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Neutral Universe Machine:

An Empirical Model for the Evolution of HI and H2 Gas in the Universe

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arXiv:2307.07078

HI-Halo Mass Relation

- HI-Halo Mass Relation is key to the intensity mapping measurements

- Brightness Temperature

$$\bar{T}_b(z) = 189h\left(\frac{H_0(1+z)^2}{H(z)}\right)\Omega_{\mathrm{H\,I}}(z)\ \mathrm{mK},$$

- Cosmic HI density

$$\Omega_{\mathrm{H\,I}}(z) = \frac{1}{\rho_c^0}\int_0^\infty n(M,z)M_{\mathrm{H\,I}}(M,z)dM,$$

- HI bias

$$b_{\mathrm{H\,I}}(z) = \frac{1}{\rho_c^0\Omega_{\mathrm{H\,I}}(z)}\int_0^\infty n(M,z)b(M,z)M_{\mathrm{H\,I}}(M,z)dM,$$

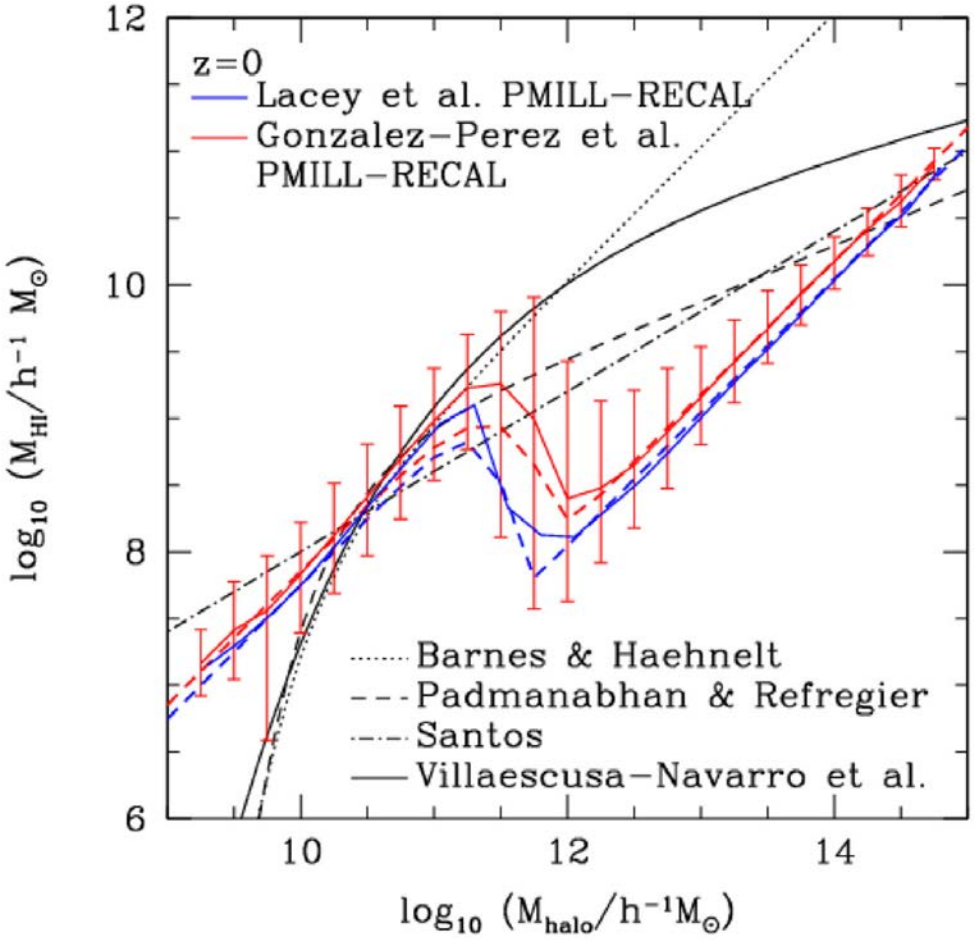
- Power spectrum shot noise

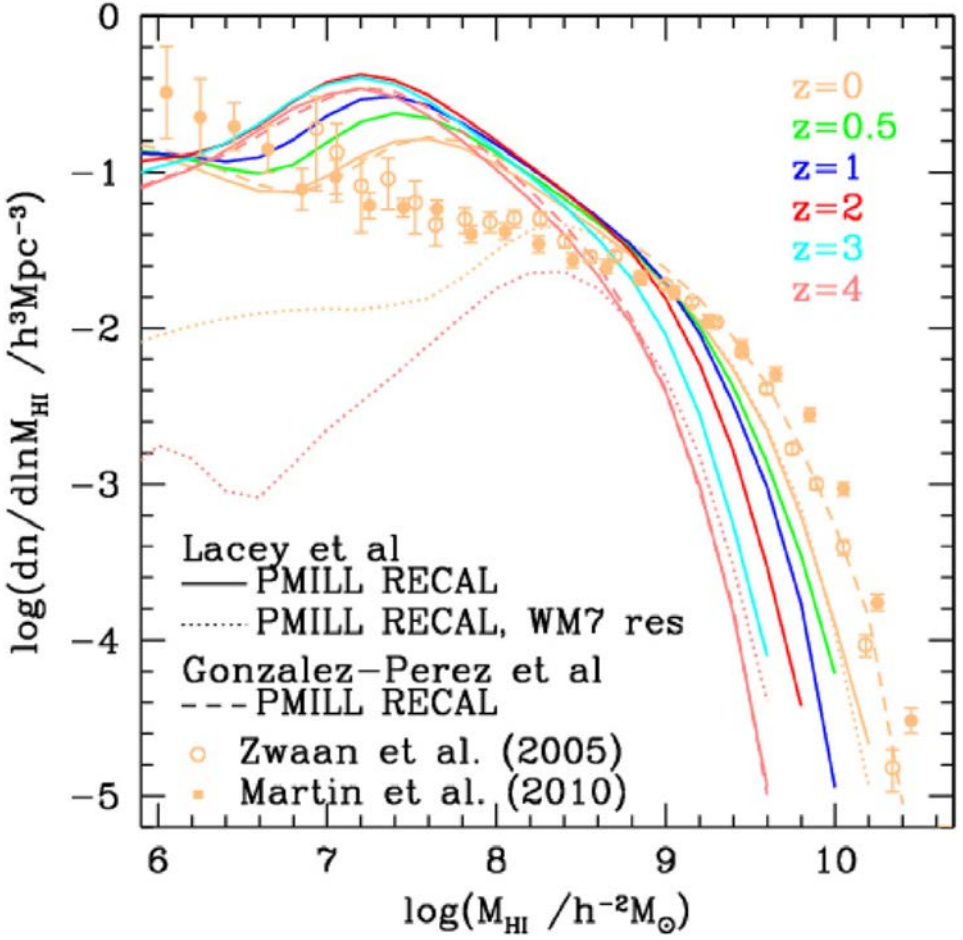
$$P_{\mathrm{SN}}(z) = \frac{1}{(\rho_c^0\Omega_{\mathrm{H\,I}}(z))^2}\int_0^\infty n(M,z)M_{\mathrm{H\,I}}^2(M,z)dM,$$

- Villaescusa-Navarro et al. (2018)

How to make a halo model for HI?

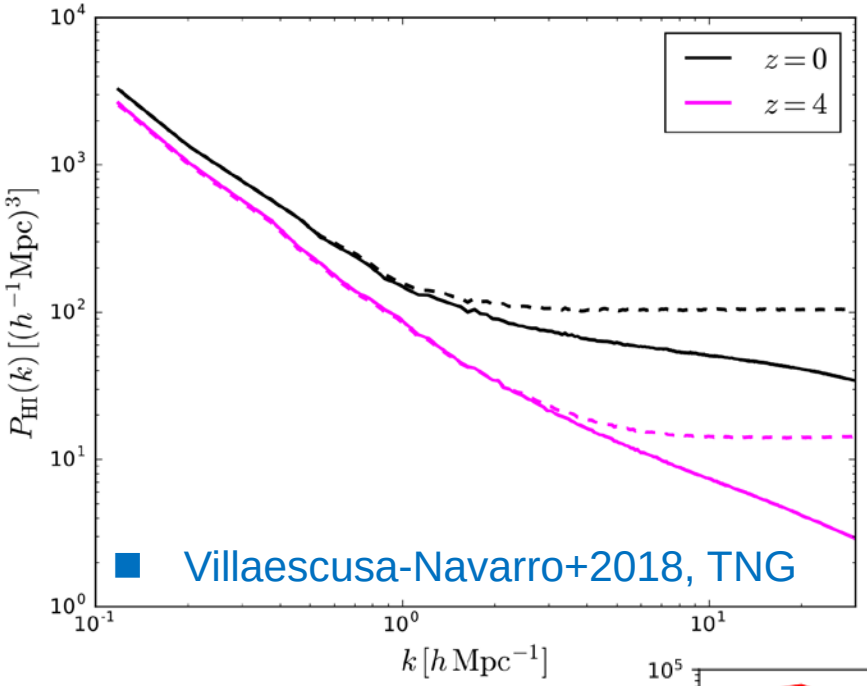
- The HI-halo relation varies significantly for different theoretical models.



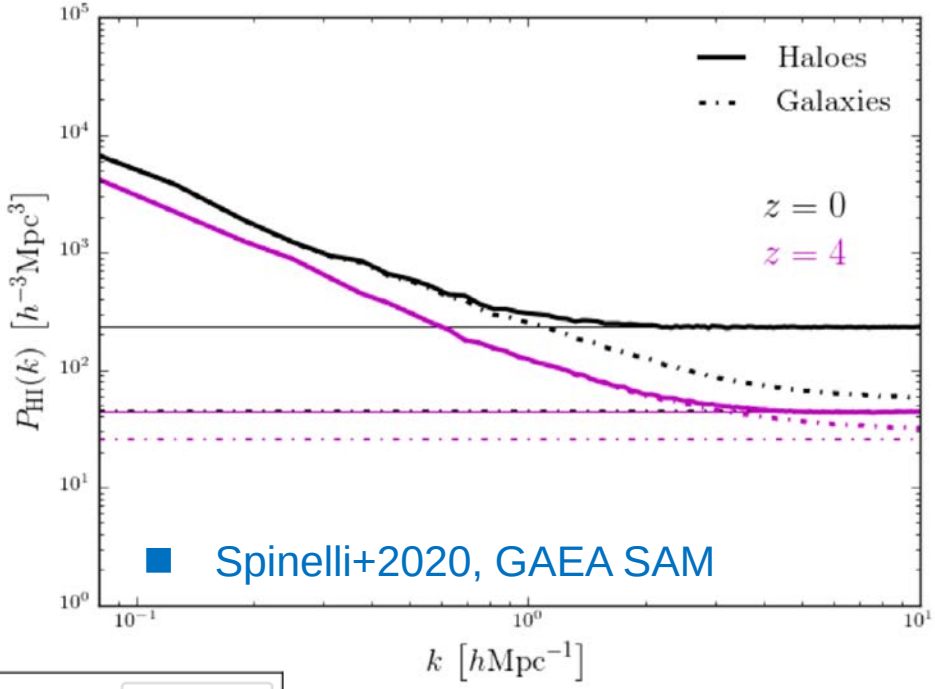


- Baugh et al. (2019)

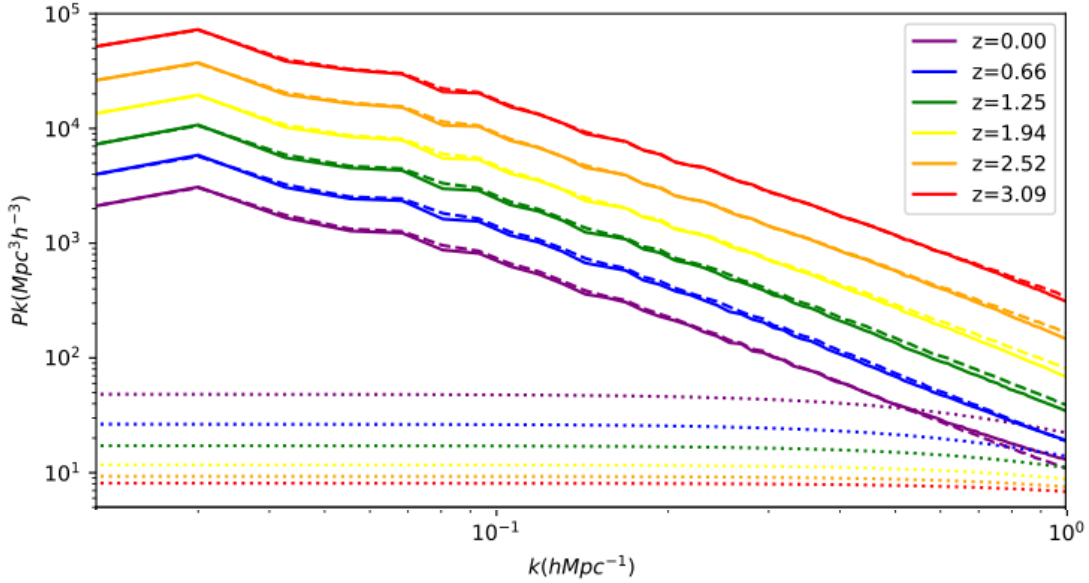
HI-Halo Mass Relation Significantly Affects the HI Power Spectrum



- Villaescusa-Navarro+2018, TNG

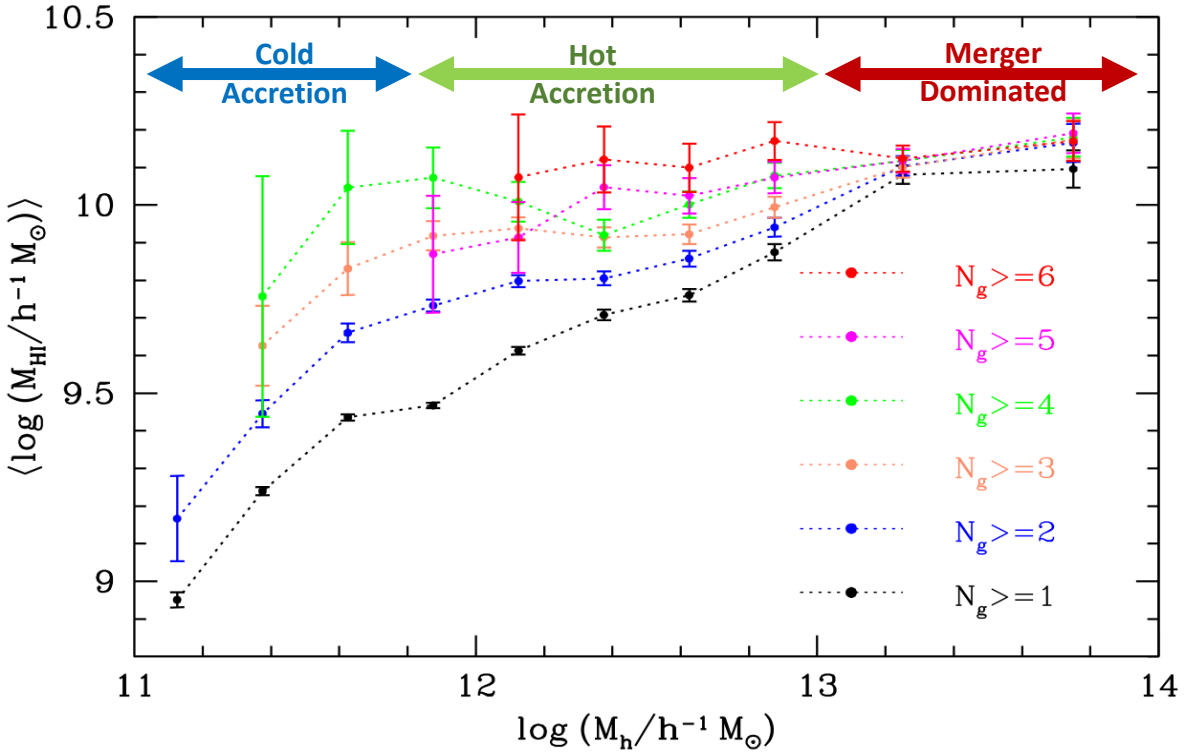


- Spinelli+2020, GAEA SAM

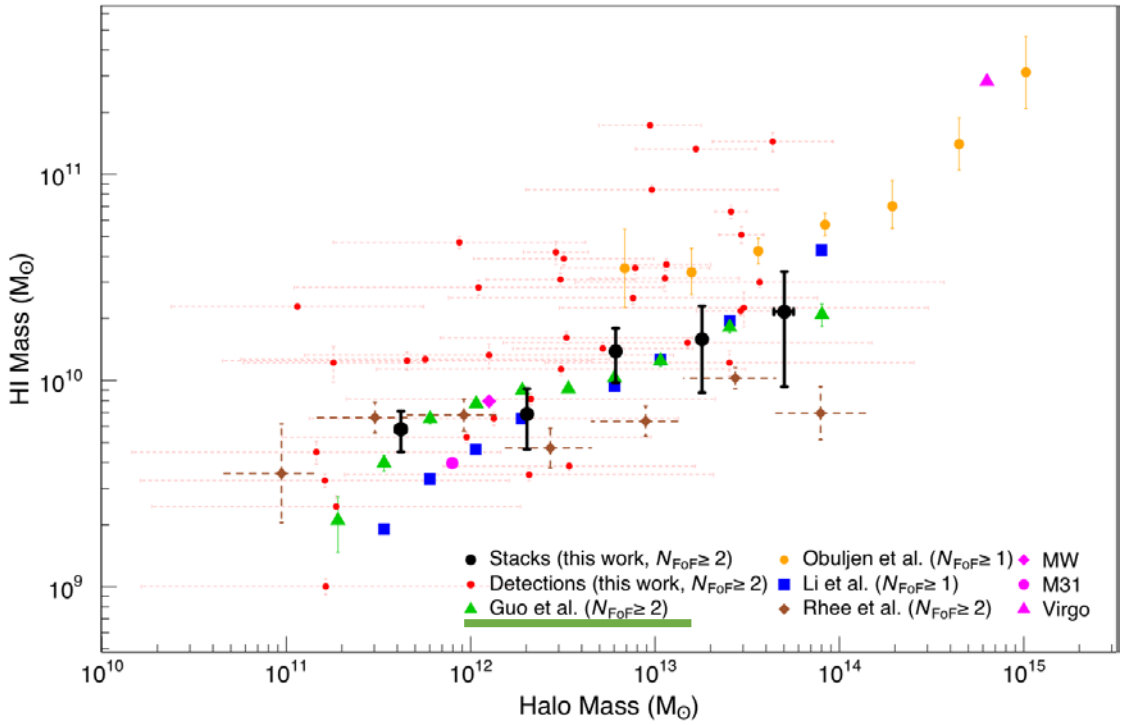


- Zhang+2020, L-Galaxies SAM

Direct Measurements of HI-halo Mass Relation



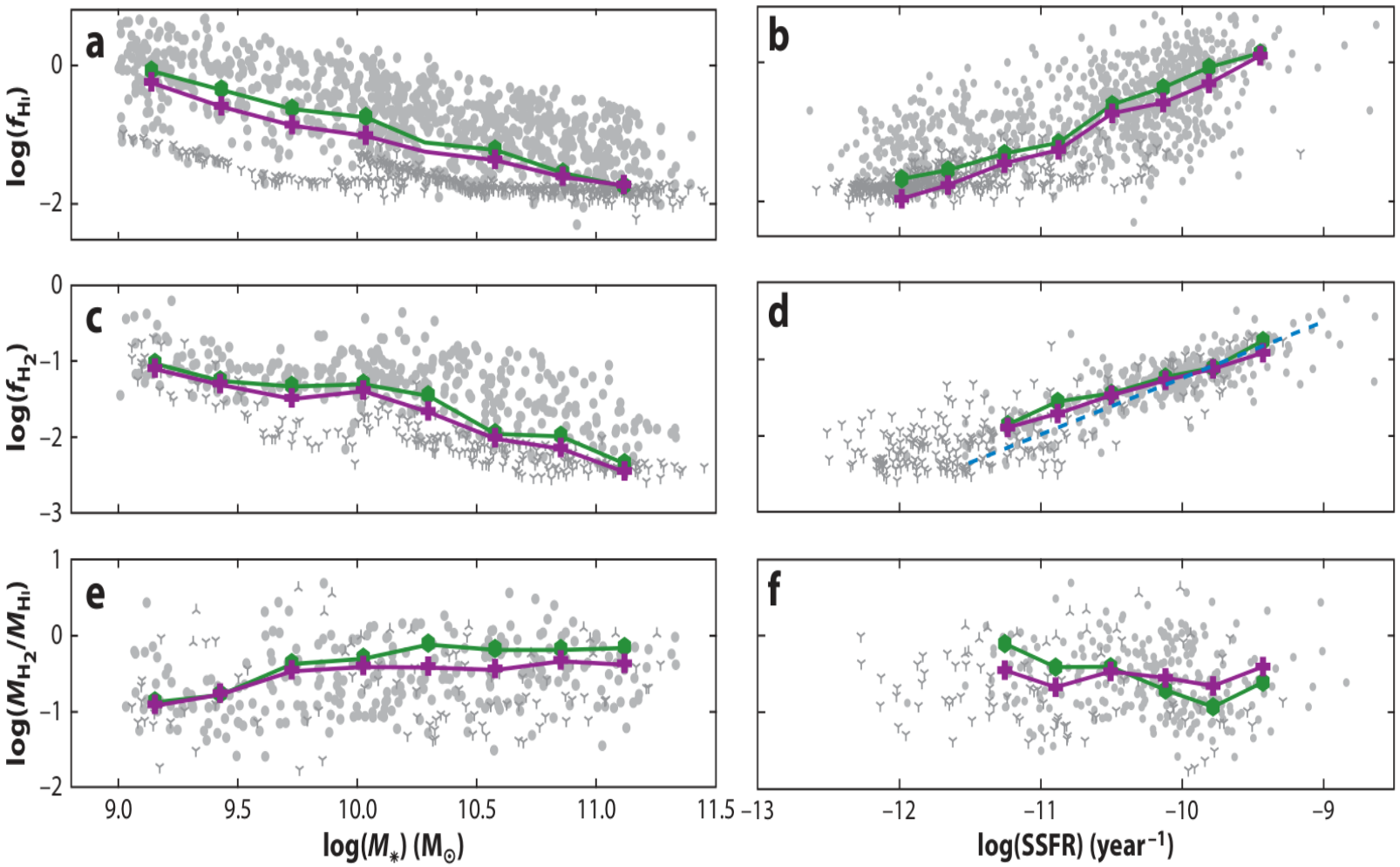
Guo et al. (2020), ALFALFA+SDSS,
HI spectral stacking



Dev et al. (2023), ALFALFA+GAMA

HI Mass is not a simple function of halo mass! $M_{\rm H\,I}(M, z)$

What we know about the cold gas: HI Gas

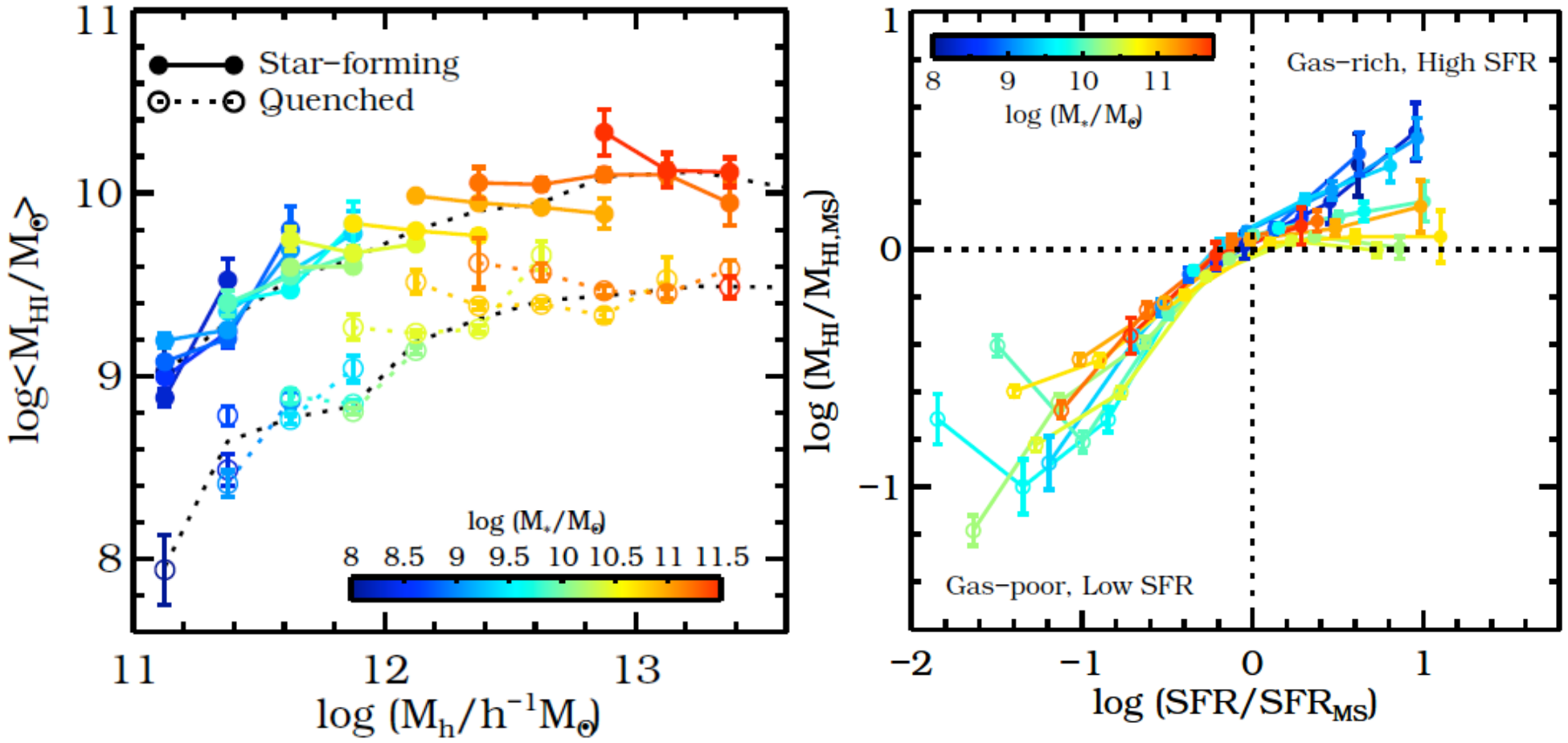


- Cold gas fractions are decreasing with M* & increasing with sSFR
- The conversion efficiency from HI to H2 seems to be weakly dependent on M* and sSFR

Saintonge et al. 2022, ARA&A, based on xGASS & xCOLD GASS

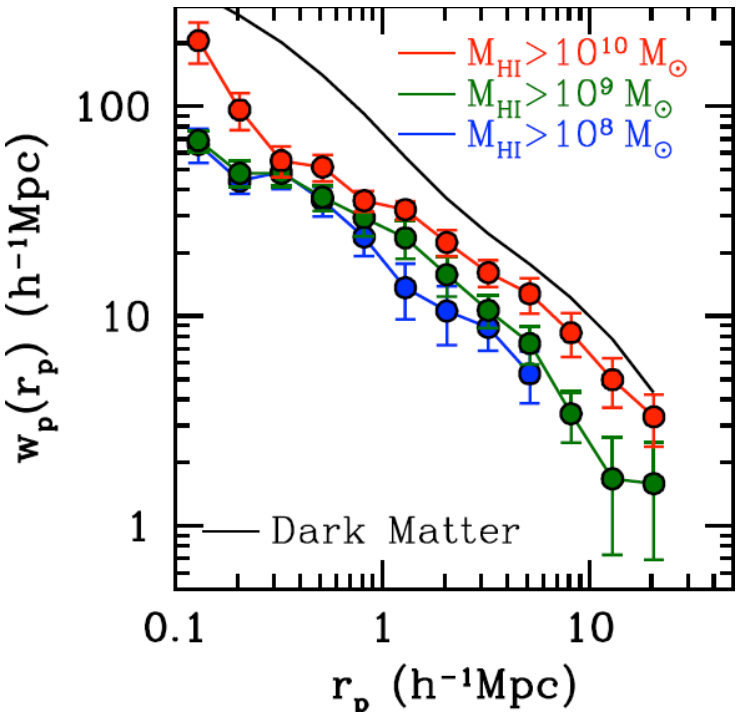
HI-SFR Relation

- HI mass is directly related to the SFR

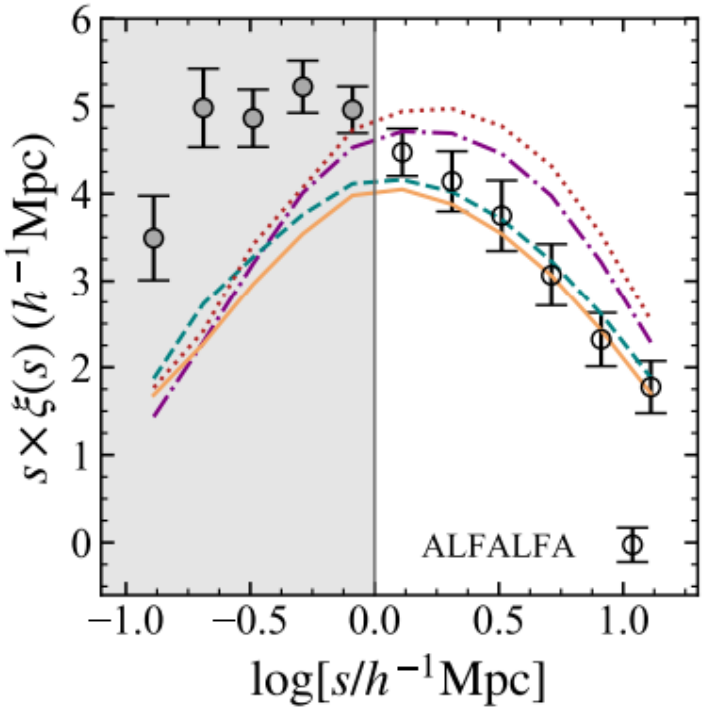


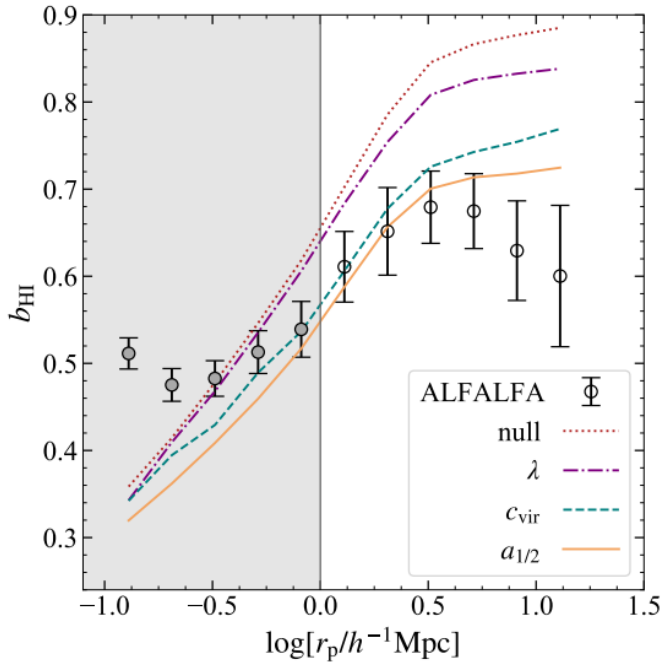
Guo et al. (2021), HI stacking of ALFALFA

HI Clustering



Guo et al. (2017)





Li, Guo, & Mao (2022)

- HI gas is distributed in underdense regions

NeutralUniverseMachine Model

Halo Mass | Formation History | SFR

$$M_{\mathrm{H\,I}} = \frac{\kappa M_{\mathrm{vir}}}{\mu^{-\alpha} + \mu^{\beta}} \left(\frac{1+z}{1+z_{\mathrm{form}}} \right)^{\gamma} \left(\frac{\mathrm{SFR}}{\mathrm{SFR}_{\mathrm{MS,obs}}} \right)^{\lambda}$$

Stellar Mass | SFR

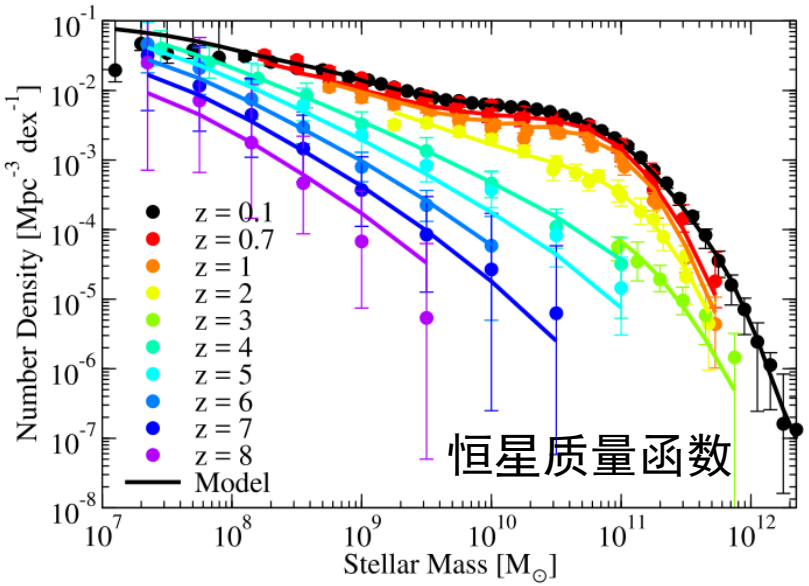
$$M_{\mathrm{H_2}} = \zeta M_{*}^{\nu} \left(\frac{\mathrm{SFR}}{\mathrm{SFR}_{\mathrm{MS,obs}}} \right)^{\eta}$$

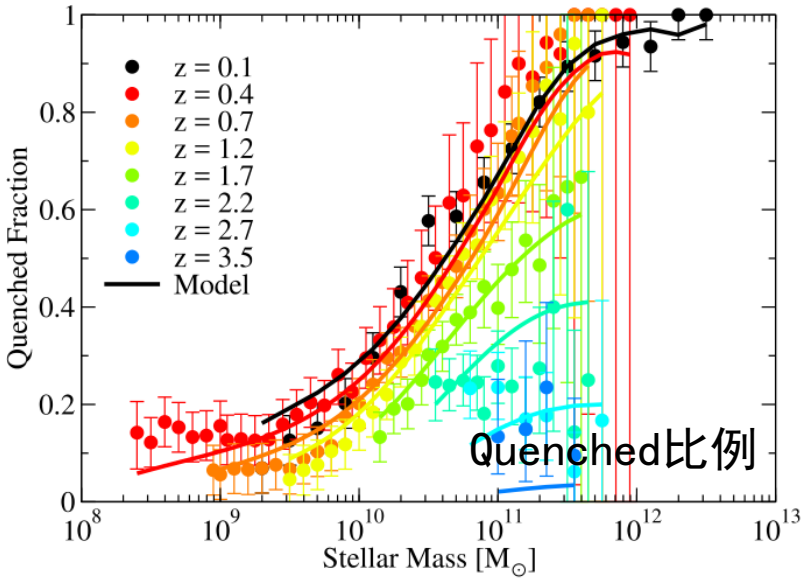
- 15 parameter Empirical Halo Model
- Redshift dependence included

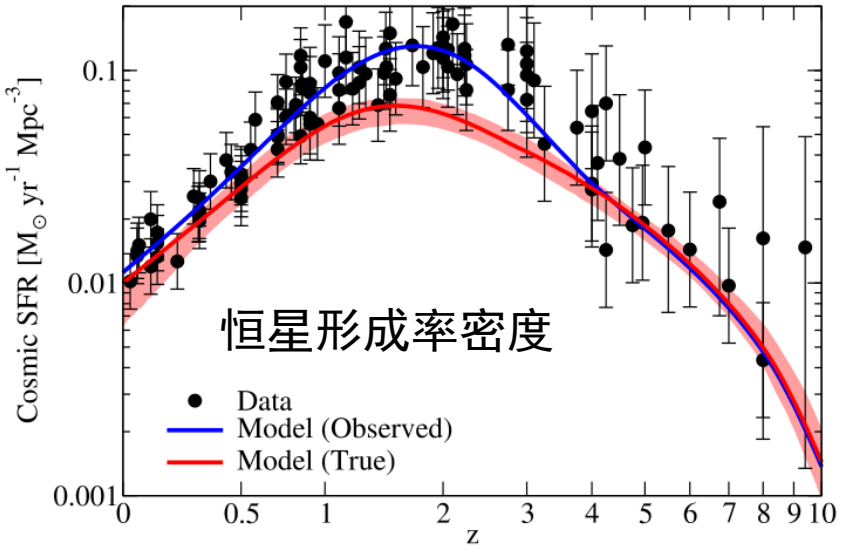
Base Model：UniverseMachine

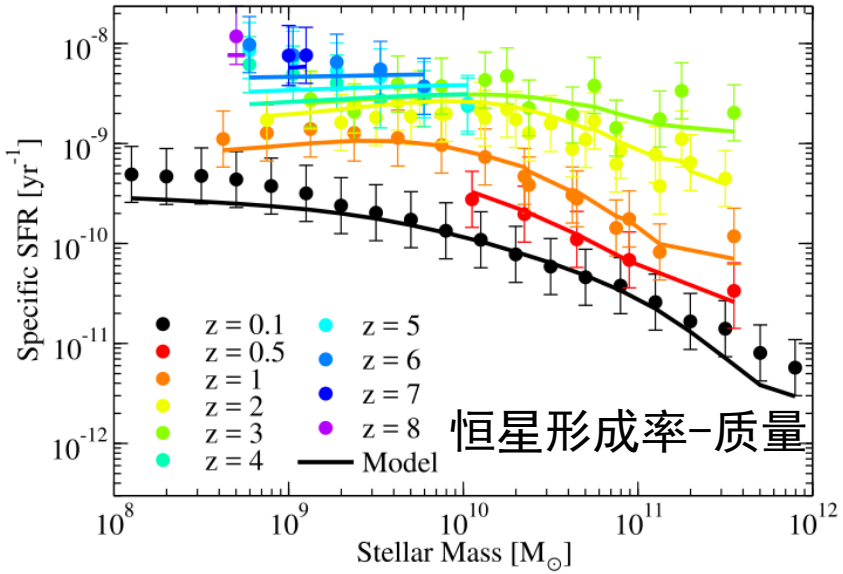
$P(SFR|M_h, \dot{M}_h, z)$

- Empirical Halo Model based on N-body simulations









Behroozi et al. (2019)

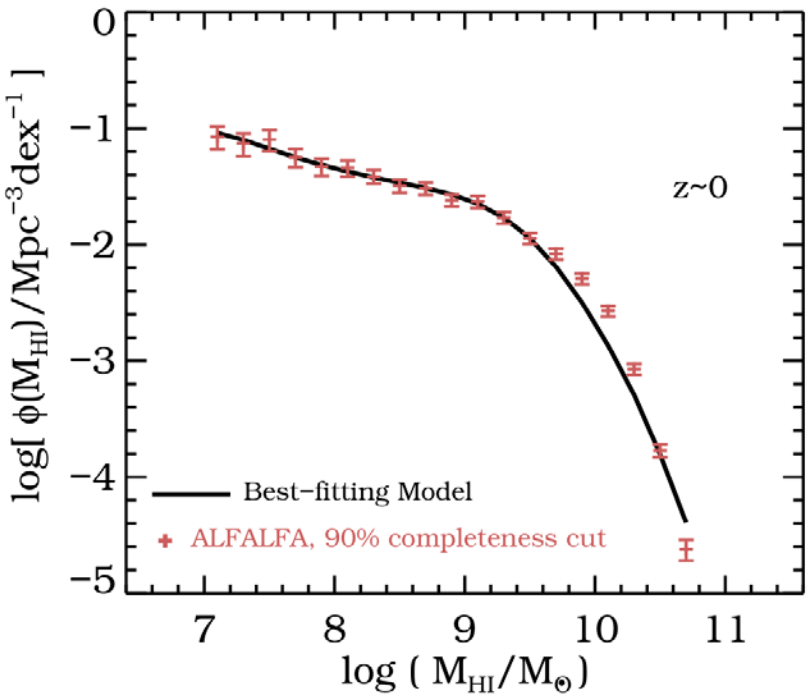
NeutralUniverseMachine：Model Fitting

Table 1. Observational Constraints

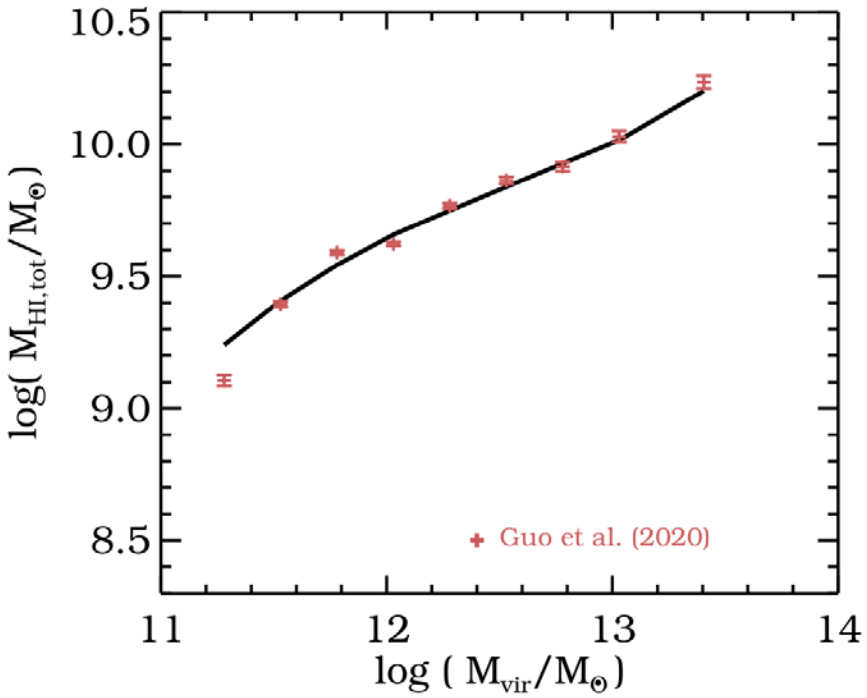
	Measurements	References	Redshifts
ALFALFA	H I Mass Function	Jones et al. (2018)	$z \sim 0$
	H I-Halo Mass Relation	Guo et al. (2020)	$z \sim 0$
	H I-Stellar Mass Relation	Guo et al. (2021)	$z \sim 0$
xCOLD GASS	H_2 Mass Function	Fletcher et al. (2021)	$z \sim 0$
	H_2-Stellar Mass Relation	Saintonge et al. (2017)	$z \sim 0$
	H_2-to-H I mass ratio	Catinella et al. (2018)	$z \sim 0$
GMRT HI stacking	H I-Stellar Mass Relation	Chowdhury et al. (2022)	$z \sim 1.1$
	cosmic H I density	Walter et al. (2020)	$0 < z < 5$
	cosmic H_2 density	Walter et al. (2020)	$0 < z < 5$

NeutralUniverseMachine：Model Fitting

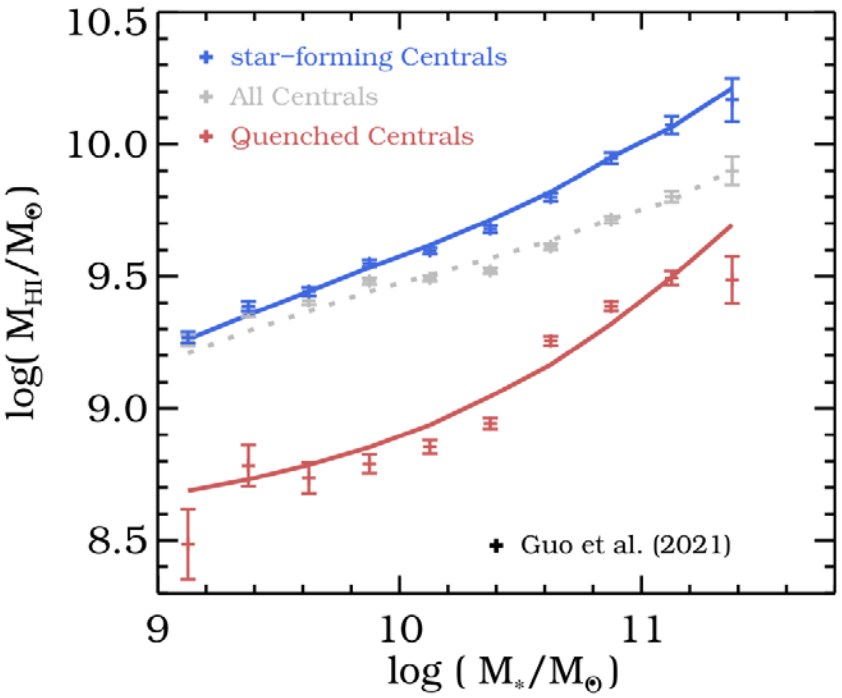
HI Mass Function



HI-Halo Mass Relation



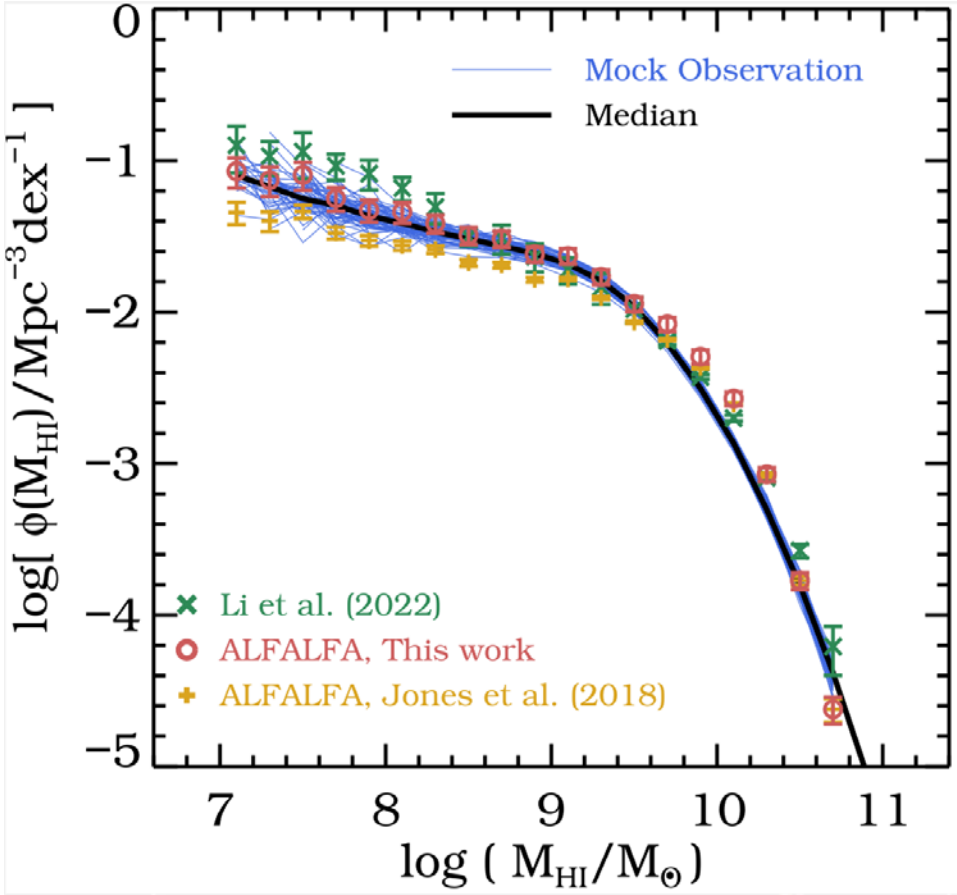
HI-Stellar Mass Relation



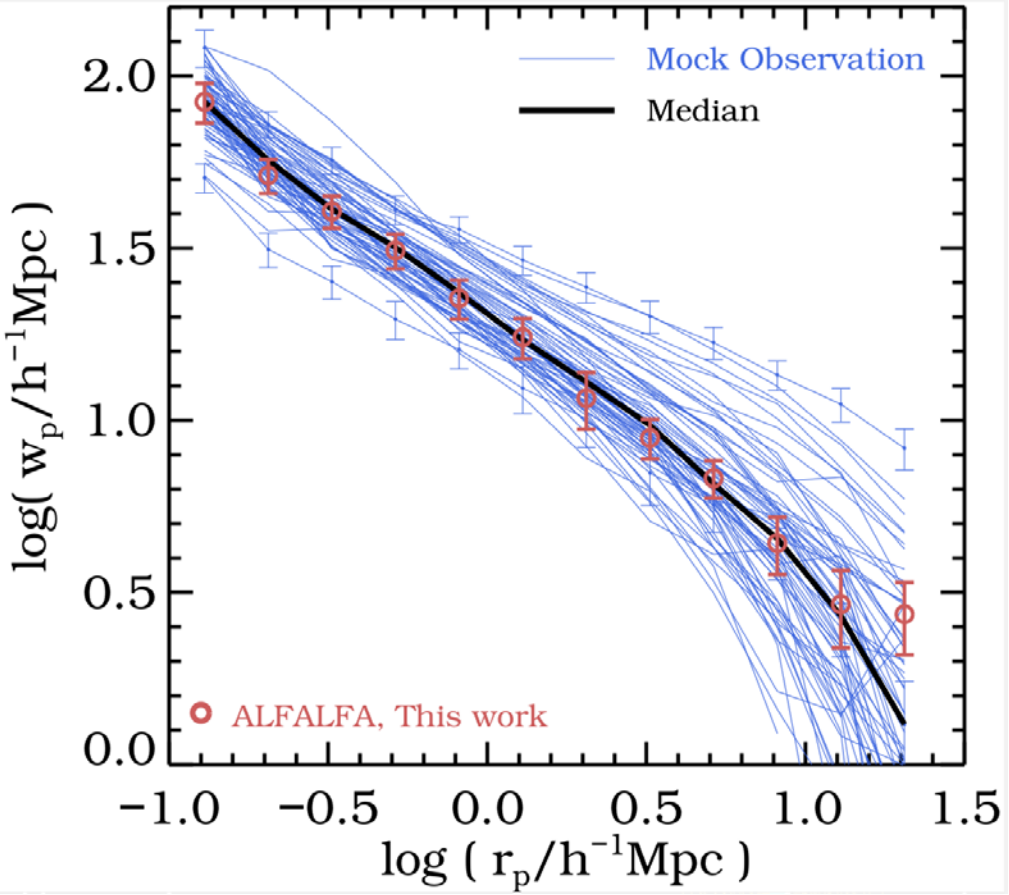
Guo et al. (2023)

NeutralUniverseMachine：Model Fitting

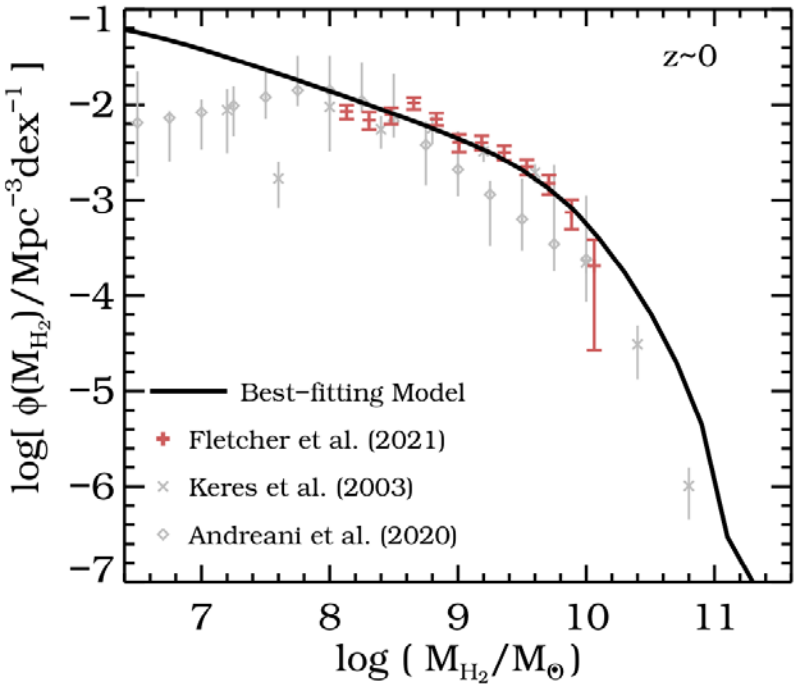
Corrected HI Mass Function



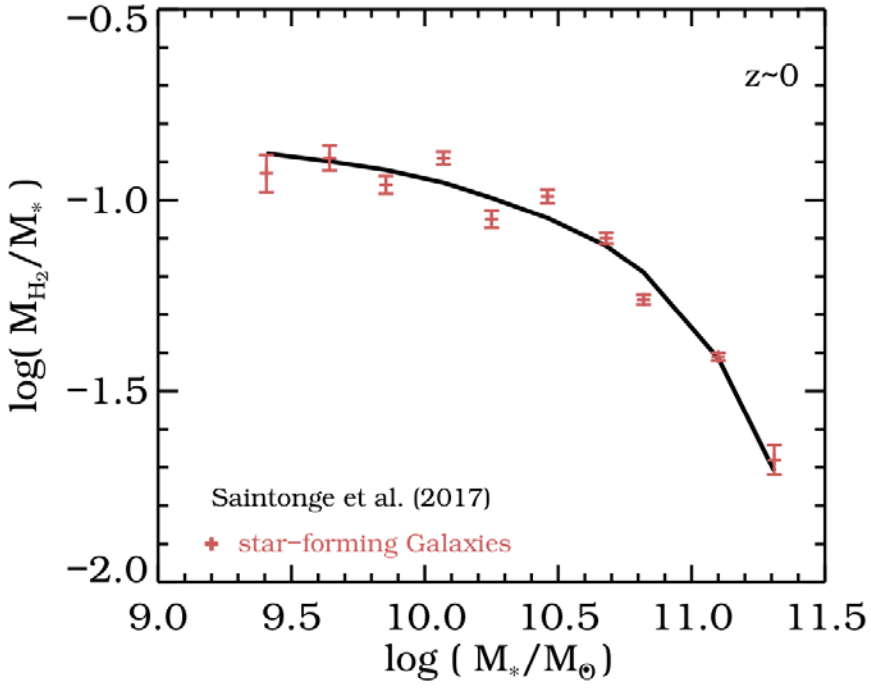
HI Clustering



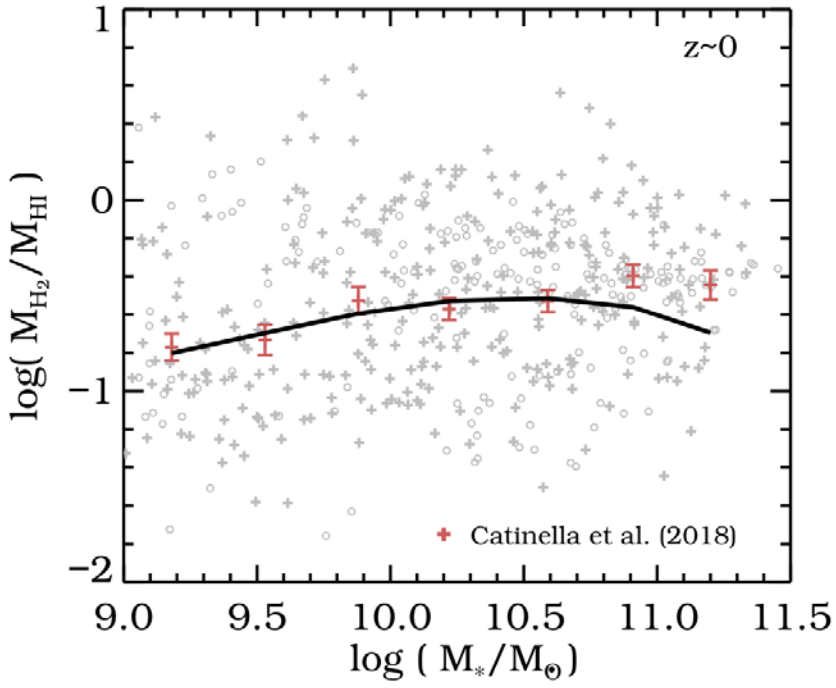
NeutralUniverseMachine： Model Fitting



H2 Mass Function

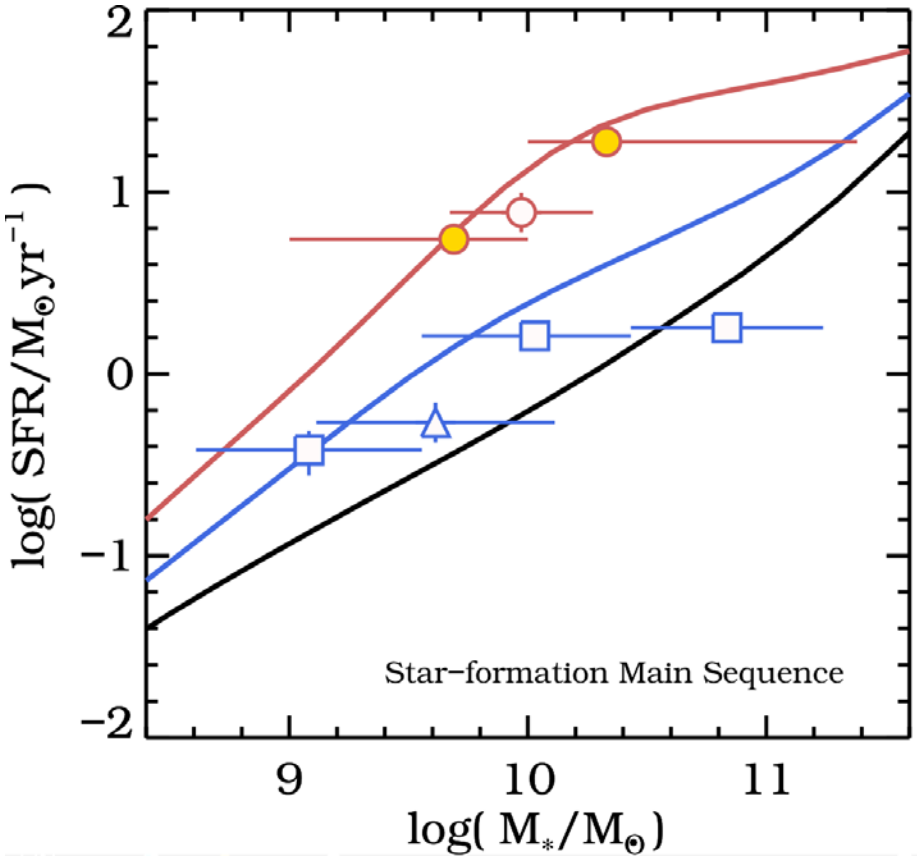


H2-Stellar Mass Relation

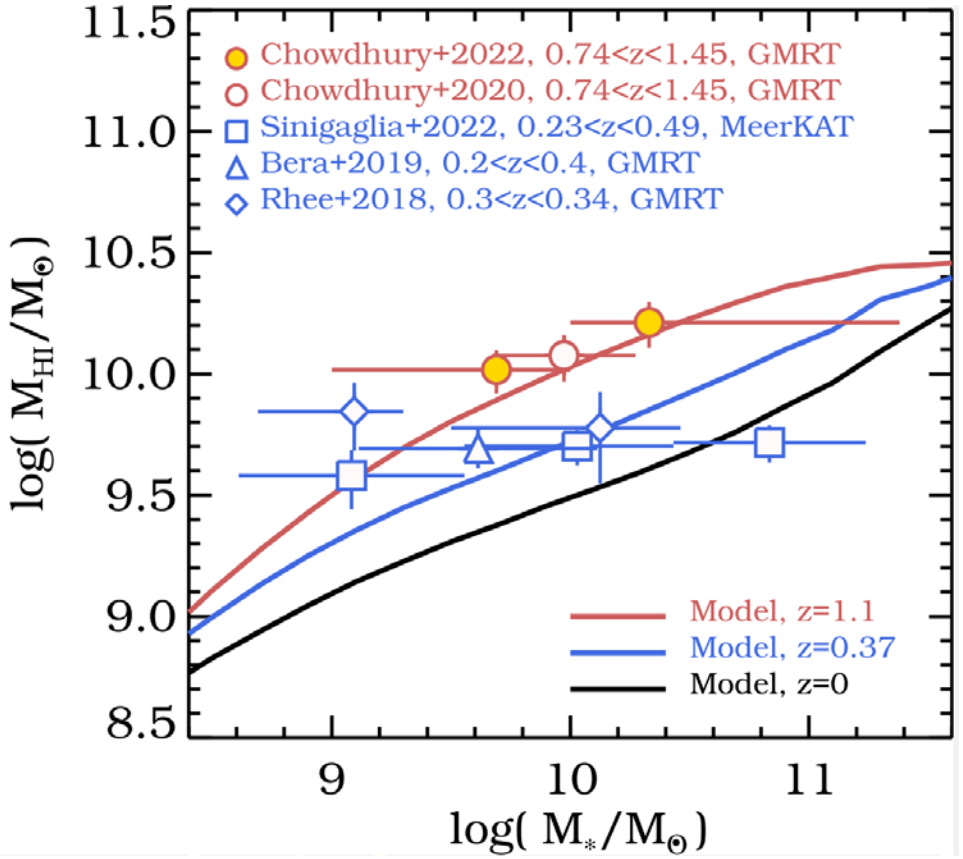


H2/HI Ratio

NeutralUniverseMachine： Model Fitting

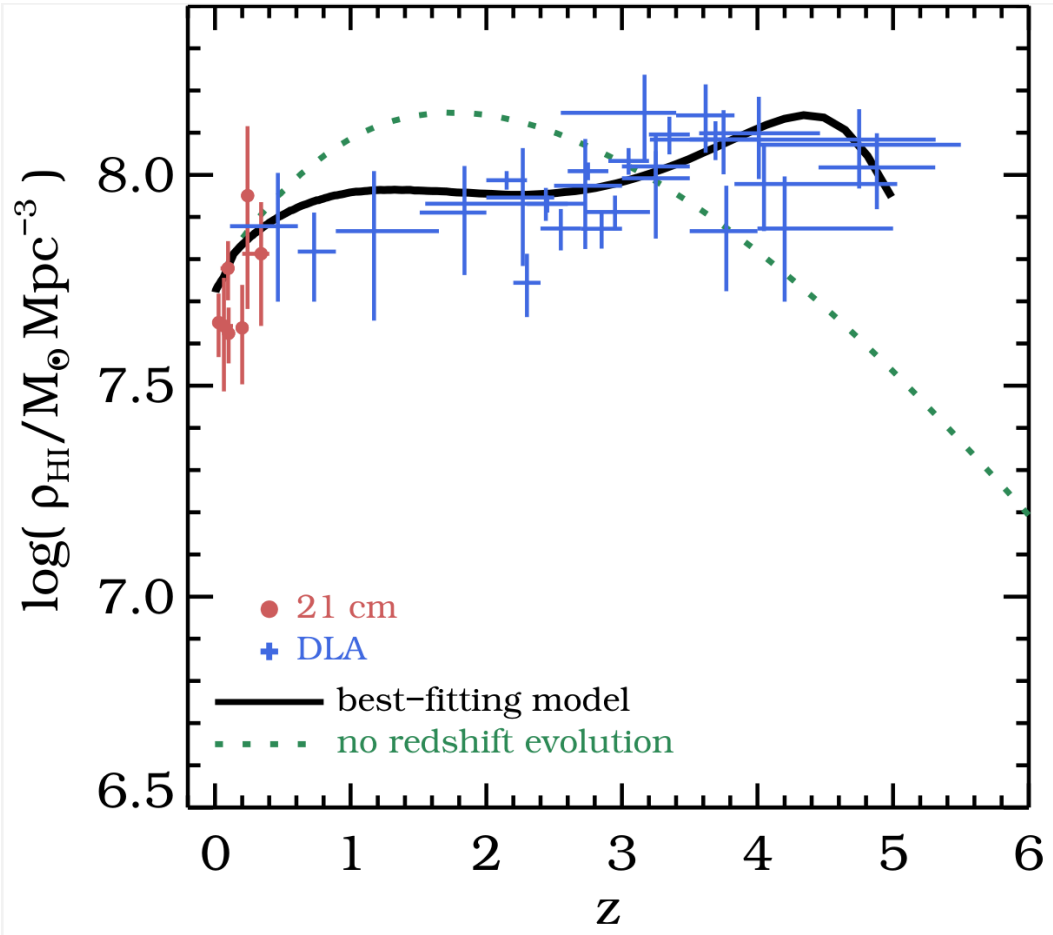


SFR vs M*

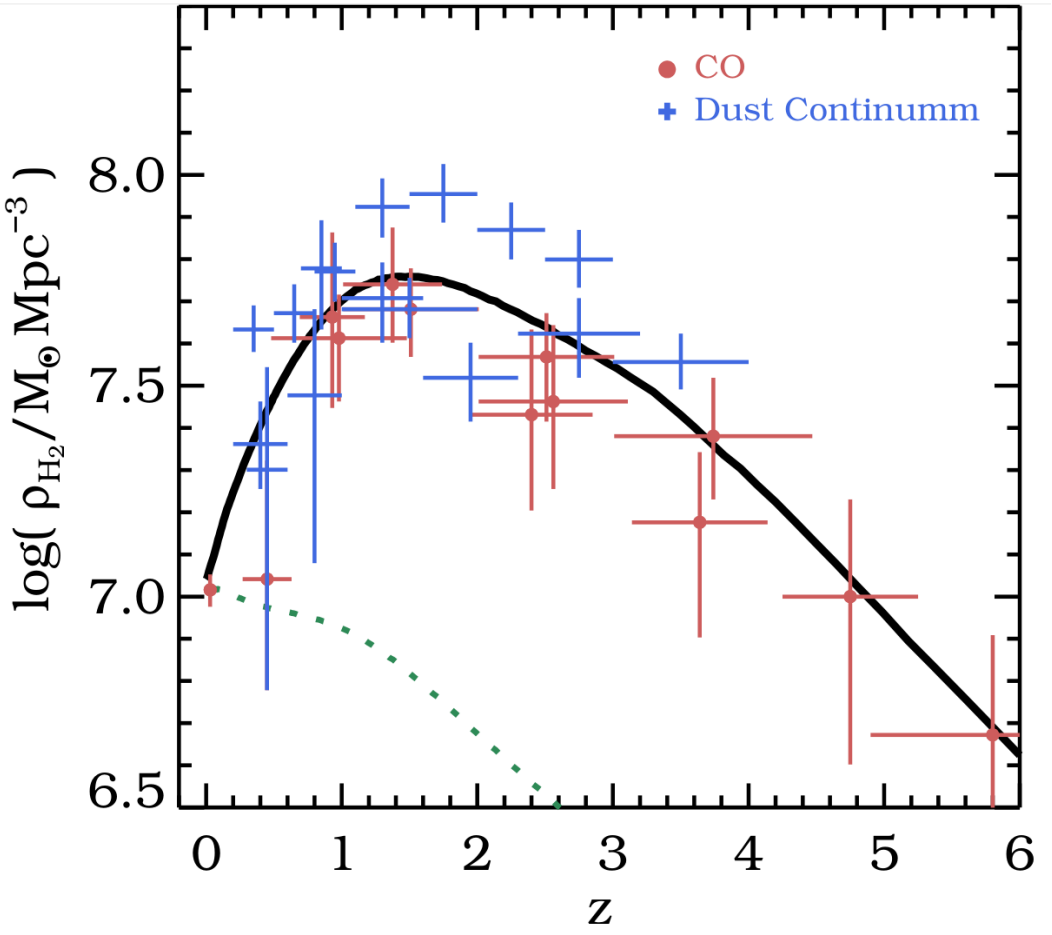


HI-Stellar Mass Relation at high redshifts

NeutralUniverseMachine： Model Fitting

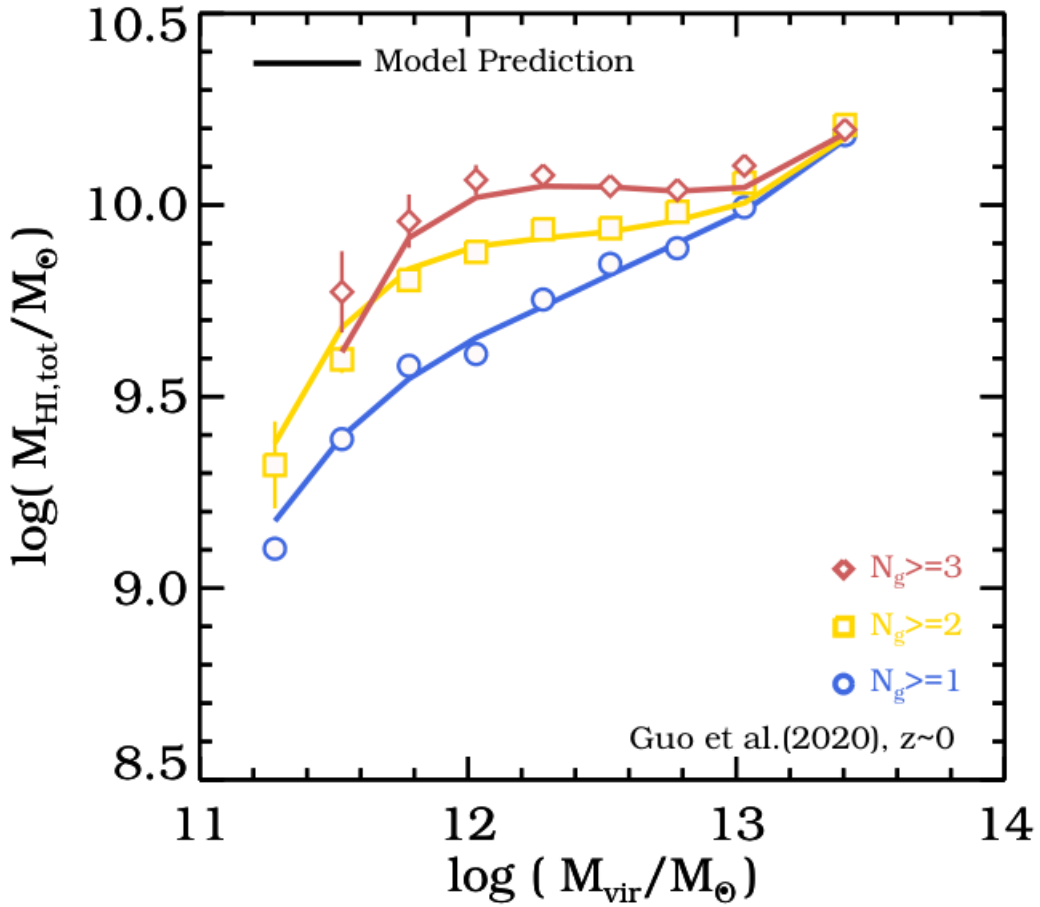


Cosmic HI Gas Density

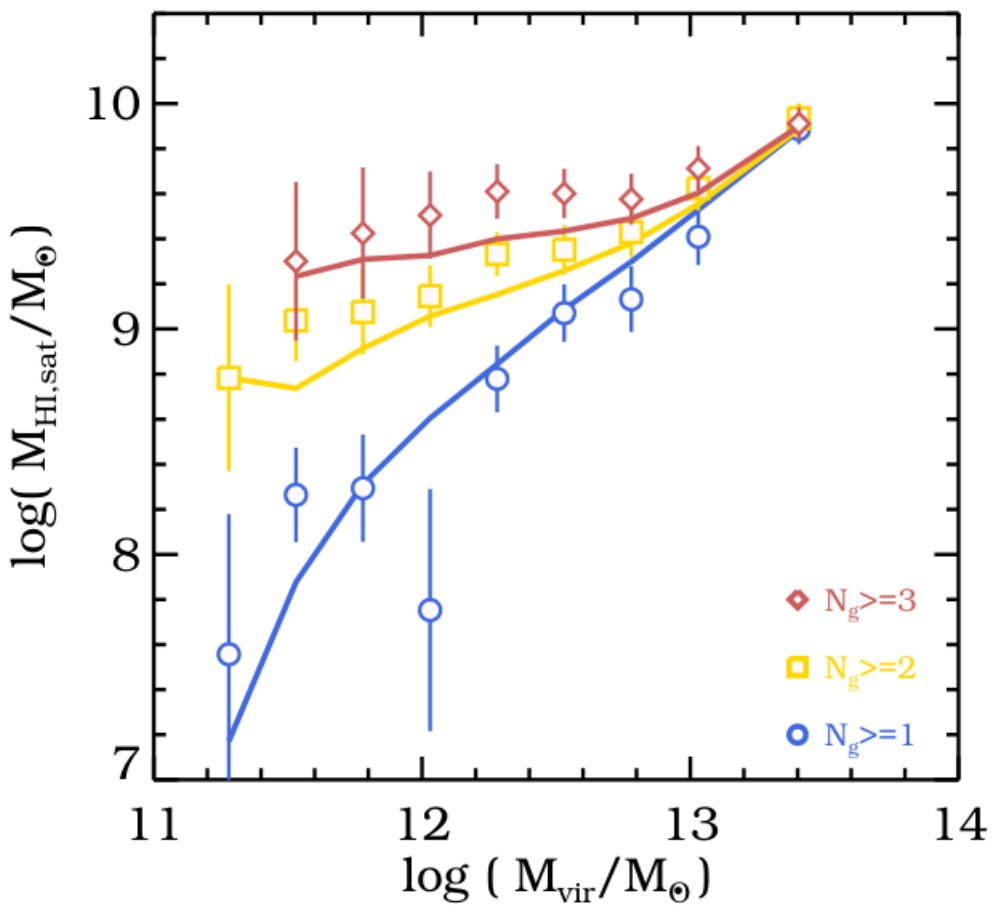


Cosmic H2 Gas Density

NeutralUniverseMachine： Model Prediction

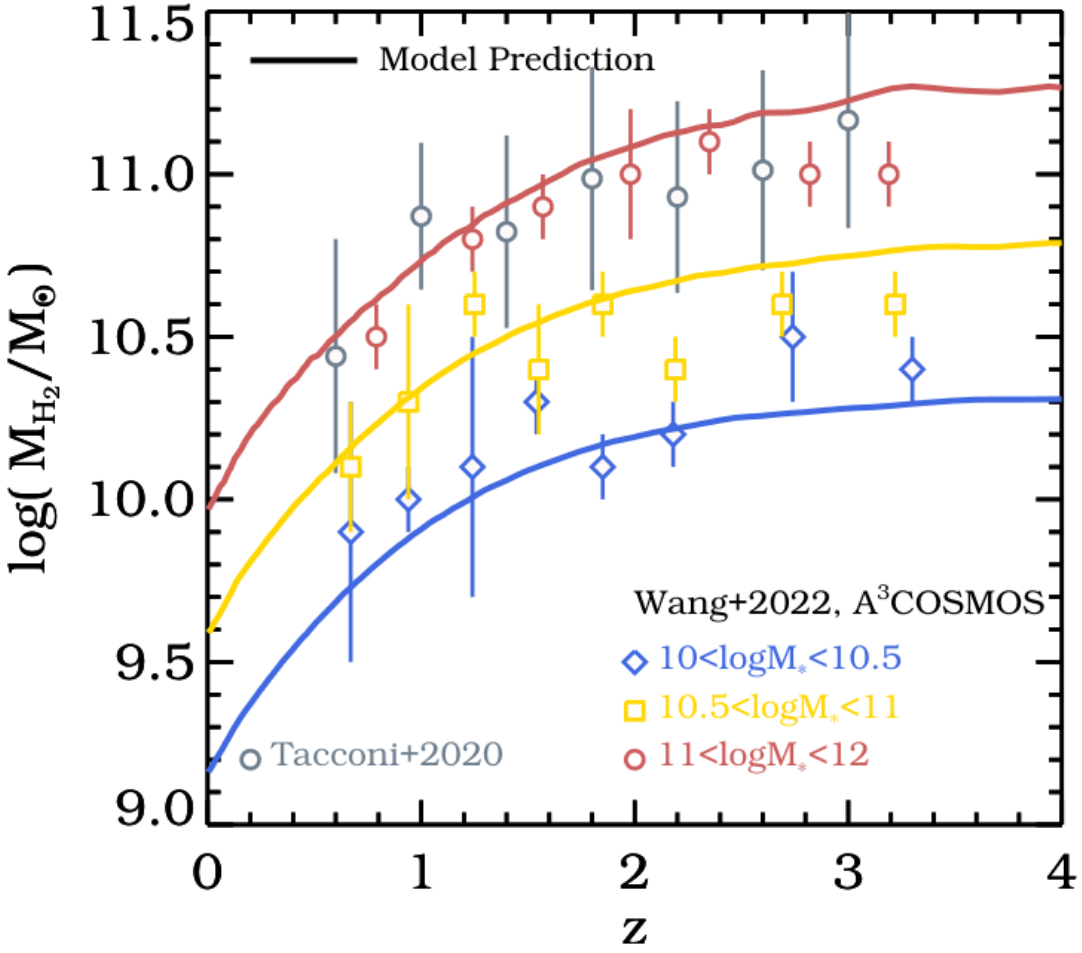


HI-Halo Mass Relation



For satellites

NeutralUniverseMachine： Model Prediction

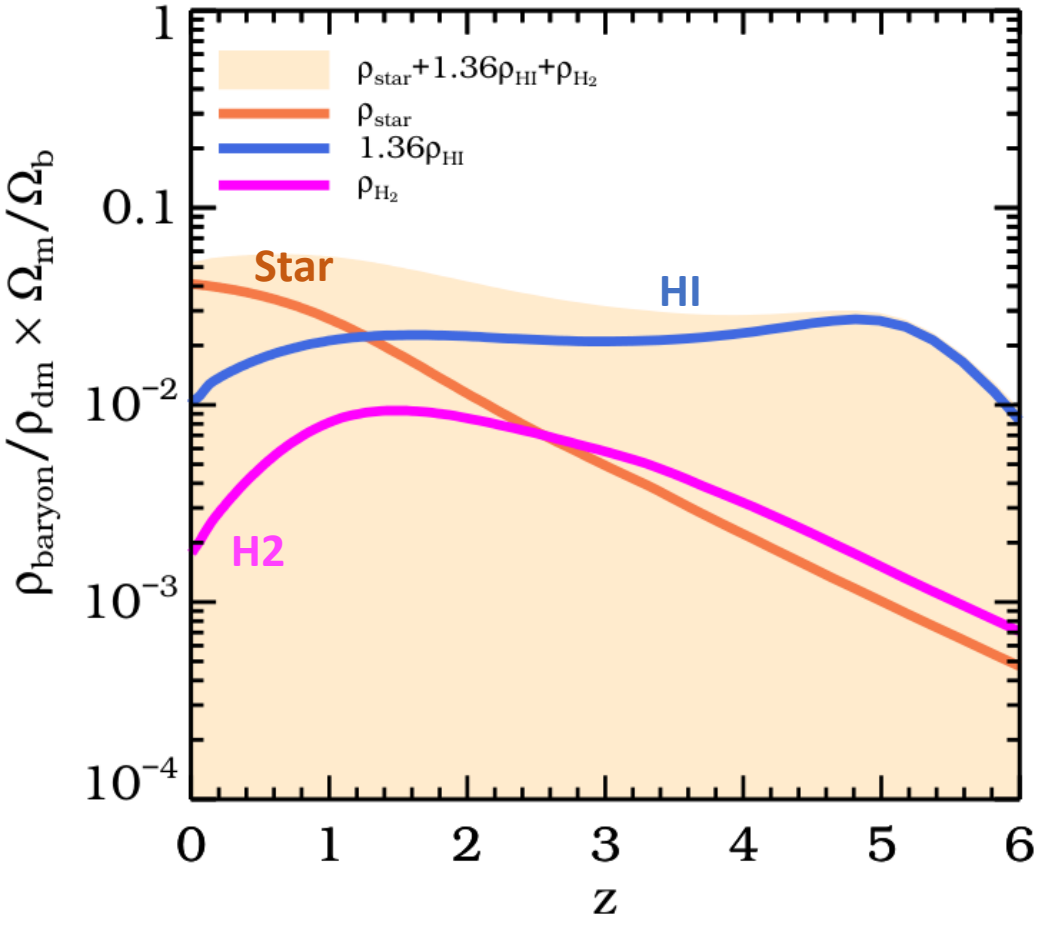


H2-Stellar Mass Relation

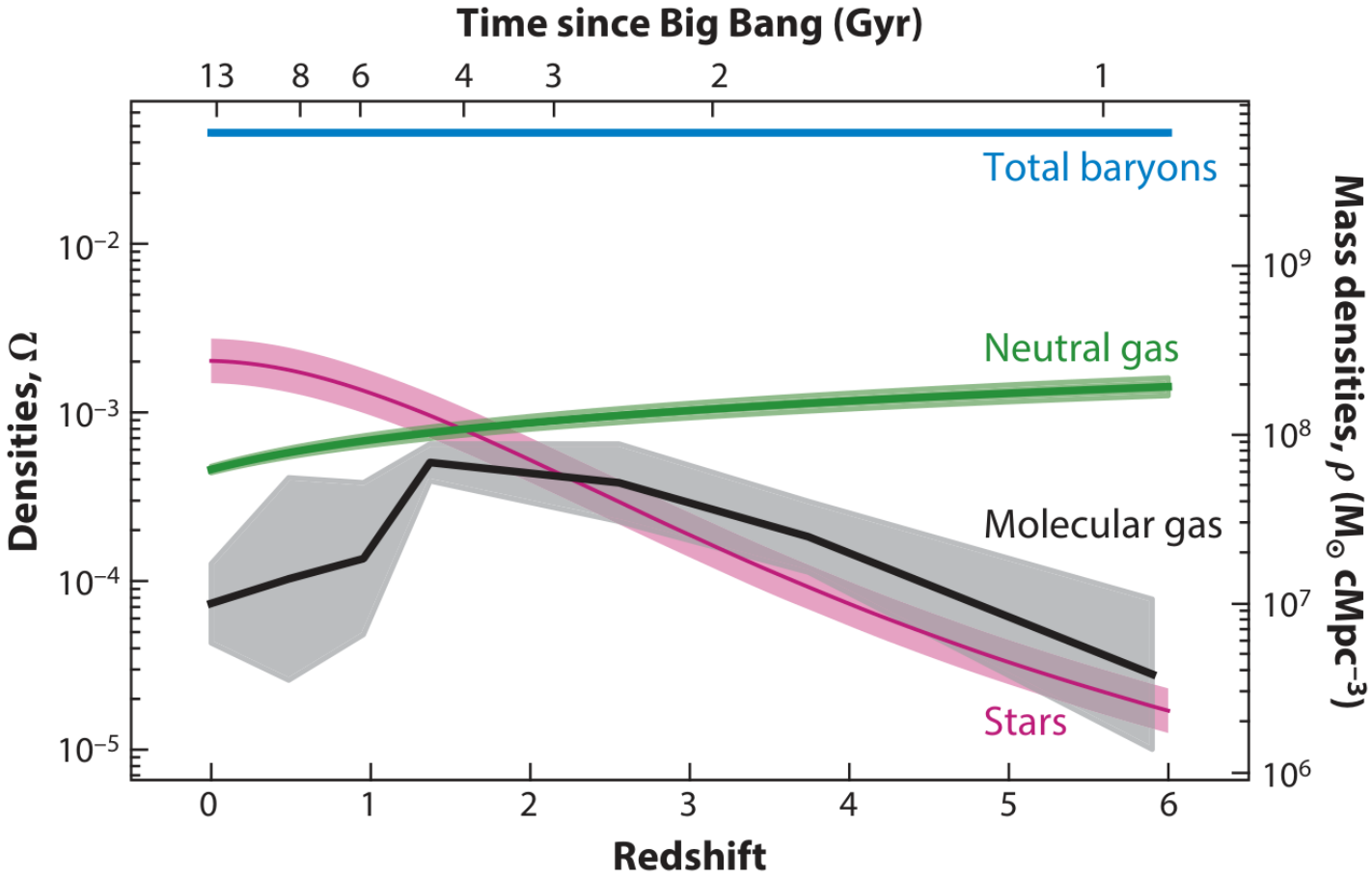
A^{3}COSMOS:

ALMA observation in COSMOS area

NeutralUniverseMachine： Model Prediction

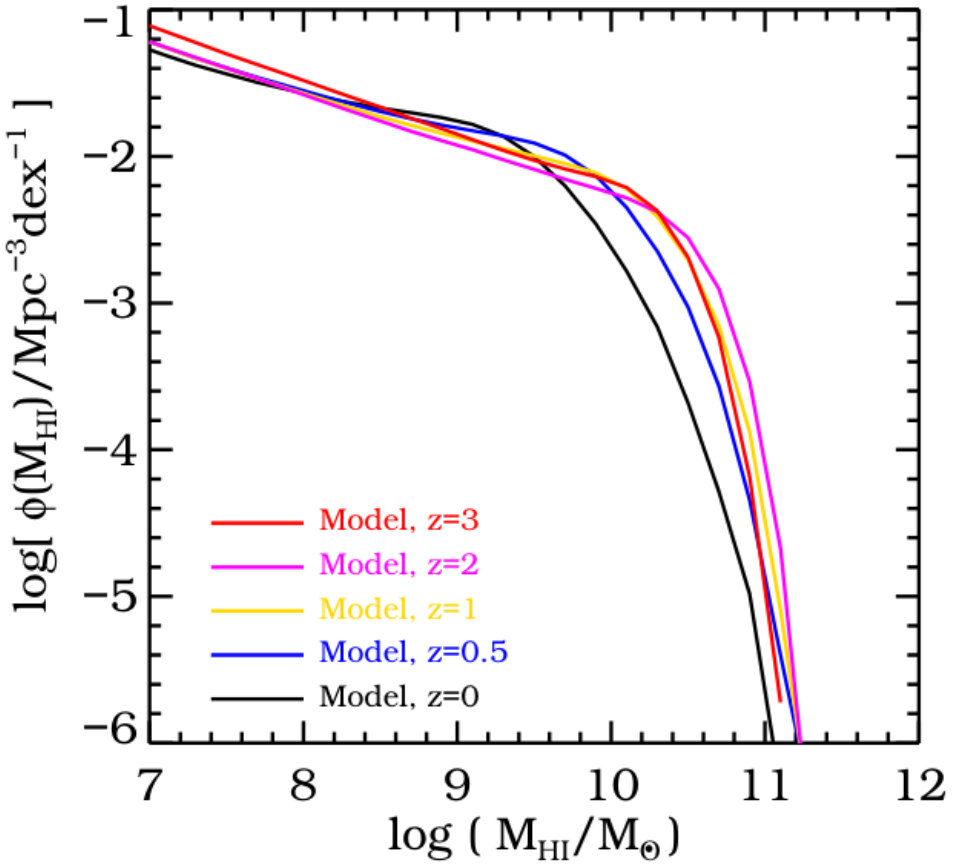


Evolution of baryon content

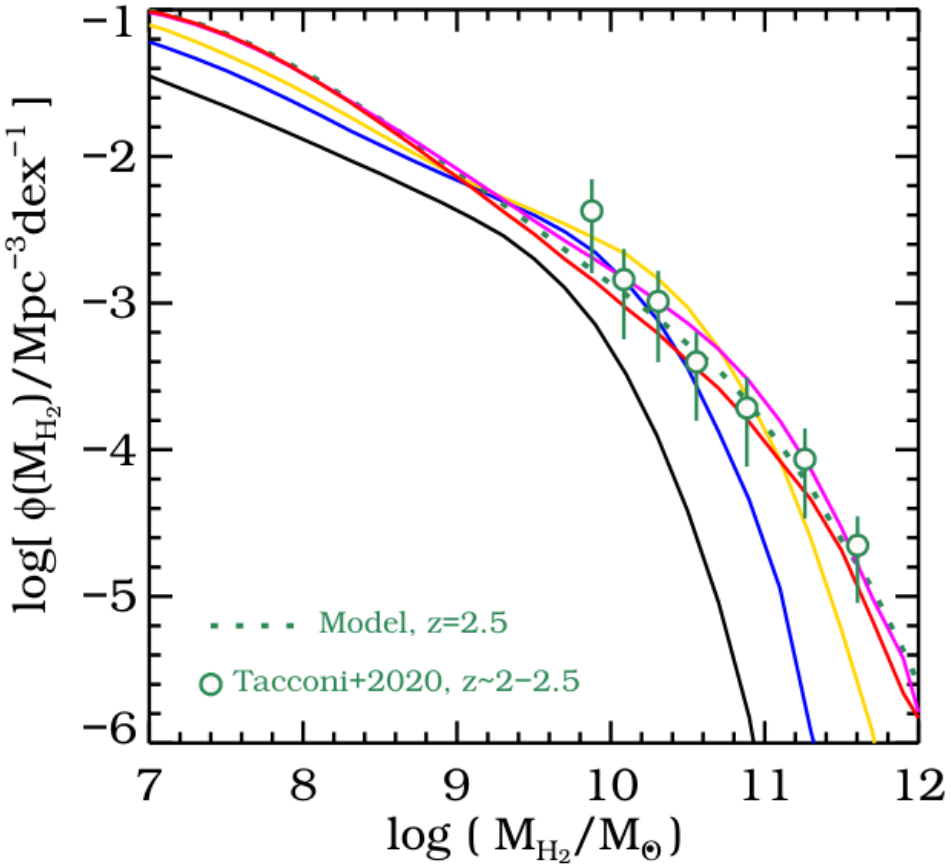


Peroux & Howk, 2020, ARA&A

NeutralUniverseMachine： Model Prediction

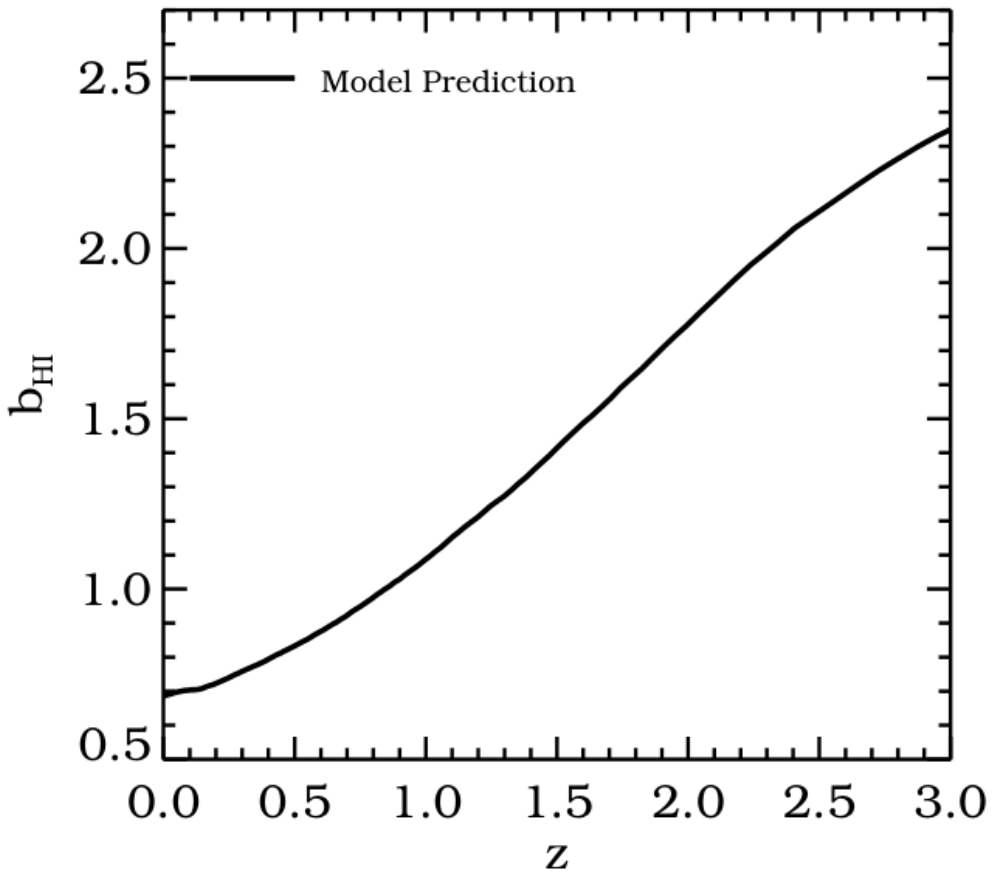


Evolution of HI Mass Function

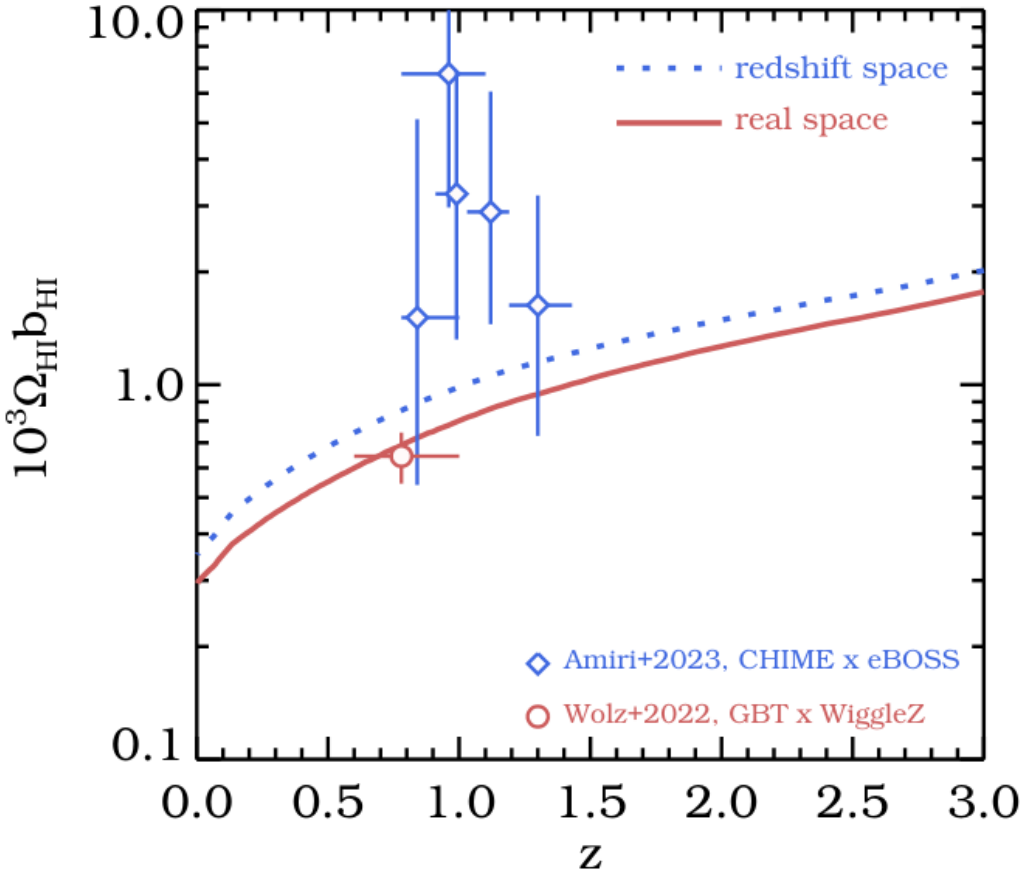


Evolution of H2 Mass Function

NeutralUniverseMachine： Model Prediction



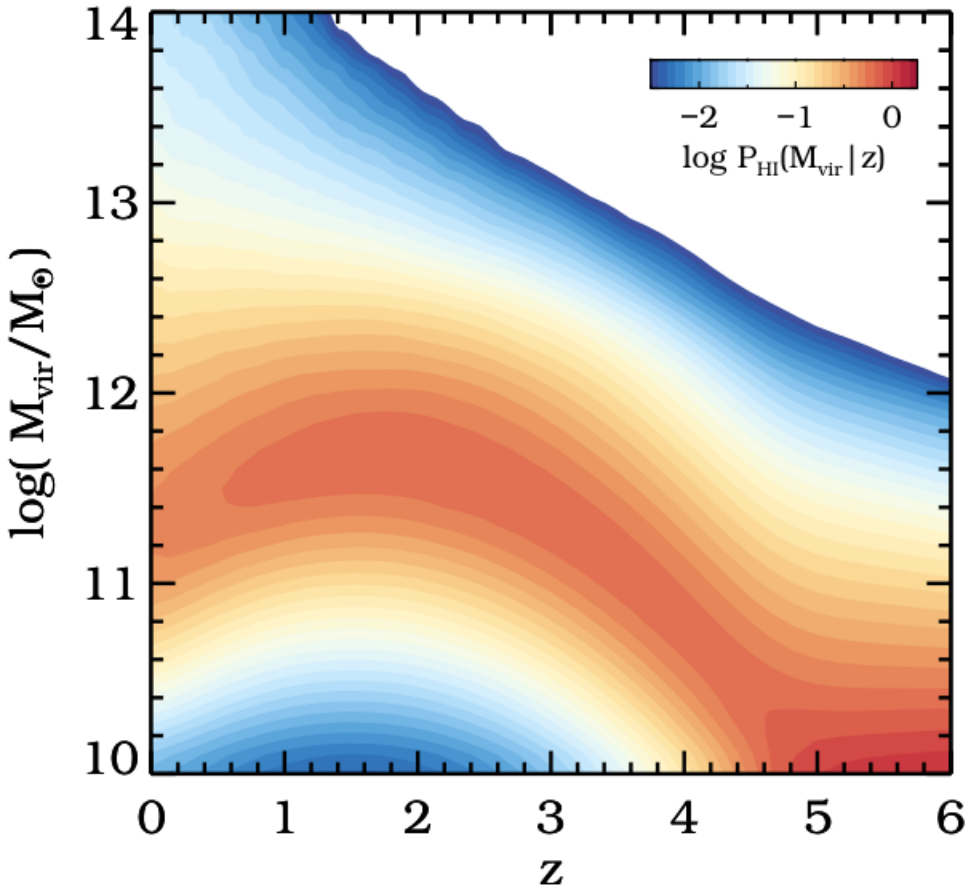
HI bias



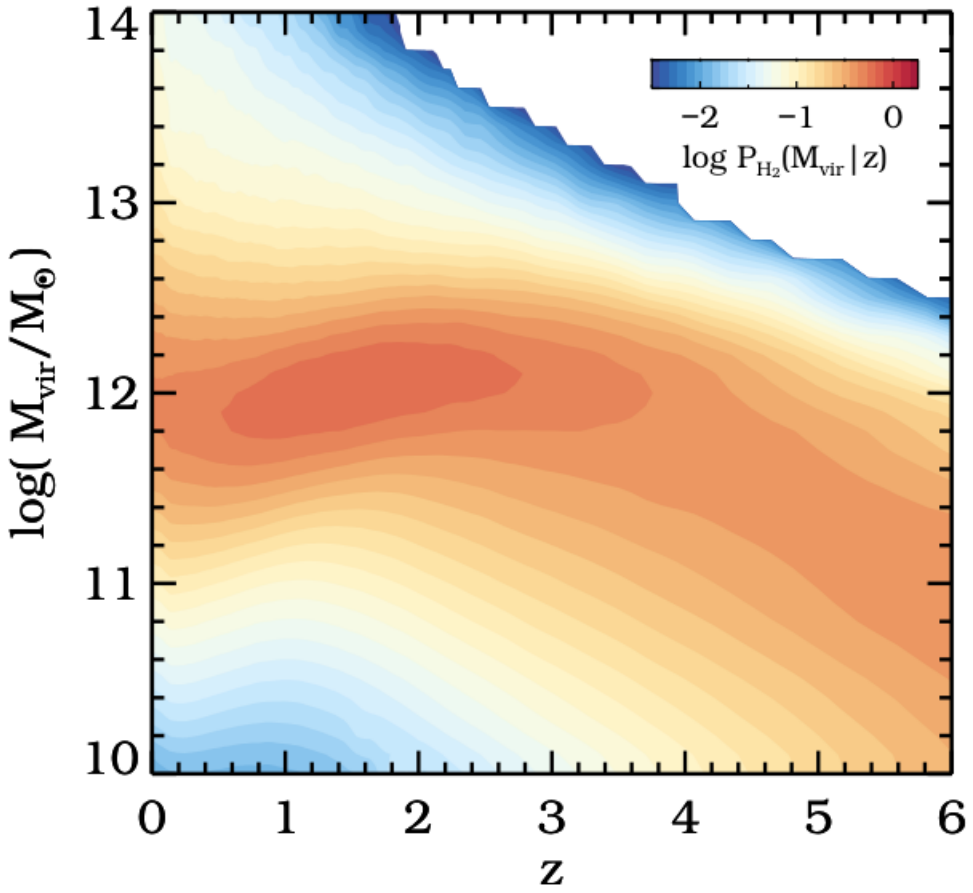
HI intensity mapping

See Zhixing Li's talk tomorrow for the HI power spectrum predictions!

NeutralUniverseMachine： Model Prediction



HI distribution



H2 distribution

NeutralUniverseMachine: Summary

- Based on halo models of HI and H2 gas, it is able to match and predict the distribution of cold gas in the post-reionization era, including:

- （1）HI-halo Mass relation, HI/H2 mass functions, H2-to-HI ratios, HI/H2-stellar mass relations, cosmic HI/H2 densities

- （2）predictions for HI-Halo mass relations, HI mass functions, HI clustering, HI bias