MHD Turbulence from the Observations

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Astrophysical Magnetized Turbulence: A Difficult Problem

Fact 1: It is difficult to measure magnetic fields in the ISM/IGM
Fact 2: "Turbulence is one of the most important unsolved problems…" –R. Feynman
Fact 3: The ISM/solar wind are complicated MHD flows with a range of temperatures, scales; instabilities…

This makes the study of turbulence & magnetic fields unpopular with some astronomers…

Quotes from anonymous IAU participants:

Indifference... "Magnetic fields are too complicated for our models…they are too numerically expensive.."

Disgust... "You study turbulence and magnetic fields… ugh!"

Aversion... "I hate magnetic fields!!"

We know Turbulence and Magnetic Fields Are Important at Every Scale…

Cosmic ray acceleration, small scale dynamos, (some) reconnection…

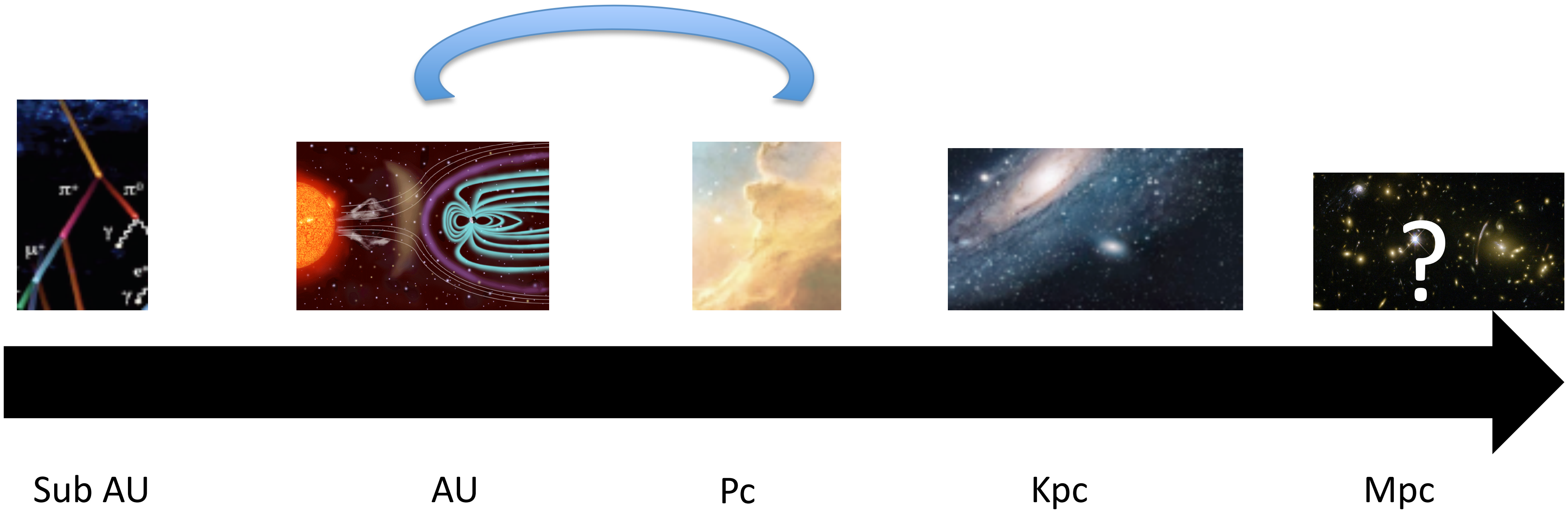
Solar wind spectrum agrees with theoretical predictions

Diffuse CNM/WNM and dense cold molecular both show line broadening due to turbulence

The big power law (e.g. Armstrong, Rickett & Spangler 1995; Chepurnov & Lazarian 2010)

Galactic Fountain, Spiral arm motions, Tidal interactions inject turbulence

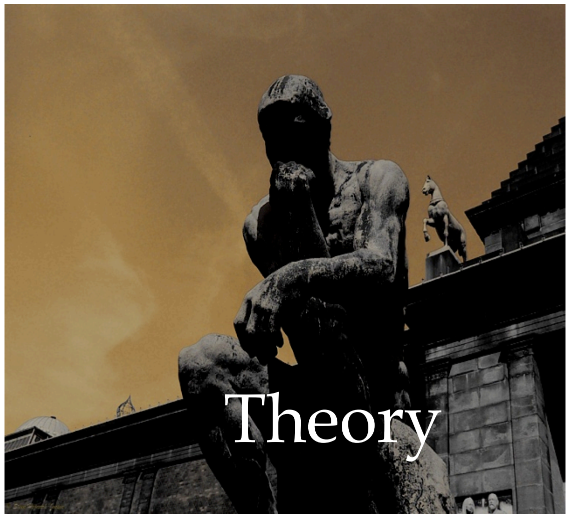
Collisionless regime; thermally dominated; line tracers such as OVI

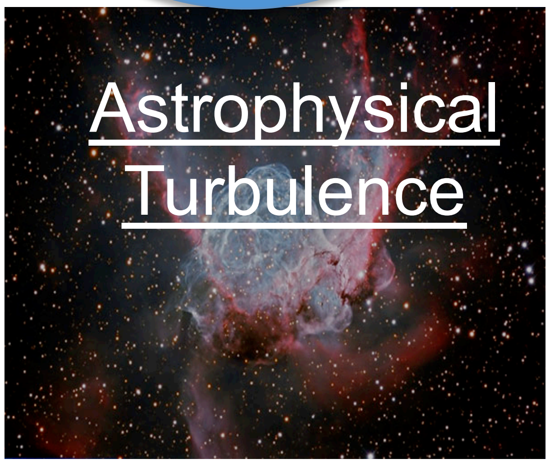


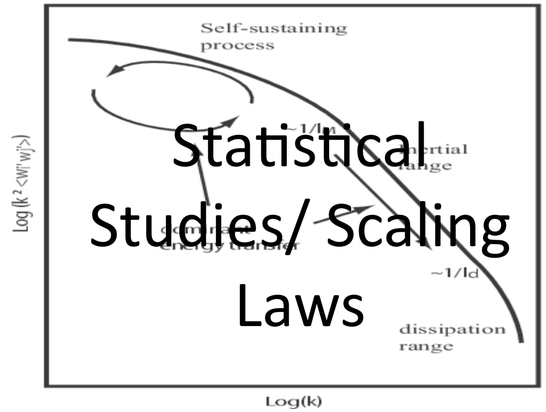
How to Study MHD Turbulence Observationally?

Tool box for studying MHD turbulence:

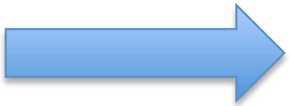
This is my talk outline!

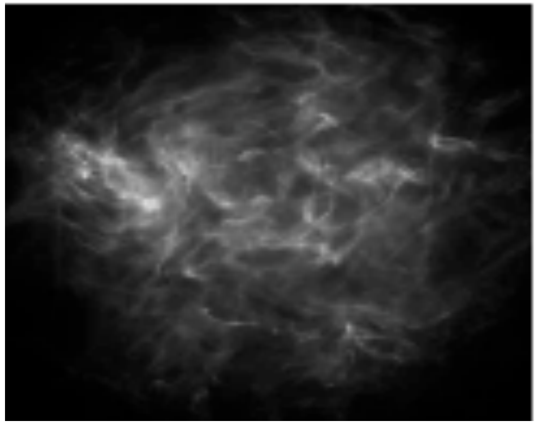






Numerical Simulations as Low-Reynolds Number Gauges to: Test Theory





Many different turbulence simulations exist and examine different physical environment and test different theories of the ISM

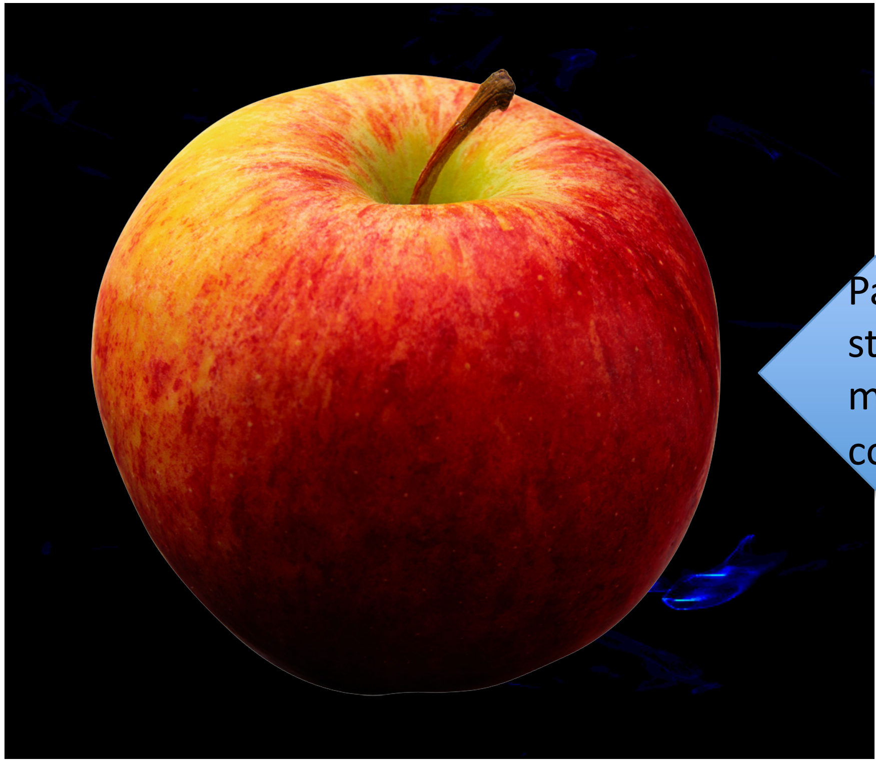
Type	Pro	Con
Ideal MHD; isothermal	Resolved Inertial range	Too simplified physics
multiphase	Heating/cooling can capture the WNM/CNM physics	More complex, simplified heating/cooling function/ turbulence maybe not well resolved
Full chemistry/Radiative transfer	GMC formation/ radiatve processes	Numerically expensive!

Numerics to guide interpretation of observations

How to find the common ground?…. Synthetic observations!

Full information…density (PPP), velocity, magnetic fields etc…

Synthetic observations (PPV) MHD 512^3 M_s=7

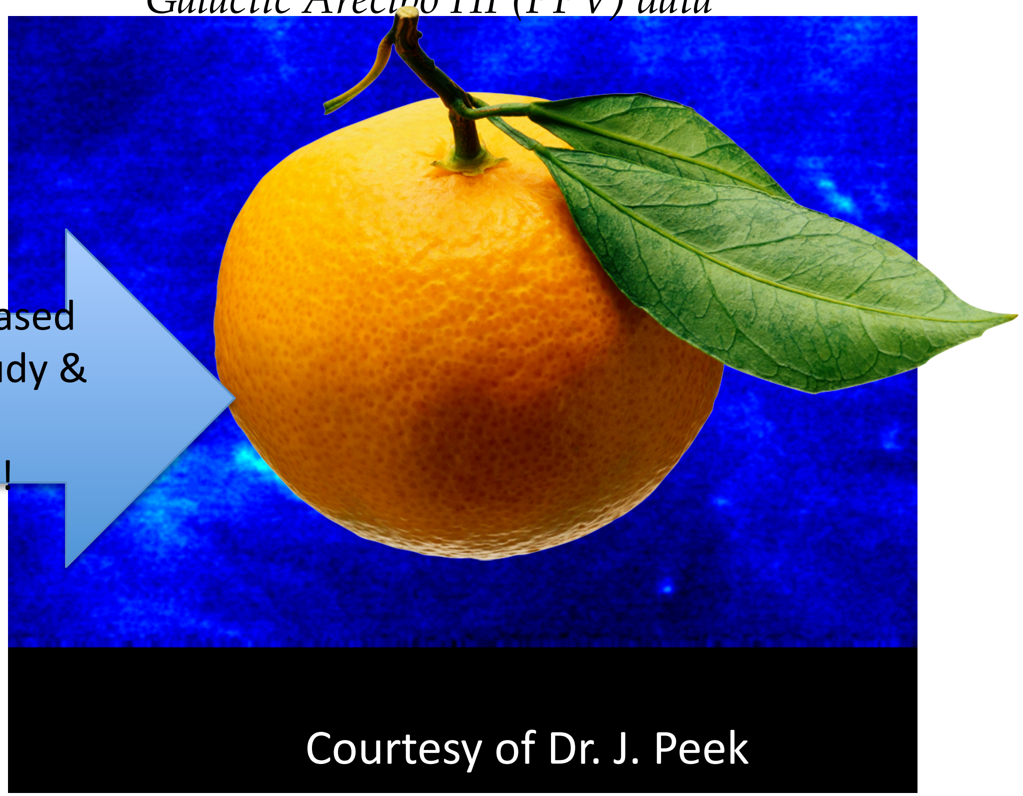


Very Idealized environment
Spatial scales do not match the real world
Currently we can get max Re of order <10^4

Parameter based statistical study & morphology comparisons!

Partial Picture… column density (PP), velocity + density fluctuations (PPV), some magnetic fields…

Galactic Arecibo HI (PPV) data

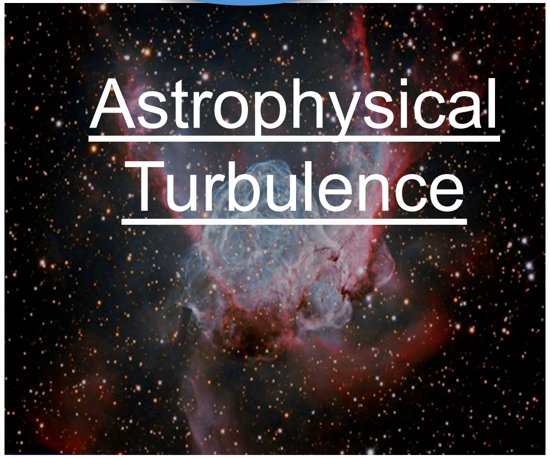


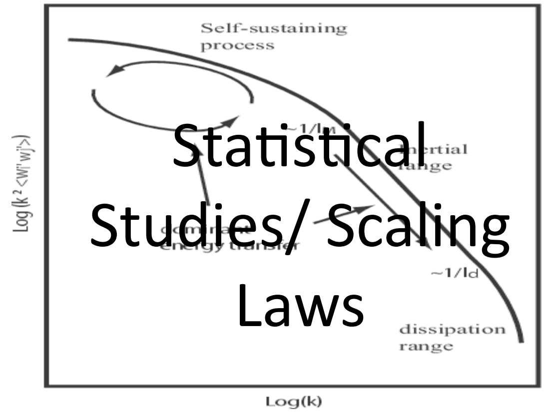
Can only get column density….noise and instrument effects are contaminants

Re ~VL/ν ~10^{10}

How to Study MHD Turbulence Observationally?

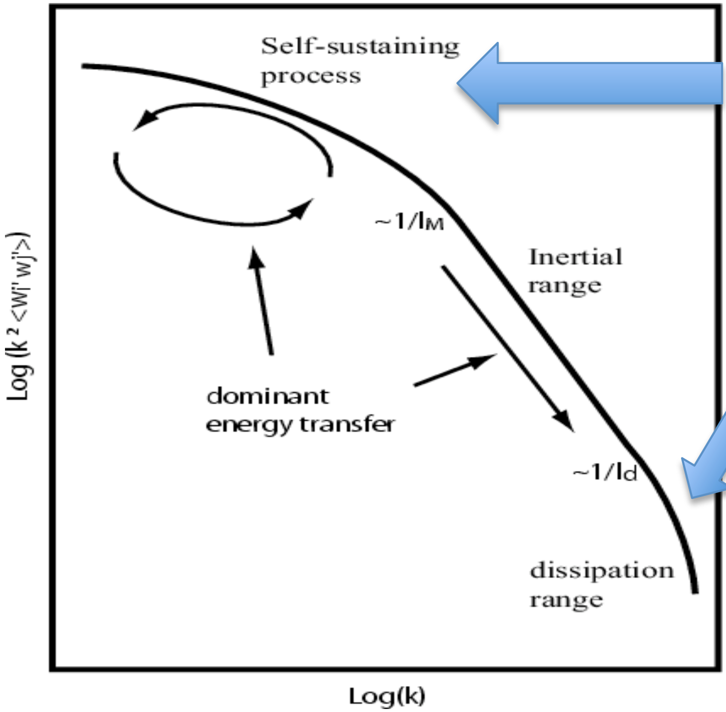
Tool box for studying
MHD turbulence:





Turbulence Theory: What do we need from the observations?

Andrey Beresnyak gave an overview of the turbulence theory….so what can we take away that we need? What are our big questions?



What is the ISM driving scale ?

What is the dissipation scale?

Density/velocity
Power spectrum

And at scales from AU -> Kpc…

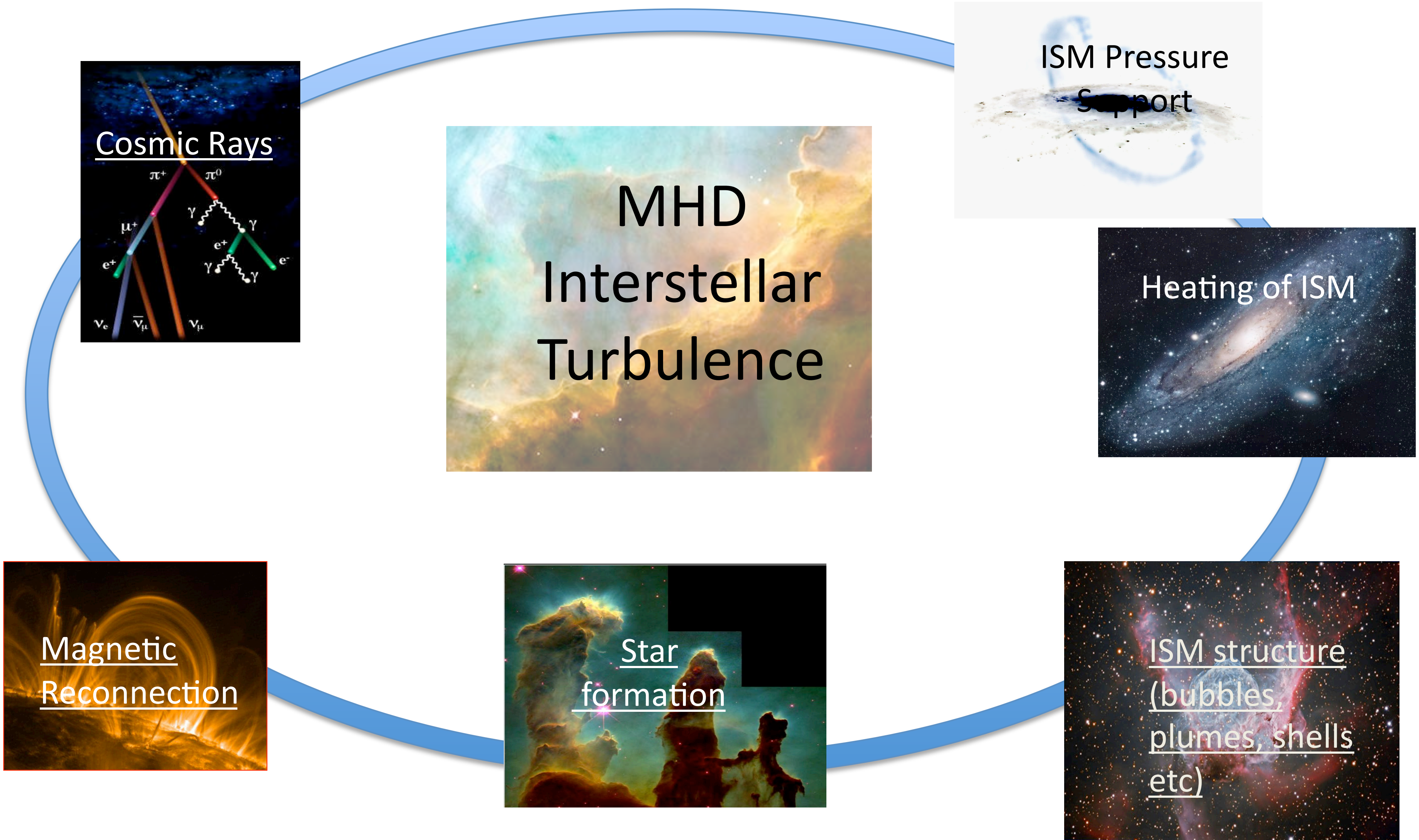
What is the influence of the magnetic field?

What is the role of compressible Motions?

Sonic and Alfvenic Mach Numbers

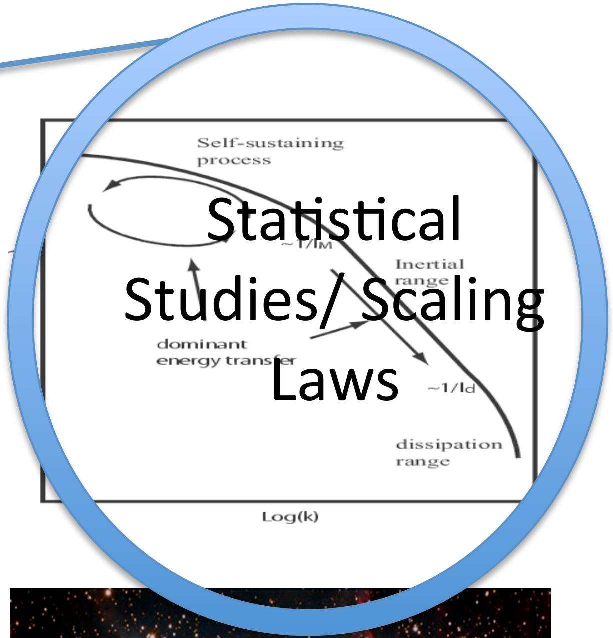
What should we measure?

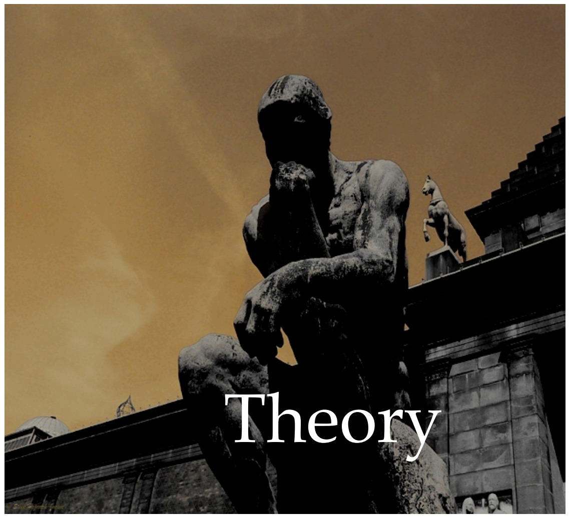
$E(k)$ $M_A = V/V_A$ $M_s = V/c_s$

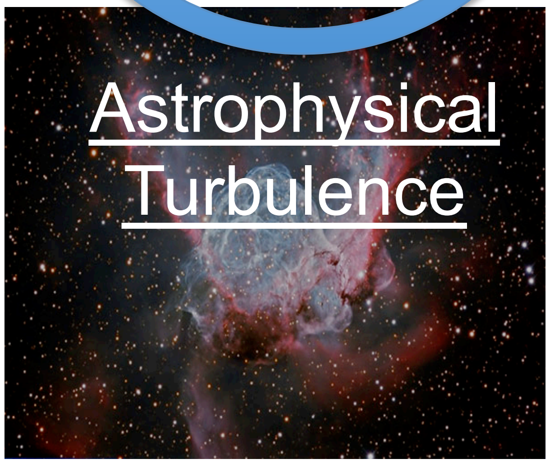


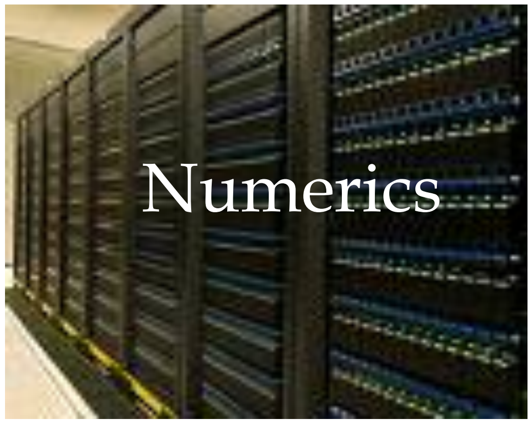
How should we measure them?

Tool box for studying MHD turbulence:

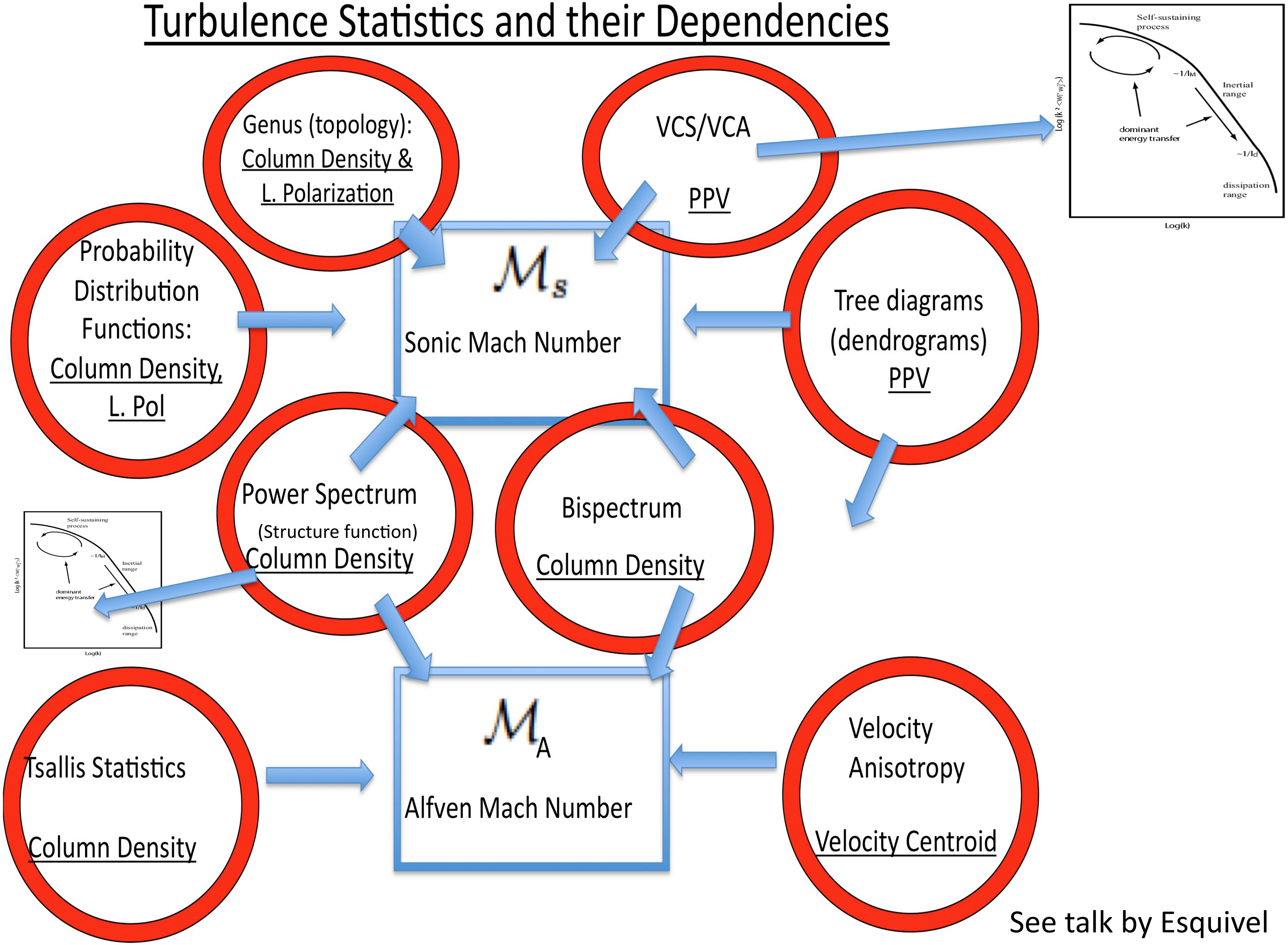








Turbulence Statistics and their Dependencies



1. M_s

PDF Moments of Column Density-M_s

2nd moment: Variance (σ^2 linear and log PDF) vs. M_s
3rd moment: Skewness(linear PDF) vs. M_s
4th moment: Kurtosis(linear PDF) vs. M_s

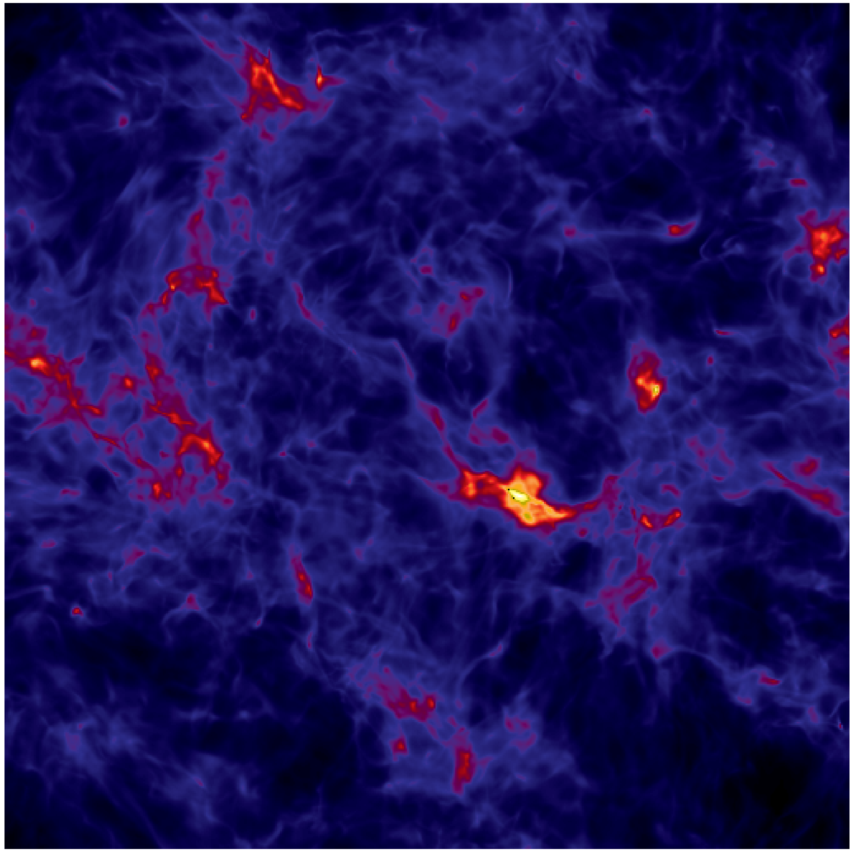
$$\sigma^2_{\rho/\rho_0} = b^2\mathcal{M}_s^2$$

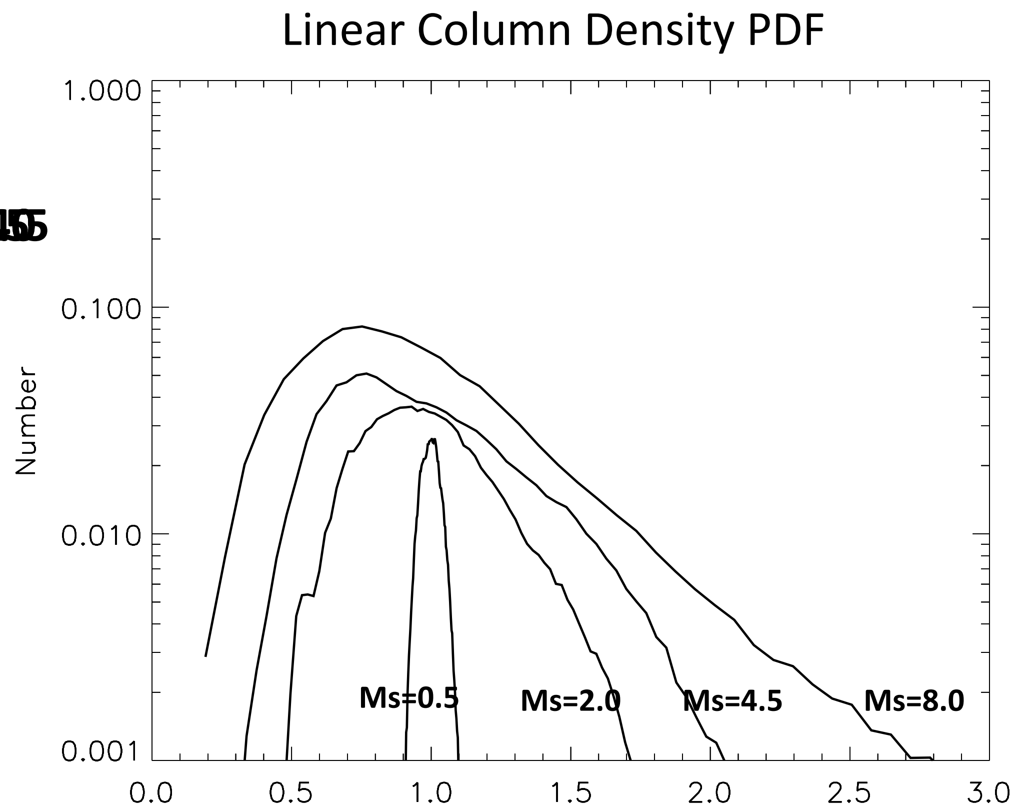
$$\sigma_s^2 = ln(1 + b^2\mathcal{M}_s^2)$$

Skewness=A*M_s+b

Kurtosis=A*M_s+b

Column density PDFs:
Kowal et al. 07; Burkhart et al. 09; Burkhart & Lazarian 12; Kainulainen & Tan 13





2. M_A

Alfvenic Mach Number Via Fourier Phase Analysis

See Talk by A. Esquivel for methods which utilize anisotropy

Fourier phase analysis techniques have also shown sensitive to the magnetic field!

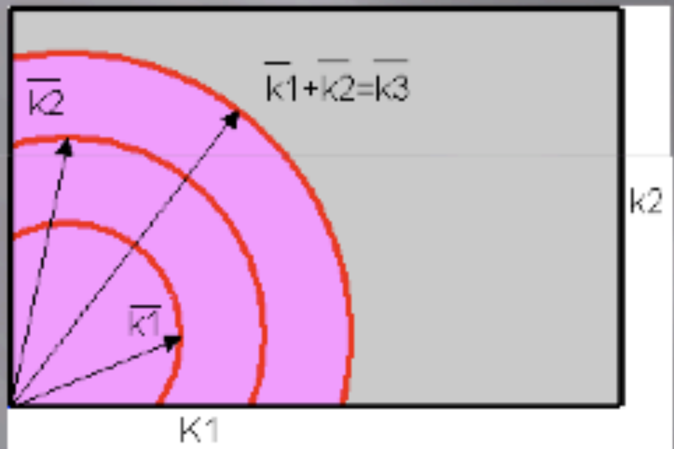
For example the bispectrum….

Bispectrum

$$P(\vec{k}) = \sum_{\vec{k}=const.} \hat{A}(\vec{k}) \cdot \hat{A}^*(\vec{k})$$

$$B(\vec{k_1},\vec{k_2}) = \sum_{\vec{k_1}=const} \sum_{\vec{k_2}=const} \hat{A}(\vec{k_1}) \cdot \hat{A}(\vec{k_2}) \cdot \hat{A}^*(\vec{k_1}+\vec{k_2})$$

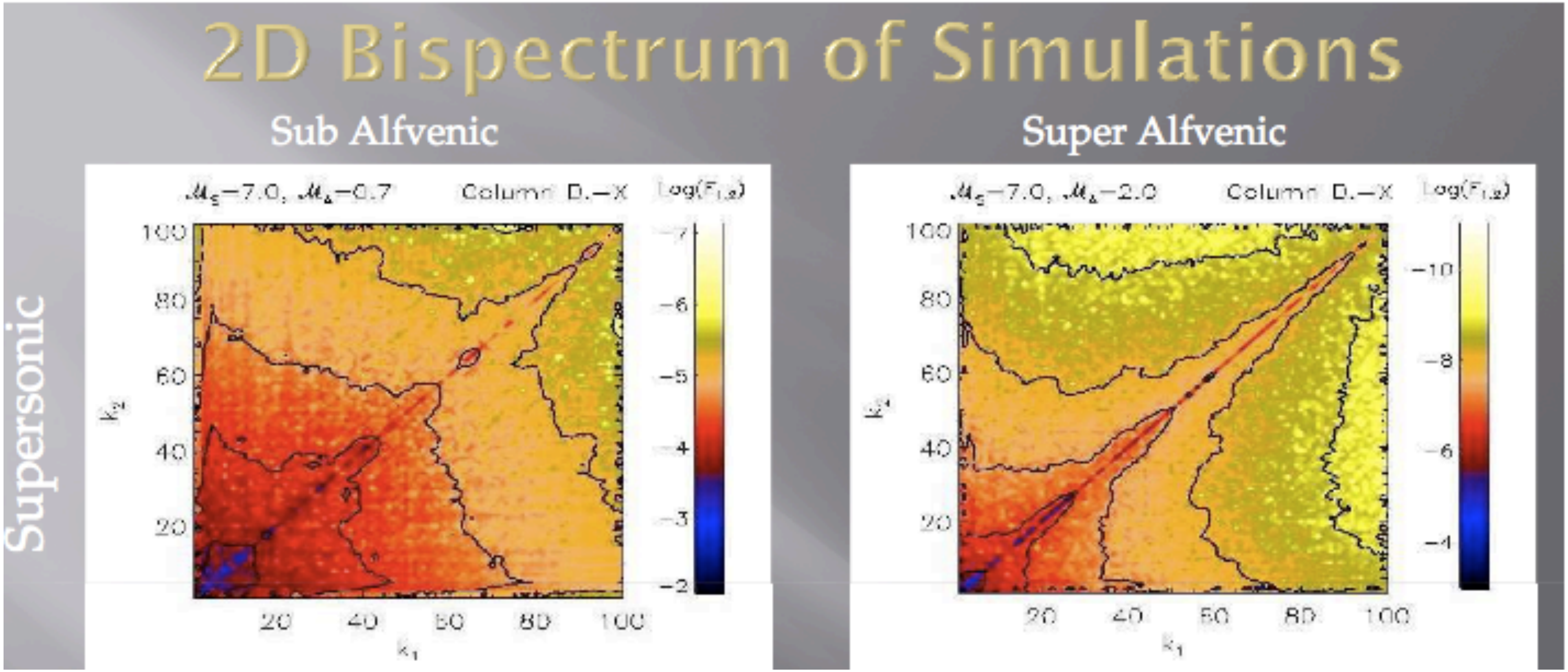
Bispectrum is the three point correlation function in Fourier space. Unlike power spectrum it is complex and 2D and preserves both amplitude and phase information of wave-wave interactions



How our algorithm works

1. Image → FFT(Image)
2. Randomly choose two point wave vectors, K1, K2 and K3=K1+K2
3. Calculate these positions in Fourier Space and compute bispectrum.

Alfvenic Mach Number Via Fourier Phase Analysis:
Bispectrum of isothermal MHD simulations



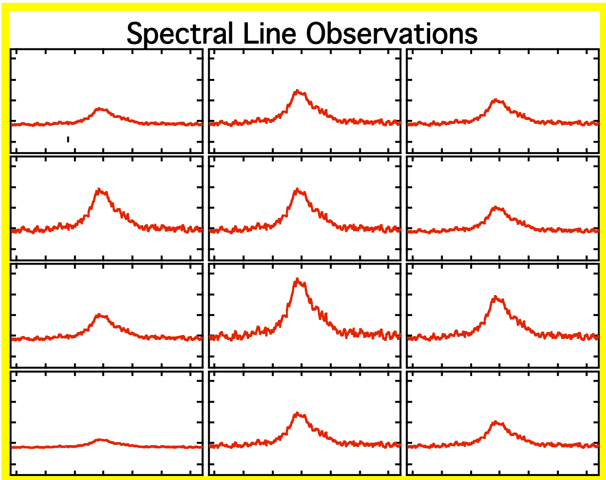
Applied to the SMC in HI in Burkhart et al. 2010

3. Turbulence Spectrum

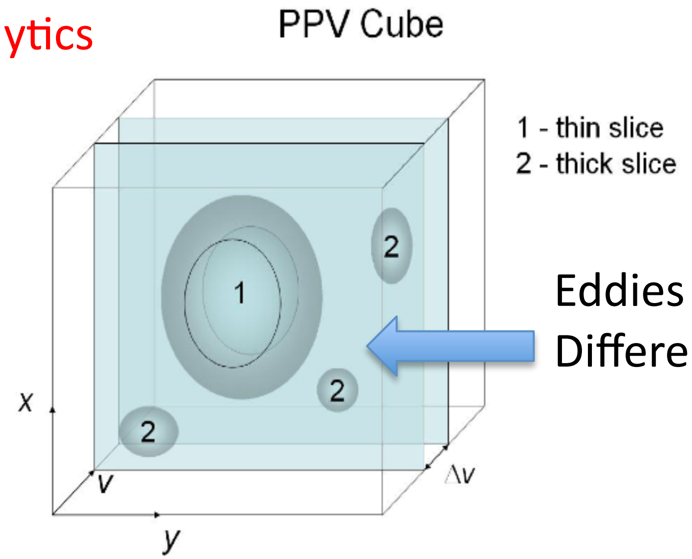
Turbulence Velocity and Density Power Spectrum

Turbulence broadens emission and absorption lines and this can be used to study turbulence with VCA/VCS techniques which provide:

Velocity Coordinate Analysis (VCS): Take power spectrum along velocity axis and relate back to analytics.



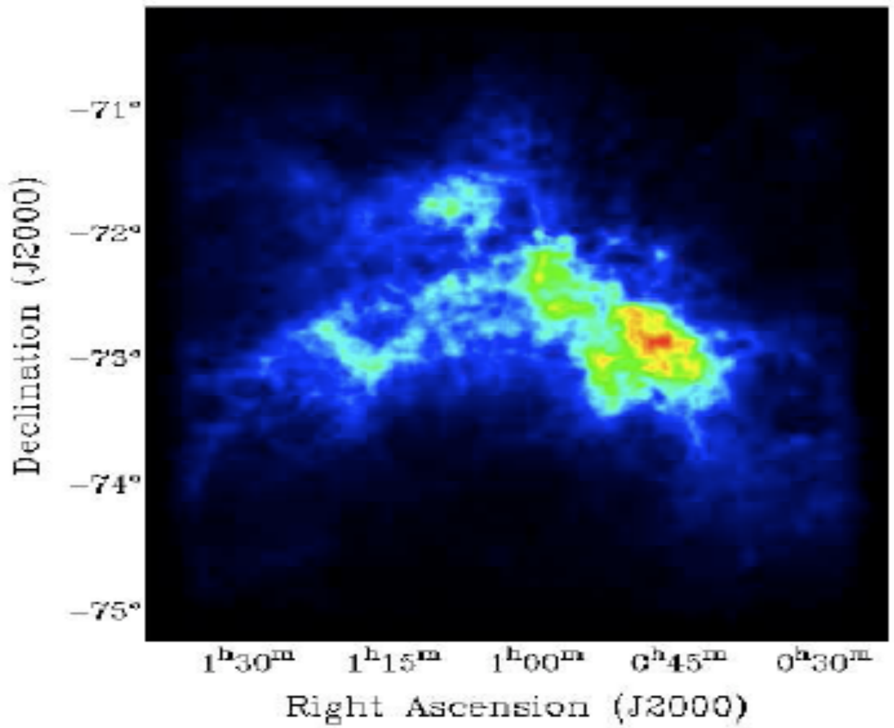
Velocity Channel Analysis (VCA): Vary PPV slice thickness to disentangle density/ velocity power spectrum and relate back to analytics



Eddies of Different size

Developed in Lazarian & Pogosyan 00, 04, 06, 08

VCS reveals observational turbulence velocity spectra in HI data



Kolmogorov slope in 3D:
-11/3=3.66

Density is shallow and velocity
Is steep, agreeance with predictions
For supersonic turbulence

VCS Results: SMC HI: E_v=-3.82, E_p=-3.3, Chepurnov, Burkhart, Lazarian 2013 (in prep.)

GALFA HI : Ev=-3.87 E_p =-2.98: Chepurnov et al. 2010

VCA (Lazarian & Pogosyan 00, 04, 06) reveal observational turbulence velocity spectra in agreement with theoretical and numerical expectations for supersonic turbulence

For Supersonic Turbulence: density spectrum become shallower and velocity spectrum becomes steeper (relative to Kolmogorov)

Compare to -11/3 Compare to -5/3

VCA Results:

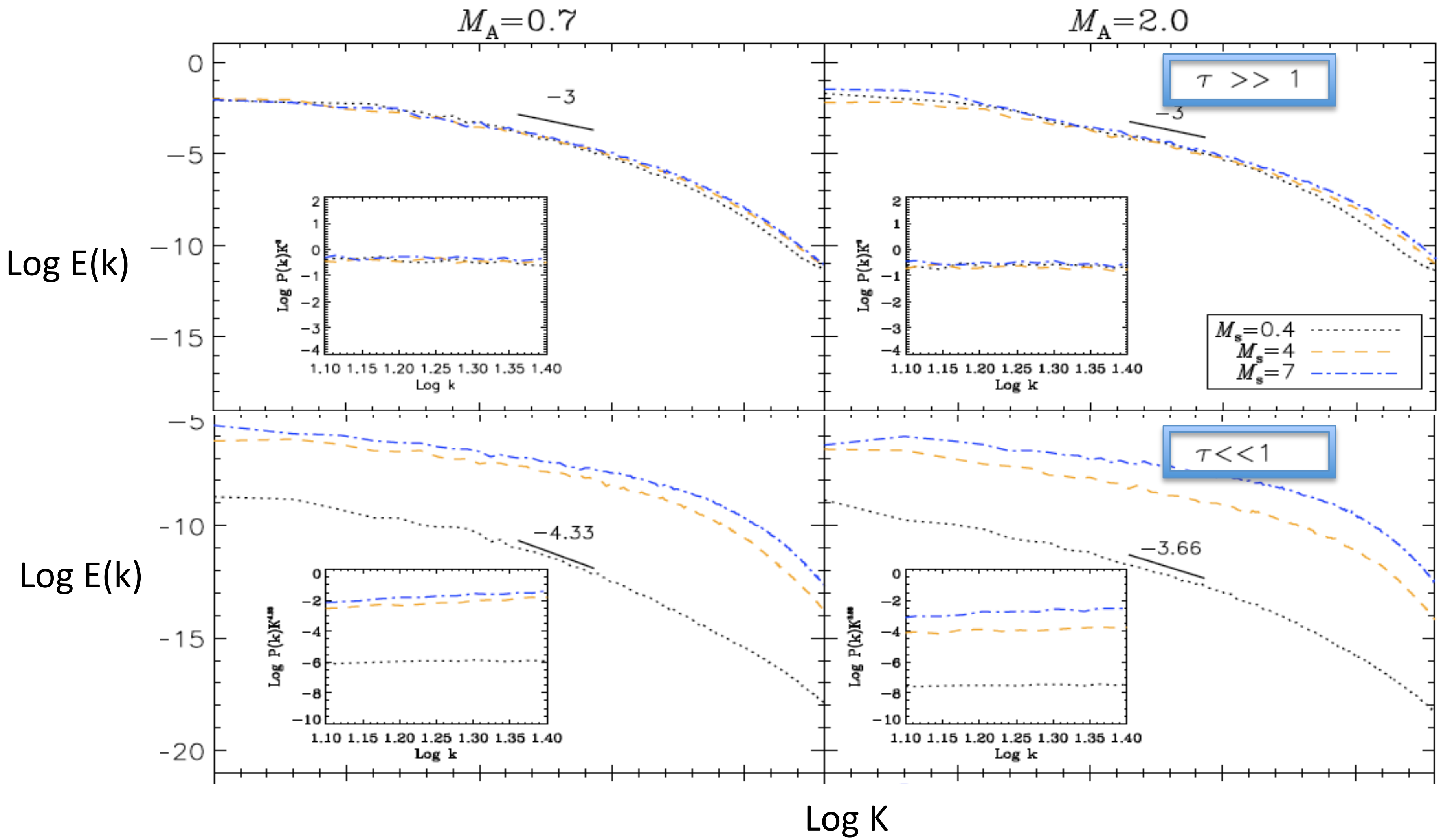
N	data	Object	P_{PPV}^{thin}	P_{PPV}^{thick}	depth	E_v	E_ρ
1	HI	Anticenter[g]	$K^{-2.7}$	N/A	Thin	$k^{-1.7}$	N/A
2	HI	→CygA	$K^{-(2.7)}$	$K^{-(2.8)}$	Thin	N/A	$k^{-(0.8)}$
3	HI	SMC[e]	$K^{-2.7}$	$K^{-3.4}$	Thin	$k^{-1.7}$	$k^{-1.4}$
4	HI	Center[g]	K^{-3}	K^{-3}	Thick	N/A	N/A
5	HI	B. Mag.[g]	$K^{-2.6}$	$K^{3.4}$	Thin	$k^{-1.8}$	$k^{-1.2}$
6	HI	Arm[g]	K^{-3}	K^{-3}	Thick	N/A	N/A
7	HI	DDO 210[e]	K^{-3}	K^{-3}	Thick	N/A	N/A
8	^{12}CO	L1512	N/A	$K^{-2.8}$	Thick	N/A	$k^{-0.8}$
9	^{13}CO	L1512	N/A	$K^{-2.8}$	Thick	N/A	$k^{-0.8}$
10	^{13}CO	Perseus	$K^{-(2.7)}$	K^{-3}	Thick	$k^{-(1.7)}$	N/A
11	^{13}CO	Perseus	$K^{-2.6}$	K^{-3}	Thick	$k^{-1.8}$	N/A
12	C^{18}O	L1551	$K^{-2.7}$	$K^{-2.8}$	Thin	$k^{-1.7}$	$k^{-0.8}$

Why -3 slope for density?

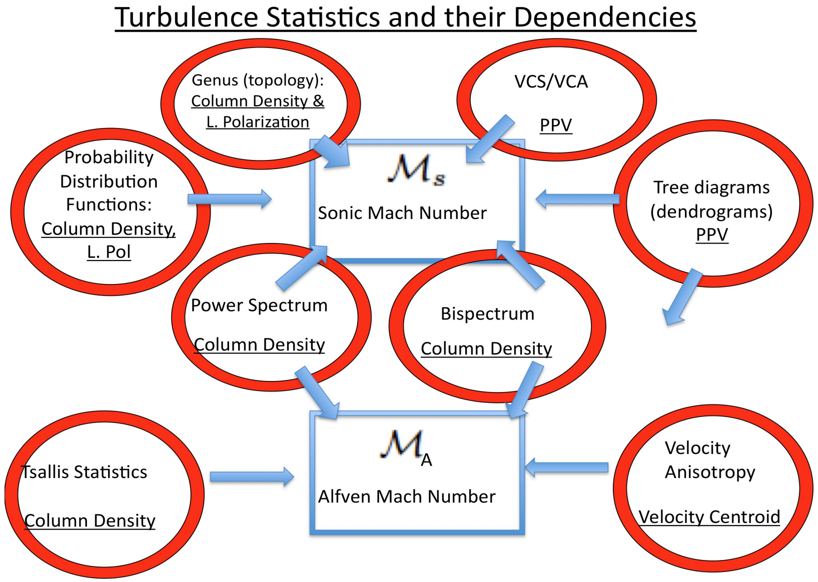
- Lazarian & Pogosyan 2004 predicted a universal slope of -3 for optically thick medium
- Many studies (Padoan 2006; Begum et al. 2006; Dickey et al. 2001 etc.) obtain -3 slope…..
- What is going on?

Why -3 slope for density?

Include radiative transfer effects of 13CO in our MHD Simulations with varying Density/abundance values to change the optical depth… (Burkhart, Ossenkopf, Lazarian, Stutzki 2013, submitted)



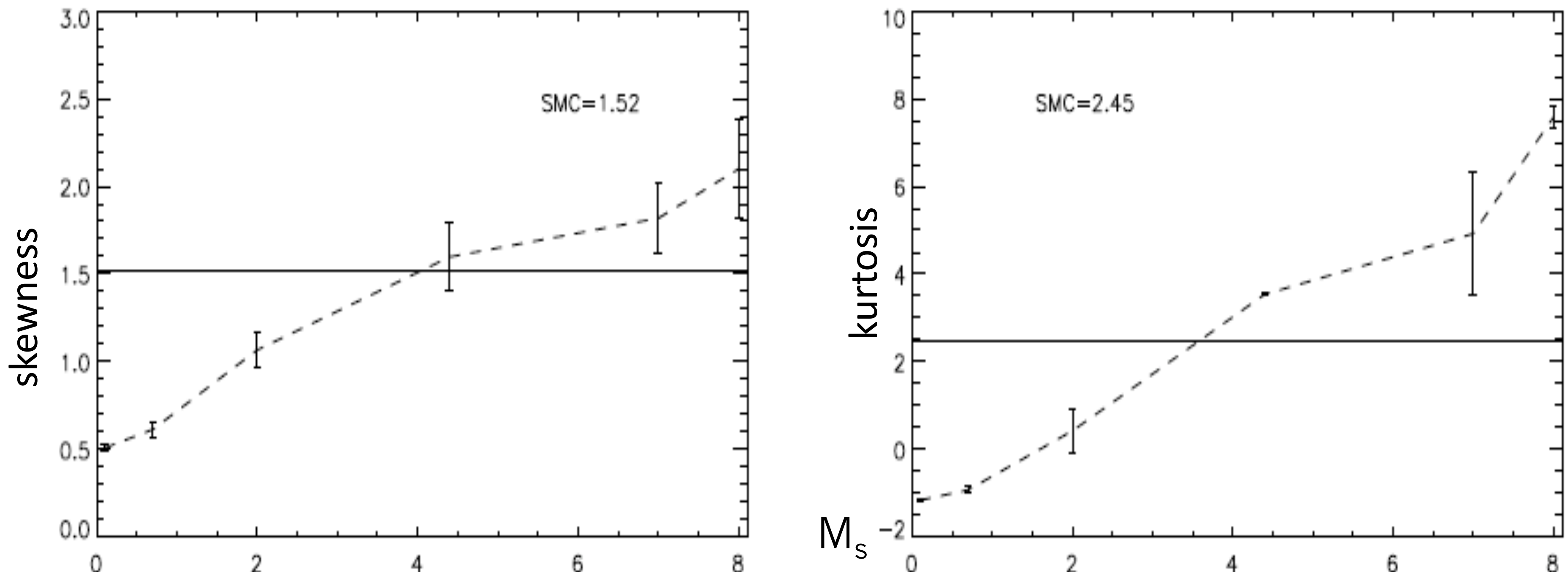
The Last word…Multiple statistics should be used together



Take the example of studies of the SMC in HI using statistics to estimate sonic Mach numbers (Burkhart et al. 2010)

Sonic Mach number estimated from:

1) PDFs (statistical, column density)
2) Spectrum (statistical, column density)
3) Spin/Kintetic temperature ratios (observational, line widths)



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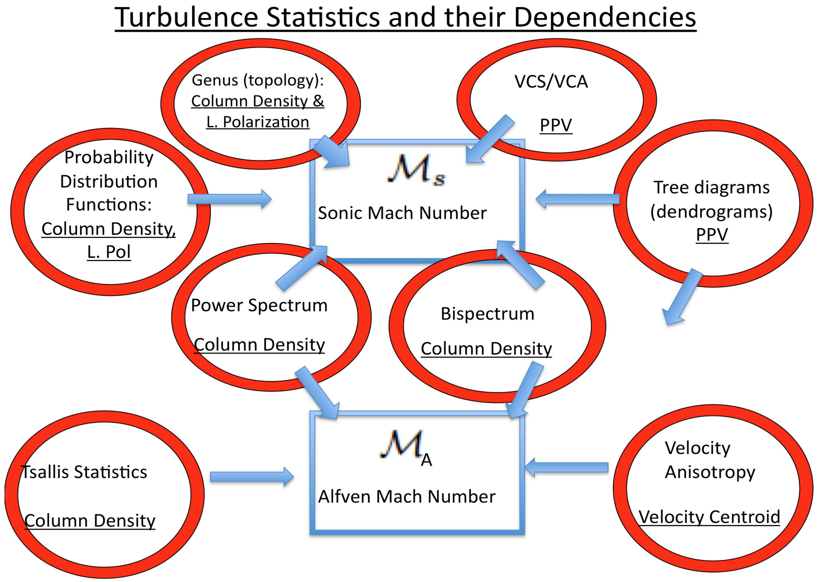

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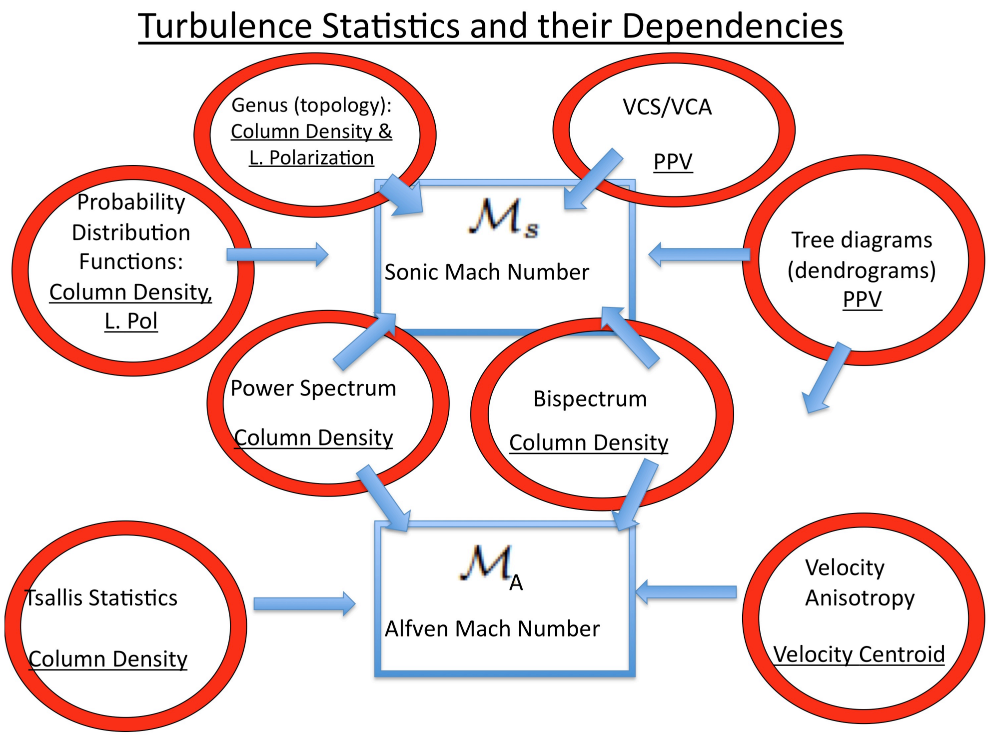
Three independent methods pointing to WNM/CNM sonic Mach numbers of 2-5

Summary



1) Diagnostics should target getting the sonic and Alfven Mach numbers as well as the spectrum (velocity and density)
2) Many techniques exist and are being developed to compare simulations and observations and test theoretical predictions.

PDFs - Burkhart et al., 09, ApJ, 693, 250; Kowal et al. 07, ApJ, 658, 423
Velocity Power Spectrum (VCS)- Lazarian & Pogosyan,08, ApJ, 686, 350
Dendrograms- Goodman et al.,09 Nature, 457, 63; Burkhart et al. , 12, arXiv1206
Genus- Chepurnov et al. 10, ApJ, 688, 1021; Burkhart, Lazarian, Gaensler, 12, ApJ, 739, 145
Anisotropy- Esquivel & Lazarian, 12, ApJ, ; Leao et al. 13 in prep.
Bispectrum- Burkhart et al., 10, ApJ., 708, 1204
Tsalis Statistics- Tofflemire, Burkhart, Lazarian, 12, ApJ, 736, 60