Conditional HI mass function and the HI-to-halo mass relation in the local universe

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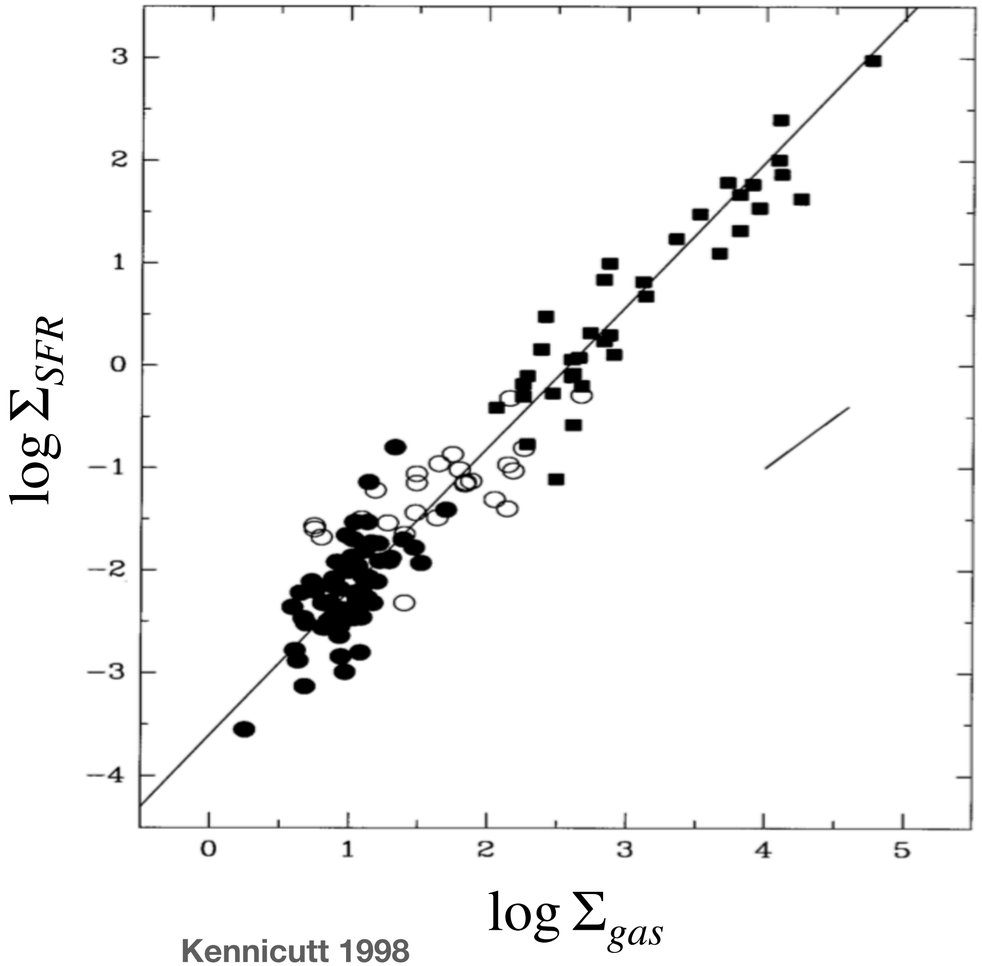
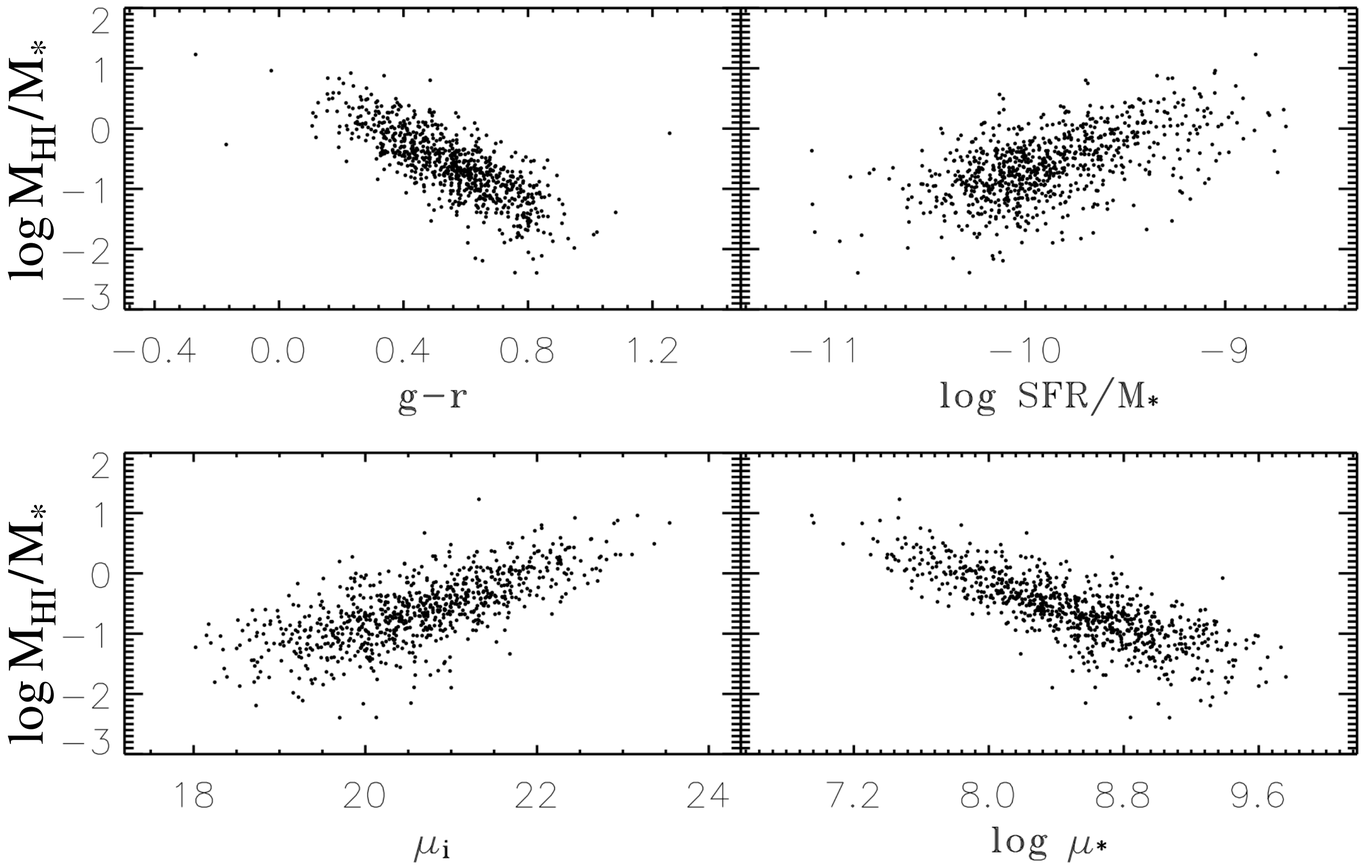
Collaboration Workshop on Cosmology and Galaxy Formation, June 19-23, 2023

Atomic hydrogen (HI) is important for galaxy formation and evolution

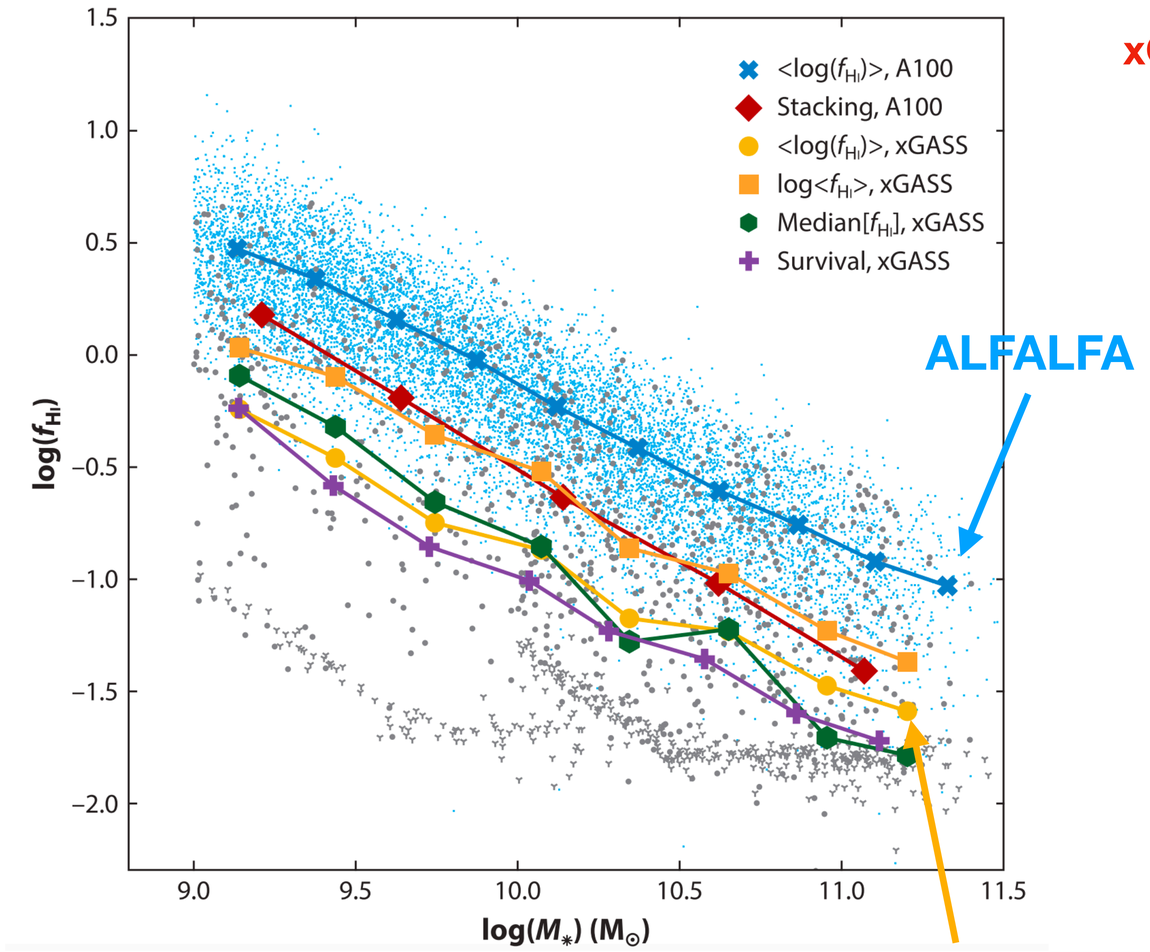


Kennicutt 1998

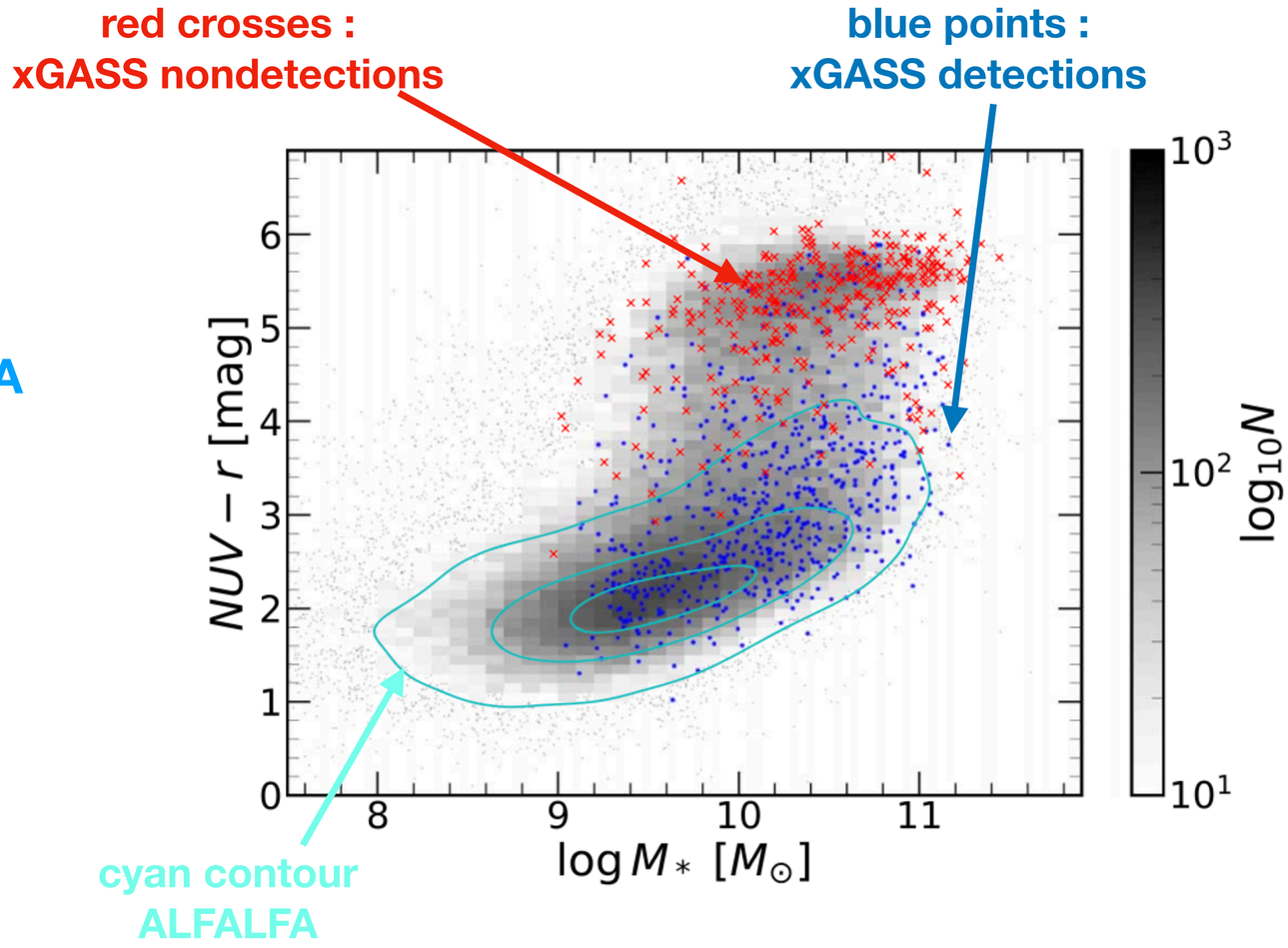


Zhang et al. 2009

Current HI surveys are shallow and biased



Saintonge & Catinella 2022

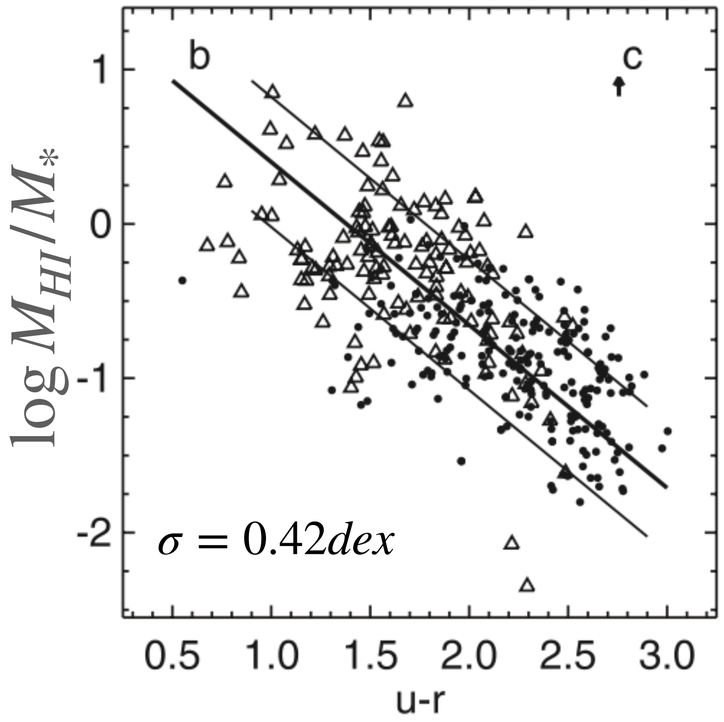


From optical to HI : HI estimator

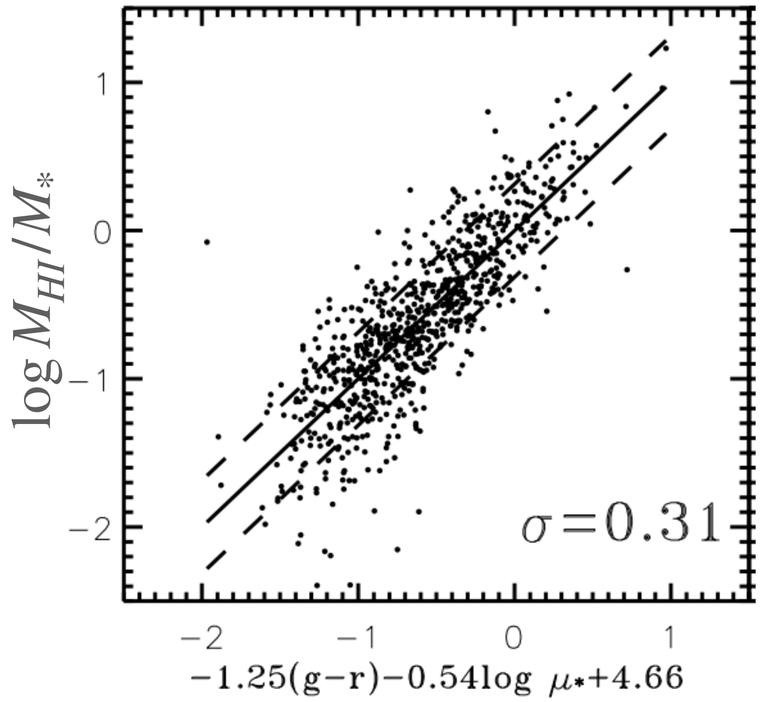
Estimating the HI gas fraction from galaxy optical properties

$$\log M_{HI}/M_* = f(p_1, p_2, \ldots)$$

Kannappan, 2004



Zhang et al., 2009

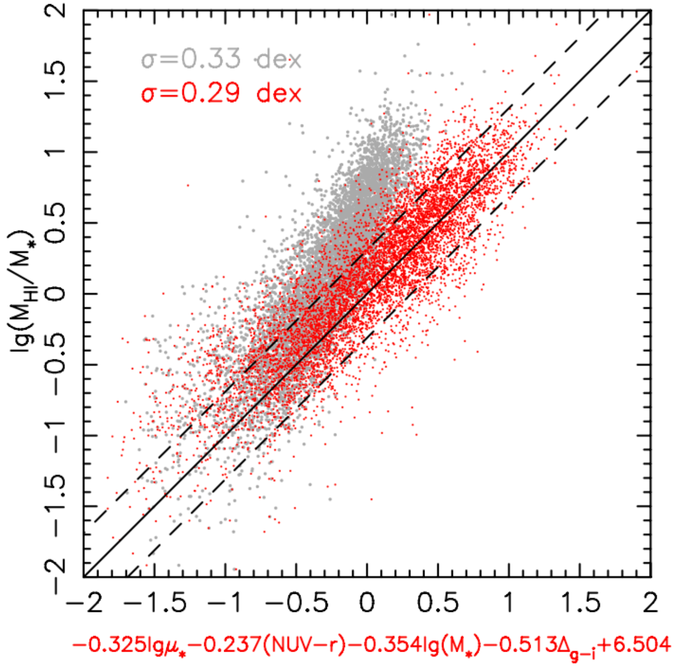


Catinella et al. 2010; Eckert et al. 2015; Teimoorinia et al. 2017; Rafieferantsoa et al. 2018; Ying Zu, 2020 …

previous works :

- biased calibration sample (Kannappan2004, Zhang2009)
- HI upper limits are not used (Li 2012)

Li et al. 2012



HI estimator model

estimating the HI gas mass in galaxies from their optical properties

stellar surface mass density *color index* *stellar mass* *concentration* *Gaussian random number*

$$\log M_{HI}/M_* = a \times \log \mu_* + b \times (u - r) + c \times \log M_* + d \times \log R_{90}/R_{50} + h + N(\sigma)$$

$$\textbf{scatter} : \sigma = \begin{cases} c_a \times m_0 + c_b \ , & m_0 > m_{0,t} \\ c_a \times m_{0,t} + c_b \ , & m_0 \leq m_{0,t} \end{cases}$$

m_0 is the logarithm of the predicted HI mass, $m_{0,t}$ is a transition mass, below which the scatter is a constant

Probability model

$$P(\boldsymbol{\theta}|\Phi_{\rm HI}, \boldsymbol{D}) = \frac{P(\Phi_{\rm HI}, \boldsymbol{D}|\boldsymbol{\theta}) \cdot P(\boldsymbol{\theta})}{P(\Phi_{\rm HI}, \boldsymbol{D})}$$

$$= \frac{P(\Phi_{\rm HI}|\boldsymbol{\theta}) \cdot P(\boldsymbol{D}|\boldsymbol{\theta}) \cdot P(\boldsymbol{\theta})}{P(\Phi_{\rm HI}) \cdot P(\boldsymbol{D})}$$

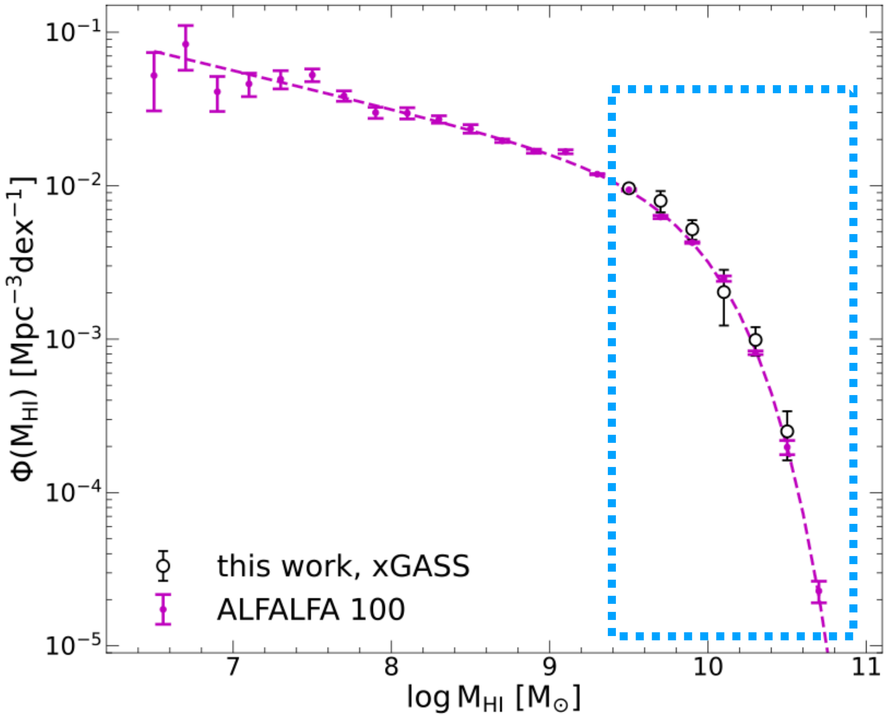
$$= \frac{P(\Phi_{\rm HI}|\boldsymbol{\theta}) \cdot P(\boldsymbol{\theta}|\boldsymbol{D})}{P(\Phi_{\rm HI})},$$

HIMF

xGASS sample

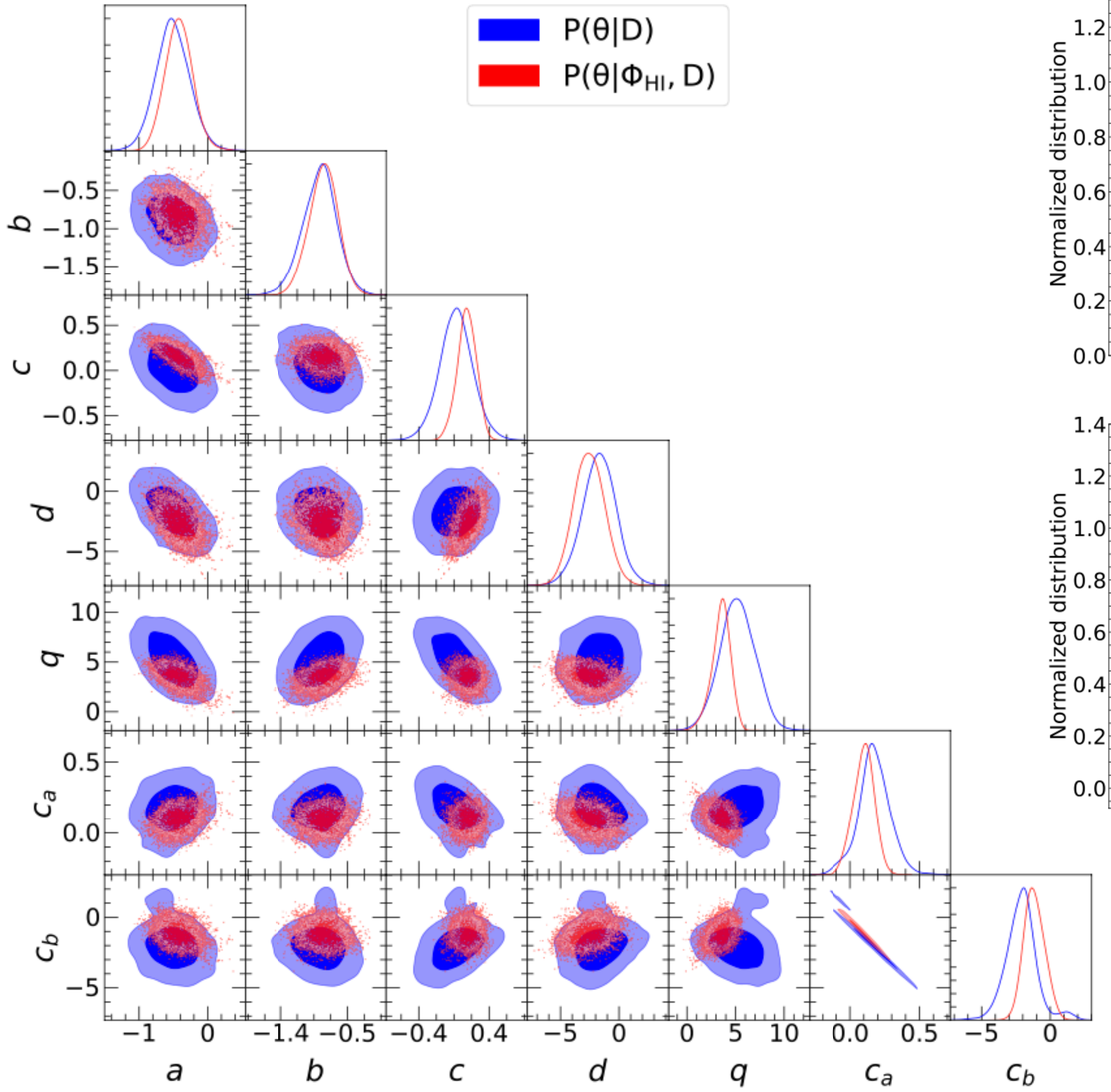
Constrain from HIMF

Constrain from xGASS, serve as prior

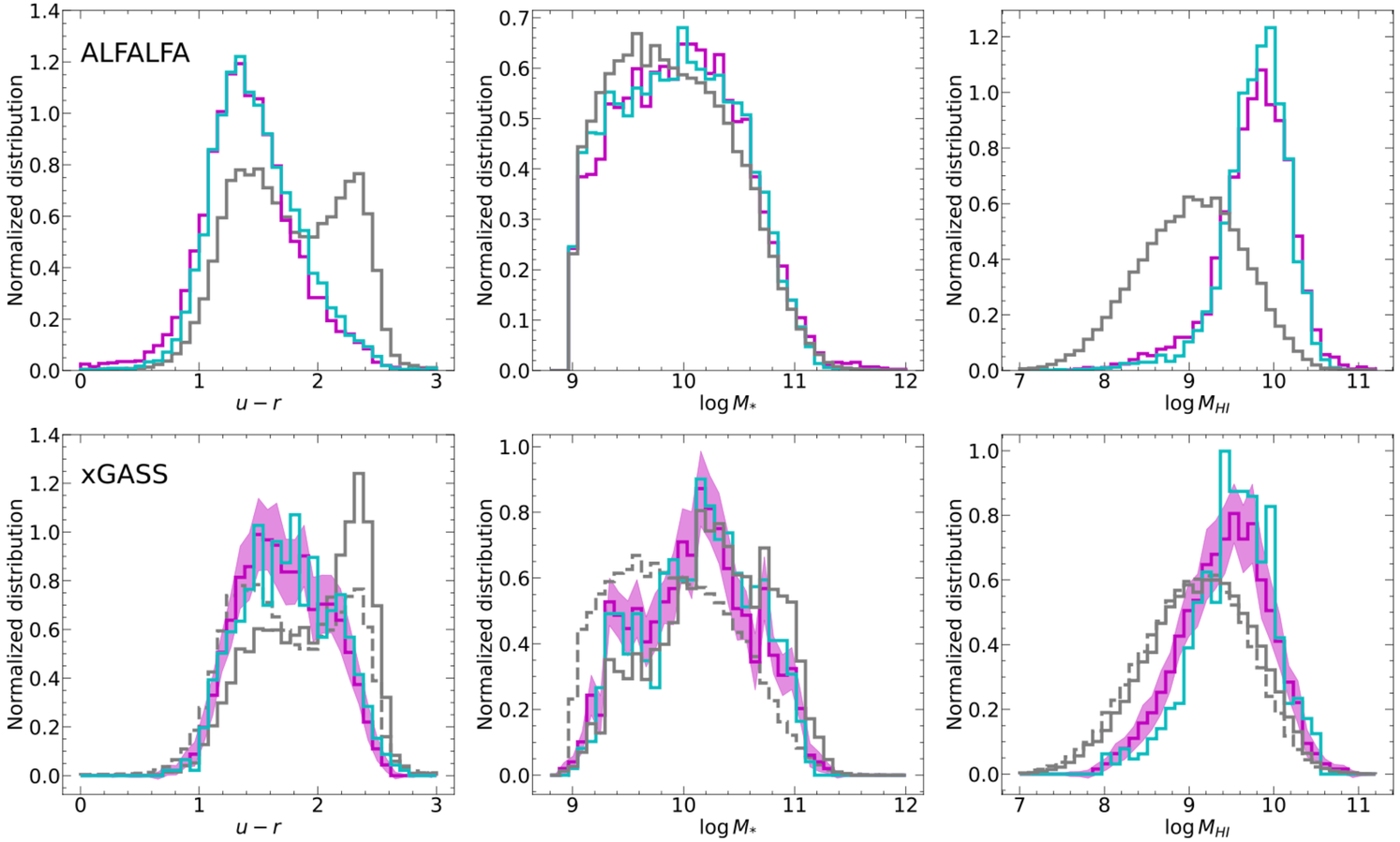


Posterior and mock HI surveys

cyan : observation magenta : mock
gray : SDSS volume-limited sample

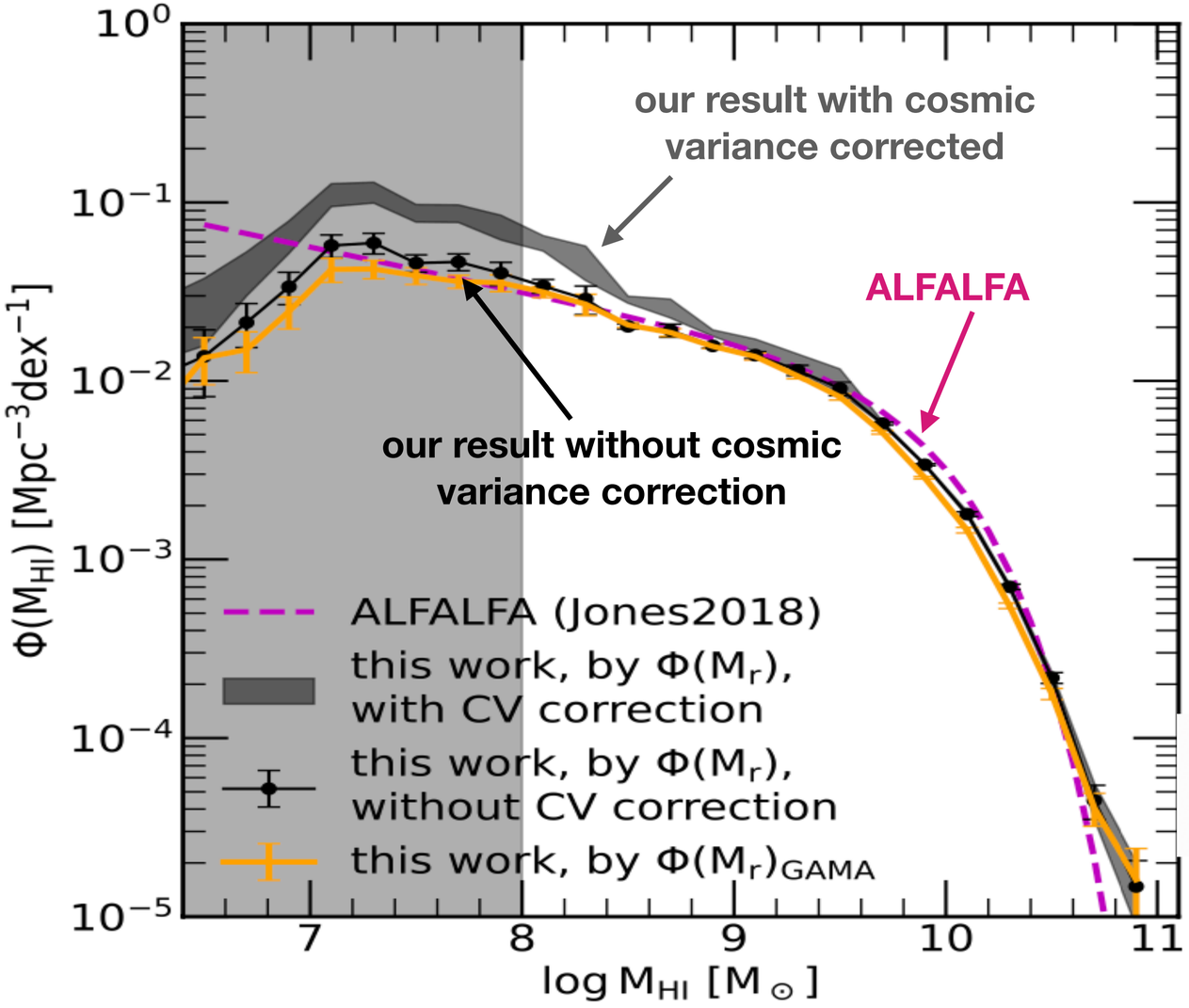


HI-detected galaxy distribution



Our mock survey can very reproduce the results of real HI surveys

ALFALFA underestimates the number density of galaxies with $\mathrm{M_{HI}} < 10^9 \mathrm{M_\odot}$



The very nearby universe (z < 0.06) detected by ALFALFA is an underdense region compared to the average density of the local universe

Cosmic Variance correction

$$\Phi(\mathrm{M_{HI}})\Delta \log \mathrm{M_{HI}} = \sum_i (f_{\mathrm{sp},i} V_{\mathrm{max},i})^{-1} \frac{\rho_\mathrm{u}}{\rho(V_{\mathrm{max},i})},$$

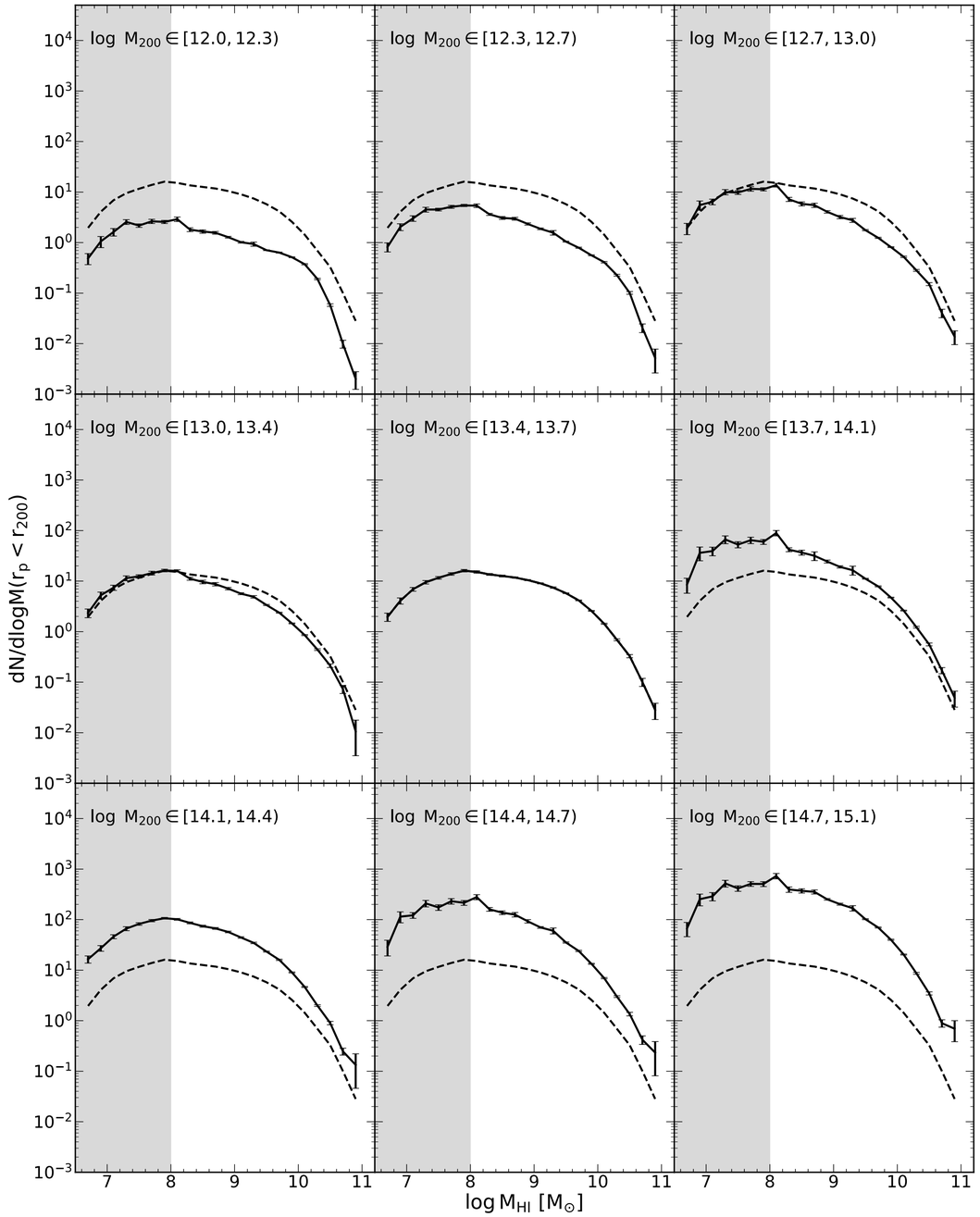
HI gas content in dark matter halos

Conditional HI Mass Function (CHIMF)

- The CHIMFs can be described by a single Schechter function
- The total HI gas mass increases with halo mass
- In halos of $M_h \gtrsim 10^{13}\ M_\odot$

  - the HI gases are mainly in satellite galaxies

  - red galaxies host similar amount of HI gas as blue galaxies



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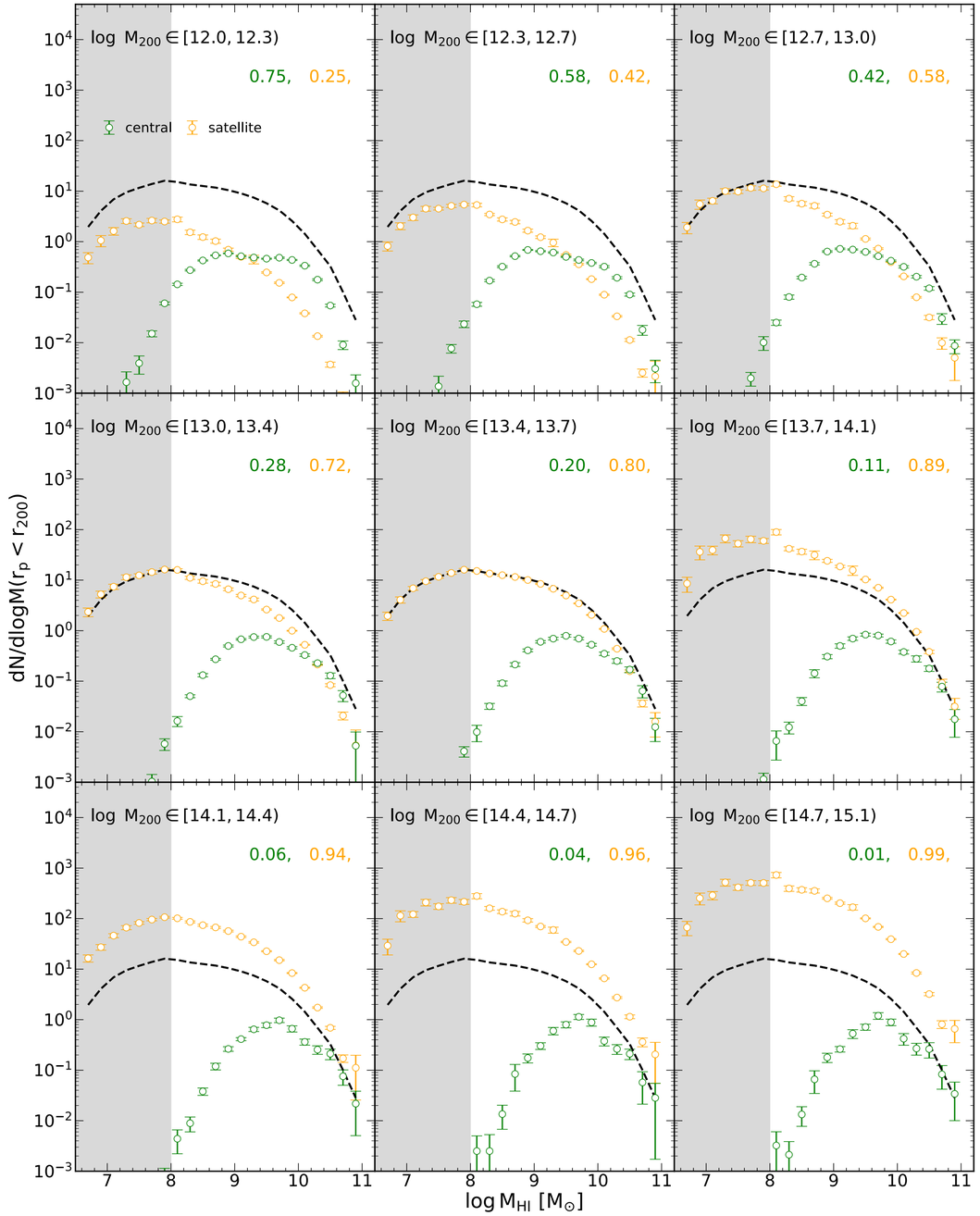

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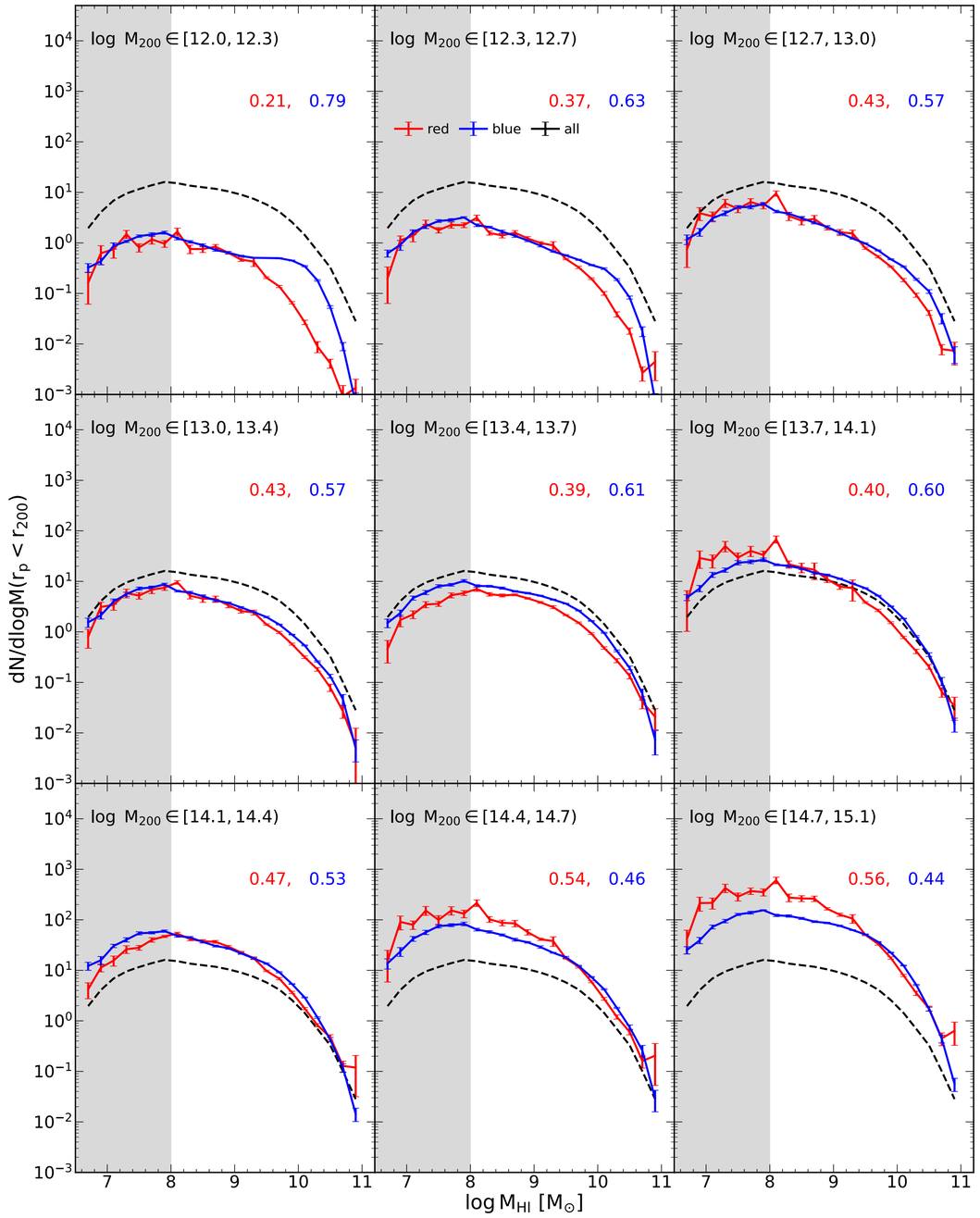


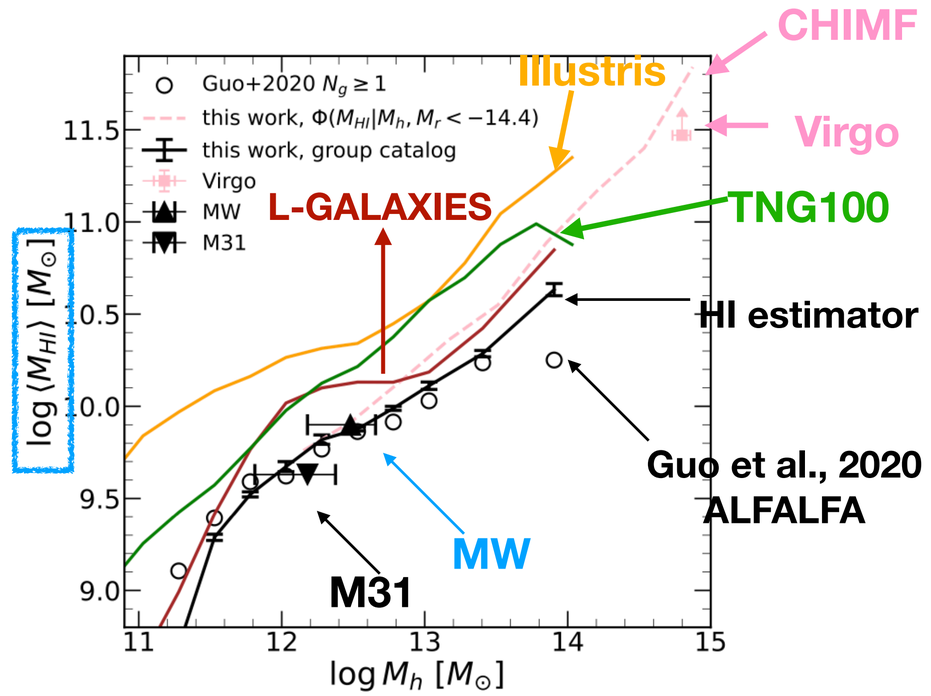
HI gas content in dark matter halos

HI-halo mass relation

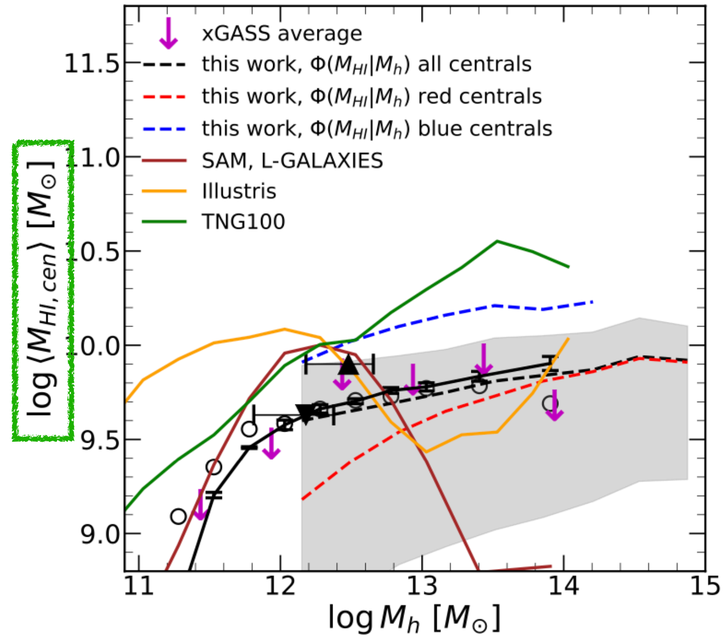
- our result (black solid line) is consistent with observation (black open circles)

- Semi-analytic models (SAM) and hydro simulations overpredict the HI gas in halos and wrongly predict the HI gas in central galaxies

HI gas mass in halos

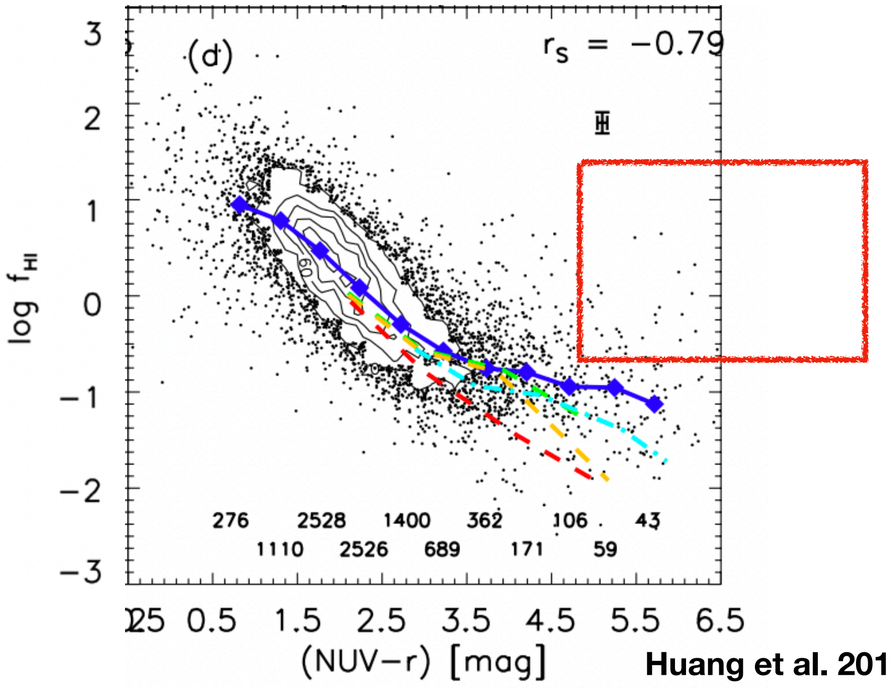


HI gas mass in central galaxies



From general population to outliers

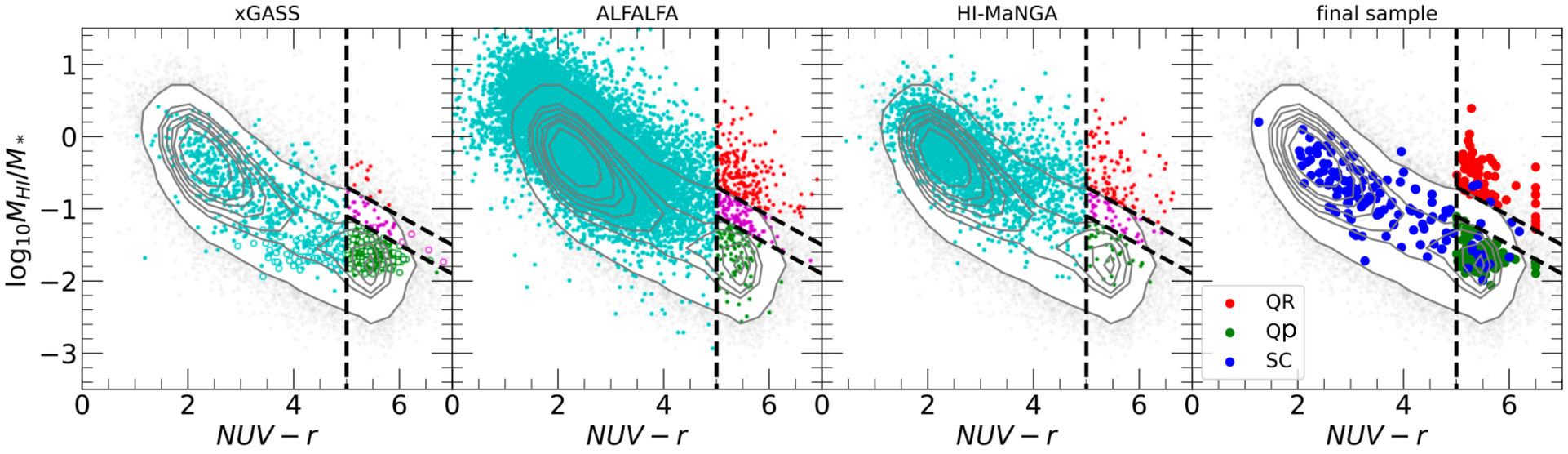
There exists some galaxies with little star formation but significant amount of HI gas



Huang et al. 2012

gray contours : SDSS volume-limited sample predicted by our HI estimator

colored data points : HI observation data



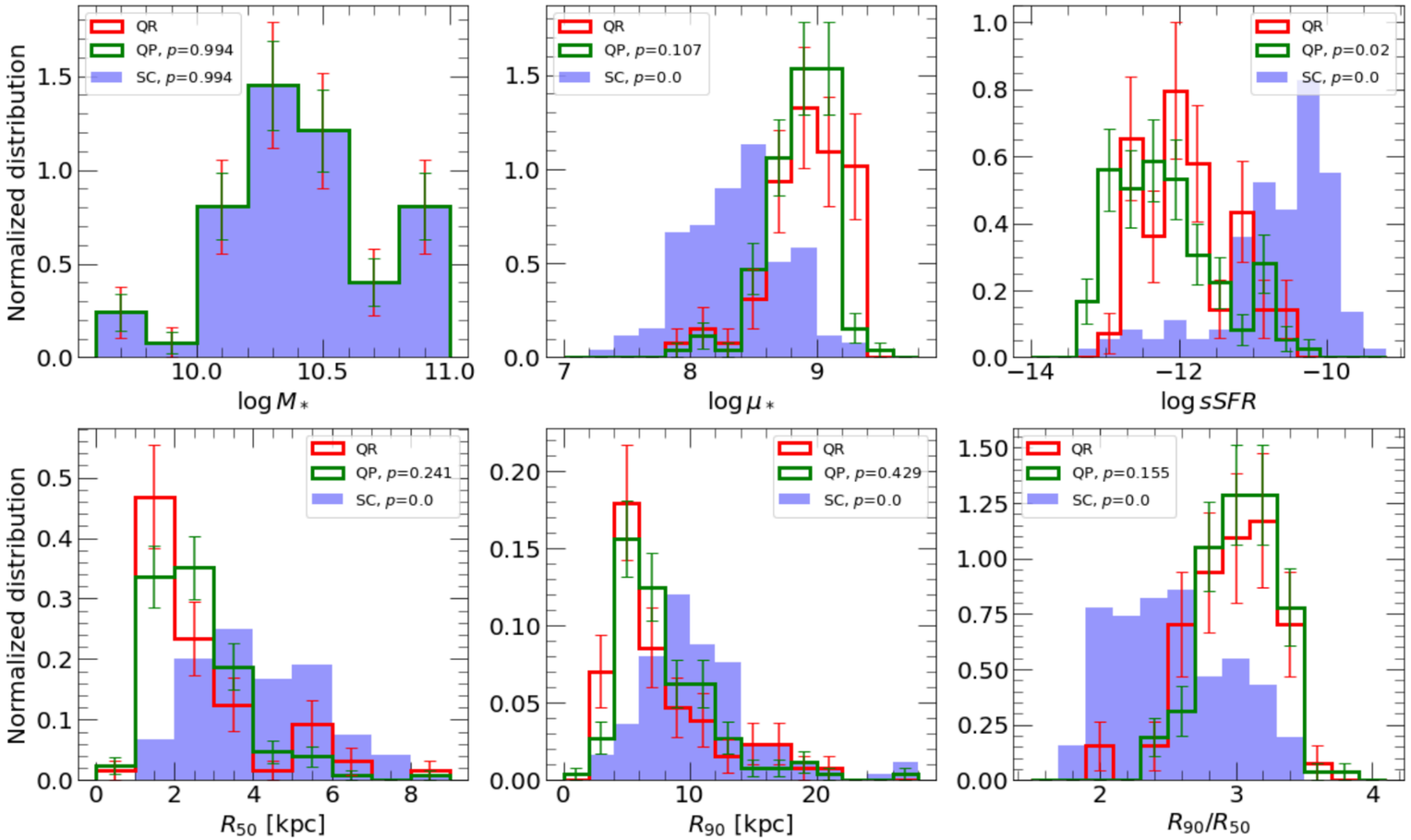
QR : quenched but HI-rich

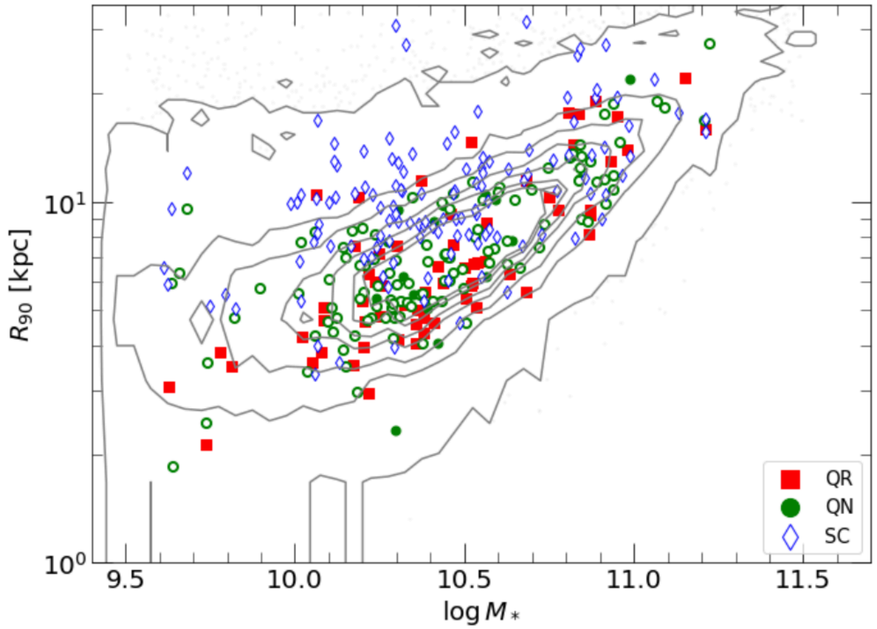
QP : quenched and HI-poor

SC : only stellar mass controlled

Quenched but HI-rich galaxies

QR : quenched but HI-rich
QP : quenched and HI-poor
SC : only stellar mass controlled



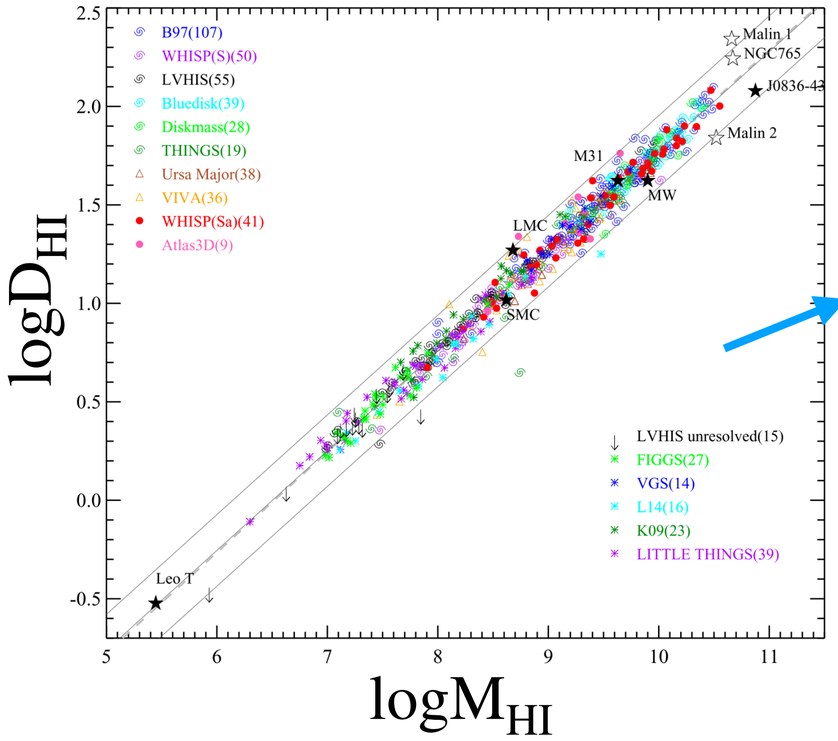


We do not find any significant difference between QR and QP sample in their optical properties

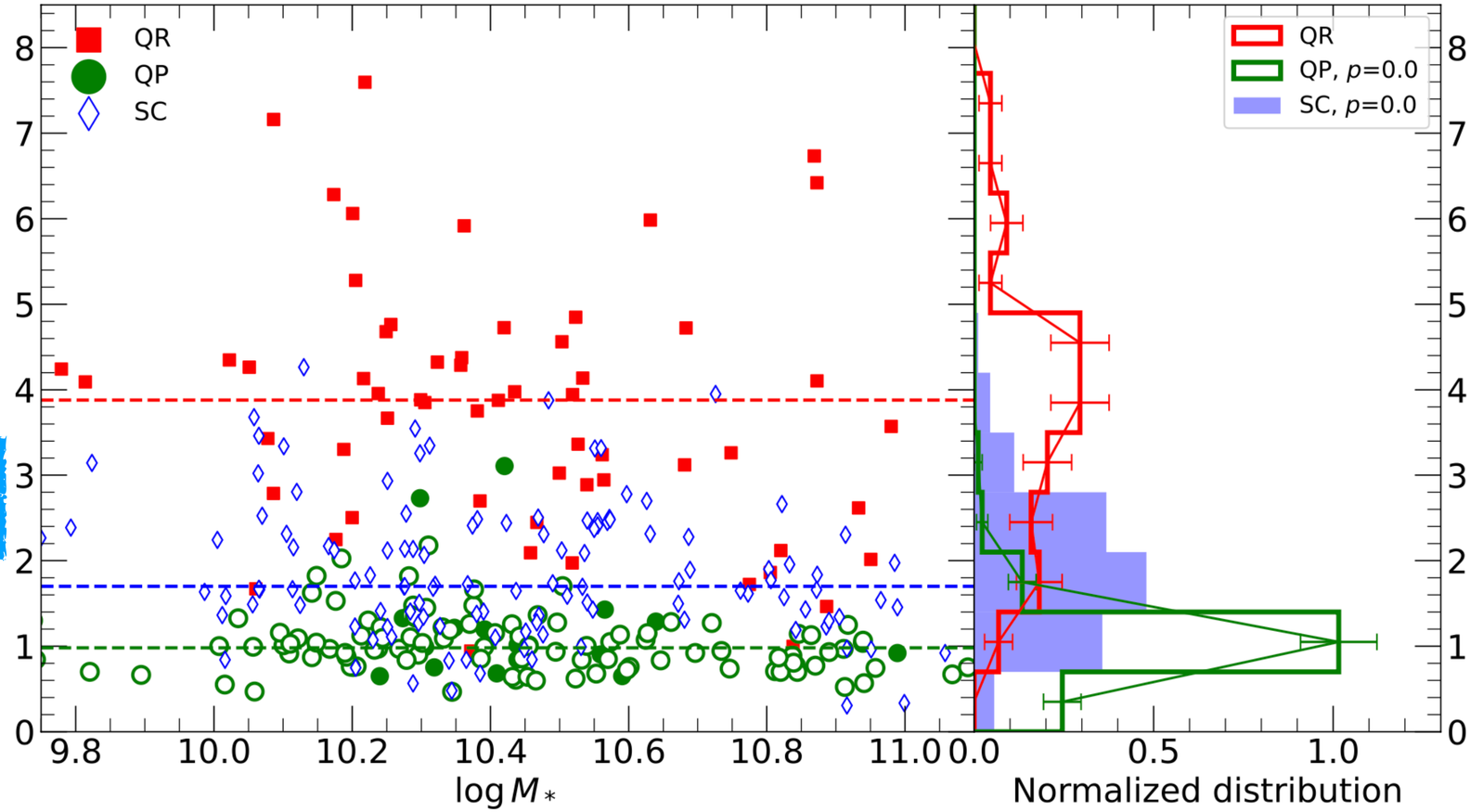
Quenched but HI-rich galaxies

QR : quenched but HI-rich
QN : quenched and HI-poor
SC : only stellar mass controlled

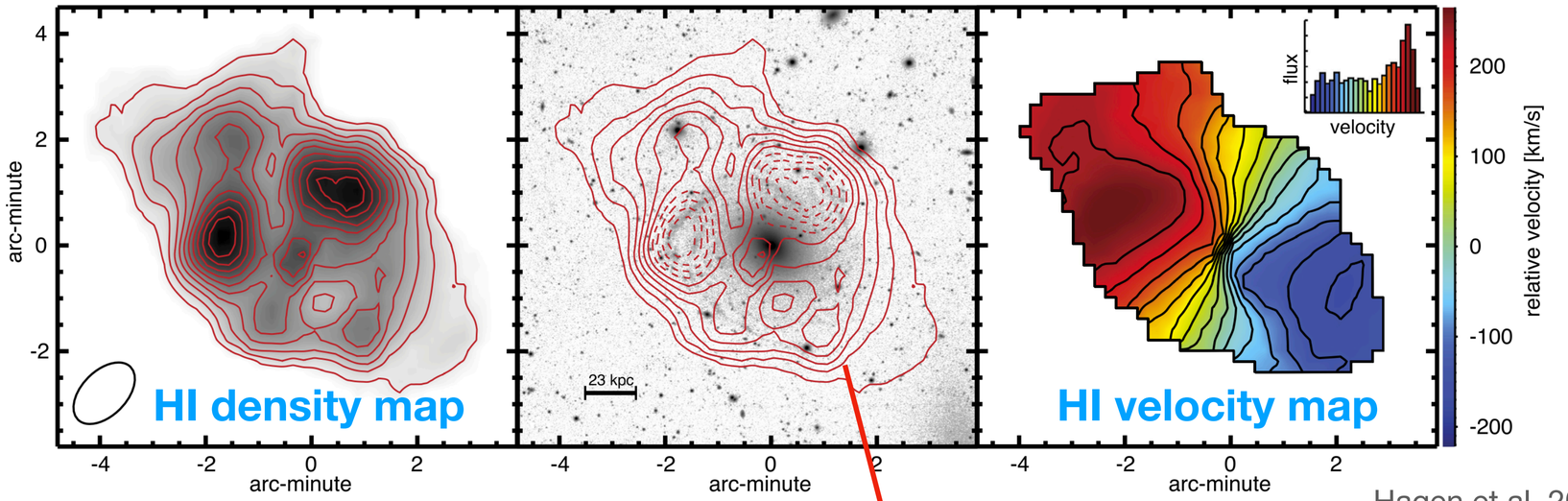
QR galaxies have HI gas disks (estimated from HI size-mass relation) much larger than the optical part



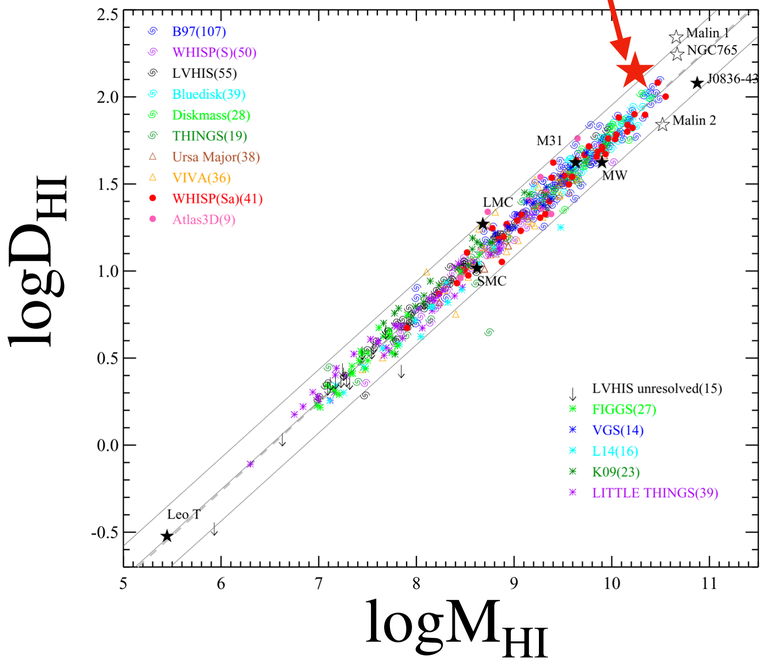
R_{HI}/R_{90}



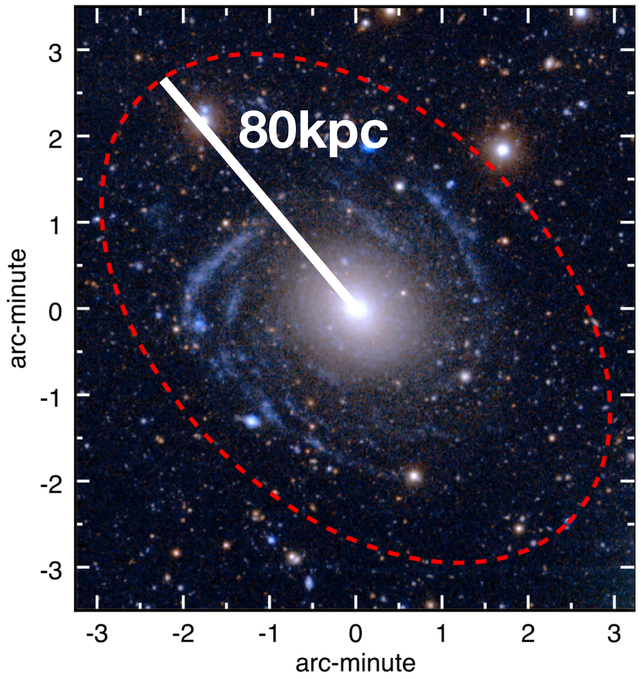
A case study of quenched but HI-rich galaxies



Hagen et al. 2016



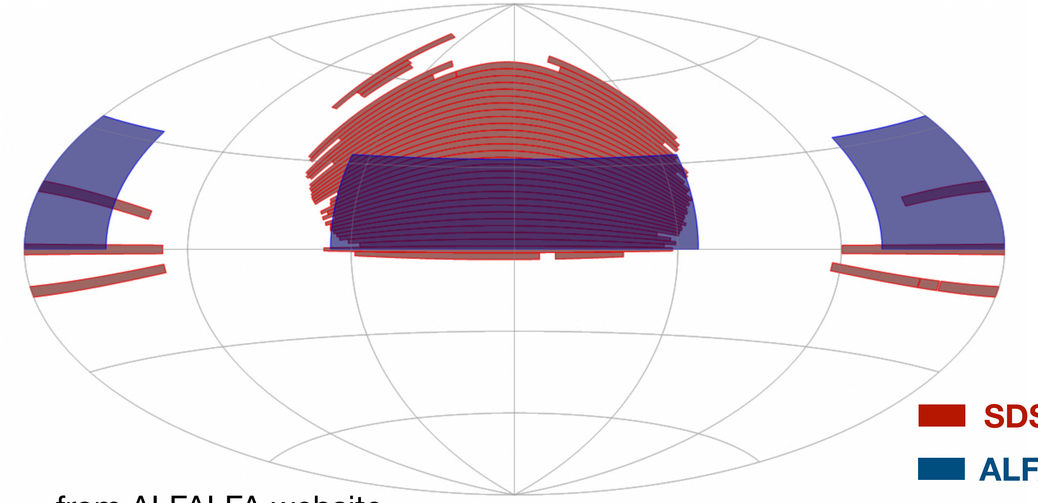
i + r + g + NUV



Summary

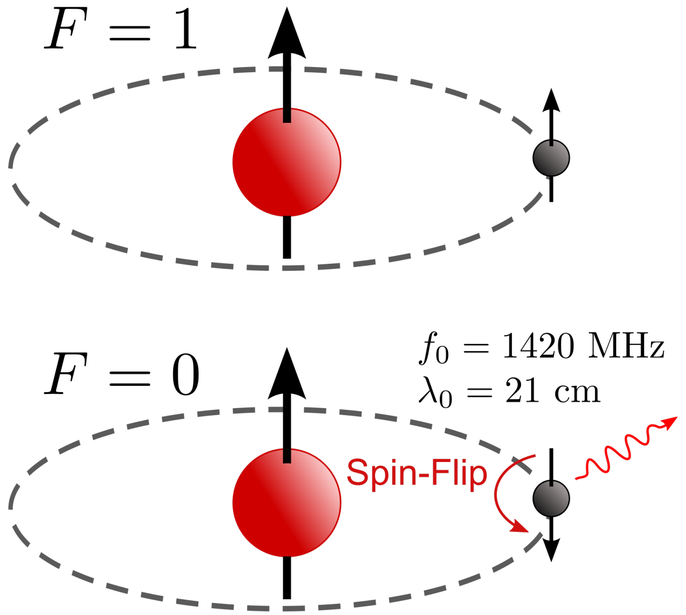
- We calibrate a new HI estimator which can predict the HI content of the general galaxy population statistically very well
- ALFALFA probably underestimates the number density of low HI mass galaxies
- CHIMF can be described by a single Schechter function. The HI gases are mainly in central (satellite) galaxies in low (high) mass halos
- Our HI-halo mass relation is consistent with observations and inconsistent with SAMs and hydrodynamical simulations
- Quenched but HI-rich galaxies have very similar optical properties as quenched HI-poor galaxies. The distribution of their HI gas is much more extended than that of stars.

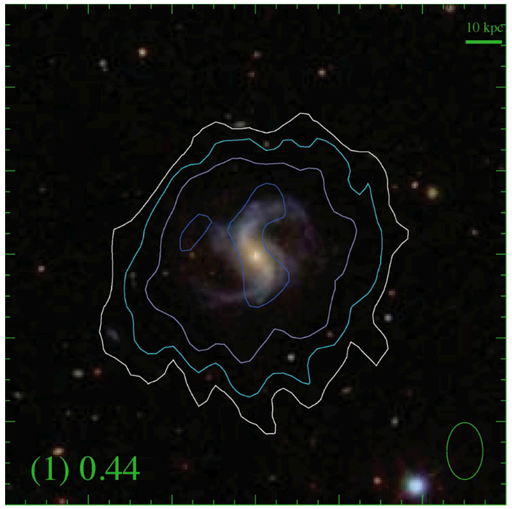
HI observation



from ALFALFA website

21 cm emission line

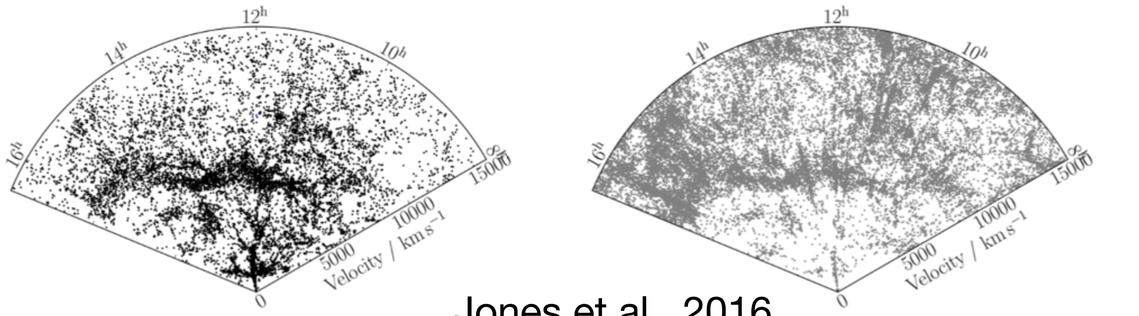




UGC 4283, Wang et al. 2013

ALFALFA

Sloan Digital Sky Survey



Jones et al., 2016

- Blind survey : ALFALFA, HIPASS, …

  large sample, but shallow

- Targeted survey : xGASS, HI-MaNGA, …

  small sample, but deep

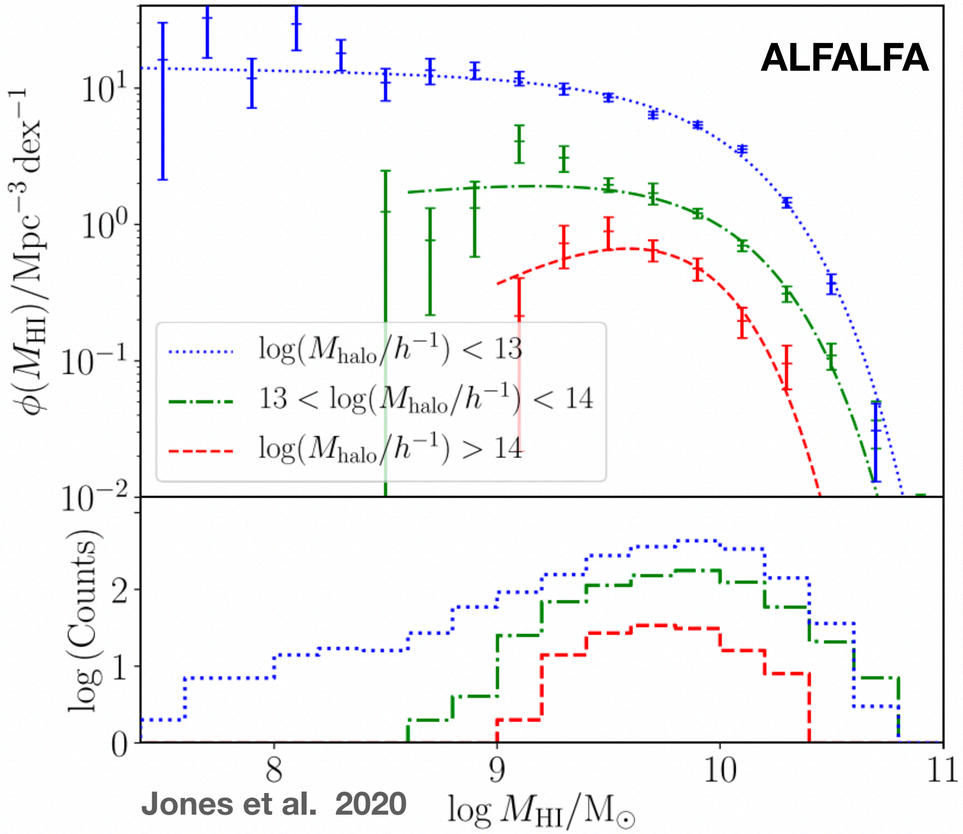
HI gas content in dark matter halos

conditional HI mass function (CHIMF)

- the number density of different HI masses in a given halo mass
- direct measurement of CHIMF is still difficult because current HI surveys are too shallow

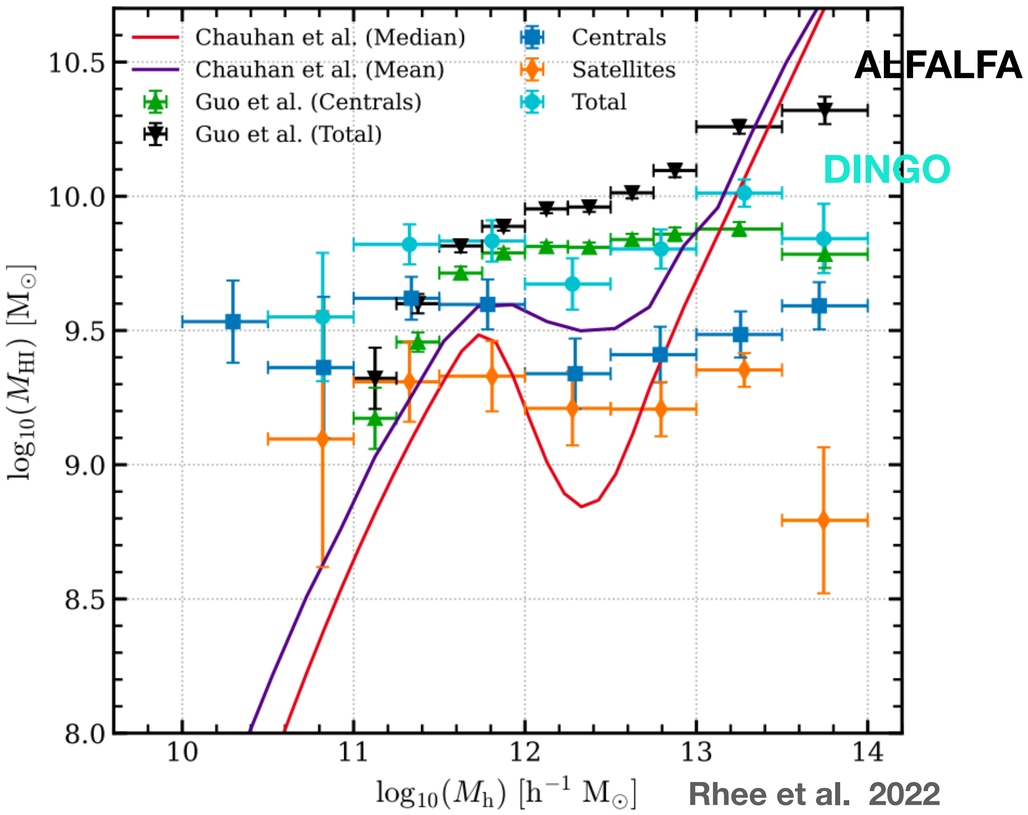
HI-halo mass relation

- how the total HI gas content in dark matter halos changes with halo mass
- direct measurement of this relation can only be reached by stacking the HI spectra of galaxies or halos

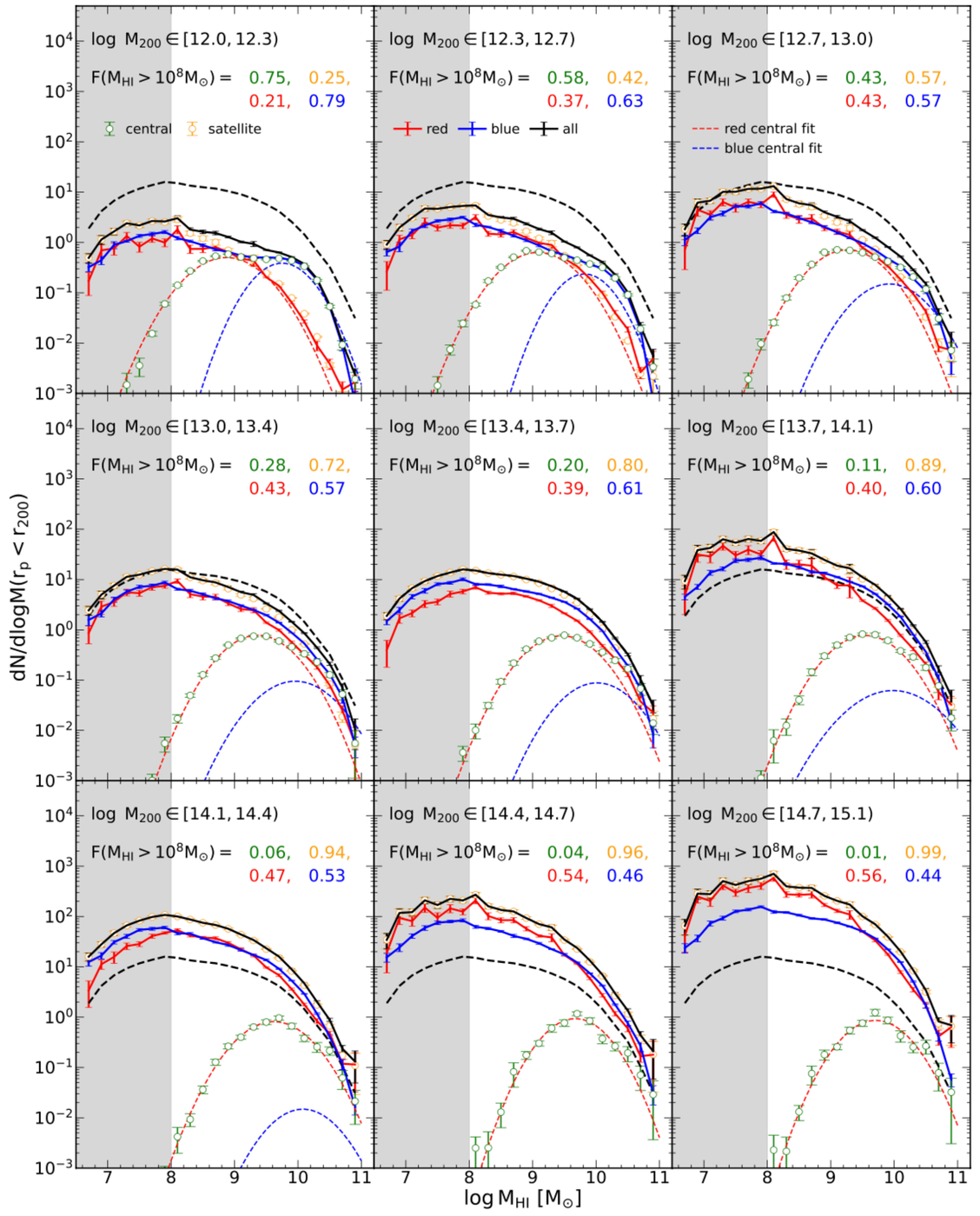


Jones et al. 2020

Using our photometrically-estimated HI sample, we can overcome the shallowness of current HI surveys and measure these statistics properly



Rhee et al. 2022


log M200 ∈ [12.0, 12.3)
F(MHI > 10^8 M⊙) = 0.75, 0.25, 0.21, 0.79
central
satellite
log M200 ∈ [12.3, 12.7)
F(MHI > 10^8 M⊙) = 0.58, 0.42, 0.37, 0.63
red
blue
all
log M200 ∈ [12.7, 13.0)
F(MHI > 10^8 M⊙) = 0.43, 0.57, 0.43, 0.57
red central fit
blue central fit
log M200 ∈ [13.0, 13.4)
F(MHI > 10^8 M⊙) = 0.28, 0.72, 0.43, 0.57
log M200 ∈ [13.4, 13.7)
F(MHI > 10^8 M⊙) = 0.20, 0.80, 0.39, 0.61
log M200 ∈ [13.7, 14.1)
F(MHI > 10^8 M⊙) = 0.11, 0.89, 0.40, 0.60
log M200 ∈ [14.1, 14.4)
F(MHI > 10^8 M⊙) = 0.06, 0.94, 0.47, 0.53
log M200 ∈ [14.4, 14.7)
F(MHI > 10^8 M⊙) = 0.04, 0.96, 0.54, 0.46
log M200 ∈ [14.7, 15.1)
F(MHI > 10^8 M⊙) = 0.01, 0.99, 0.56, 0.44
dN/dlogM(rp < r200)
log MHI [M⊙]