Basics of Astrophysical Turbulence: Star Formation Perspective

Alex Lazarian

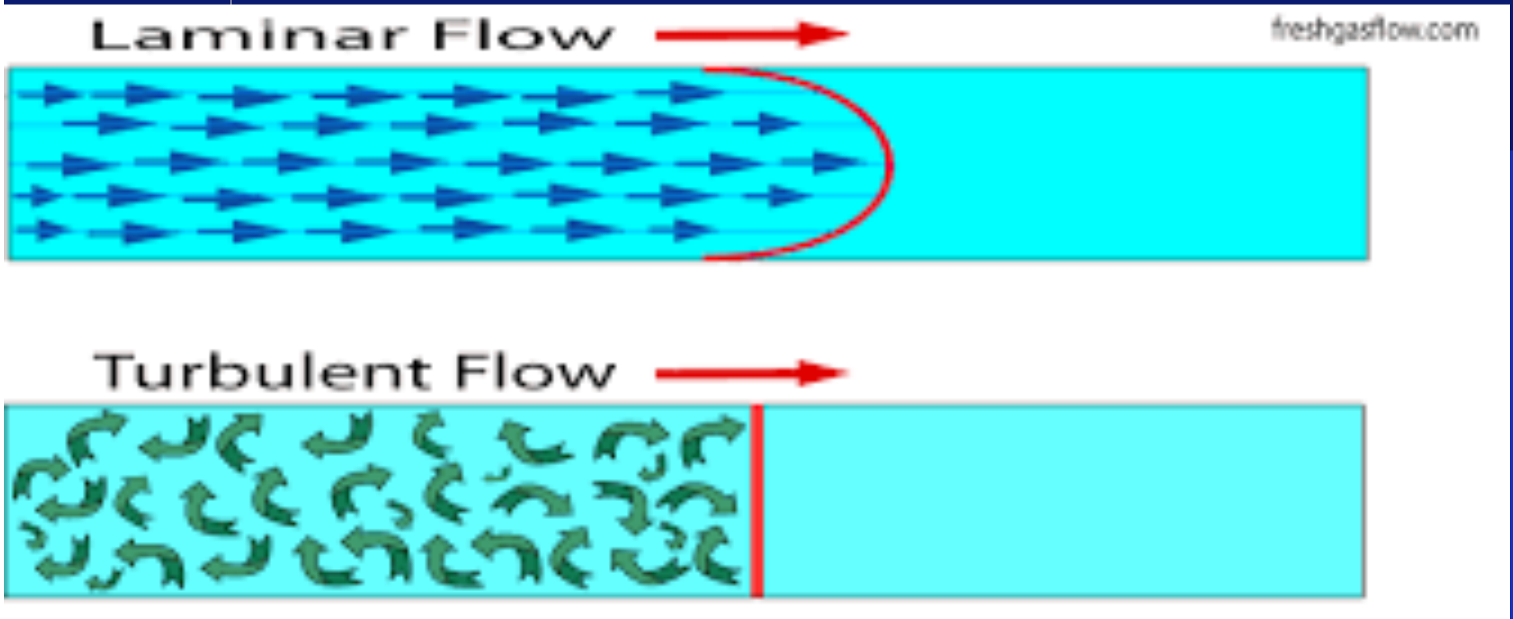
Astronomy & Physics

THE UNIVERSITY of WISCONSIN MADISON

The mature branches of science are most impressive, but they develop slowly.

FUNCTIONAL
PERFORMANCE
INDEX

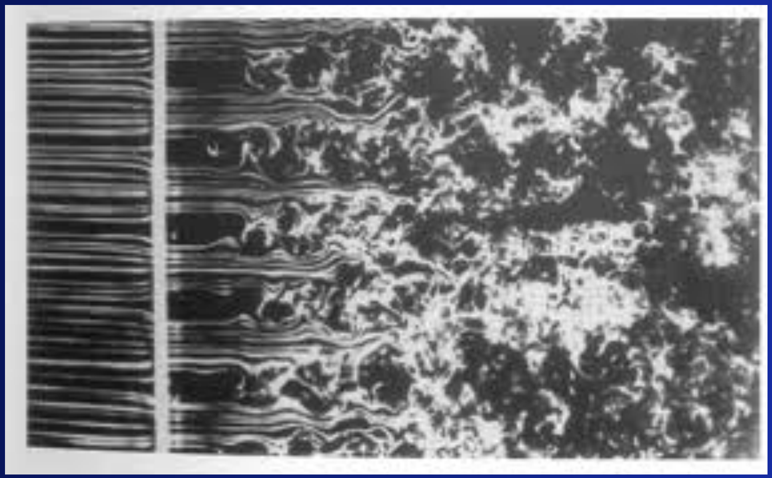
Facts about Turbulence

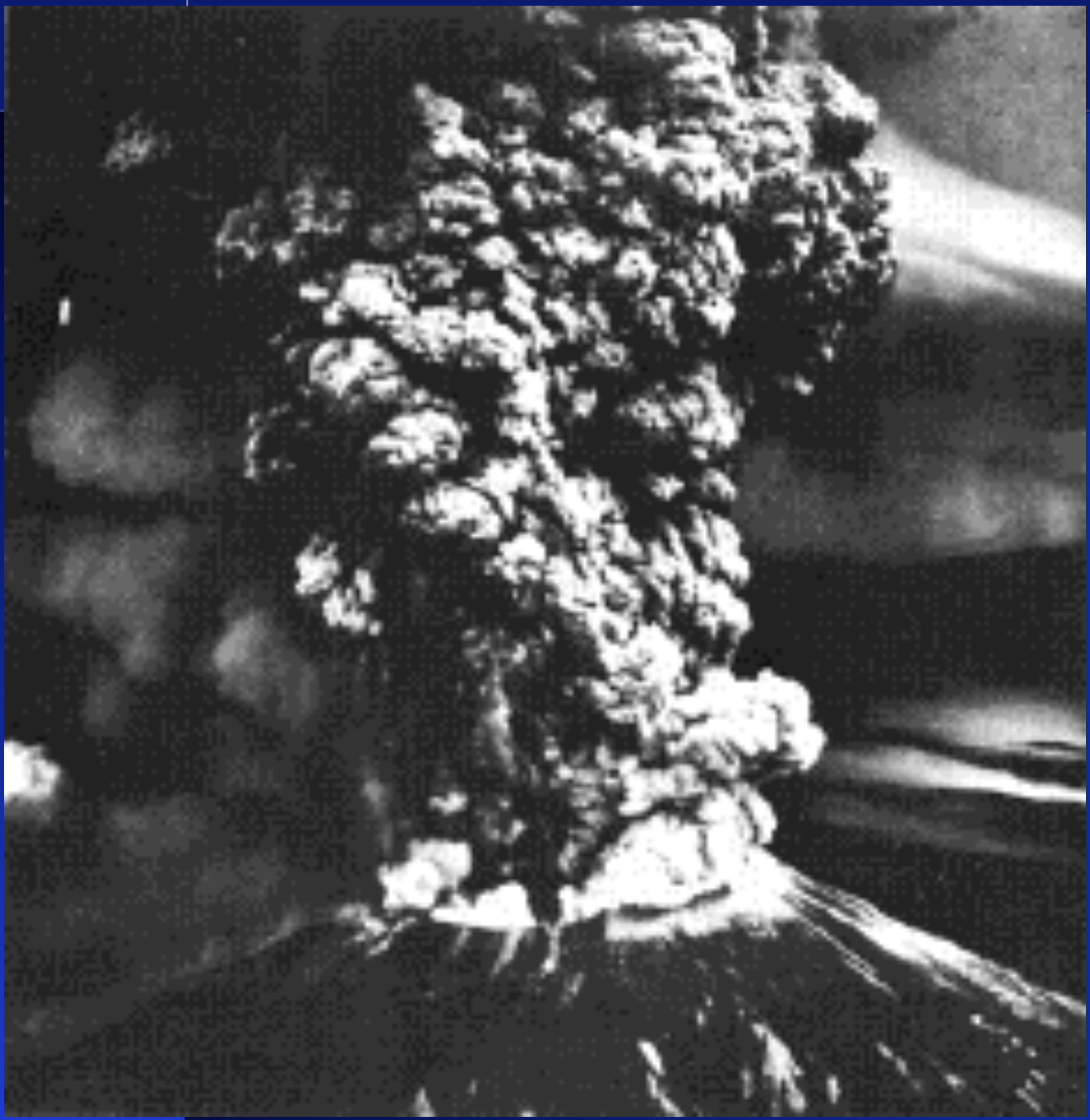


Laminar Flow
freshgasflow.com
Turbulent Flow


Laminar Flow

Turbulence





Earths and astro turbulence look similar

Earths and astro turbulence look similar

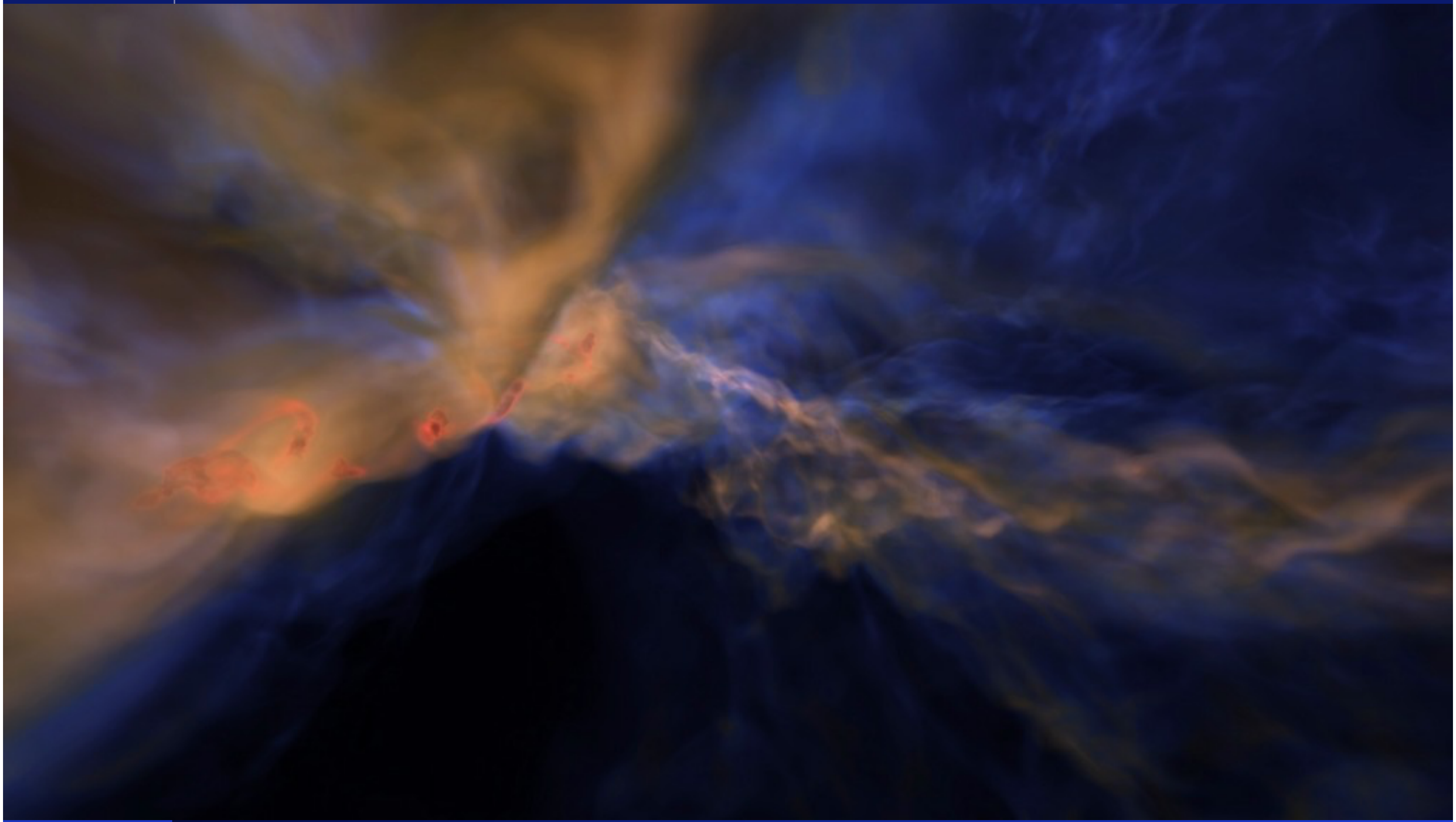
Earths and astro turbulence look similar

Earths and astro turbulence look similar

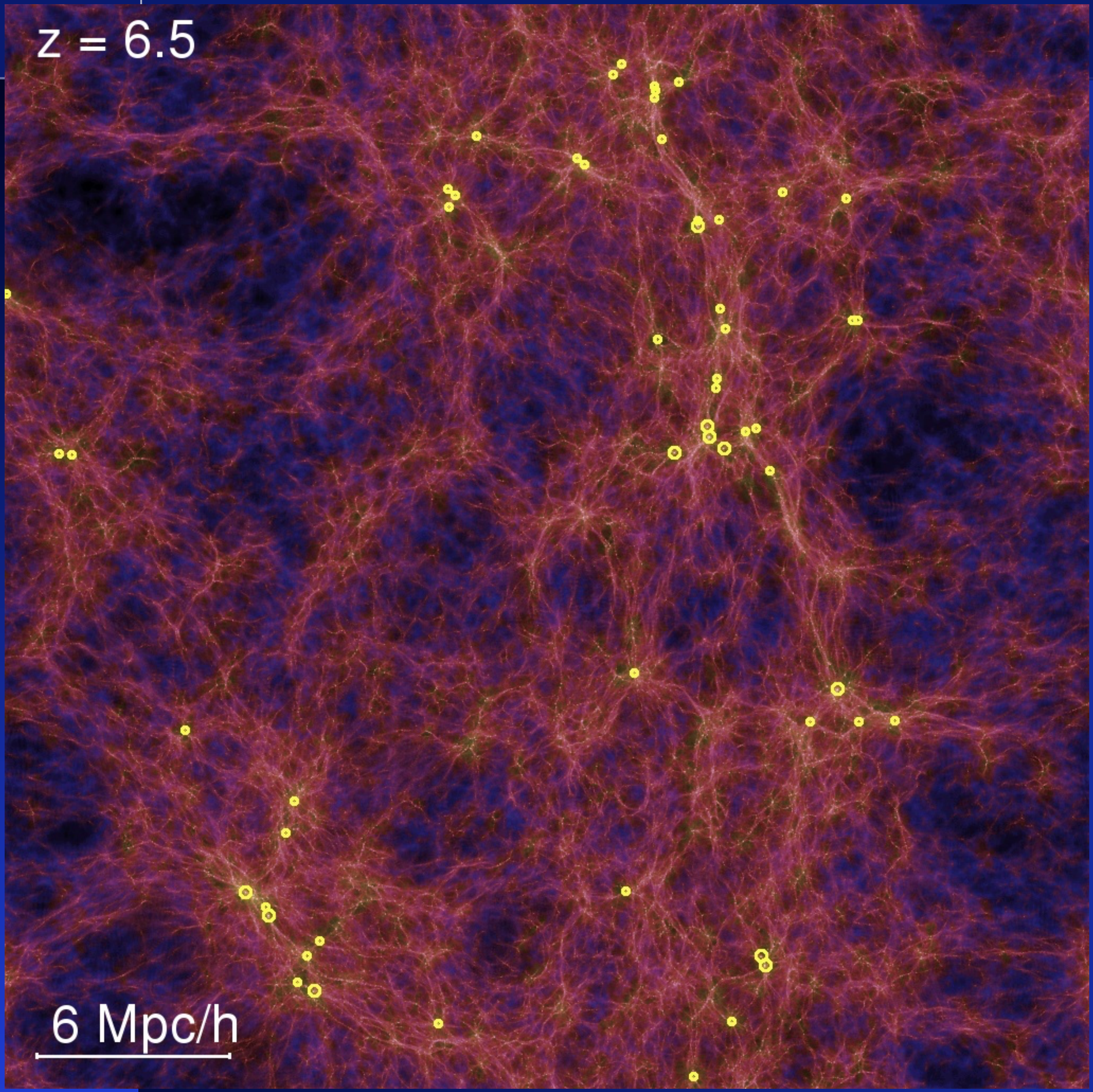
Earths and astro turbulence look similar

Pure similarity of chaotic patterns does not mean that the physics is exactly the same

Pure similarity of chaotic patterns does not mean that the physics is exactly the same



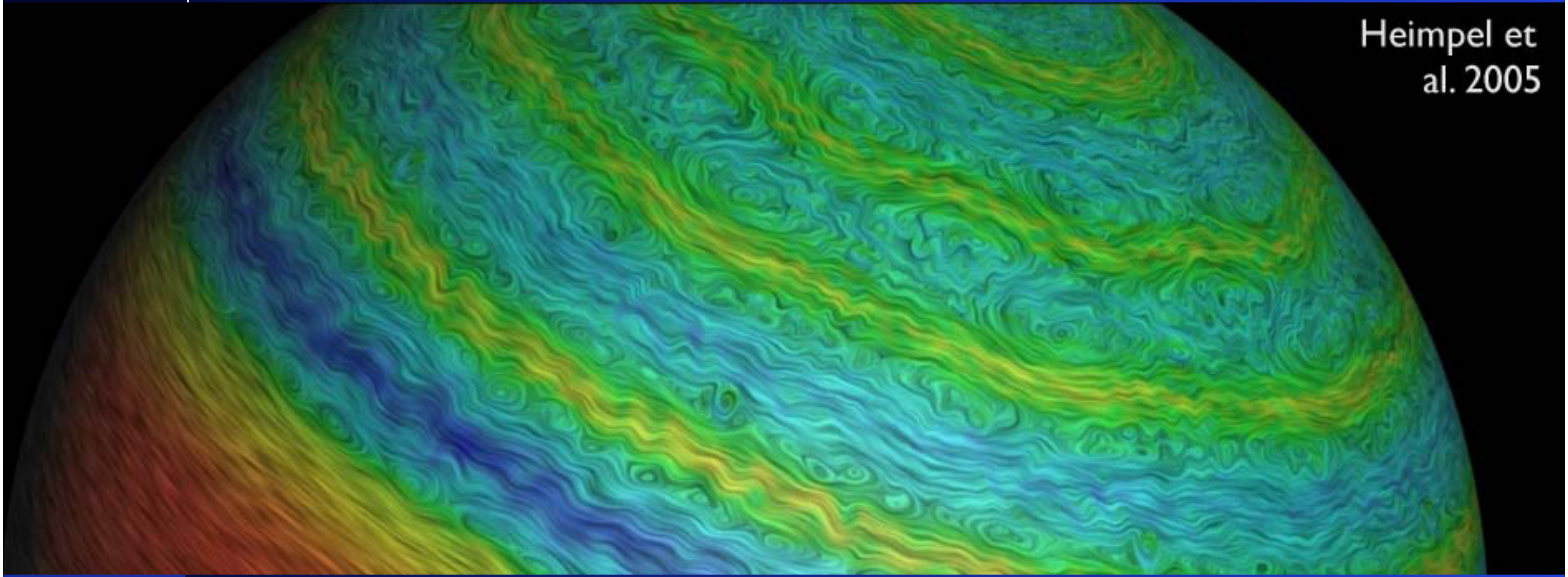
Pure similarity of chaotic patterns does not mean that the physics is exactly the same



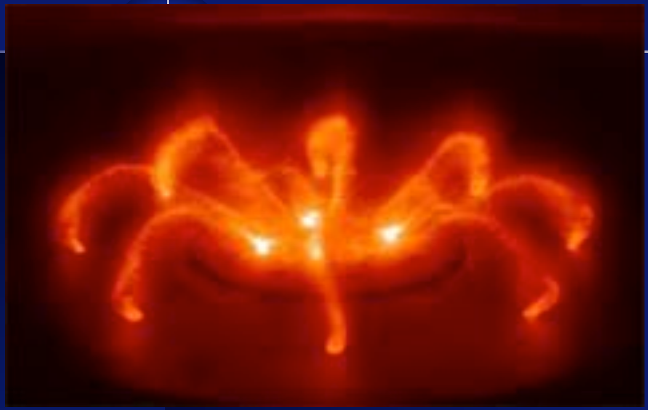
2D turbulence is very different from 3D (general statement for most physical processes)

2D turbulence is very different from 3D

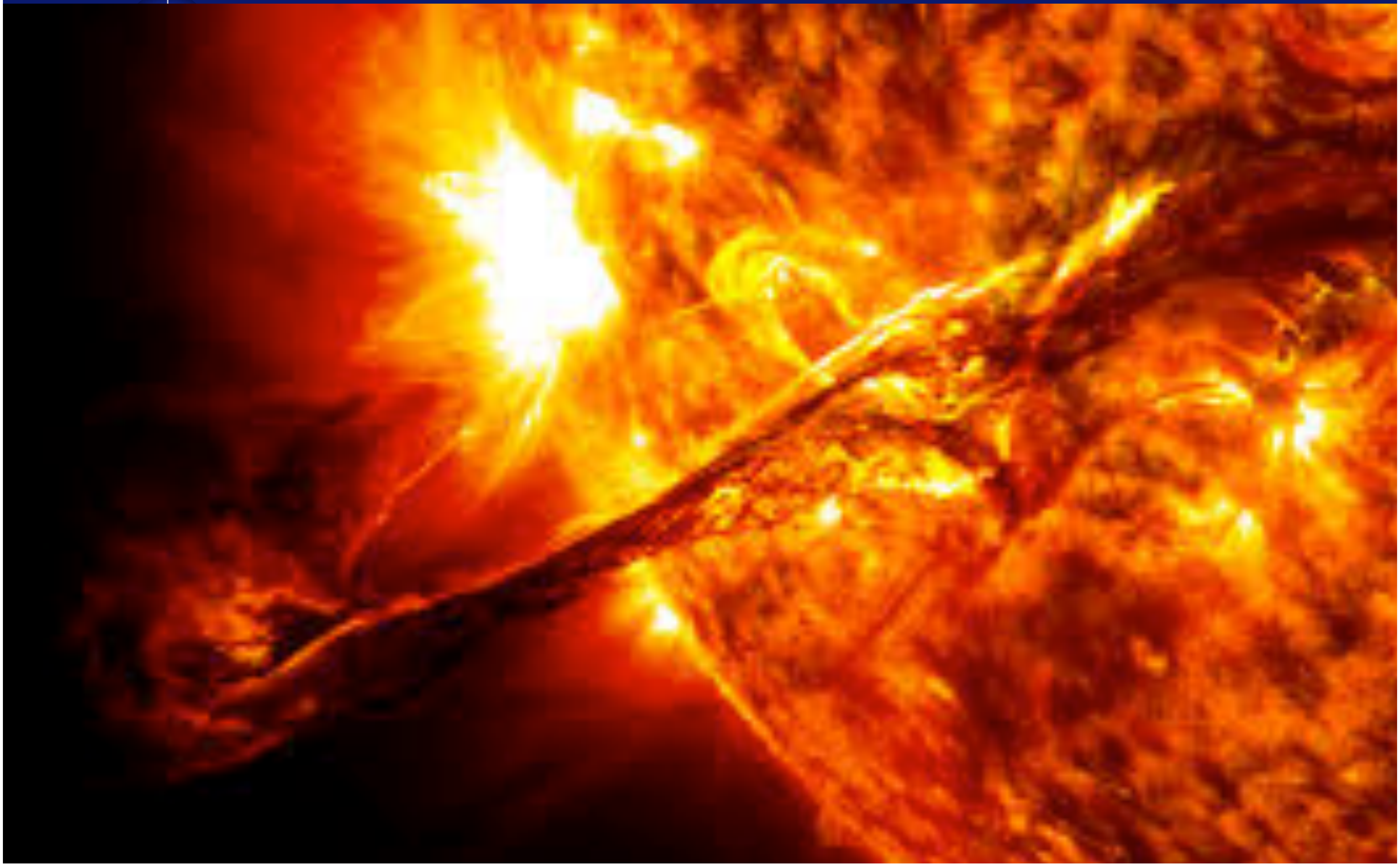
2D turbulence is very different from 3D



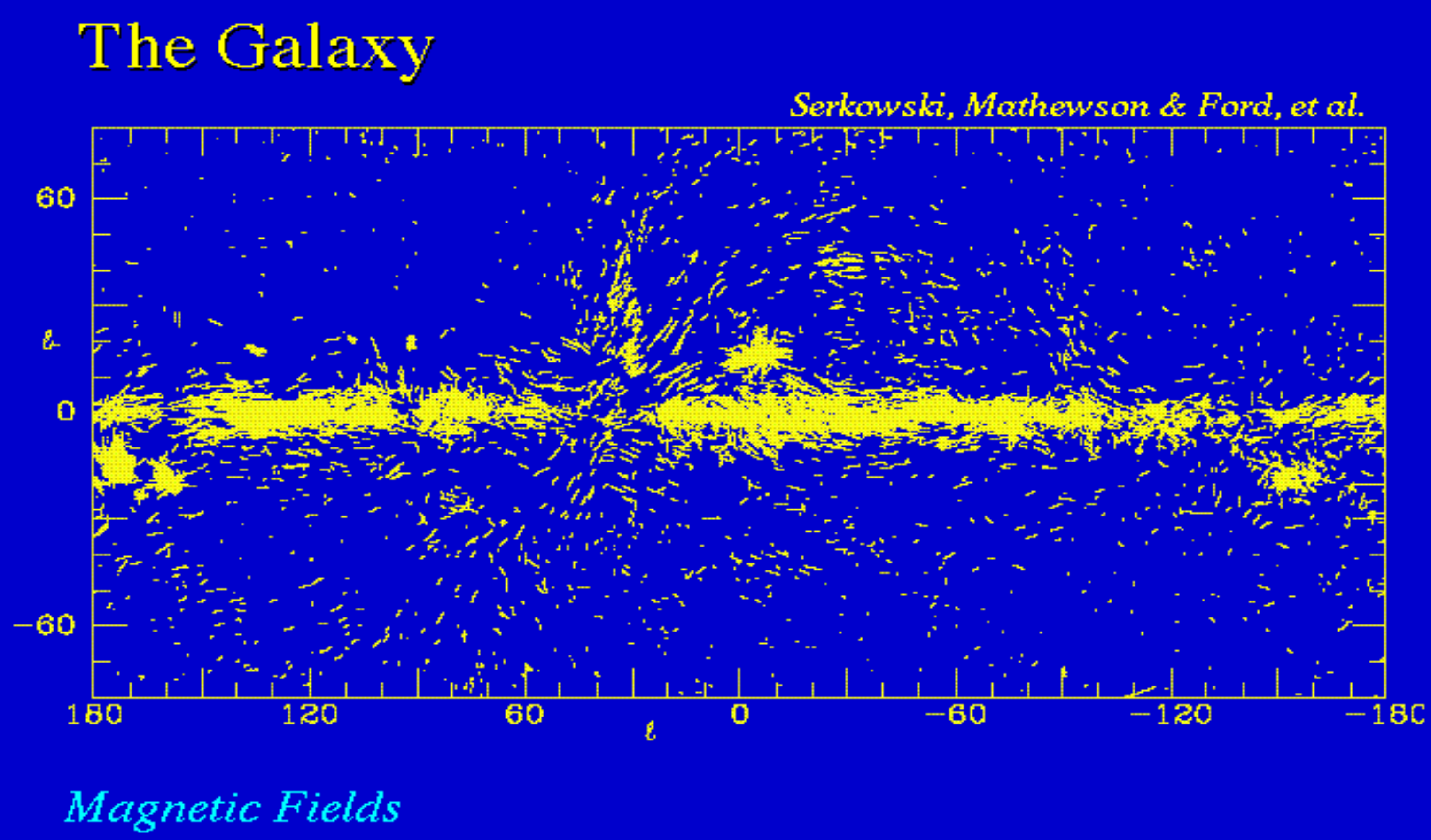
Plasma fills astrophysical space



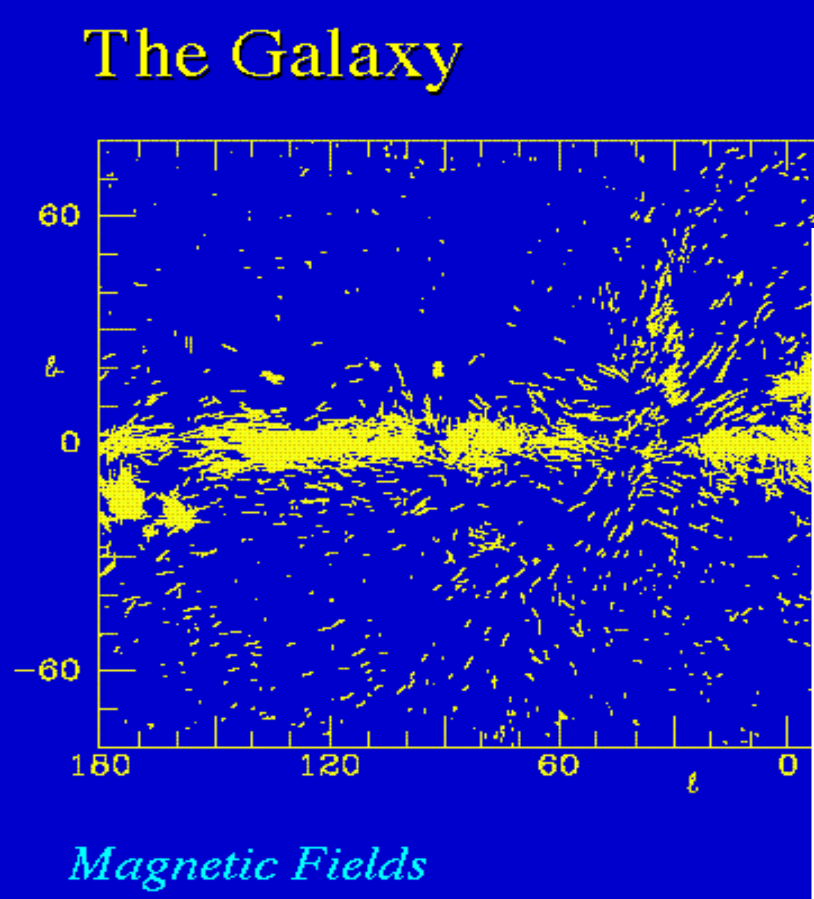
Solar Physics: Magnetized Plasmas

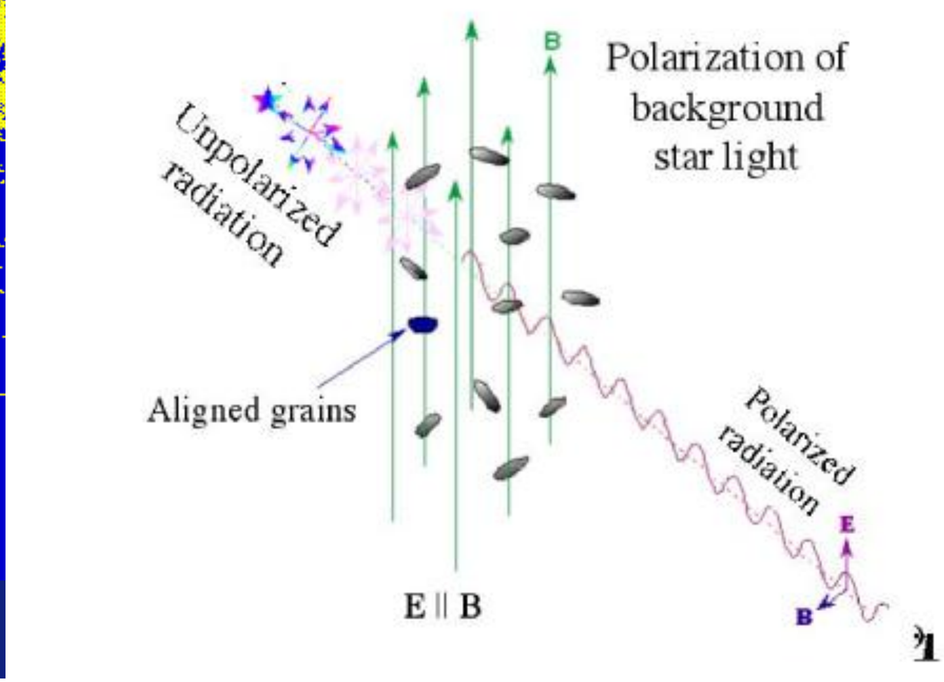


ISM large scale magnetic fields

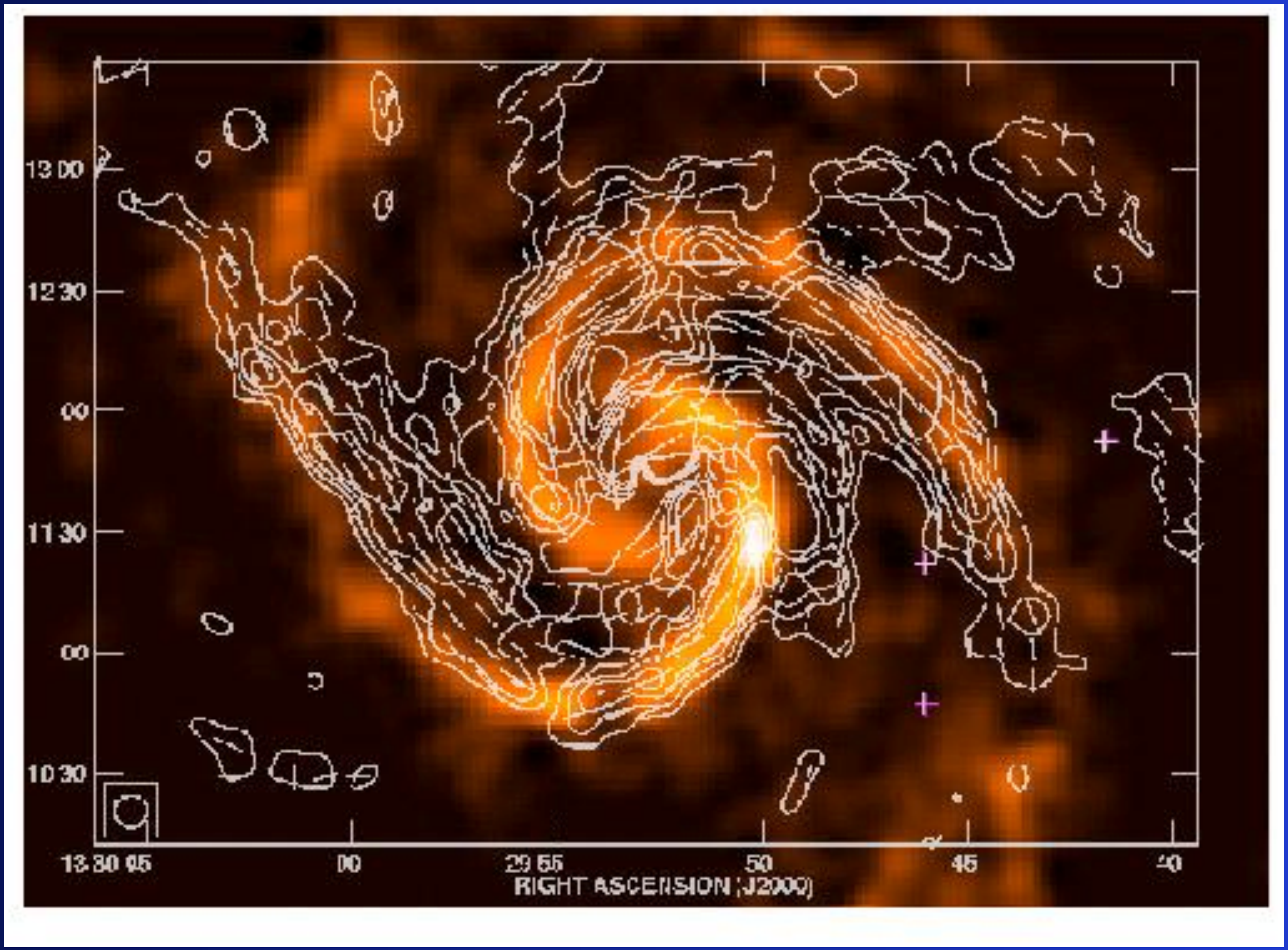


Grains trace magnetic fields by aligning their long axes perpendicular to magnetic field

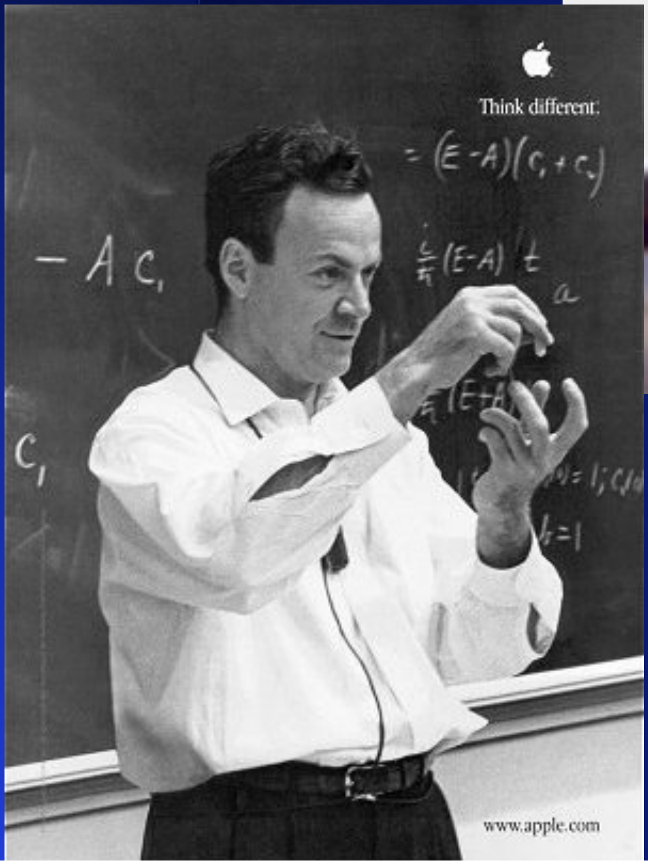




Polarized synchrotron emission also reveals the ISM magnetic fields



Turbulence is both dynamically and scientifically important



"Turbulence is the last great unsolved problem of classical physics"

R. Feynman

Our world depends on fluids being turbulent

Without turbulence:

molecular diffusion coefficient D ~10^{-5} cm^2/sec

(← It's for small molecules in water.)

→ Mixing time ~ (size of the cup)^2/D ~ 10^7 sec ~ 0.3 year !

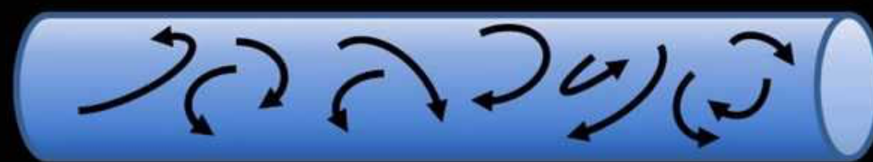
How can we deal with Turbulence?

Werner Heisenberg believed that turbulence is more mysterious than quantum mechanics. What do we know about turbulence?

When does turbulence happen?

Laminar flow

Turbulent flow



Osborne Reynolds
(1842-1917)

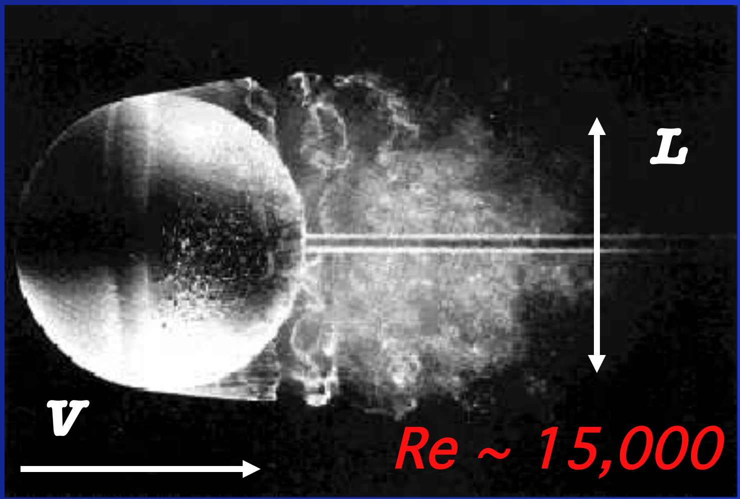
Reynolds Number – Single best predictor of the type of flow.

$$Re = \frac{\text{Inertia force}}{\text{Viscous force}}$$

Inertia force → *Promotes turbulent flow*

Flows get turbulent for large Reynolds numbers

$$Re = LV/\nu = (L^2/\nu)/(L/V) = \tau_{diff}/\tau_{eddy}$$



Point for numerical simulations: flows are similar for similar Re. Numerical $Re<10^4$, while Re of astro flows > 10^{10}

Reynolds number gauges the relative importance of inertia and viscous terms

- Reynolds number: $Re = VL/\nu$ ← $(V^2/L) / (\nu V/L^2)$

$$\frac{\partial \mathbf{v}}{\partial t} = -(\mathbf{v} \cdot \nabla)\mathbf{v} + \nu \nabla^2 \mathbf{v}$$

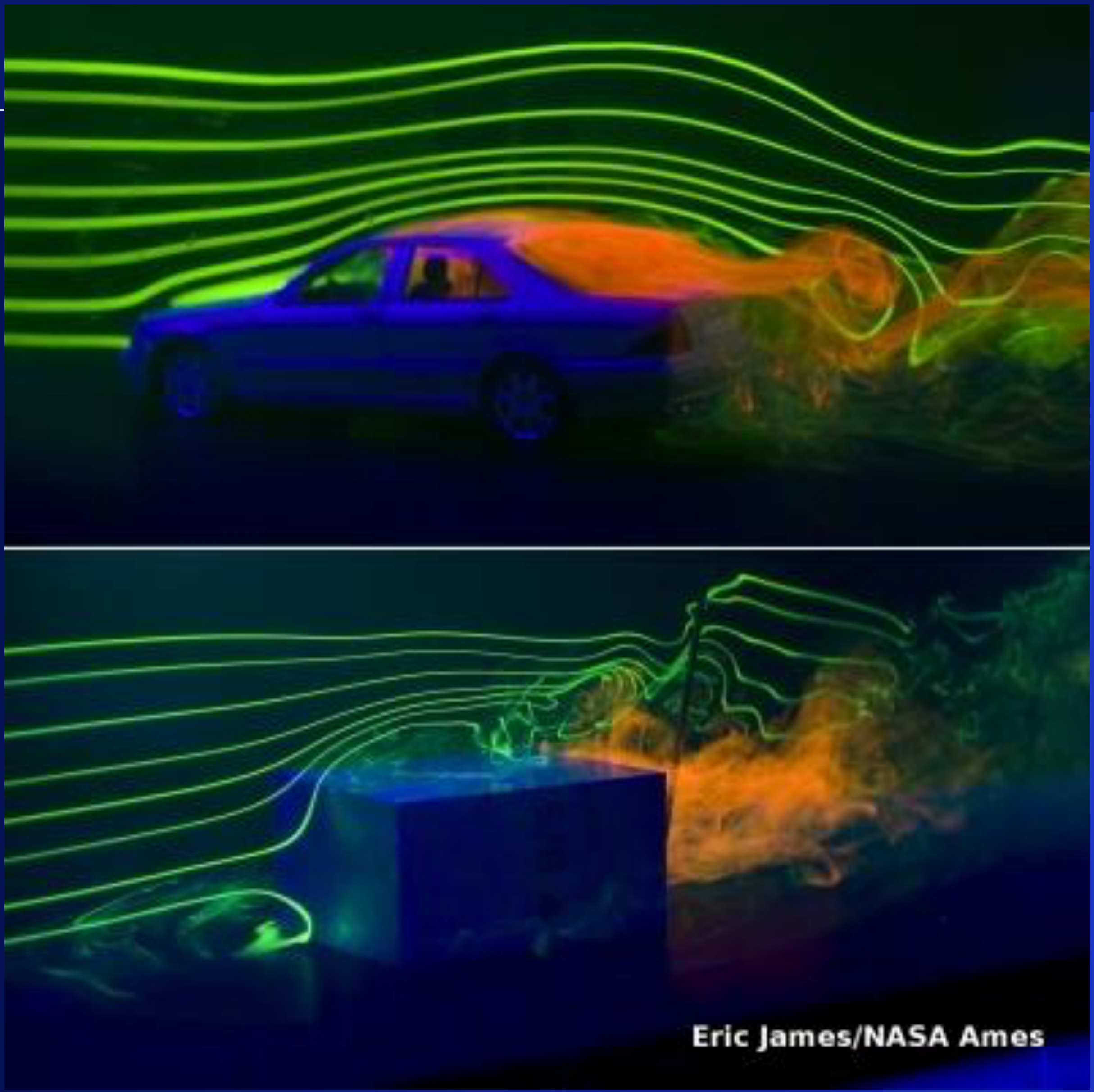
$(\mathbf{v} \cdot \nabla)\mathbf{v}$ ↑ V^2/L

$\nu \nabla^2 \mathbf{v}$ ↑ $\nu V/L^2$

- When $Re \ll Re_{critical}$, flow = laminar

  When $Re \gg Re_{critical}$, flow = turbulent

Turbulence requires an interaction to be excited, but generically difficult to be avoided

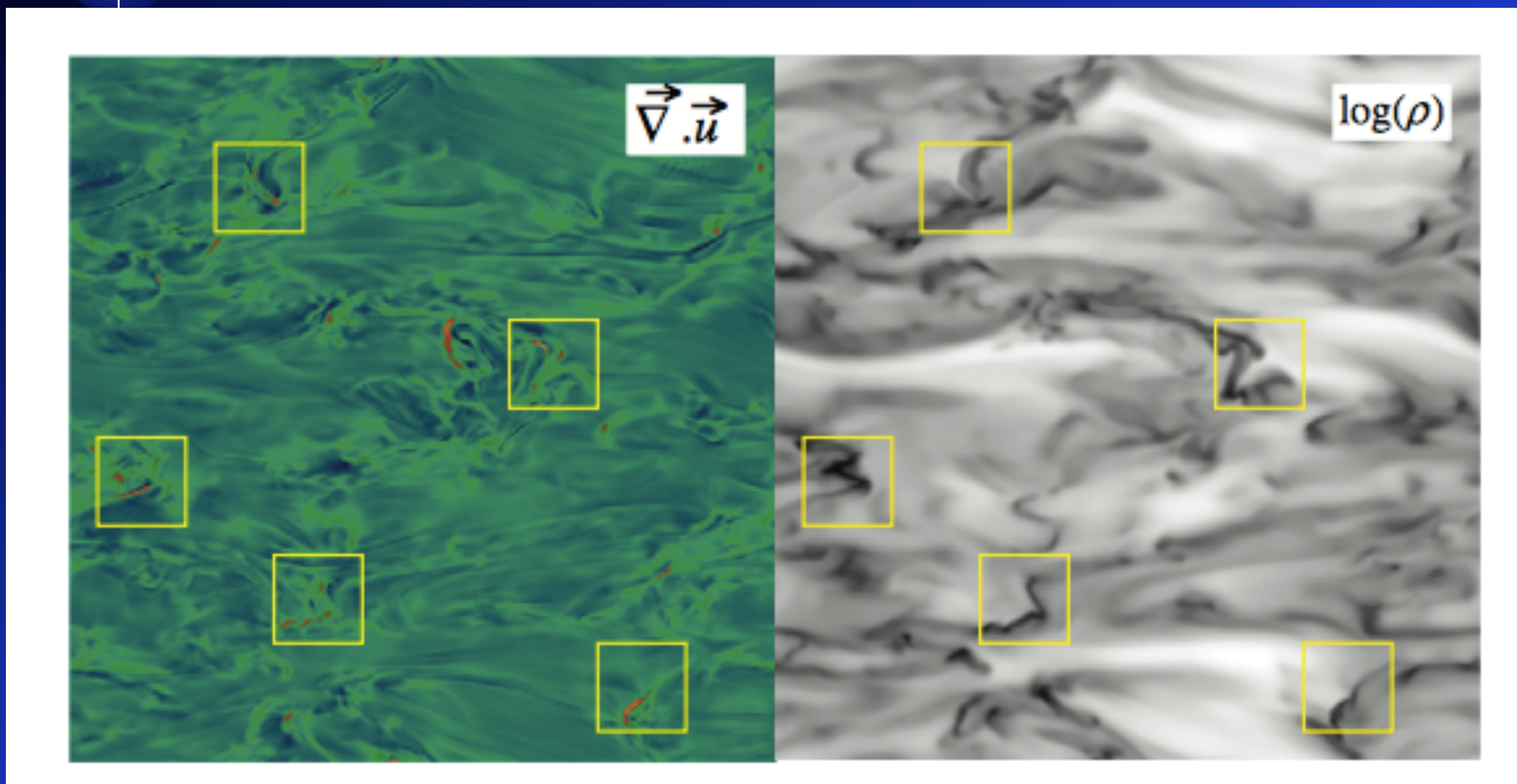


Turbulence is a natural state of high Re number fluid

Numerical simulations are attempts to simulate the reality and not the reality itself

Clouds from the point of view of turbulence are accumulations of gas by the flow

Falceta-Goncalves & AL 2011

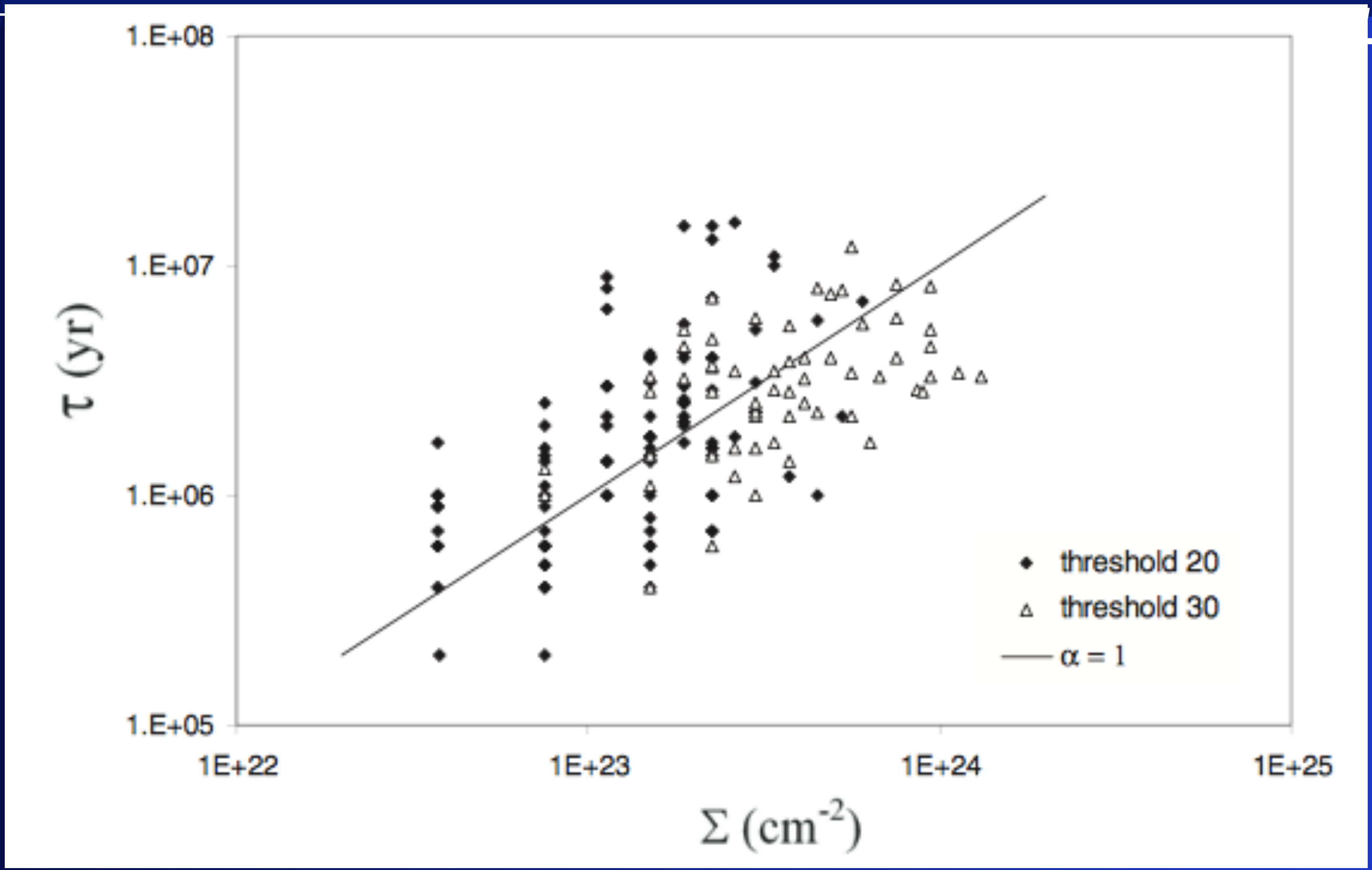


$$\rho v_L \tau_l \sim \rho_l l,$$

The thinner the structure the larger the density

Clouds from the point of view of turbulence are accumulations of gas by the flow

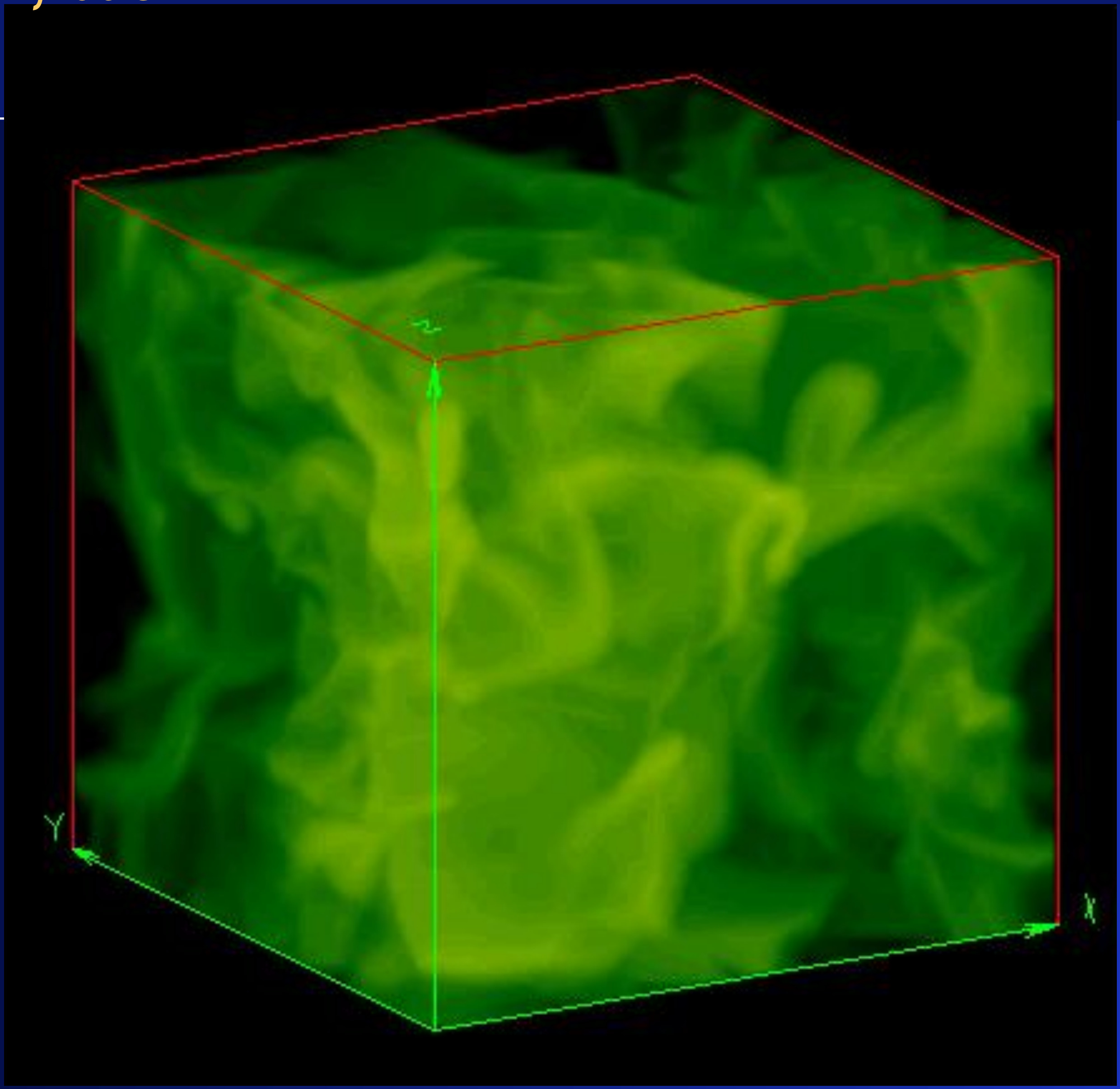
L 2011



$$\rho v_L \tau_l \sim \rho_l l,$$

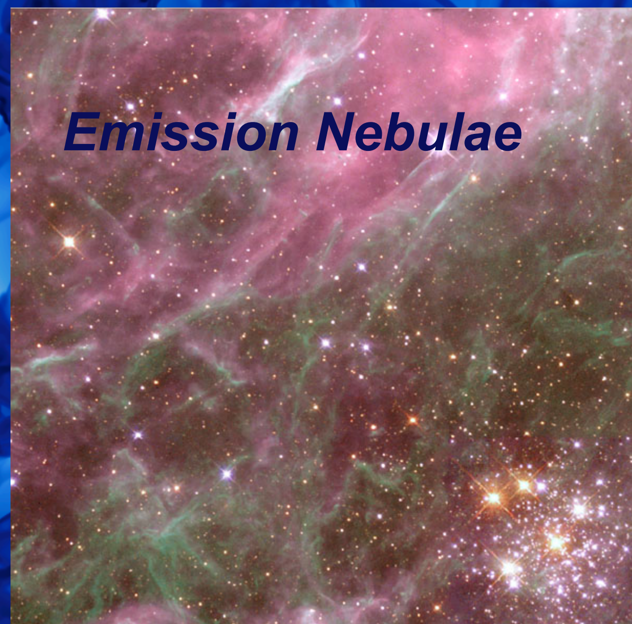
The thinner the structure the larger the density

Visual comparison of numerical simulations and observations is an approach, but …



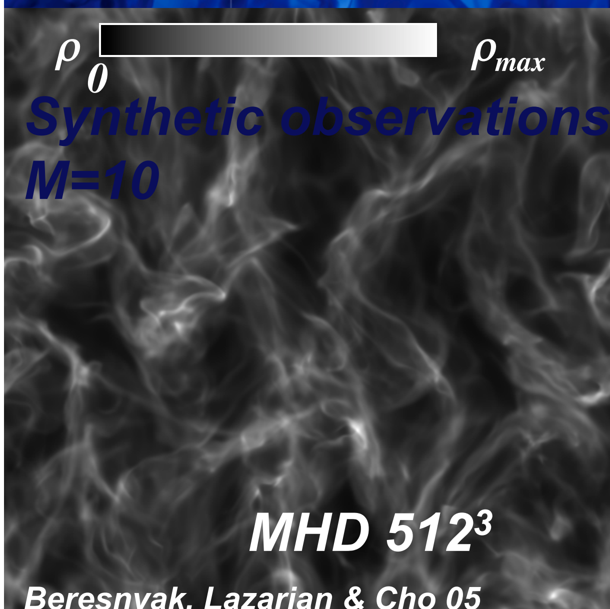
Numerics is useful when we understand what the eifference in Re numbers does for the answer

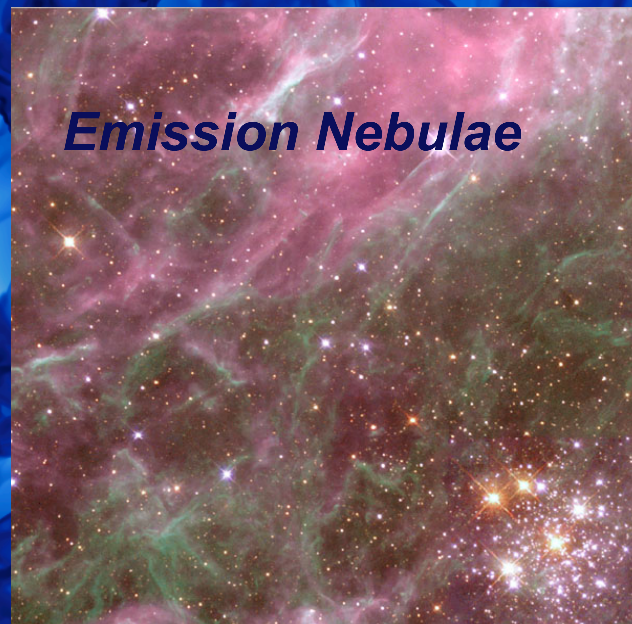
Astrophysical flows:



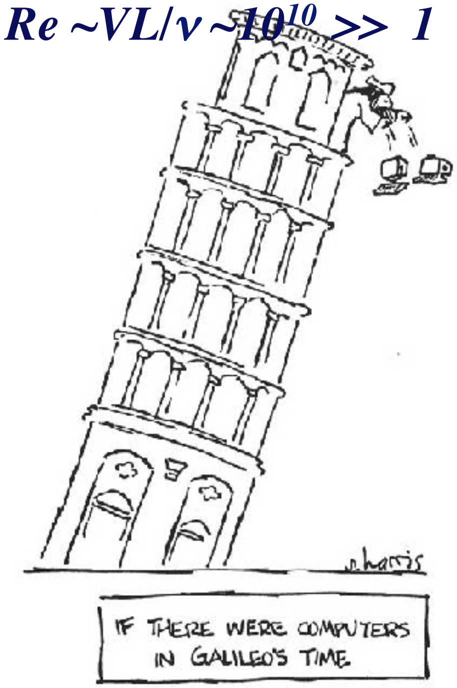
Numerics is useful when we understand what the eifference in Re numbers does for the answer

Astrophysical flows:





$Re \sim VL/\nu \sim 10^{10} >> 1$



Computational efforts scale as Re^4!!!
Currently max Re of order $<10^4$

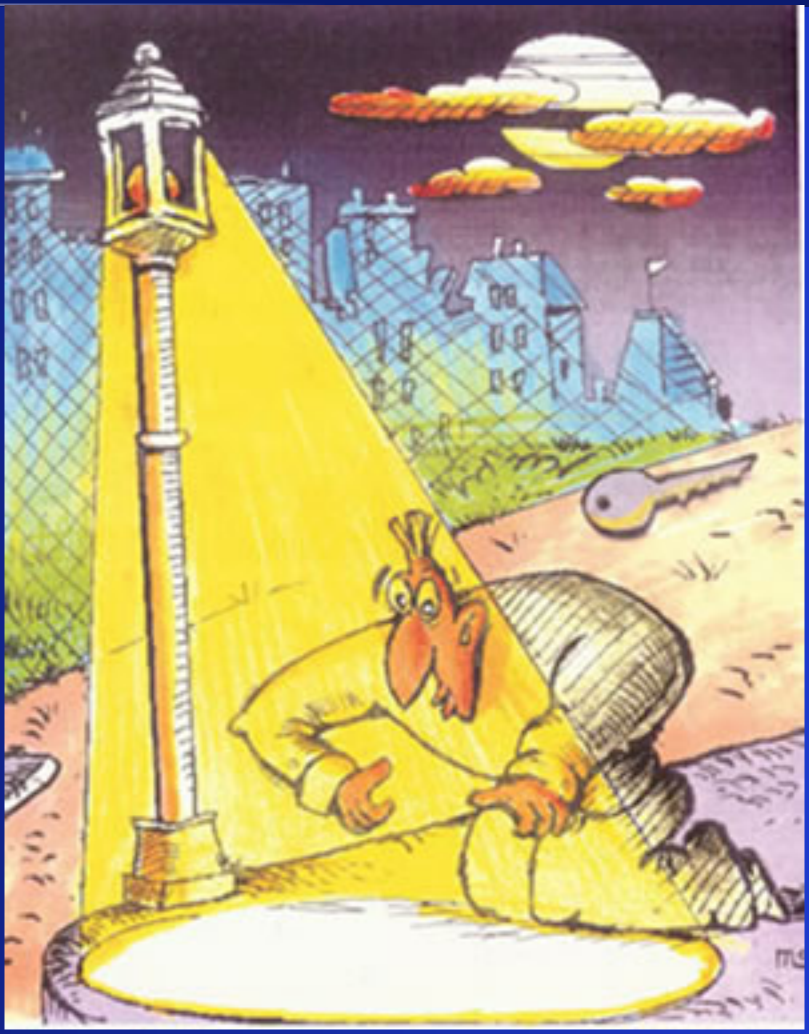
Numerics will not get to astro Re in foreseeable future. Flows in ISM and computers are and will be different!

A lot of research is driven by what we can currently simulate, but simulating realistic turbulence is challenging/impossible

Real world

↑

Numerical simulations



The studies extrapolate from low resolution numerical simulations to very different astrophysical regimes, while turbulence does require high resolution

Real world

↑

Numerical simulations

Efforts scale as Re^4

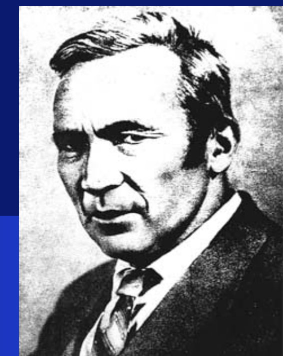
Differences in Re can be more than 10^{10}

Quantitative description of hydro and MHD turbulence

Turbulence is a chaotic order

It is good to know the laws of this order and use them

Kolmogorov theory reveals order in chaos for incompressible hydro turbulence

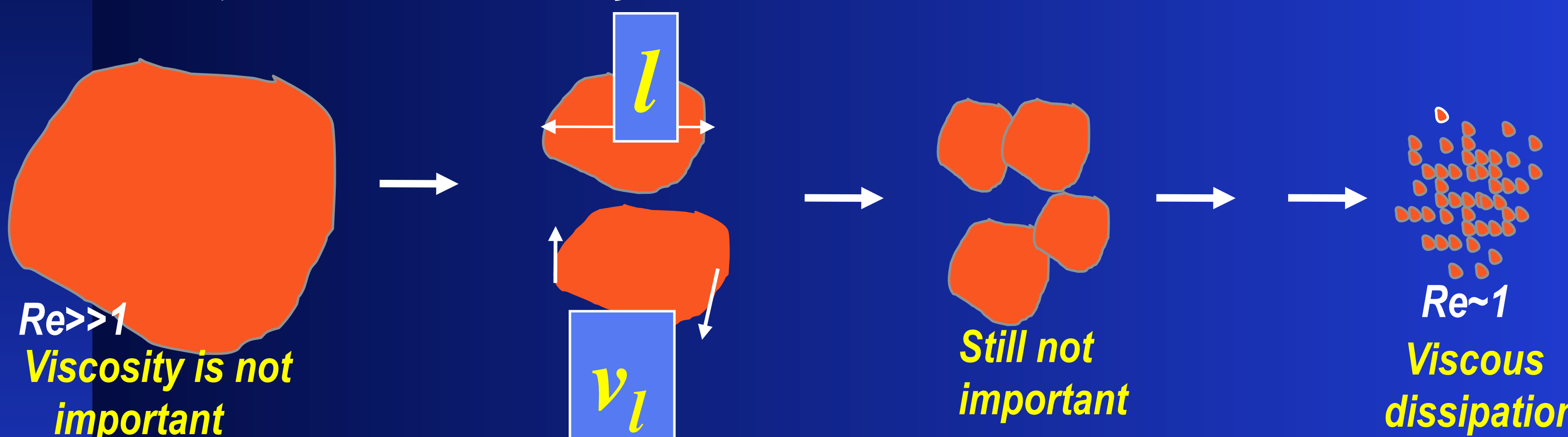


$$\frac{V_l^2}{t_{cas,l}} = const$$

$$t_{cas,l} = l/V_l$$

$$\frac{V_l^3}{l} = const, V_l \sim l^{1/3}$$

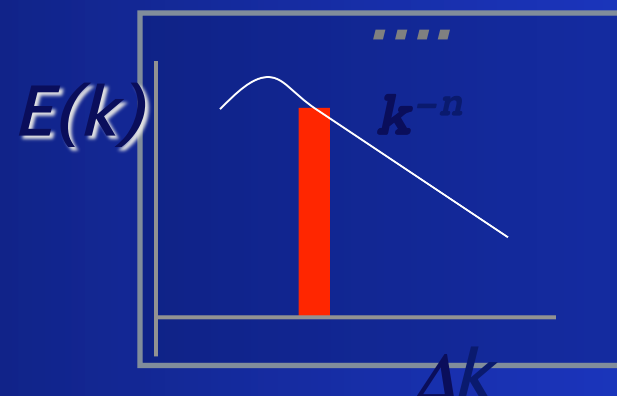
Or, $E(k) \sim k^{-5/3}$



Statistical descriptions of turbulence in real space and Fourer space are connected

$v(r), \rho(r), \ldots$

Fourier analysis of correlations



correlations

$<(v_1-v_2)^2> \sim r^m$

m=2/3 for Kolmogorov model

<…> is averaging

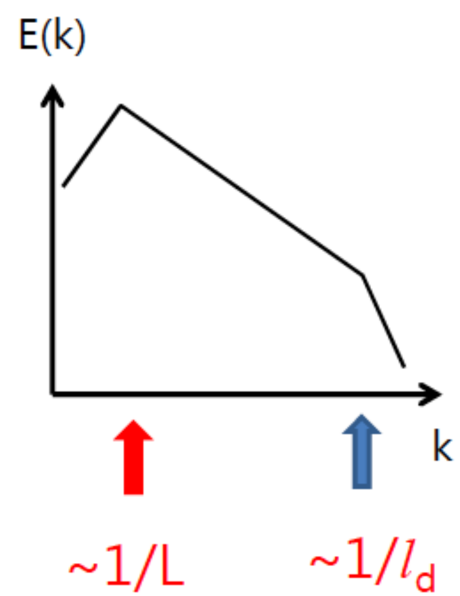
n=5/3 for Kolmogorov model

Spectrum : $E(k) \sim k^{-n}$

For turbulence the cascade is self-similar, injection and dissipation scales are important

-Outer scale L
(=energy injection scale ~integral scale)

$$L_{int} = 2\pi \frac{\int E_b(k)/k\ dk}{\int E_b(k)\ dk} \sim \text{outer scale}$$

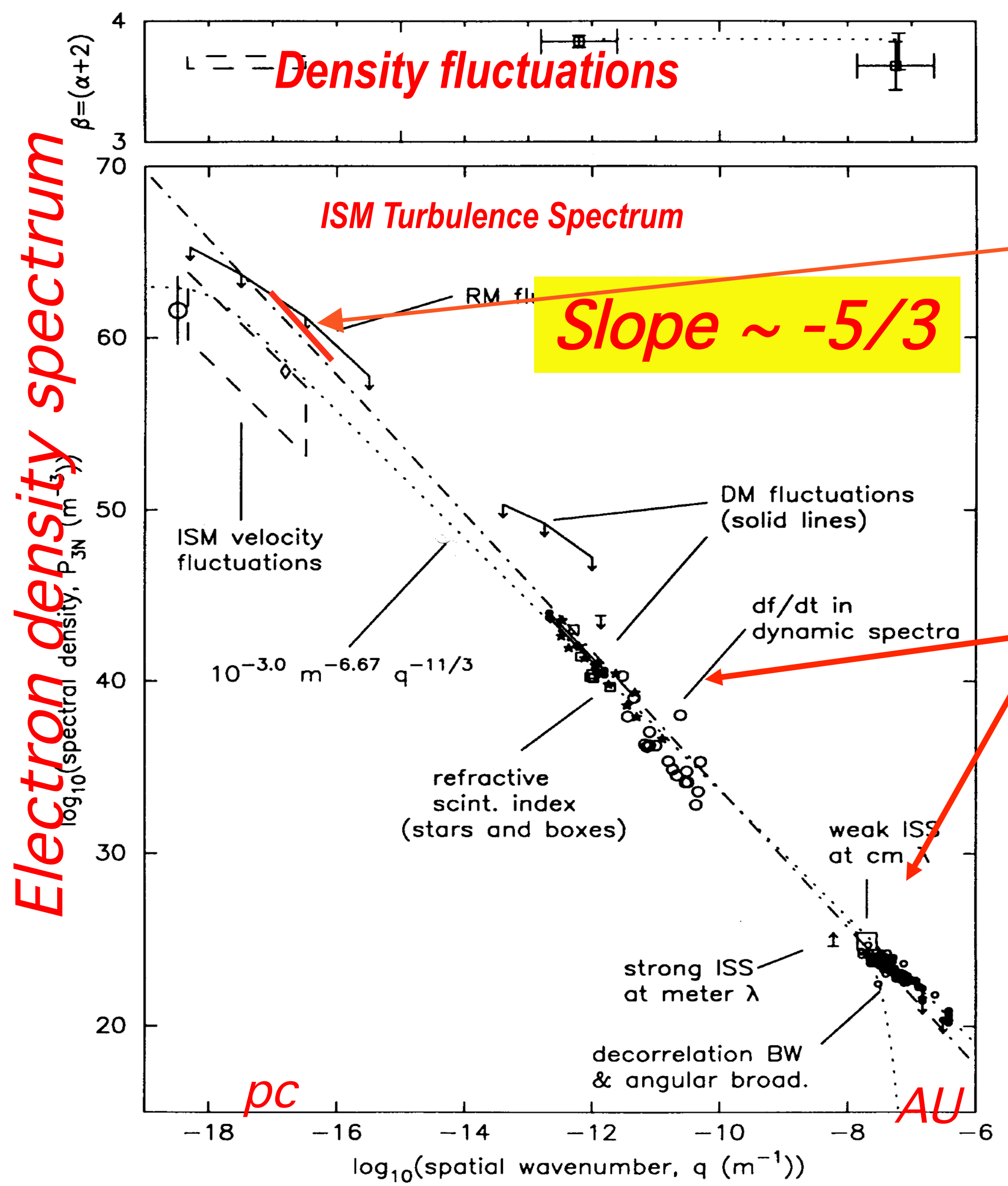


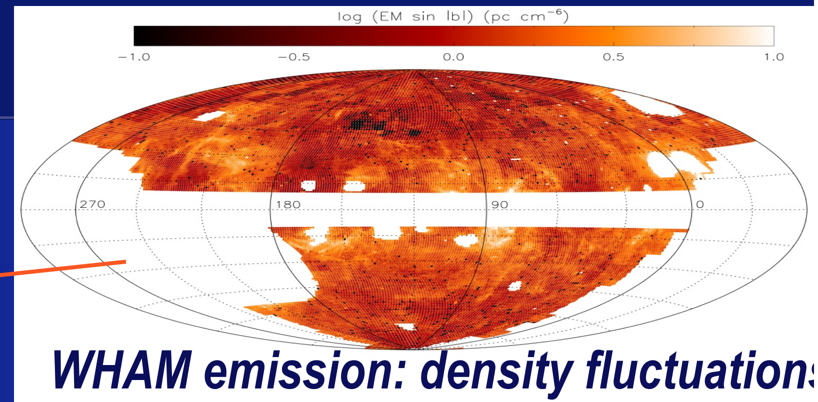
-Kolmogorov scale l_d (=dissipation scale)
← Reynolds number $(l_d v_d/\nu) = 1$

Since $v_d = v_L (l_d/L)^{1/3}$, we have $v_L (l_d)^{4/3} L^{-1/3} / \nu = 1$

➔ $l_d = L\,(Re)^{3/4}$

ISM reveals Kolmogorov spectrum of density fluctuations.



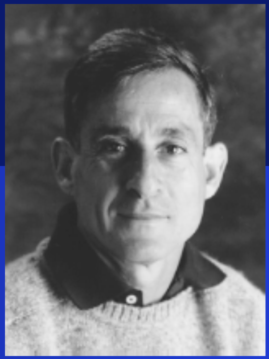


Scincillations and scattering

from Armstrong, Rickett & Spangler(1995)

Chepurnov & AL 2009

Strong MHD turbulence is characterized by a "critical balance".



- Critical balance

$$\frac{l_\perp}{b_{\perp l}} = \frac{l_\parallel}{B_0}$$

- Constancy of energy cascade rate

$$\frac{b_{\perp l}^2}{t_{cas}} = const$$

$$\frac{b_{\perp l}^2}{(l_\perp / b_{\perp l})} = const$$

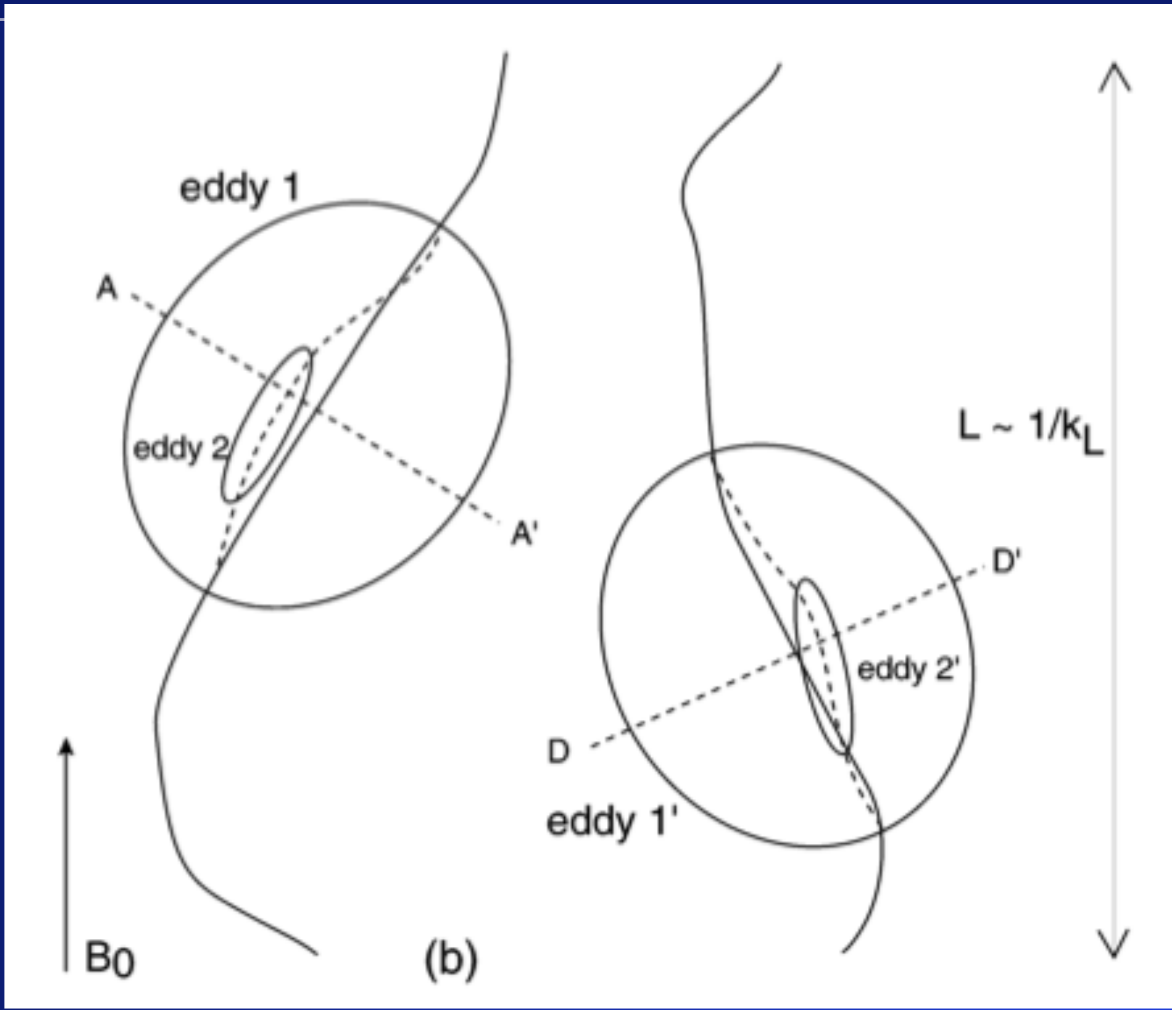
$$b_\perp \sim l_\perp^{1/3}$$

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

$$l_\parallel \sim l_\perp^{2/3}$$

Goldreich-Sridhar model (1995)

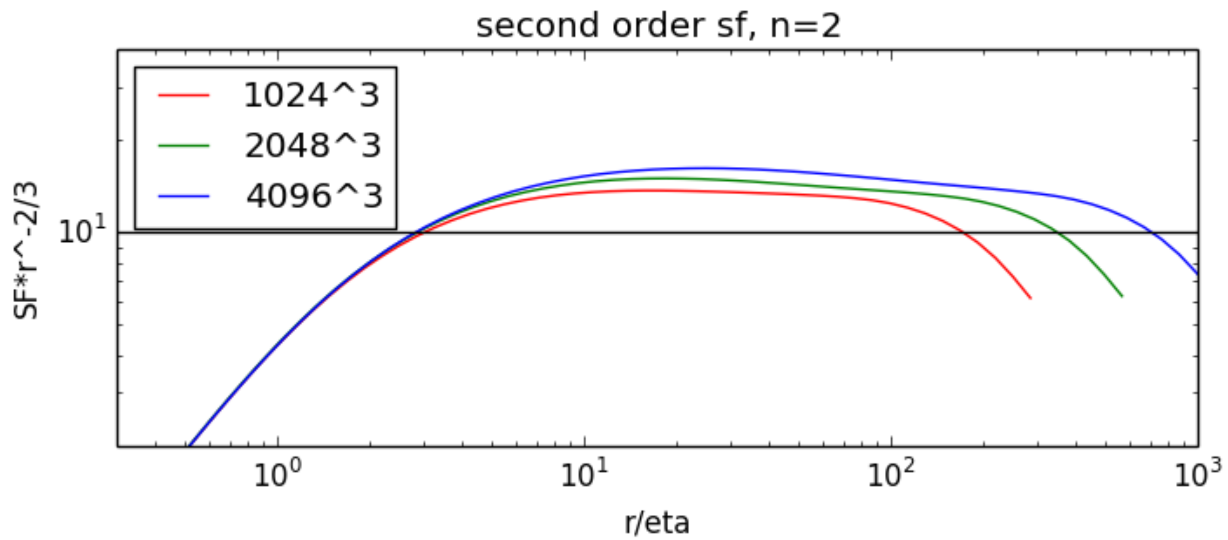
Local system of reference is essential. GS95 relations are only valid in the local system.

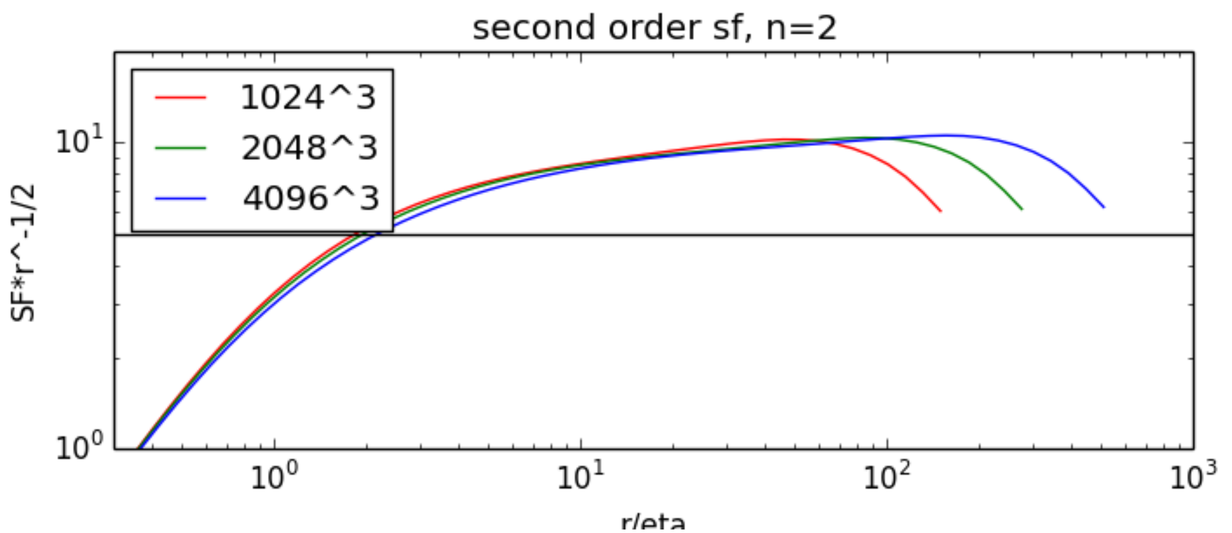


The effect of the local magnetic field (AL & Vishniac 1999) is the key element for interpreting the GS95 relations

Second order SF (total energy)

Demonstrates r^2/3 scaling

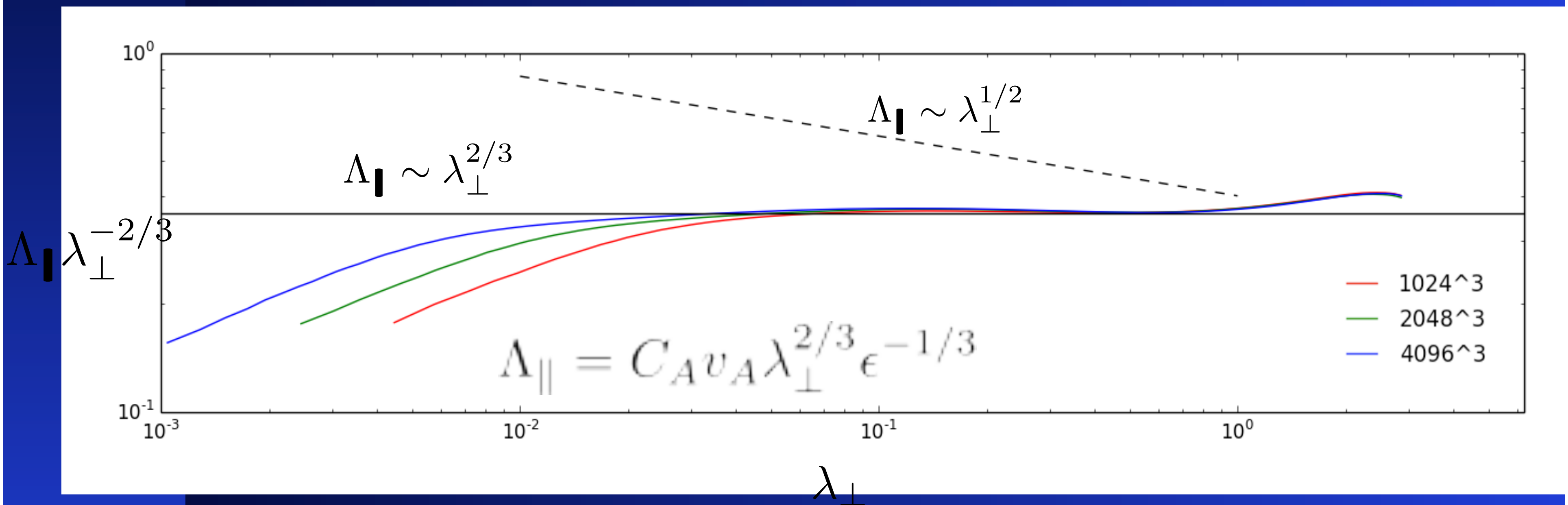




Anisotropy in SF

GS95:

Boldyrev $l_{\|} \sim l_{\perp}^{1/2}$



Beresnyak 15

Scaling of Alfvenic turbulence are applicable if the injection velocity is different from Alfven one

GS95 theory assumes that the injection scale L velocity is equal to Alfven speed. If it is less, then turbulence is initially weak up to scale $l_A = LM_A^2$ (M_A is the Alfven Mach number $V_L/V_A<1$) but gets strong at smaller scales (see AL & Vishniac 1999). If the turbulence is SuperAlfenic, i.e. $M_A>1$, at it gets Alfvenic at a smaller scale $l_{trans} = LM_A^{-3}$ (see AL 2006).

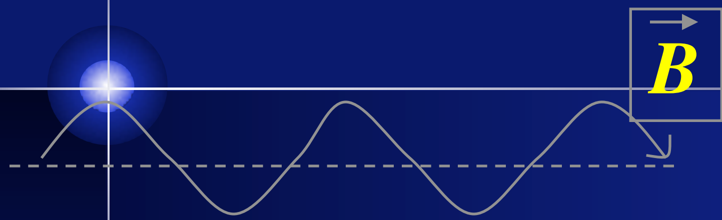
Table 1

Regimes and ranges of MHD turbulence

Type of MHD turbulence	Injection velocity	Range of scales	Motion type	Ways of study
Weak	$V_L < V_A$	$[L, l_{trans}]$	wave-like	analytical
Strong subAlfvenic	$V_L < V_A$	$[l_{trans}, l_{min}]$	eddy-like	numerical
Strong superAlfvenic	$V_L > V_A$	$[l_A, l_{min}]$	eddy-like	numerical

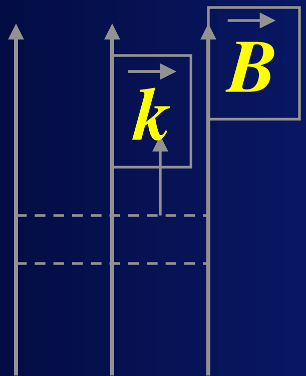
L and l_{min} are injection and dissipation scales

Simple considerations give hope that compressible MHD turbulence can be understood and described



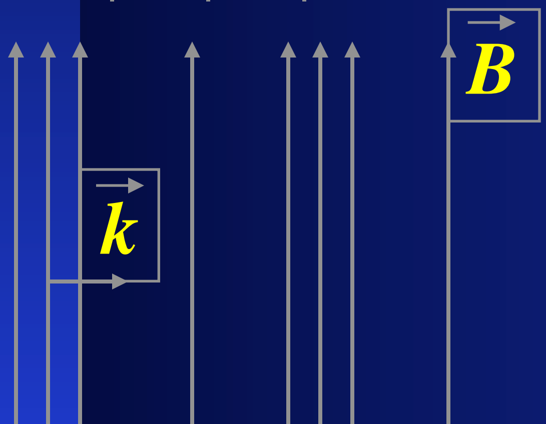
Alfven mode ($v=V_A \cos\theta$)

incompressible;
restoring force=mag. tension



slow mode ($v=c_s \cos\theta$)

restoring force = P_{gas}



fast mode ($v=V_A$)

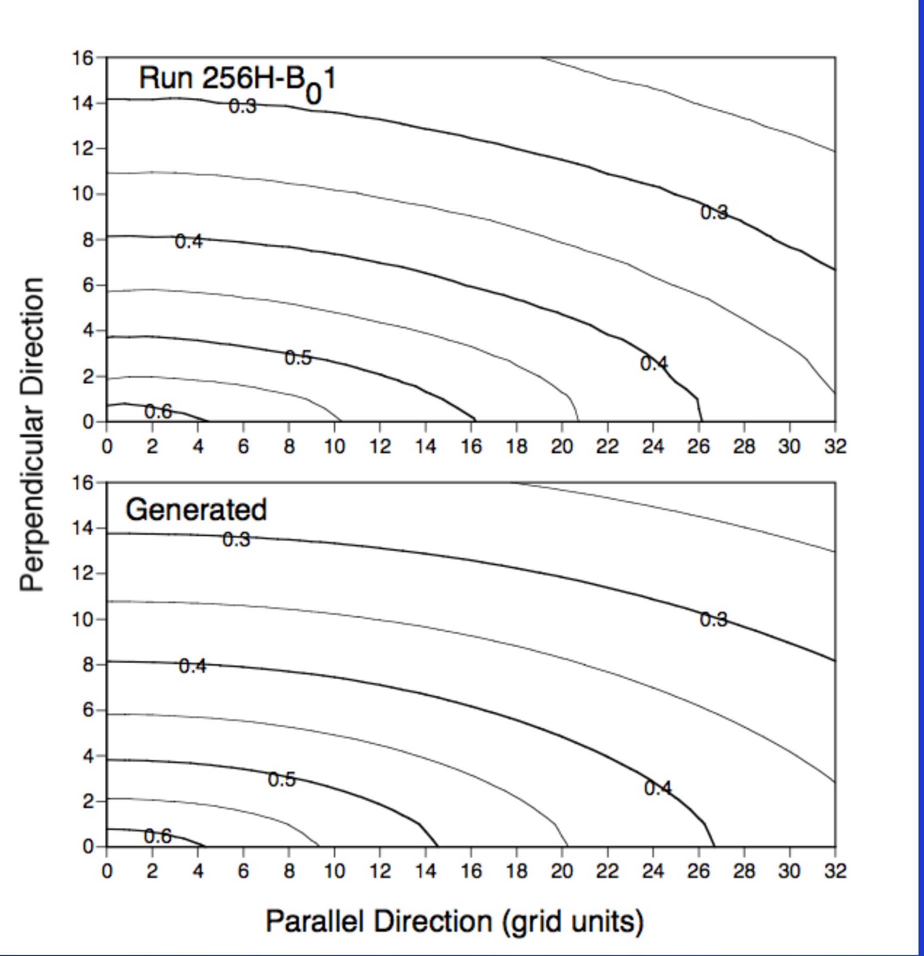
restoring force = $P_{mag} + P_{gas}$

Theoretical discussion in Lithwick & Goldreich 01
Cho & Lazarian 02

Anisotropy and scaling of Alfven modes in compressible and incompressible turbulence are the same

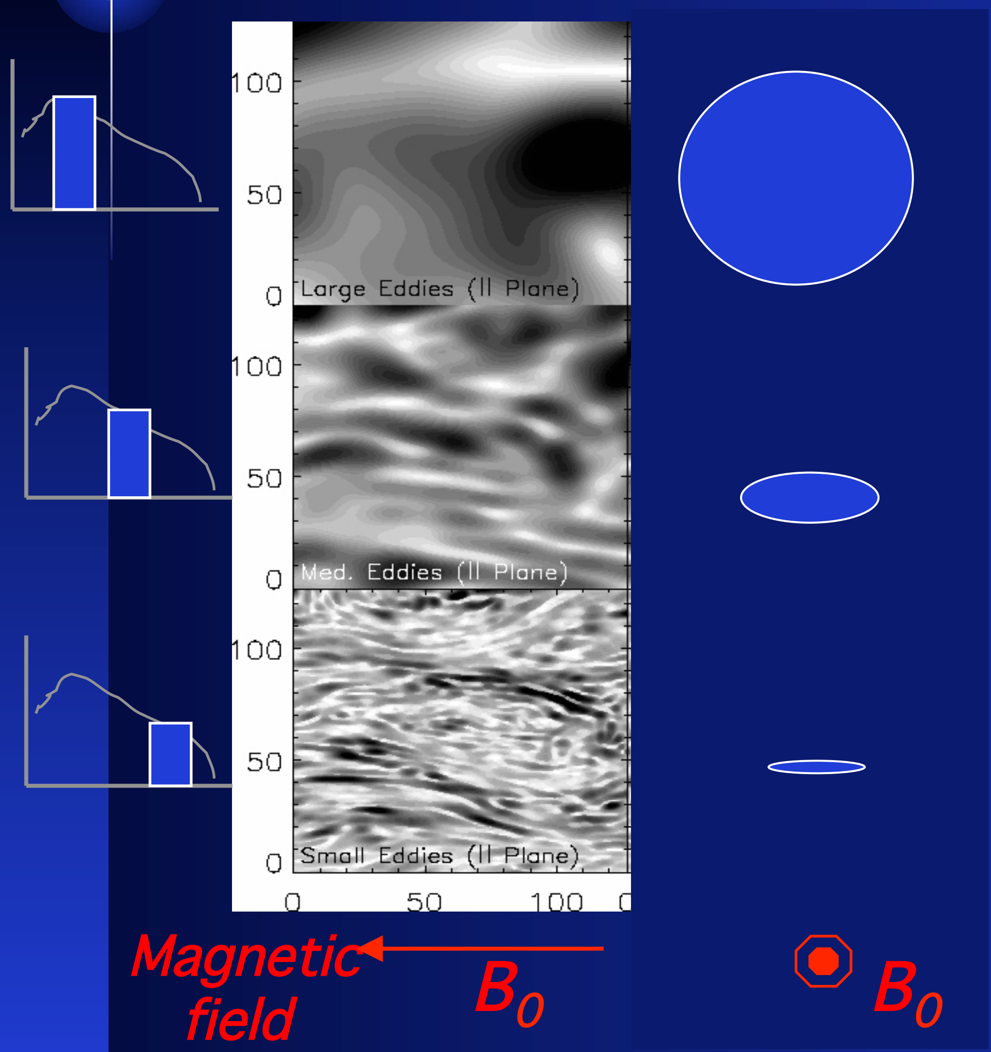
Analytical fit

$$E(k_\perp, k_\parallel) = \left(\frac{B_0}{L^{1/3}}\right) k_\perp^{-10/3} \exp\left(-L^{1/3}\frac{k_\parallel}{k_\perp^{2/3}}\right),$$



Cho, AL & Vishniac 2002

Alfvenic eddies get more and more elongated with the decrease of the scale



Cho, AL & Vishniac 2002

Transfer of energy from Alfven modes to slow and fast modes is rather marginal for many total, i.e. $M_{total} = v/(v_A^2+v_s^2)^{1/2}$, Mach number

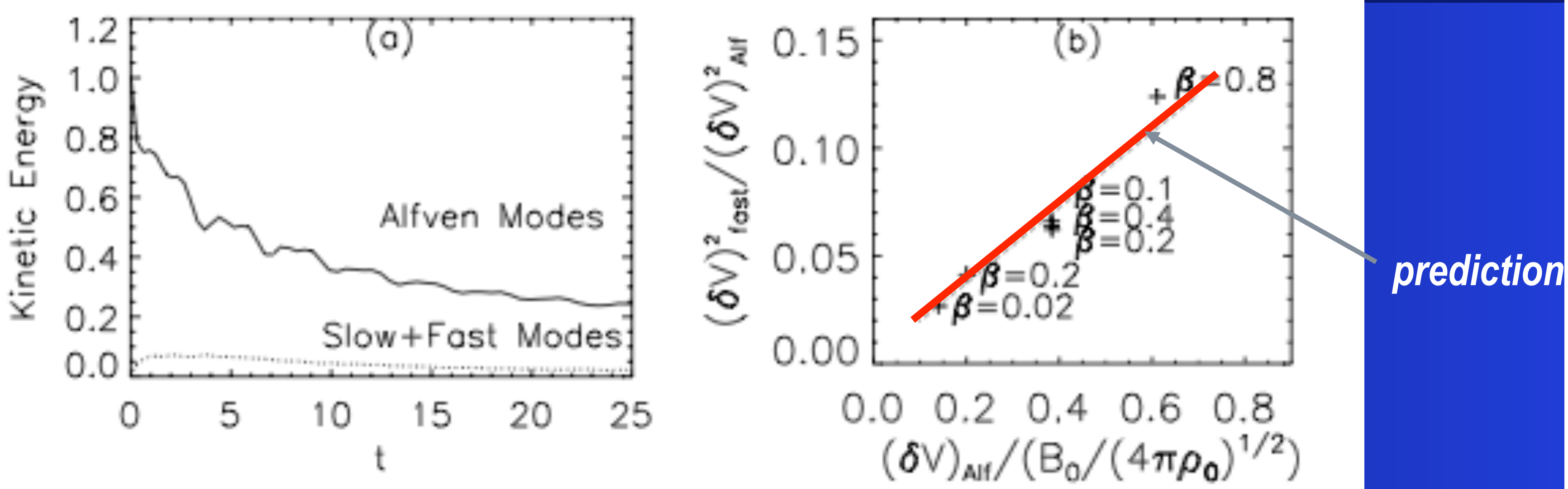
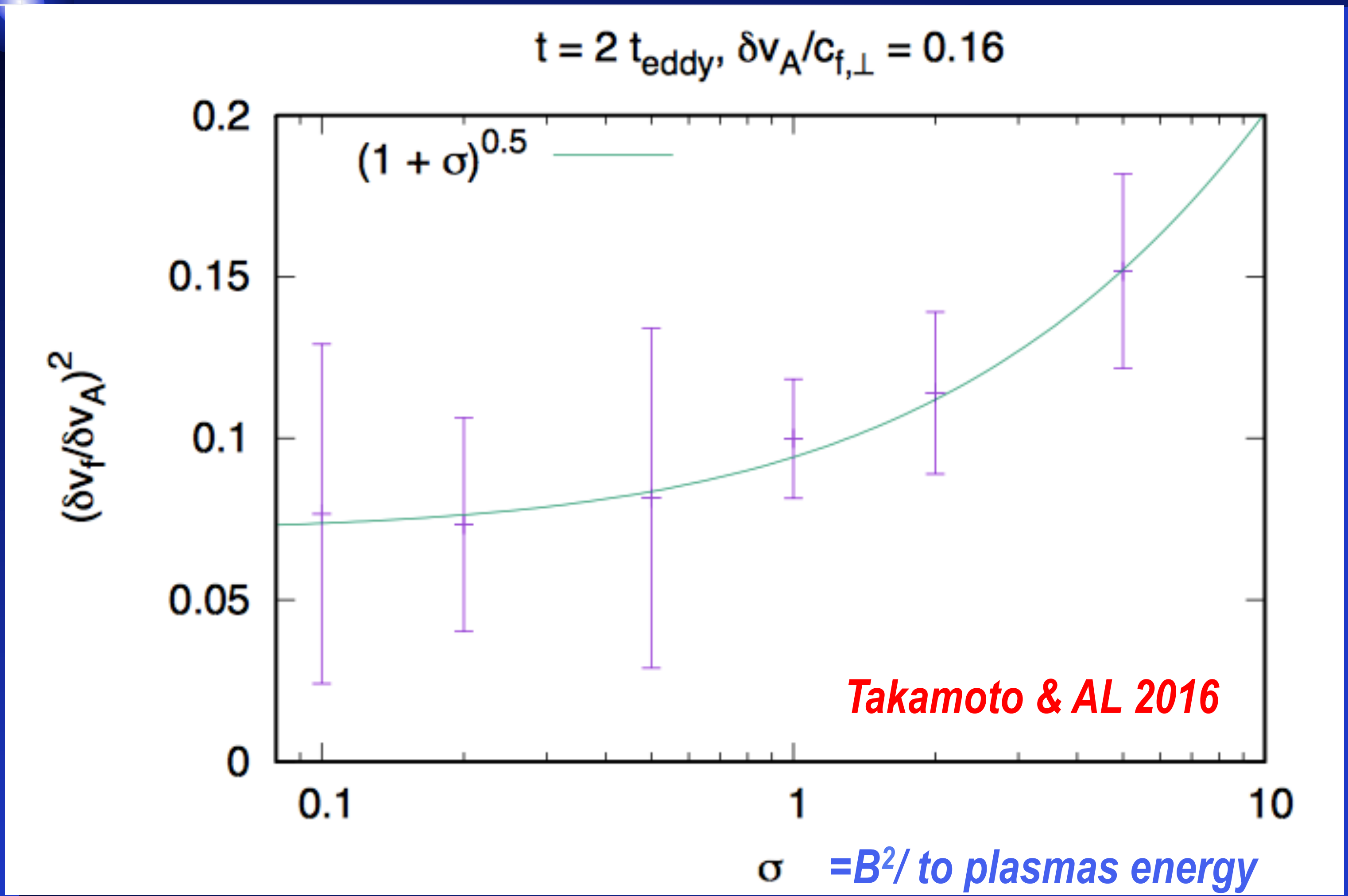


FIG. 1. (a) Decay of Alfvénic turbulence. The generation of fast and slow waves is not efficient. Initially, $\beta \sim 0.2$ and $B_0/\sqrt{4\pi\rho_0} = 1$. (b) The ratio of $(\delta V)^2_f$ to $(\delta V)^2_A$. The ratio is measured at $t \sim 3$ for all simulations. The ratio strongly depends on B_0, but only weakly on (initial) β. The initial Mach numbers span 1–4.5.

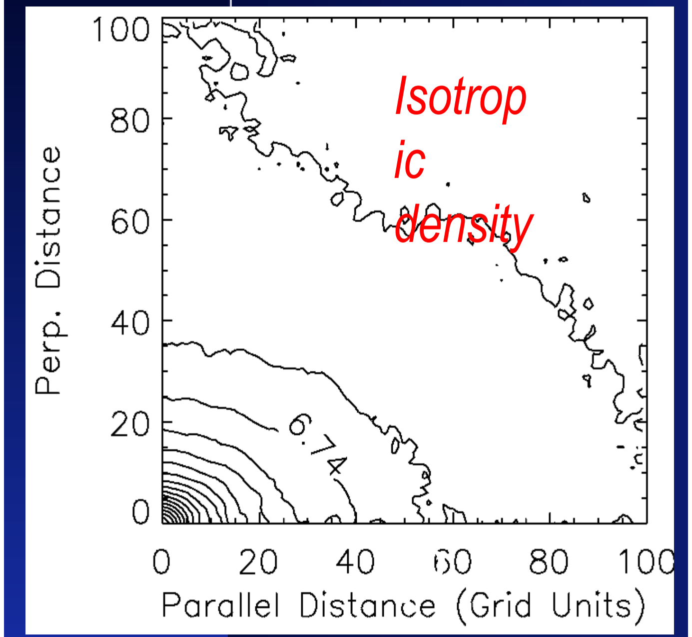
Cho & AL 2002

Coupling of Alfvenic, fast and slow modes is weak for $M_{total} \ll 1$. Thus Alfvenic motions persist.

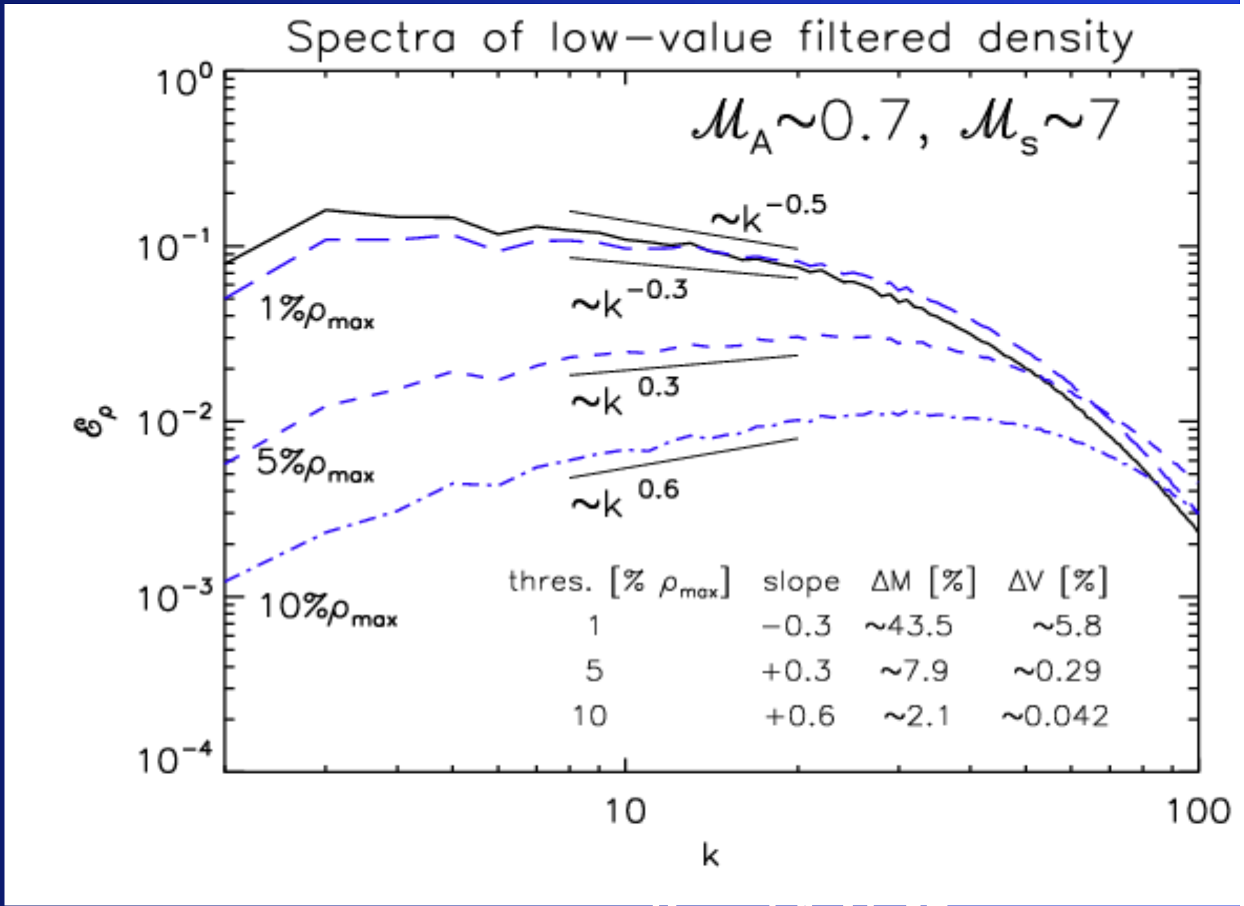
Compressibility in relativistic Limit: Coupling of Alfven and fast modes increases in relativistic MHD



High amplitude density fluctuations in supersonic turbulence get isotropic and lose anisotropy



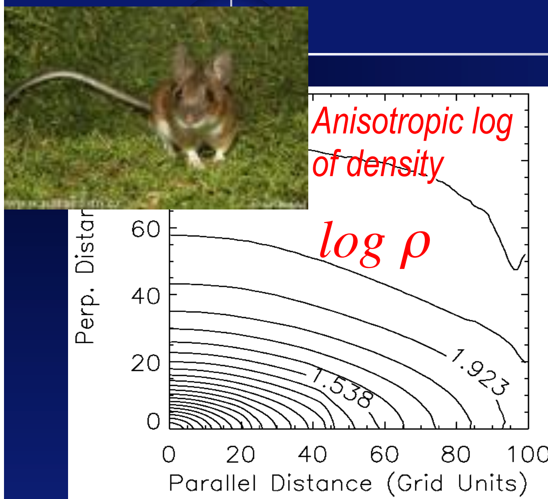
Beresnyak, AL & Cho 05



Kowal & AL 07

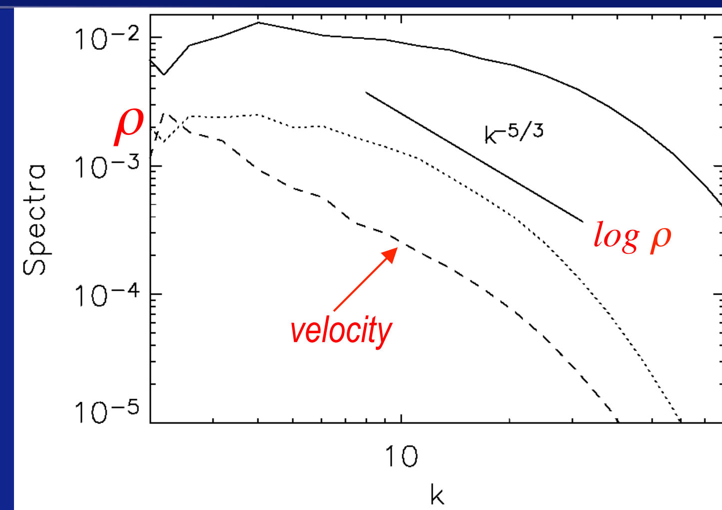
Density is pretty messy. Statistics changes with the Mach number!

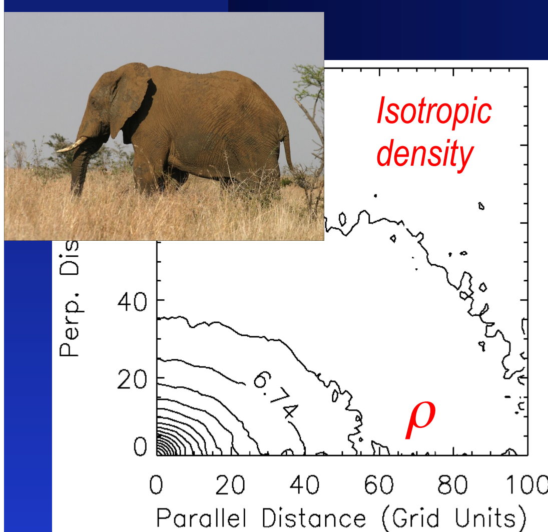
High amplitude density fluctuations in supersonic turbulence are isotropic. Low amplitude fluctuations are GS95 type.

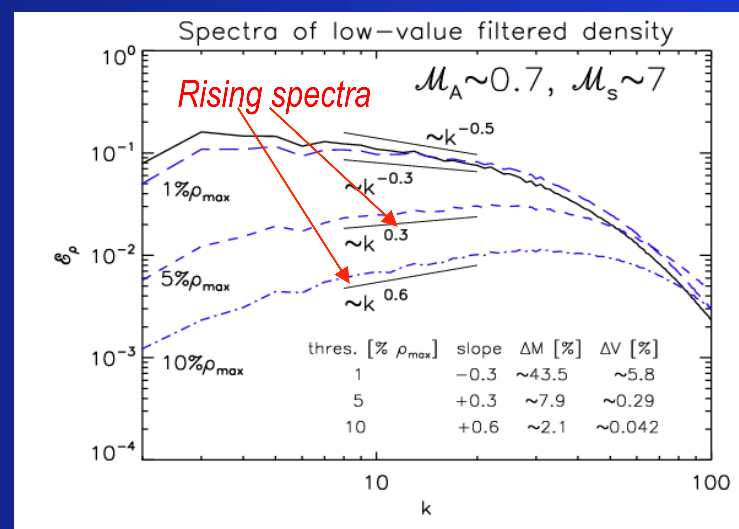


Max number

M_s=7





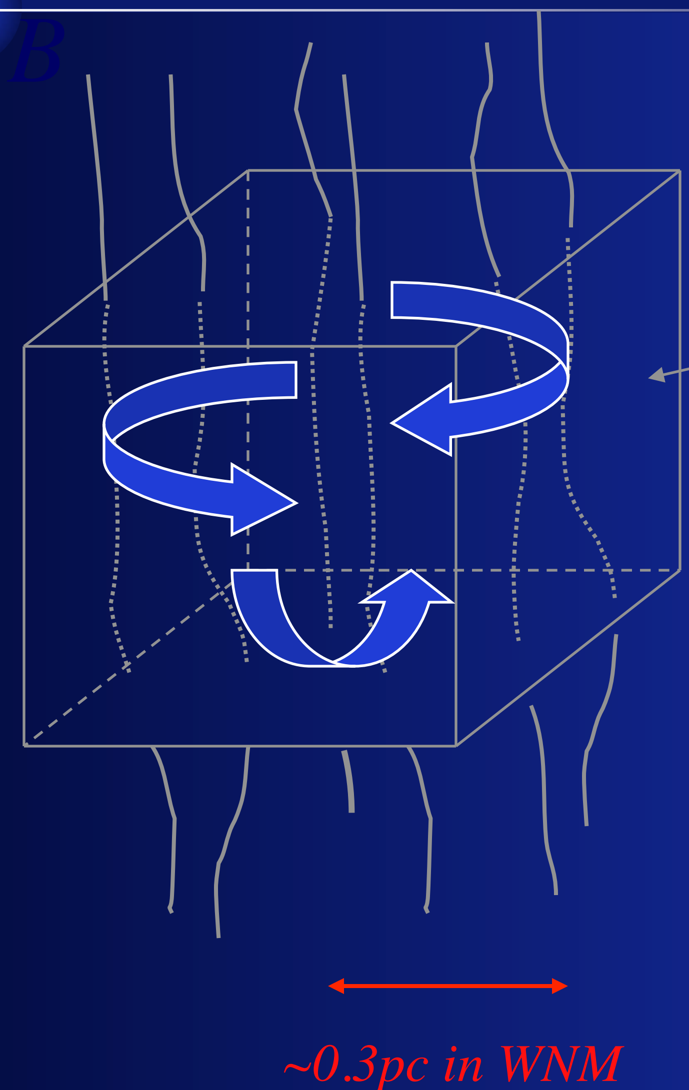


Beresnyak, AL & Cho 2005

Kowal & AL 2007

What do neutrals do to MHD turbulence?

What does happen to turbulence in partially ionized gas?



Viscosity is important while resistivity is not.

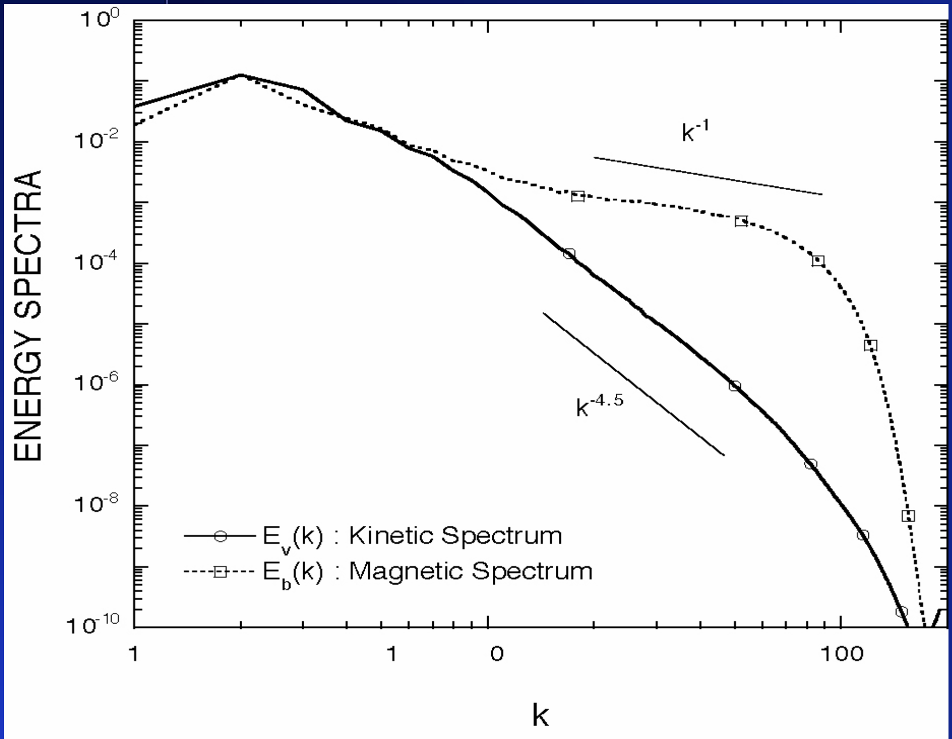
Viscous magnetized fluid

Is viscous damping scale the scale at which MHD turbulence stops?

A new viscosity-dominated regime was predicted and demonstrated numerically

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

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

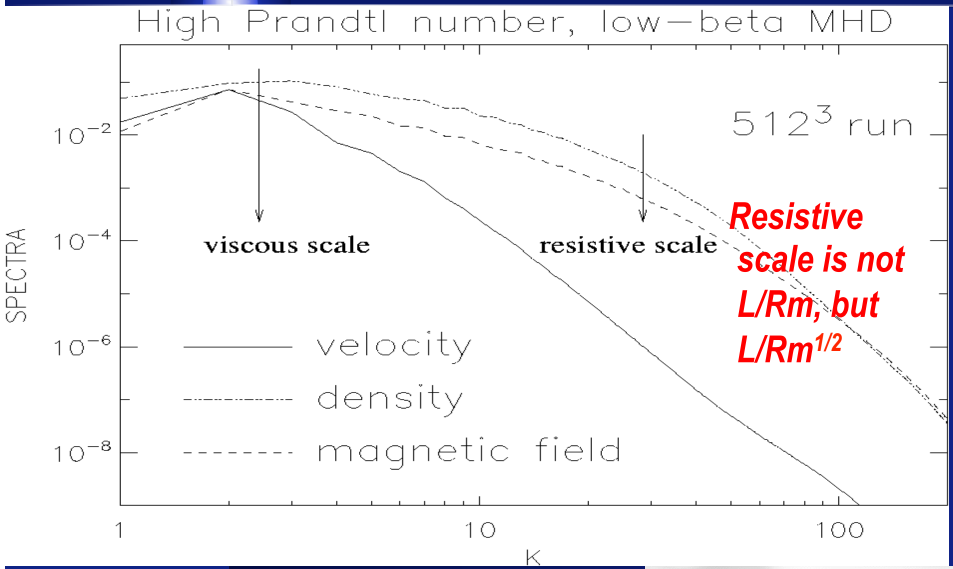


Cho, Lazarian & Vishniac 02

Predictions in Lazarian, Vishniac & Cho 04:

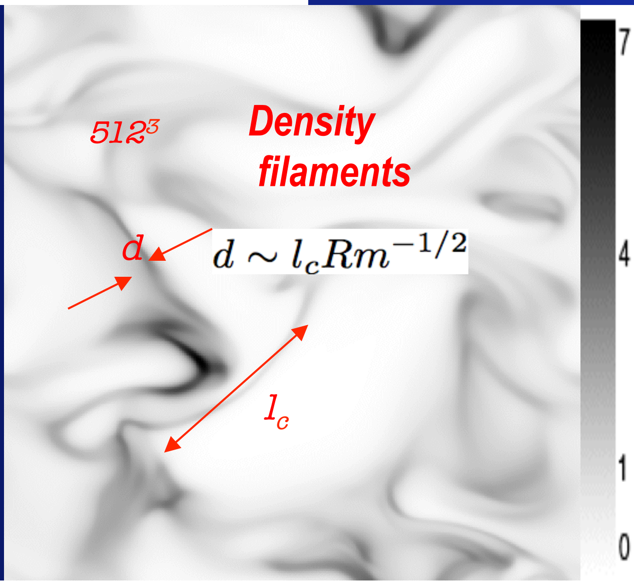
- MHD turbulence does not vanish at the viscous damping scale. Magnetic energy cascades to smaller scales.
- Magnetic intermittency increases with decrease of the scale.
- Turbulence gets resurrected at ion decoupling scale.

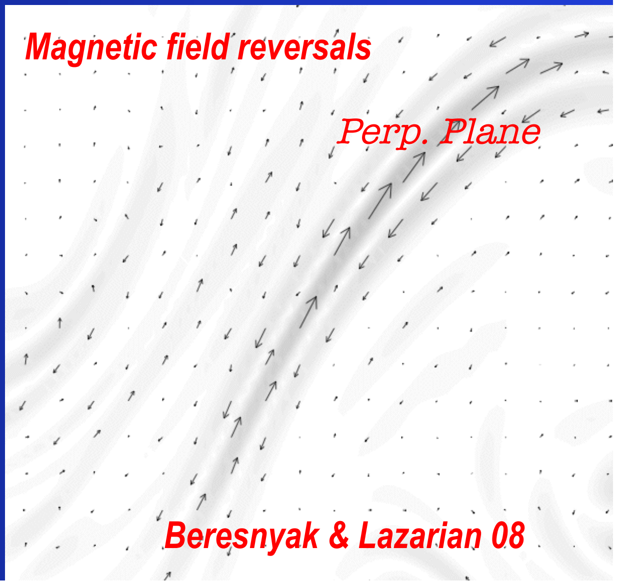
Turbulence in partially ionized gas creates filaments with high density contrast



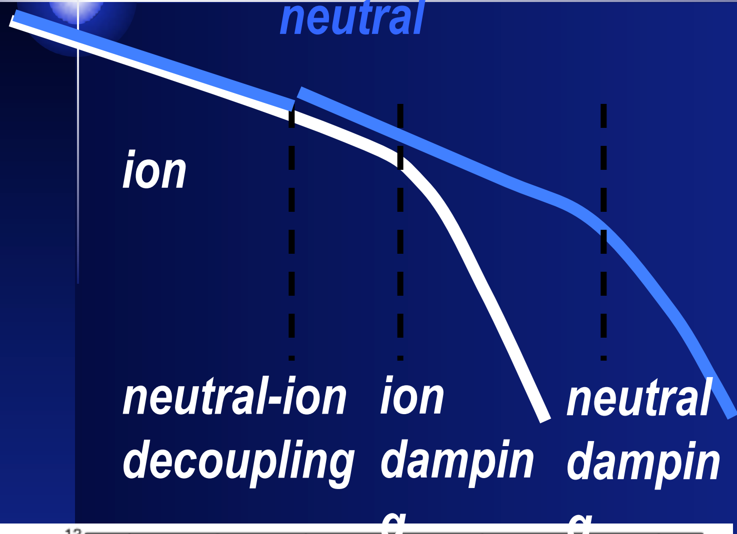
Density filaments are observed in different phases of ISM

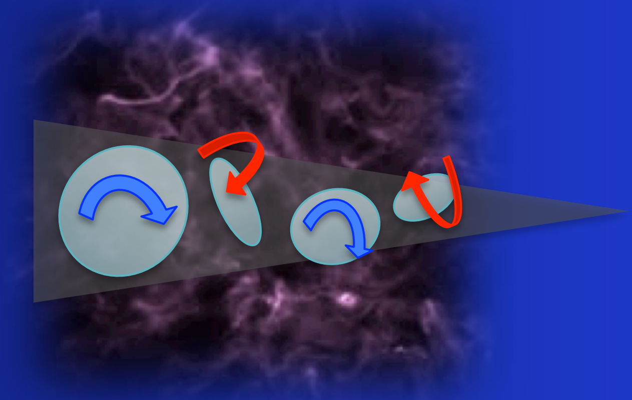
Beresnyak & Lazarian 08

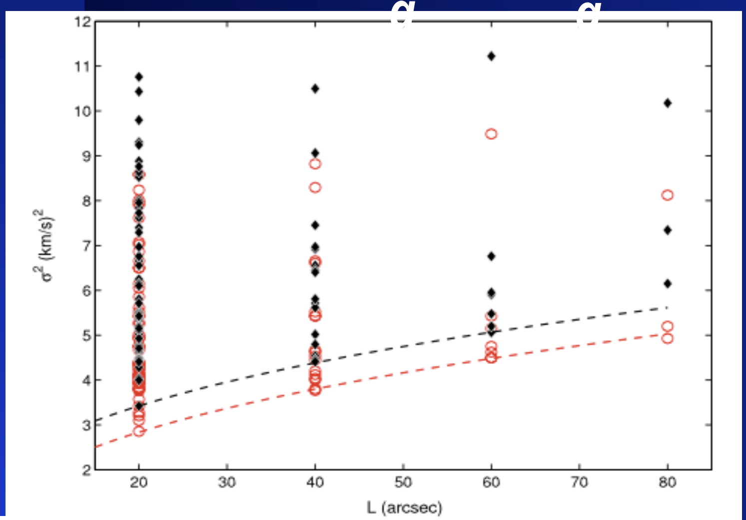




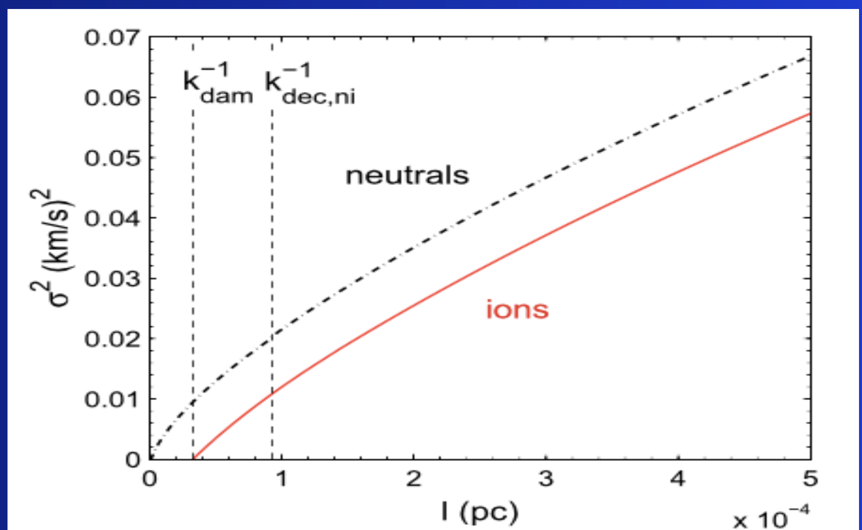
Turbulence damping and line width difference





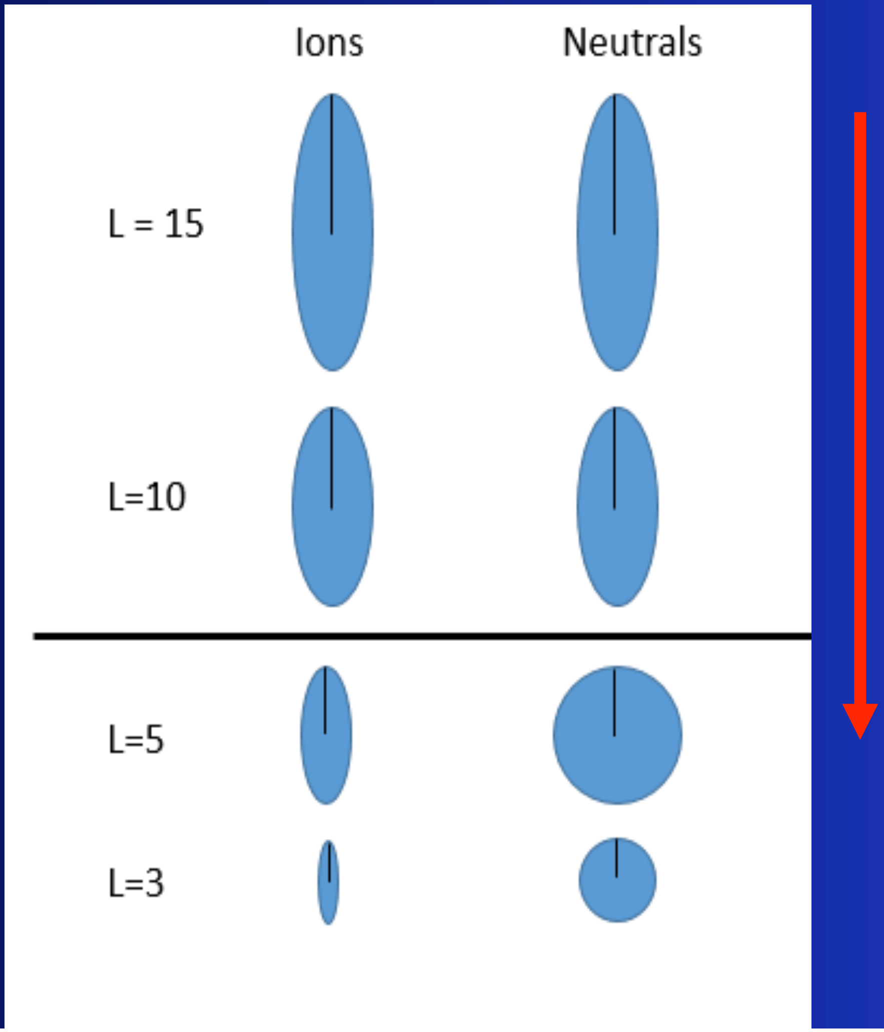


Li & Houde 2008



Xu, AL, & Yan 2015

Ion-neutral decoupling

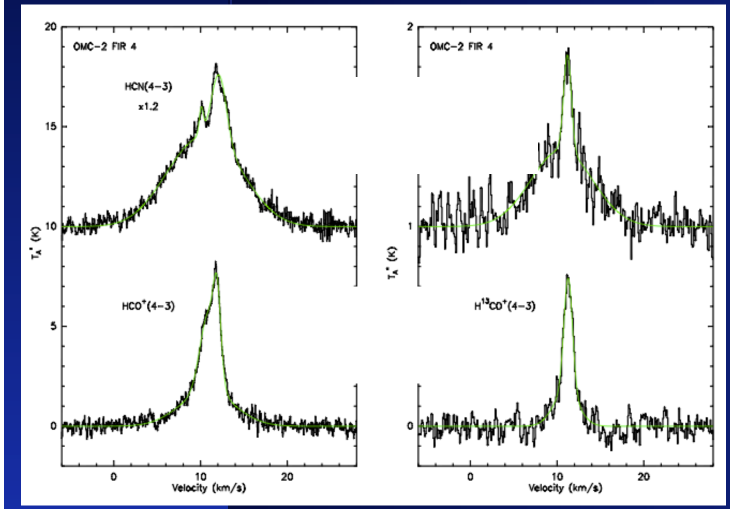


Magnetic field direction

Decoupling scale

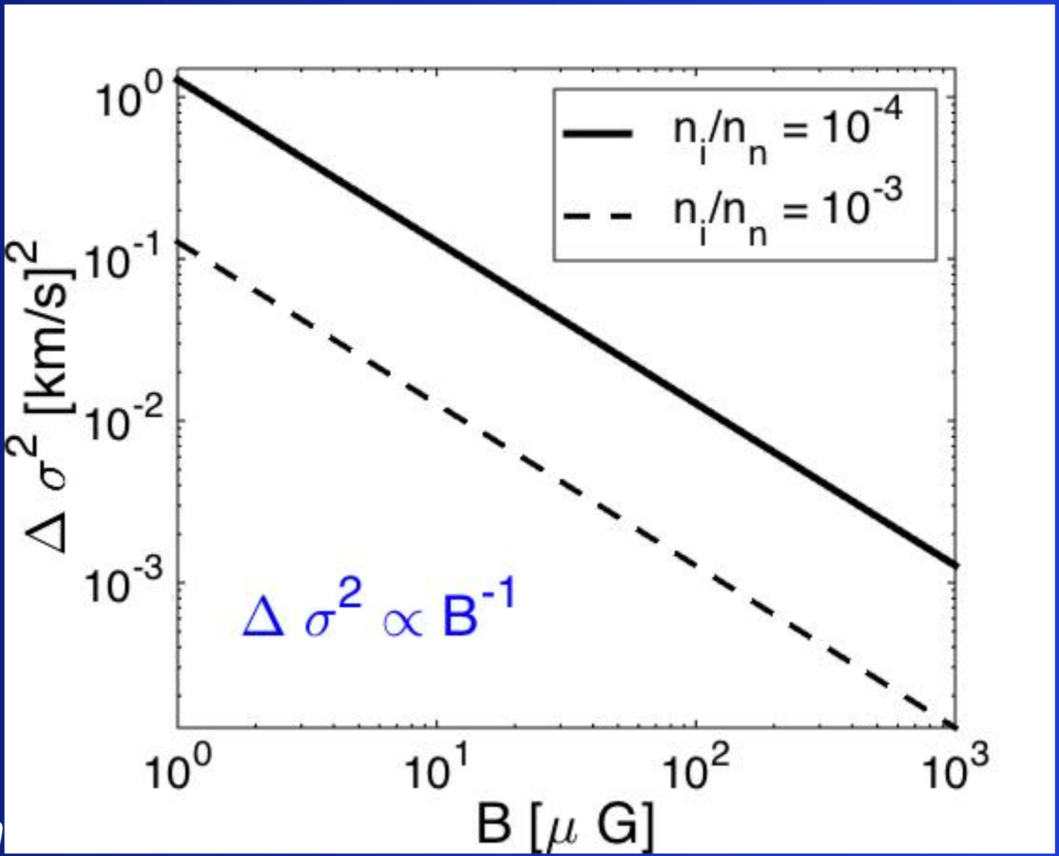
Turbulence damping and line width difference

New method for measuring magnetic field strength



Houde et al. 2009

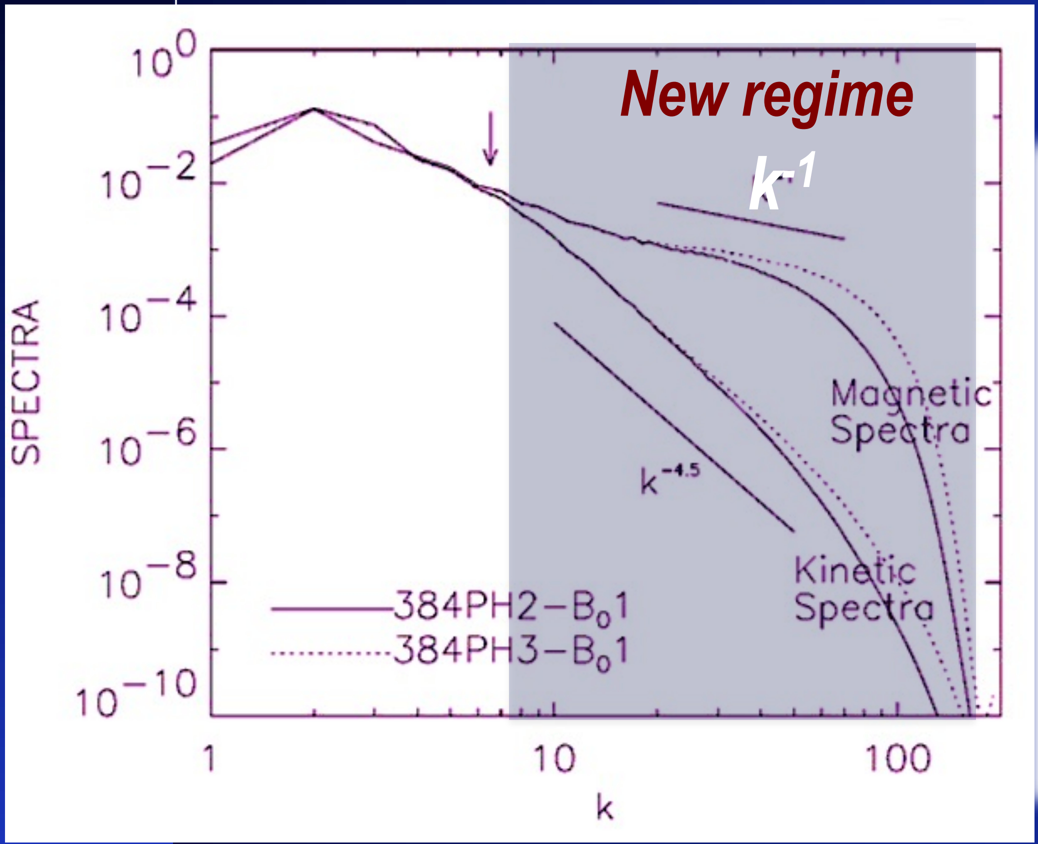
A typical sub-Alfvenic molecular cloud



We suggest different expression

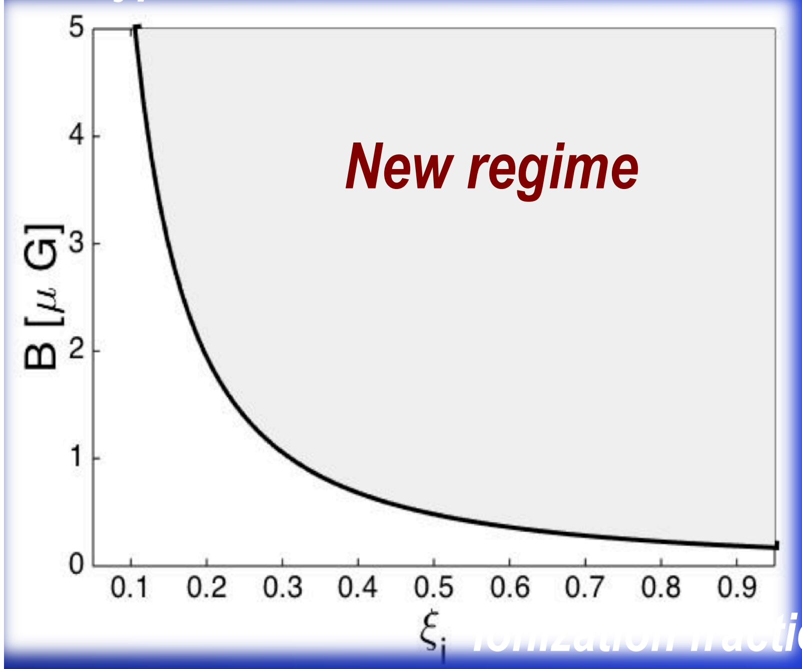
Xu & AL 2016

Turbulence damping and
new regime of MHD turbulence



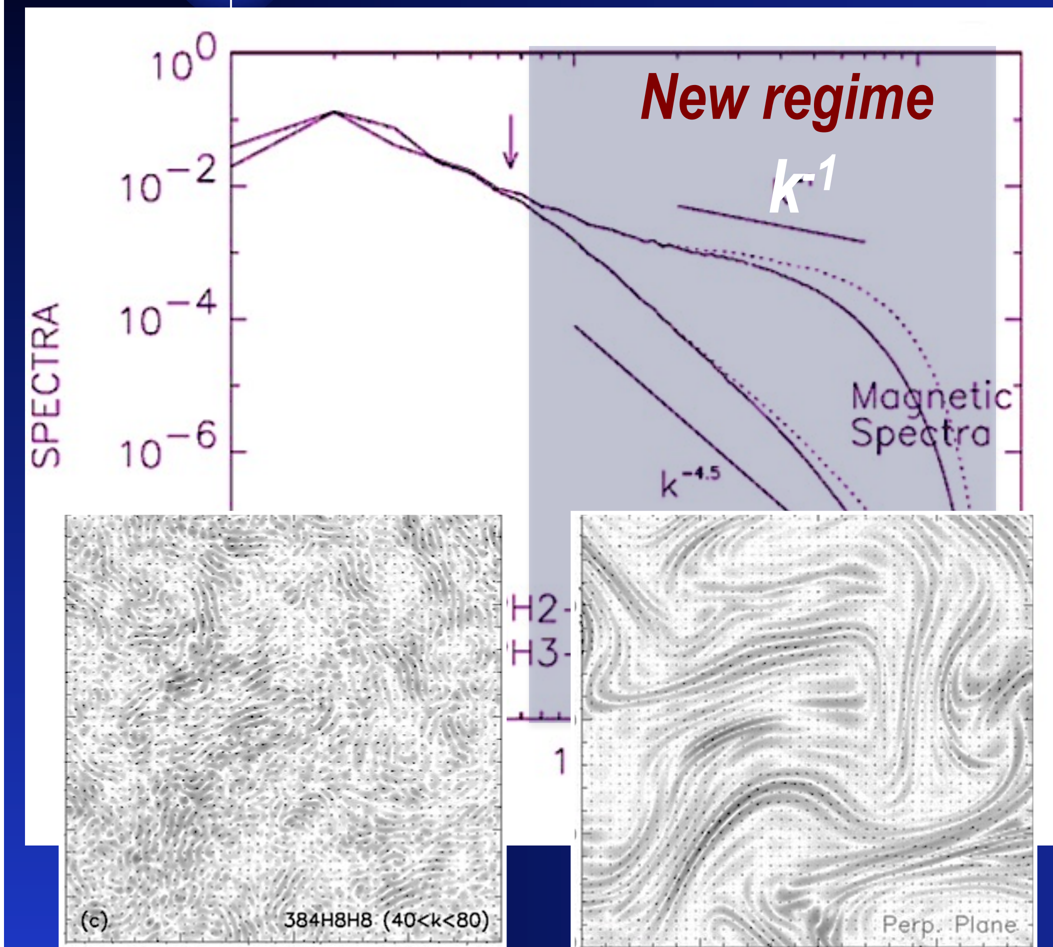
Cho, AL, & Vishniac 2002,2003
AL, Vishniac & Cho 2004

A typical sub-Alfvenic molecular cloud



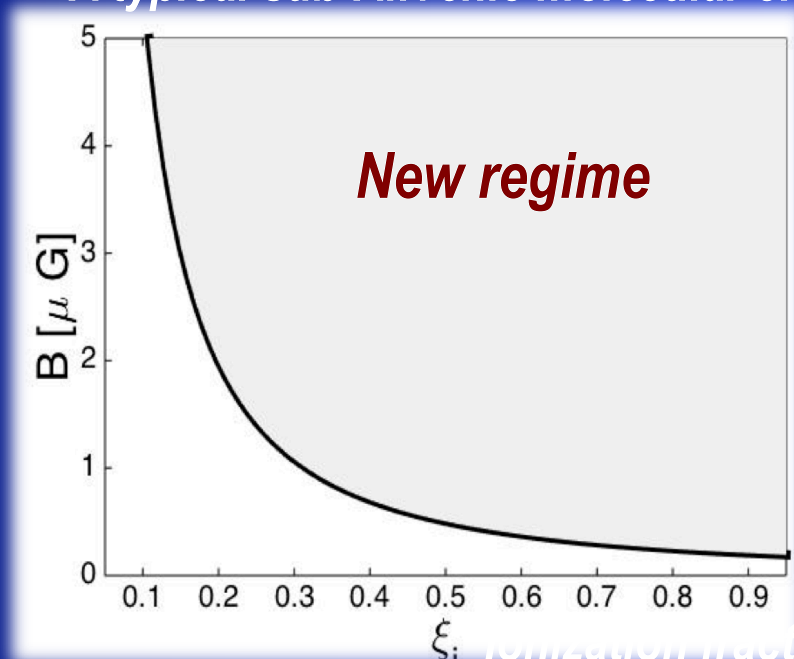
Xu & AL 2016

Turbulence damping and new regime of MHD turbulence



Cho, AL, & Vishniac 2002,2003

A typical sub-Alfvenic molecular cloud



Xu & AL 2016

More information about turbulence are provided at my Researchgate site:

https://www.researchgate.net/profile/A_Lazarian

In particular at the project site

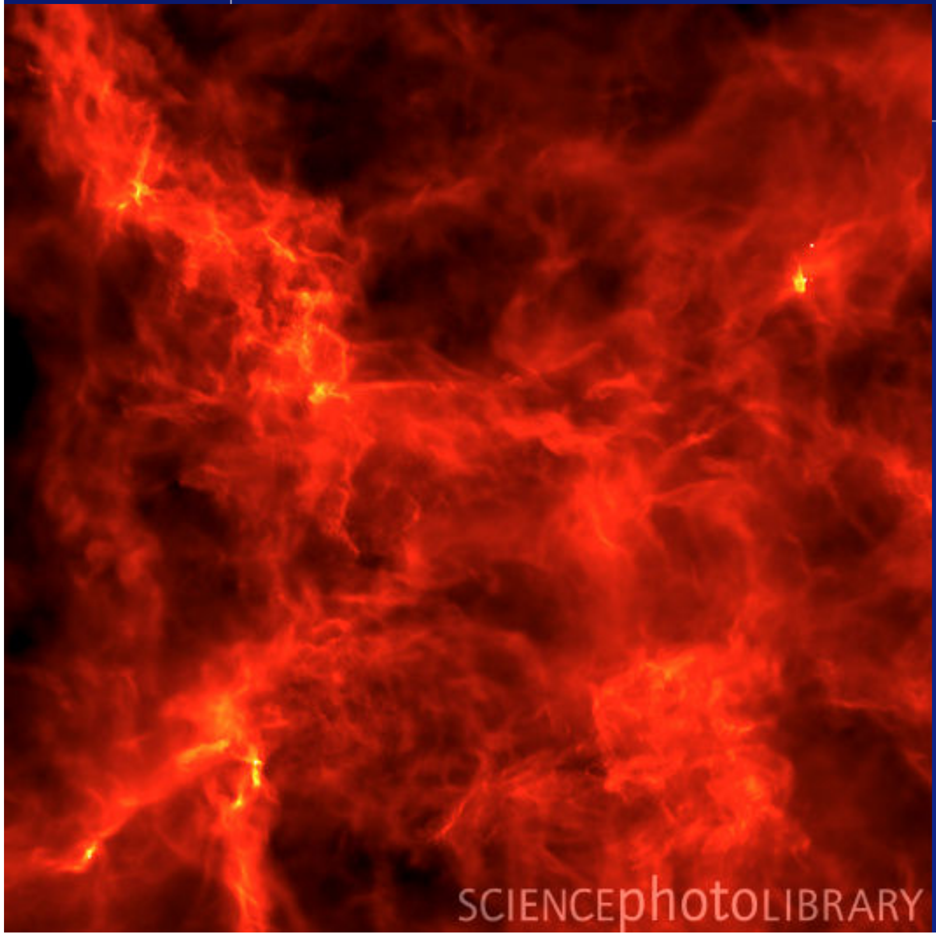
www.researchgate.net/project/Magnetic-Turbulence-in-Non-Relativistic-and-Relativistic-Plasmas

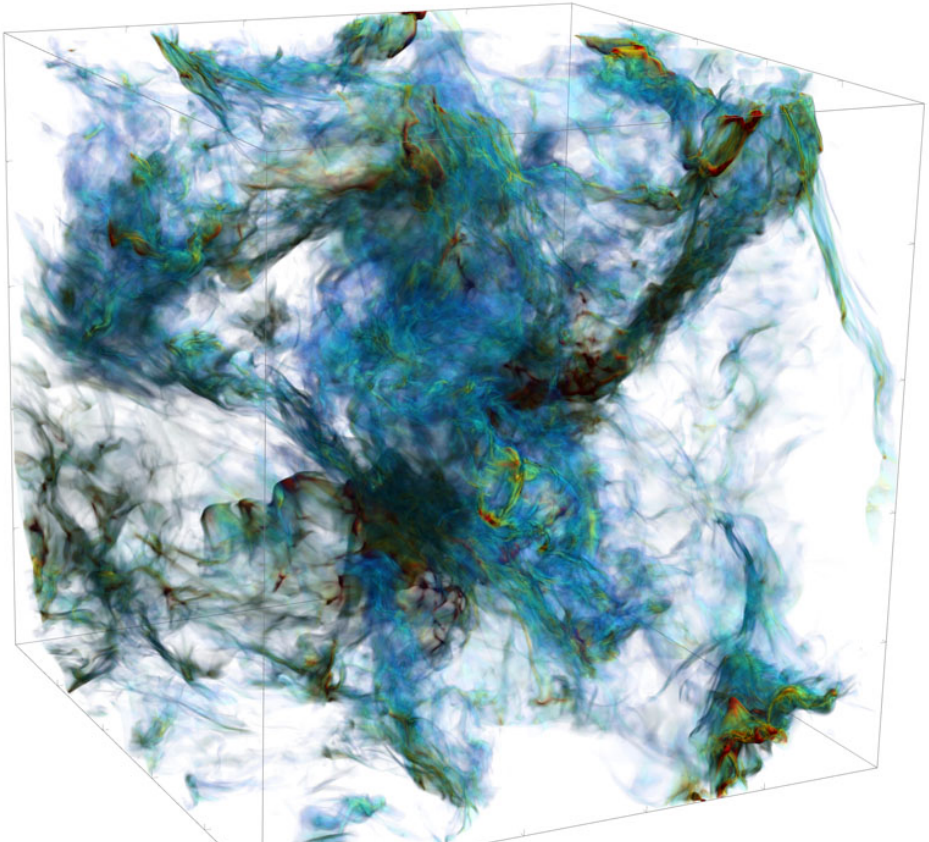
Where the references to the reviews and major papers are provided

Easy way to find:
Google *researchgate*
At researchgate site type the name of a person you want to search, e.g. *Lazarian*
Then you can study research projects there

Turbulent Magnetic Reconnection

Star formation simulations look impressive





Padoan: 8.5 billion computational zones

But we need to understand basic processes to know how realistic they are

Point II. Theory of astrophysical reconnection: requirements are very restrictive

1. Reconnection must be both fast and slow to explain solar flares. Just one reconnection velocity, e.g. 0.1 V_A is not sufficient.
2. Reconnection rates should be consistent with the requirements of MHD turbulence theory preventing formation of magnetic knots, making magnetic spectrum shallow.
3. Reconnection mechanism is better to be applicable to different media to correspond to the principle of parsimony. E.g. satisfying both 1 and 2 for different ISM phases with different mechanisms is not natural.

Ockham's razor: "entities should not be multiplied needlessly

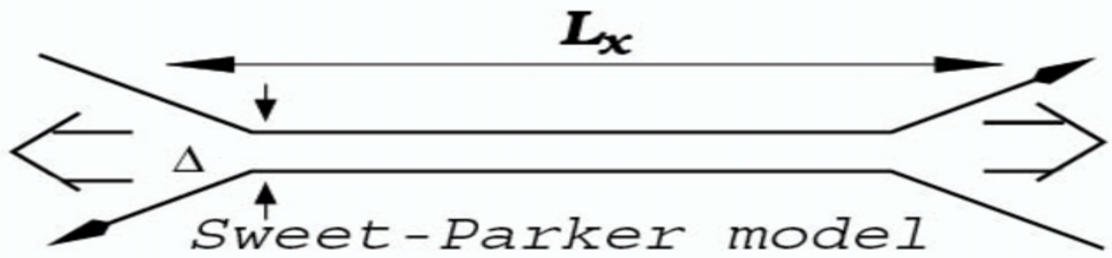
William Ockham 1288-1348

LV99 model extends Sweet-Parker model for realistically turbulent astrophysical plasmas

Turbulent reconnection:

1. Outflow is determined by field wandering.

2. Reconnection is fast with Ohmic resistivity only.



Without turbulence:

molecular diffusion coefficient D ~10^{-5} cm^2/sec

(← It's for small molecules in water.)

→ Mixing time ~ (size of the cup)^2/D ~ 10^7 sec ~ 0.3 year !

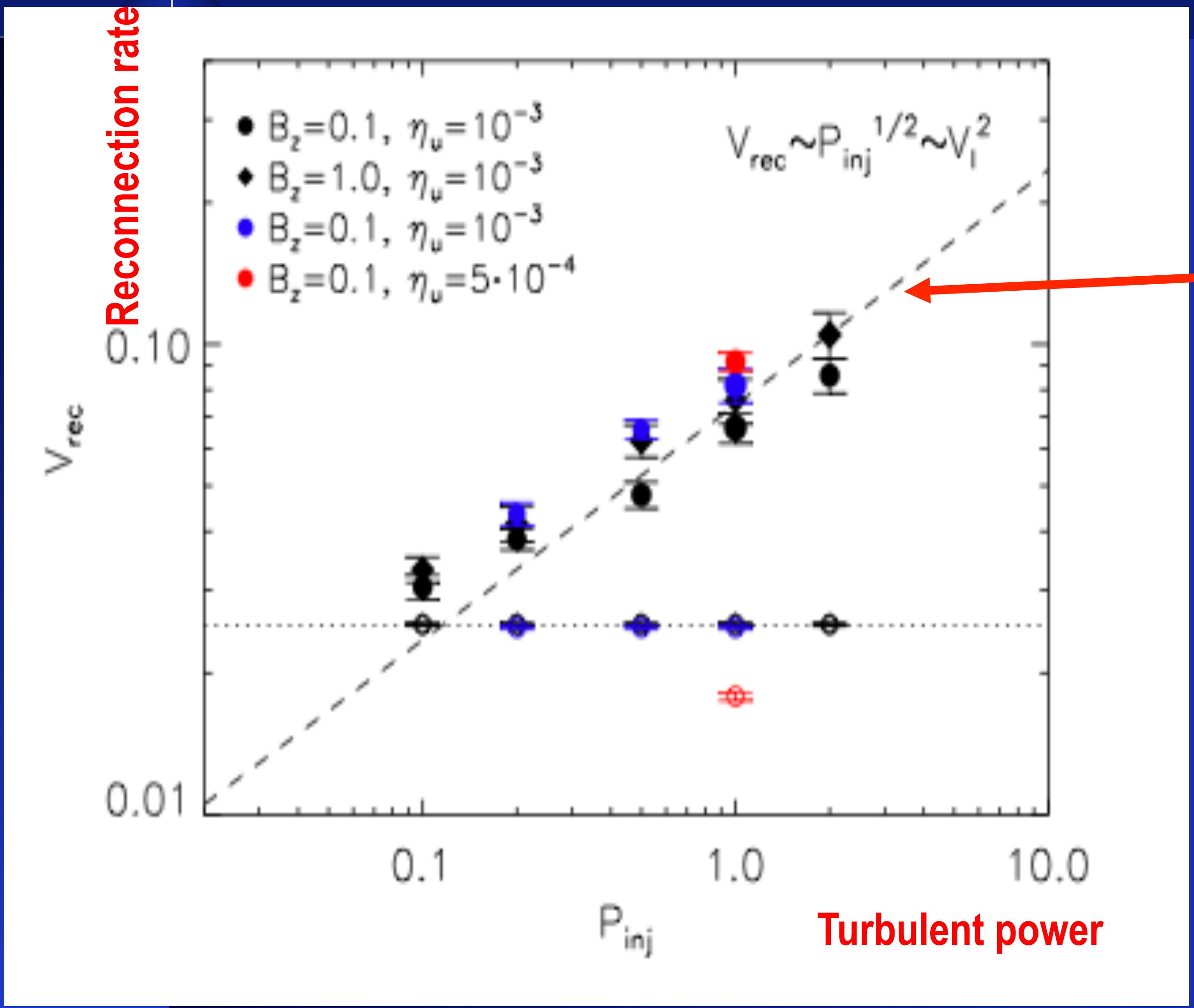
Key element:

$L/\lambda_{\|}$ reconnection simultaneous events

Lazarian & Vishniac (1999)

henceforth referred to as LV99

The reconnection rate increases with input power of turbulence

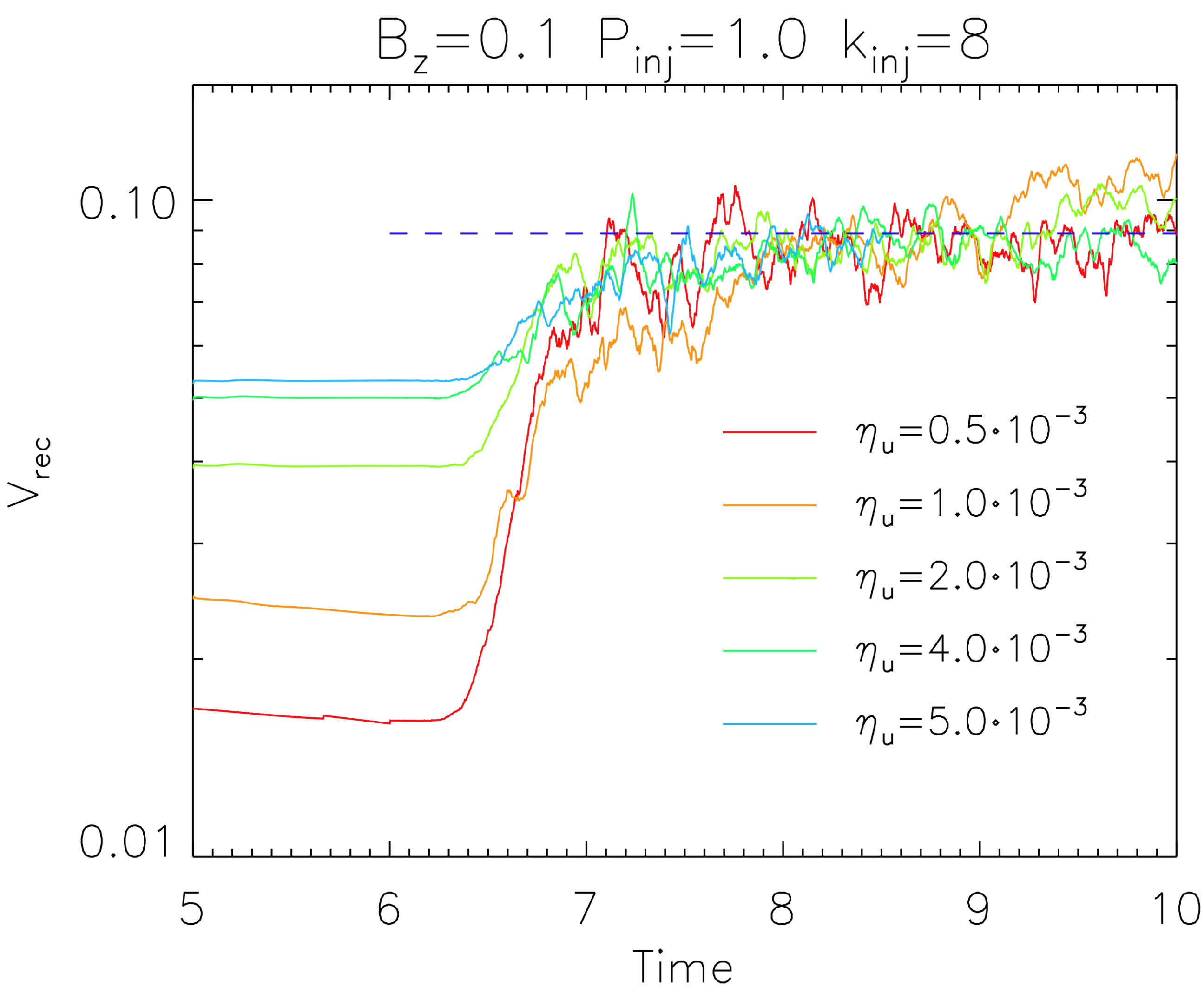


Lazarian & Vishniac (1999) prediction is $V_{rec} \sim P_{inj}^{1/2}$

Results do not depend on the guide field

Kowal et al. 2012

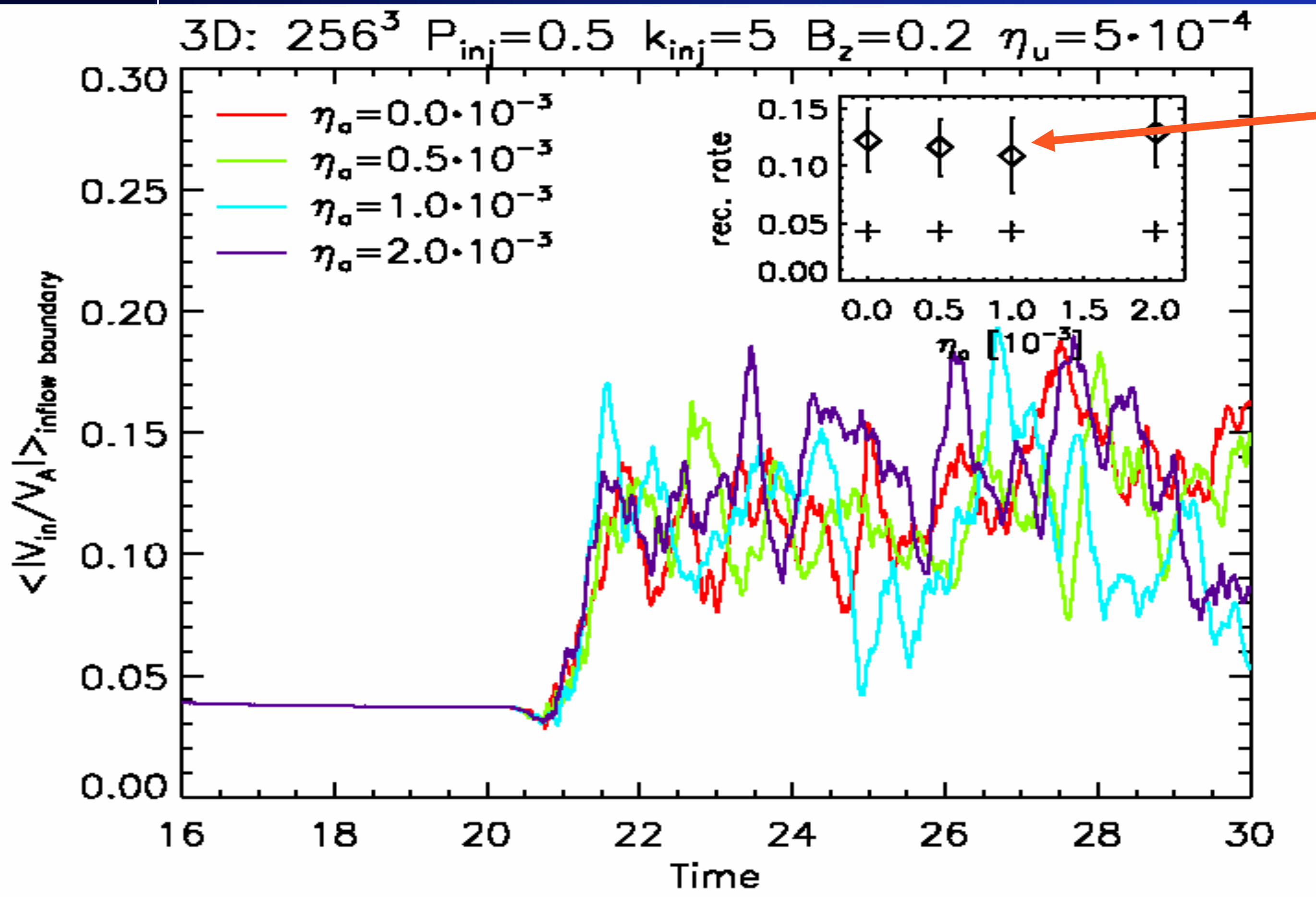
Reconnection is Fast: speed does not depend on Ohmic resistivity!



Lazarian & Vishniac 1999 predicts no dependence on resistivity

Results do not depend on the guide field

Reconnection rate does not depend on anomalous resistivity



Flat dependence on anomalous resistivity

Reconnection does not require Hall MHD

Numerical simulations are OK in terms of reconnection for turbulent environments

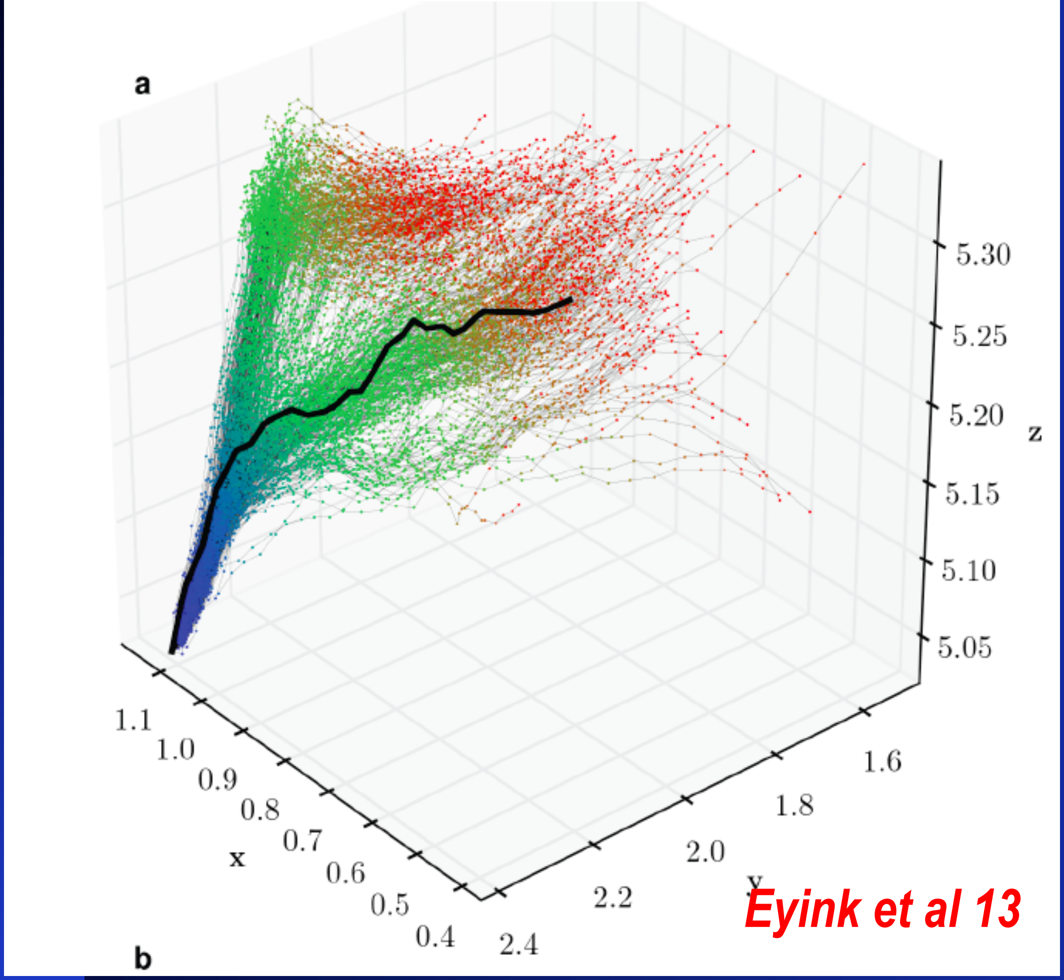
Eyink, Lazarian & Vishniac 2011 related LV99 to the well-known concept of Richardson diffusion

$$\langle|\mathbf{x}_1(t) - \mathbf{x}_2(t)|^2\rangle \sim t^3.$$

Richardson's law

Numerical evidence for MHD is in Eyink et al (2012, Nature submitted)

Eyink, AL & Vishniac 2011 related LV99 to the well-known concept of Richardson diffusion

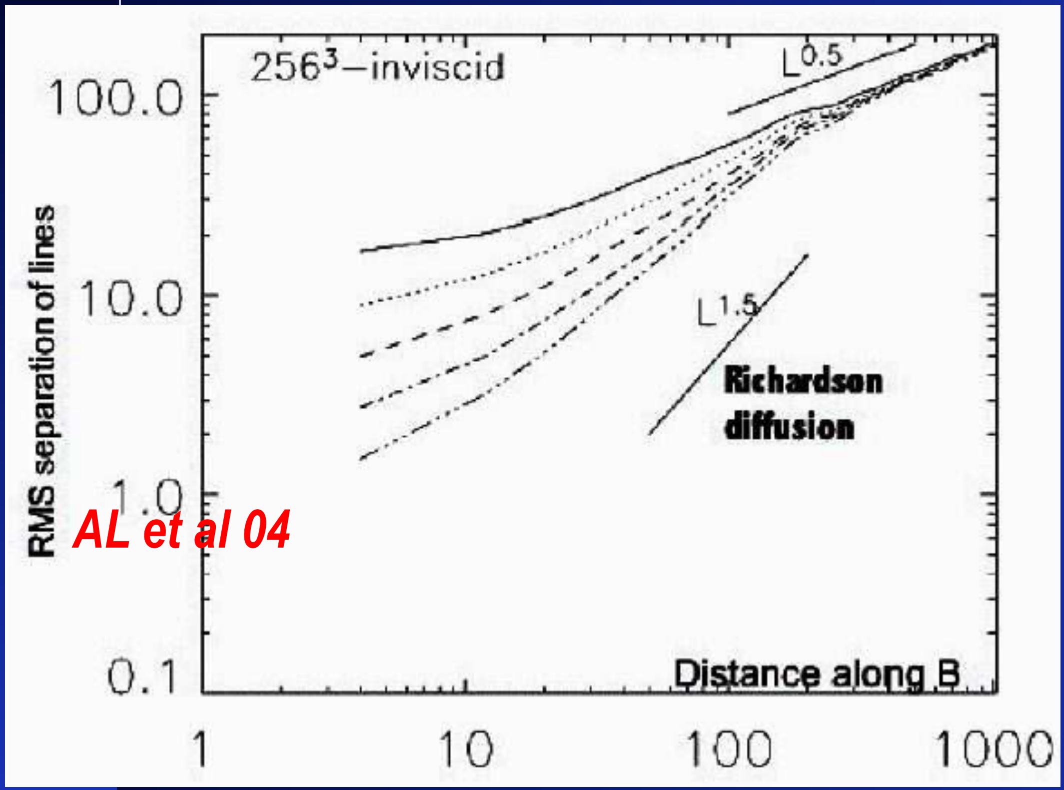


$$\langle |\mathbf{x}_1(t) - \mathbf{x}_2(t)|^2 \rangle \sim t^3$$

Magnetic diffusion in time

If one traces magnetic field lines in the presence of Richardson diffusion than one gets the LV99 result for field wandering

Richardson diffusion measured in MHD



Magnetic diffusion in space: field wandering

$$\langle (\delta y)^2 \rangle \sim x^3$$

LV99

We decided to keep the term Richardson diffusion

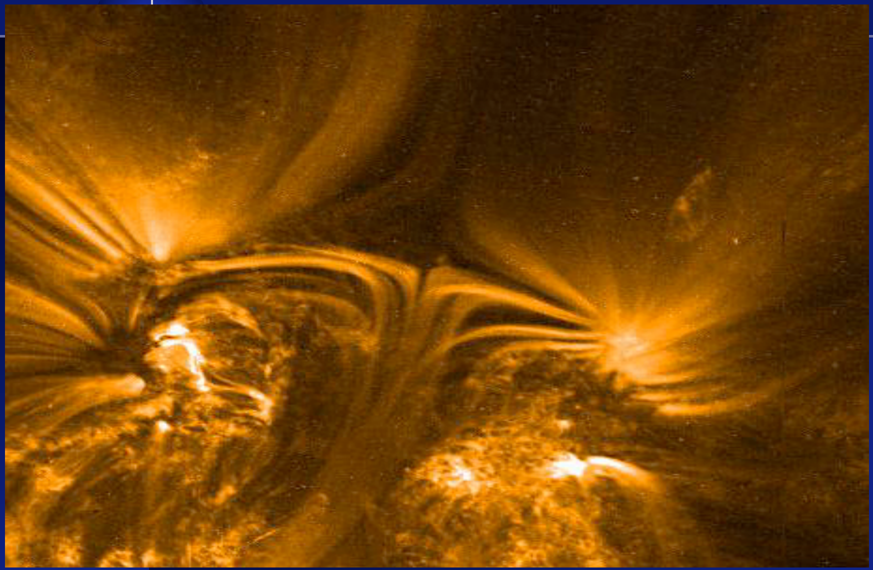
Some other research directions do not compete with LV99 model, but may be complementary

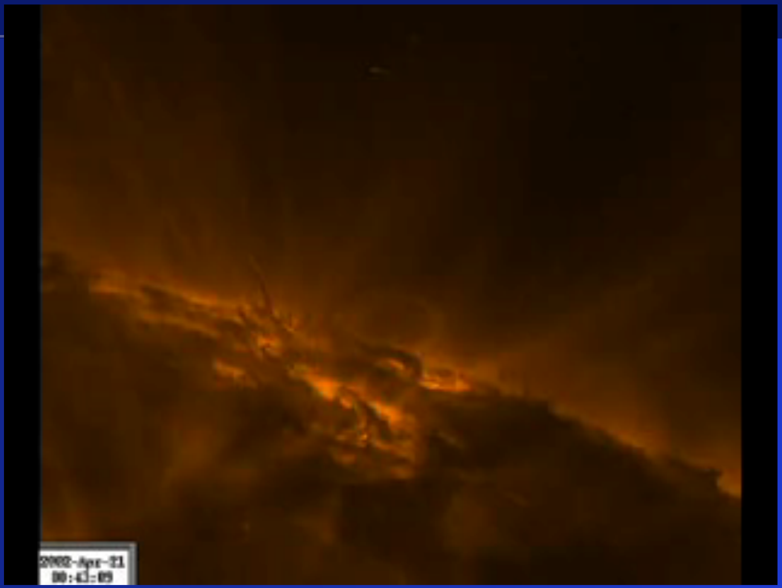
1. Tearing mode: Nonlinear merging island numerical calculations are claimed to produce fast reconnection for $S>10^4$ providing velocity $<10^2 V_A$ (Loureiro et al. 2007). May be related to plasmoids by Shibata (1999).

   This is too slow to disentangle magnetic field lines in turbulence, does not generate flares. But may help to initiate flares through LV99 process.

2. Explosions of reconnection were observed in MHD simulations by Lapenta (2008).

LV99 model of reconnection gains support from Solar flare observations

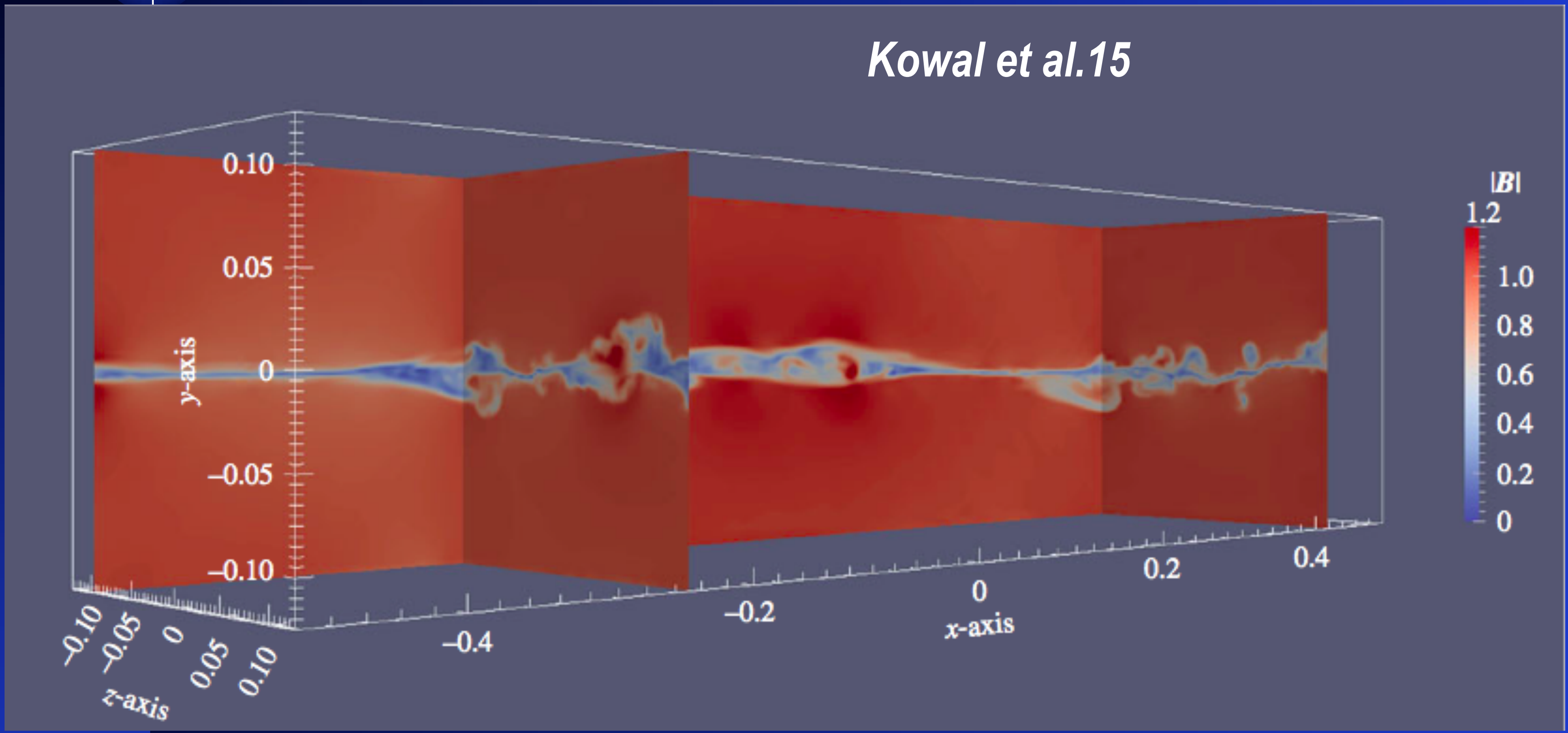




1. Solar flares can only be explained if magnetic reconnection can be initially slow (to accumulate flux) and then fast (to explain flares). Level of turbulence can do this (LV99)
2. Thick current layers predicted by LV99 have been observed in Solar flares (Ciaravella, & Raymond 2008).
3. Predicted by LV99 triggering of magnetic reconnection by Alfven waves was observed by Sych et al. (2009).
4. Reconnection is fast in collisional and collisionless plasmas (Shibata et al. 2012)

Magnetic field dissipation

Simulations demonstrate the development of turbulence through Kelvin-Helmholz instability



$$V_\Delta \approx (C_K r_A)^{3/4} V_{Ay} \beta^{1/2}$$

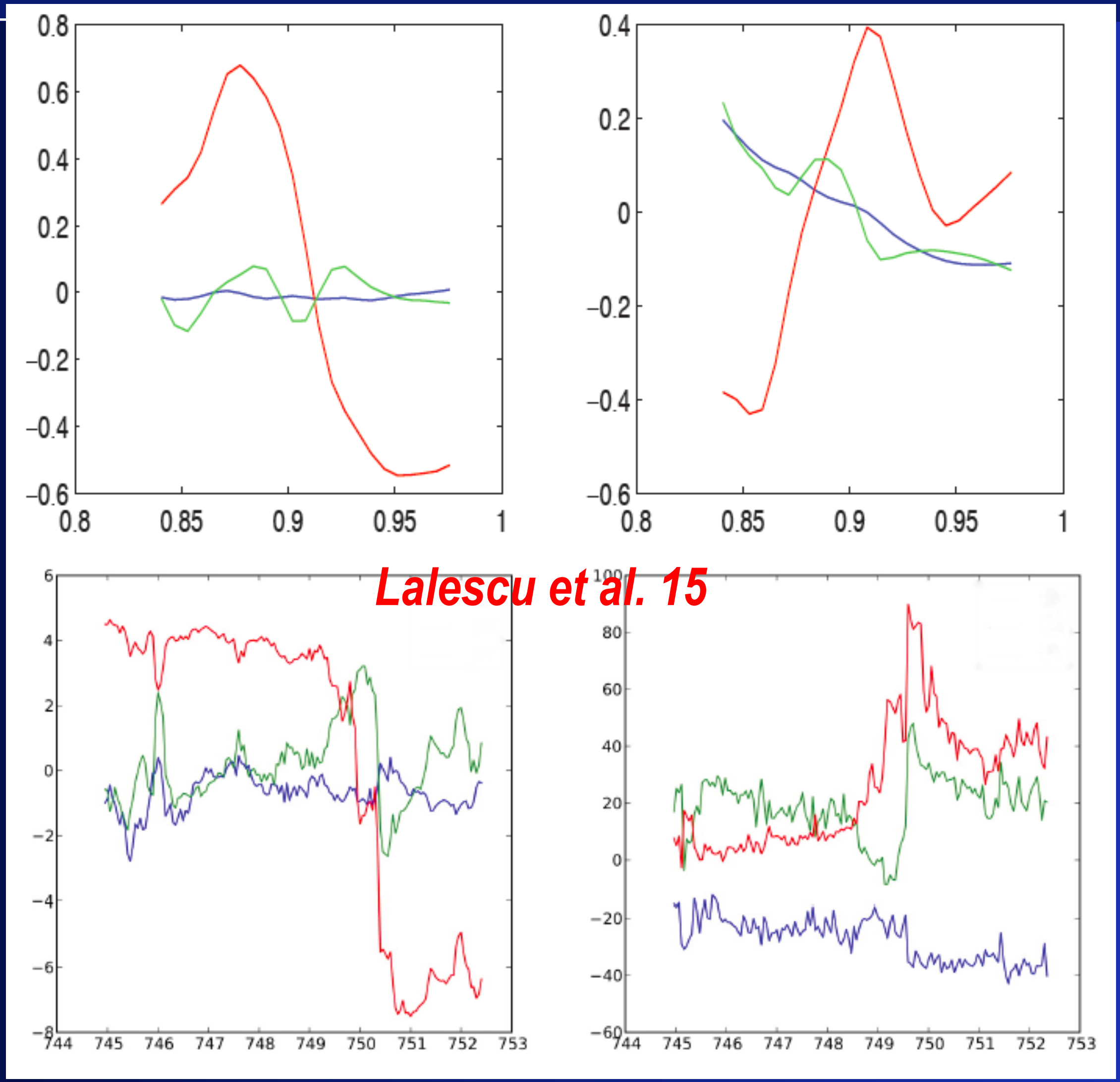
Expected reconnection rate, Ck is Kolmogorov constant, r_A is magnetization

Correcting a claim in Karimabadi & Lazarian (2014) review on no evidence of LV99 reconnection signatures in Solar Wind

The complex structure of magnetic reconnection similar to one in solar wind is revealed in simulations of MHD turbulence

Lalescu et al. 2015

Turbulent reconnection is consistent with Solar wind measurements (cf. Karimabadi & AL 14)

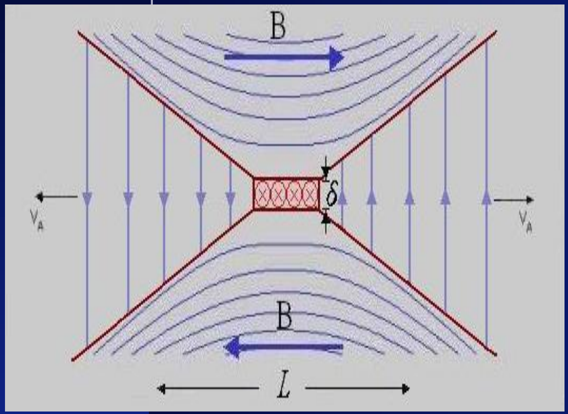


MHD turbulence data set events

Solar wind reconnection events

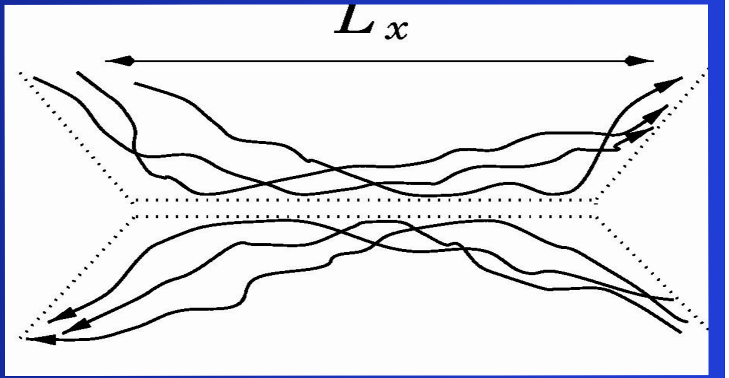
Convergence between the plasma-based reconnection and turbulent model is evident!

Alternative in 1999



Hall effect is required

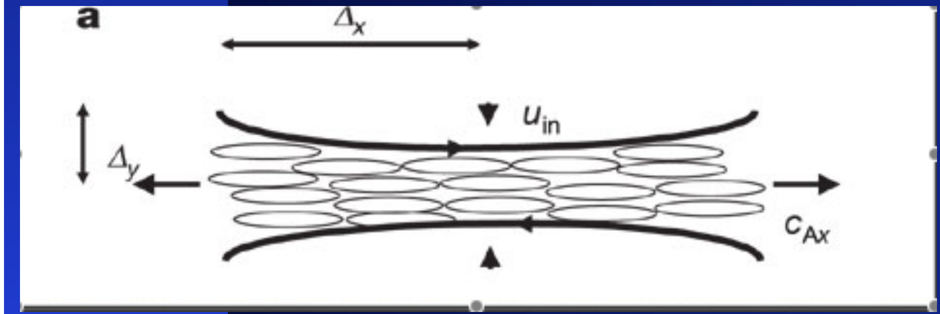
LV99 model



Hall effect is not required

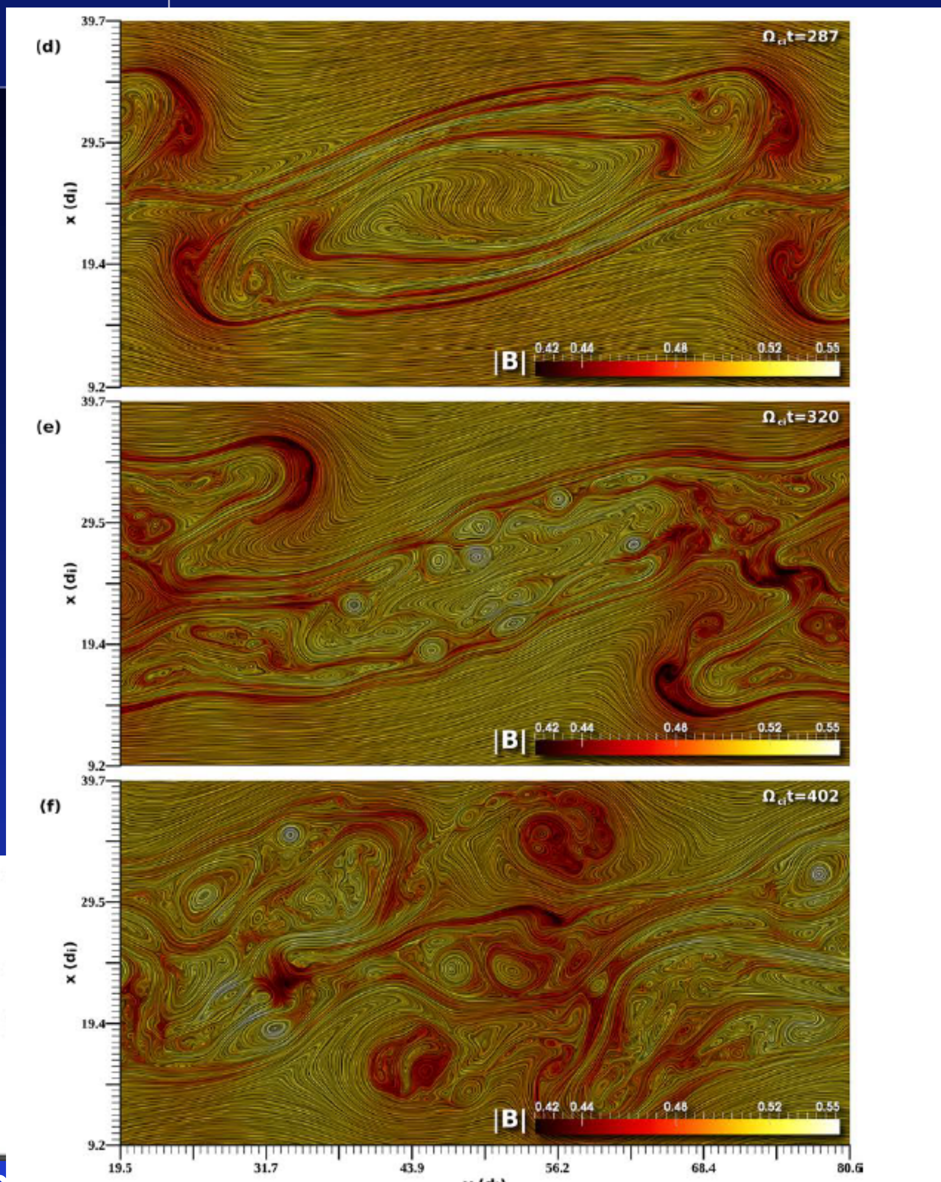
(Fully 3D, turbulence)

Alternative in 2015

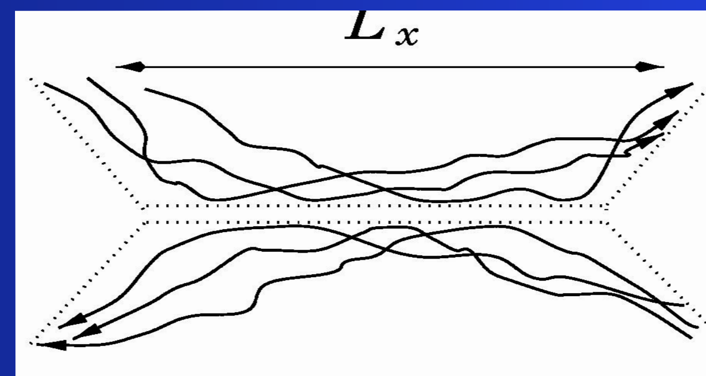


Tearing reconnection (Hall effect is not required)

Convergence between the plasma-based reconnection and turbulent model is evident!



LV99 model



Hall effect is not required

(Fully 3D, turbulence)

3D simulations without turbulence show transfer to turbulent state (e.g. Karimabadi 2012)

Tearing reconnection (Hall effect is not required)

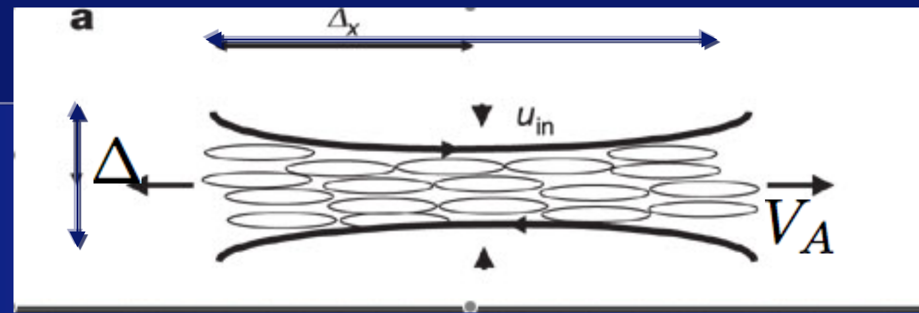
Plasmoids/tearing is a transient regime transferring to fully turbulent reconnection in 3D

$$S = \frac{LV_A}{\eta}$$

$$Re = \frac{\Delta V_A}{\nu}$$

$$\Delta = L\frac{V_{rec}}{V_A}, \text{ i.e. } \Delta \propto S$$

$$S \rightarrow \infty \text{ means } Re \rightarrow \infty$$

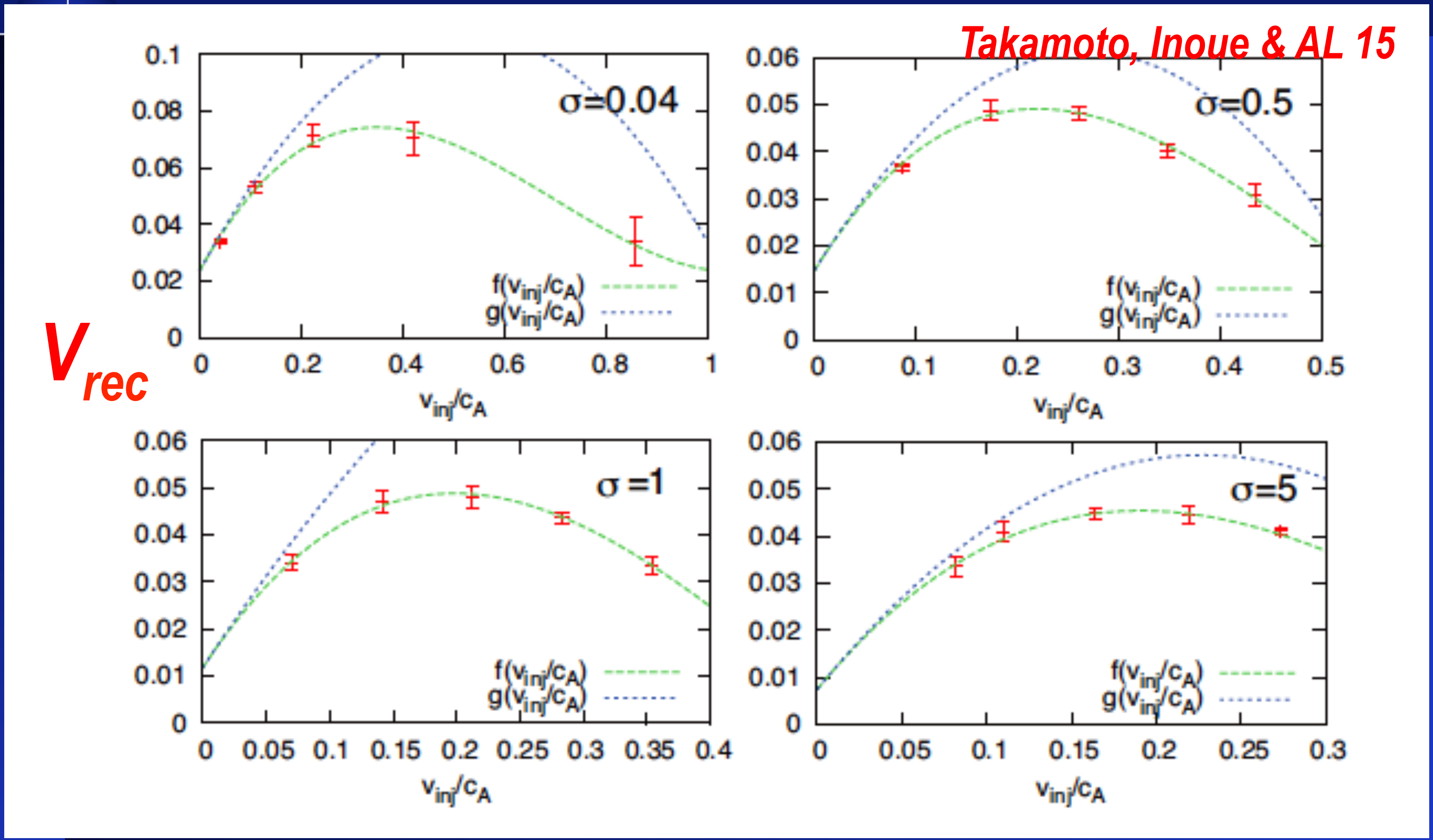


- *Sweet-Parker happened to be a transient reconnection up to $S=10^4$. After that tearing happens. Fast reconnection means that the outflow thickness Δ grows in proportion to S. Thus the Reynolds number $Re = \frac{\Delta V_A}{\nu}$ of the outflow grows as S. This entails to the transition to turbulent regime.*

- *Turbulence is known to suppress the instabilities and therefore one expects tearing to be suppressed. If turbulence does not make reconnection fast then Delta will stop growing after a critical Re is achieved. Thus reconnection would not be fast and would scale as 1/S.*

- *Many phenomena require reconnection larger that the 0.01 or even 0.1 of V_A. Tearing cannot provide this!*

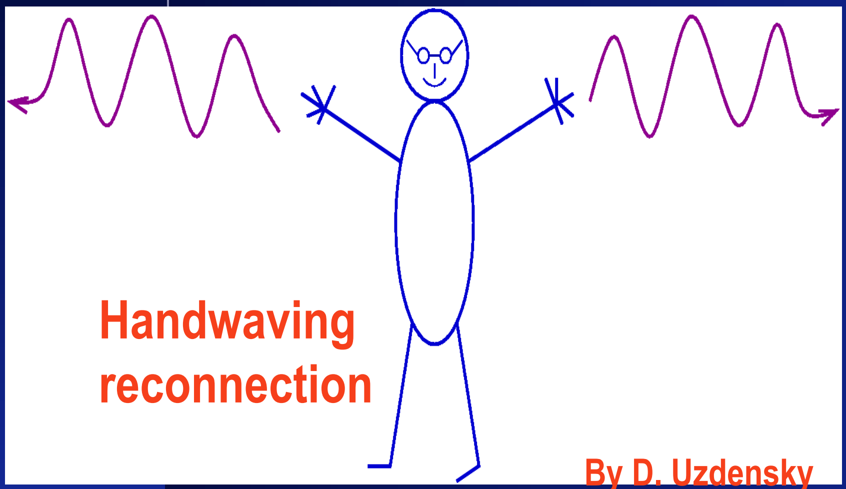
Relativistic simulations agree well with compressible turbulent reconnection prediction

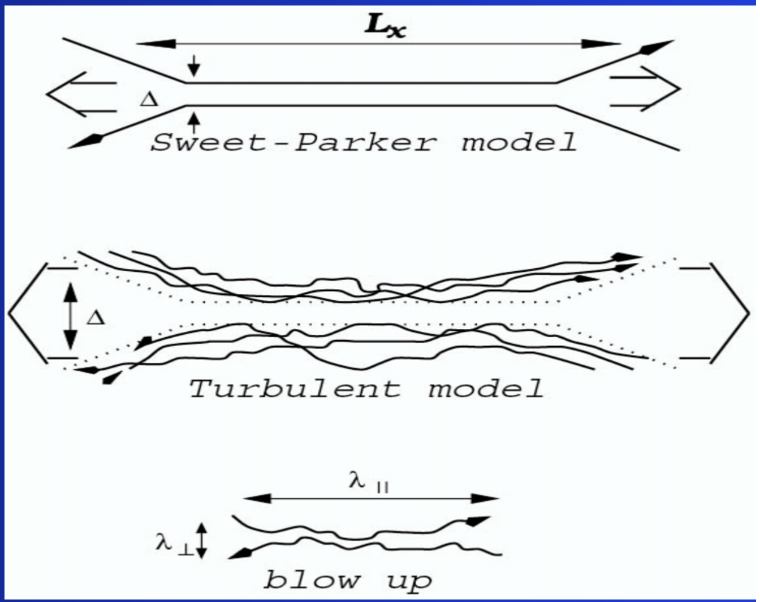


$$V_{rec} \approx 0.3 c_A (\rho_s/\rho_{in})(l/L_x)^{1/2} \frac{v_{inj}(1 - C_2 v_{inj}/c_A)}{c_A}$$

Max reconnection $\sim 0.3\ c_A$

Change in Reconnection: From Hand-waving to Alfven waves





Idea of magnetic flux being frozen in a highly conducted fluid was at the heart of star formation paradigm.

Hannes Alfven

Alfven theorem 1942:

Textbook derivation:

$$\Psi = \int_S \mathbf{B} \cdot d\mathbf{S}.$$

The time rate change is a sum of

$$\left(\frac{\partial \Psi}{\partial t}\right)_1 = \int_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S}.$$

$$\left(\frac{\partial \Psi}{\partial t}\right)_2 = \int_C \mathbf{B} \cdot \mathbf{V} \times d\mathbf{l} = \int_C \mathbf{B} \times \mathbf{V} \cdot d\mathbf{l}.$$

$$\left(\frac{\partial \Psi}{\partial t}\right)_1 = -\int_S \nabla \times \mathbf{E} \cdot d\mathbf{S}.$$

$$\left(\frac{\partial \Psi}{\partial t}\right)_2 = \int_S \nabla \times (\mathbf{B} \times \mathbf{V}) \cdot d\mathbf{S}.$$

Adding this up one gets

$$\frac{d\Psi}{dt} = -\int_S \nabla \times (\mathbf{E} + \mathbf{V} \times \mathbf{B}) \cdot d\mathbf{S}.$$

But for perfectly conducting fluids

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \mathbf{0},$$

Big Implication: LV99 means that magnetic field in *turbulent fluids* is not frozen in

Hannes Alfven

Instead of flux freezing condition one should consider flux diffusion by turbulent flow. This has dramatic consequences for many areas of astrophysics including star formation!

Violation of magnetic field frozen in condition in turbulent fluids proven in Eyink (2011). The equivalence of this and LV99 approach was demonstrated in Eyink, Lazarian & Vishniac 2011.

Violation of Flux Freezing: reconnection diffusion

Reconnection diffusion is a key process for star formation

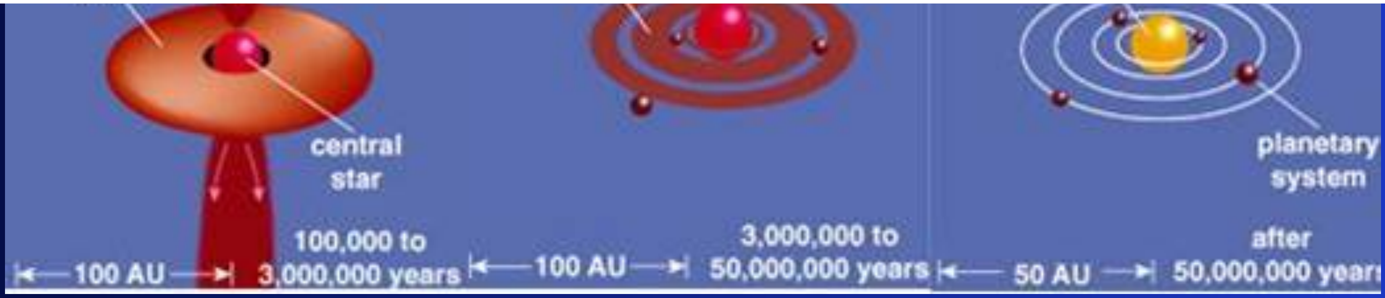
AIP Conference Proceedings / Volume 784

Astrophysical Implications of Turbulent Reconnection: from cosmic rays to star formation

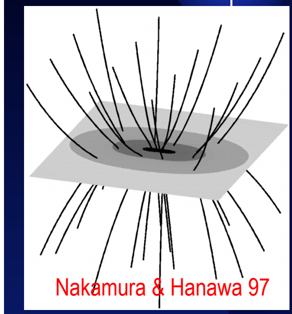
AIP Conf. Proc. 784, pp. 42-53; doi:http://dx.doi.org/10.1063/1.2077170 (12 pages)

MAGNETIC FIELDS IN THE UNIVERSE: From Laboratory and Stars to Primordial Structures
Date: 28 November - 3 December 2004
Location: Angra dos Reis (Brazil)

A. Lazarian
Department of Astronomy, University of Wisconsin, 475 N. Charter St., Madison, WI 53706



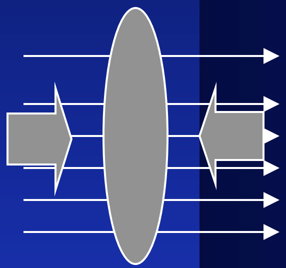
Ambipolar diffusion and turbulent accumulation of gas are two major star formation paradigms: any alternatives?



Ambipolar diffusion allows magnetic flux to leave the cloud.

Pros: Associated with big astrophysical names. Tons of well cited papers.

Cons: Dependence on star formation on galactic metallicity contradicts to observations. Not efficient for diffuse gas (cf. Troland & Heiles 86), may be too slow for dense gas (Shu et al. 06).



Turbulence can collect gas keeping magnetic flux the same.

Pros: ISM is definitely turbulent, changes of the flux to mass ratio may be fast.

Cons: Does not solve the magnetic flux problem for young stars. One dimensional collection of matter can be criticized.

Troland & Heiles 1986, ApJ, 301, 339
Shu, Gali, Lizano, & Cai 2006, ApJ, 647, 382

Basic parameters to be considered in turbulent ISM

$M_A = V/V_A$ $M_s = V/c_s$ $c_s = \sqrt{\frac{\gamma p}{\rho}}$ $v_A = \frac{B}{\sqrt{4\pi\rho}}$

$$\beta \equiv P/P_B \sim (M_A/M_s)^2$$

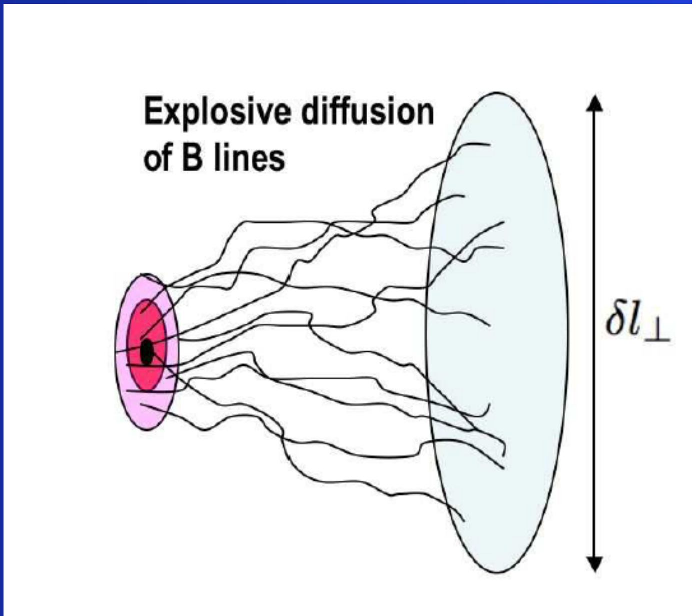
$$M_\Phi \equiv \sqrt{5/2}\left(\frac{\Phi_B}{3\pi G^{1/2}}\right)$$

"sub-critical": no collapse!
"super-critical": gravity wins over B-fields

Idea of collecting matter for cores along magnetic field lines is problematic as the spread of magnetic field lines during the matter collection is much larger than the size of the cores

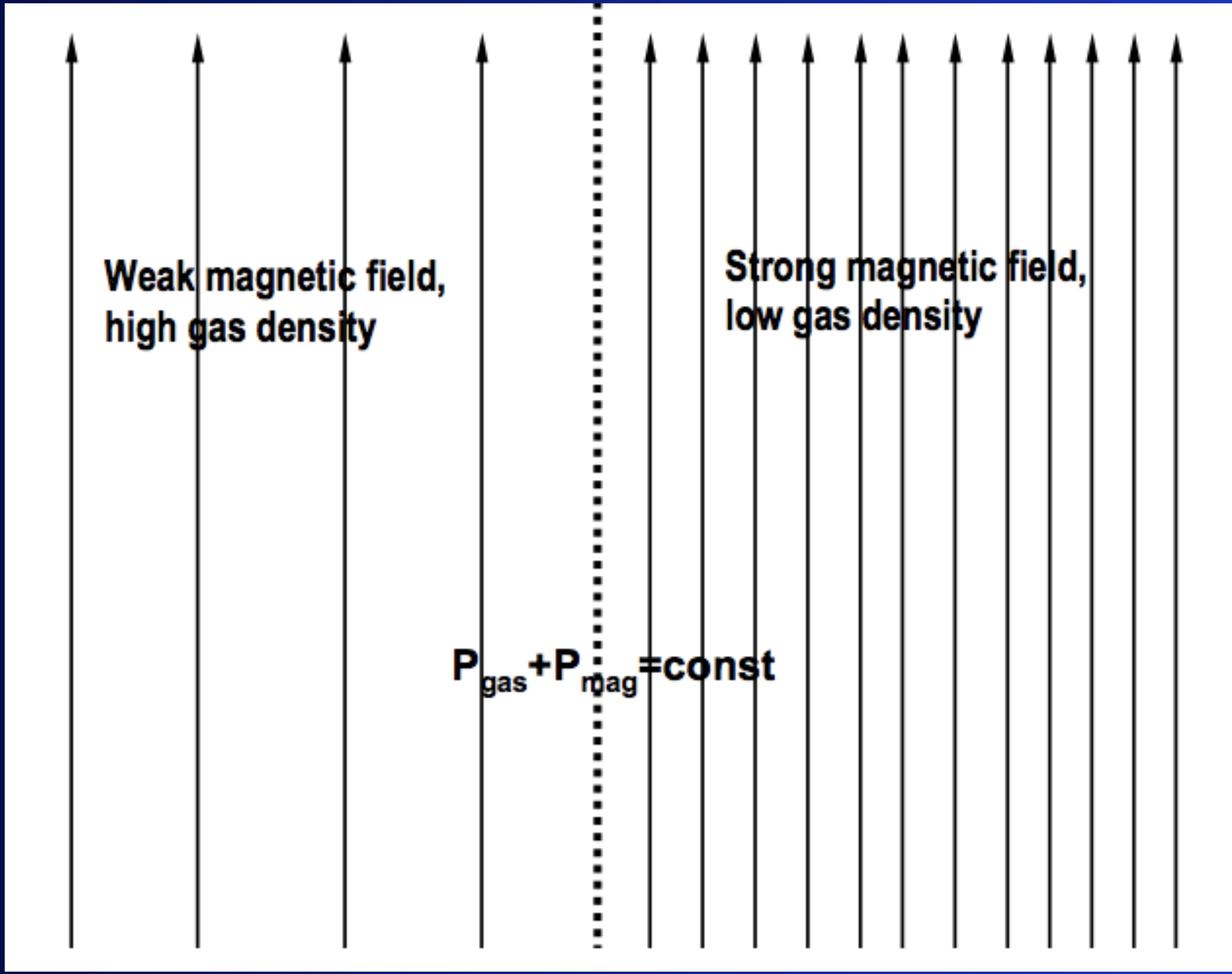
$$\langle y^2 \rangle \approx V_L^3 t_{collec}^3 / L$$

$$t_{collec} \approx \frac{n_{core}}{n_{ISM}} d_{core} / V_L$$

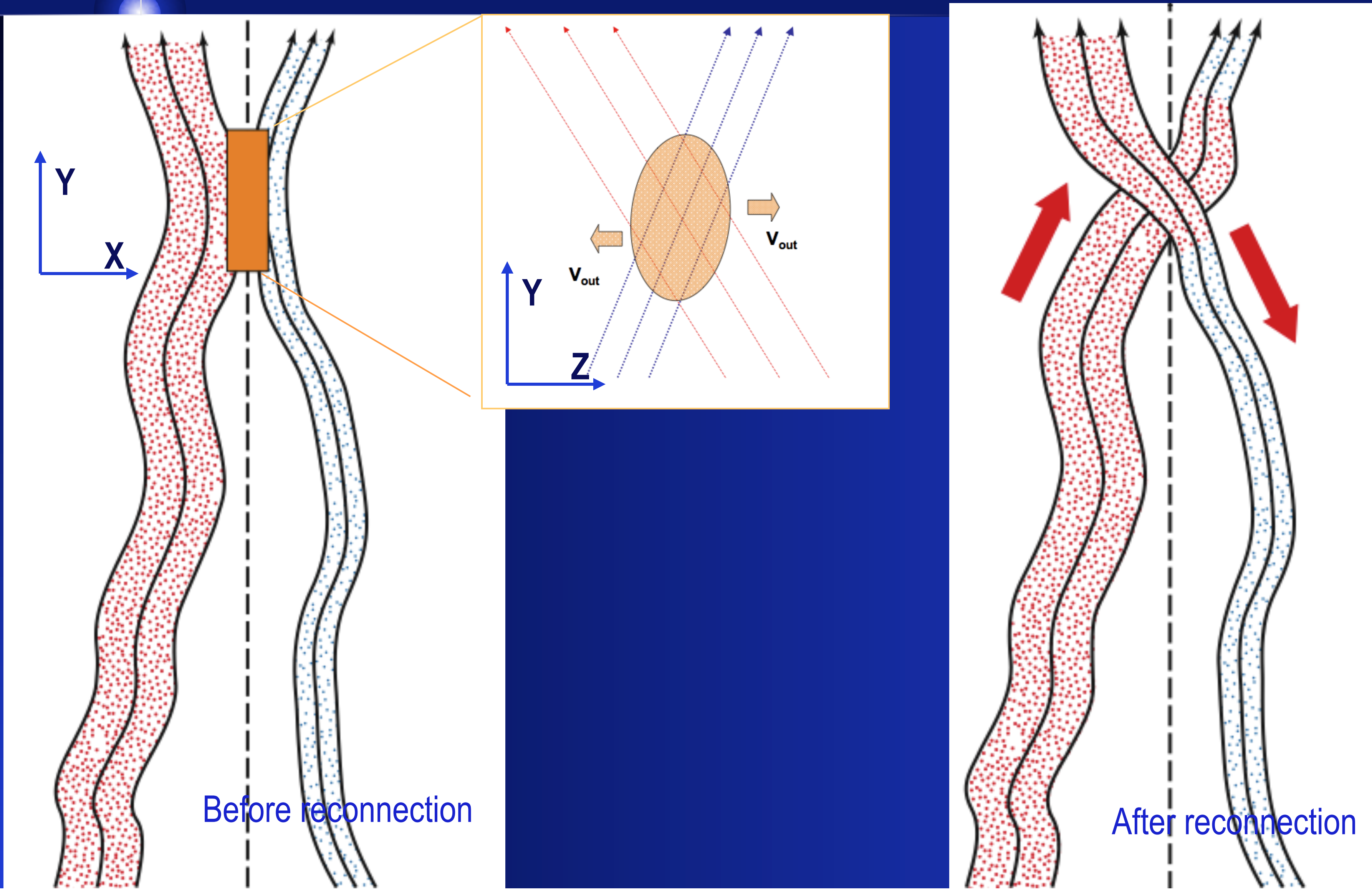


For cores of 10^4 cm^{-3} and size 0.2 pc the collection distance is larger than 100pc and the spread of matter moving along magnetic field lines is larger than 100pc. Diffusion during the motion is all important.

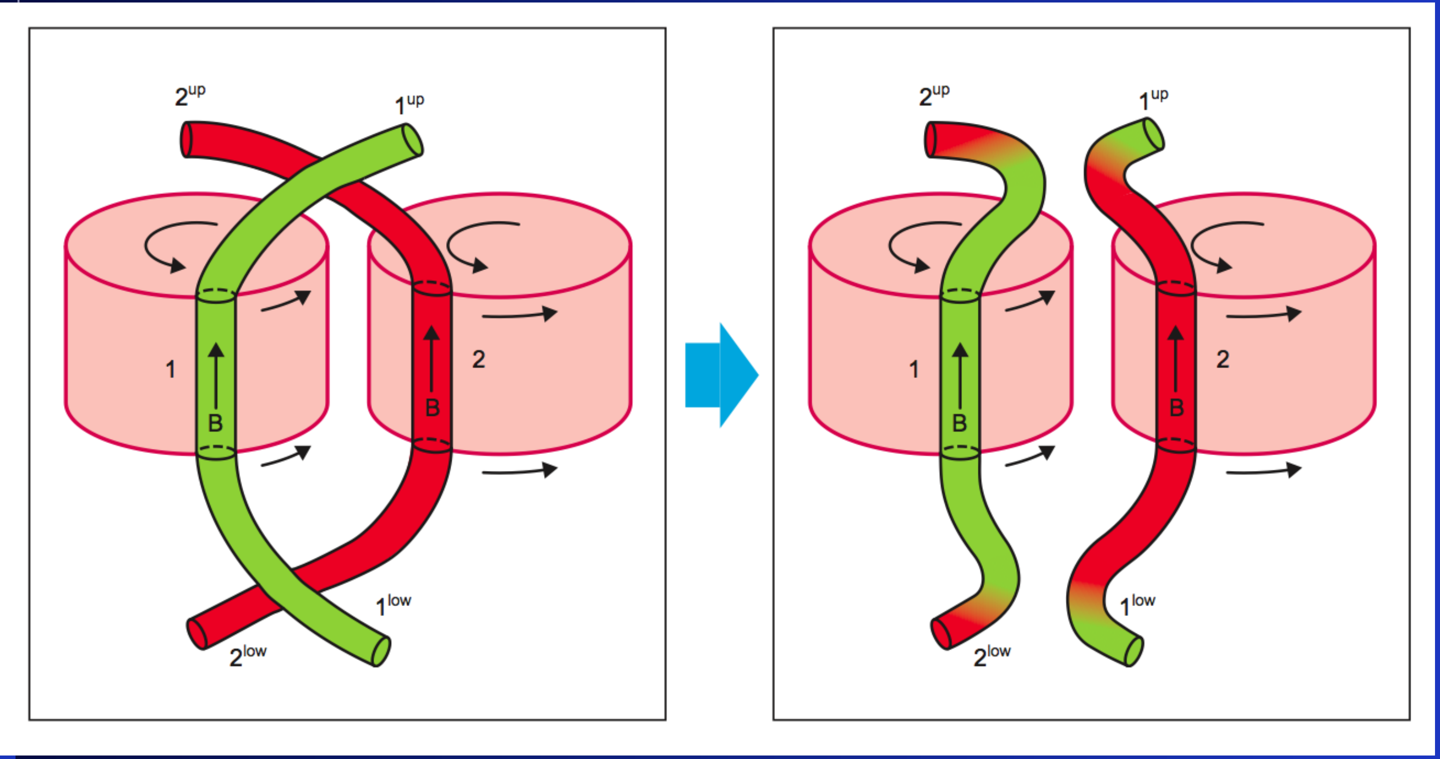
Reconnection can do mixing without ambipolar diffusion, as discussed in Lazarian 05. Consider idealized case:



Reconnection between flux turbulent flux tubes with different gas pressure in them results in changes of P_{gas}/P_{mag}



Reconnection can provide diffusion with the turbulent diffusion rates



Reconnection diffusion is different from turbulent ambipolar diffusion

Turbulent ambipolar diffusion is proposed by Zweibel (2001), Heitch & Zweibel (2003). Assumes that turbulence accelerates ambipolar diffusion. However:

1. In reality the diffusion of magnetic field is independent of ambipolar diffusion.

2. It is impossible without reconnection.

3. Thus it is reconnection diffusion that governs the magnetic field diffusion in turbulent media.

It is useless to talk about molecular turbulent diffusion of sugar if the diffusivity does not depend on the molecular diffusivity of sugar!

Without turbulence:

molecular diffusion coefficient D ~10^{-5} cm^2/sec

(← It's for small molecules in water.)

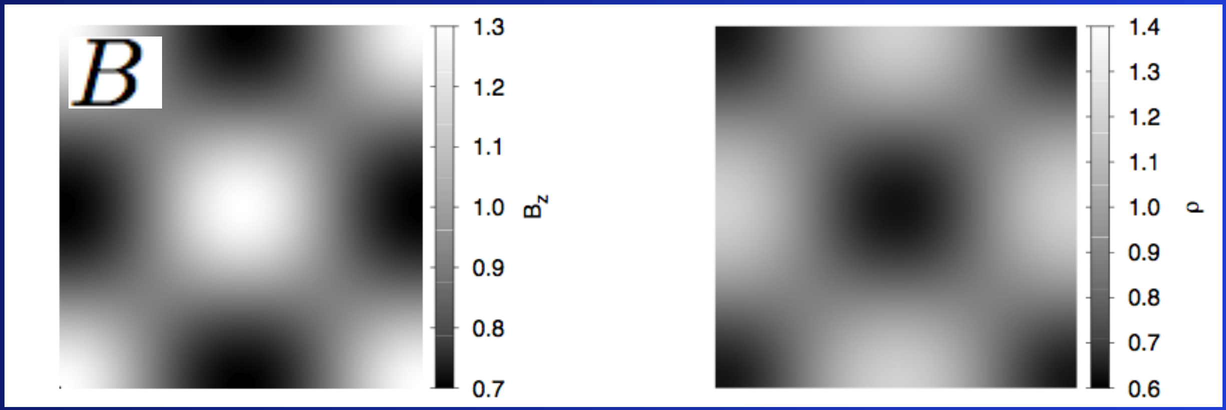
➔ Mixing time ~ (size of the cup)^2/D ~ 10^7 sec ~ 0.3 year !

Ambipolar diffusion is not required if media is turbulent

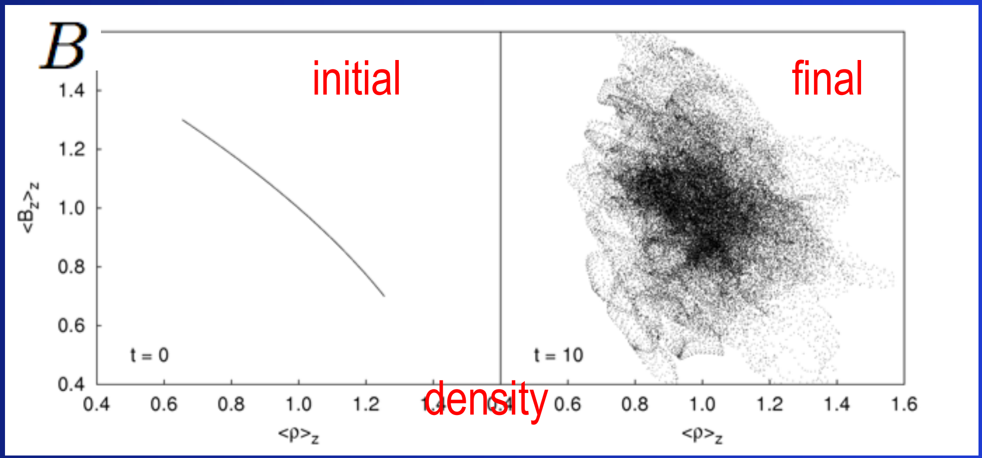
Reconnection diffusion in diffuse media: 3D MHD 512^3 simulations with the initial anti-correlation of magnetic field and density

No gravity case:

Initial configuration →



Reconnection diffusion in turbulent media destroys correlation of magnetic field and density without ambipolar diffusion.



Turbulent reconnection in partially ionized gas is discussed in Lazarian, Vishniac & Cho 2004

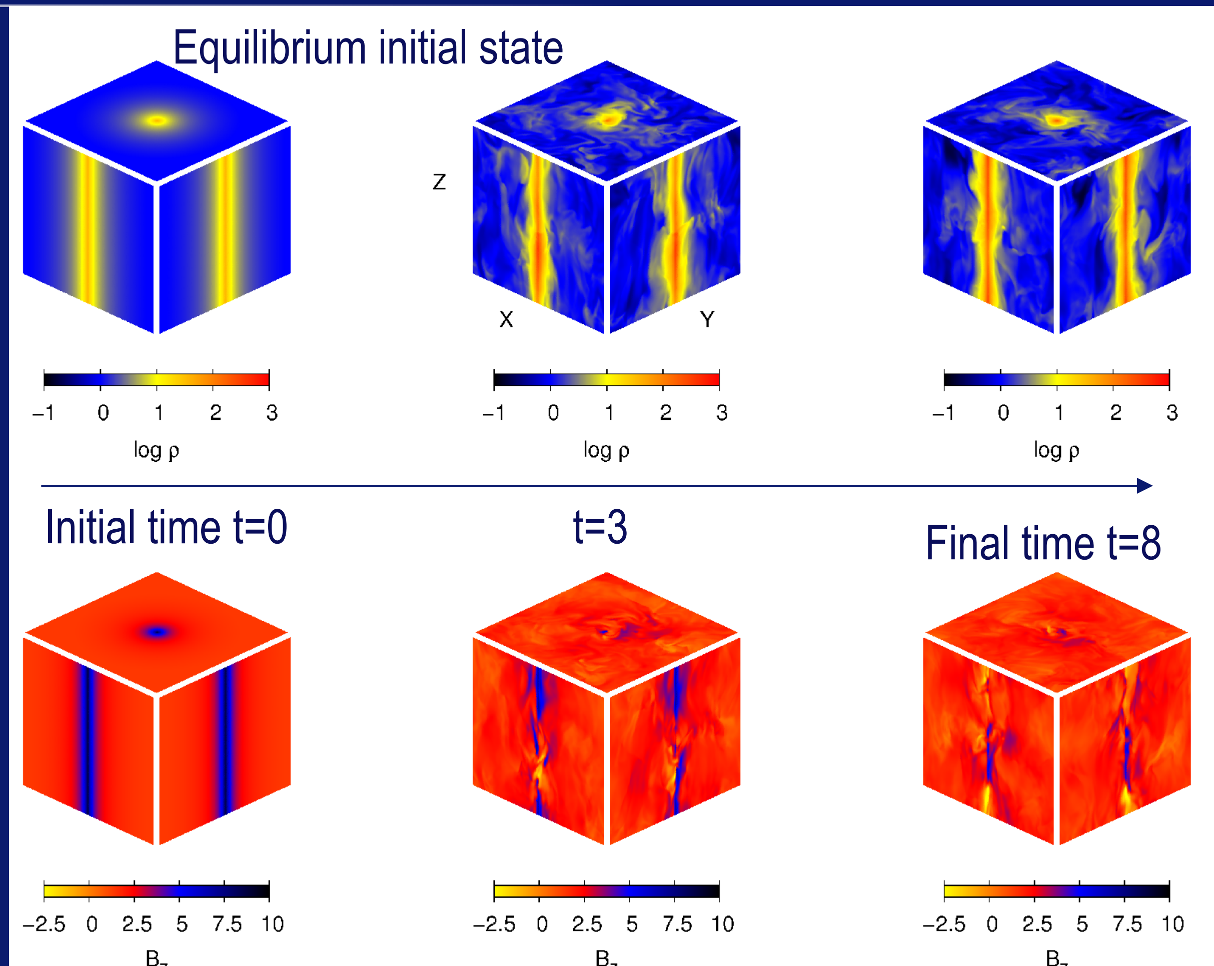
In the presence of weak turbulence and gravity magnetic field diffuses away from the core

Gravitational potential:

$$\Psi(R \leq R_{max}) = -\frac{A}{R + R_*}$$

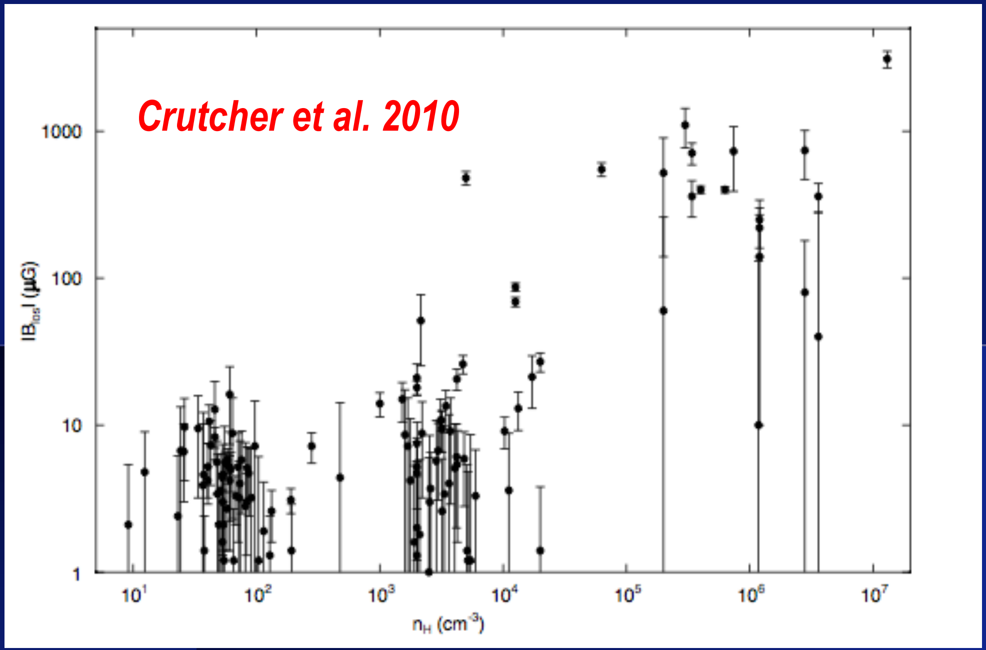
$$\Psi(R > R_{max}) = -\frac{A}{R_{max} + R_*}$$

Santos de Lima et al. 2010



Models starting in equilibrium simulate the evolution of subcritical clouds, while those starting in non-equilibrium reproduce some features of supercritical collapse.

Reconnection diffusion explains the distribution of magnetic fields in atomic and molecular clouds



Time scales $t_{rec.diff} = l^2/\kappa$

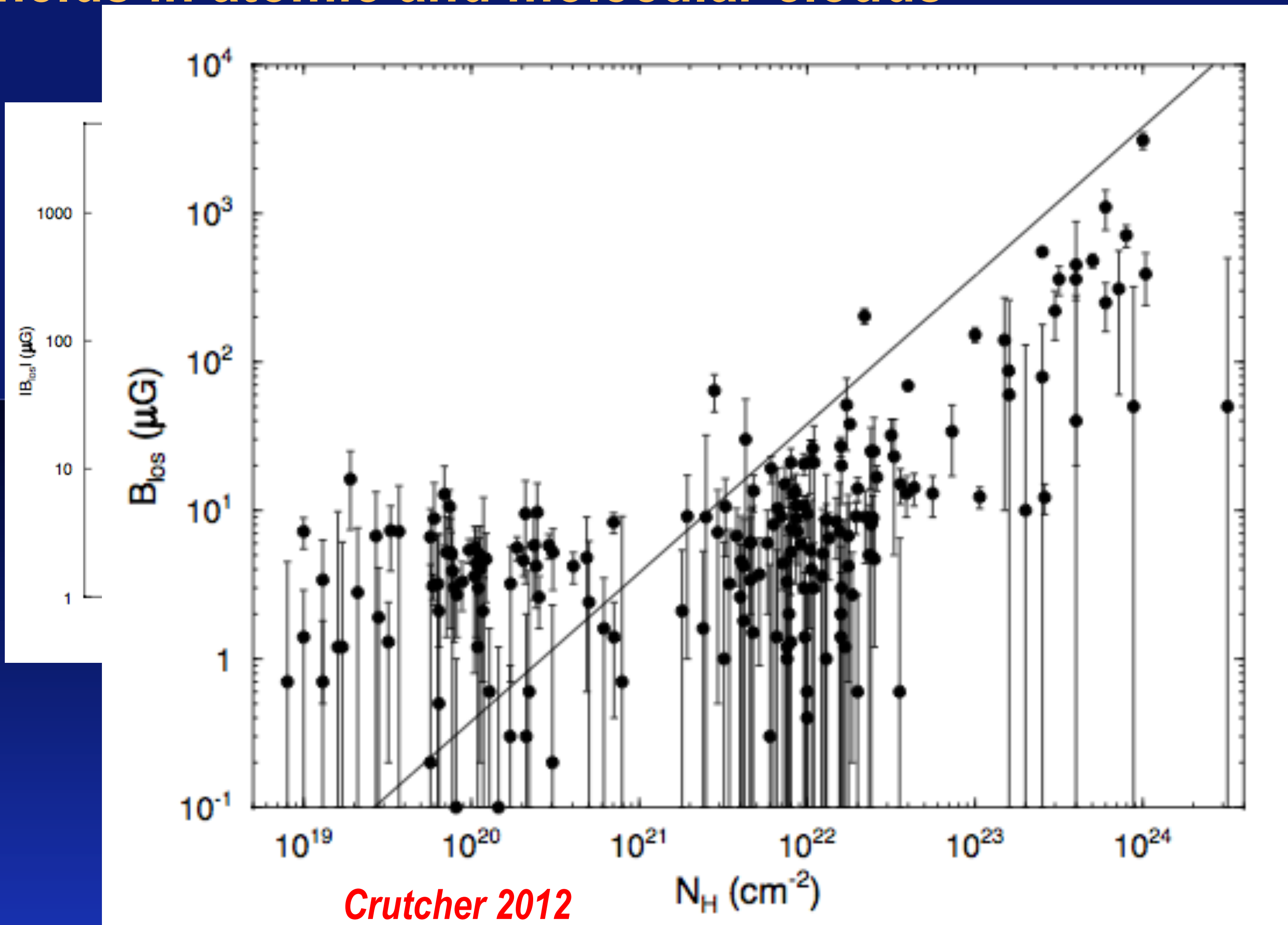
and $t_{ff} = \sqrt{3\pi/(32G\rho)}$ *are compared*

$$l_{upper} < \left(\frac{3\pi}{32}\right)^{3/4} \frac{V_{inj}^{3/2}}{L_{inj}^{1/2}} \frac{1}{(G\rho)^{3/4}}.$$

$$N_{crit} \sim l \times n \approx 10^{23}\mathrm{cm}^{-2}$$

AL et al. 2012

Reconnection diffusion explains the distribution of magnetic fields in atomic and molecular clouds



$.diff = l^2/\kappa$

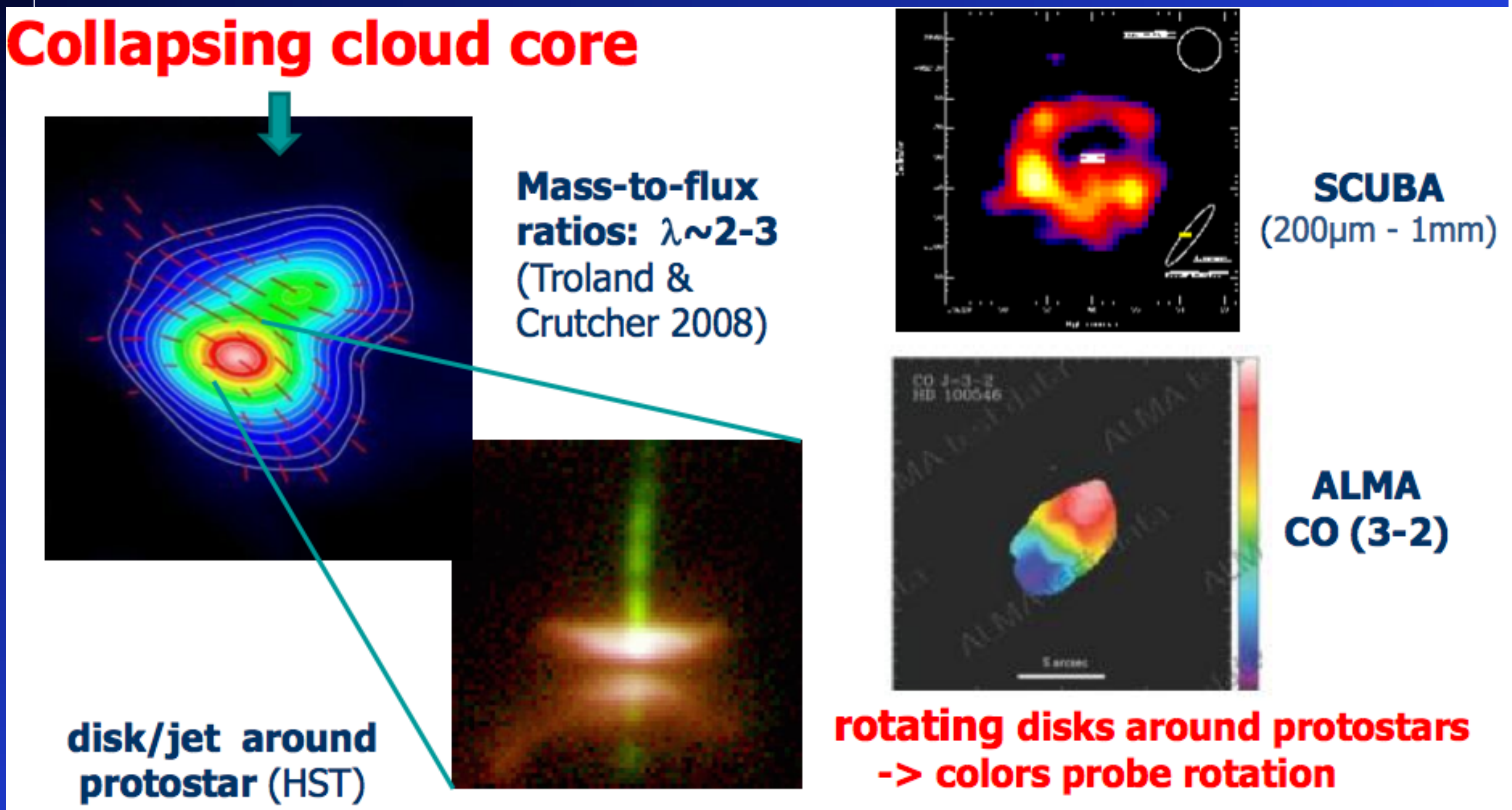
are compared

$\frac{1}{(G\rho)^{3/4}}.$

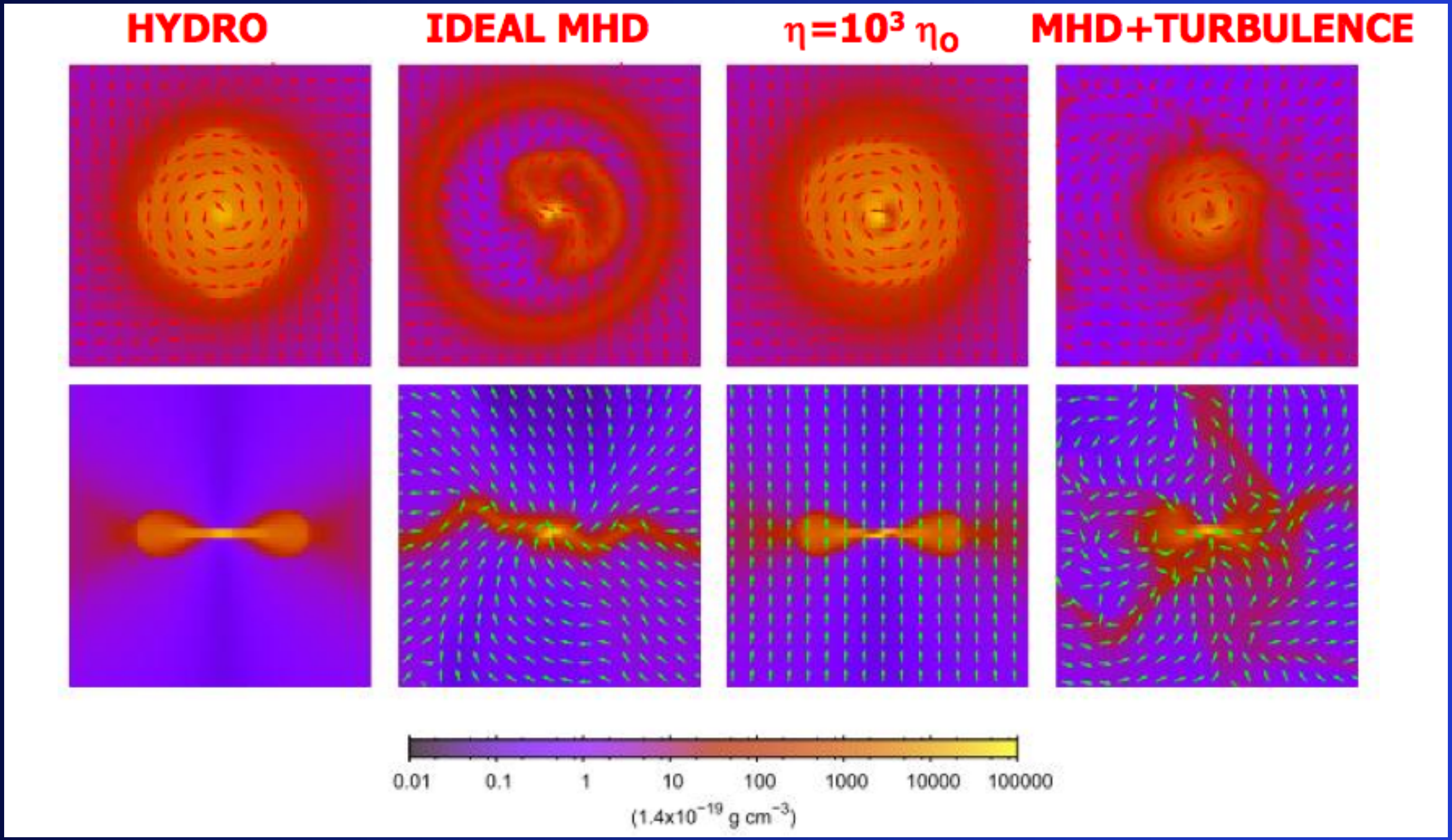
$$N_{crit} \sim l \times n \approx 10^{23}\mathrm{cm}^{-2}$$

AL et al. 2012

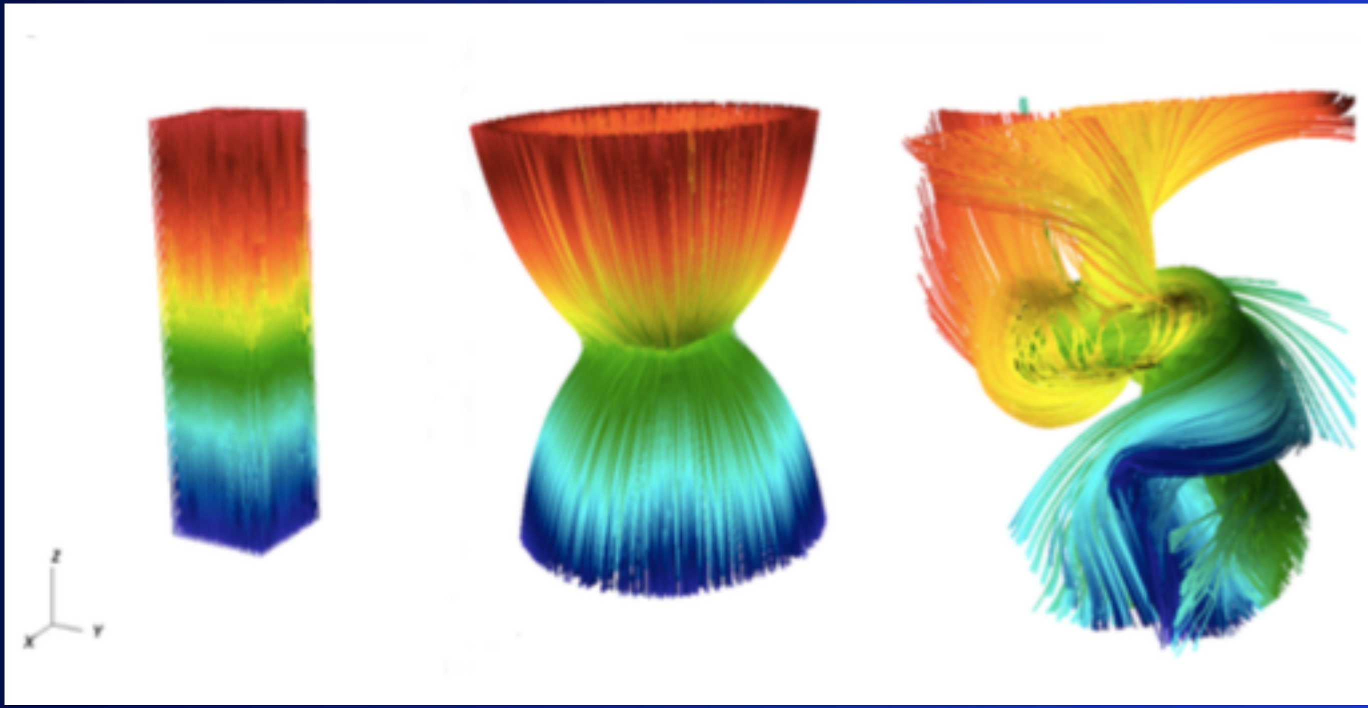
Accretion disks exist around stars



Results for different set ups

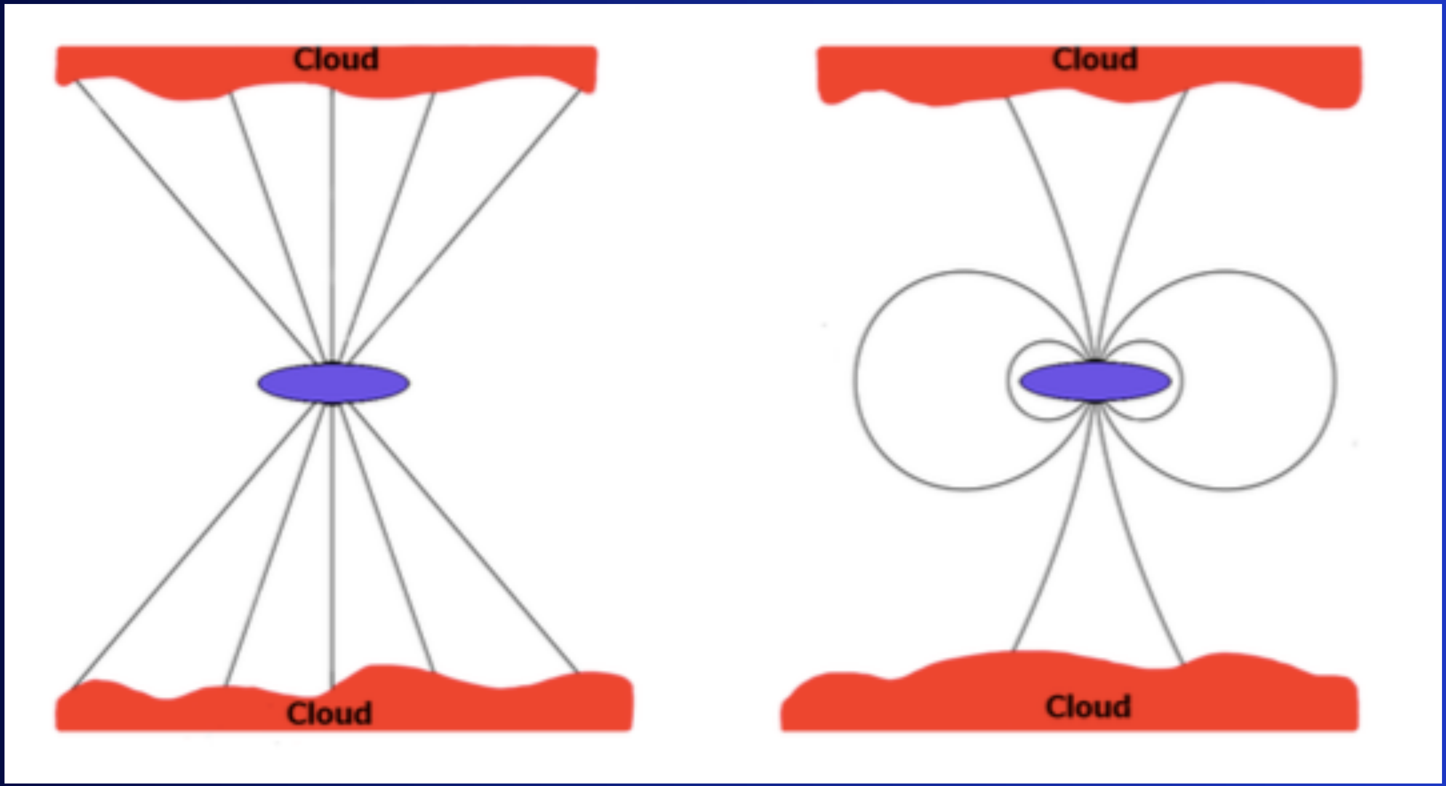


Magnetic field show complicated structure and reconnection is inevitable

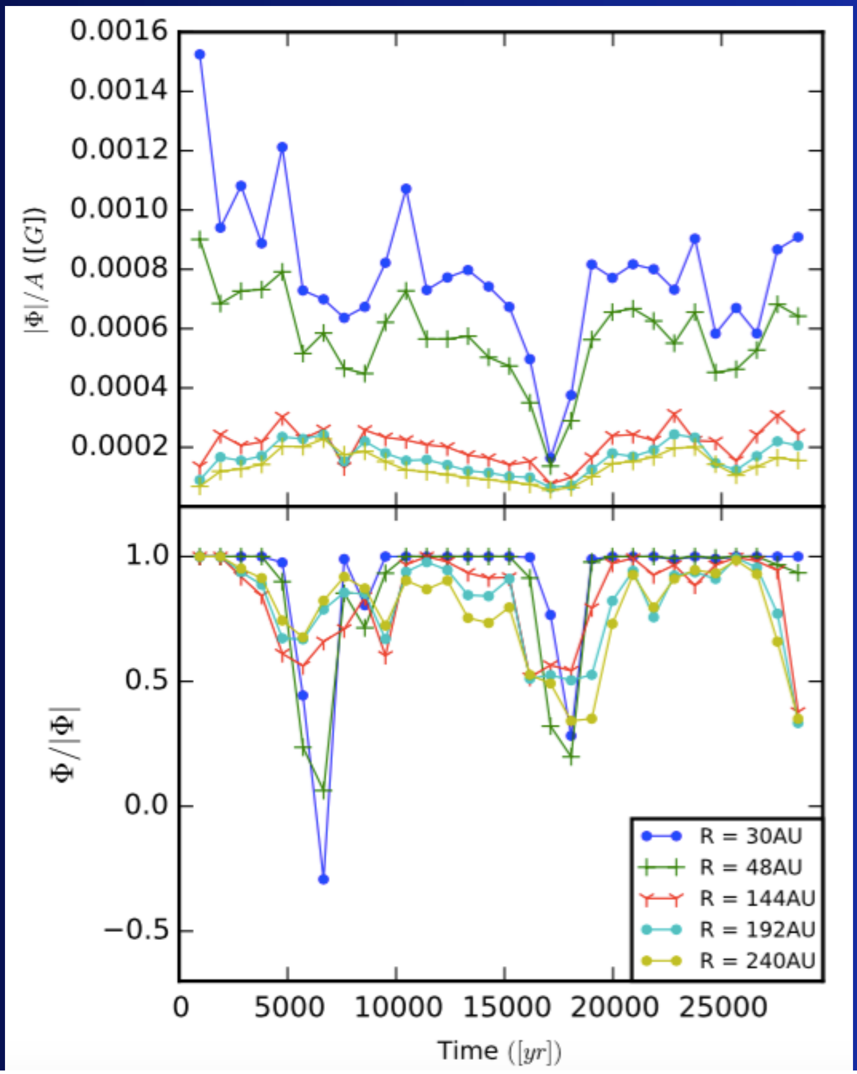


Casanova, AL, Santos-Lima 15

Change of magnetic field topology can decrease the connection between the disk and the ambient matter



In simulations we see changes of magnetic field topology

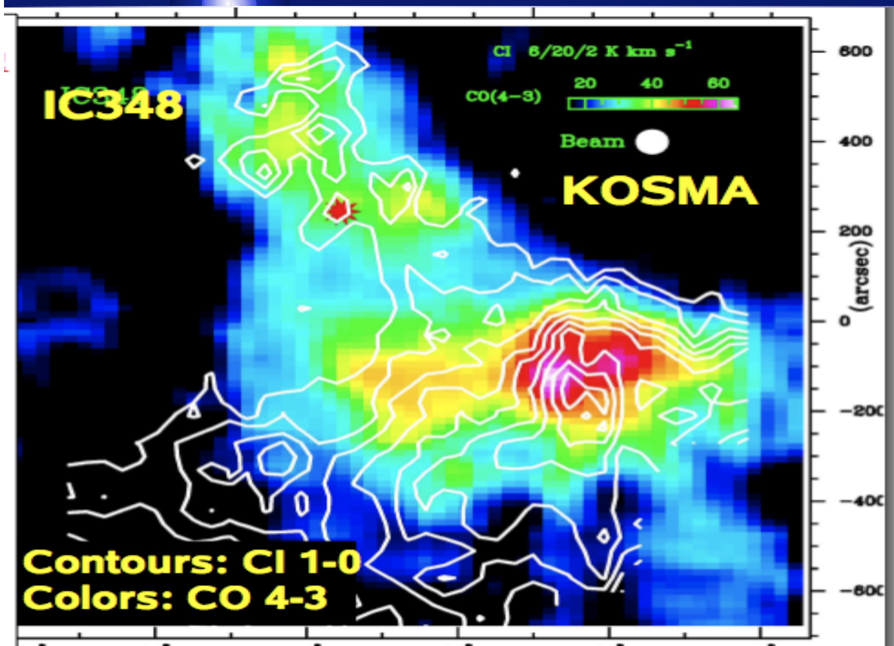


Casanova, AL, Santos-Lima 15

Implications for numerical simulations

1. *If for the structures that we study (e.g. molecular clouds) turbulence is suppressed the simulations probably are wrong in terms of reconnection effects. Convergence study with limited range may not give a good answer: reconnection diffusion may be still suppressed in a box several times larger.*
2. *For reconnection diffusion the largest scales of turbulent motions are important thus not power law decaying turbulence may still be OK (needs more exploration).*
3. *Numerical diffusion may be disregarded, if reconnection diffusion is higher than the numerical diffusion.*

Reconnection diffusion solves many long standing problems of star formation



The process explains

1. observations of no magnetic field --density correlation in diffuse media;
2. observations of the fast removal of magnetic field;
3. why no difference in star formation is observed for galaxies with different metallicities;
4. why cores of clouds may be stronger magnetized than envelopes;
5. increase of the magnetic field at a critical density

More information about turbulent reconnection are provided at my Researchgate site:

https://www.researchgate.net/profile/A_Lazarian

In particular at the project site

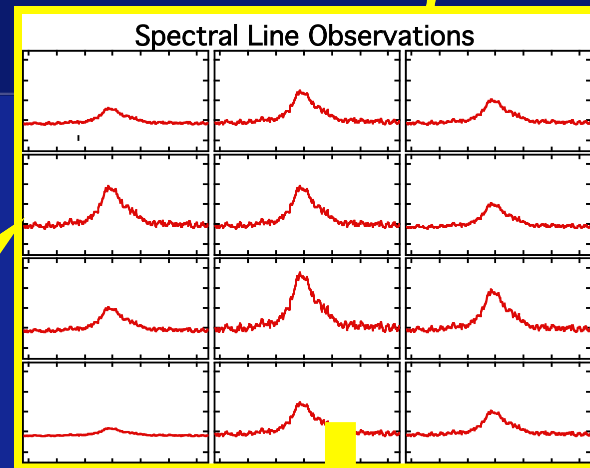
https://www.researchgate.net/project/Turbulent-Reconnection-and-its-Implications

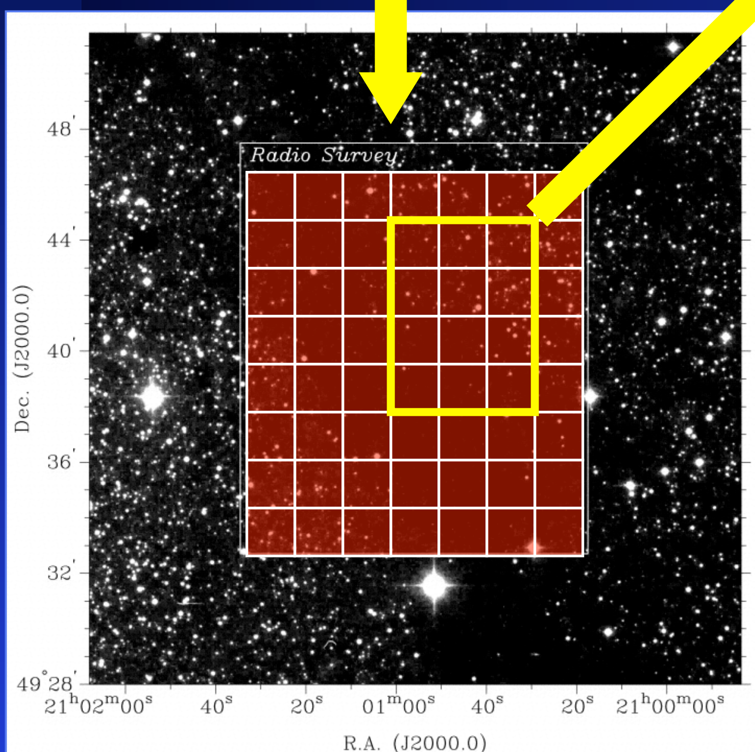
Where the references to the reviews and major papers are provided

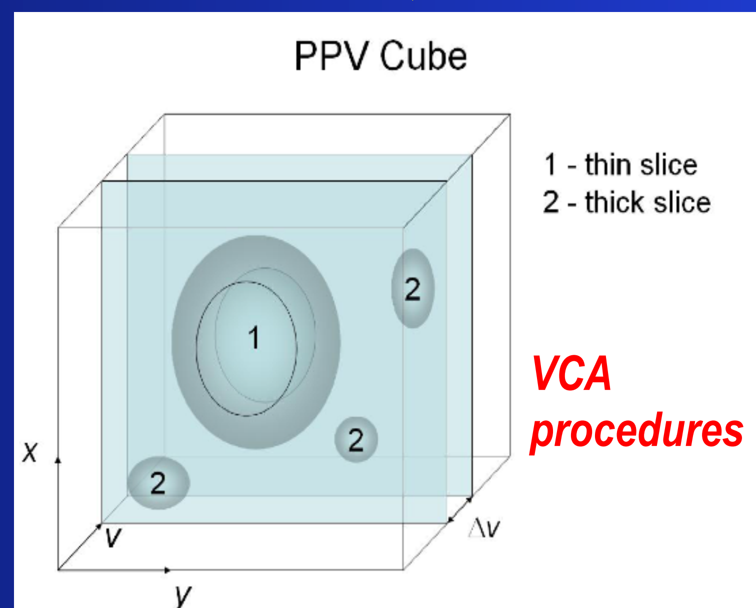
Obtaining quantitative information about turbulence

See Researchgate entry:
www.researchgate.net/project/Quantitative-Studies-of-Turbulence-from-Spectral-Line-Observations

Turbulence broadens emission and absorption lines and this can be used to study turbulence with VCA techniques

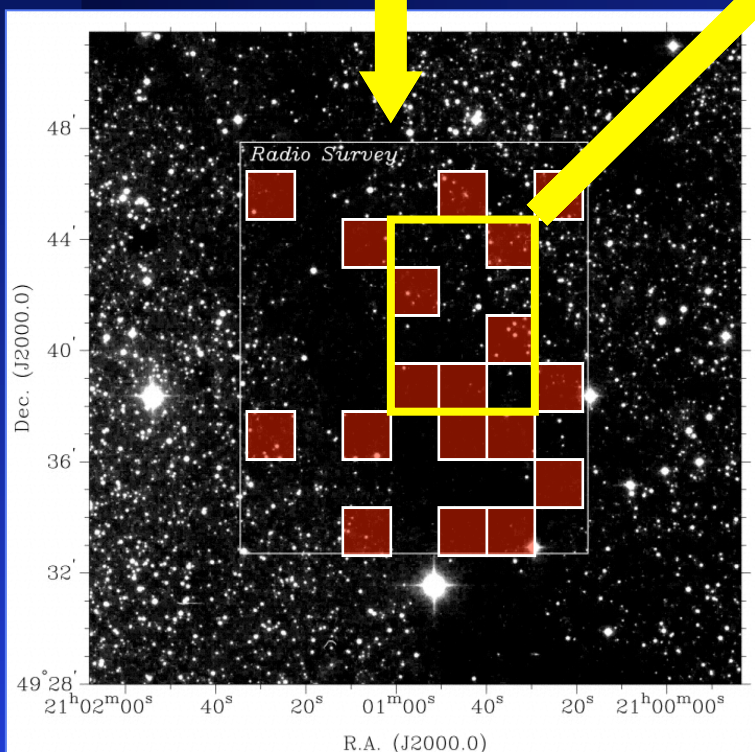


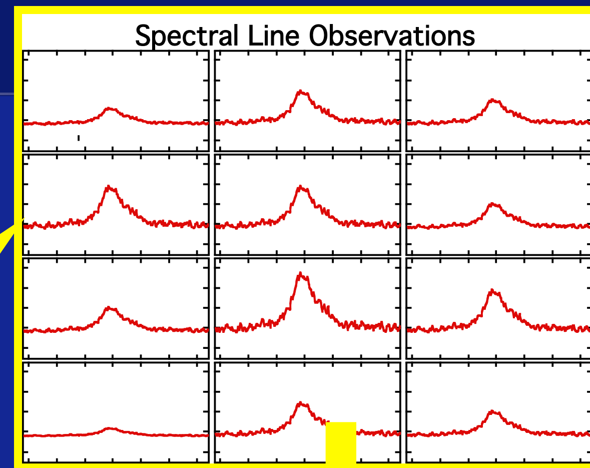


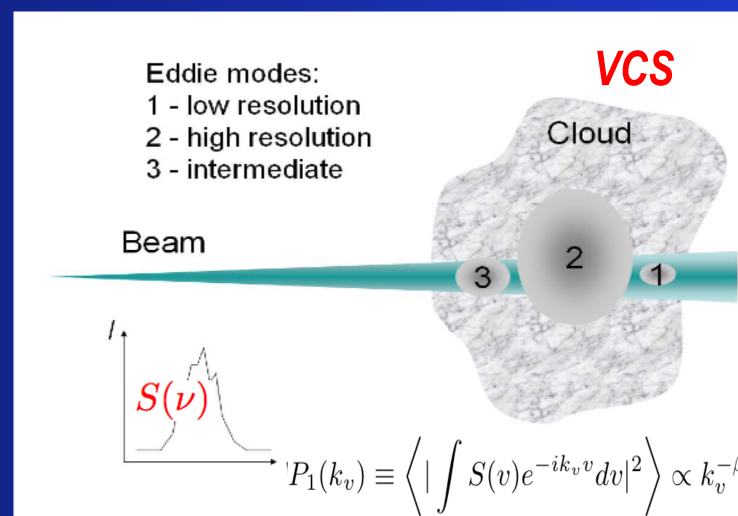


Developed in Lazarian & Pogosyan 00, 04

Sparsely sampled data can be studied with our VCS techniques

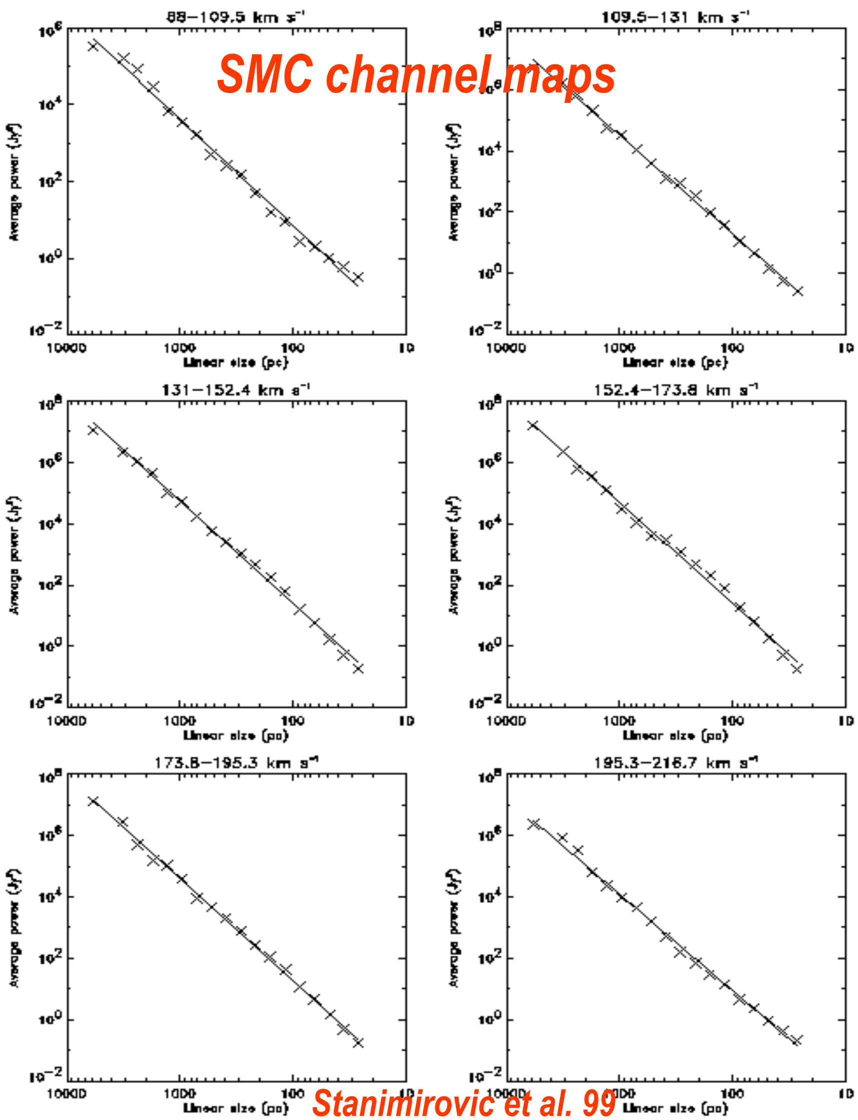




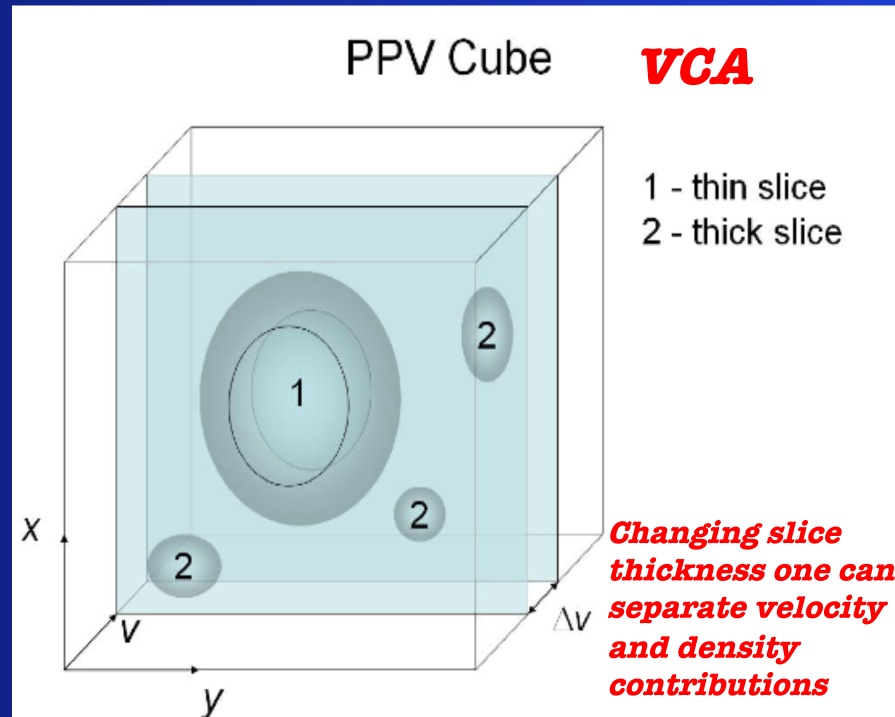


Developed in Lazarian & Pogosyan 06, 08

Spectra of HI channel maps reveals power law fluctuations

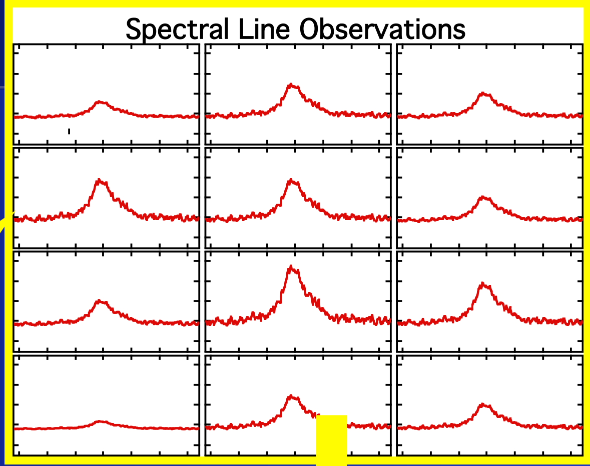


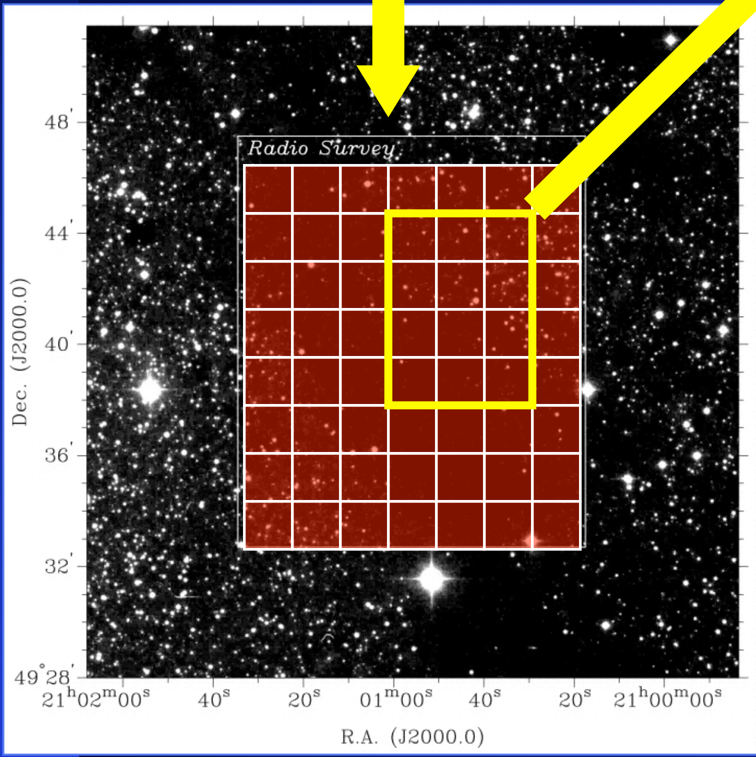
Stanimirovic et al. 99

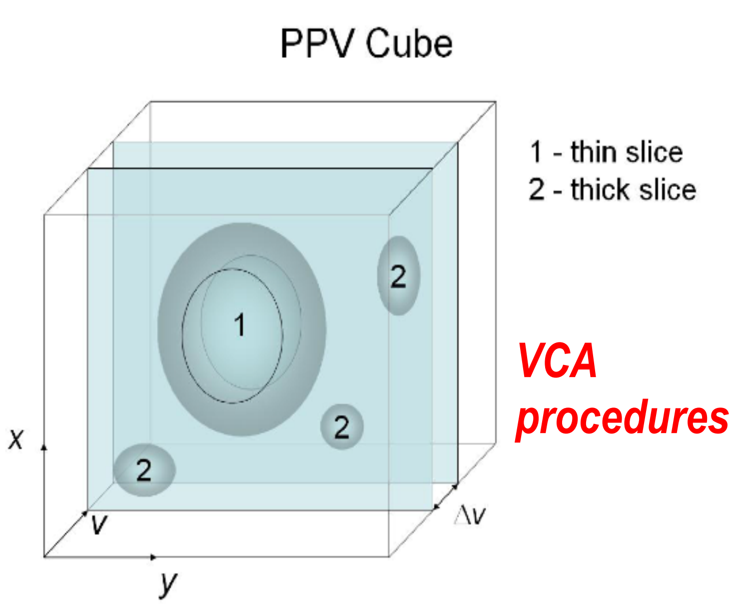


Can be dealt with the VCA technique by Lazarian & Pogosyan (00, 04)

Turbulence broadens emission and absorption lines and this can be used to study turbulence with VCA techniques

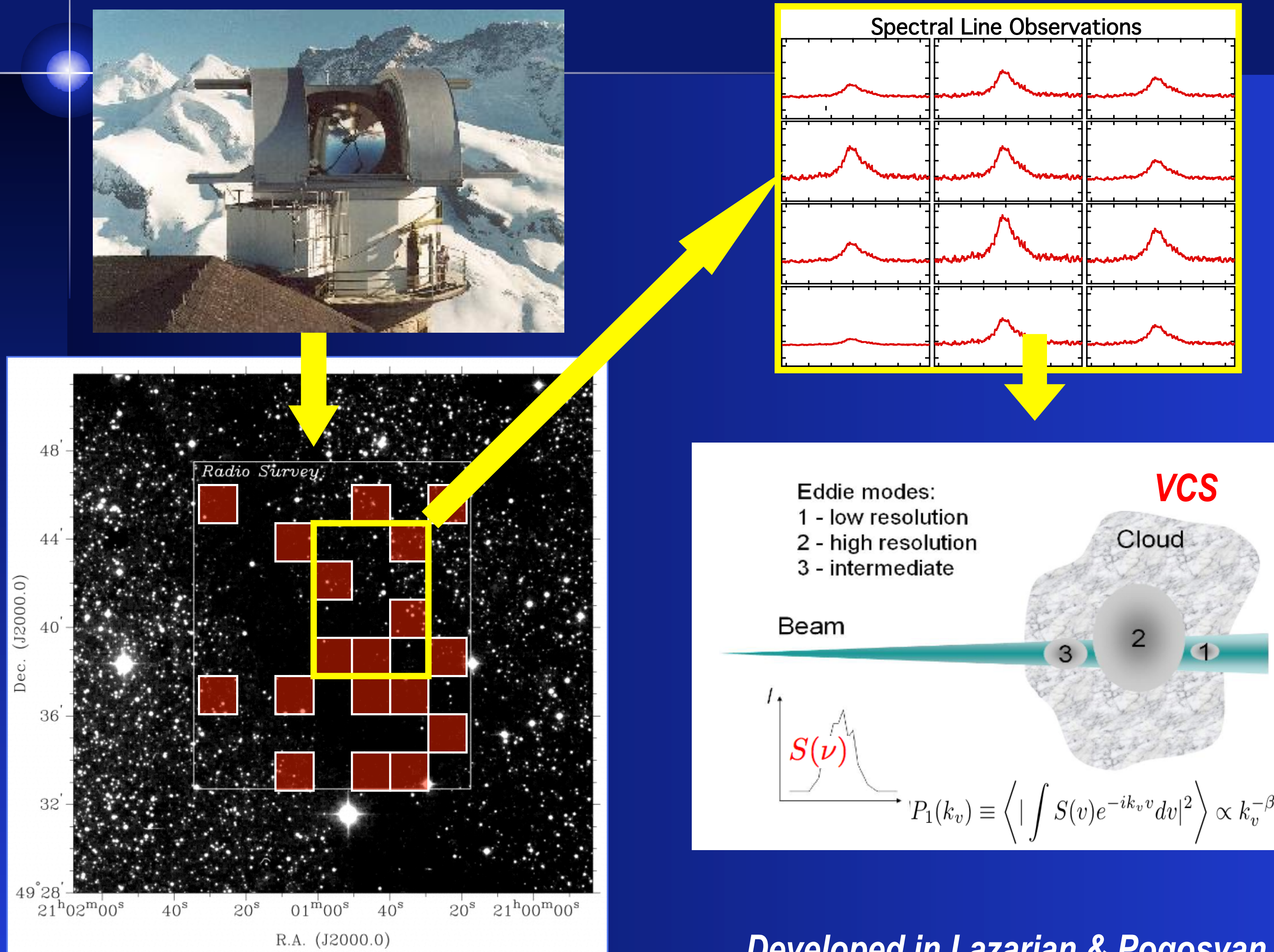






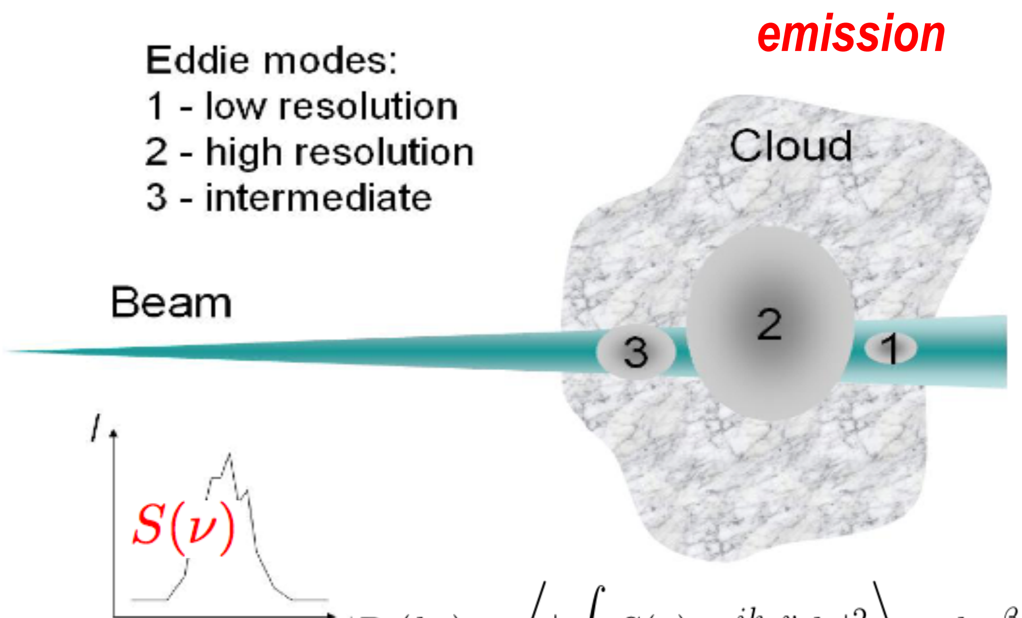
Developed in Lazarian & Pogosyan 00, 04

Sparsely sampled data can be studied with our VCS techniques



Developed in Lazarian & Pogosyan 06, 08

The relations of the spectral index of fluctuations along V-axis and the underlying velocity and density spectra were obtained



$$P_1(k_v) \equiv \left\langle \left| \int S(v) e^{-ik_v v} dv \right|^2 \right\rangle \propto k_v^{-\beta}$$

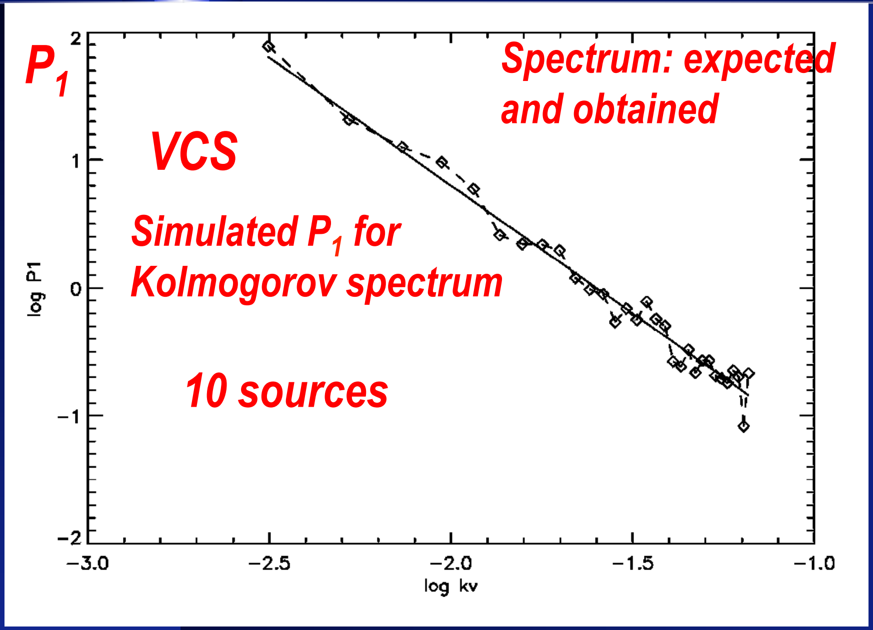
VCS is a new technique in Lazarian & Pogosyan 06, 08. Can work for resolved and unresolved objects.

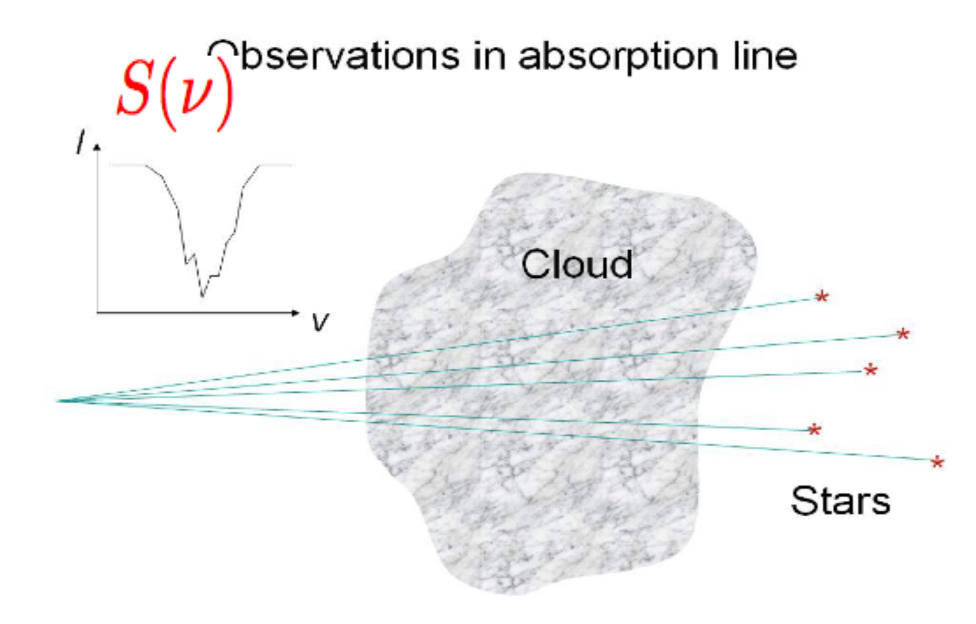
$\gamma < 0$

LOS geometry	high resolution		low resolution
	pencil beam	flat beam	
parallel	$2(1+\gamma)/m$	$2(2+\gamma)/m$	$2(3+\gamma)/m$
crossing	$2(1+\gamma)/m$	(not a power law)	$2(2+\gamma)/m$

$\gamma = 0$ *for steep density*

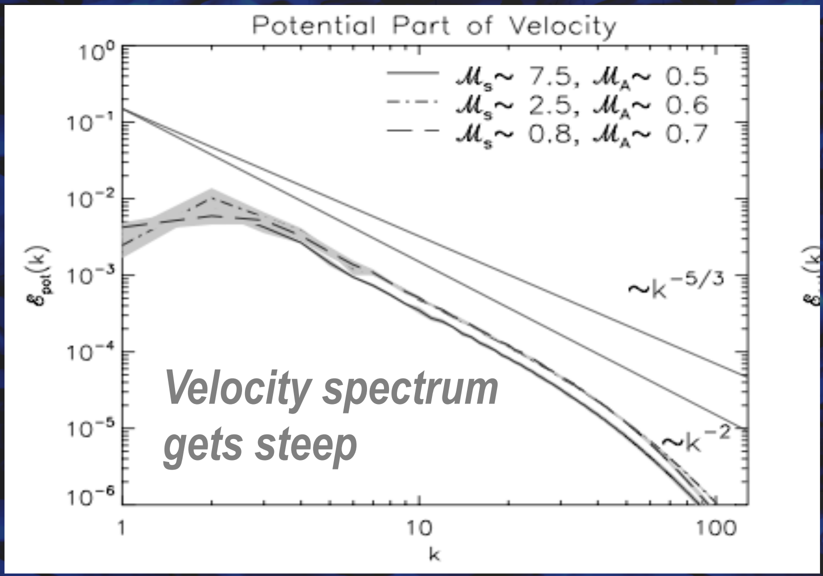
The VCA technique is also applicable to absorption lines



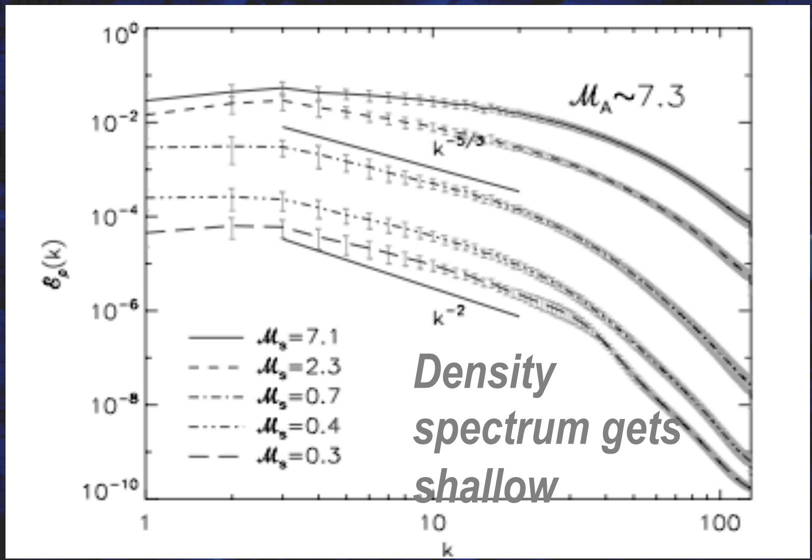


VCA and VCS techniques (Lazarian & Pogosyan 00, 04, 06, 08) reveal turbulence velocity spectra in agreement with expectations for supersonic turbulence

Expectations for supersonic turbulence



Kowal & Lazarian 2010



Kowal, Lazarian & Beresnyak 2007

VCS gets
for high latitude galactic HI $E_v \sim k^{-1.87}$ (Chepurnov et al.08,10)
for ^{13}CO for the NGC 1333 $E_v \sim k^{1.85}$ (Padoan et al. 09) indicating supersonic turbulence. Density is shallow $\sim k^{-08}$

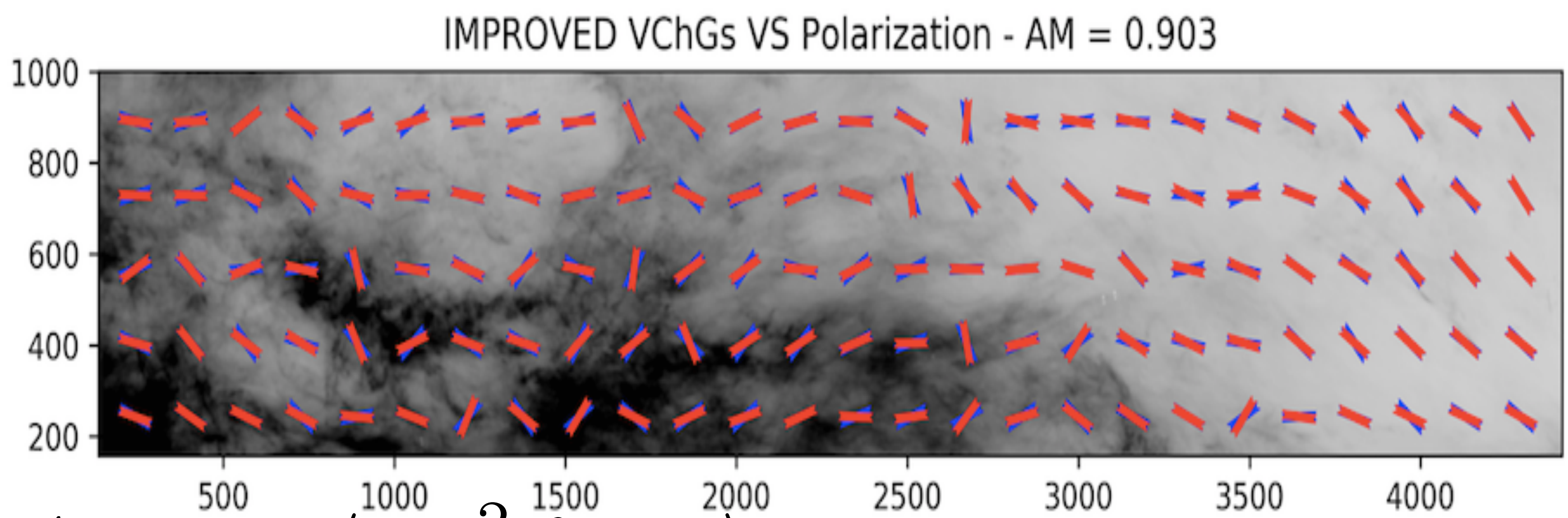
New Ways to Study Magnetic fields

See more:

www.researchgate.net/project/tracing-magnetic-fields-with-velocity-gradients

www.researchgate.net/project/Tracing-magnetic-fields-with-gradients-of-synchrotron-intensity

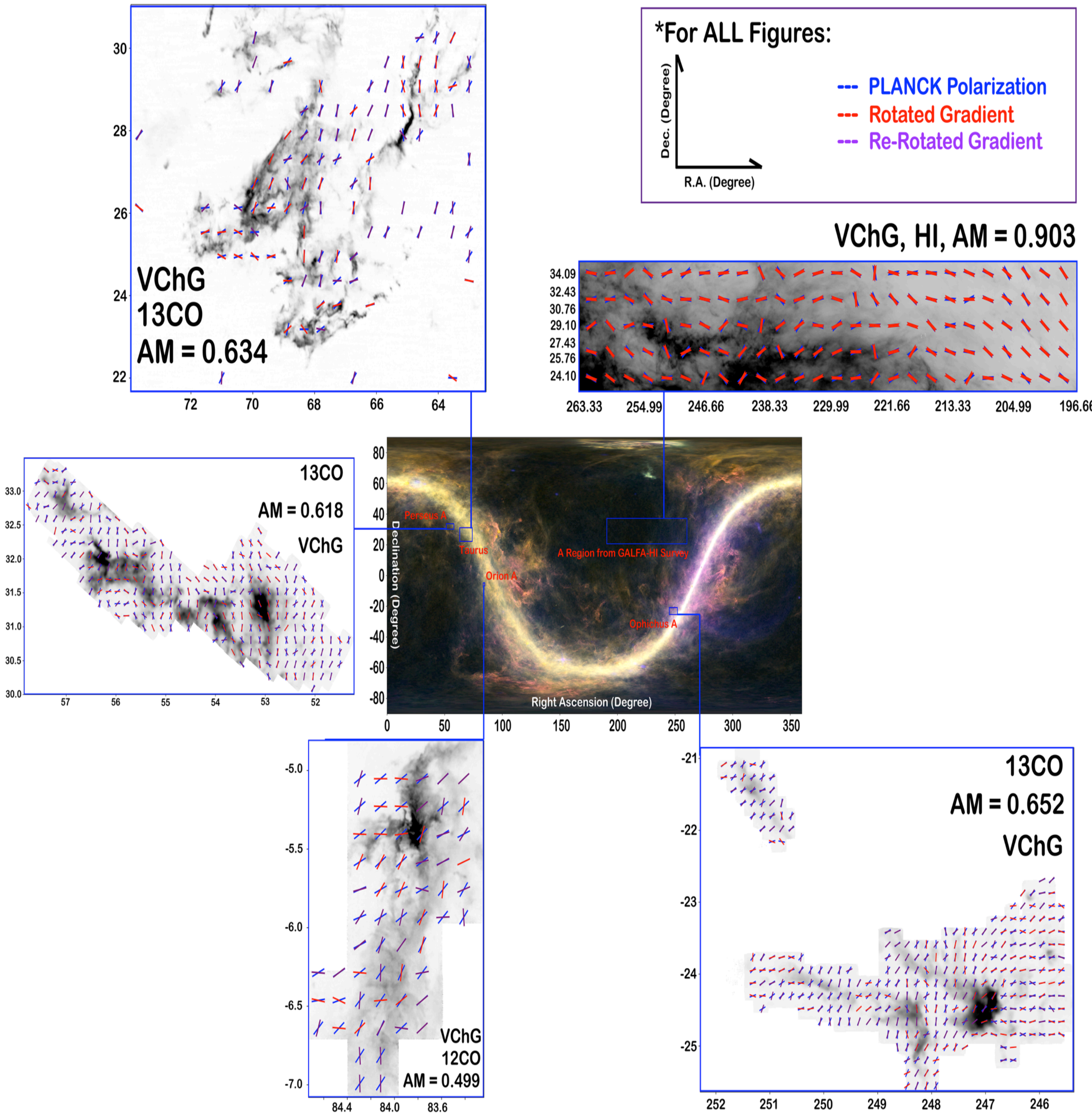
Velocity gradients in HI channel maps



$$AM = 2\langle \cos^2\theta - 1\rangle \quad \theta$$ ***Is angle between projected B and grad V***

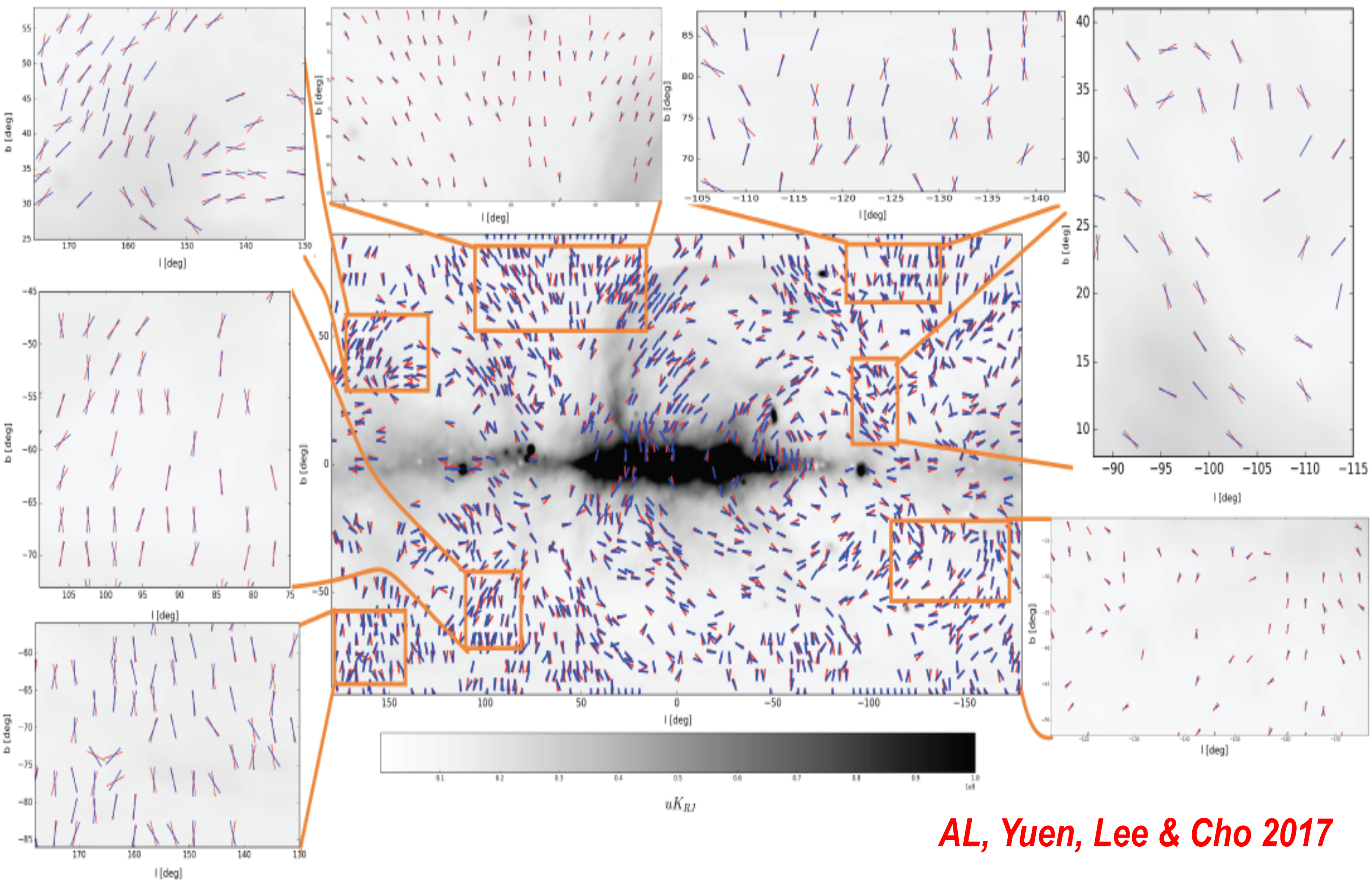
The fact that the dispersion of angle is the same at different scales is used

AL, Yuen & Sun 2017



VChGs are proven to work for different species

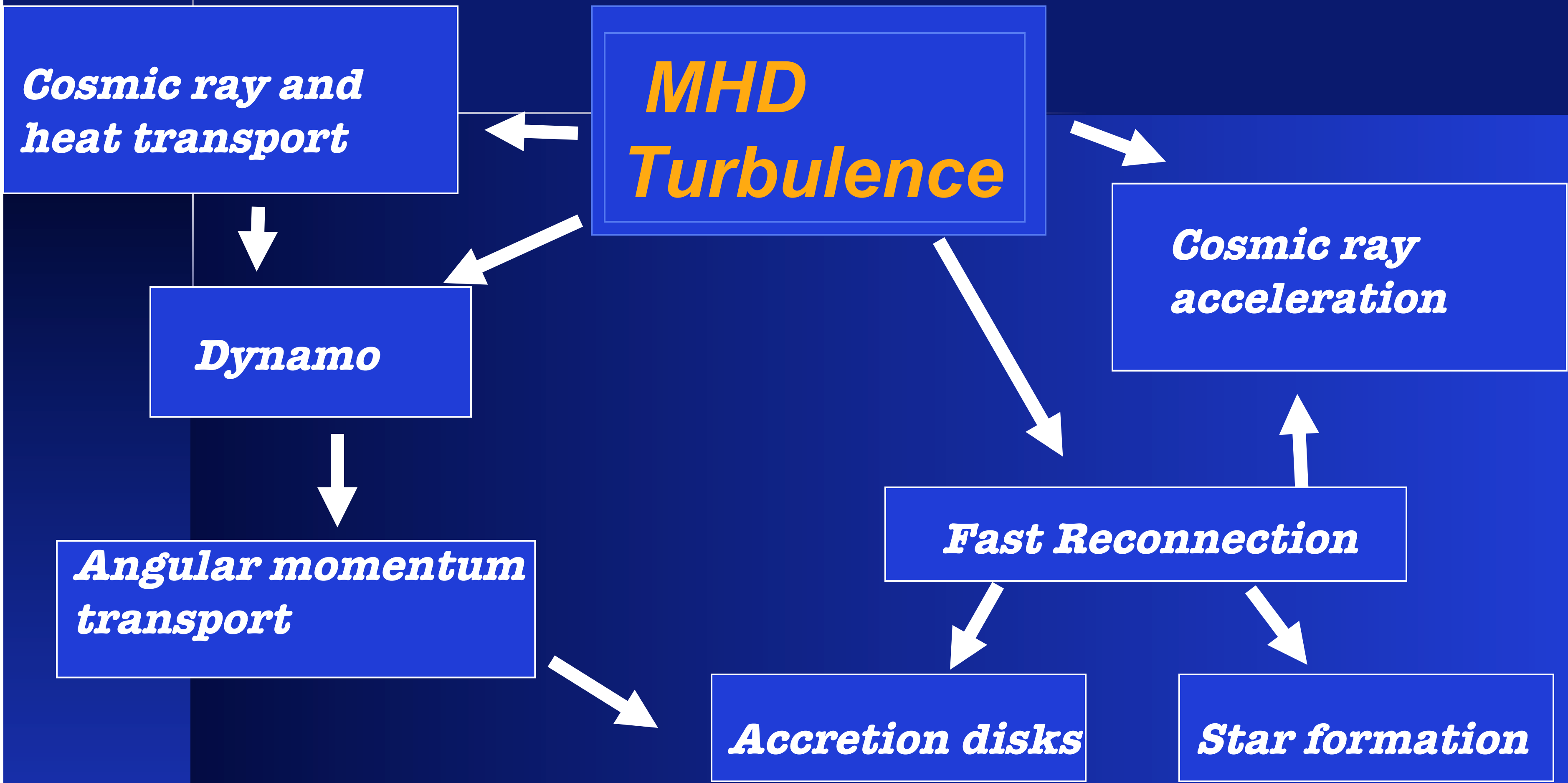
Synchrotron gradients

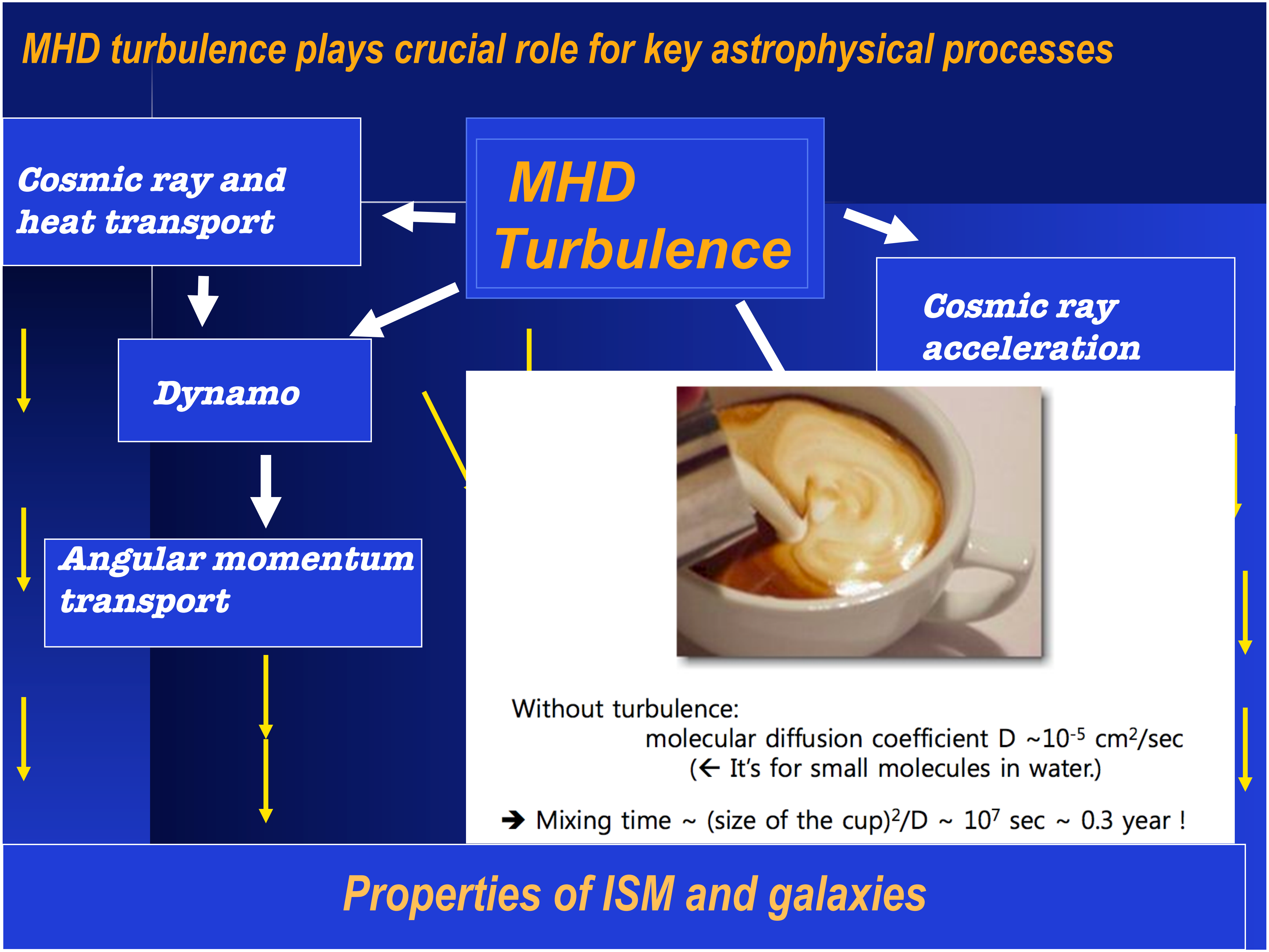


AL, Yuen, Lee & Cho 2017

Importance of MHD turbulence

MHD turbulence plays crucial role for key astrophysical processes



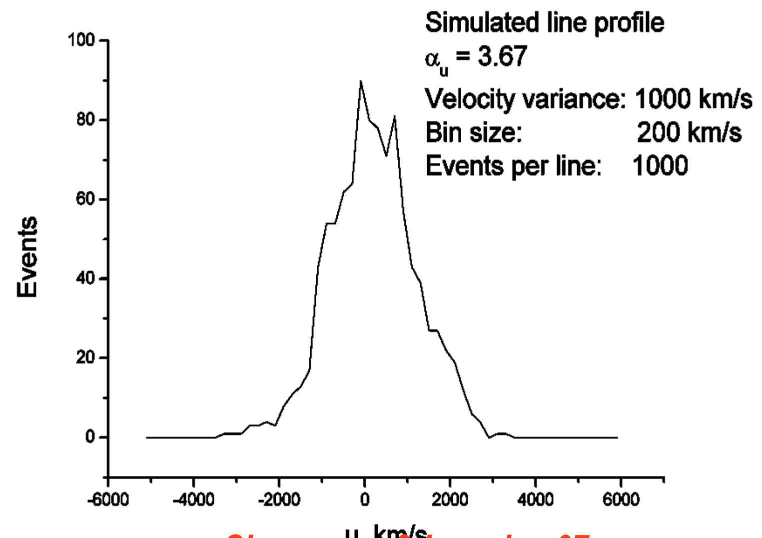

MHD turbulence plays crucial role for key astrophysical processes
Cosmic ray and heat transport
MHD Turbulence
Cosmic ray acceleration
Dynamo
Angular momentum transport
Without turbulence:
molecular diffusion coefficient D ~10^-5 cm^2/sec
(← It's for small molecules in water.)
→ Mixing time ~ (size of the cup)^2/D ~ 10^7 sec ~ 0.3 year !
Properties of ISM and galaxies

Solar Physics: Magnetized Plasmas

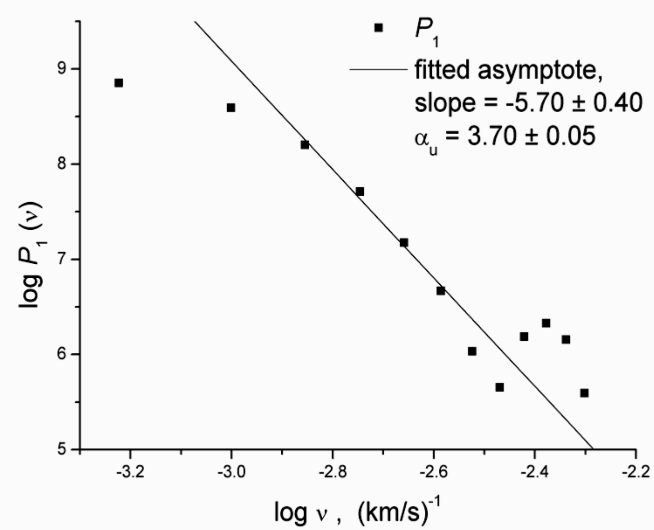
Information that we can use:

1. Turbulent velocities: Doppler line broadening
2. Turbulent magnetic fields:
   a. Synchrotron intensity fluctuations
   b. Synchrotron polarization fluctuations
   c. Dust polarization fluctuations
   d. Faraday rotation fluctuations
   e. Velocity gradients variations
   f. Synchrotron intensity gradient variations
3. Turbulent density: intensity fluctuations

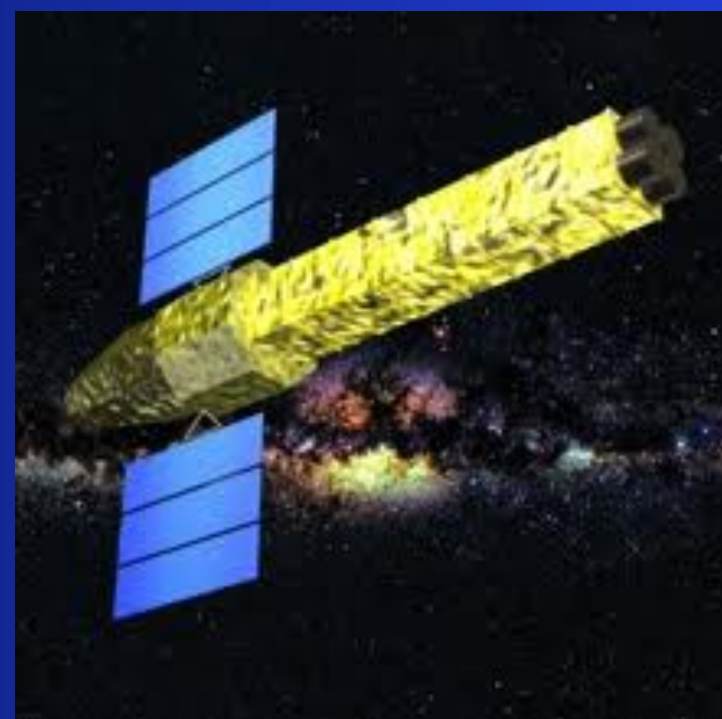
VCA technique is promising for studying galaxy clusters with Astro-H and other future X ray spectroscopic missions



Chepurnov & Lazarian 07



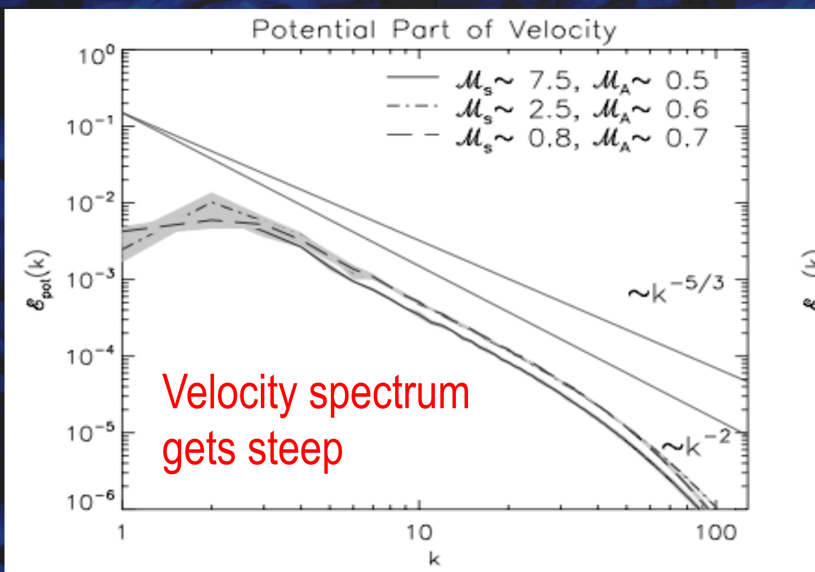
Lazarian & Pogosyan 2006
Chepurnov & Lazarian 2010



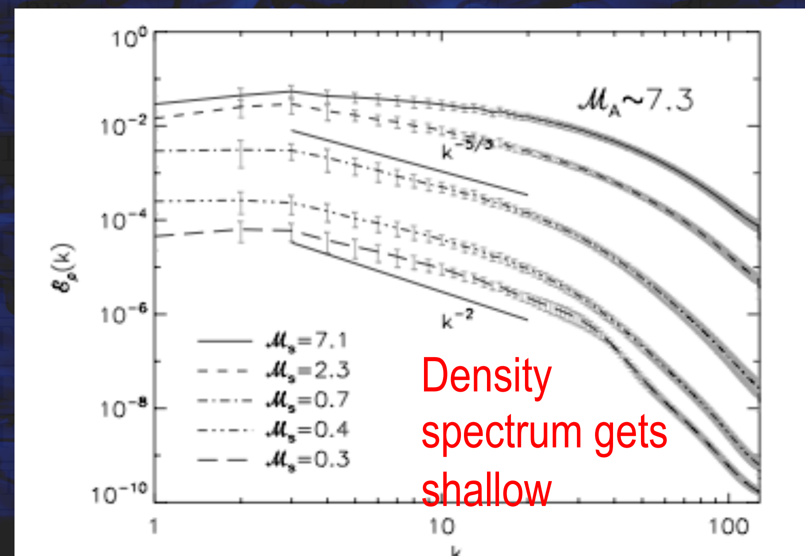
Astro-H would get turbulent spectra with VCS technique in 1 hour

VCA and VCS techniques (AL & Pogosyan 00, 04, 06, 08) reveal turbulence velocity spectra in agreement with expectations for supersonic turbulence

Expectations for supersonic turbulence



Kowal & Lazarian 2010



Kowal, Lazarian & Beresnyak 2007

Sel

VCS gets

for high latitude galactic HI $E_v \sim k^{-1.87}$ (Chepurnov et al.08,10)

for ^{13}CO for the NGC 1333 $E_v \sim k^{-1.85}$ (Padoan et al. 09)

indicating supersonic turbulence. Density is shallow $\sim k^{-0.8}$

Big Implication: LV99 means that magnetic field in *turbulent fluids* is not frozen in

Hannes Alfven

In the presence of Ohmic effects the separation of field lines is

$$\langle r^2(t)\rangle \le 6\lambda \frac{\exp(2\|\nabla \mathbf{u}\| t) - 1}{\|\nabla \mathbf{u}\|}.$$

where $\|\nabla \mathbf{u}\|$ is the maximum value of the velocity-gradient $\nabla \mathbf{u}$.

For finite gradients $\langle r^2(t)\rangle \to 0$ as $\lambda \to 0$. *Condition for the laminar flows*

For turbulent flows the energy dissipation cascade is V^3/l is also and gradients get large $\varepsilon = \nu\langle|\nabla \mathbf{u}|^2\rangle$

$\exp[2(\epsilon/\nu)^{1/2} t]$ *Grows fast and for finite ratio of the viscosity to Ohmic diffusivity ratio beats the decrease of resistivity*

Theory of turbulent dynamo

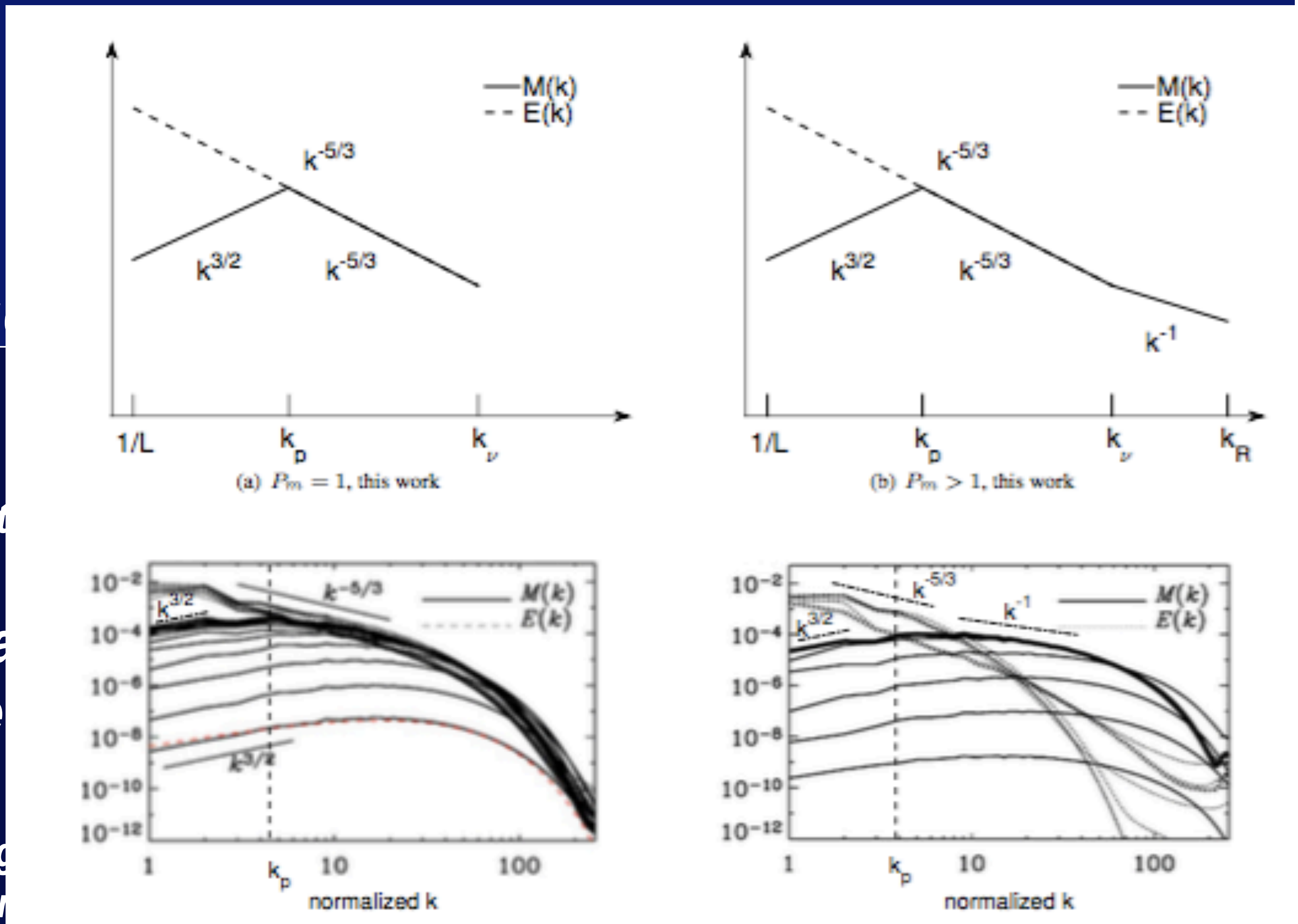
P_m=1 P_m>1

Xu & AL 201

P_m=viscosit

Numerica evidence

Brandenburg
Subramanian



(a) $P_m = 1$, this work

(b) $P_m > 1$, this work

(c) $P_m = 1$, figure. 5.1 in Brandenburg & Subramanian (2005)

(d) $P_m = 50$, figure. 5.2 in Brandenburg & Subramanian (2005)