中国科学院上海天文台
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Cosmic Evolution of Atomic and Molecular Gas within Dark Matter Halos

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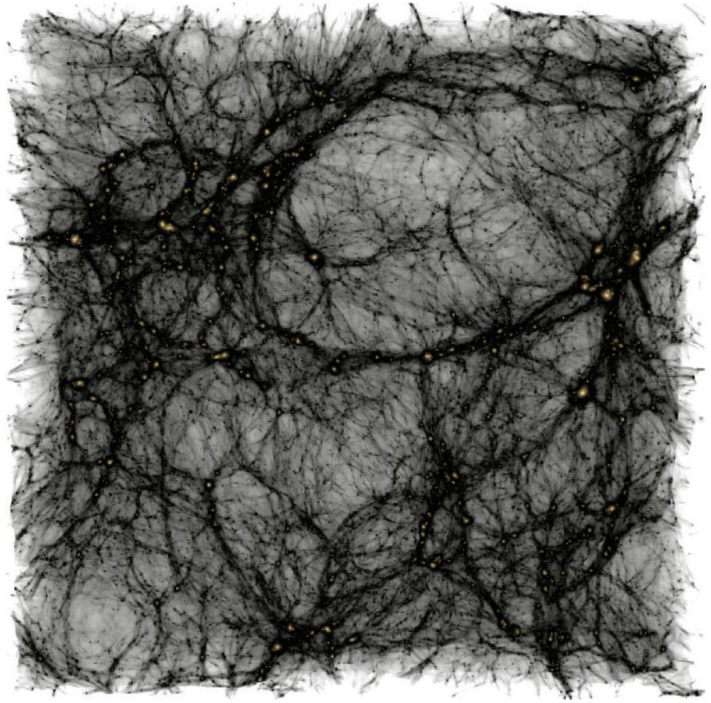
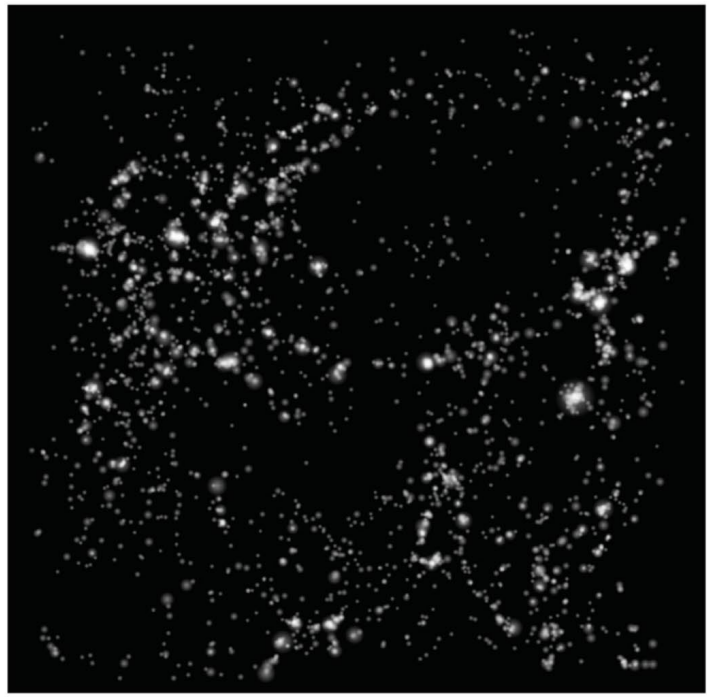


Galaxy–halo connection



Approaches to modeling the galaxy–halo connection

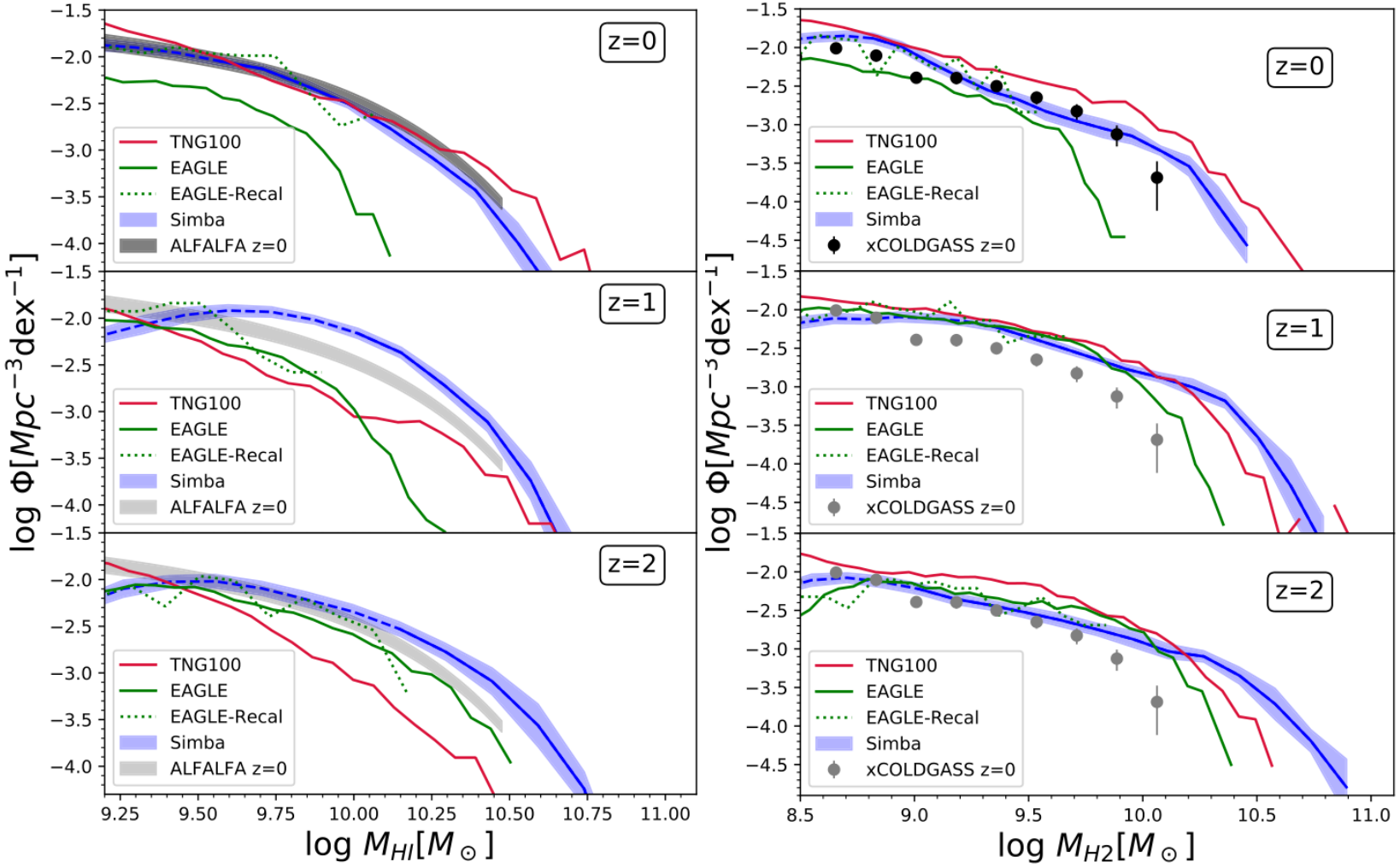
← Physical models — Empirical models →

Hydrodynamical simulations	Semianalytic models	Empirical forward modeling	Subhalo abundance modeling	Halo occupation models
Simulate halos and gas; star formation and feedback recipes	Evolution of density peaks plus recipes for gas cooling, star formation, feedback	Evolution of density peaks plus parameterized star formation rates	Density peaks (halos and subhalos) plus assumptions about galaxy–(sub)halo connection	Collapsed objects (halos) plus model for distribution of galaxy number given host halo properties

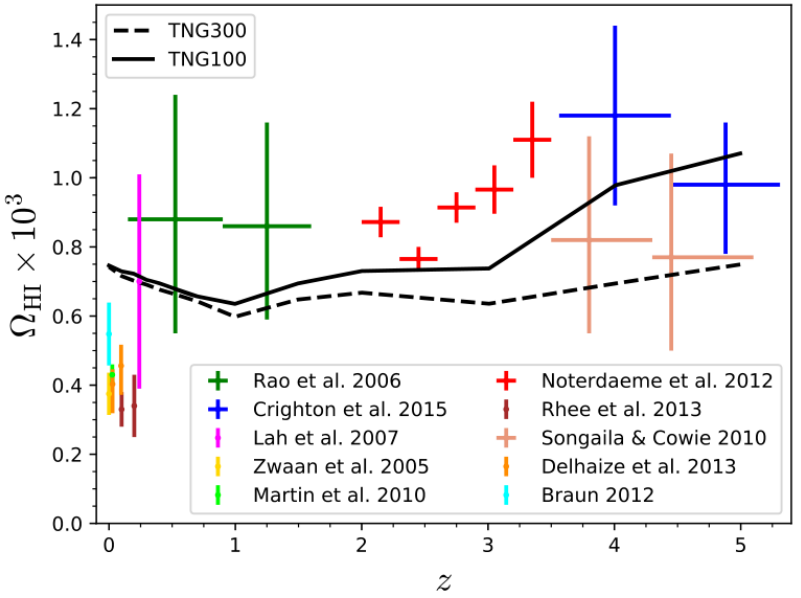
- Wechsler & Tinker (2018)

- The Galaxy-halo connection has been well explored for the stellar mass components
- But not well studied for the gas component

Hydrodynamical Models



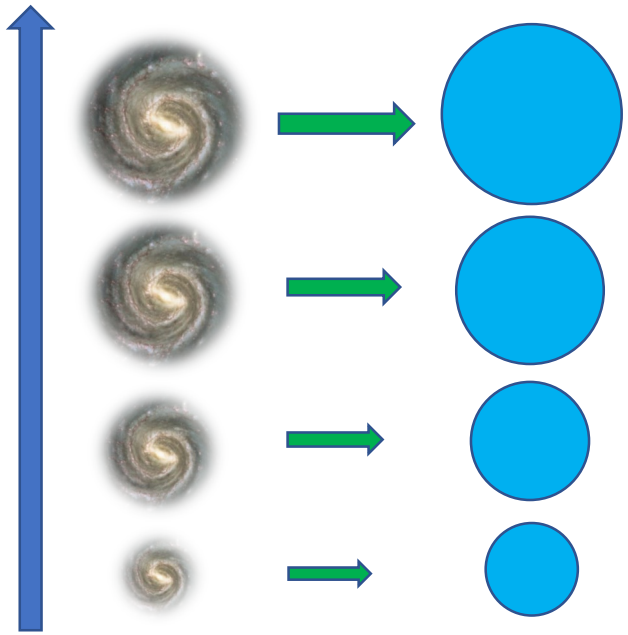
Dave et al. (2020)



Villaescusa-Navarro et al. (2018)

- Significant differences between simulations!

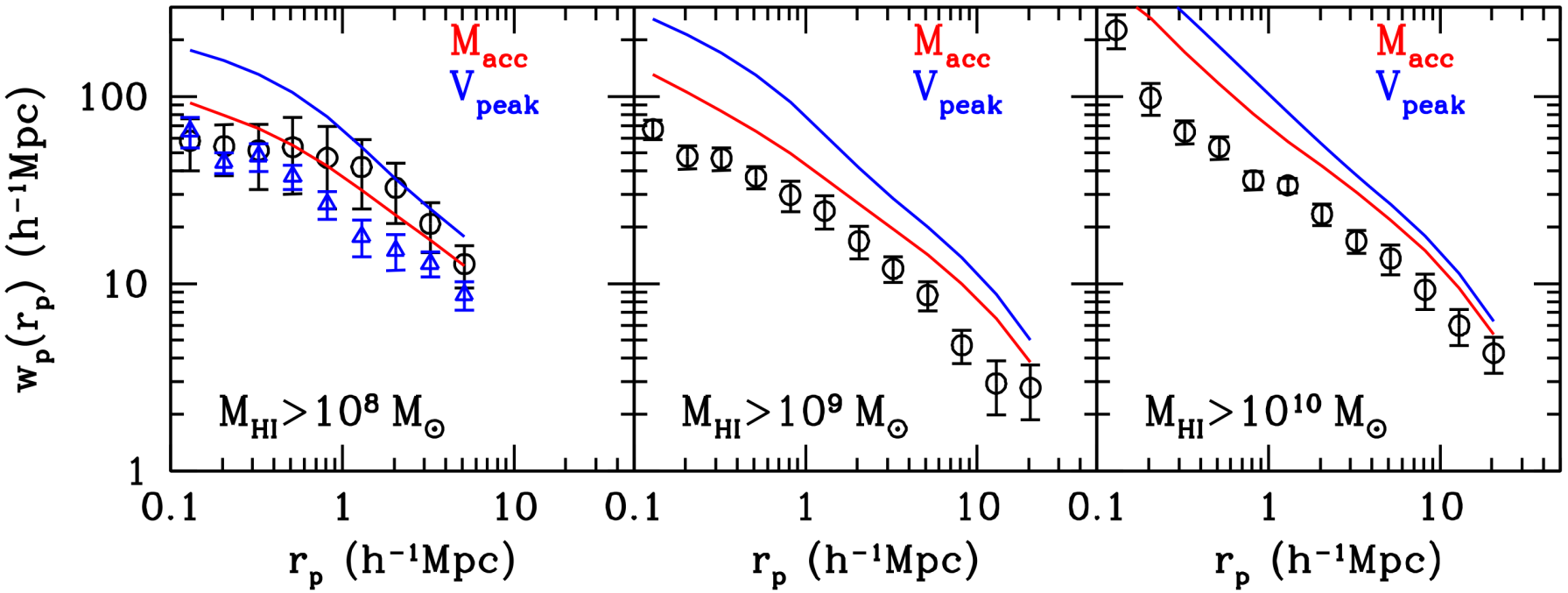
Abundance Matching Model



Rank order by HI Mass

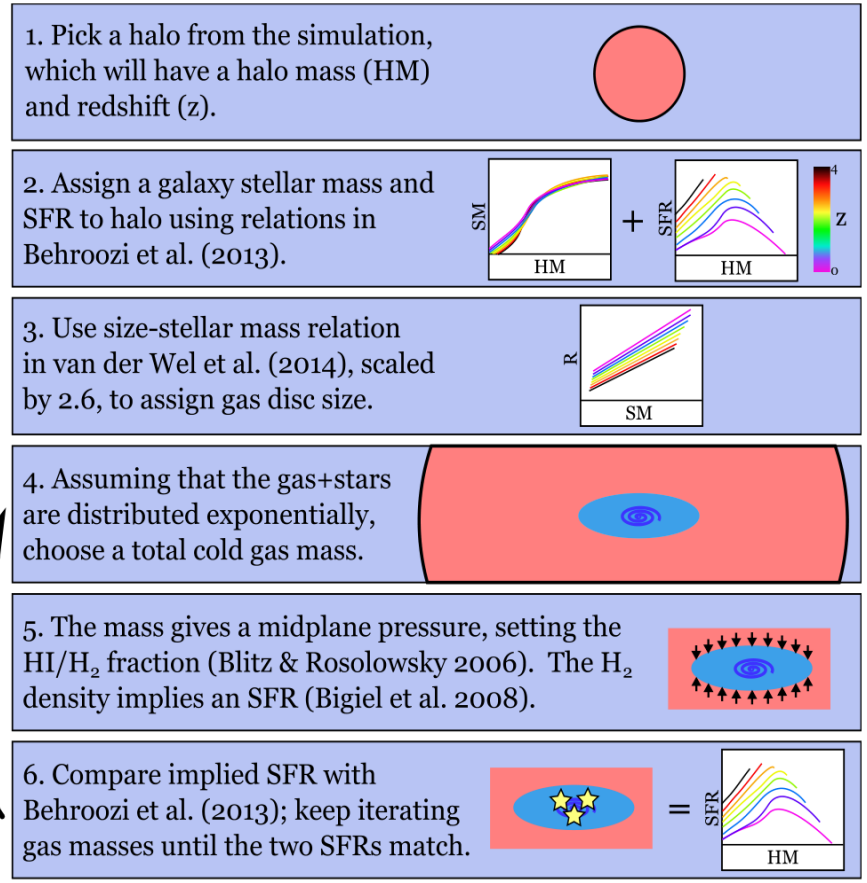
Rank order by halo maximum circular velocity

- Abundance Matching overpredicts the HI clustering!



Guo et al. (2017)

Empirical Cold Gas Model



Empirical Halo Model

M*、SFR distribution

Galaxy size-mass relation

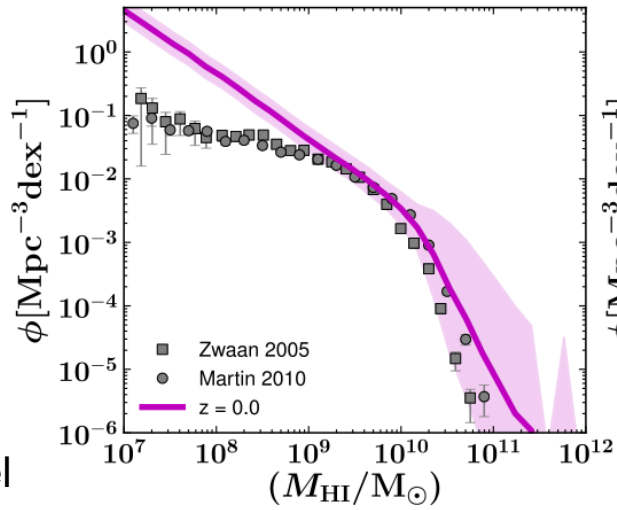
Stellar+gas disk model

Gas distribution

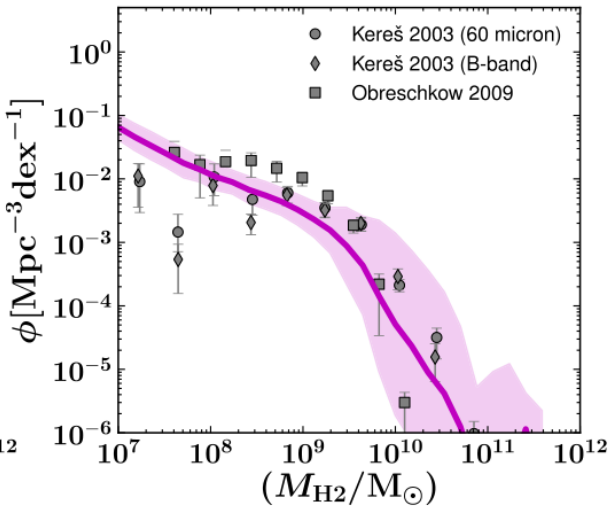
Fit SFR

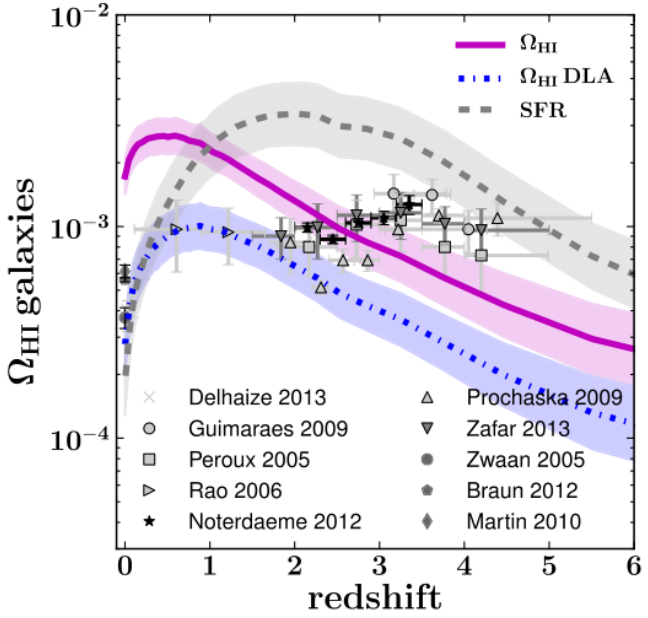
Popping et al. (2015)

HI Mass Function



H2 Mass Function





HI density

Conditional Stellar Mass Function

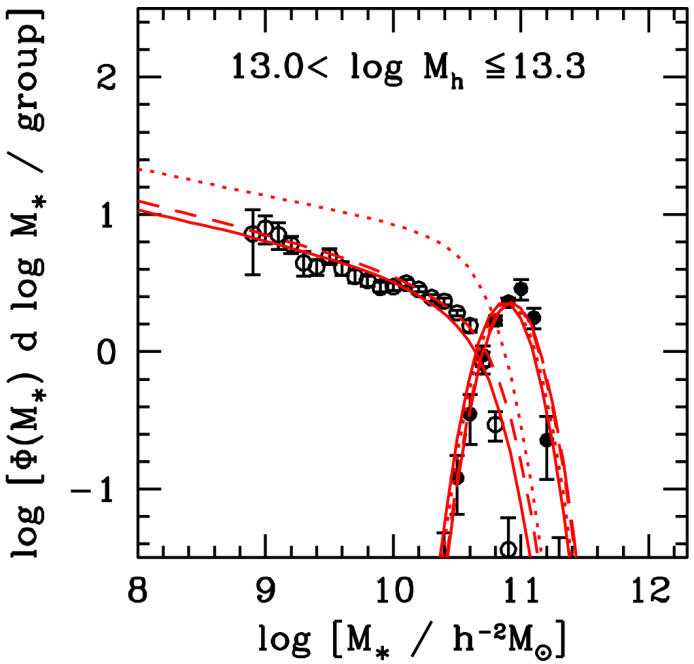
$$\Phi_{\rm c}(M_*|M,z) = \frac{1}{\sqrt{2\pi}\sigma_c}\exp\left[-\frac{(\log M_*/M_{*,c})^2}{2\sigma_c^2}\right]$$

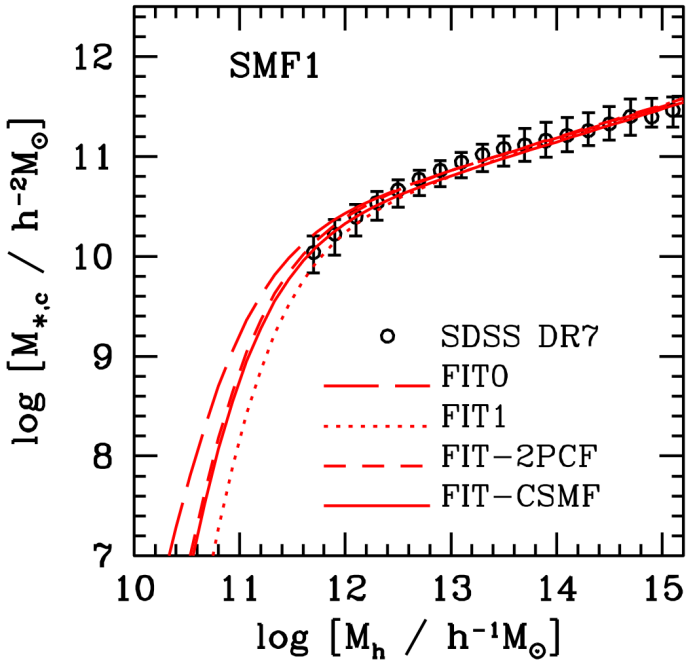
$$M_{*,c} = M_{*,0}\frac{(M/M_1)^{\alpha+\beta}}{(1+M/M_1)^{\beta}}$$

$$\Phi(M_*,z) = \int_0^\infty \Phi(M_*|M,z)\, n_{\rm h}(M,z)\, dM,$$

$$\langle N|M,z\rangle = \int_{M_{*,1}}^{M_{*,2}} \Phi(M_*|M,z)\, dM_*$$

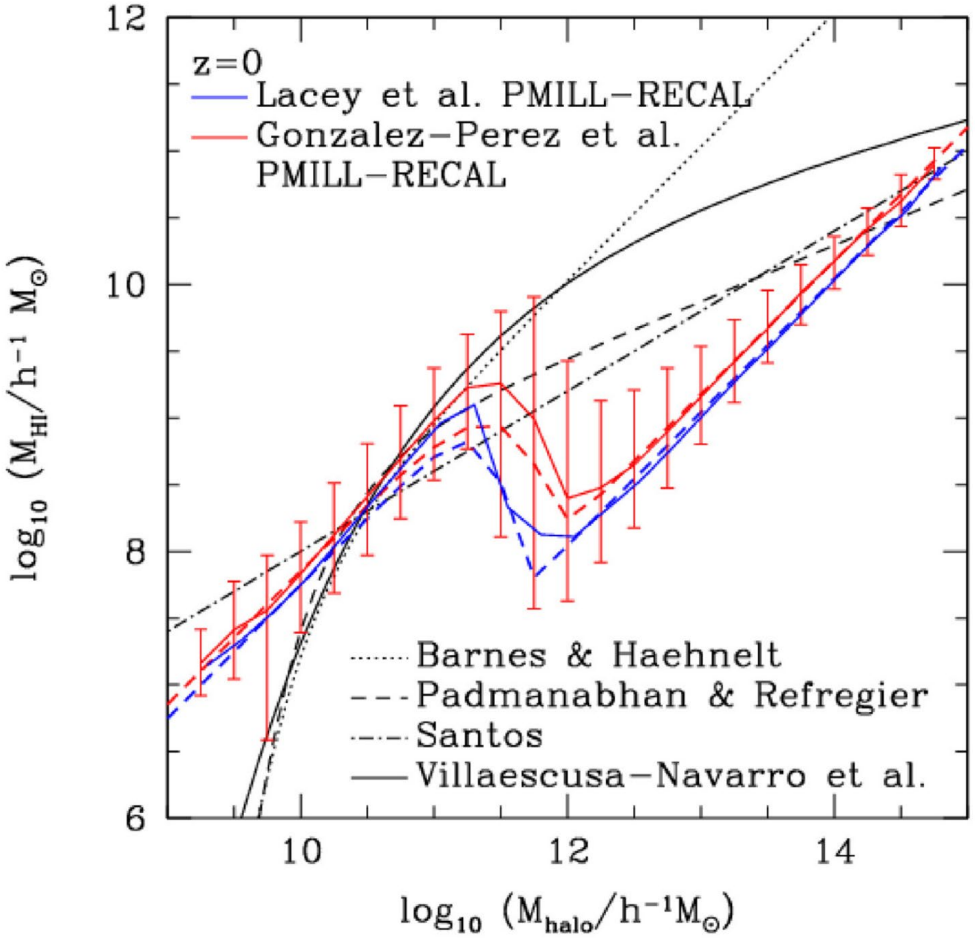
- Yang et al. (2012)

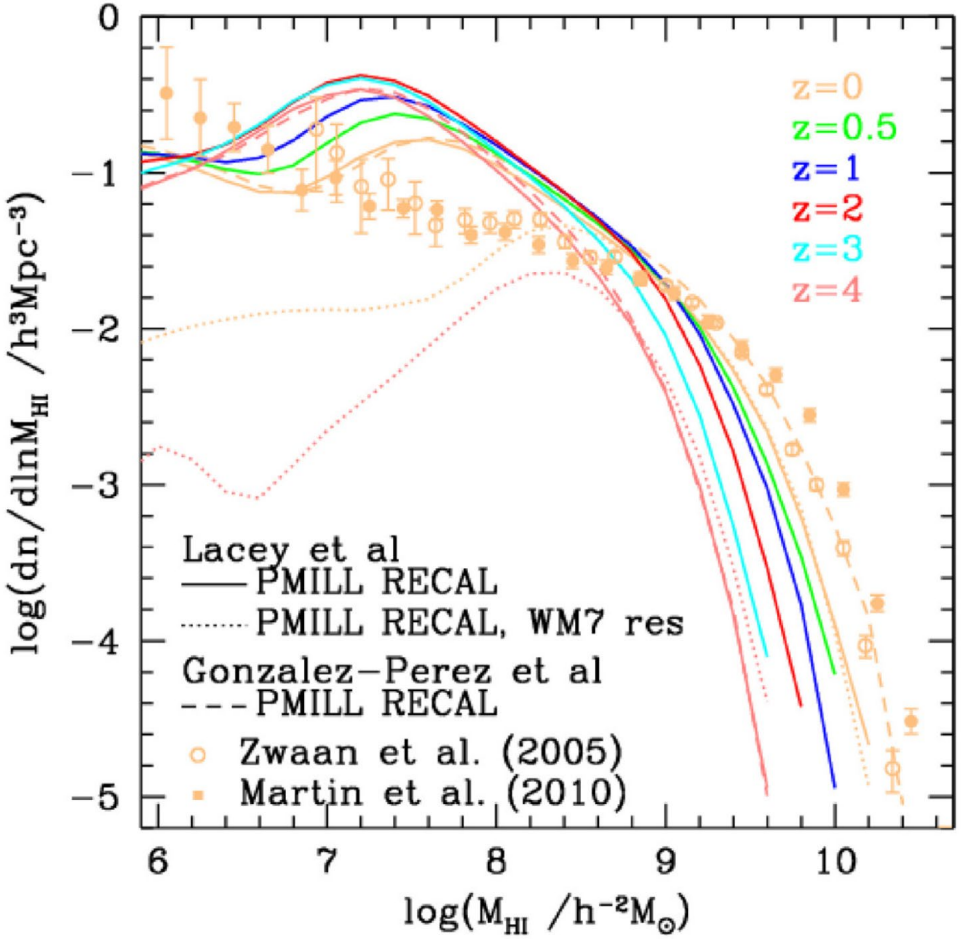




How to make a halo model for HI?

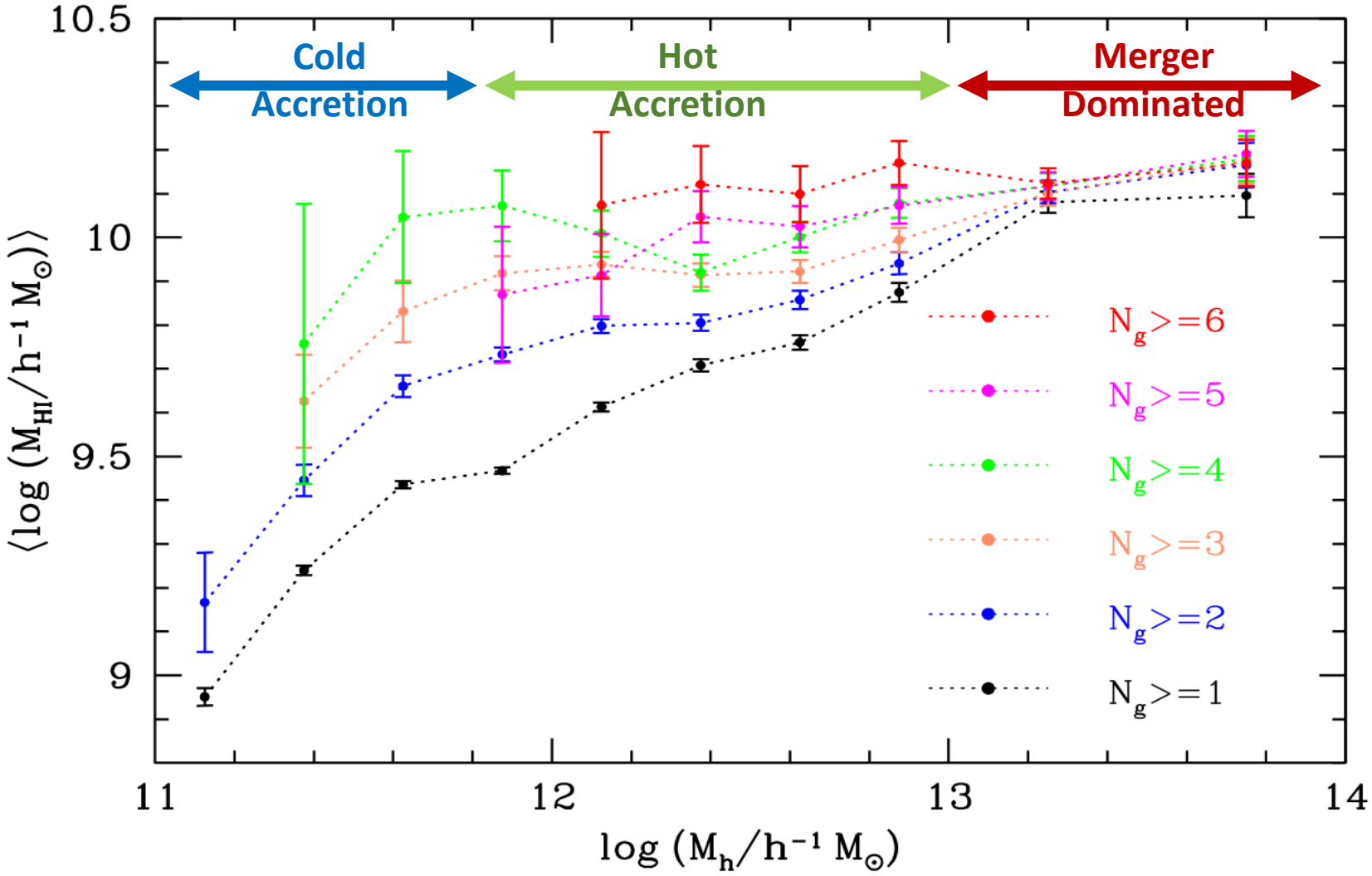
- The HI-halo relation varies significantly for different theoretical models.





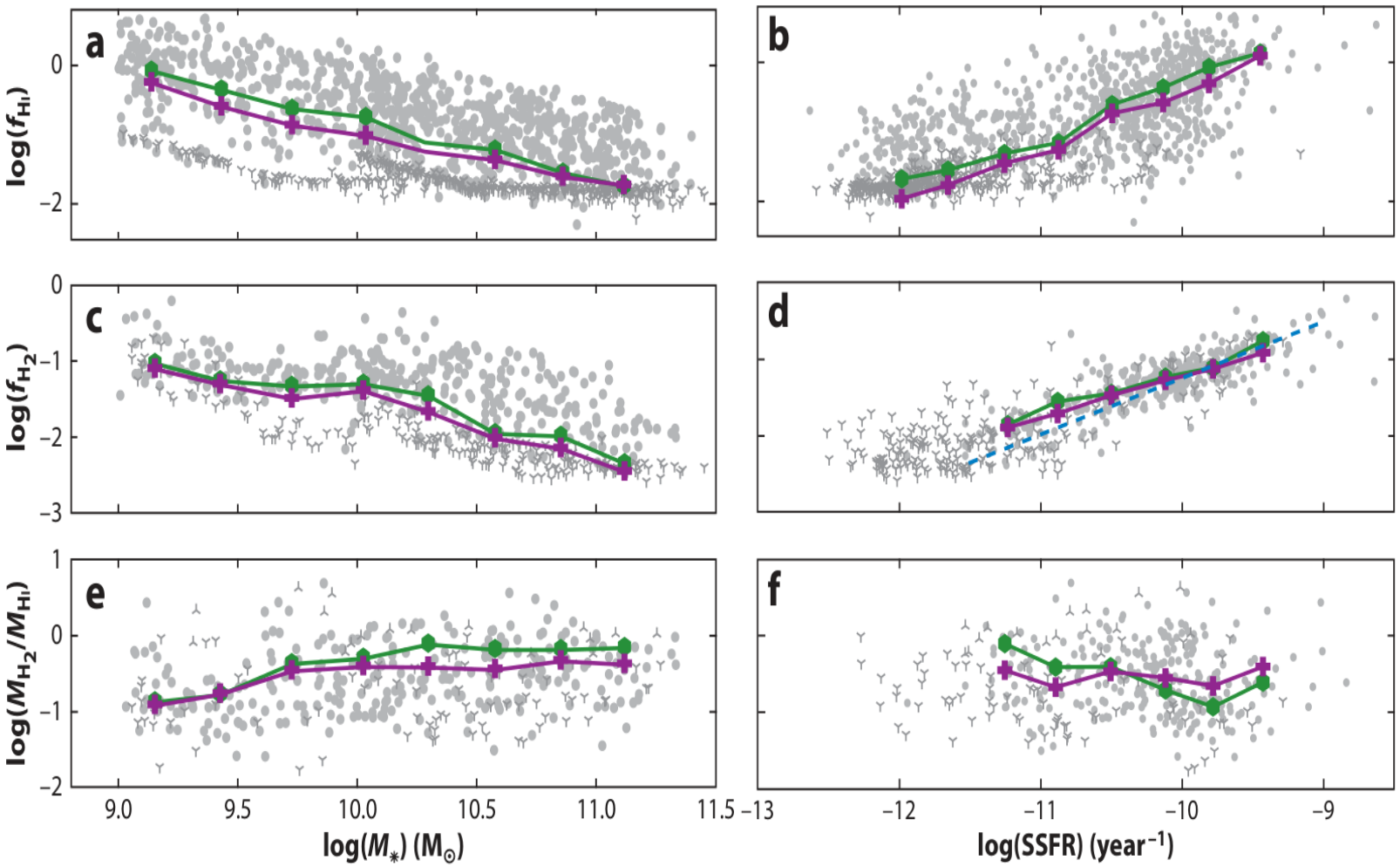
- Baugh et al. (2019)

Measurements of HI-halo Mass Relation



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

What we know about the cold gas: HI Gas

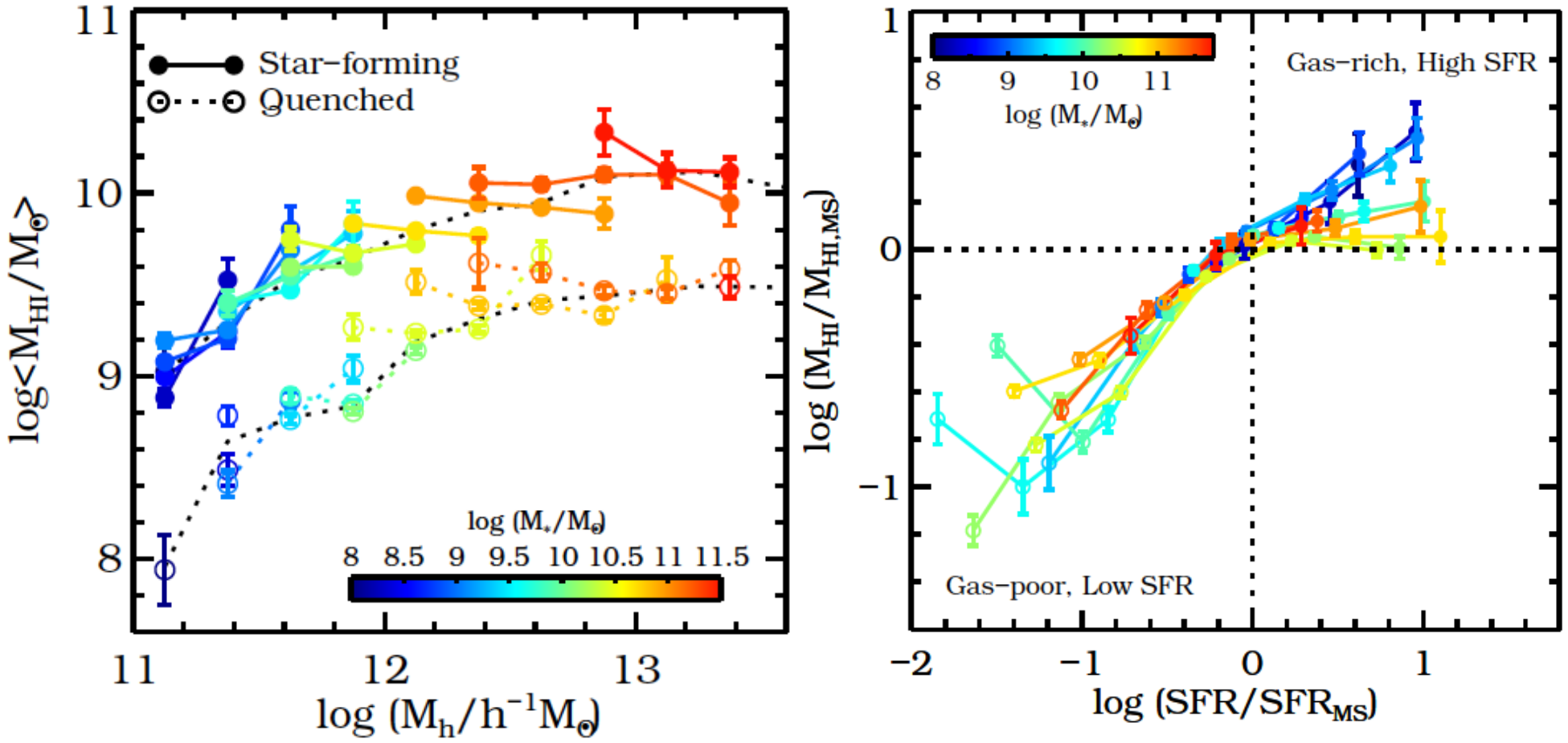


- Cold gas fractions are decreasing with M*
  & increasing with sSFR
- The conversion efficiency from HI to H2 seems to be weakly dependent on M* and sSFR

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

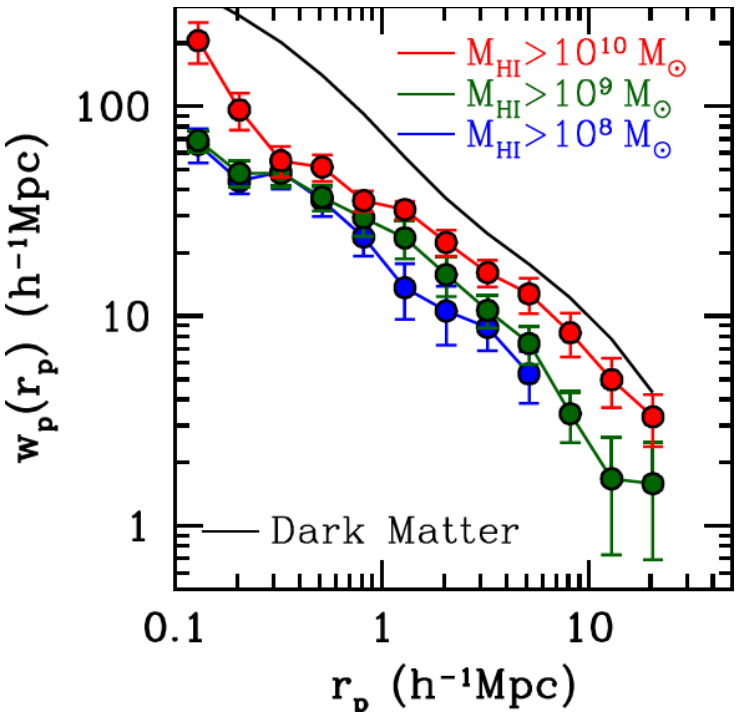
HI-SFR Relation

- HI mass is directly related to the SFR

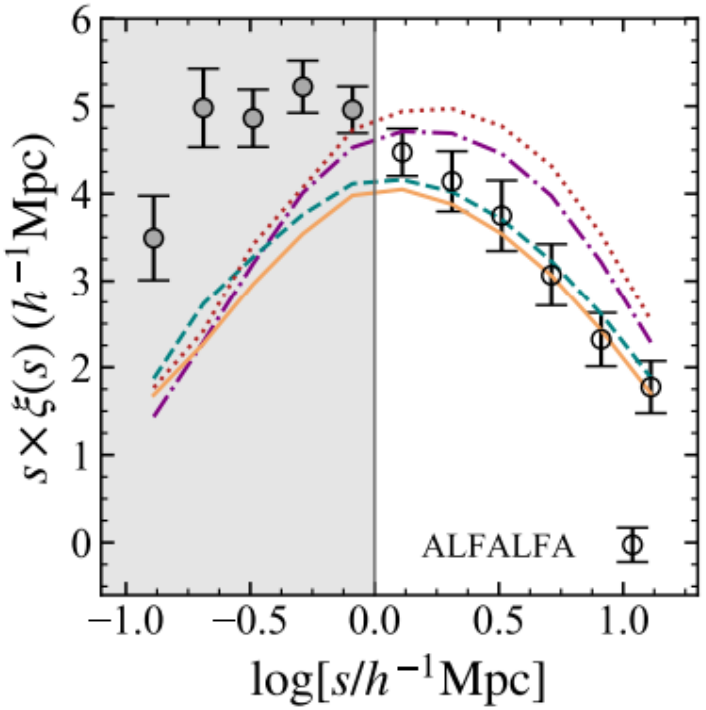


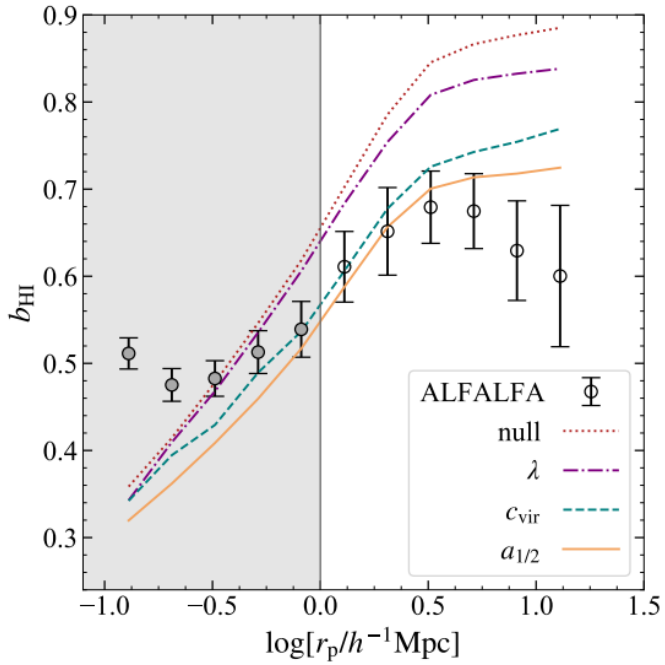
Guo et al. (2021), HI stacking of ALFALFA

HI Clustering



Guo et al. (2017)





Li, Guo, & Mao (2022)

- HI gas is distributed in underdense regions

NeutralUniverseMachine Model

Halo Mass | Formation History | SFR

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

Stellar Mass | SFR

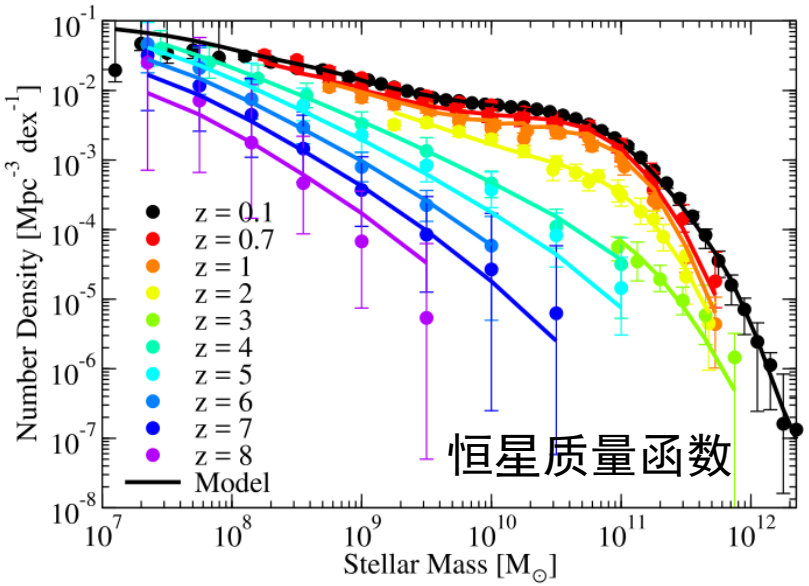
$$M_{\rm H_2} = \zeta M_*^{\nu} \left(\frac{\rm SFR}{\rm SFR_{MS,obs}} \right)^{\eta}$$

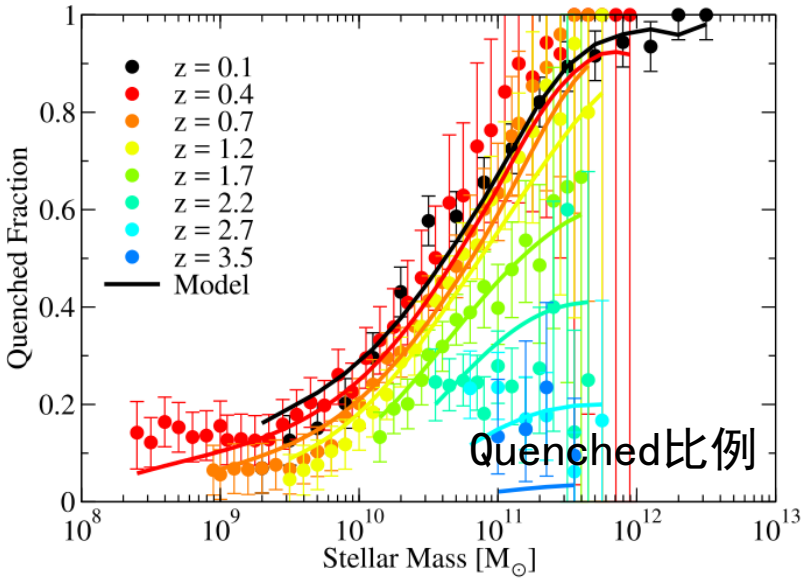
- 16 parameter Empirical Halo Model
- Redshift dependence included

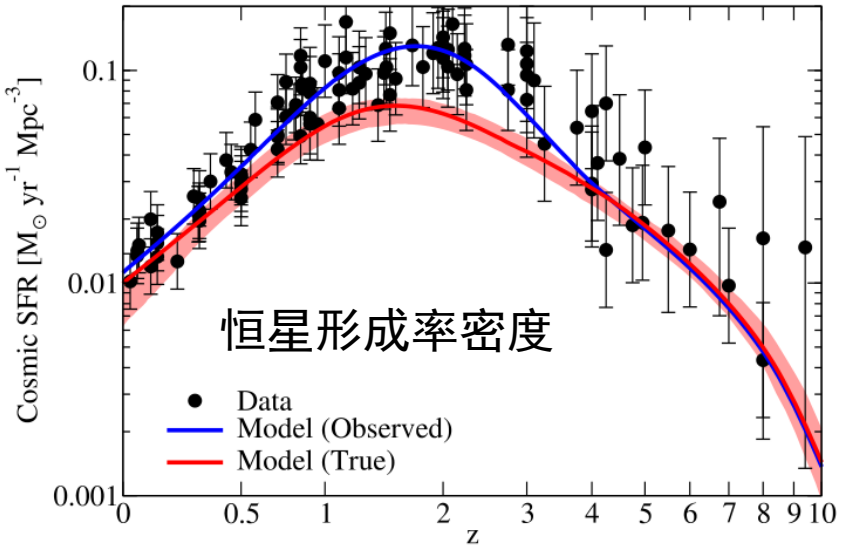
Base Model：UniverseMachine

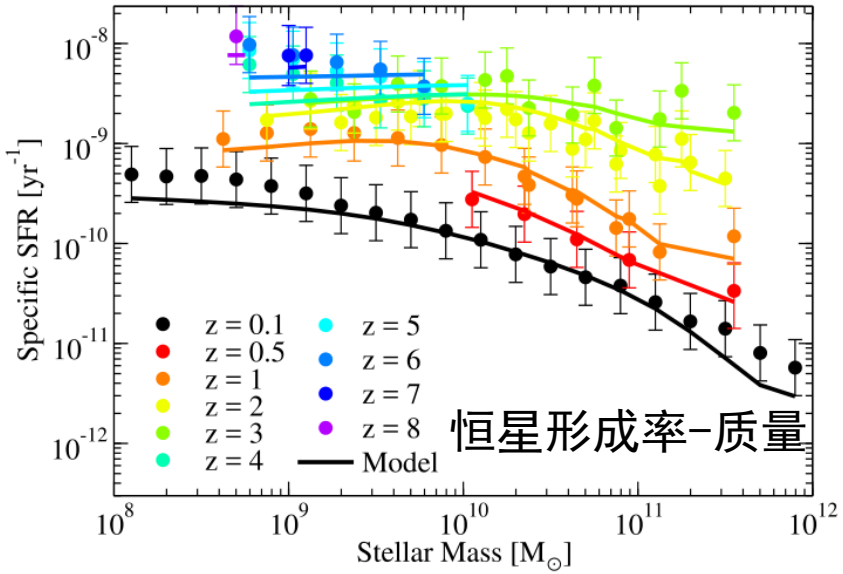
$P(SFR|M_h, \dot{M}_h, z)$

- Empirical Halo Model based on N-body simulations









Behroozi et al. (2019)

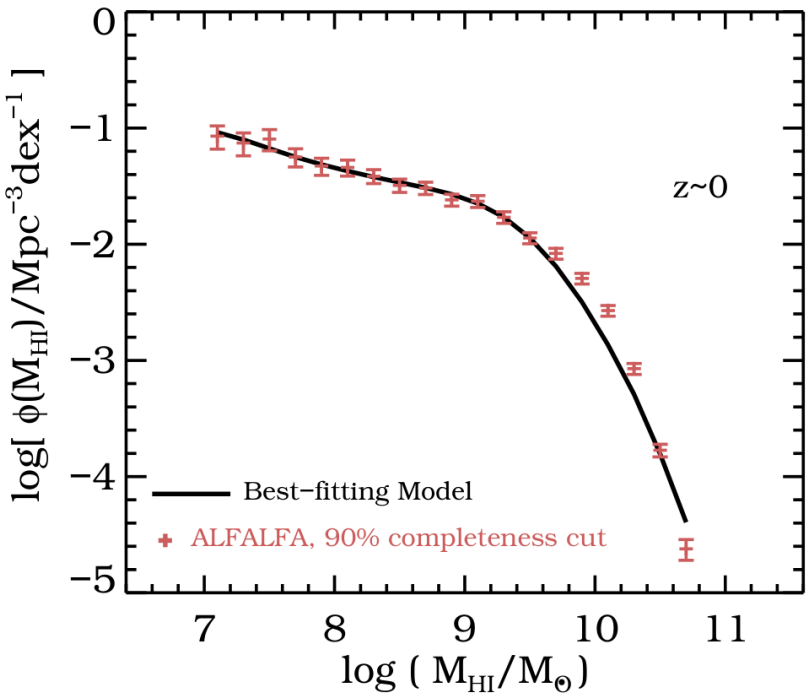
NeutralUniverseMachine：Model Fitting

Table 1. Observational Constraints

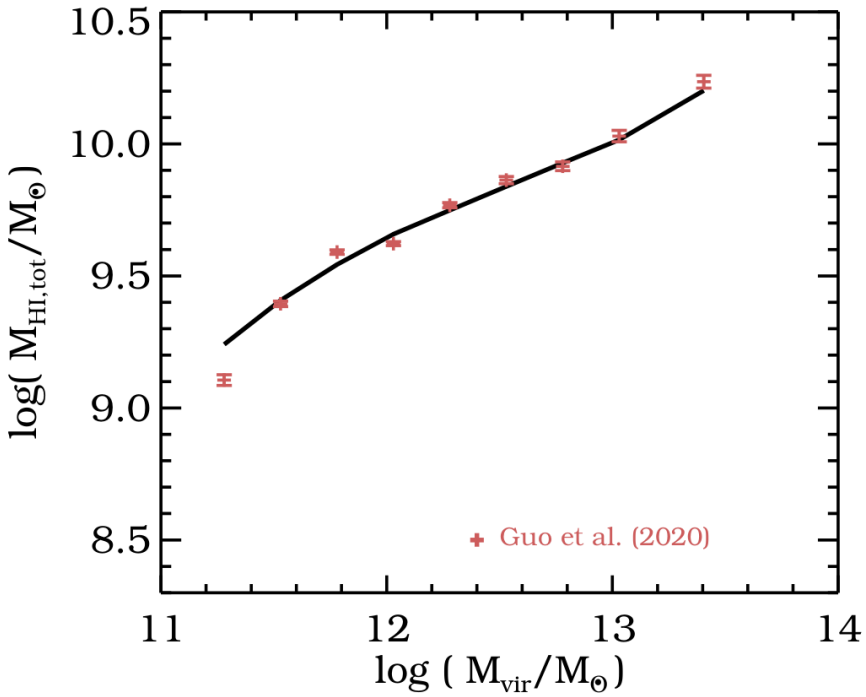
	Measurements	References	Redshifts
ALFALFA	H I Mass Function	Jones et al. (2018)	$z \sim 0$
	H I-Halo Mass Relation	Guo et al. (2020)	$z \sim 0$
	H I-Stellar Mass Relation	Guo et al. (2021)	$z \sim 0$
	H I clustering	Li et al. (2022b)	$z \sim 0$
xCOLD GASS	H_2 Mass Function	Fletcher et al. (2021)	$z \sim 0$
	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

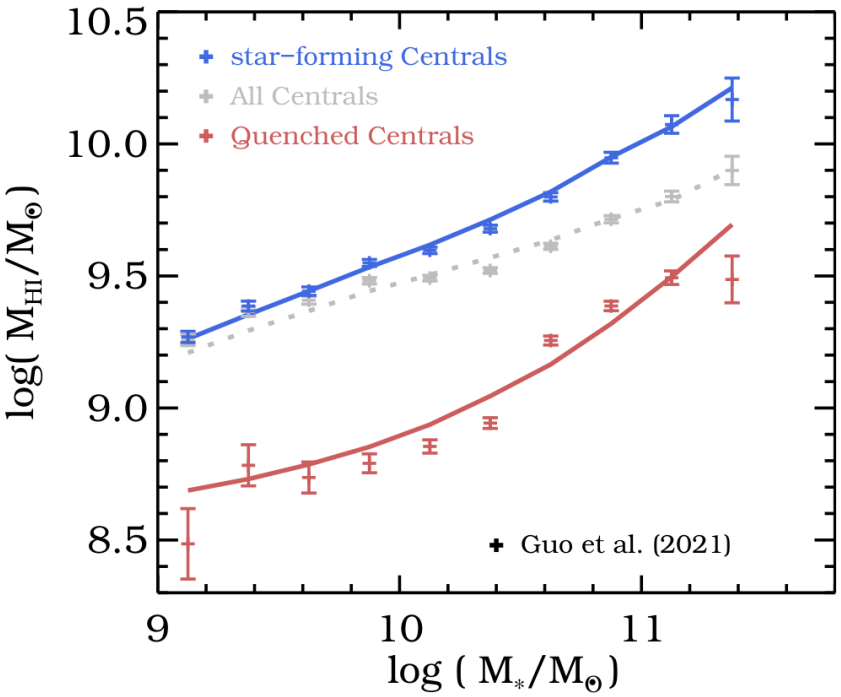
HI Mass Function



HI-Halo Mass Relation



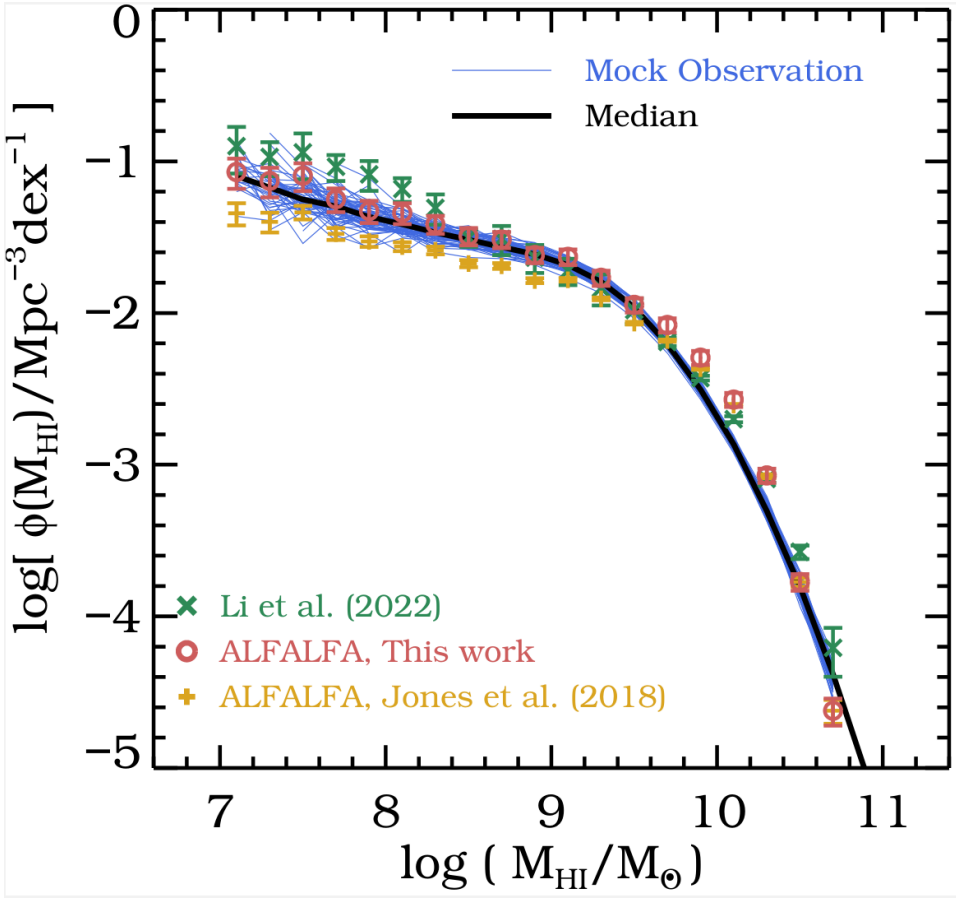
HI-Stellar Mass Relation



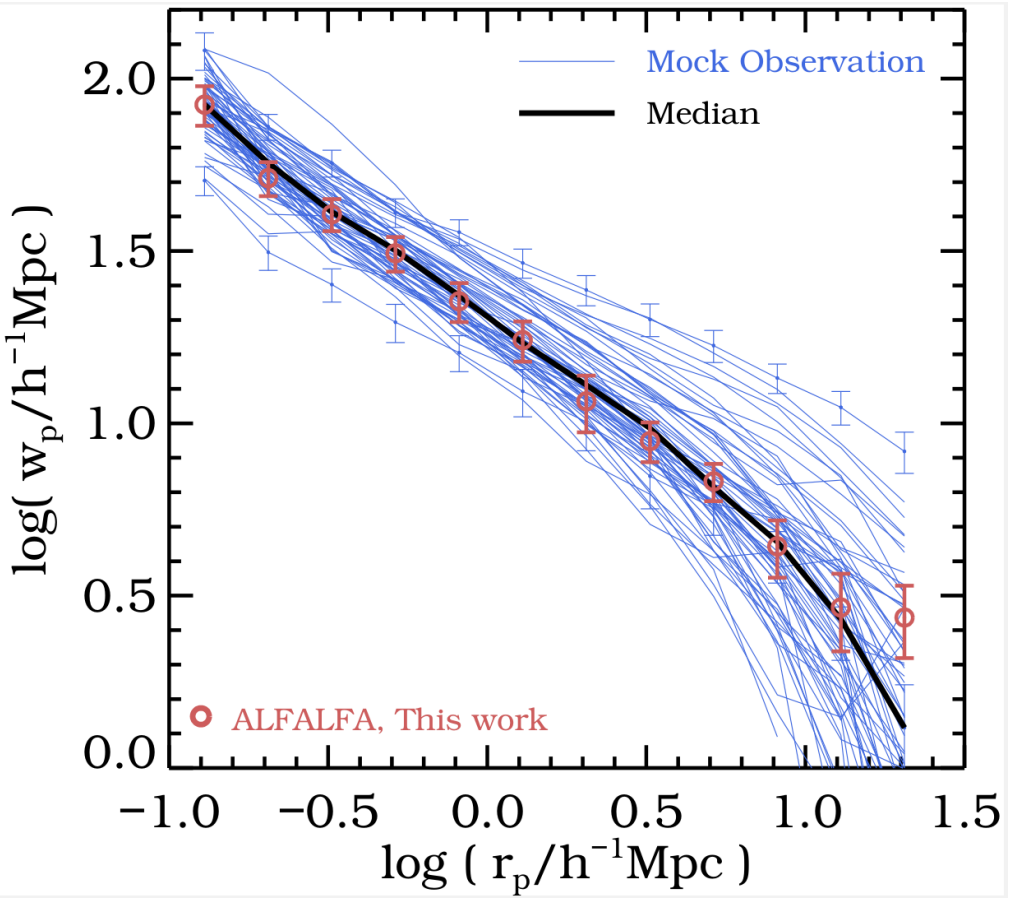
Guo et al. (2023)

NeutralUniverseMachine：Model Fitting

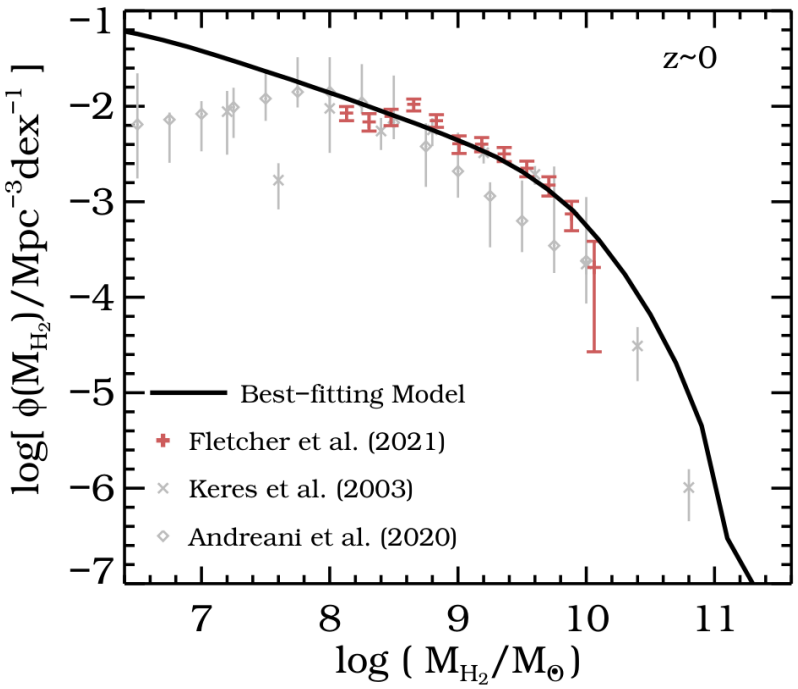
Corrected HI Mass Function



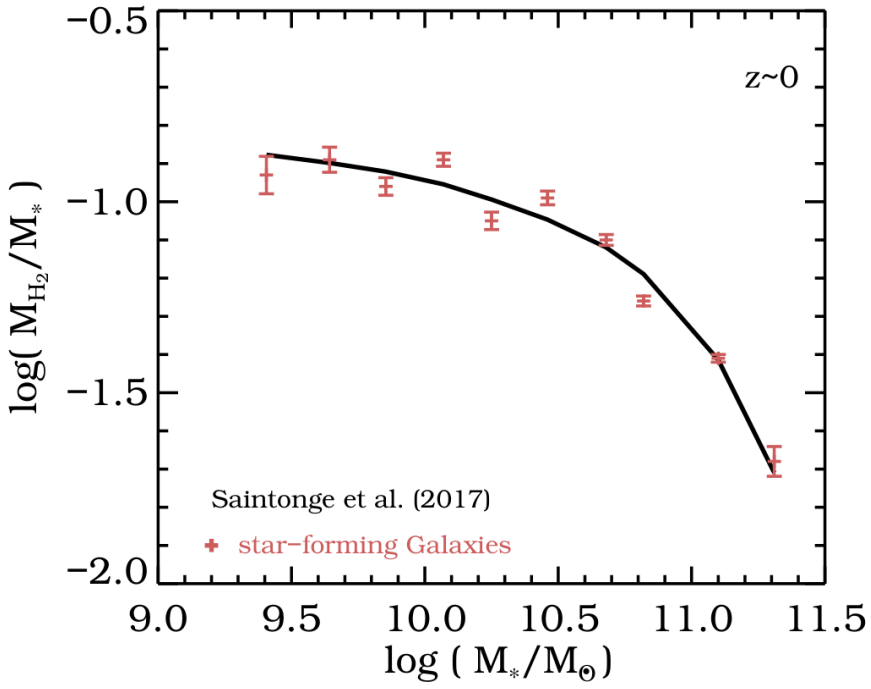
HI Clustering



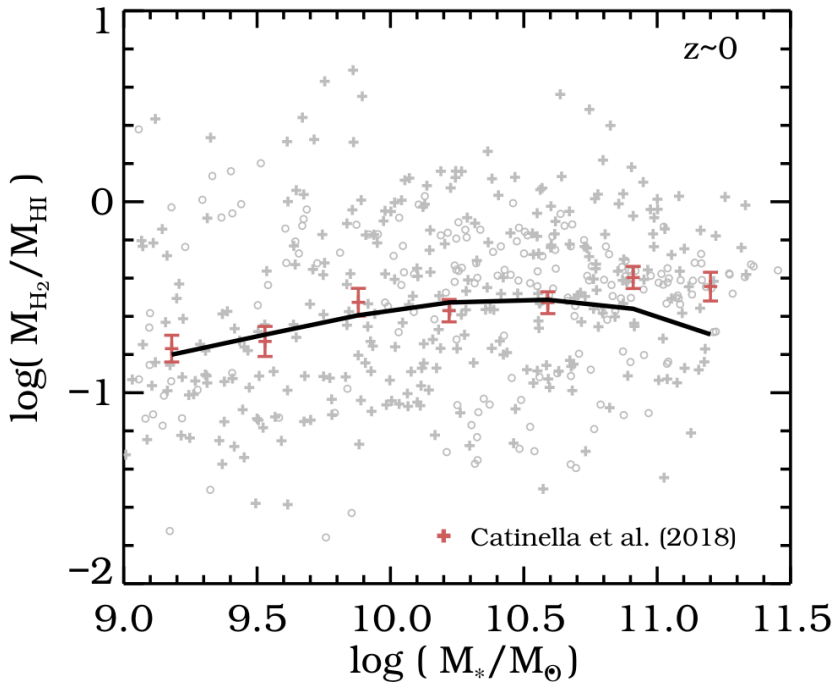
NeutralUniverseMachine： Model Fitting



H2 Mass Function

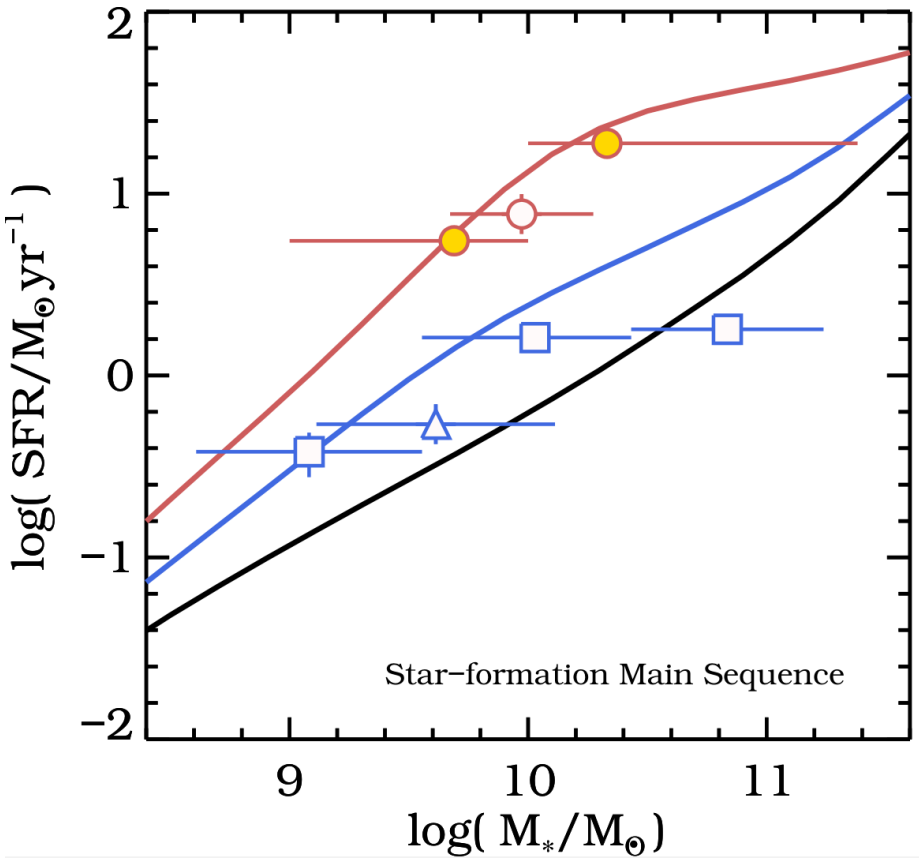


H2-Stellar Mass Relation

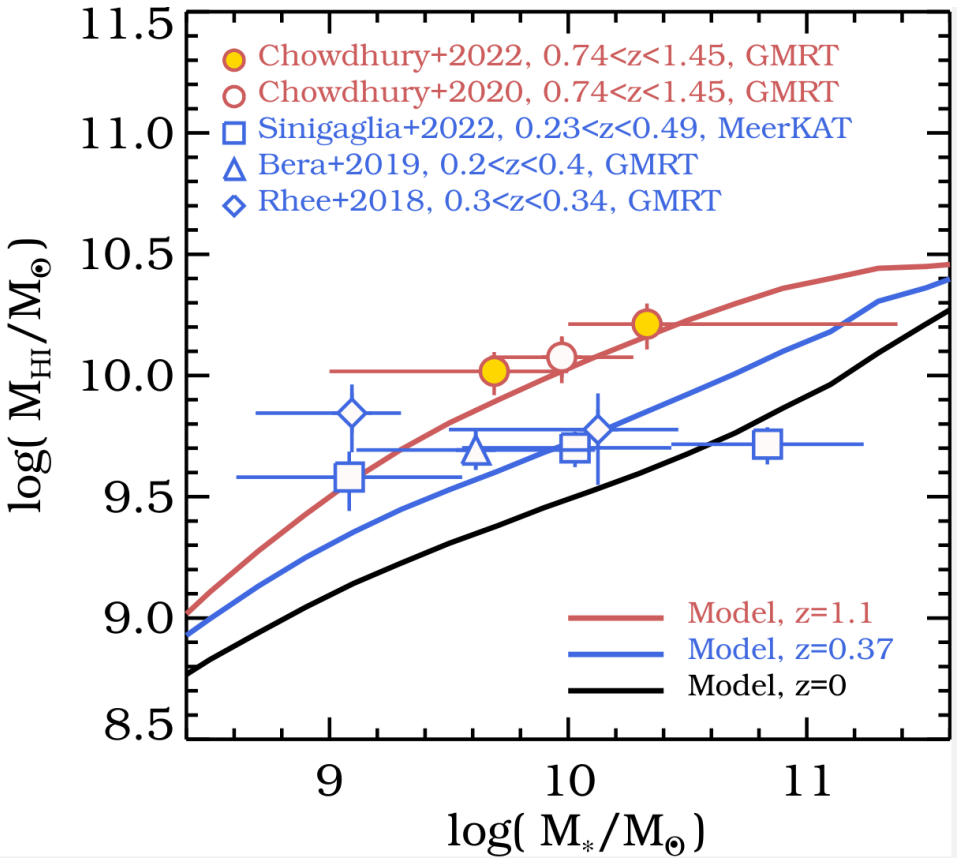


H2/HI Ratio

NeutralUniverseMachine： Model Fitting

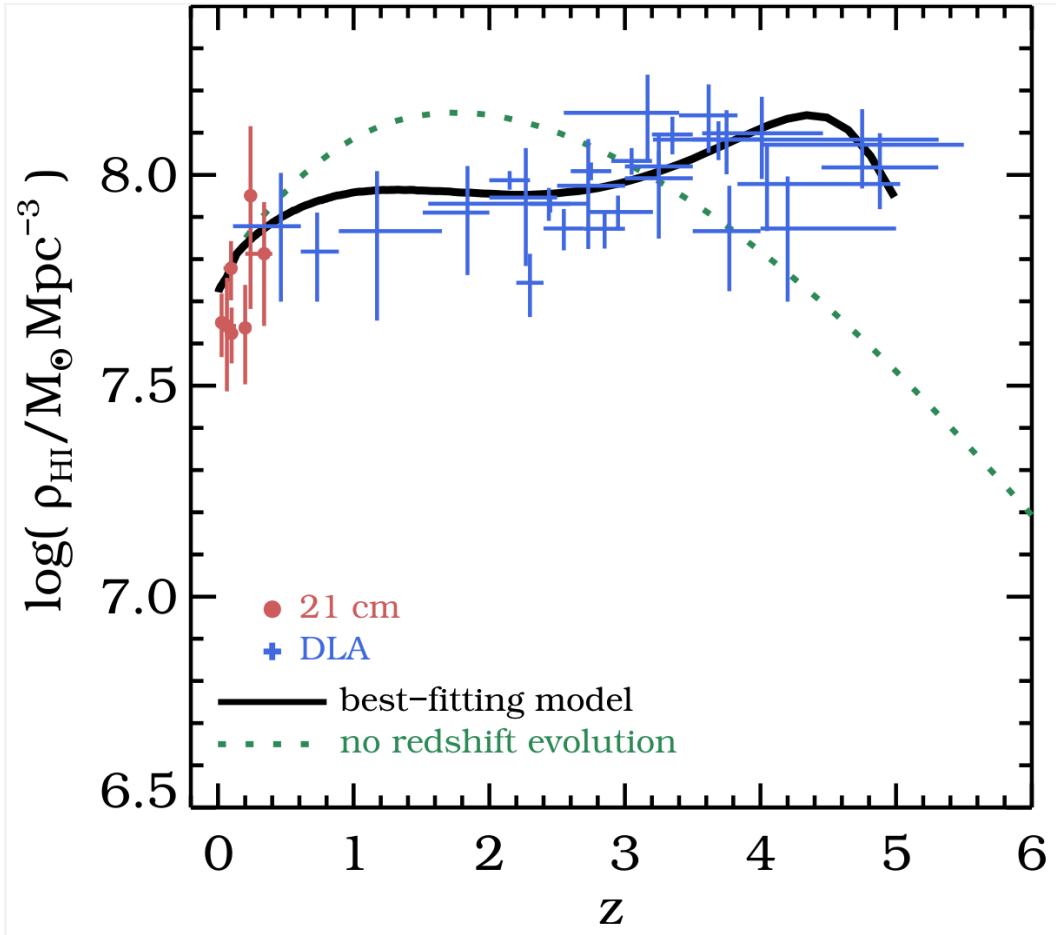


SFR vs M*

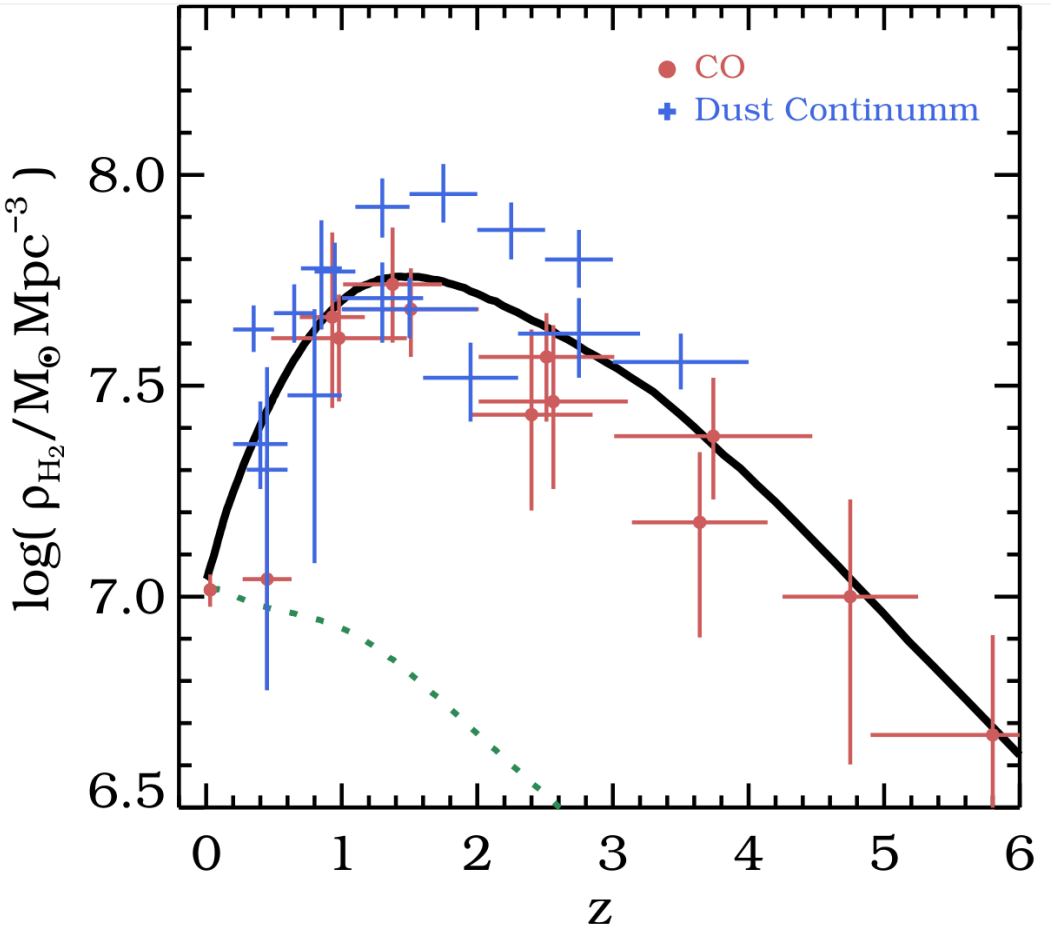


HI-Stellar Mass Relation at high redshifts

NeutralUniverseMachine： Model Fitting

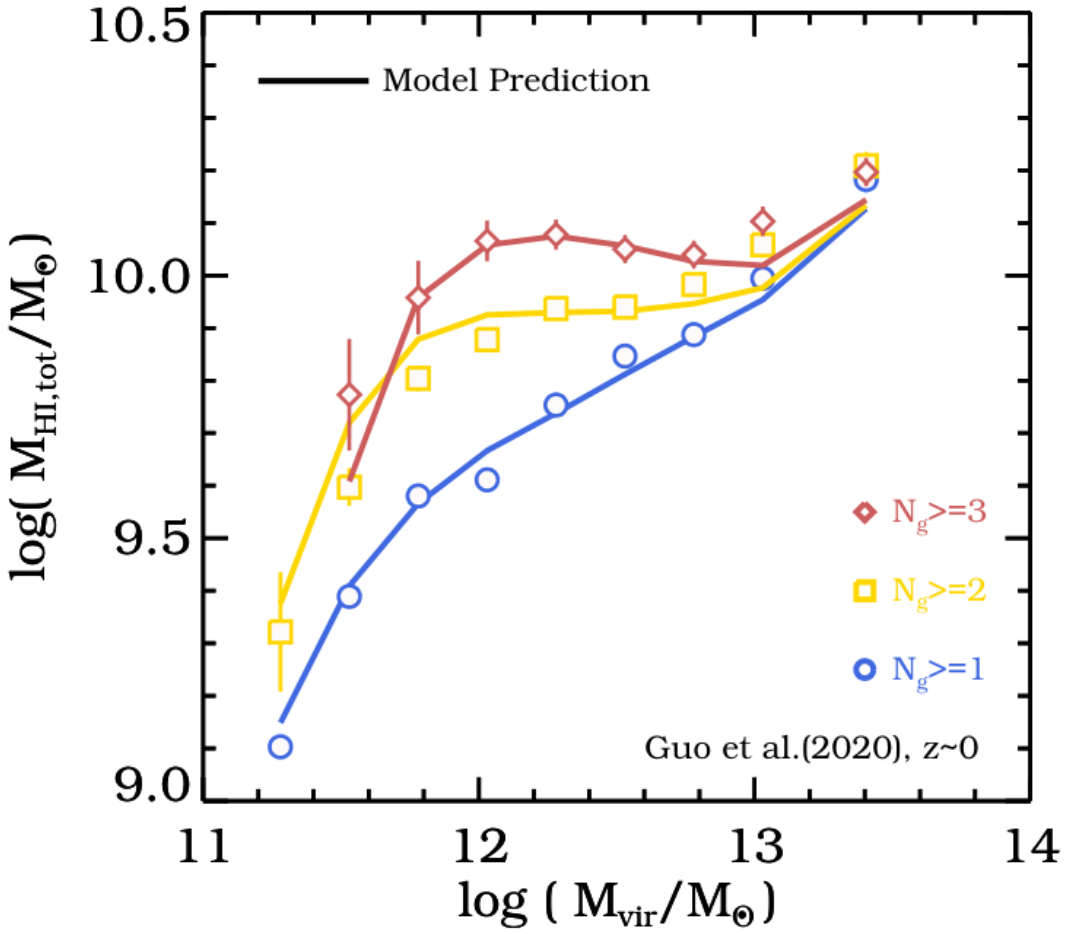


Cosmic HI Gas Density

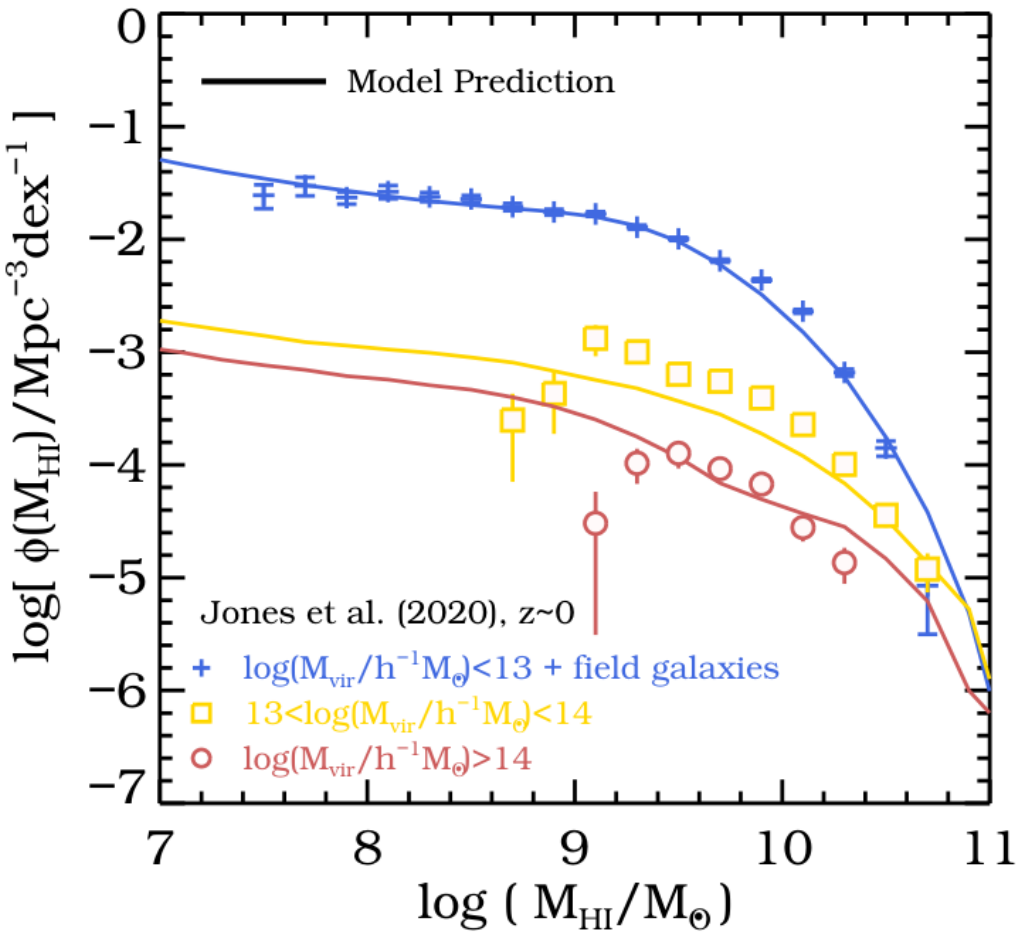


Cosmic H2 Gas Density

NeutralUniverseMachine： Model Prediction

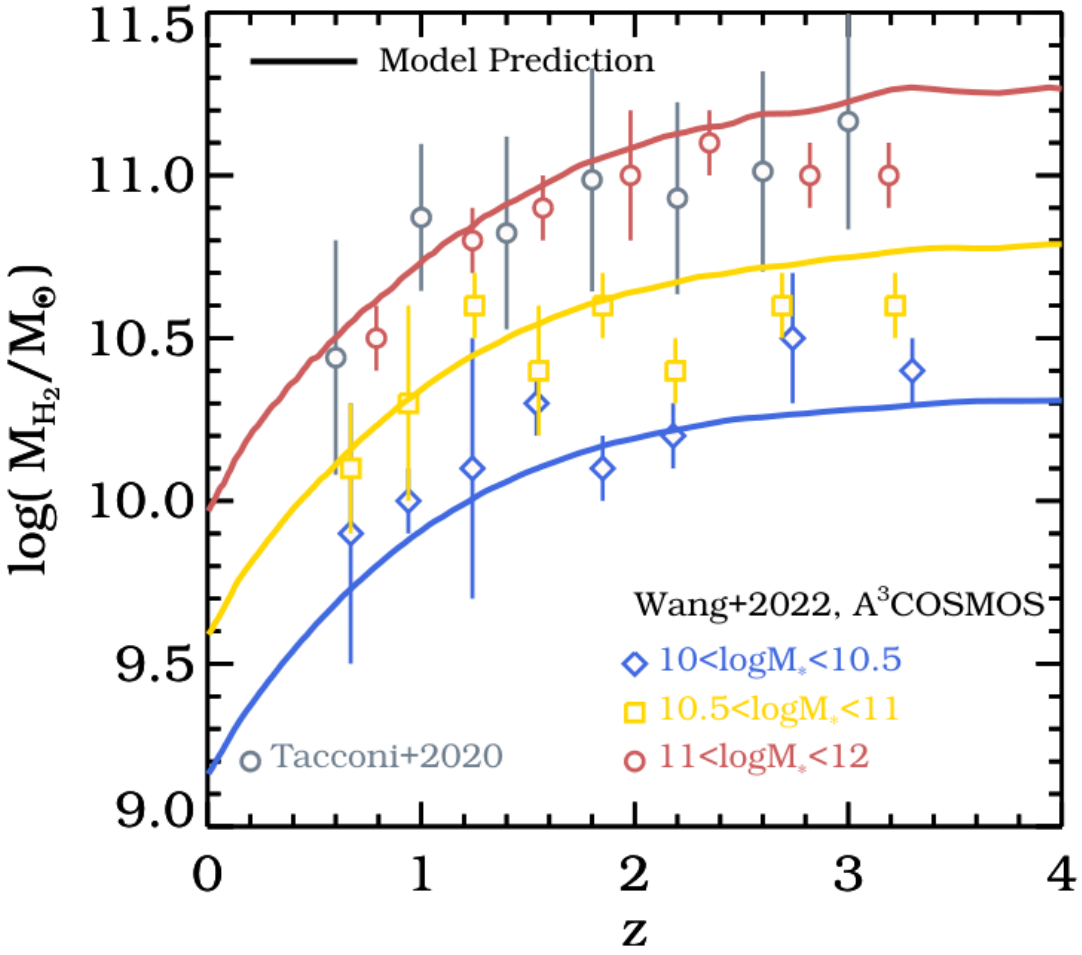


HI-Halo Mass Relation



HI Mass Function in different halo mass bins

NeutralUniverseMachine： Model Prediction

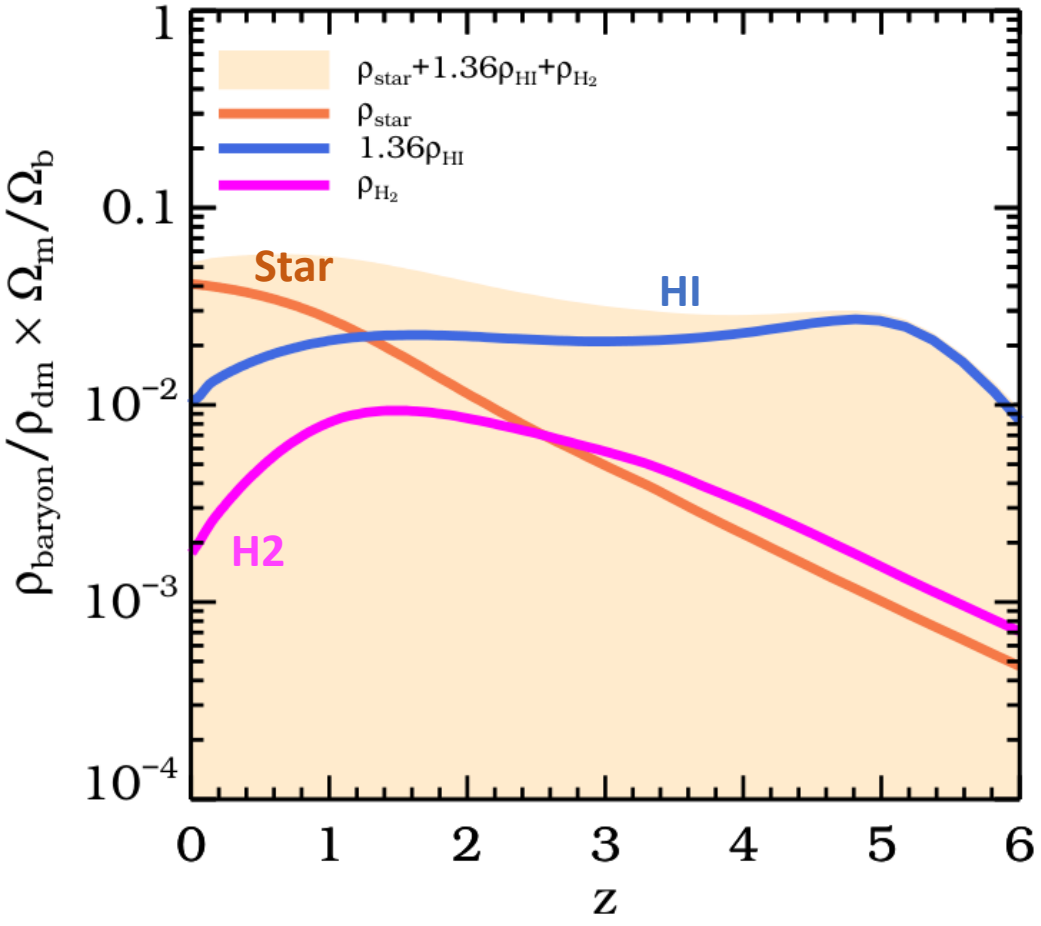


H2-Stellar Mass Relation

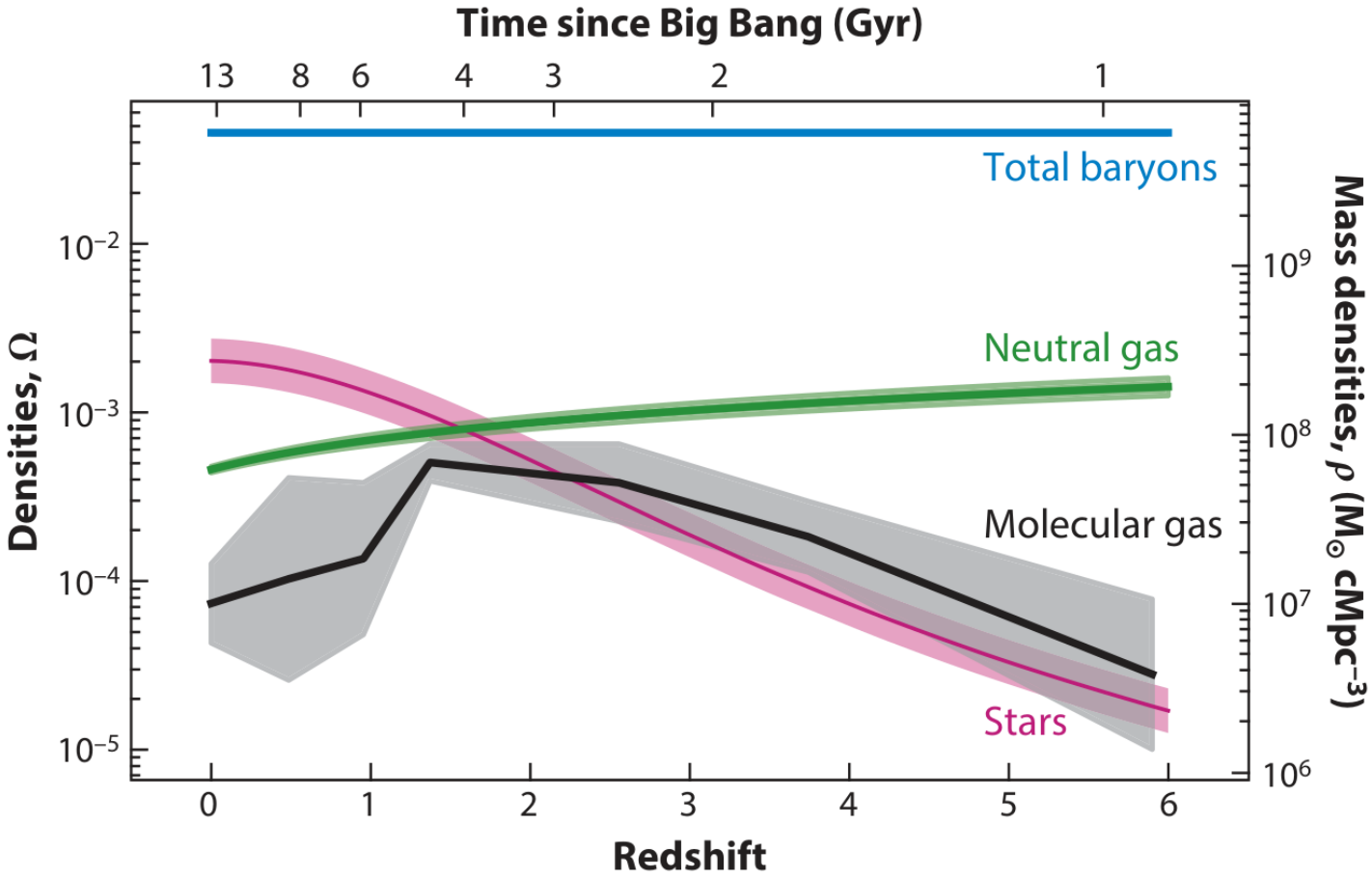
A^{3}COSMOS:

ALMA observation in COSMOS area

NeutralUniverseMachine： Model Prediction

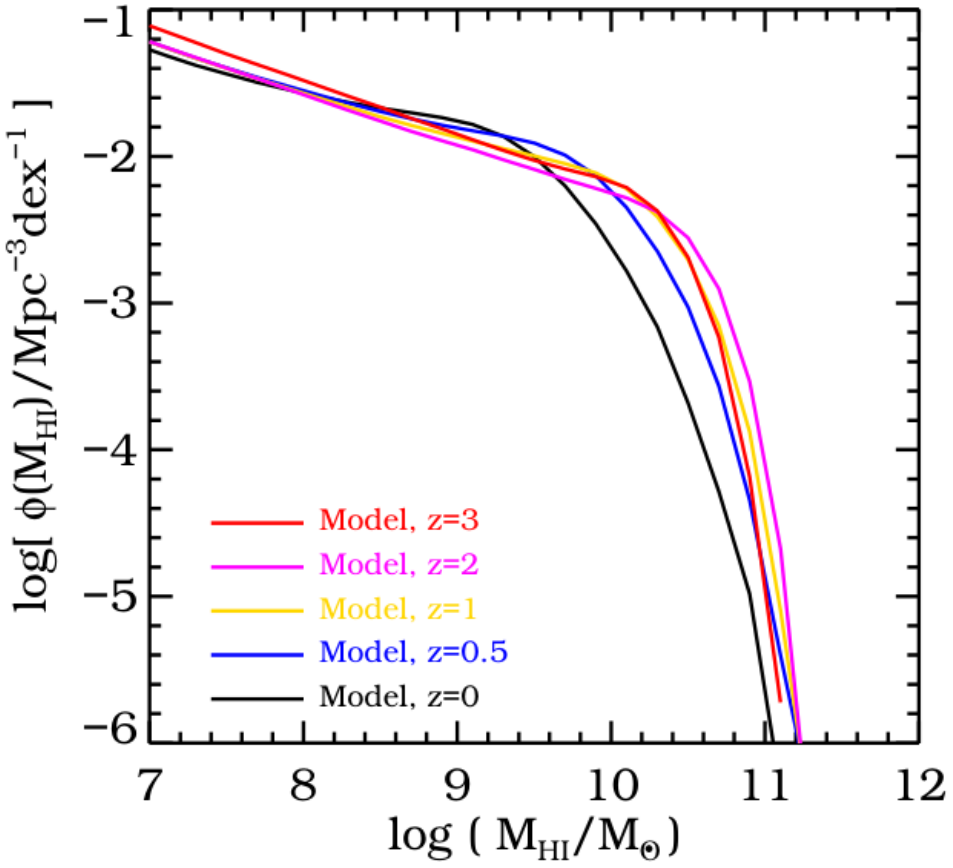


Evolution of baryon content

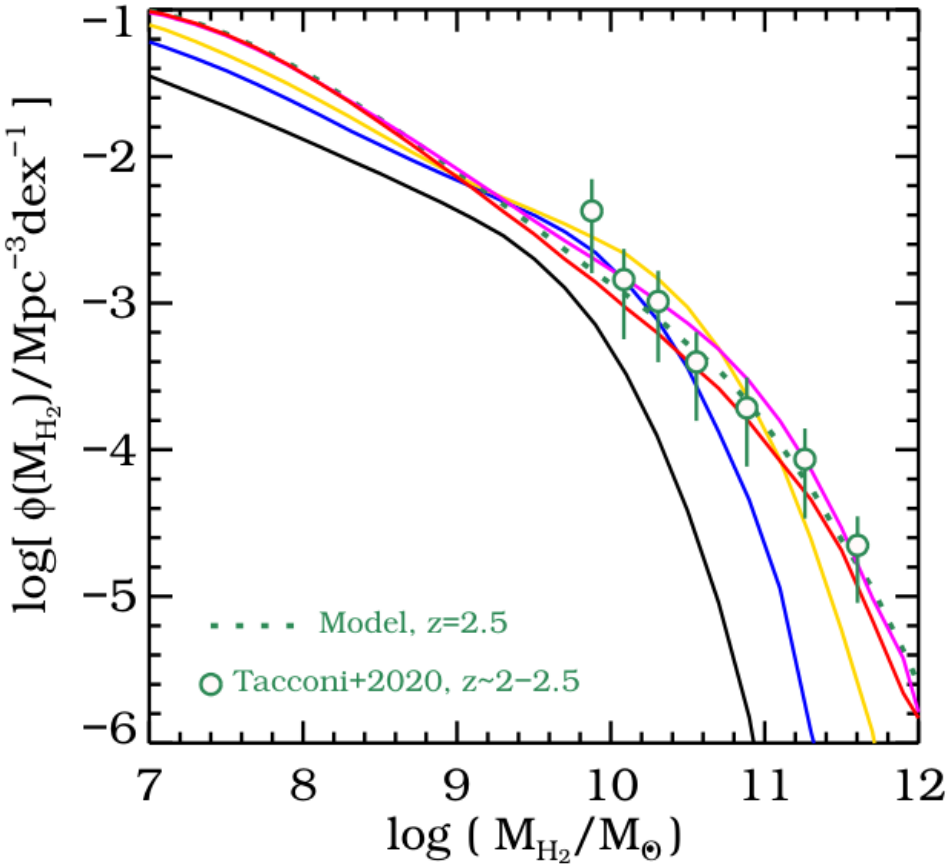


Peroux & Howk, 2020, ARA&A

NeutralUniverseMachine： Model Prediction

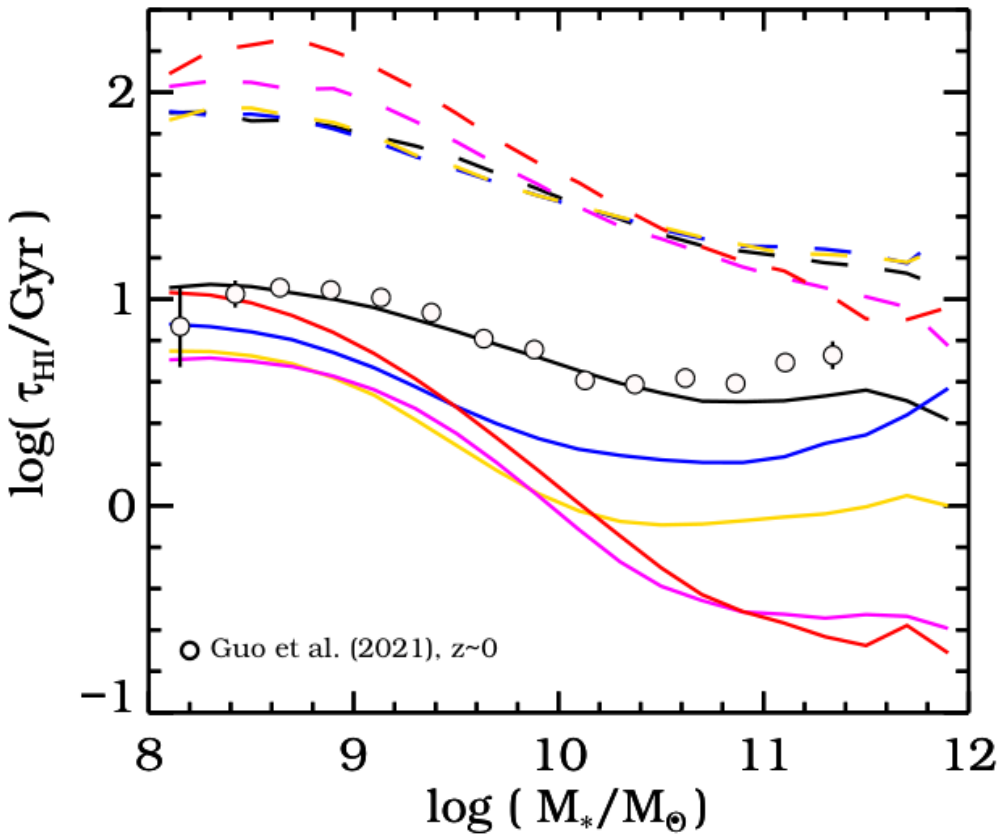


Evolution of HI Mass Function

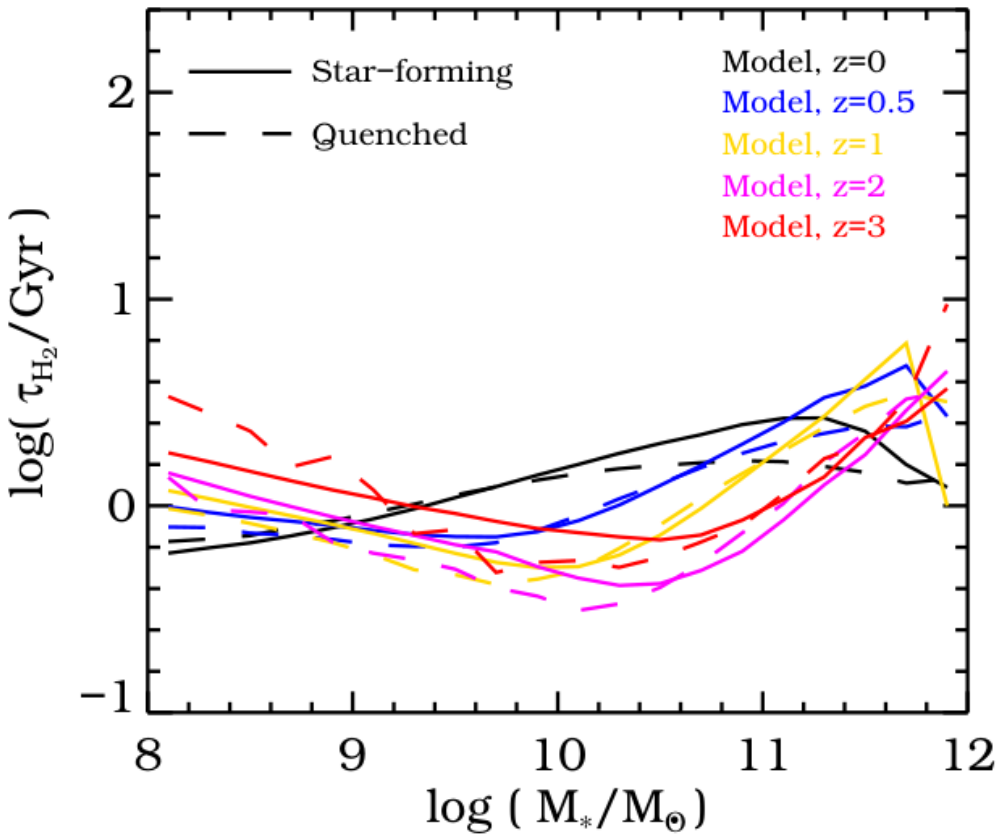


Evolution of H2 Mass Function

NeutralUniverseMachine： Model Prediction



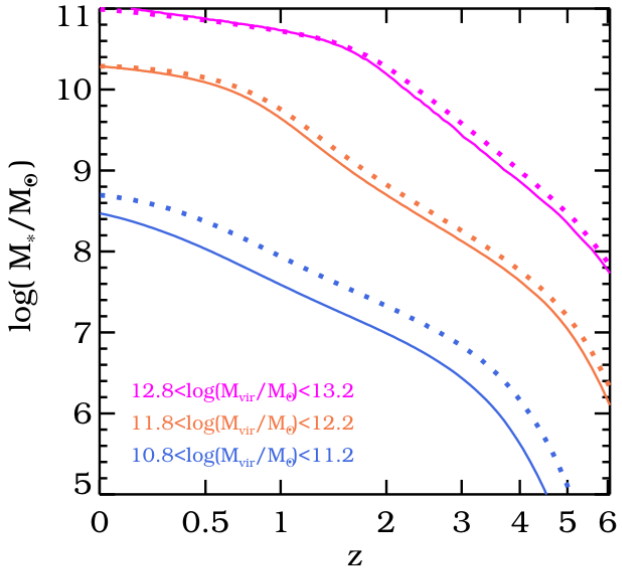
HI depletion time scales



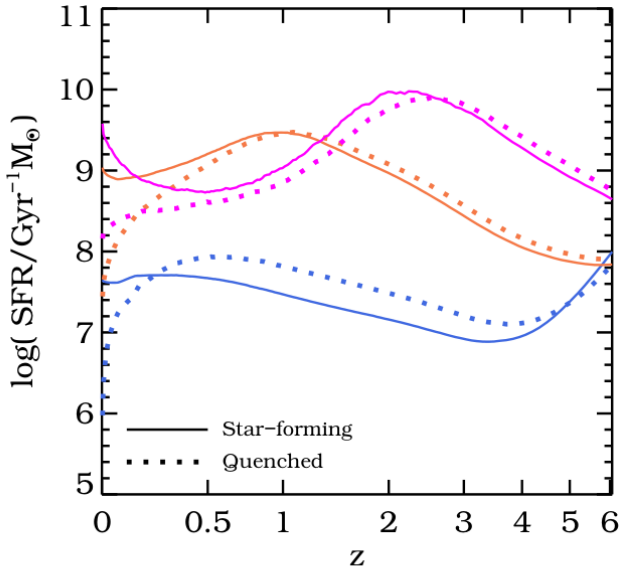
H2 depletion time scales

NeutralUniverseMachine： Model Prediction

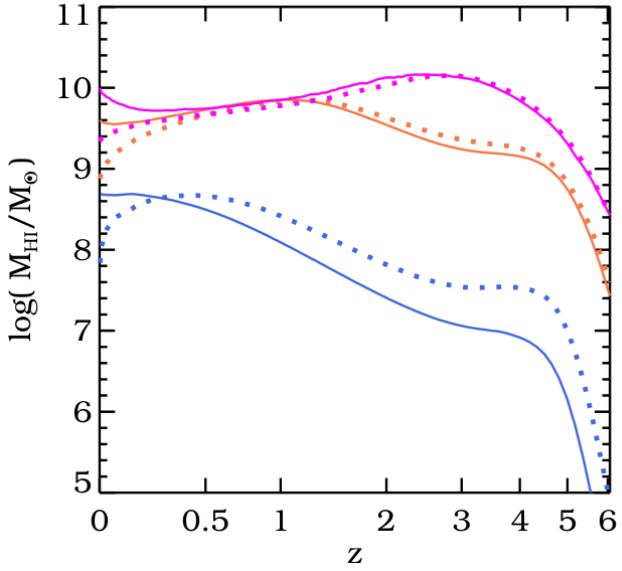
Stellar Mass



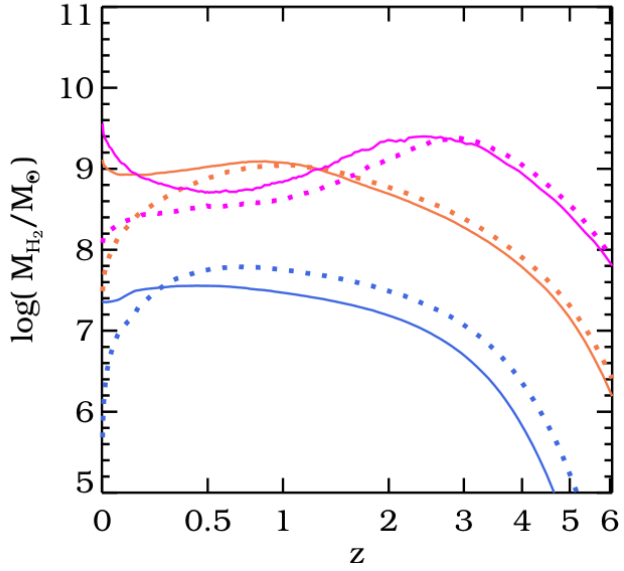
SFR



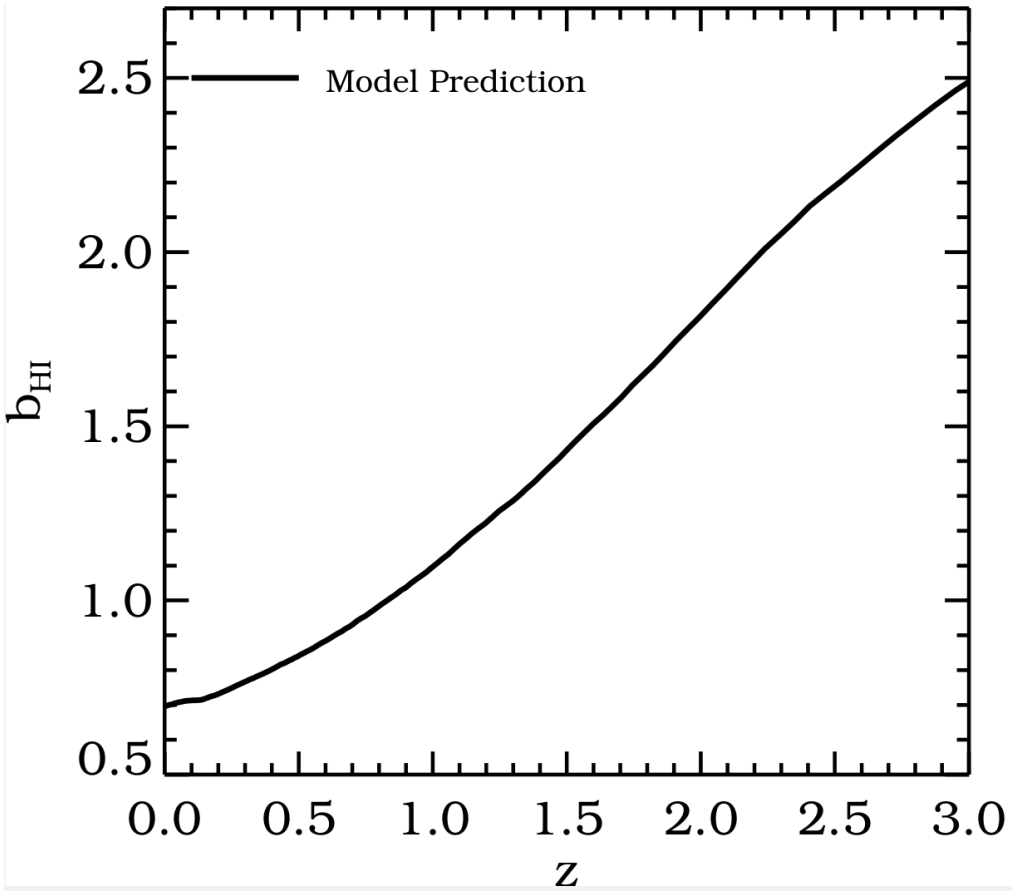
HI Mass



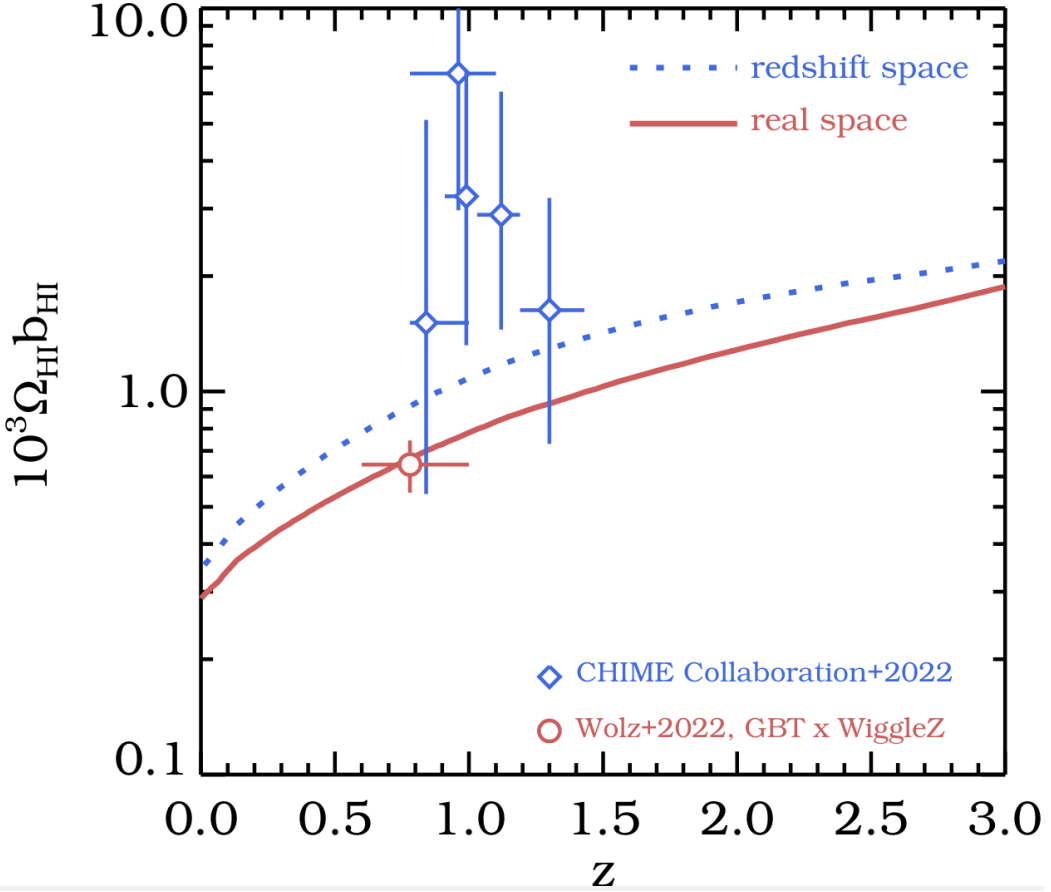
H2 Mass



NeutralUniverseMachine： Model Prediction

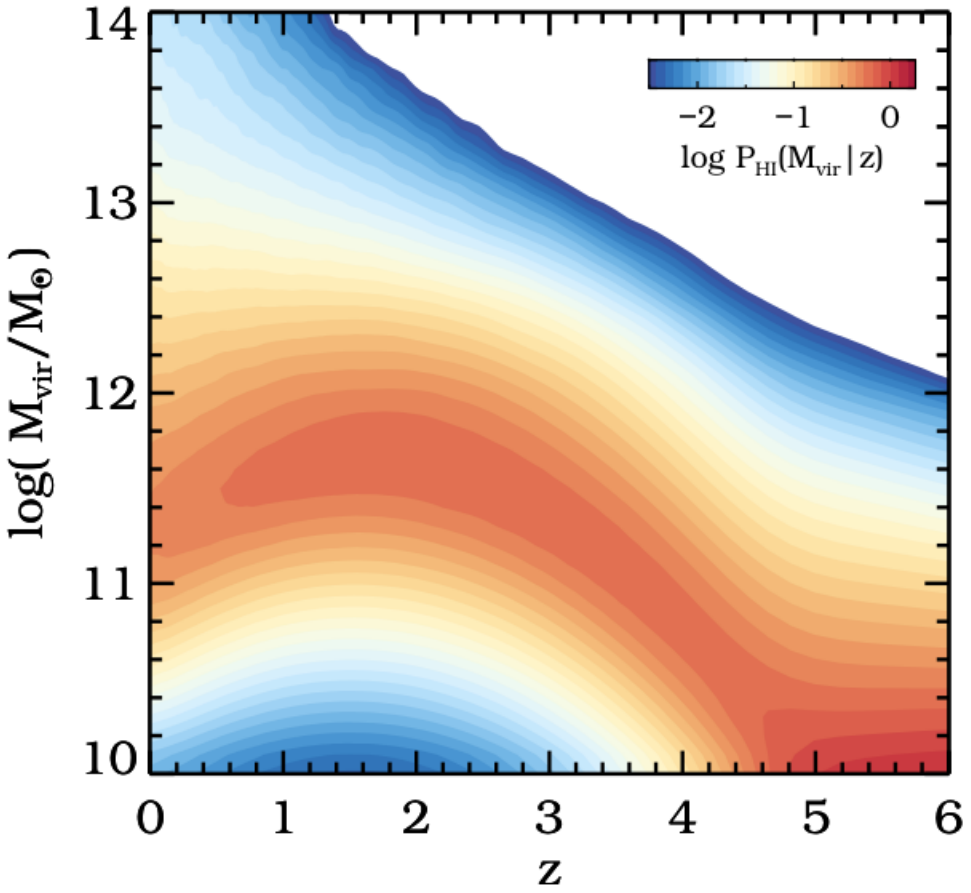


HI bias

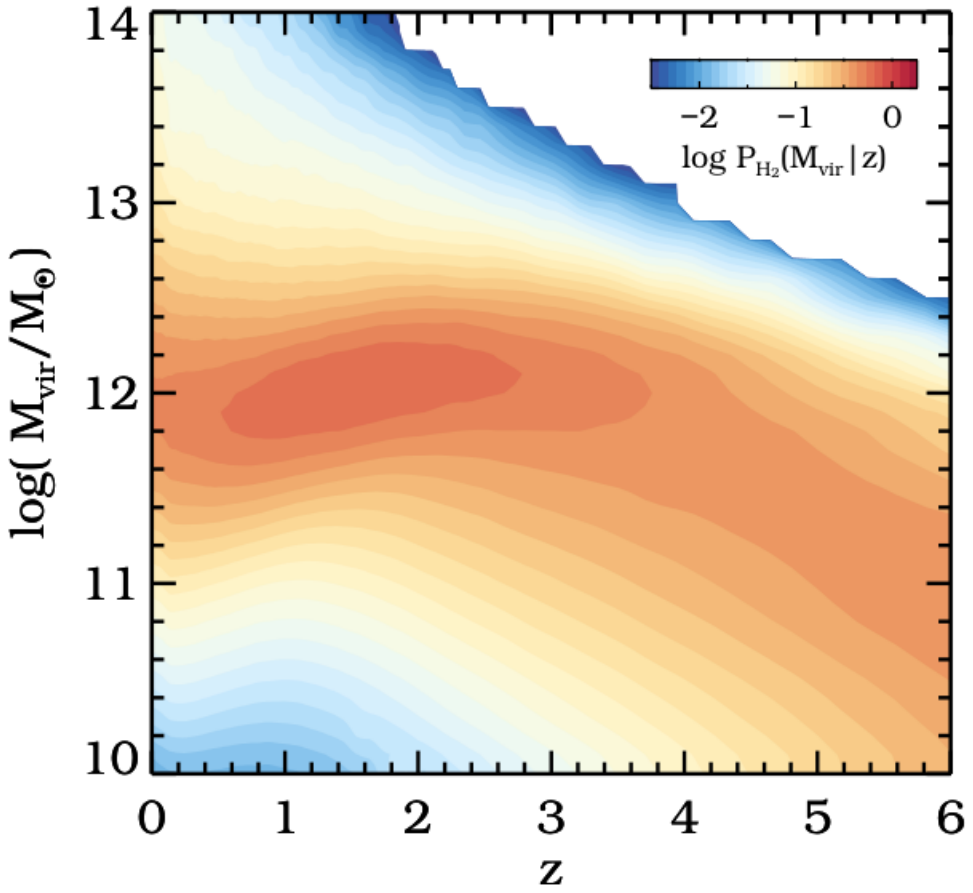


HI intensity mapping

NeutralUniverseMachine：Model Prediction



HI distribution



H2 distribution

Summary

- NeutralUniverseMachine is able to reproduce lots of cold gas observations.

- It has also important predictions that can be verified in future：
- （1）weak evolution in HIMF but stronger evolution in the H2MF

- （2）Cold gas mass for star-forming galaxies deceased by 10 times from z=3

- （3）HI depletion time scale for SF galaxies is only 0.1-10Gyr，but longer for quenched galaxies