Measuring MHD Turbulence through Studies of Radio Polarimetry

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MFU III 8/26/2011

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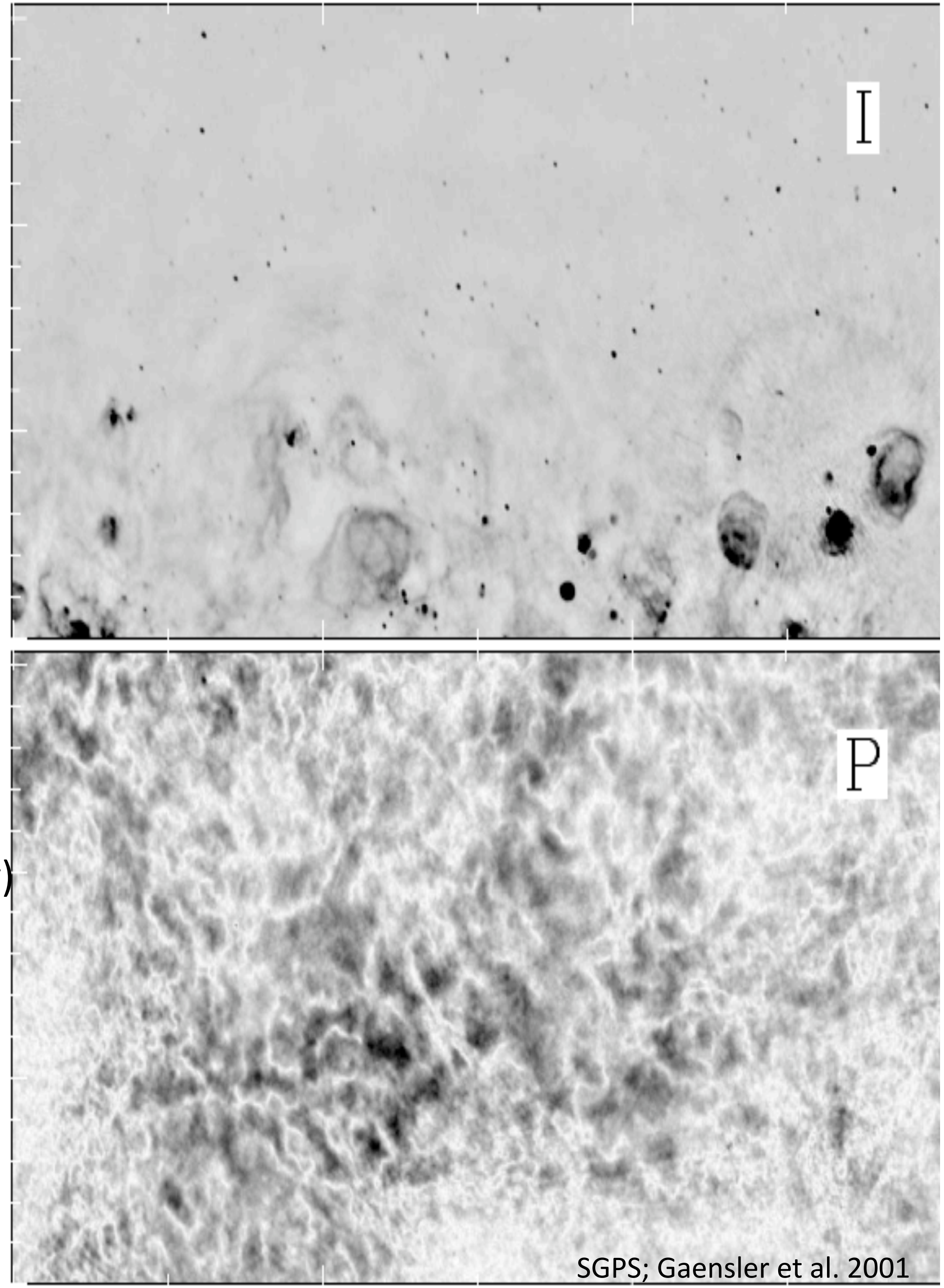
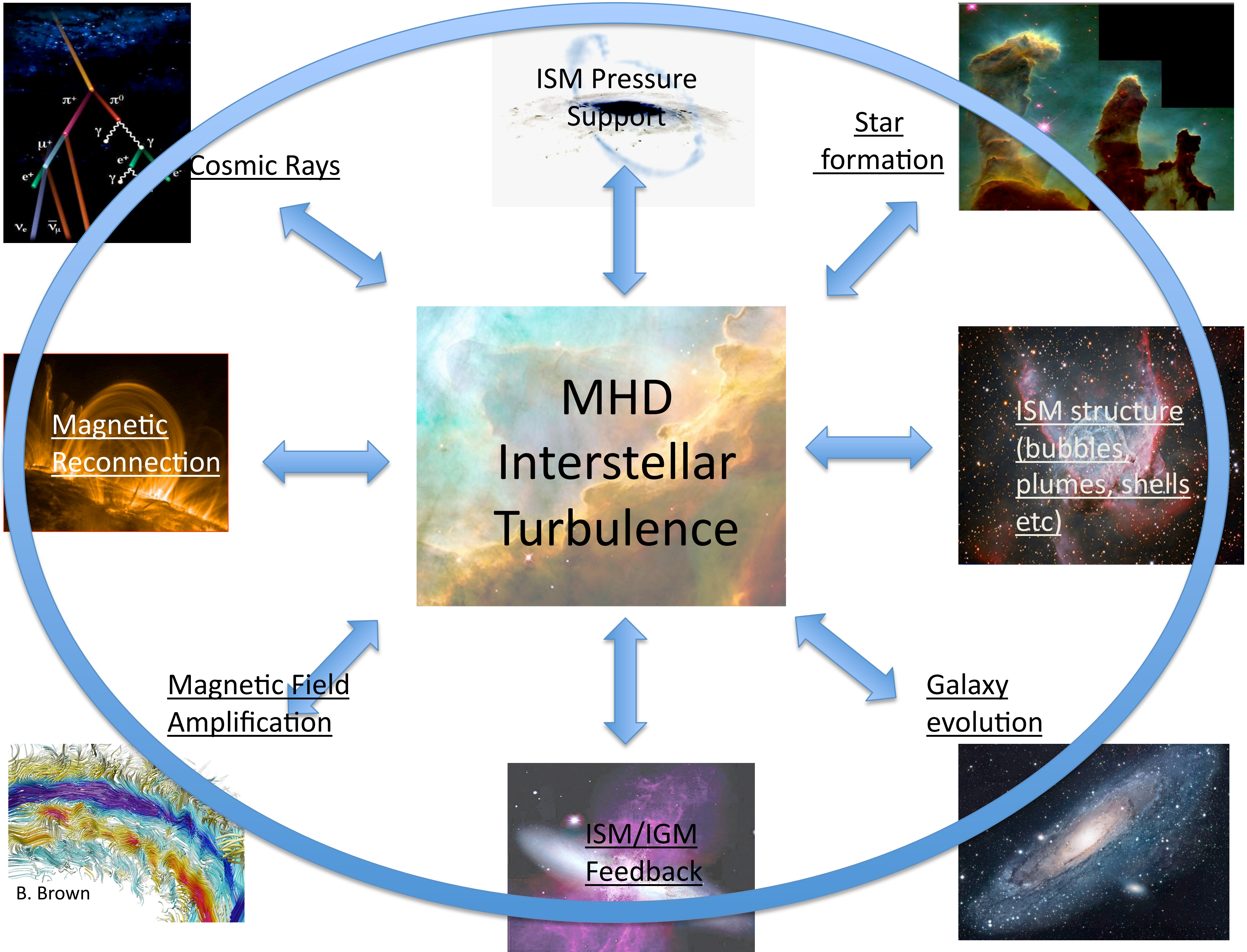
Collaborators: Bryan Gaensler (Univ. Sydney)
Jungyeon Cho (Chungnam National Univ.)

Based on:

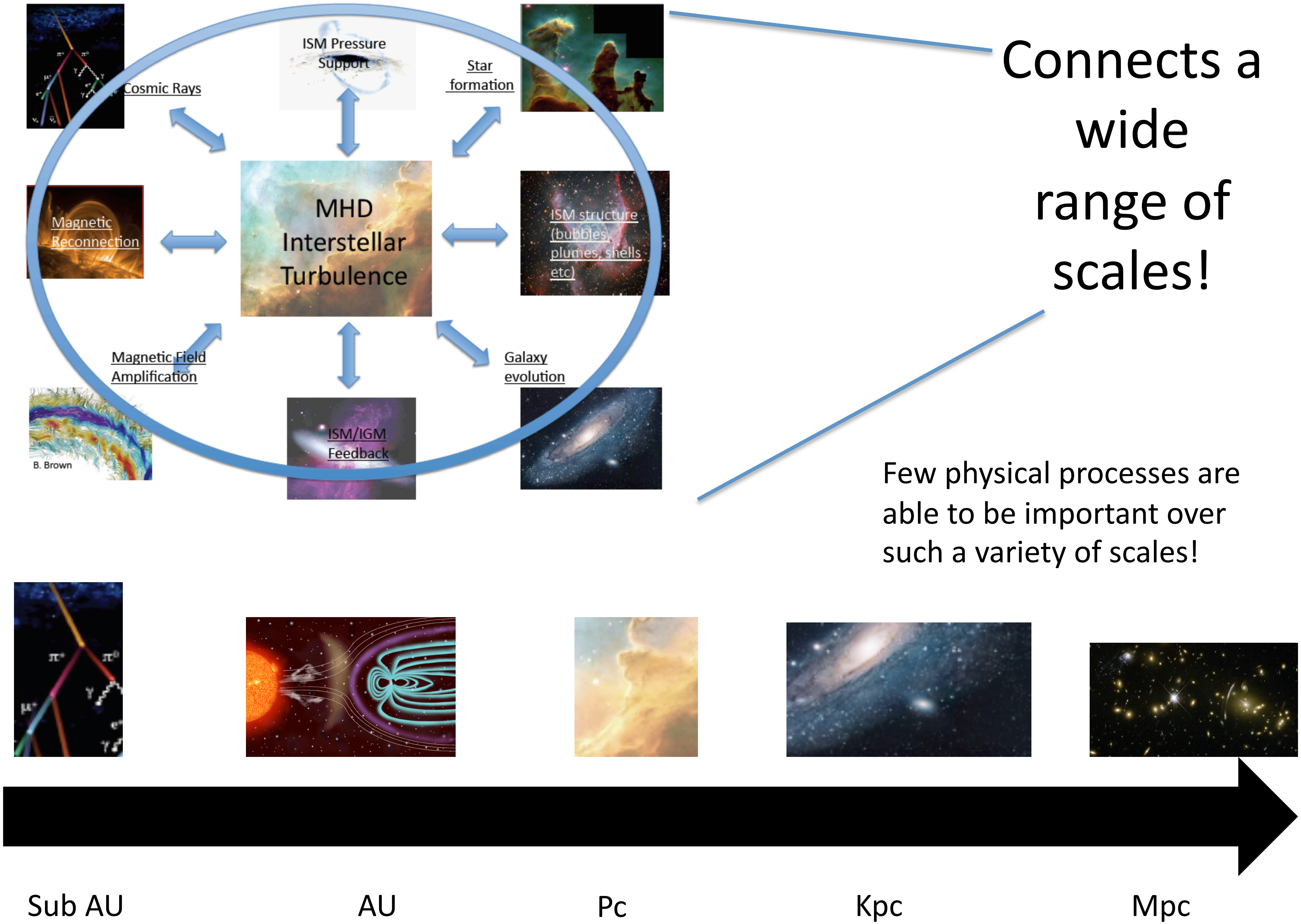
1. Gaensler, Haverkorn, Burkhart et al., 2011, Nature, accepted
2. Burkhart, Lazarian, Gaensler, 2011, ApJ, in prep.



SGPS; Gaensler et al. 2001



ISM Pressure Support
Cosmic Rays
Star formation
MHD Interstellar Turbulence
Magnetic Reconnection
ISM structure (bubbles, plumes, shells etc)
Magnetic Field Amplification
Galaxy evolution
ISM/IGM Feedback
B. Brown



Cosmic Rays
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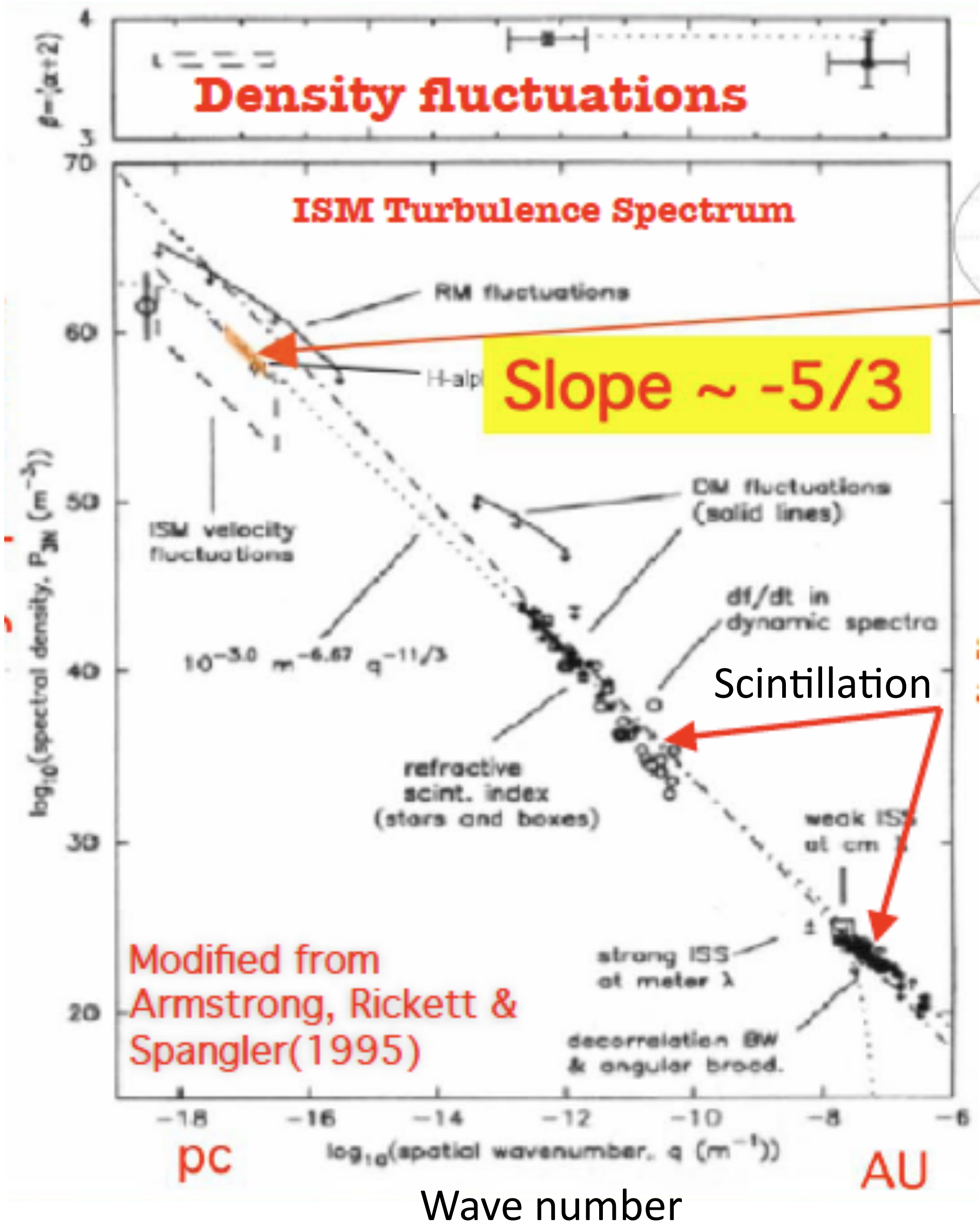
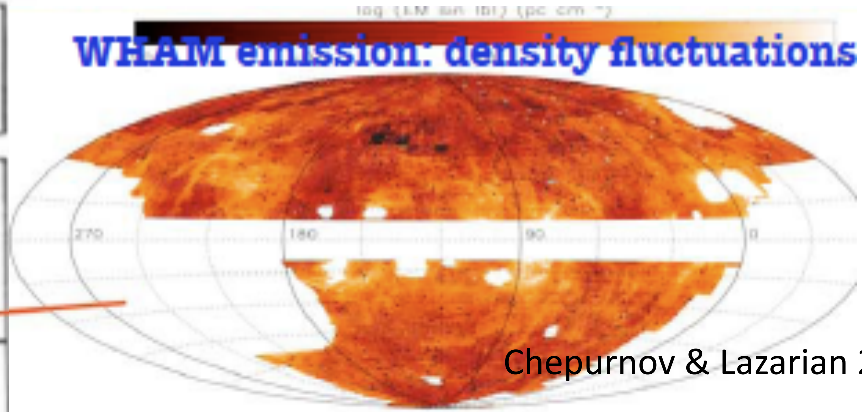
B. Brown
Connects a wide range of scales!
Few physical processes are able to be important over such a variety of scales!
Sub AU
AU
Pc
Kpc
Mpc

The "Big Power Law"



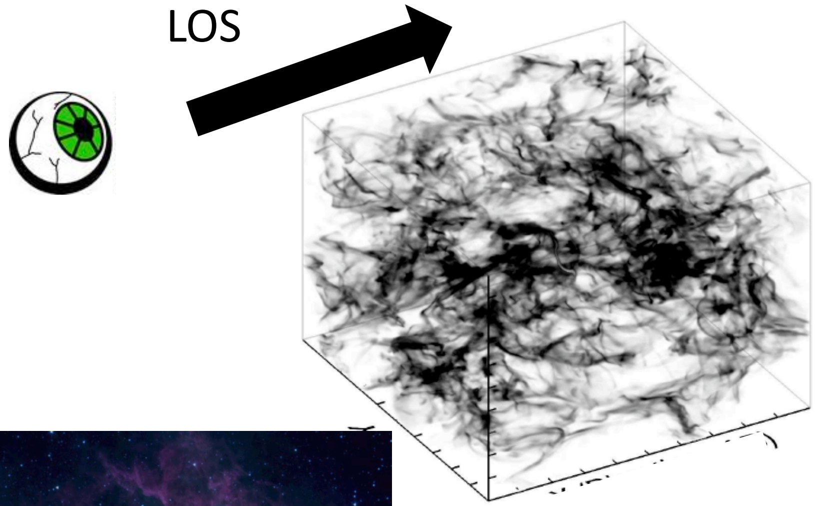


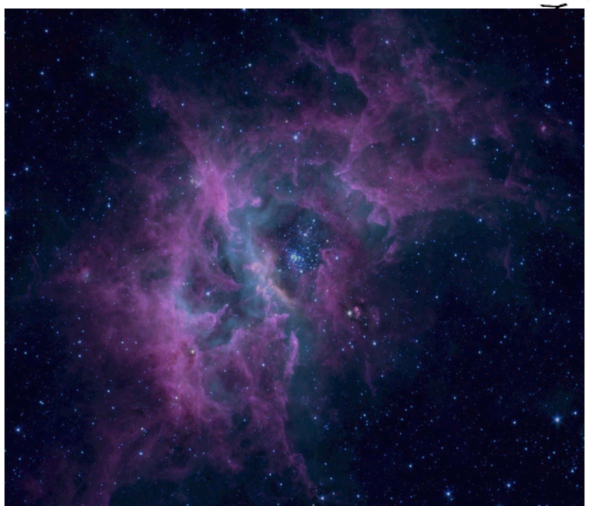
Chepurnov & Lazarian 2010

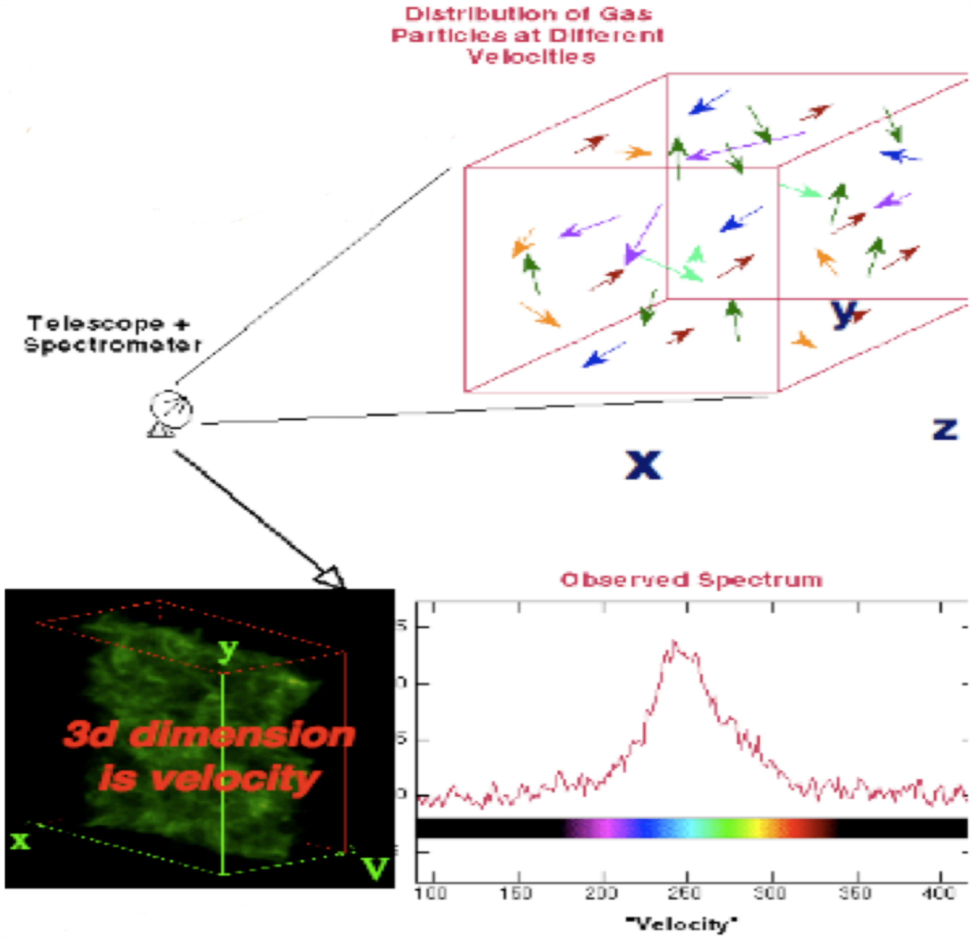
"One of the most important developments in the field of interstellar gas dynamics during the last half-century was renewed perception that most processes and structures are strongly affected by turbulence. This is a paradigm shift unparalleled in many other fields of astronomy, comparable perhaps to the discovery of extrasolar planets and cosmological structure at high redshift." –Scalo and Elmegreen 2004

Magnetic Turbulence in the ISM: Difficult to Study

- No full theory of MHD turbulence exists
- Can not make direct measurements. We are passive observers.
- Only Line of Sight Information (LOS).
- Complicated plasma physics coupled with gravity at a huge range of densities, temperatures!

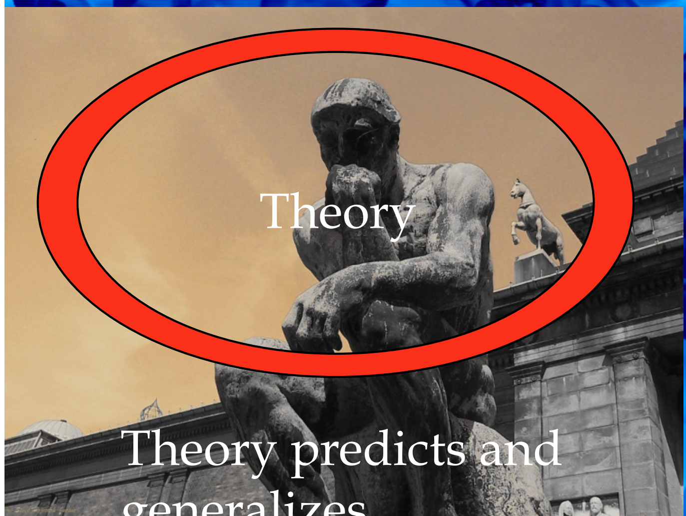


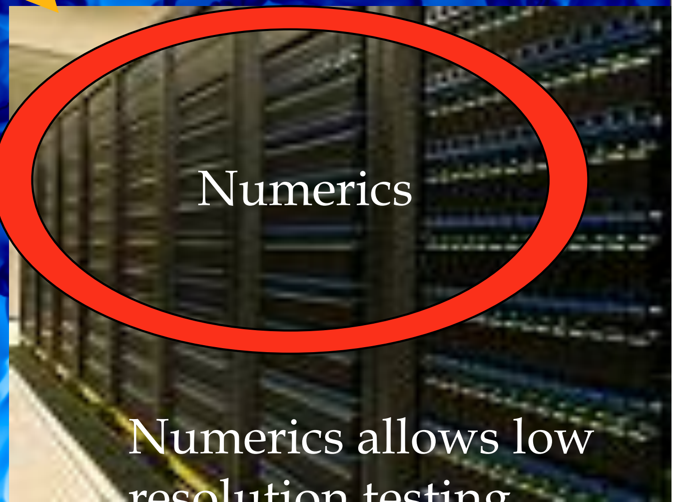




How To Study ISM Turbulence

"We need common ground for conversation!" –Carl Heiles (yesterday during discussion)





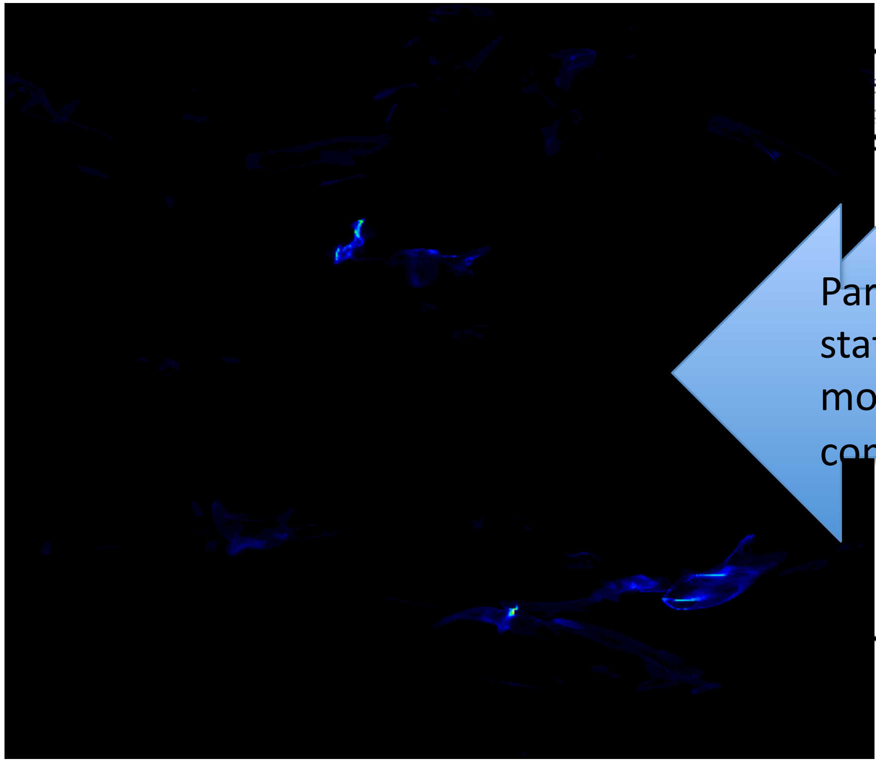
Numerics vs. Observations

How to find the common ground? Apples vs. oranges?

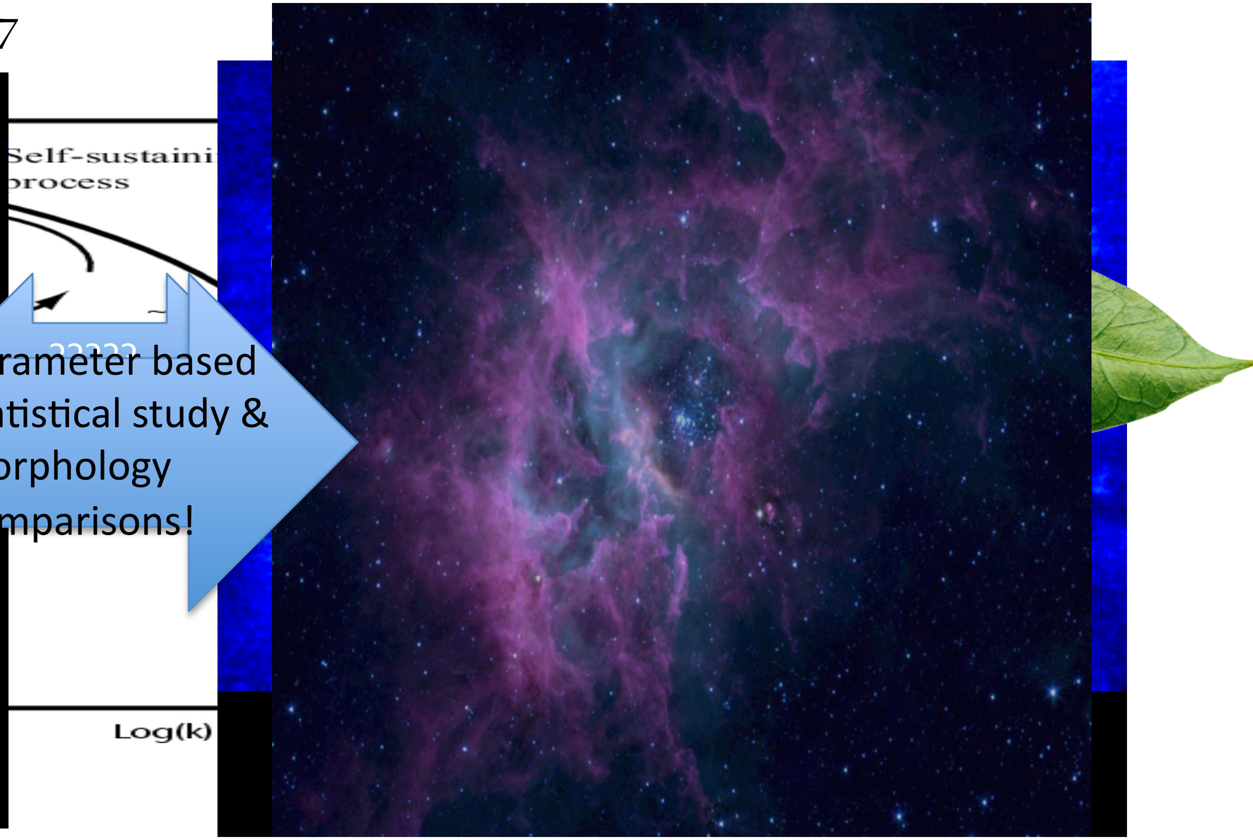
Full information…density (PPP), velocity, magnetic fields etc…

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

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



Parameter based statistical study & morphology comparisons!



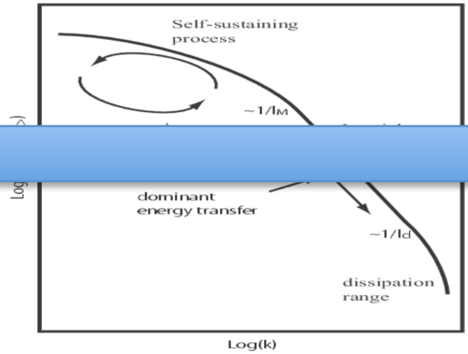
Very Idealized environment
Spatial scales do not match the real world
Currently we can get max Re of order $<10^4$

Can only get column density….noise and instrument effects are contaminants   Re ~VL/ν ~10^{10}

Characterizing Turbulence in the Observational ISM: Our Approach

Numerical Turbulence

Statistical Studies



Observational Turbulence

1) Isothermal
2) Two Phase
3) Multi Injection Scale
4) Two Fluid
5) Radiative Transfer

Physical Parameters:

1) Compressibility
2) Alfven Mach Number
3) Driving Scale
4) Velocity/density spectrum
5) Temperatures

1) Column Density
2) PPV Radio
3) Molecular Line
4) Rotation Measure
5) Emission Measure

Obtaining the Parameters of Turbulence from the Observations…

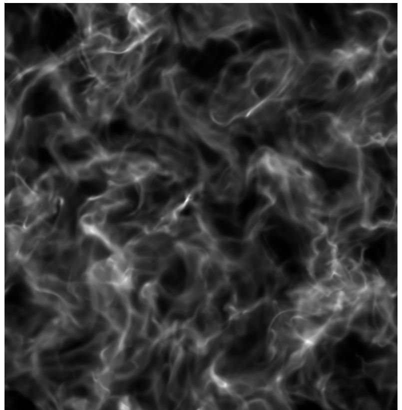
Turbulence is characterized by the cascade! Cascade is effected by the parameters of the fluid, such as the sonic and Alfvenic Mach numbers.

Turbulence parameters of interest:

$M_A = V/V_A$

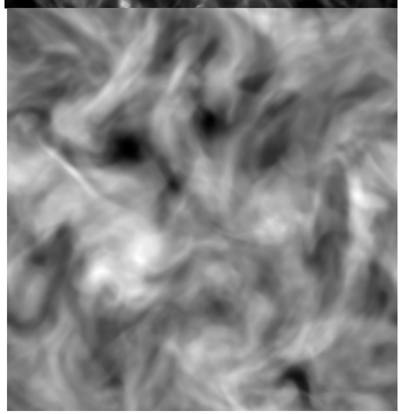
$M_s = V/c_s$

$$V_A = \frac{B}{\sqrt{4\pi\rho}}$$

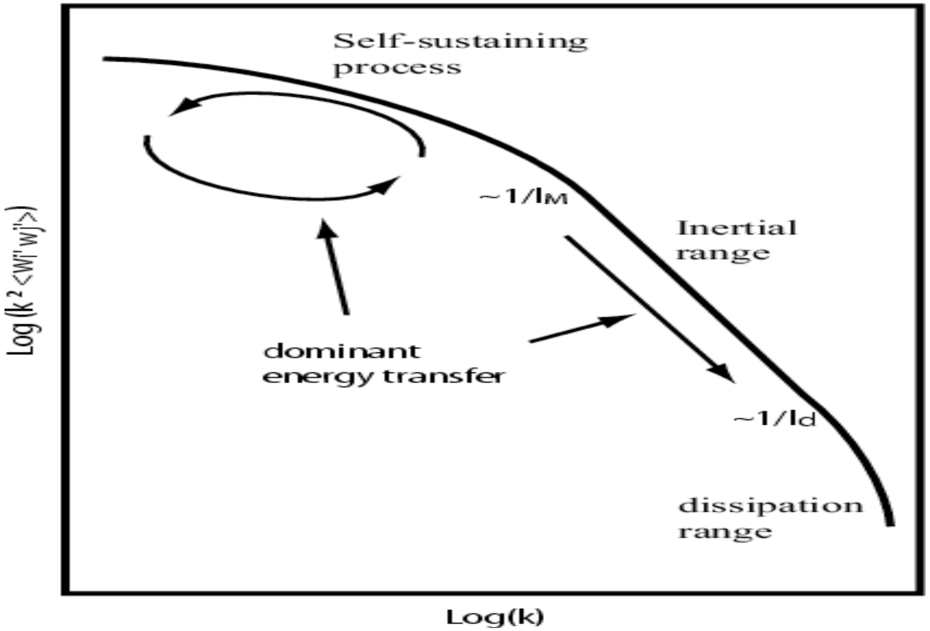


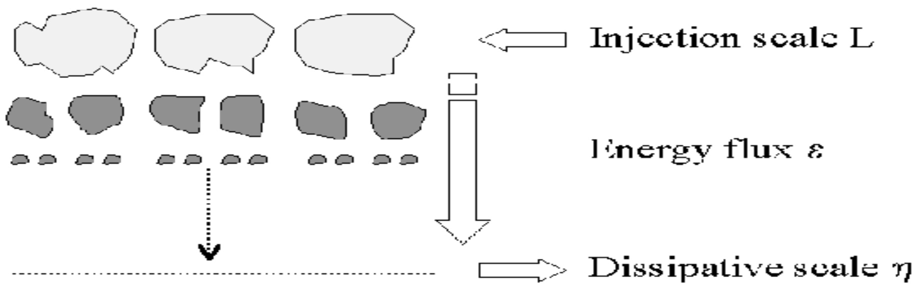
$M_s=7$

Supersonic Structures Different from subsonic



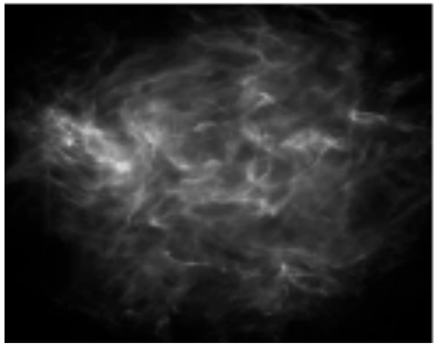
$M_s=0.7$





Our Approach for getting Turbulence Mach Numbers

Data base of MHD simulations



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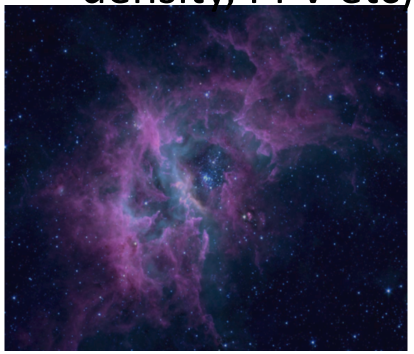
Observational Data (column density, PPV etc)



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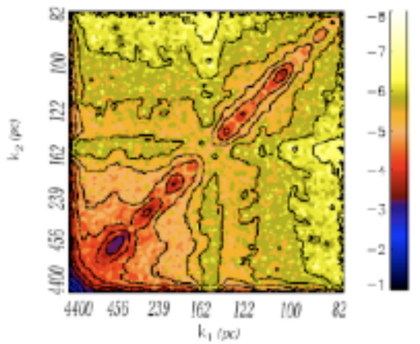
Statistical Studies

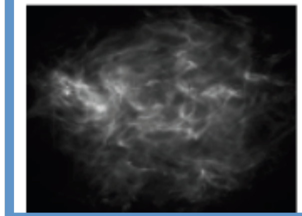


= Parameters of turbulence M_s, M_A,

- We characterize the compressibility (sonic number) and Alfvenic Mach number (M_s, M_A). → very useful for observations of star forming regions and diffuse gas!
- We compare results of several statistics applied to the observational data with those of scaled simulations to gauge turbulence properties.
- Each tools has its own strengths and weaknesses…some more sensitive to shocks others to magnetic enhancements.
- Synergetic use of many tools provides most accurate information
- If many independent tools give similar results then this can be trusted!

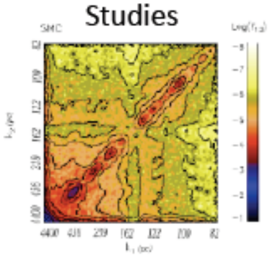
Characterizing Turbulence in the Observational ISM: Our Approach

Data base of MHD simulations



+ Observational Data (column density, PPV etc)

+ Statistical Studies



= Parameters of turbulence M_s, M_A,

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\mathbf{v} + \left(p + \frac{B^2}{8\pi} \right) \mathbf{I} - \frac{1}{4\pi} \mathbf{B}\mathbf{B} \right] = \mathbf{f},$$

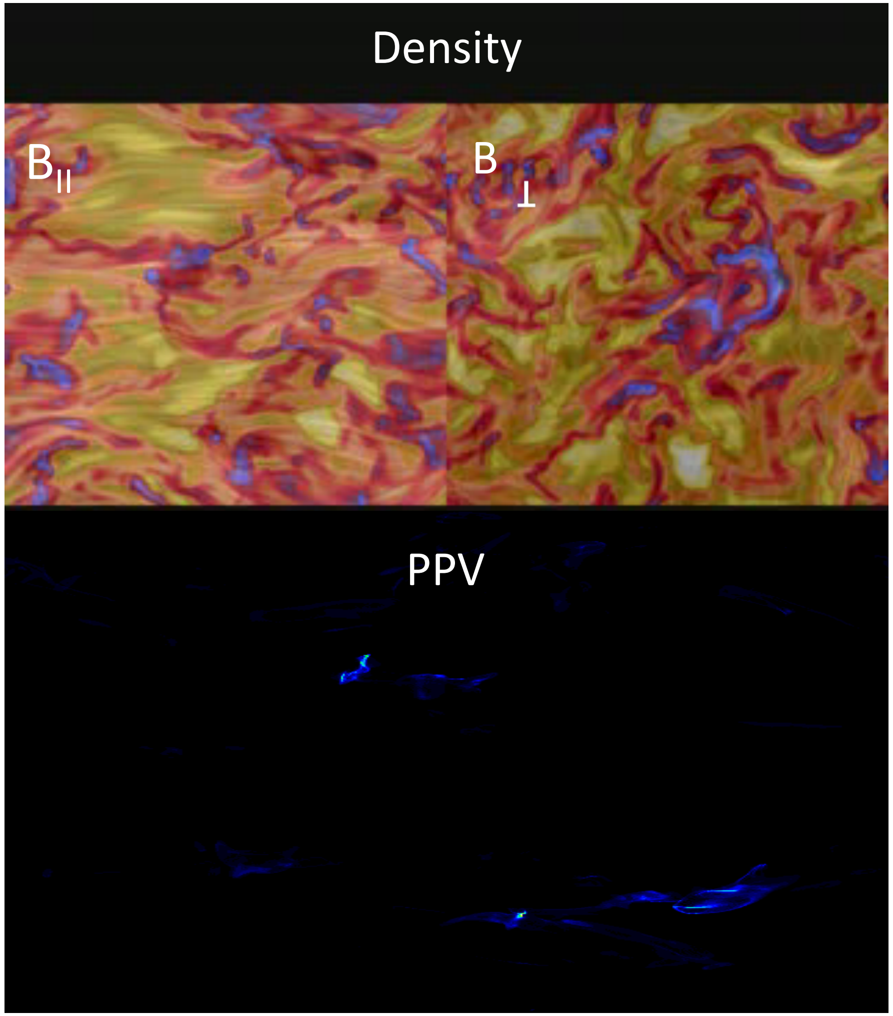
$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0,$$

Simulations:

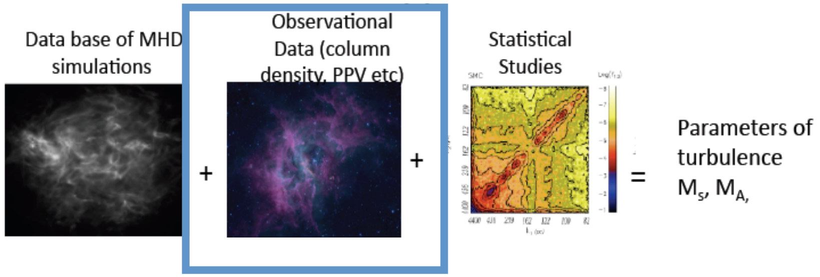
-Ideal isothermal MHD (Cho & Lazarian 2003). Self-Gravity option. Good for diffuse media/ molecular cloud studies.
-Solenoidal large scale driving in Fourier Space
-Periodic B.C.

-Generate 16 simulation with resolution 512^3
M_s=0.1,0.7,2.0,3.5,4.5,7.0,8.0,10
M_A=0.7,2.0

-Also exploring two fluid effects, multiple driving scales, varying EoS, and addition of optical depth effects



Observations

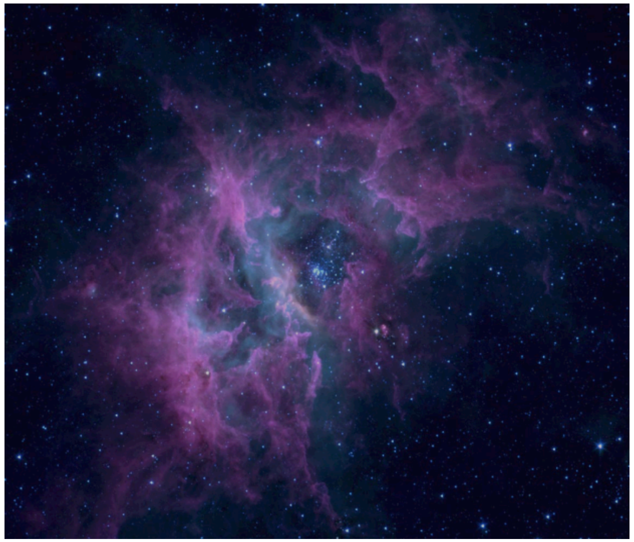


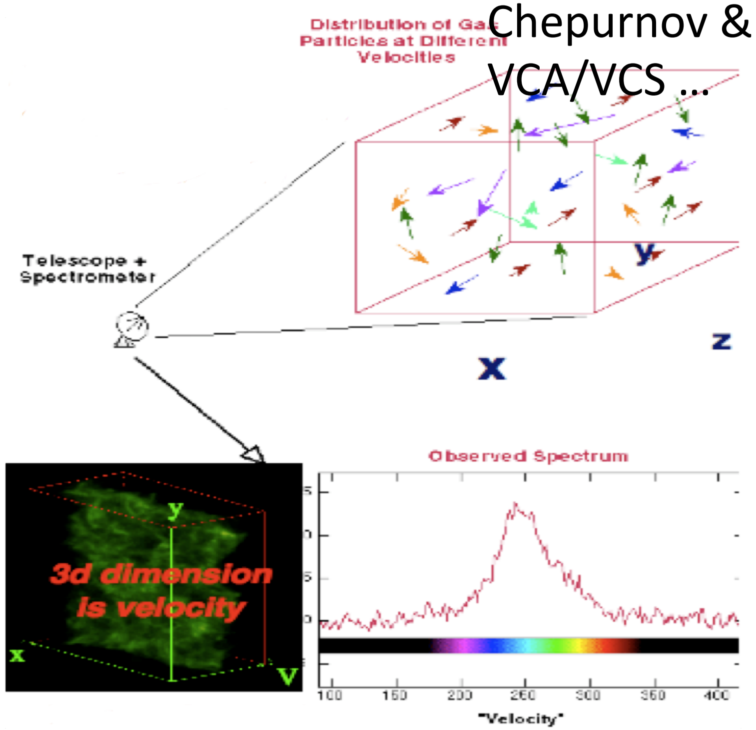
- Column density data (HI, CO, Hα…)
- Radio Scintillation data
- Position- Position-Velocity data
- Polarization maps…

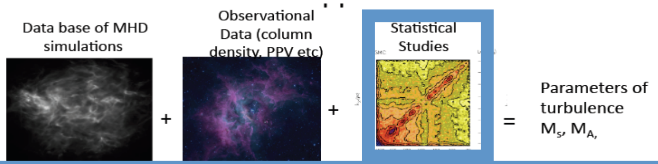
PDFs, spectrum etc. studied in Burkhart et al. 2009, 2010, 2011 with HI and CO

'Big power law' Armstrong et al. 1994, Chepurnov & Lazarian 2010

Lazarian & Pogosyan 2000/ Chepurnov & Lazarian 2009 VCA/VCS …







Statistics of Turbulence

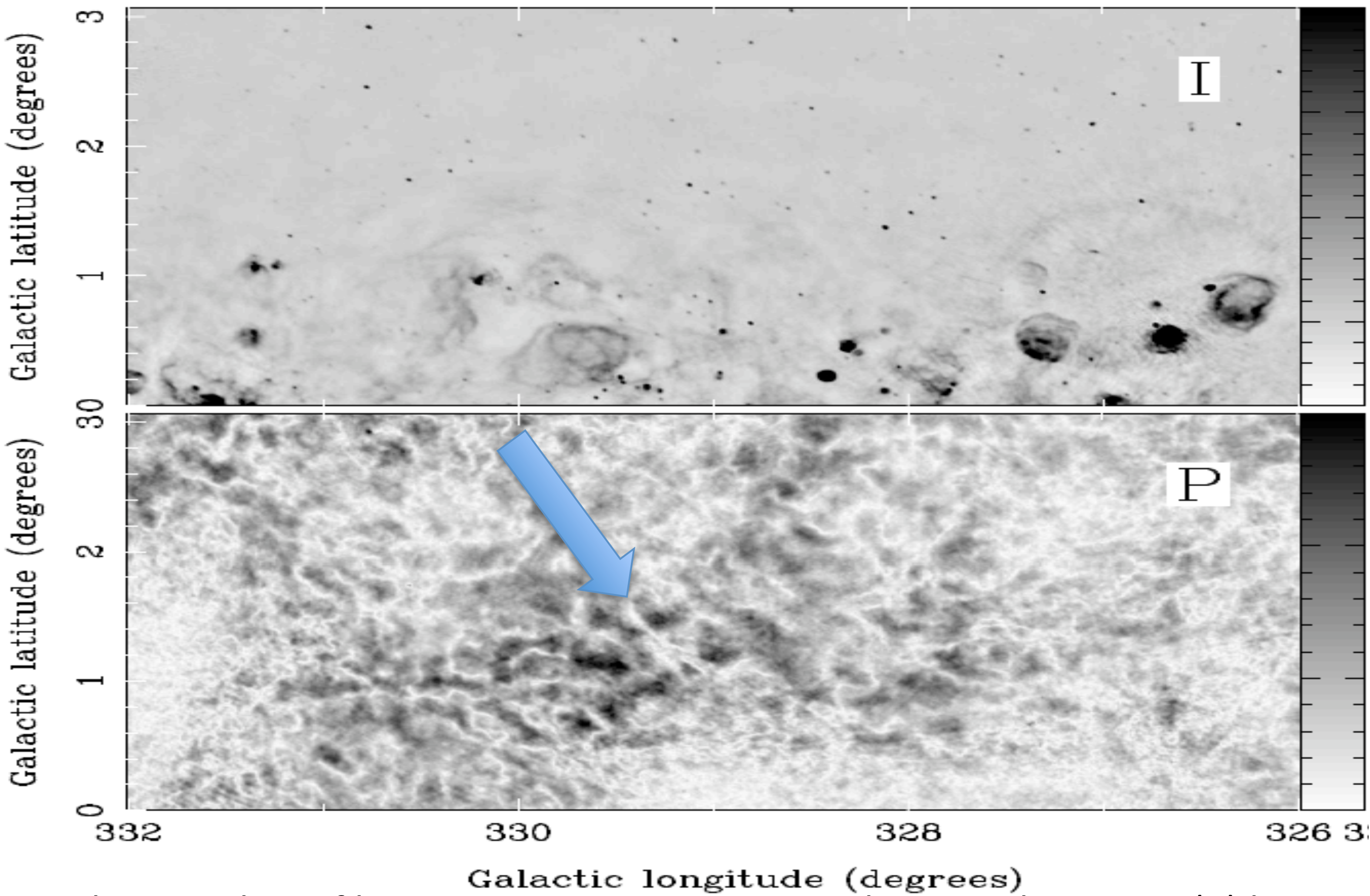
Statistic	Purpose	Use	Observational data
Velocity Channel Analysis and Velocity Coord. Sepctrum	Turbulence Velocity Spectrum	Entangles the velocity and density fluctuations in PPV data to give the turbulence velocity spectrum!	PPV data. Tested on WHAM and SMC HI Lazarian & Pogsoayn 2000 2004 2006 Chepurnov & Lazarian 2009
PDFs: Moments And Tsallis Fit	Characterize Density fluctuations	Sonic and Alfvenic numbers Distribution of density fluctuations	Column density and PPV Esquivel et al. 2009, Kowal et al. 2007, Burkhart et al.
Spectrum Bispectrum	Density spectral index	Sonic and Alfvenic numbers Cascade information Bisp. Preserves information on phases!	Column Density …PS tested on EVERYTHING! BS new to ISM…testing on simulations and SMC! Burkhart et al. 2008,2009 Cho et al. 2009
Genus Tree Diagrams	Emission Topology	Topology, sonic and Alfvenic numbers, & Emission hierarchy	PPV emission Data & Column D. Goodman et al. 2009, Kowal et al. 2007

Polarization Maps:

1.4 Ghz Southern Galactic Plane Survey

Gaensler et al. 2011

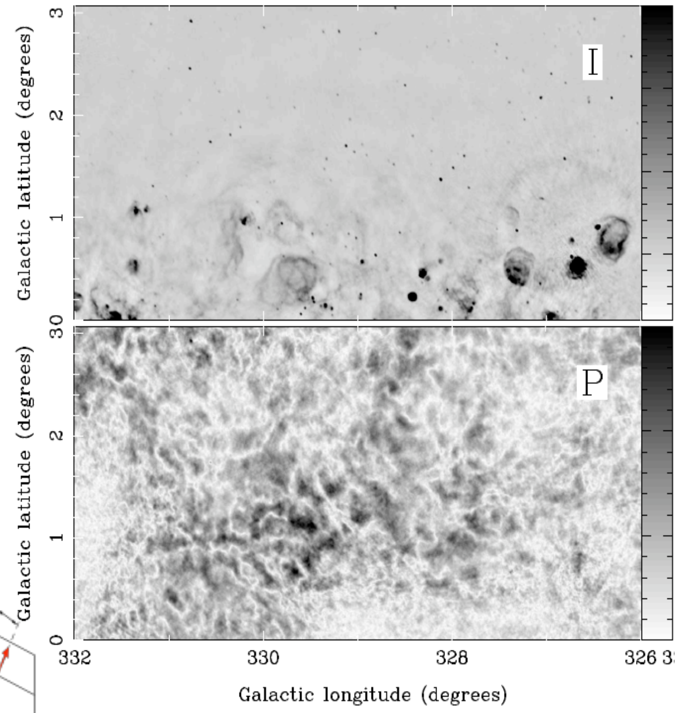
ATCA interferometer



Question: What are these filamentary structures seen in linear polarization (P) but not intensity?

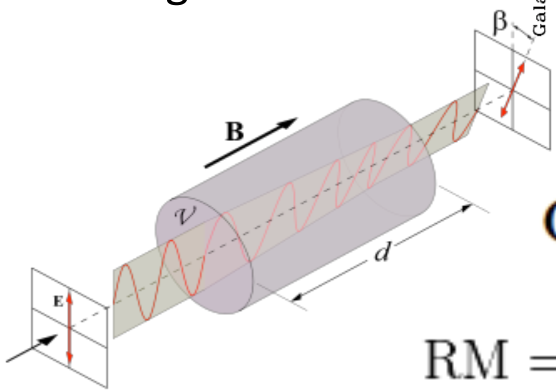
Linear polarization gradients → Turbulence

Structures are due to Faraday Rotation along LOS…



Sharp changes in n_e or B along the LOS can be due to random (subsonic) fluctuations and/or shocks propagating through the ISM

Characterize sharp changes with polarization gradients. Two main reasons:



1) Need a quantity that will not care about zero spacing being missing
2) $\nabla \mathbf{P}$ can be related to more theoretically motivated ∇RM

$$\Theta = \Theta_0 + \mathrm{RM}\lambda^2$$

$$\mathrm{RM} = \frac{e^3}{2\pi m^2 c^4} \int_0^d n_e(s) B_{||}(s)\, \mathrm{d}s$$

$$|\nabla \mathbf{P}| = \sqrt{\left(\frac{\partial Q}{\partial x}\right)^2 + \left(\frac{\partial Q}{\partial y}\right)^2 + \left(\frac{\partial U}{\partial x}\right)^2 + \left(\frac{\partial U}{\partial y}\right)^2}$$

$$\mathbf{P} = |P| e^{2iRM\lambda^2}$$

$$|\nabla RM| = |\nabla \mathbf{P}|\lambda^2/2|\mathbf{P}|$$

We scale our simulations using typical values for the WIM with P=1

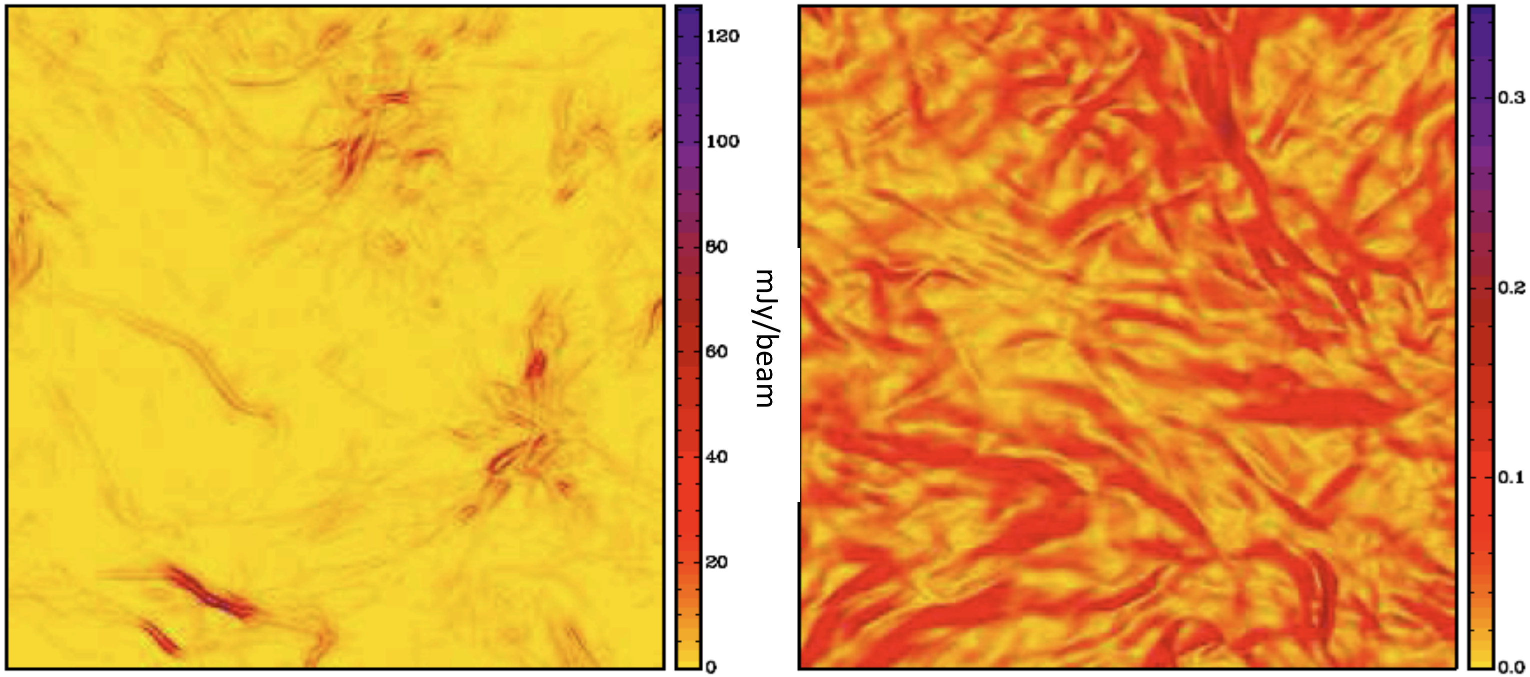
Gradients of Polarization Data: Simulations and Statistics

Qusestion: Can this data give insight into ISM turbulence parameters?

Answer: On going yes!

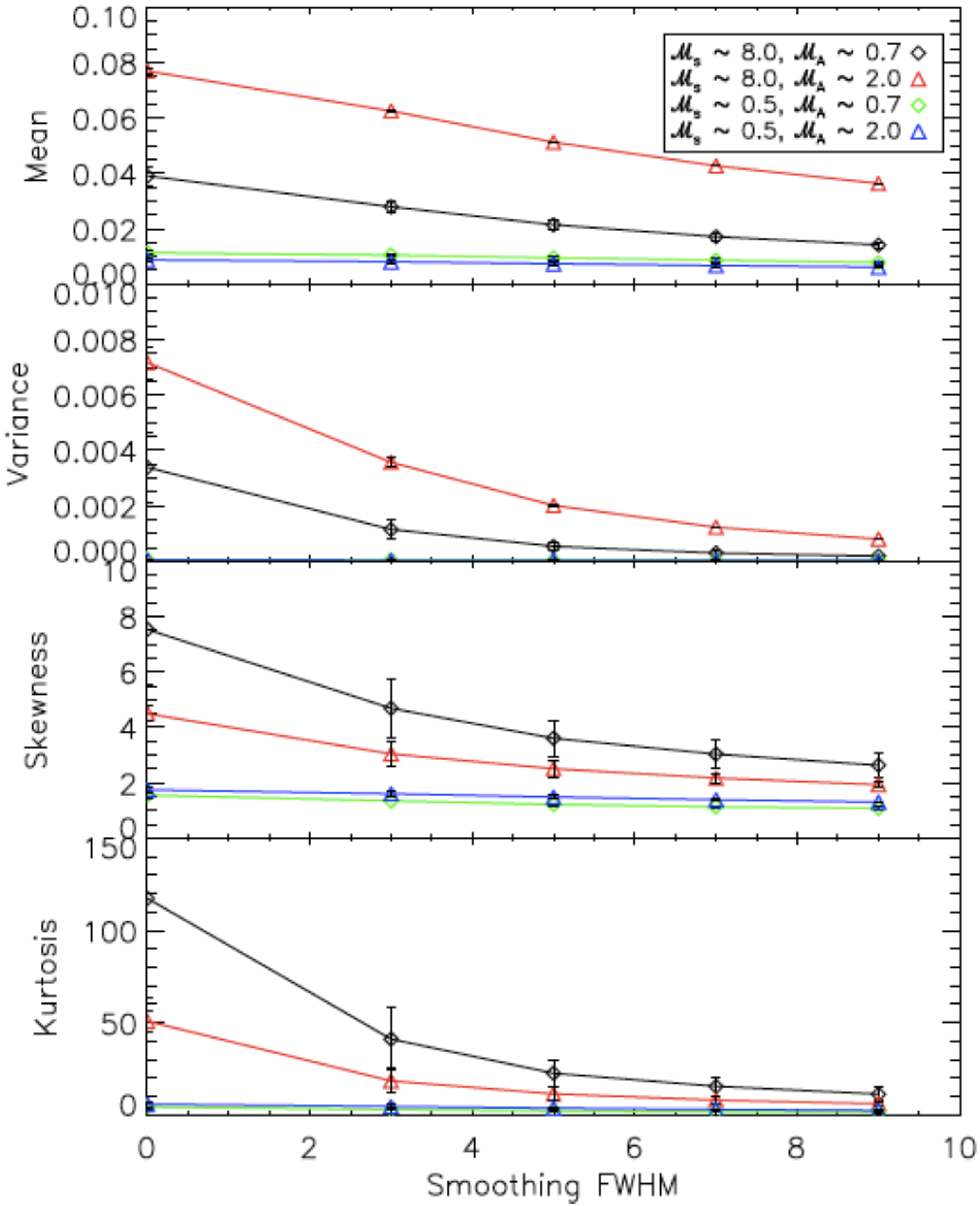
Two papers underway to compute polarization/rotation measure gradients in simulations and observations and compare statistically (Gaensler, Haverkorn, Burkhart et al. 2011 Nature (accepted), and Burkhart et al. 2011 ApJ (in prep.))

Supersonic ∇P Subsonic ∇P

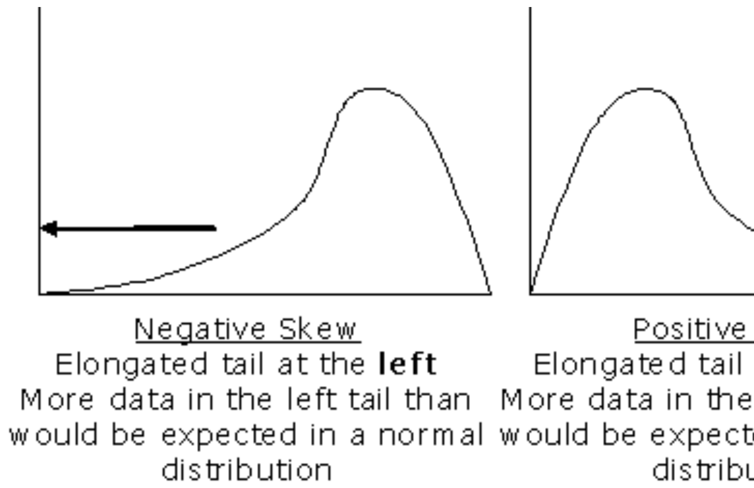


Filaments due to supersonic and subsonic turbulence are different in:

1) Topology
2) PDFs



Moments of the ∇RM Distribution can characterize the Mach numbers !!



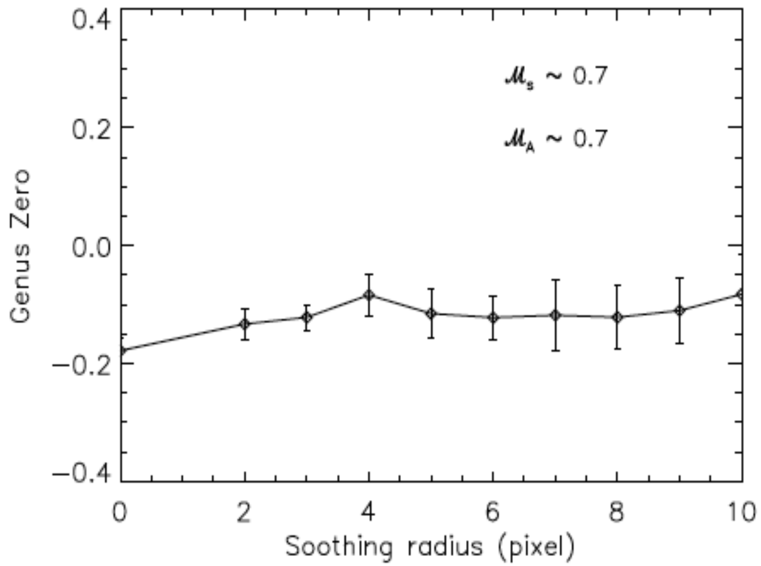
Skewness

$$\gamma_\rho = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\rho_i - \bar{\rho}}{\sigma_\rho}\right)^3$$

Kurtosis

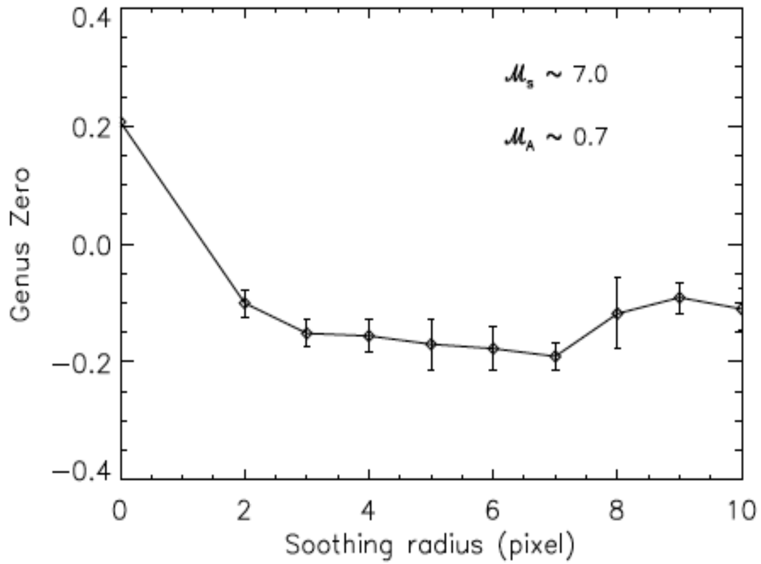
$$\beta_\rho = \frac{1}{N}\sum_{i=1}^{N}\left(\frac{\rho_i - \bar{\rho}}{\sigma_\rho}\right)^4 - 3.$$

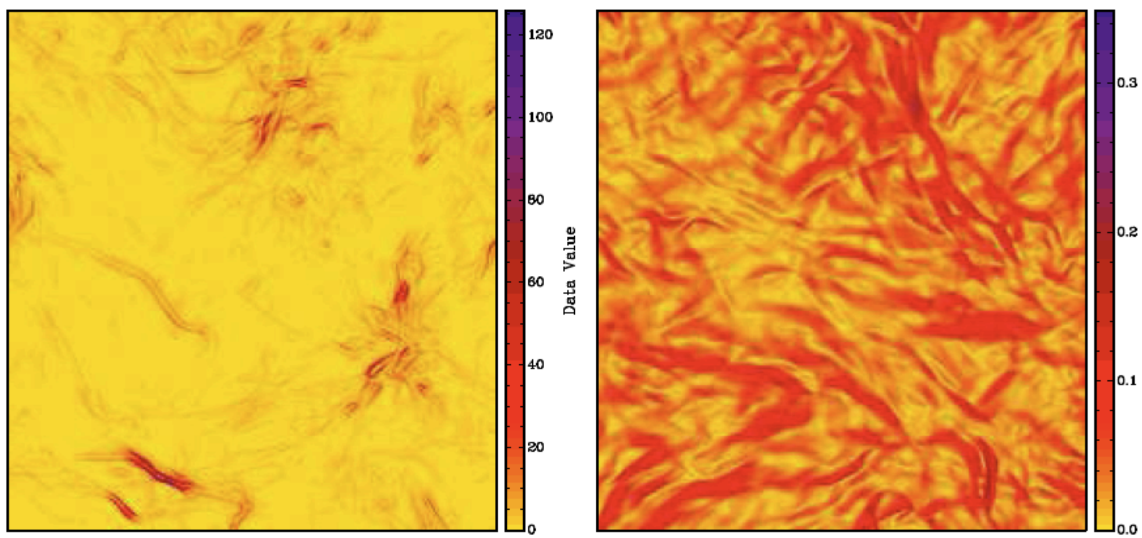
Topology: Genus statistic



G = (isolated high-density regions) - (isolated low-density regions). Relative to a set threshold value

- This is able to distinguish between a Swiss-cheese and Clump topology for a given threshold value.





Conclusions

In addition to column density and PPV data, polarization maps may also be used to measure ISM turbulence.

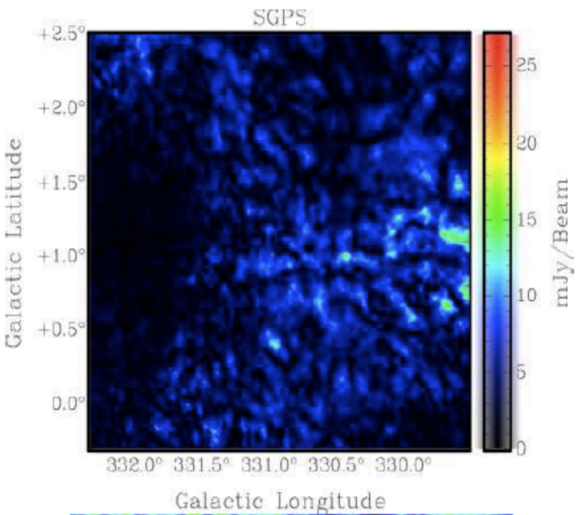
Structures seen in linear polarization maps are related to turbulence fluctuations in the ISM along the LOS. Different structures are reveled for different Mach number regimes of turbulence.

The sonic Mach numbers can be obtained from studies of polarization gradients, which do not require single dish data to be included.

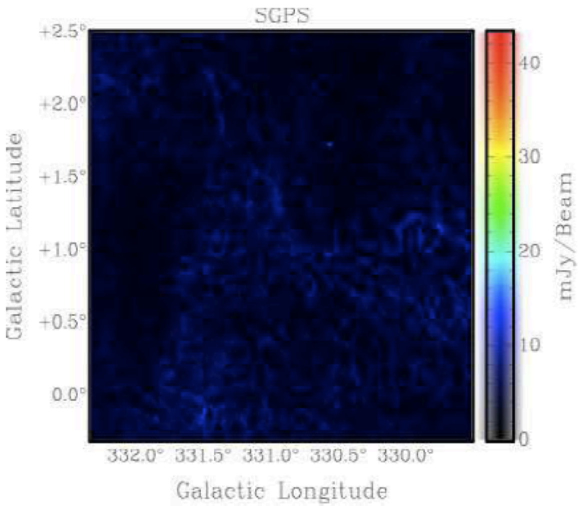
Statistical studies are indispensable for the comparison of turbulence numerics with observations or even different numerical simulations.

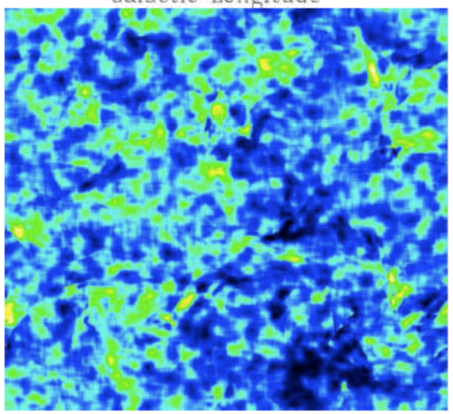
Application to Southern Galactic Plane Survey 1.4 Ghz data

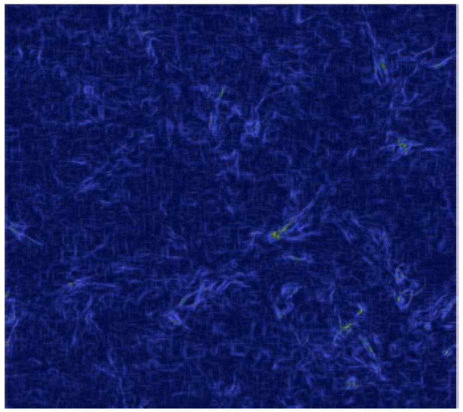
SGPS



SGPS ∇P







∇P

Subsonic Simulation

We find that the SGPS data has skewness of 0.825 and kurtosis of 0.928.

Taking smoothing into account, this falls into the range of subsonic-transonic turbulence.

Confirms what is obtained in Hill et al. 2008 for warm ionized medium.

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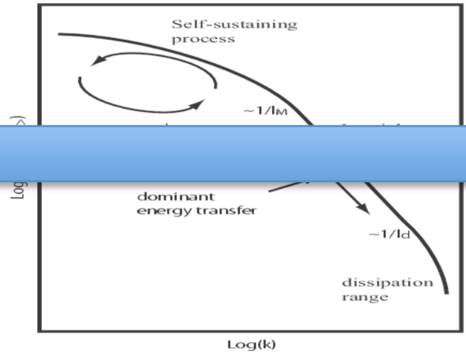
Statistical Studies



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