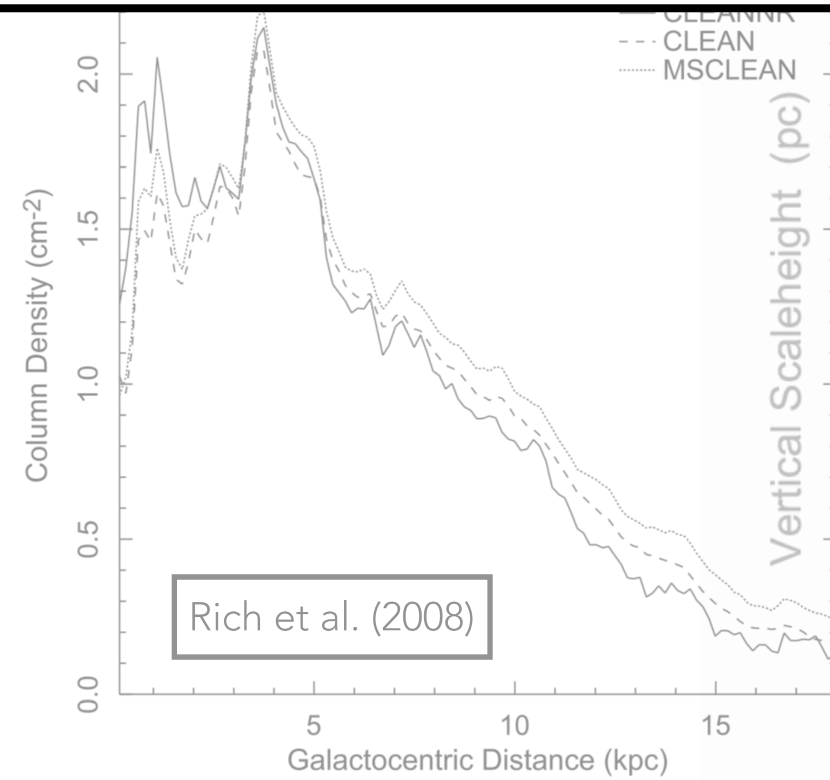
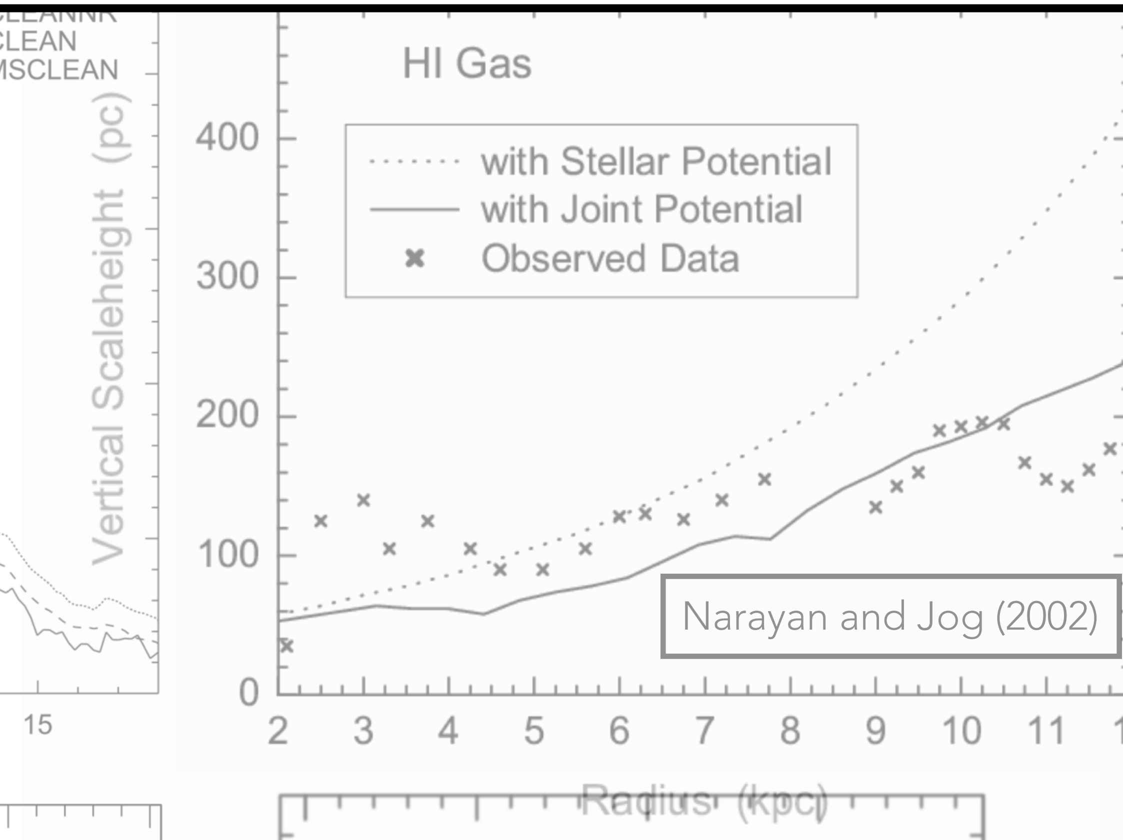
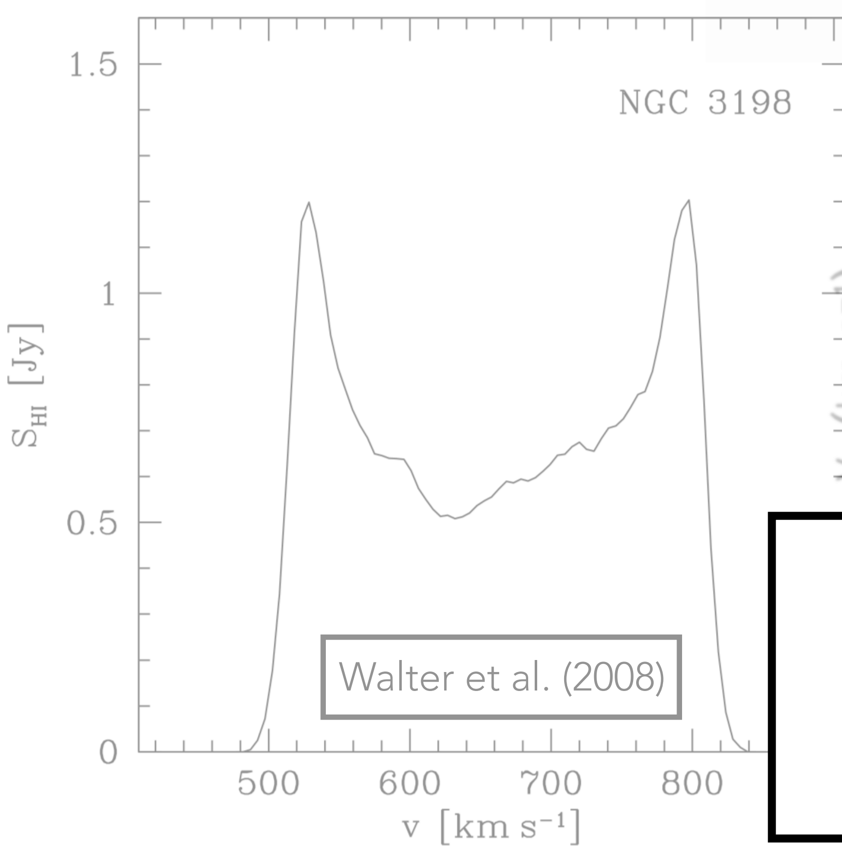
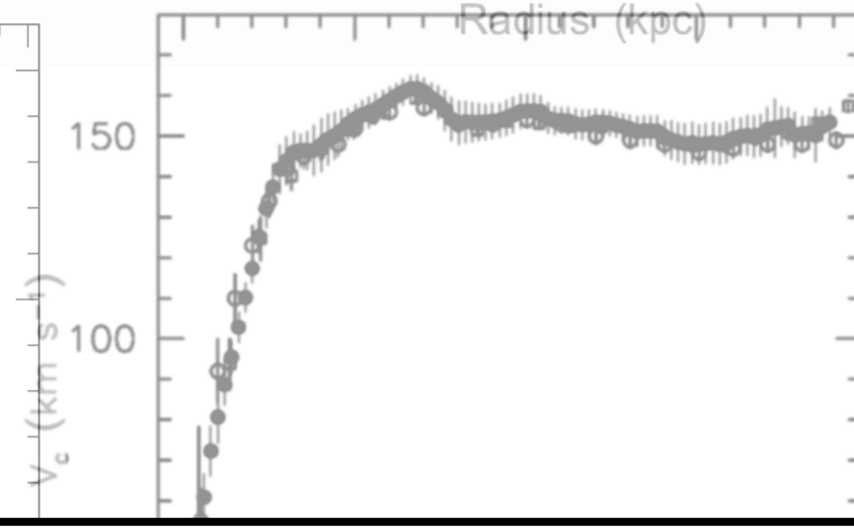
Structures and Dynamics of the HI in the interstellar medium of Galaxies









Background

Motivation

Techniques

Results

Implications

Prasun Dutta

IIT (BHU), Varanasi

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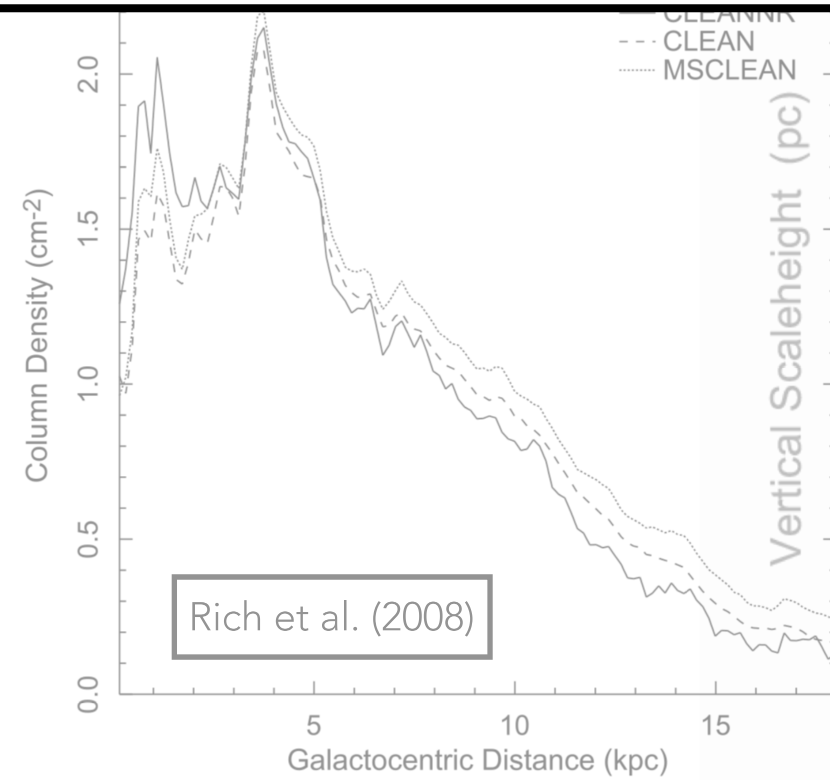

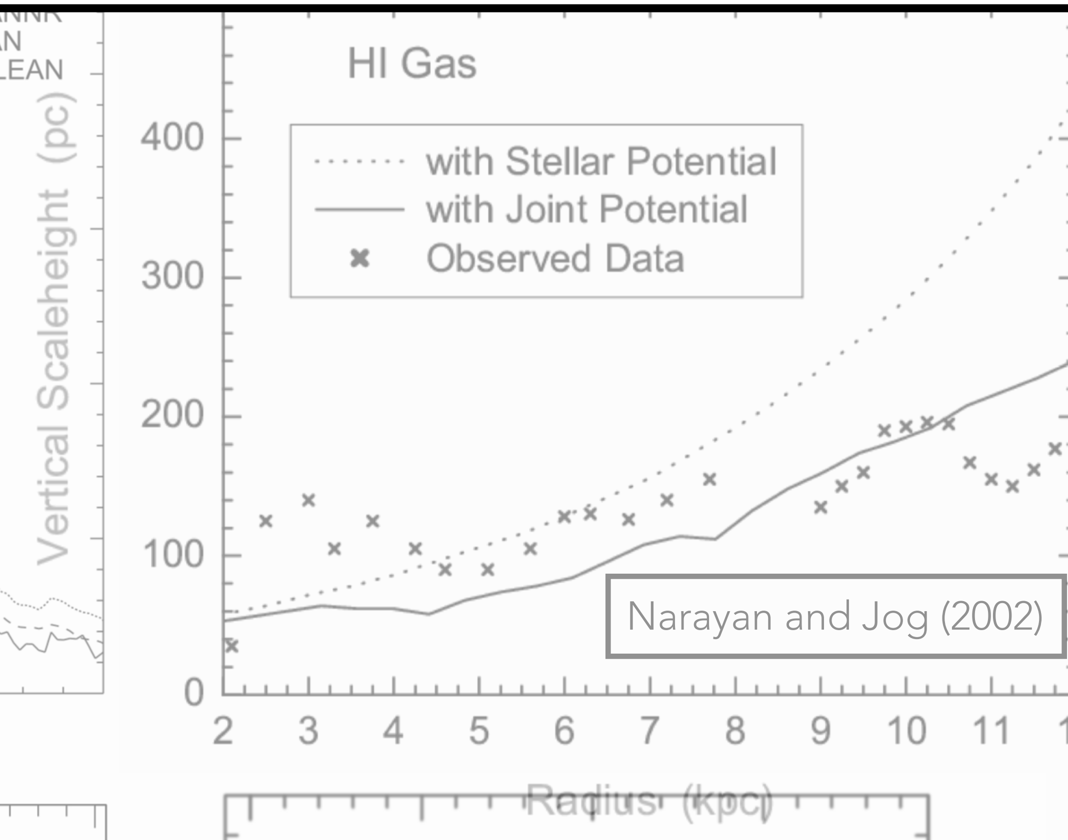

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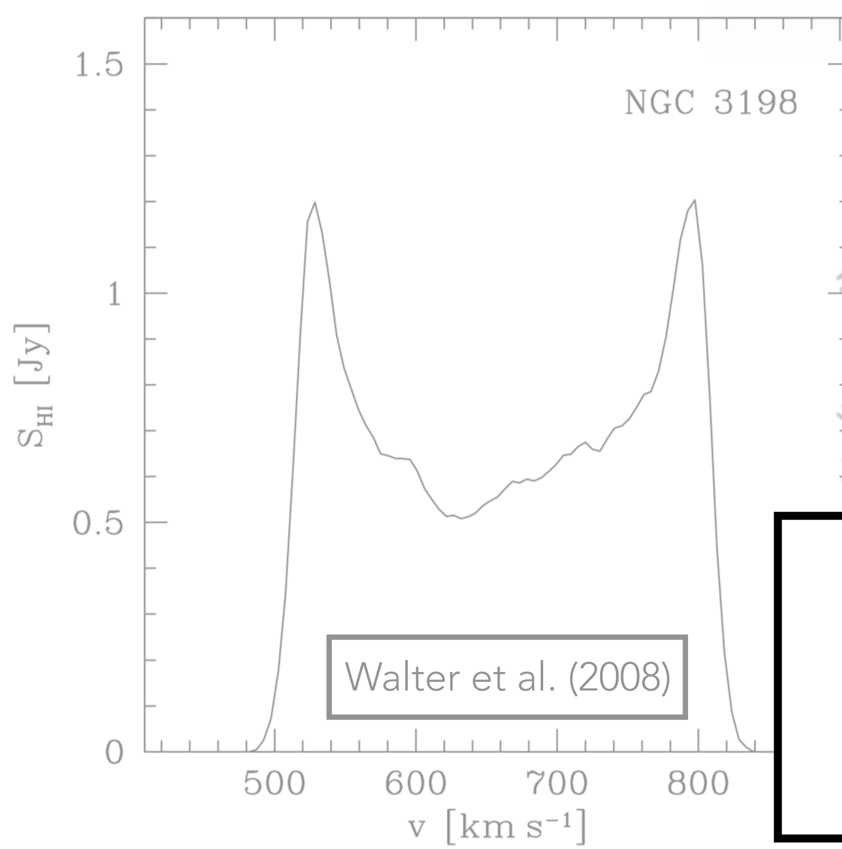

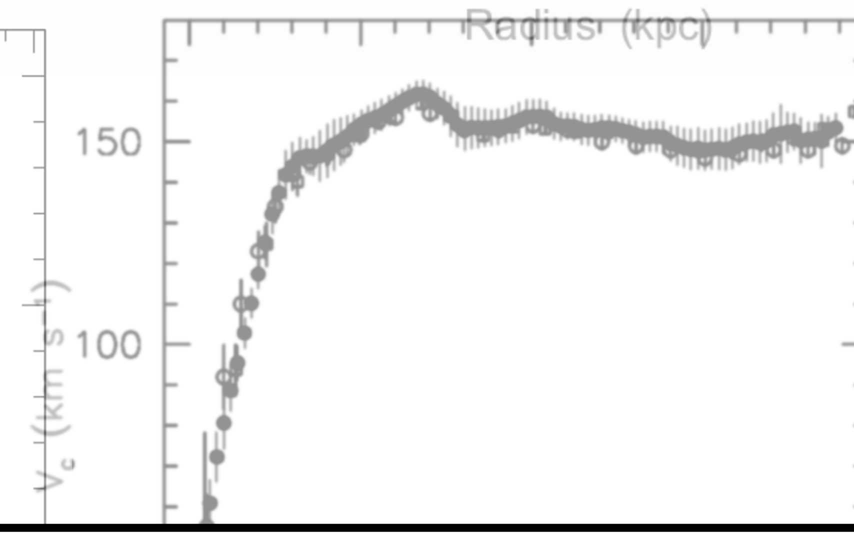

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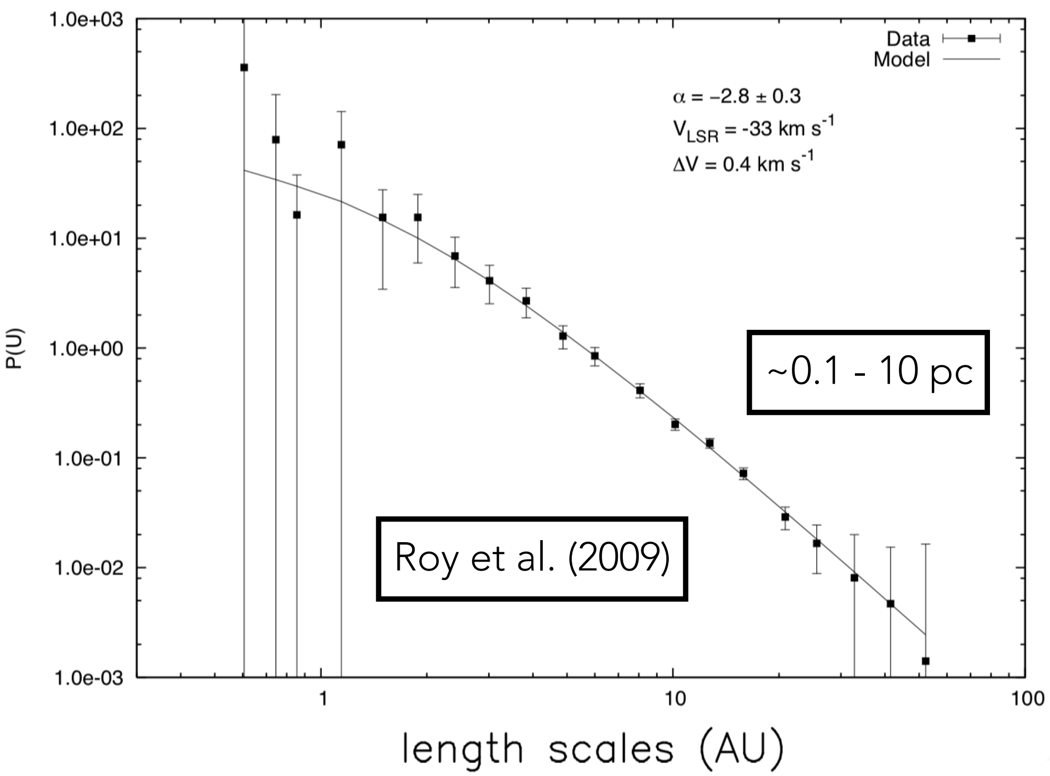
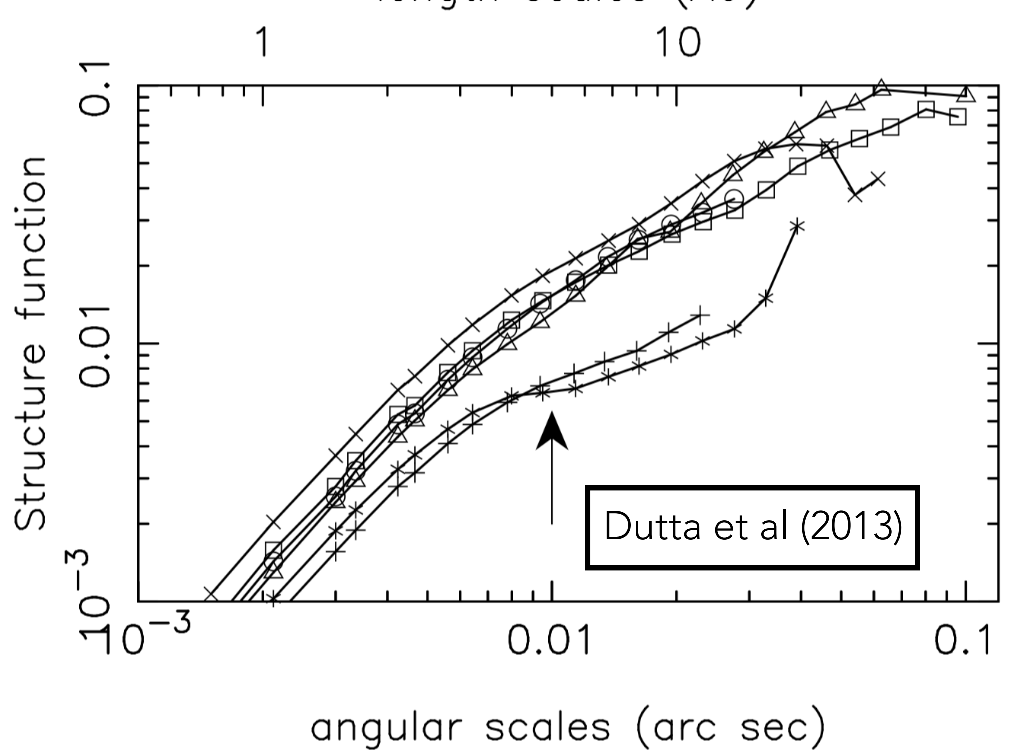
Scale invariant structures: Column density

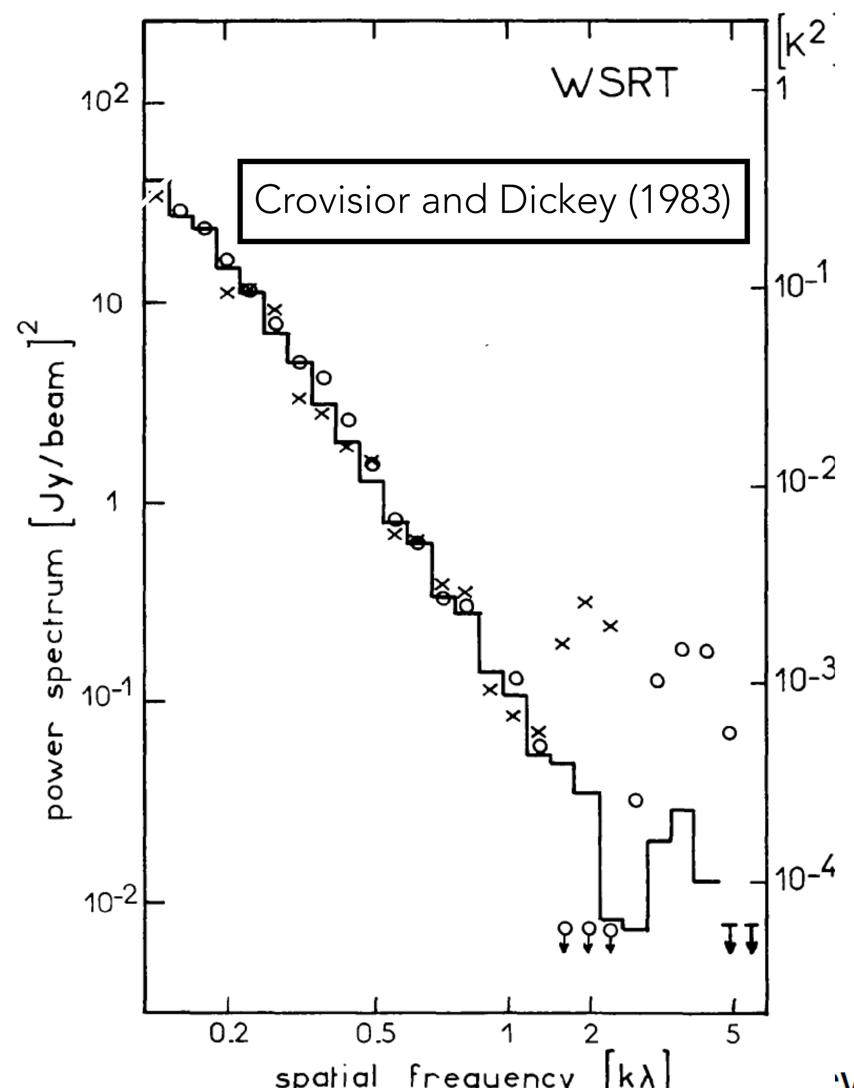
10 Au 0.1pc 10 pc 100 pc 1 kpc

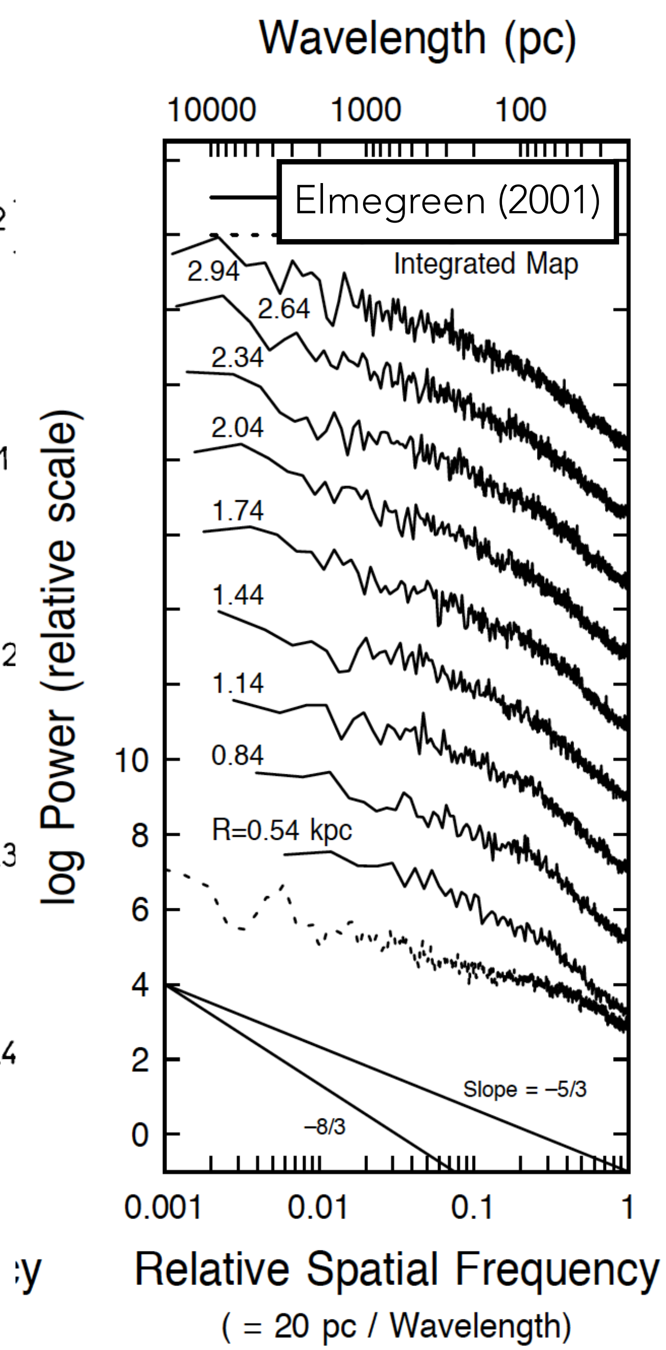
Absorption Studies

Emission Studies

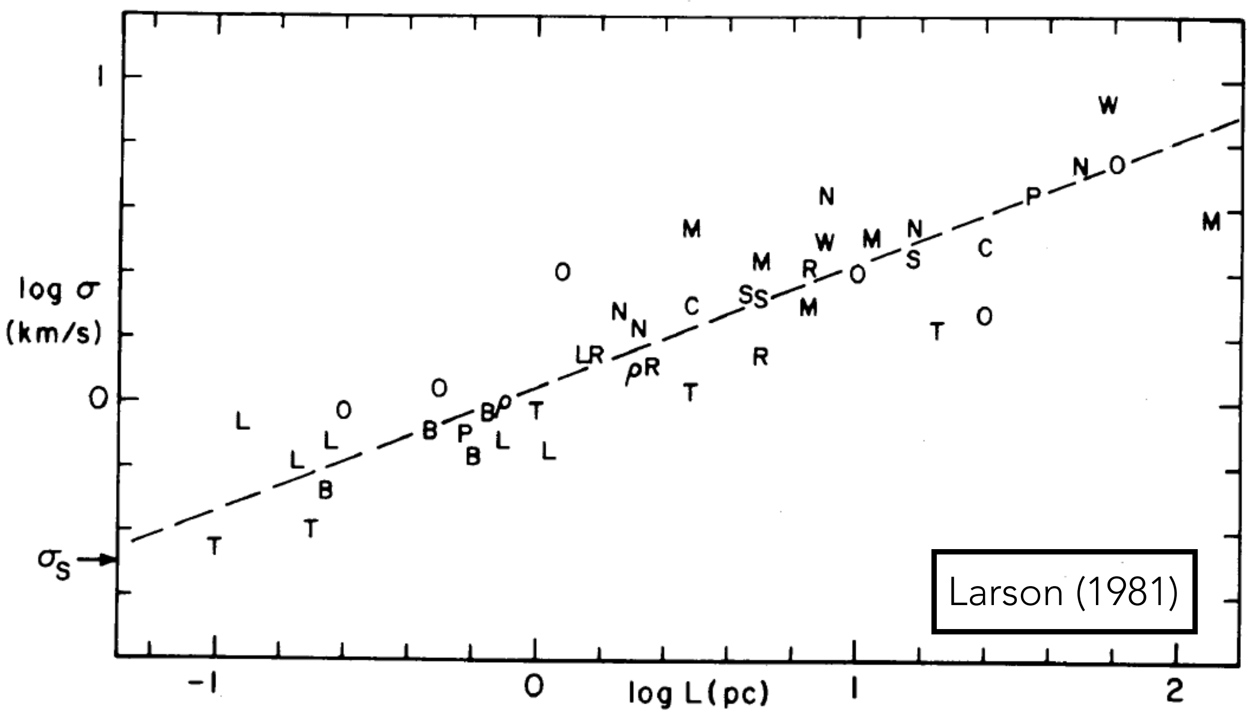


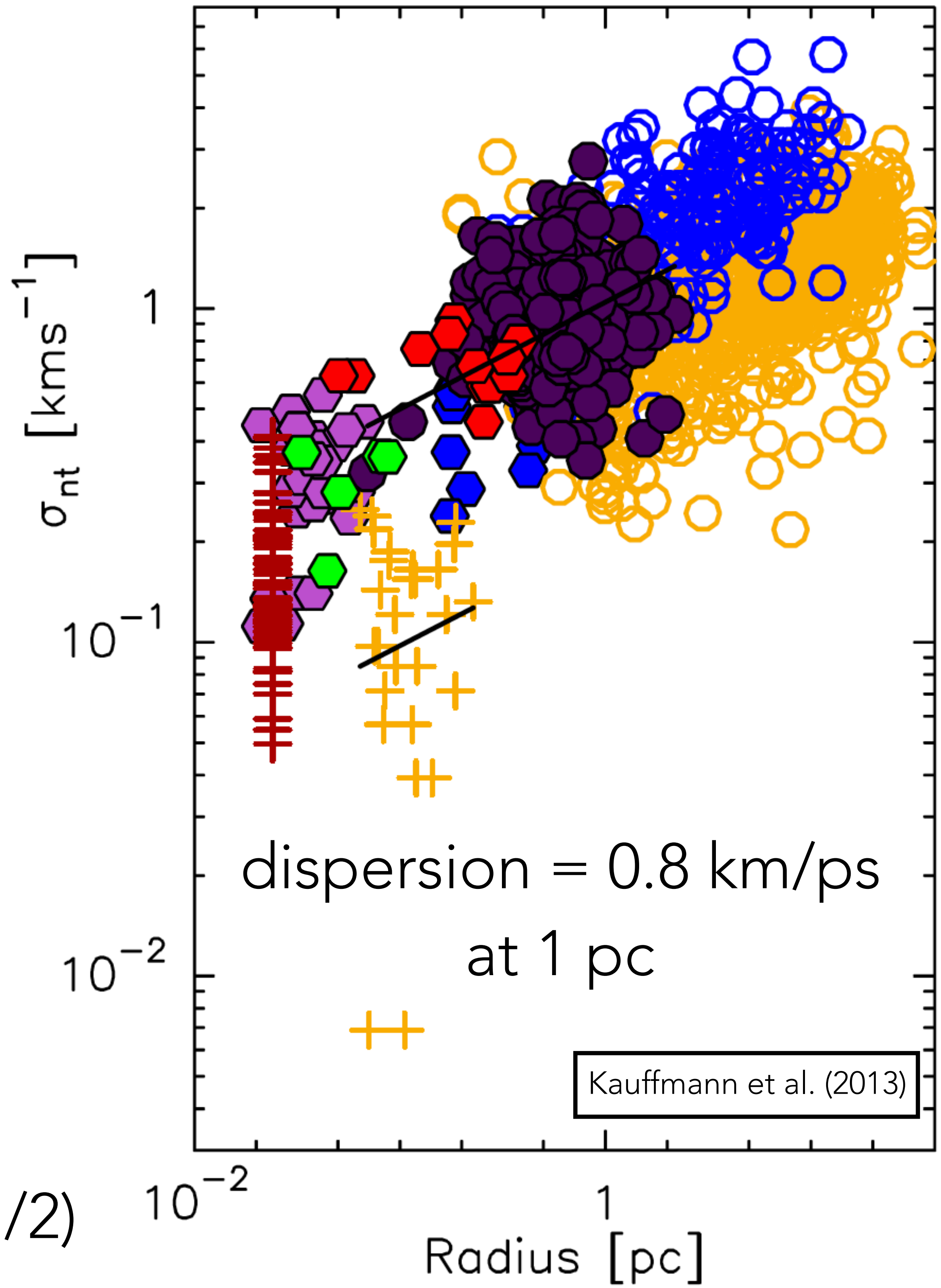






Scale invariant structures: Larson Relation





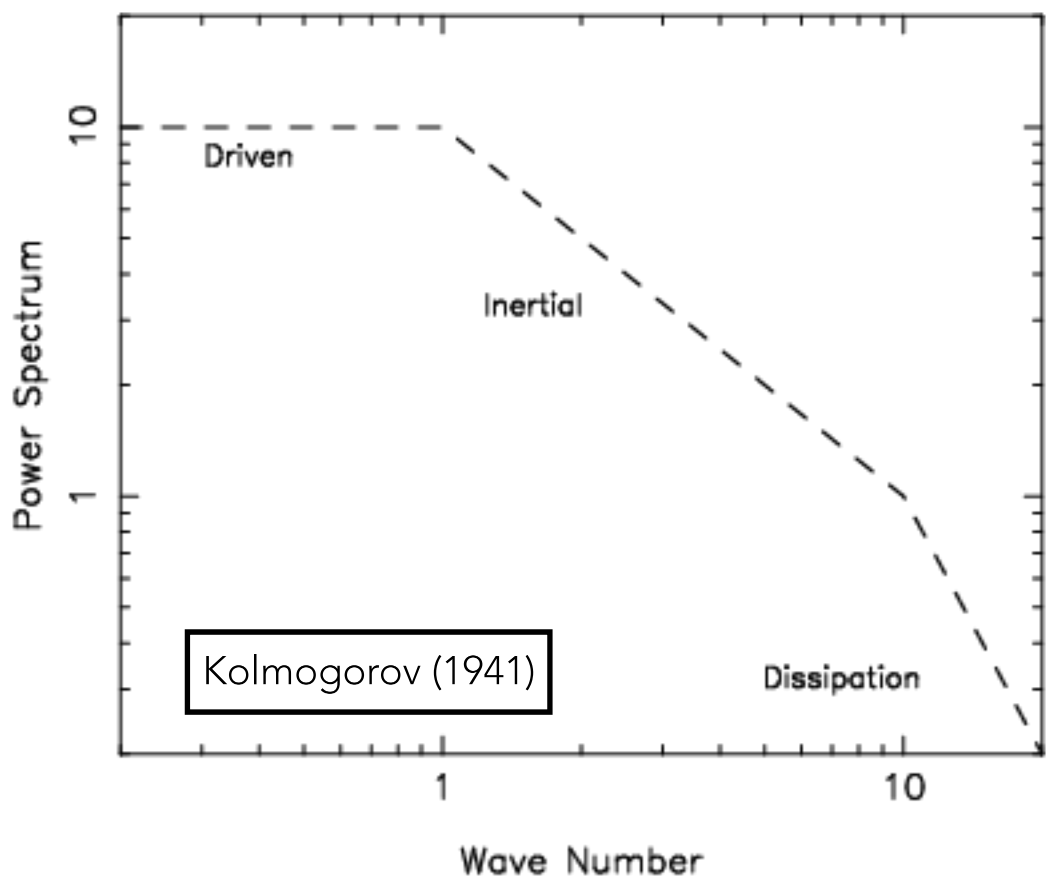
$$\sigma_v \propto l^{\beta}$$

$$\beta = (0.3 - 0.5)$$

Kolmogorov (1/3), Supersonic (1/2)

Physical Picture: Interstellar turbulence

- Incompressible fluid



$$\frac{\partial \vec{v}}{\partial t} + \left(\vec{v}.\vec{\nabla}\right)\vec{v} \quad - \nu \nabla^2 \vec{v} = \vec{F}$$

$$Re_l = \frac{v_l l}{\nu} \qquad E(k) \ \sim k^{-5/3}$$

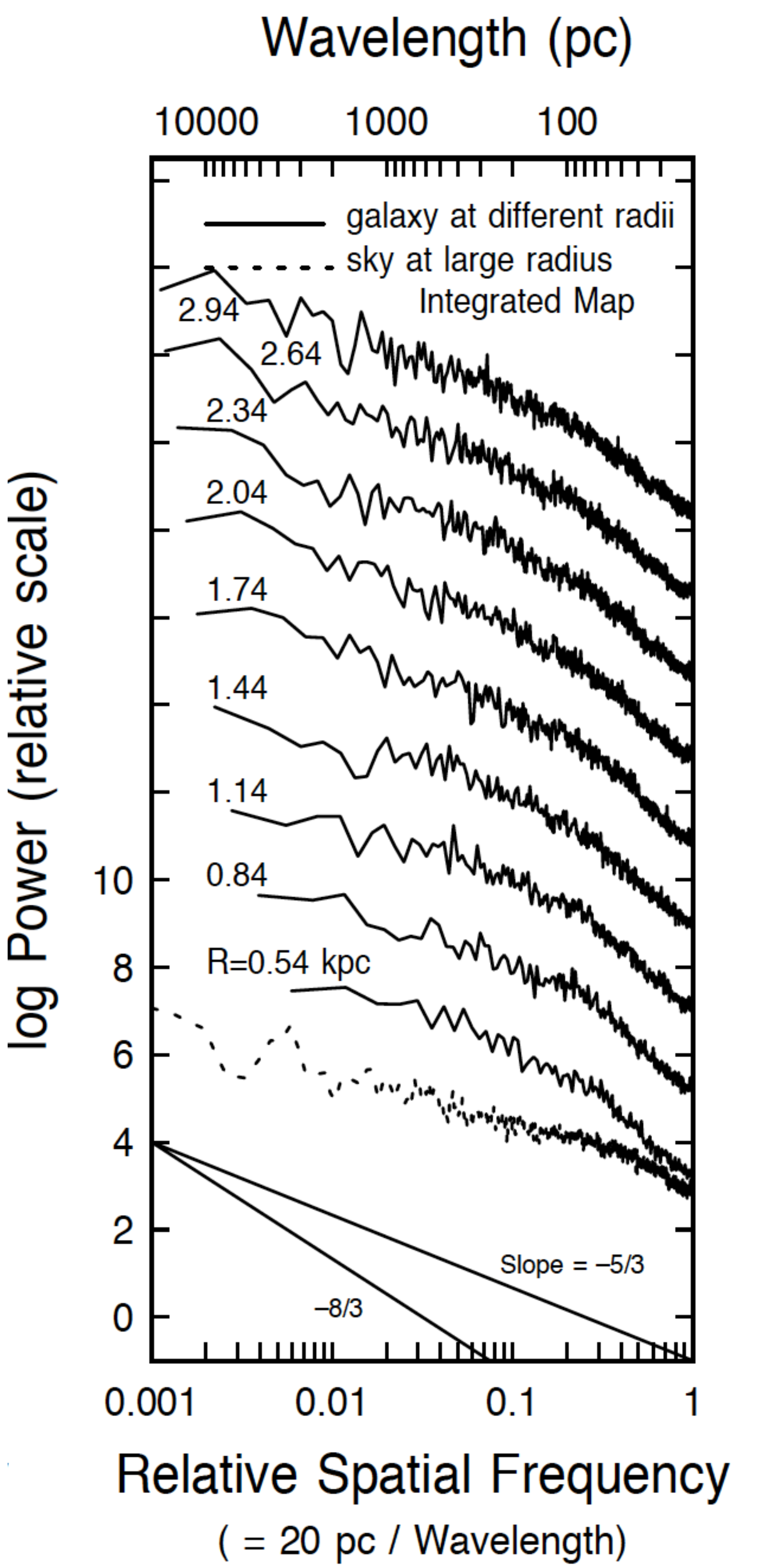
- Compressible fluid (ISM)

$$P_u(k) \propto k^{-5/3-2\alpha} \qquad P_\rho(k) \propto k^{6\alpha-1}$$

Lighthill (1955), Fleck (1996)

- Turbulence generates scale invariant density and velocity structures in the ISM (Elmegreen and Scalo 2004)
- As the Hi clouds fragments at the highest densities regions, it help provide the initial mass function for star formation (Hennebelle and Audit 2007)
- The turbulent pressure in the high density regions, however balance some of them from collapse, reducing the star formation rate per over densities (Maclow 2003, Audit 2005)
- Two possible sources of the energy input to the ISM turbulence are the supernovae feedback and galactic differential rotation (Fleck 1981, Boomsma et al. 2008)

Motivation and direction



$$P_u(k) \propto k^{-5/3-2\alpha} \qquad P_\rho(k) \propto k^{6\alpha-1}$$

- Supernovae shocks come to pressure equilibrium with the ISM at around 100 pc, but coherent scale invariant structures exist well beyond 100 pc.
- Nature of the ISM turbulence, what is the value of alpha?
- How much energy is carried from the larger scales to the smaller scales?
- What is the actual injection scale of the ISM turbulence (must be greater than 1 kpc from observations)?
- It is clear that there are several injection scale to ISM turbulence, then what keeps the scale invariant structures?

- Answering these questions, one requires to observe the scale property of the ISMdensity and velocity over large range of length scales
- The 21-cm line from the warm neutral hydrogen (HI) is a good tracer of the ISM structure and dynamics
- Probing larger scales, need us to look at external spiral galaxies using radio interferometers.

Method of visibility moments

$$I(\vec{\theta},\nu) = \frac{3h\nu_0 A_{21}}{16\pi}\int dz\; n_{HI}(\vec{\theta},z)\phi(\nu; v_z(\vec{\theta}),\sigma_v)$$

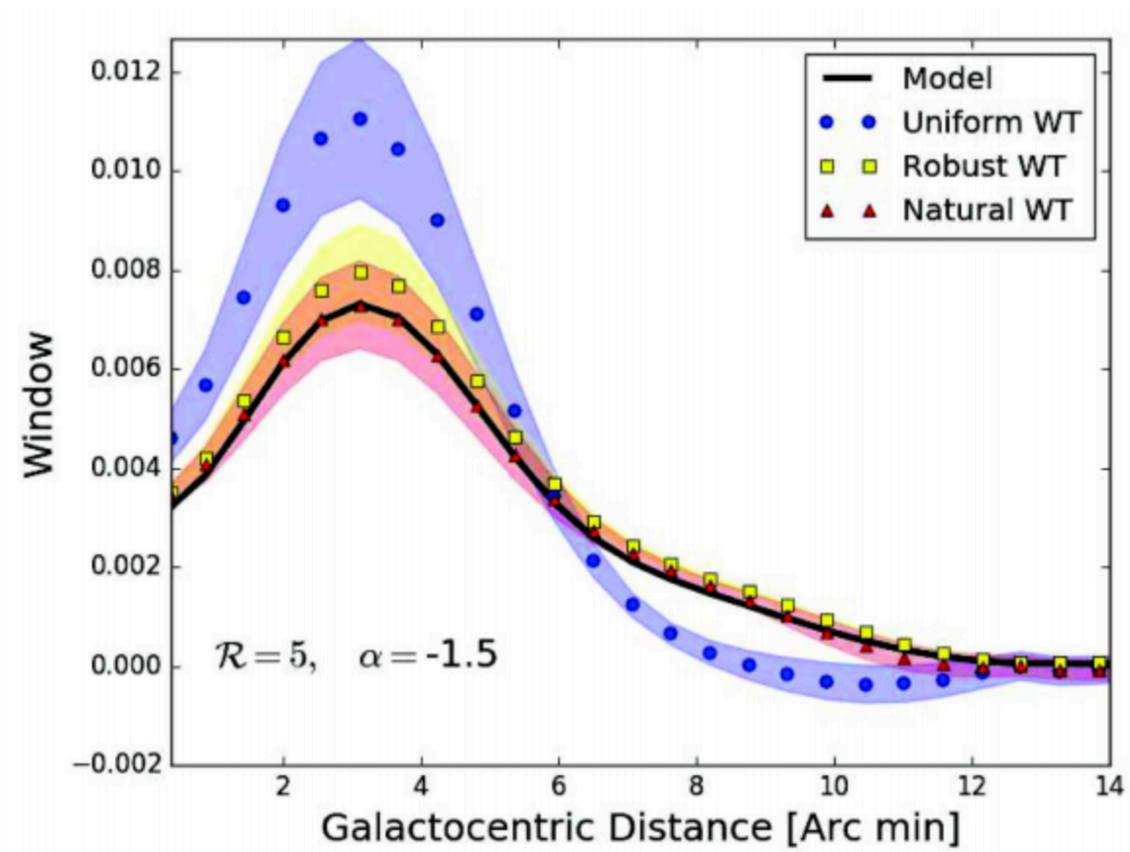
$$N_{HI}(\vec{\theta}) \propto \int d\nu\; I(\vec{\theta},\nu), \qquad v_z(\vec{\theta}) \propto \int d\nu \nu I(\vec{\theta},\nu)$$

$$N_{HI}(\vec{\theta}) = W_{HI}(\vec{\theta})\left[\bar{N}_{HI} + \hat{\delta}_{HI}(\vec{\theta})\right]$$

$$V(\vec{U},\nu) = \left[\int d\vec{\theta}\; e^{-i2\pi\vec{U}.\vec{\theta}}\; A(\vec{\theta})I(\vec{\theta},\nu)\right] \times S(\vec{U})$$

$$I_D(\vec{\theta},\nu) = I(\vec{\theta},\nu) \otimes B(\vec{\theta},\nu)$$

- Our controlled test (simulated observations) showed that the large scale density (and also velocity) structures can be well estimated using the “cleaned” image.



Dutta and Nandakumar (2018)

Column density Power Spectrum

$$I(\vec{\theta},\nu) = \frac{3h\nu_0 A_{21}}{16\pi}\int dz\; n_{HI}(\vec{\theta},z)\phi(\nu;v_z(\vec{\theta}),\sigma_v)$$

$$N_{HI}(\vec{\theta}) \propto \int d\nu\; I(\vec{\theta},\nu), \qquad v_z(\vec{\theta}) \propto \int d\nu\nu I(\vec{\theta},\nu)$$

$$N_{HI}(\vec{\theta}) = W_{HI}(\vec{\theta})\left[\bar{N}_{HI} + \hat{\delta}_{HI}(\vec{\theta})\right]$$

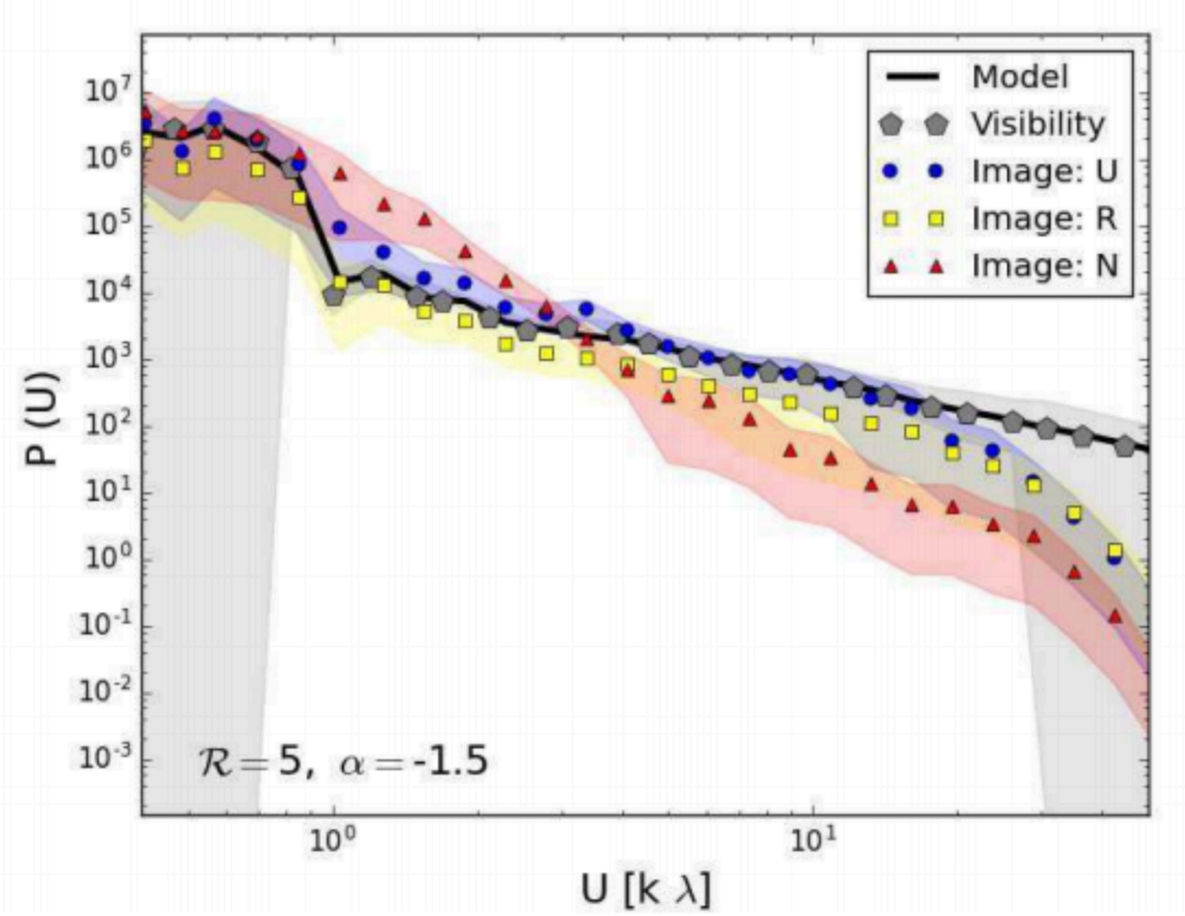
- Visibility moment and power spectrum

$$V_0(\vec{U}) = \int d\nu V(\vec{U},\nu)$$

$$P_{HI}(U) = \langle \mid V_0(\vec{U}) \mid^2 \rangle$$

$$V(\vec{U},\nu) = \left[\int d\vec{\theta}\; e^{-i2\pi\vec{U}.\vec{\theta}}\; A(\vec{\theta})I(\vec{\theta},\nu)\right] \times S(\vec{U})$$

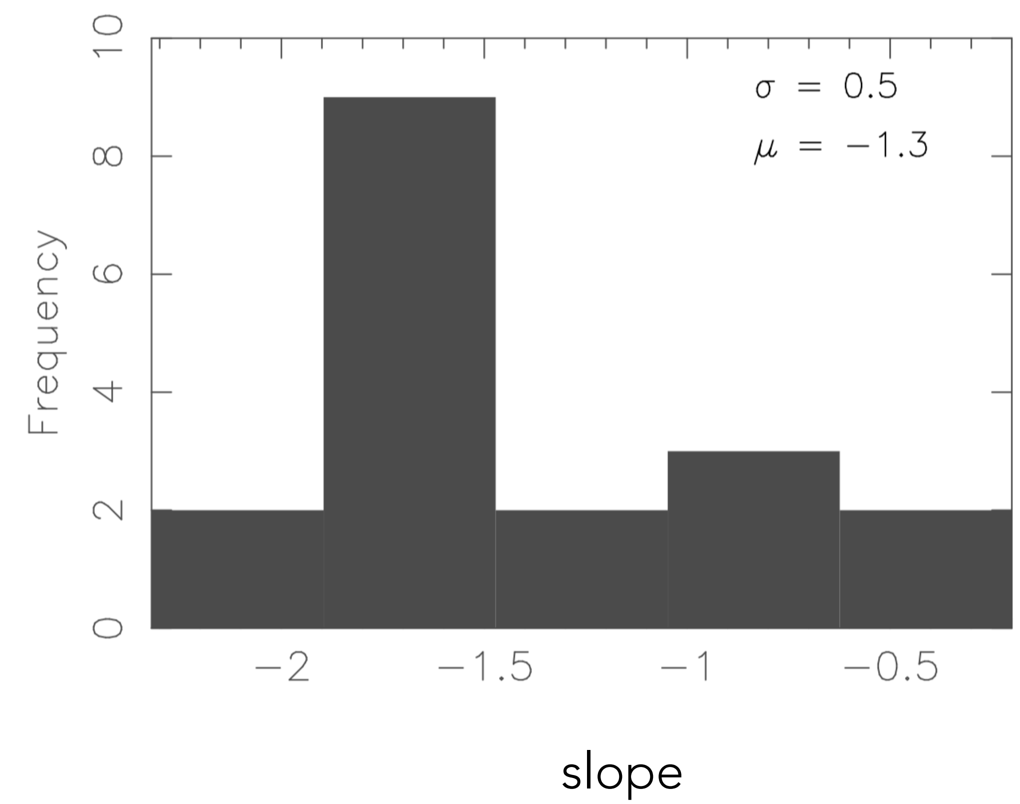
$$I_D(\vec{\theta},\nu) = I(\vec{\theta},\nu) \otimes B(\vec{\theta},\nu)$$

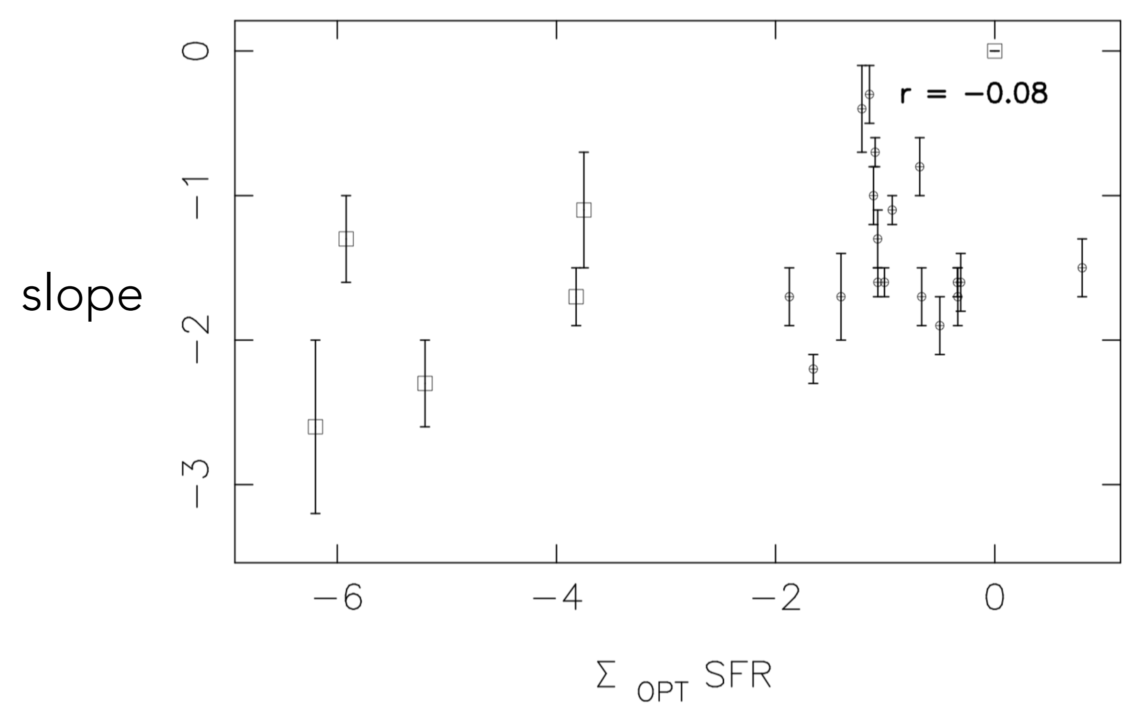


Dutta and Nandakumar (2018)

Column density Power Spectrum: THINGS

Galaxy	R_{min} (kpc)	R_{max} (kpc)	slope
NGC 628	0.8	7.5	-1.6 ± 0.1
NGC 925	0.9	9.2	-1.0 ± 0.2
NGC 2403	0.6	4.0	-1.1 ± 0.1
NGC 2841N	1.4	14.0	-1.7 ± 0.2
NGC 2841S	1.4	14.0	-1.5 ± 0.2
NGC 2903	1.1	11.1	-1.5 ± 0.2
NGC 3031N	0.4	1.8	-0.7 ± 0.1
NGC 3184	1.6	15.8	-1.3 ± 0.2
NGC 3198	1.4	8.6	-0.4 ± 0.3
NGC 3521N	0.6	10.7	-1.8 ± 0.1
NGC 3521S	0.6	10.7	-1.6 ± 0.2
NGC 3621	0.6	6.6	-0.8 ± 0.2
NGC 4736	0.5	7.8	-0.3 ± 0.2
NGC 5055	1.0	10.0	-1.6 ± 0.1
NGC 5194	1.0	8.0	-1.7 ± 0.2
NGC 5236	0.8	7.5	-1.9 ± 0.2
NGC 5457	0.6	12.3	-2.2 ± 0.1
NGC 6946	0.3	4.0	-1.6 ± 0.1
NGC 7793	0.6	6.5	-1.7 ± 0.2
IC 2574	0.4	3.3	-1.7 ± 0.3

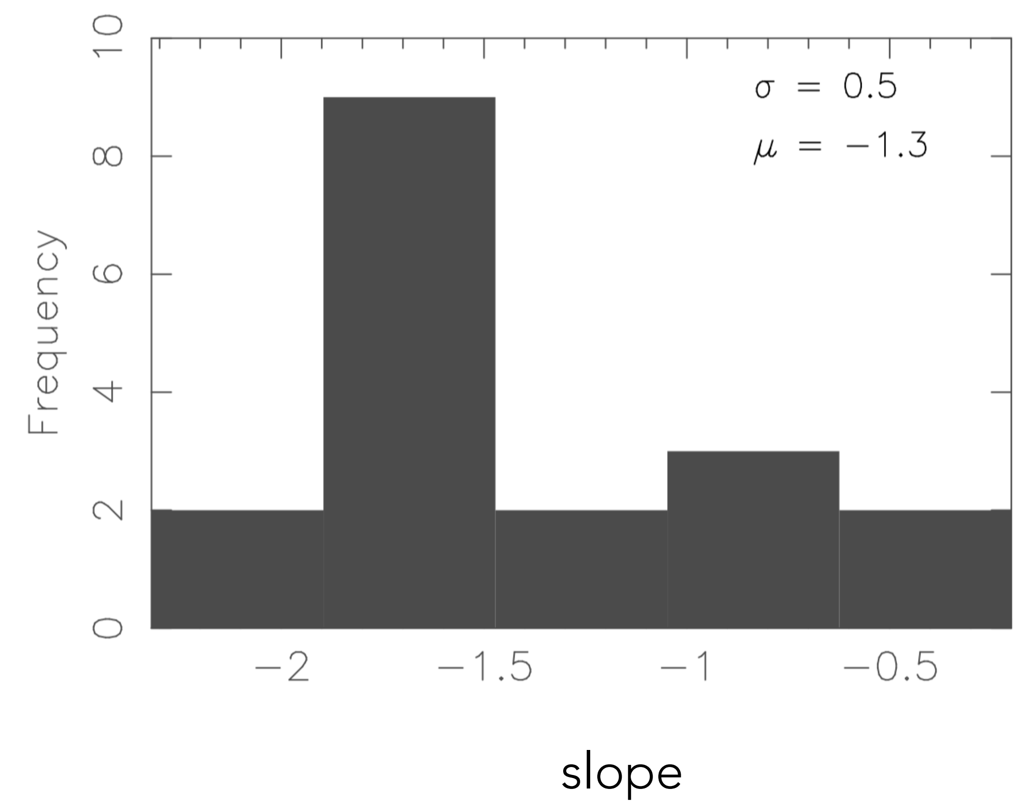




Dutta et al. 2009, 2013, 2014

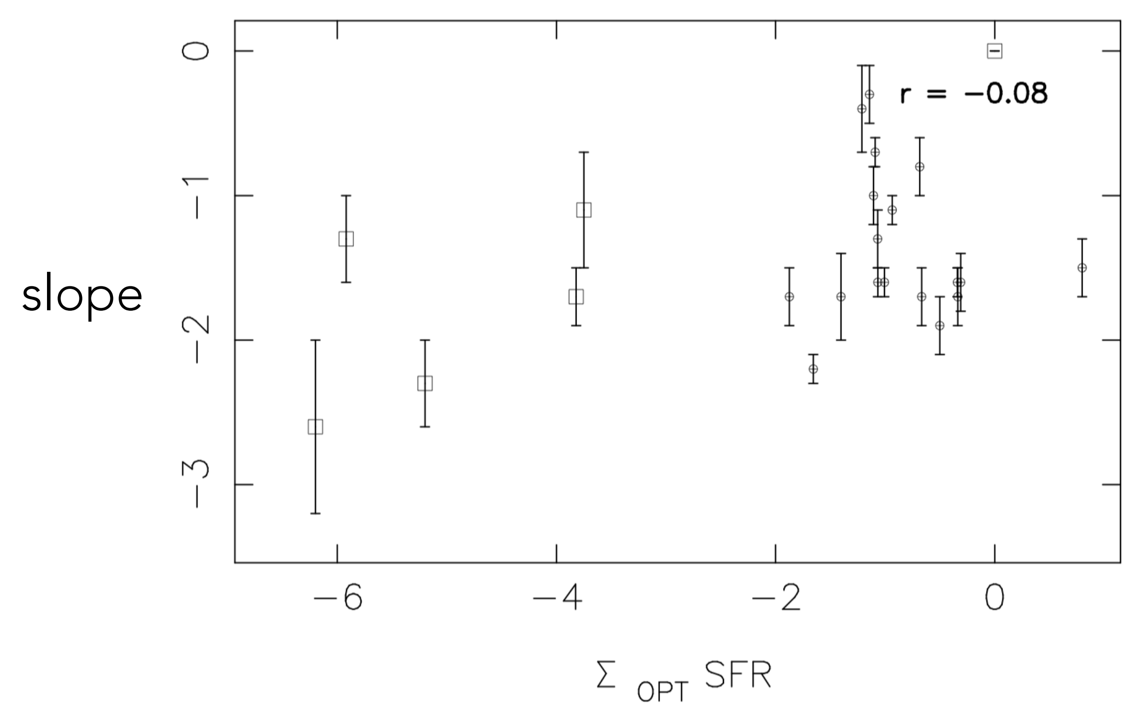
Column density Power Spectrum: THINGS

- Column density power spectra follow power law over length scale ranging ~300 pc to 16 Kpc considering all galaxies, need to do better.
- The average value of the slope of the power spectra is about -1.5
- The fluctuations in HI column density is about 1/10th of the mean column density.
- The global star formation rate is not correlated with the type of turbulence (slope)



$$P_{N_{HI}}(U) \propto U^{6\alpha-2} \qquad P_v(U) \propto U^{-8/3-2\alpha}$$

- For our observation the mean value of alpha is ~ 1/12
- Corresponds to velocity power spectrum of slope -11/6, a mix of passive incompressible and compressible supersonic turbulence



Dutta et al. 2009, 2013, 2014

Line of sight Velocity Power Spectrum

- Visibility Moment estimator

$$I(\vec{\theta},\nu) = \frac{3h\nu_0 A_{21}}{16\pi}\int dz\; n_{HI}(\vec{\theta},z)\phi(\nu; v_z(\vec{\theta}),\sigma_v)$$

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$$v_z(\vec{\theta}) = v_z^{\Omega}(\vec{\theta}) + v_z^{T}(\vec{\theta})$$

- The column density estimator

$$V_0(\vec{U}) = \int d\nu V(\vec{U},\nu) \qquad P_{HI}(U) = \langle \mid V_0(\vec{U}) \mid^2 \rangle$$

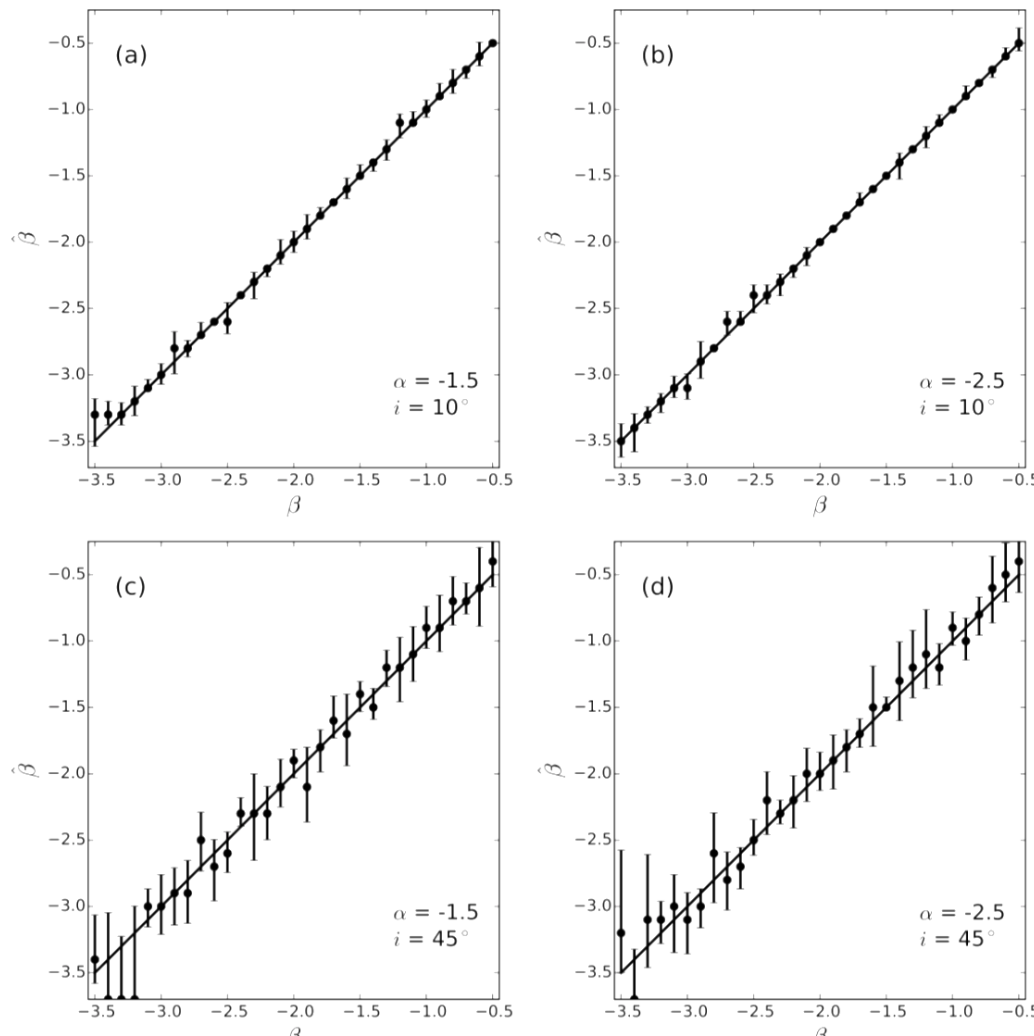
- Velocity fluctuation power spectrum

$$V_1(\vec{U}) = \int d\nu\; \nu V(\vec{U},\nu)$$

$$\langle V_1(\vec{\theta})\rangle = \int d\vec{\theta}\left[\int d\vec{\theta}' L(\vec{\theta}-\vec{\theta}') \int d\nu \nu I(\vec{\theta}',\nu)\right] e^{2\pi i \vec{U}.\vec{\theta}}$$

$$\chi(\vec{U}) = V_1(\vec{U}) - \langle V_1(\vec{\theta})\rangle$$

$$P_{\chi}(U) = P_{HI}(U) \otimes P_{v^T}(U)$$



- Possible to do for galaxies with larger angular extent and low inclination angle.. requires high signal to noise data

Dutta 2015

Line of sight Velocity Power Spectrum

- Visibility Moment estimator

$$I(\vec{\theta},\nu) = \frac{3h\nu_0 A_{21}}{16\pi}\int dz\, n_{HI}(\vec{\theta},z)\phi(\nu; v_z(\vec{\theta}),\sigma_v)$$

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- The column density estimator

$$V_0(\vec{U}) = \int d\nu V(\vec{U},\nu) \qquad \boxed{P_{HI}(U) = \langle | V_0(\vec{U}) |^2\rangle}$$

- Velocity fluctuation power spectrum

$$V_1(\vec{U}) = \int d\nu\; \nu V(\vec{U},\nu)$$

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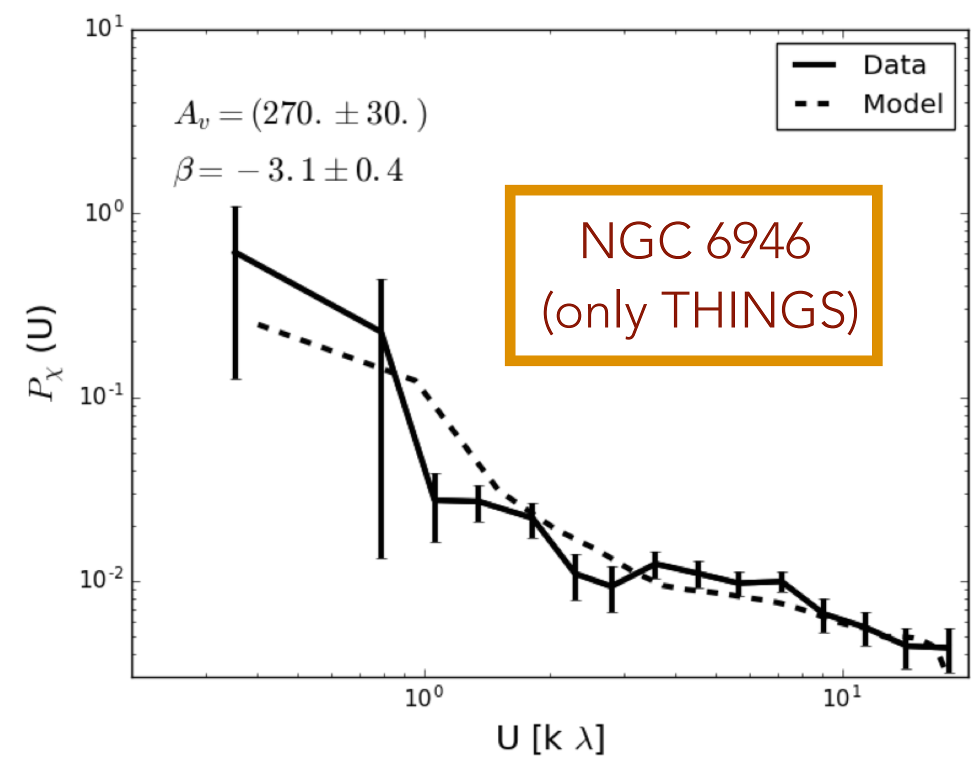
$$\chi(\vec{U}) = V_1(\vec{U}) - \langle V_1(\vec{\theta})\rangle$$

$$\boxed{P_{\chi}(U) = P_{HI}(U)\otimes P_{v^T}(U)}$$



NGC 6946, 10 km/sec at 4 kpc

- Possible to do for galaxies with larger angular extent and low inclination angle.. requires high signal to noise data

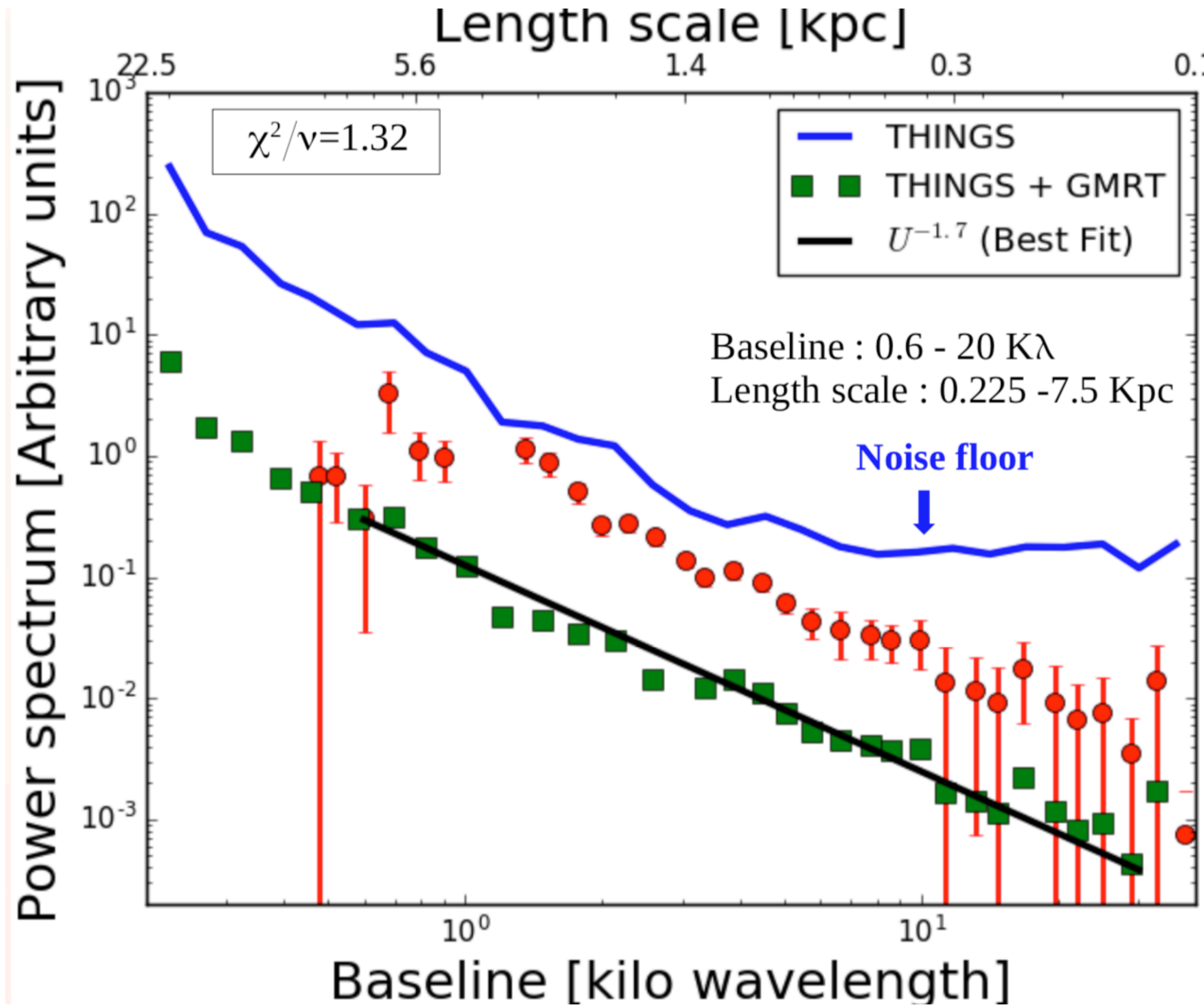
Dutta 2015

Selection of subsample and observation plan

GLAXY	INCLINATION ANGLE	LENGTH SCALE RANGE	PROPOSALS	STATUS	INTEGRATION TIME
	DEGREES	KPC			HOURS
NGC 5236	**31**	**0.200 - 8.0**	**GMRT CYCLE 34**	**DATA ANALYSIS COMPLET**	**FOURTEEN**
NGC 4736	44	0.200 - 8.0	GMRT CYCLE 35	OBSERVED	FOURTEEN
NGC 6946	35	0.150-20.0	VLA 18A + 19A	OBSERVATION PARTIALLY	SIXTEEN

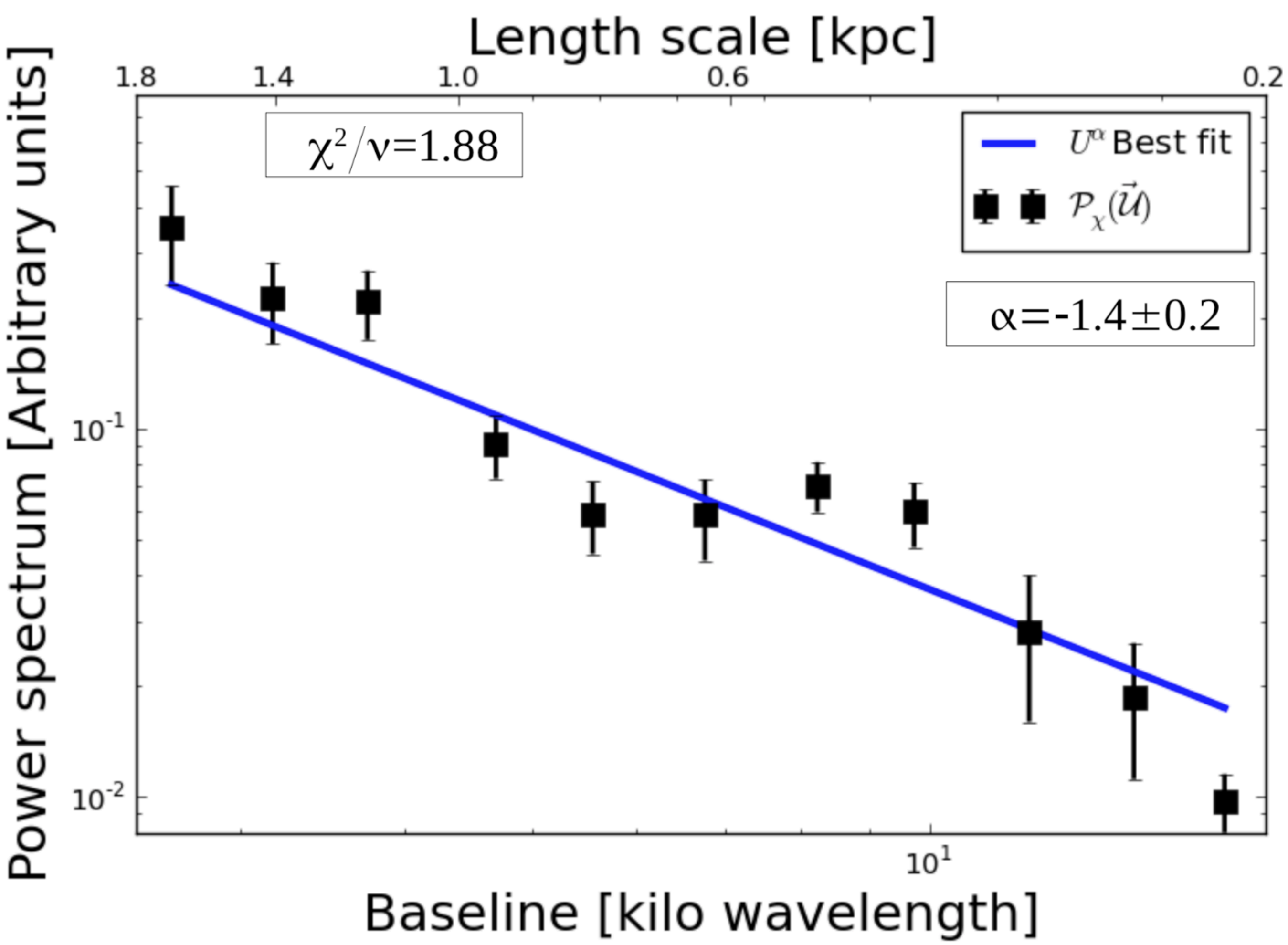
- We shall combine the THINGS data with these observations to gain signal to noise required for velocity power spectrum measurements.

Results: NGC 5236, column density

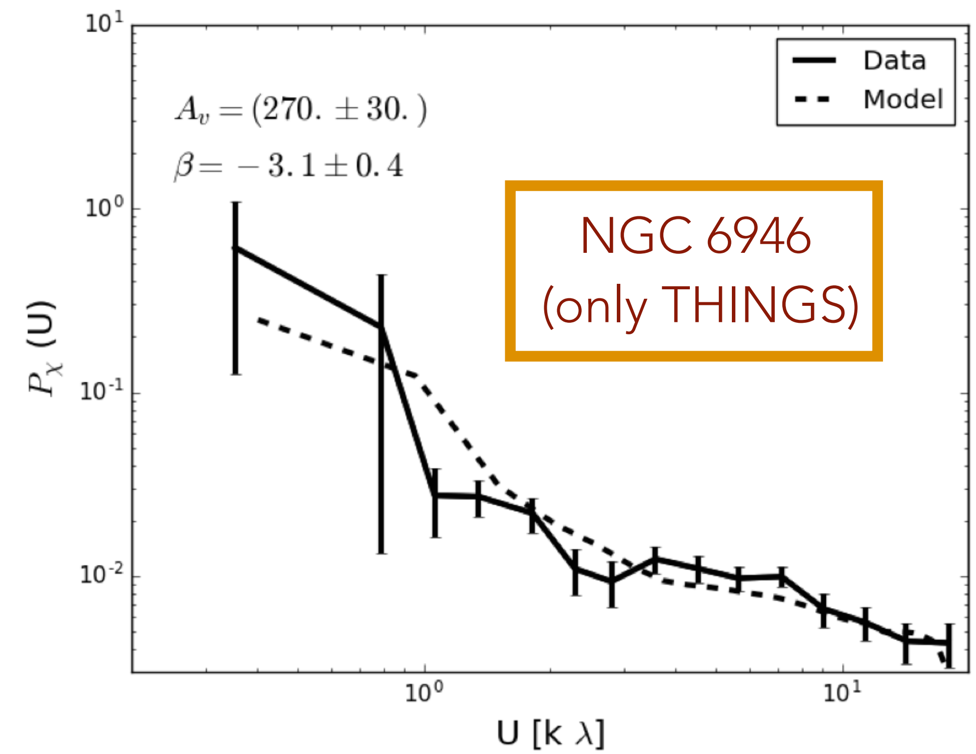


- Significant improvement over THINGS when the two data are combined.
- Power spectra assumes power law over two orders of magnitude of length scales.
- Average scale height upper limit for NGC 5236 is 225 pc.
- Certainly, supernovae is not the only energy input to ISM turbulence, galactic differential rotation plays a significant role.

Results: NGC 5236, turbulent velocity



$$P_\chi(U) = P_{HI}(U) \otimes P_{v^T}(U)$$



NGC 6946, 10 km/sec at 4 kpc

- We are one step away from measuring the turbulent velocity power spectra from external spiral galaxy.
- The power spectra could be measured for a length scale ranging 300 pc to 4 kpc.

Conclusions and a guess!

Main findings:

- Density fluctuation over two decade of length scales starting from ~ 10 npc and downwards.
- Density fluctuation slope suggest mixed passive incompressible and supersonic turbulence.
- Velocity fluctuations follow power law at 300 pc to 4 kpc scales
- RMS velocity at 4 kpc scale is~ 10 km/sec
- There is significant energy cascade from length scales of 10 Kpc and higher to smaller scales….. something more than differential rotation ?

A Guess:

- Galaxies resides in a dark matter halo of mass 100 times ISM mass
- Recent simulations show substructure in the dark matter halo
- Differentially rotating galactic disk is dragged by the dark matter halo substructures
- Results in large scale hierarchical structures, rotation slows down and random motion dominates
- Eventual evolution to ellipticals (without mergers) ? $t_{evol} \sim 10 \;\; \mathrm{G\ yr}$

Marinacci et al. (2017), Zhang (2003), Boylan-Kolchin et al. (2007)