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# A halo model for cosmological neutral hydrogen

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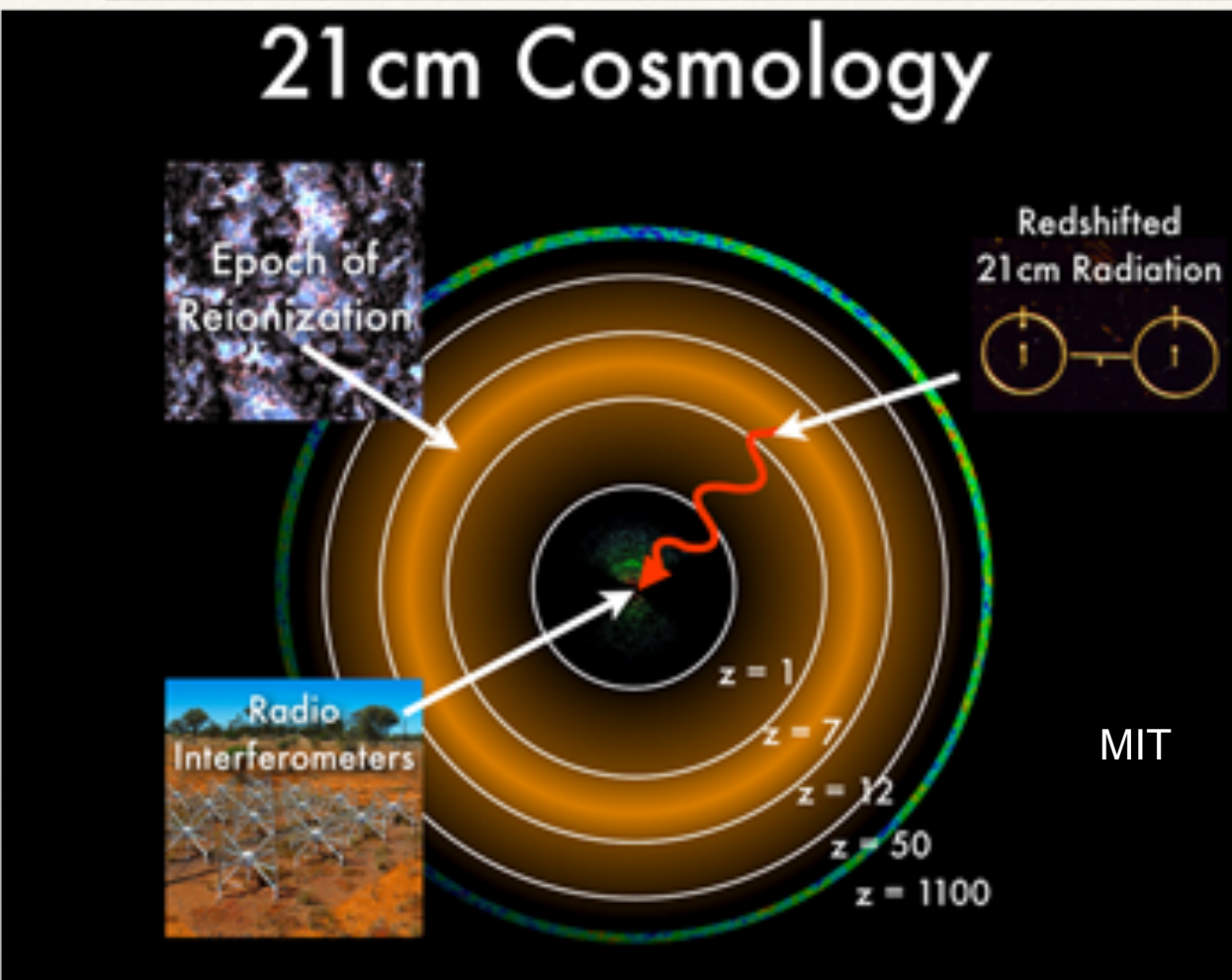
**Hamsa Padmanabhan**  
ETH Zurich, Switzerland

with Alexandre Refregier, Adam Amara, T. Roy Choudhury, Girish Kulkarni

**arXiv:1407.6366, 1505.00008, 1607.01021, 1608.00007, 1611.06235, 1706.01471**

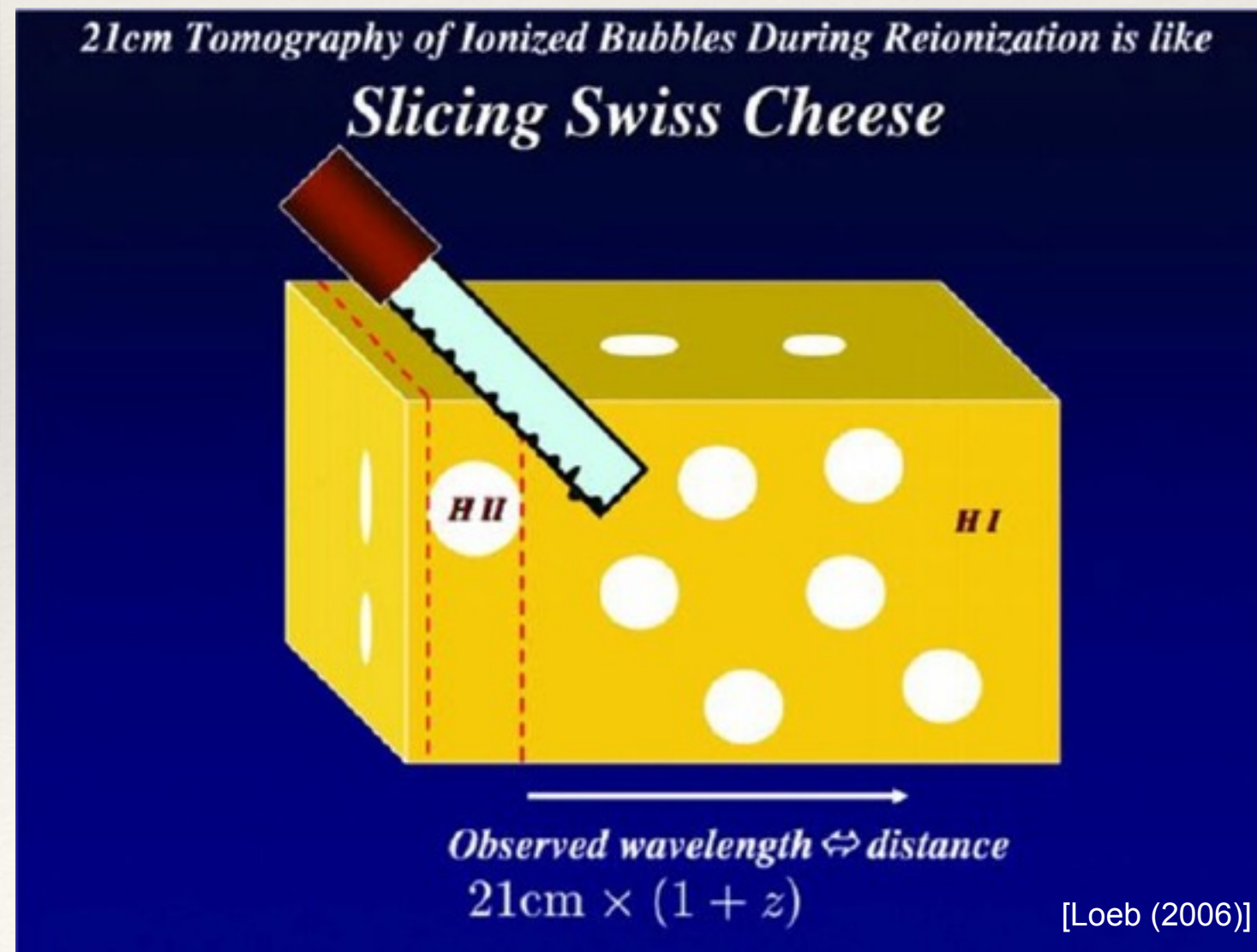
# 21-cm cosmology

Tomography: each frequency is a different epoch



$N \sim 3 \times 10^{16}$  modes,  
much smaller scales than  
CMB

[Loeb & Zaldariagga (2004)]



[Loeb (2006)]



# Efforts to map the neutral hydrogen distribution

- LOFAR (Netherlands)
- GMRT (Pune, India)
- PAPER, MEERKAT (South Africa)
- BINGO, CHIME, TianLai, HIRAX...
- SKA (South Africa/Australia)

....





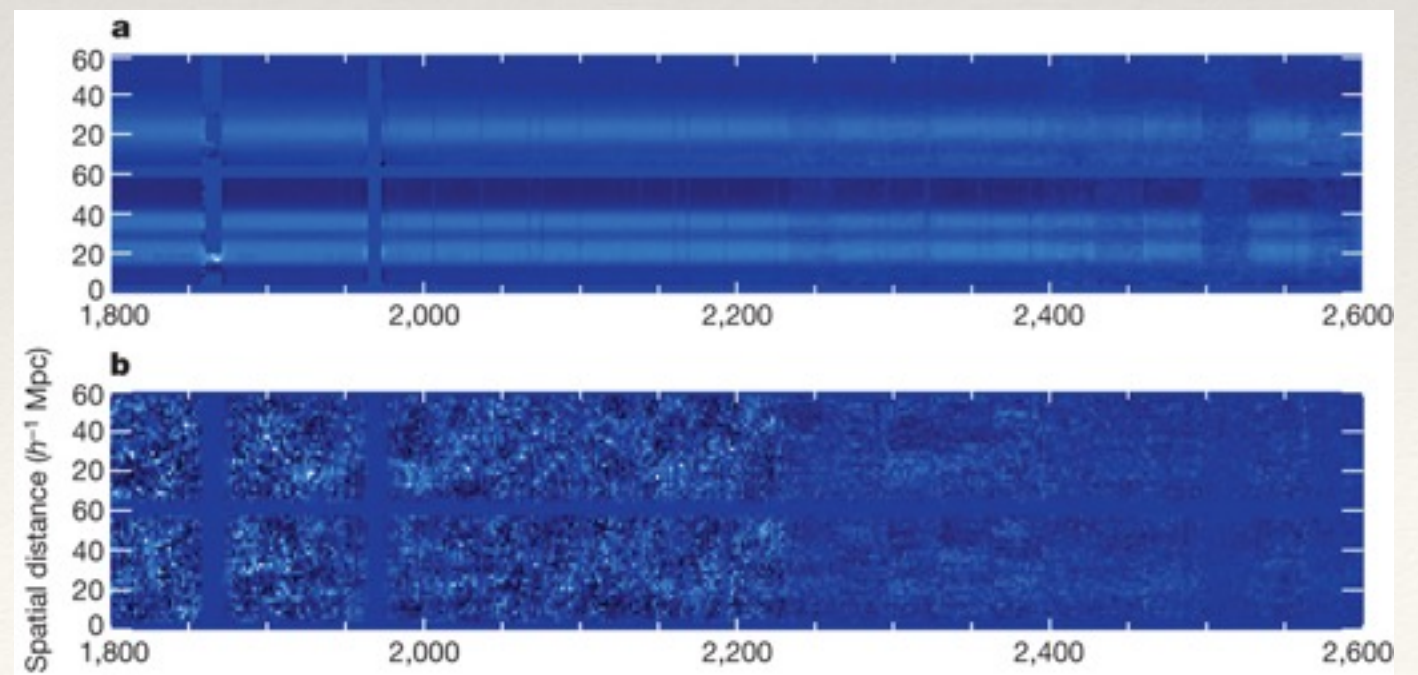
# Post-reionization universe: HI intensity mapping

Map distribution of HI without resolving individual galaxies

Constrains neutral hydrogen density parameter and bias

Auto/cross-correlation function of HI & DEEP2/WiggleZ  
optical galaxies at  $z \sim 0.8$

[Chang+, *Nature* (2010)], Masui+ (2013), Switzer+ (2013)]



# HI Intensity mapping

$$P_{\text{HI}} \equiv [\delta T_{\text{HI}}(k, z)]^2 = \bar{T}(z)^2 [b_{\text{HI}}(k, z)]^2 \frac{k^3 P_{\text{cdm}}(k, z)}{2\pi^2}$$

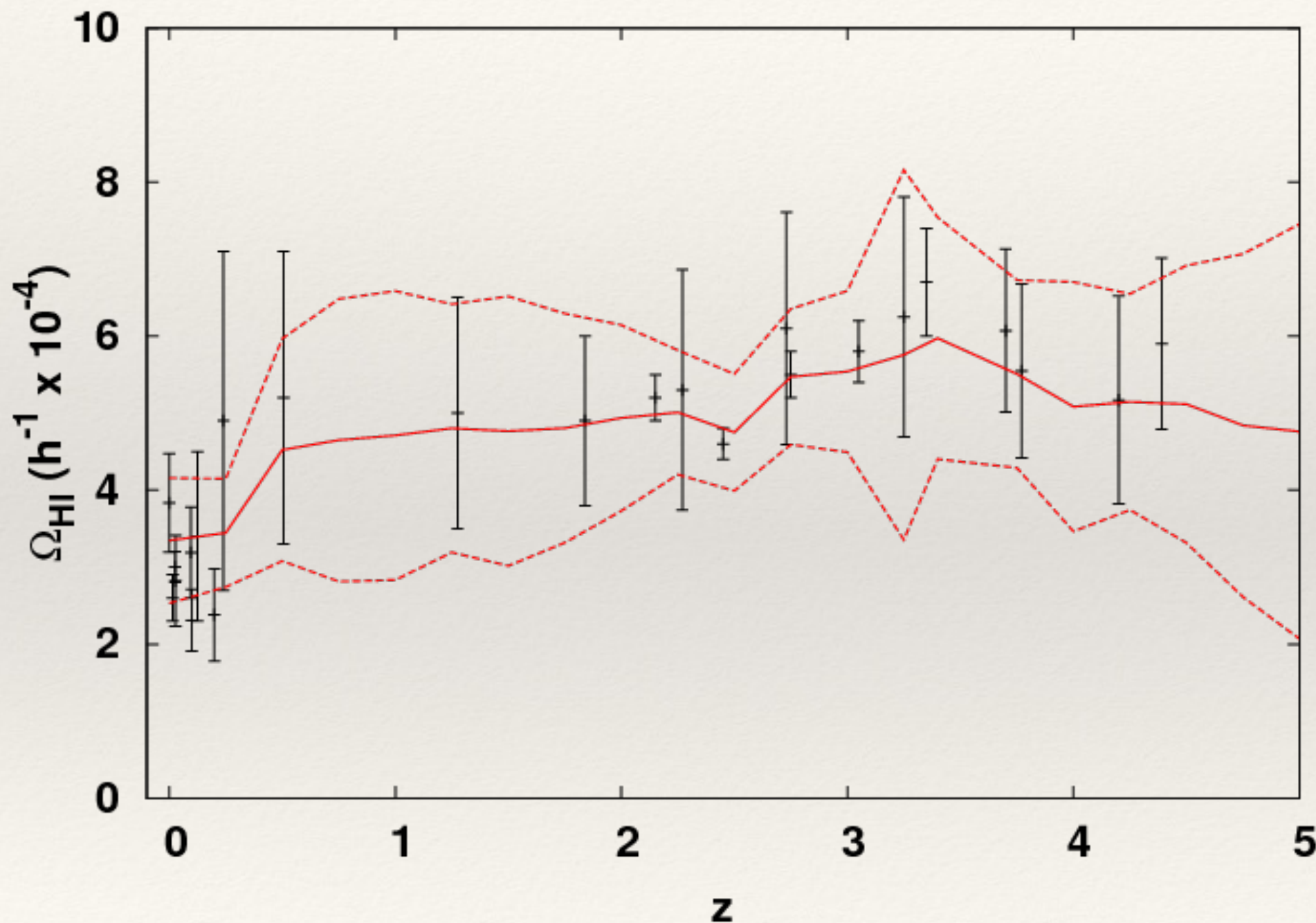
$$\bar{T}(z) = 44 \mu\text{K} \left( \frac{\Omega_{\text{HI}}(z) h}{2.45 \times 10^{-4}} \right) \frac{(1+z)^2}{E(z)}$$

**ASTROPHYSICS**      **COSMOLOGY**

*Compiling the current constraints on  $b_{\text{HI}}$ ,  $\Omega_{\text{HI}}$  ...*



# The ‘astrophysical systematic’



Press and  
Rybicki's  
minimum  
variance  
“snake”  
estimator  
(1992)

***Predictions for (post-reionization) HI  
observations,  
all scales including nonlinear scales***

*Efficiently model the astrophysics*

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# The halo model : rationale

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[e.g. Cooray & Sheth (2002)]

- ❖ Powerful tool in cosmology to discuss non-linear gravitational clustering
- ❖ Three ingredients: Halo mass function, halo bias and halo profile
- ❖ Describes abundance and clustering of dark matter, also used widely for galaxy evolution

***Can we develop a halo model framework for neutral hydrogen?***

***Can we constrain it with the latest observations?***



# Surveying the data

## *21 cm emission*

HIPASS mass function [Zwaan+ (2005a)]  
WHISP column density [Zwaan+ (2005b)]  
ALFALFA clustering, bias [Martin+ (2012)]

## *21 cm intensity mapping*

GBT/DEEP2  
[Switzer+ (2013)]

## *DLA HI absorption*

Mg II selected:  $z \sim 1$  [Rao+ (2006)]  
 $z \sim 2.3$  bias [Font-Ribera+ (2012)]  
 $z \sim 2.3$  SDSS [Noterdaeme+ (2012)]  
 $z \sim 5$  GGG survey [Crighton+ (2015)]

$z \sim 0-4$  incidence [Zafar+ (2013)] SDSS III [Bird+ (2016)]

0

1

2

3

4

5

$z$

# The HI halo model

*Painting neutral hydrogen on dark matter*

## Two HI ingredients

$$M_{\text{HI}}(M, z)$$

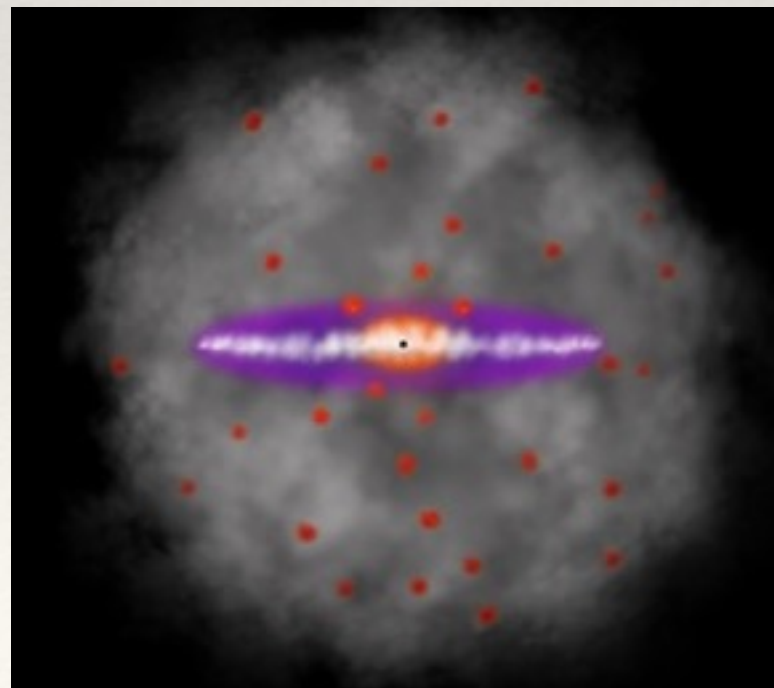
$$\rho_{\text{HI}}(r, M, z)$$

How much HI is associated with a mass M halo?

How is HI distributed in the halo?

from which we can derive HI  
observables

[HP, Choudhury, Refregier, MNRAS (2016)]



(NASA / CXC / M.Weiss)



# The HI-halo mass relation

$$M_{\text{HI}}(M) = \alpha f_{H,c} M \left( \frac{M}{10^{11} h^{-1} M_{\odot}} \right)^{\beta} \exp \left[ - \left( \frac{v_{c0}}{v_c(M)} \right)^3 \right]$$



**Overall normalization; fraction of hydrogen relative to cosmic**

**Slope**

**Lower cutoff**

HP, Refregier, Amara, MNRAS (2017)

[cf. Barnes & Haehnelt (2010, 2014),  
Villaescusa-Navarro + (2015), ...]

# HI radial profile

[HP, Refregier, Amara, MNRAS (2017)]

Exponential:

$$\rho_{\text{HI}}(r, M) = \rho_0 \exp(-r/r_s)$$

[Wang + (2014), Bigiel & Blitz (2012) ...]

$$r_s \equiv R_v(M)/c_{\text{HI}}(M, z)$$

$$c_{\text{HI}}(M, z) = c_{\text{HI},0} \left( \frac{M}{10^{11} M_{\odot}} \right)^{-0.109} \frac{4}{(1+z)^{\gamma}}$$

[Maccio+ (2007)]

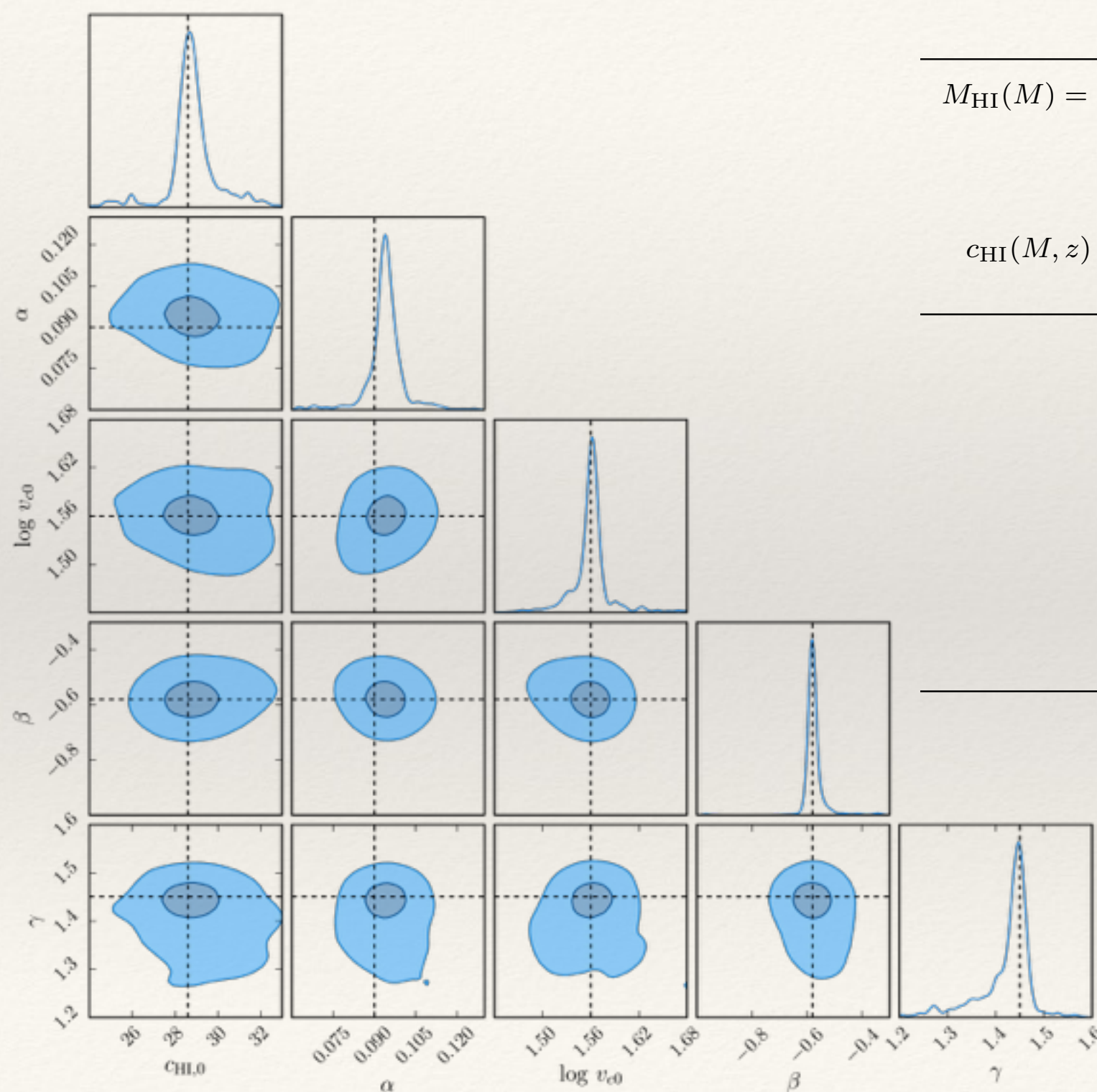
Also considered an altered NFW profile:

$$\rho_{\text{HI}}(r, M) = \frac{\rho_0 r_s^3}{(r + 0.75 r_s)(r + r_s)^2}$$

[Maller & Bullock (2004),  
Barnes & Haehnelt (2010, 2014),  
HP, Choudhury, Refregier (2016)]



# Constraining the parameters : MCMC



$$M_{\text{HI}}(M) = \alpha f_{H,c} M \left( M / 10^{11} h^{-1} M_{\odot} \right)^{\beta} \exp \left[ - (v_{c0} / v_c(M))^3 \right]$$

$$\rho_{\text{HI}}(r) = \rho_0 \exp(-r/r_s);$$

$$c_{\text{HI}}(M, z) \equiv R_v / r_s = c_{\text{HI},0} \left( M / 10^{11} M_{\odot} \right)^{-0.109} 4 / (1 + z)^{\gamma}$$

$$c_{\text{HI},0} = 28.65 \pm 1.76$$

$$\alpha = 0.09 \pm 0.01$$

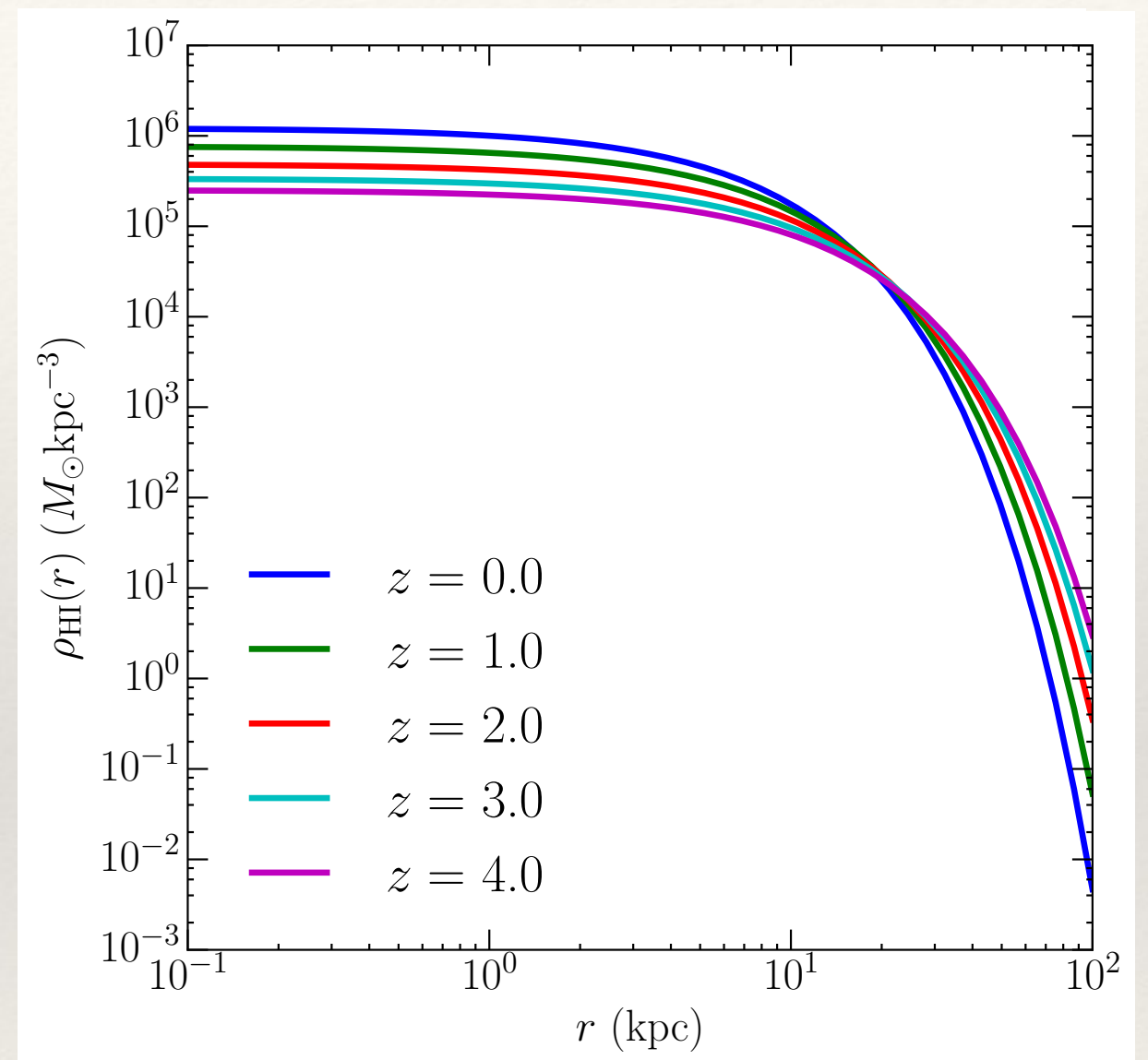
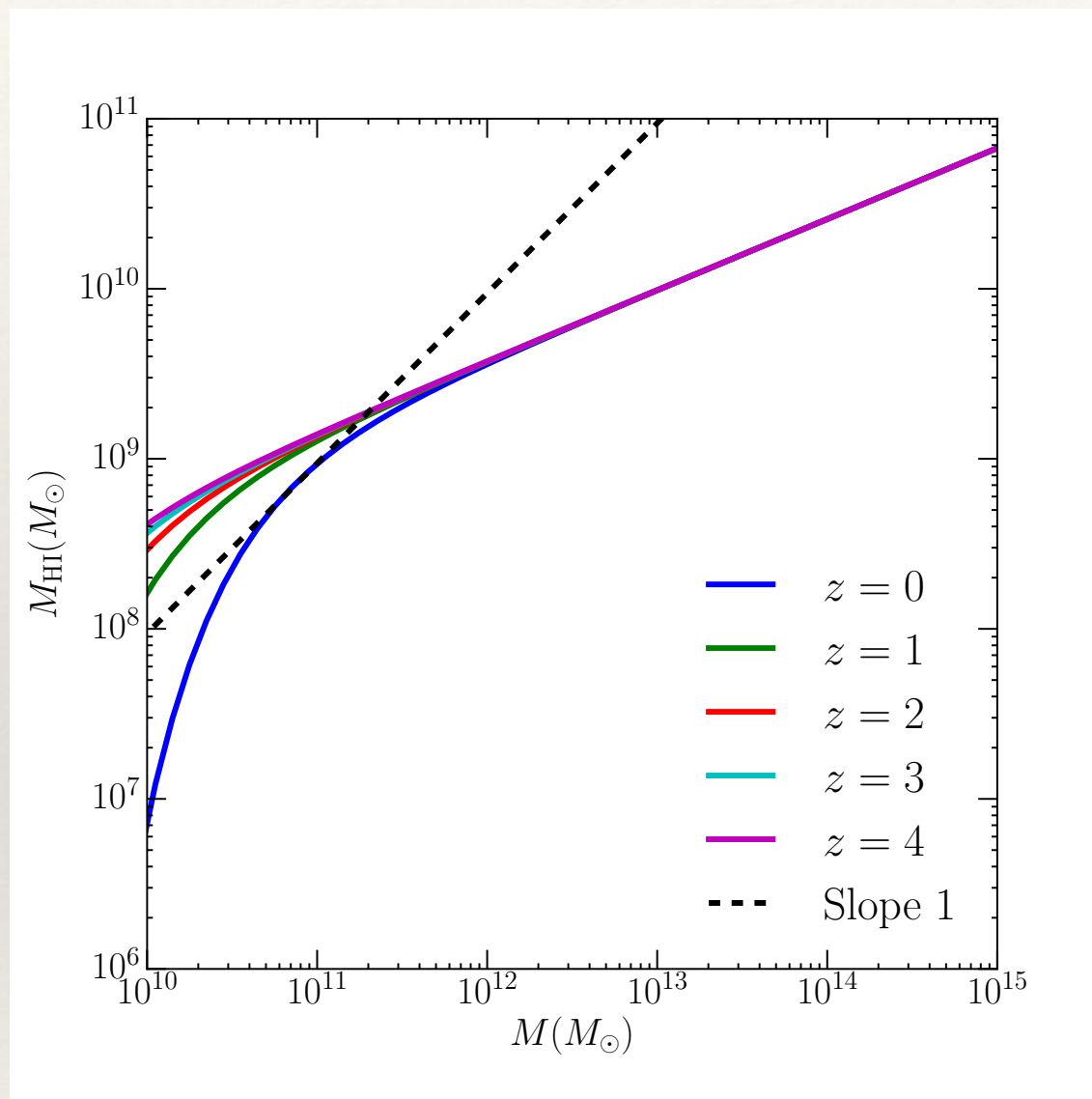
$$\log v_{c,0} = 1.56 \pm 0.04$$

$$\beta = -0.58 \pm 0.06$$

$$\gamma = 1.45 \pm 0.04$$

[HP, Refregier, Amara, MNRAS (2017)]

# Best fit halo model



[HP, Refregier, Amara, MNRAS (2017)]

**Non - unit slope, exponential profile**

**Consistent with abundance matching, stellar-cold gas relations**

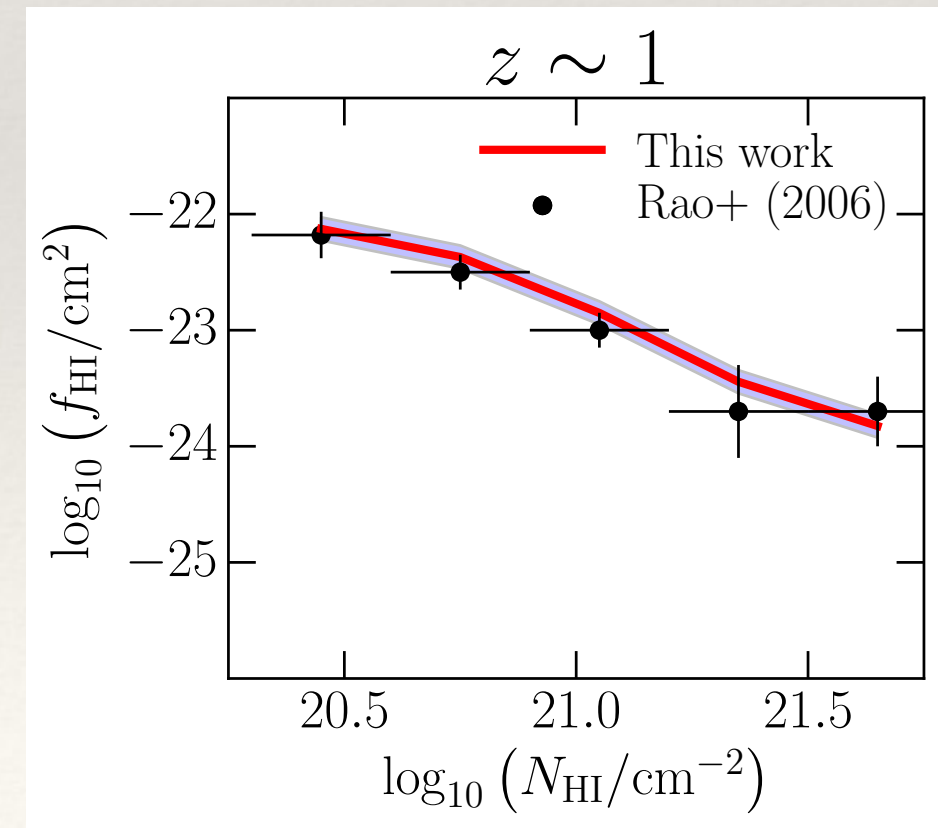
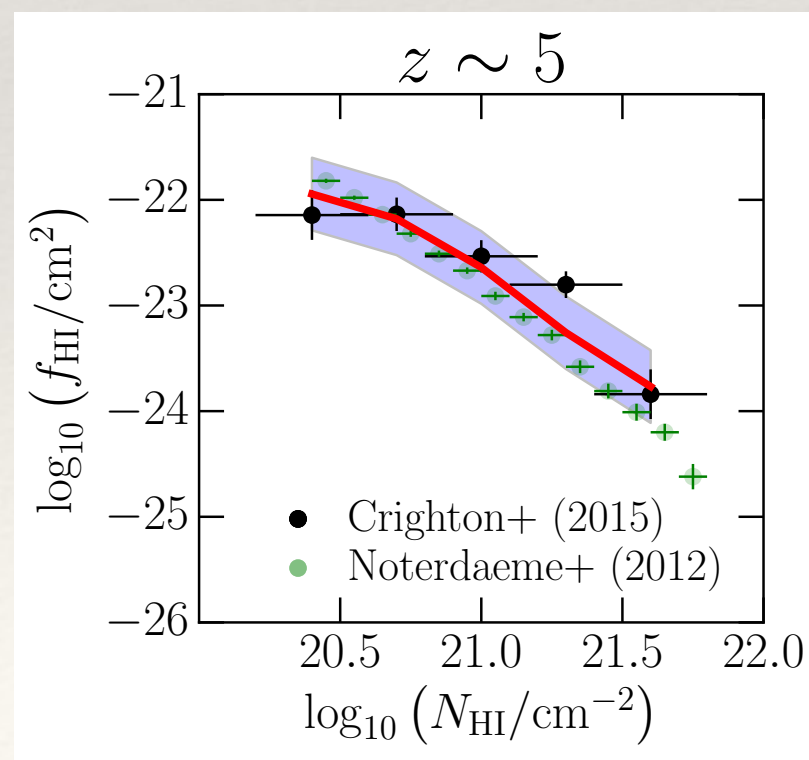
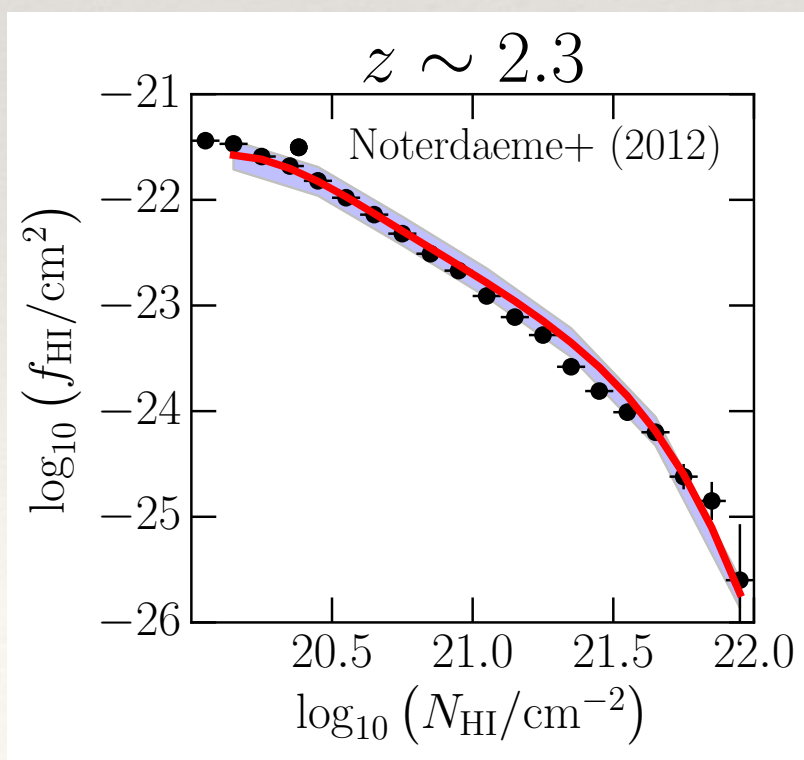
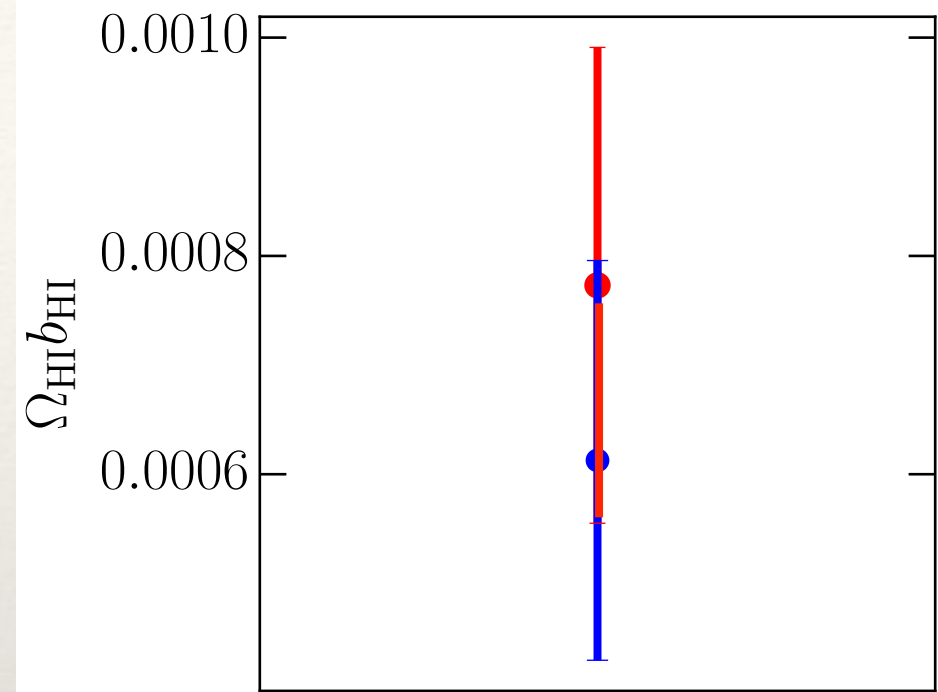
[HP & Kulkarni, MNRAS (2017)]



# Data at various redshifts

- ❖ Intensity mapping measurements with DEEP2/GBT survey [Switzer+ (2013)]
- ❖ DLA data from GGG, SDSS surveys
- ❖ Mg II selected DLA galaxies at redshifts  $\sim 1$  [Rao+ (2006)]

**INDEPENDENT DATASETS,  
MATCHED WELL BY HALO MODEL**



***What do we learn?***



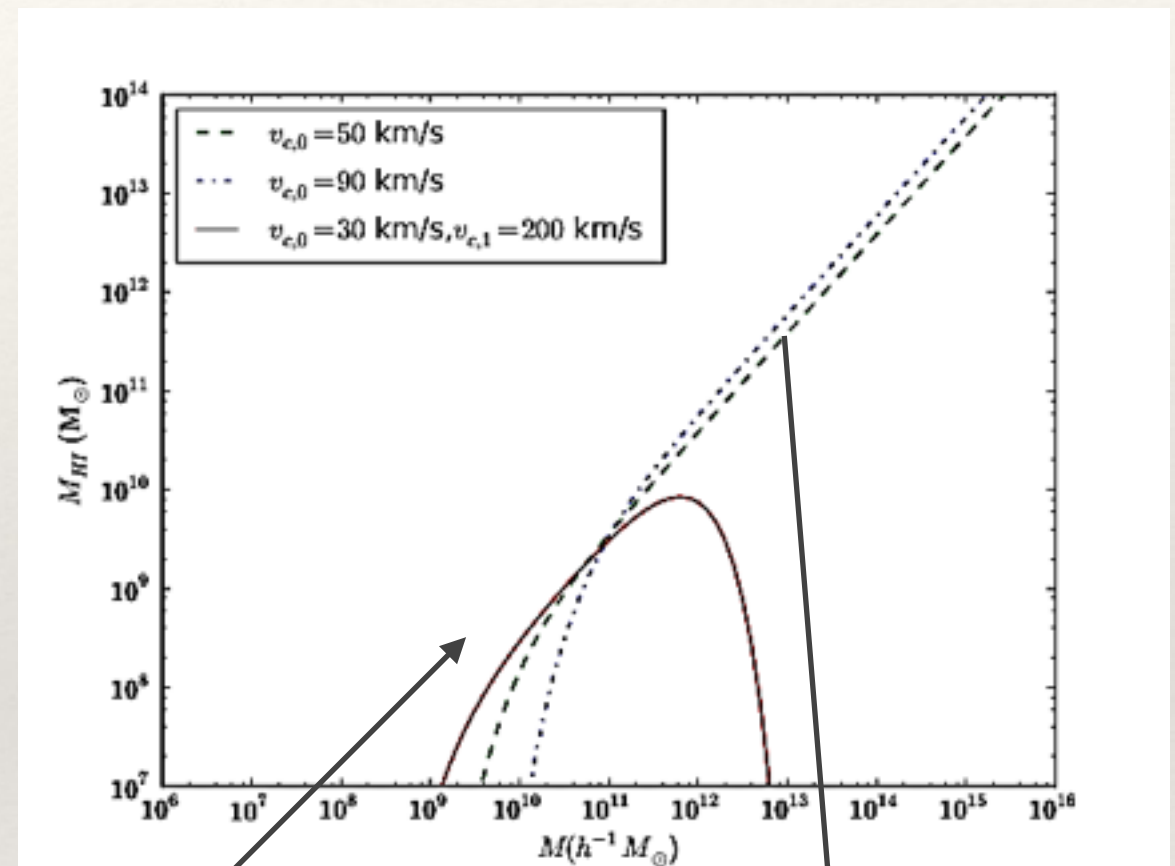
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# Insights from the modelling

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- ❖ HIHM relations adopted in the literature [Barnes & Haehnelt 2014; Bagla + (2010)]



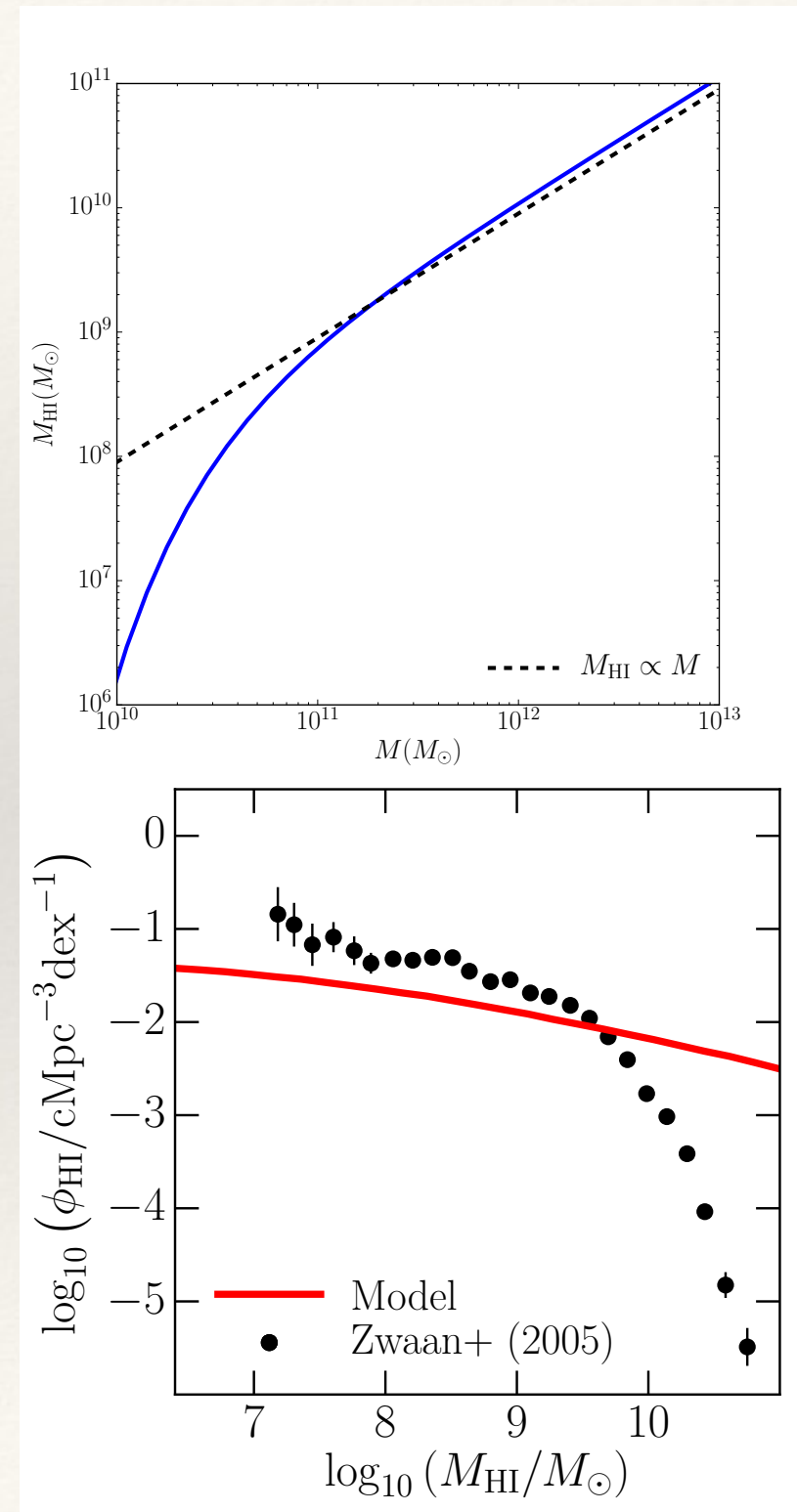
21-cm based

DLA based



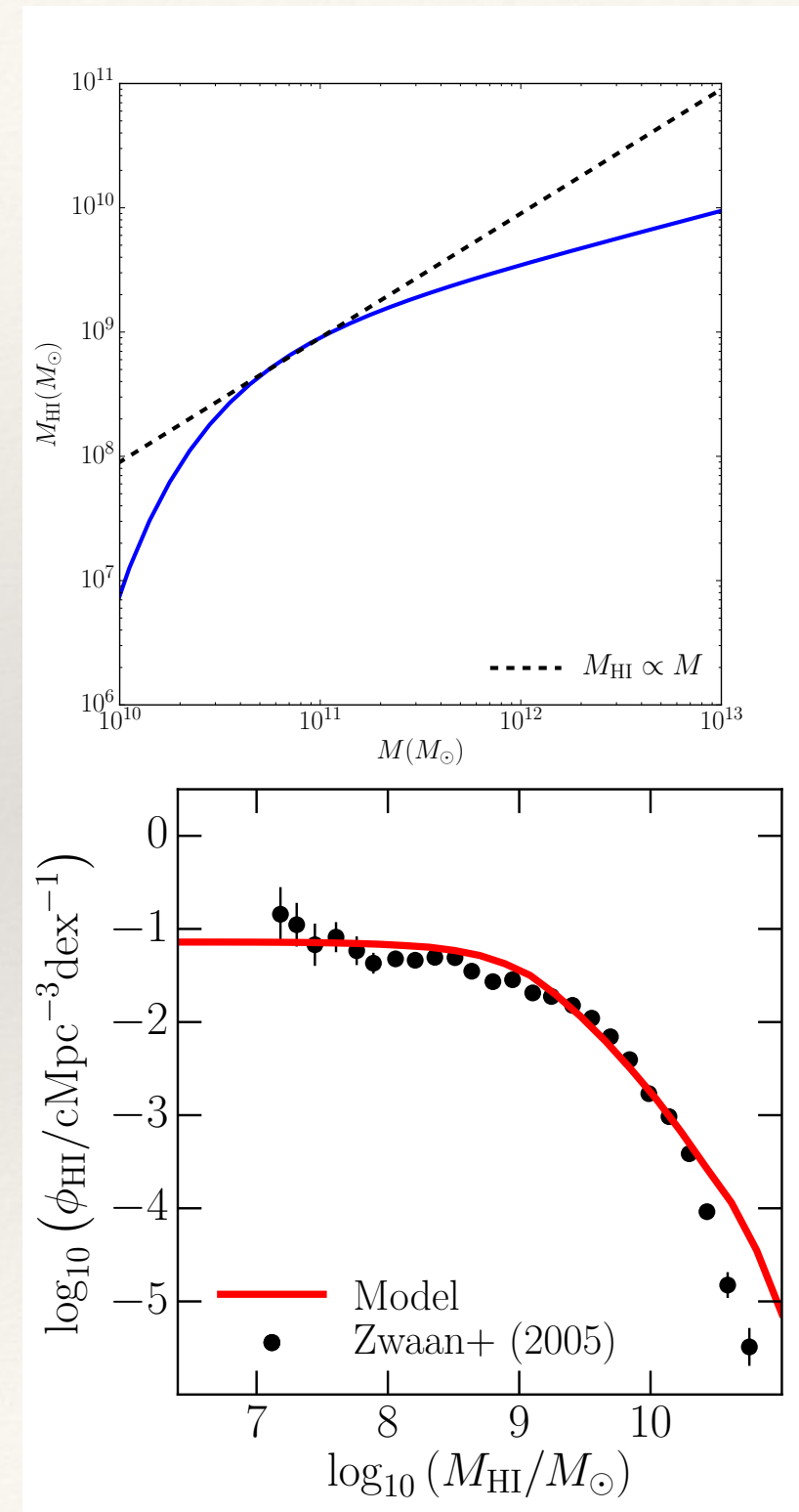
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- ❖ Combining the relations [HP, Choudhury, Refregier, MNRAS (2016)] does not fit HI mass function well



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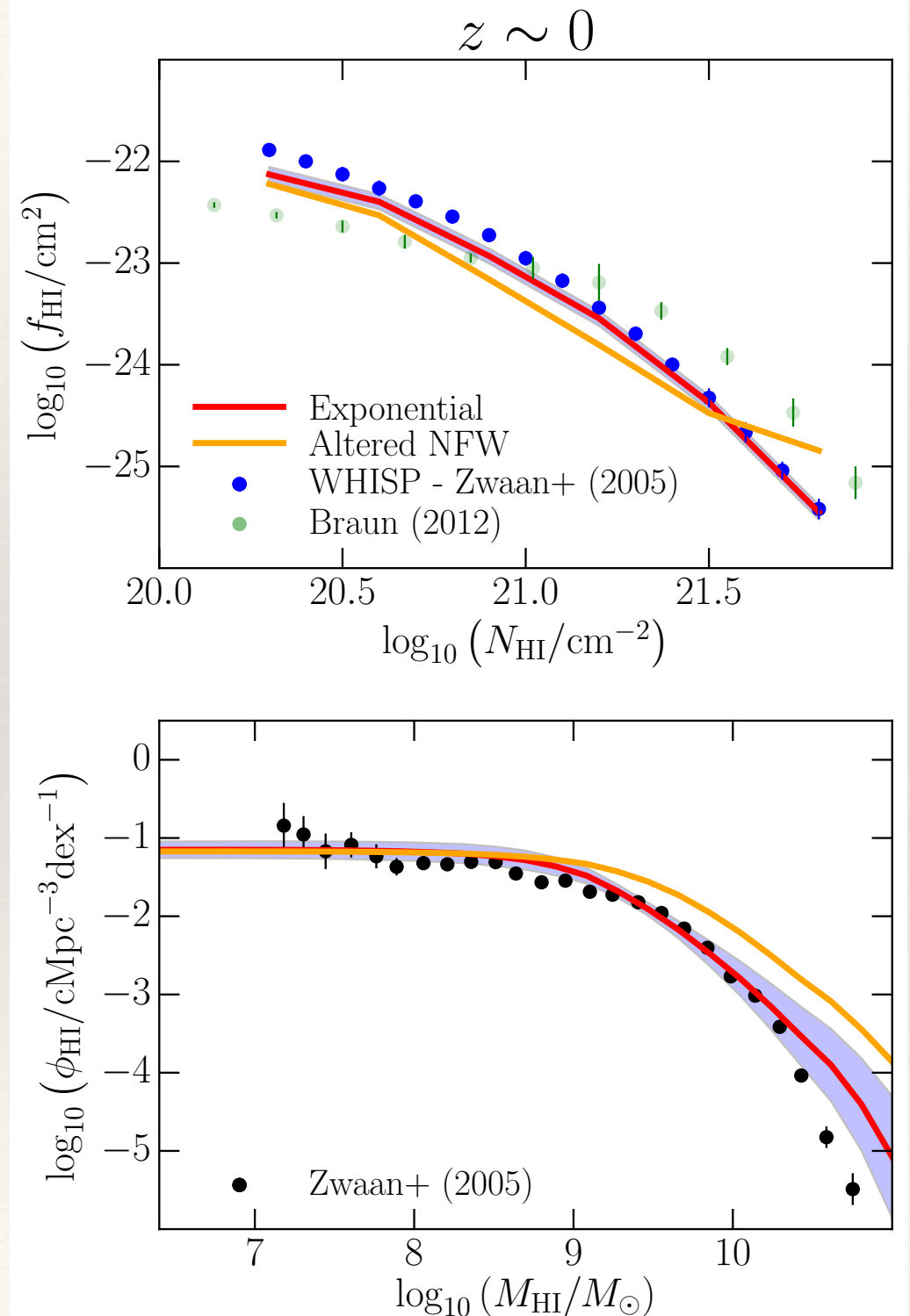
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- ❖ Fitting the mass function requires a **non-unit slope** of HIHM [HP & Refregier, MNRAS (2017)]





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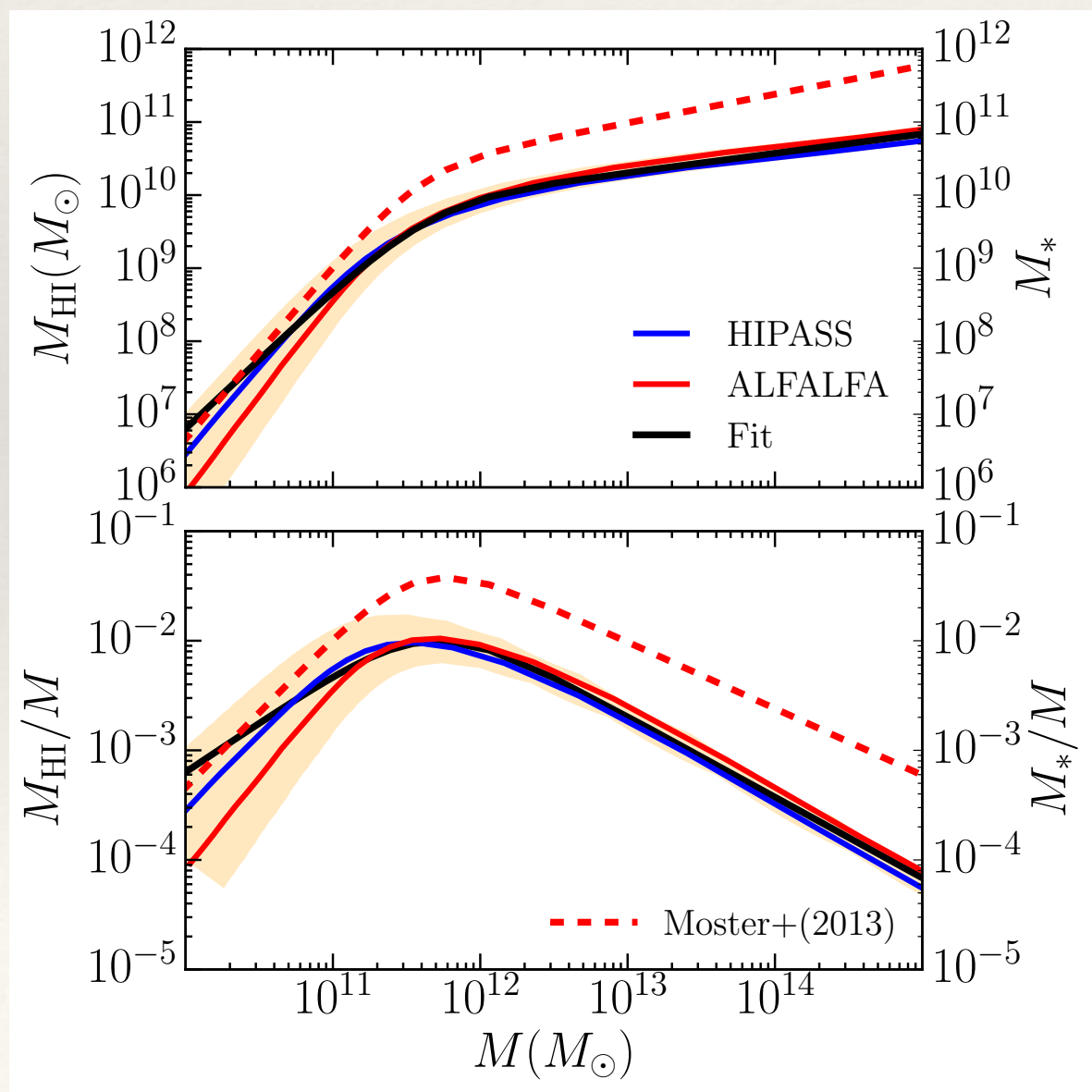
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- ❖ Fitting the mass function requires a **non-unit slope** of HIHM [HP & Refregier, MNRAS (2017)]
- ❖ An **exponential profile** reduces previously observed tension between the HIHM and the column density [HP, Refregier, Amara, MNRAS (2017)]



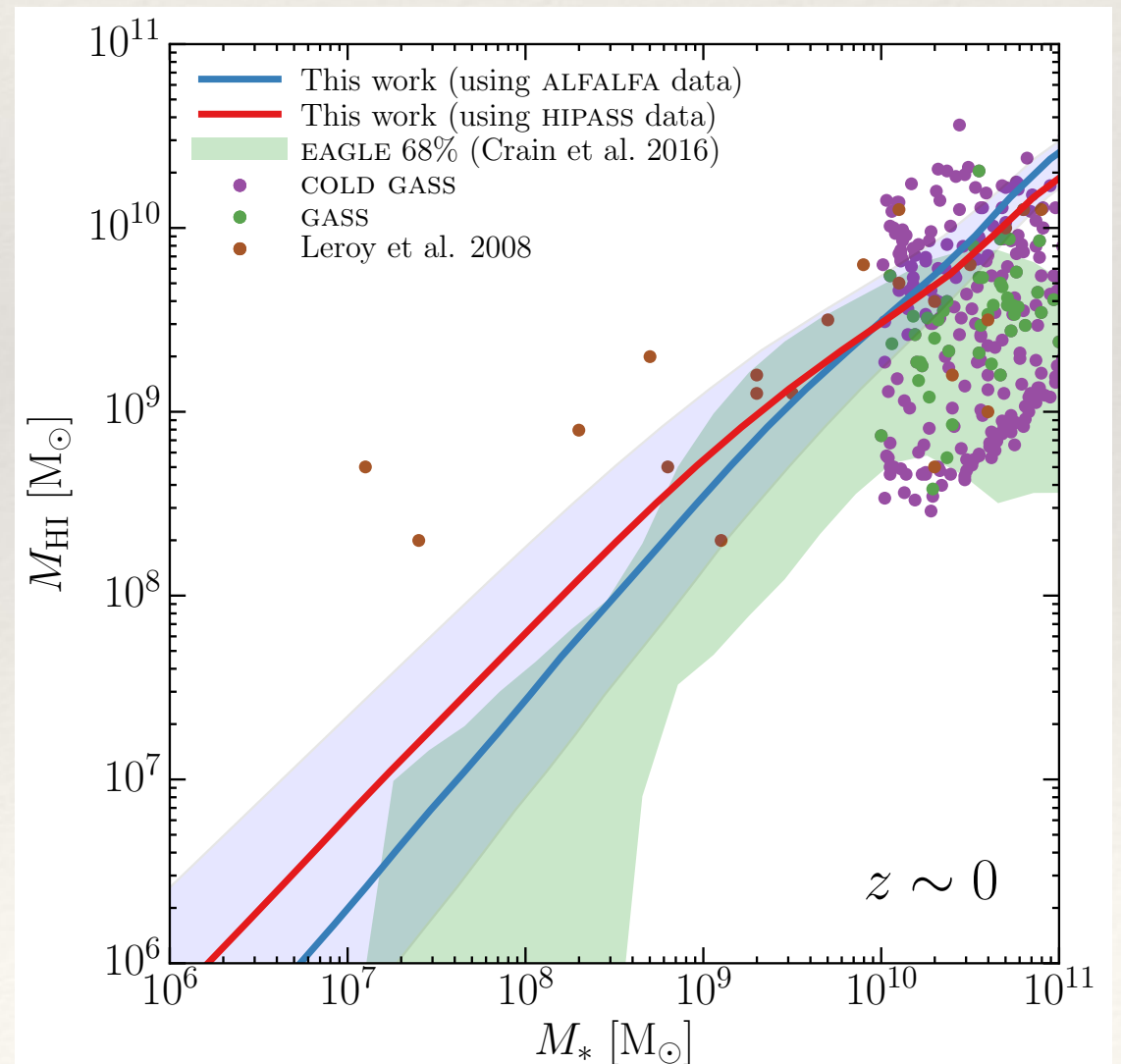
# Reverse engineering ...

Start with the HI mass function and empirically determine the HI-halo mass relation

**Abundance matching** [HP & Kulkarni, MNRAS (2017)]



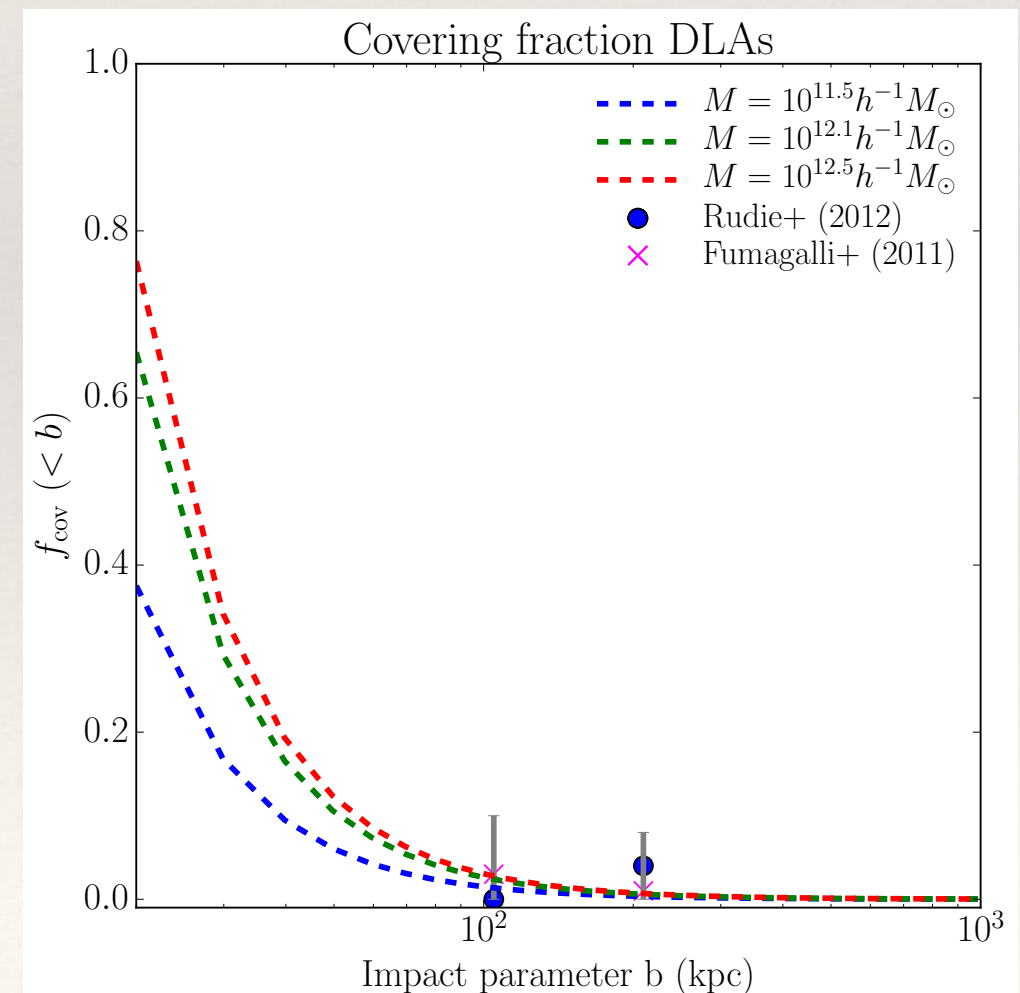
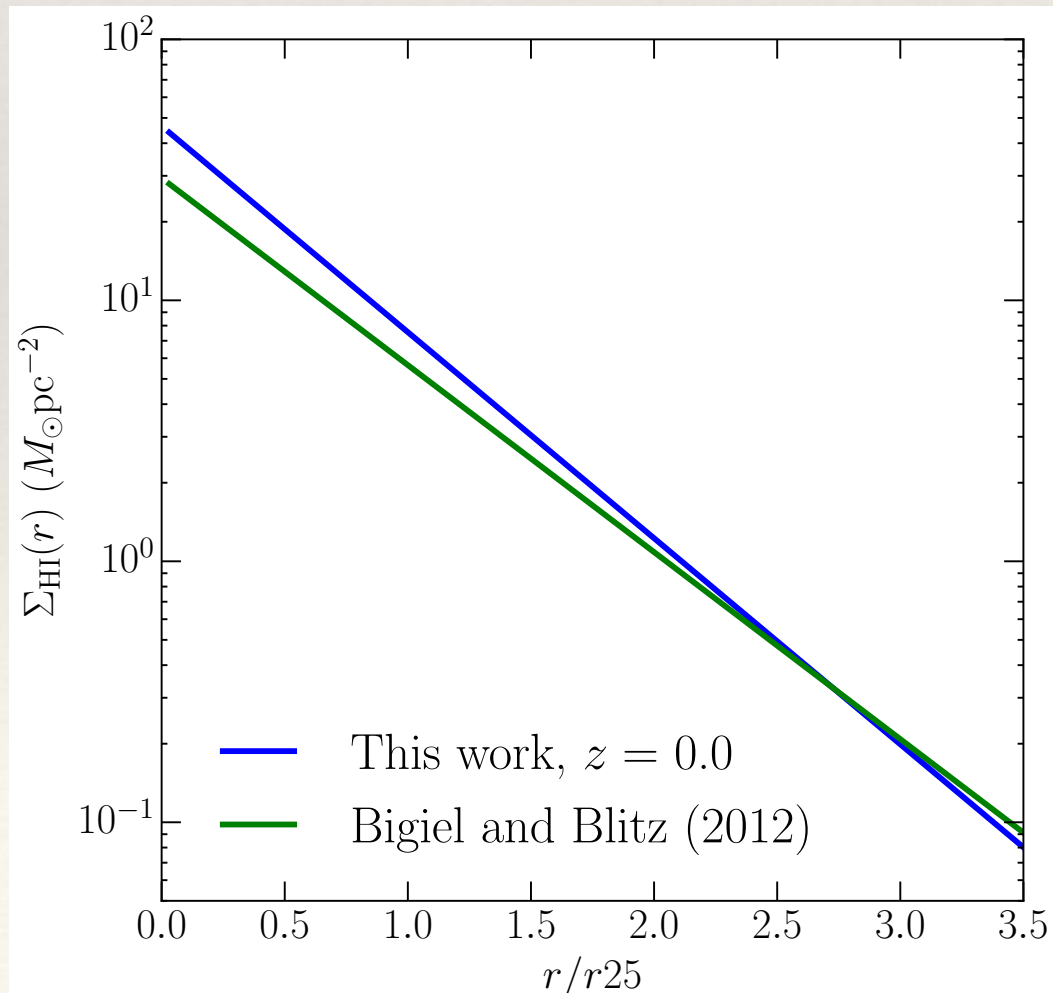
**Good match to HI-stellar relations**





# Consistency with other observations

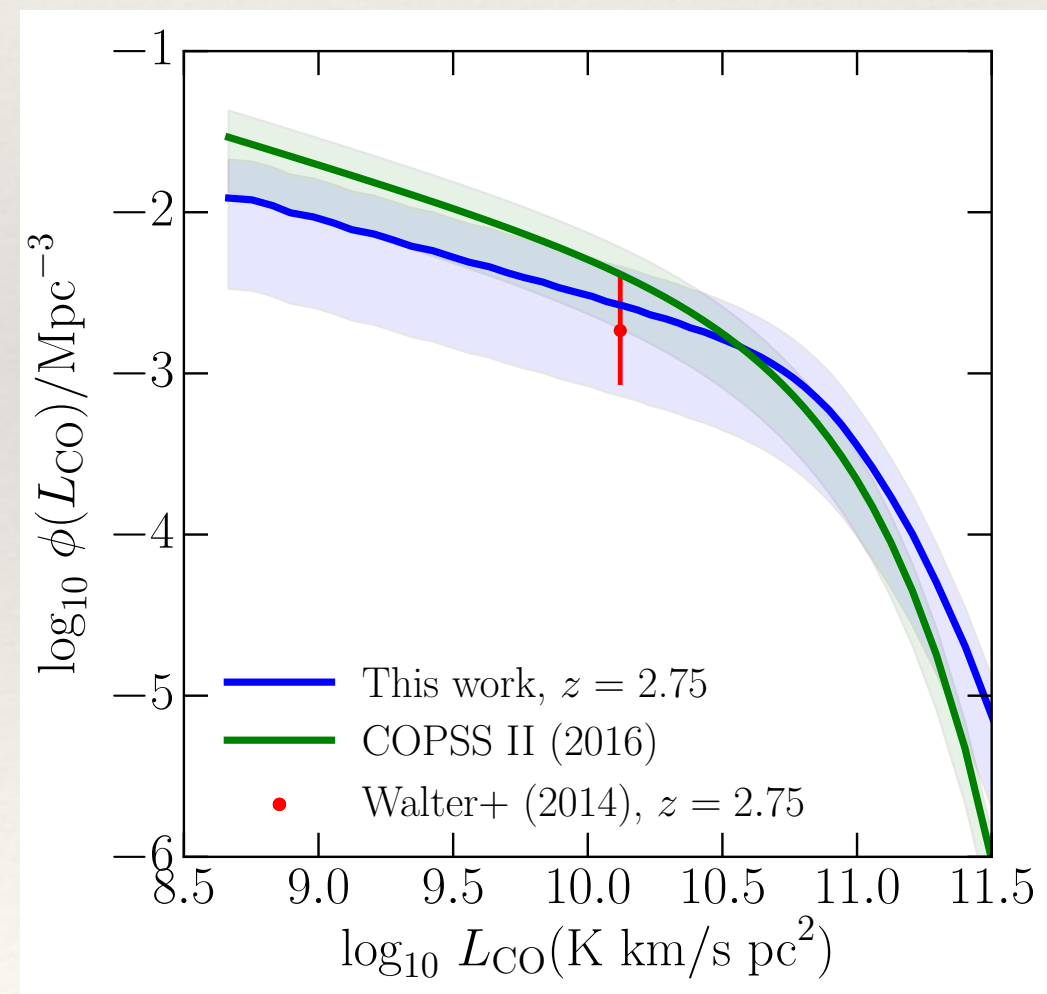
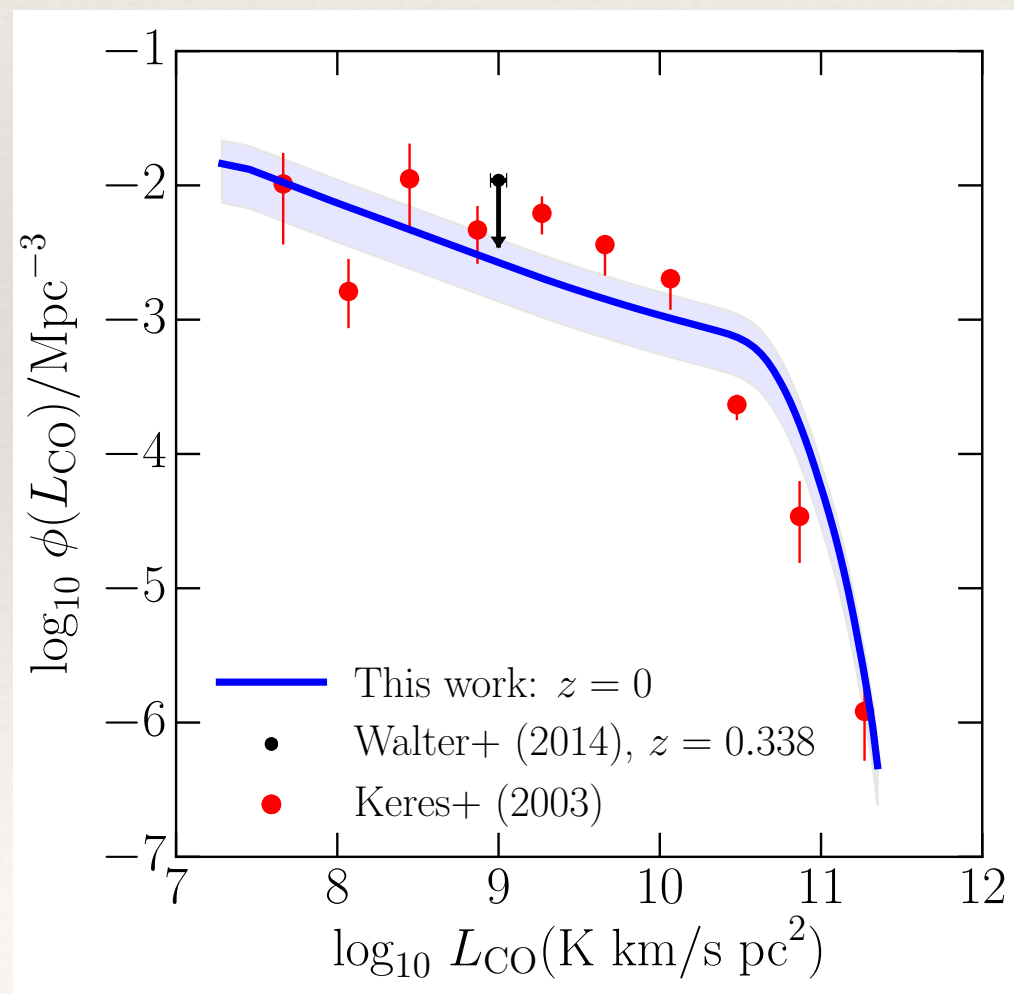
- ❖ Low-redshift observations for the HI surface density  
[Bigiel & Blitz (2012), Leroy+ (2008)]
- ❖ Anti-correlation between impact parameter - column density of DLAs  
[Rao+ (2011), Krogager+ (2012), Peroux + (2013)]
- ❖ Impact parameter - covering fractions of DLAs [Rudie+ (2012)]



# Extending the HI model to other tracers

[HP, arXiv:1706.01471]

- ❖ CO 1-0 line: Abundance matching :  $z \sim 0$  galaxy survey constraints combined with  $z \sim 3$  intensity mapping constraints  
[Keres+ (2003), Keating+ (2016)]
- ❖ Fitting forms for the evolution of the parameters

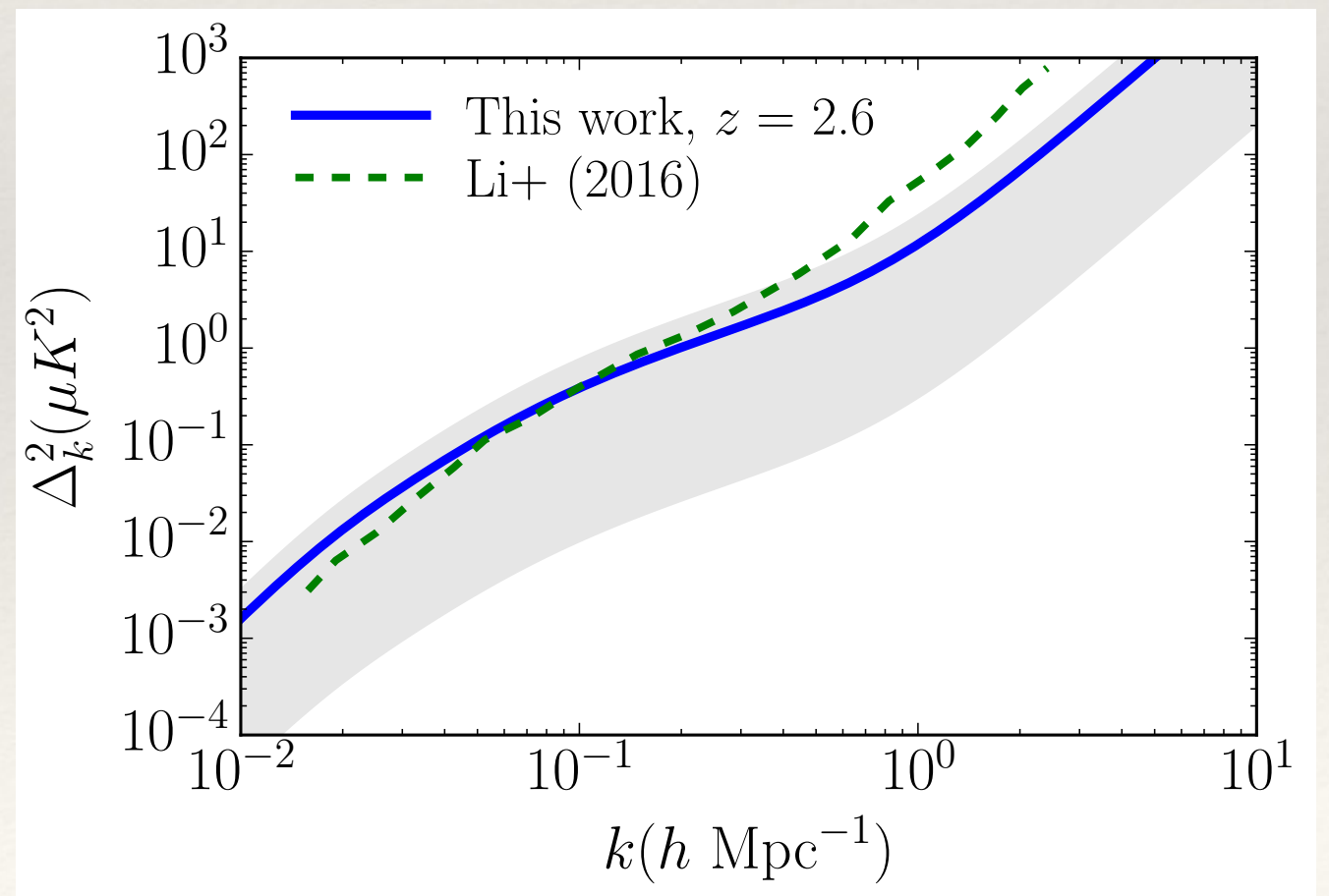
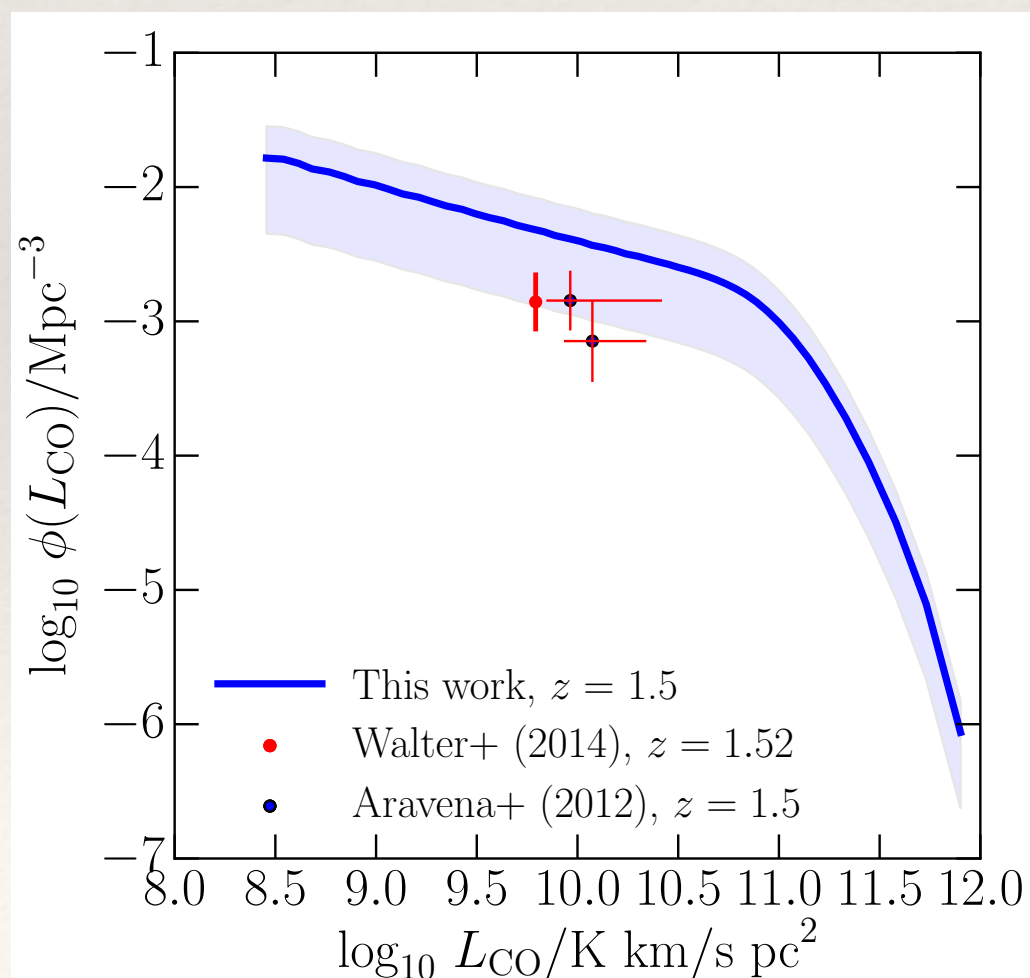




# Implications for power spectrum

[HP, arXiv:1706.01471]

- ❖ Combining current constraints leads to predictions for mean and uncertainties on the CO signal
- ❖ Consistent with results from models and simulations [Li+ (2016), Pullen+ (2013) ...]
- ❖ Consistent with CO galaxy luminosity data at  $z \sim 1.5$



***To summarize ...***



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# Conclusions and outlook

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- ❖ Built a framework for halo model of cosmological HI
- ❖ Two important ingredients : (i) HI-halo mass relation and (ii) HI profile
- ❖ Constrained well by emission line experiments, high redshift DLA data, intensity mapping data
- ❖ Best fitting HIHM and profile obtained by Bayesian analysis
- ❖ Model predictions consistent with
  - (i) abundance matching and stellar - cold gas relations
  - (ii) low-redshift observations for the HI surface density
  - (iii) Impact parameter - covering fraction results for DLAs

Extend to other species (like CO), evaluate the ‘astrophysical systematic’ for future experiments

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**THANK YOU!**