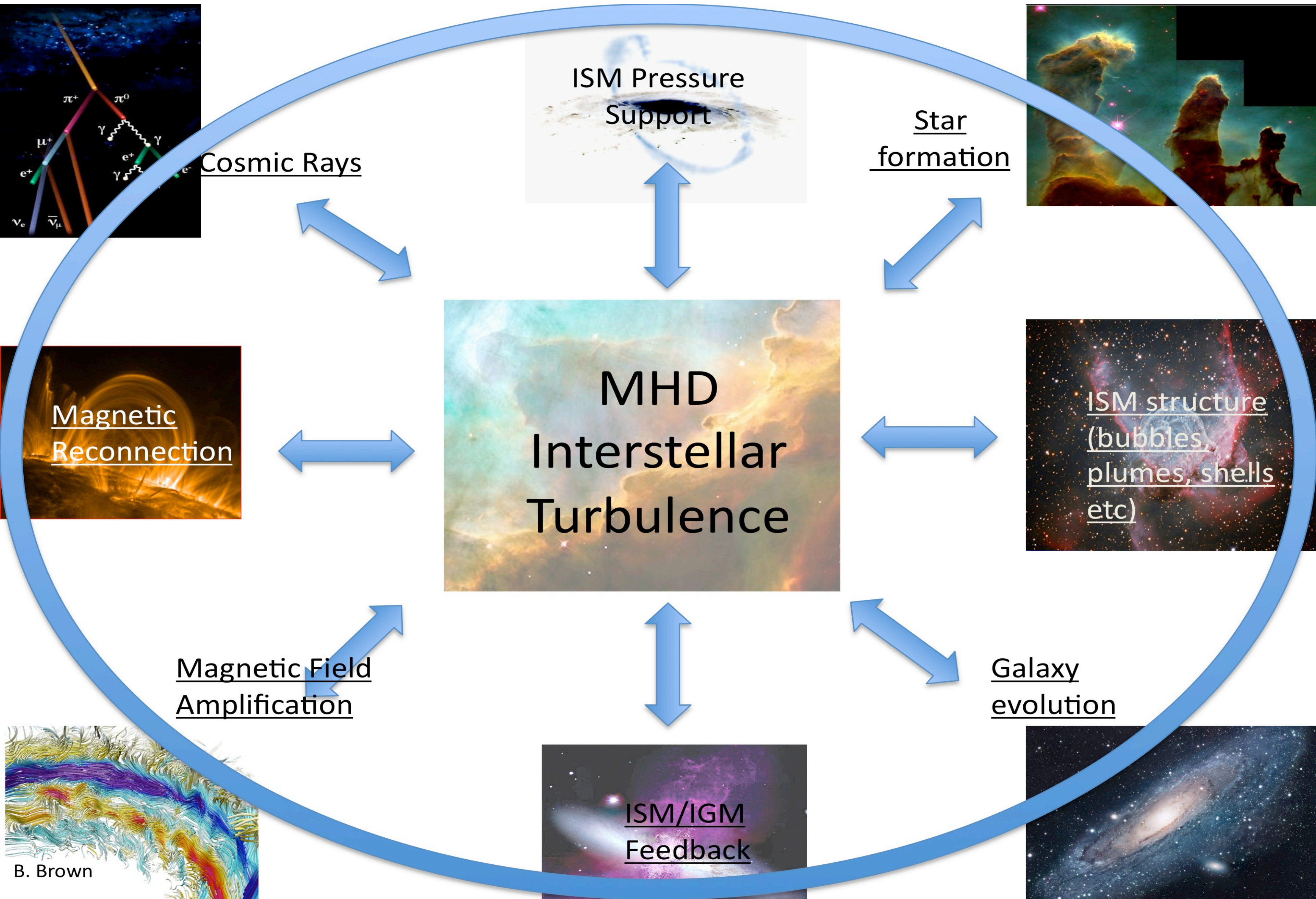
The Origins and Implications of MHD Turbulence

Blakesley Burkhart
Einstein Fellow
Harvard-Smithsonian Center for Astrophysics

With Alexey Chepurnov, Lars Hernquist, Alex Lazarian, Annalisa Pillepich, Shy Genel, & Snezana Stanimirovic

Implications of MHD Turbulence

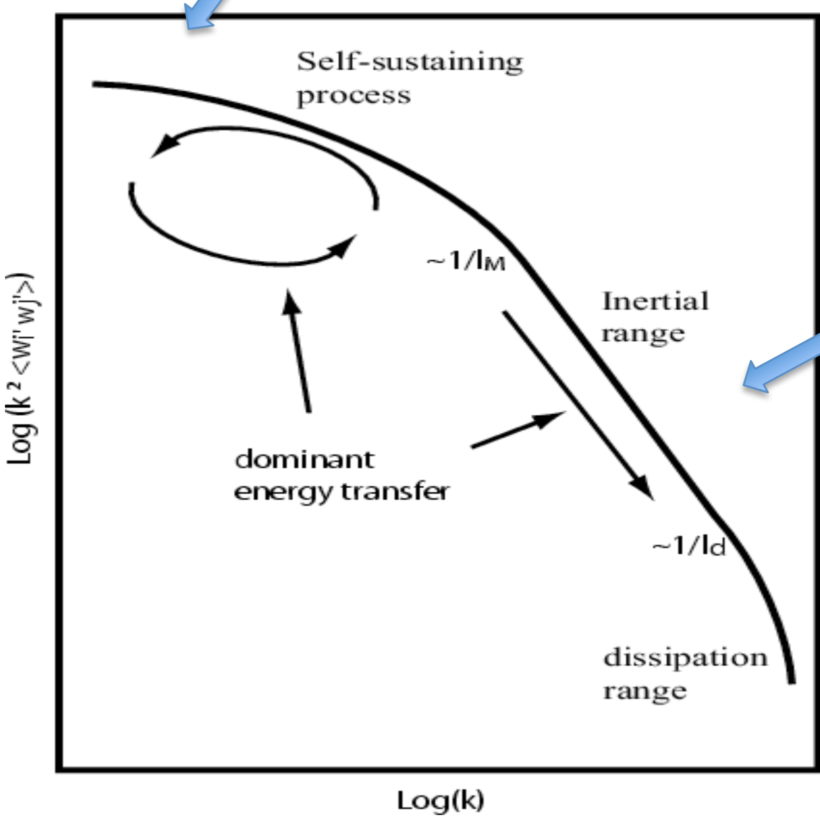


Outline

- The ISM turbulence cascade.
- The origin of MHD turbulence in galaxies on the very largest scales (kpc):
  - Star formation/supernova: Observation and Simulations (Illustris).
  - Galaxy interactions: Observations (HI in the SMC) and Simulations (Illustris).

Turbulence as an Energy Transfer Process

Driving scale: Where energy is injected into the cascade



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

<u>e.g., $E(k) \sim k^{-5/3}$</u>

Energy dissipated at the small scales ~ 0.01pc via heat or ion/neutral friction

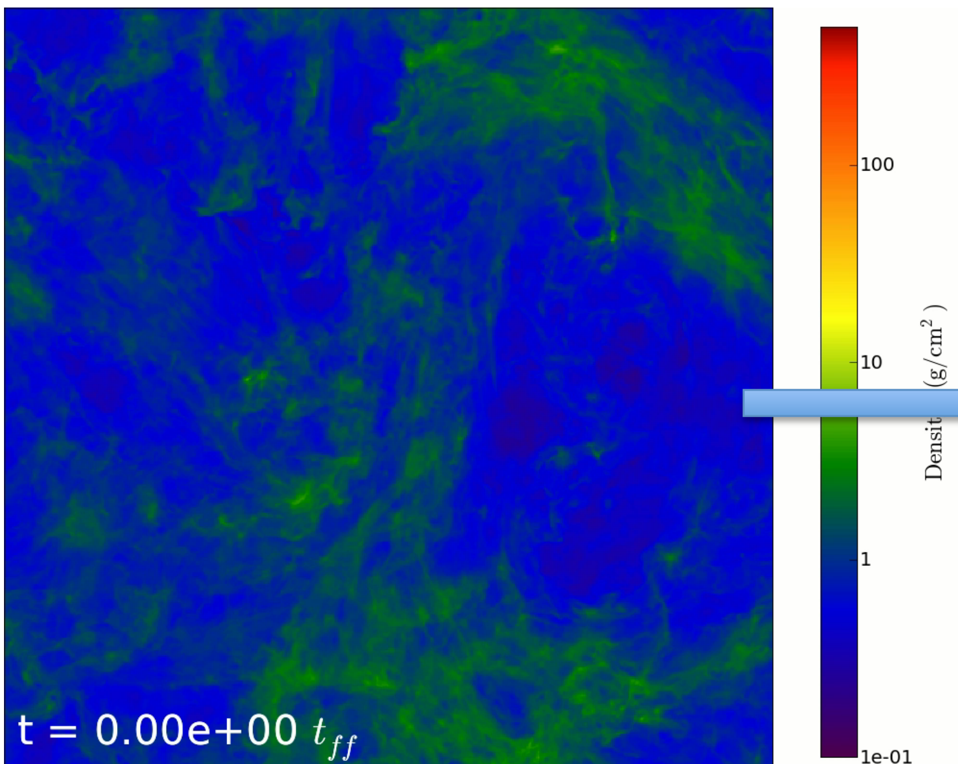
Inertial range example: GMC Density Statistics Set by Turbulence

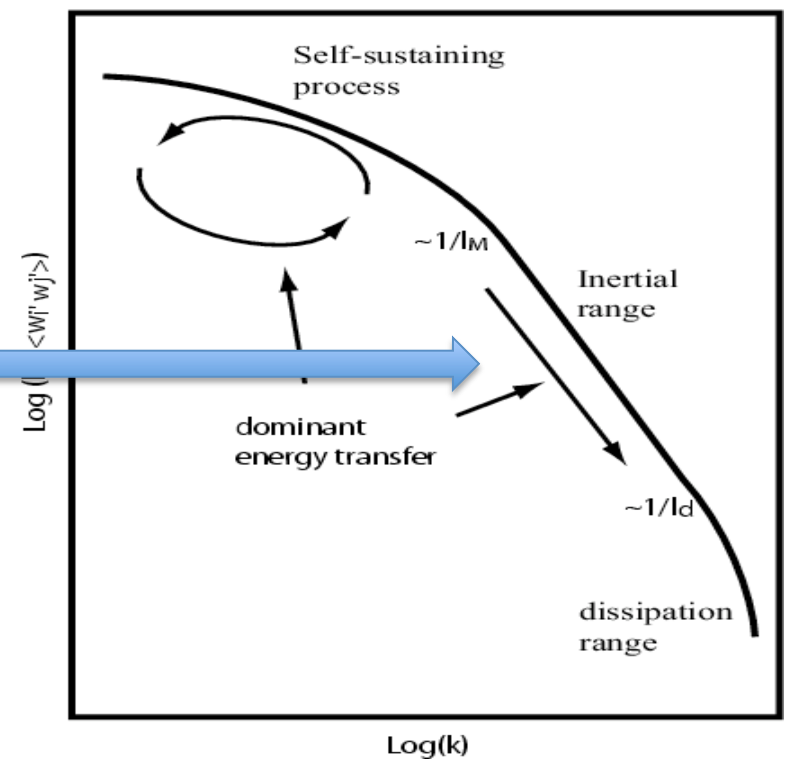
Star formation rates are set by the statistics of <u>magnetized</u> supersonic turbulence!

(see papers by: Burkhart, Collins, Elmegreen, Federrath, Klessen, Kritsuk, Mac Low, McKee, Offner, Ostriker, Padoan, Robertson, Walch, Vazequez…etc.)

Burkhart, Collins, Lazarian 2015

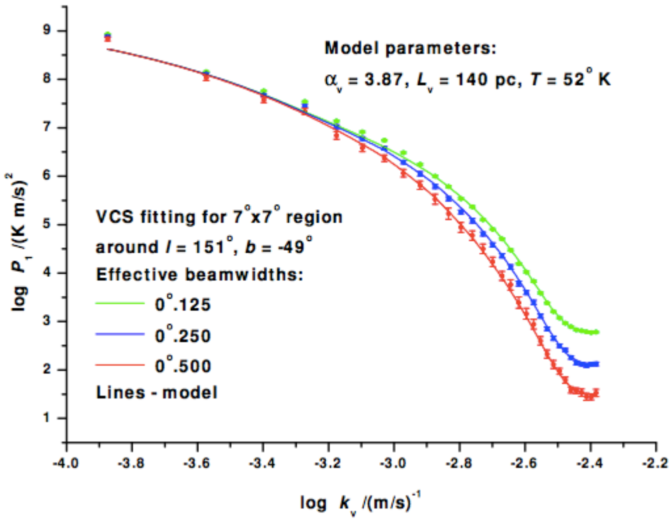
See talk by Lukas Konstandin



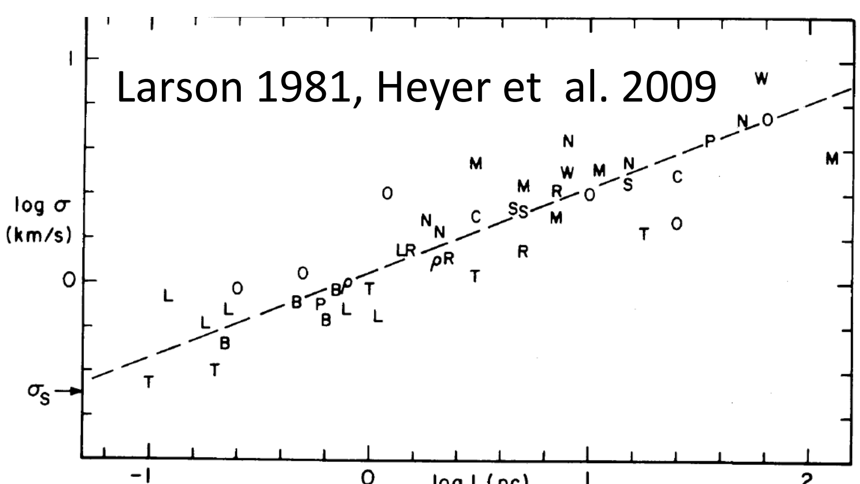


Observations of driving scale in multiphase ISM suggest driving on scales larger than clouds (L > 1pc-10pc).

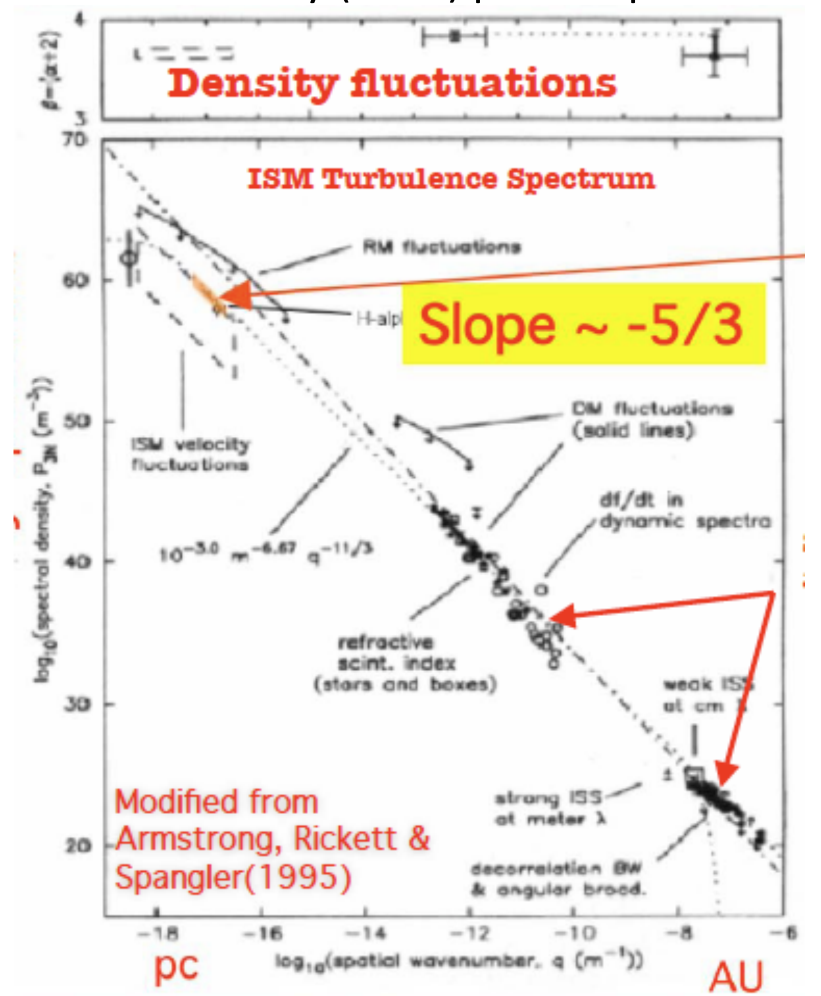
WNM/CNM High Lat. Clouds (Chepurnov et al. 2010), VCS



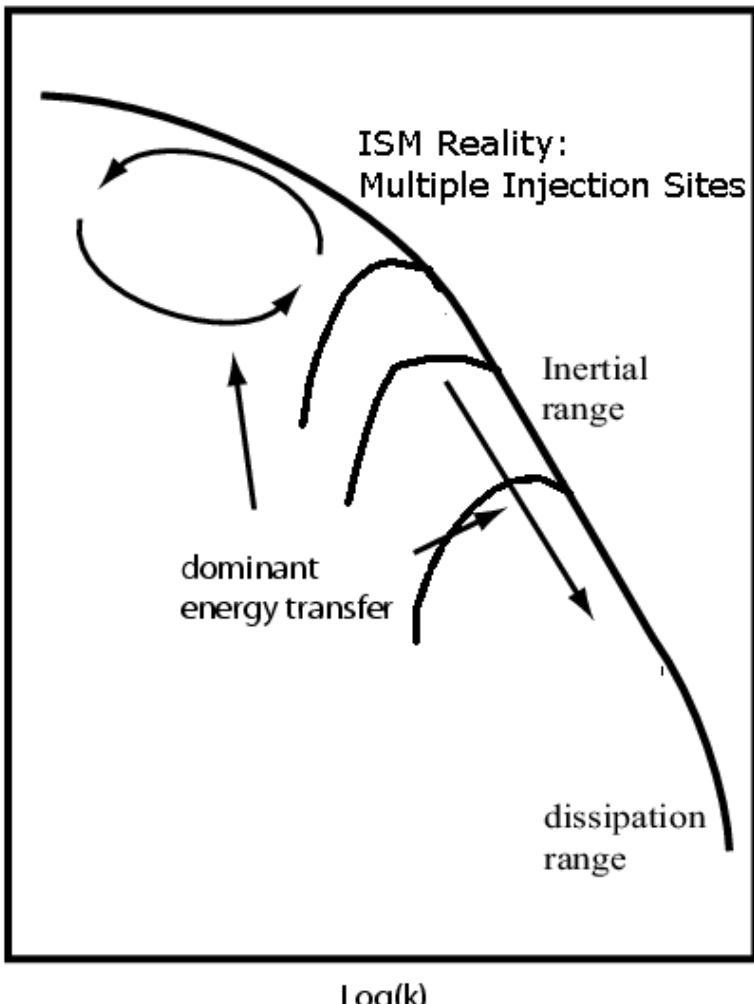
Molecular medium (line width-size)



Electron density (WIM) power spectrum:



Origins of Turbulence: Multiple Drivers



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

<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

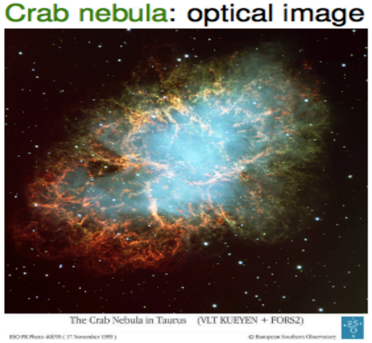
Driving mechanism	ε_V, $\mathrm{erg\,cm^{-3}\,s^{-1}}$
Supernova explosions	3×10^{-26}
Stellar winds	3×10^{-27}
Protostellar outflows	2×10^{-28}
Stellar ionizing radiation	5×10^{-29}
Galactic spiral shocks	4×10^{-29}
Magneto-rotational instability	3×10^{-29}
H II regions	3×10^{-30}

Turbulence driven by supernovae

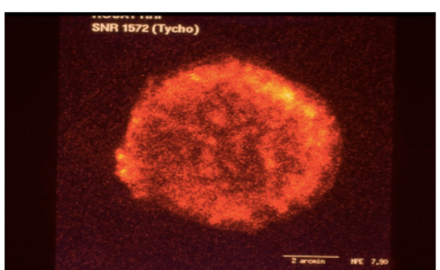
Mac Low & Klessen 2004; Elmegreen Scalo 2004

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

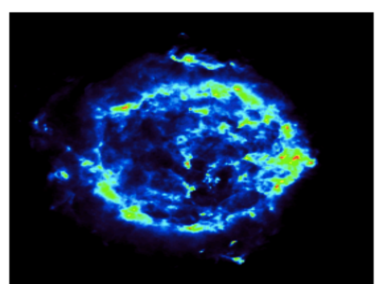
Crab nebula: optical image



Tycho supernova: X-rays

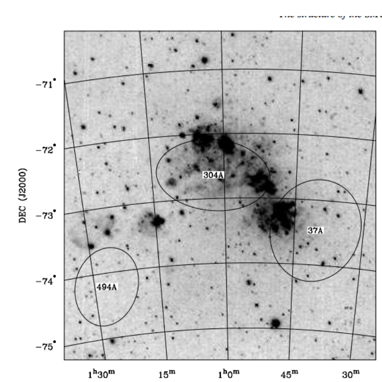


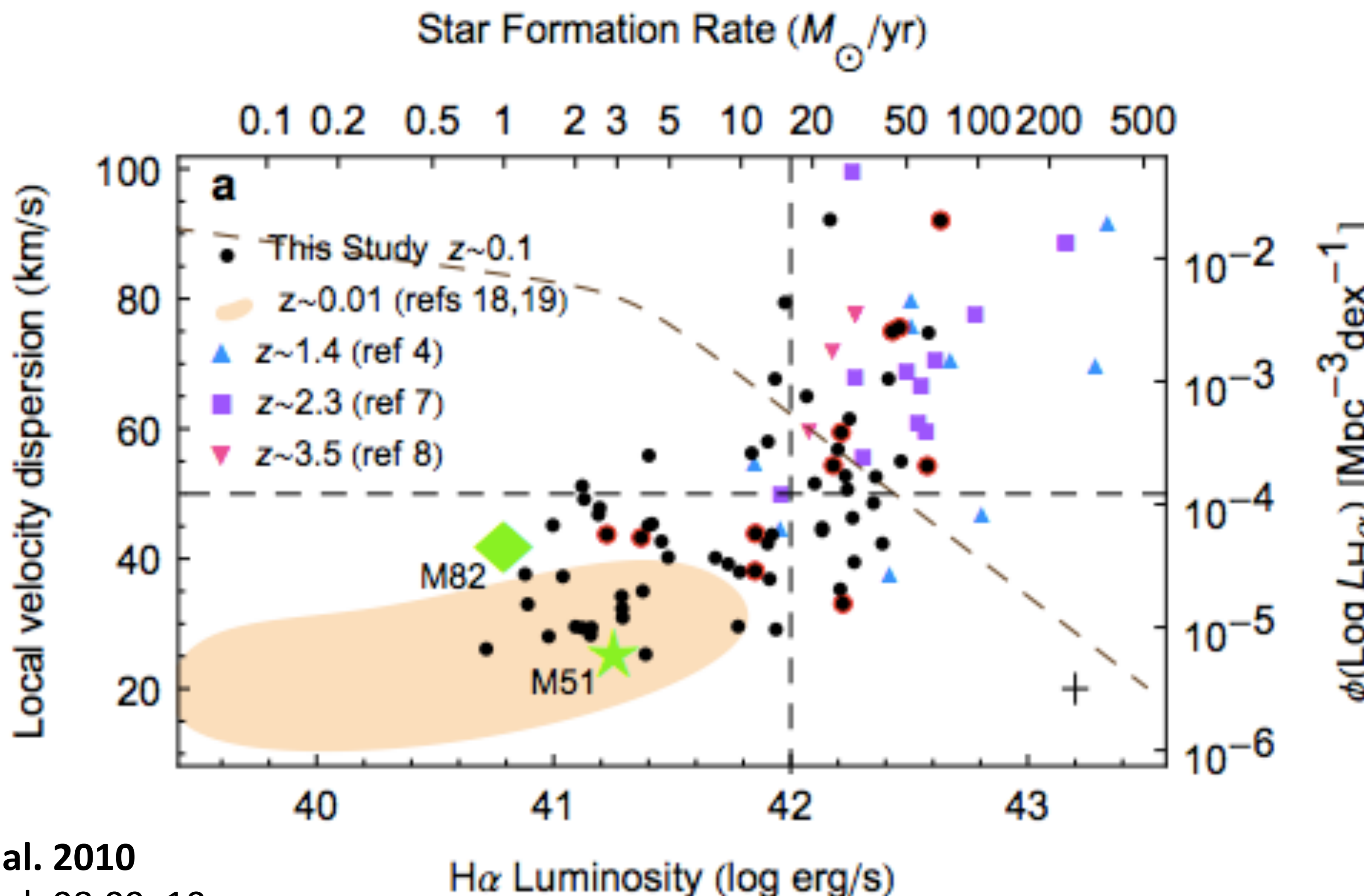
Cas A: radio image ($\lambda 6\,\mathrm{cm}$)



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

HI shells (Stanimirovic et al. 1999)

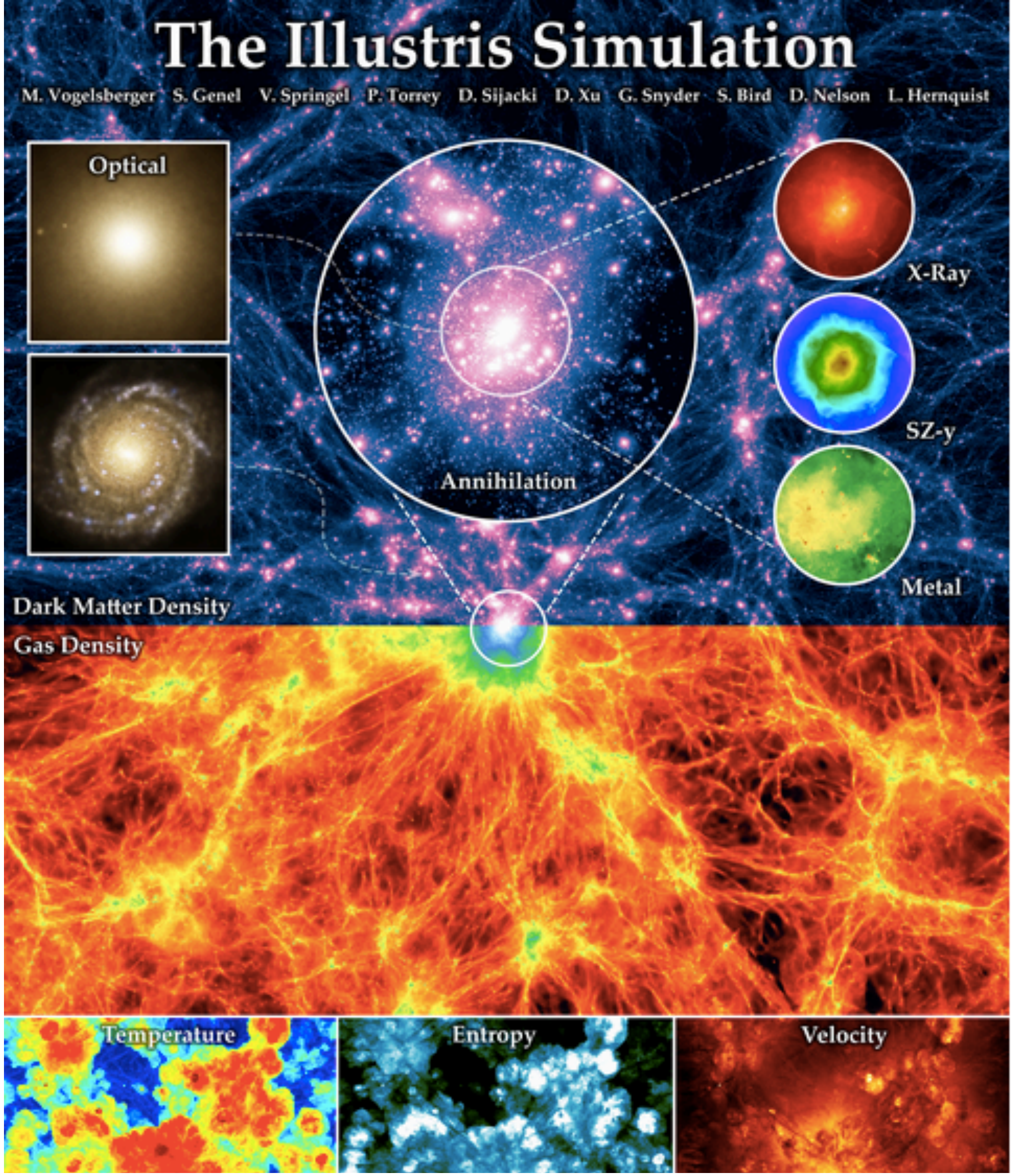




Green et al. 2010
Epinat et al. 08,09, 10
Law et al. 2009
Lemoine-Busserolee et al. 2010

~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!

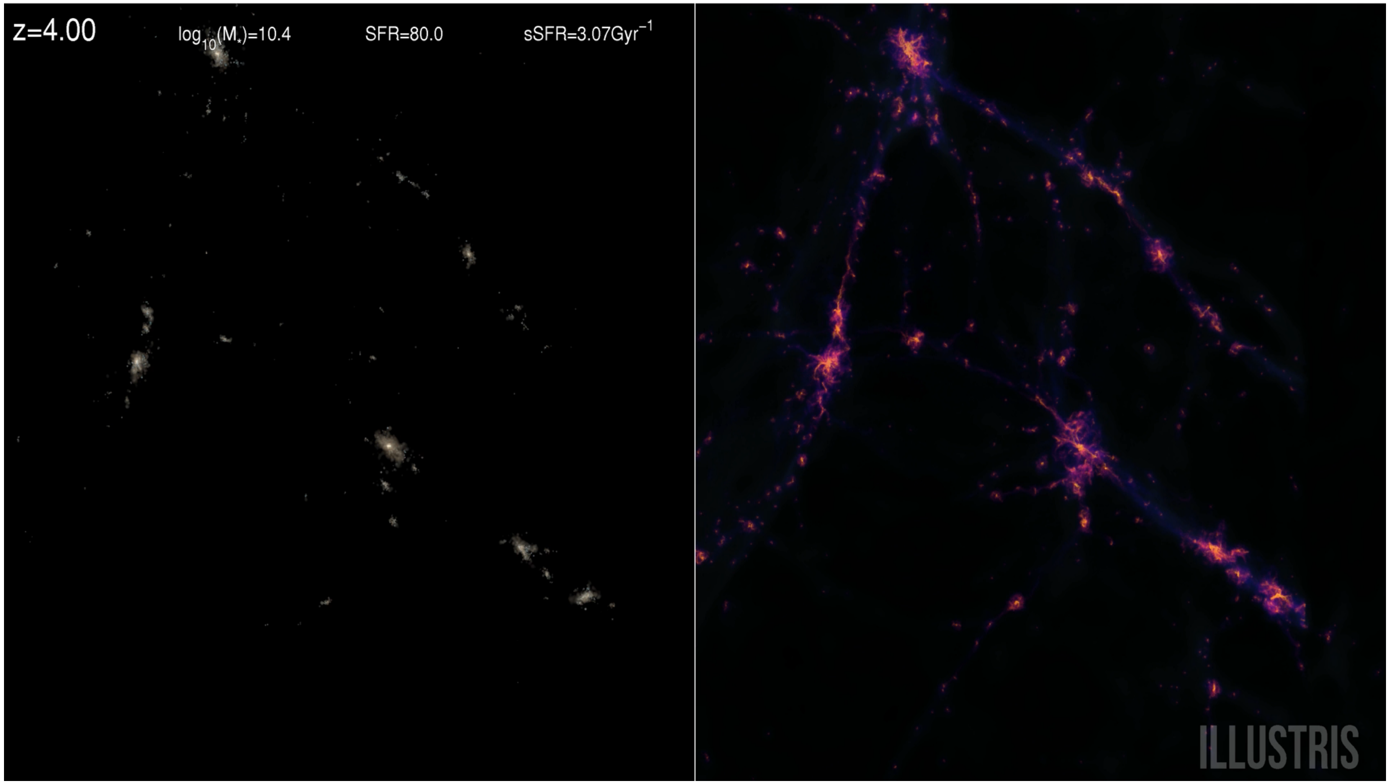
$$\rho_{\rm th} = 0.13\ {\rm cm}^{-3}$$

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

Image Credit: Illustris Collaboration

name	volume $[({\rm Mpc})^3]$	DM particles / hydro cells / MC tracers	$\epsilon_{\rm baryon}/\epsilon_{\rm DM}$ [pc]	$m_{\rm baryon}/m_{\rm DM}$ $[10^5\ {\rm M}_\odot]$	$r_{\rm cell}^{\rm min}$ [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

Can Mergers Drive Turbulence?



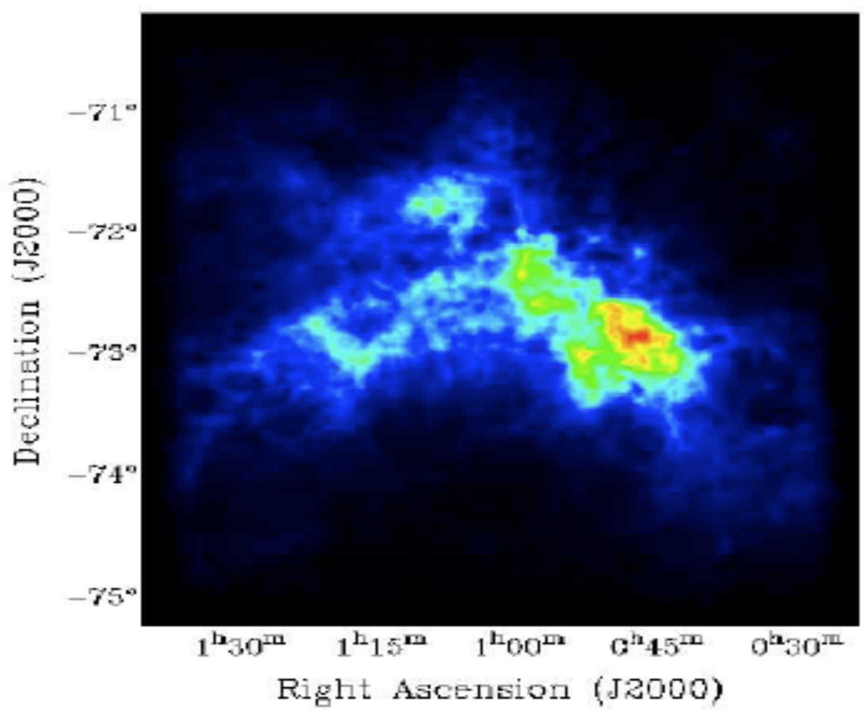
Panels show stellar light (left) and gas density (right) in a region of 1 Mpc on a side.

Movie Credit: Illustris Collaboration

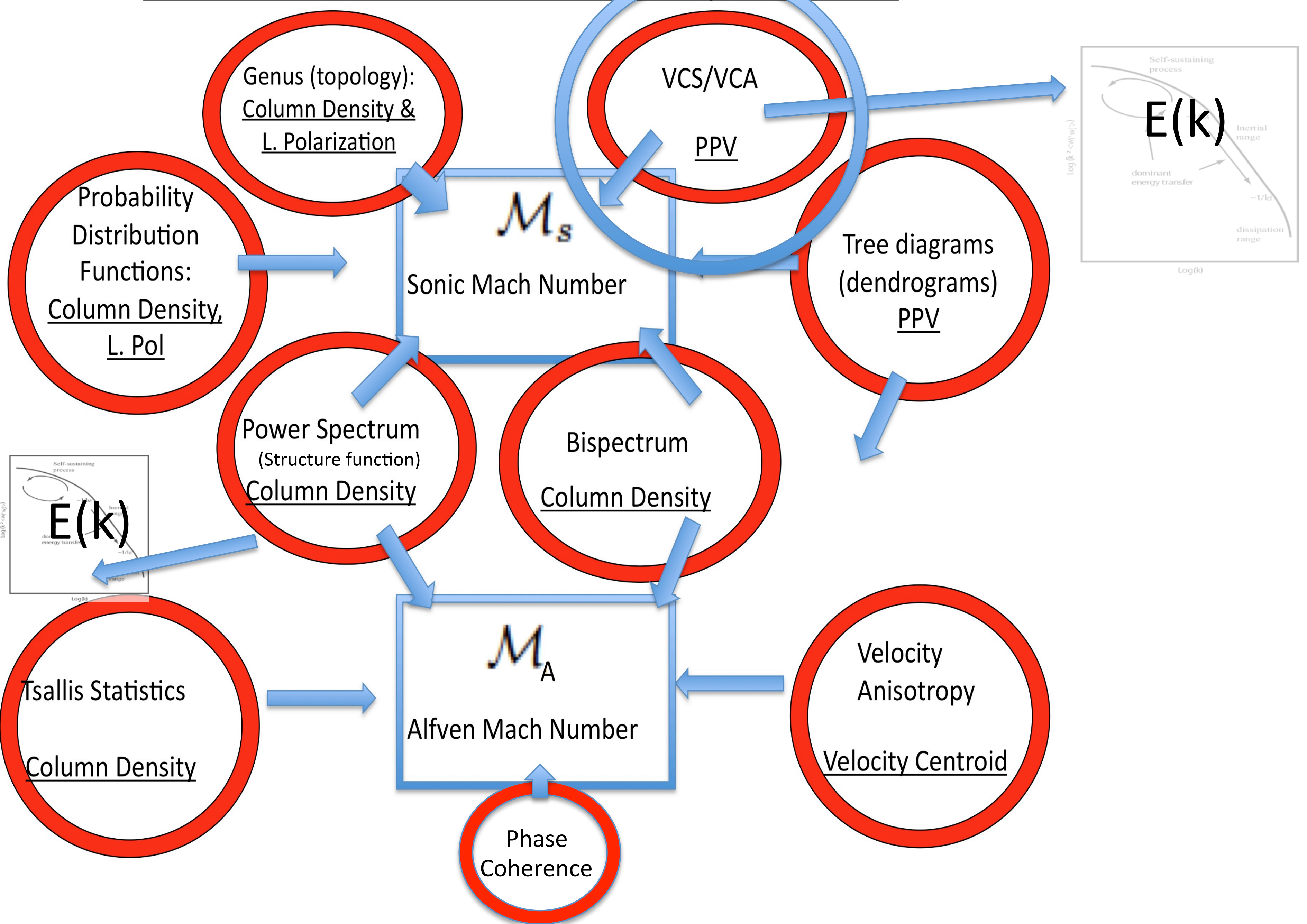
Observational test case: SMC in 21 cm emission

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

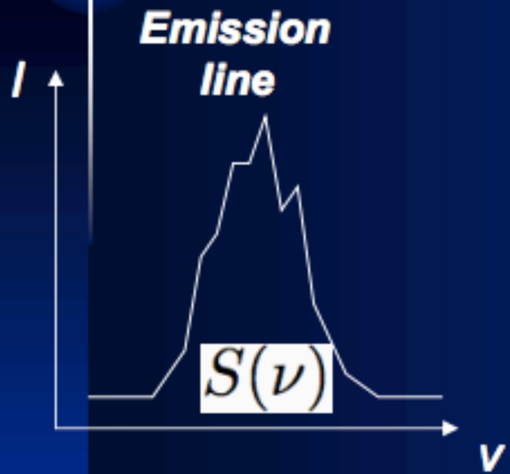
Stanimirovic et al. 1999 data set has good spatial (98”) and spectral resolution (1.65kms^{-1}) and contains both single dish (Parkes Telescope) and interferometer (ATCA telescope) data (30pc-4kpc).



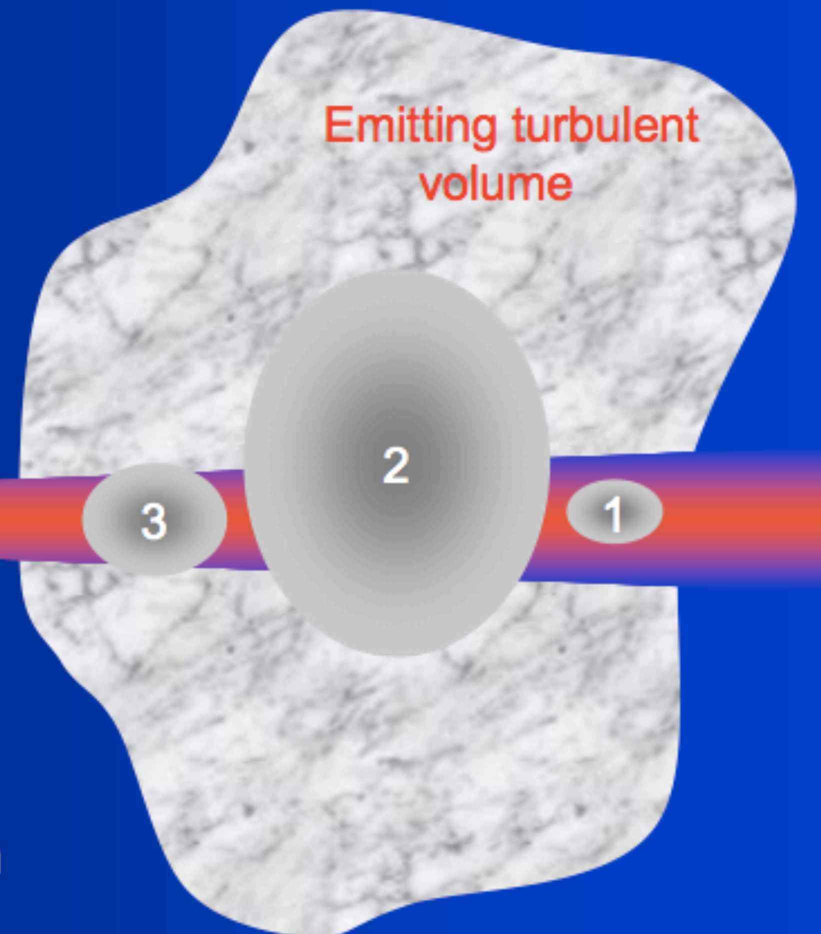
Turbulence Statistics and their Dependencies



VCS with Emission Lines



Observations of turbulence in emission lines



Instrument beam

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

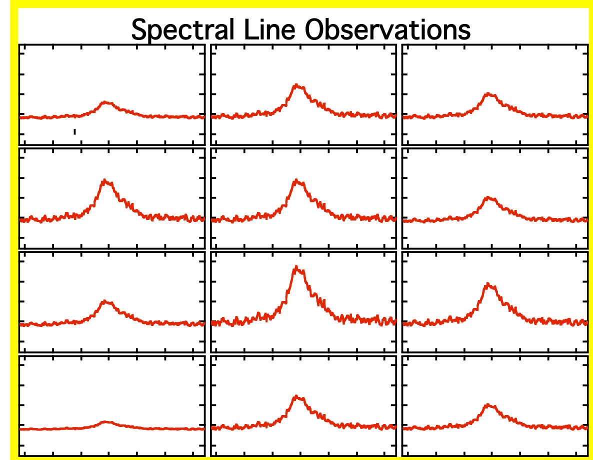
Eddie modes:

1 - low resolution
2 - high resolution
3 - intermediate

Scaling of VCS changes with the resolution.

Turbulence Velocity and Density Power Spectrum: VCS

Velocity Coordinate Spectrum (VCS):



1) Take power spectrum of 2D column density for density spectrum (steep vs. shallow spectrum) Density spectral index=-3.3 for SMC (supersonic! Lazarian & Stanimirovic 2001)

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	$\frac{2(\alpha_\varepsilon - 2)}{\alpha_v - 3}$	$\frac{2(\alpha_\varepsilon - 1)}{\alpha_v - 3}$	$\frac{2\alpha_\varepsilon}{\alpha_v - 3}$

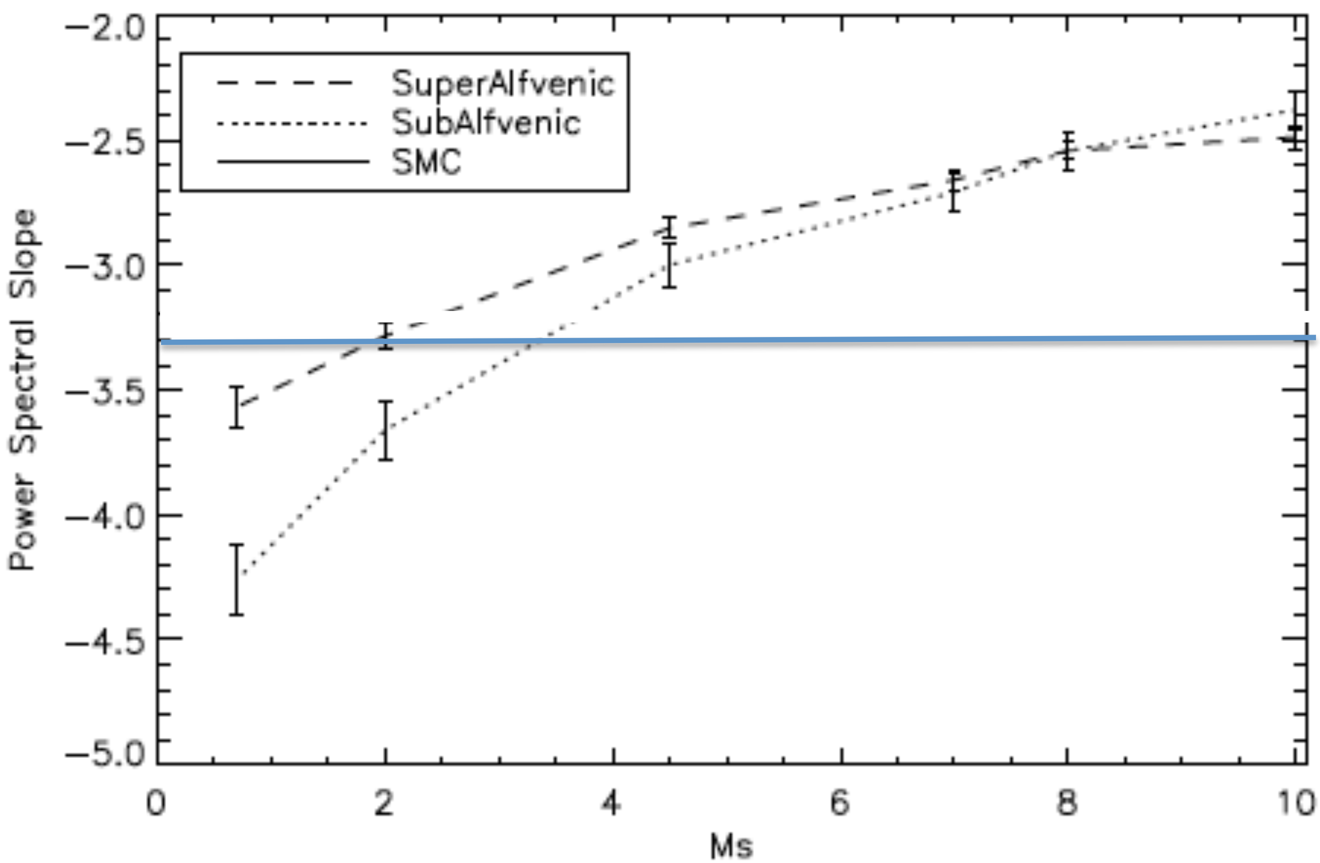
2) Take power spectrum along velocity axis for varying beam sizes

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

Developed in Lazarian & Pogosyan 2008

Density Spectrum Compared with 3D MHD Simulations

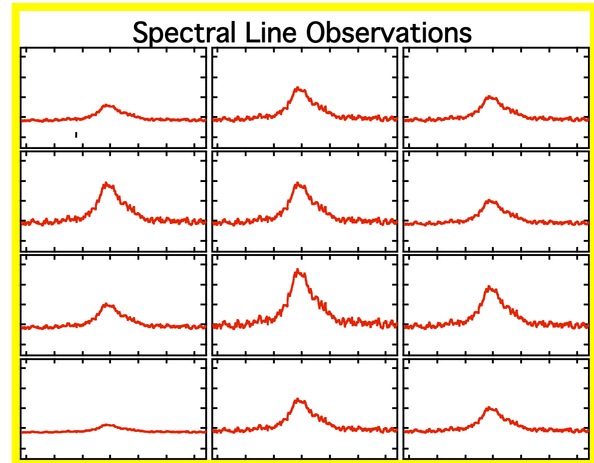
Density spectral index=-3.3 for SMC (Lazarian & Stanimirovic 2001)



Burkhart et al. 2010

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

Turbulence Velocity and Density Power Spectrum: VCS



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

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

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	$\frac{2(\alpha_\varepsilon - 2)}{\alpha_v - 3}$	$\frac{2(\alpha_\varepsilon - 1)}{\alpha_v - 3}$	$\frac{2\alpha_\varepsilon}{\alpha_v - 3}$

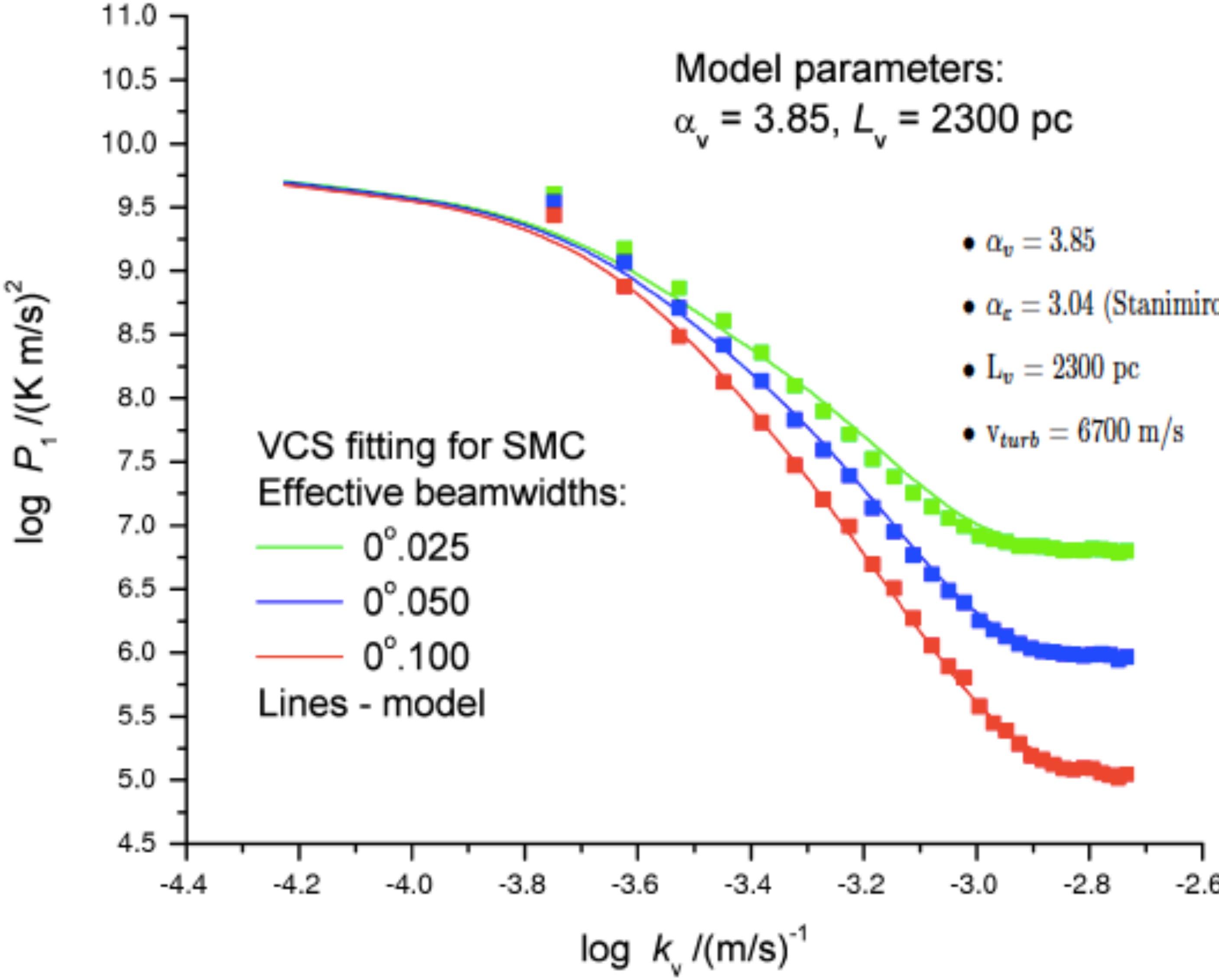
$$F_{ij}(\mathbf{k}) = \frac{V_0^2}{k^{\alpha_v}} e^{-\frac{k_0^2}{k^2}}$$

From analytical expression
For velocity correlation function

Developed in Lazarian & Pogosyan 2008

VCS of SMC (21cm)

Chepurnov, Burkhart, Lazarian & Stanimirovic 2015

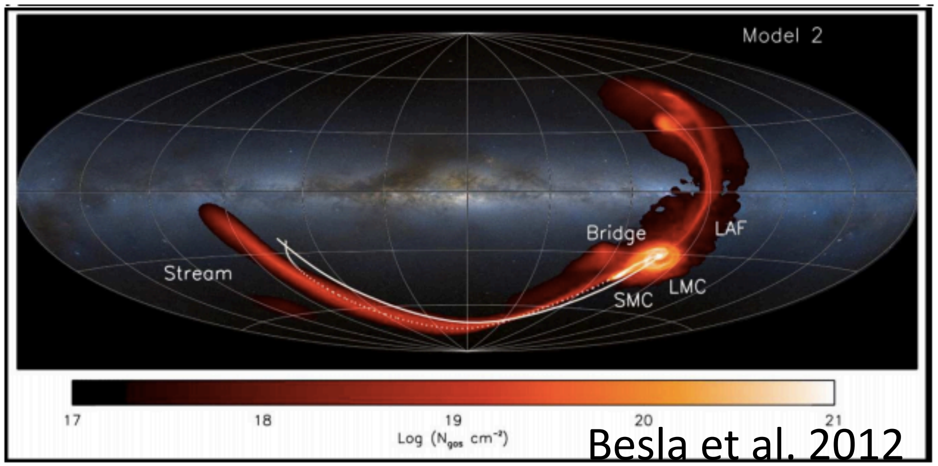


$$F_{ij}(\mathbf{k}) = \frac{V_0^2}{k^{\alpha_v}} e^{-\frac{k_0^2}{k^2}}$$

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

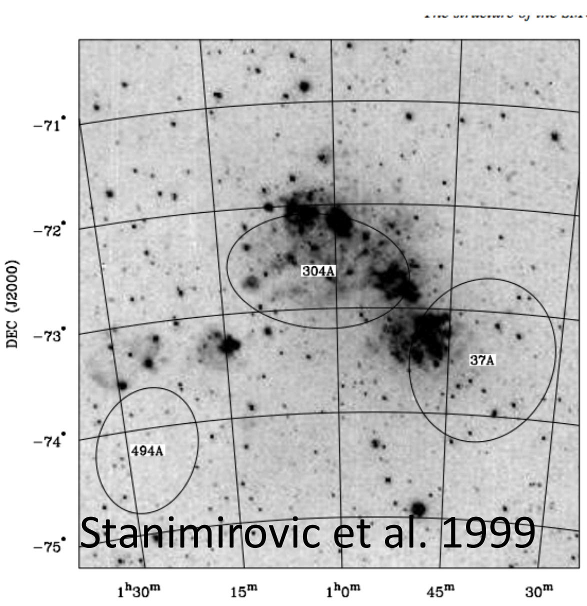
Q: What drives turbulence in the SMC?

A: Combination of both SF and Mergers!



Besla et al. 2012

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

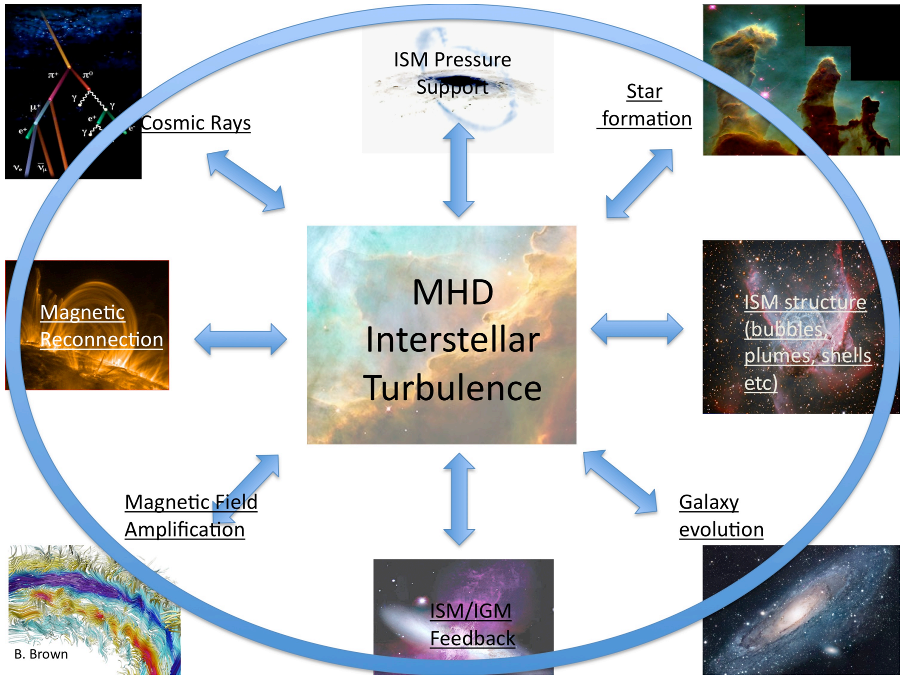


Stanimirovic et al. 1999

HI Supershells seen on kpc sizes!

Chepurnov, Burkhart, Lazarian & Stanimirovic 2015

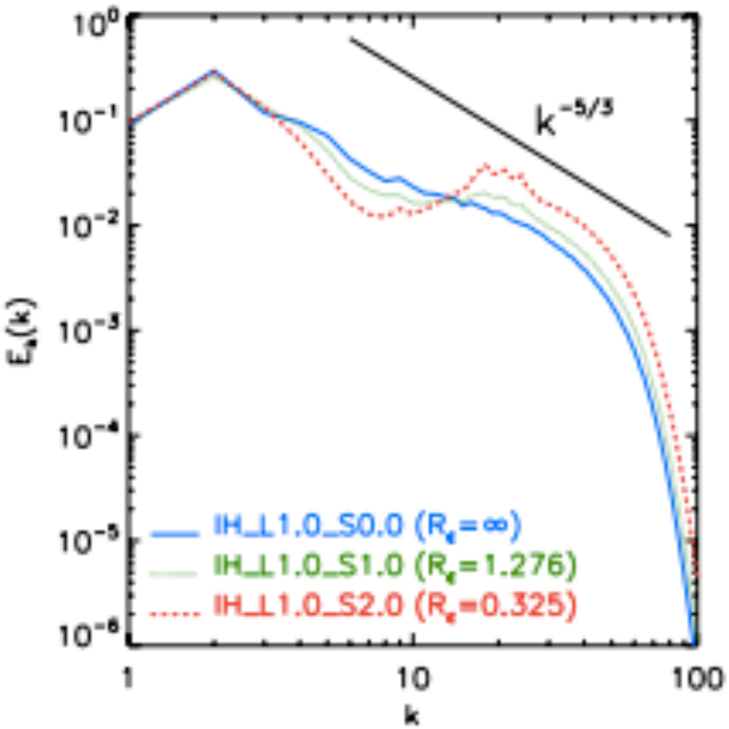
The Implications of Turbulence:



The Origins of Turbulence:

- Supernova and galaxy mergers can drive turbulence on the largest scales.
- Cosmological simulations that resolve down to kpc scales (such as the Illustris simulation) are able to reproduce the SFR-velocity dispersion relationship observed in spiral galaxies.
- Turbulence in the SMC galaxy in HI is supersonic and driven on kpc scales (merger with LMC and/or expanding superbubbles).

What is the dominate driver of turbulence?



$$\frac{E(k_L)}{E(k_S)} \sim \left(\frac{\epsilon_L}{\epsilon_S}\right)^{2/3} \left(\frac{l_L}{l_S}\right)^{5/3}.$$

Yoo & Cho 2013

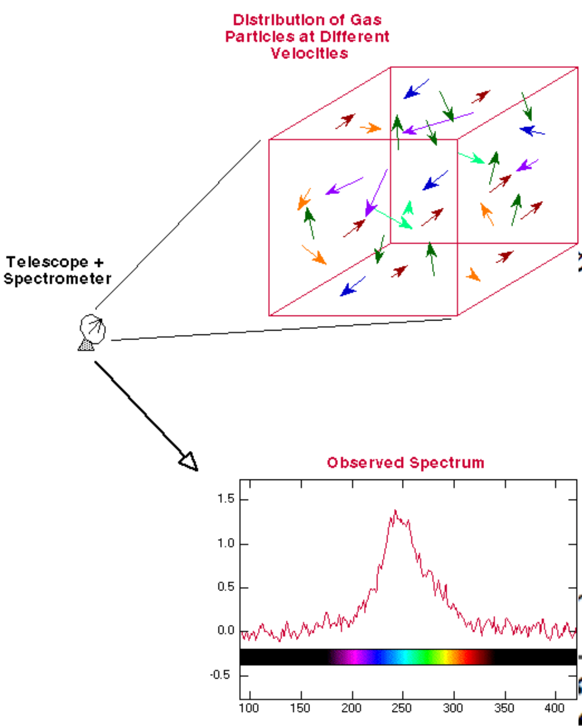
Implies that even a tiny amount of energy injection at E_L will suffice to make the spectral peak at k_L larger than that at k_S!

What is the largest and dominate driving scale?

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