From Parsecs to Megaparsecs: New Diagnostics of Turbulence in the ISM and ICM

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Astrophysical Magnetized Turbulence: A Difficult Problem to Study

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…

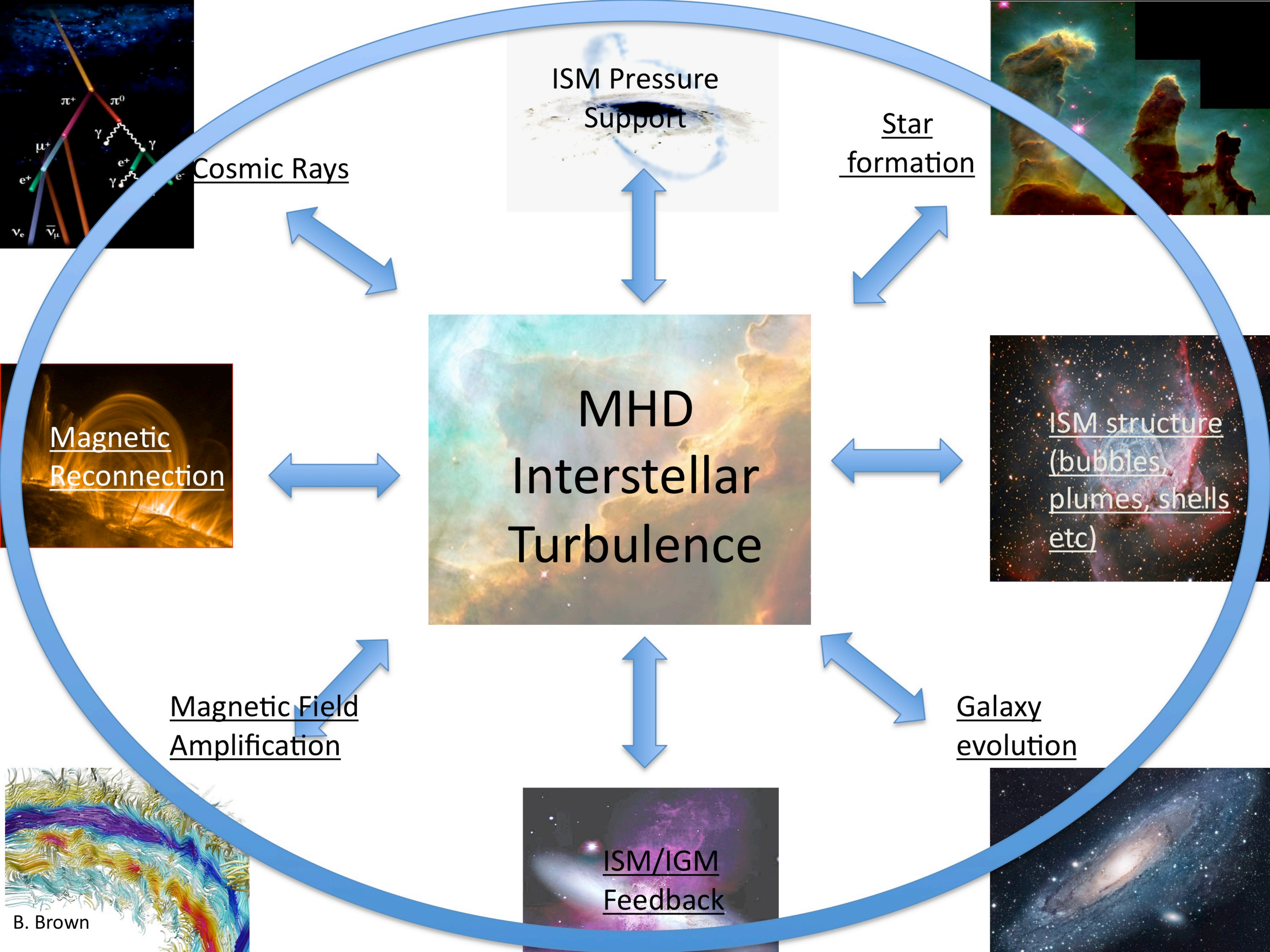
This makes the study of turbulence & magnetic fields unpopular with some astronomers…

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!!"



MHD Interstellar Turbulence

ISM Pressure Support

Star formation

Cosmic Rays

Magnetic Reconnection

ISM structure (bubbles, plumes, shells etc)

Magnetic Field Amplification

ISM/IGM Feedback

Galaxy evolution

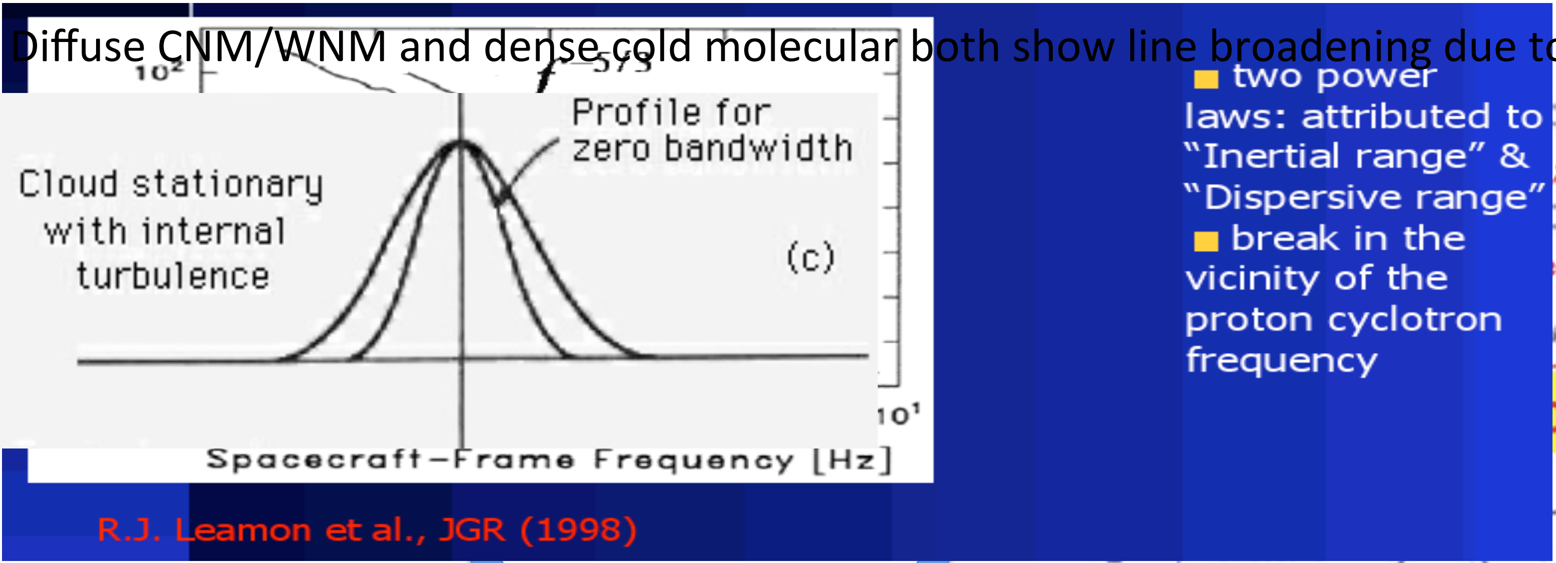
B. Brown

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

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

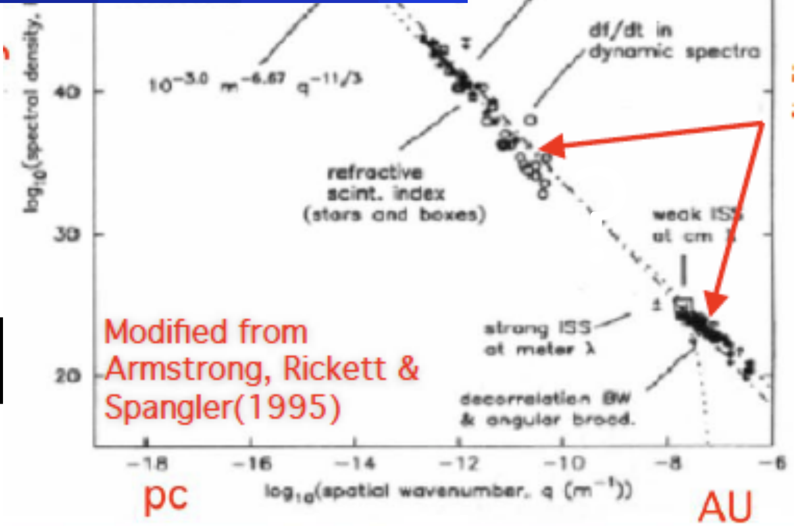
Solar wind spectrum agrees with theoretical predictions

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

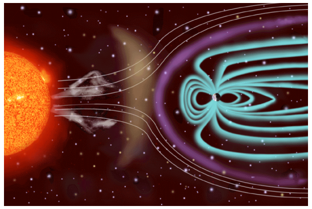


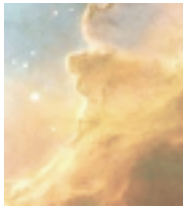
- two power laws: attributed to "Inertial range" & "Dispersive range"
- break in the vicinity of the proton cyclotron frequency

R.J. Leamon et al., JGR (1998)



Modified from Armstrong, Rickett & Spangler(1995)





Sub AU

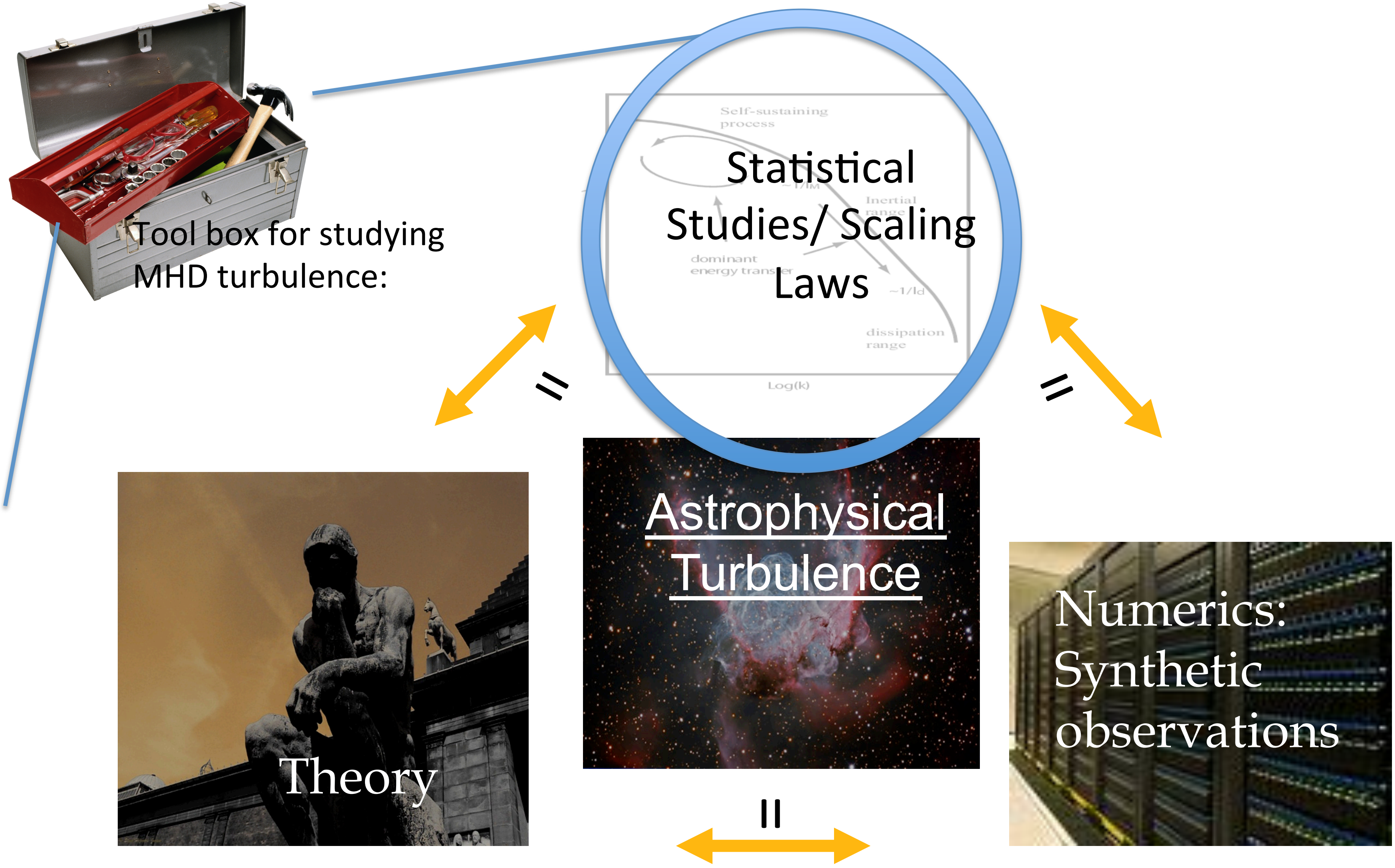
AU

Pc

Outline

- How to measure turbulence in astrophysical environments.
- Measuring velocity power spectrum
- Application to ISM
- Application to galaxy clusters.

How should we measure properties of turbulence?



Tool box for studying MHD turbulence:

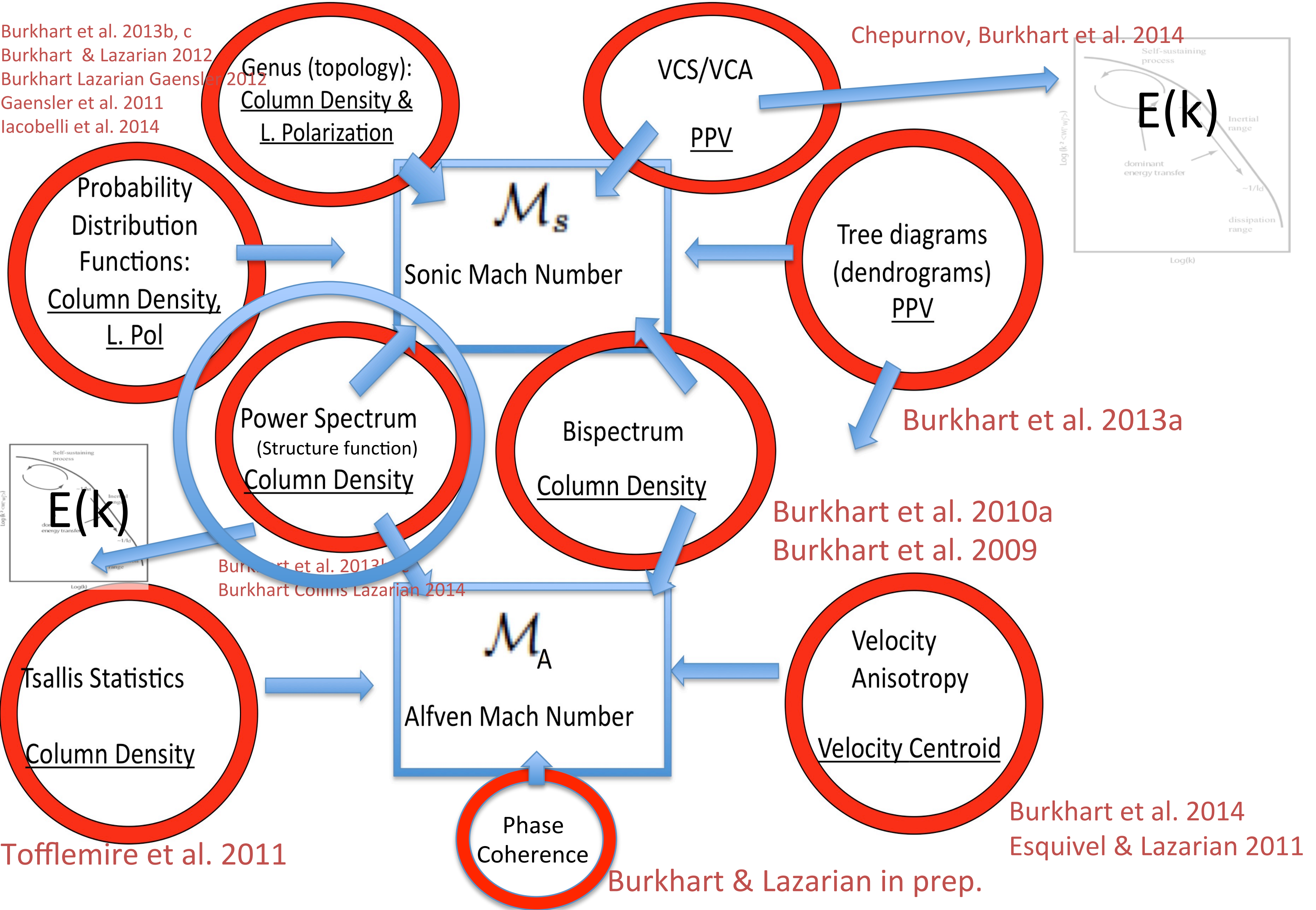
Statistical Studies/ Scaling Laws

Astrophysical Turbulence

Theory

Numerics: Synthetic observations

Turbulence Statistics and their Dependencies



Burkhart et al. 2013b, c
Burkhart & Lazarian 2012
Burkhart Lazarian Gaensler 2012
Gaensler et al. 2011
Iacobelli et al. 2014

Genus (topology):
Column Density &
L. Polarization

VCS/VCA
PPV

Chepurnov, Burkhart et al. 2014

Probability
Distribution
Functions:
Column Density,
L. Pol

$\mathcal{M}_s$
Sonic Mach Number

Tree diagrams
(dendrograms)
PPV

Burkhart et al. 2013a

Power Spectrum
(Structure function)
Column Density

Bispectrum
Column Density

Burkhart et al. 2010a
Burkhart et al. 2009

Burkhart et al. 2013b, c
Burkhart Collins Lazarian 2014

Tsallis Statistics
Column Density

$\mathcal{M}_A$
Alfven Mach Number

Velocity
Anisotropy
Velocity Centroid

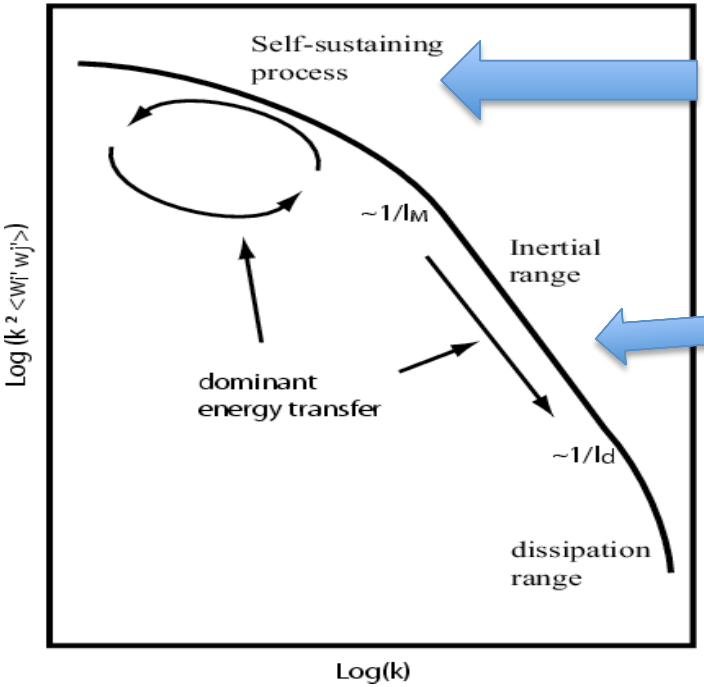
Burkhart et al. 2014
Esquivel & Lazarian 2011

Tofflemire et al. 2011

Phase
Coherence

Burkhart & Lazarian in prep.

1). Turbulence Density/Velocity Fourier Power Spectrum



What is the ISM driving scale ?

Inertial range provides: compressibility of the media, dynamic range of the cascade, and comparison with analytical predictions.

What is the ISM dissipation scale?

Kolmogorov scaling:

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

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

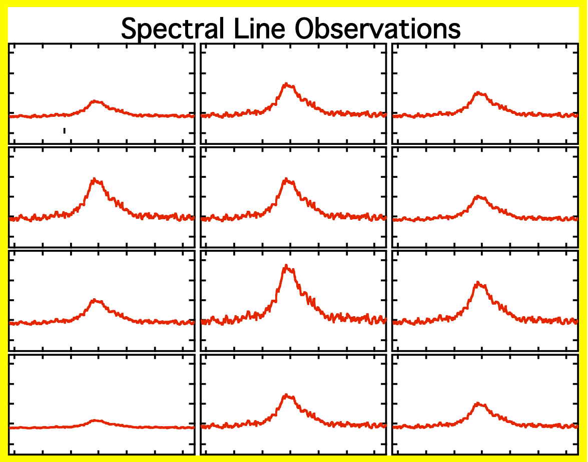
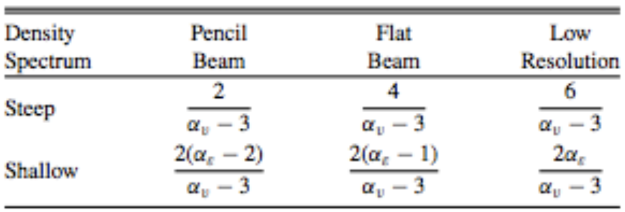


Table 2
VCS Predictions about P_1 Spectral Index, Parallel Lines of Sight



Density Spectrum	Pencil Beam	Flat Beam	Low Resolution
Steep	$\frac{2}{\alpha_v - 3}$	$\frac{4}{\alpha_v - 3}$	$\frac{6}{\alpha_v - 3}$
Shallow	$\frac{2(\alpha_\epsilon - 2)}{\alpha_v - 3}$	$\frac{2(\alpha_\epsilon - 1)}{\alpha_v - 3}$	$\frac{2\alpha_\epsilon}{\alpha_v - 3}$

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

PPV Cube

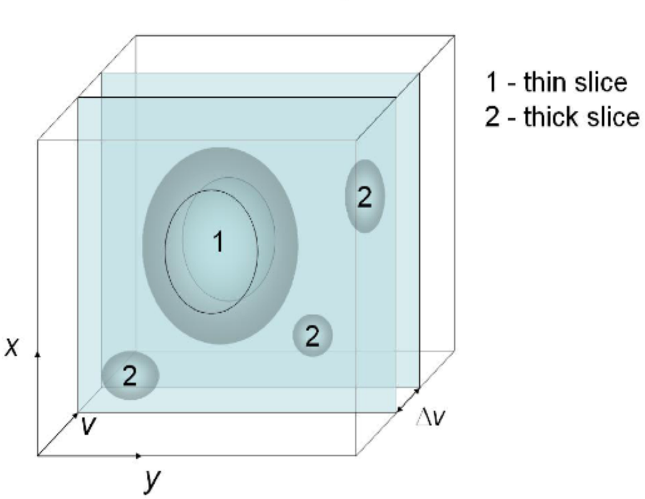
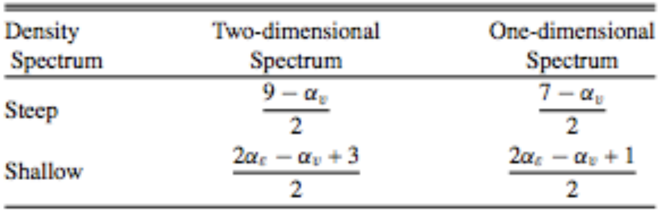


Table 1
VCA Predictions about P_2 Spectral Index, Steep Density



Density Spectrum	Two-dimensional Spectrum	One-dimensional Spectrum
Steep	$\frac{9 - \alpha_v}{2}$	$\frac{7 - \alpha_v}{2}$
Shallow	$\frac{2\alpha_\epsilon - \alpha_v + 3}{2}$	$\frac{2\alpha_\epsilon - \alpha_v + 1}{2}$

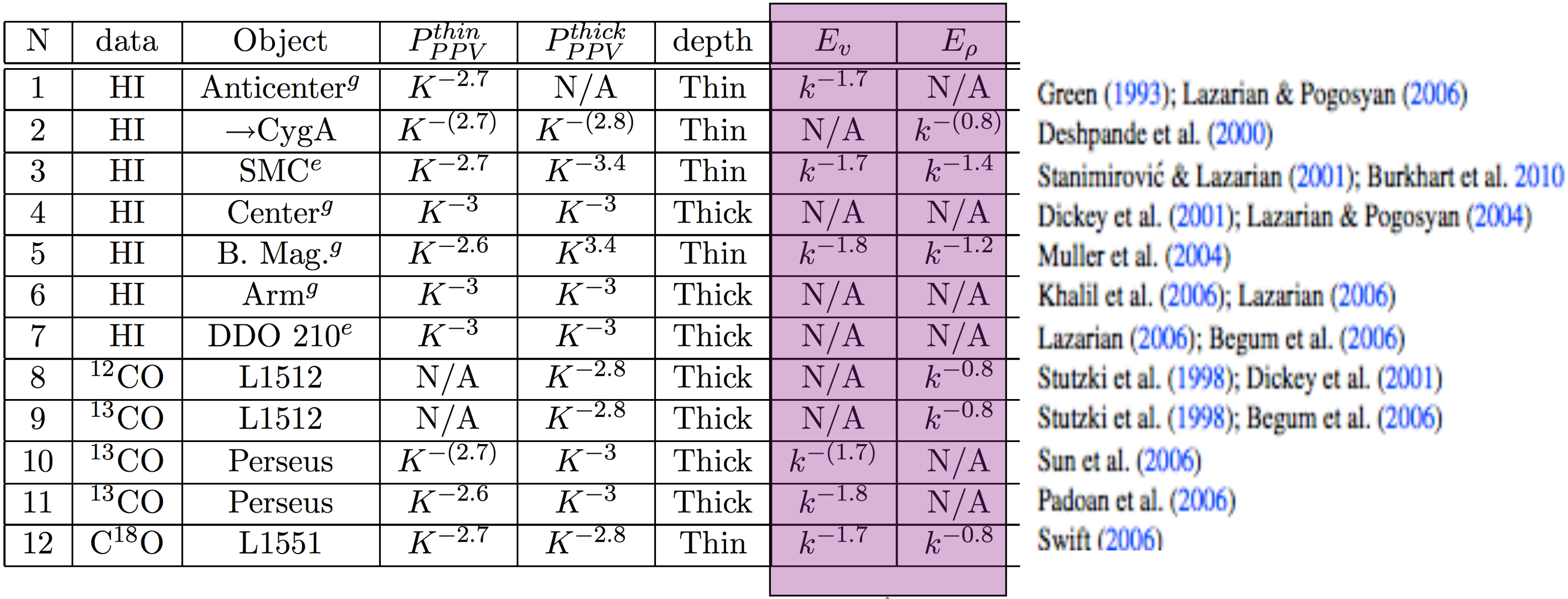
ze

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

Velocity/density power spectrum reveal multiphase ISM spectra in agreement with expectations for supersonic turbulence

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

Compare to -5/3=-1.66



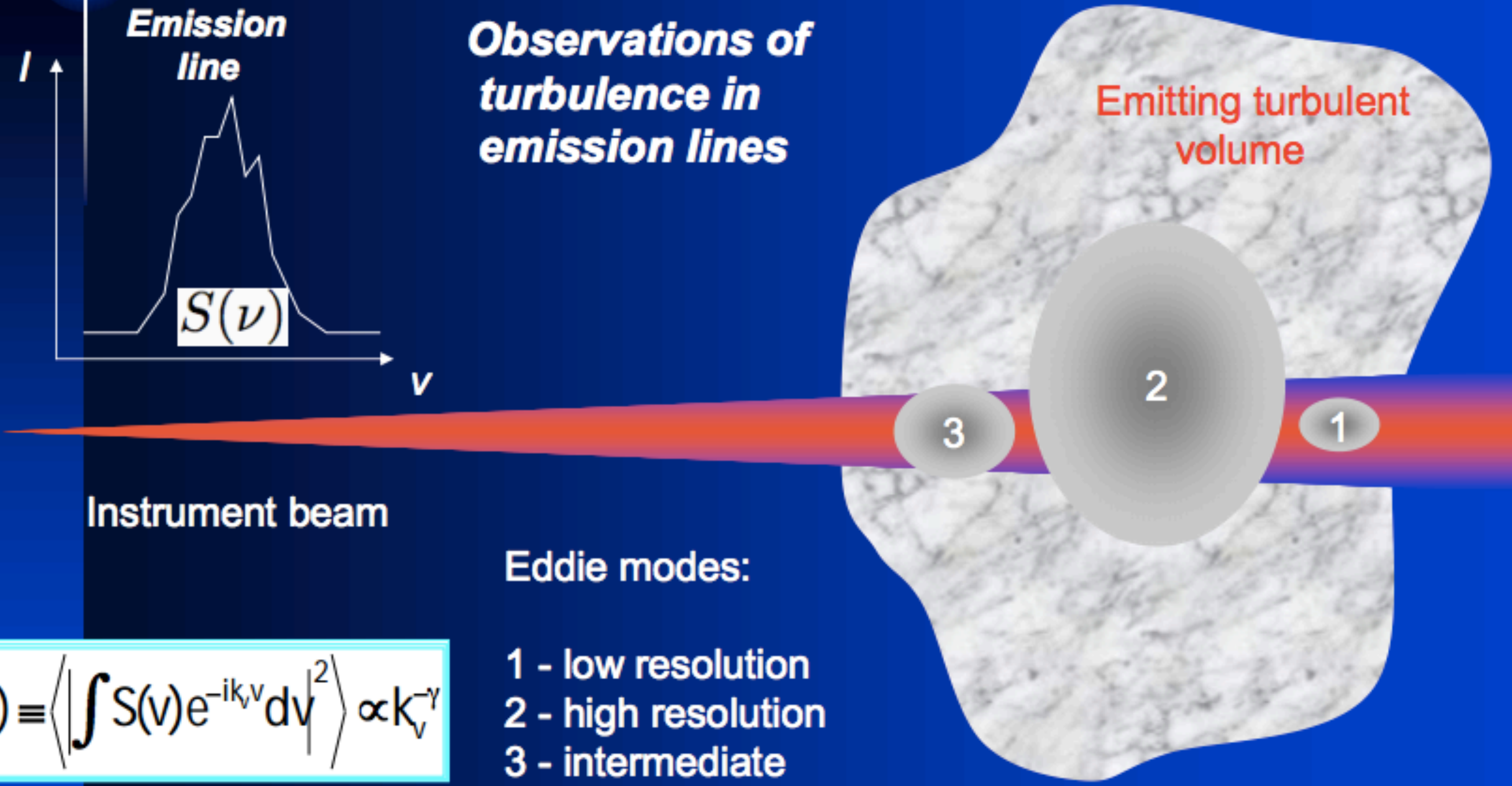
N	data	Object	P_{PPV}^{thin}	P_{PPV}^{thick}	depth	E_v	E_ρ	
1	HI	Anticenter[g]	$K^{-2.7}$	N/A	Thin	$k^{-1.7}$	N/A	Green (1993); Lazarian & Pogosyan (2006)
2	HI	→CygA	$K^{-(2.7)}$	$K^{-(2.8)}$	Thin	N/A	$k^{-(0.8)}$	Deshpande et al. (2000)
3	HI	SMC[e]	$K^{-2.7}$	$K^{-3.4}$	Thin	$k^{-1.7}$	$k^{-1.4}$	Stanimirović & Lazarian (2001); Burkhart et al. 2010
4	HI	Center[g]	K^{-3}	K^{-3}	Thick	N/A	N/A	Dickey et al. (2001); Lazarian & Pogosyan (2004)
5	HI	B. Mag.[g]	$K^{-2.6}$	$K^{3.4}$	Thin	$k^{-1.8}$	$k^{-1.2}$	Muller et al. (2004)
6	HI	Arm[g]	K^{-3}	K^{-3}	Thick	N/A	N/A	Khalil et al. (2006); Lazarian (2006)
7	HI	DDO 210[e]	K^{-3}	K^{-3}	Thick	N/A	N/A	Lazarian (2006); Begum et al. (2006)
8	^{12}CO	L1512	N/A	$K^{-2.8}$	Thick	N/A	$k^{-0.8}$	Stutzki et al. (1998); Dickey et al. (2001)
9	^{13}CO	L1512	N/A	$K^{-2.8}$	Thick	N/A	$k^{-0.8}$	Stutzki et al. (1998); Begum et al. (2006)
10	^{13}CO	Perseus	$K^{-(2.7)}$	K^{-3}	Thick	$k^{-(1.7)}$	N/A	Sun et al. (2006)
11	^{13}CO	Perseus	$K^{-2.6}$	K^{-3}	Thick	$k^{-1.8}$	N/A	Padoan et al. (2006)
12	C^{18}O	L1551	$K^{-2.7}$	$K^{-2.8}$	Thin	$k^{-1.7}$	$k^{-0.8}$	Swift (2006)

Burkhart et al. 2010

Density and velocity power spectrum from Lazarian & Pogosyan (2000, 2004) Velocity Coordinate Analysis (VCA) method.

VCS with Emission Lines

Observations of turbulence in emission lines



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

Eddie modes:

1 - low resolution
2 - high resolution
3 - intermediate

Scaling of VCS changes with the resolution.

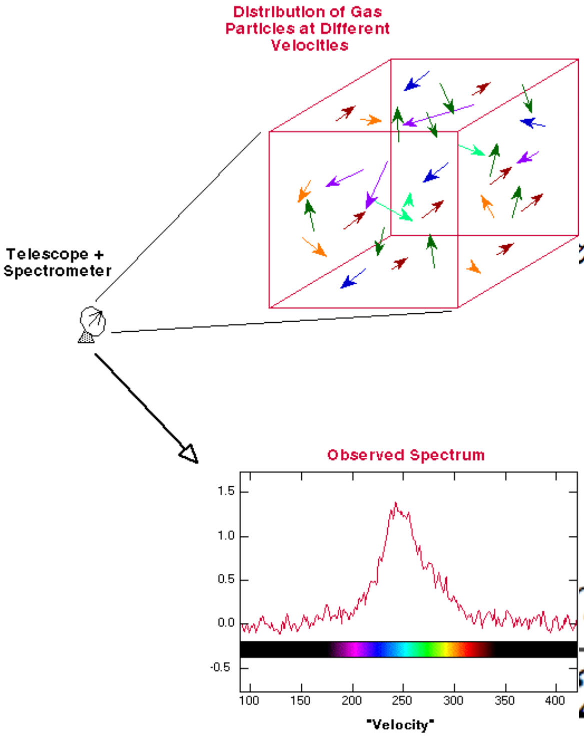
Velocity Coordinate Spectrum: Mathematical Setting

$$\rho_s(\mathbf{X}, v)\mathrm{d}\mathbf{X}dv = \left[\int_0^S \mathrm{d}z\ \rho(\mathbf{x})\phi_v(\mathbf{x})\right]\mathrm{d}\mathbf{X}dv$$

Intensity in PPV (xyv)

$$\phi_v(\mathbf{x})\mathrm{d}v = \frac{1}{(2\pi\beta)^{1/2}}\exp\left[-\frac{(v - v_{gal}(\mathbf{x}) - u(\mathbf{x}))^2}{2\beta}\right]\mathrm{d}v$$

Velocity distribution



$$, v_1)\rho_s(\mathbf{X}_2, v_2)\rangle$$

Correlation function in PPV

$$\int_{|z|/2}^{S-|z|/2} \mathrm{d}z_+\ \xi(\mathbf{r})\ [D_z(\mathbf{r})+2\beta]^{-1/2}\exp\left[-\frac{(v - v_{gal})^2}{2(D_z(\mathbf{r}) + 2\beta)}\right]$$

$$\rangle = C_1 r^n$$

Real (xyz) density correlation

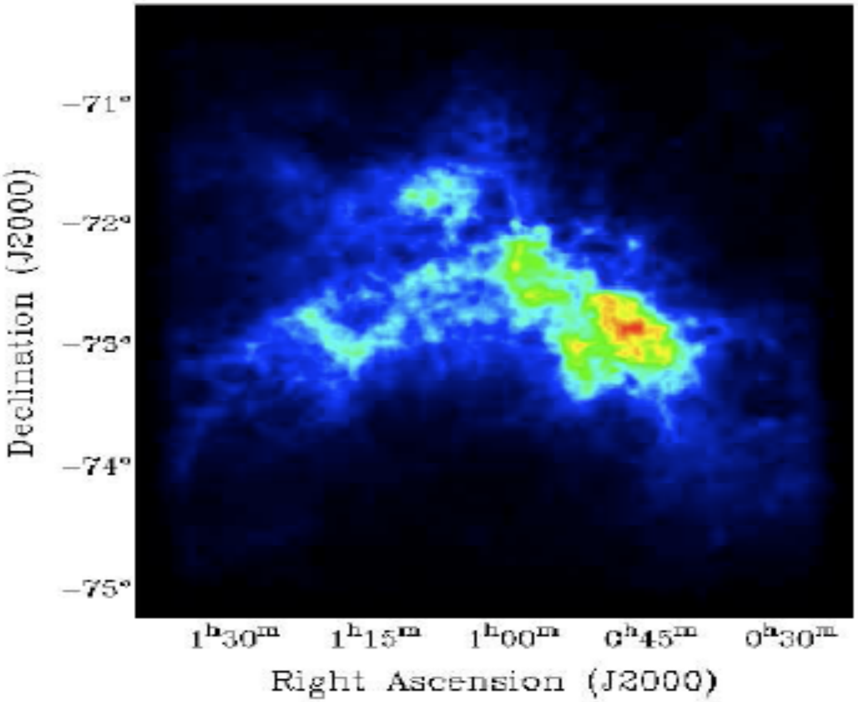
$$\frac{n}{2}(1 - \cos^2\theta)]$$

Velocity correlation

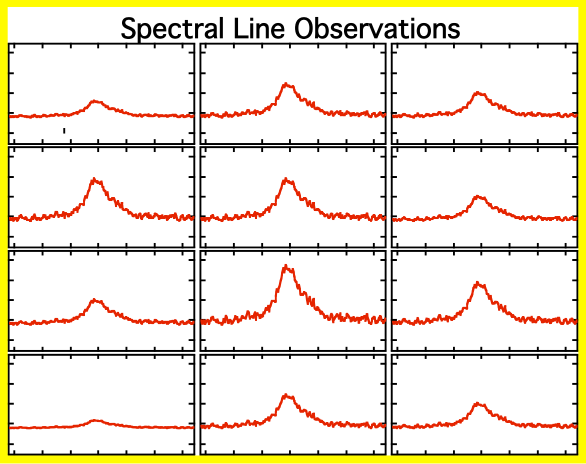
SMC in 21 cm emission

Radio data is ideal for studies of turbulence because it contains information about turbulence velocity along the LOS

Stanimirovic et al. 1999 data set has good spatial (98”) and spectral resolution (1.65kms^{-1}) and contains both single dish (Parkes Telescope) and interferometer (ATCA telescope) data (30pc-4kpc).



Turbulence Velocity and Density Power Spectrum: VCS

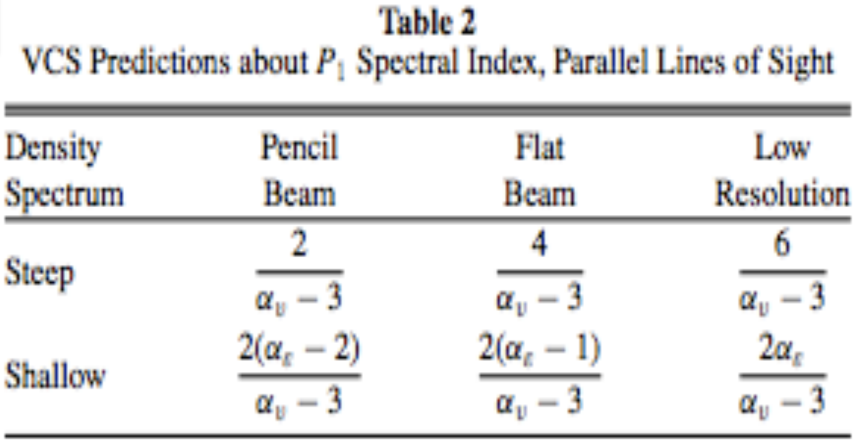


Spectral Line Observations

Velocity Coordinate Spectrum (VCS):

1) Take power spectrum of 2D column density for density spectrum (steep vs. shallow spectrum)

2) Take power spectrum along velocity axis for varying beam sizes



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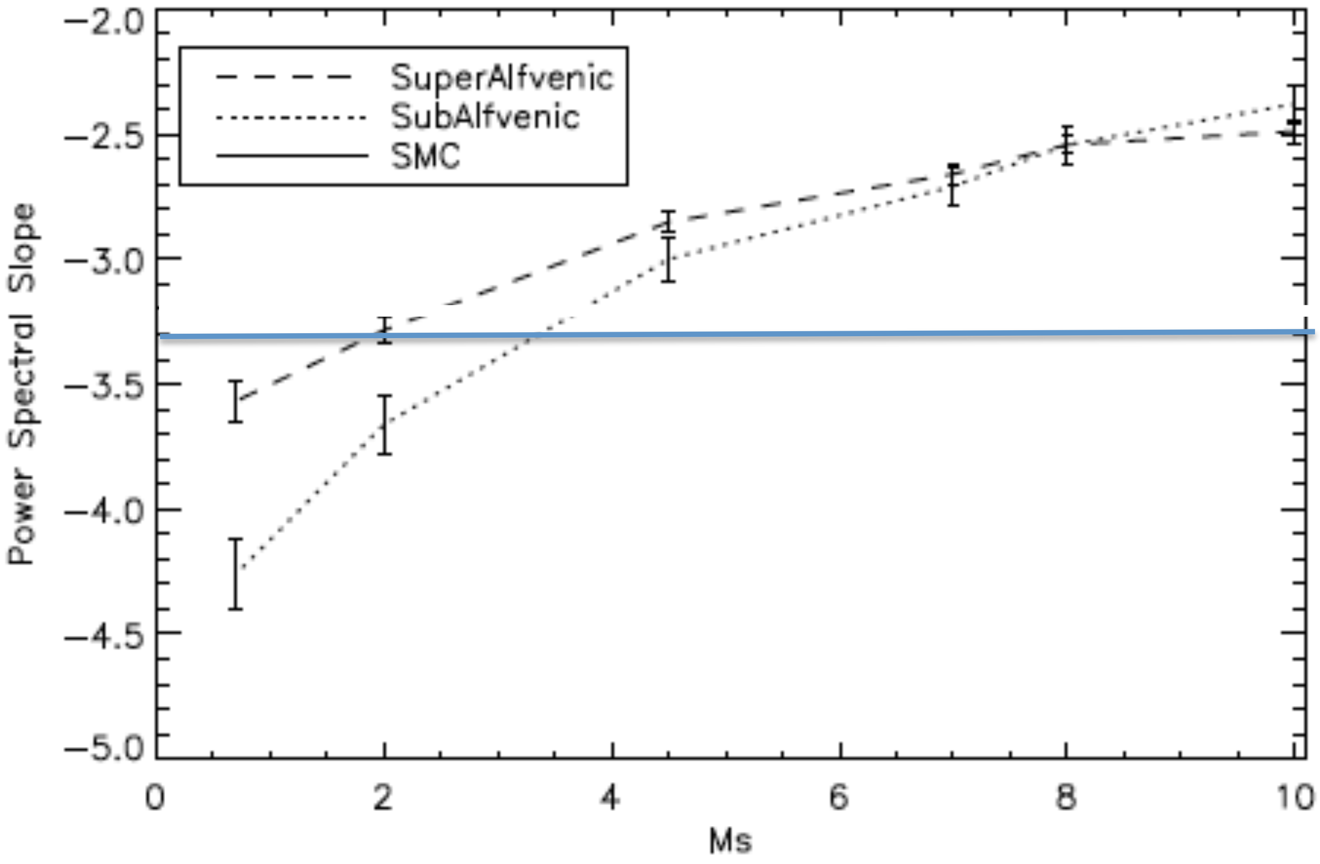
3) Fit measured power spectrum with expected behavior to recover velocity slope, driving scale, and turbulence amplitude.

$$F_{ij}(\mathbf{k}) = \frac{V_0^2}{k^{\alpha_v}} e^{-\frac{k_0^2}{k^2}}$$

Developed in Lazarian & Pogosyan 2008

Density Spectrum Compared with 3D MHD Simulations

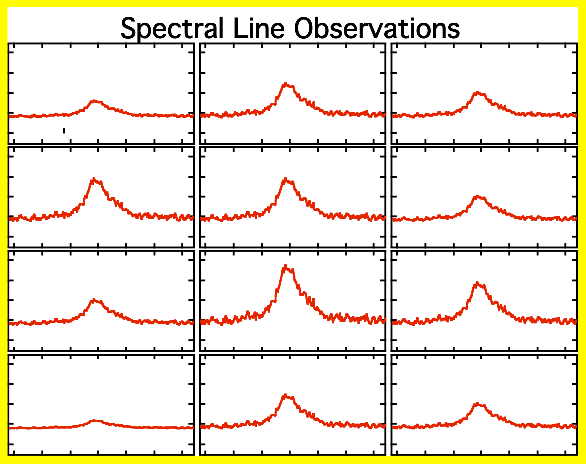
Density spectral index=-3.3 for SMC (Lazarian & Stanimirovic 2001)



Burkhart et al. 2010

Kolmogorov ~ k $^{-11/3}$

Turbulence Velocity and Density Power Spectrum: VCS



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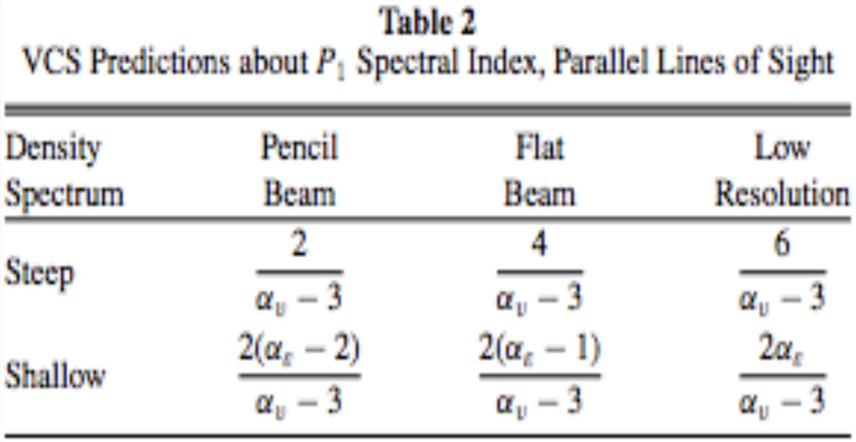

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2) Take power spectrum along velocity axis for varying beam sizes

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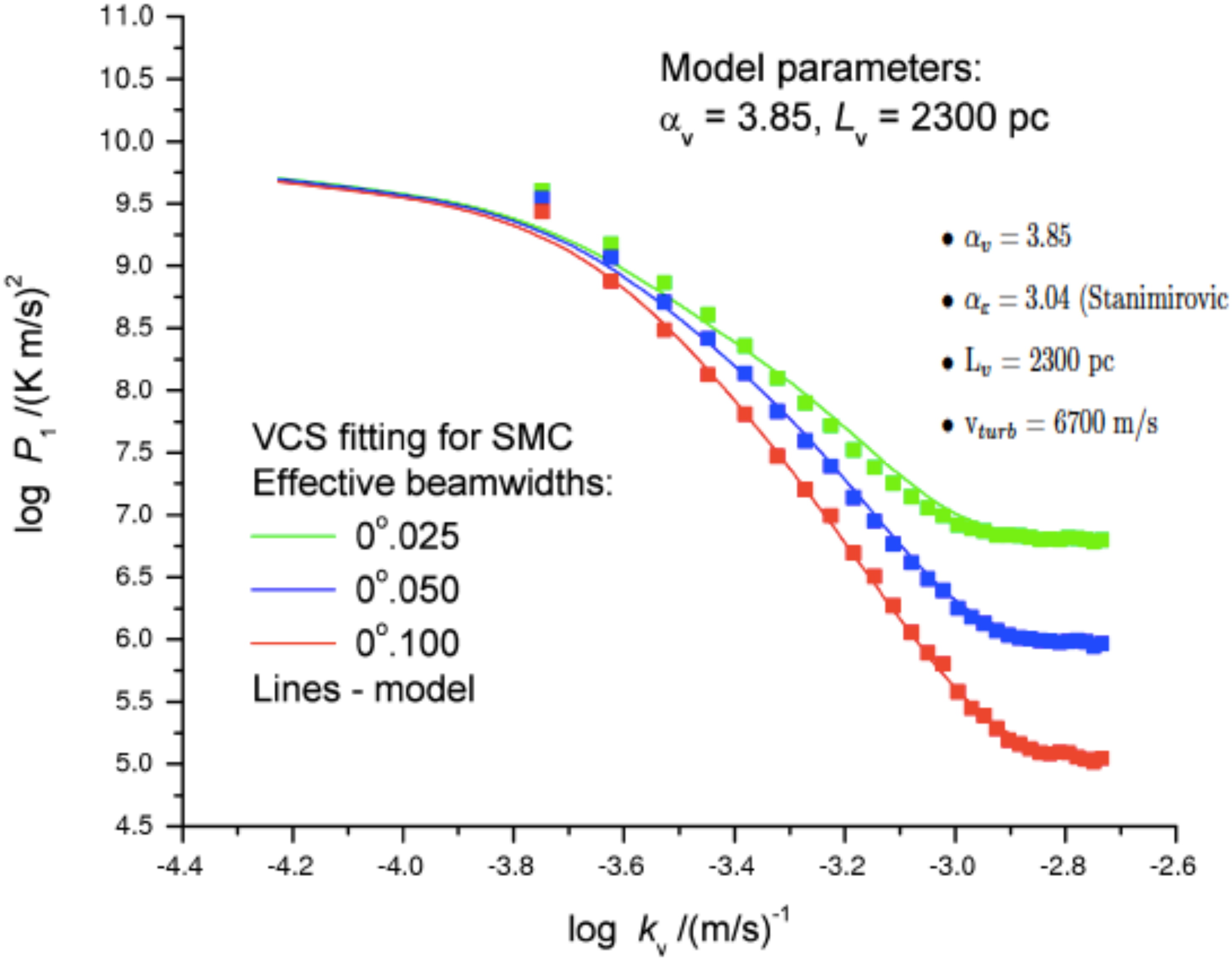
$$F_{ij}(\mathbf{k}) = \frac{V_0^2}{k^{\alpha}} e^{-\frac{k_0^2}{k^2}}$$

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

VCS of SMC (21cm)

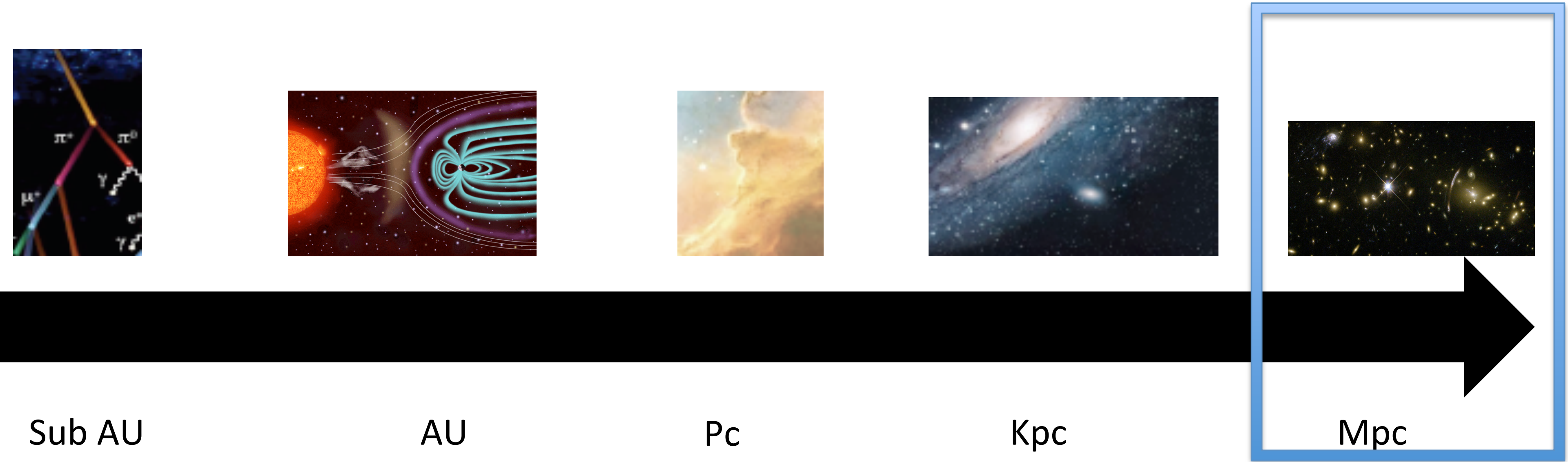
Chepurnov, Burkhart, Lazarian & Stanimirovic 2014, in prep.



$$F_{ij}(\mathbf{k}) = \frac{V_0^2}{k^{\alpha_v}} e^{-\frac{k_0^2}{k^2}}$$

- $\alpha_v = 3.85$
- $\alpha_\varepsilon = 3.04$ (Stanimirovic & Lazarian 2001)
- $L_v = 2300$ pc
- $v_{turb} = 6700$ m/s

Turbulence in Galaxy Clusters with VCS…..?



Sub AU

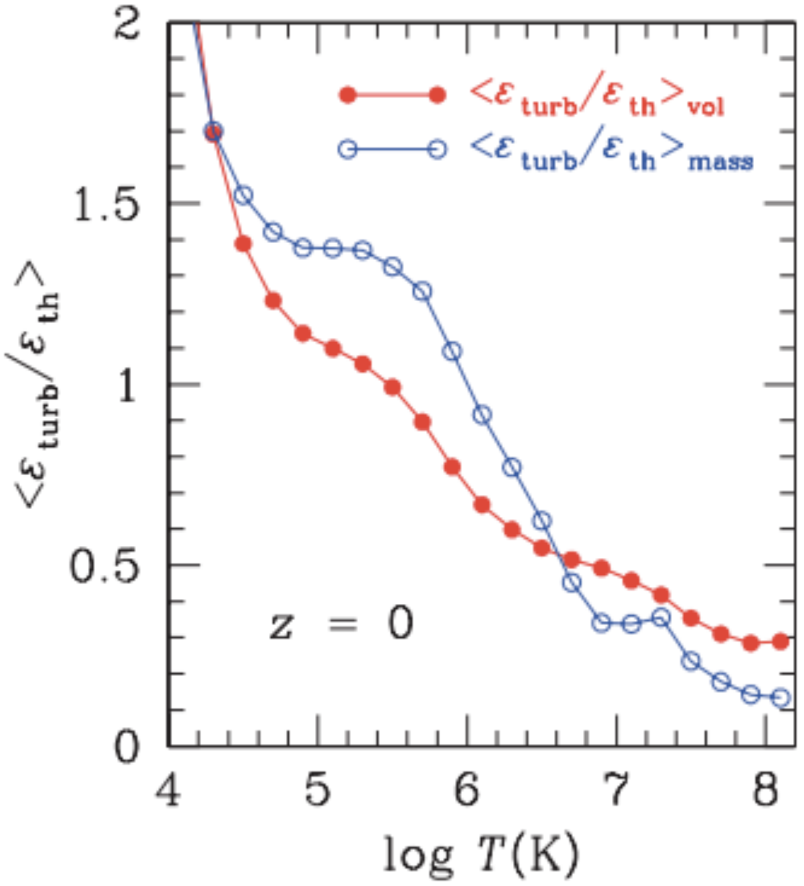
AU

Pc

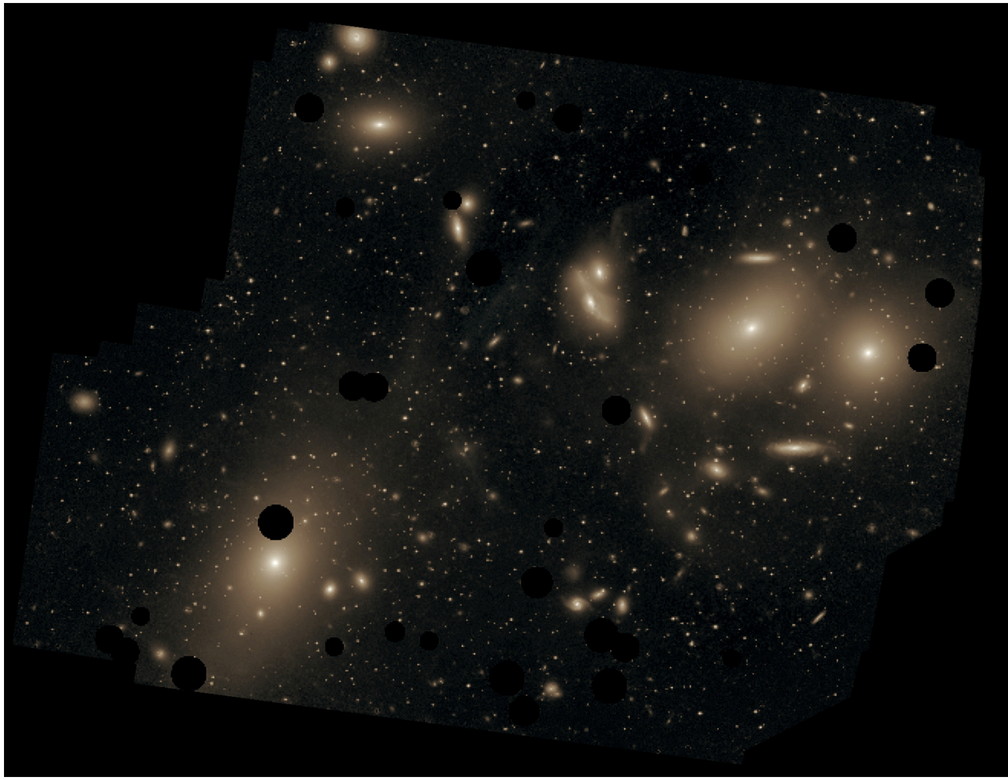
Kpc

Mpc

Studies of turbulence in clusters

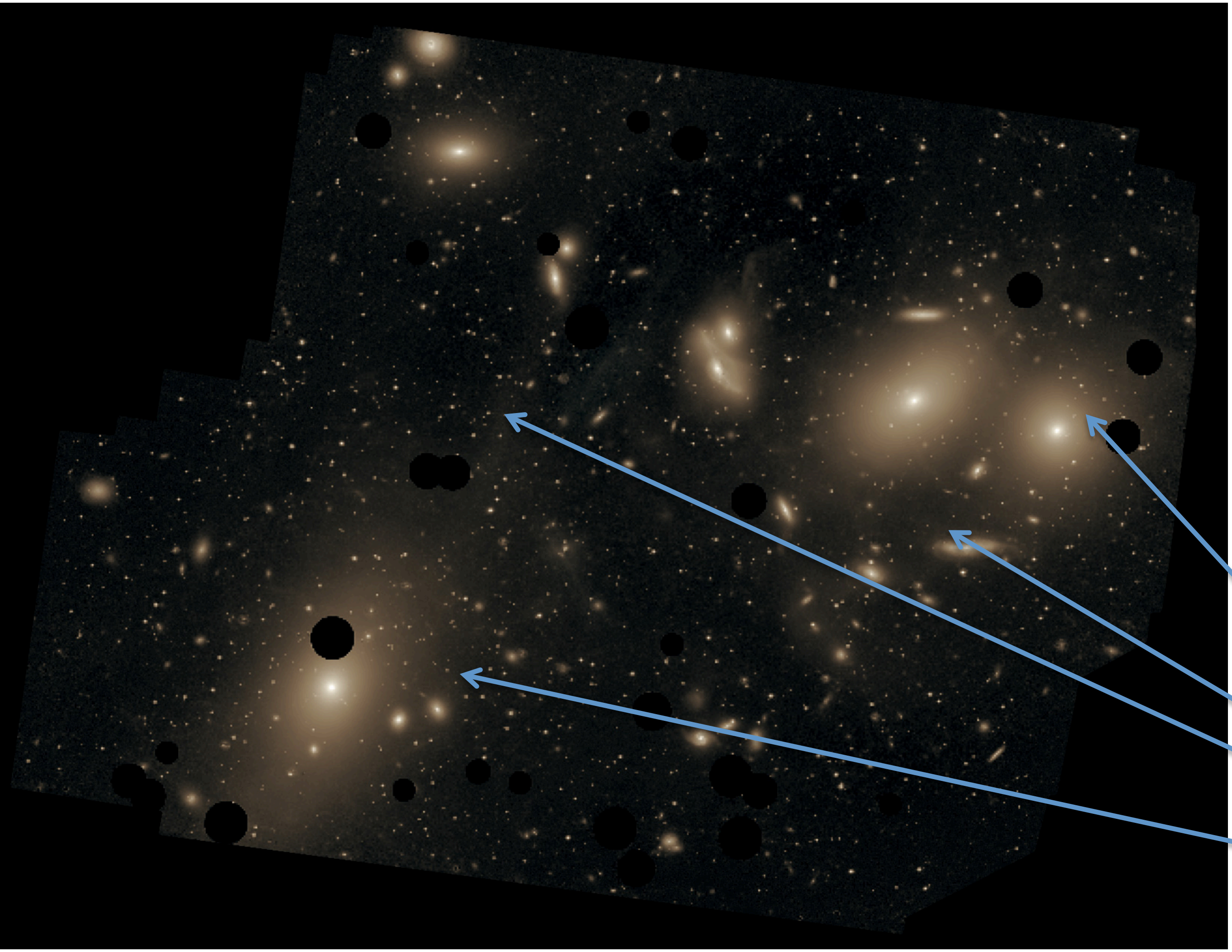


Simulations by Ryu et al. 2008



Current x-ray missions have good spatial resolution but poor spectral resolution and can not resolve v_{turb}

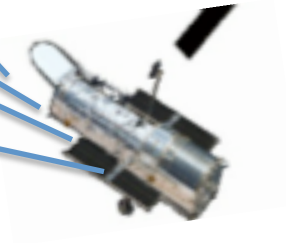
Application of Velocity Coordinate Spectrum to Virgo Cluster

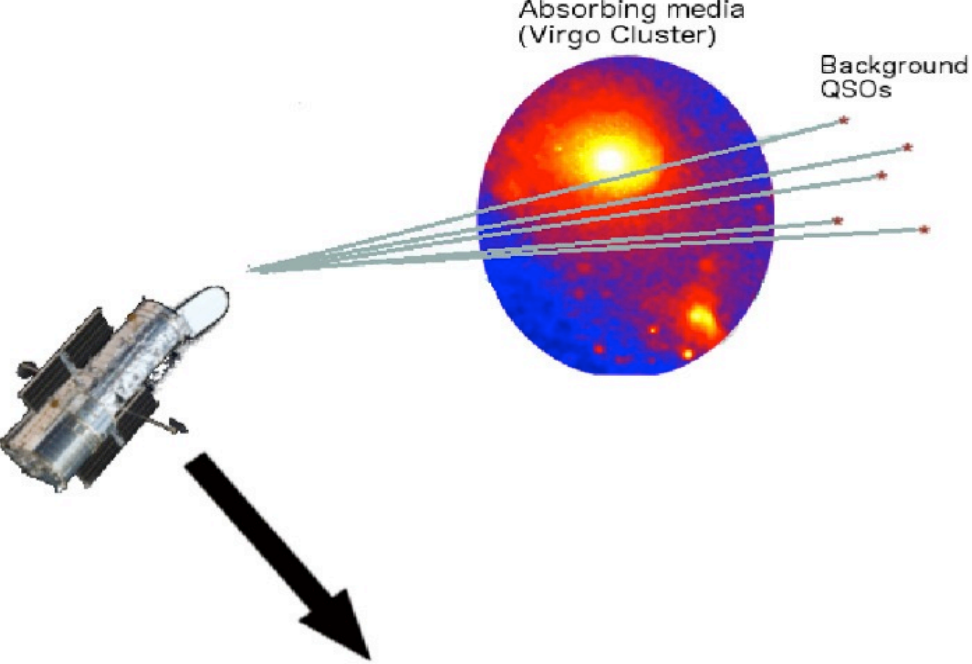


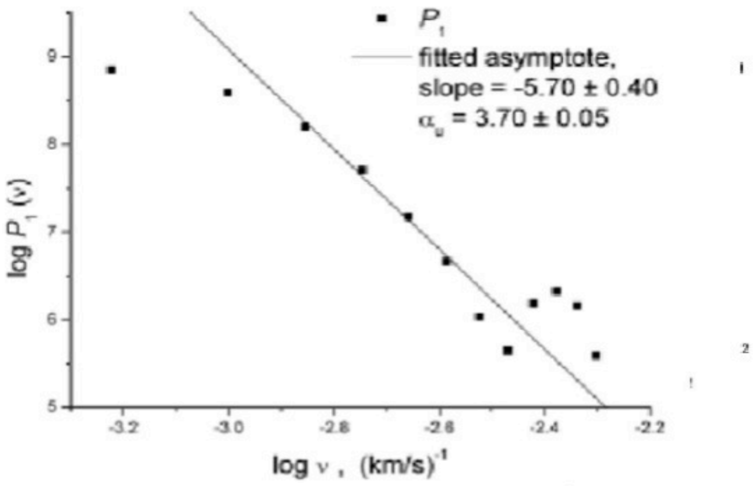
Hot X-ray gas at $T=10^8$

Current X-ray telescopes can not observe high resolution velocities.

We use absorption lines from warm gas (lyman alpha) with Hubble COS to obtain high resolution spectra.

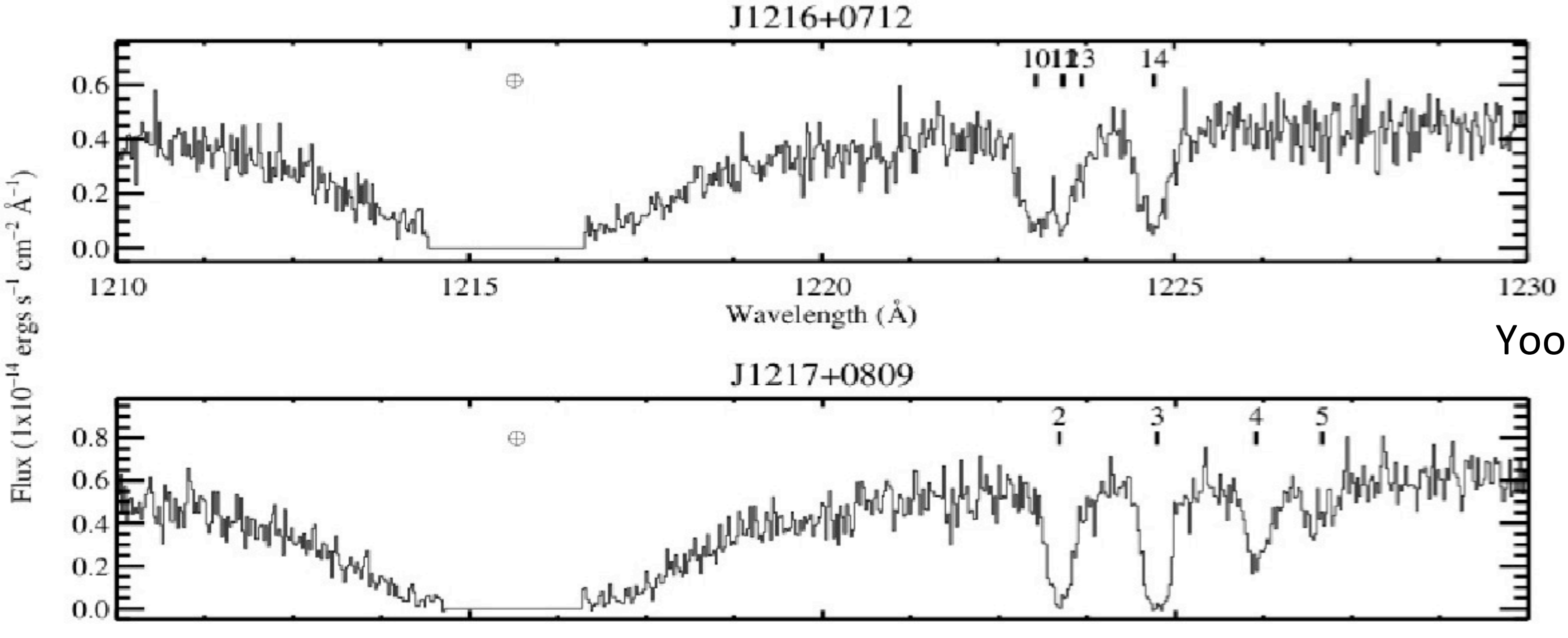






VCS
Application

- STAY TUNED!



Yoon et al. 2012

Summary

- The velocity and density power spectrum are critical for studies of turbulence, and in turn, important for a range of astrophysical problems.

- VCS/VCA can recover velocity/density spectrum and are the only such techniques related to analytical behavior.

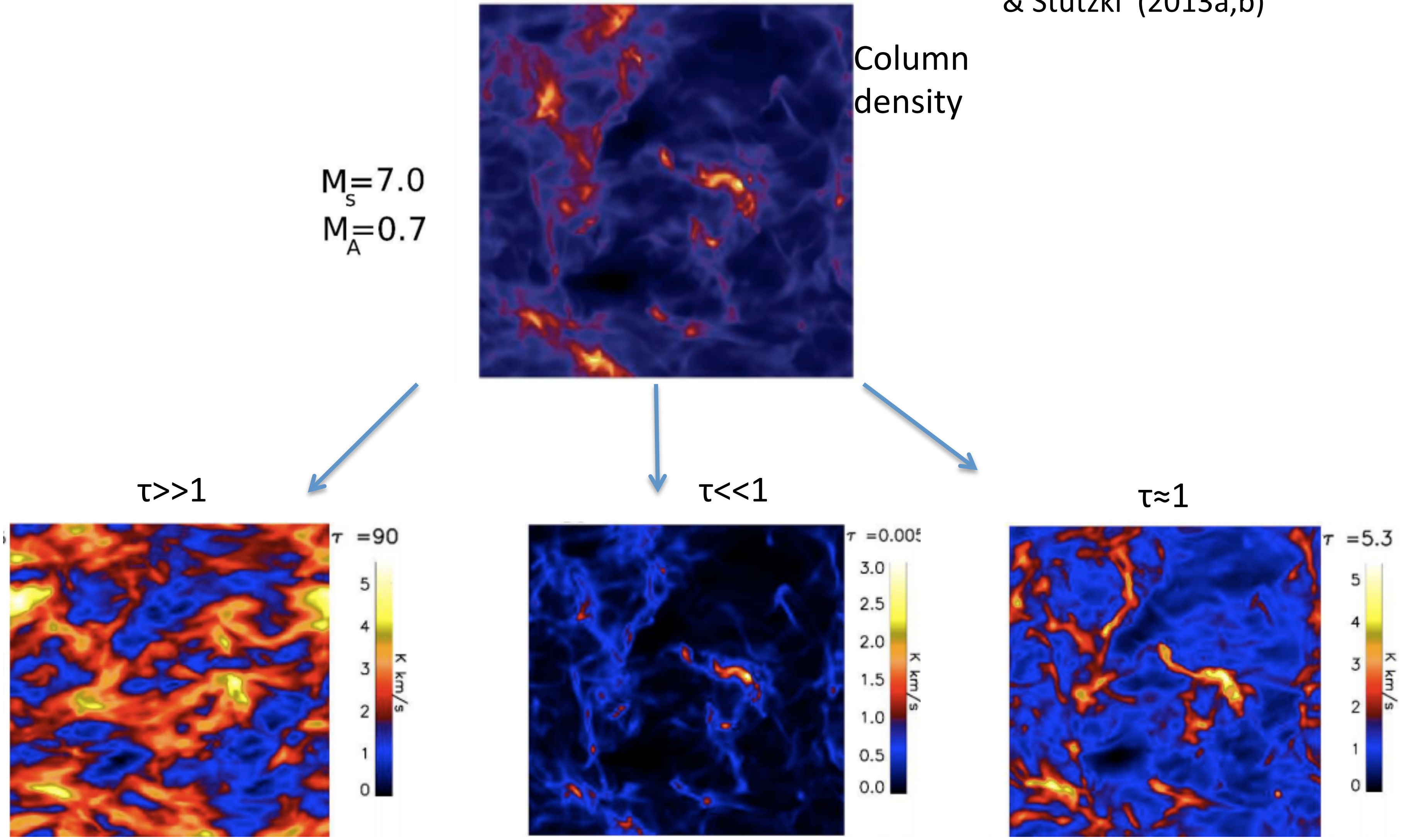
- Turbulence in the ISM is generally supersonic across a large range of phases/tracers.

- VCS applied to the SMC shows a supersonic spectrum and kpc driving scale (suggestive of super-bubbles/tidal driving?).

- VCS can be applied to absorption lines in galaxy clusters to recover the power spectrum of turbulence.

PDFs of ^{13}CO 2-1 synthetic maps

Burkhart, Ossenkopf, Lazarian
& Stutzki (2013a,b)



Column density

M_s=7.0
M_A=0.7

τ>>1

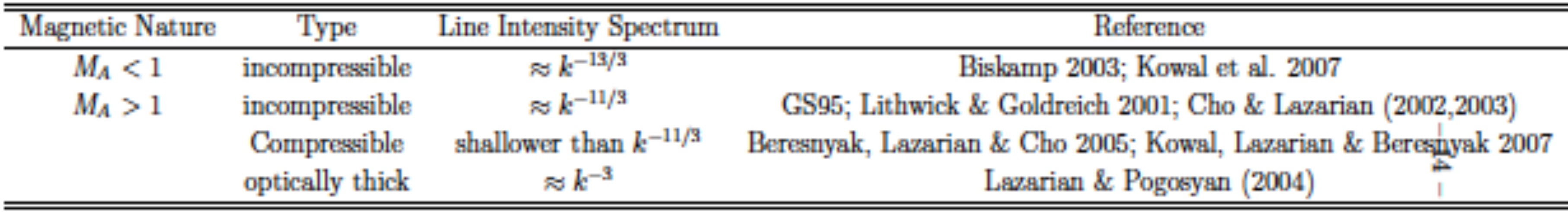
τ<<1

τ≈1

Post-processing radiative transfer for CO:
5pc cloud, T=10K, d=450pc, beam FWHM = 18''

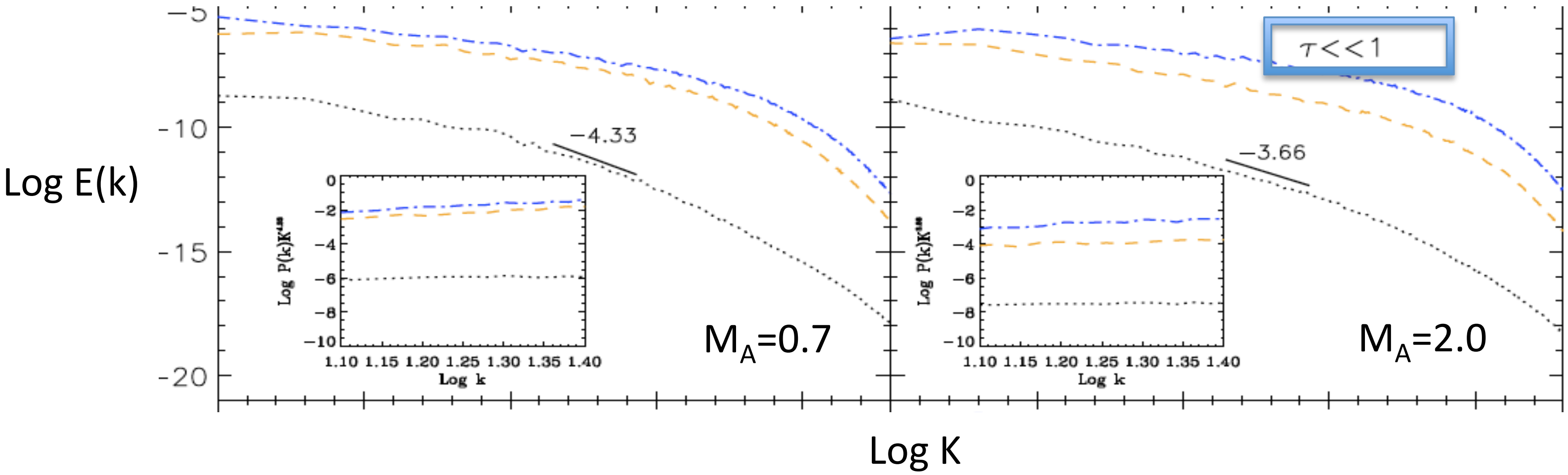
Why -3 slope for intensity power spectrum: Numerical Confirmation

Burkhart, Lazarian, Ossenkopf, & Stutzki 2013b



Magnetic Nature	Type	Line Intensity Spectrum	Reference
$M_A < 1$	incompressible	$\approx k^{-13/3}$	Biskamp 2003; Kowal et al. 2007
$M_A > 1$	incompressible	$\approx k^{-11/3}$	GS95; Lithwick & Goldreich 2001; Cho & Lazarian (2002,2003)
	Compressible	shallower than $k^{-11/3}$	Beresnyak, Lazarian & Cho 2005; Kowal, Lazarian & Beresnyak 2007
	optically thick	$\approx k^{-3}$	Lazarian & Pogosyan (2004)

Table 2: Power spectra slopes of turbulence for different environments. Corresponding references to theoretical and numerical are in the far right column.



MHD Turbulence must be understood in

- Cosmic ray acceleration and diffusion/scattering
- Solar wind
- Dynamo (generation of primordial and galactic magnetic fields)
- Magnetic reconnection (solar flares, star formation)
- Star formation (GMC scale; supersonic turbulence)
- Star formation (core scale; subsonic gravitational collapse)
- Star formation (disk scale; MRI, magnetic breaking)
- Structure formation in the ISM
- Galaxy formation (B field/spiral arms correlation)
- IGM dynamics
- Galaxy cluster dynamics (subsonic heat transfer, hierarchical structure)