The Origins and Implications of MHD Turbulence

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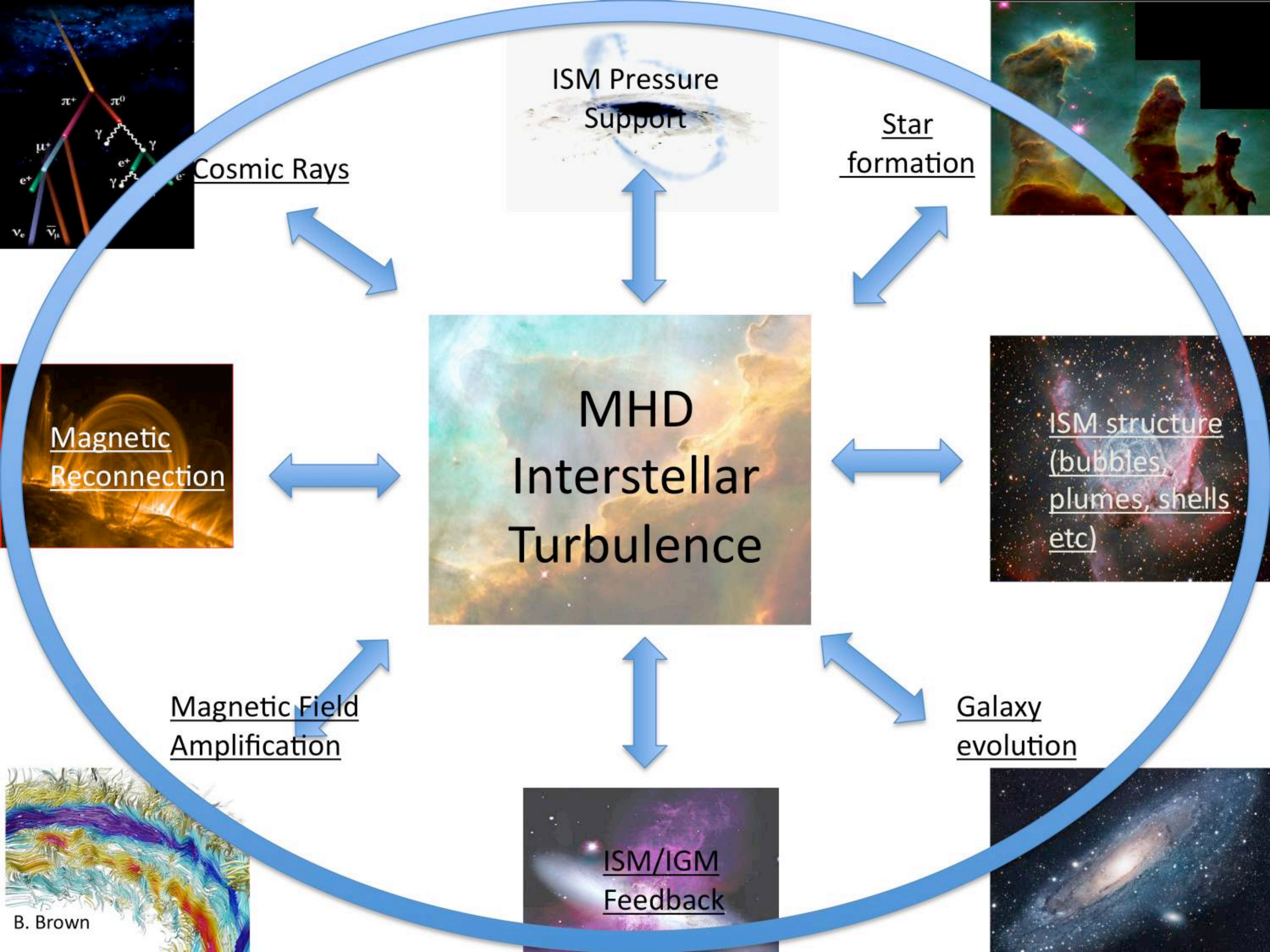


MHD Interstellar Turbulence

ISM Pressure Support

Star formation

ISM structure (bubbles, plumes, shells etc)

Galaxy evolution

ISM/IGM Feedback

Magnetic Field Amplification

Magnetic Reconnection

Cosmic Rays

B. Brown

Outline

- What is turbulence and how to study it in the ISM.

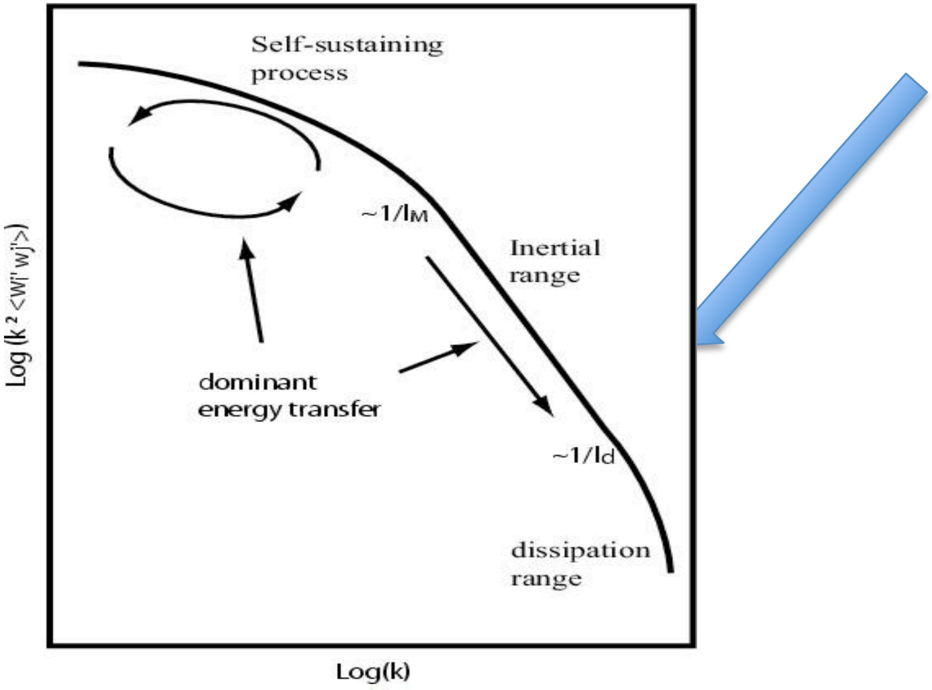
-Origins of Turbulence:

- The large scale injection of turbulence energy in galaxies (kpc driving scales): Simulations (Illustris) and observations (velocity power spectrum of the SMC in 21cm).

- Measuring Turbulence using Synchrotron

What is turbulence?

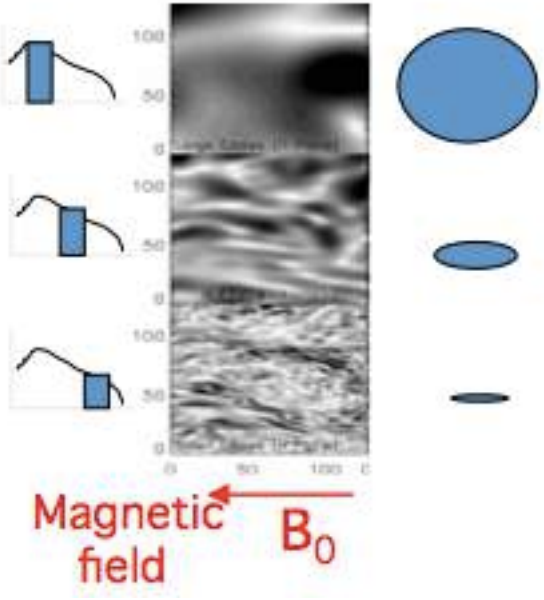
Inertial range provides: compressibility of the media, dynamic range of the cascade, and comparison with analytical predictions.



Kolmogorov 1941 scaling:
E/t~C, t~L/v →
$v \sim L^{1/3}$

$E(k) * k \sim E \sim v^2$,
$k \sim 1/L$
→

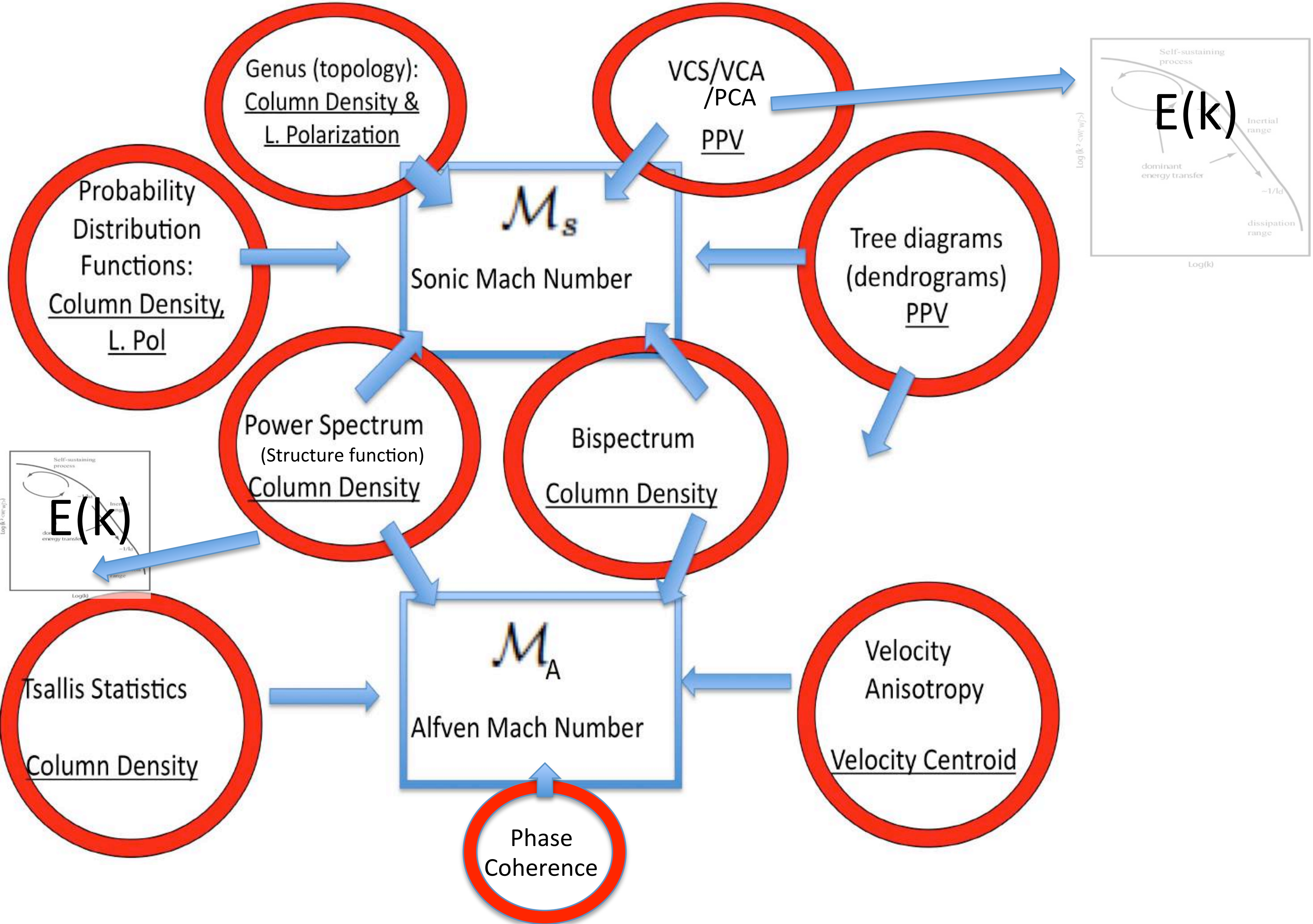
$E(k) \sim k^{-5/3}$



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

- Eddies becoming increasingly anisotropic along B with $k_{para.} \sim k_{perp.}^{2/3}$ *(scale dependen anisotropy; Goldreich & Sridhar 1995, Cho Lazarian 2003)*

Turbulence Statistics and their Dependencies



Genus (topology): Column Density & L. Polarization

VCS/VCA /PCA PPV

$\mathcal{M}_s$ Sonic Mach Number

Probability Distribution Functions: Column Density, L. Pol

Tree diagrams (dendrograms) PPV

Power Spectrum (Structure function) Column Density

Bispectrum Column Density

$\mathcal{M}_A$ Alfven Mach Number

Tsallis Statistics Column Density

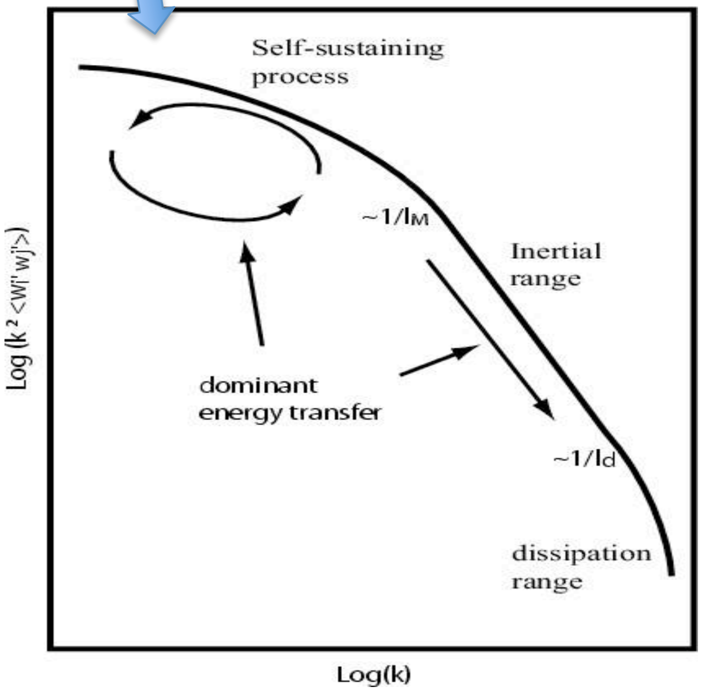
Velocity Anisotropy Velocity Centroid

Phase Coherence

The Power Spectrum and Driving of Turbulence

Where does turbulence come from?

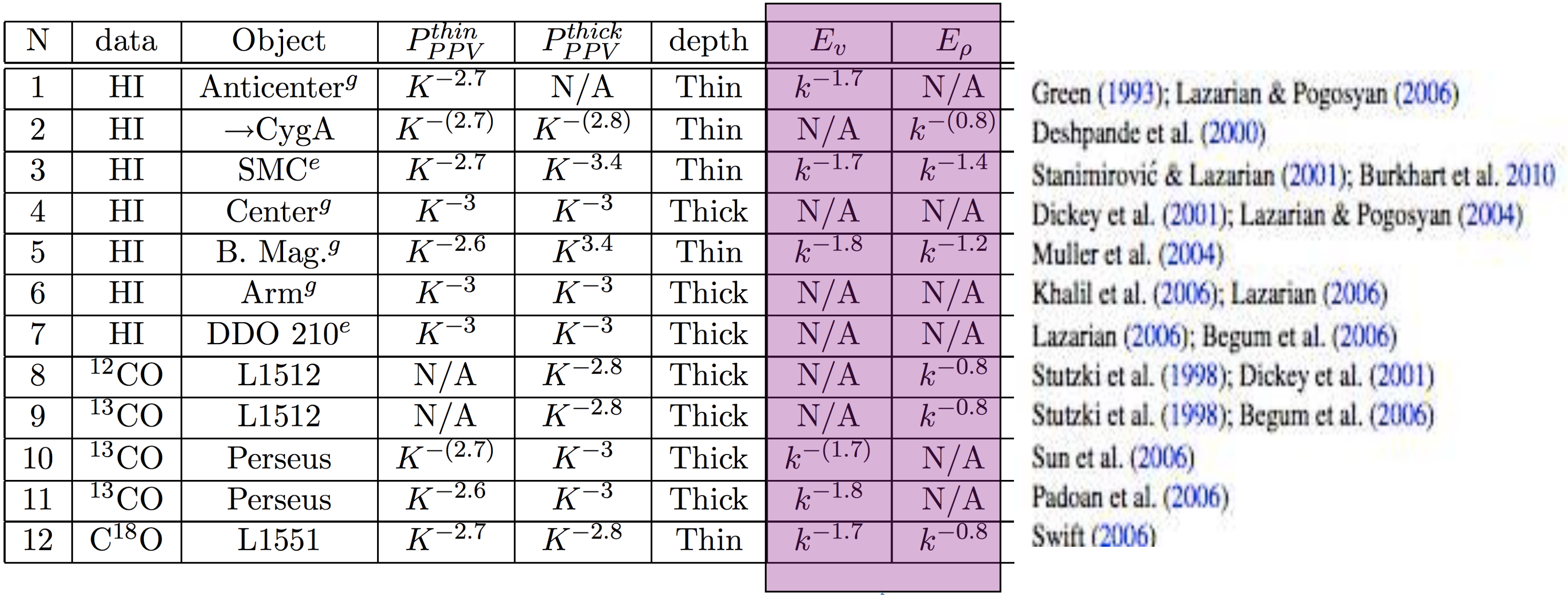
Inertial range provides: compressibility of the media, dynamic range of the cascade, and <u>comparison with analytical predictions.</u>



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



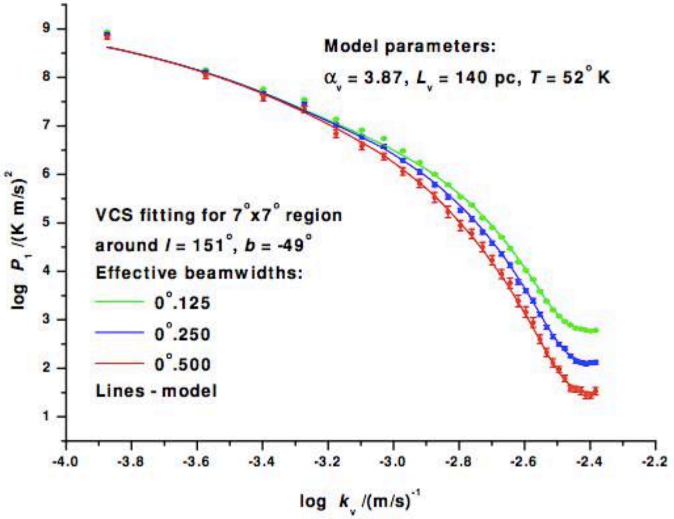
N	data	Object	P_{PPV}^{thin}	P_{PPV}^{thick}	depth	E_v	E_ρ	
1	HI	Anticenter^g	$K^{-2.7}$	N/A	Thin	$k^{-1.7}$	N/A	Green (1993); Lazarian & Pogosyan (2006)
2	HI	→CygA	$K^{-(2.7)}$	$K^{-(2.8)}$	Thin	N/A	$k^{-(0.8)}$	Deshpande et al. (2000)
3	HI	SMC^e	$K^{-2.7}$	$K^{-3.4}$	Thin	$k^{-1.7}$	$k^{-1.4}$	Stanimirović & 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)

From Burkhart et al. 2013

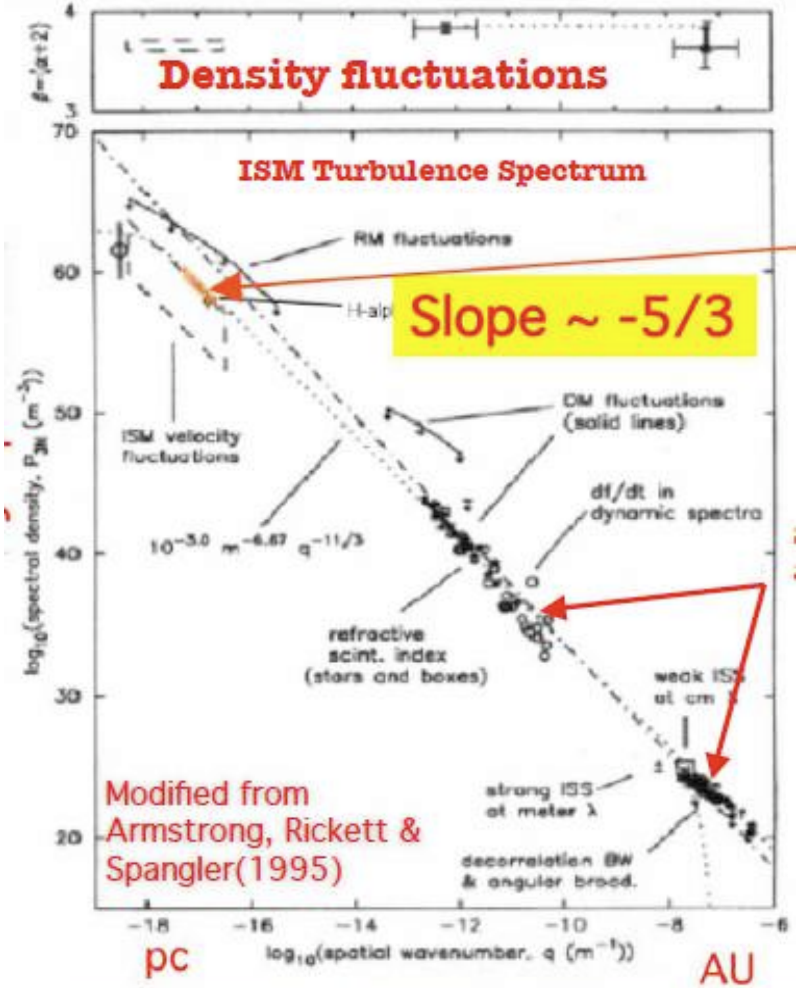
Density and velocity power spectrum from Lazarian & Pogosyan (2000, 2004) Velocity Coordinate Analysis (VCA) method.

Observations of driving scale in multiphase ISM suggest driving on scales larger than clouds (L > 1pc-10pc).

WNM/CNM High Lat. Clouds (Chepurnov et al. 2010), VCS



Electron density (WIM) power spectrum:



Density fluctuations

ISM Turbulence Spectrum

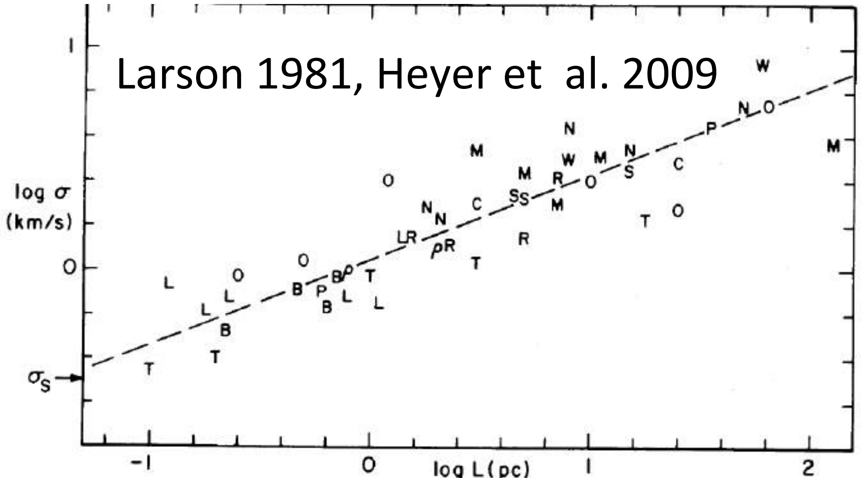
Slope ~ -5/3

Modified from Armstrong, Rickett & Spangler(1995)

pc

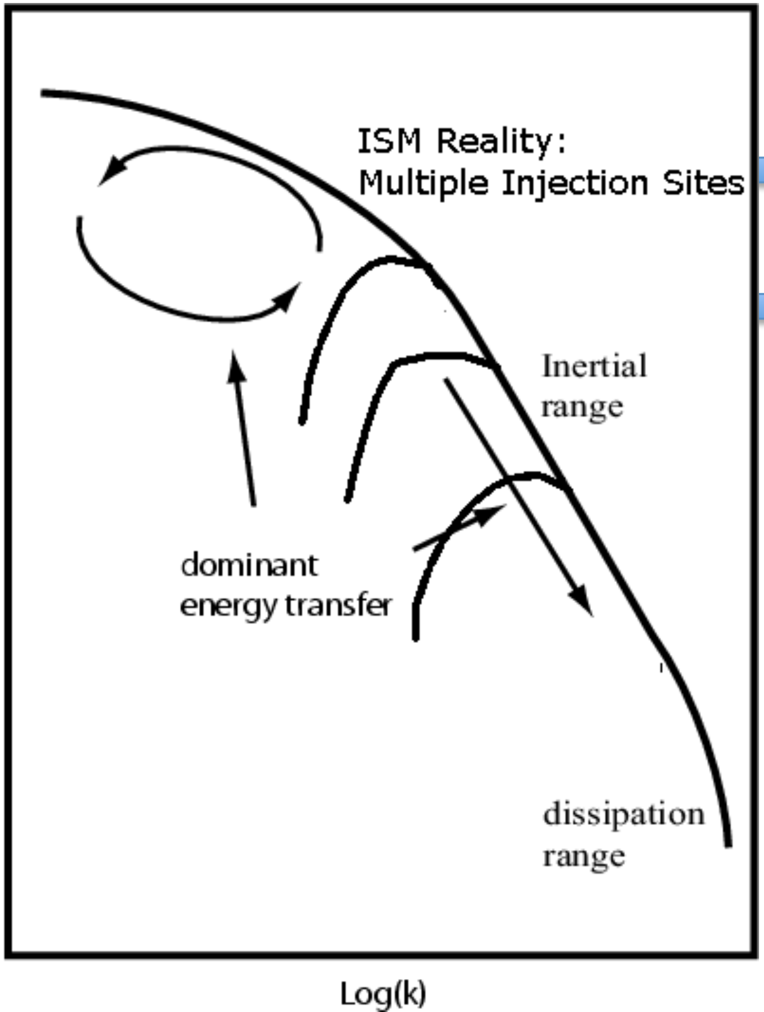
AU

Molecular medium (line width-size)



Larson 1981, Heyer et al. 2009

Origins of Turbulence: Multiple Drivers



<u>1000 Pc scales:</u>
Galaxy mergers (major/minor),
Expanding shells, Gravitational instability

<u>100 Pc scales:</u>
supernova, expanding shells,
MRI, cloud collisions

<u>10 pc-sub-pc scales:</u>
Winds, outflows, stellar feedback,
stellar wakes

Supernova as Driver of Turbulence

Energy dissipation rate per unit volume: $\varepsilon_V \simeq \rho \frac{v_0^3}{l_0} \simeq 5 \times 10^{-27}\,\mathrm{erg\,cm^{-3}\,s^{-1}}$.

- Energy sources of the interstellar turbulence

Driving mechanism	ε_V, $\mathrm{erg\,cm^{-3}\,s^{-1}}$
Supernova explosions	3×10^{-26}
Stellar winds	3×10^{-27}
Protostellar outflows	2×10^{-28}
Stellar ionizing radiation	5×10^{-29}
Galactic spiral shocks	4×10^{-29}
Magneto-rotational instability	3×10^{-29}
H II regions	3×10^{-30}

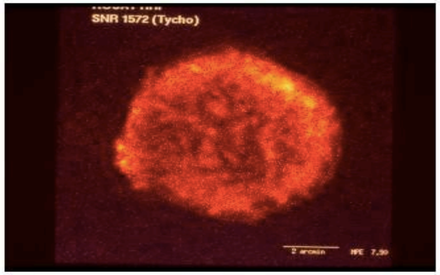
Mac Low & Klessen 2004; Elmegreen & Scalo 2004

Turbulence driven by supernovae

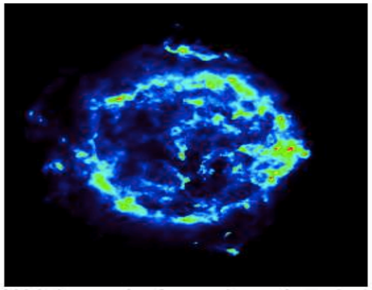
Supernova remnants: expanding bubbles of hot gas, magnetic fields & relativistic particles

Crab nebula: optical image

Tycho supernova: X-rays

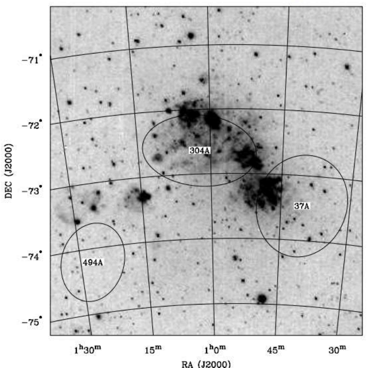


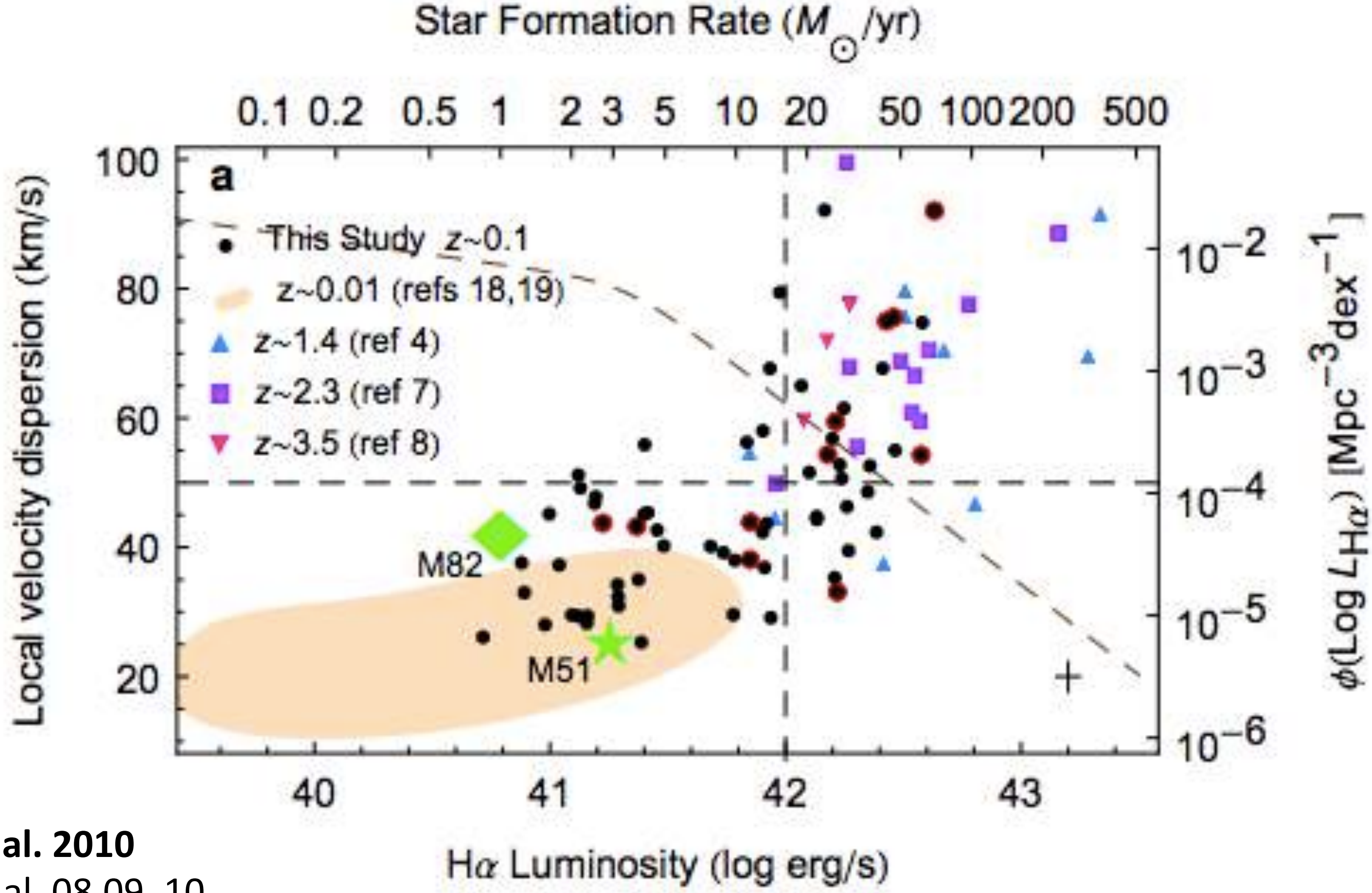
Cas A: radio image ($\lambda 6\,\mathrm{cm}$)



Wright et al., Astrophys. J. **518**, 284, 1

HI shells (Stanimirovic et al. 1999)



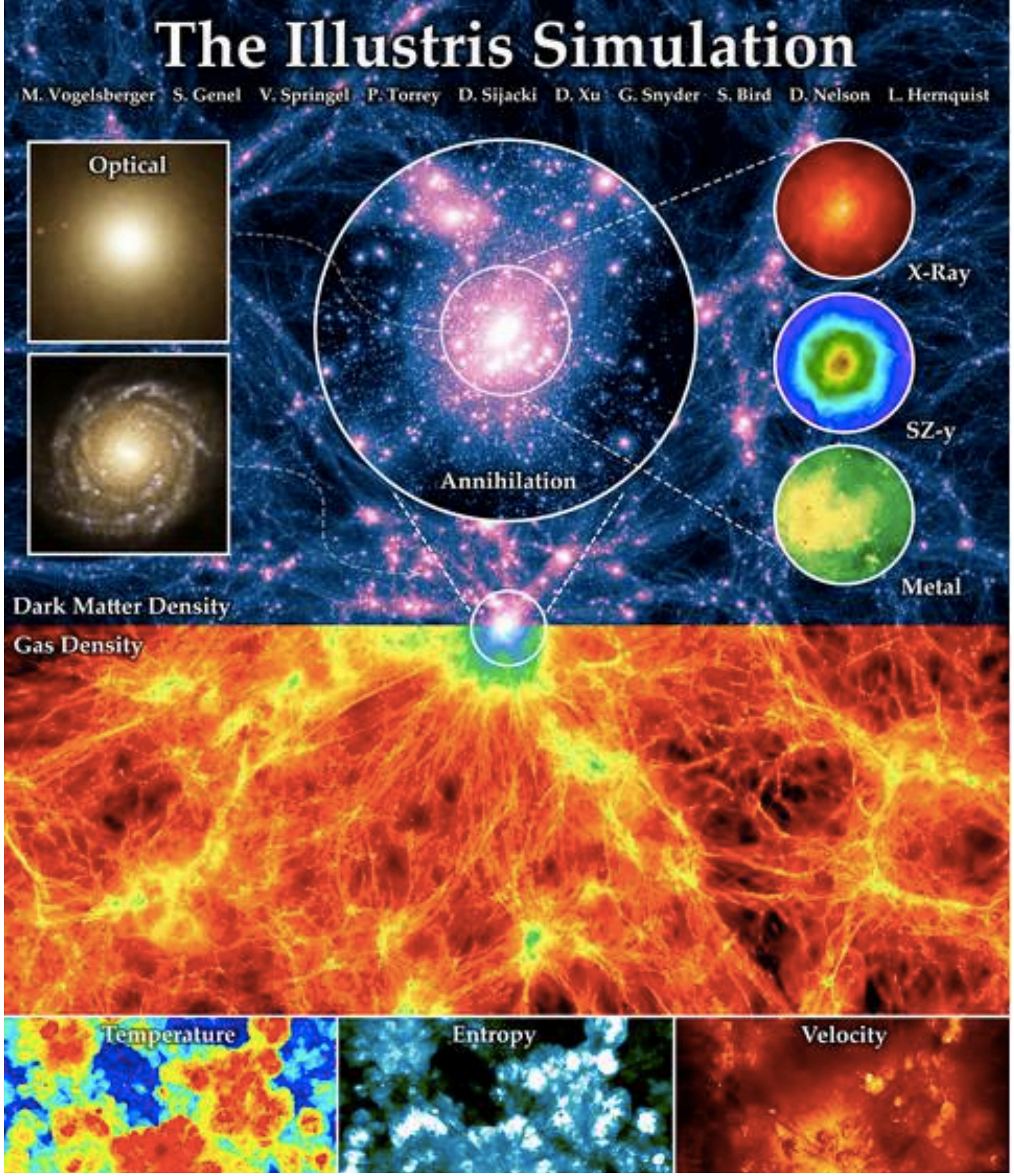


Green et al. 2010
Epinat et al. 08,09, 10
Law et al. 2009
Lemoine-Busserolee et al. 2010

~2.3 kpc resolution

What sets this correlation on kpc scales? GMC physics?

Do cosmological simulations reproduce the observations of the SFR- velocity dispersion relation?

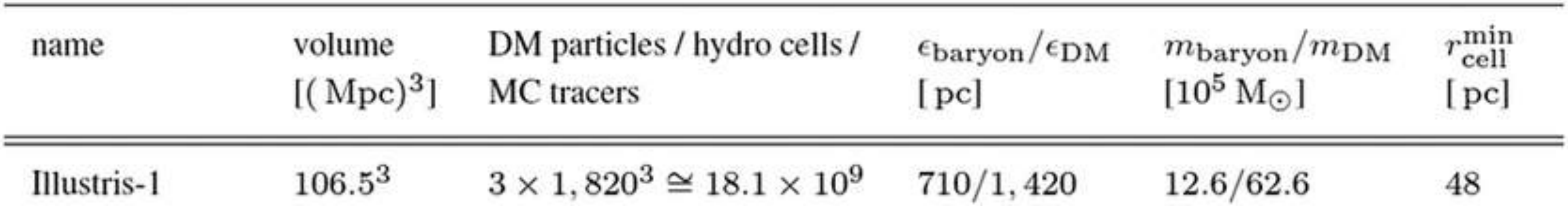


~1kpc resolution
No GMC physics is resolved!

$$\rho_{\rm th} = 0.13\ {\rm cm}^{-3}$$

$$t_\star(\rho) = t_0^\star \left(\frac{\rho}{\rho_{\rm th}}\right)^{-1/2} \quad t_0^\star = 2.2\ {\rm Gyr.}$$

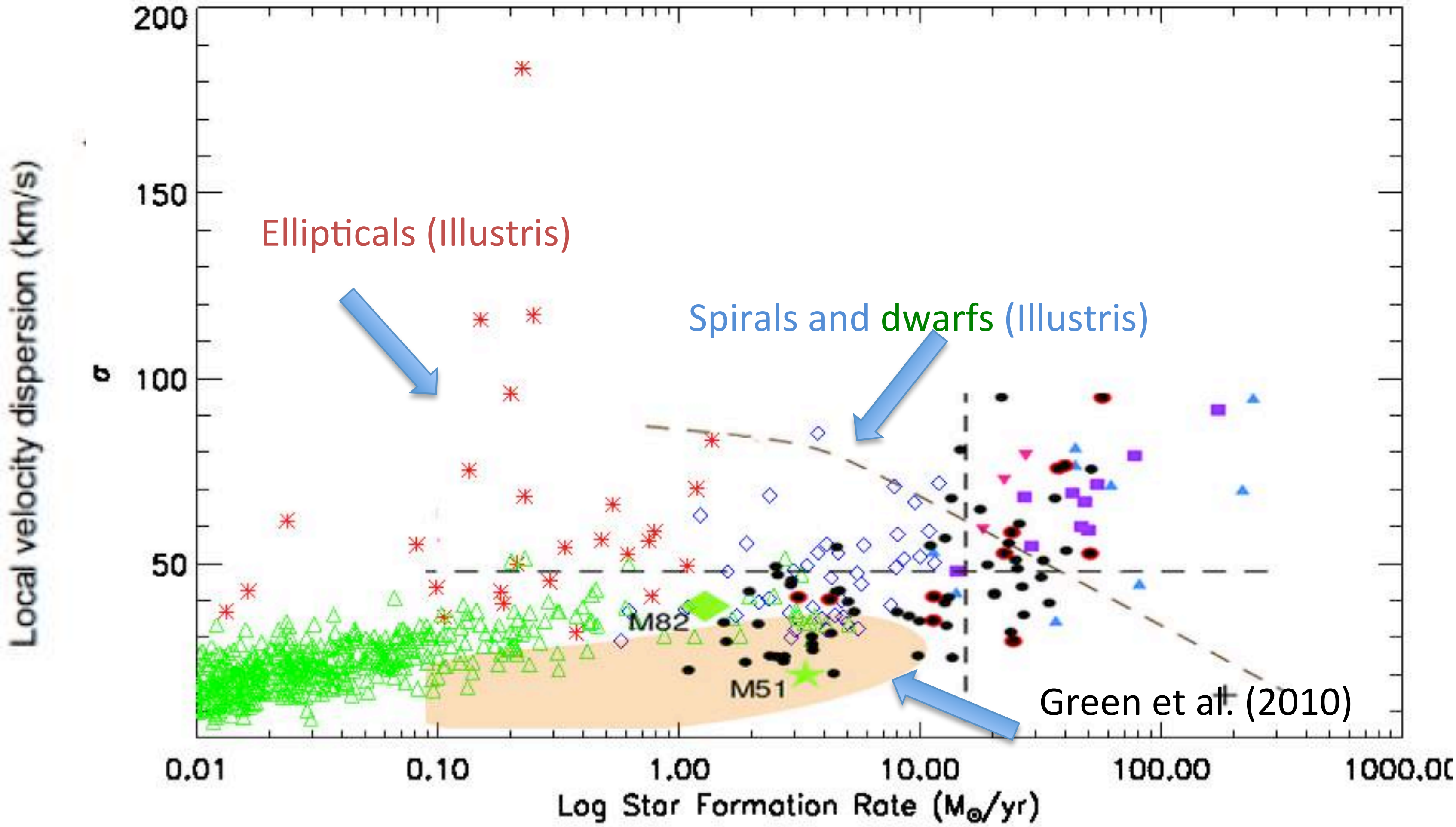
Image Credit: Illustris Collaboration



name	volume [(Mpc)^3]	DM particles / hydro cells / MC tracers	$\epsilon_{\rm baryon}/\epsilon_{\rm DM}$ [pc]	$m_{\rm baryon}/m_{\rm DM}$ [10^5 M$_\odot$]	$r_{\rm cell}^{\rm min}$ [pc]
Illustris-1	106.5^3	$3 \times 1,820^3 \cong 18.1 \times 10^9$	$710/1,420$	$12.6/62.6$	48

Star formation rate vs. velocity dispersion

GMC/cloud scale physics not required to set this relationship!



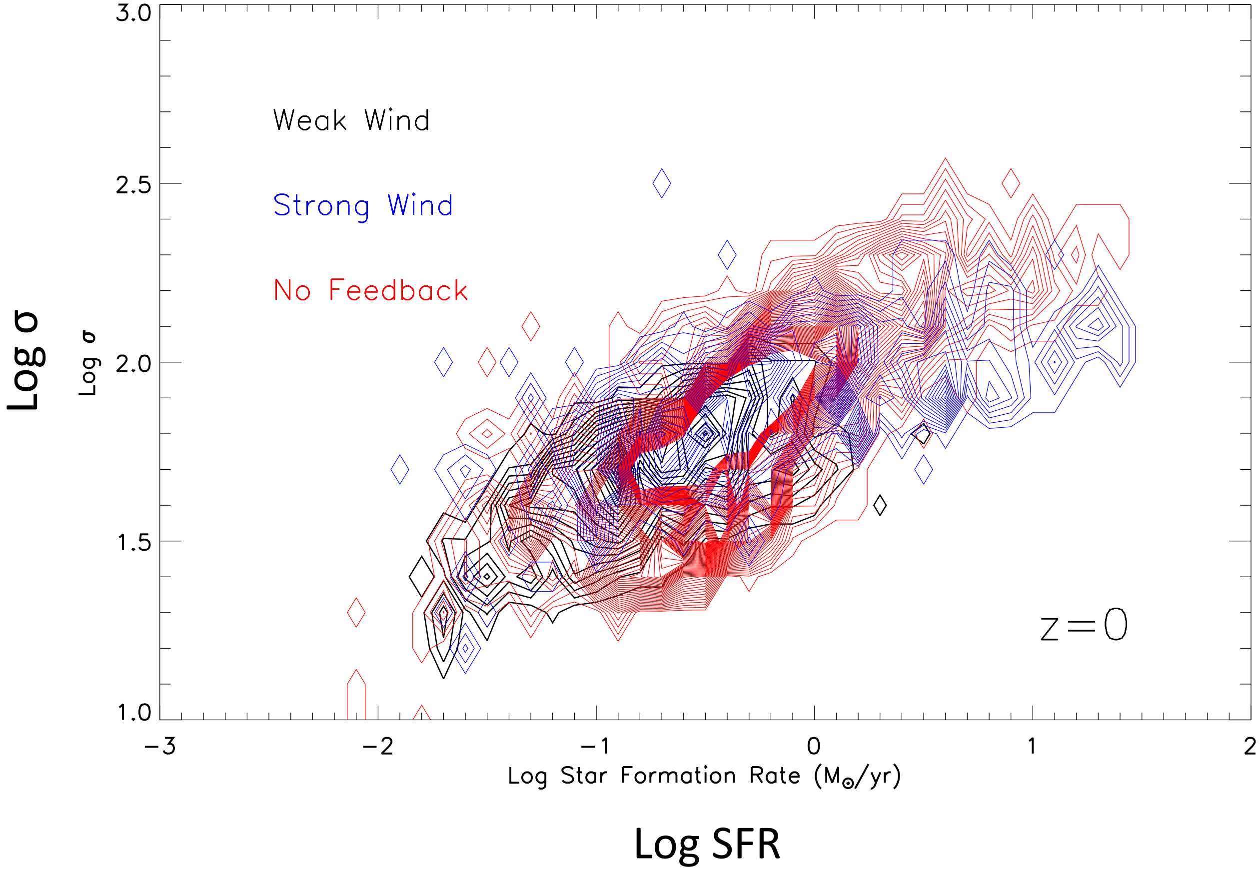
Ellipticals (Illustris)

Spirals and dwarfs (Illustris)

Green et al. (2010)

Burkhart, Genel, Pillepich, Hernquist, 2015, in prep.

SFR-σ relation is not caused by sub-grid feedback model



Alternative explanation!

High velocity dispersions set by mergers and gravitational instability (i.e. see Forbes et al. 2013)

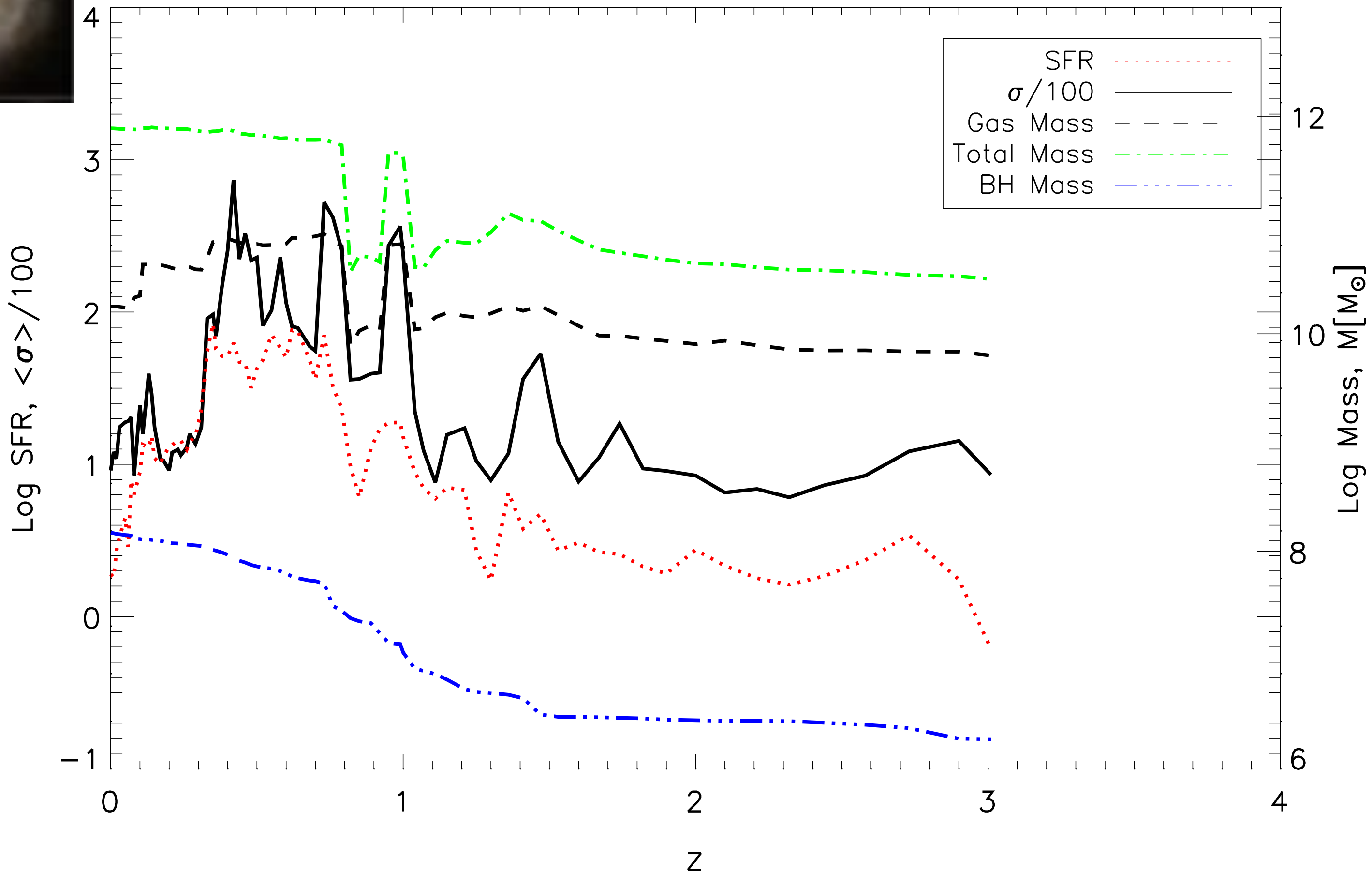
$$Q_{\mathrm{Toomre}} = \frac{\kappa \sigma_{\mathrm{d}}}{\pi G \Sigma_{gas}}$$

$$\Sigma_{SFR} \propto (\Sigma_{gas})^n$$

Burkhart, Genel, Pillepich, Hernquist, 2015, in prep.

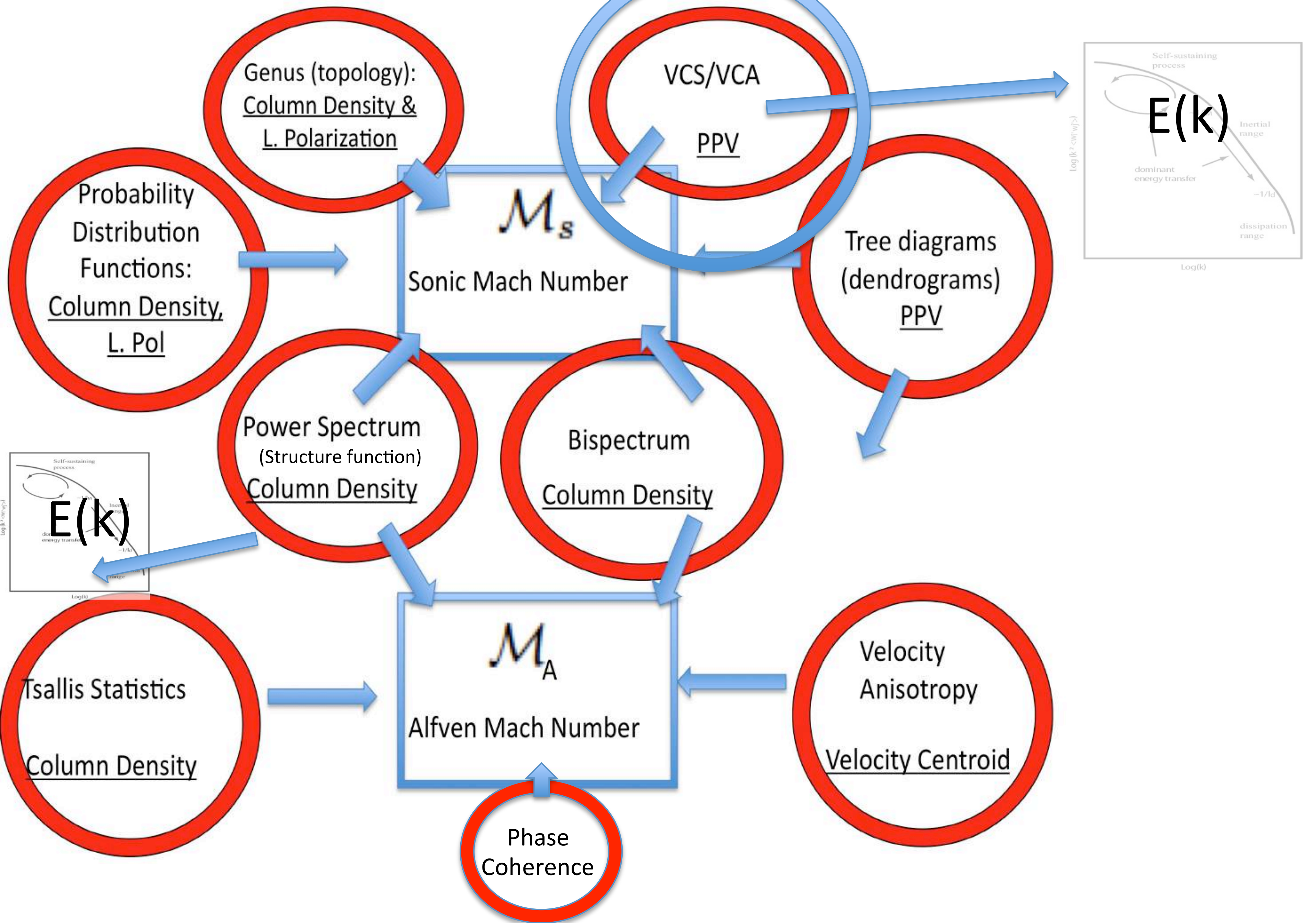
Mergers can also inject turbulence at kpc scales

Is there observational evidence for merger induced driving of turbulence?


Illustris Simulation

Burkhart, Genel, Pillepich, Hernquist, 2015, in prep.

Turbulence Statistics and their Dependencies



Genus (topology):
Column Density &
L. Polarization

VCS/VCA

PPV

E(k)

Probability
Distribution
Functions:
Column Density,
L. Pol

$\mathcal{M}_s$

Sonic Mach Number

Tree diagrams
(dendrograms)
PPV

Power Spectrum
(Structure function)
Column Density

Bispectrum

Column Density

E(k)

$\mathcal{M}_A$

Alfven Mach Number

Tsallis Statistics

Column Density

Velocity
Anisotropy

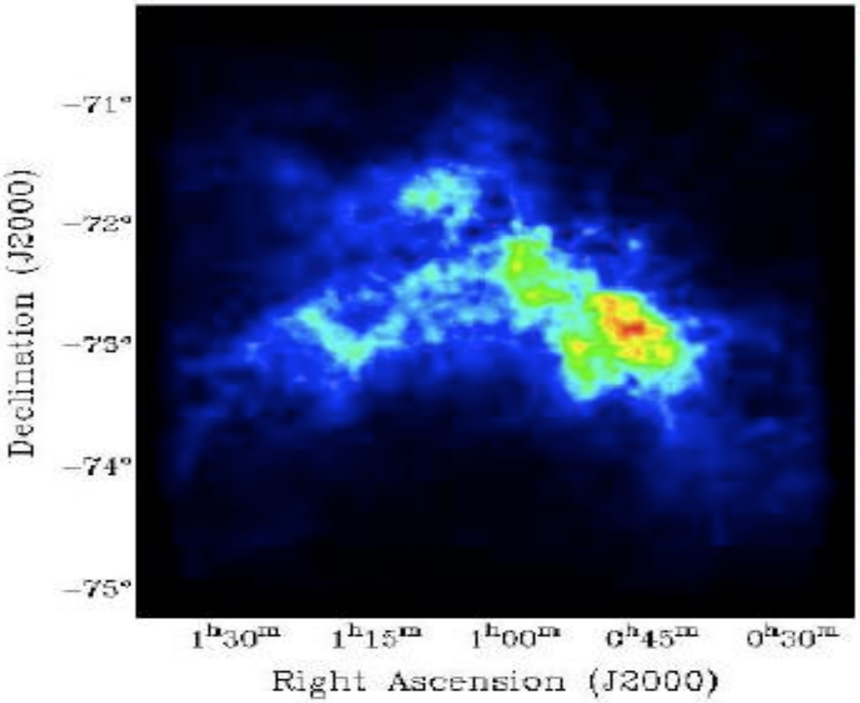
Velocity Centroid

Phase
Coherence

Observational test case: SMC in 21 cm emission

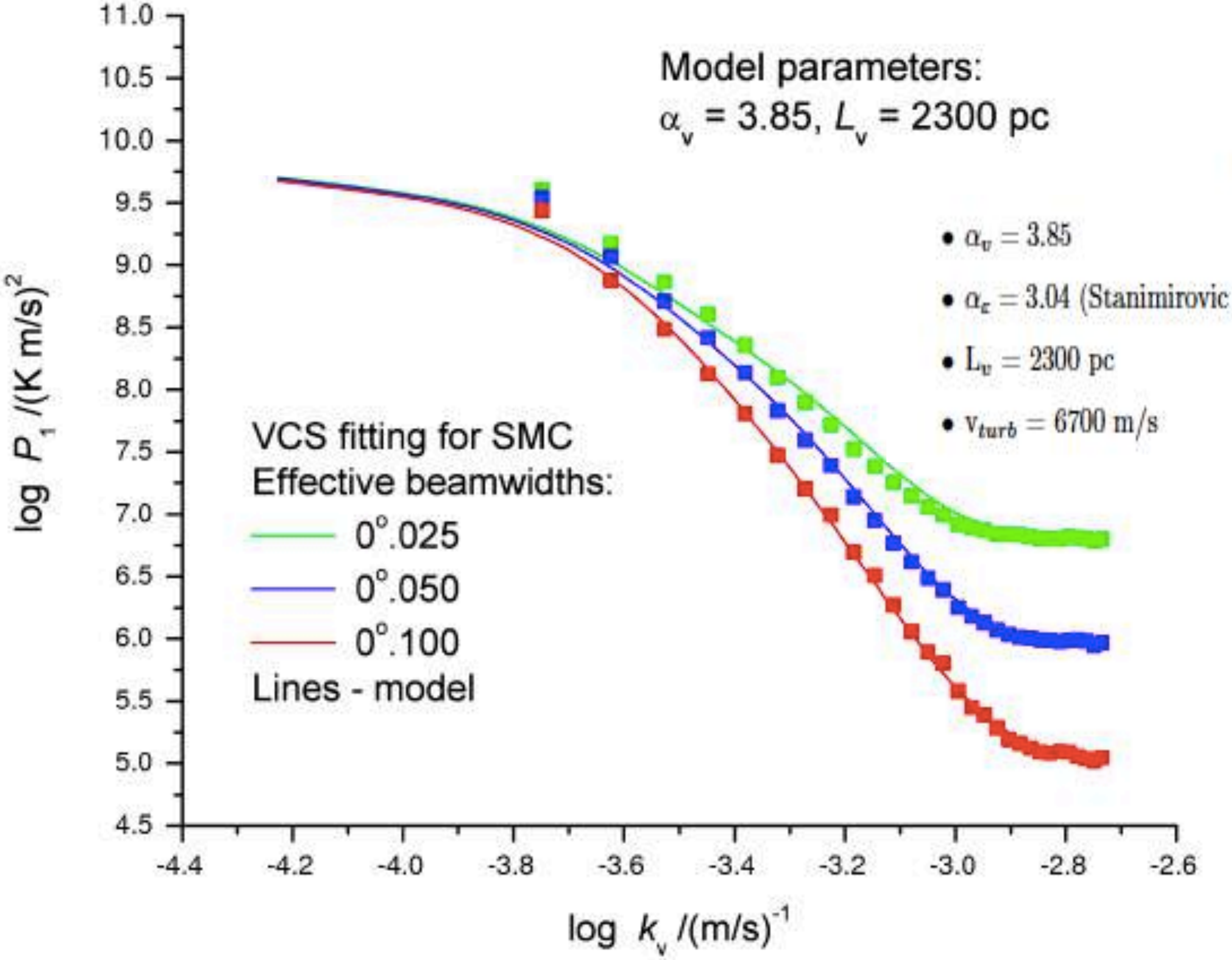
Radio data is ideal for studies of turbulence because it contains information about turbulence velocity along the LOS

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).



VCS of SMC (21cm)

Chepurnov, Burkhart, Lazarian & Stanimirovic 2015

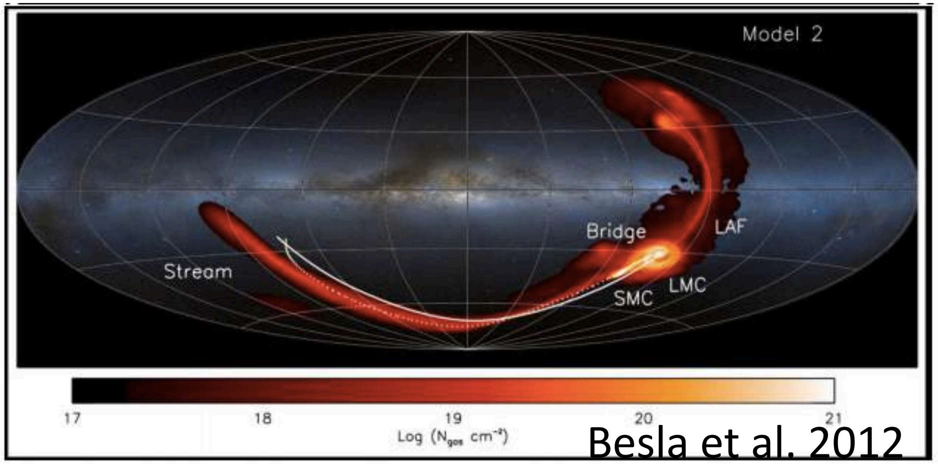


$$F_{ij}(\mathbf{k}) = \frac{V_0^2}{k^{\alpha_v}} e^{-\frac{k_0^2}{k^2}}$$

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

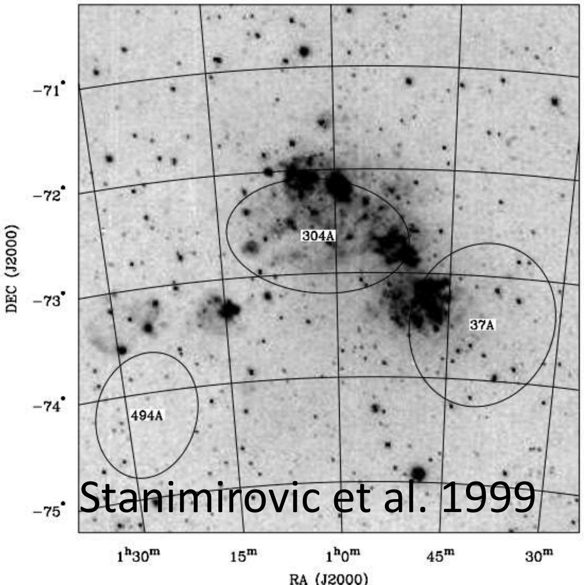
Q: What drives turbulence in the SMC?

A: Combination of both SF and Mergers!



Besla et al. 2012

LMC/SMC most likely have already interacted: Tidal stripping of SMC



Stanimirovic et al. 1999

HI Supershells seen on kpc sizes!

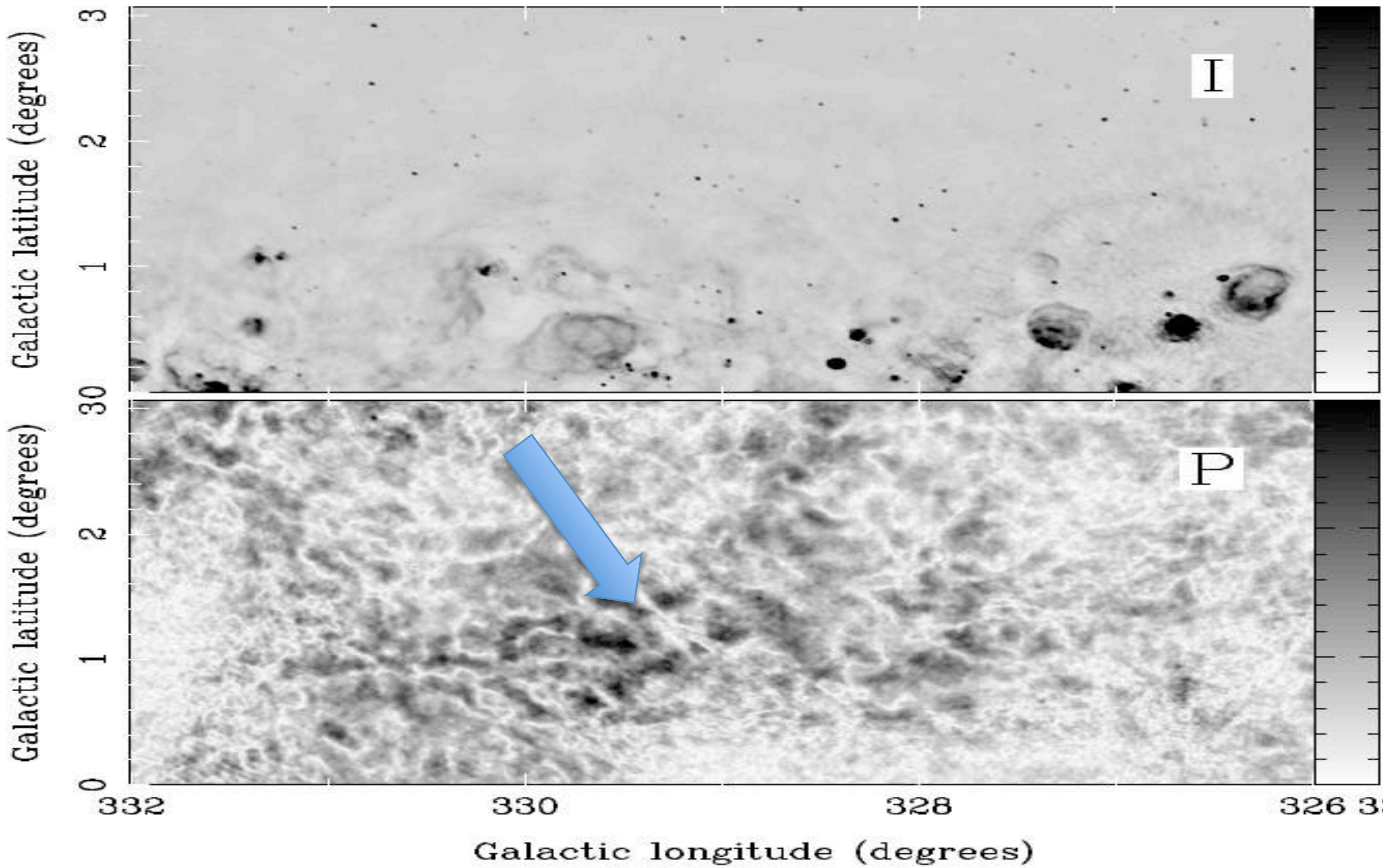
Chepurnov, Burkhart, Lazarian & Stanimirovic 2015

Turbulence & Polarization Maps:

1.4 Ghz Southern Galactic Plane Survey (SGPS)

Gaensler et al. 2001

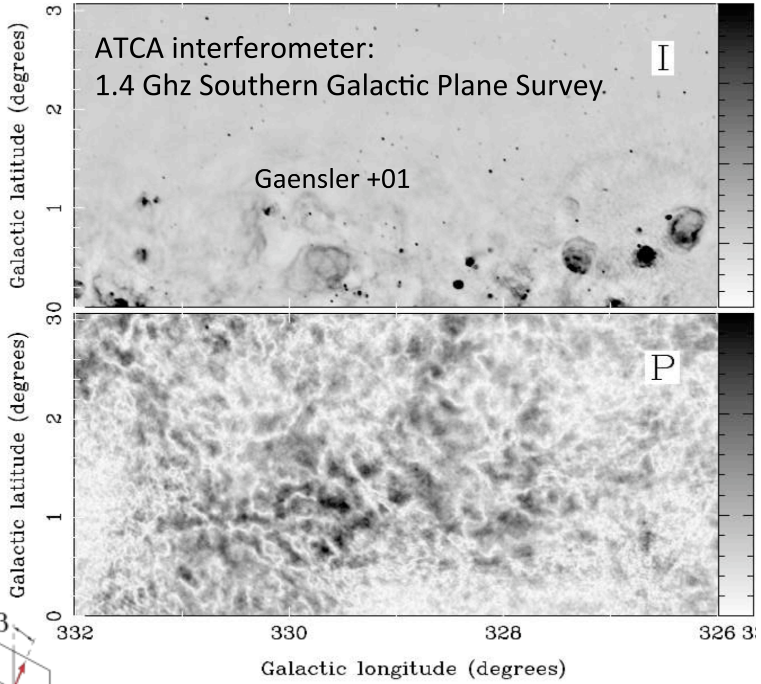
ATCA interferometer



Question: What are these filamentary structures seen in Stokes P but not total intensity?

Linear polarization gradients → Turbulence

Structures are due to Faraday Rotation along LOS…



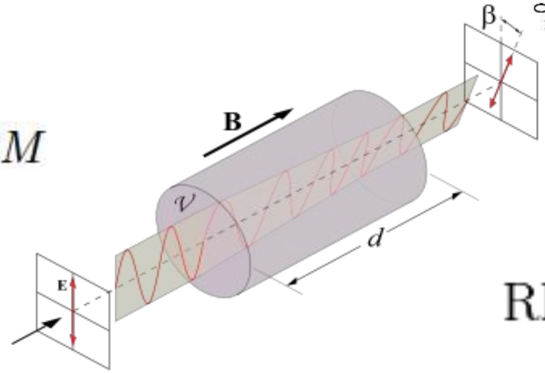
ATCA interferometer:
1.4 Ghz Southern Galactic Plane Survey

Gaensler +01

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.

$\nabla \mathbf{P}$ can be related to more theoretically motivated ∇RM



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

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

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

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

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

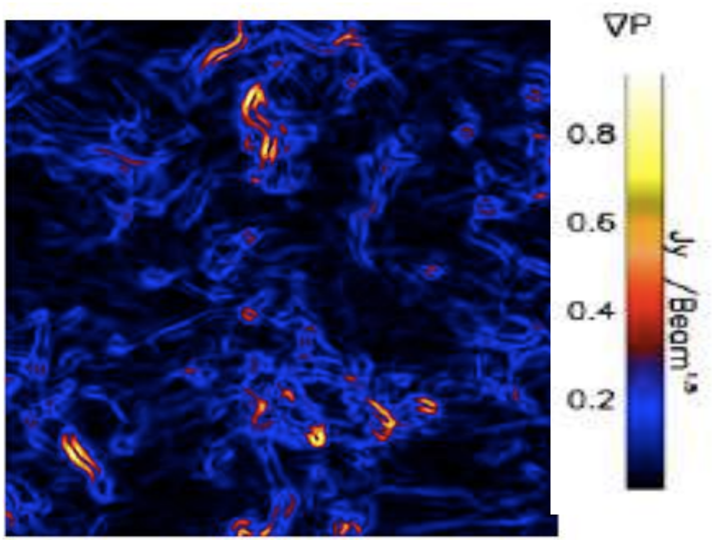
Gradients of Polarization Data: Simulations and Statistics

Post process simulations to linear polarization with external Faraday rotation

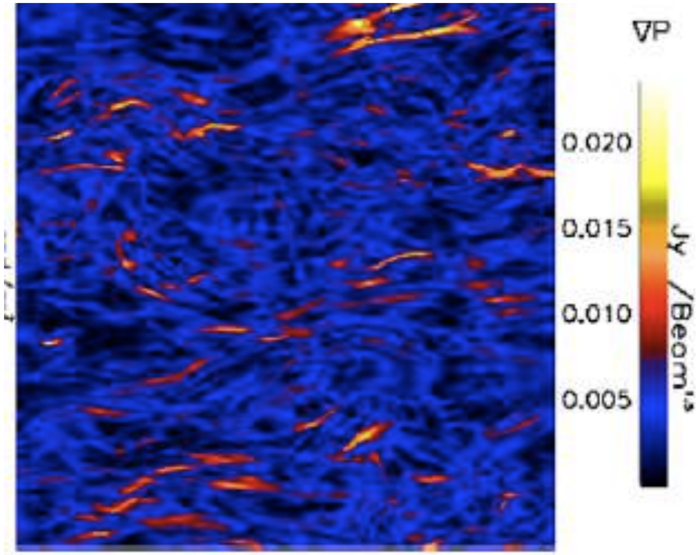
$$\mathrm{RM} = \frac{e^3}{2\pi m^2 c^4} \int_0^d n_e(s) B_{||}(s)\, \mathrm{d}s \qquad |\nabla RM| = |\nabla \mathbf{P}|\lambda^2/2|\mathbf{P}|$$

(Gaensler et al. 2011 Nature and Burkhart, Lazarian & Gaensler 2012 ApJ)

Supersonic ∇P



Subsonic ∇P



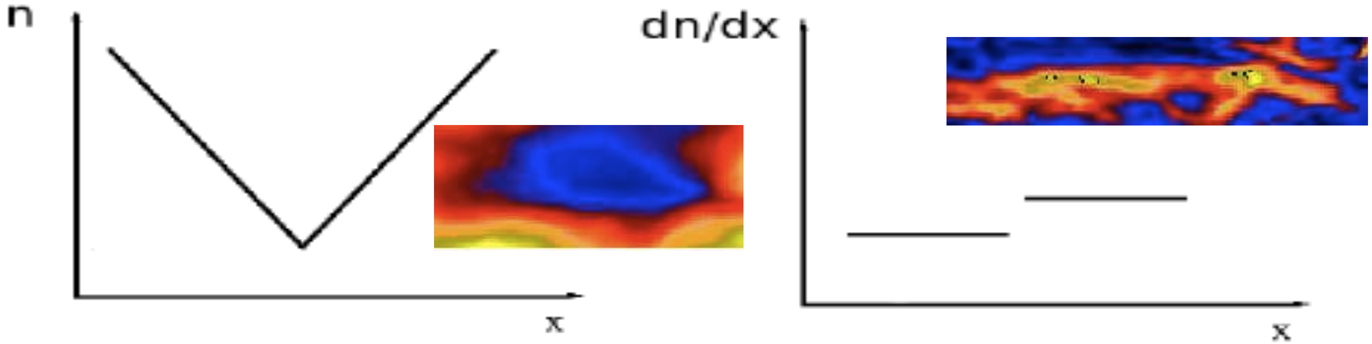
Filaments due to supersonic and subsonic turbulence are different in:

1) Topology
2) PDFs

Gradients of Turbulent Fields: Topology

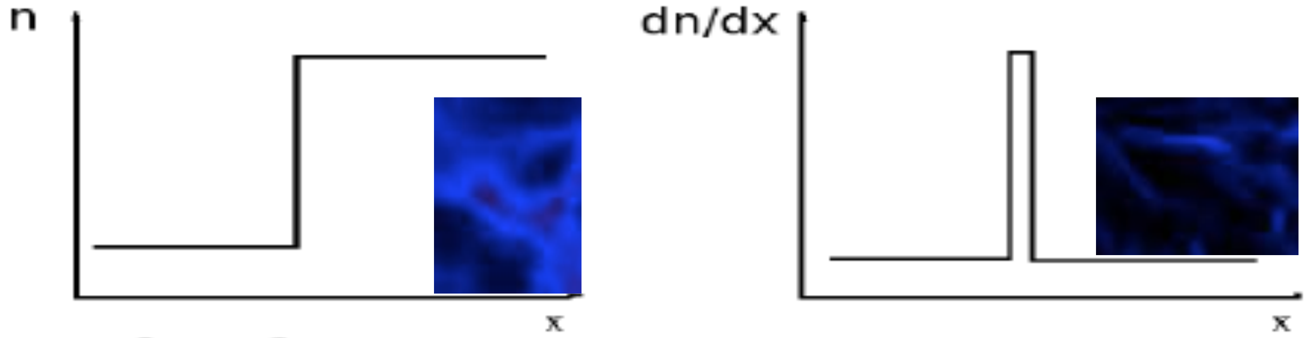
Burkhart, Lazarian & Gaensler 2012

Case 1



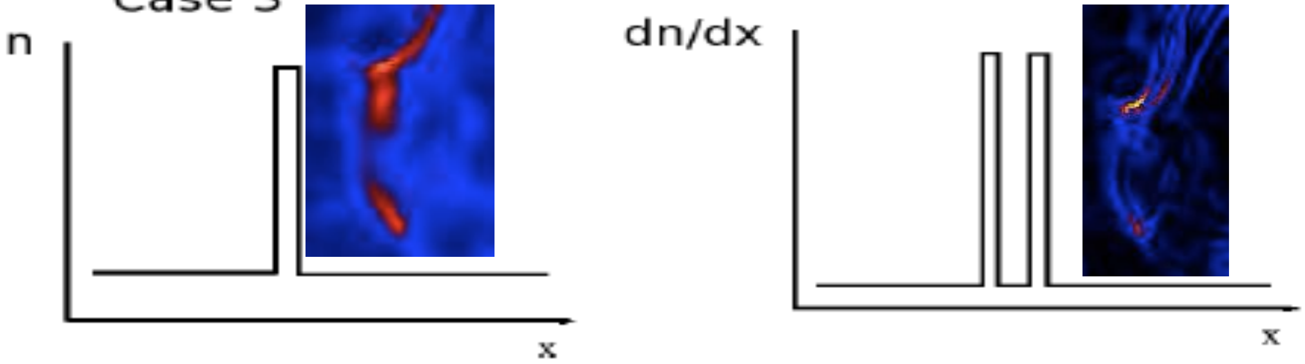
Example:
Any fractal function..
All turbulence!

Case 2



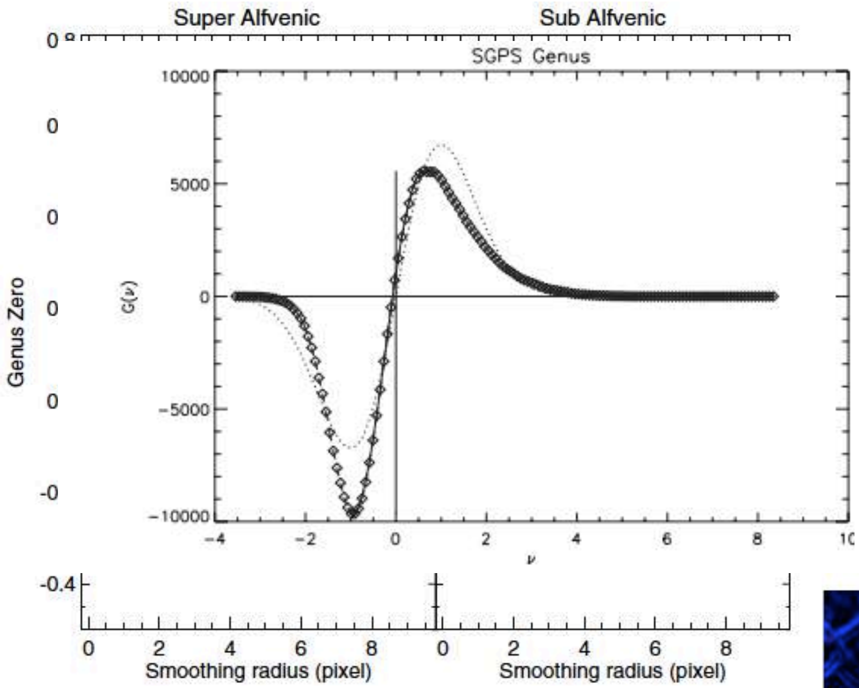
Example:
Strong fluctuations,
weak shocks…
transsonic turbulence

Case 3



Example:
Strong interacting
Shocks…high Mach
number!

Topology: Genus statistic

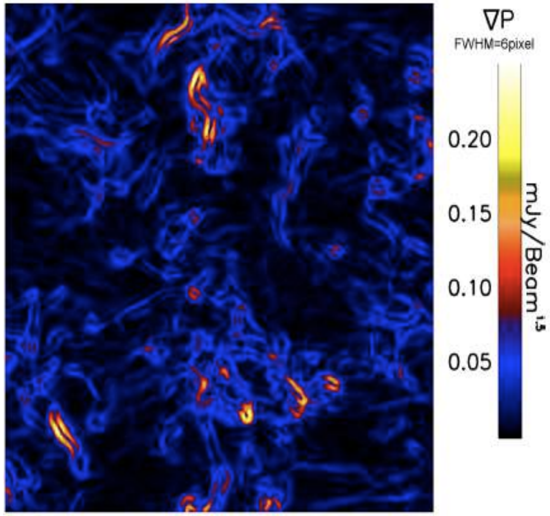


G = (isolated high-density regions) - (isolated low-density regions). Relative to a set threshold value

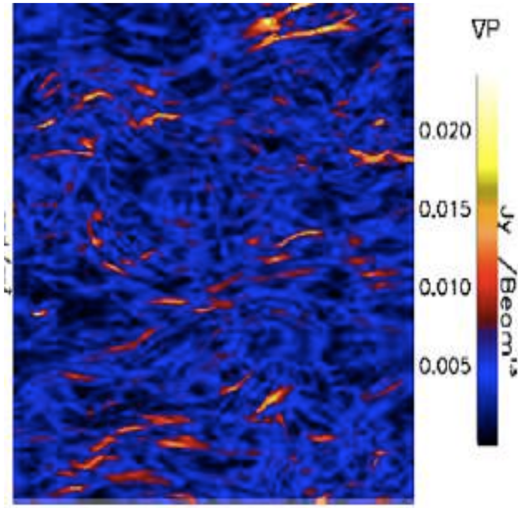
This is able to distinguish between a Swiss-cheese and Clump topology for a given threshold value.

Positive Genus zero implies hole topology.

Negative genus zero implies clump topology.



supersonic



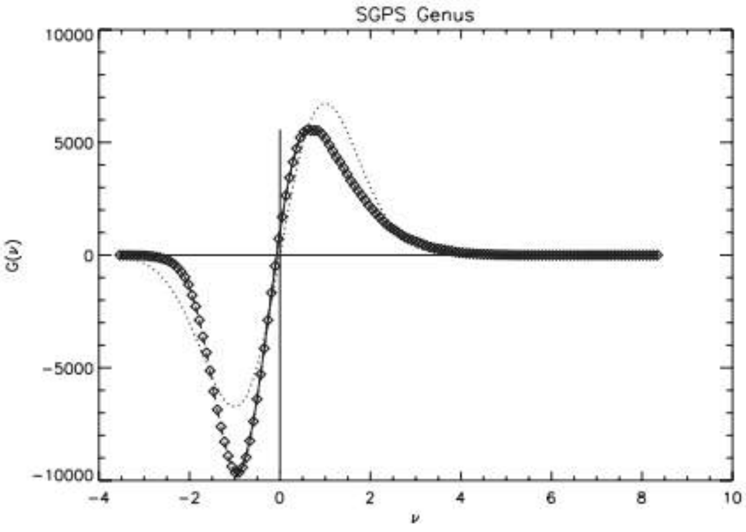
subsonic

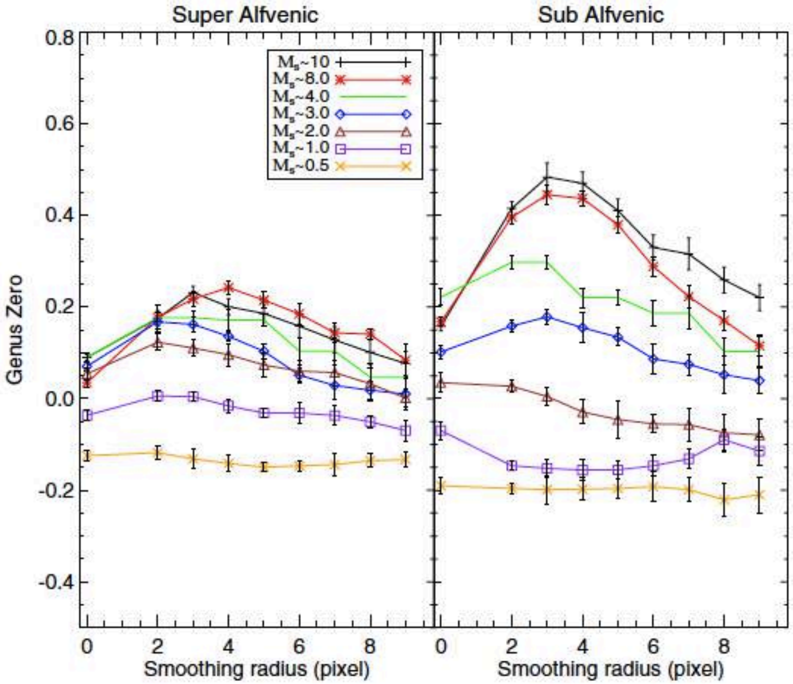
Burkhart, Lazarian & Gaensler 2012

Application: SGPS test region

Burkhart, Lazarian & Gaensler 2012

Genus SGPS



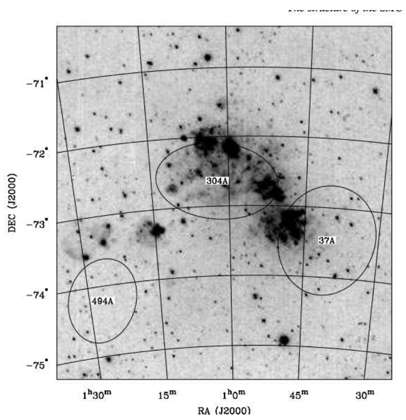


Genus zero of SGPS test region for different smoothing degree is: -0.09 to -0.03; Indicating M_s=1-2

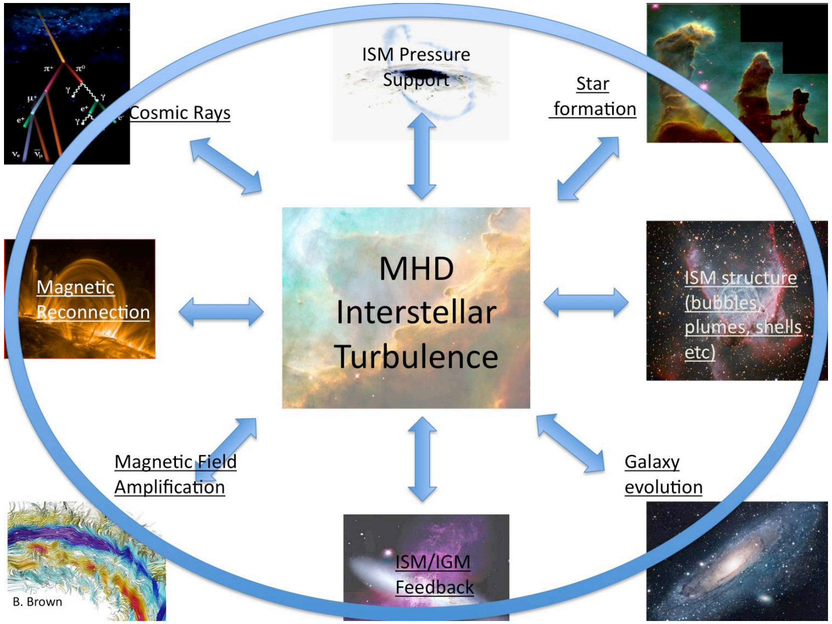
<u>WIM in the SGPS test region is subsonic to transonic which agrees with Hill et al. 2008 dispersion measure analysis</u>

Summary

Origins of Turbulence



Implications of Turbulence



MHD Interstellar Turbulence

ISM Pressure Support

Star formation

Cosmic Rays

Magnetic Reconnection

ISM structure (bubbles, plumes, shells etc)

Magnetic Field Amplification

Galaxy evolution

ISM/IGM Feedback

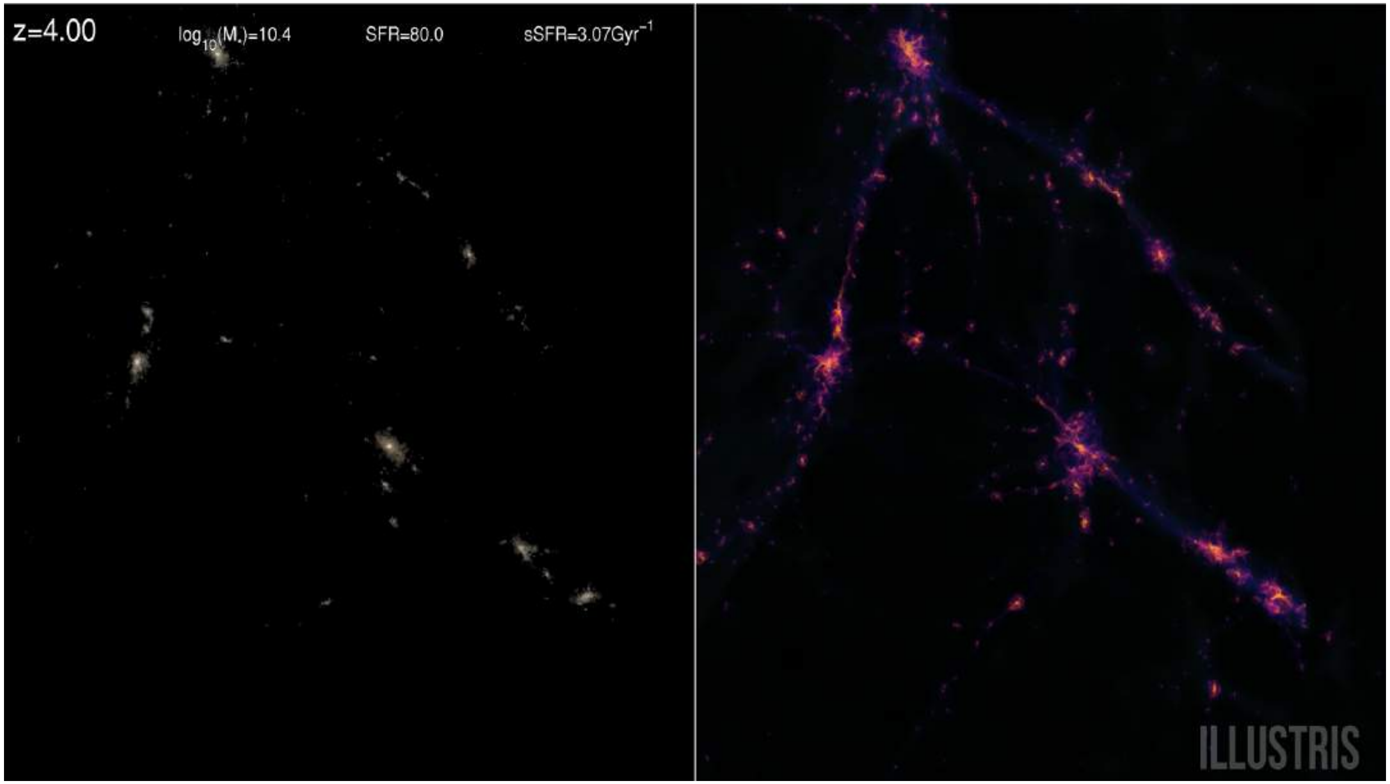
1) Diagnostics for studies of turbulence are able to obtain the sonic and Alfven Mach number and power spectrum!

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

3) Turbulence can be driving on kpc scales by expanding shells, gravitational instabilities, and galaxy-galaxy interactions (e. g. SMC).

4) Topology of linear polarization gradients can trace the sonic and Alfvenic Mach number.

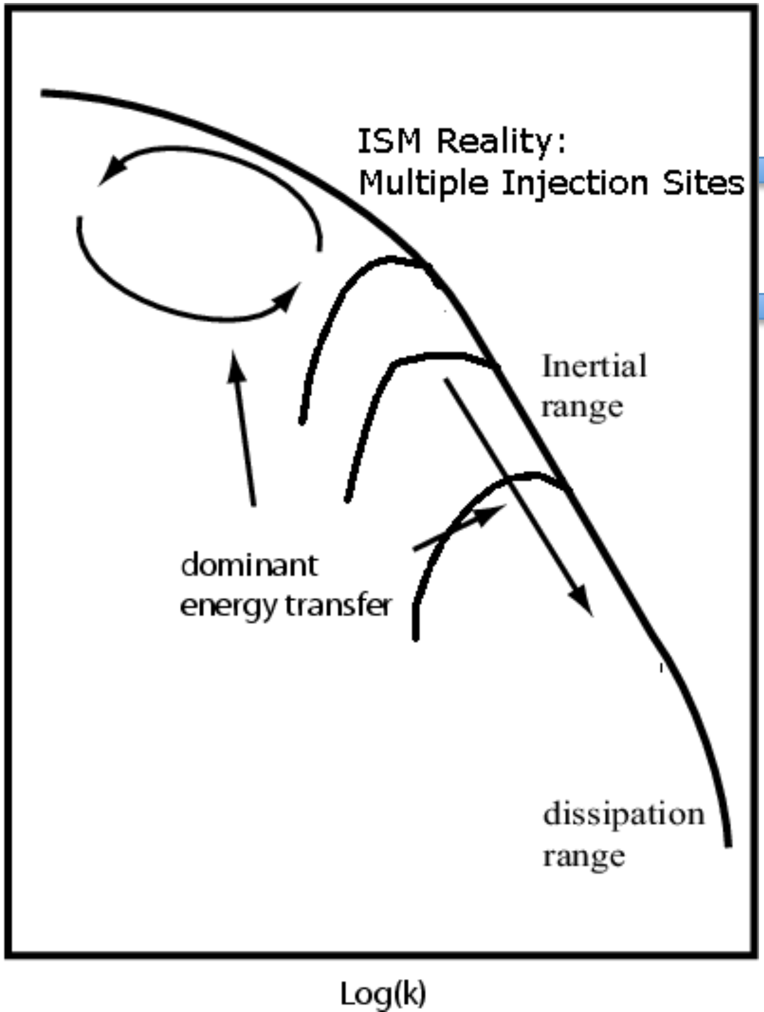
Can Mergers Drive Turbulence?



Panels show stellar light (left) and gas density (right) in a region of 1 Mpc on a side.

Movie Credit: Illustris Collaboration

Origins of Turbulence: Multiple Drivers

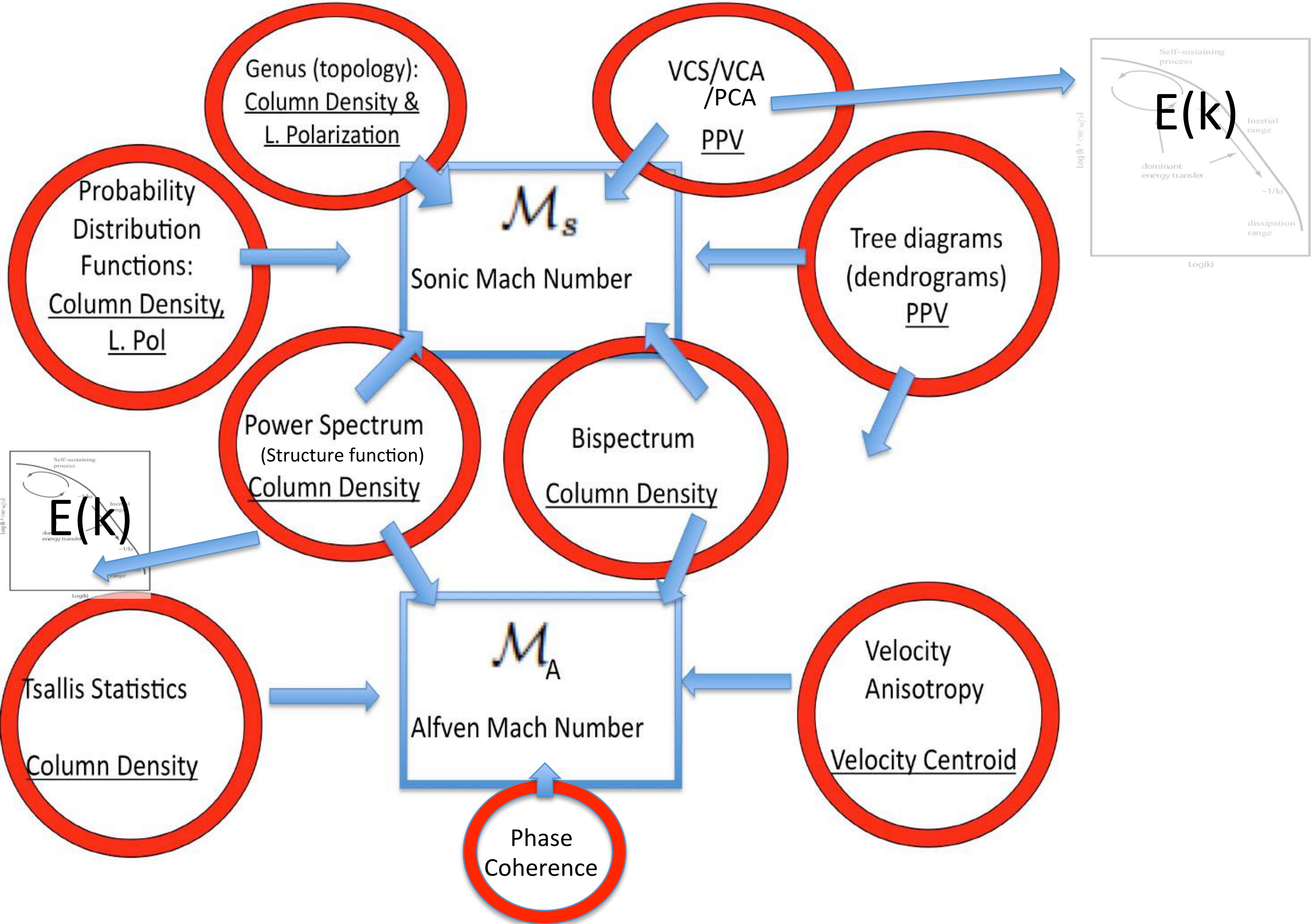


<u>1000 Pc scales:</u>
Galaxy mergers (major/minor),
Expanding shells, Gravitational instability

<u>100 Pc scales:</u>
supernova, expanding shells,
MRI, cloud collisions

<u>10 pc-sub-pc scales:</u>
Winds, outflows, stellar feedback,
stellar wakes

Turbulence Statistics and their Dependencies



Genus (topology):
Column Density &
L. Polarization

VCS/VCA
/PCA
PPV

E(k)

Probability
Distribution
Functions:
Column Density,
L. Pol

$\mathcal{M}_s$
Sonic Mach Number

Tree diagrams
(dendrograms)
PPV

Power Spectrum
(Structure function)
Column Density

Bispectrum
Column Density

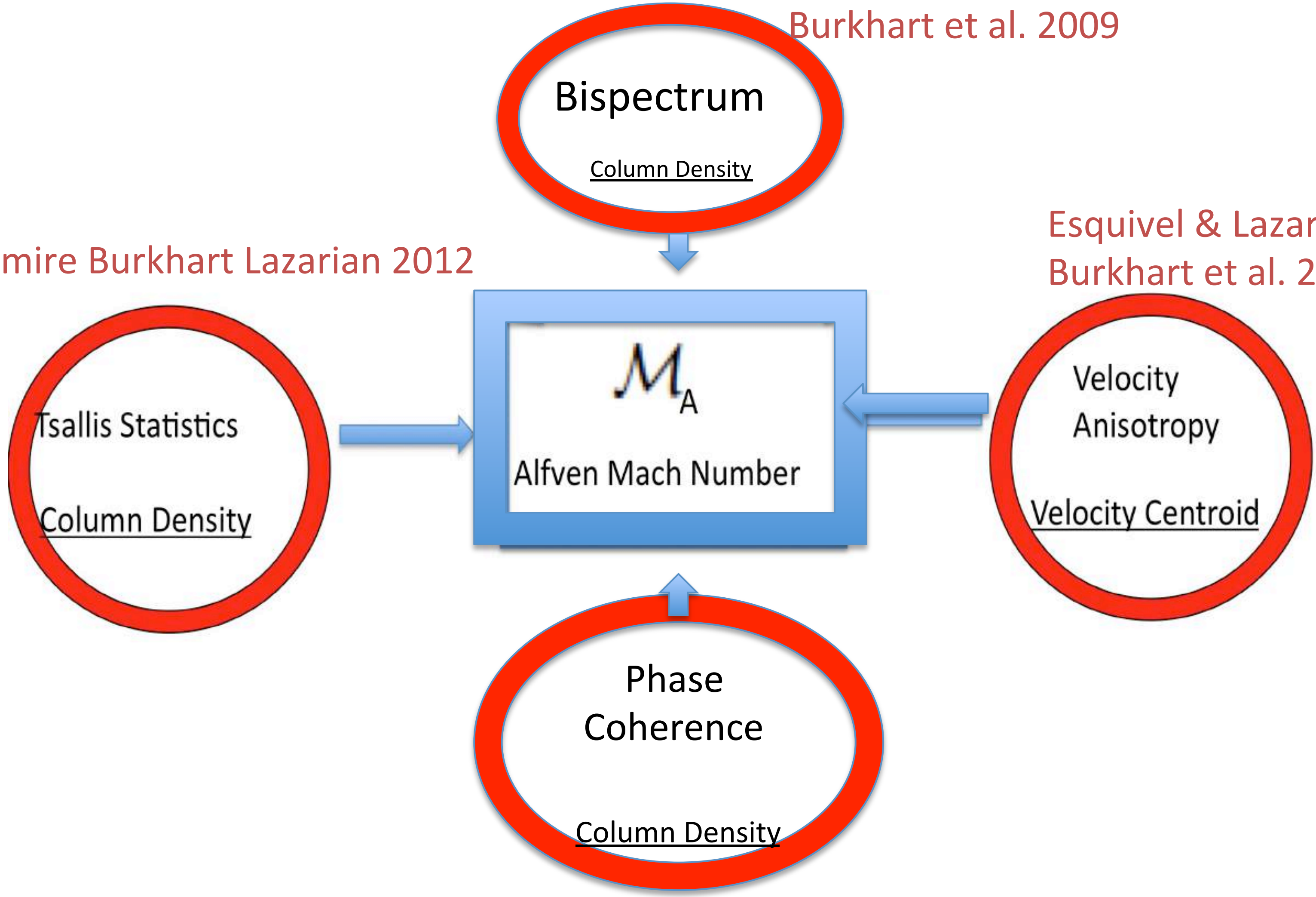
E(k)

$\mathcal{M}_A$
Alfven Mach Number

Tsallis Statistics
Column Density

Velocity
Anisotropy
Velocity Centroid

Phase
Coherence



Burkhart & Lazarian 2015
Burkhart et al. 2010
Burkhart et al. 2009

Bispectrum

Column Density

Tofflemire Burkhart Lazarian 2012

Tsallis Statistics

Column Density

$\mathcal{M}_A$

Alfven Mach Number

Esquivel & Lazarian 2011
Burkhart et al. 2014

Velocity Anisotropy

Velocity Centroid

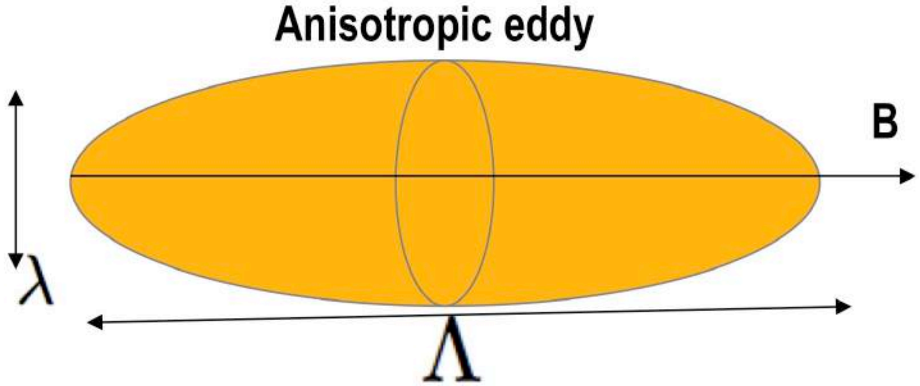
Phase Coherence

Column Density

Burkhart & Lazarian 2015

Velocity Anisotropy

1) Eddies are elongated along the mean magnetic field creating anisotropy in Turbulent flows



2) Anisotropy is reflected in the line of sight velocity field and in velocity centroids

$$C_x(y,z) \equiv \int_{(y,z)} V_z \rho_s dV_z / \int_{(y,z)} \rho_s dV_z ,$$

3) Quantify level of observed anisotropy in 2nd order structure functions of velocity centroid maps

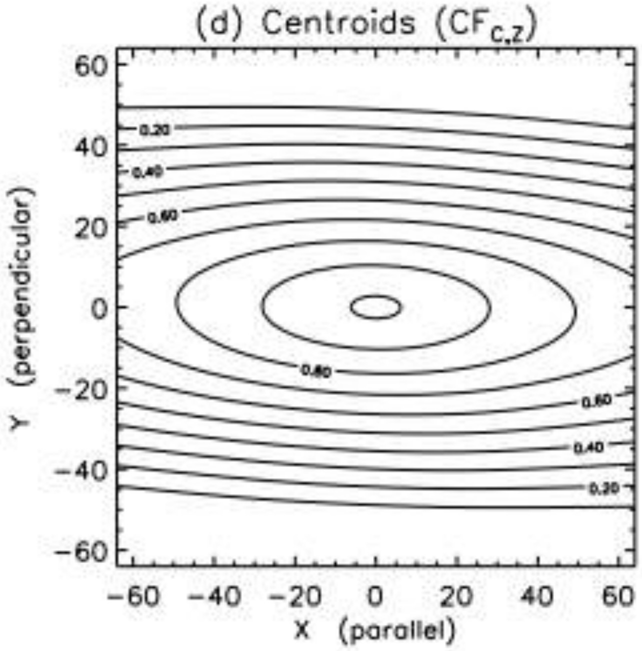
$$SF(\mathbf{r}) = \left\langle [f(\mathbf{x}) - f(\mathbf{x}+\mathbf{r})]^2 \right\rangle ,$$

Gives perpendicular component of B field!

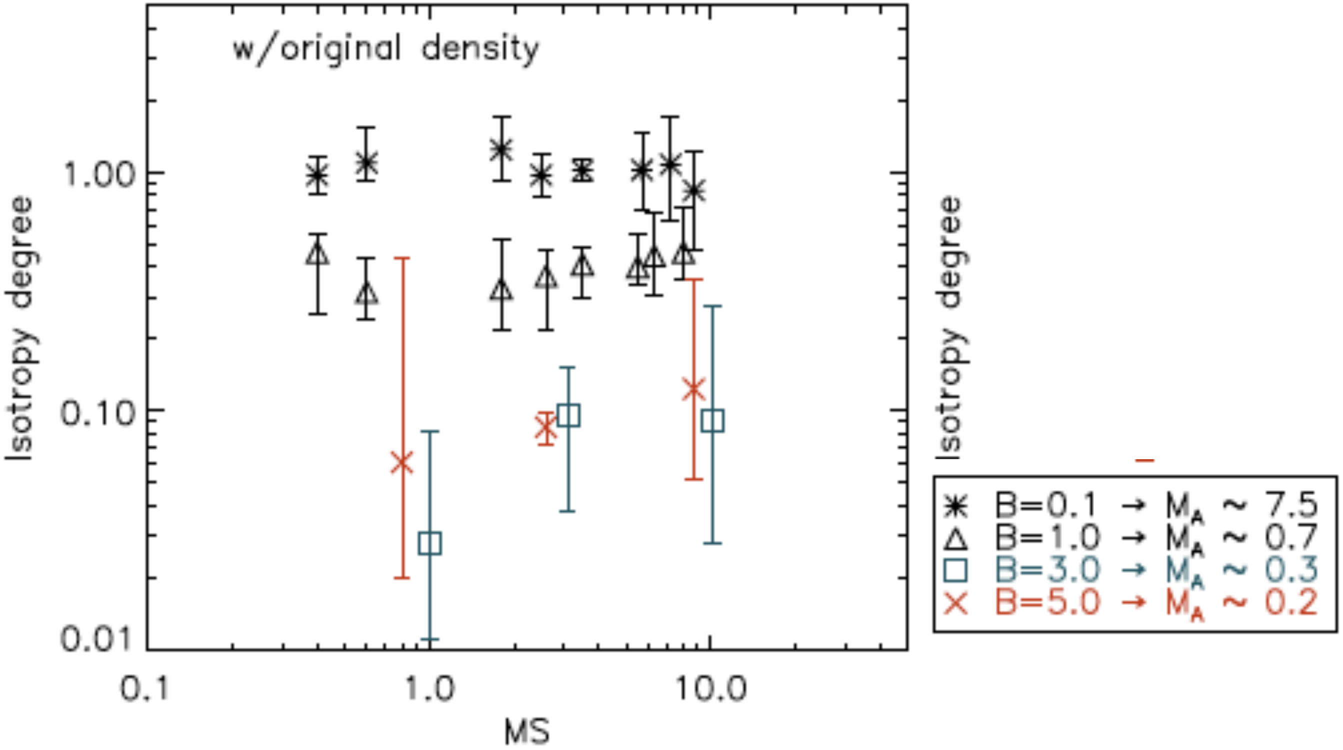
Velocity Centroids

Esquivel & Lazarian11
Burkhart et al. 2014

1) Implies B-perp can be obtained via statistics
2) Little dependency on sonic Mach number
3) Complimentary to PCA anisotropy methods (Heyer et al 2008)



(a) Velocity Centroids



PDFs 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

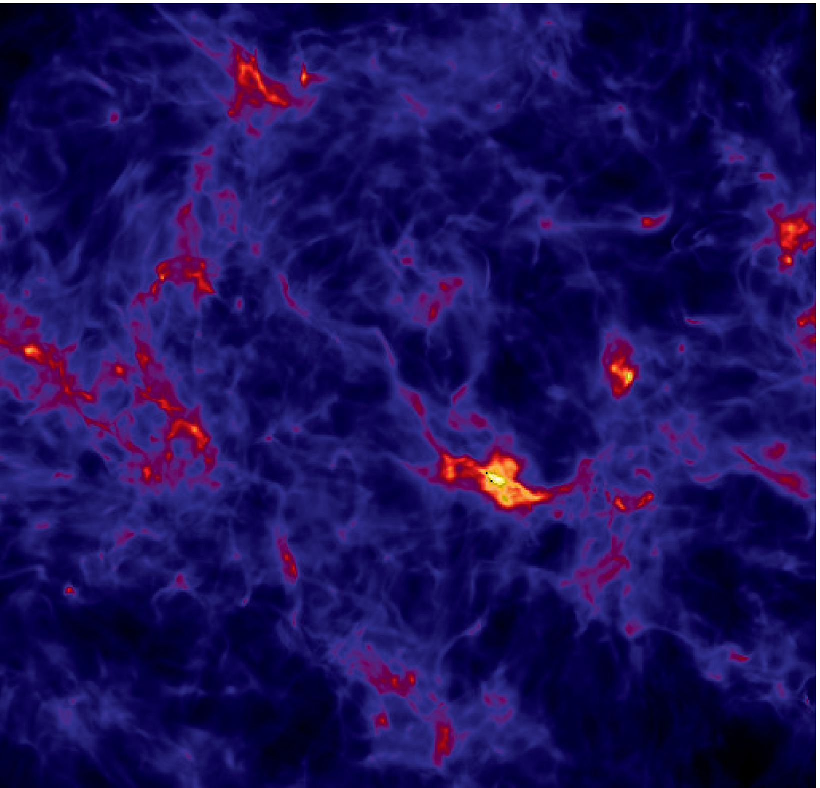
$$\sigma^2_{\rho/\rho_0} = b^2 \mathcal{M}_s^2$$

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

Skewness=A*M_s+b

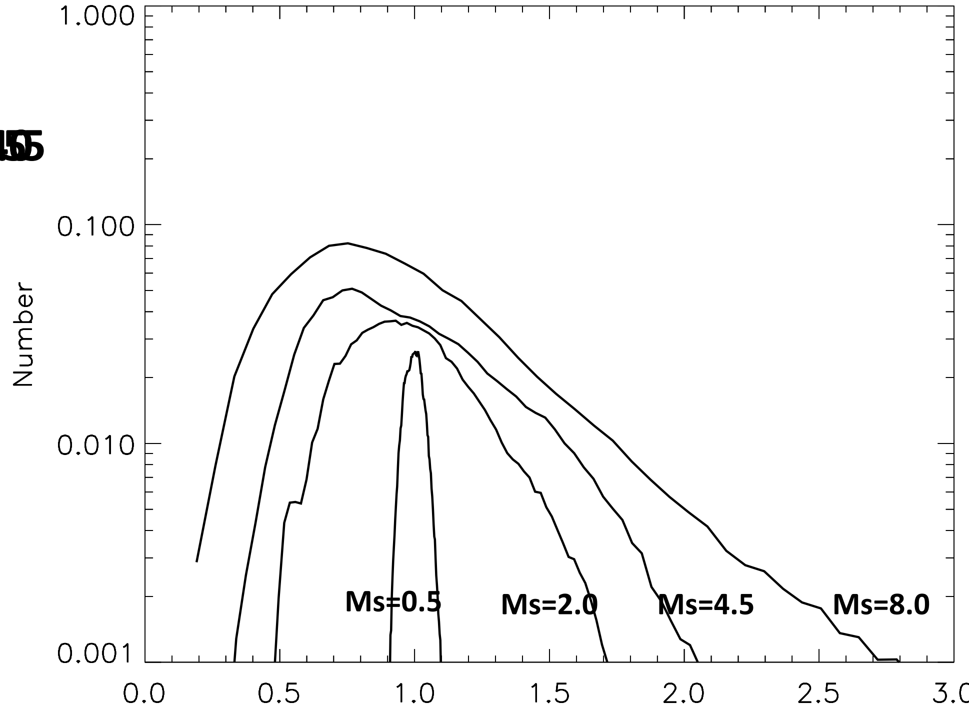
Kurtosis=A*M_s+b

Column density PDFs:
Kowal et al. 07; Burkhart et al. 09,10; Burkhart & Lazarian 12; Kainulainen & Tan 13



[illegible]

Linear Column Density PDF



MHD Simulations (no gravity)

-Cho et al. 2003, ENZO (Collins et al.) codes

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

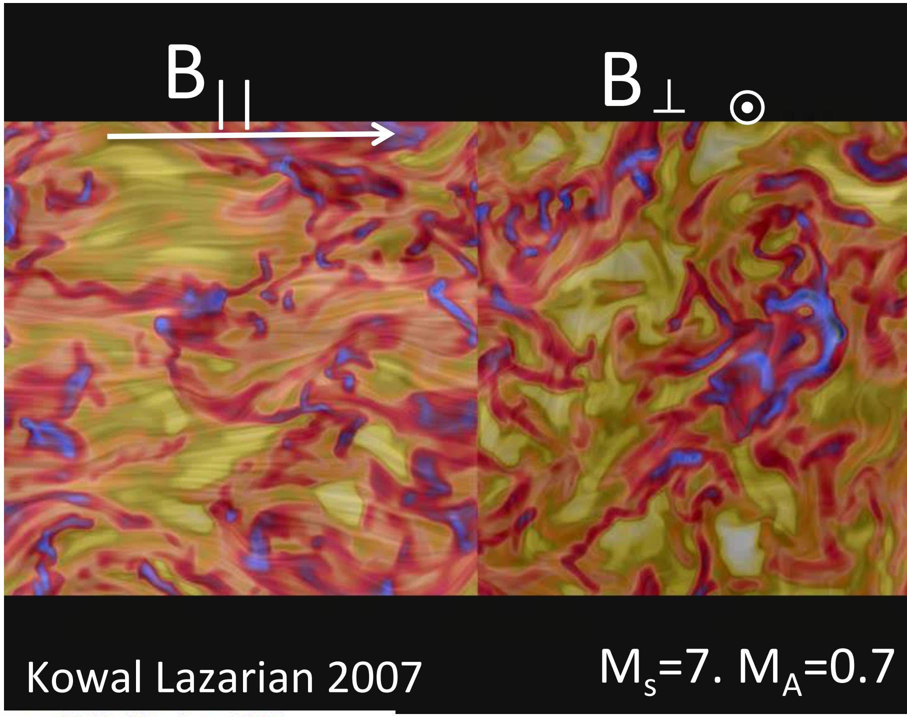
$$\partial\boldsymbol{v}/\partial t + \boldsymbol{v}\cdot\nabla\boldsymbol{v} + \rho^{-1}\nabla(a^2\rho) - (\nabla\times\boldsymbol{B})\times\boldsymbol{B}/4\pi\rho = \boldsymbol{f}$$

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

-Solve the ideal MHD equations in a periodi box and assume an isothermal equation of state $P=c_s^2 p$.

-Generate 3D simulation with resolution 512^3
$M_s=v/c_s$= 0.7,2.0,4.5,7.0,8.0, 10
$M_A=v/v_A$= 0.7,2.0

$$c_s = \sqrt{\gamma\cdot\frac{p}{\rho}} \qquad V_A = \frac{B}{\sqrt{4\pi\rho}}$$



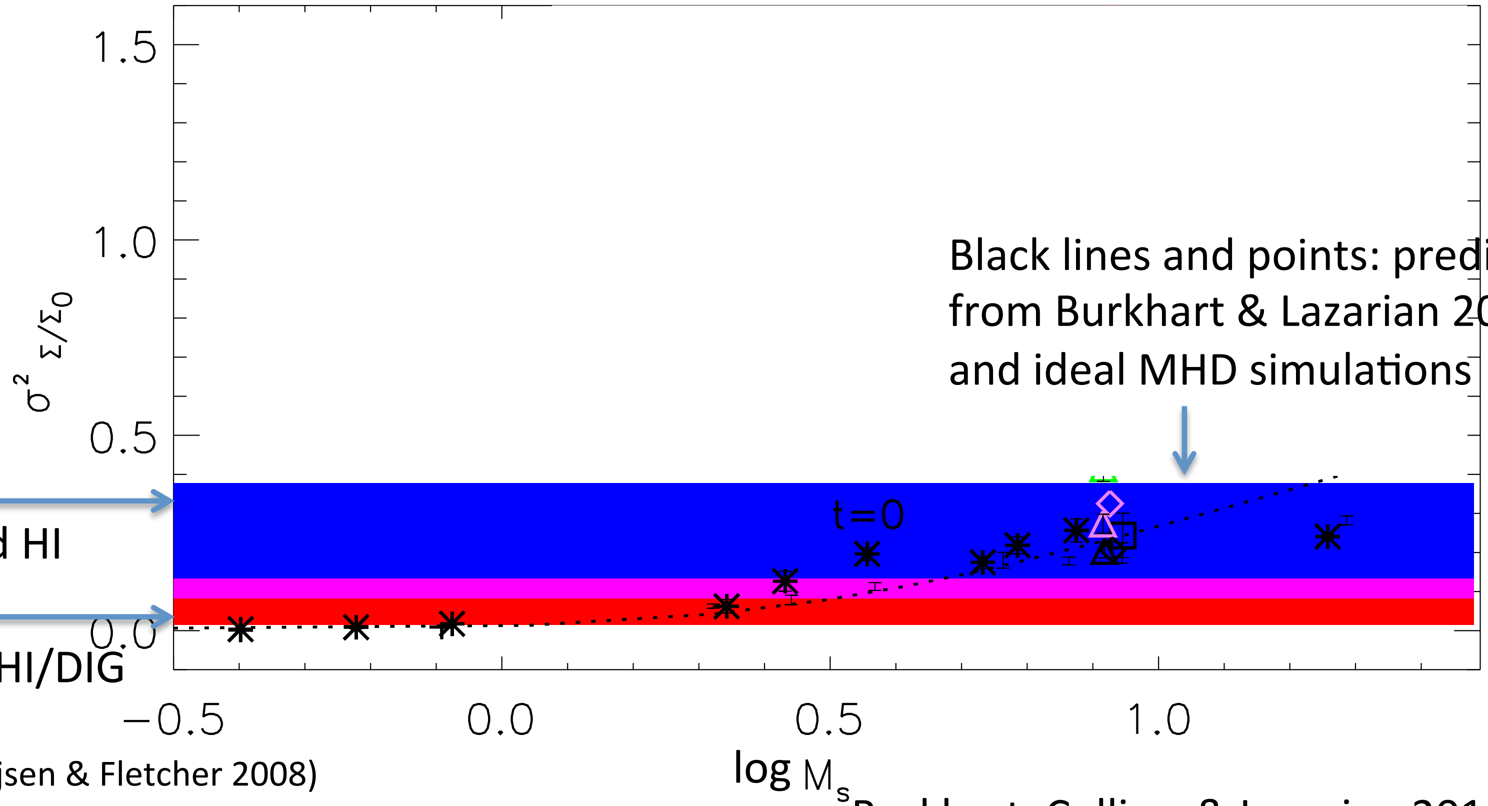
Kowal Lazarian 2007

M_s=7. M_A=0.7

Similar to many other MHD 'turbulence in box' simulations

e.g., Vazquez 1994, Padoan+1997, Passot+1998, Stone+1998, Mac Low 1999, Klessen+2000, Ostriker+2001, Heitsch+2001, Cho+2002, Boldyrev+2002, Li+2003, Haugen+2004, Padoan+2004, Jappsen+2005, Ballesteros+2006, Mee+Brandenburg 2006, Kritsuk+2007, Dib+2008, Offner+2008, Kowal+2008, Schmidt+2009, Cho+2009, Lemaster+2009, Glover+2010, Burkhart+2010, Price+2011, DelSordo+2011, Collins +2012, Walch+2012, Scannapieco+2012, Pan+2012, Robertson+2012, +++

The WNM/CNM ISM PDF: Sonic Mach Number vs. Variance



Black lines and points: prediction from Burkhart & Lazarian 2012 and ideal MHD simulations

Cold HI

Warm HI/DIG

(Berkhuijsen & Fletcher 2008)

Burkhart, Collins, & Lazarian 2014
Burkhart & Lazarian 2012

PDFs of Collapsing GMCs are Different than WNM/CNM….

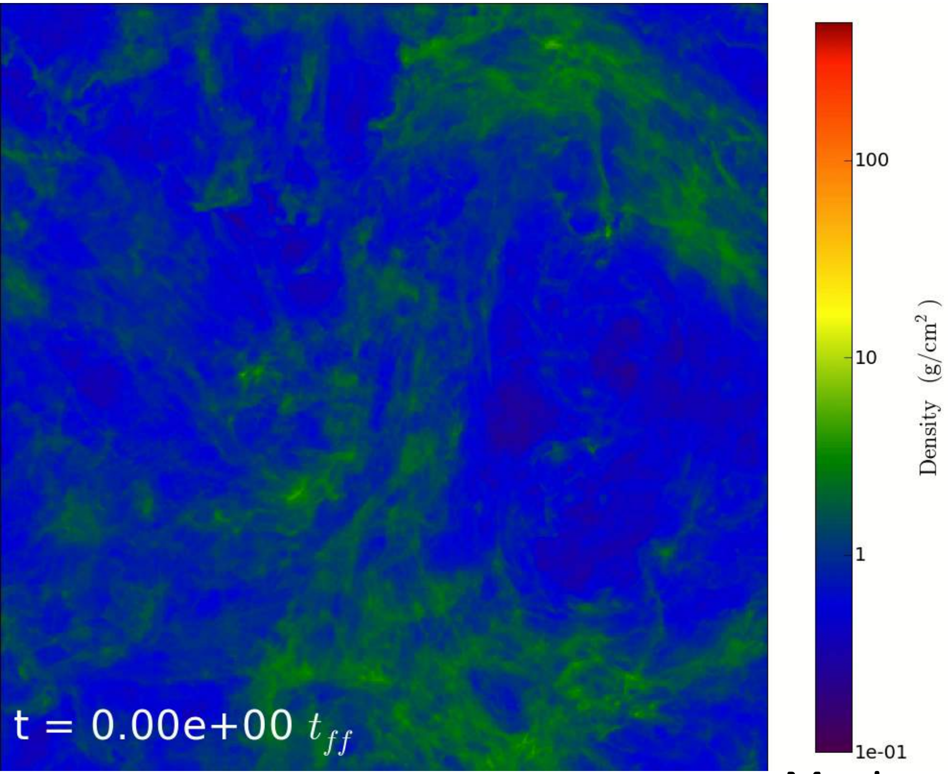
t=0 supersonic turbulence
t>0 re-run with ENZO AMR self-gravity

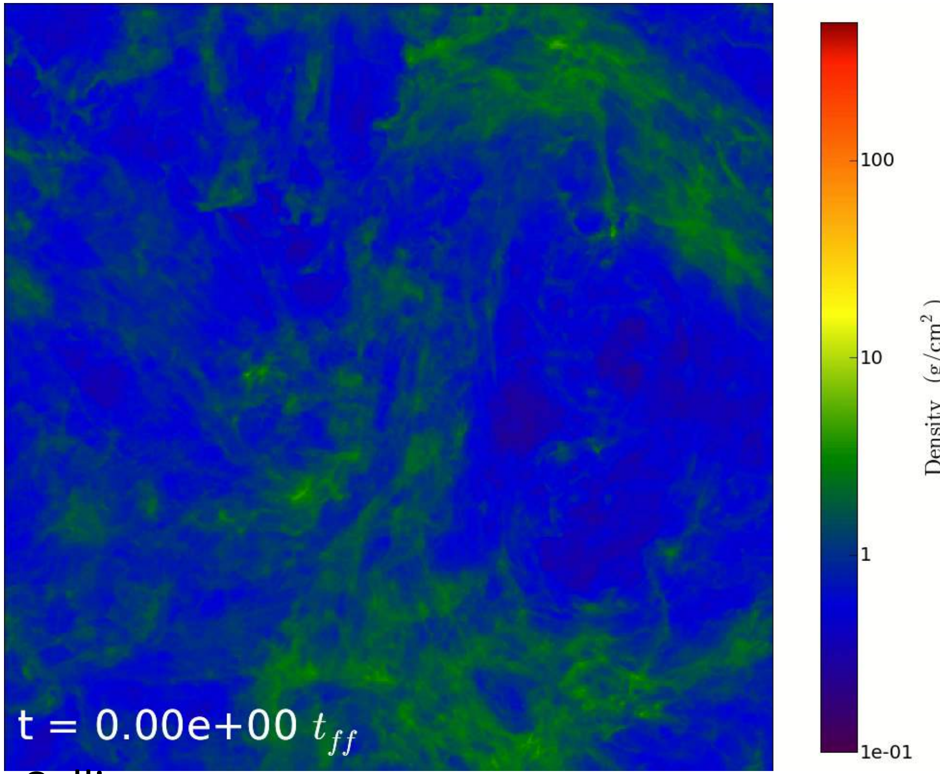
$$\mathcal{M} = \frac{v_{\rm rms}}{c_{\rm s}} = 9$$

$$\alpha_{\rm vir} = \frac{5 v_{\rm rms}^2}{3 G \rho_0 L_0^2} = 1$$

$$\beta_0 = \frac{8\pi c_{\rm s}^2 \rho_0}{B_0^2} = 0.2,\ 2,\ 20,$$

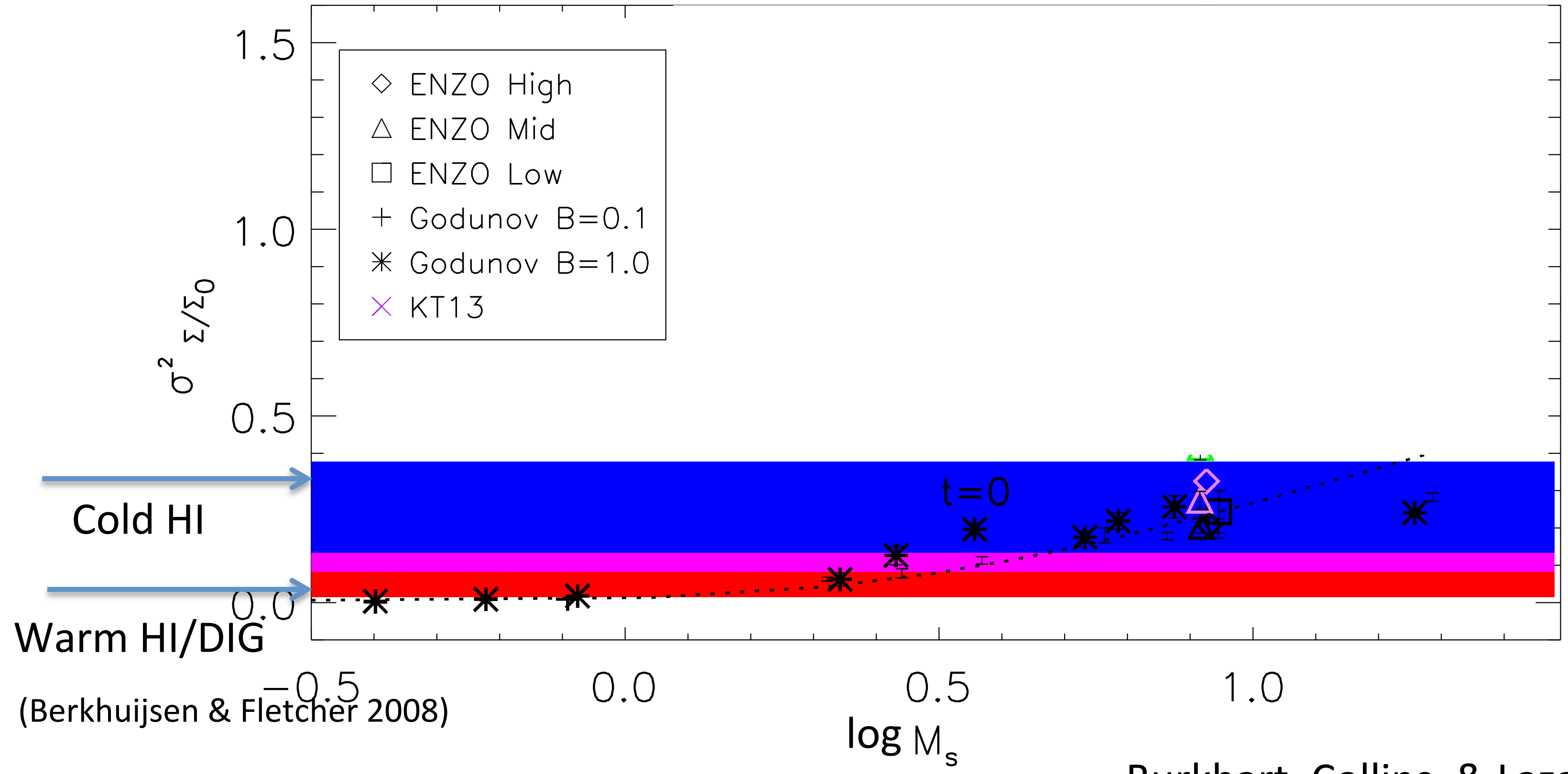
Collins et al. 2012; Burkhart, Collins, Lazarian 2014, submitted





Movies: D. Collins

Sonic Mach Number vs. Variance Relation: Where do the Self-Gravitating?



Cold HI

Warm HI/DIG

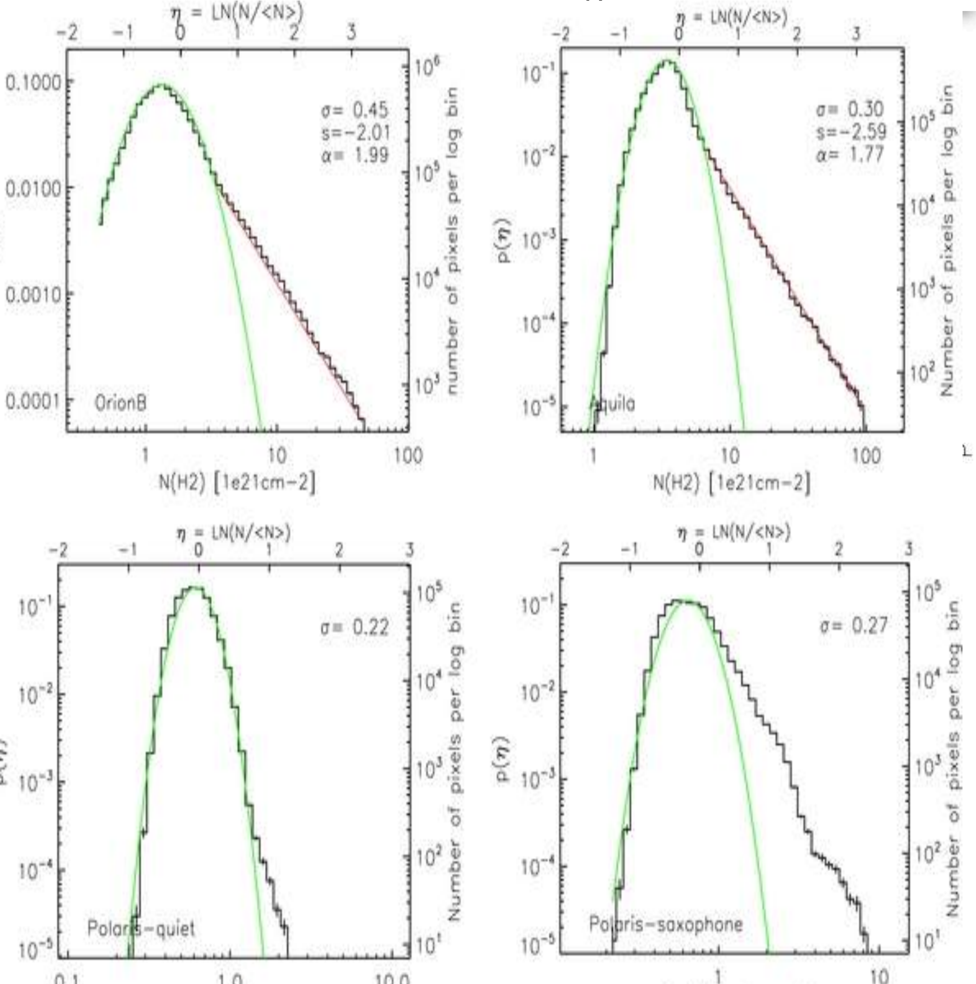
(Berkhuijsen & Fletcher 2008)

Burkhart, Collins, & Lazarian 2015
Burkhart & Lazarian 2012

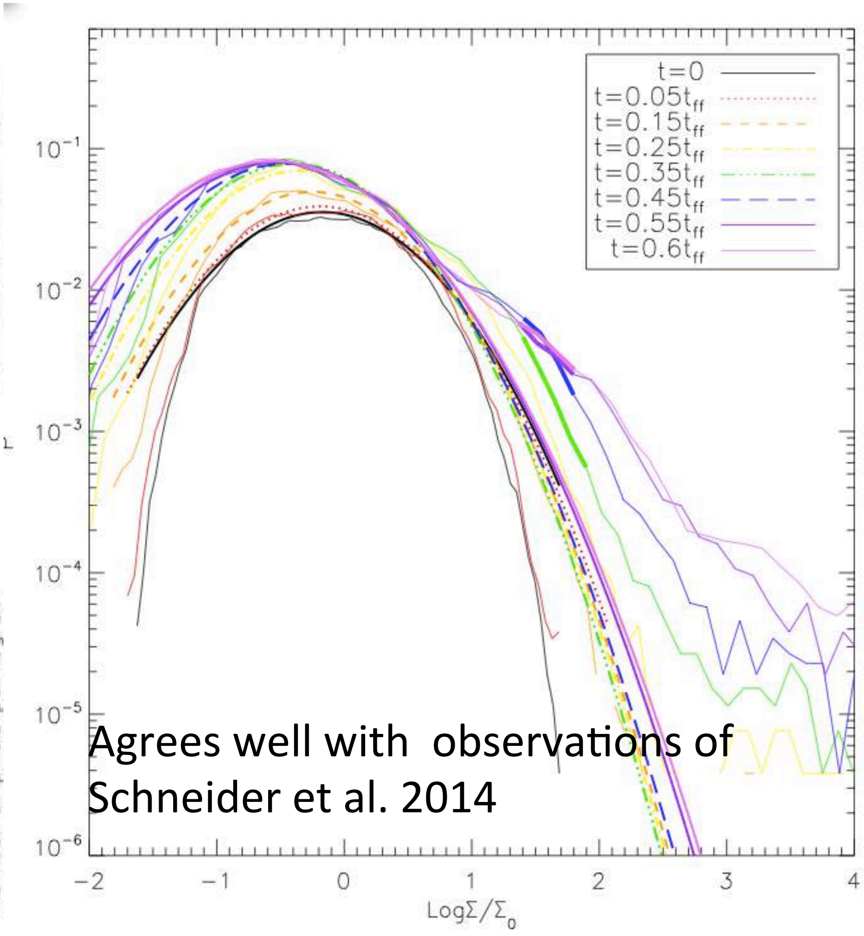
PDFs of Magneto gravoturbulence

Power law tails observed in column density: Burkhart, Collins, Lazarian (2014, submitted)

“High B”, M_A=7



“Low B”, M_A=20

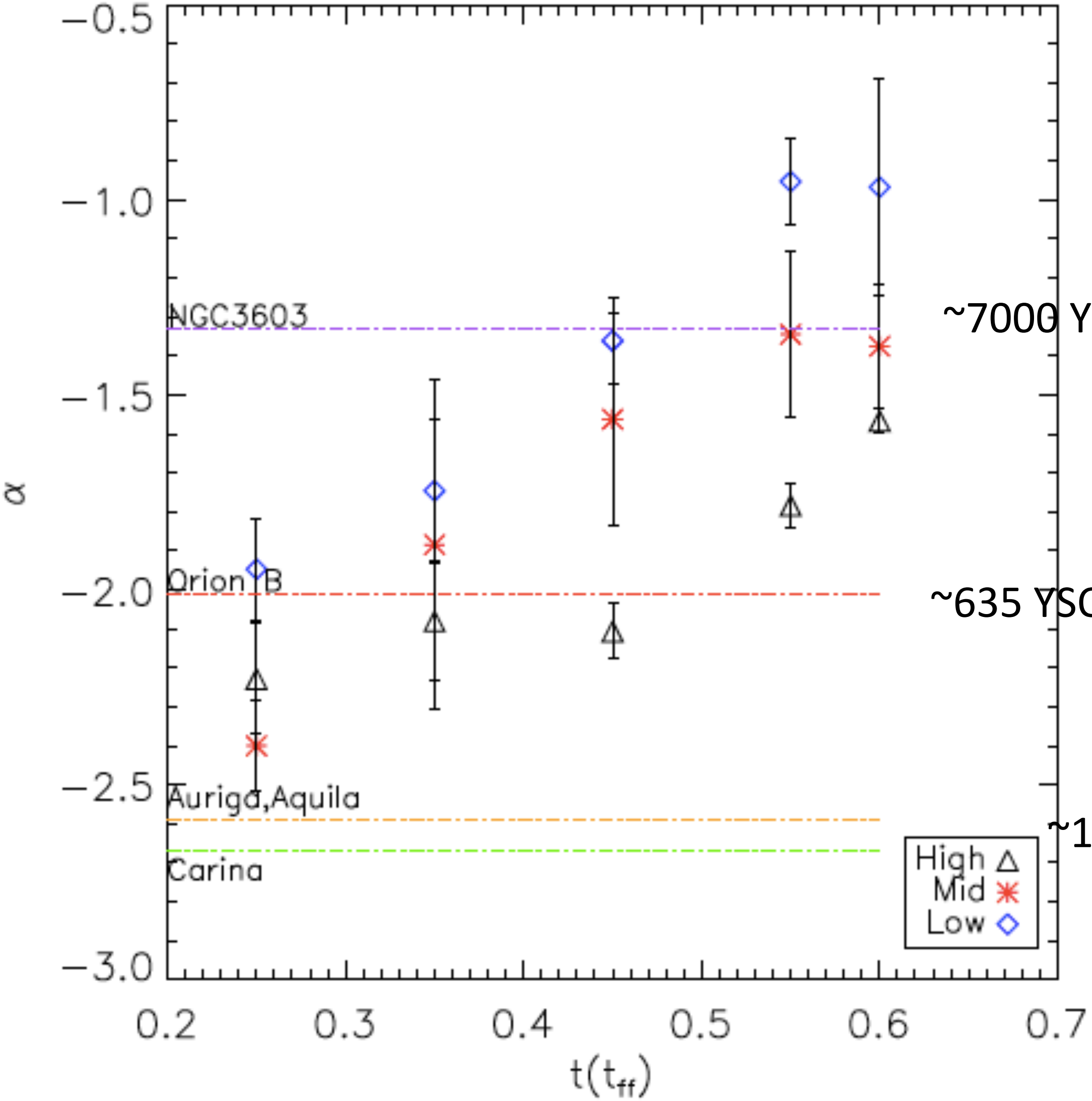


Agrees well with observations of Schneider et al. 2014

Power Law Tail Slopes

Burkhart Collins Lazarian 2015

Implications: PDF Power Law tails can be used to asses the evolutionary stage of the cloud!



~7000 YSOs

~635 YSOs

~175 YSOs

Maddalena Cloud, slope -3.5, YSO ~33

Conclusions

1) The PDF can diagnose the turbulent state of the gas (sonic Mach number) for the diffuse medium.

2) For self-gravitating gas the PDF is a better indicator of the evolutionary stage of the cloud.

3) Orion B seems to be in an intermediate state of evolution compared with other clouds (as traced by the PDF).

4) Additional tracers for PDFs beyond dust are need to to get the full dynamic range of the PDF in molecular clouds, i.e. to probe the ‘lognormal’ portion (Lombardi, Alves & Lada 2015).