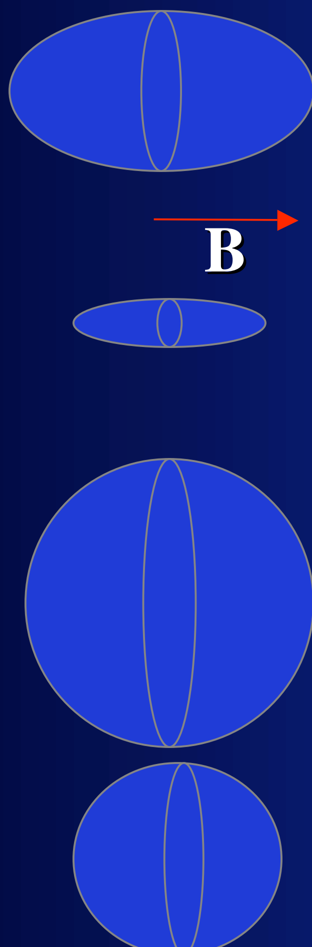
Alfven and slow modes correspond to GS95 incompressible scaling. Fast modes are isotropic for strong turbulence.



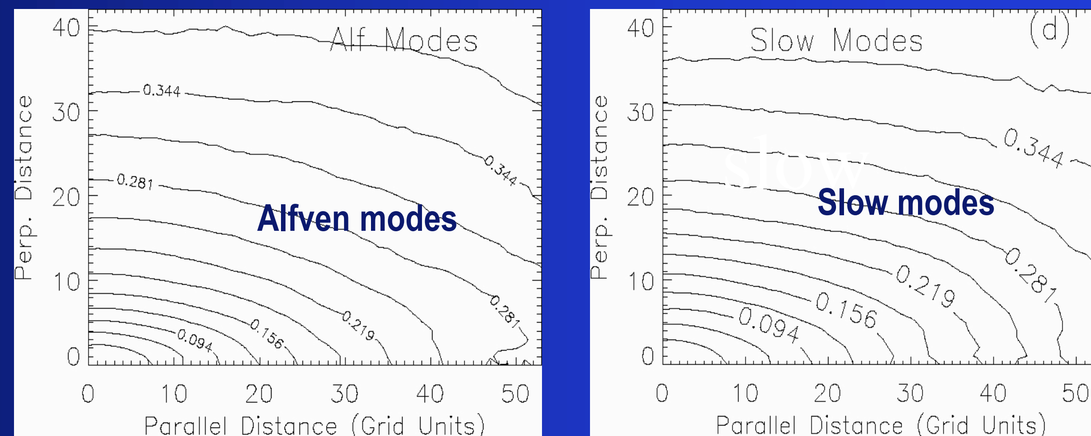
Basic MHD

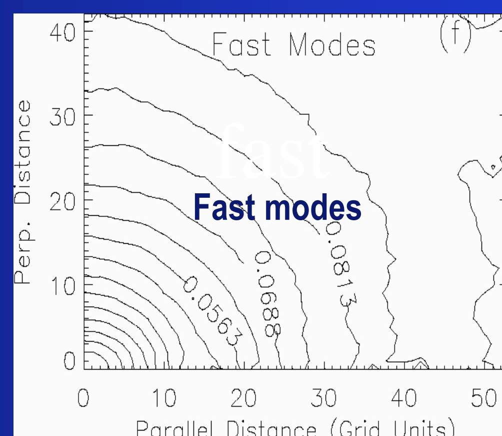
Alfven and slow modes (GS95)

fast modes



Equal velocity correlation contours





Alfven and slow spectrum

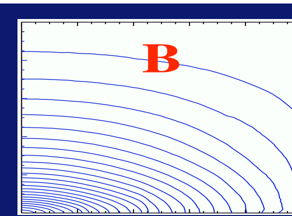
$E(k) \sim k^{-5/3}$

Fast spectrum

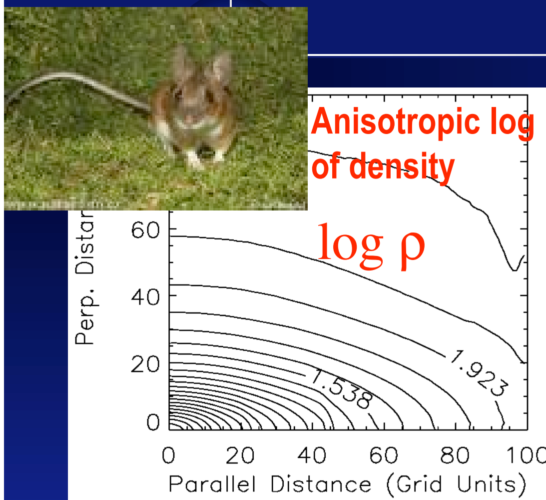
$E(k) \sim k^{-3/2}$

Results in Cho & Lazarian (2002, 2003), Kowal & Lazarian (2008)

High amplitude density fluctuations in supersonic turbulence are isotropic. Low amplitude fluctuations are GS95 type.

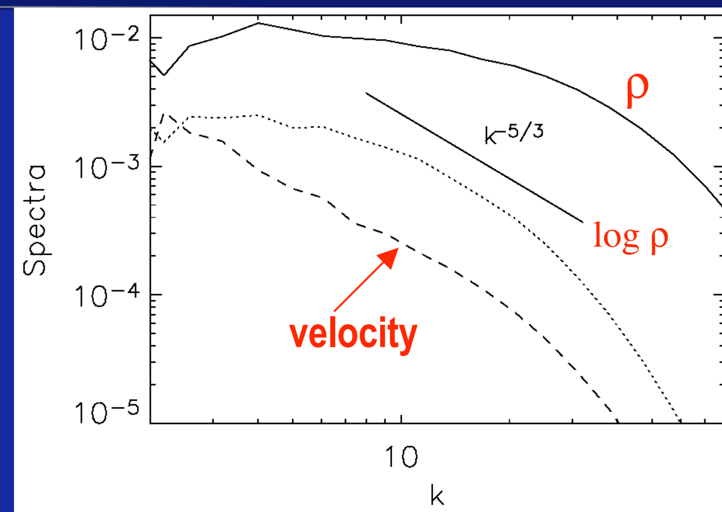


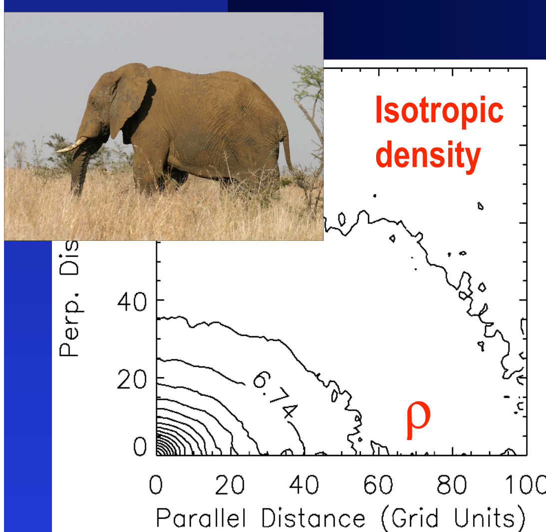
Basic MHD

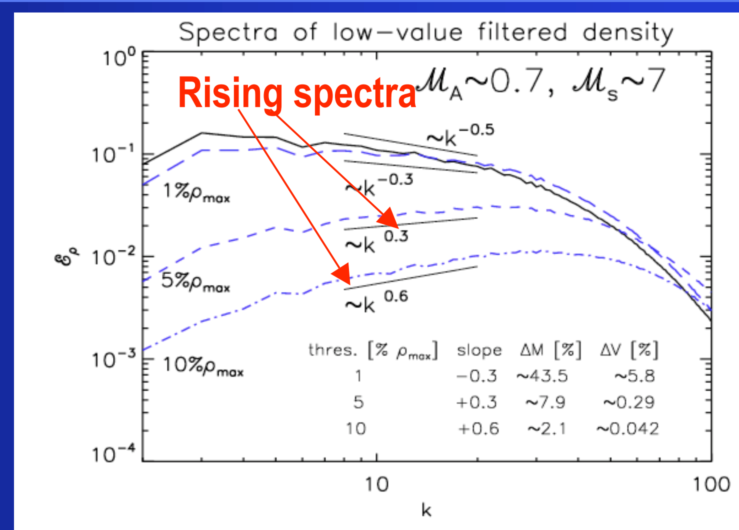


Max number

$M_s=7$



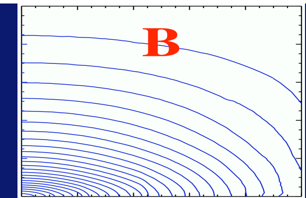




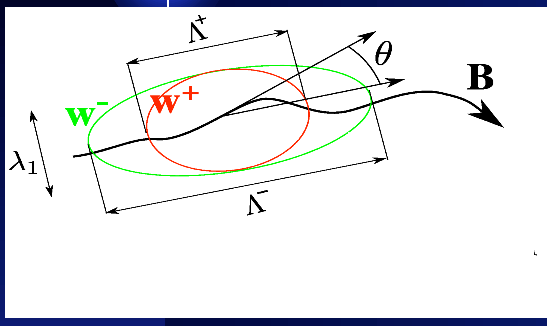
Beresnyak, Lazarian & Cho 05

Kowal & Lazarian 07

Sources and sinks make turbulence imbalanced. It lives longer. Stronger flux has less anisotropic fluctuations.

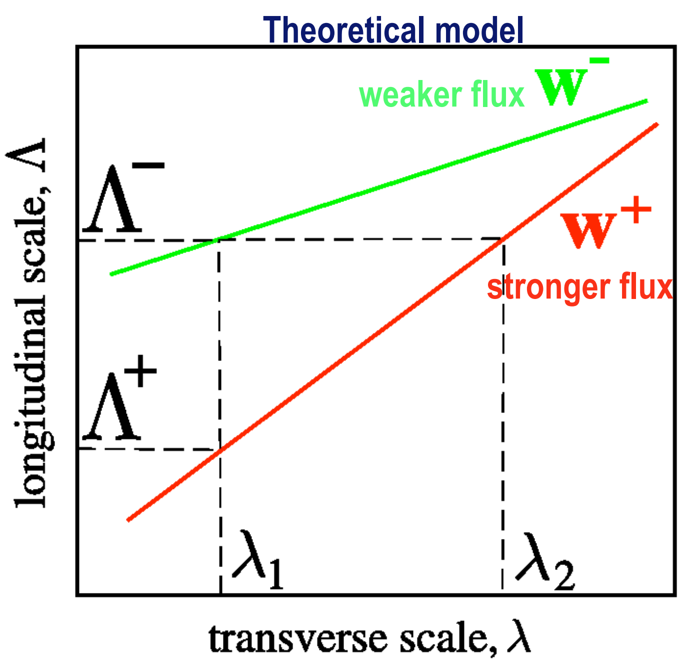


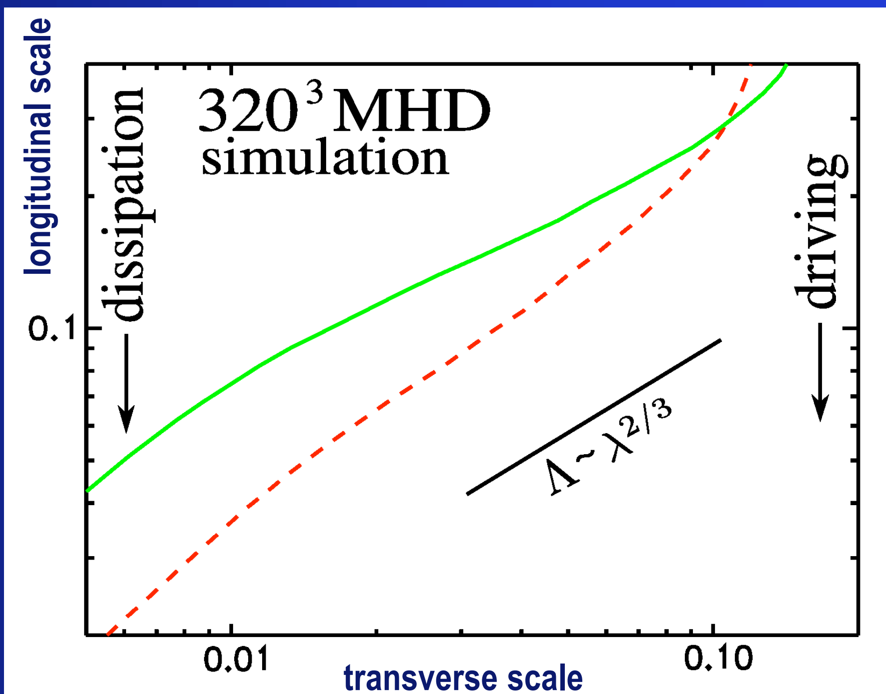
Basic MHD



Lithwick, Goldreich & Sridhar 07 predicts the same anisotropy for opposite fluxes.

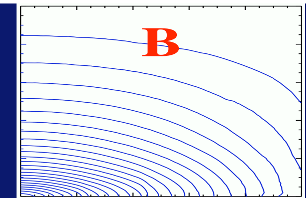
Our model of strong imbalanced Alfvenic turbulence is consistent with simulations.





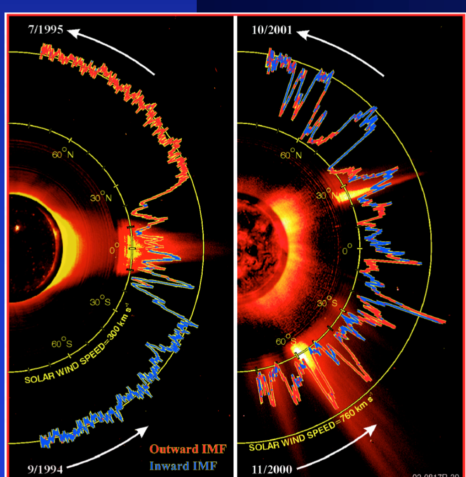
Beresnyak & Lazarian 07

Our model predicts weak flux spectrum to be shallower with longer inertial range and large amplitude difference.

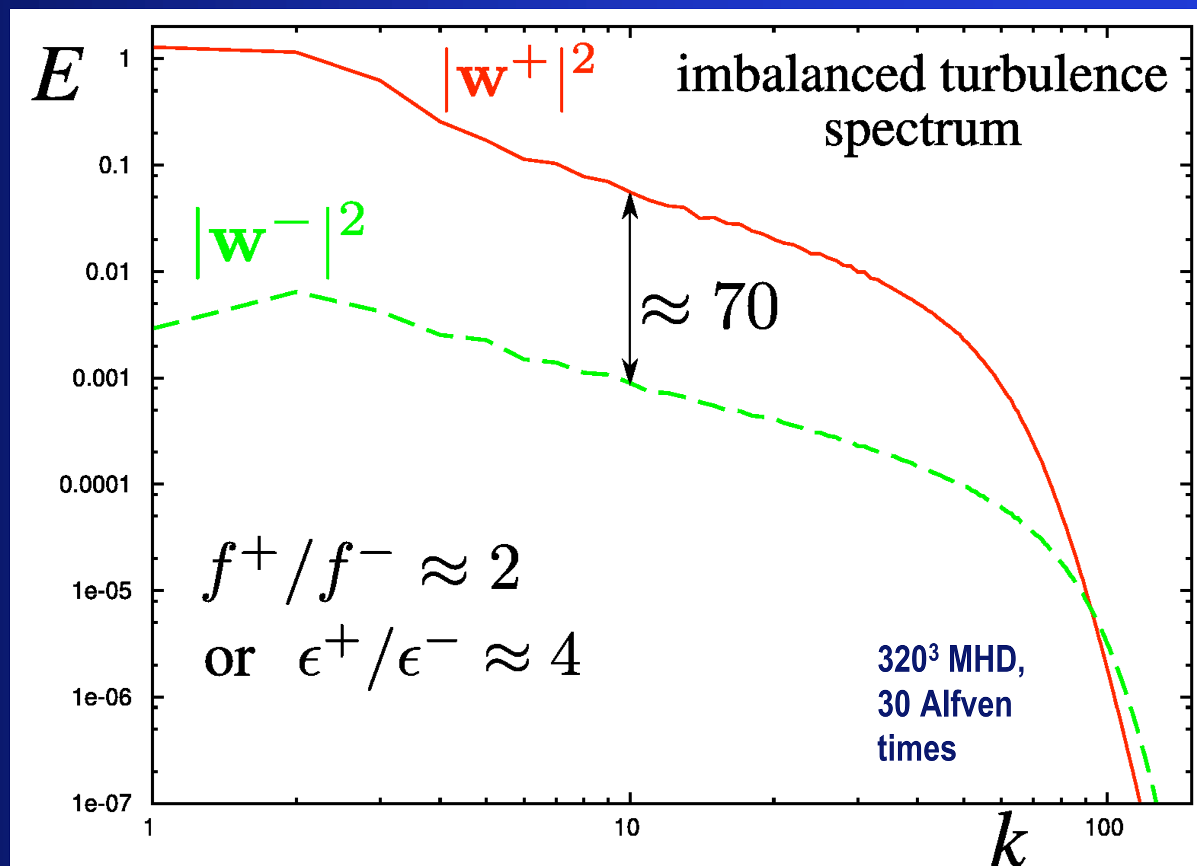


Basic MHD

LGS07 predicts the same slope, damping scale and the spectra difference of 16 for the parameters given.

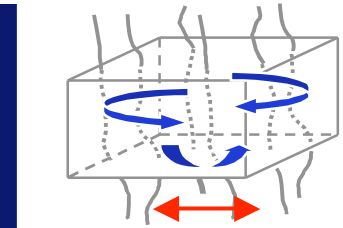


Example: Solar wind

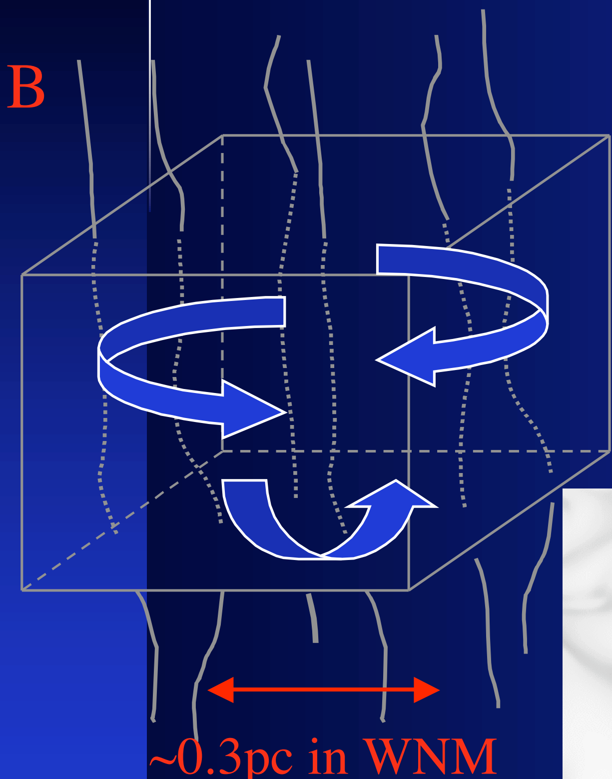


Beresnyak & Lazarian 07

Turbulence protrudes further than viscous damping scale. We predict it resurrects when atoms and neutrals decouple.



More Physics



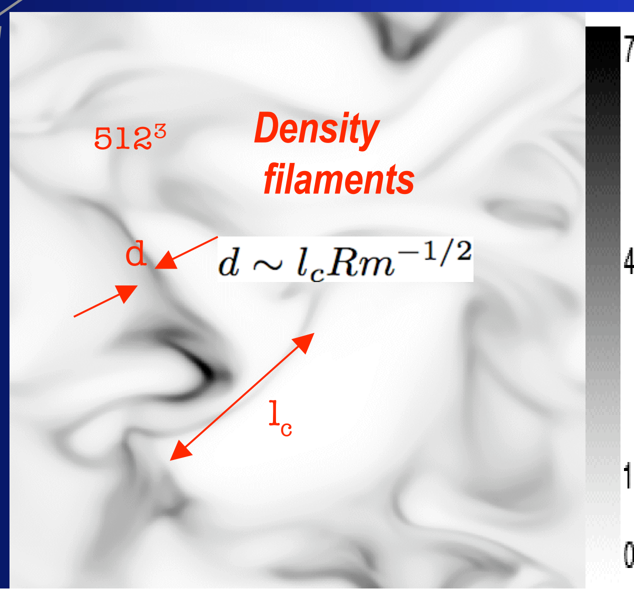
Viscosity-damped regime of turbulence (Lazarian, Vishniac, Cho 04):

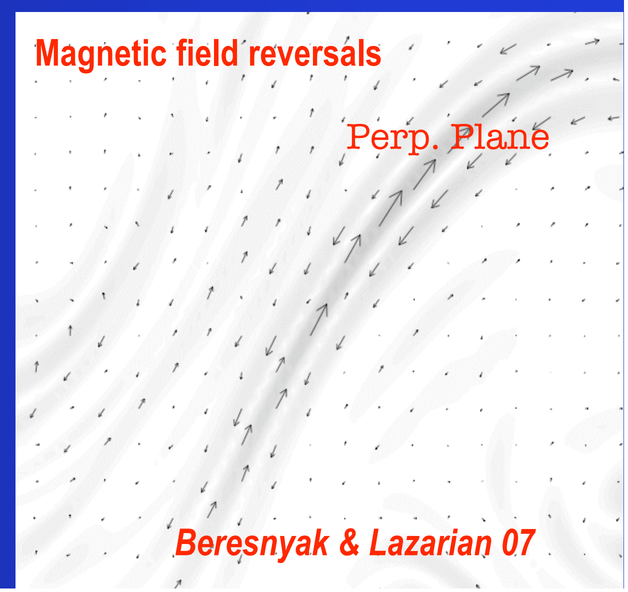
Magnetic field spectrum $E_B \sim k^{-1}$

Velocity spectrum $E_v \sim k^{-4}$

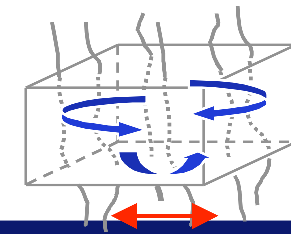
High density contrasts can be related to SINS (Lazarian 06)

Applicable to partially ionized gas





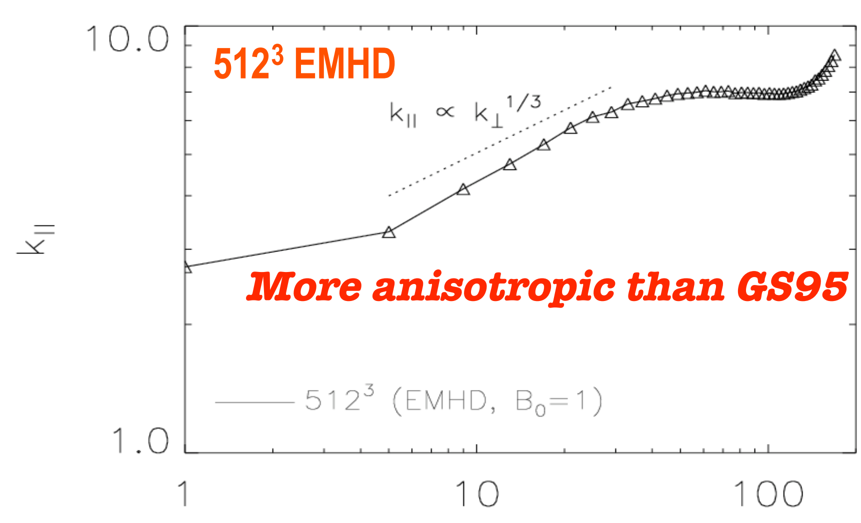
Alfvenic turbulence cascade continues as whistler turbulence, which is very anisotropic.



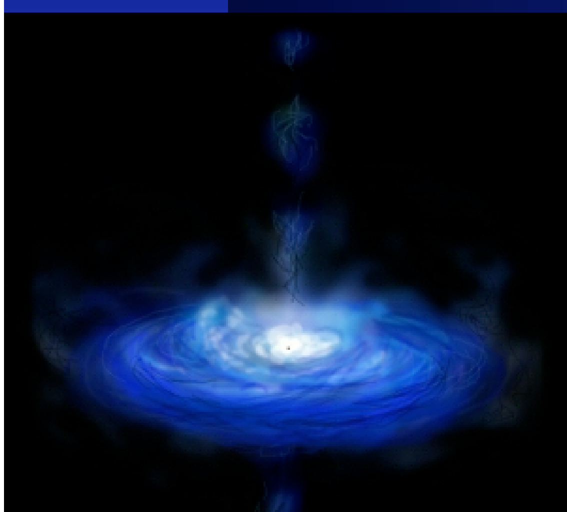
More Physics

Anisotropy

$k_{paral} \sim k_{perp}^{1/3}$ (Cho & Lazarian 04)

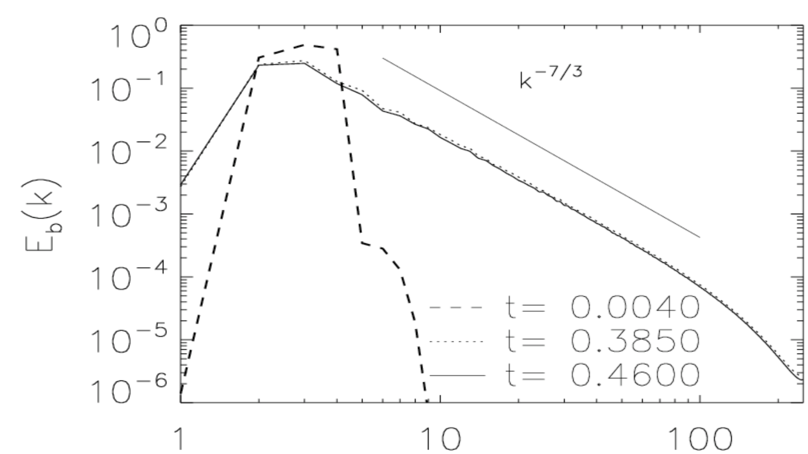


Cho & Lazarian 08


Black hole accretion

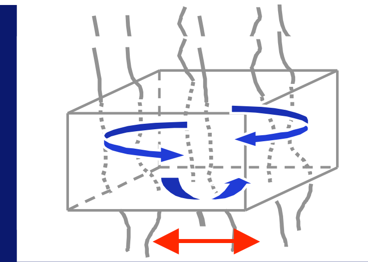
Spectrum $k^{-7/3}$

(Ng et al. 03)

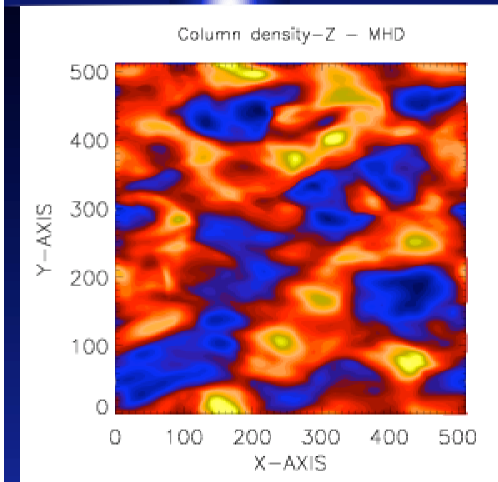


Cho & Lazarian 08

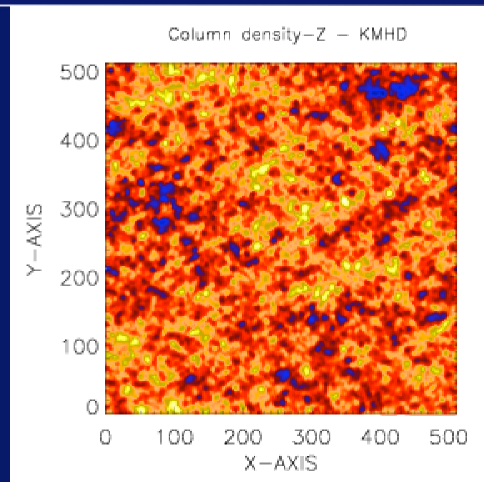
Fire-hose and mirror instabilities in collisionless plasmas modify spectrum and anisotropy of turbulence



More Physics

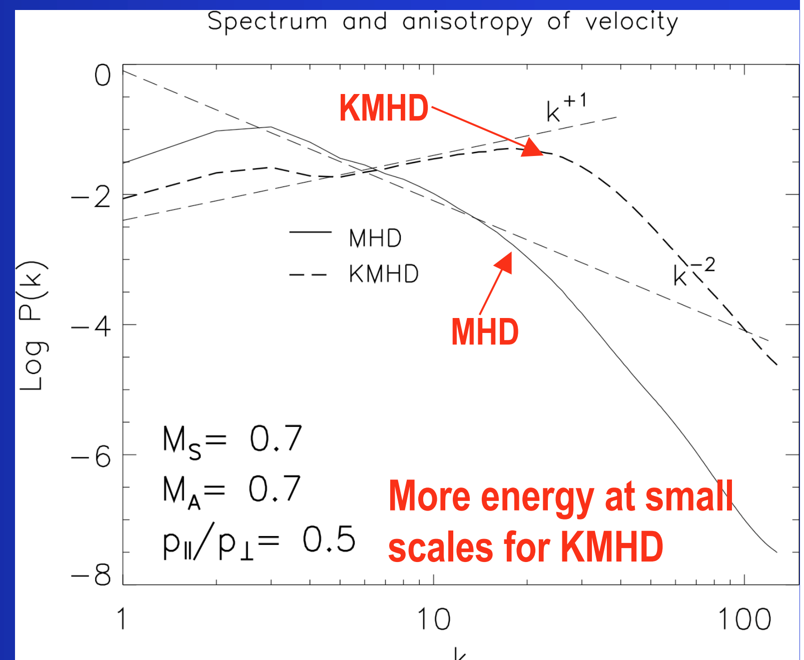


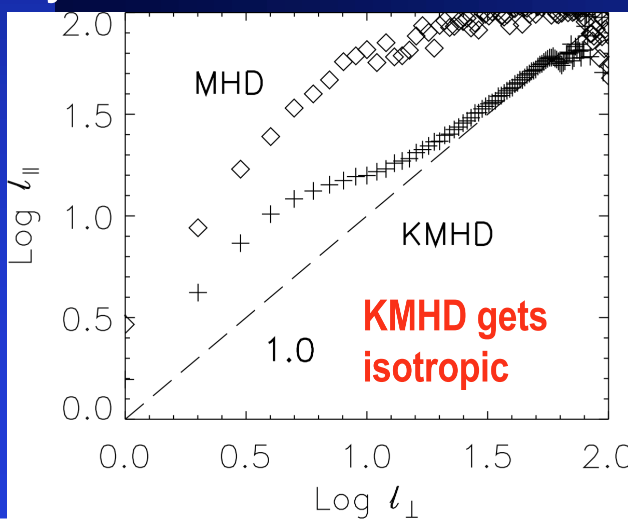
MHD column density



Kinetic MHD column density

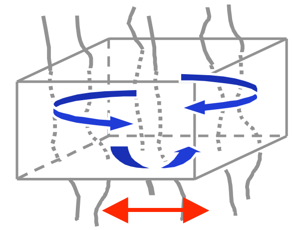
Important for galaxy clusters and galaxy halos



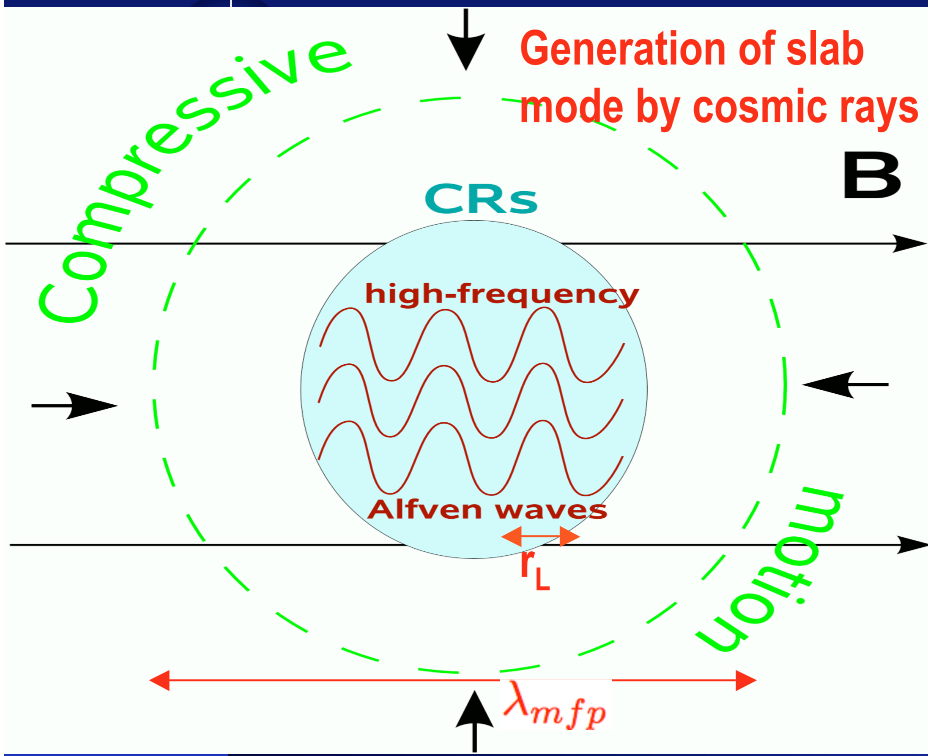


Falseta-Gonzales, Kowal & Lazarian 08

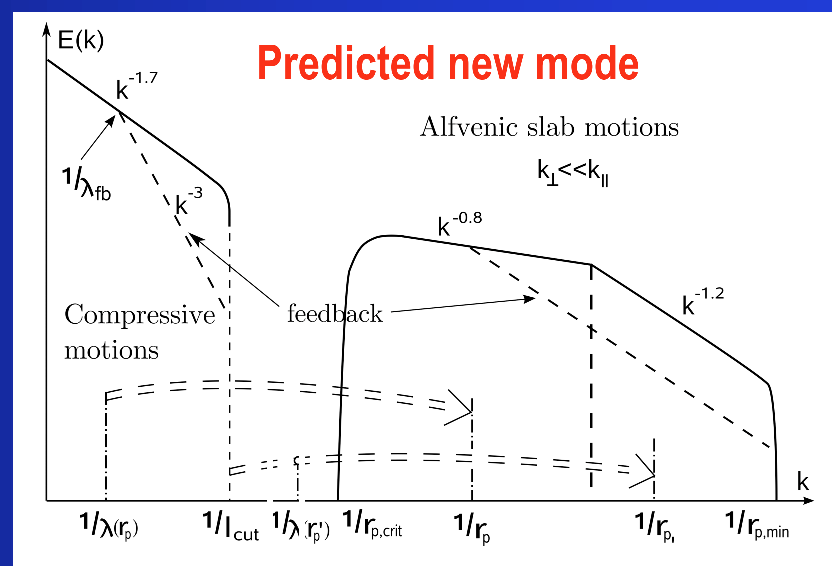
Compression of cosmic rays by turbulence at the scale of their mean free path creates new slab Alfven modes.



More Physics



Cosmic rays constitute most of the ISM pressure. They are compressed by magnetic field and this induces gyroresonance instability.



Predicted spectra of slab-type Alfven modes: $k^{-0.8}$ and $k^{-1.2}$ (Lazarian & Beresnyak 07)

Real astrophysical turbulence has many facets, some cases have not been studied yet.

"Turbulence is the last unsolved problem in classical statistical mechanics"

R. Feinman

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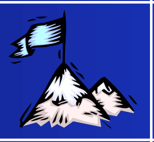
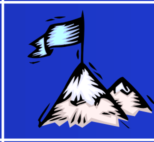
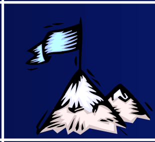
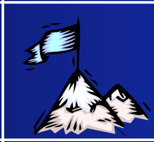
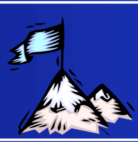
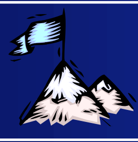
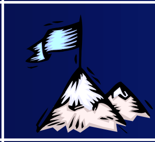
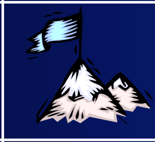
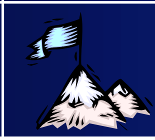
incompr essible	◎					
compre ssible		◎				
with neutrals			◎			
collision less				◎		
imbalan ced					◎	
weak						◎

Combinations:

 **work in progress**

□ **no work done**

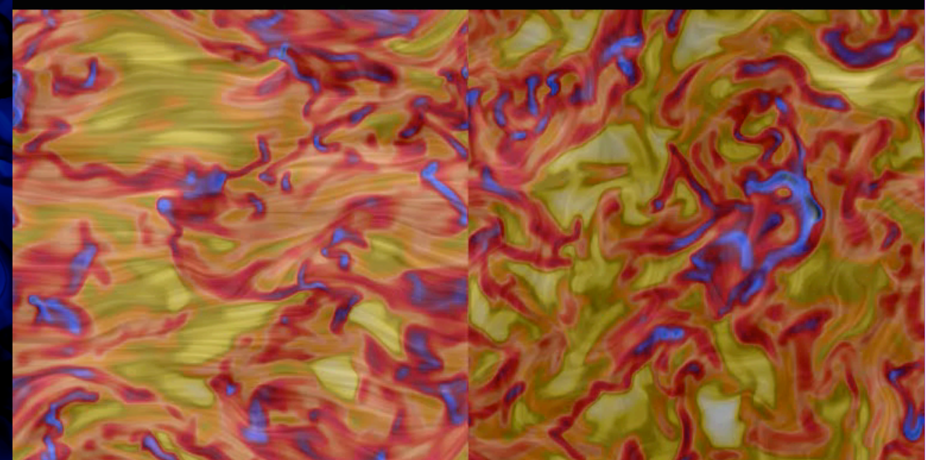
◎ **trivial**

Simplified representation of theoretical work in the field

In summary, astrophysics requires better knowledge of magnetized turbulence. Our main points are:

- Turbulence has many facets, e.g. be imbalanced or collisionless.
- Additional physics, e.g. neutrals, cosmic rays, result in new effects like resurrection of cascade, new types of turbulence etc.
- A lot of work is ahead!

Turbulence is fascinating,
it is not a mess!



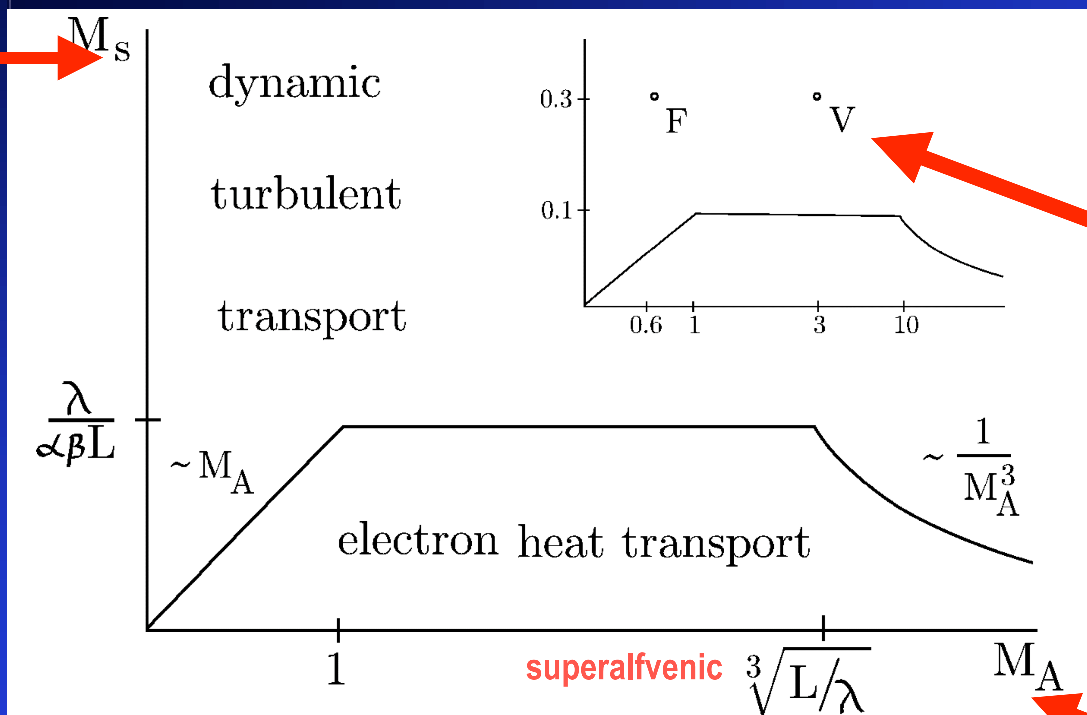
512^3 Compressible MHD

Kowal & Lazarian 07

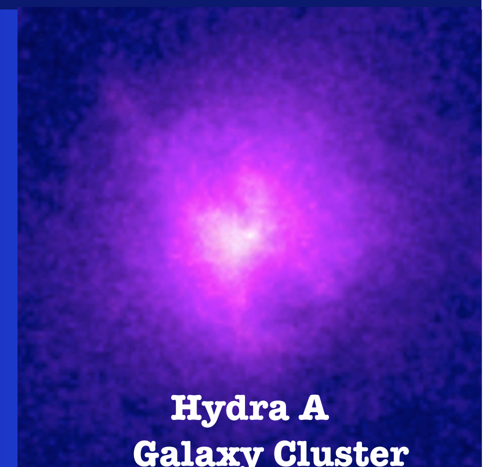
Example: Advection of heat by turbulent motions is faster than electron heat conduction for galaxy clusters.

Relative importance of turbulent heat advection and heat conduction

Mach number



Lazarian 06



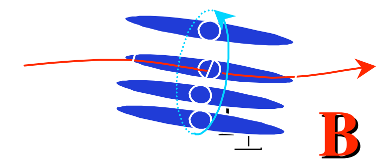
Application for parameters of Hydra A cluster

Advection is Dominant!

Alfven Mach number

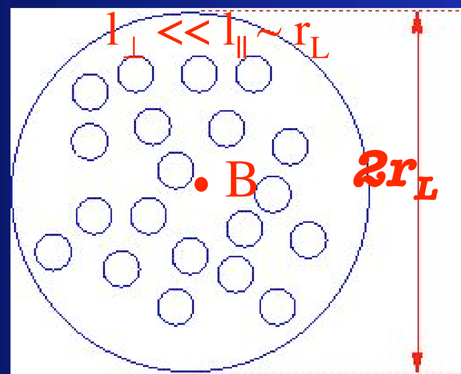
Evaporation of clusters (Loeb 06, Lazarian & Loeb 08)

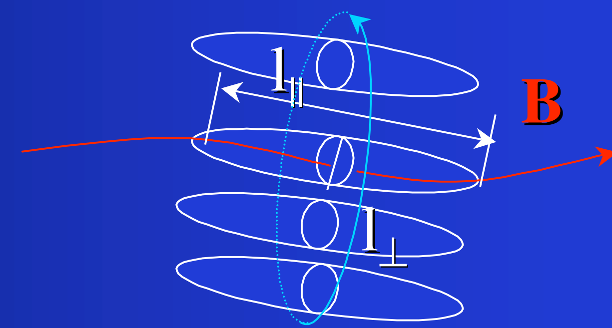
Alfvenic turbulence does not scatter and accelerate cosmic rays. Fast modes do.



Implications

Anisotropic Alfvenic and isotropic fast modes

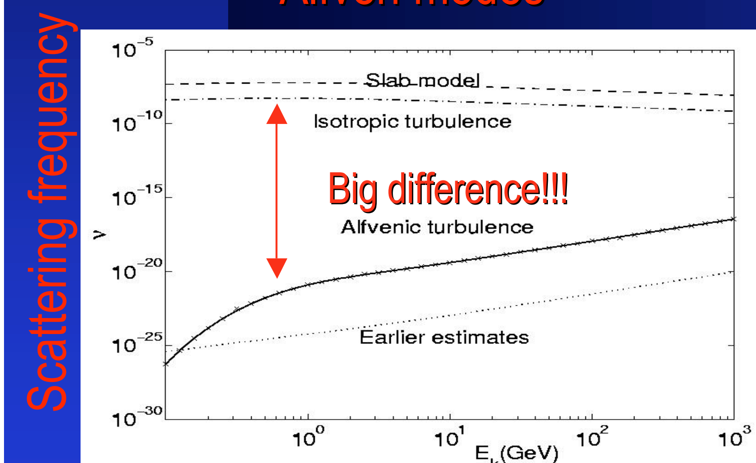




eddies

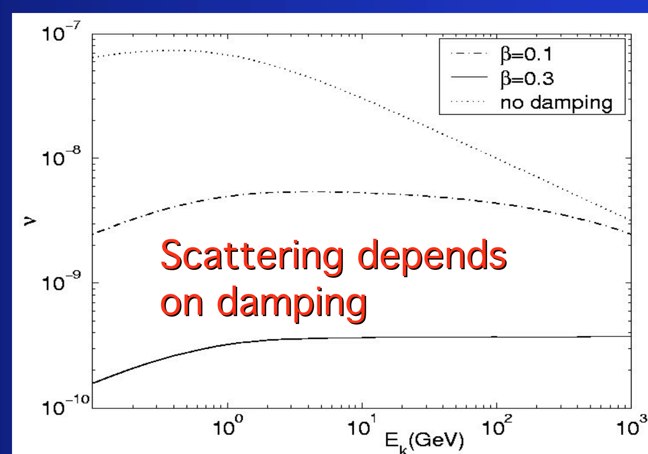
Similar effect for heating protons by whistlers

Alfven modes



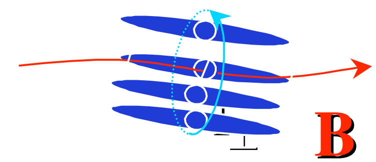
Yan & Lazarian 04

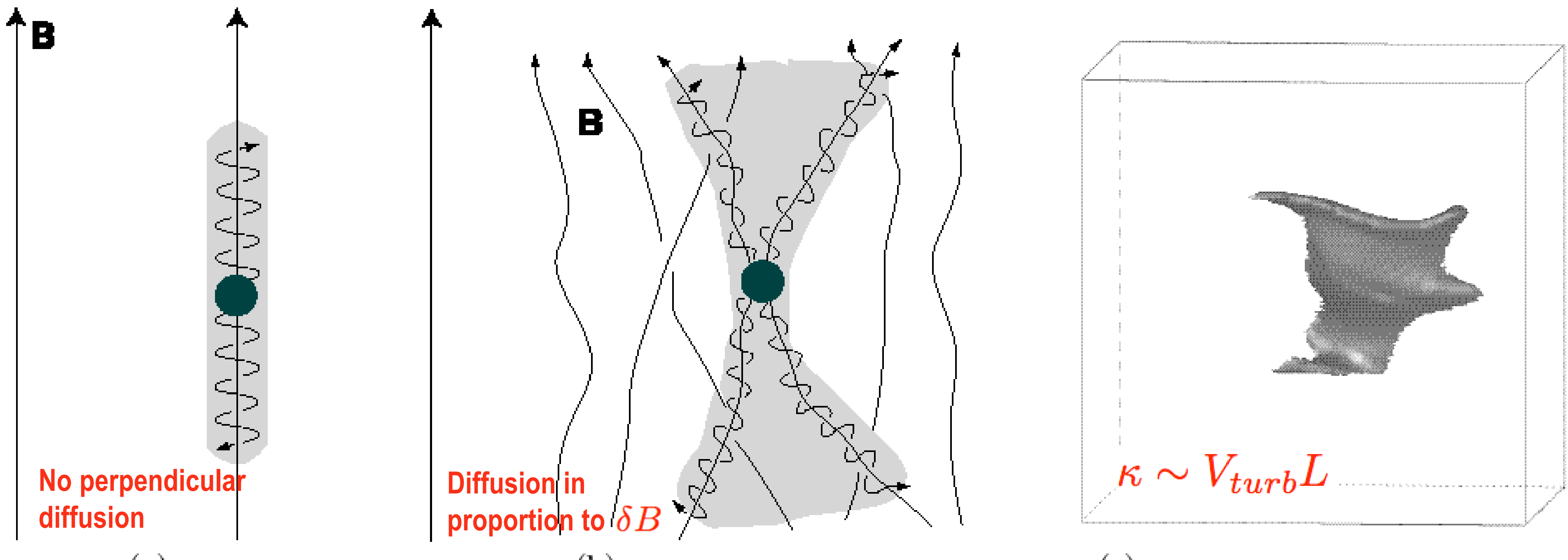
Fast modes



Scattering and acceleration by fast modes was calculated for ISM phases of in Yan & Lazarian 04,08, Cho & Lazarian 06

Turbulence induces field wandering allowing heat to transfer perpendicular to B. It also induces advection.





Cho, Lazarian et al. 03

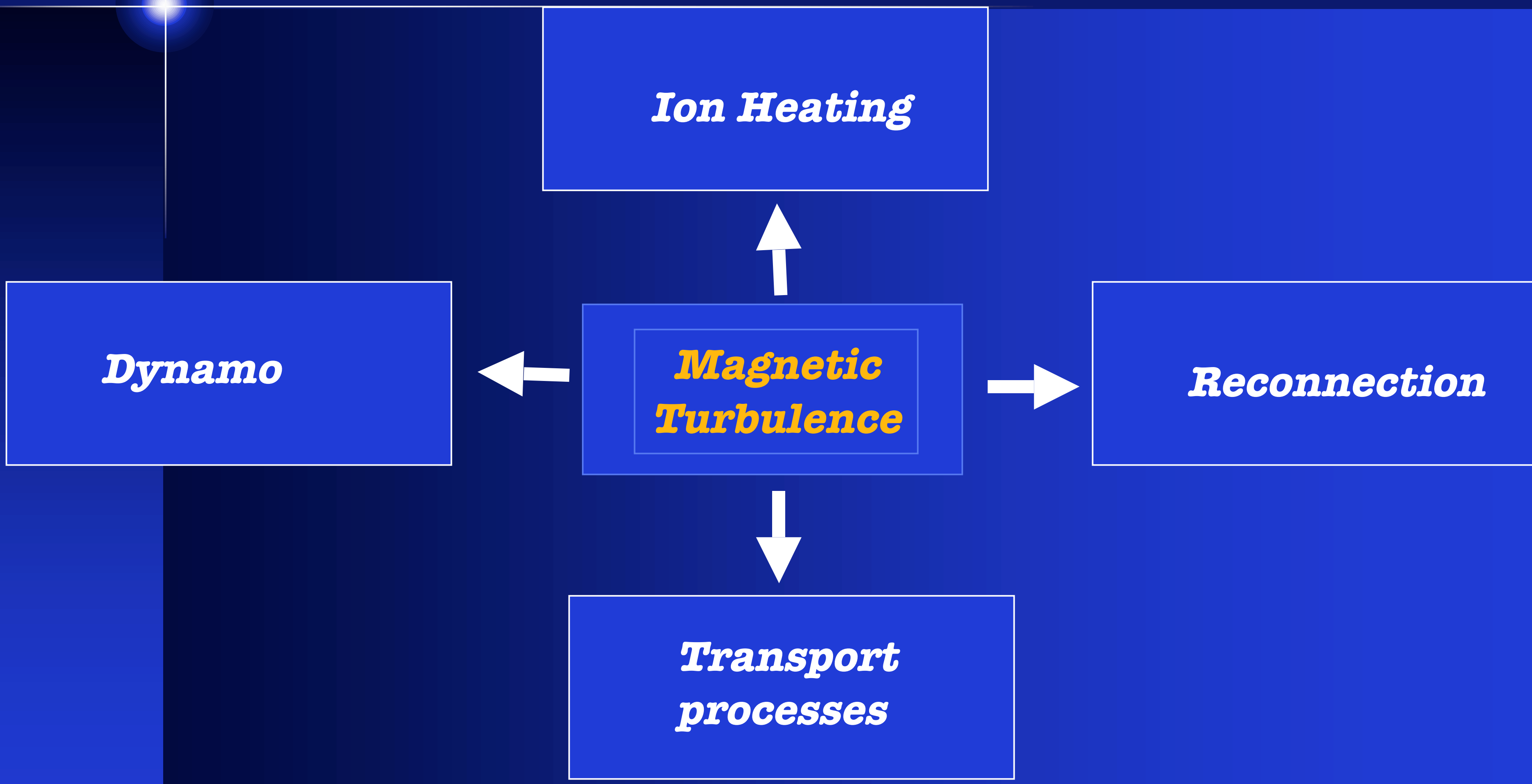
Regular field only:
huge suppression perpendicular to B

Regular B + turbulence:
field line wandering decreases suppression

Turbulent Advection:
hydro motions induce turbulent diffusion

Turbulence plays crucial role for key astrophysical processes. Advances in turbulence advance other fields.

Example:



Main directions of research of the Center for Magnetic Self-Organization

Which wavelets are good for decomposition?

Results from numerical simulations are described on discrete meshes, so we use

Fast Discrete Wavelet Transform (FDWT)

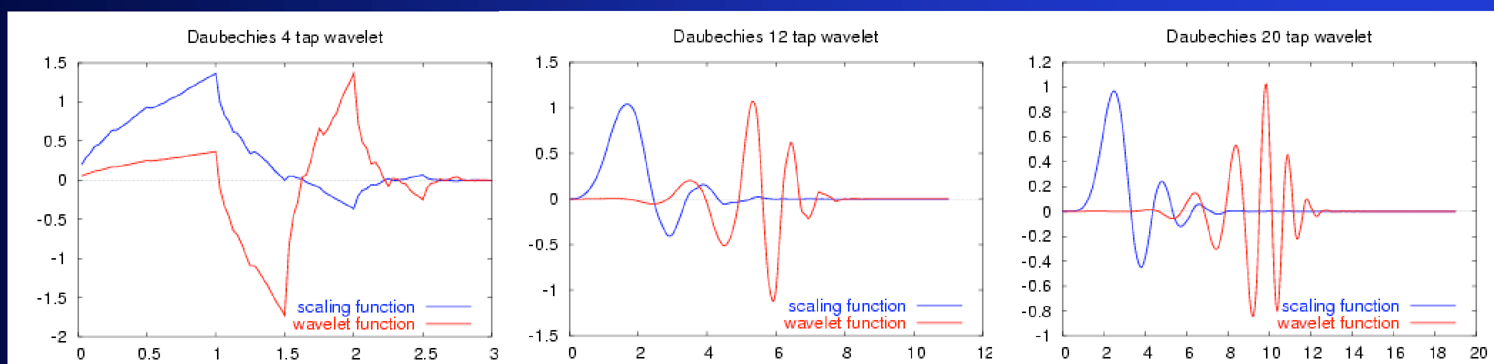
+ fast algorithms for transforms

+ good space and frequency localization

+ orthonormal bases of wavelets guarantee a perfect reversibility

Daubechies wavelets

- **very easy to implement**
- **well localized in Real and Fourier spaces**
- **orthonormal bases**



Localization:
in space
in frequency

WORSE **BETTER**

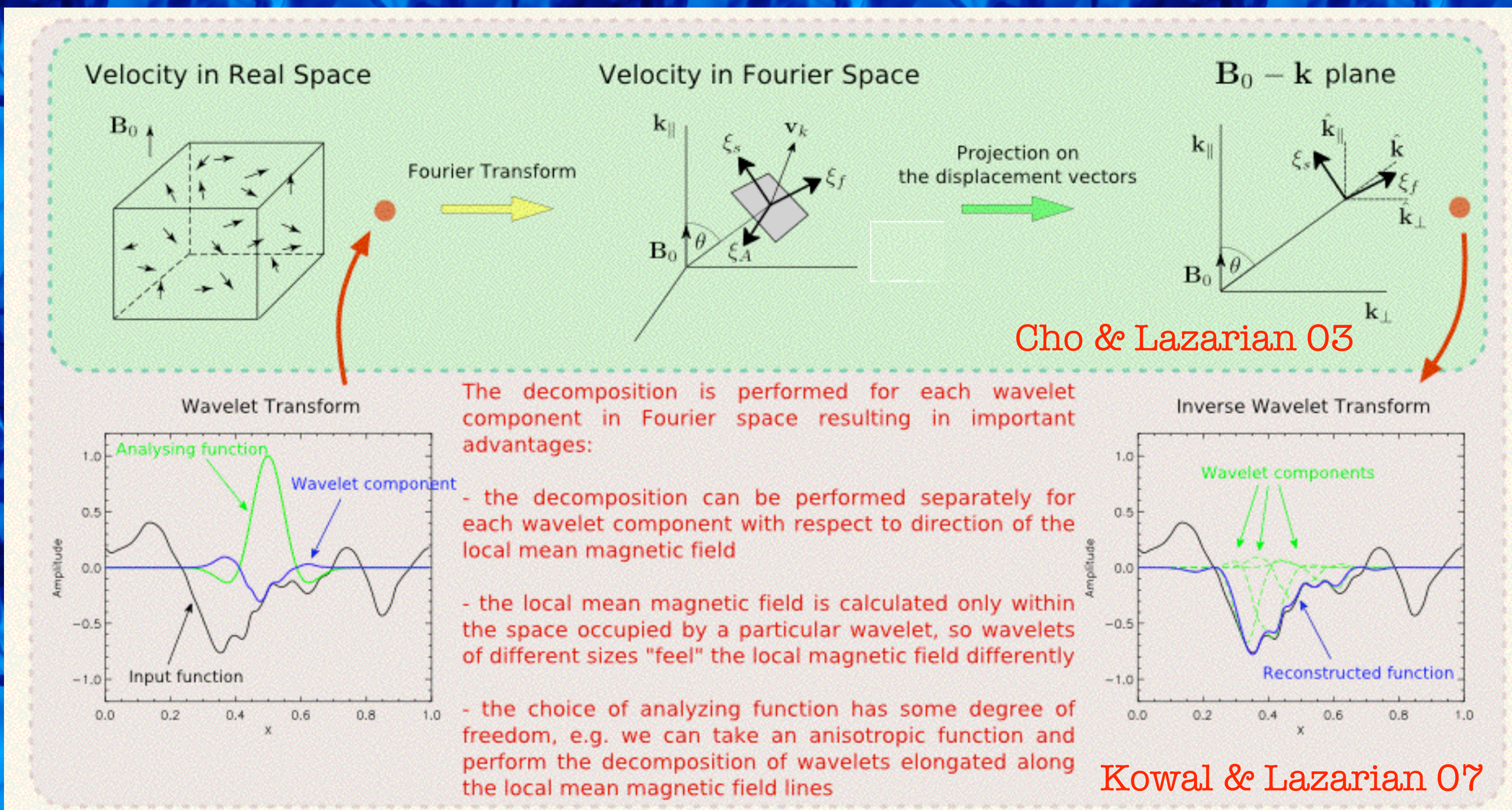
Wavelet function is high band filter, scaling function is low band filter

Different Types of MHD Turbulence

- SuperAlfvenic Turbulence (mostly hydro to the scale with $v_l = v_A$)
- Turbulence in partially ionized gas (viscosity is much larger than resistivity)
- Strong Alfvenic Turbulence (turbulence with critical balance $k_{||} \sim k_{perp}^{2/3}$)
- Weak Turbulence (only k_{perp} increases, analog of 2D modes)
- Low entropy turbulence (slab modes)

MHD waves decomposition using wavelets

The solution for problem of non-locality of decomposition comes from wavelet transforms:



$$W(r,\mathbf{x}) = C_\Psi^{-1/2}\, r^{-1/2} \int \Psi^*(\mathbf{y}-\mathbf{x}) / r\; V(\mathbf{y})\, d^3\mathbf{y} = C_\Psi^{-1/2}\, r^{-1/2} \int \Psi^*(r\,\mathbf{k}) / r\; V(\mathbf{k})\, e^{ixk}\, d^3\mathbf{k}$$

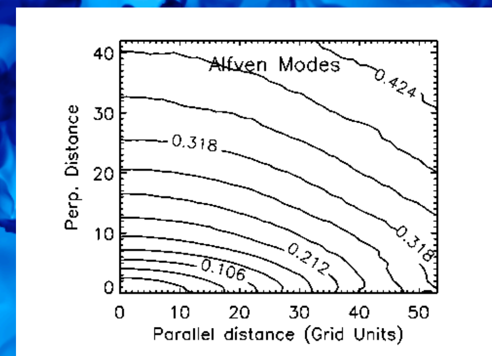
Compressible MHD Turbulence

Simulations in Cho & Lazarian 03, 05:

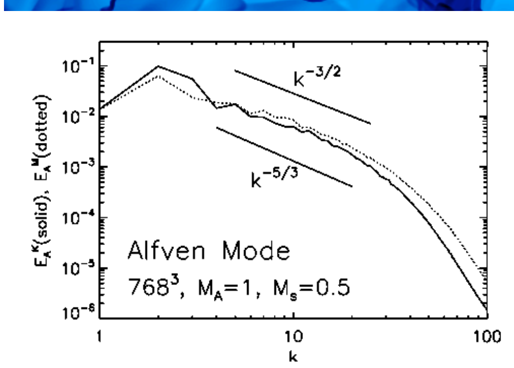
1. GS95 scaling for Alfven and slow modes:

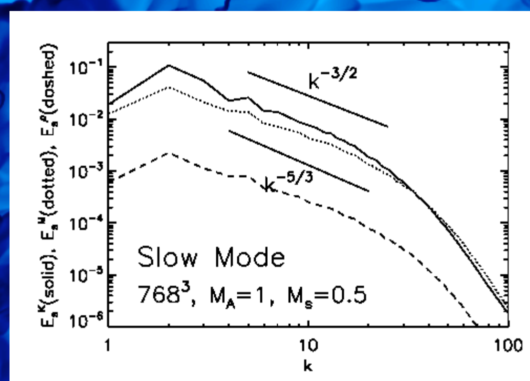
$$k_{\|} \sim k_{\perp}^{2/3} L^{-1/3} \quad \text{anisotropic}$$
$$E(k_{\perp}) \sim k^{-5/3} \quad \text{Kolmogorov}$$

Relates to incompressible



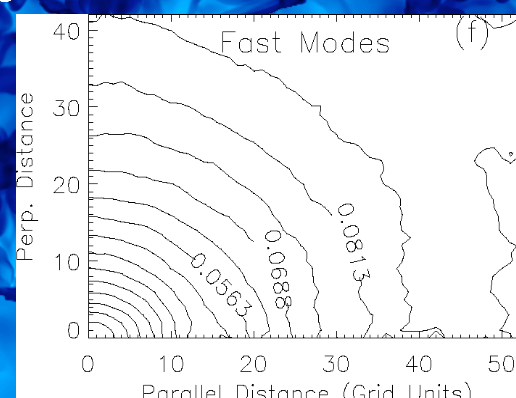
Elongated Alfven eddies





Coupling of modes is weak

Computations in Beresnyak & Lazarian 07



2. Isotropic acoustic-like fast modes:

$$E(k) \sim k^{-3/2} \quad \text{isotropic}$$

Fast modes are isotropic