Investigating the structure and dynamics of the Interstellar Medium from radio interferometric observations

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Plan of the talk

We would use HI as a proxy for the ISM

Spatially resolved structures in HI

- Why to investigate structure and dynamics
- Observing HI using radio interferometers
- Measuring HI column density statistics
- Measuring the line of sight velocity statistics
- What have we learnt so far and where to go from there

Why to investigate structure and dynamics

- The radial HI profile: How does the stellar and Gas structures correlates with each other [Wang et al. (2014)-WSRT,   Walter et al. 2008 - VLA)]
- Large scale properties, interactions, spiral arms, how are they generated [Egusa et al. (2016), Speights et al (2011)]
- HI holes and fine scale structures: association of HI depletion with star formation [Bagetakos et al. (2011)]
- HI column density power spectrum, turbulence in ISM [Green (1991), Dutta et al. (2014)

- Tangential rotational velocity, missing matter (?) [de Block et al. (2008)]
- Anomalous velocities, galactic fountain, interactions, angular momentum [Kelly et al (2009),]
- Velocity dispersion and relation to star formation [Tamburro et al. (2009)]
- Turbulent velocity power spectrum [Lazarian and Pogosyan (2000)]

Why to investigate structure and dynamics

- We are mostly interested in turbulence in the ISM
- Evidence of large scale (10 kpc) turbulence [Dutta et al. (2014)]
- What drives the turbulence ?
- Can it influence the star formation ? [Klessen (2000)]

This talk: Measuring the statistics (local mean and power spectrum) of the turbulence generated density and velocity structures from the radio interferometric observations

Observing HI using interferometers

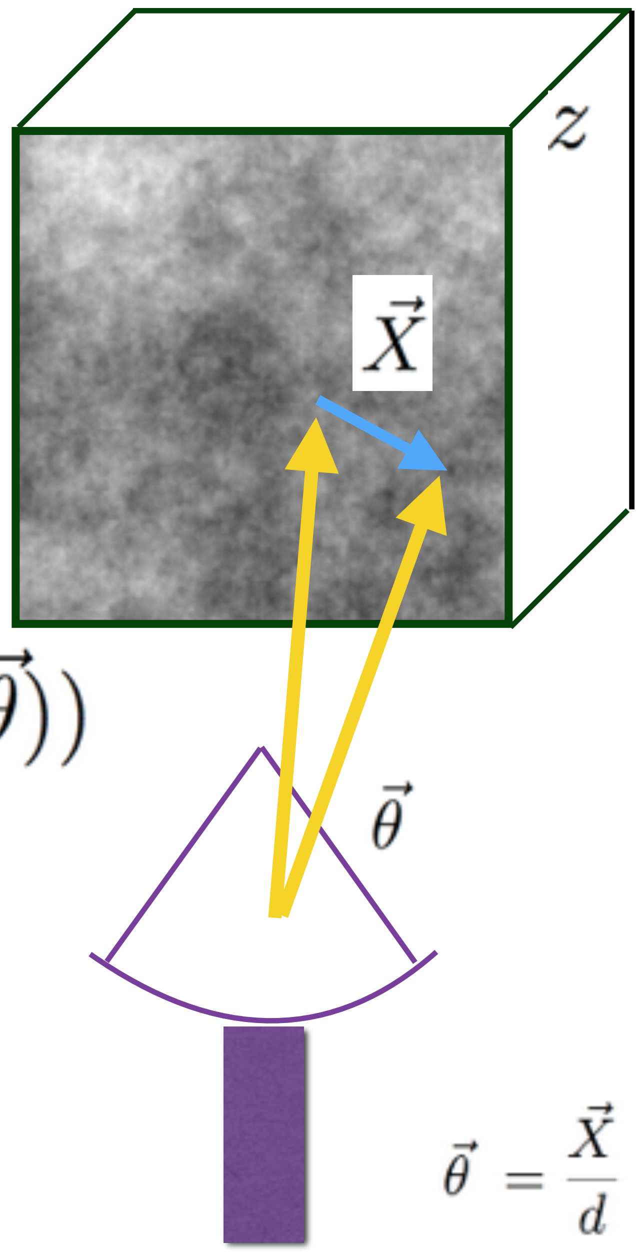
- To measure the fluctuations in a quantity we measure the mean first

$$N_{HI}(\vec{\theta}) = W(\vec{\theta}) \left[N_0 + \delta N_{HI}(\vec{\theta}) \right]$$

$$v_{LOS}(\vec{\theta}) = v^{\Omega}(\vec{\theta}) + \delta v(\vec{\theta})$$

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

$$V(\vec{U}, v) = \int d\vec{\theta} \; e^{i2\pi \vec{U}.\vec{\theta}} I(\vec{\theta}, v)$$



Measuring HI column density statistics

$$N_{HI}(\vec{\theta}) = W(\vec{\theta})\left[N_0 + \delta N_{HI}(\vec{\theta})\right]$$

Reconstructed image

- We get the structures of HI
- Can estimate the window function

- Deconvolution noise bias:
  - Measurement noise gets correlated
  - Artifacts by interpolation in visibility plane

Zhang et al (2012)

Visibilities

- A more direct method
- No deconvolution noise issue
- Measurement noise bias can be avoided

- We can not get the structures of HI

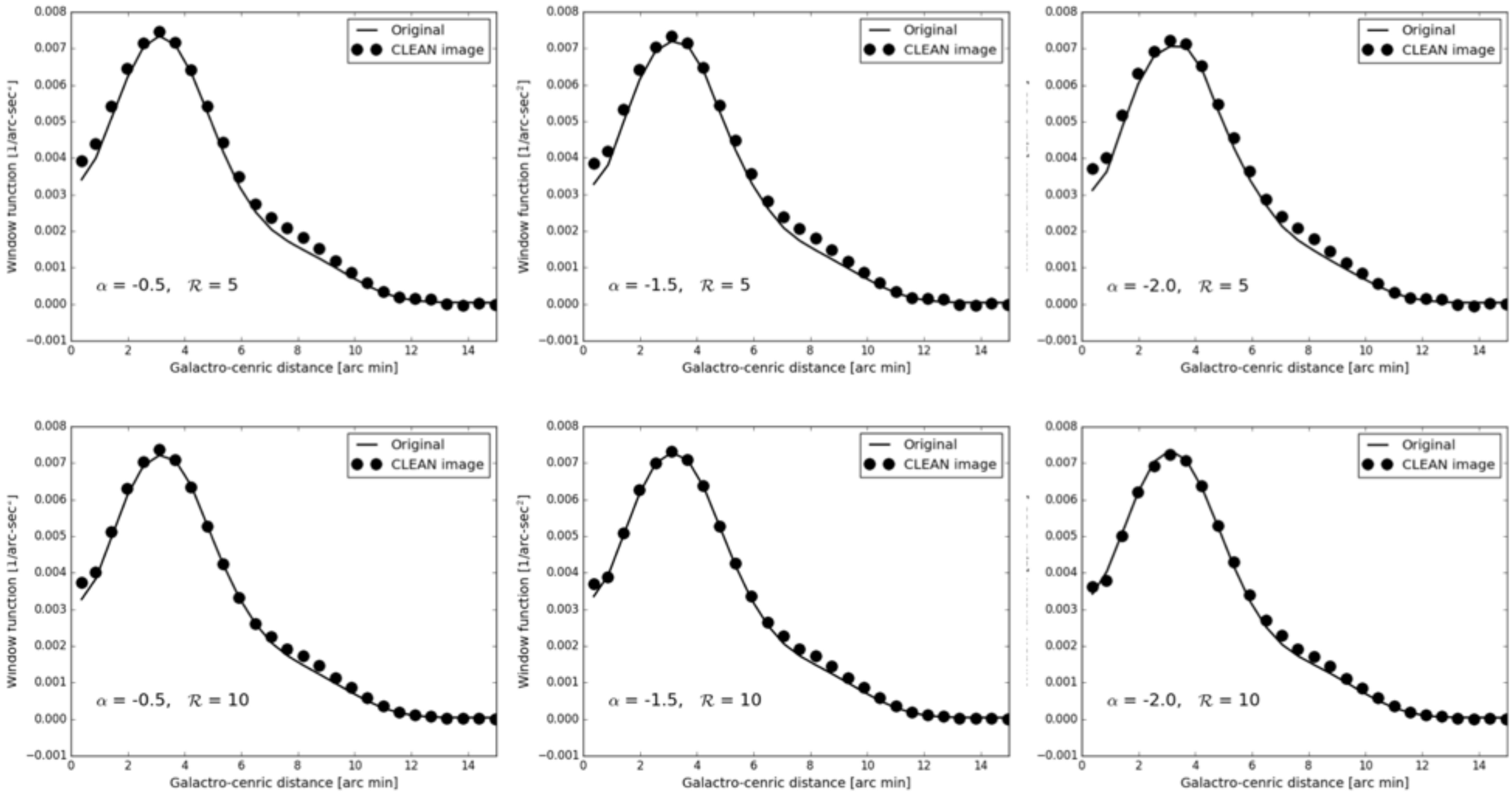
Dutta et al (2009)

Measuring HI column density statistics

$$N_{HI}(\vec{\theta}) = W(\vec{\theta}) \left[N_0 + \delta N_{HI}(\vec{\theta})\right]$$

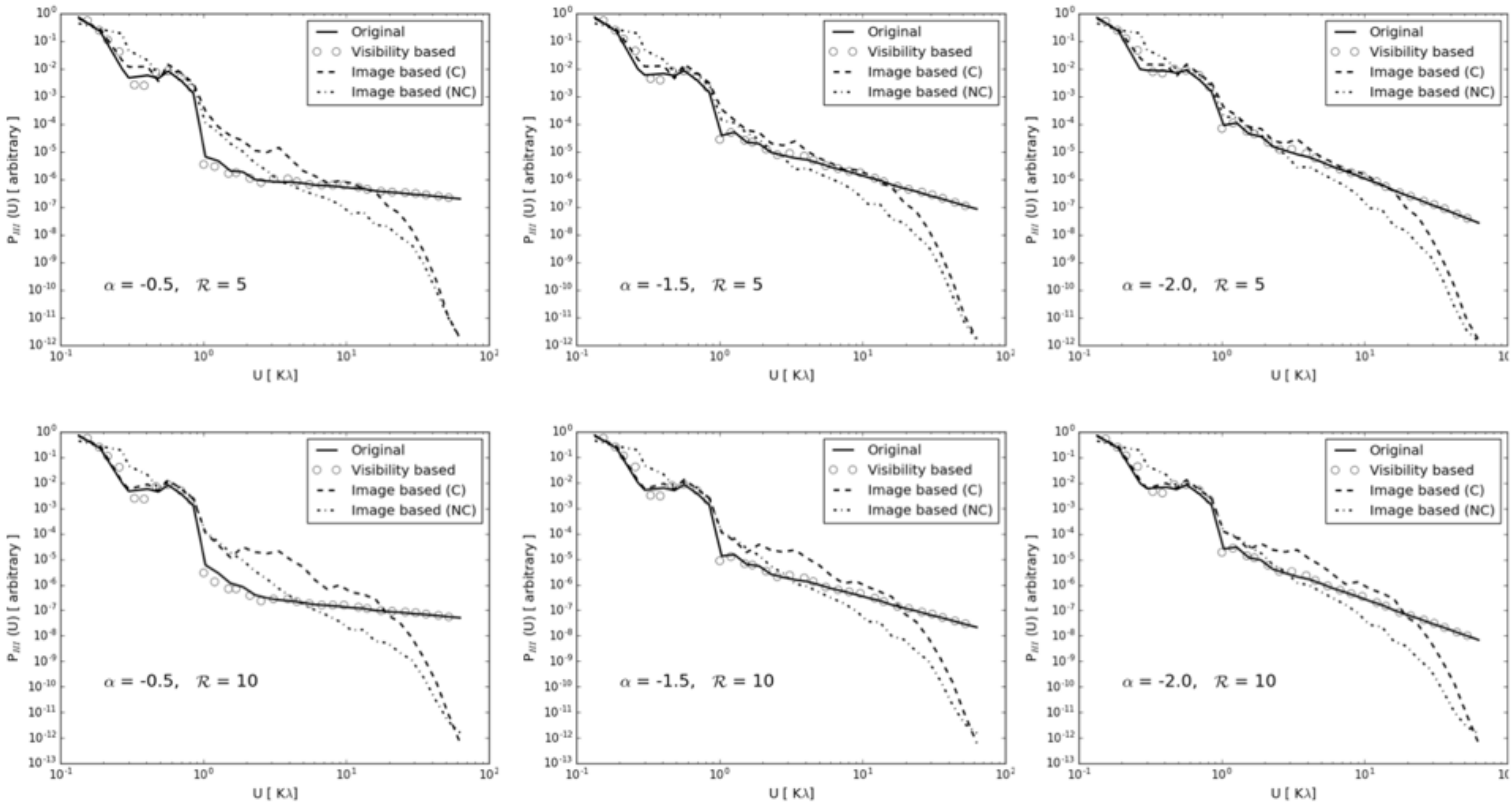
- We performed numerical simulation to generate synthetic interferometric observation of HI from a model spiral galaxy
- The column density fluctuations is taken to have a power law power spectrum
- We integrate over velocities and use CLEAN to reconstruct HI moment 0 maps
- We estimate the window function from the moment 0 maps and compare
- We estimate the power spectrum from the visibilities and the moment 0 maps and compare

Measuring HI column density statistics



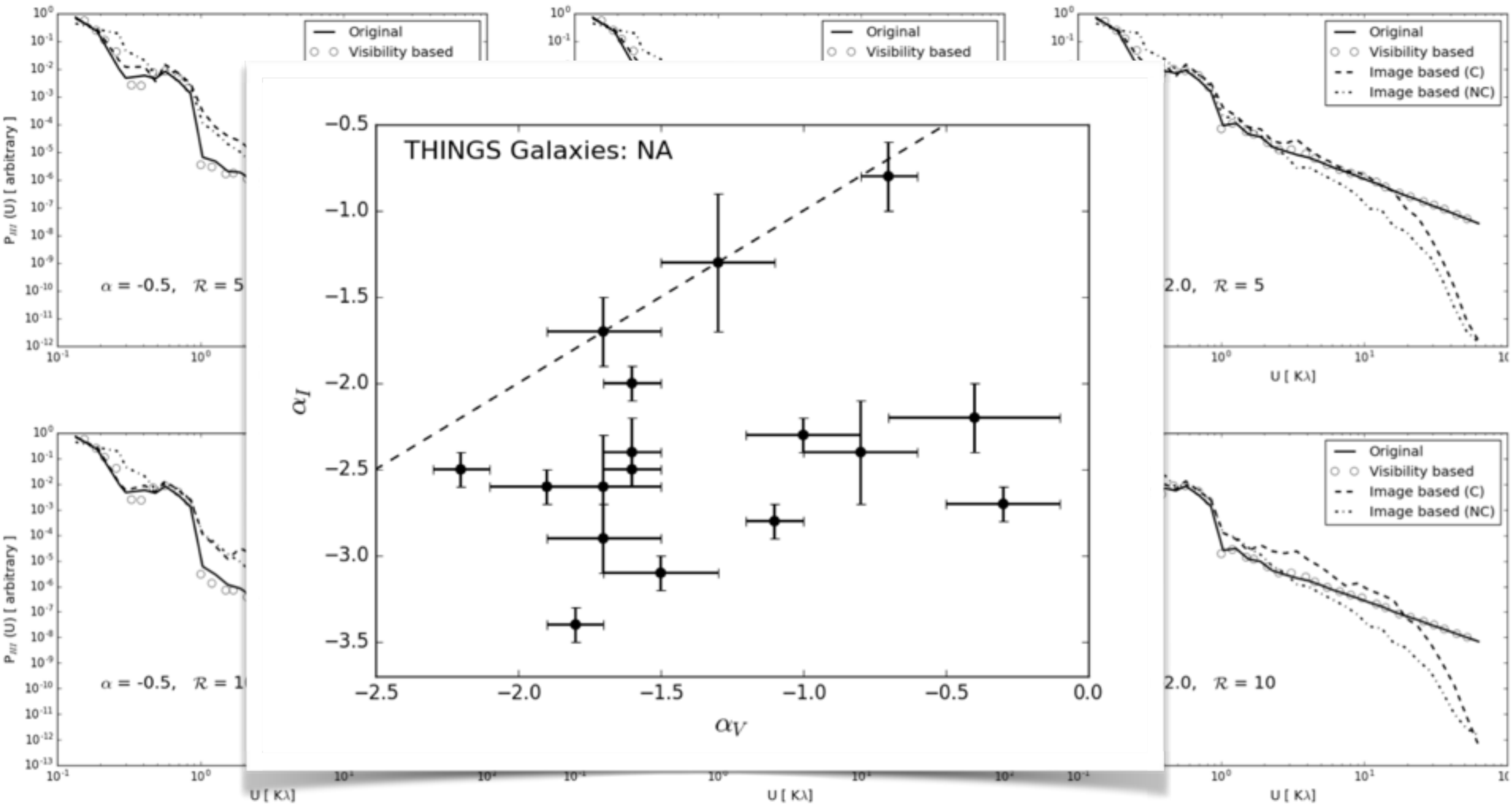
Dutta & Nandakumar (2017), submitted

Measuring HI column density statistics



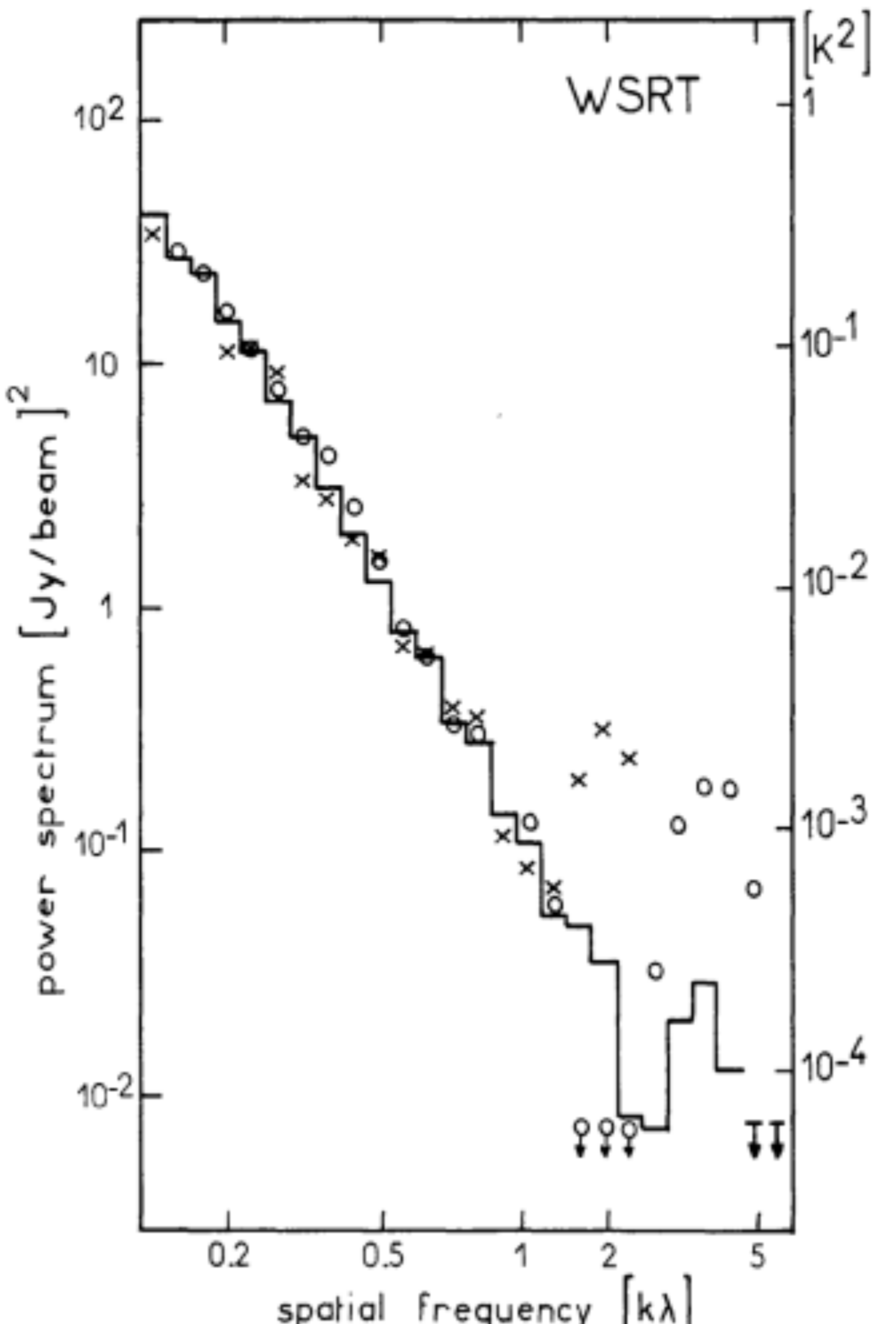
Dutta & Nandakumar (2017), submitted

Measuring HI column density statistics

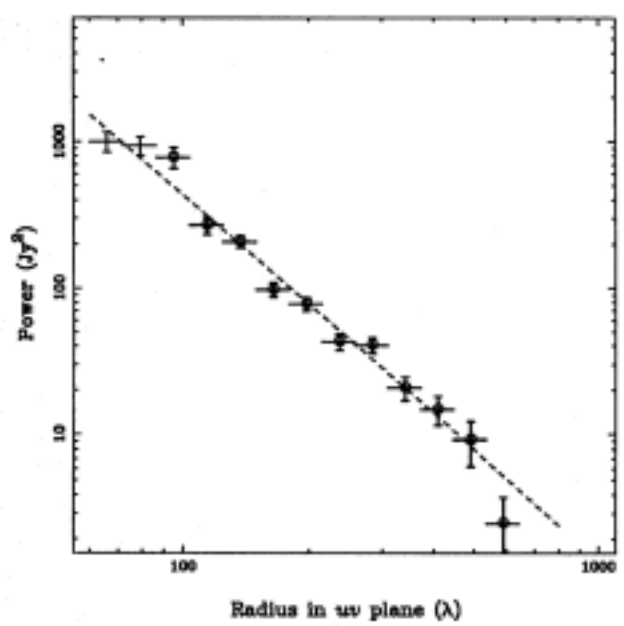


Dutta & Nandakumar (2017), submitted

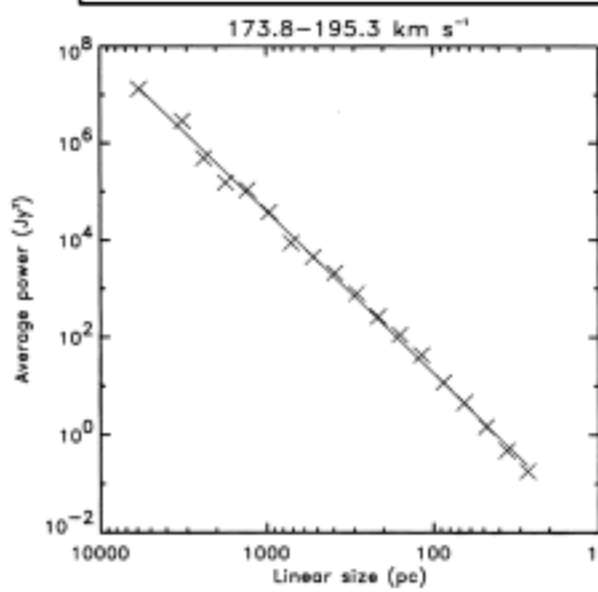
Measuring HI column density statistics



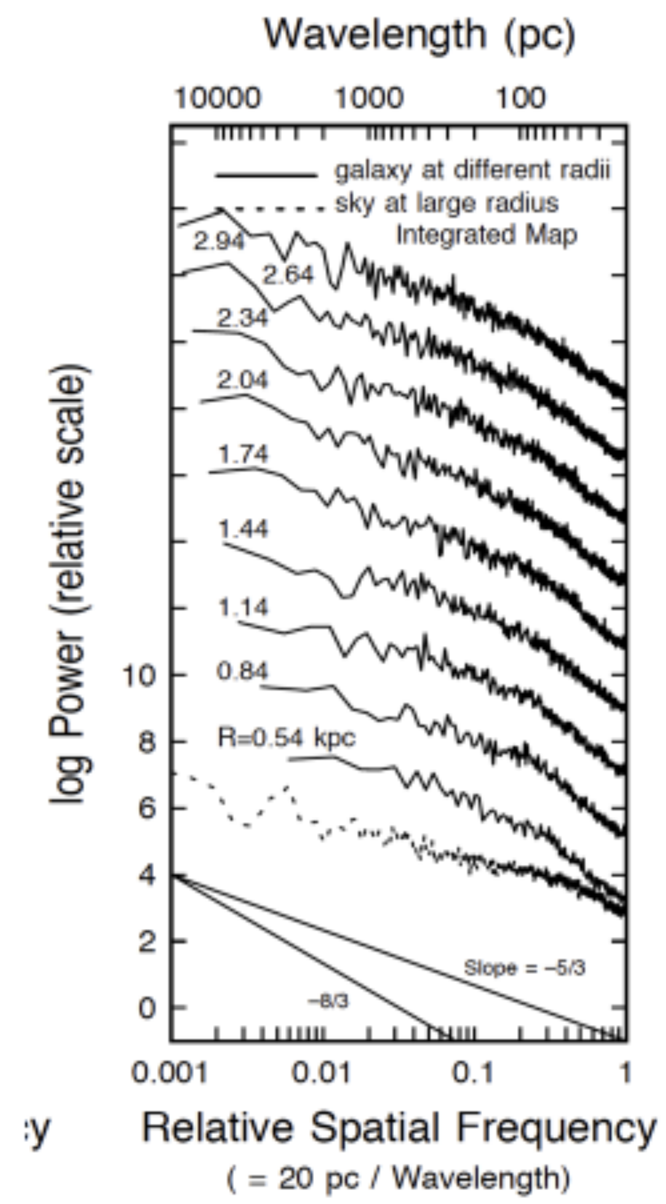
MW: Crovisior (1983)



MW : Green (1993)

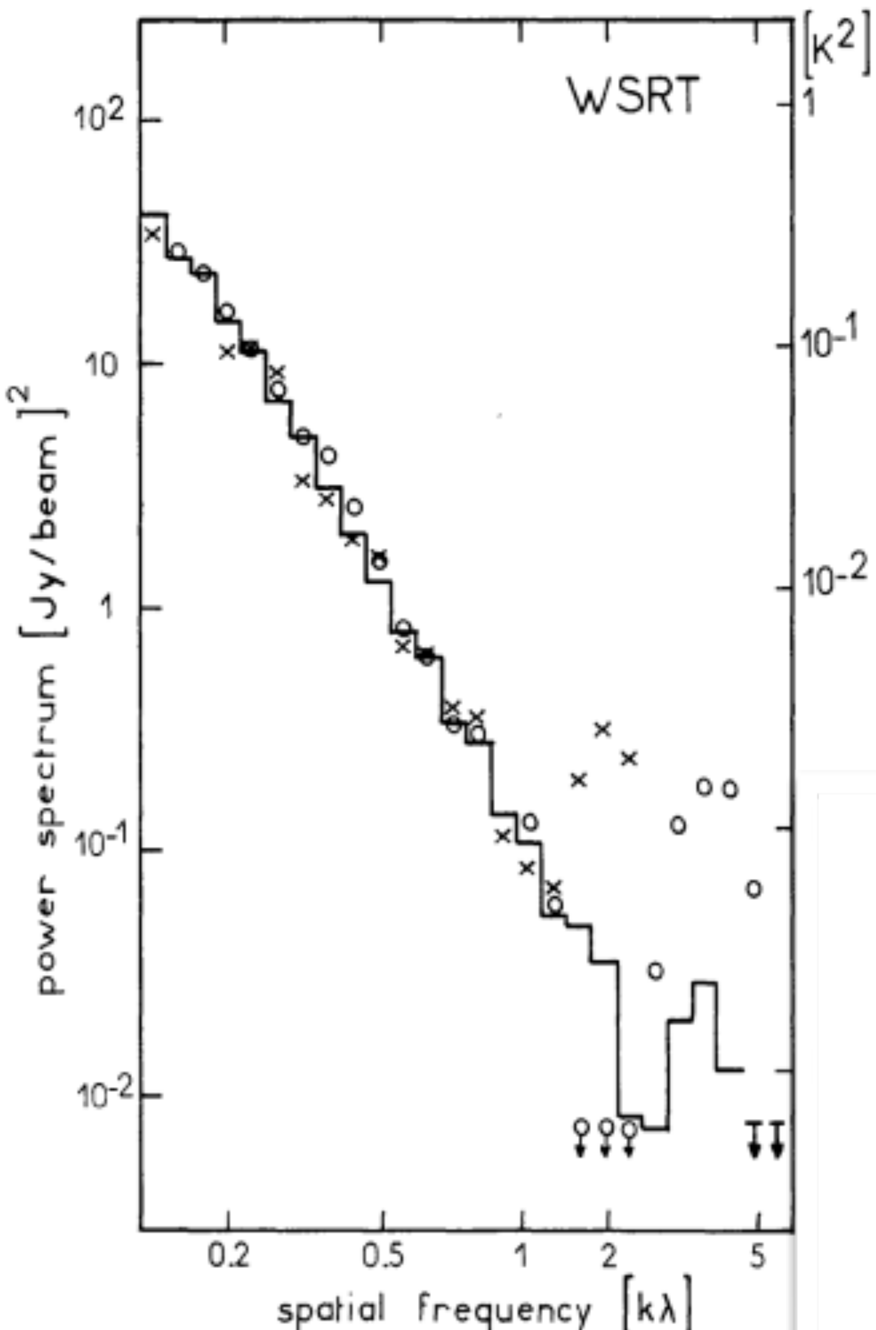


SMC: Stanimirovic (1999)

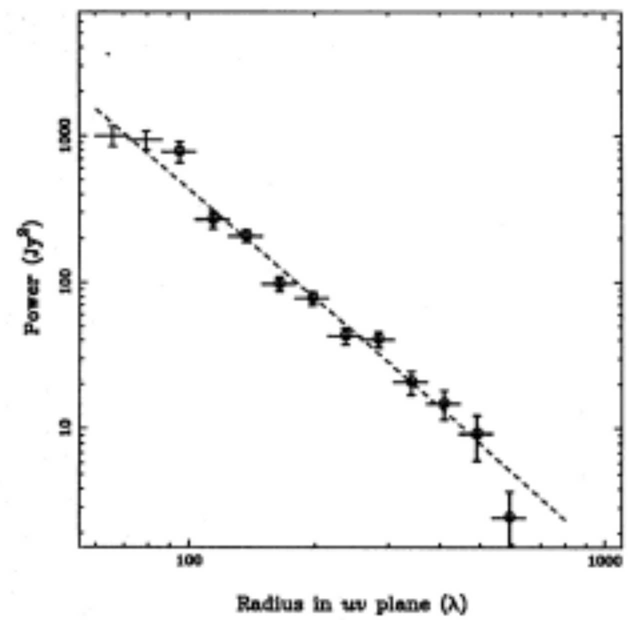


LMC: Elmegreen (2001)

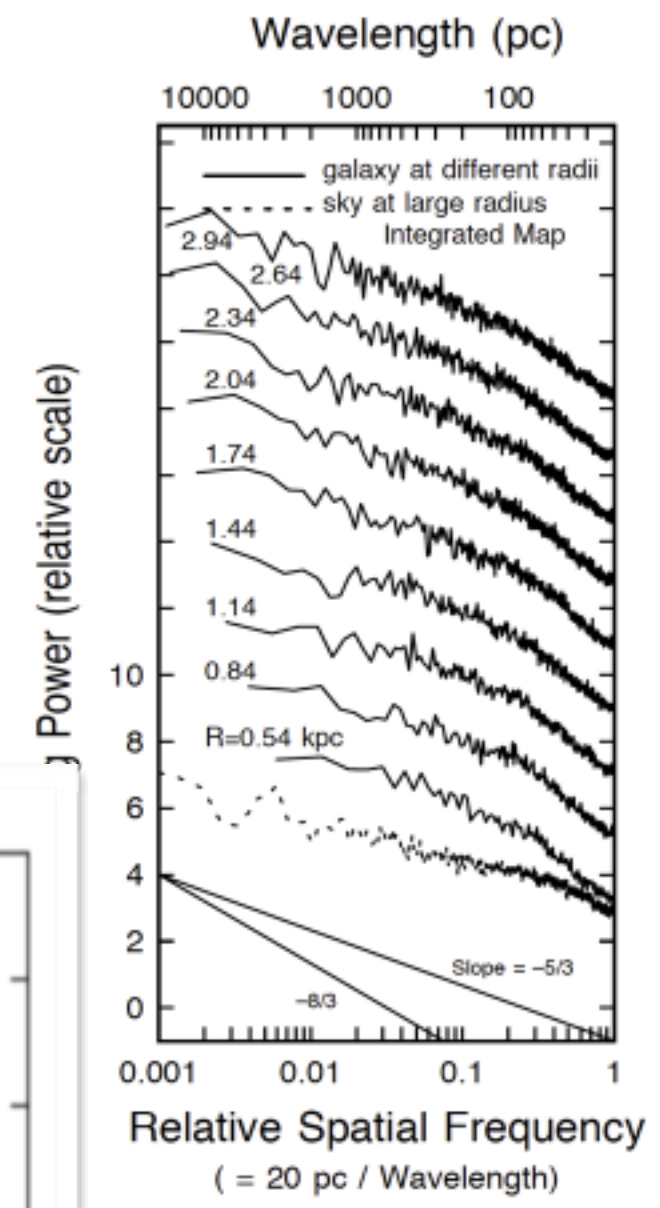
Measuring HI column density statistics



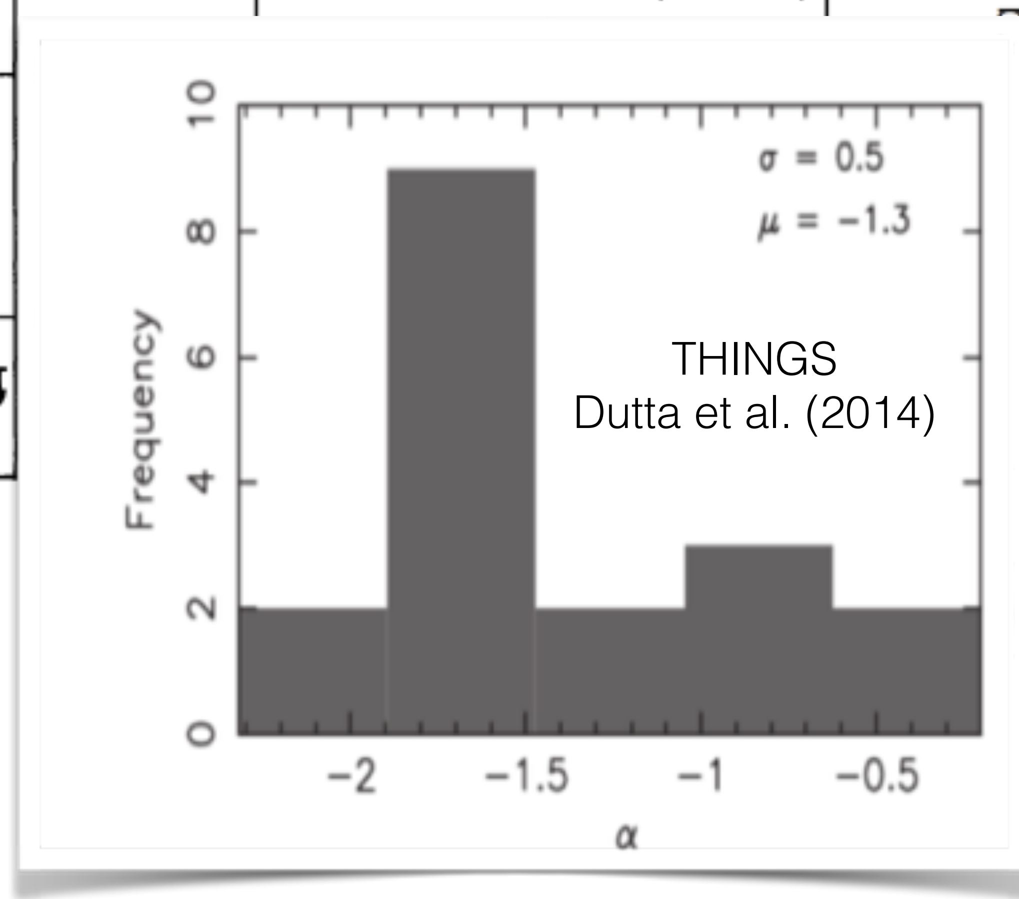
MW: Crovisior (1983)



MW : Green (1993)

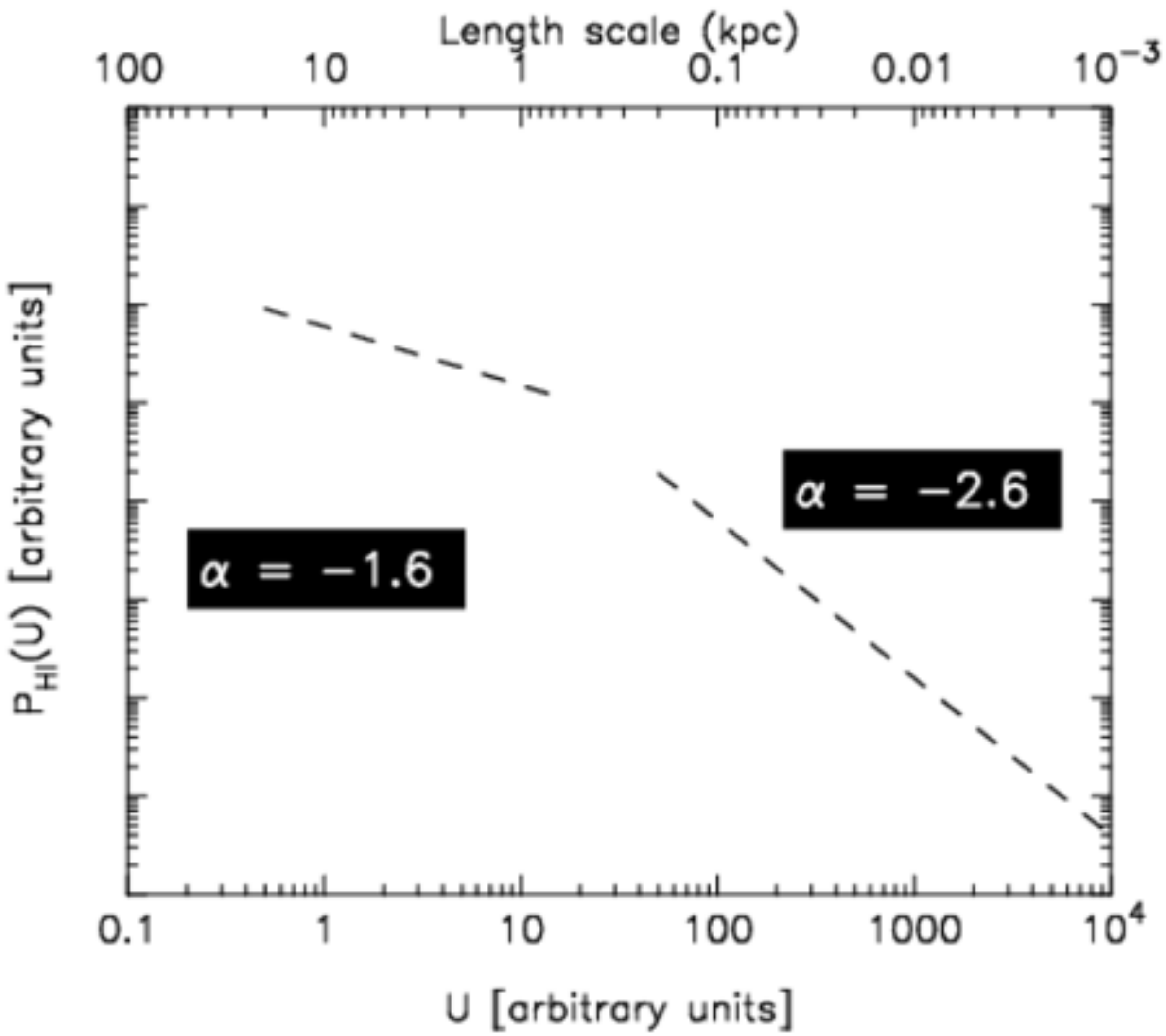


MC: Elmegreen (2001)



THINGS
Dutta et al. (2014)

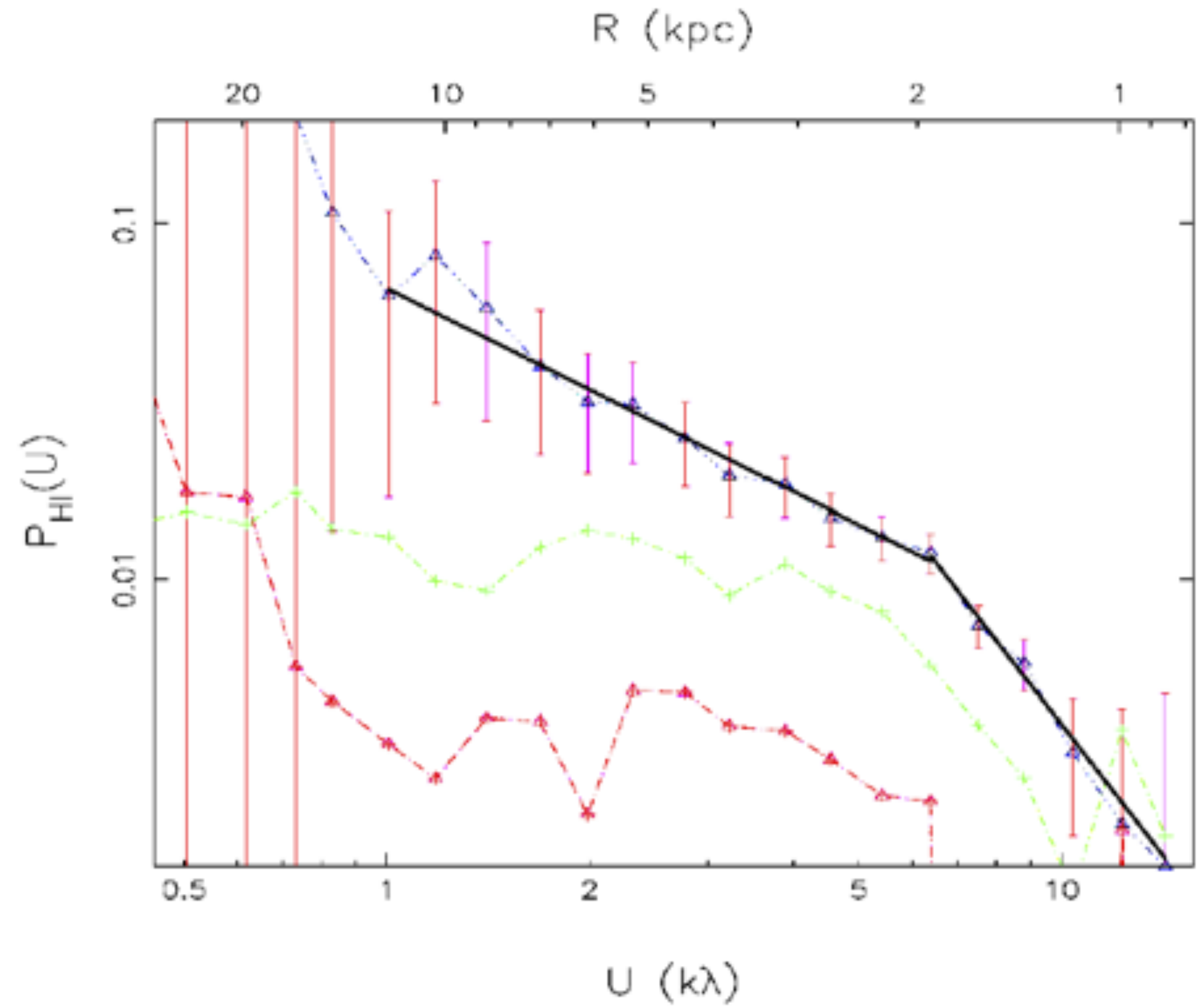
Measuring HI column density statistics



3D for scales < scale height

2D at larger scales

Dutta et al. (2009), MNRAS Lett, 397, L60



NGC 1058

scale height ~ 490 pc.

Measuring HI V_LOS statistics

$$v_{LOS}(\vec{\theta}) = v^{\Omega}(\vec{\theta}) + \delta v(\vec{\theta})$$

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

Different Methods

- Velocity coordinate spectrum [Pogosyan et al. (2009)]
- Velocity channel analysis [Lazarian and Pogosyan (2000)]
- Statistics of centroid of velocities [Esquivel et al. (2009)]
- **Method of visibility moments [Dutta (2016)]**

Measuring HI V_LOS statistics

- Milky-way at 100 pc scales in the disk, velocity power spectrum estimated using VCA have a slope of ~-2.6 [Lazarian et al (2007)]
- Milky-way at 100 pc scales higher latitude, slope is steeper -3.8 [Chepurnov et al. (2010)]
- LMC, SMC slope ~ -3.0 (!) [Stanimirovic (1999)]
- Larger scale (10 kpc !) velocity structures ?

Measuring HI V_LOS statistics
Visibility Moments

$$V(\vec{U}, v) = \int d\vec{\theta}\ e^{i2\pi\vec{U}.\vec{\theta}} I(\vec{\theta}, v) \qquad v_{LOS}(\vec{\theta}) = v^{\Omega}(\vec{\theta}) + \delta v(\vec{\theta})$$

$$\mathcal{V}_0(\vec{U}, v) = \int\ dv\ V(\vec{U}, v) \qquad \mathcal{M}_0(\vec{\theta}) = \int dv I(\vec{\theta}, v)$$

$$\mathcal{V}_1(\vec{U}, v) = \int\ dv\ v\ V(\vec{U}, v) \qquad \mathcal{M}_1(\vec{\theta}) = \int dv\ v I(\vec{\theta}, v)/\mathcal{M}_0(\vec{\theta})$$

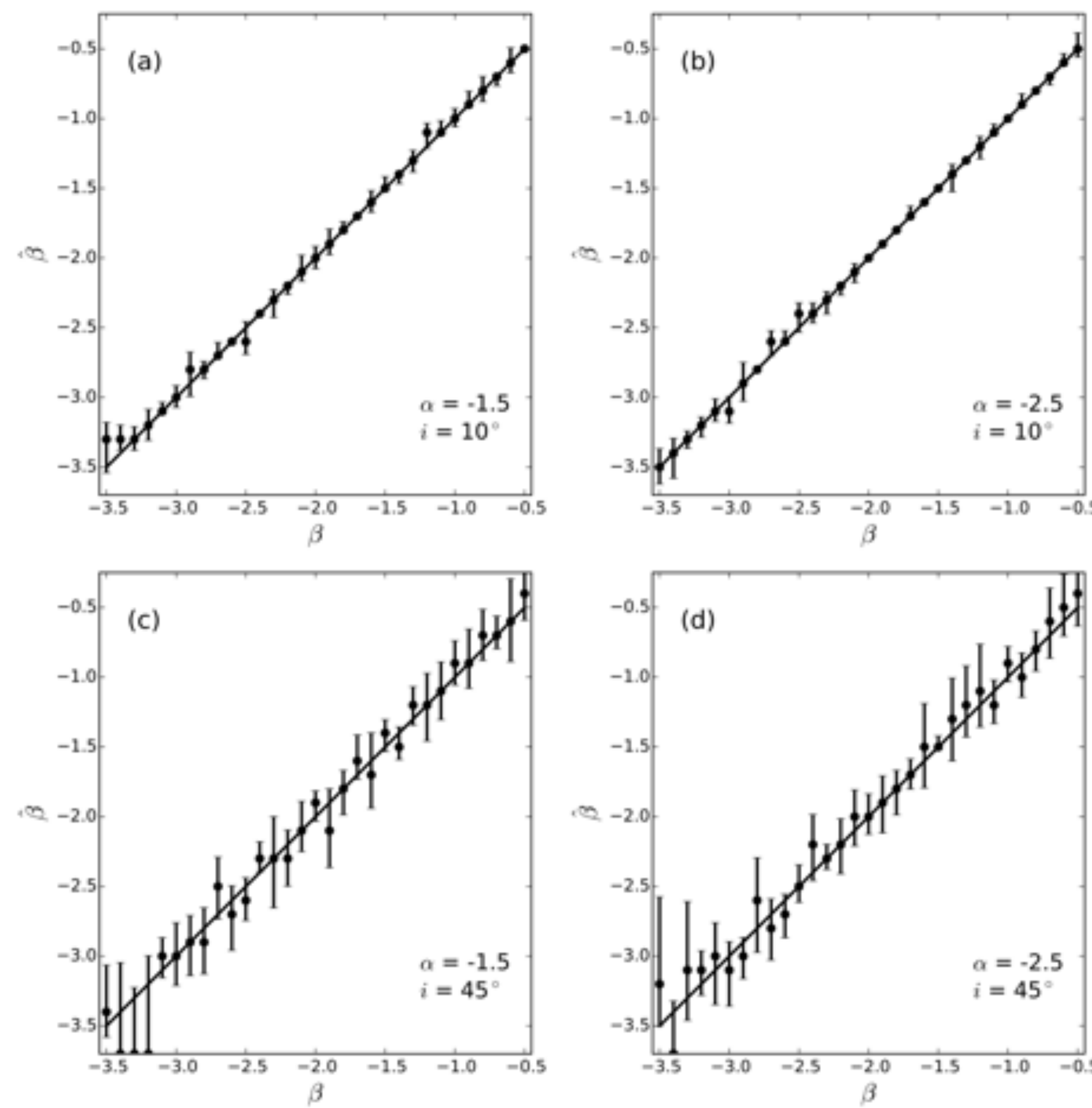
$$\mid \mathcal{V}_1(\vec{U}, v) \mid^2 => W(\vec{\theta}), v^{\Omega}(\vec{\theta}), P_{HI}(U), P_v^T(U)$$

$$P_\chi = P_{HI} \otimes P_v^T$$

Dutta (2016) MNRAS, 456, L117

Measuring HI V_LOS statistics Visibility Moments

- We do not need to use a mapping between line of sight velocity and distance.
- Estimator works (almost) entirely in the visibility plane.
- Challenge is to estimate the rotational velocity with sufficient accuracy.
- Effective for only galaxies with inclination angle < 45 degrees.



Dutta (2016) MNRAS, 456, L117

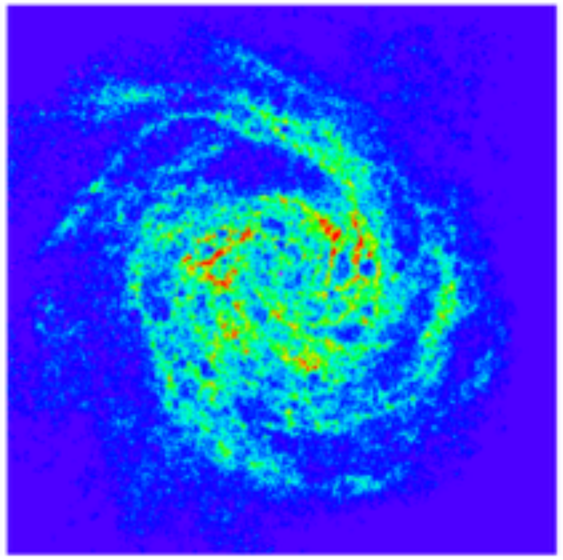
Measuring HI V_LOS statistics
Visibility Moments

NGC 6946
THINGS

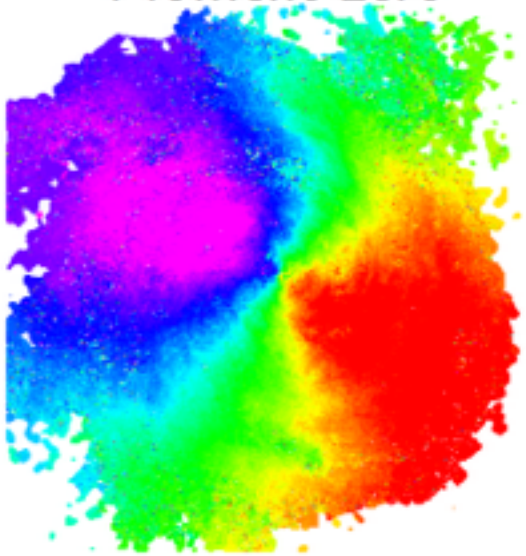
- Criteria: Thin disk and low inclination angle.

Inclination angle	33^o
Scale length	20 Kpc
Scale height	< 600 pc
Angular resolution	75 pc
Velocity resolution	5 Km/sec

Walter et al. (2008)



Moment zero

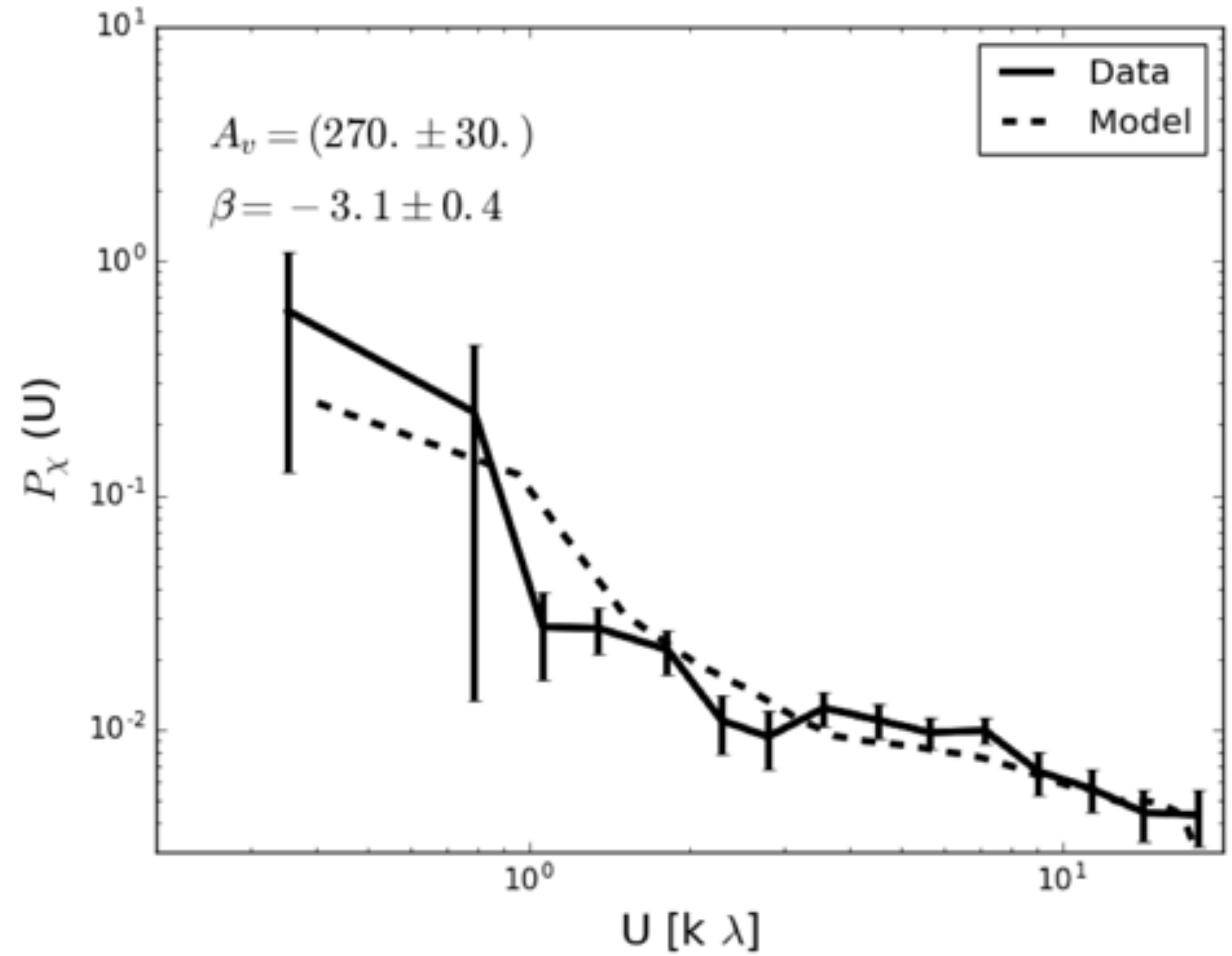


Moment one

Measuring HI V_LOS statistics
Visibility Moments

$$P_\chi = P_{HI} \otimes P_v^T$$

We estimate P_χ and P_v^T from the visibilities
We use a parametric mode (power law) for P_v^T and estimate ampııtude and slope

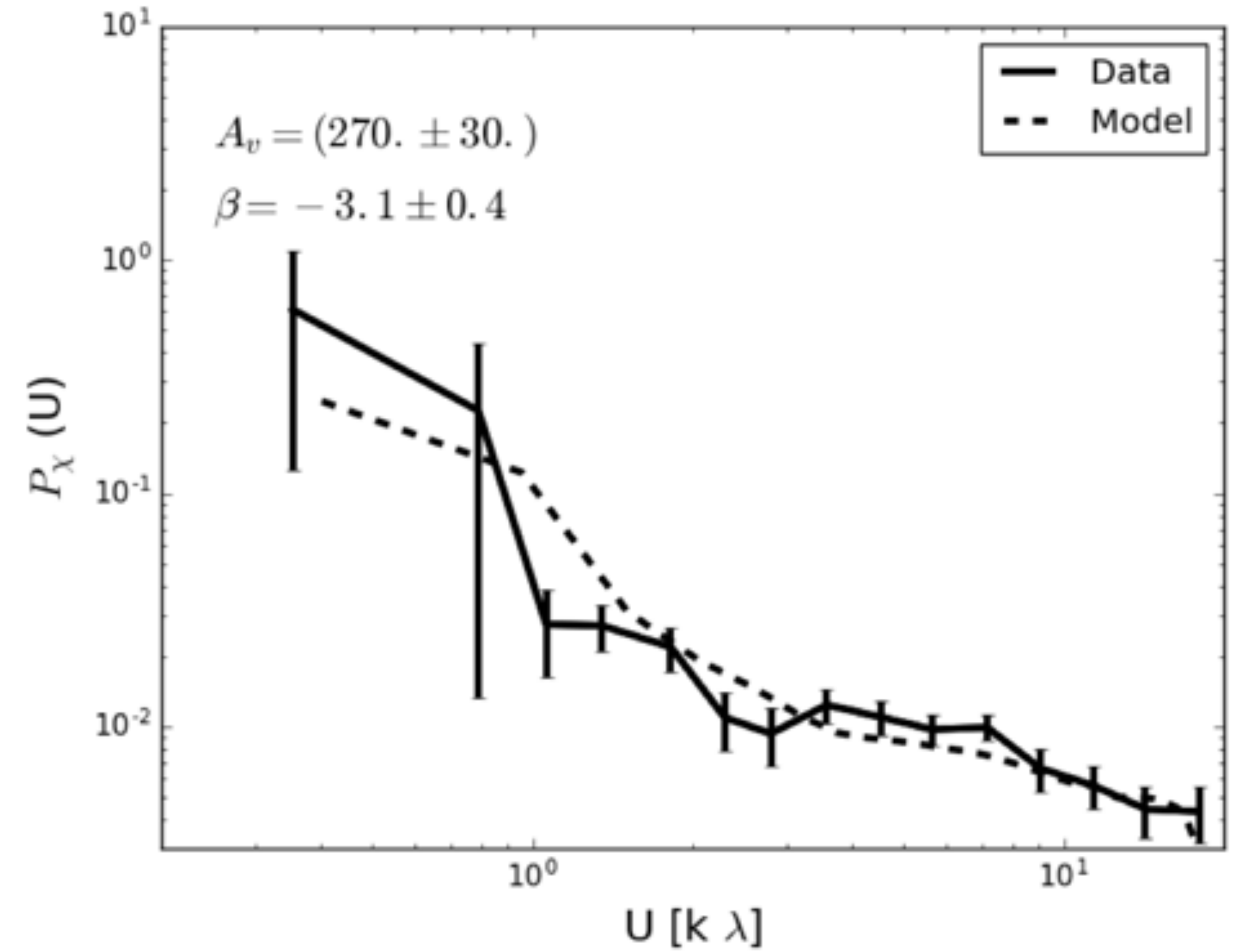


At 300 pc to 4 kpc scales

Nandakumar & Dutta (2017), in preparation

Measuring HI V_LOS statistics Visibility Moments

- Slope is not very well determined, it favors the compressive forcing following Federrath (2010)
- Amplitude of the spectra suggests a velocity dispersion of at least 16 km/sec, consistent with observed HI velocity dispersion [Tamburro et al. (2009)]



At 300 pc to 4 kpc scales

Nandakumar & Dutta (2017), in preparation

Summary and Future directions

- Observations are consistent with the fact that the HI column density power spectrum follow a single power law from ~10 kpc to ~1 pc [However, the budge between the different length scales need to be checked]
- Slope of the 2D HI column density power spectrum is ~ -1.6, what is expected to be created by compressive forcing, can not be self gravity [Agertz et al. (2009)]
- The velocity spectrum is not well measured, but favors compressive forcing again. Measured values at the largest length scale is consistent with the observed HI velocity dispersion
- A dark guess: Fluctuations in the dark matter halo + differential rotational velocity => Large scale energy injection => cascading to small scales => influence star formation : Need to be tested.. Simulation ? [Marinacci et al. (2017)]