H I as a probe of LSS in post reionization universe - SAM approach

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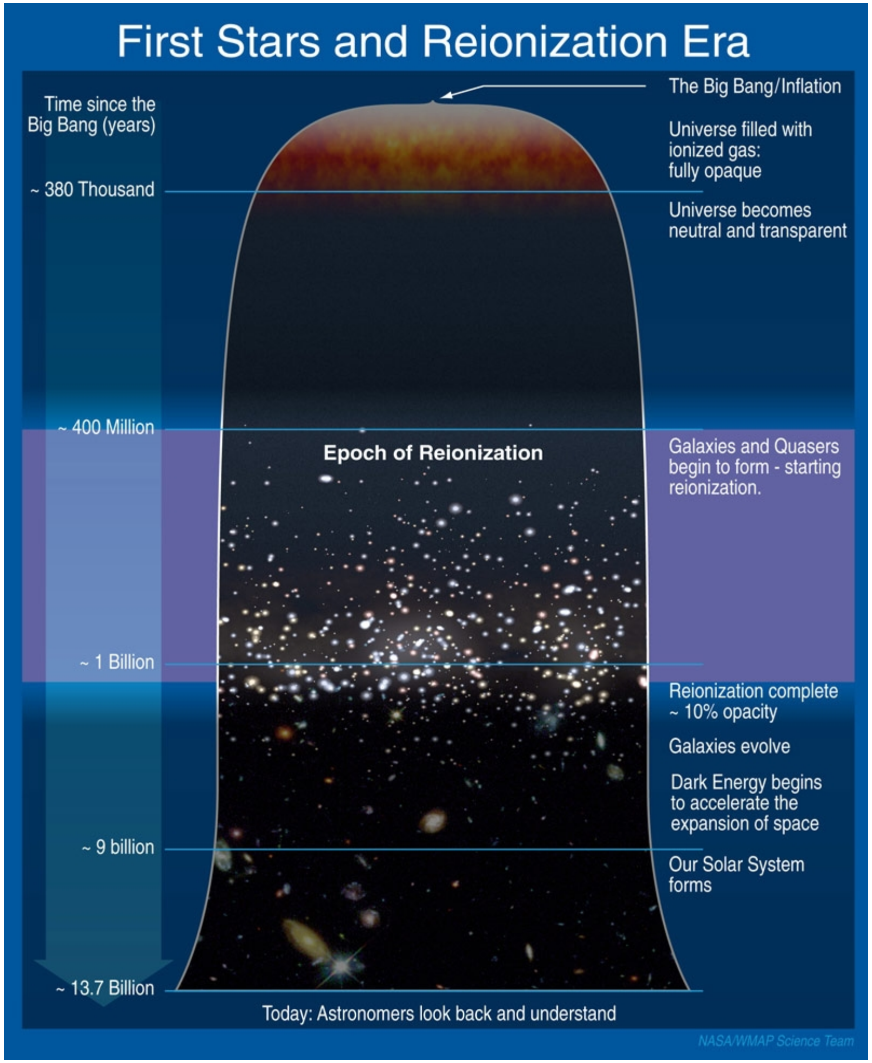
5th KIAS WS on Cosmology and Structure Formation

Seoul

Motivation



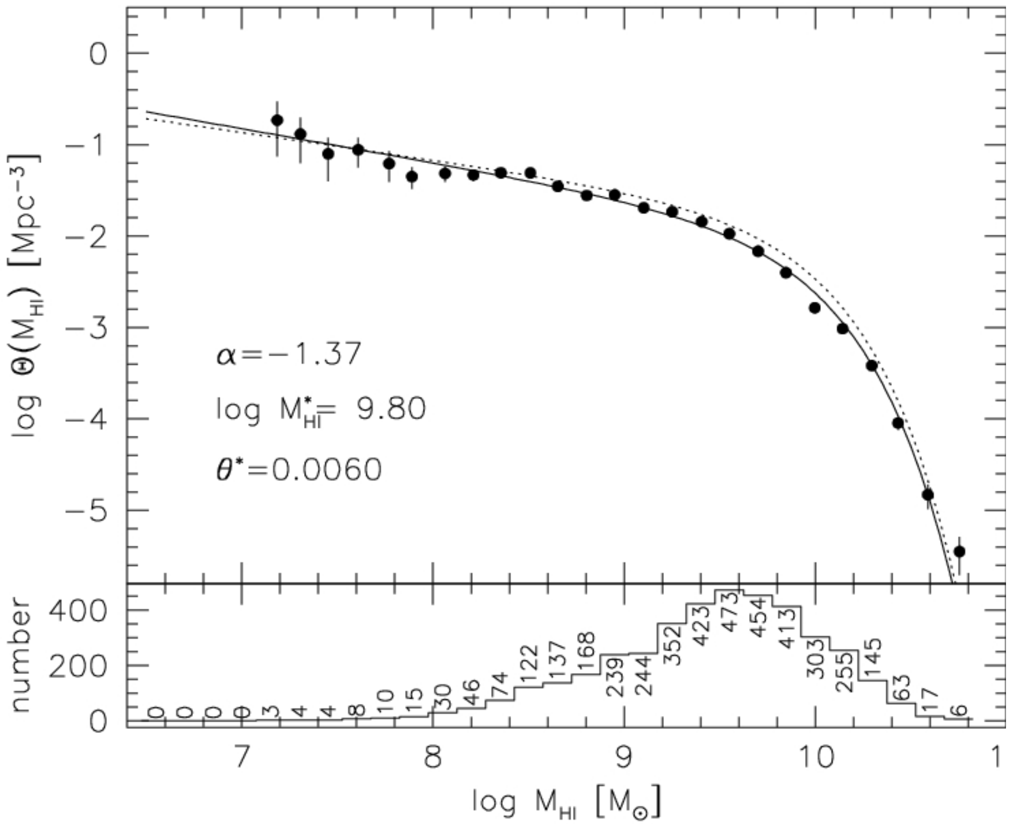
The period of transition of IGM from neutral to ionized state is known as EoR.

Through the EoR, almost no HI is left in IGM, all of HI is in ISM of galaxies.

Many ongoing and upcoming radio surveys such as GMRT, MWA, THINGS, ALFALFA, SKA, etc trying to look for HI in ISM.

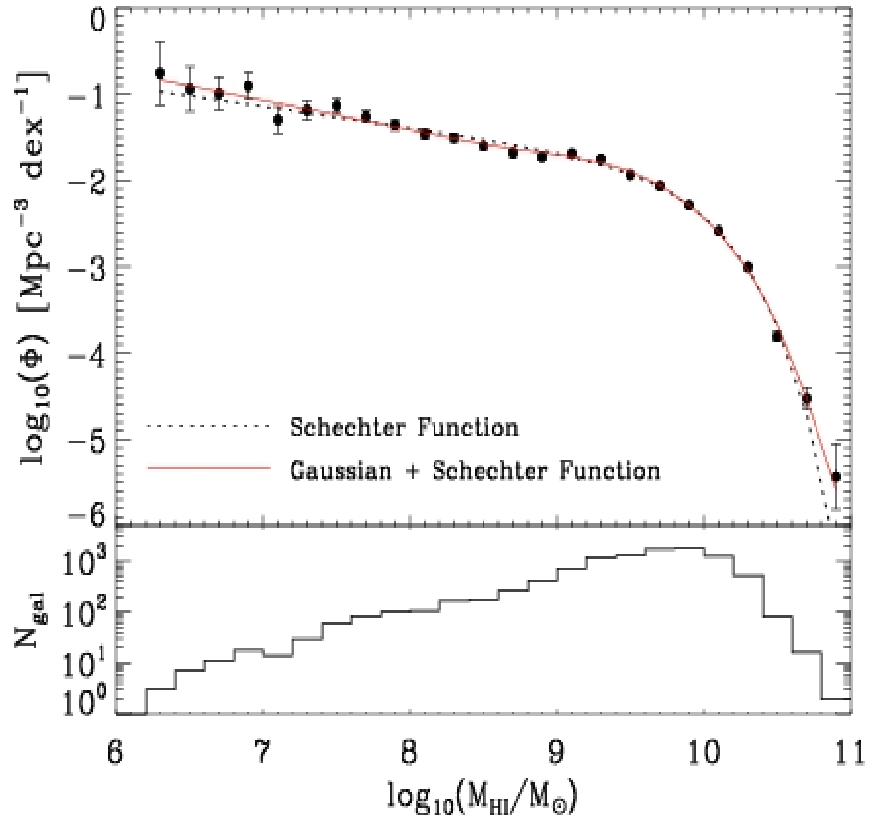
Hence, theoretically, important to know the amount and distribution of cold gas at these redshifts (e.g. at $z=1.3$, 3.34, 5.1 in this work)

Observation Front



HIPASS HI mass function.(Zwann et. al 2005)

$$\Omega_{H\,\mathrm{I}} \sim 3.5 \times 10^{-4} h_{75}^{-1}$$



ALFALFA HI mass function.
(Martin et. al. 2010.)
16% Higher estimate of $\Omega_{H\,\mathrm{I}}$

High Redshift Observations

- HI content in Damped Lyman Alpha (DLAs) indicate an almost constant value of HI with

  $\Omega_{H\,\mathrm{I}} \sim 0.001$ **Wolfe et al. (2005)**

- Future HI observations will help us better understand the process of cosmic evolution, hence theoretical understanding of HI distribution in LCDM model is equally important

Galaxy Formation

- Objects like galaxies form when gas collapses at the center of DM Halos after radiative cooling of Baryons (White & Rees – 1978)

  We can study these processes via

  1. Hydrodynamic Simulations
  2. HOD Model
  3. **Semi Analytic Model (SAM)**

Simulations Specifics

BOX(h^-1Mpc)	Particles^1/3	Particle Mass(Solar)	Final Redshift	Total Snapshots
23.04	512	6.7 X 10^6	5.0	24
51.20	512	7.0 X 10^7	3.0	29
76.80	512	2.3 X 10^8	1.0	19
153.6	512	7.5 X 10^9	0.0	24

FoF Algorithm used to identify Halos

1. Most bound particle of Halo is the location of galaxy formation.
2. Virial Mass is the total mass of all particles in the Halo
3. Mass, radius and circular velocity of halo are related via

$$\frac{GM_{vir}}{100H^2}^{1/3} = R_{vir} = \frac{GM_{vir}}{V_{circ}^2}$$

Implementation of SAM

1. Construct a ***Merger Tree*** by connecting Dark Matter Halos across different snapshots of DM only simulation.

2. Apply simple recipes of SAM on each branch of merger tree, starting from earliest time in the simulation.

3. Main process to Model are Cooling, Star Formation and Feedback mechanisms and Chemical evolution.

Movie software courtesy P. Behrooji

Gas Cooling

- Gas distribution traces DM distribution prior to formation of structure with

$$T_{vir} = \frac{1}{2}\frac{\mu m_H}{k}V_{circ}^2$$

At early times, the cooling is mainly due to IC scattering of CMB photons by electrons.

$T_v < 10^4 K$: Deexcitation of fine structure lines of heavy elements and rotational levels of molecules

$10^4 K < T_v < 10^{7.5} K$: Decay through recombination of electrons and ions. Much dependent on metallicity

$T_v > 10^7.5 K$: Bremsstrahlung emmision. Cooling dominated by free free transition in electron ion collision.

Cooling rate **also** depends on size of halos

Star Formation

$$\dot{M}_* = \alpha M_{cold}/t_{dyn}$$

In spherical collapse Model

$$R_{vir} \propto V_c(1+z)^{-3/2}$$

* Halos are smaller and denser at earlier epochs

* SFR is higher in halos at earlier z, even for the same cold gas

Feedback From SN

- Supernovae reheat the cold gas and may drive a wind.

$$\Delta m_{reheated} = \epsilon_{gal} \Delta m_*$$

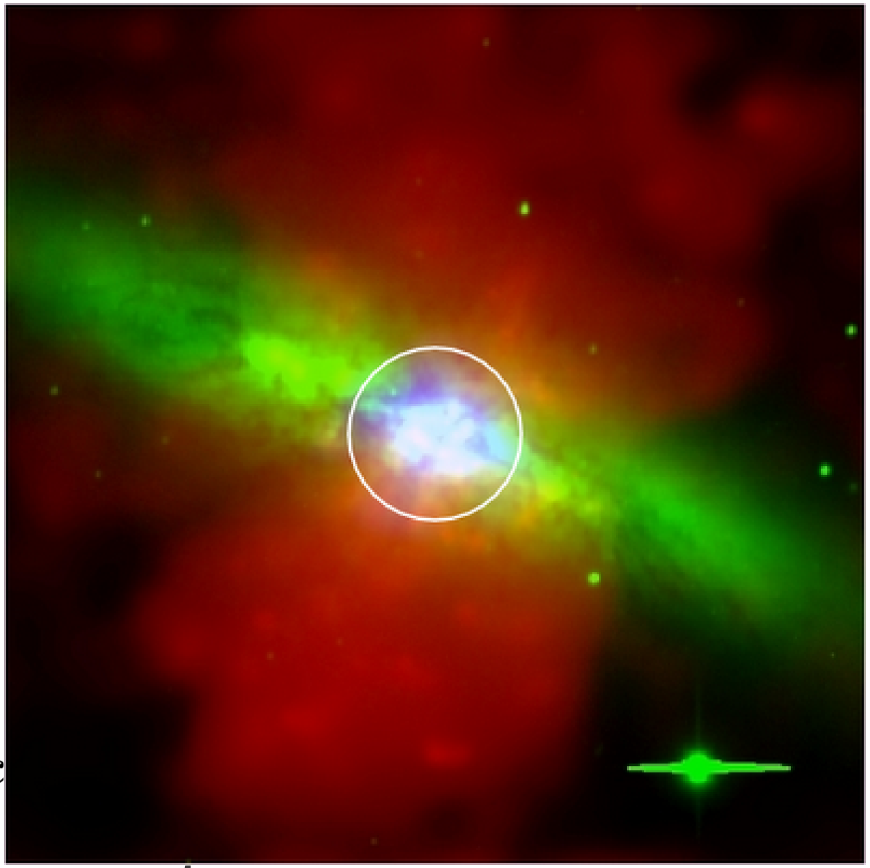
- Energy in SN ejecta

$$E_{SN} = 0.5 \epsilon_{Halo} \Delta m_* V_{SN}^2$$

- Change in thermal energy

  of Halo

$$\Delta E_{hot} = 0.5 \Delta m_{reheated} V_{circ}^2$$



- Condition for reheated gas to eject

$$\Delta E_{excess} = E_{SN} - \Delta E_{hot}$$

Feedback From AGN

Increase in mass of Black hole in merger

$$\Delta m_{BH} = \frac{f_{BH} m_{cold}}{1 + (200 kms^{-1}/V_{vir})^2}$$

Accretion due to radio mode of feedback

$$\dot{m}_{\rm BH} = \kappa \left(\frac{m_{\rm BH}}{10^8 {\rm M}_\odot}\right)\left(\frac{f_{\rm hot}}{0.1}\right)\left(\frac{V_{\rm vir}}{200\, kmps}\right)^3$$

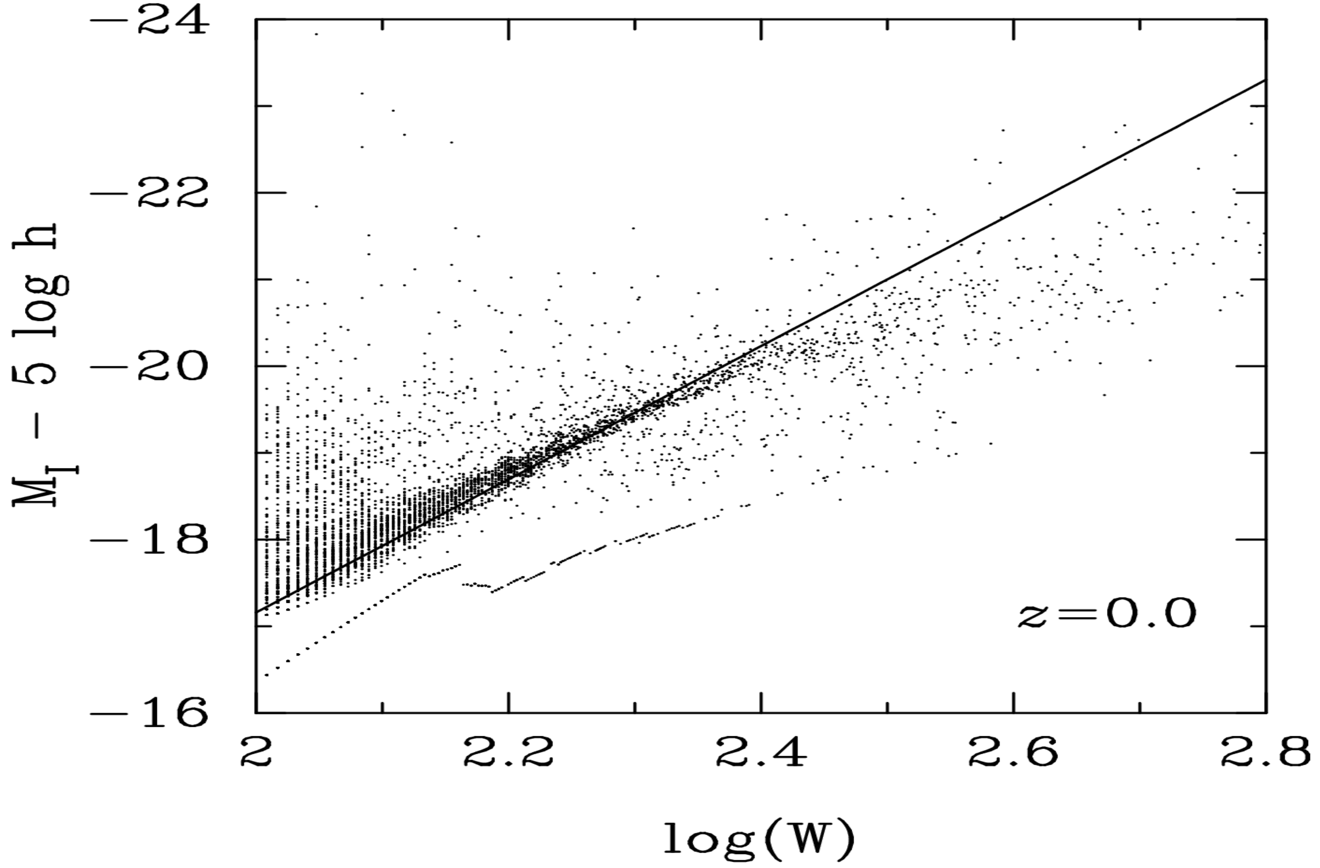
Mechanical heating generated by this mode

$$L_{BH} = \eta \dot{m}_{BH} c^2$$

This modifies the cooling rate to

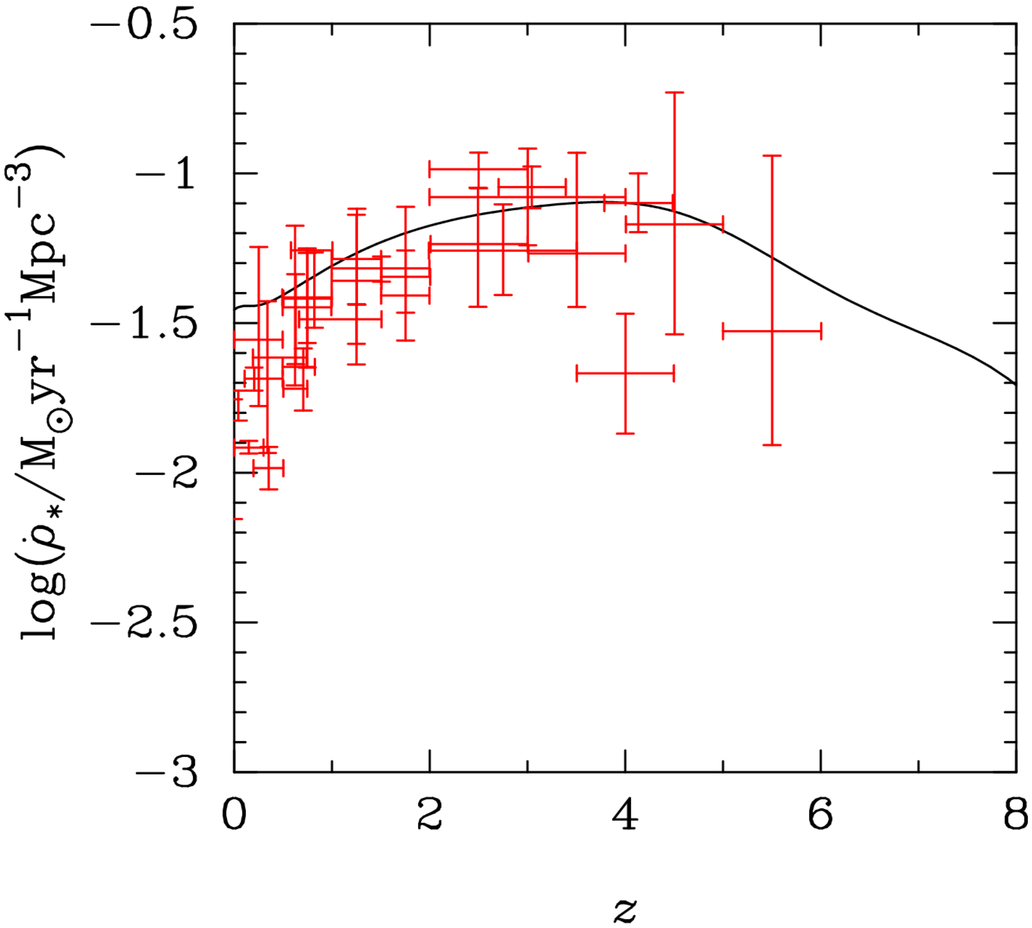
$$\dot{m}'_{\rm cool} = \dot{m}_{\rm cool} - 2L_{\rm BH}/V_{\rm vir}^2$$

Model Calibration : Local TF Relation



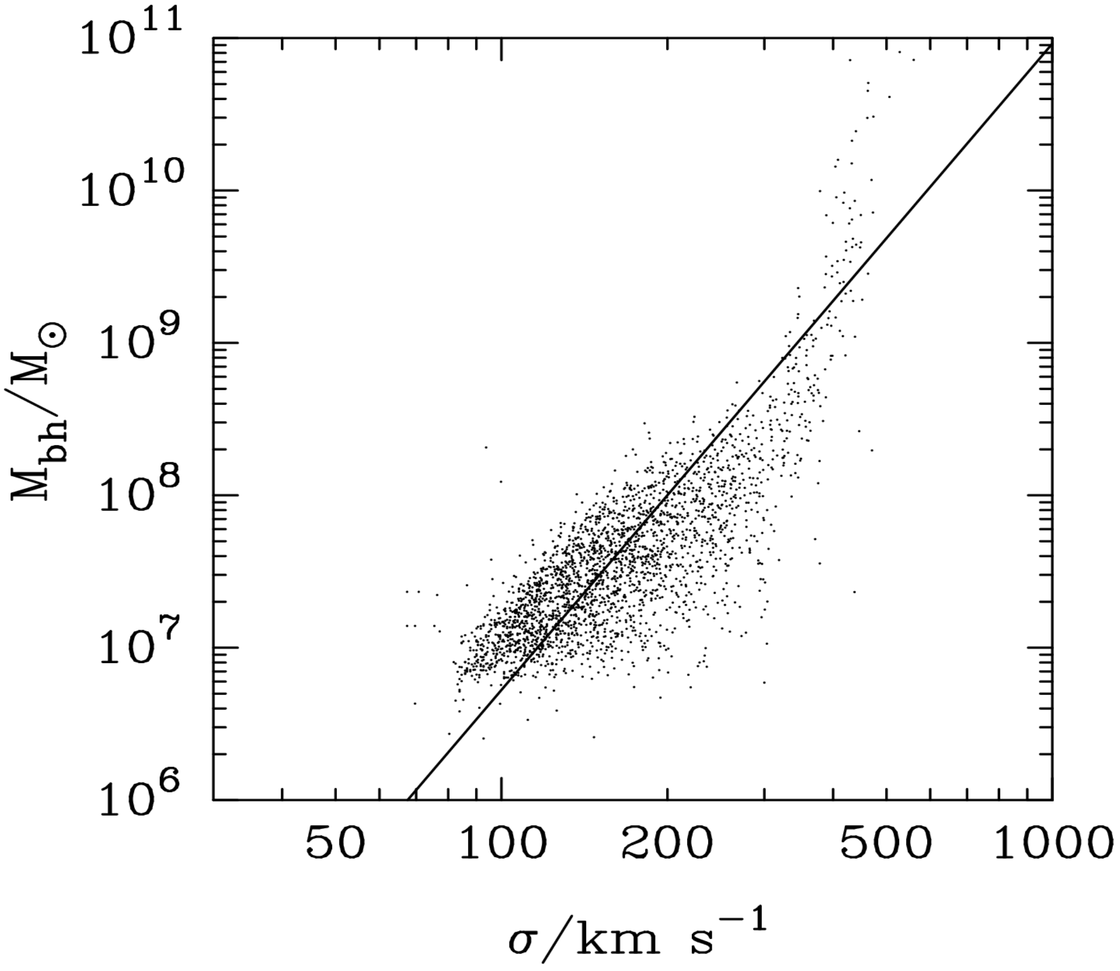
Local Tully Fisher relation of Model galaxies compared with observations of **Giovanelli et al. 1997**

SFR Density



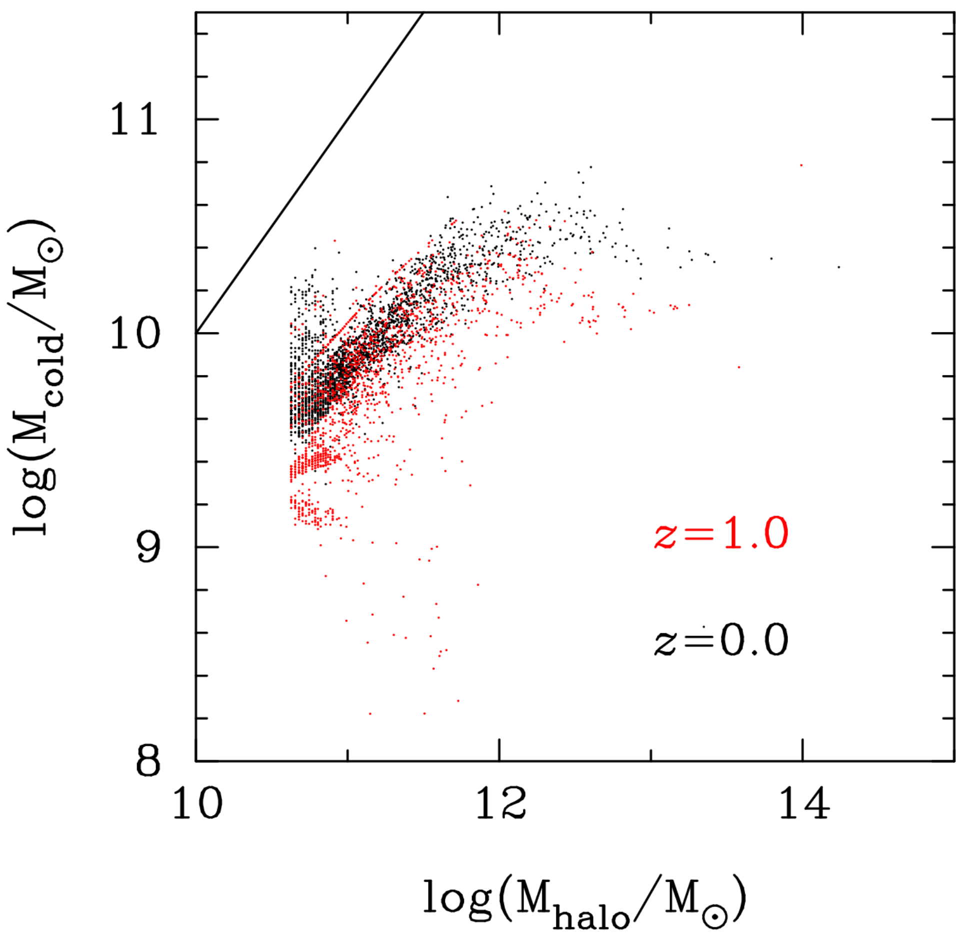
Data points with error bars are a compilation of observations as in **Springel and Hernquist (2003)**

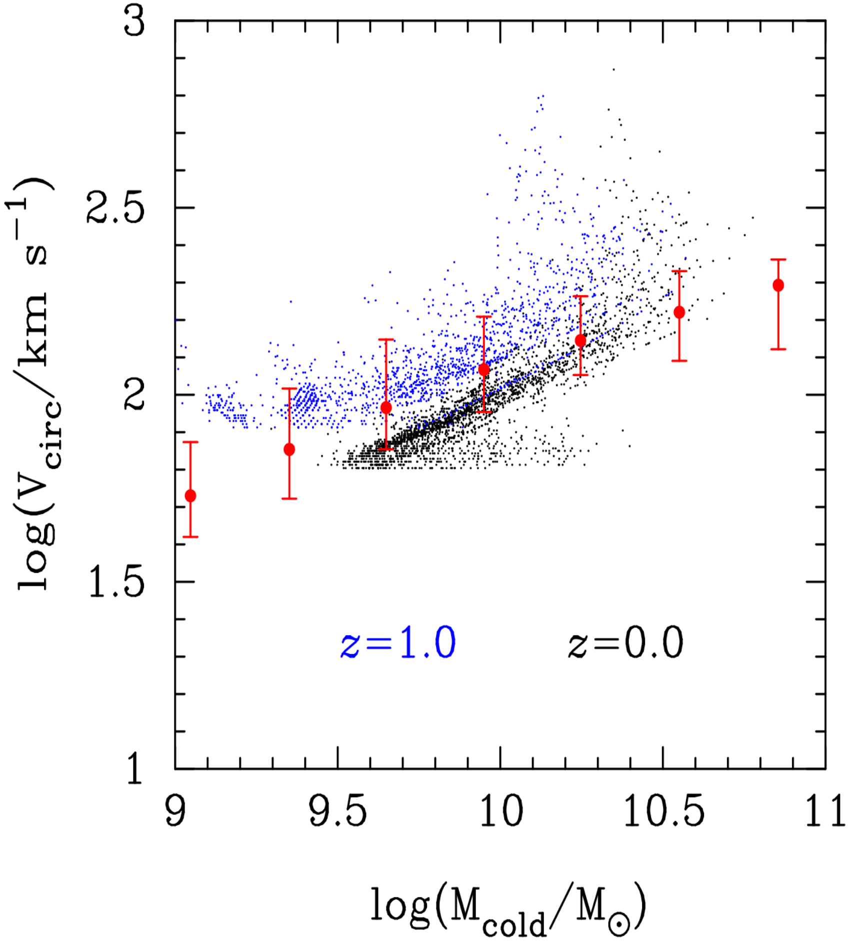
Black Hole Mass Sigma Relation



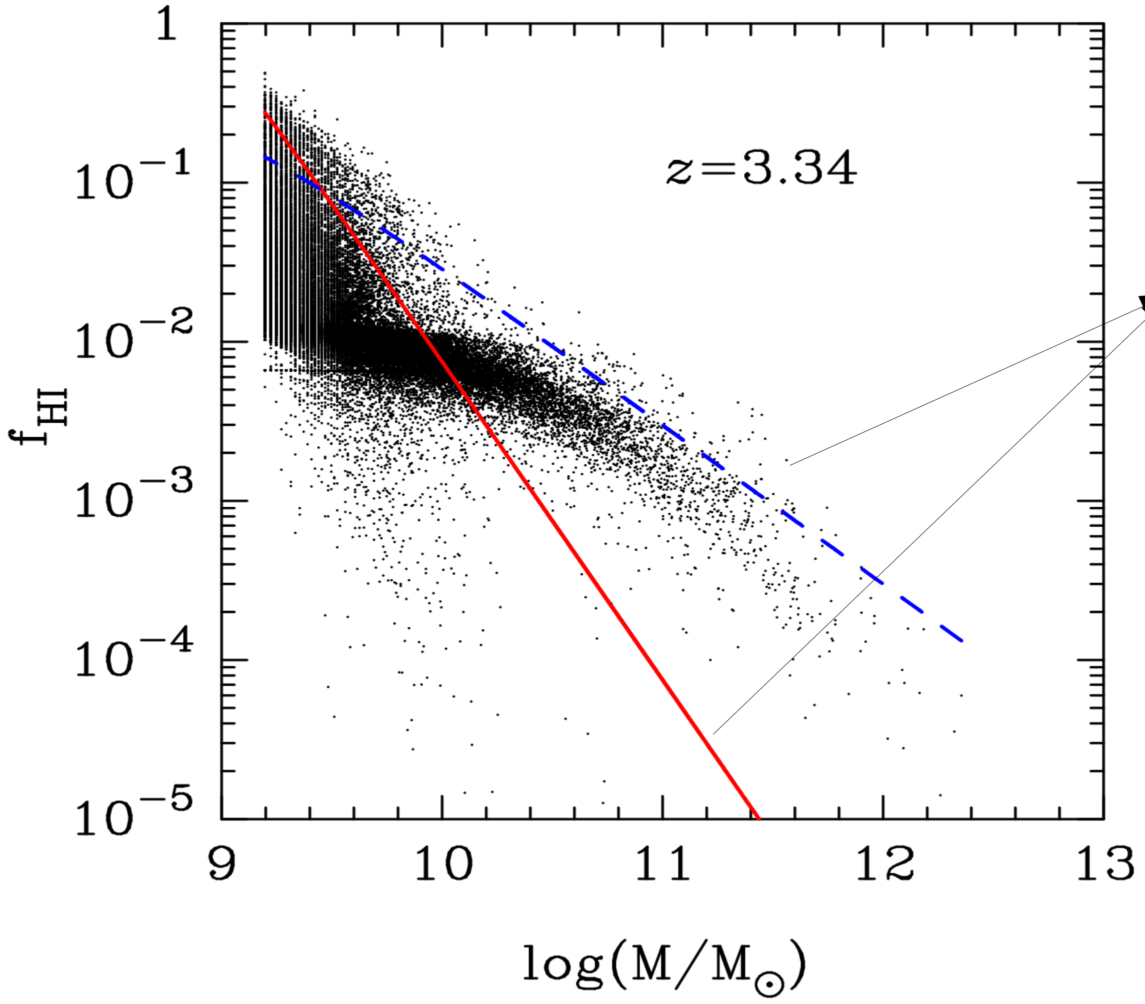
Relation of our model galaxies compared to observations by **Kayhan et al. (2009)**

Cold Gas Inside Halos



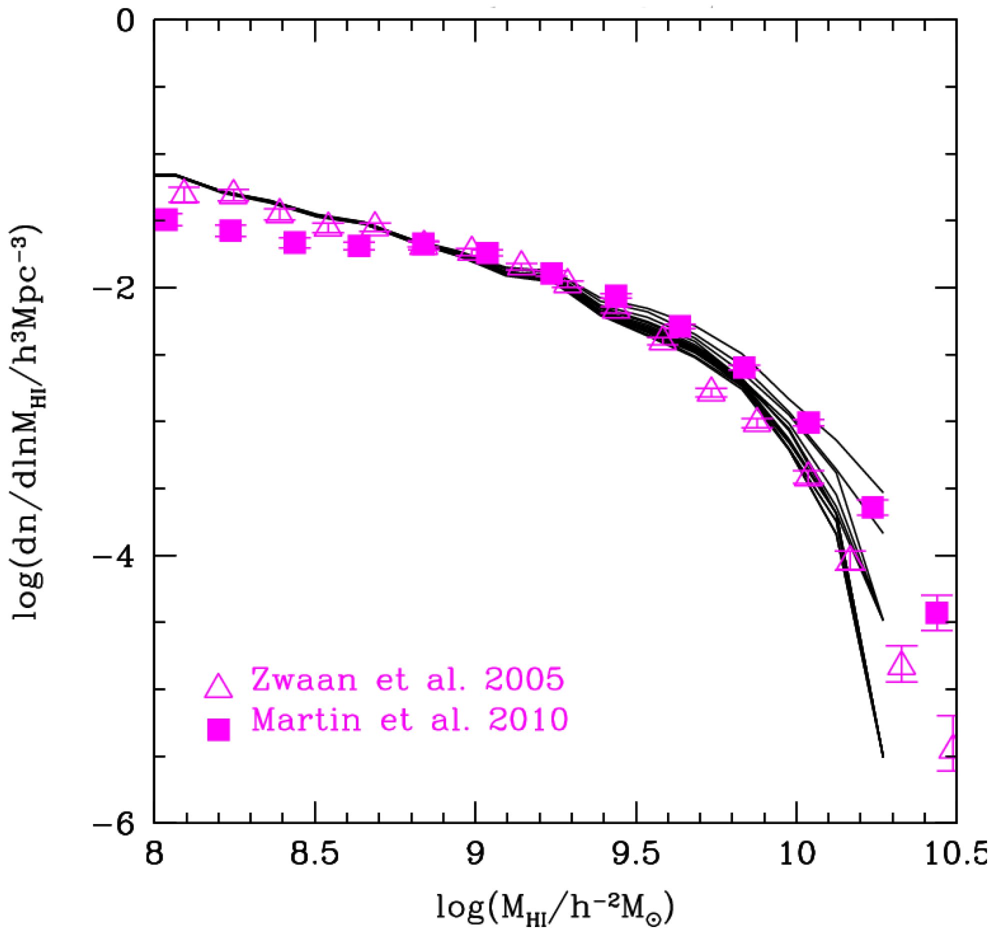


Fraction of HI in halos



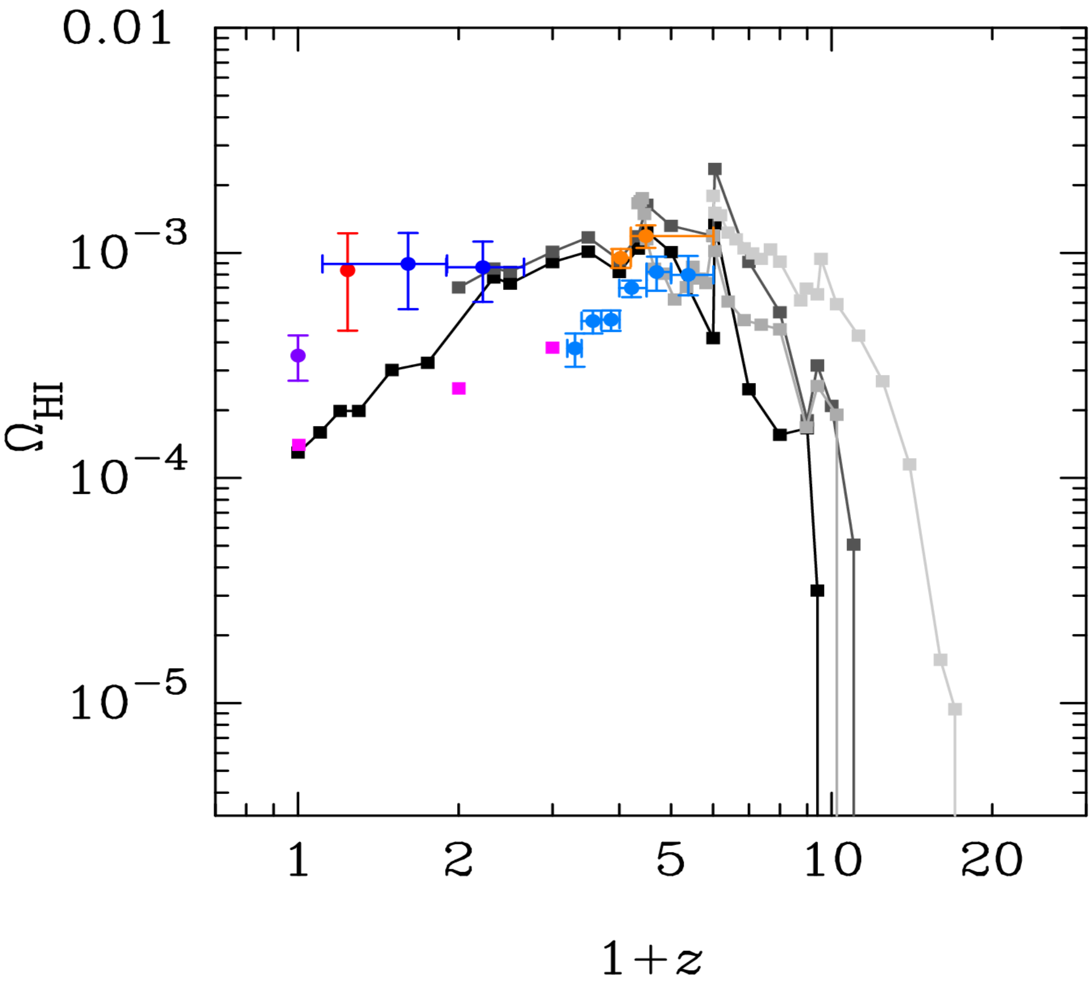
Estimates from
Bagla et al. (2010)

HI Mass Function

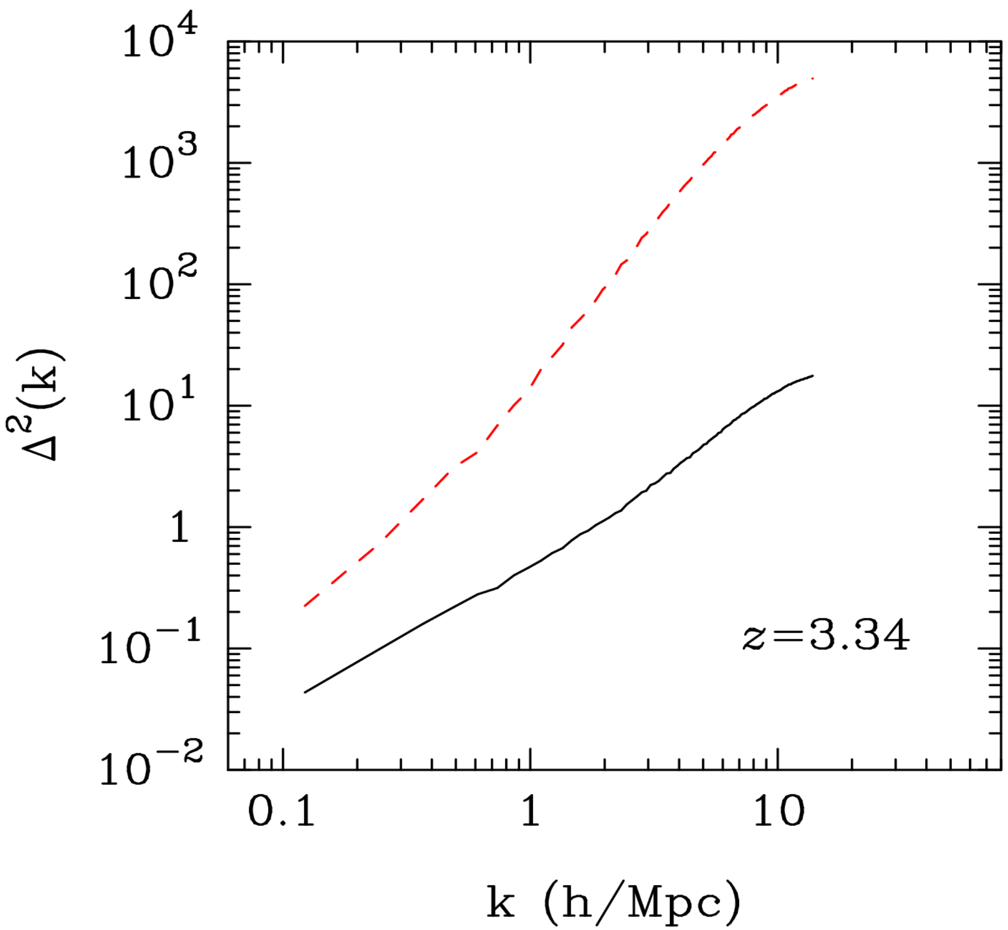


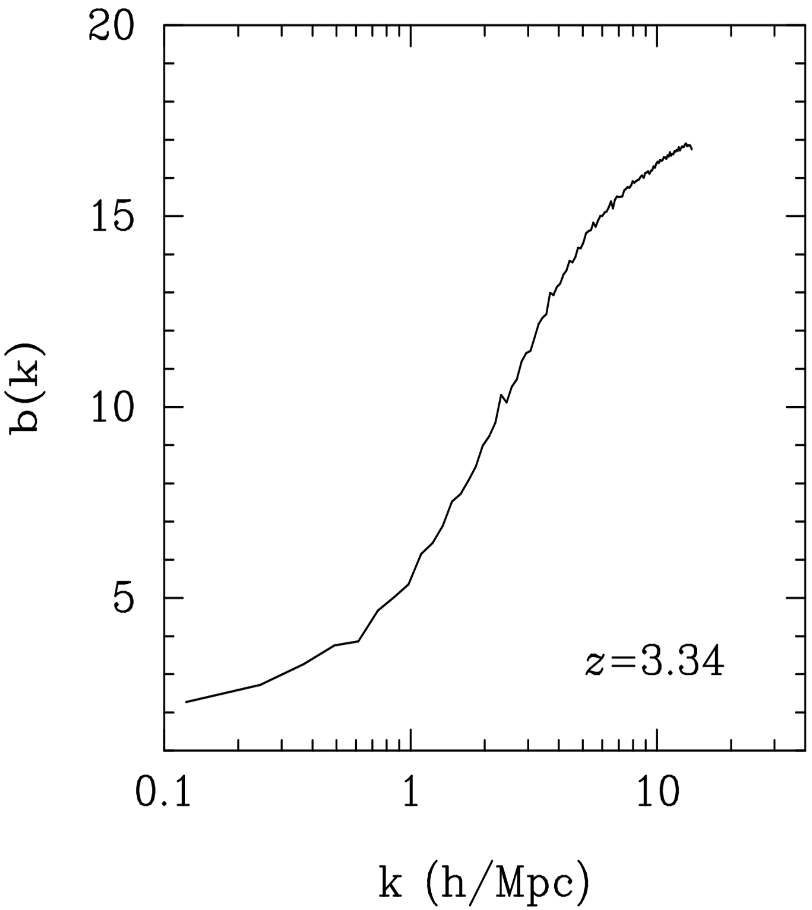
Mass function of HI compared with observations
(Also see **Kim H-S et al.(2012)** for a comparison)

Cosmic Density of HI



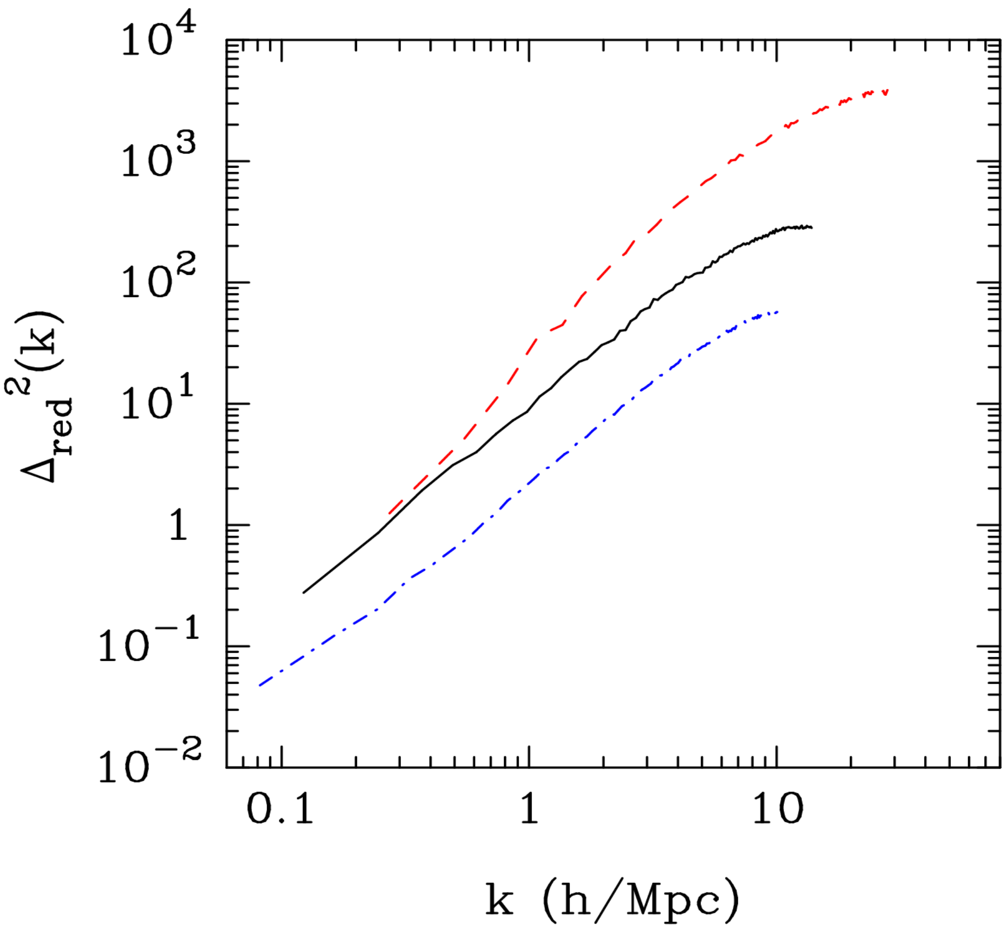
Power Spectrum and Bias of HI



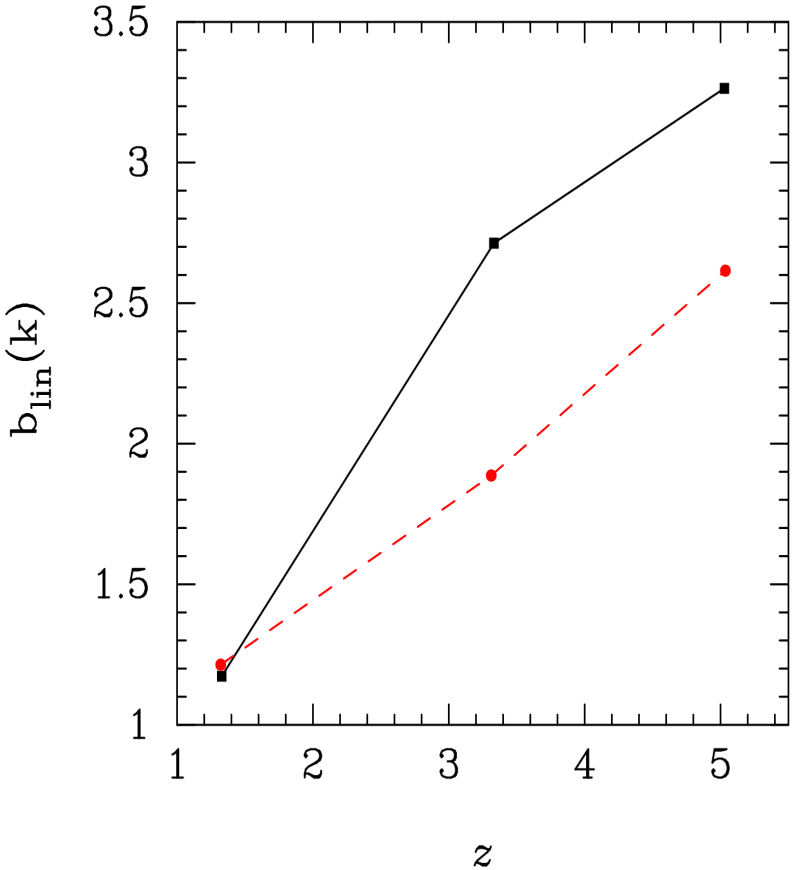


Red Dashed – H I
Gray – Dark matter

Evolution of PS and Bias



Redshift Space Power Spectrum at 5.1, 3.3 and 1.1 redshift.



Bias evolution in this work Compared with Bagla et al (2010)

Conclusions

- An improved and self consistent calculation of H I is presented using a SAM of galaxy formation.
- We find the clustering of HI at small scales is very strong, stronger than what was found using earlier simple models
- This reinforces the point that direct detection of rare peaks in H I distribution may require less time than statistical detection of PS at large scales.

Thank You For Your Attention.

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