Modeling the mass distribution of neutral Hydrogen in dark matter halos.

APPLICATIONS OF QUANTUM INFORMATION IN ASTROPHYSICS AND COSMOLOGY
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Outline

1. Introduction

- Why are neutral Hydrogen (HI) studies important in Cosmology?

2. Motivation and Objectives

- Improve on Cunnington et al. (2023) Ω_{HI} constraints.
- Model the HI distribution in dark matter halos from **REAL DATA.**

3. Data

- MeerKAT
- WiggleZ

4. Theory

- Galaxy-HI cross-power and halo occupation distribution (HOD) modeling.

Outline

5. Methodology

- Fitting cross-power and Ω_{HI} with HI HOD modelling.

6. Results (PRELIMINARY!)

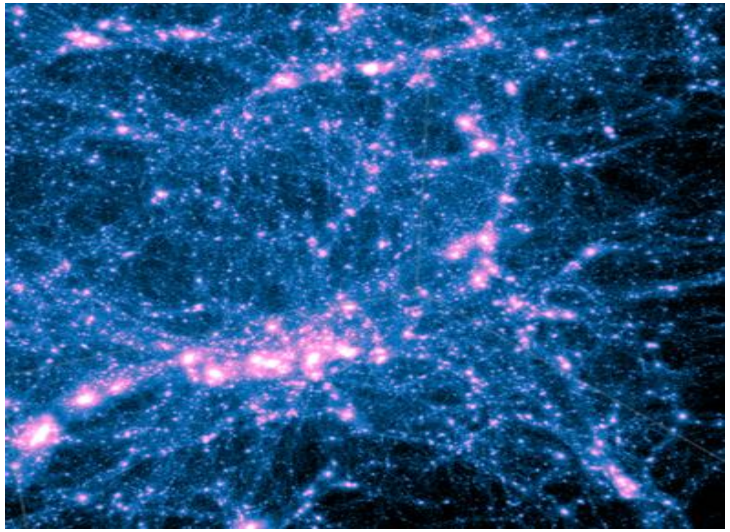
- HI HOD
- Galaxy-HI cross-power
- Ω_{HI}, b_{HI} and $\bar{T}_{HI}$.
- Posterior distribution.

7. Summary

8. Future work

1.1 Neutral Hydrogen (HI)

Abundant and universal:
→ Good tracer
→ Early processes, e.g. re-ionization epoch
→ Large-scale structure (LSS)

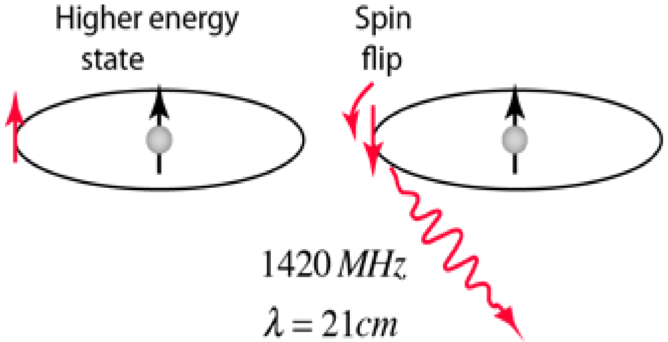


Cosmic environments and their influence in star formation – Astronomy at the University of California – Riverside (ucr.edu)

Star Formation:
→ Galaxy formation and evolution

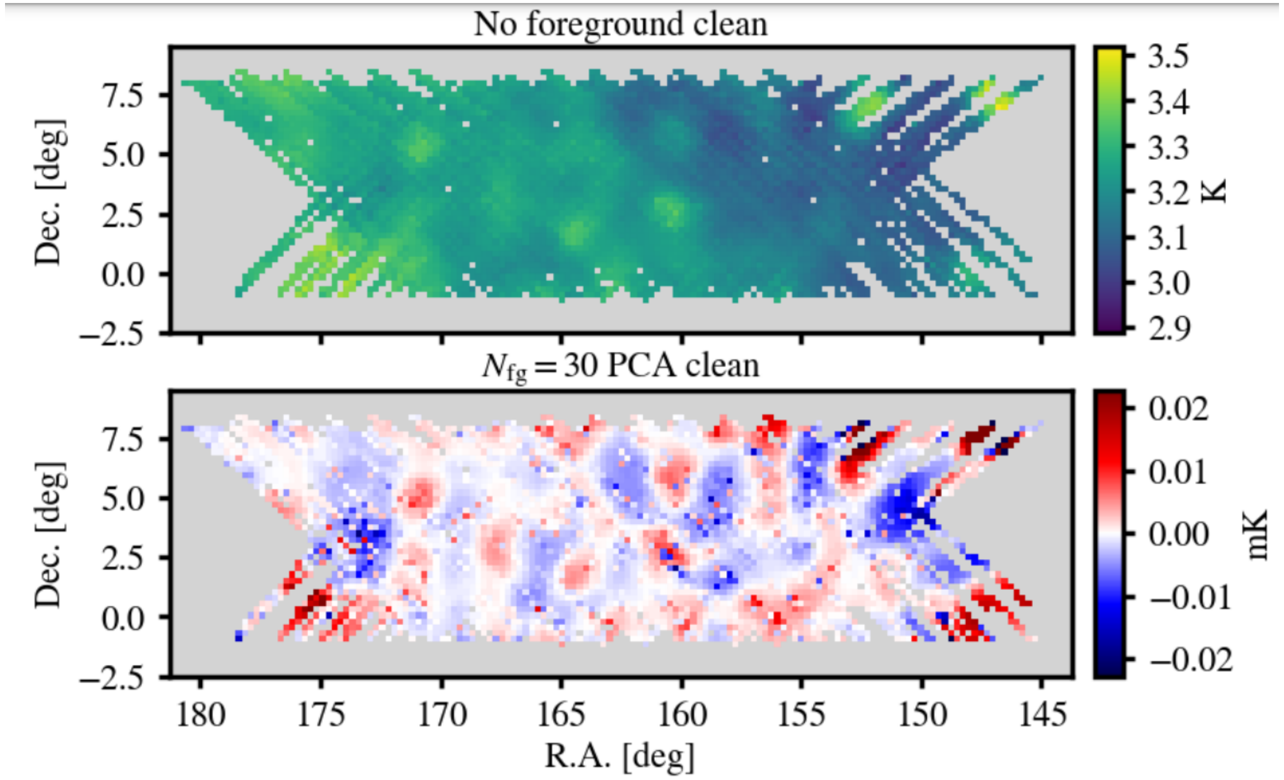
https://www.nasa.gov/mission_pages/chandra/multimedia/photo09-062.html

Detectable:
→ 21 cm line-intensity mapping (LIM)

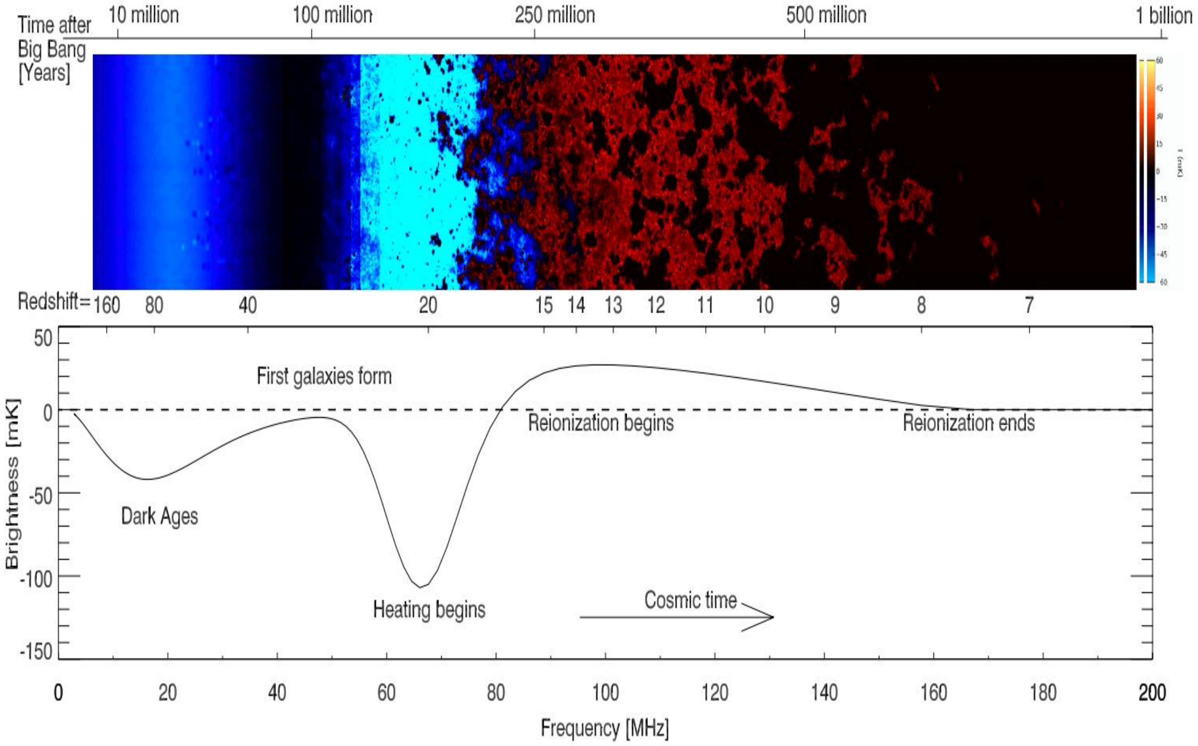


http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/h21.html

1.2 HI LIM



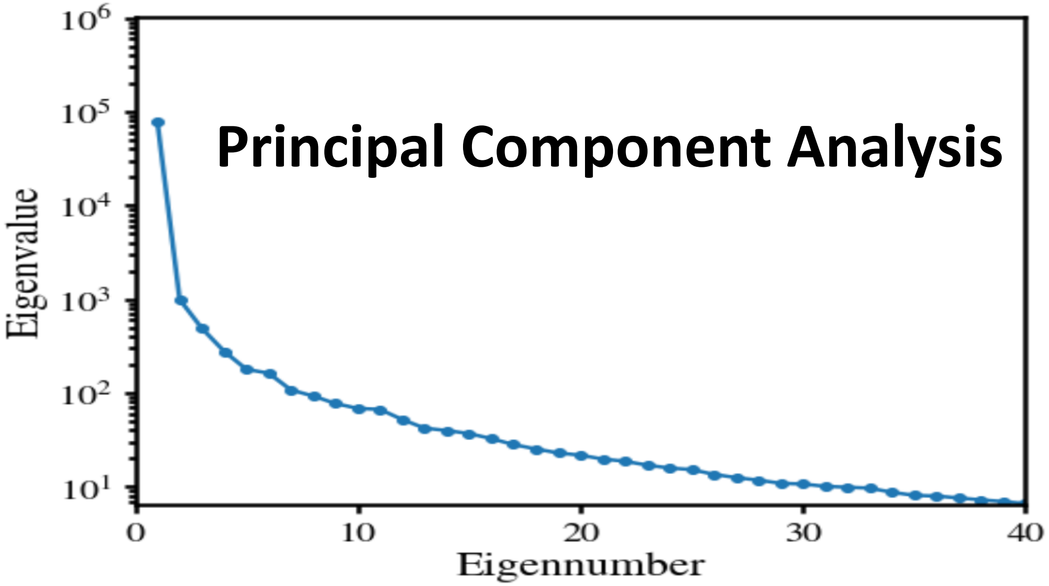
Cunnington et al. (2023)



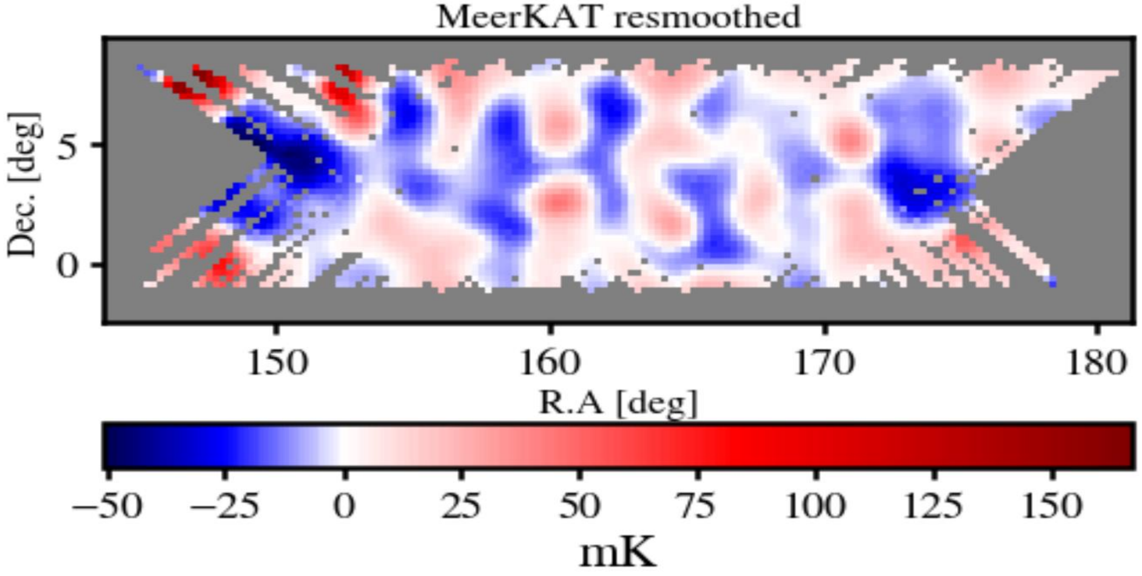
Pritchard et al. (2012)

1.3 Cleaning Approaches:

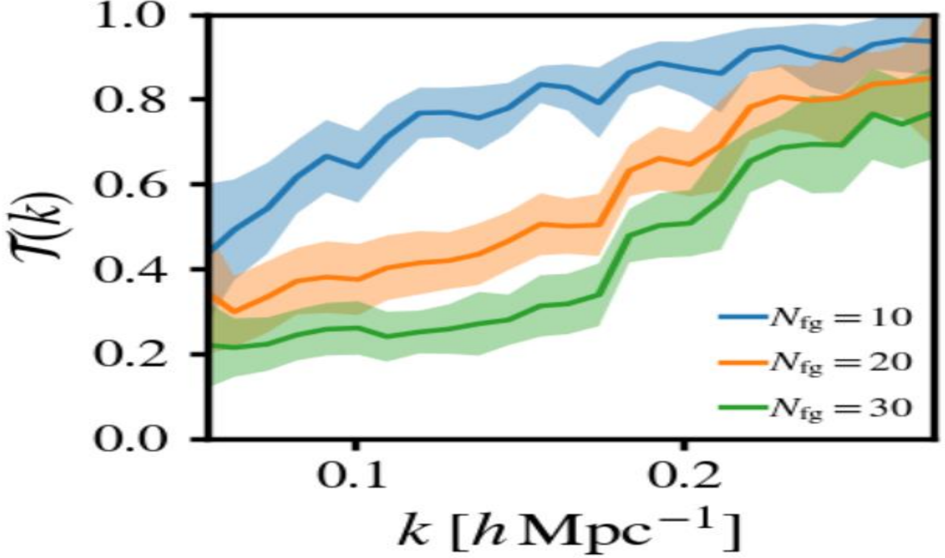
Cunnington et al. (2023):

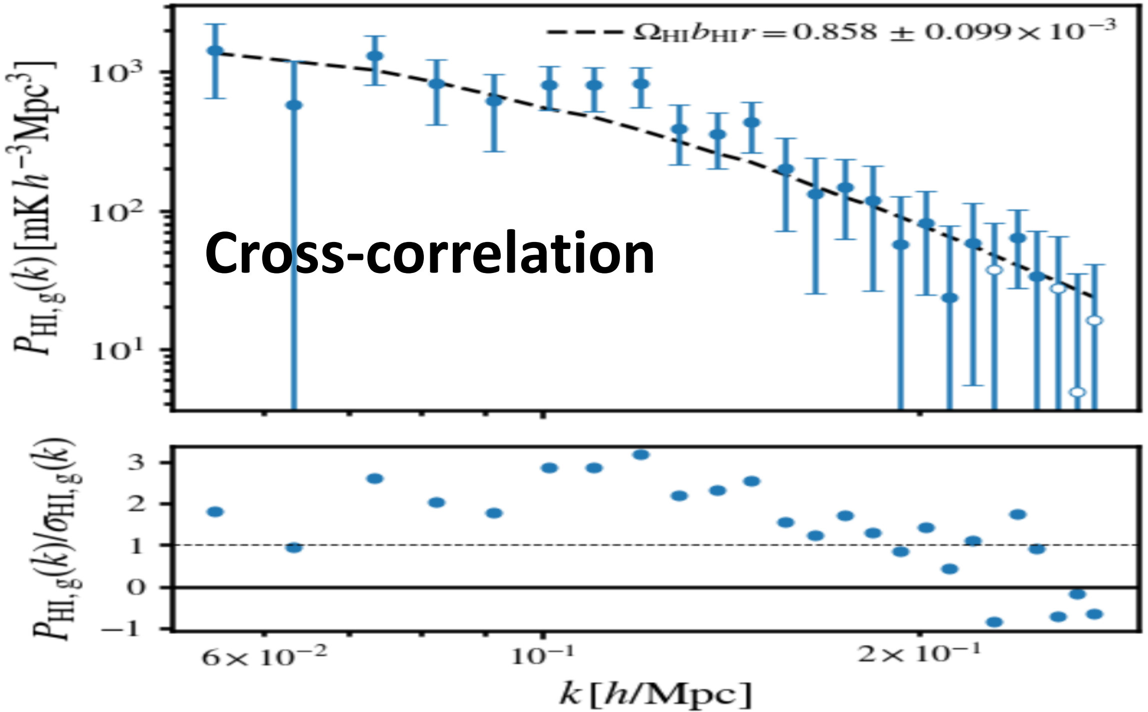

Principal Component Analysis

Weighted re-smoothing



Transfer function




Cross-correlation

2. Motivation and Objectives

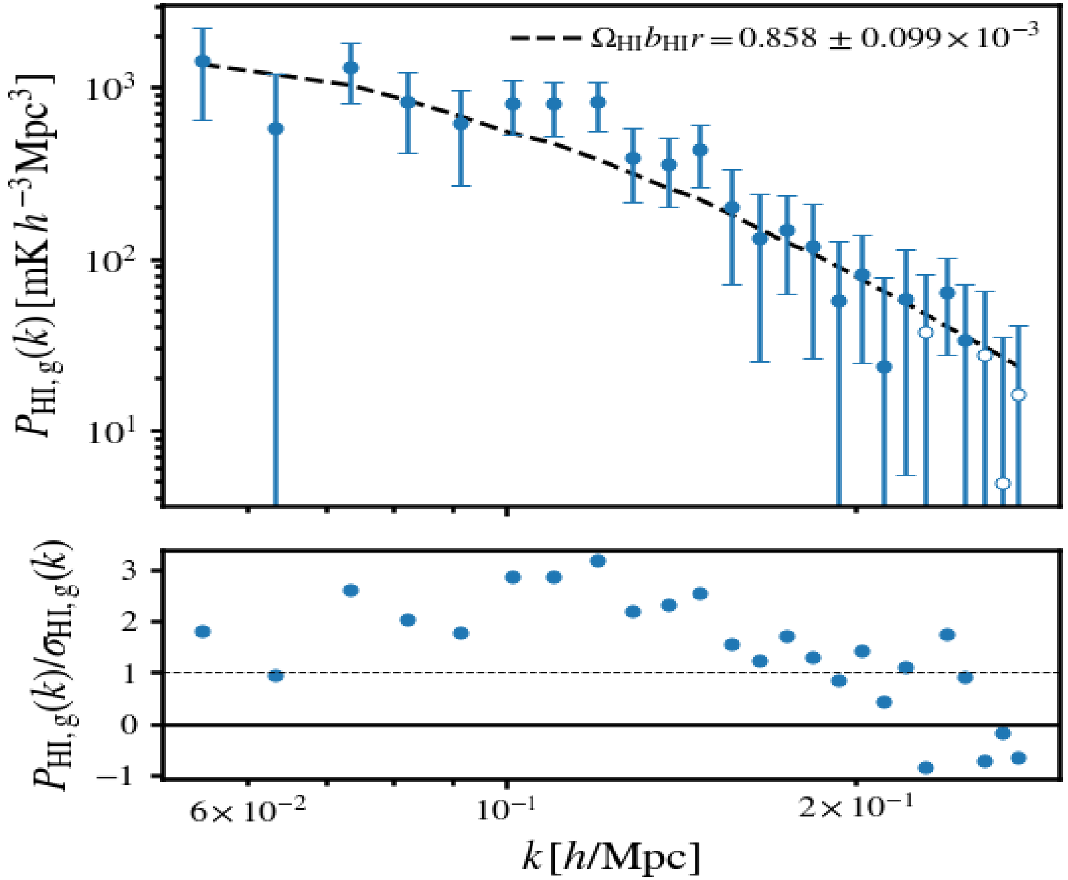
Cunnington et al., 2023:

1. Cross-correlated HI and galaxy data.
2. No halo occupation distribution (HOD).
3. Ω_{HI} depends on b_{HI} and r.

Objectives:

1. Model HI HOD
2. Model Ω_{HI} independently of b_{HI} and r.
3. Derive b_{HI} and $\bar{T}_{HI}$.

Cunnington et al., 2023:



HI-galaxy cross-power spectrum:

$\mathbf{0.05 < k < 0.28}$ **[h Mpc $^{-1}$].**

3.1 HI LIM Data (MeerKAT)

Band:
Radio (L-band), between $973.2 - 1014.6$ MHz (199 channels)

Redshift:
$0.400 < z < 0.459$, at $z_{eff} = 0.425$

Target area:
$153° < \mathrm{R.A.} < 172°$ and $-1° < \mathrm{Dec.} < 8°$

Survey area:
$200\ \mathrm{deg}^2$

Observation mode:
Single dish

MeerKAT radio telescope:
South Africa, Northern Cape

https://www.sarao.ac.za/gallery/meerkat/

3.2 Galaxy Data (WiggleZ)

Catalogue:
WiggleZ Dark Energy Survey (Photometric)
Reference:
Drinkwater et al. (2018)
Band:
UV (FUV, NUV), between $1090.2 - 2220.7$ THz
Survey area:
$1000\ \mathrm{deg}^2$
Survey Redshift:
$0.1 < z < 1.3$
Study Target area:
11 h field: $170.5\ \mathrm{deg}^2$
$153° < \mathrm{R.A.} < 172°$ and $-1° < \mathrm{Dec.} < 8°$

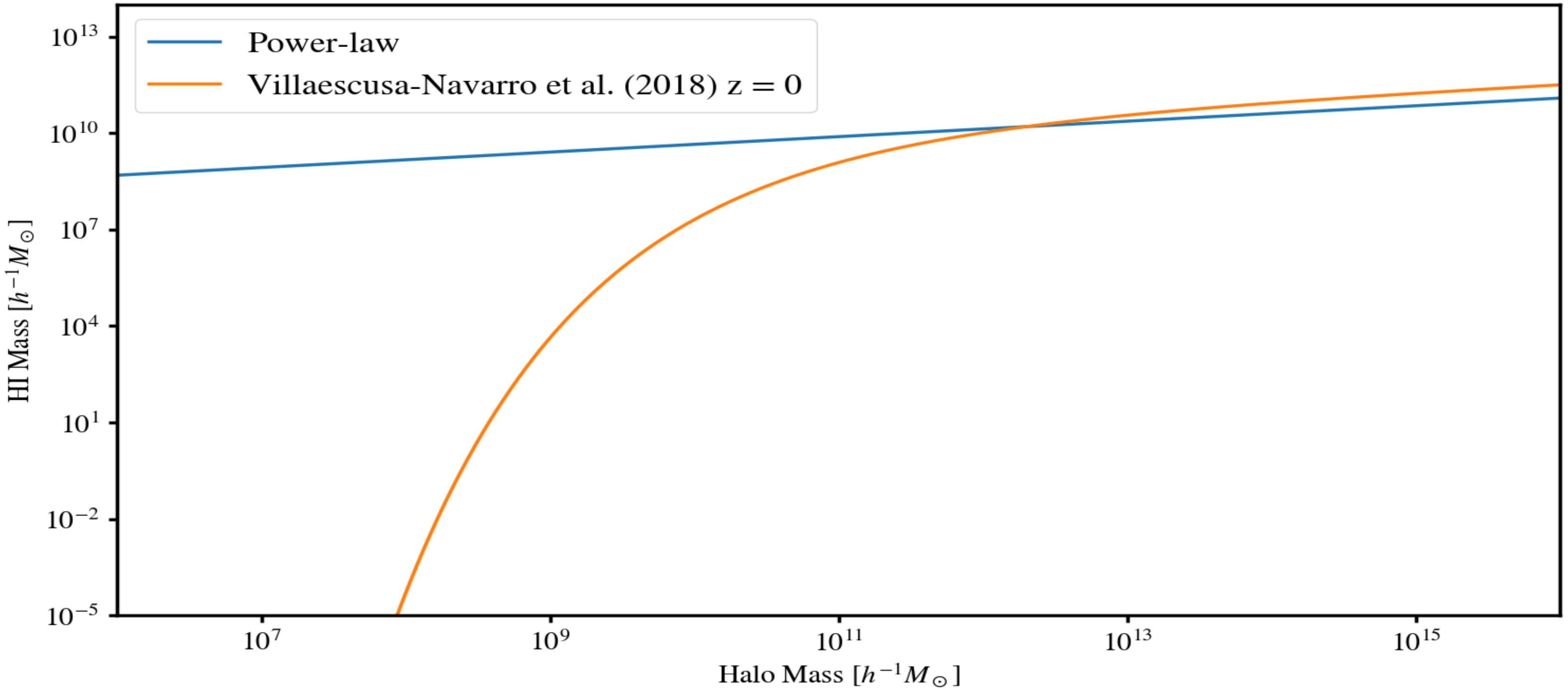
Anglo-Australian Telescope:
Siding Spring Observatory, Australia

https://rsaa.anu.edu.au/about/observatories/telescopes/anglo-australian-telescope

4.1 HI HOD

$$\bar{\rho}_{HI}(z)\ [M_\odot\,.\,\mathrm{Mpc}^{-3}] = \int dm\ \frac{dn}{dm}(m,z)\ \langle M_{HI}\ (m)\rangle$$

$$\langle M_{HI}\ (m)\rangle\ [M_\odot] = M_0 \left(\frac{m}{M_B}\right)^{\alpha} e^{-\left(\frac{m}{M_B}\right)^{-\gamma}}$$



4.2 Cross-power functions

$$P_{g,HI}^{2h}(k,z)\ [\mathrm{Mpc^3.h^{-3}}] \ = b_g(k,z)\, b_{HI}(k,z)\, P_{\mathrm{lin}}(k,z)$$

$$b_{\mathrm{tracer}}(k,z) = \frac{1}{\bar{n}_{\mathrm{tracer}}(z)} \int dm \frac{dn}{dm}(m,z)\, I_{\mathrm{tracer}}^{2h}(k,m,z)$$

$$I_{tracer}^{2h}(k,m,z) = \langle N_{\mathrm{tracer}}(m)\rangle\, u_{\mathrm{tracer}}(k|m)$$

$$\bar{n}_{\mathrm{tracer}}(z) = \int dm \frac{dn}{dm}(m,z)\, \langle N_{\mathrm{tracer}}(m)\rangle$$

4.3 HI parameters

$$P^{2h}(k,z)\ [\mathrm{K}\,.\,\mathrm{Mpc}^3.\,\mathrm{h}^{-3}] = \bar{T}_{HI}\ P^{2h}_{g,HI}$$

$$\bar{T}_{HI}(z) = C_{HI}\ \bar{\rho}_{HI}(z)$$

$$C_{HI}\ \left[\mathrm{K}\,.\,M_{\odot}^{-1}.\,\mathrm{Mpc}^3\right] = \frac{3A_{12}h_p c^3(1+z)^3}{32\pi m_H k_B \nu_{21}^2 H(z)}$$

$$\Omega_{HI}(z) = \left(\frac{\bar{T}_{HI}(z)}{180\ h}\right)\left(\frac{H(z)}{H(z=0)}\right)$$

$$\Omega_{HI}(z) = \frac{\bar{\rho}_{HI}(z)}{\rho_{crit}(z)} = \Omega_{HI,0}\ (1+z)^3\ \left(\frac{H(z=0)}{H(z)}\right)^2$$

4.4 Cross-power modifications

See Cunnington et al., 2023:

- **Beam damping and redshift-space distortions:**

$$P^{atten}_{g,HI}(k,z,\mu) = P^{m}_{g,HI}(k,z)\,(1+f\mu^2)^2\, e^{-\frac{1}{2}(1-\mu^2)k^2R^2_{beam}}$$

$(1+f\mu^2)^2$: RSD

$e^{-\frac{1}{2}(1-\mu^2)k^2R^2_{beam}}$: Beam damping

- **Survey window functions convolution:**

$$P^{conv}_{g,HI}(k,z) = P^{atten}_{g,HI}(k,z) * W_{HI}W_g$$

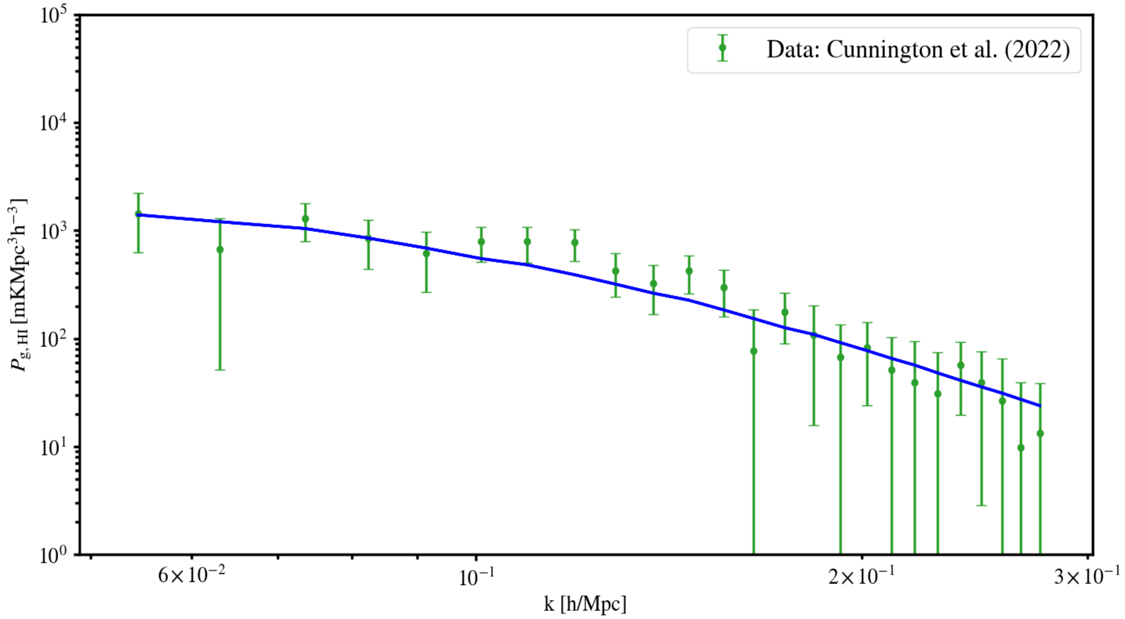
5 Methodology

Modelling: HALOMOD (python package)

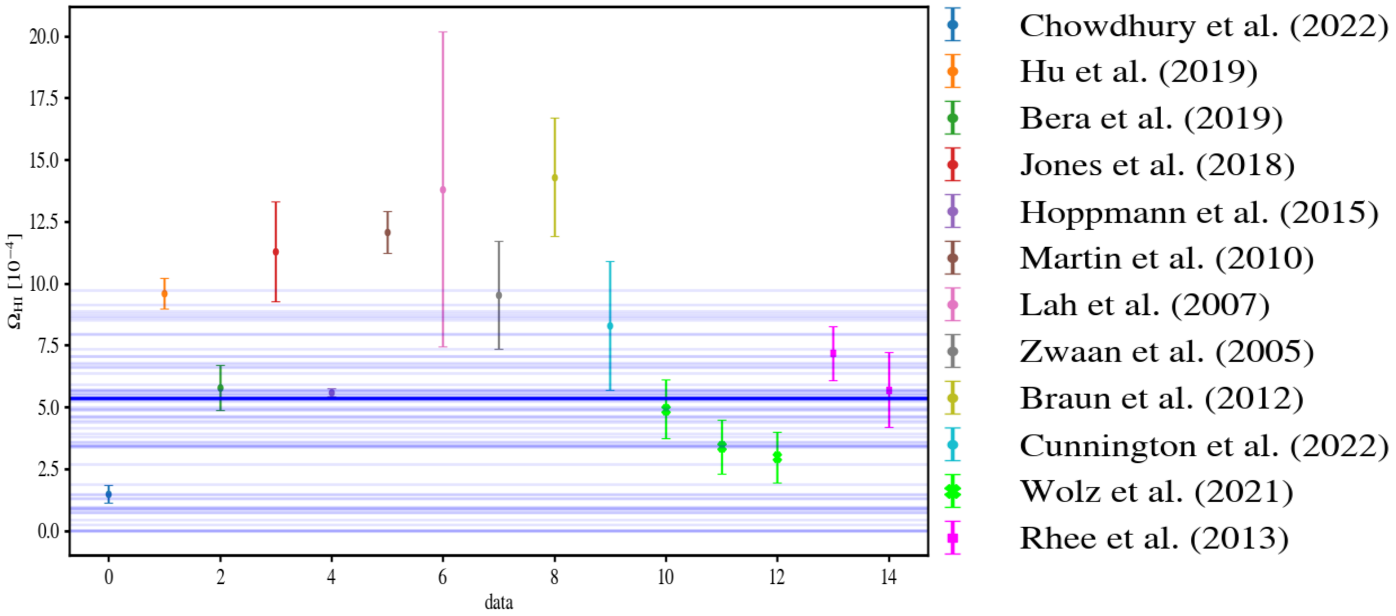
Fitting: EMCEE (python package)

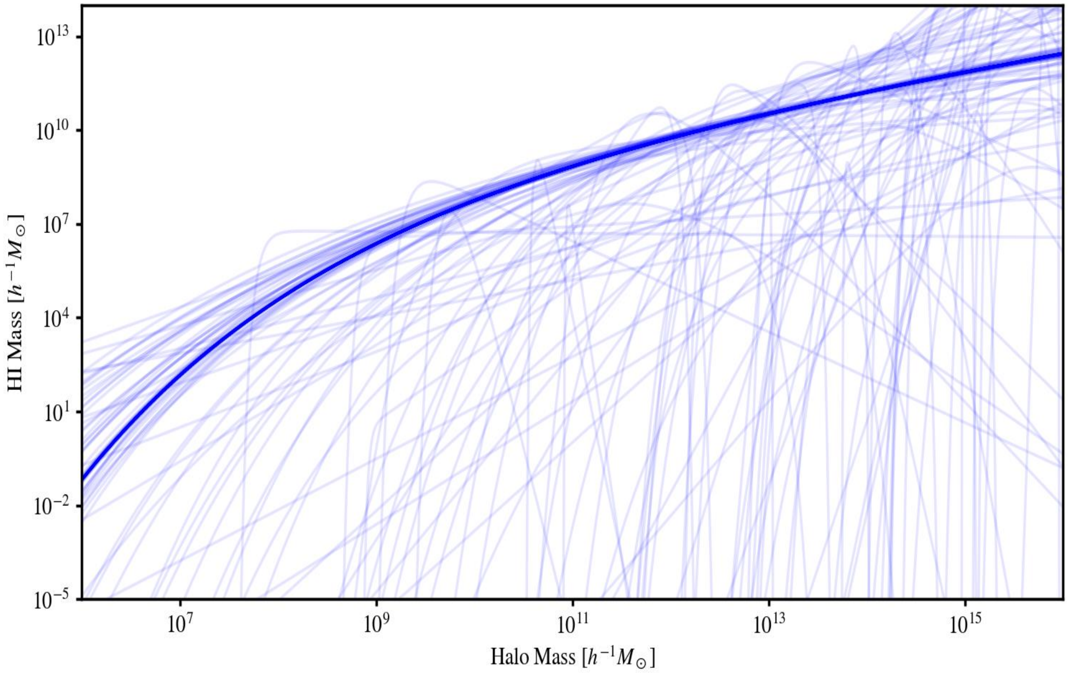
Fitting cautions:

$P^{2h}(k,z)$ can be explained by multiple HODs!
Ω_{HI} depends also on HOD!



$z = 0.425$





6. Results (Preliminary)

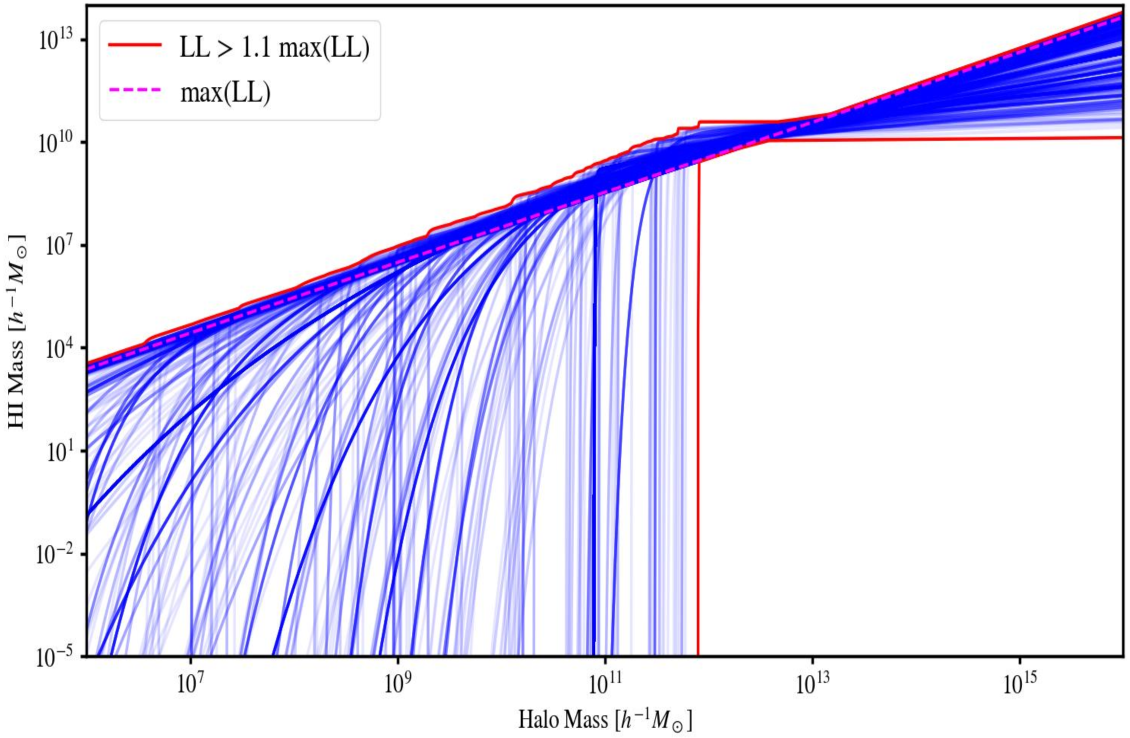
HI HOD
Galaxy-HI cross-power
Ω_{HI}, b_{HI} and $\bar{T}_{HI}$
Posterior distribution

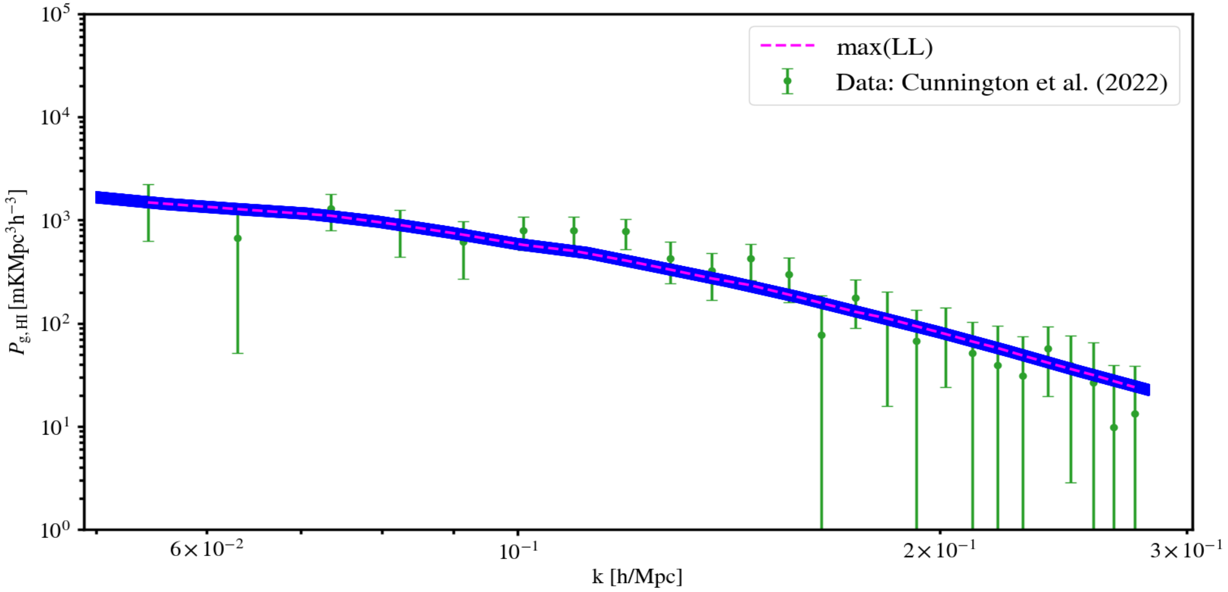
6.1 Explore parameter space

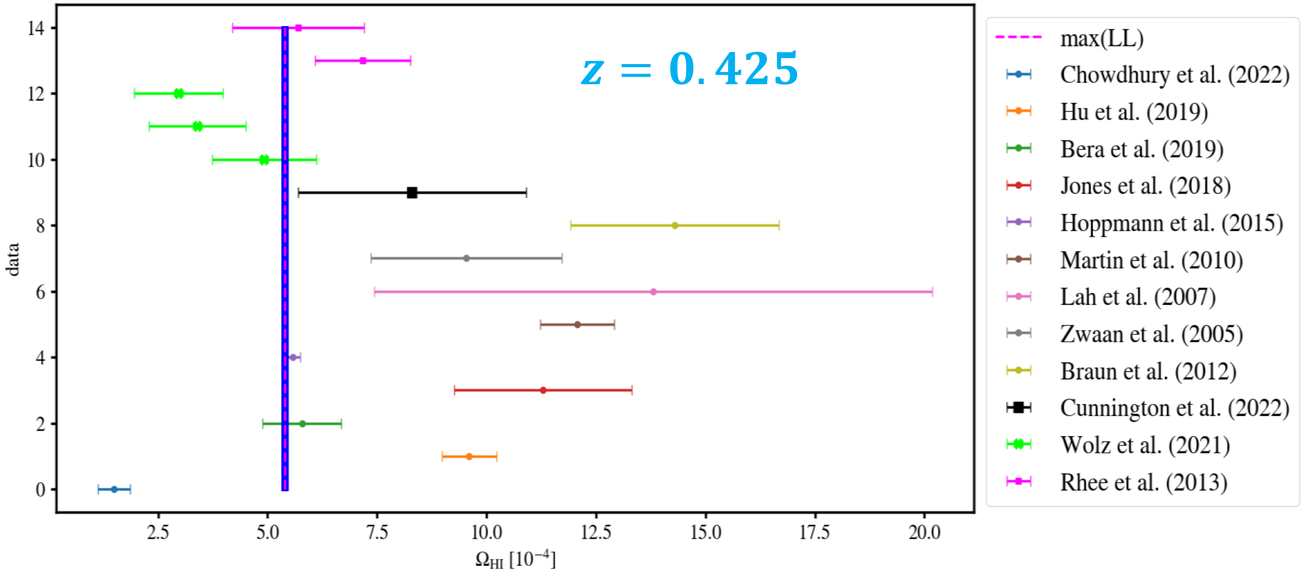
Models: $\sim 10^7$

10^3 models with $\mathcal{L} > 1.1 \times \max(\mathcal{L})$

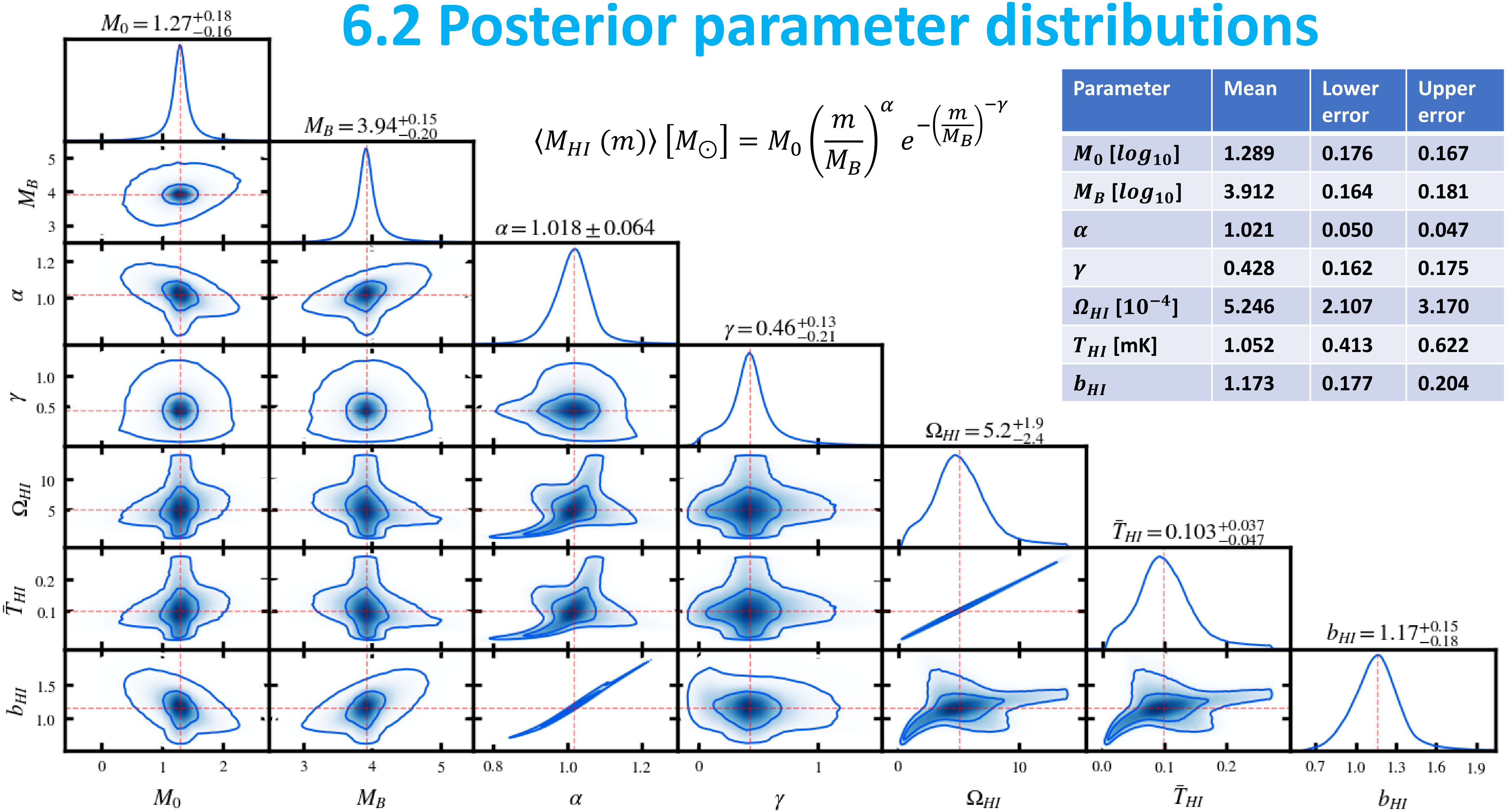
Parameter	$\max(\mathcal{L})$	Lower value	Largest value
$M_0\ [log_{10}]$	1.290	-263.295	234.362
$M_B\ [log_{10}]$	3.909	-281.125	272.198
α	1.021	-66.123	152.95
γ	0.427	-5017.663	26427.56
$\Omega_{HI}\ [10^{-4}]$	5.392	0.000	$\sim 10^{299}$
T_{HI} [mK]	1.057	0.000	$\sim 10^{298}$
b_{HI}	1.169	0.592	1898.231







6.2 Posterior parameter distributions



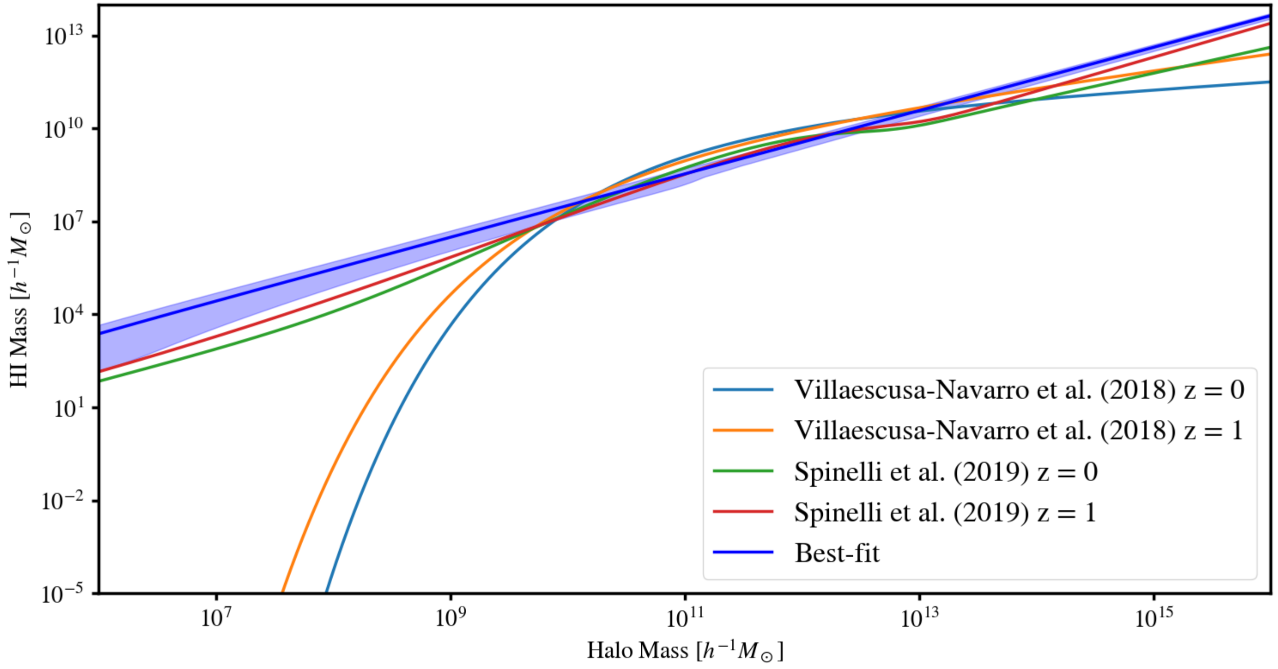
$$\langle M_{HI}\,(m)\rangle\,[M_{\odot}] = M_0 \left(\frac{m}{M_B}\right)^{\alpha} e^{-\left(\frac{m}{M_B}\right)^{-\gamma}}$$

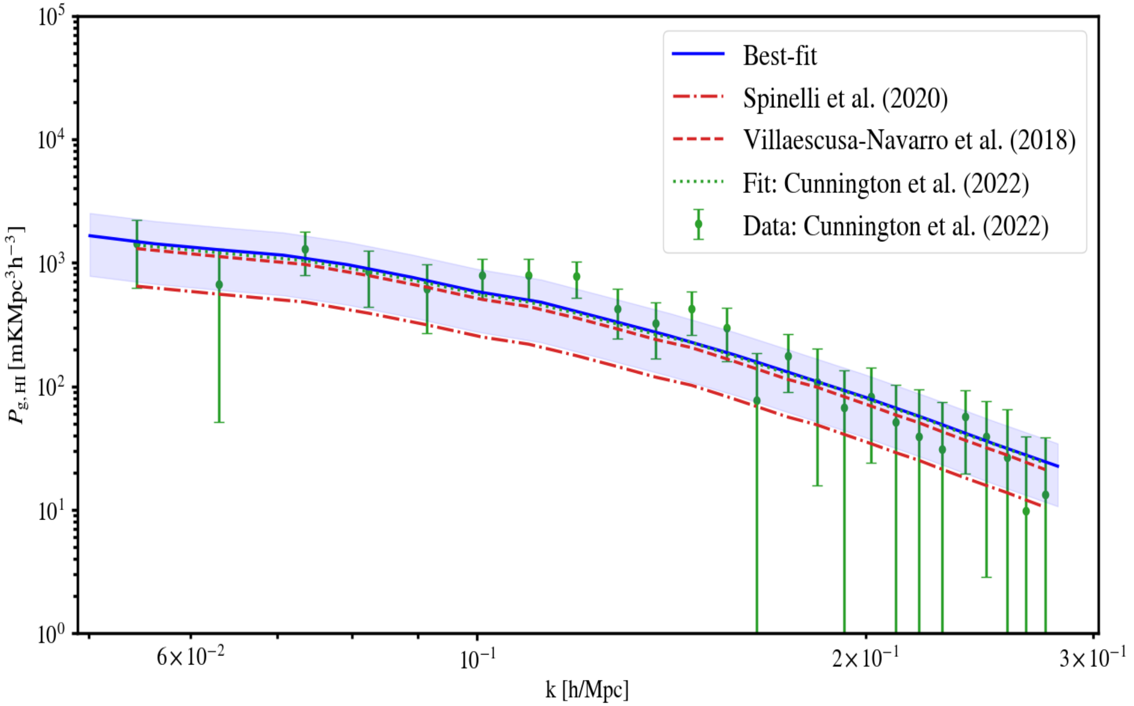
Parameter	Mean	Lower error	Upper error
$M_0\,[log_{10}]$	1.289	0.176	0.167
$M_B\,[log_{10}]$	3.912	0.164	0.181
α	1.021	0.050	0.047
γ	0.428	0.162	0.175
$\Omega_{HI}\,[10^{-4}]$	5.246	2.107	3.170
T_{HI} [mK]	1.052	0.413	0.622
b_{HI}	1.173	0.177	0.204

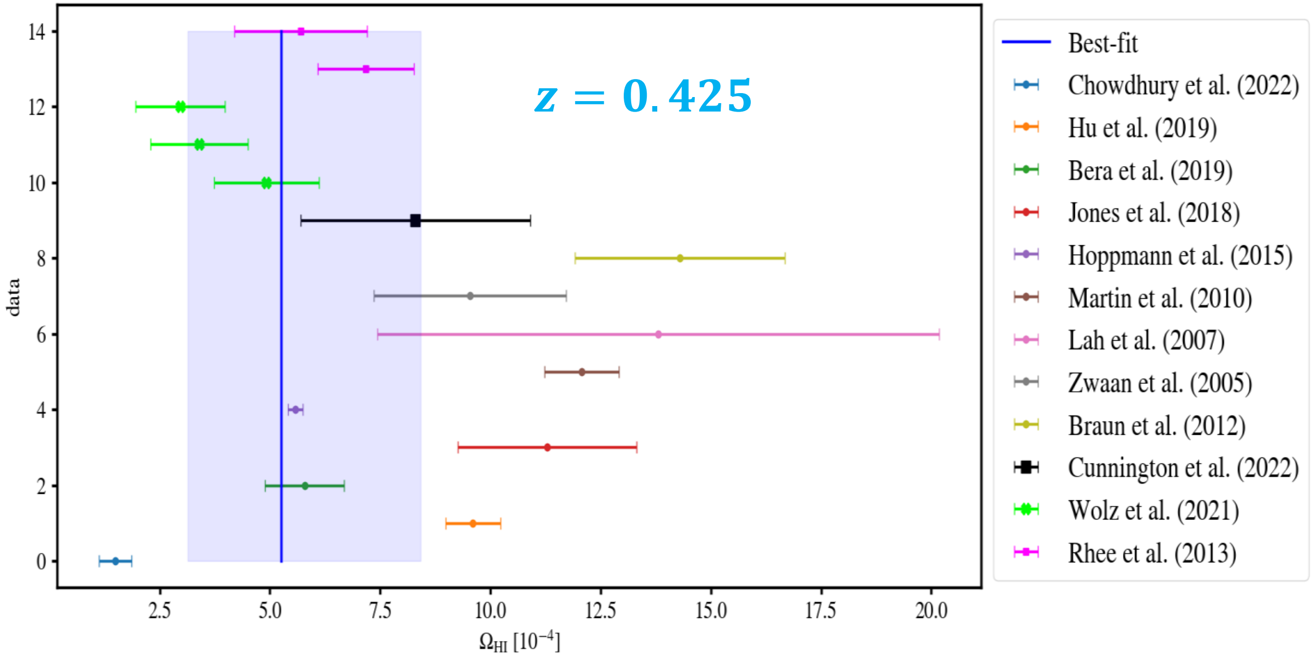
6.3 Model standard errors

Error in $P_{g,HI}\ (k,z)$ and $\langle M_{HI}\ (m)\rangle$:

1. Random sample 10^3 from posterior distribution.
2. Determine standard error for the 10^3 samples.







$z = 0.425$

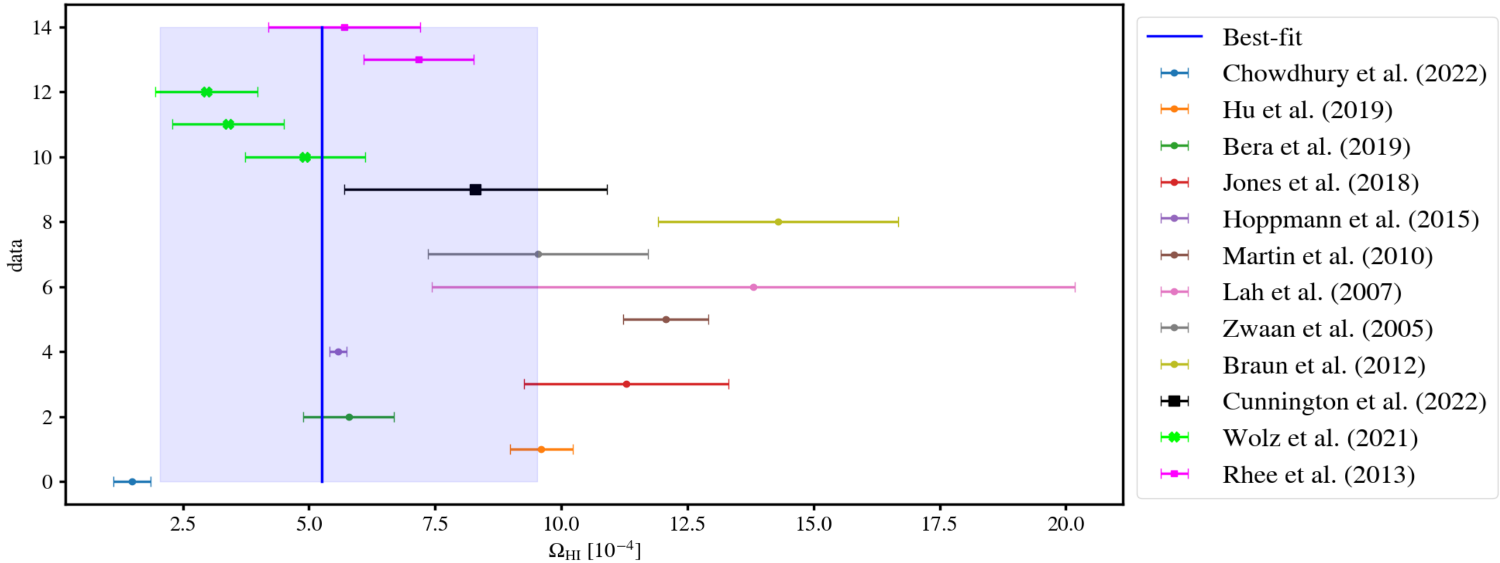
Fitted results (Derived; $z_{eff} = 0.425$)

This study:

Parameter	Mean	Lower error	Upper error
Ω_{HI} $[10^{-4}]$	5.246	2.107 (stat) + 1.1 (sys)	3.170 (stat) + 1.1 (sys)
T_{HI} [mK]	0.105	0.041 (stat) + 0.022 (sys)	0.062 (stat) + 0.022 (sys)
b_{HI}	1.173	0.177	0.204

Cunnington et al. (2022)

Parameter	Mean	Lower error	Upper error
Ω_{HI} $[10^{-4}]$	8.300	1.5 (stat) + 1.1 (sys)	1.5 (stat) + 1.1 (sys)
T_{HI} [mK]	0.167	0.029 (stat) + 0.022 (sys)	0.029 (stat) + 0.022 (sys)
b_g	0.911	-	-
b_{HI}	1.130	0.100	0.100



7. Findings

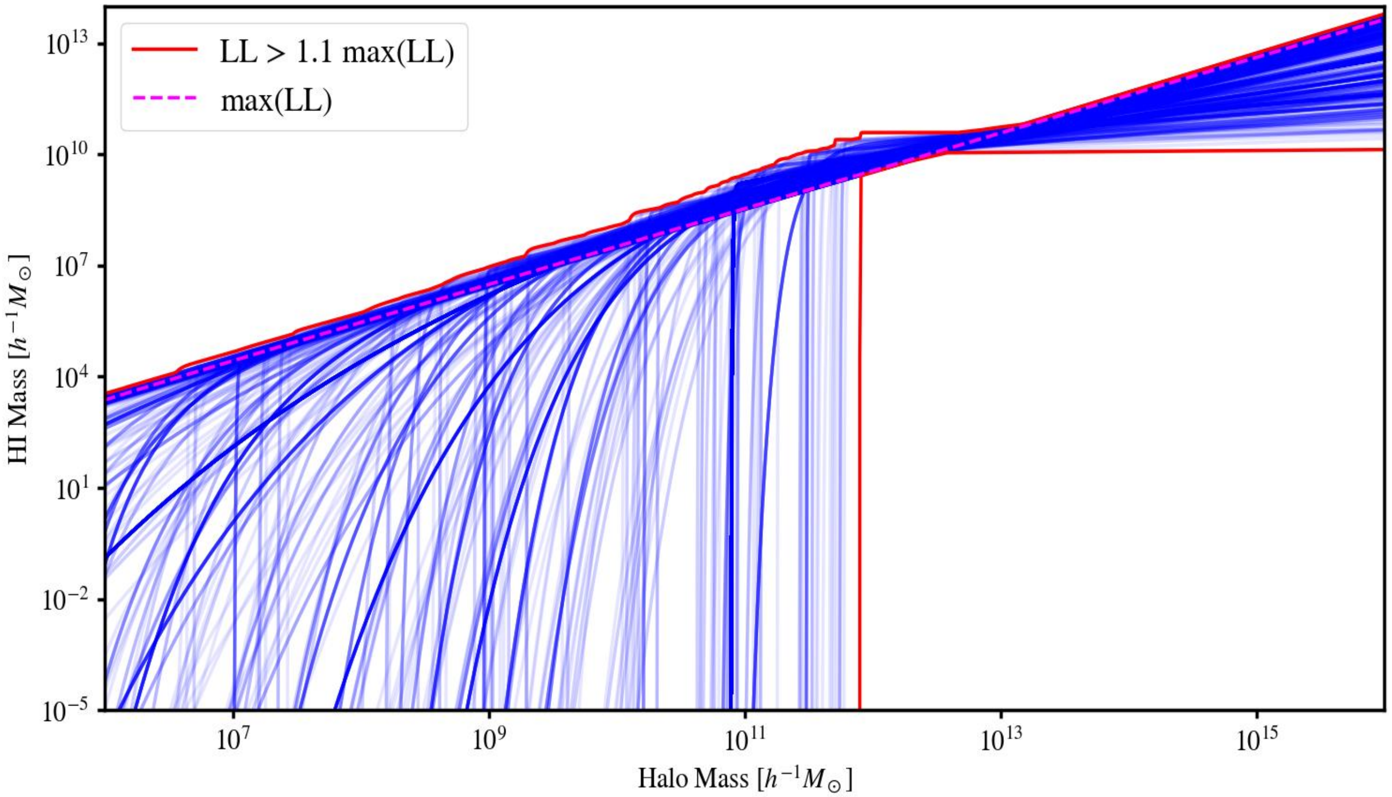
1. HI HOD can reproduce $P_{g,HI}(k, z)$ (Cunnington et al., 2022).
2. HI HOD (Study) agrees well with other HOD (literature) models.
3. Ω_{HI}, b_{HI} and $\bar{T}_{HI}$ agrees with literature.
4. Ω_{HI} and b_{HI} constrained independently of each other.
5. HI HOD models from simulations are reliable enough.

7. Findings

6. HI HOD prefers cut-off at low masses to explain $P_{g,HI}(k,z)$ data (Cunnington et al., 2022).

7. $0 \lesssim \alpha \lesssim 1$

8. Cut-off mass: $\mathrm{m} \lesssim 10^{12}\ M_{\odot}$



10. Future work

1. Auto-correlation HI with HI.
2. Cross-correlate with other survey data and compare results.
3. Derive Galaxy HOD.
4. Derive HI mass vs galaxy mass.
5. Investigate redshift uncertainty dependence on 21-cm signal.

11. References

[1] Halomod documentation: https://halomod.readthedocs.io/en/latest/examples/

[2] EMCEE documentation: https://emcee.readthedocs.io/en/stable/

[3] GetDist documentation: https://getdist.readthedocs.io/en/latest/