Neutral hydrogen in the post-reionization universe

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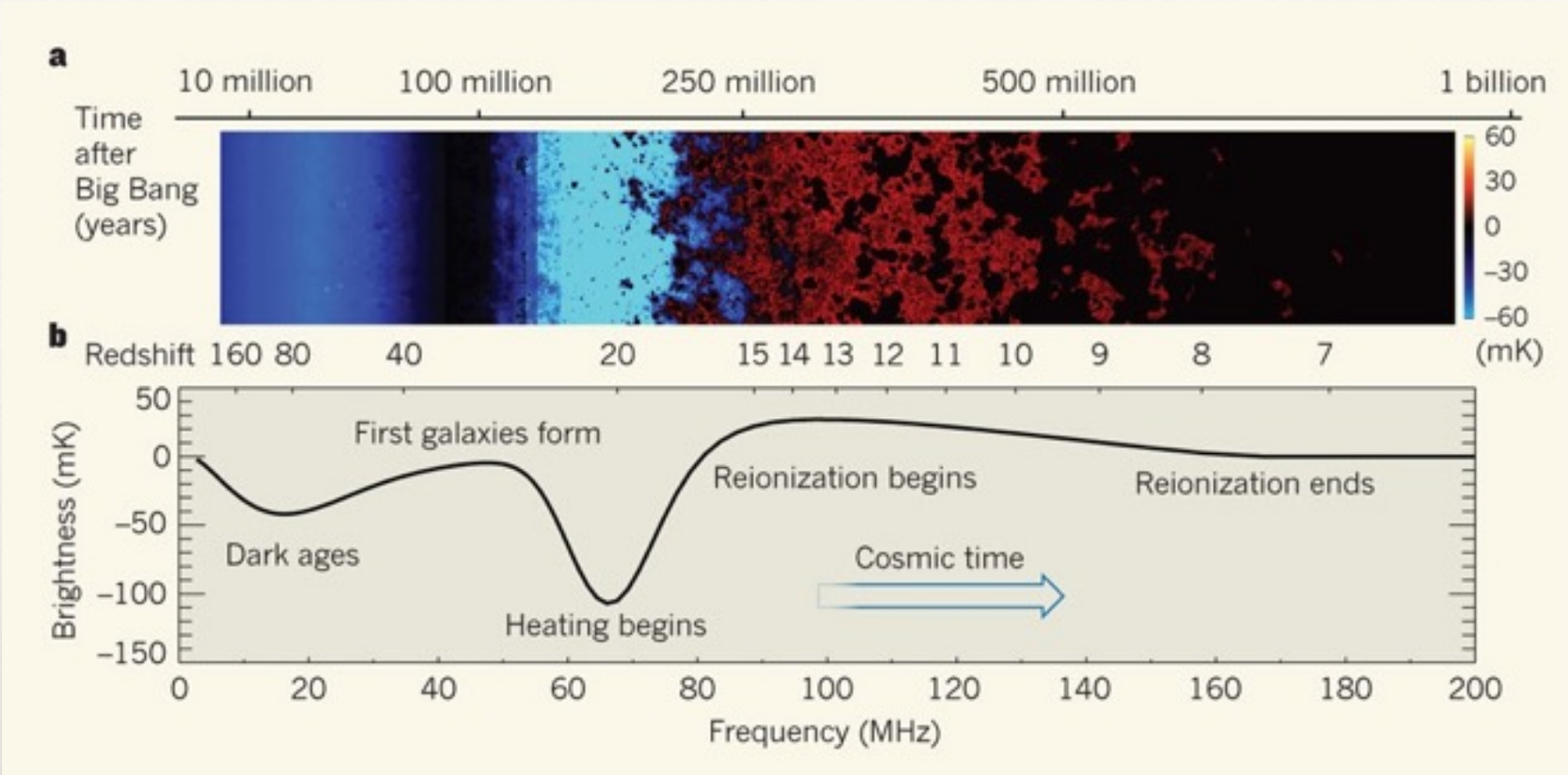
arXiv:1407.6366, 1505.00008, 1607.01021, 1608.00007, 1611.06235, 1706.01471

Across the universe in 21- cm radiation

Across the universe in 21- cm radiation



[Pritchard & Loeb (2010)]

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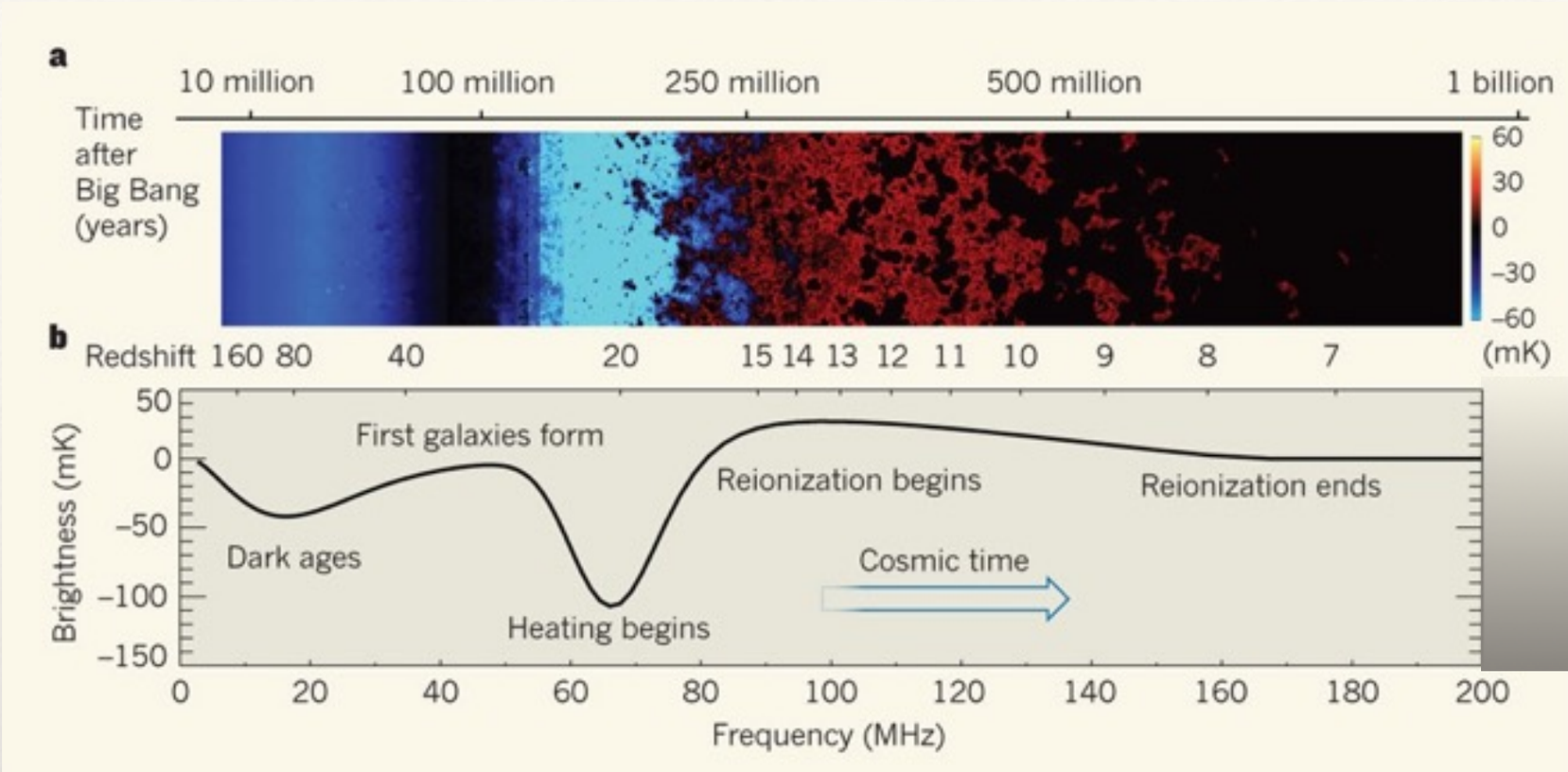


[Pritchard & Loeb (2010)]

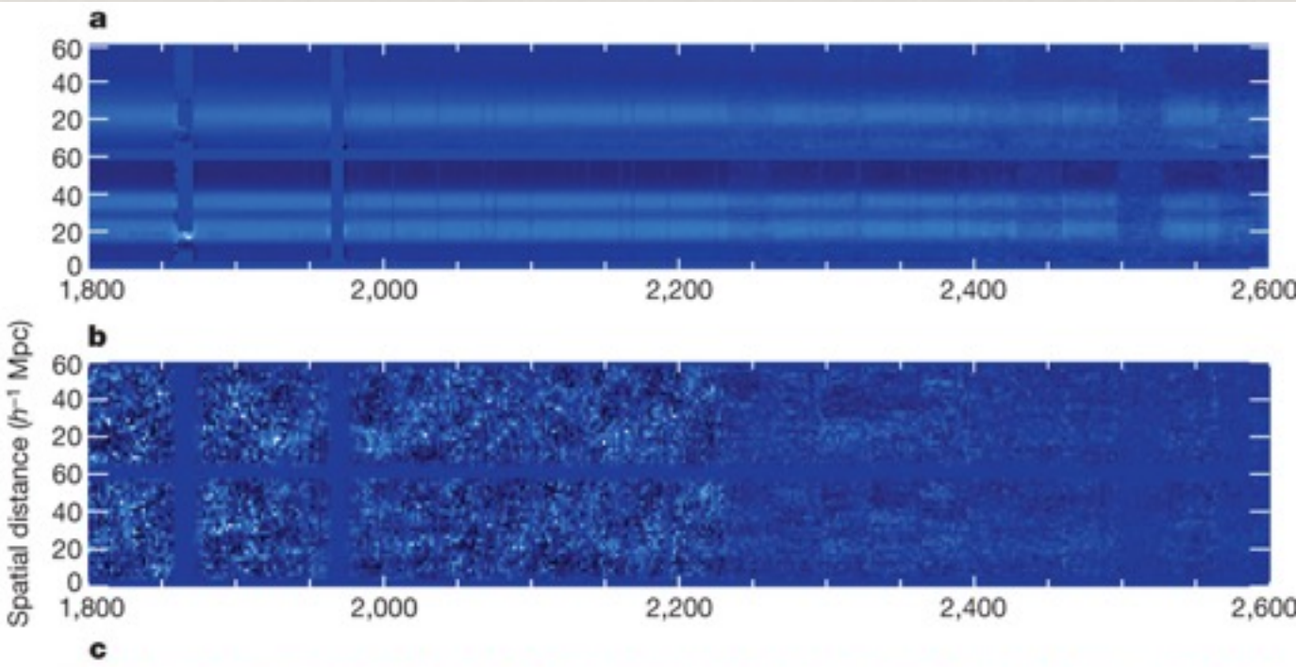
Post-reionization universe

Across the universe in 21- cm radiation

Post-reionization universe

Intensity mapping

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



Post-reionization universe: HI intensity mapping

Map distribution of HI without resolving individual galaxies

[e.g., Battye et al. (2004), McQuinn et al. (2006), Wyithe & Loeb (2008)]

Constrains neutral hydrogen density parameter and bias

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

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

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COSMOLOGY!

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ASTROPHYSICS!

The ‘astrophysical systematic’

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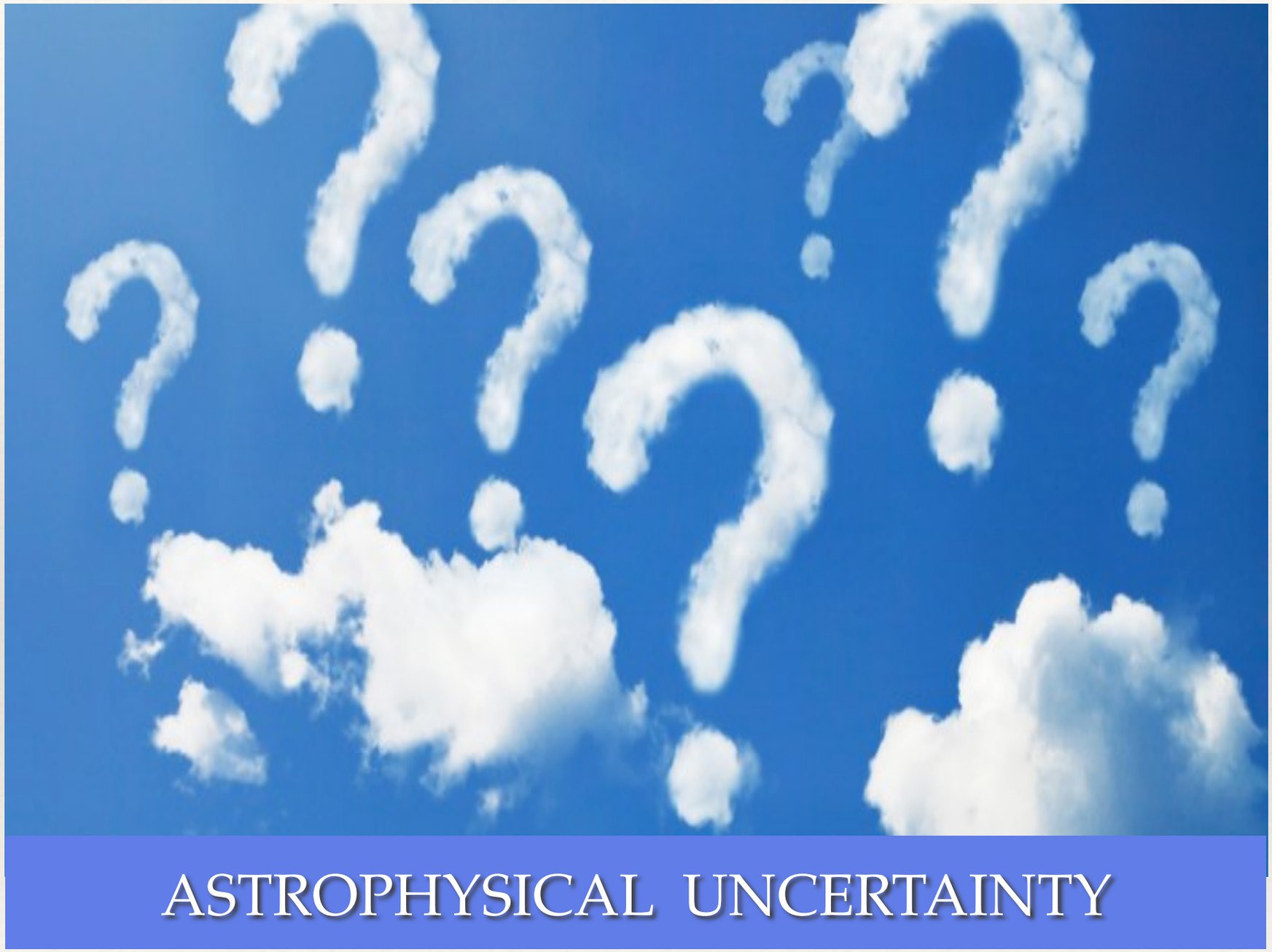

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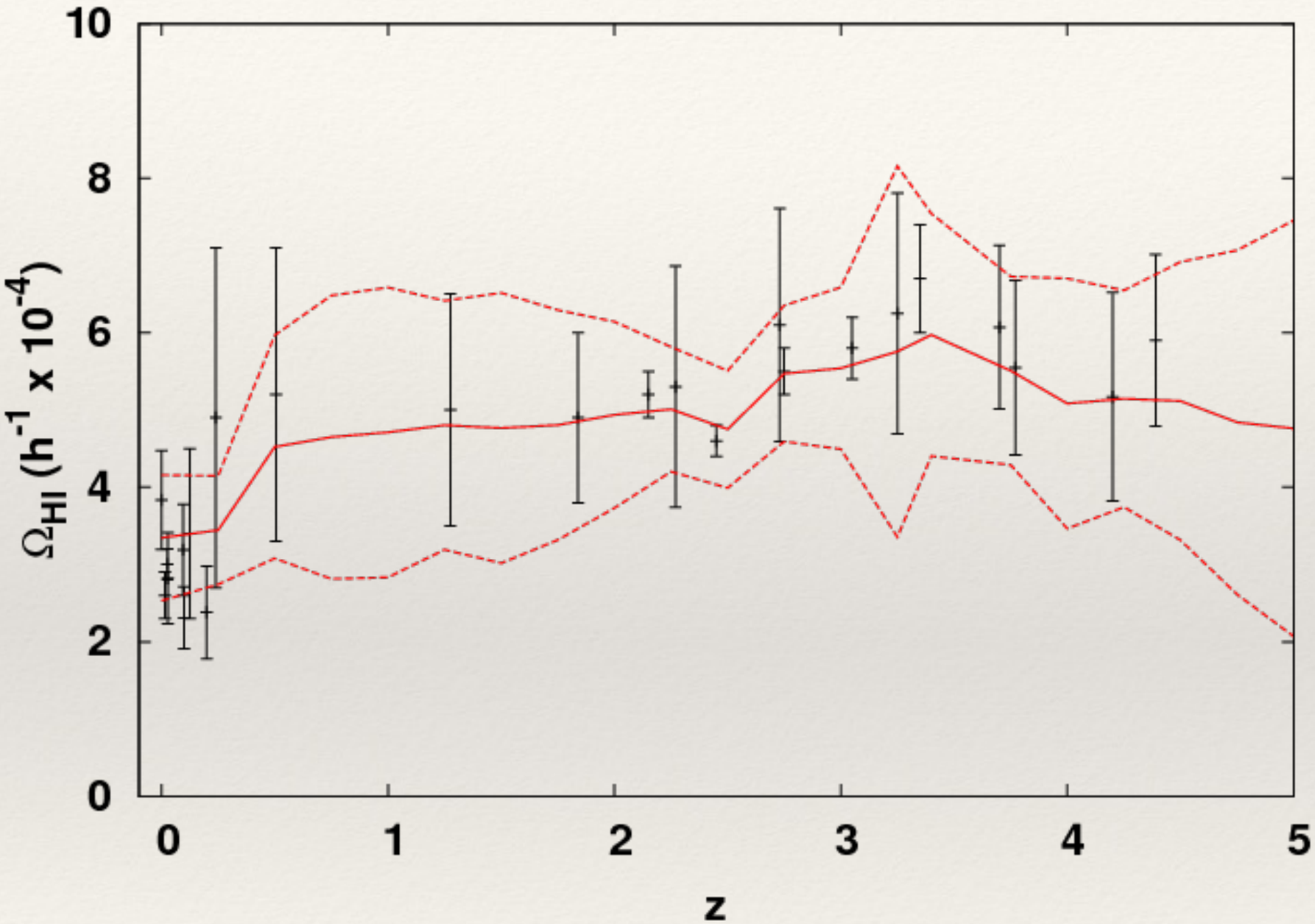


Press and Rybicki’s minimum variance “snake” estimator (1992)

Quantify uncertainty in the power spectrum

[HP, Choudhury, Refregier, MNRAS (2015)]

Predictions for (post-reionization) HI observations,

all scales including nonlinear scales

Efficiently model the astrophysics

The halo model : rationale

[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?

[c.f. Early studies: Wyithe & Brown (2010)]

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 ~ 1
[Rao+ (2006)]

z ~ 2.3 bias
[Font-Ribera+ (2012)]
z ~ 2.3 SDSS
[Noterdaeme+ (2012)]

z ~ 5
GGG survey
[Crighton+ (2015)]

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

The HI halo model

Painting neutral hydrogen on dark matter

Two HI ingredients

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

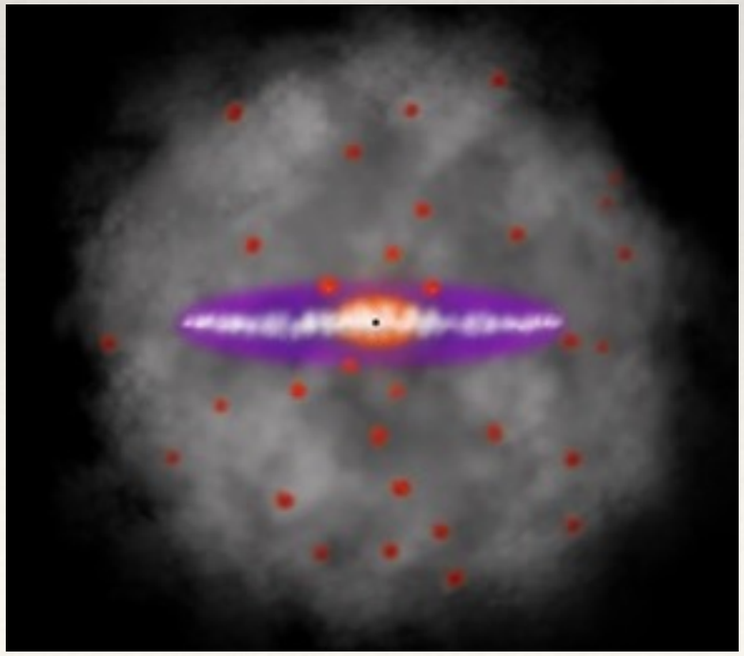
How much HI is associated with a mass M halo?

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

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

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

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:

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

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

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

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

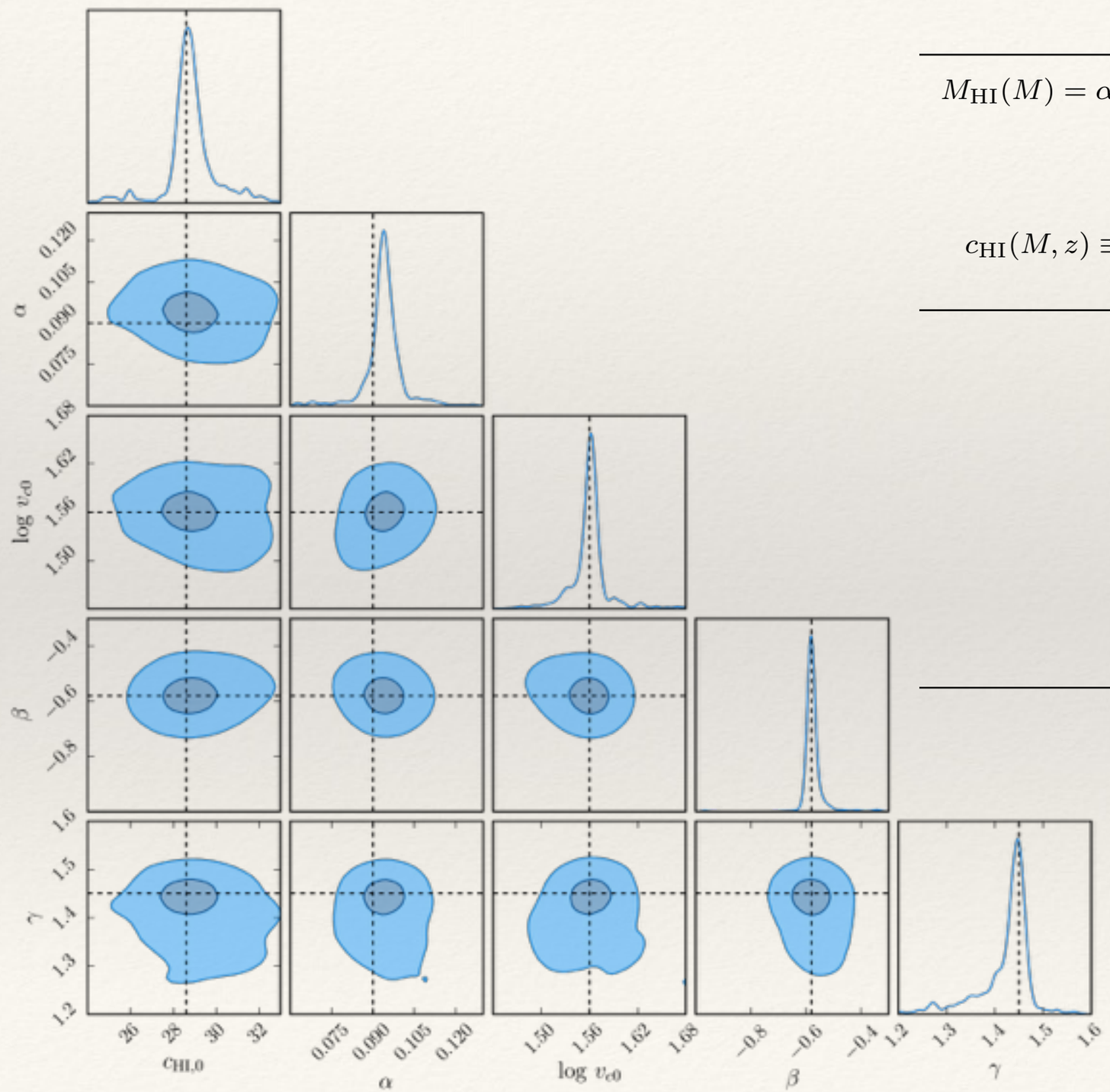
[Maccio+ (2007)]

Also considered an altered NFW profile:

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

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

Constraining the parameters : MCMC



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

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

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

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

$$\alpha = 0.09 \pm 0.01$$

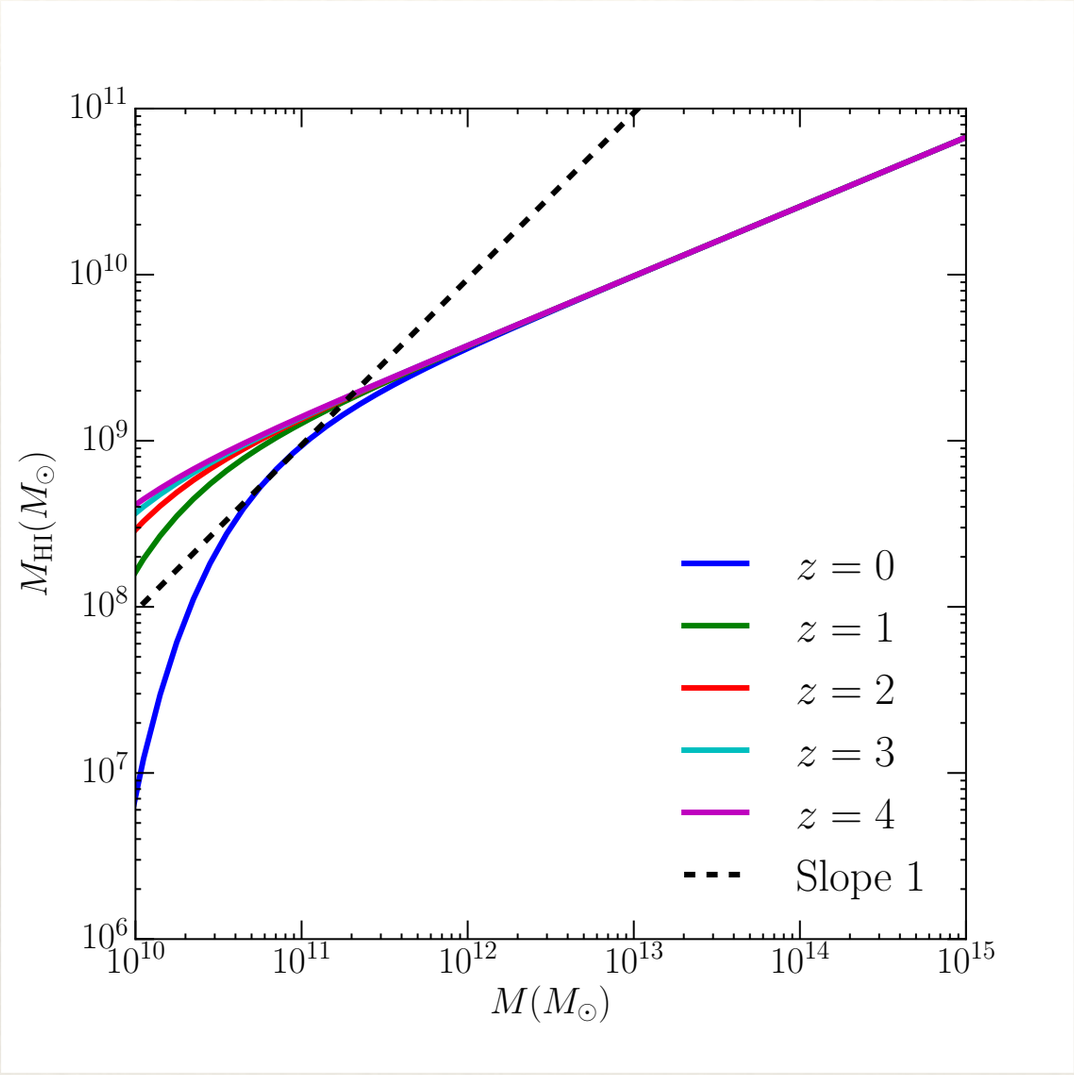
$$\log v_{c,0} = 1.56 \pm 0.04$$

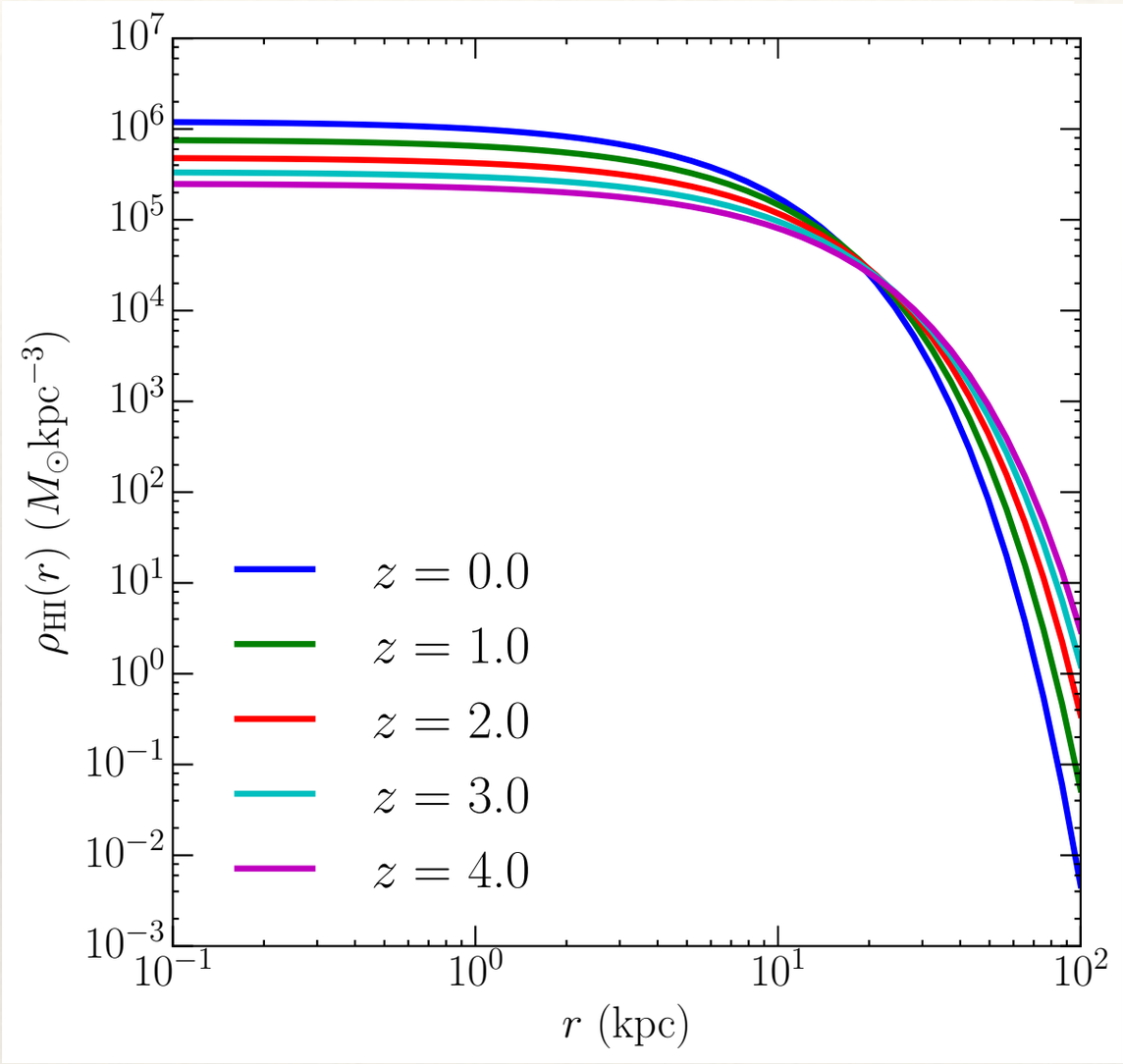
$$\beta = -0.58 \pm 0.06$$

$$\gamma = 1.45 \pm 0.04$$

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

Best fit halo model





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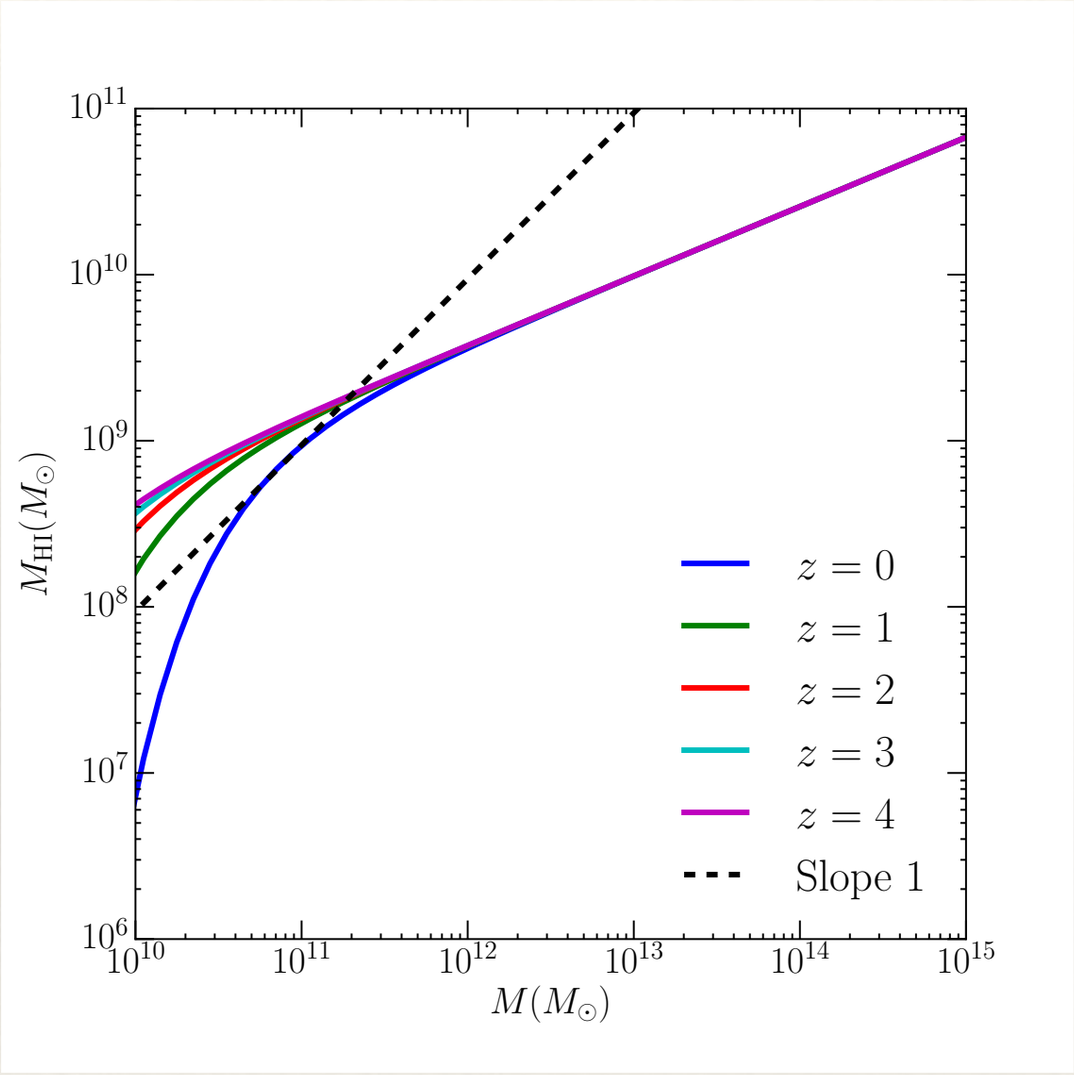
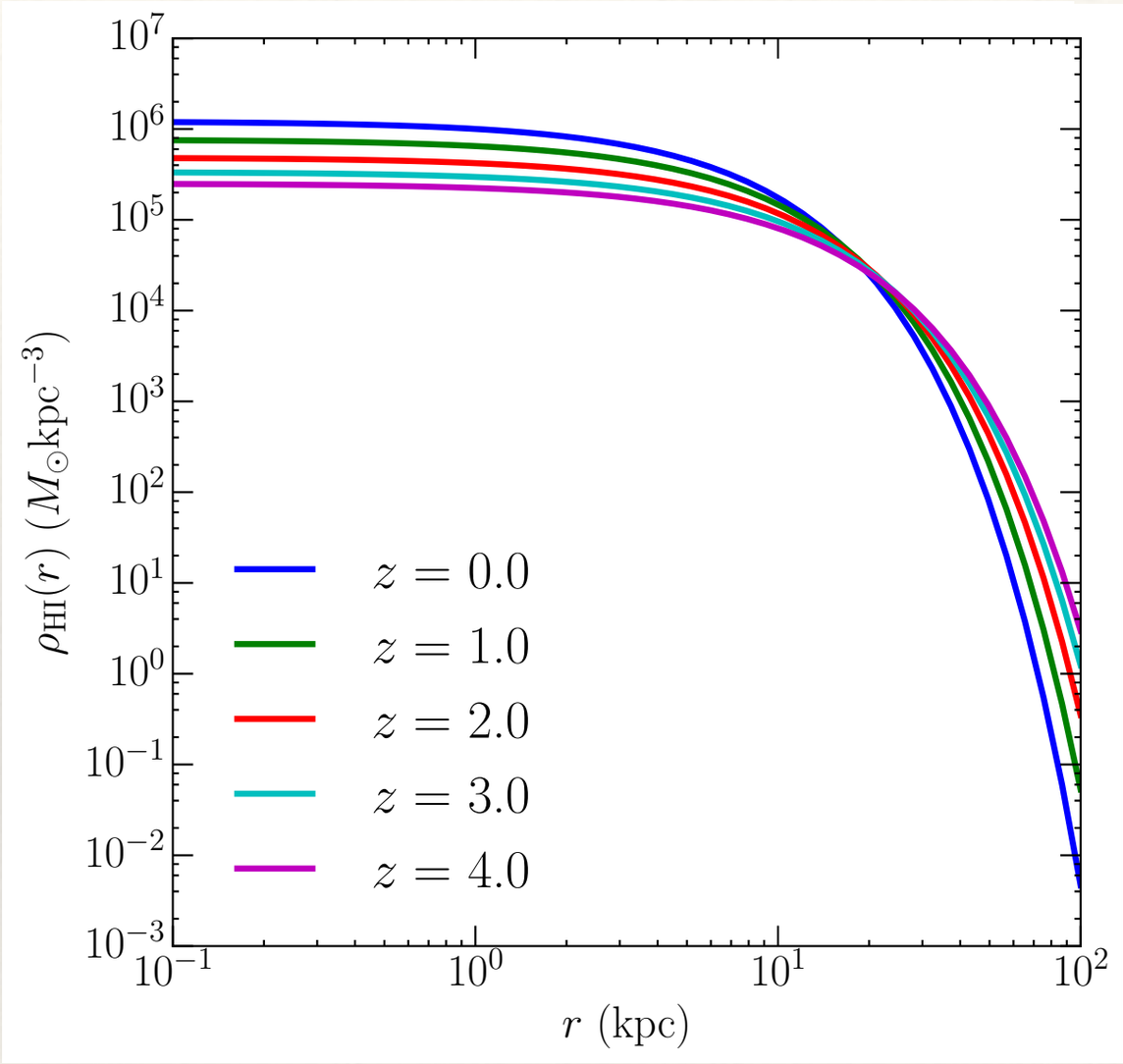




[HP, Refregier, Amara, MNRAS (2017)]

Non - unit slope, exponential profile

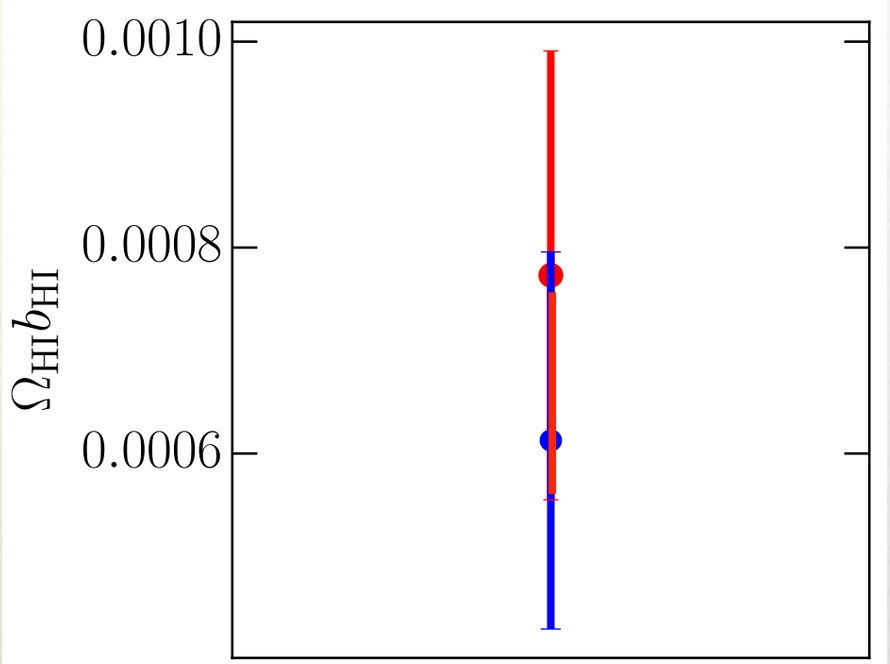
Consistent with abundance matching, stellar-cold gas relations

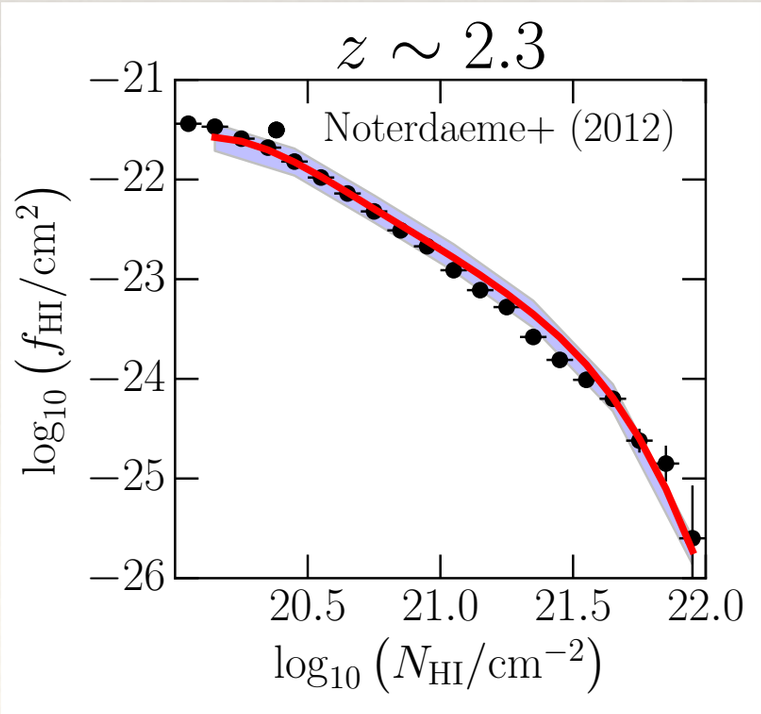
[HP & Kulkarni, MNRAS (2017)]

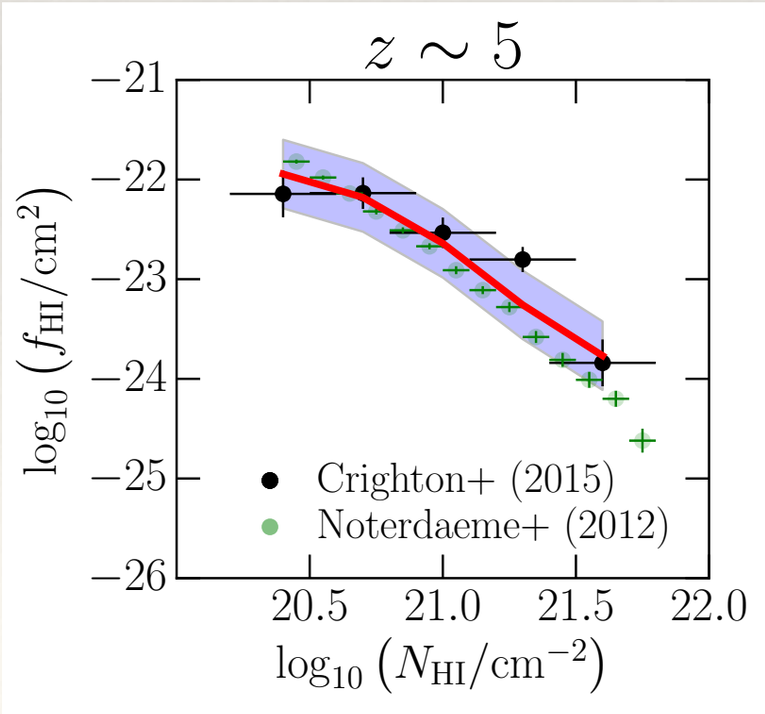
Data at various redshifts

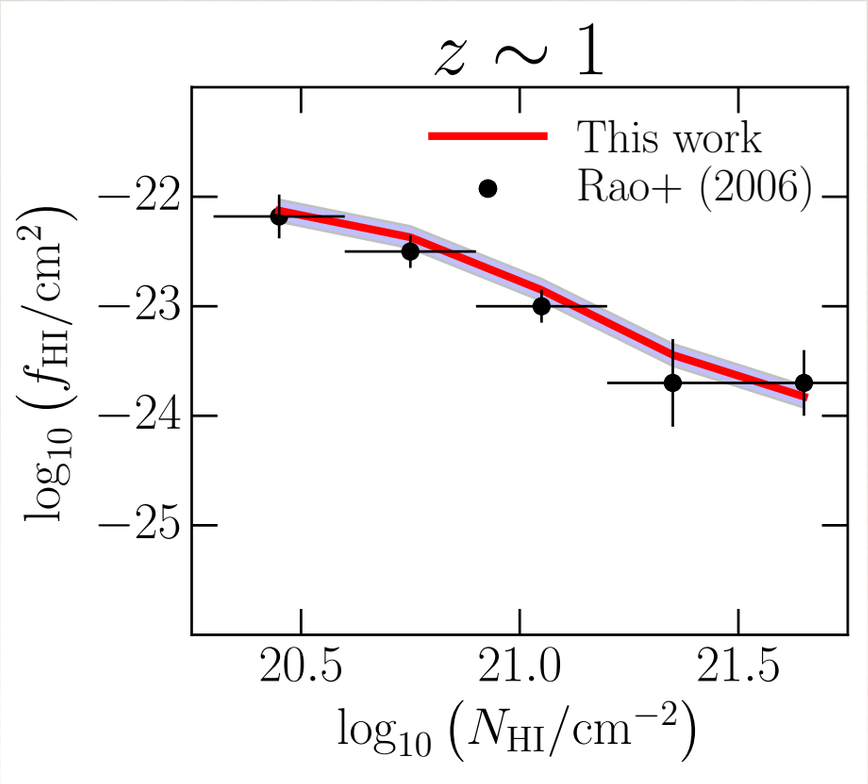
- Intensity mapping measurements with DEEP2/ GBT survey [Switzer+ (2013)]
- DLA data from GGG, SDSS surveys
- Mg II selected DLA galaxies at redshifts ~ 1 [Rao+ (2006)]

INDEPENDENT DATASETS, MATCHED WELL BY HALO MODEL









What do we learn?

Insights from the modelling

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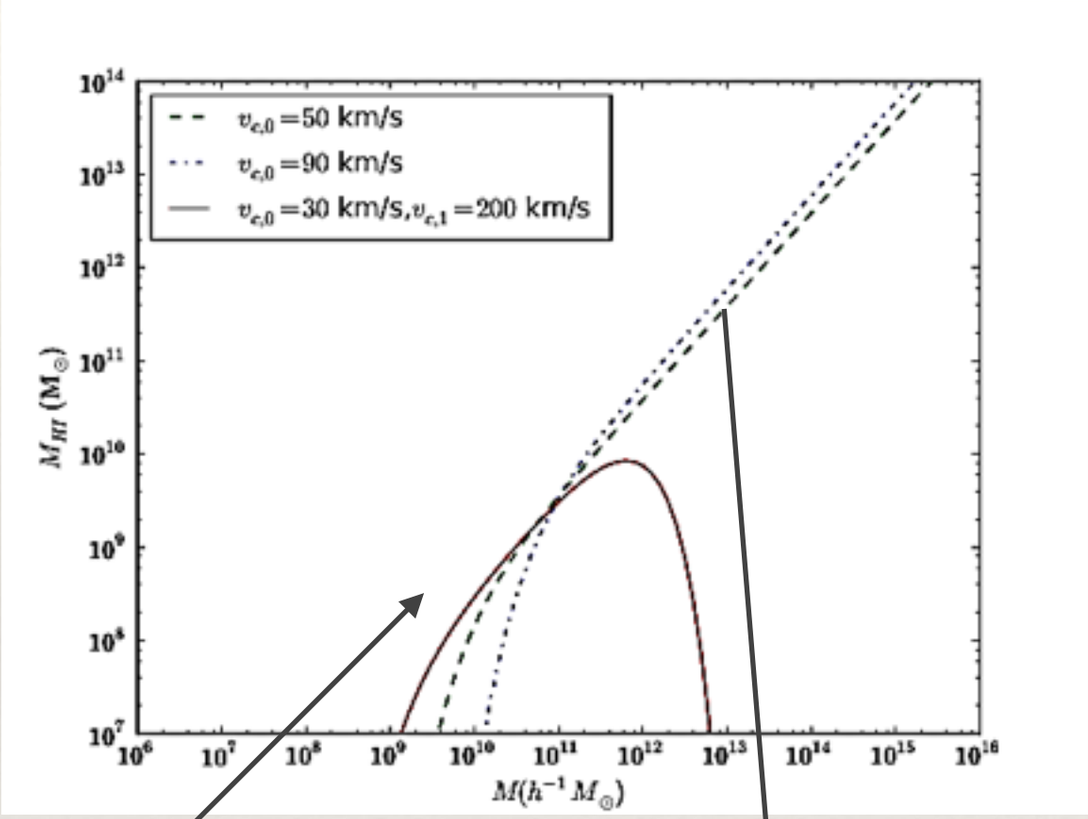
- HIHM relations adopted in the literature **[Barnes & Haehnelt 2014; Bagla + (2010)]**



21-cm based

DLA based

Insights from the modelling

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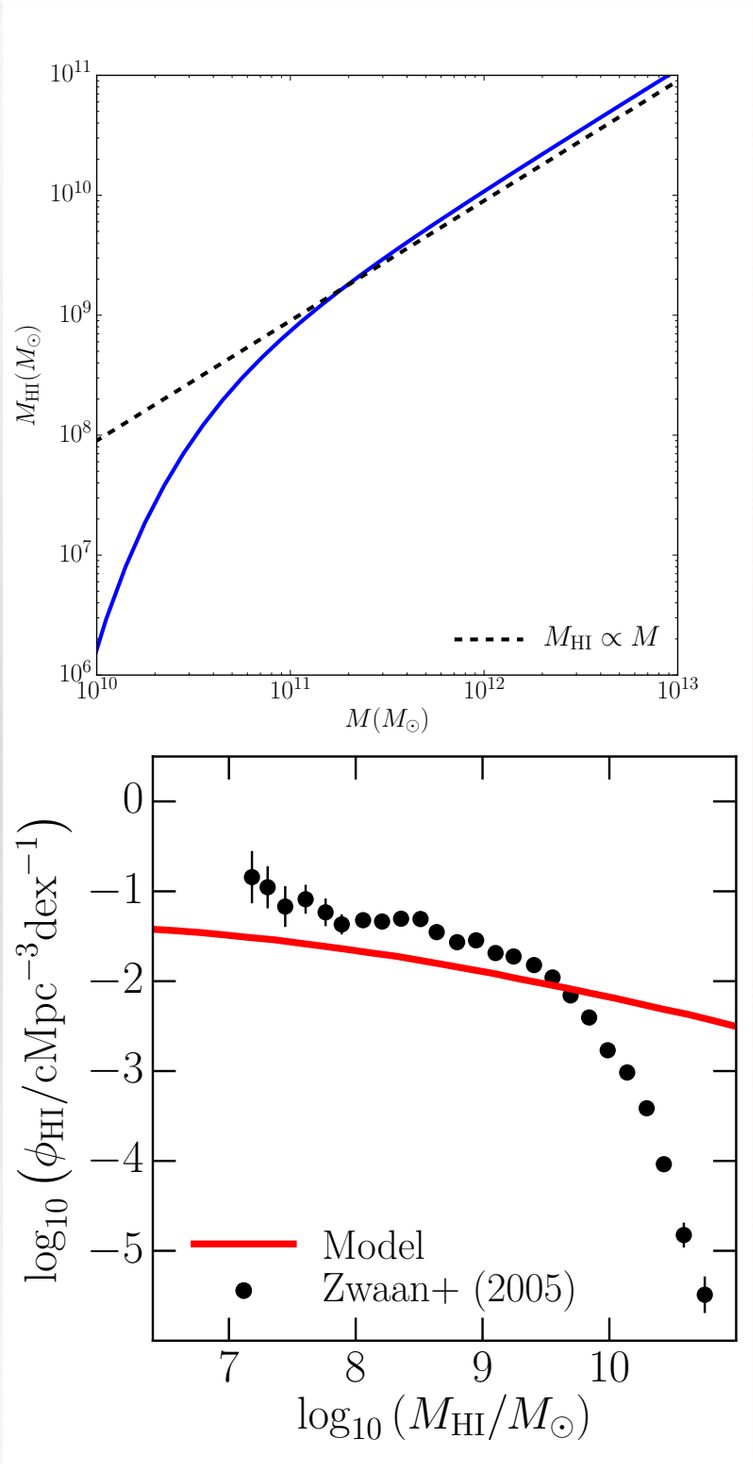
- Combining the relations **[HP, Choudhury, Refregier, MNRAS (2016)]**
  does not fit HI mass function well



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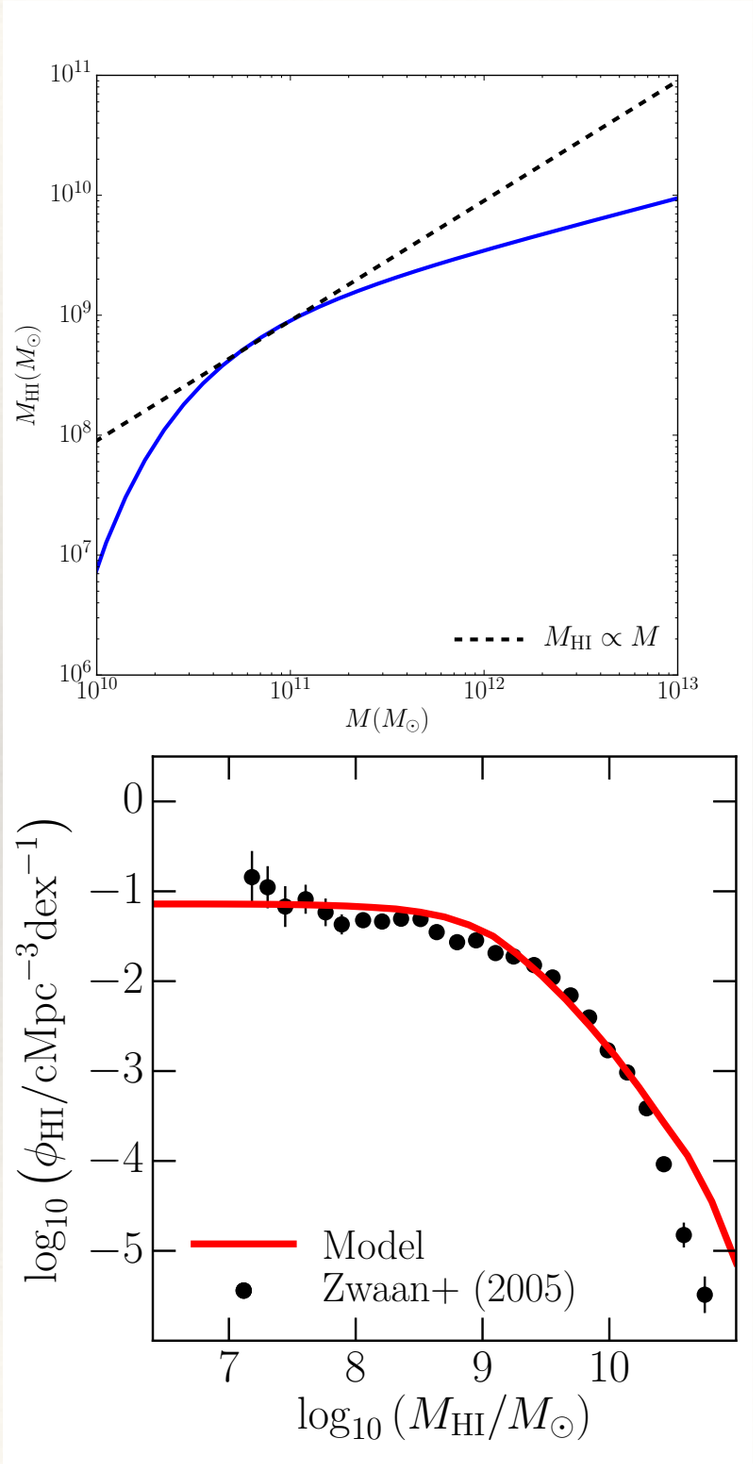
- Fitting the mass function requires a ***non-unit slope*** of HIHM **[HP & Refregier, MNRAS (2017)]**



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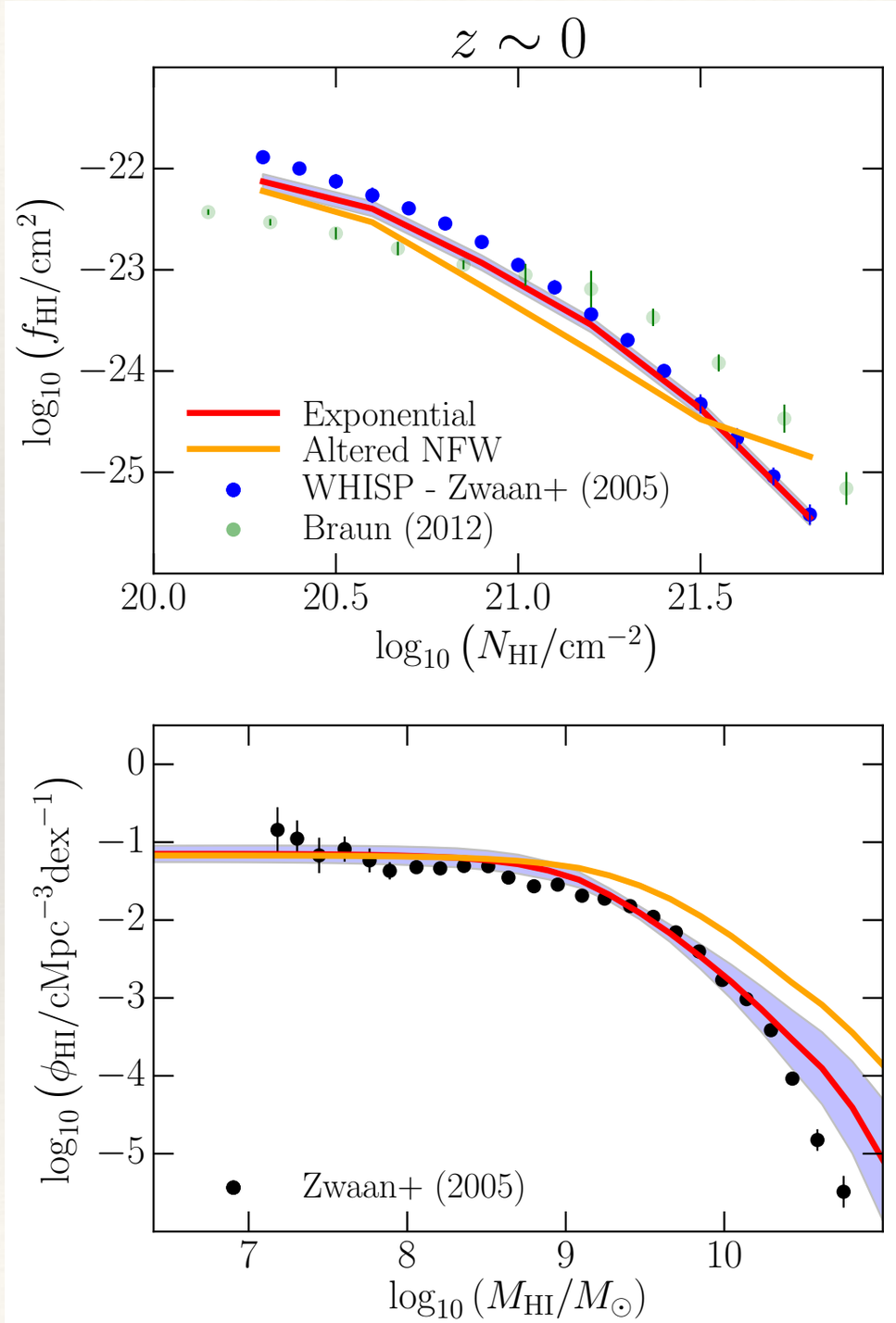
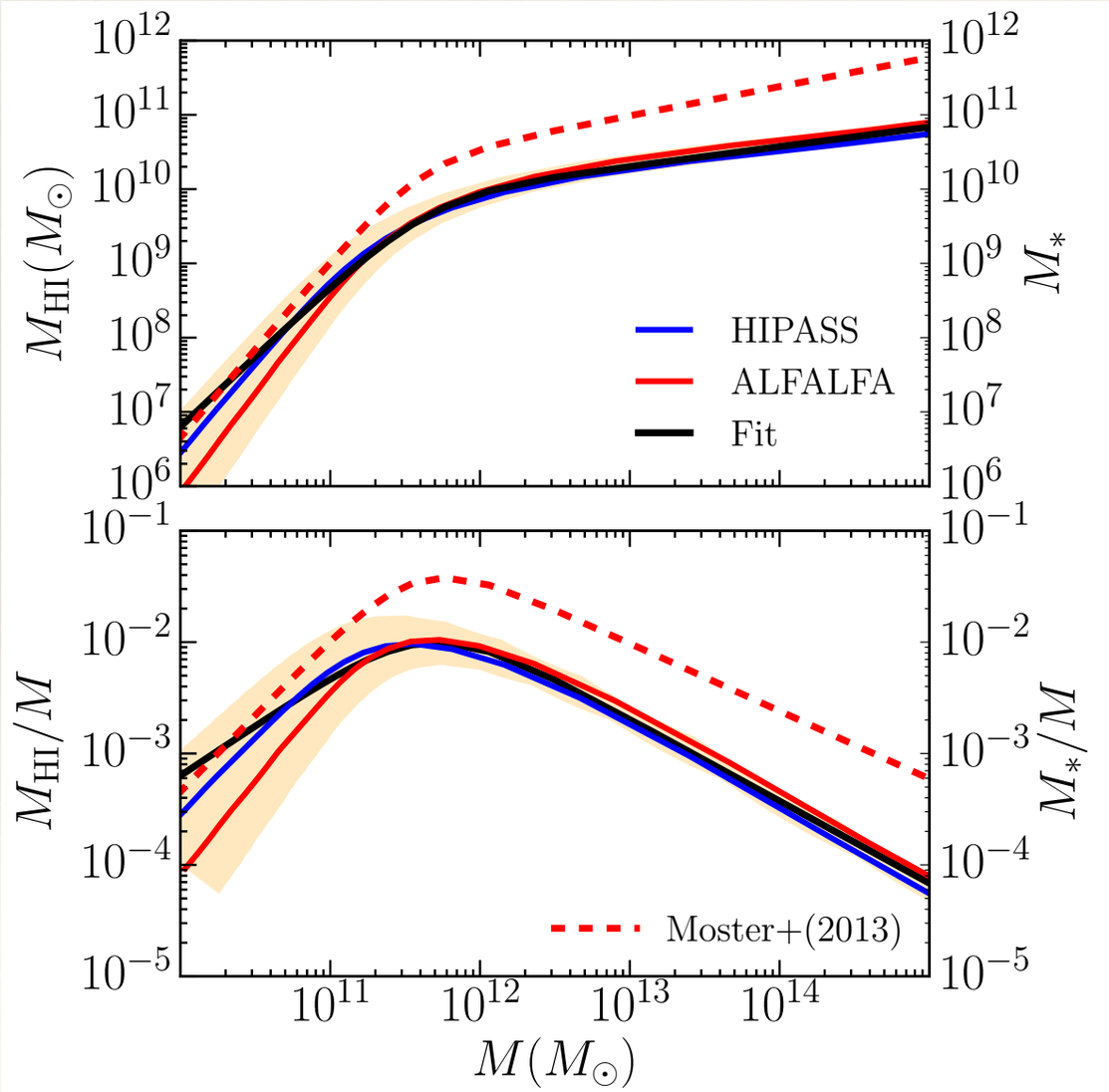
- Fitting the mass function requires a ***non-unit slope*** of HIHM **[HP & Refregier, MNRAS (2017)]**
- An ***exponential profile*** reduces previously observed tension between the HIHM and the column density **[HP, Refregier, Amara, MNRAS (2017)]**



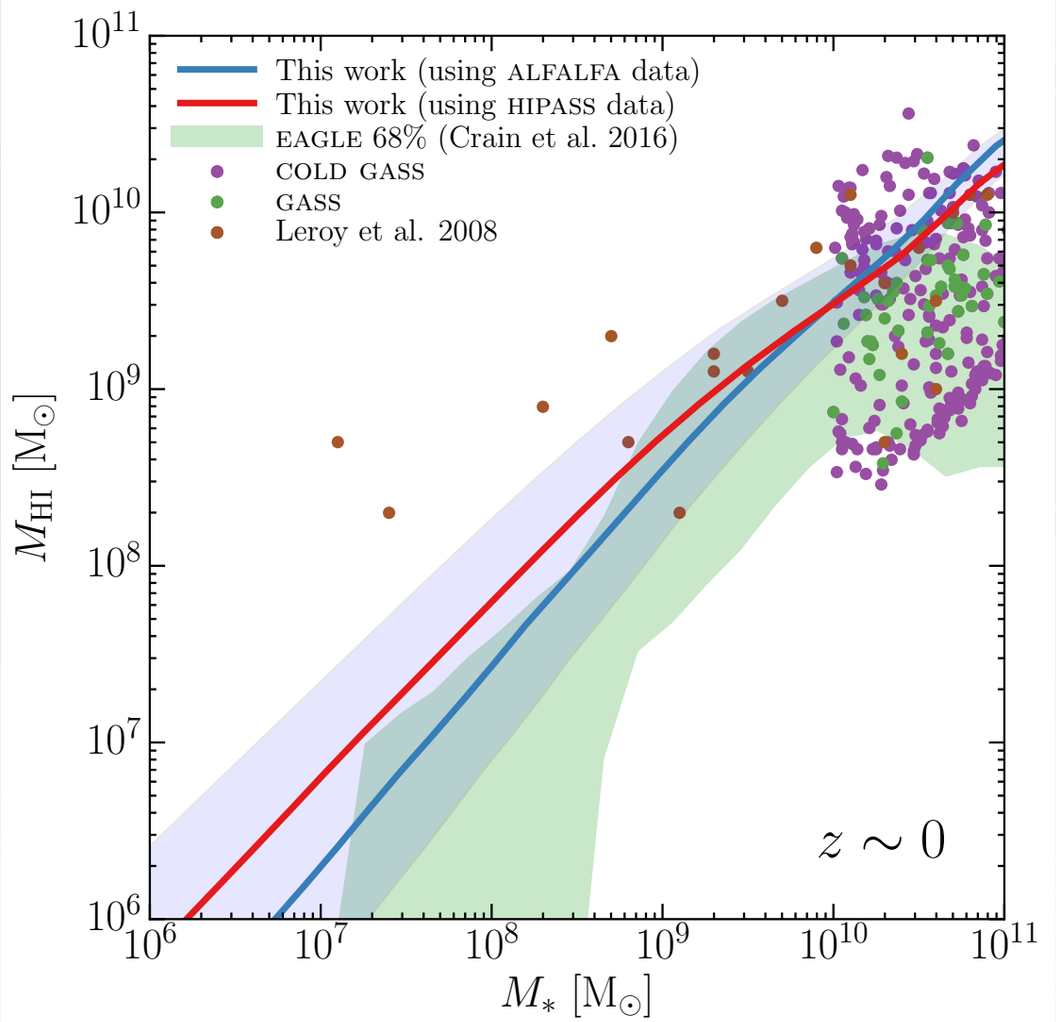
Reverse engineering …

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

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

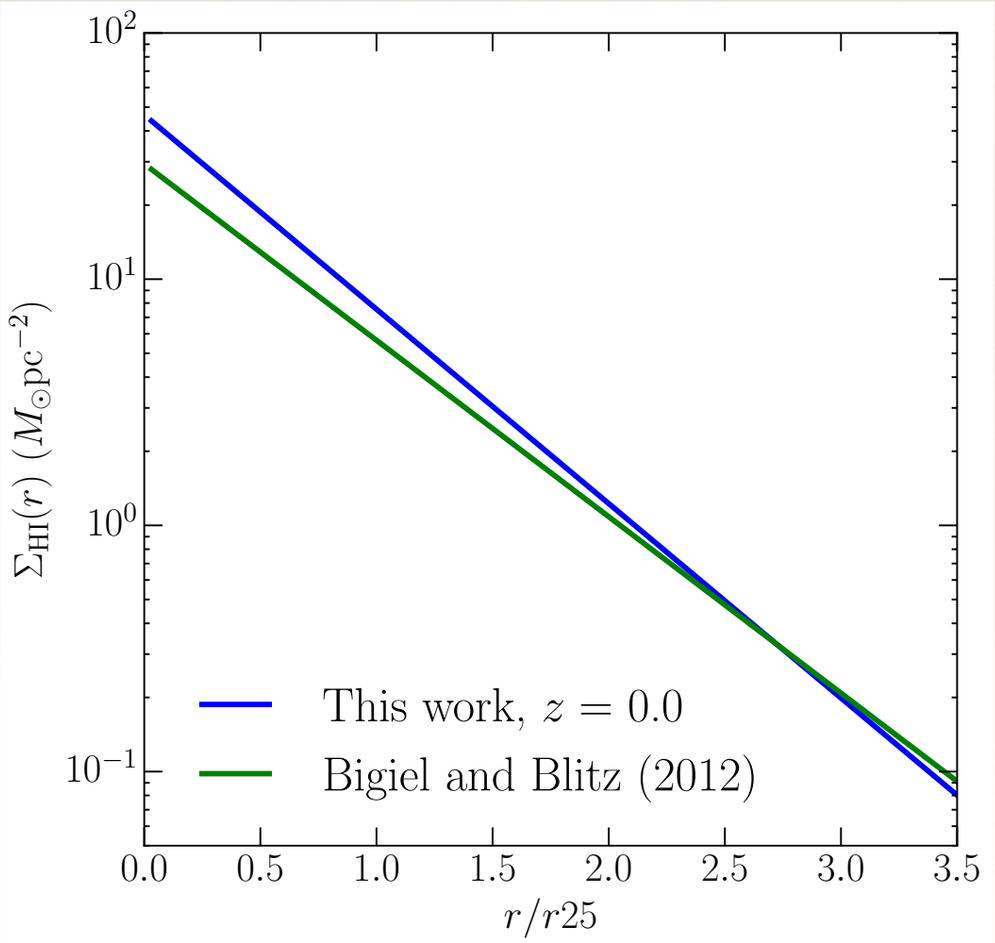


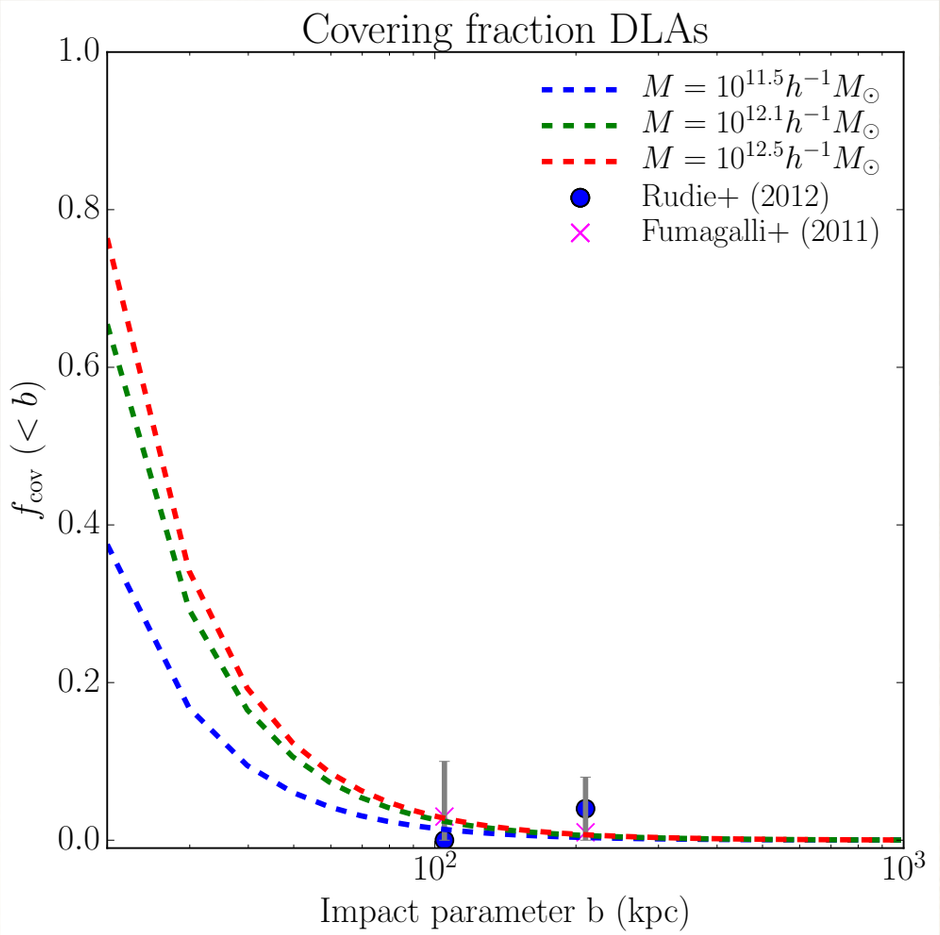
Good match to HI-stellar relations



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)]**

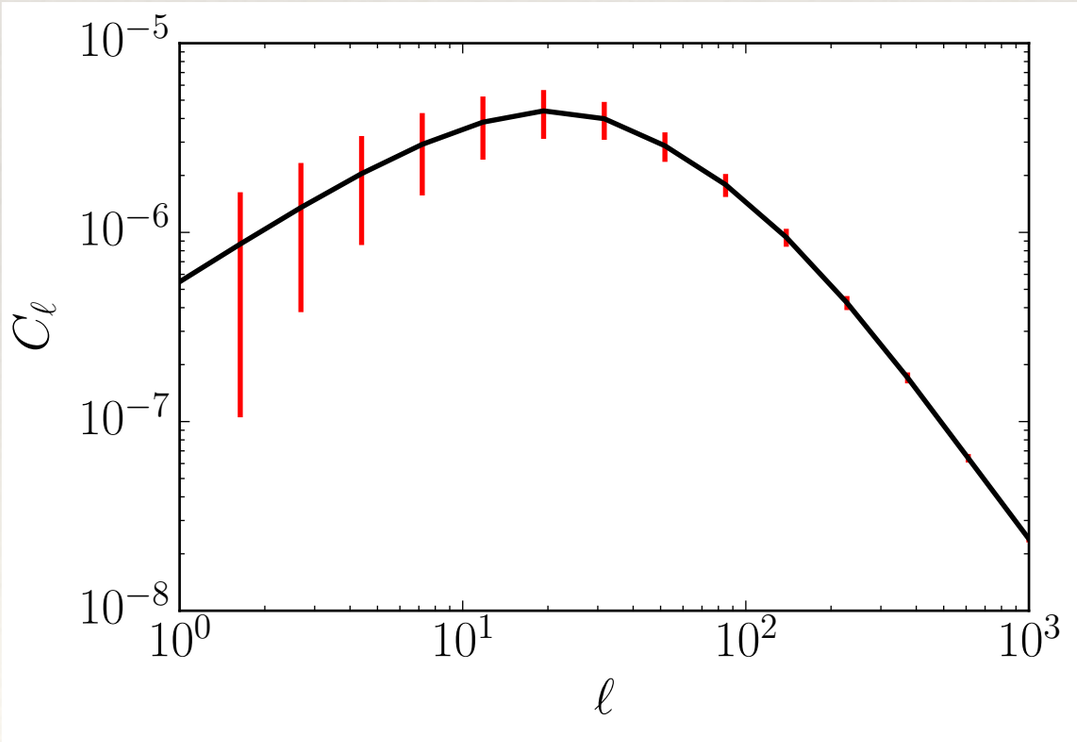




PRELIMINARY

Forecasting

- Observed angular power spectrum constraining cosmological parameters
- Explored degradation with the astrophysics - SKA 1 MID, z ~ 0.35, 1 Ghz, observing time 1 year with frequency interval 1 Mhz over 25000 sq. deg
- Fisher and MCMC forecasts quantitatively similar



$$\Delta C_\ell = \left(\frac{2}{2\ell+1}\right)(f_{\rm sky}\Delta\ell)^{-1/2}\,(C_\ell + N)$$

$$N = \left(\frac{\Delta T_{\rm pix}}{\bar{T}}\right)^2 \Omega_{\rm pix} W_\ell^{-1}$$

$$W_\ell = \exp -\ell^2\sigma^2_{\rm beam}\,;\;\; T_{\rm sys} = T_{\rm inst} + T_{\rm sky}$$

2 astrophysical and 2 cosmological parameters

PRELIMINARY

Forecasting

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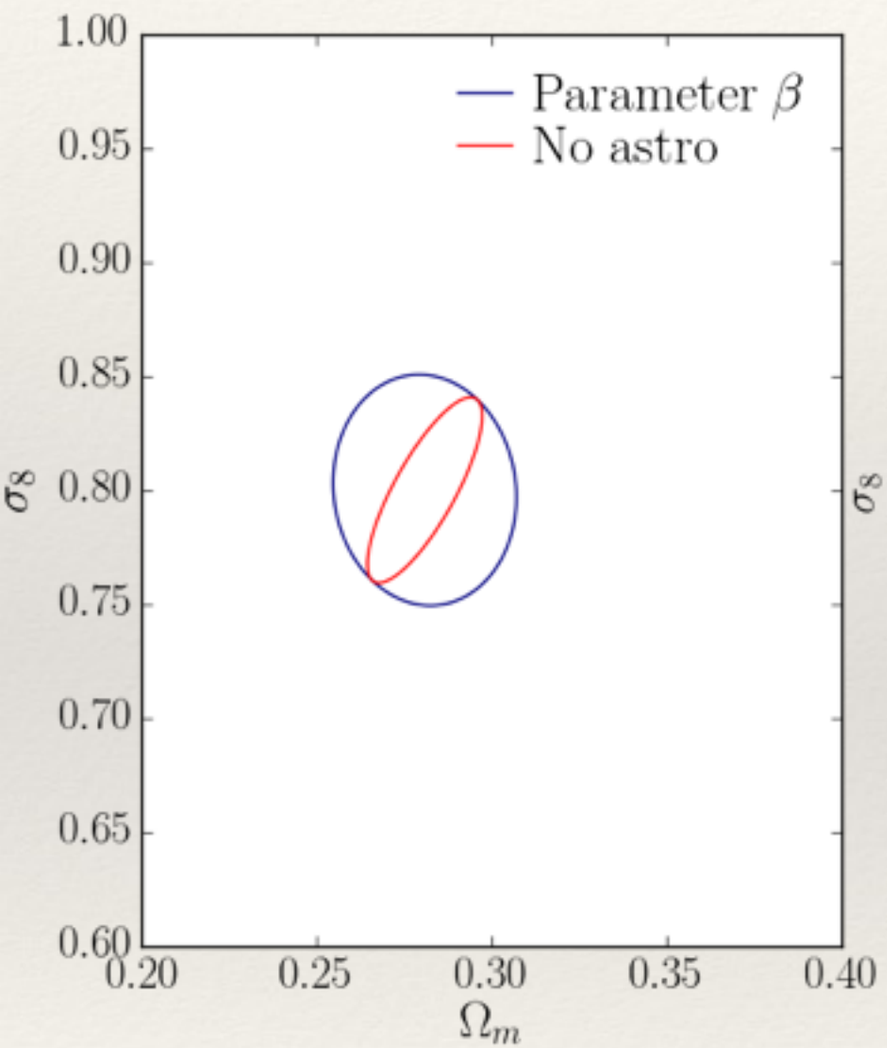
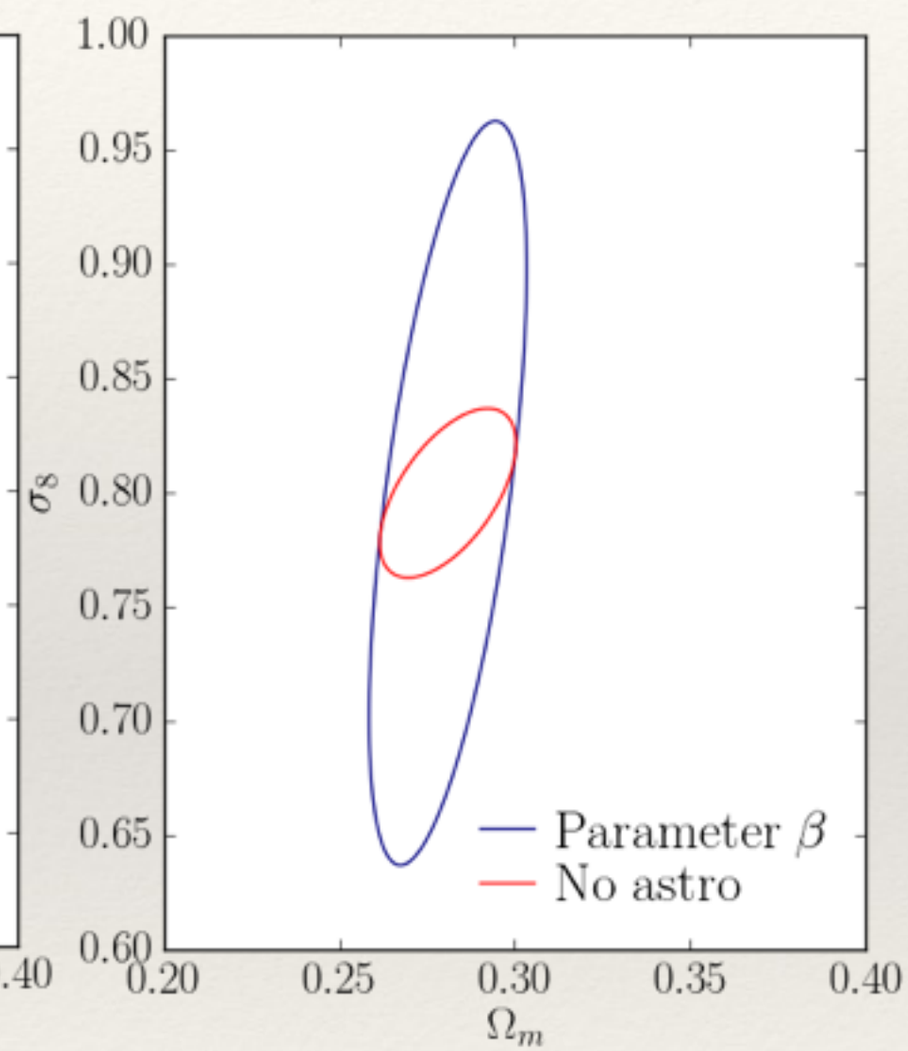
Forecasting



z = 0.1

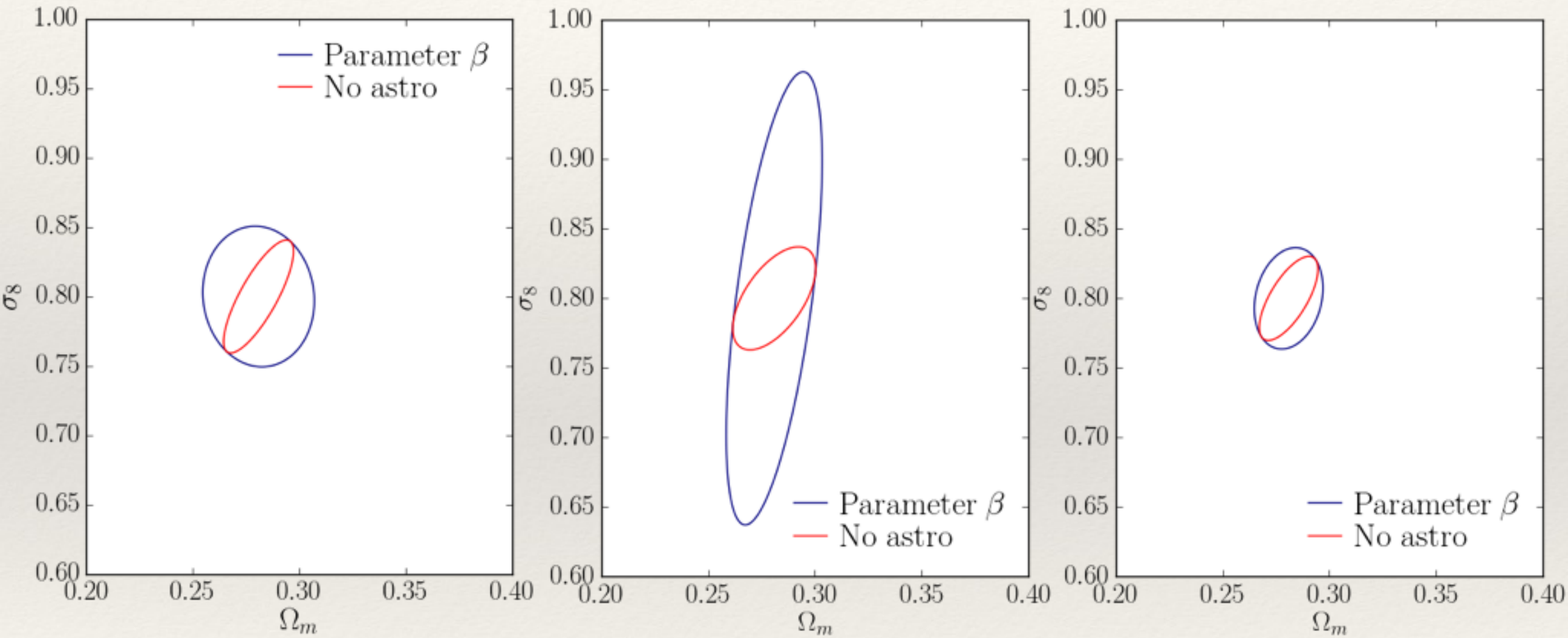


z = 0.35

Astrophysical degradation …

PRELIMINARY

Forecasting



z = 0.1 z = 0.35 Combined

Astrophysical degradation … **alleviated by tomography**

Outlook for the cosmic dawn

- Astrophysical ‘systematic’ expected to be much larger at these epochs
- Combination of analytical techniques and simulations of low-density systems
- Prospects for astrophysical separation

[c.f. Fundamental Physics with the SKA chapter on Cosmic Dawn and Reionization, HP, Jonathan Pritchard et al.]

- Opportunities for multi-tracer cosmology
- CO Mapping Array Pathfinder (COMAP)
- Halo model of CO 1-0 line [at 26-34 GHz, component of CO 2-1 from z ~ 6-8 (EoR!)]

[HP, arXiv:1706.01471]

To summarize ...

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

  Implications for the cosmic dawn: separation of astrophysical effects? + multi-tracer synergies

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THANK YOU!