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The *interstellar medium of galaxies* in simulations: predictions and expectations for ALMA and the SKA

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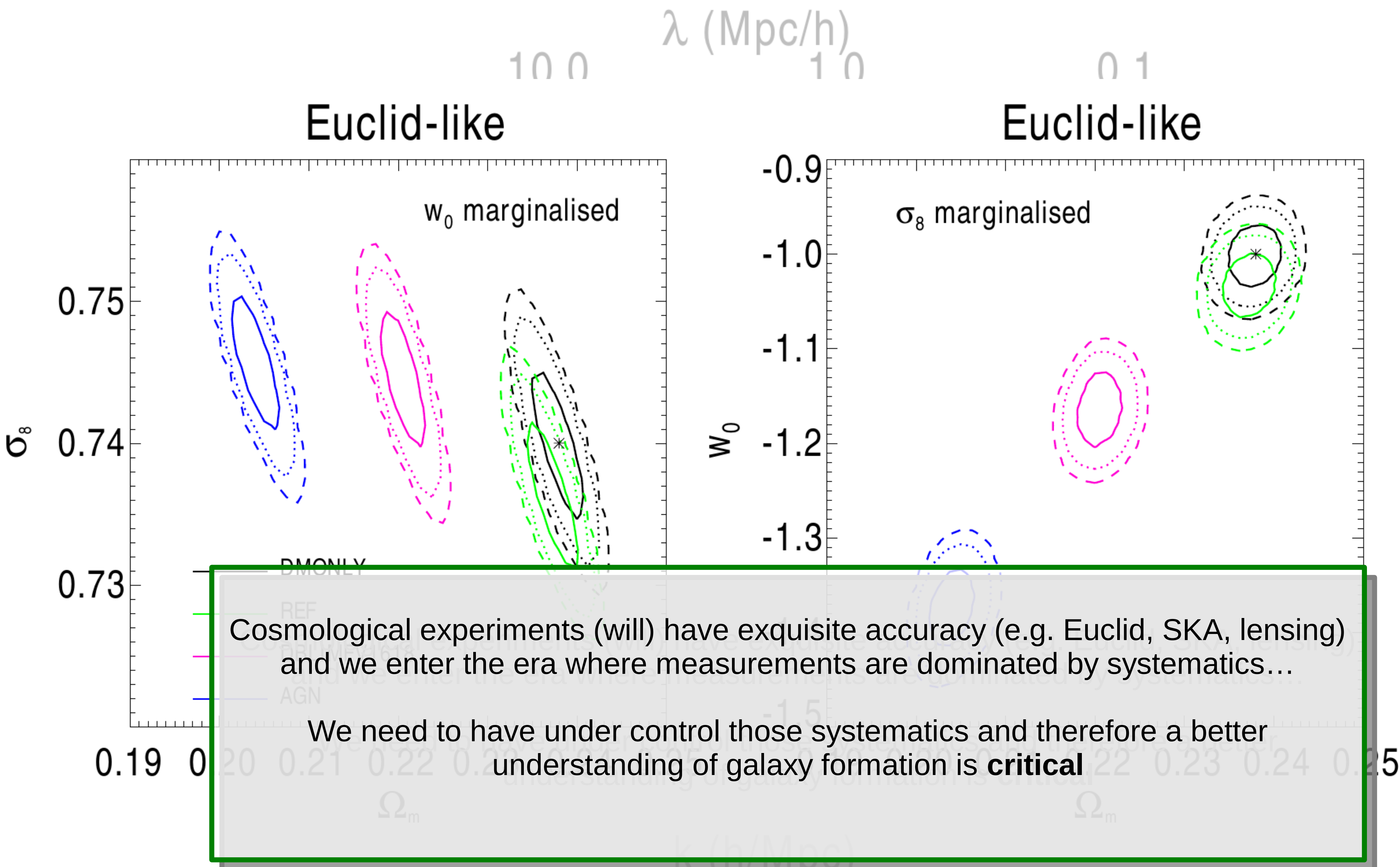
How much cosmology is affected by galaxy formation uncertainties?



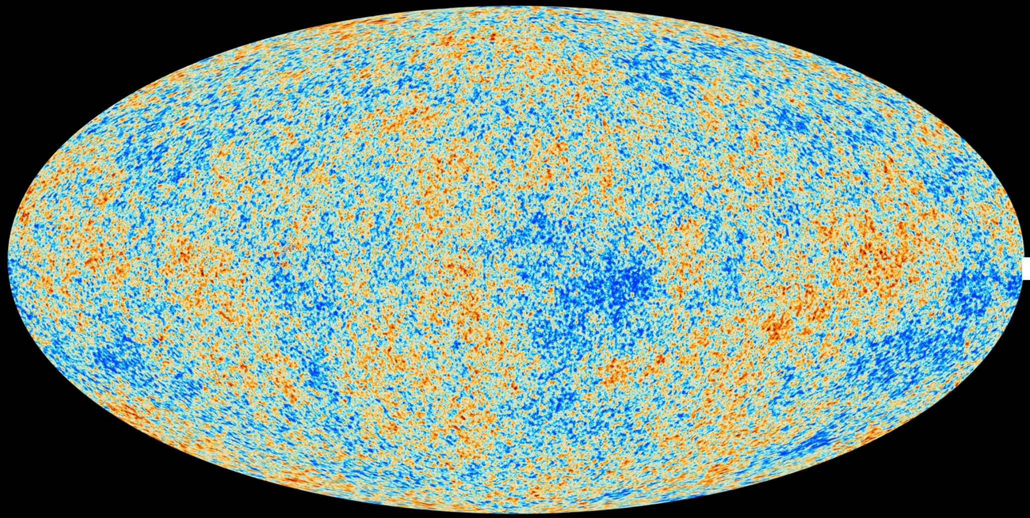
Cosmological experiments (will) have exquisite accuracy (e.g. Euclid, SKA, lensing) and we enter the era where measurements are dominated by systematics…

We need to have under control those systematics and therefore a better understanding of galaxy formation is **critical**

Sembolini et al. (2011)

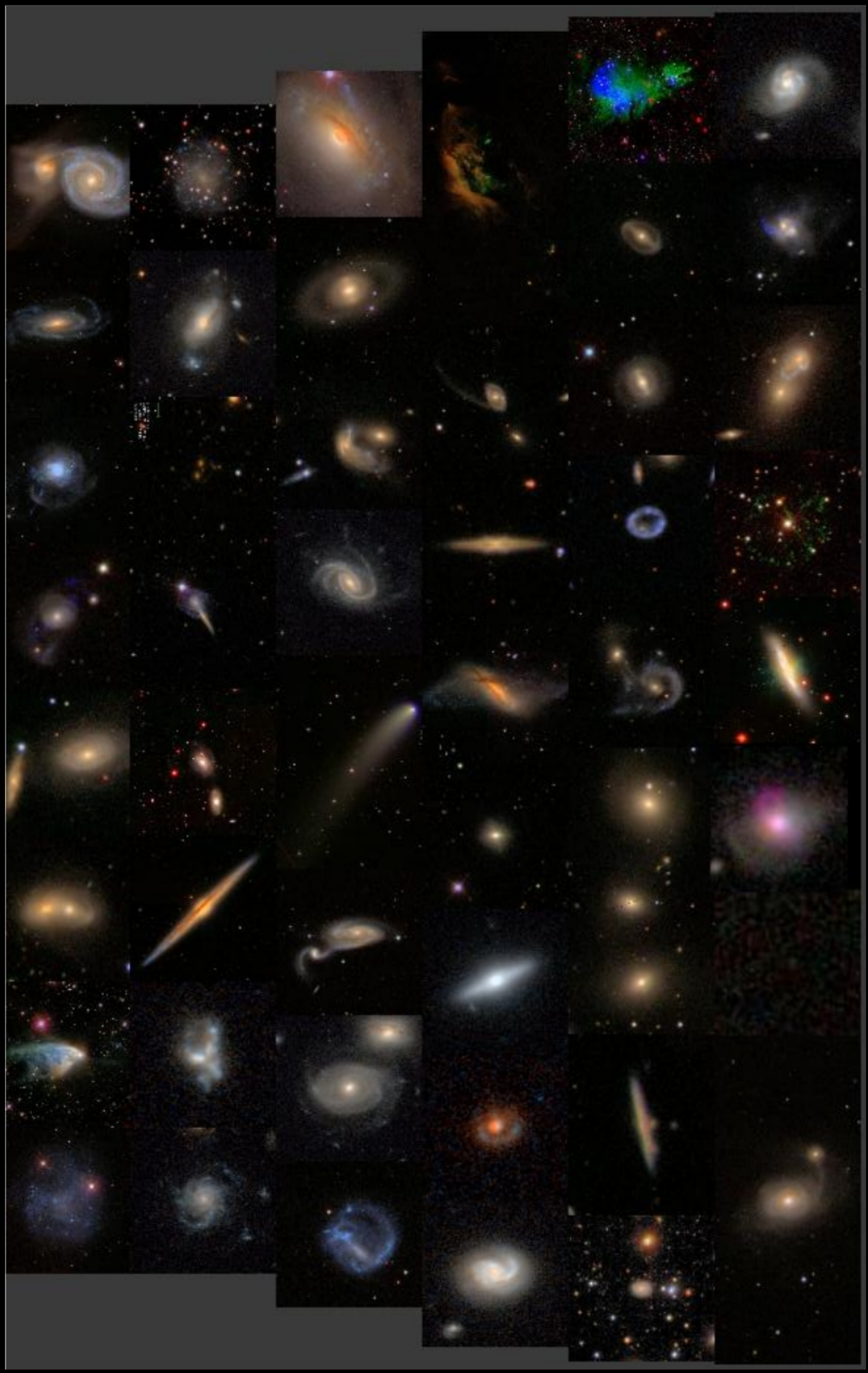
The fundamental goal of galaxy formation studies

Planck



?

Galaxy zoo



A complexity problem:

→ 8 orders in magnitude in temperature

→ 10 orders of magnitude in column density

→ 10 orders of magnitude in volume density

→ >10 orders of magnitude in scale

minimal elements of a predictive theory of galaxy formation?

Where do we stand now?

How good our current simulations are?

Are they sufficient for the new generation of telescopes?

Where do we need to put more effort/developments of the next years?

What is the SKA interested in?

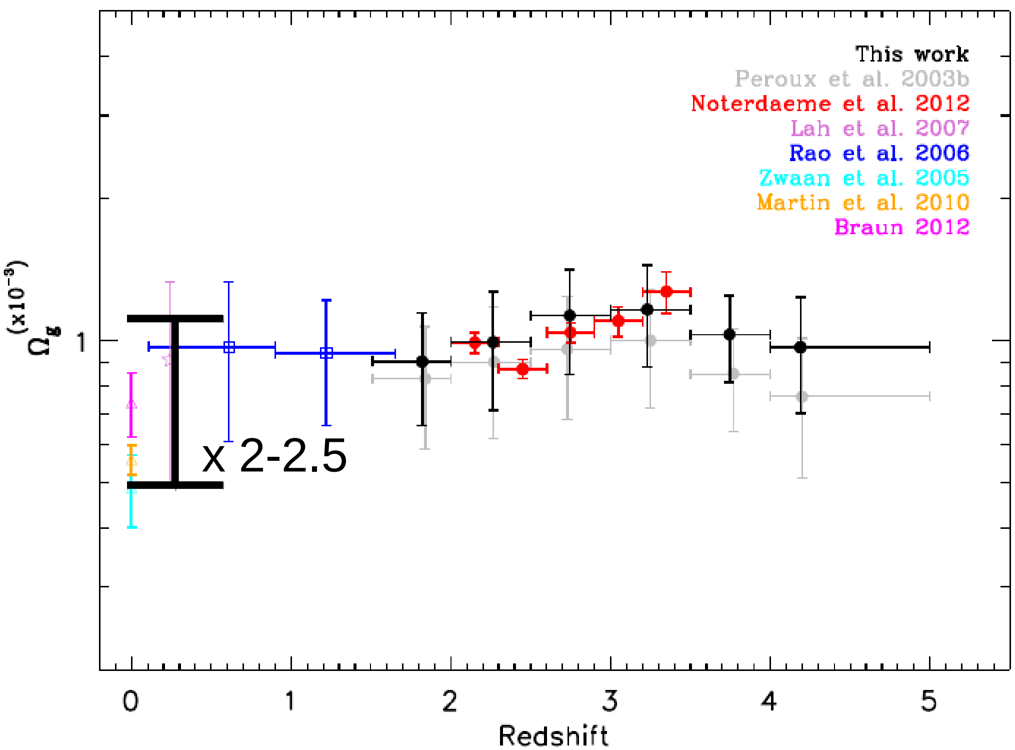
What is the HI distribution of the Universe? (Large HI-blind surveys, but also deep observations around galaxies to detect HI in circum-galactic and intergalactic media, intensity mapping and EoR)

How does HI can trace the build-up of angular momentum in galaxies? (a good census of gas accretion onto galaxies) Connection with LSS evolution.

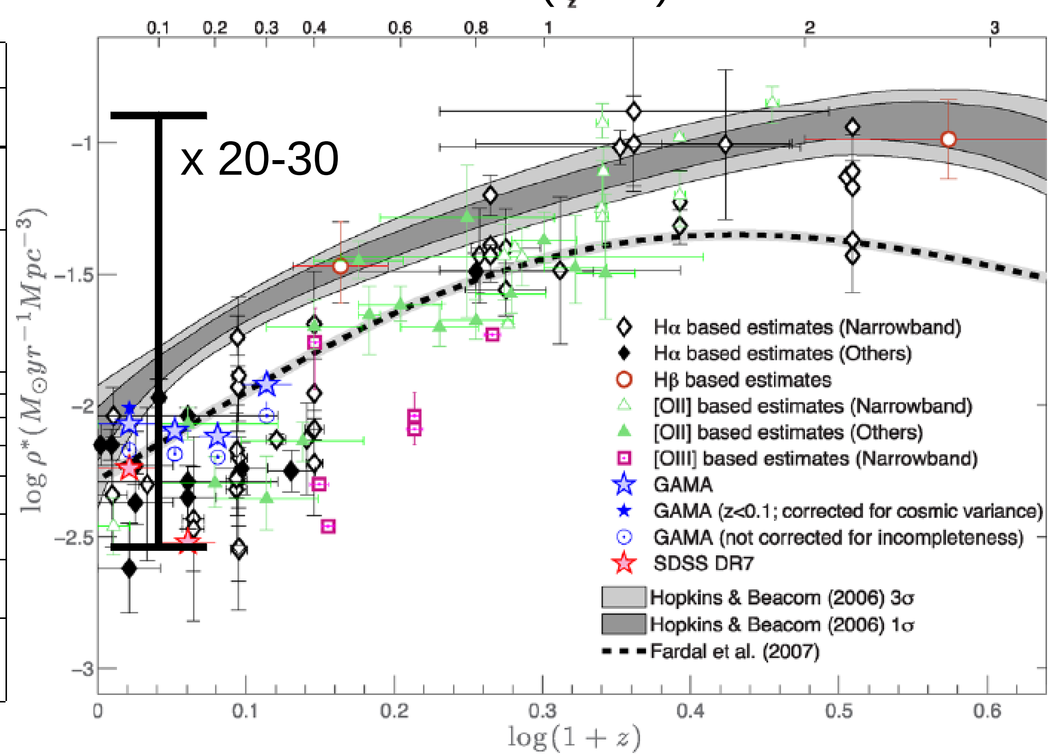
HI content of the Universe

An outstanding problem in extragalactic astrophysics:

Zafar et al. (2013)



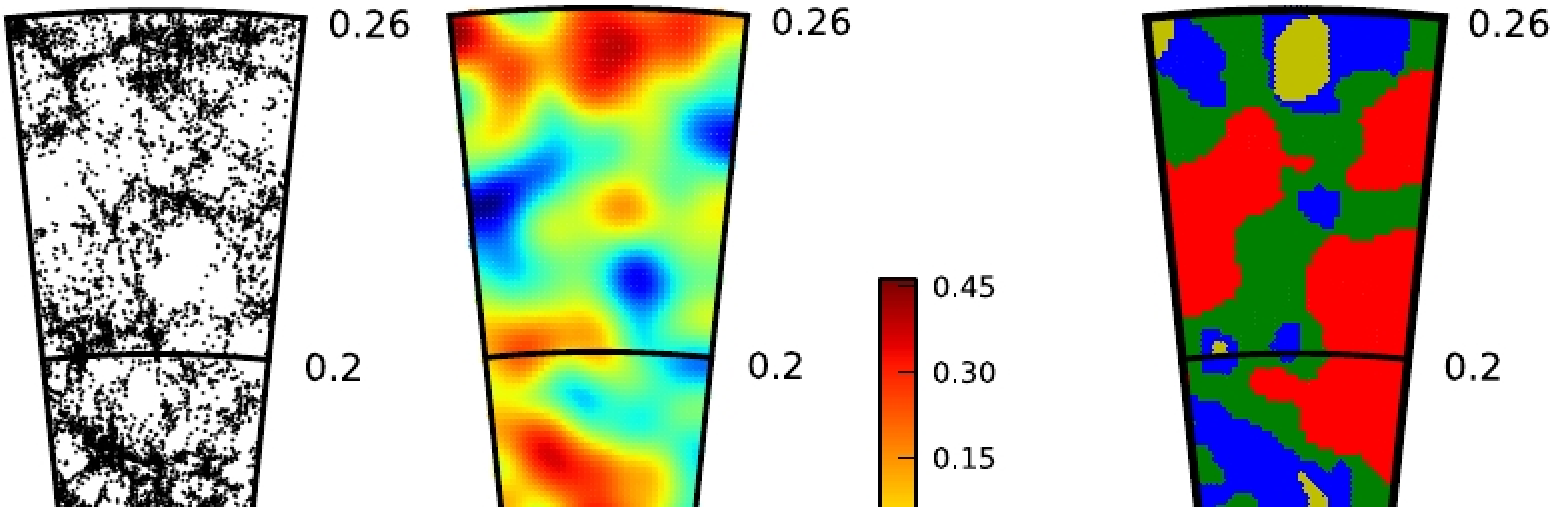
Gunawardhana et al. (2013)

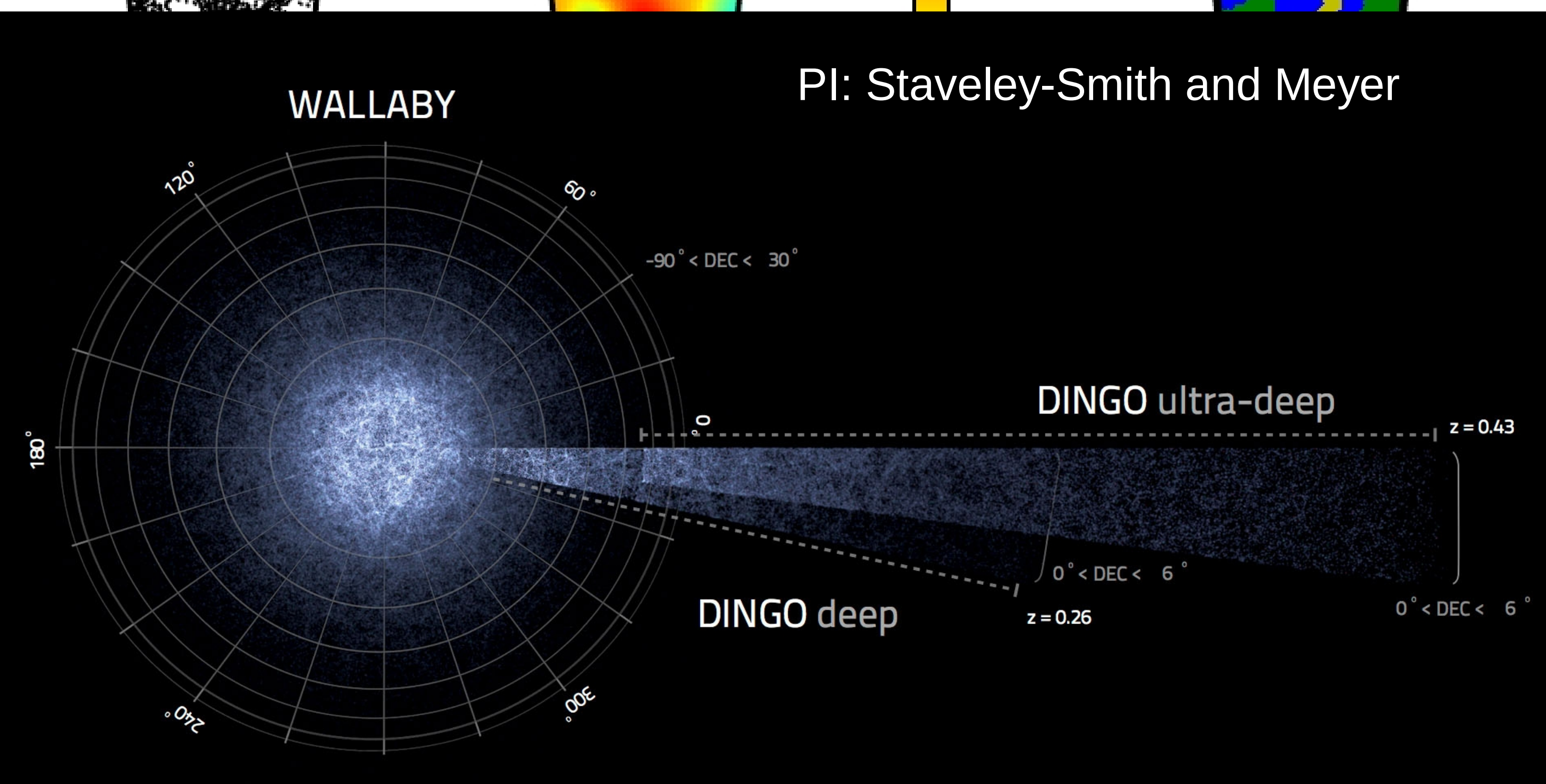


If neutral gas is the fuel for star formation, ***why the star formation history of the Universe looks so much different than the HI history of it?***

Exciting prospects in the field!

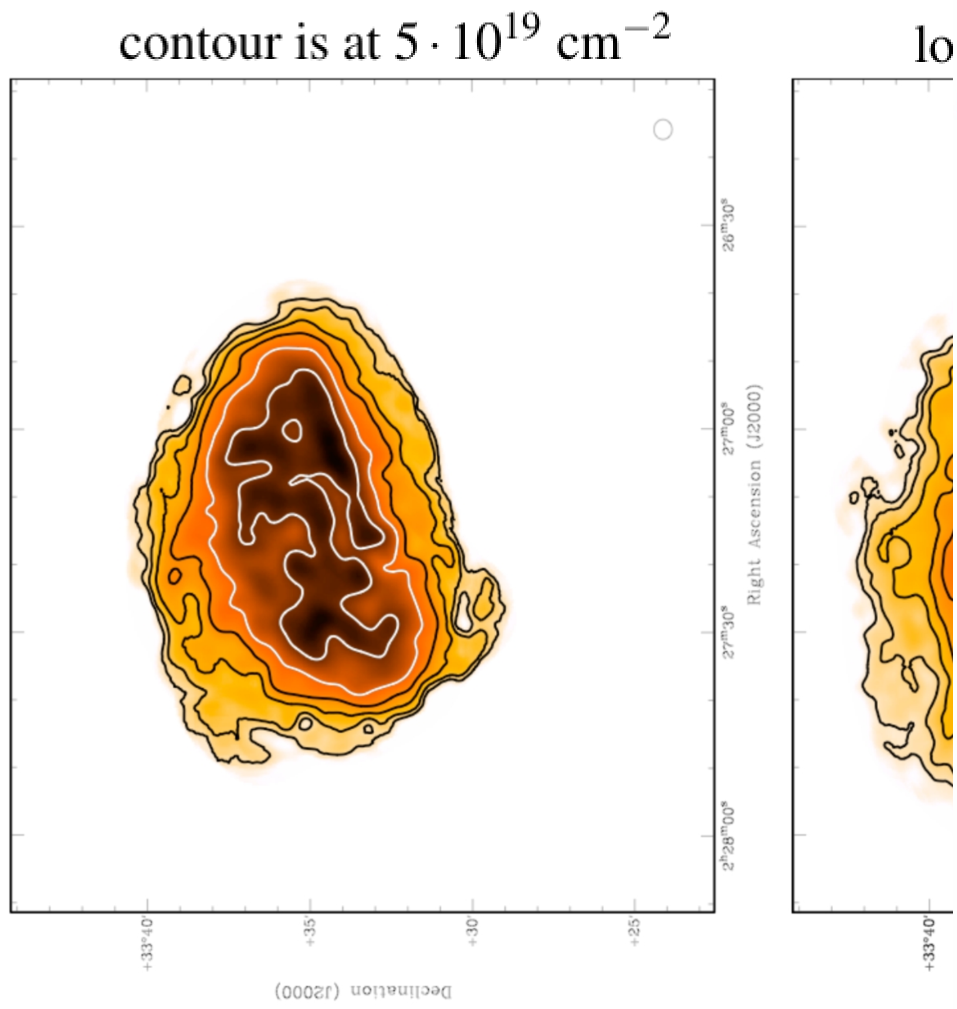
Eardley et al. (2015): the cosmic web in GAMA

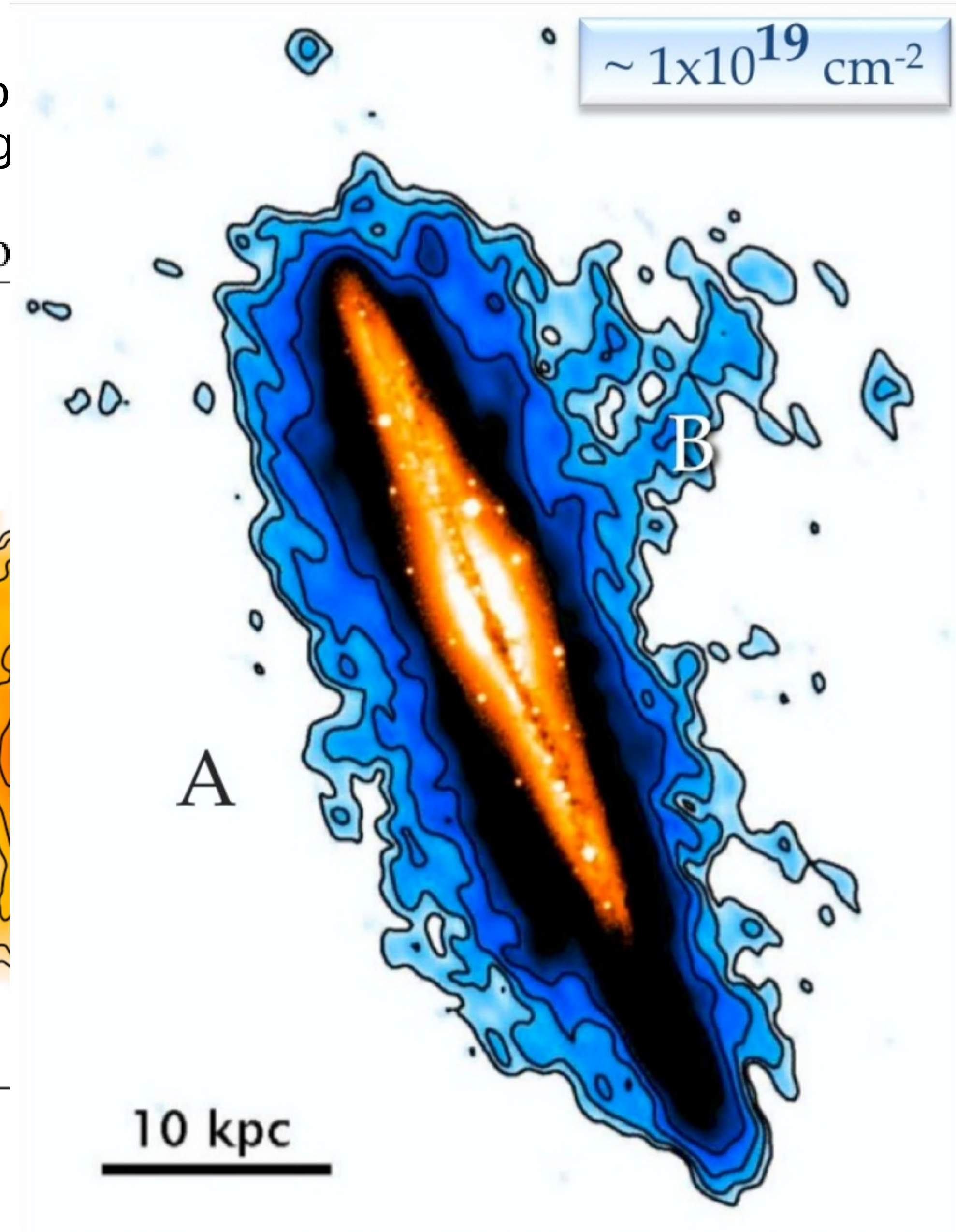




HI in the circum- and inter-galactic media

THINGS vs. HALOGAS for NGC 925 (de Blo
al. 2015): measuring the accretion rate of a g



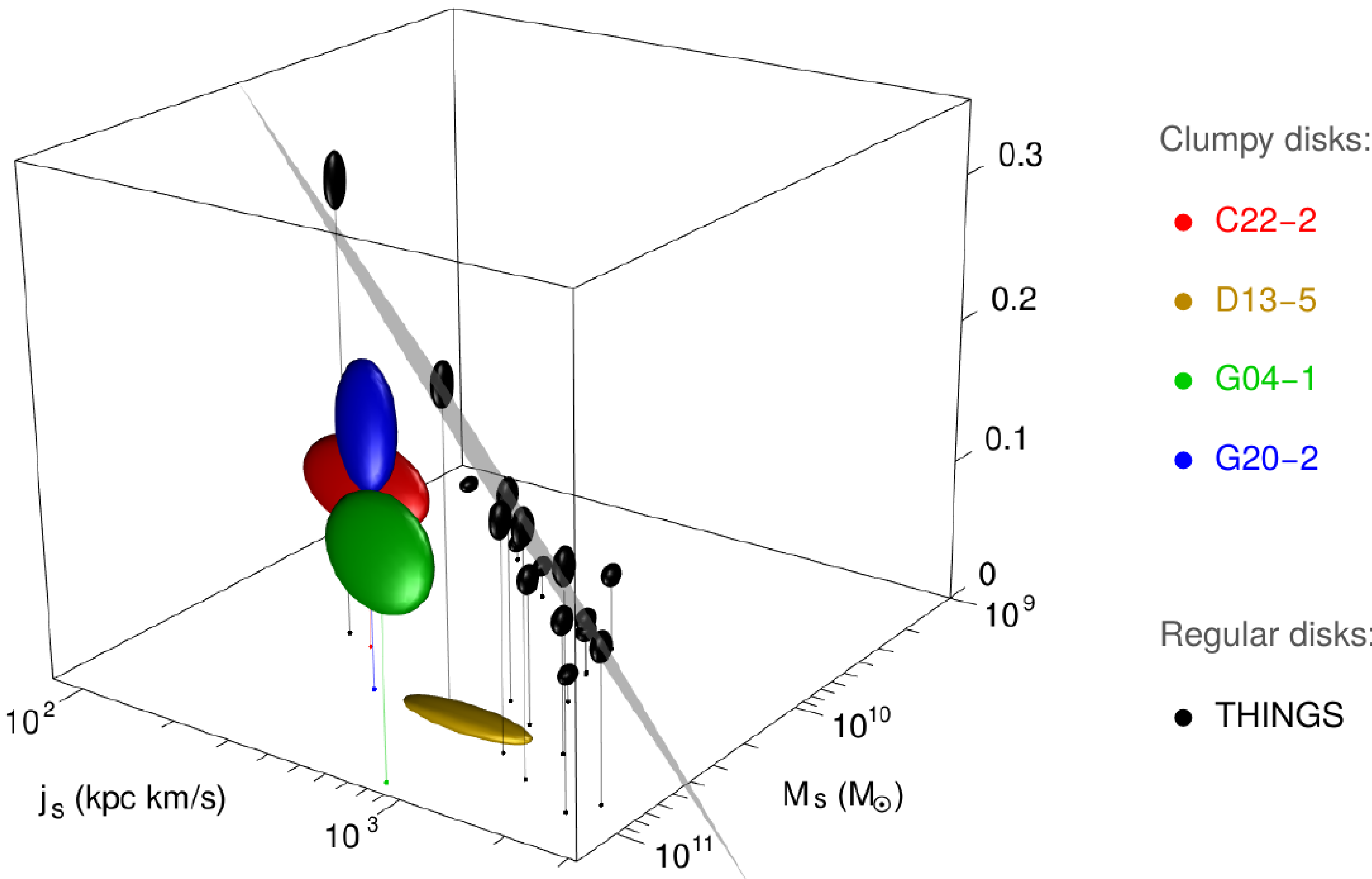


Oosterloo, Fraternali, Sancisi (2007): NGC 891

How angular momentum builds-up

Obreschkow & Glazebrook (2014)
Obreschkow et al. (2015)

Angular momentum will be a measurable quantity not in a dozen of galaxies, but in thousands!



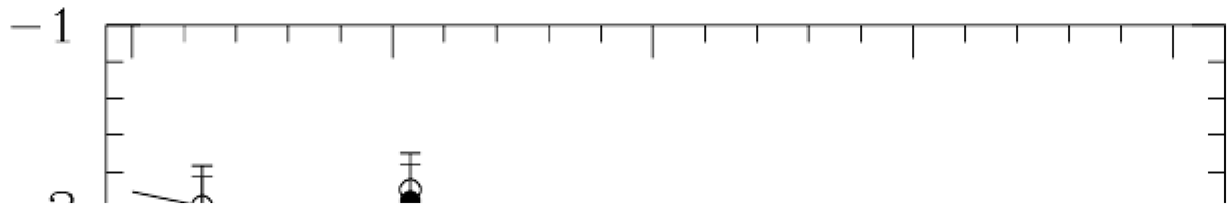
What is ALMA interested in?

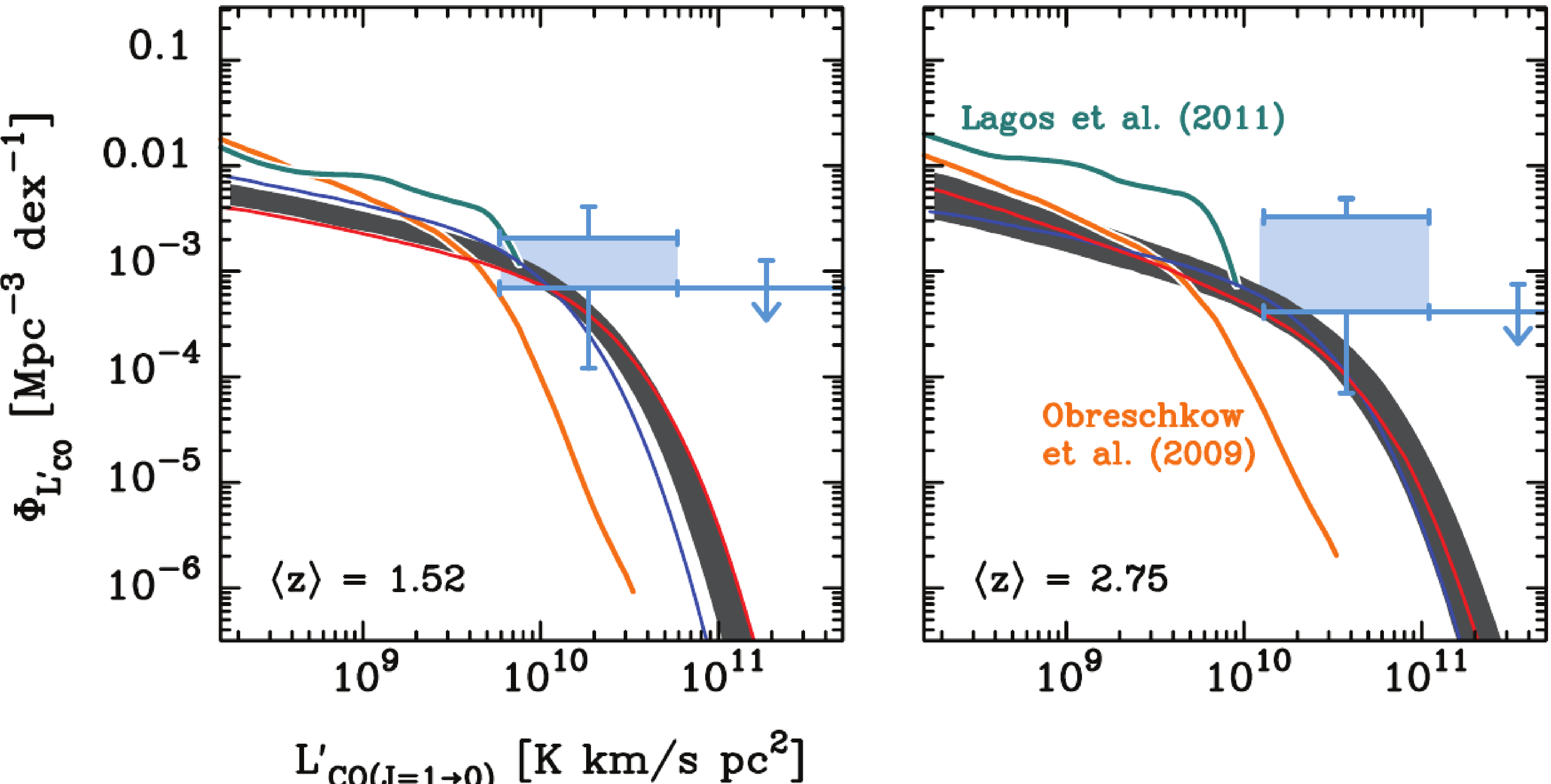
What are the properties of the ISM in galaxies throughout cosmic epochs? (ISM dynamics and content of galaxies at different redshifts)

What is the Universe's content of dense gas and how is it distributed? (blind CO-oriented surveys and targeted surveys) Connection with DM halo growth.

The H_2 content of galaxies

Keres et al. (2003)

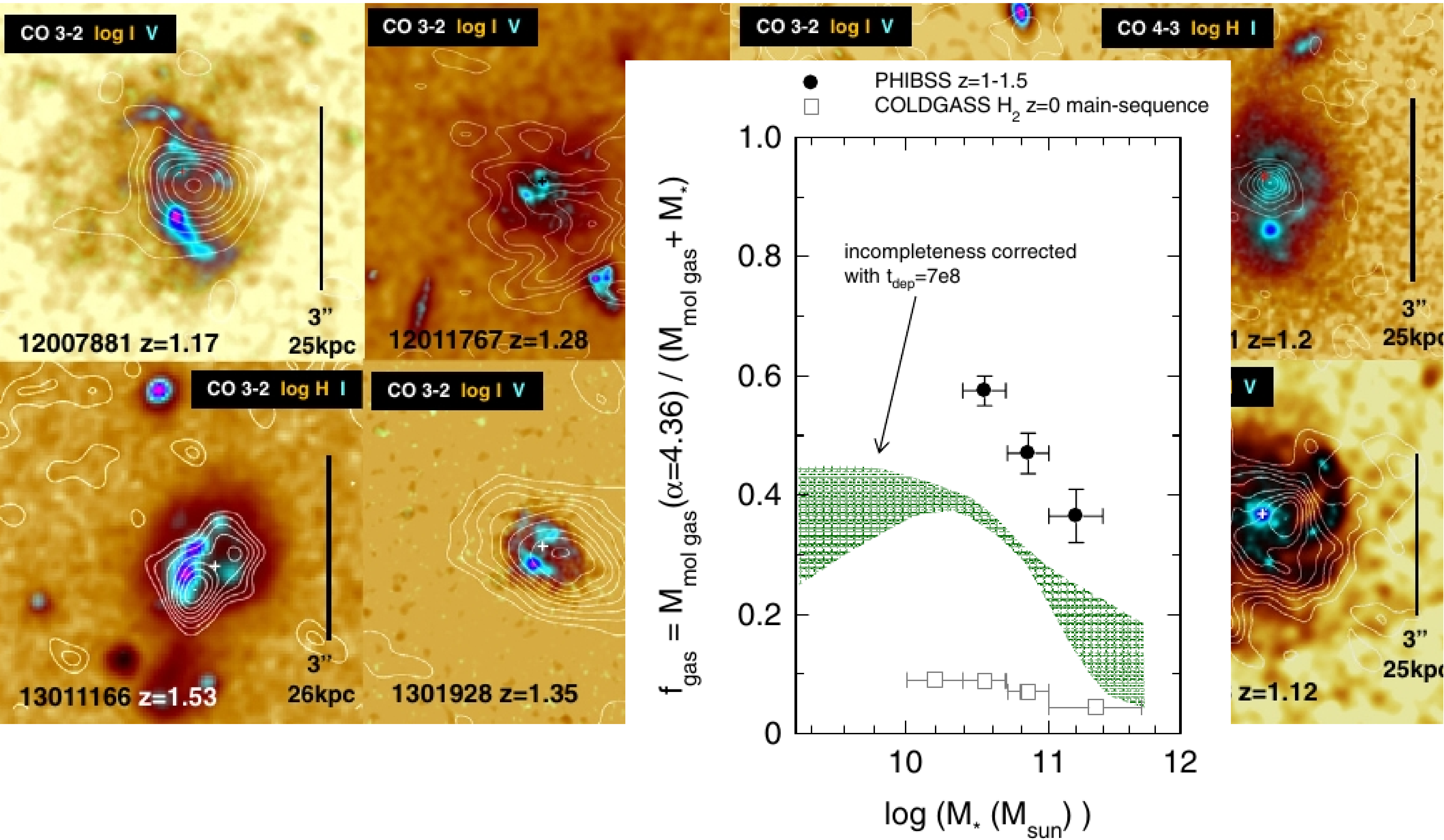




Walter et al. (2015); Decarli et al. (2015)

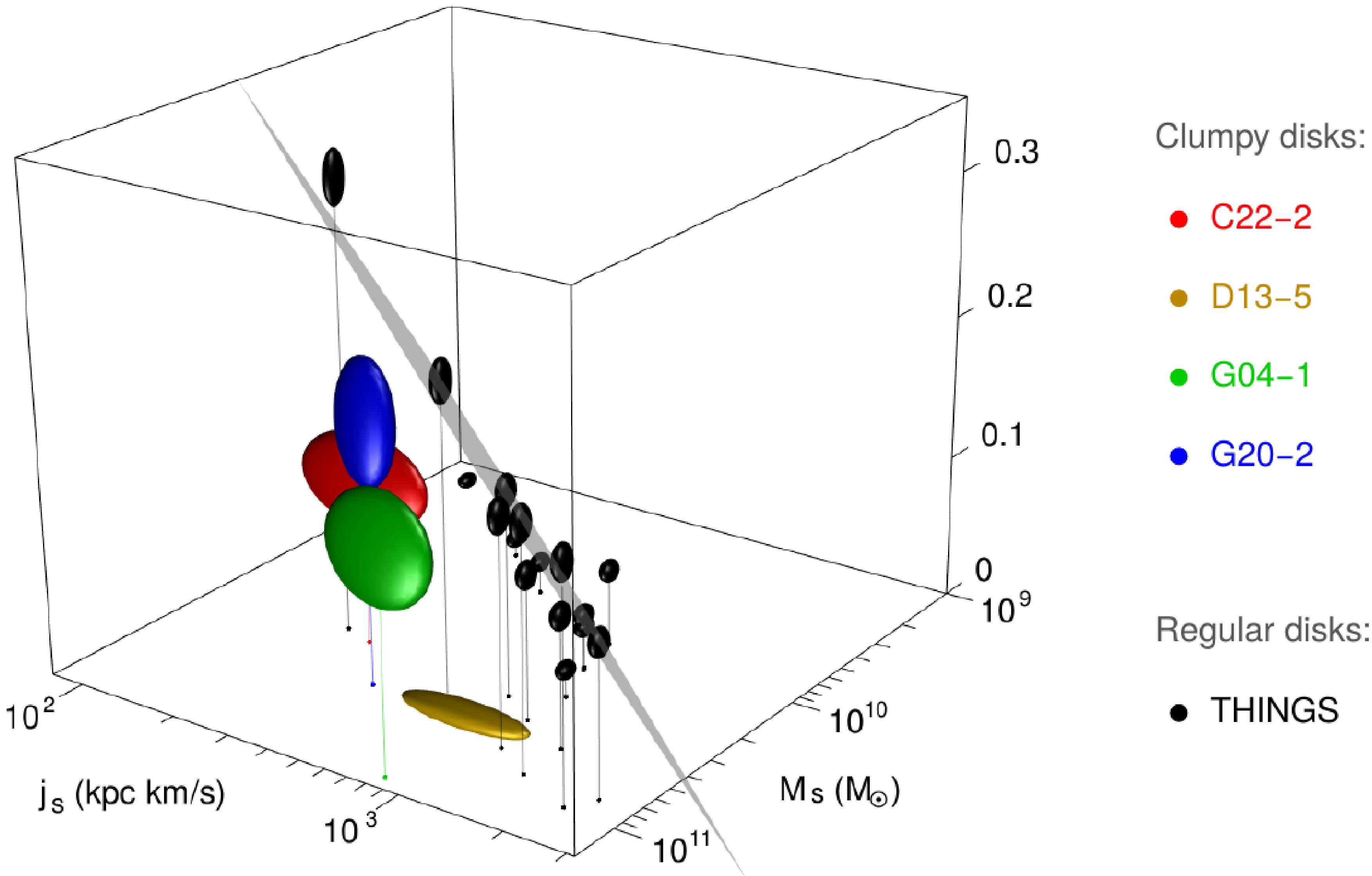
The H_2 content and distribution of galaxies

Tacconi et al. (2013)



How angular momentum builds-up

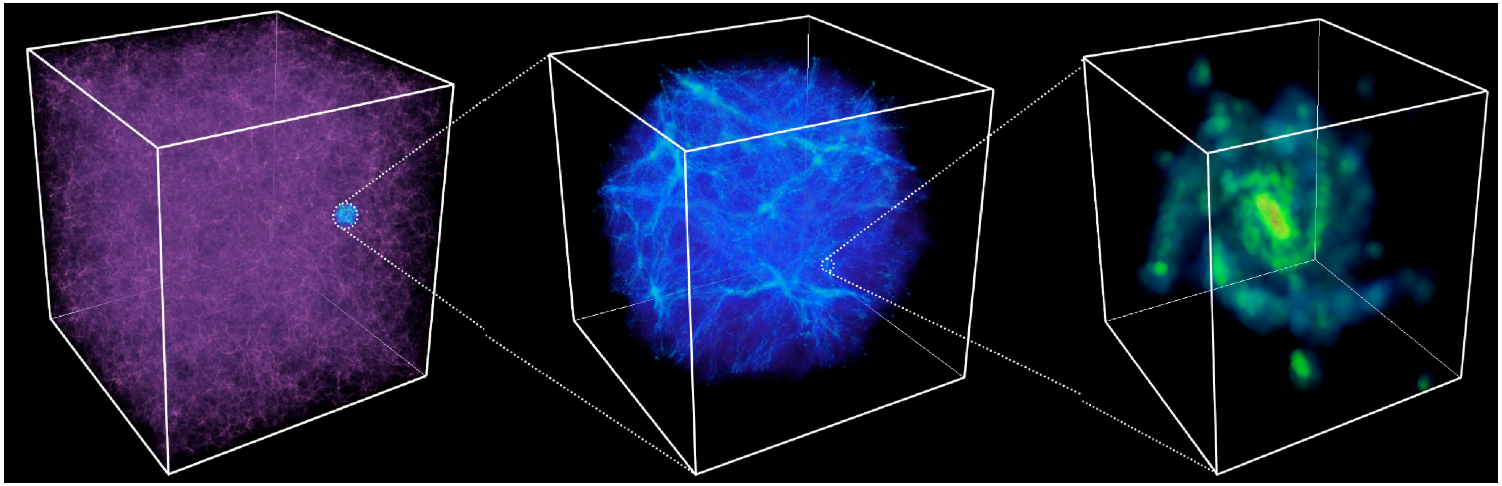
Obreschkow et al. (2015)



A widely used approach for (cosmology) galaxy formation

Cosmological hydro-dynamical simulations:

Credit: Rob Crain



1. Define the density field

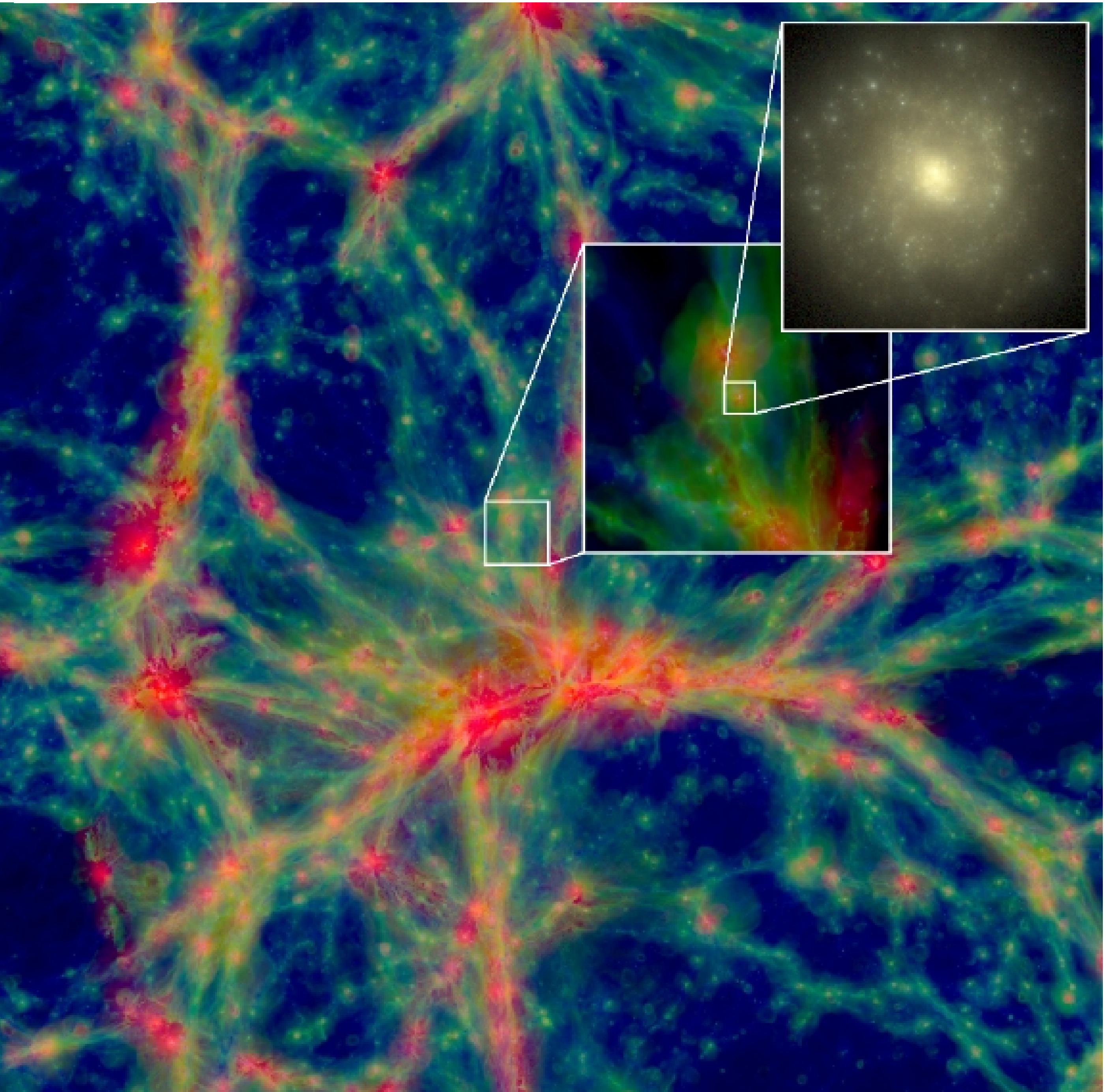
$$\rho(\mathbf{r}) = \sum_{j=1}^{N_{neigh}} m_j W(|\mathbf{r} - \mathbf{r}_j|, h)$$

2. Write the Lagrangian

3. Equation of motion for each particle (~1500^3)

The EAGLE
hydro-dynamic simulations
(testing and predictions)

The EAGLE Simulation



~700pc resolution, 1e6Msun, 100Mpc box size

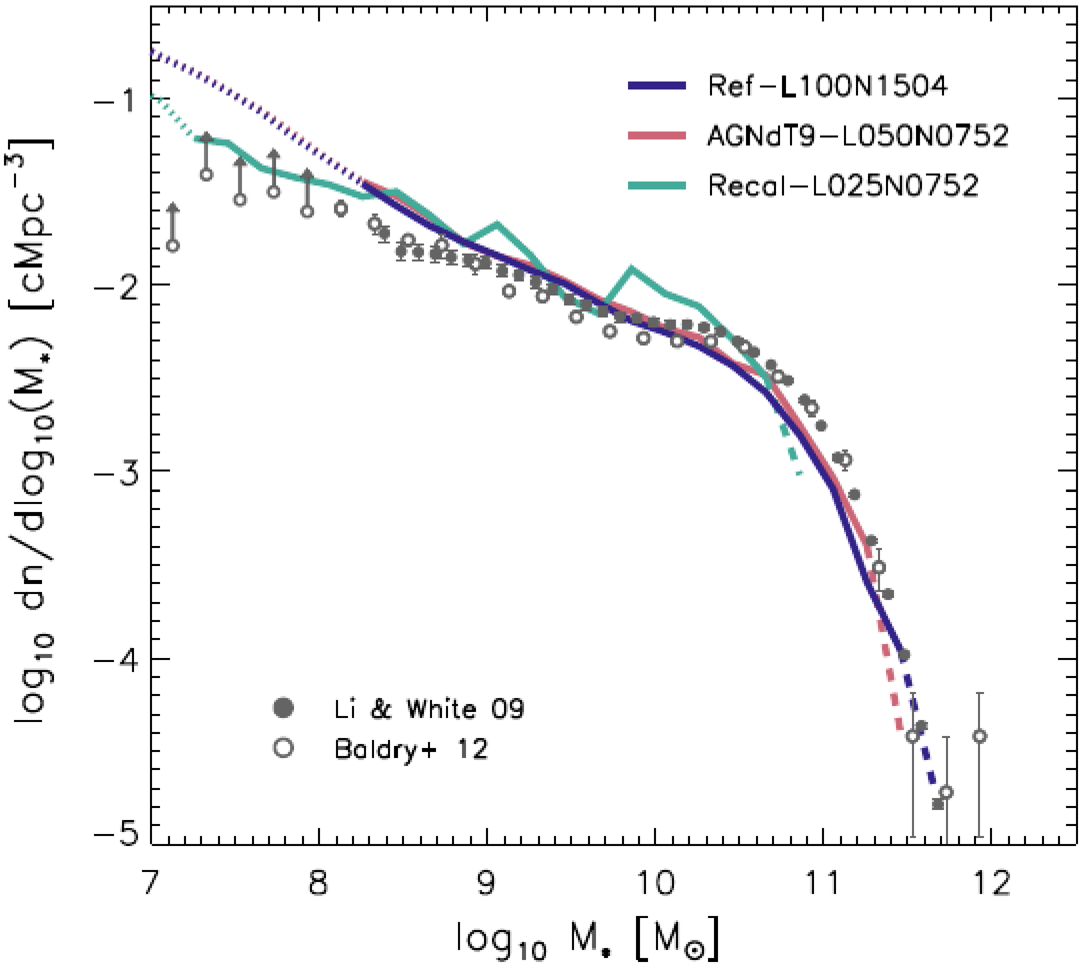
Improved hydrodynamics ("Anarchy")

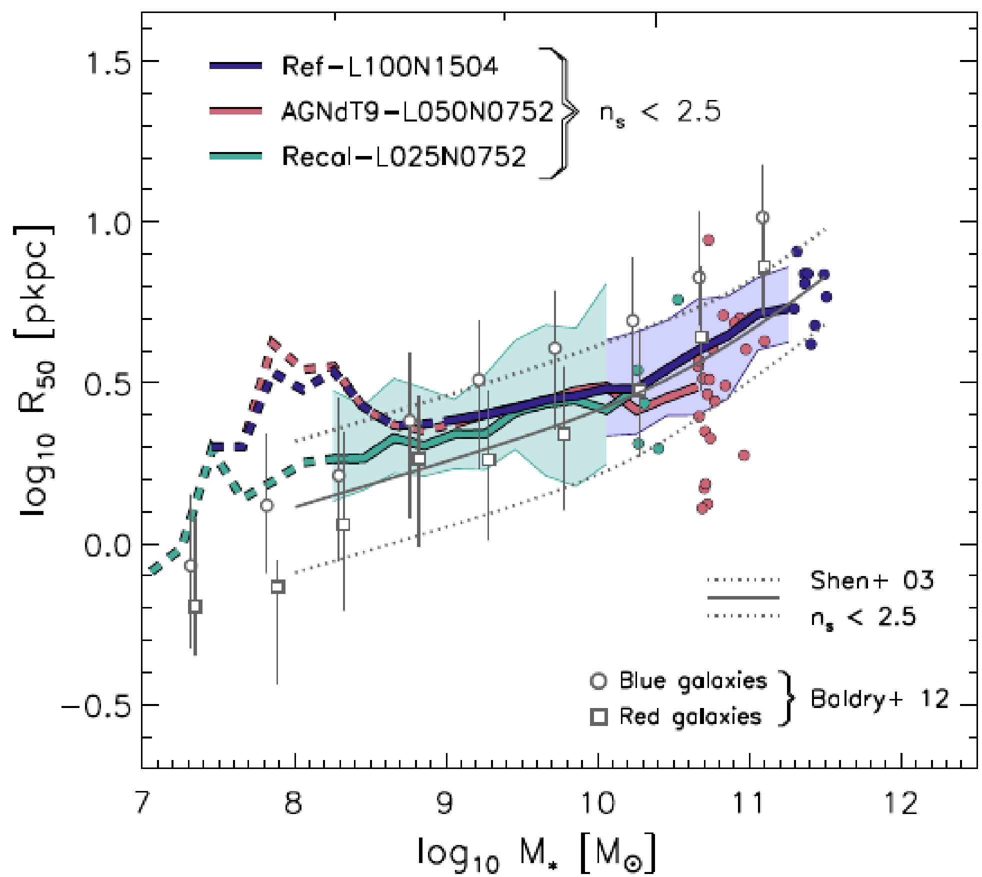
Large number of sub-grid physics module:
→ Metal-dependent cooling
→ Reionisation
→ Star formation (metallicity-dependent)
→ Stellar recycling
→ SNe feedback
→ AGN feedback

Schaye et al.(2015); Furlong et al. (2015); Crain et al. (2015); Lagos et al. (2015b,c);...

The EAGLE Simulation

Schaye et al. (2015)

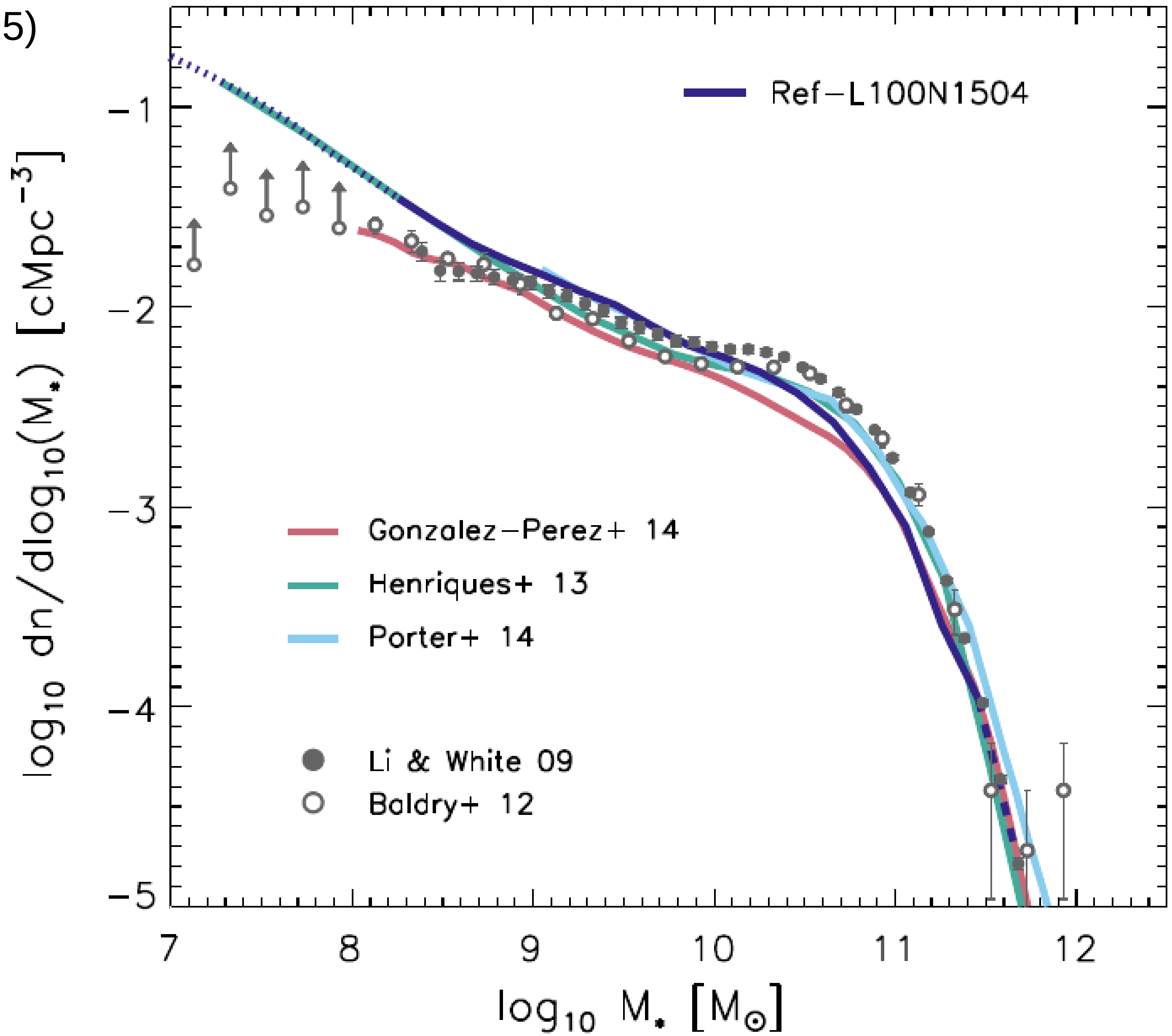




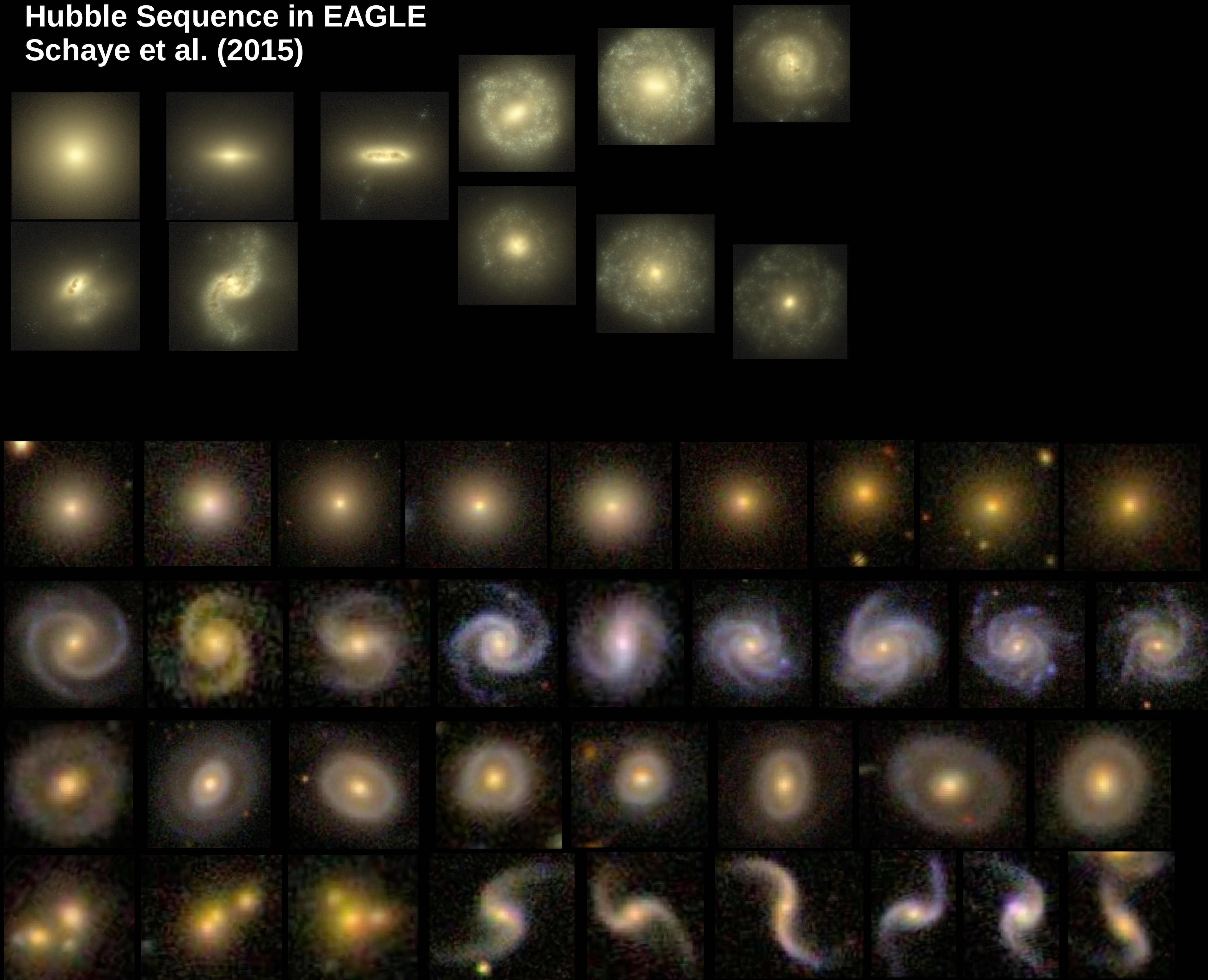
Sub-grid parameters tuned to match some observables at z=0.1

SMF compared to previous works

Schaye et al. (2015)

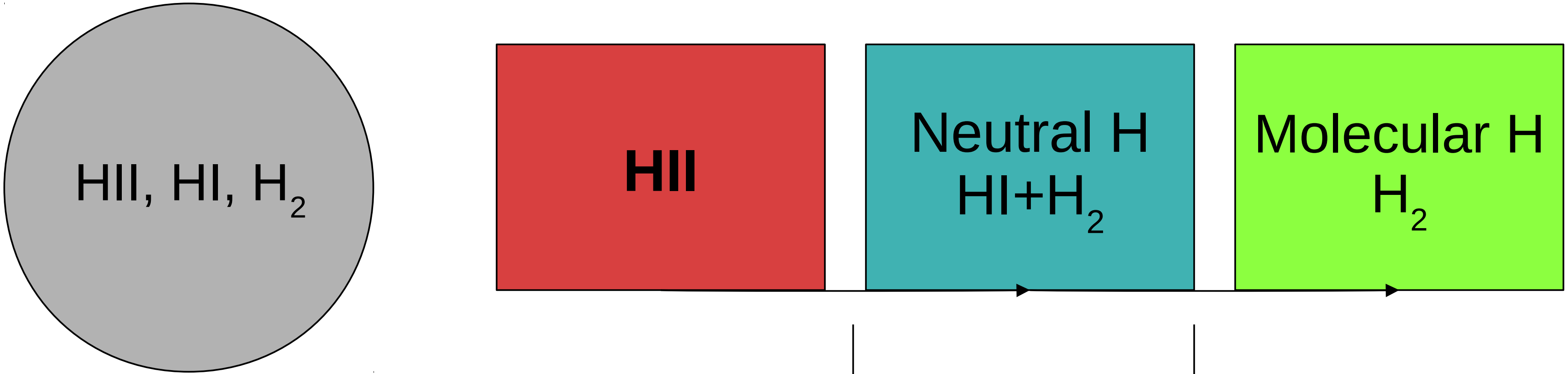


Hubble Sequence in EAGLE
Schaye et al. (2015)



Implementing gas phase transitions

Lagos et al. (2015b): description of multiphase ISM/IGM in EAGLE



Gas particle:
→ Represents a volume of the ISM/IGM

- Metallicity
- Star formation
- Pressure
- Temperature
- Density

Rahmati et al. (2013)

$\Gamma_{Phot}(\Gamma_{UVB},n_H)$: self-shielding
$\Gamma_{TOT} = \Gamma_{Phot} + \Gamma_{coll}(T,n_H)$: collisional ionisation
$f_{neutral} = \eta(\Gamma_{TOT},T,n_H)$: Ionisation equilibirum

Gnedin & Kravtsov (2011)
Krumholz (2013)

See also:
Kuhlen et al. (2011);
Murante et al. (2010);
Hopkins et al. (2012)

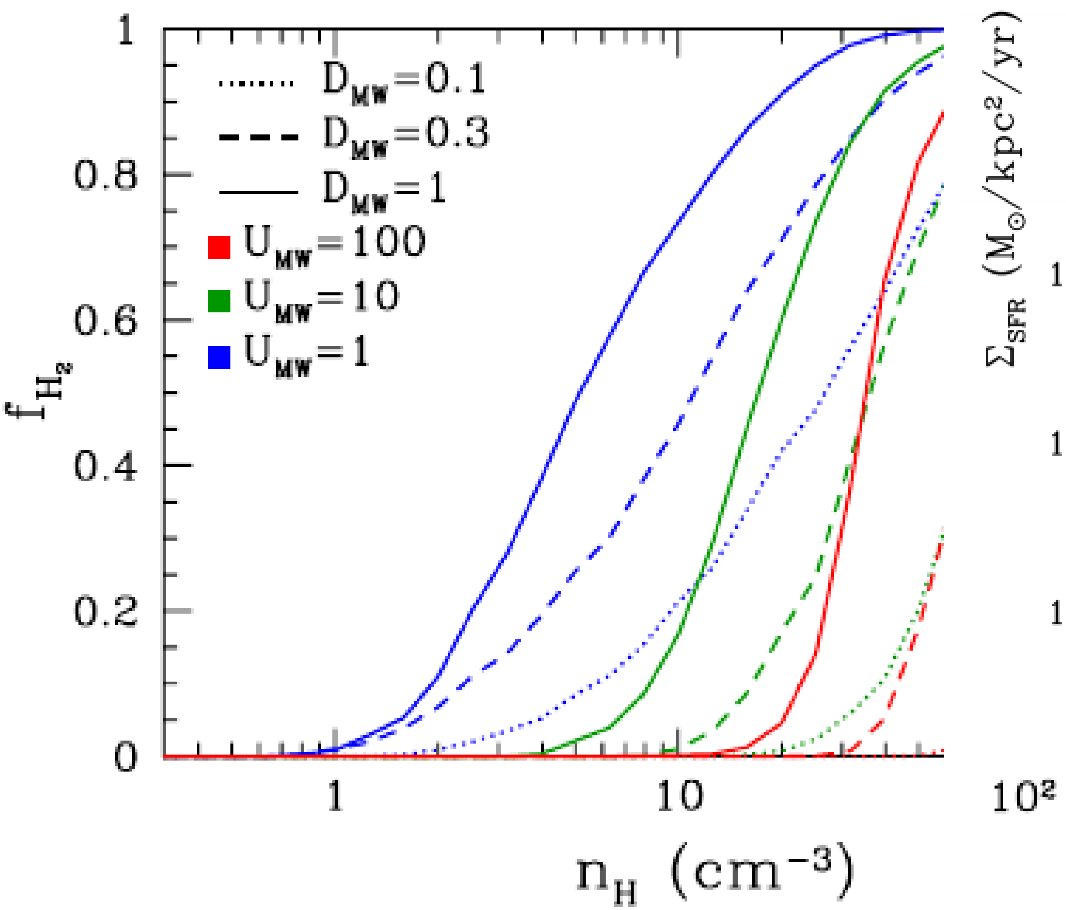
Fully characterised by the dust-to-gas mass ratio and ISRF and ***applied to ALL gas particles***

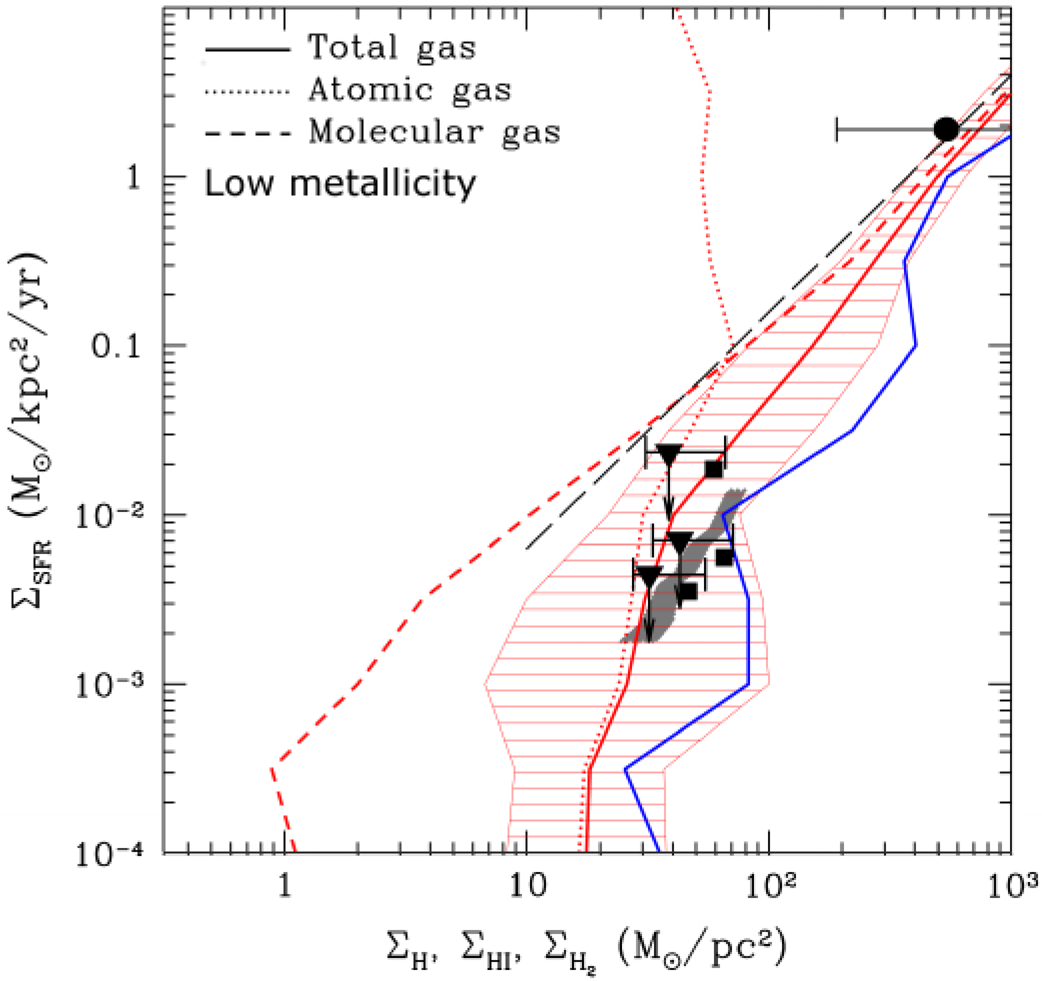
Bottom-up models: SF in individual clouds

Fraction of star-forming gas

$$\Sigma_{\rm SFR} = \boxed{f_{\rm SF}} \epsilon_{\rm ff} \frac{\Sigma}{t_{\rm ff}}$$

Gnedin & Kravtsov (2011; Also Gnedin a

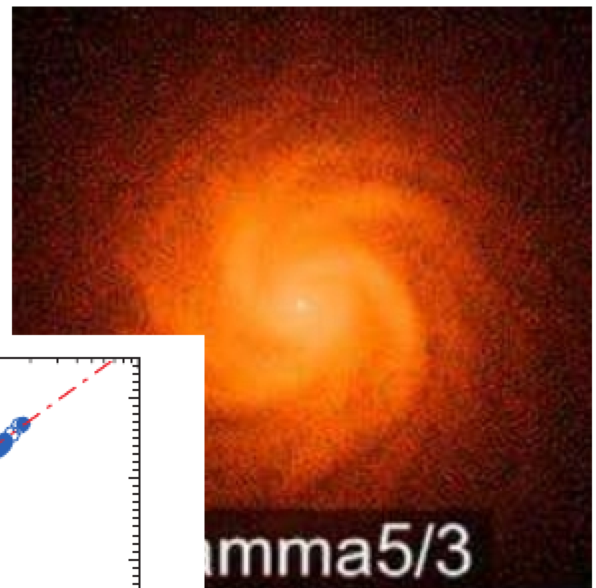


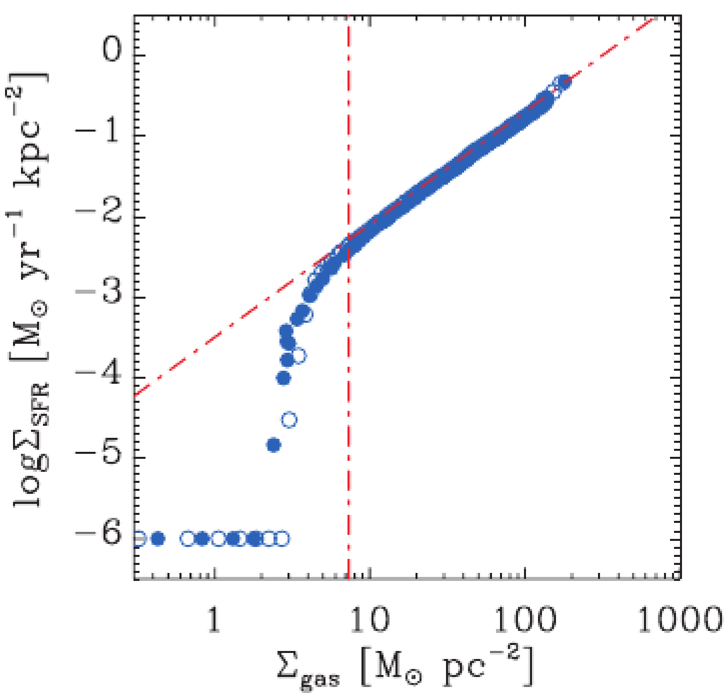


Star formation in EAGLE

Schaye et al. (2015): Use metallicity and gas density proxy of cool gas (Schaye 2004) and star formation model of Schaye & Dalla Vecchia (2008)

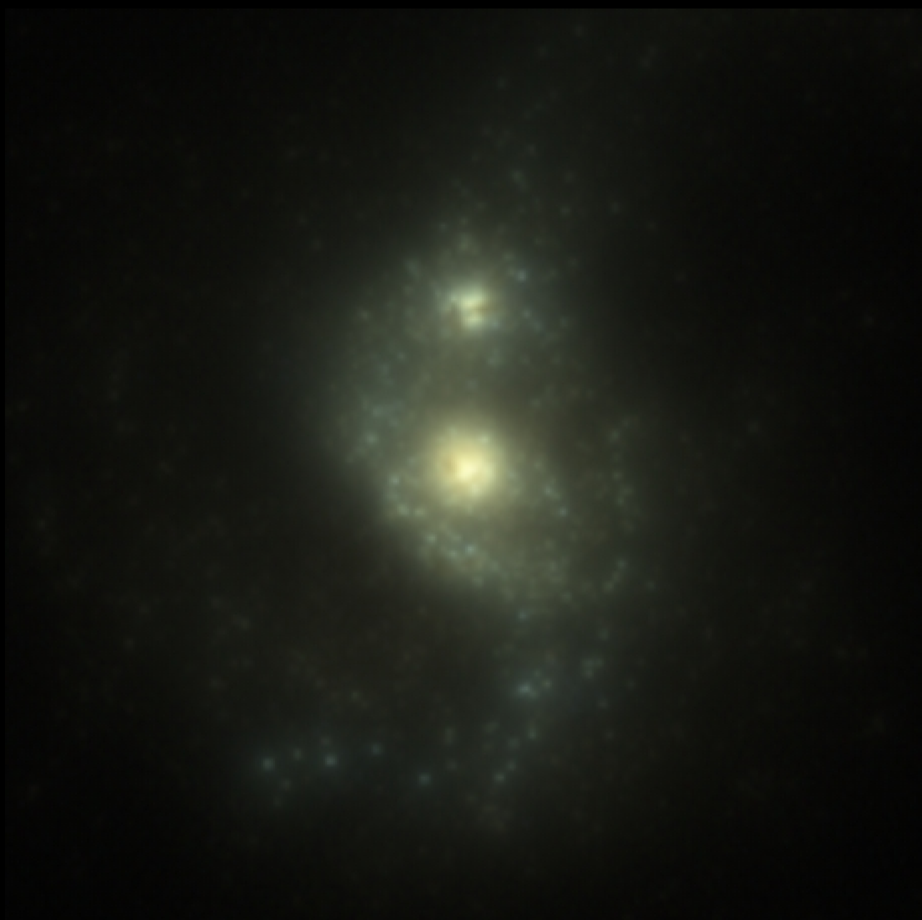
$$n_{\rm H}^{*} = 10^{-1}\,{\rm cm}^{-3}\left(\frac{Z}{0.002}\right)^{-0.64}$$



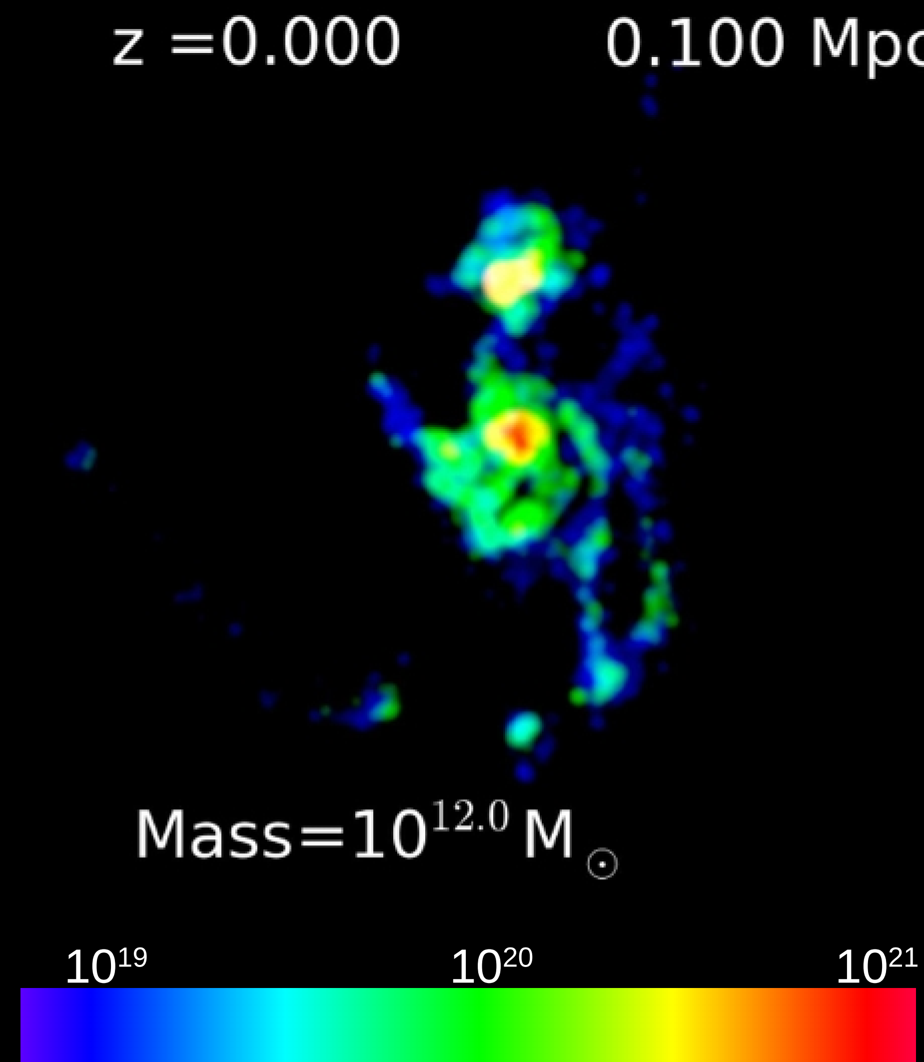


Illustrating the power of EAGLE…
HI and H_2 maps (Lagos et al. 2015b)

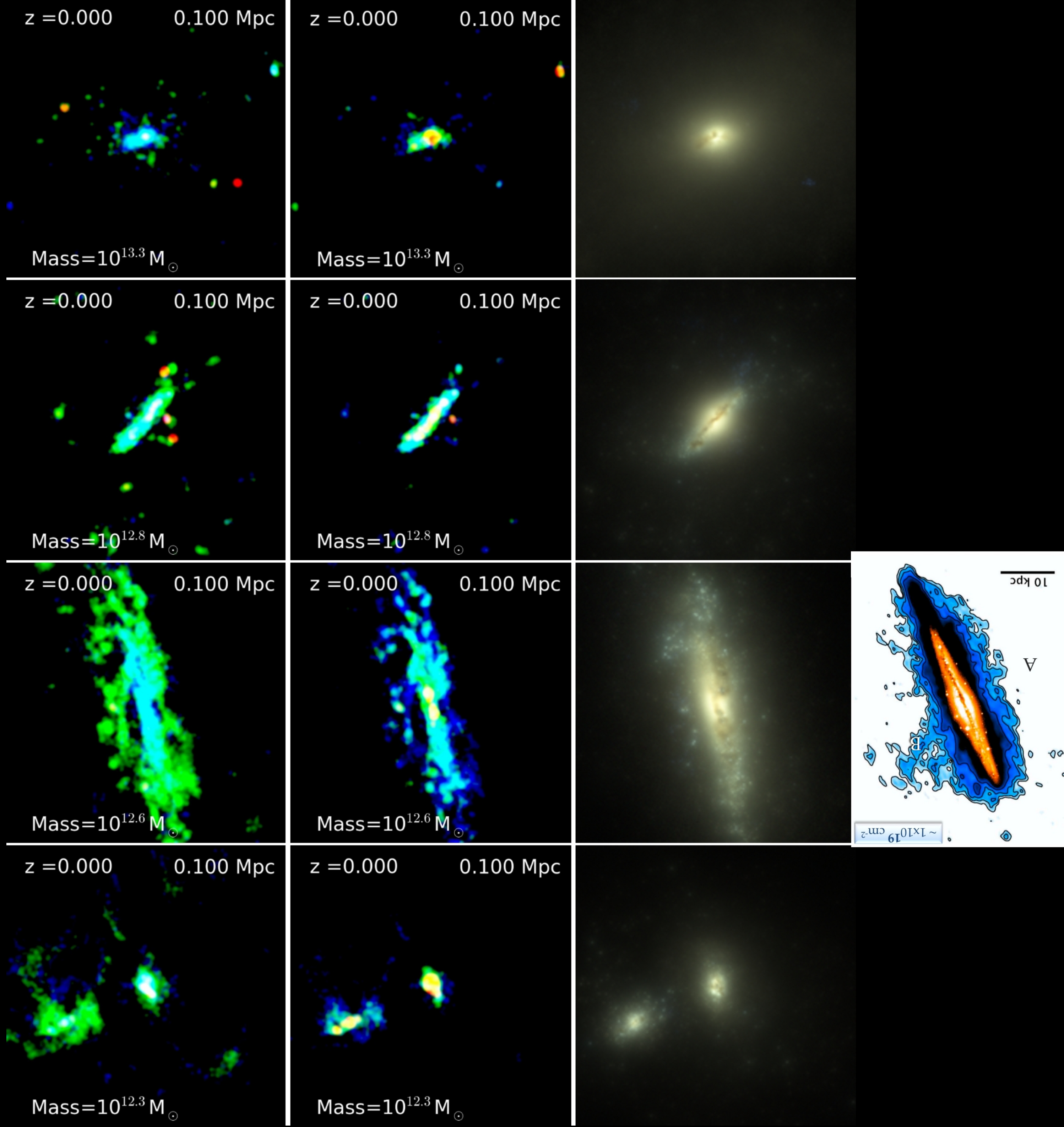
ugr image (Trayford et al. 2015)



HI map

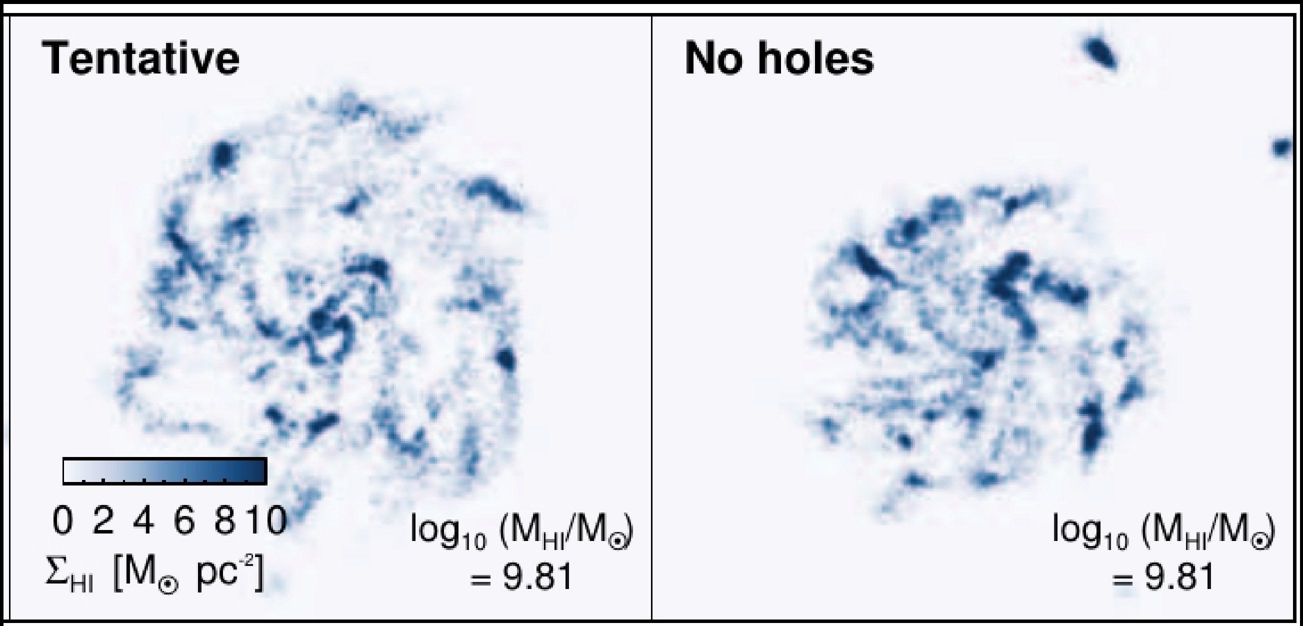


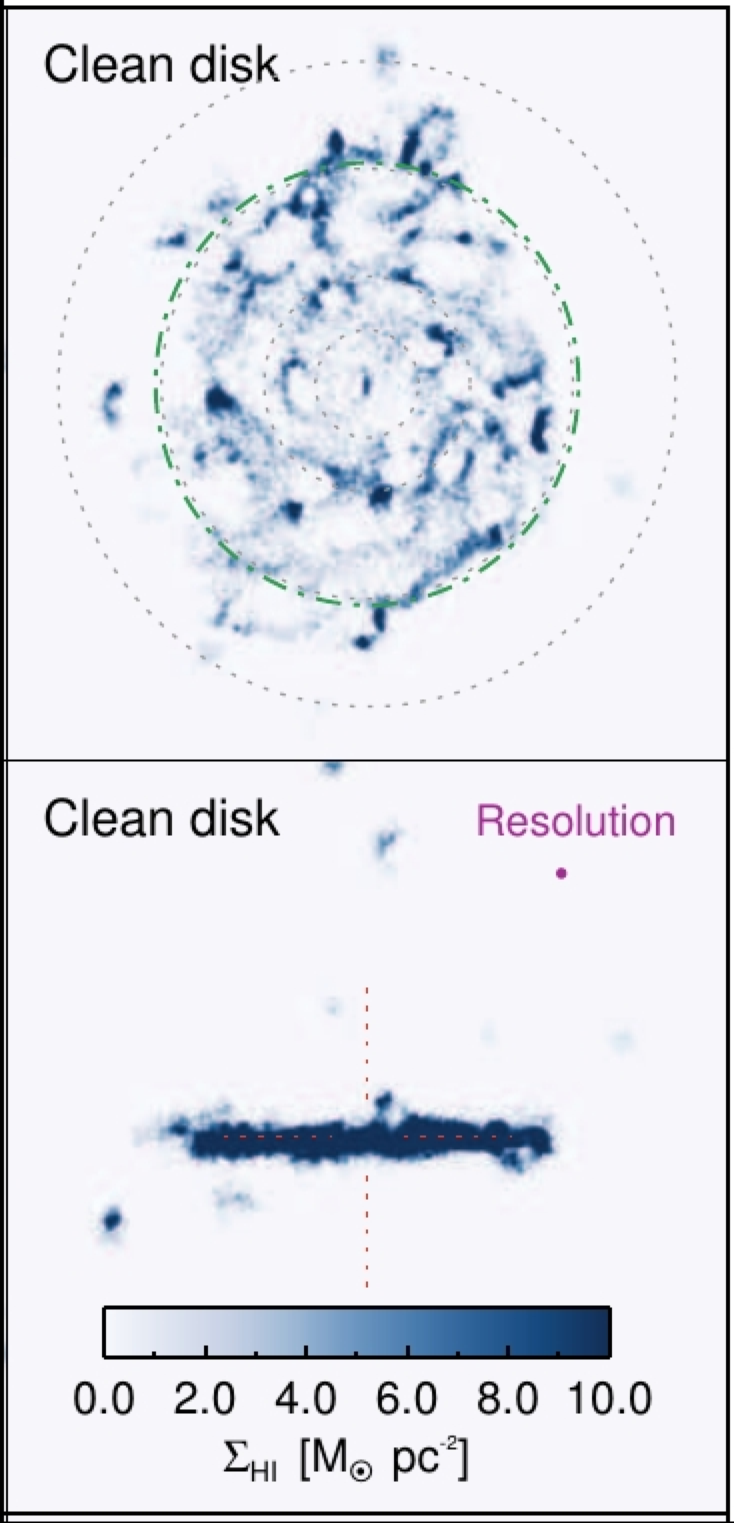
Column density



z =0.000
0.100 Mpc
Mass=$10^{13.3}$ M$_\odot$
z =0.000
0.100 Mpc
Mass=$10^{13.3}$ M$_\odot$
z =0.000
0.100 Mpc
Mass=$10^{12.8}$ M$_\odot$
z =0.000
0.100 Mpc
Mass=$10^{12.8}$ M$_\odot$
z =0.000
0.100 Mpc
Mass=$10^{12.6}$ M$_\odot$
z =0.000
0.100 Mpc
Mass=$10^{12.6}$ M$_\odot$
10 kpc
A
~ 1×10^{19} cm^{-2}
z =0.000
0.100 Mpc
Mass=$10^{12.3}$ M$_\odot$
z =0.000
0.100 Mpc
Mass=$10^{12.3}$ M$_\odot$

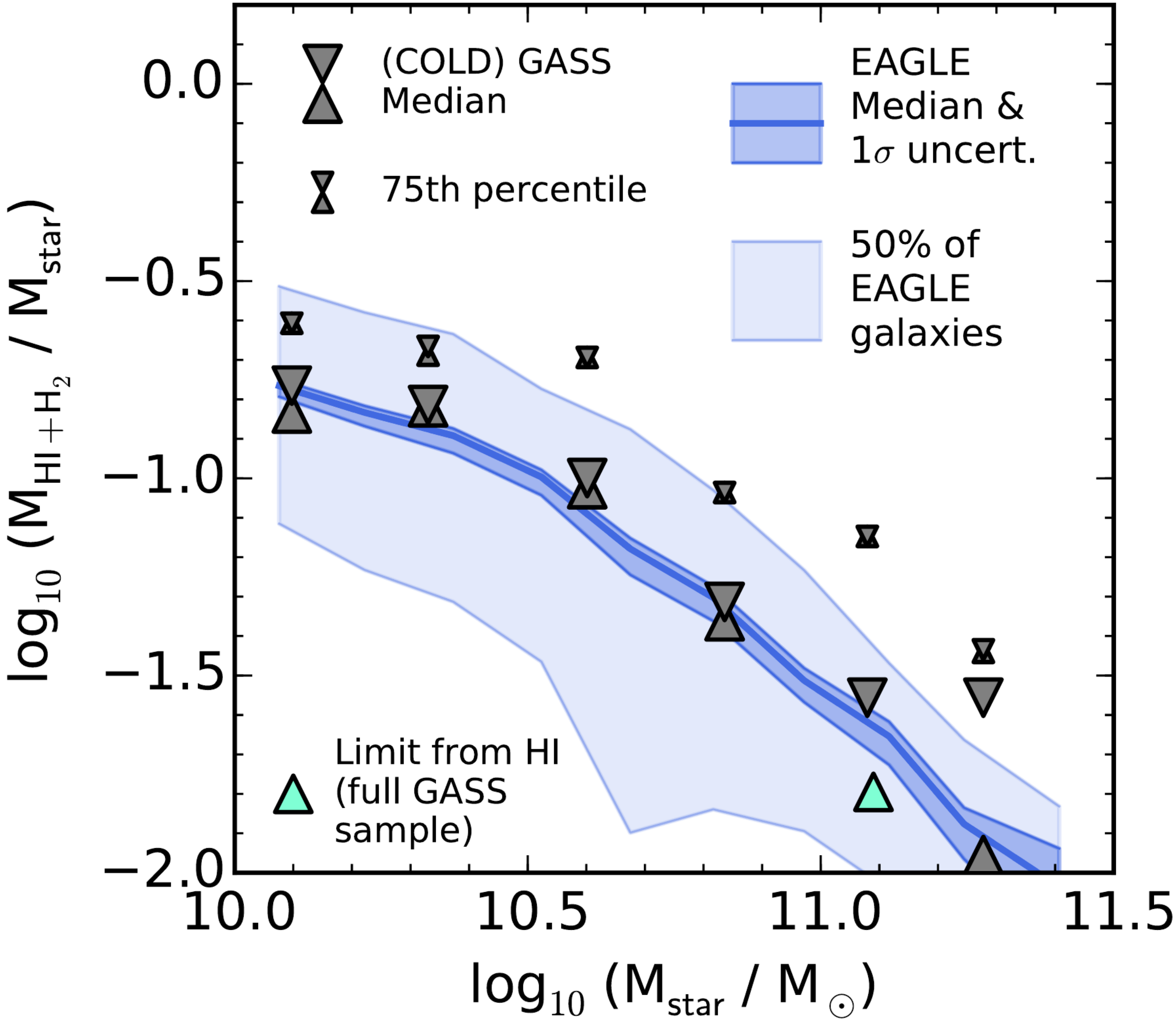
Illustrating the power of EAGLE…
HI maps of massive disks
(Bahe et al. 2015)





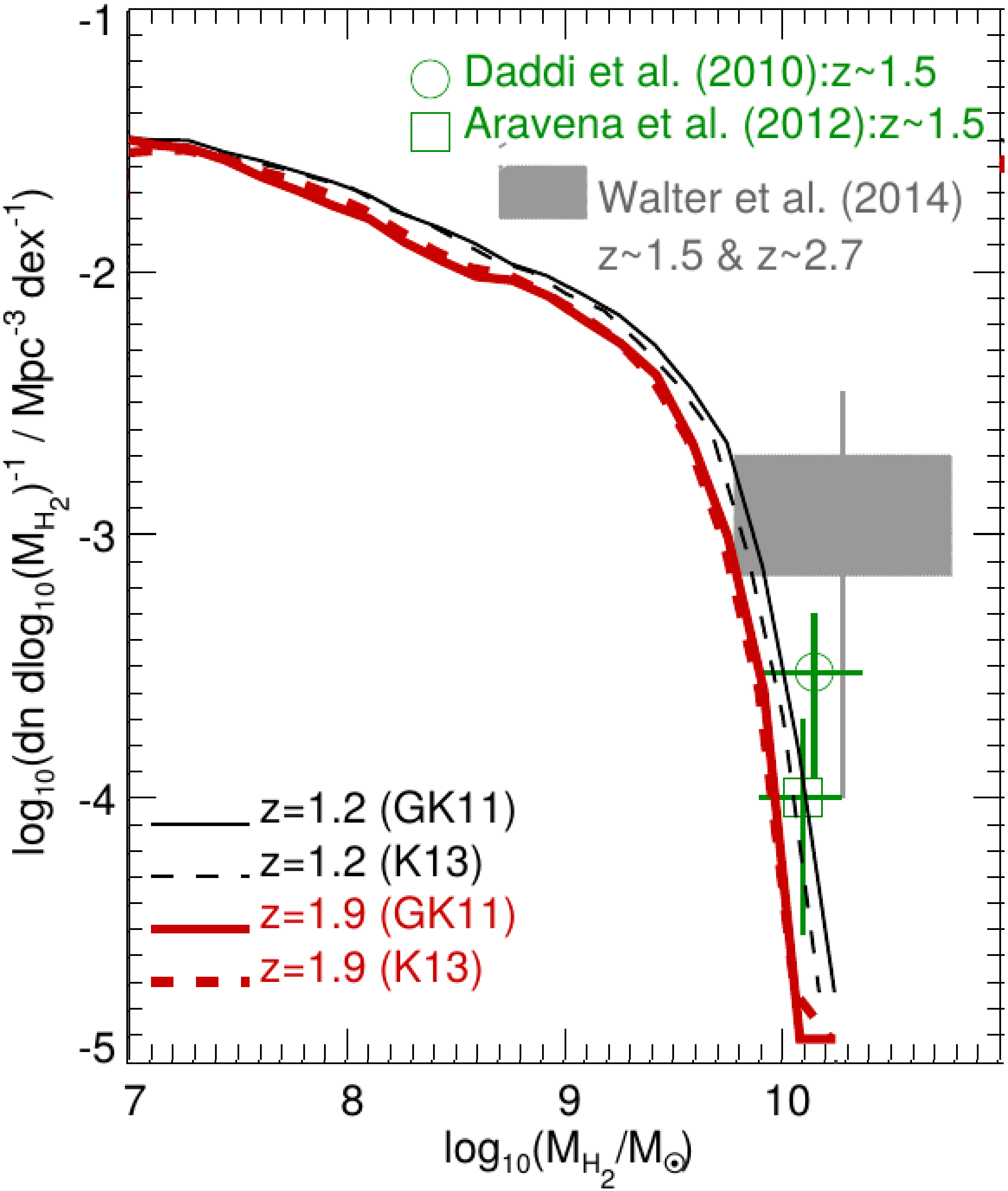
Total neutral gas fractions at z=0

Bahe et al. (2015): total neutral gas fraction



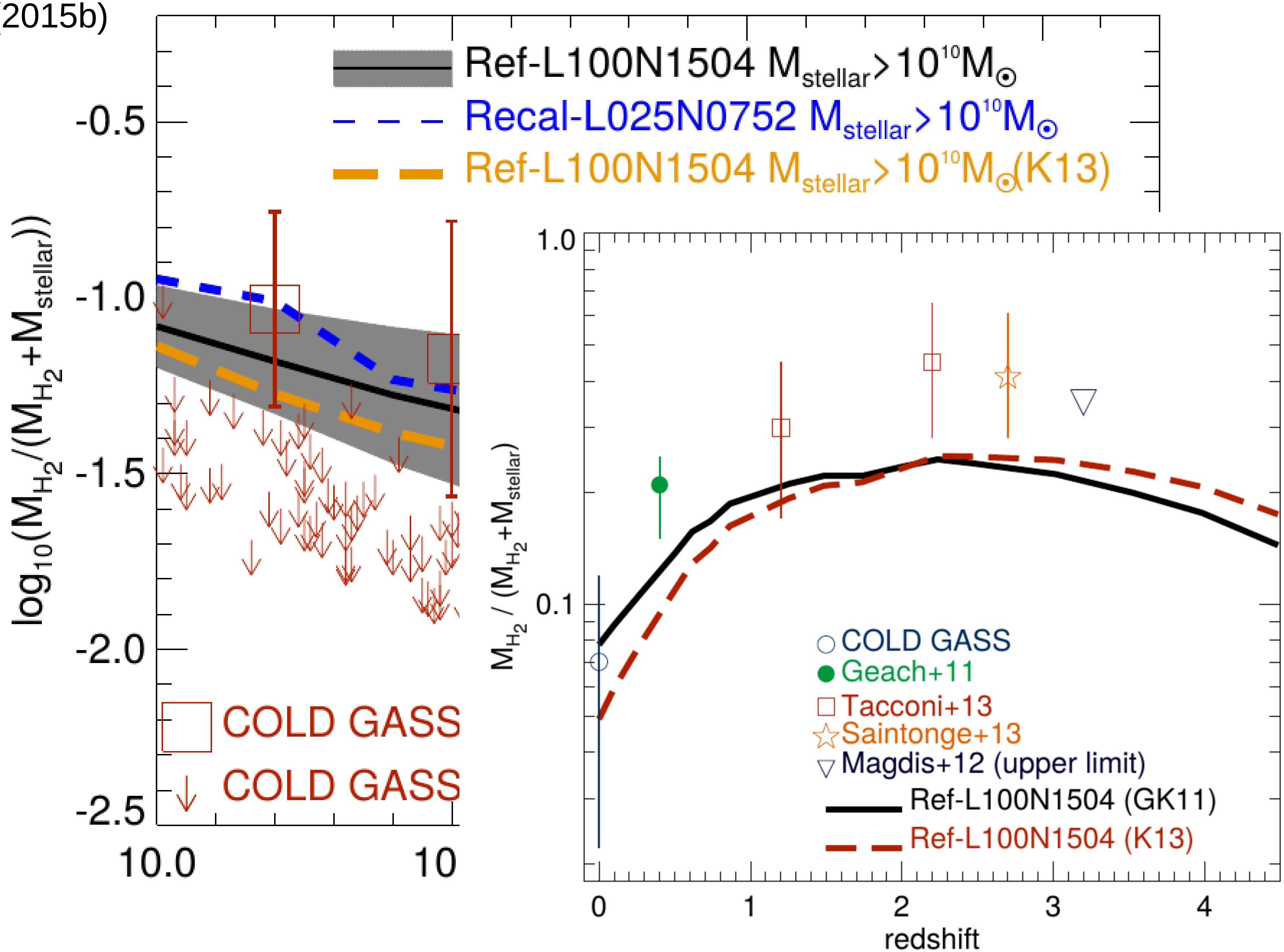
H_2 mass function

Lagos et al. (2015b)



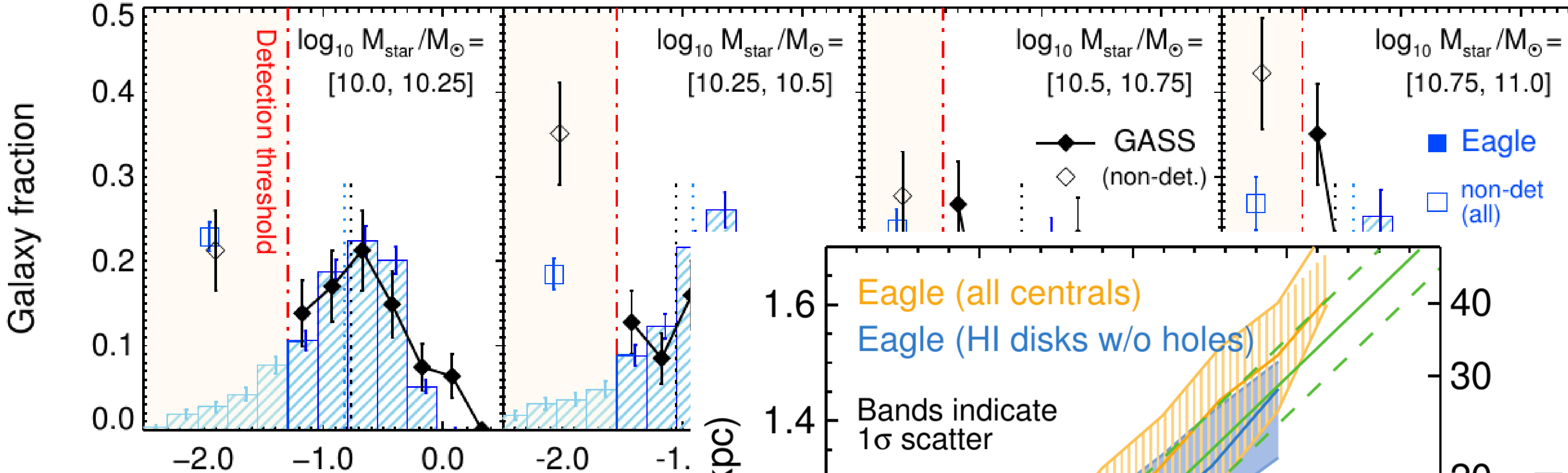
Scaling relations of H_2

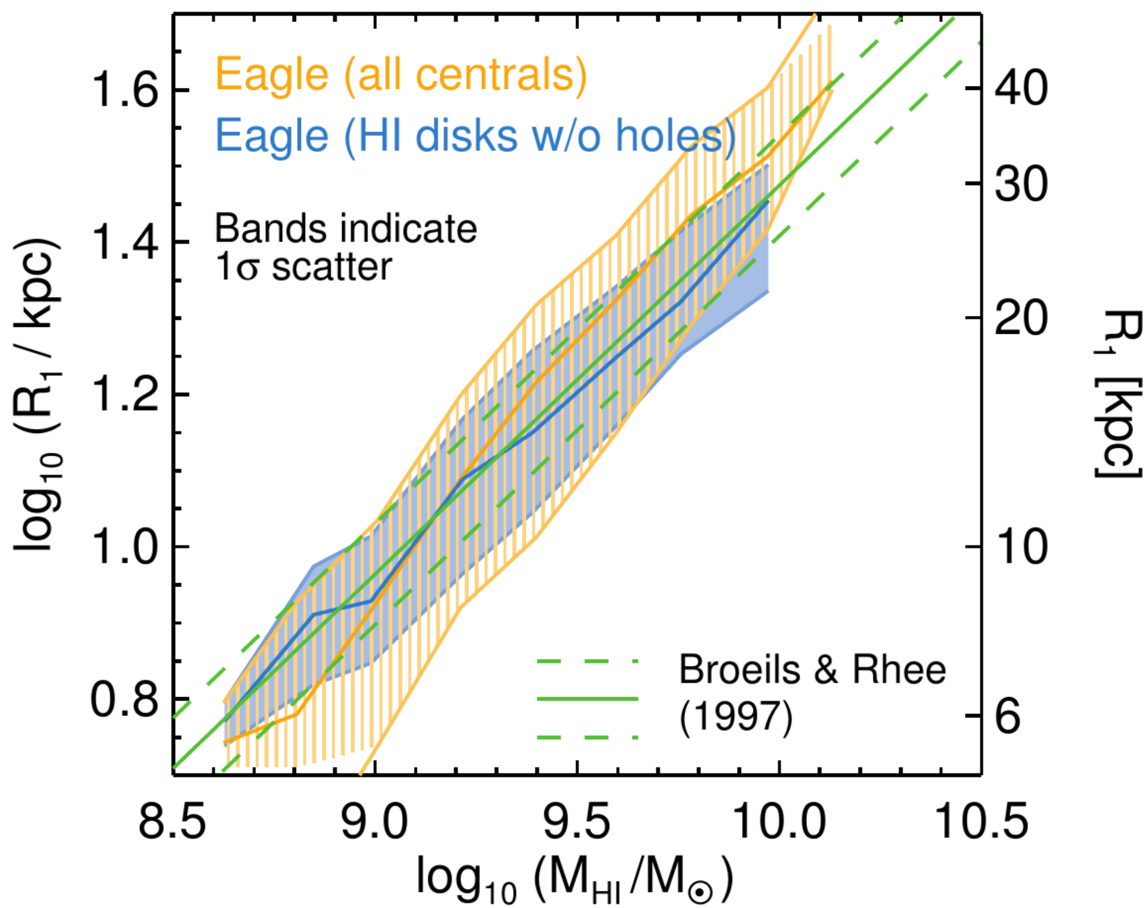
Lagos et al. (2015b)



Scaling relations of HI

Bahe et al. (2015): comparison of EAGLE with GASS

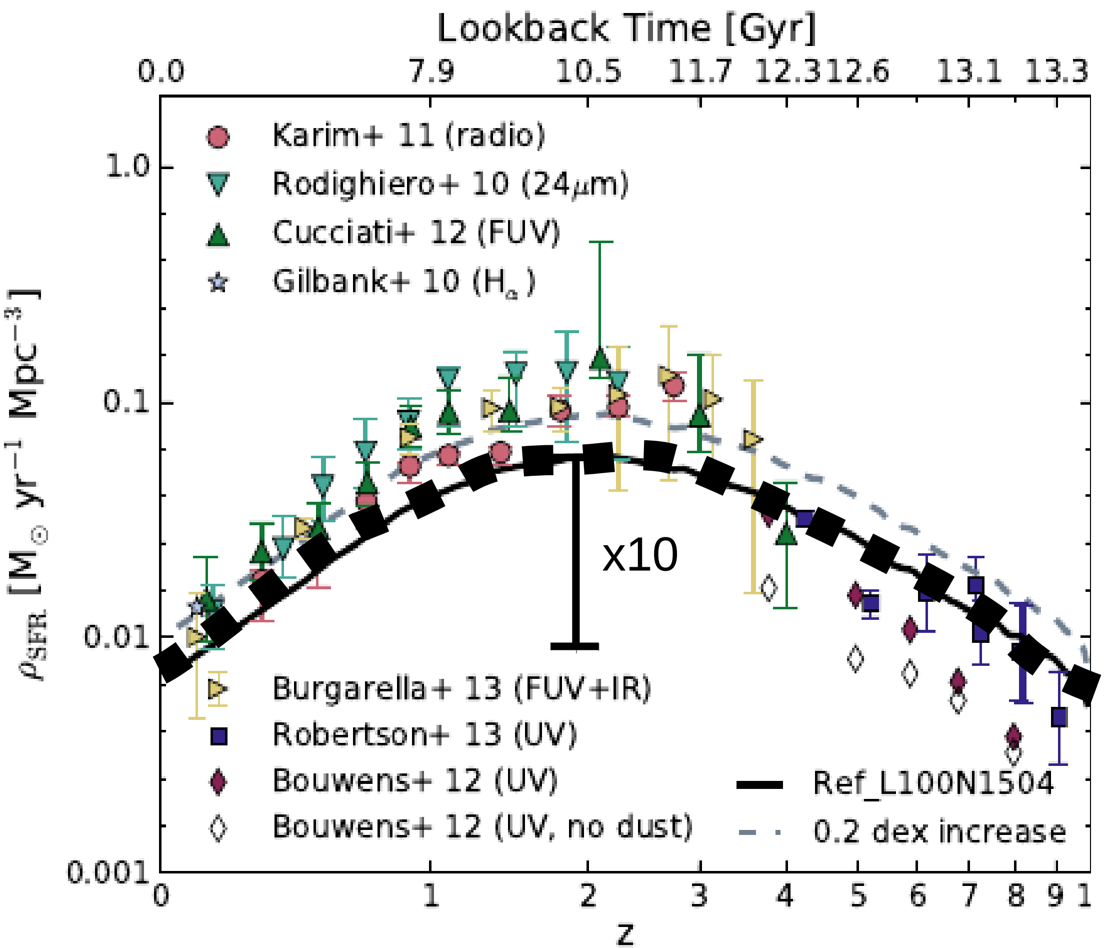




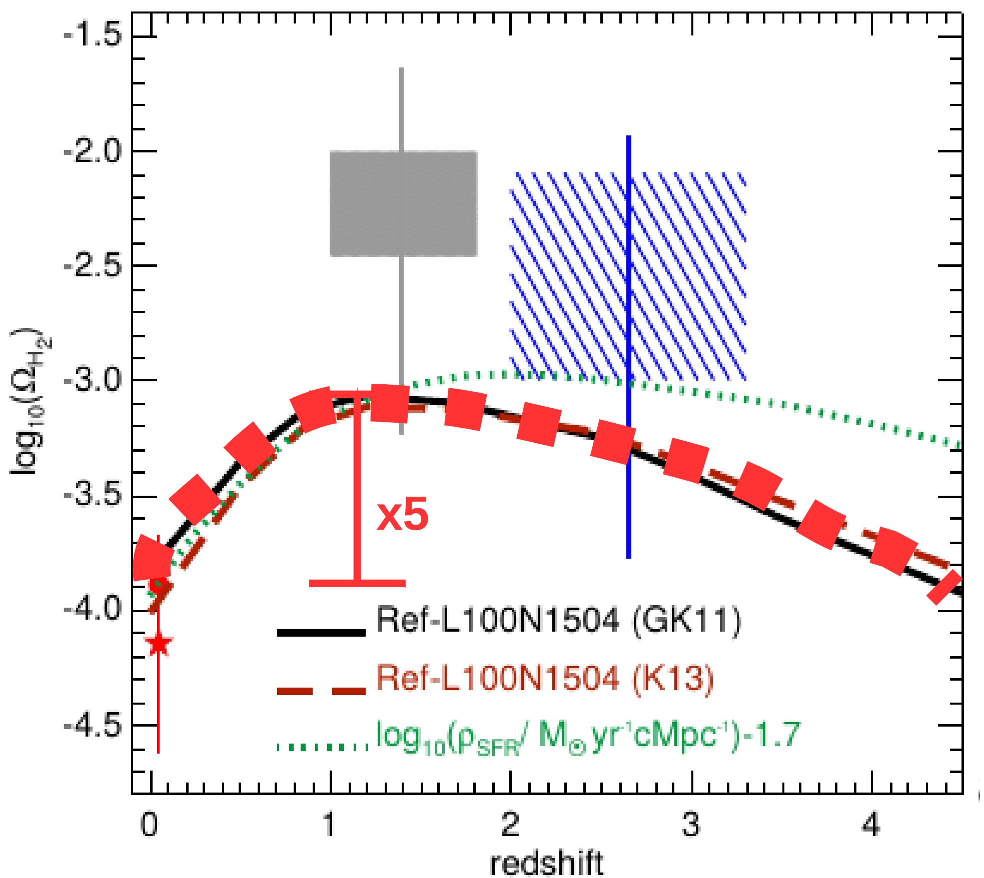
Omega HI and H_2 in the EAGLE simulations

An outstanding problem in extragalactic astrophysics...

Furlong et al. (2015)



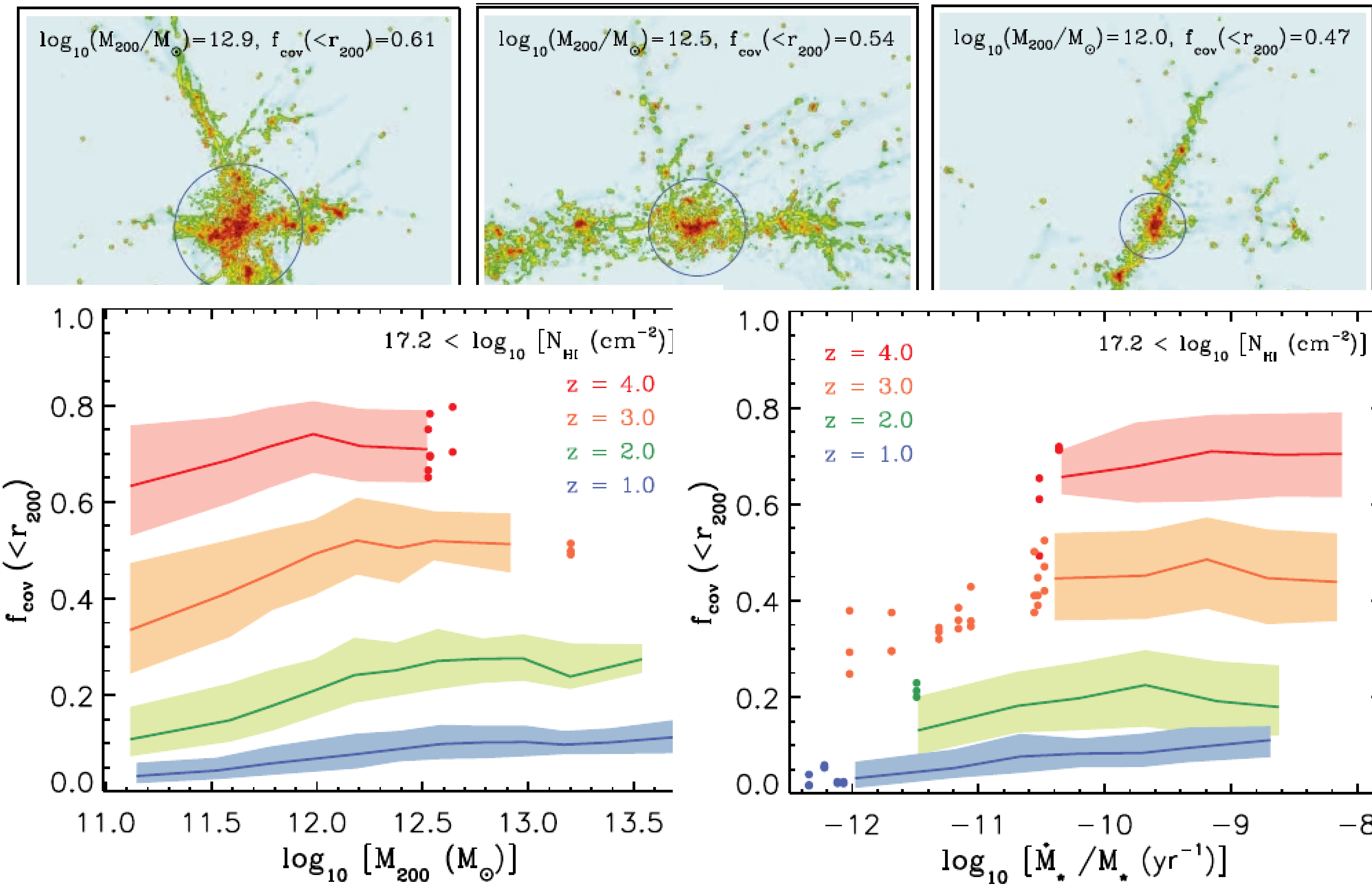
Lagos et al. (2015b)



Rahmati et al. (2015)

Where is the HI?

Rahmati et al. (2015)

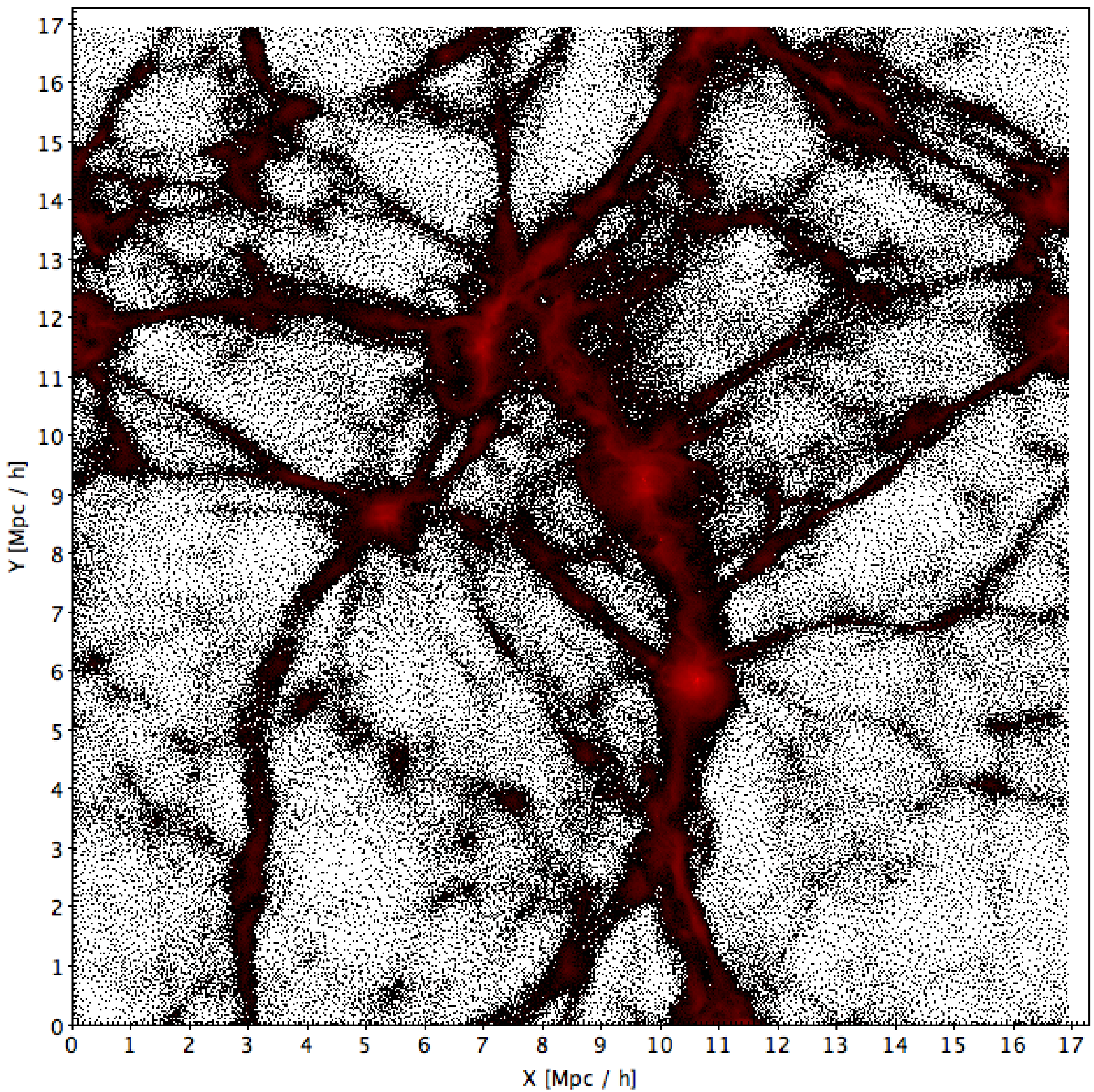


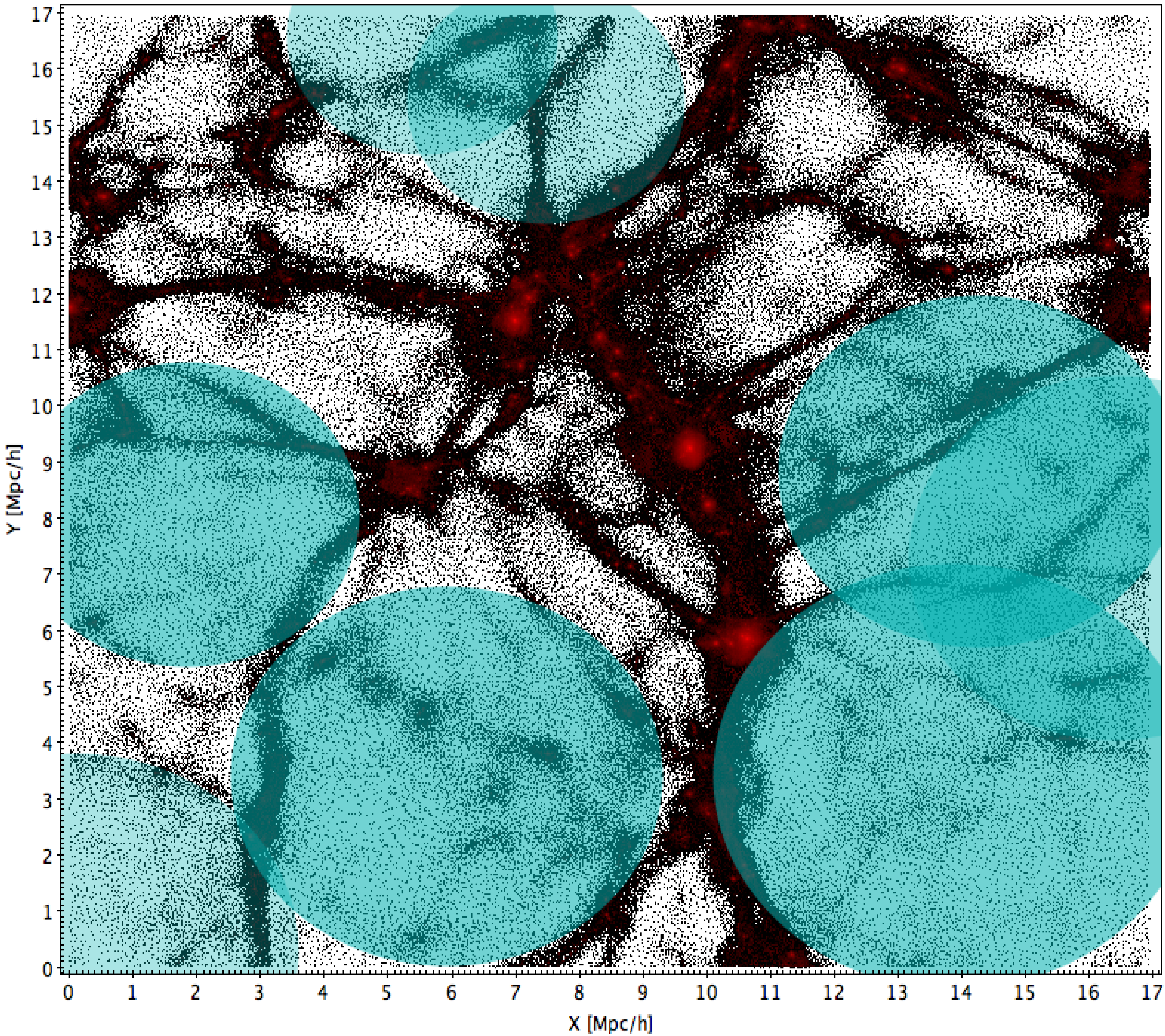
Connecting HI with the LSS

Paillas et al. (2015, in prep.)

What is the effect of baryons on the mass profiles of voids?

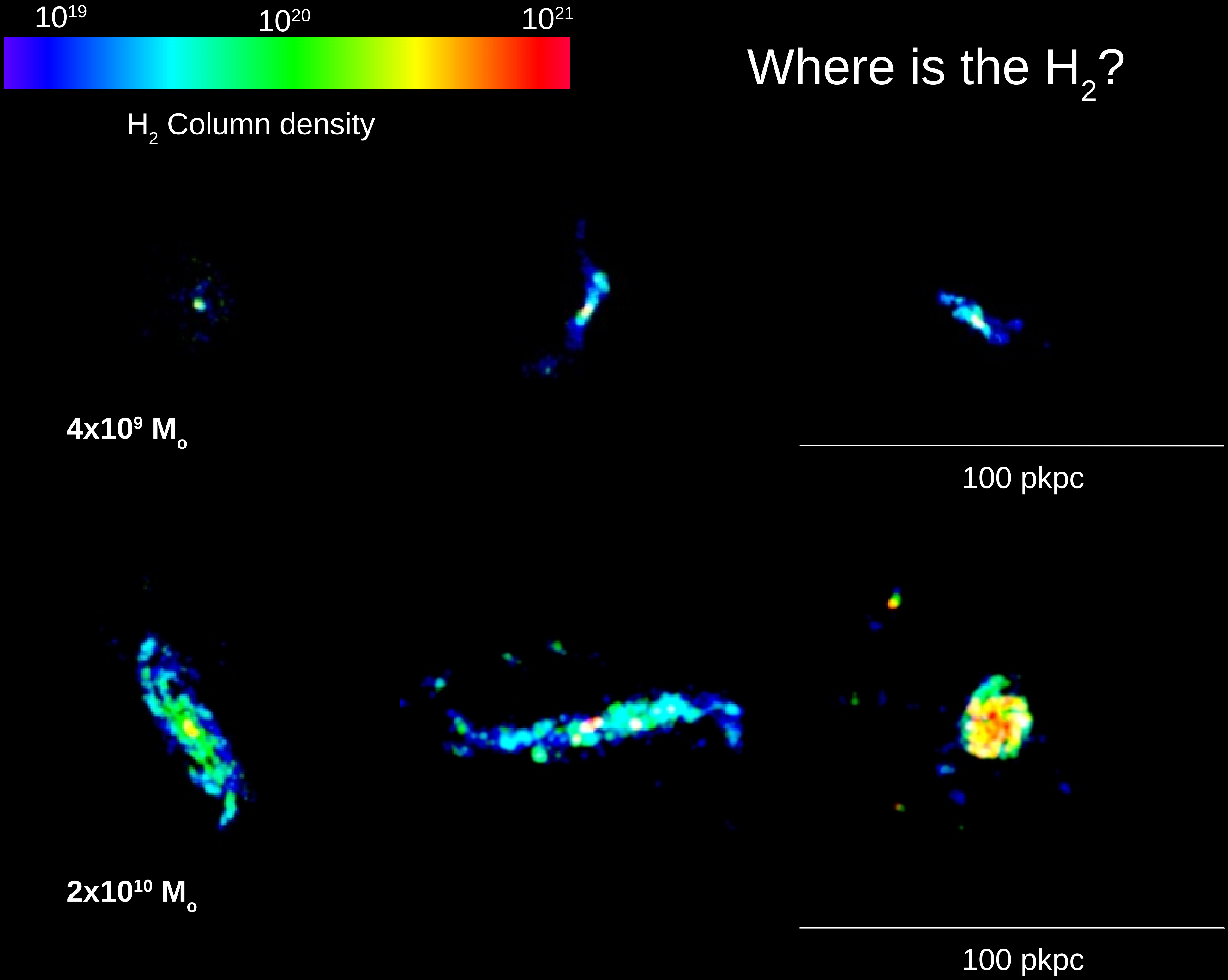
What is the typical HI column density of gas in voids? Filaments? Walls?



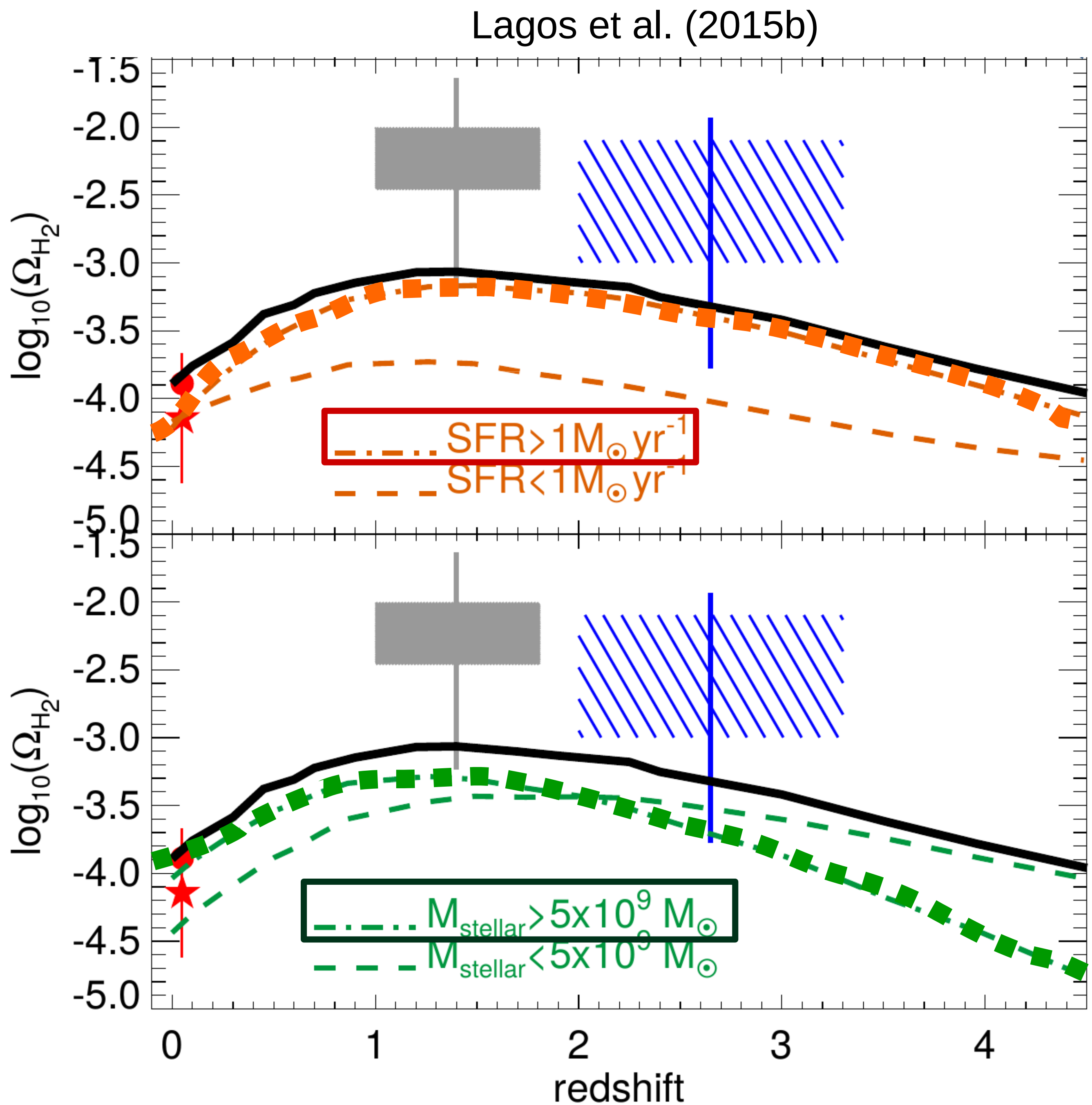


Y [Mpc/h]
X [Mpc/h]
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

Where is the H_2?

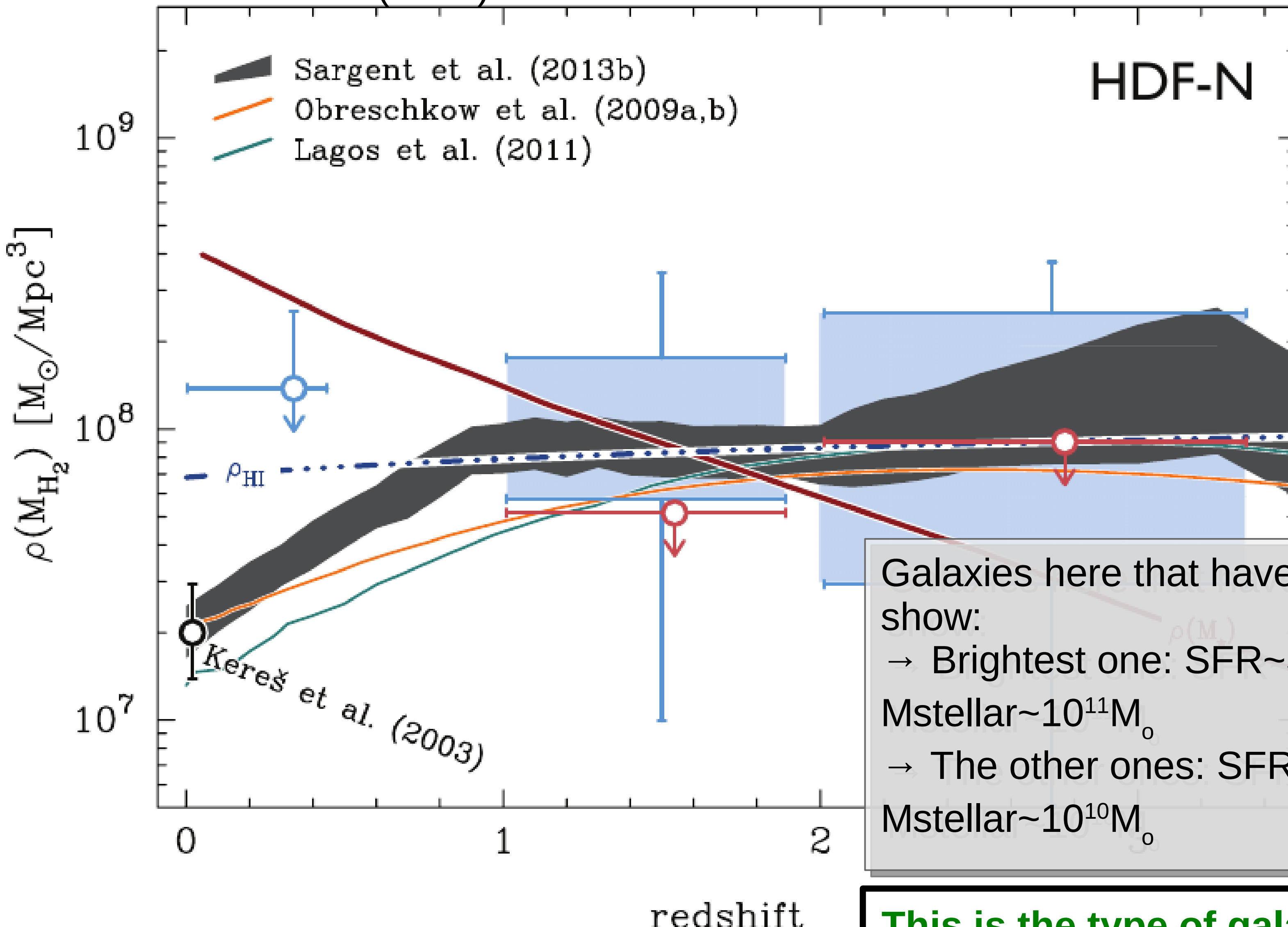


Where is the H_2?



Where is the H_2?

Walter et al. (2014)

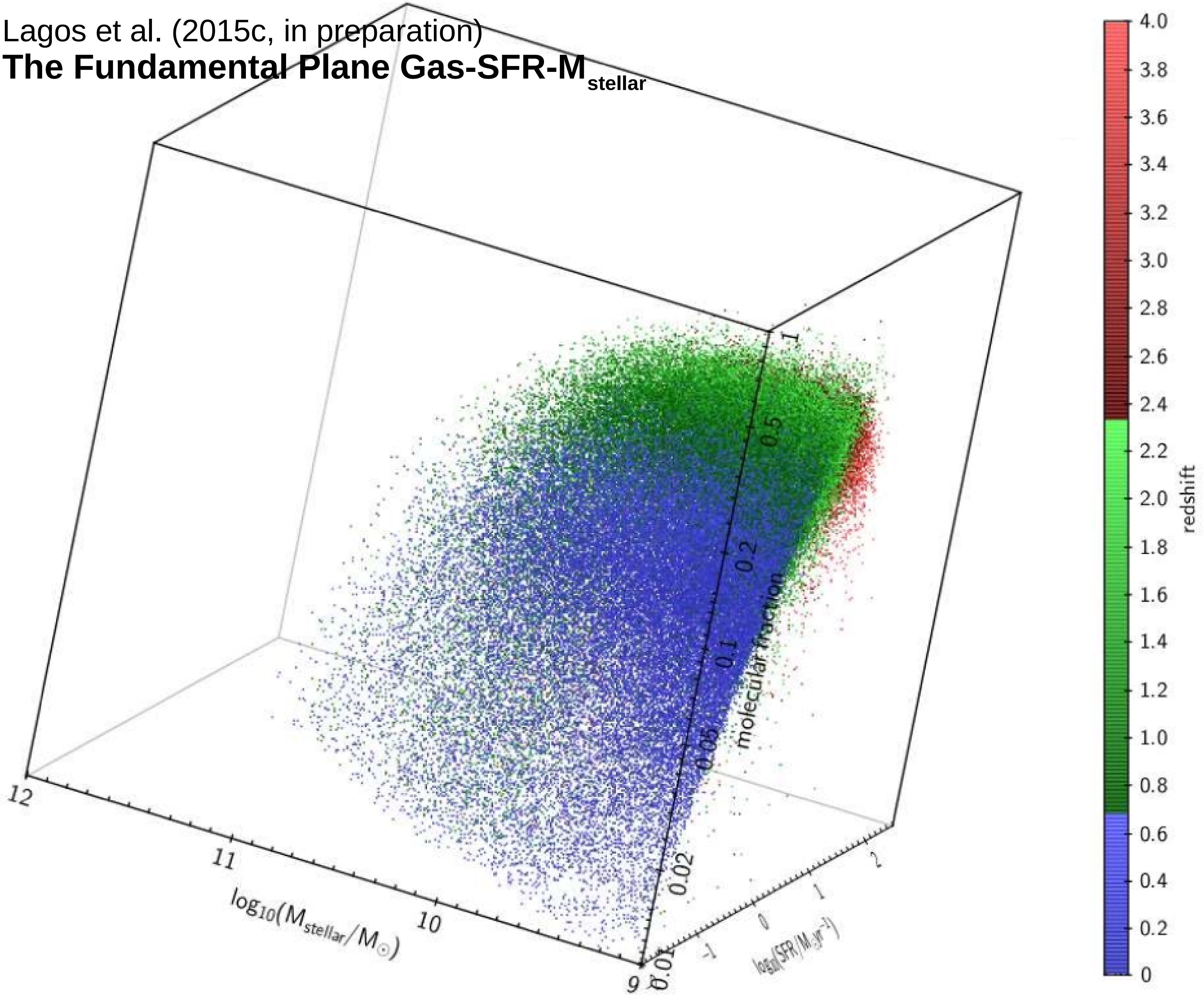


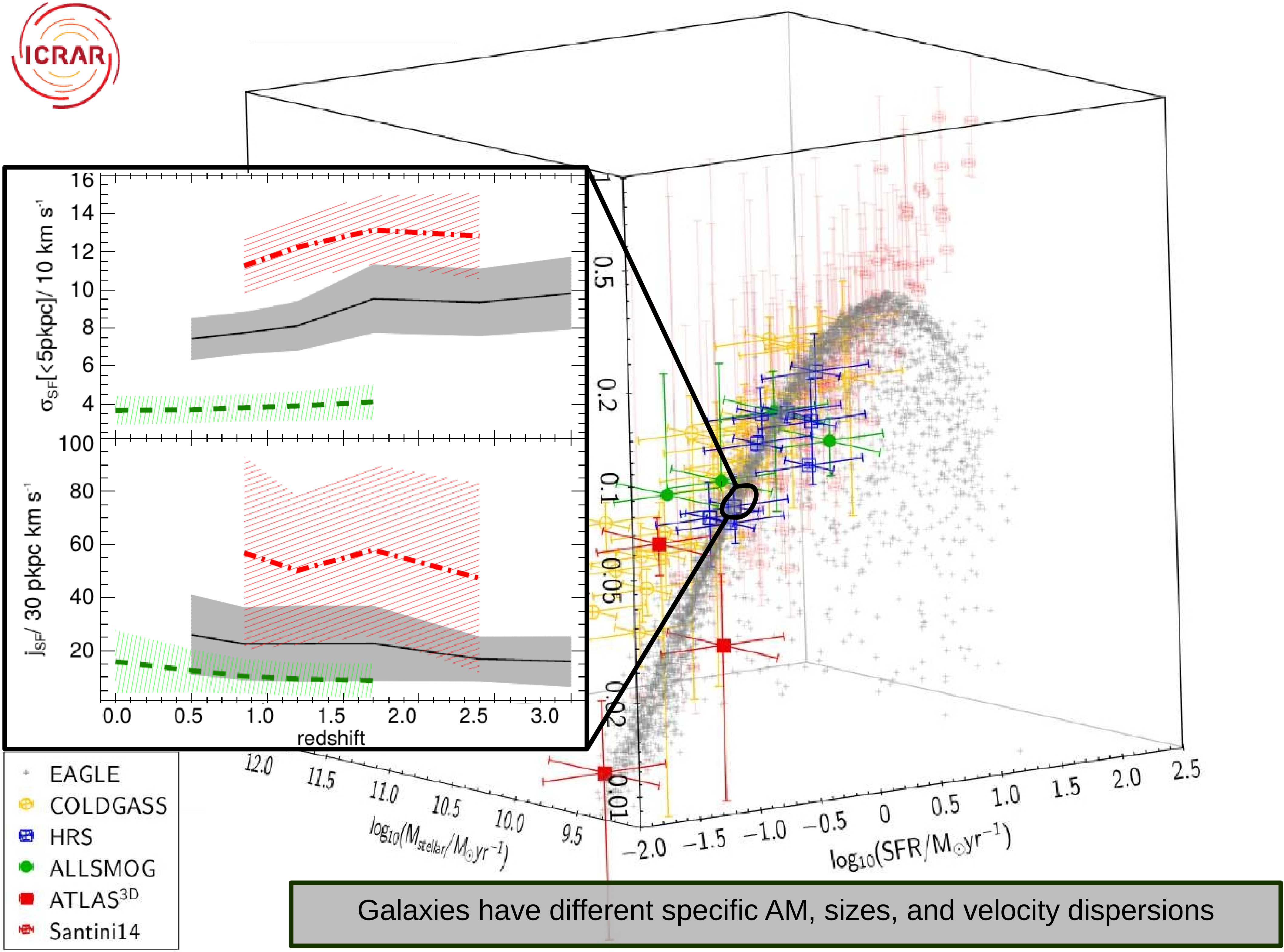
Galaxies here that have counterparts show:
→ Brightest one: SFR~30M_o/yr, Mstellar~$10^{11}M_o$
→ The other ones: SFR<~10M_o/yr and Mstellar~$10^{10}M_o$

This is the type of galaxies our model expects to dominate Omega H_2 (see also Lagos et al. 2014a)

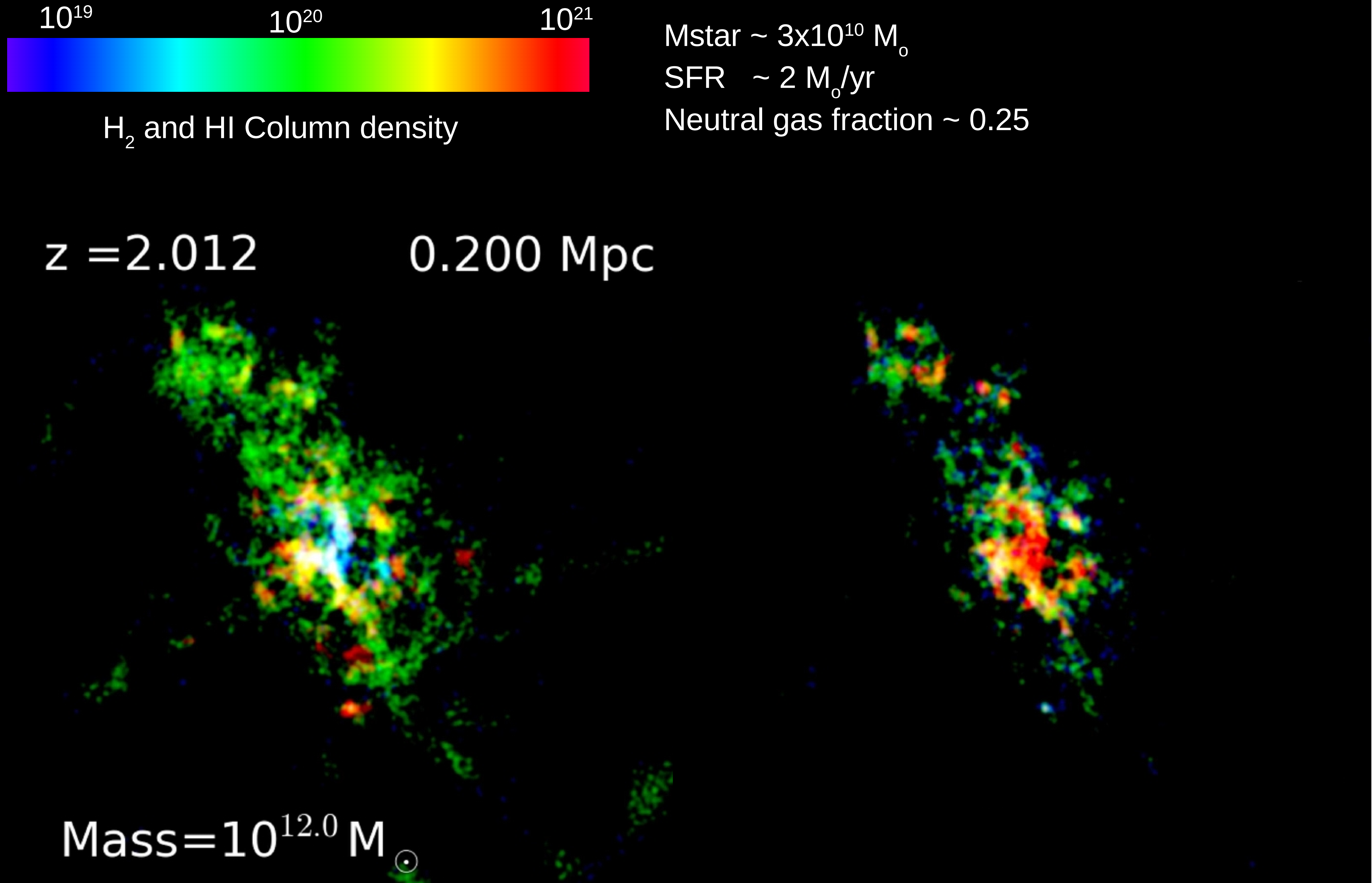
Lagos et al. (2015c, in preparation)

The Fundamental Plane Gas-SFR-$M_{stellar}$





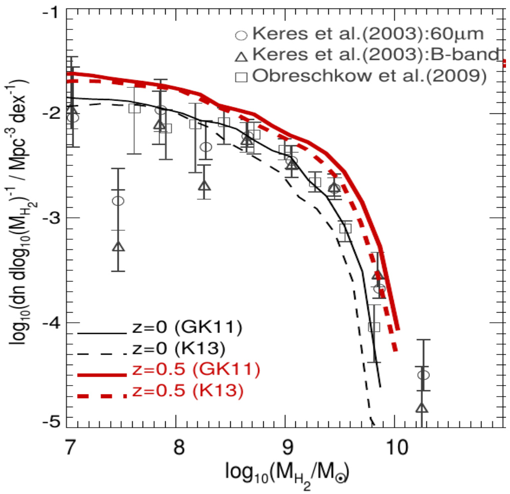
Galaxies have different specific AM, sizes, and velocity dispersions

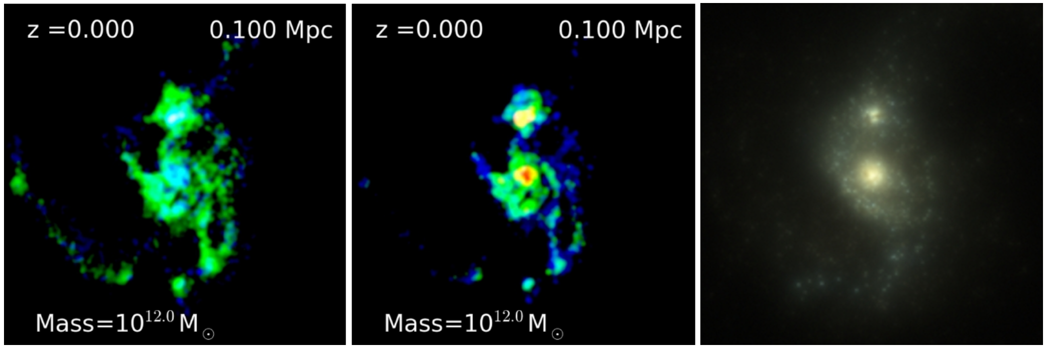


10^19
10^20
10^21
H2 and HI Column density
Mstar ~ 3x10^10 Mo
SFR ~ 2 Mo/yr
Neutral gas fraction ~ 0.25
z =2.012
0.200 Mpc
Mass=10^12.0 M⊙

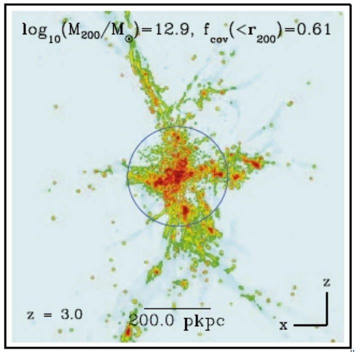
Conclusions

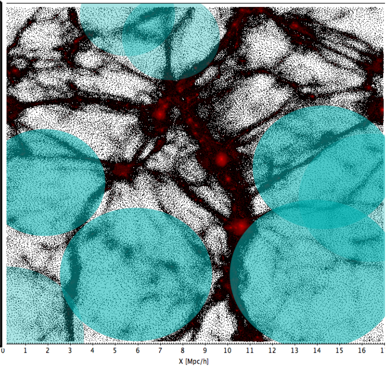
(1) Models of the HI to H_2 transition successfully applied to Hydro-sims (scaling relations and mass functions studied in detail) with *broad agreement with observations.*



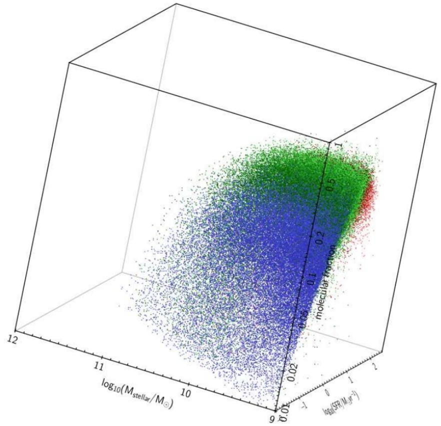


(2) HI, H2 and stellar mass built-up studied together (as integrated and resolved quantities).





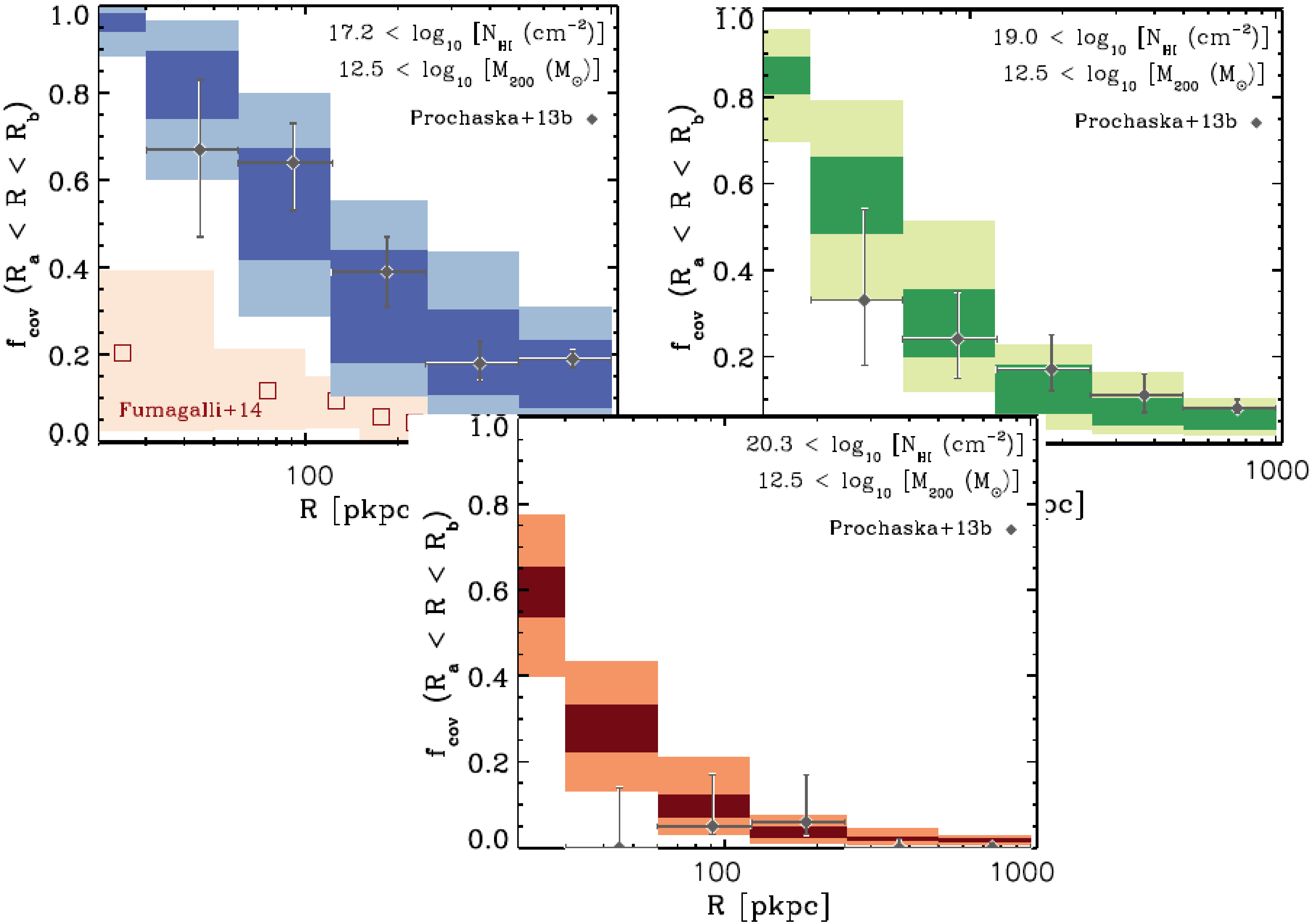
(3) We are *getting our models ready for the SKA and ALMA*:
- Exploring connection gas-LSS
- Abundance of HI and H2 in the Universe (and distribution)



(4) Existence of a fundamental relations (SFRs-Ms-gas fraction). Physical drivers of some of these. e.g. the *H_2 fraction and σ are not fundamentally correlated,* SNe feedback and grav. inst. drivers of evolution of σ.

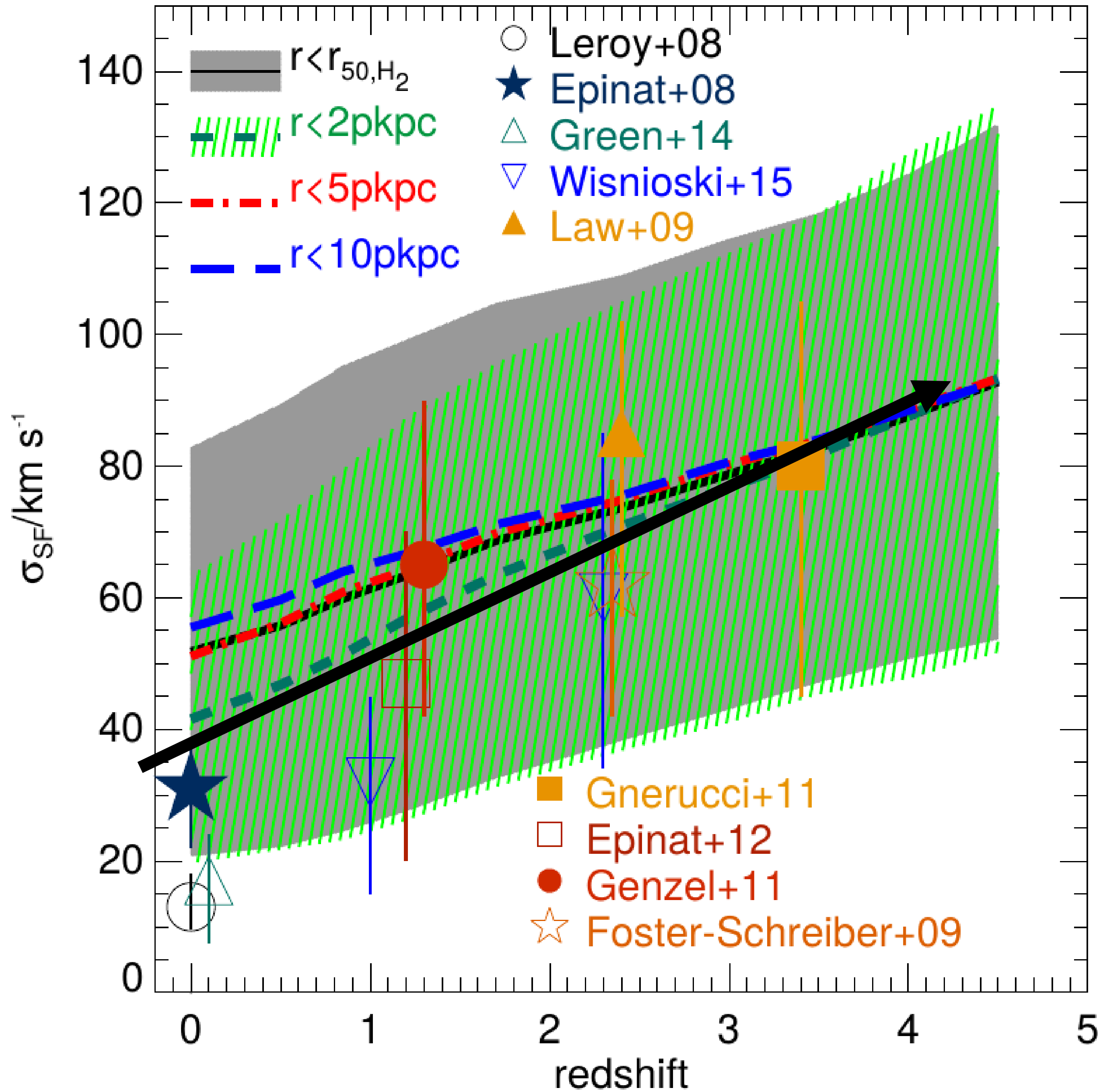
Where is the HI? Profiles around galaxies

Rahmati et al. (2015)



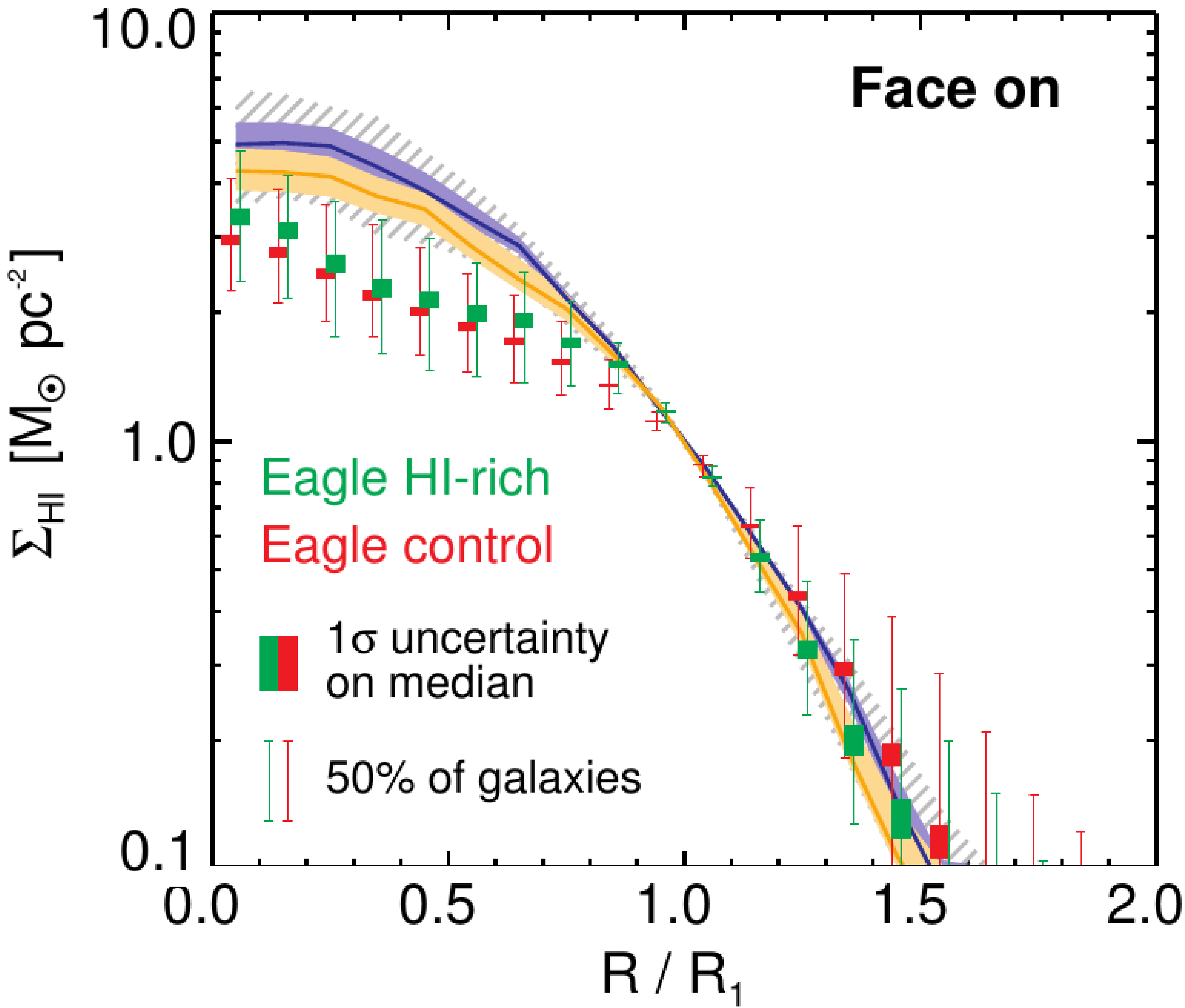
Development of the ISM turbulence

Lagos et al. (2015d, in prep.)



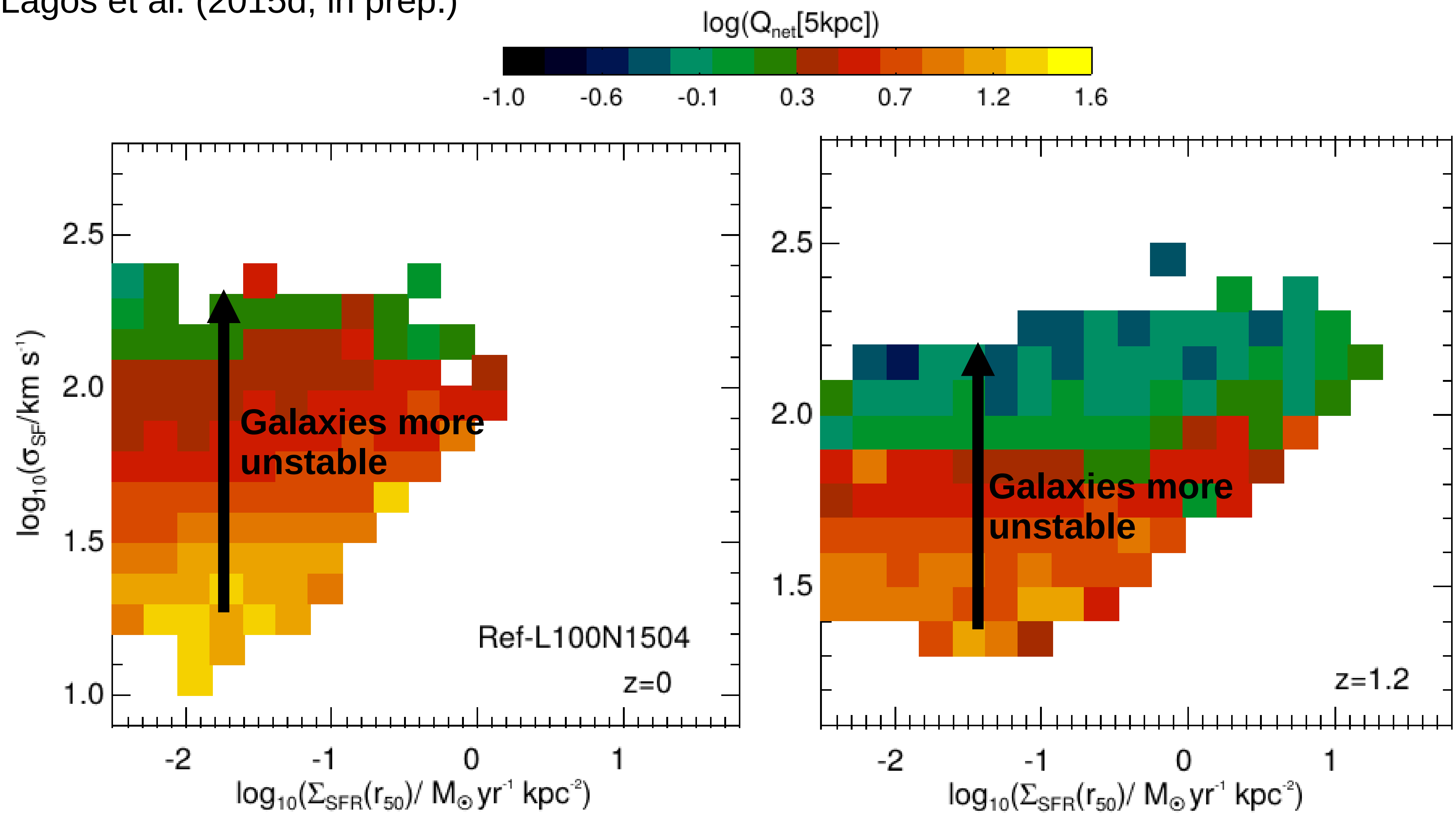
Radial profiles of HI

Bahe et al. (2015): comparison of EAGLE with GASS and Bluedisk



Clear correlation with Toomre-Parameter

Lagos et al. (2015d, in prep.)

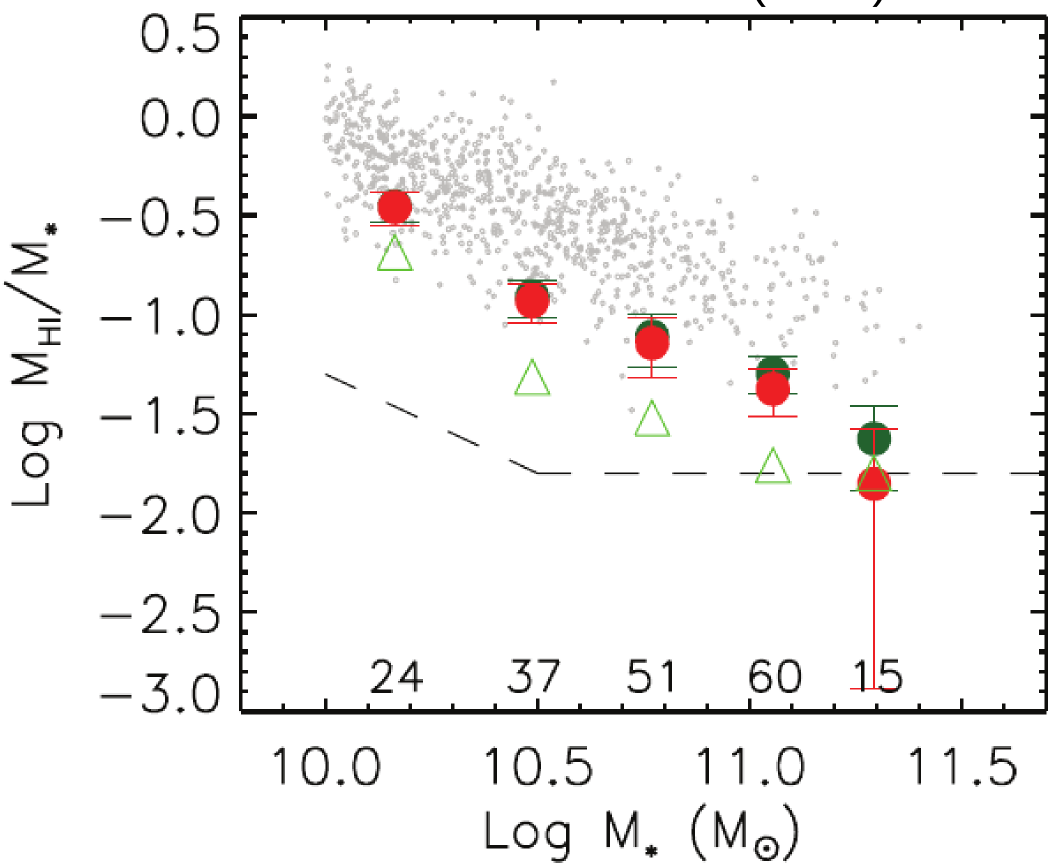


Strong connection between velocity dispersion and gravitational instabilities (but with some redshift evolution).

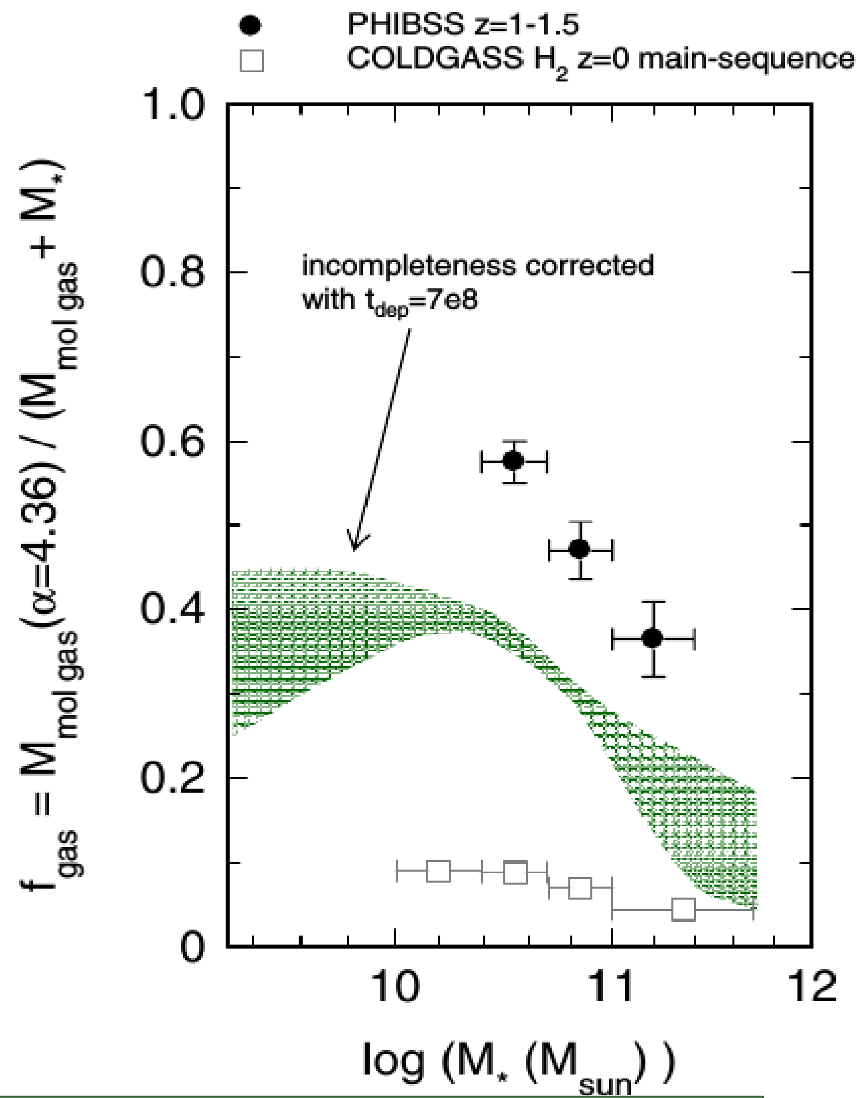
Gas in galaxies and the LSS... a hot topic!

More and more information on molecular and atomic hydrogen of galaxies. New generation of surveys:
- **HI selected** (HIPASS; ALFALFA)
- **Stellar mass selected** (GASS and COLD GASS)
- **Volume limited** ($ATLAS^{3D}$; HRS)

Catinella et al. (2010)



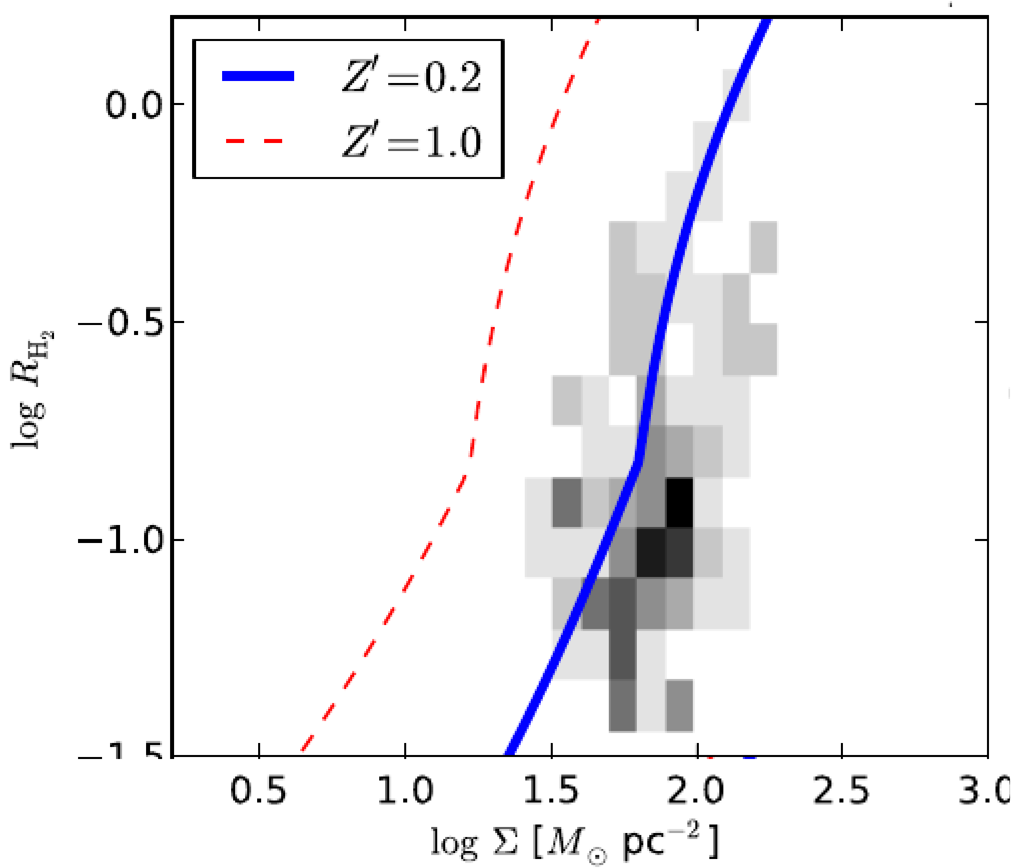
Tacconi et al. (2013)

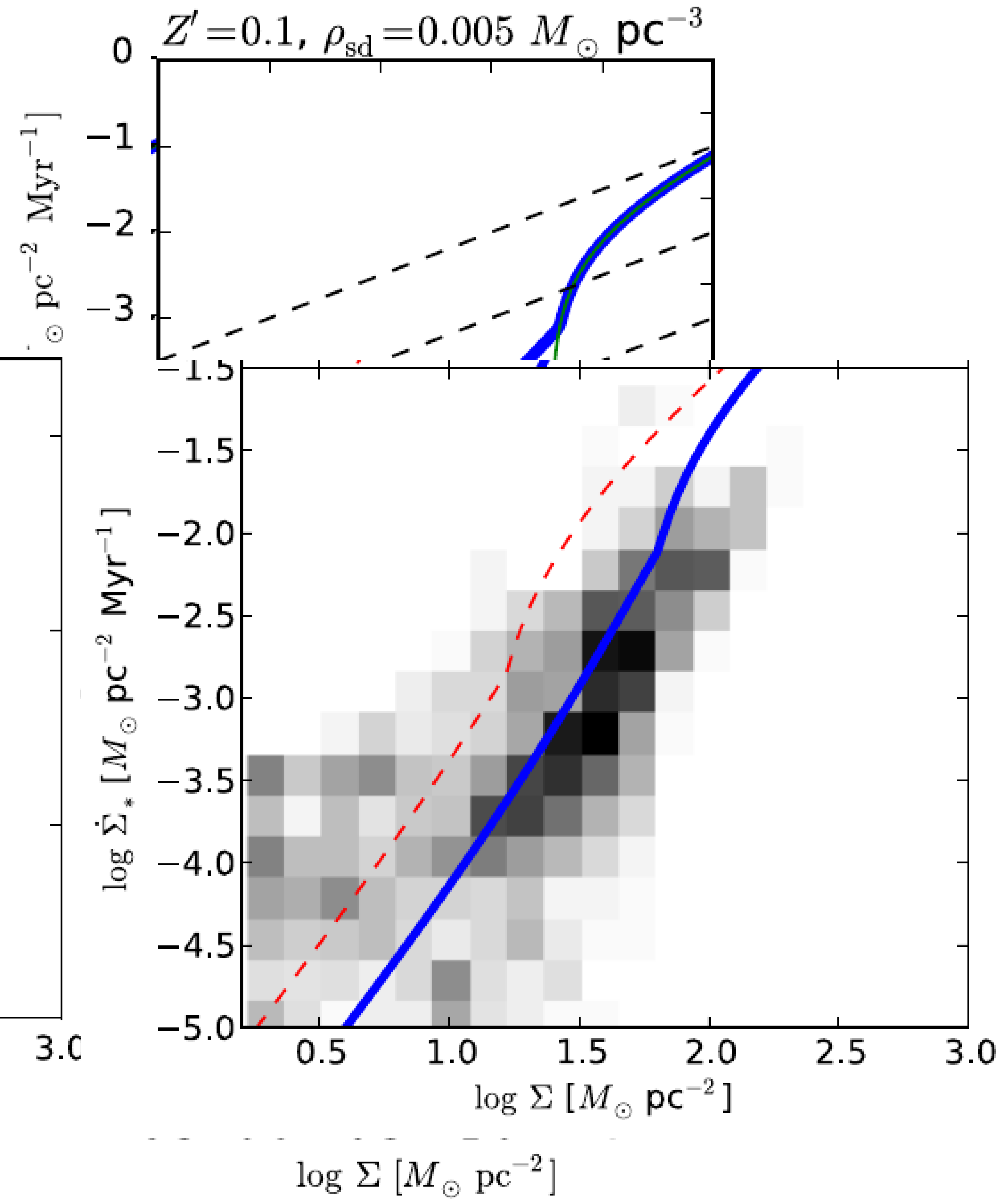


In the future: ALMA, JVLA, LOFAR, ASKAP, MeerKAT, NOEMA, SKA

Bottom-up models: SF in individual clouds

$$\Sigma_{\rm SFR} = \boxed{f_{\rm SF}} \epsilon_{\rm ff} \frac{\Sigma}{t_{\rm ff}}$$





Krumholz (2013)