Gas in galaxies: the view from the EAGLE cosmological hydrodynamic simulations

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International Centre for Radio Astronomy Research

MERAC

Australian Government

Australian Research Council

CAASTRO

ALL-SKY ASTROPHYSICS

Curtin University

The Government of Western Australia

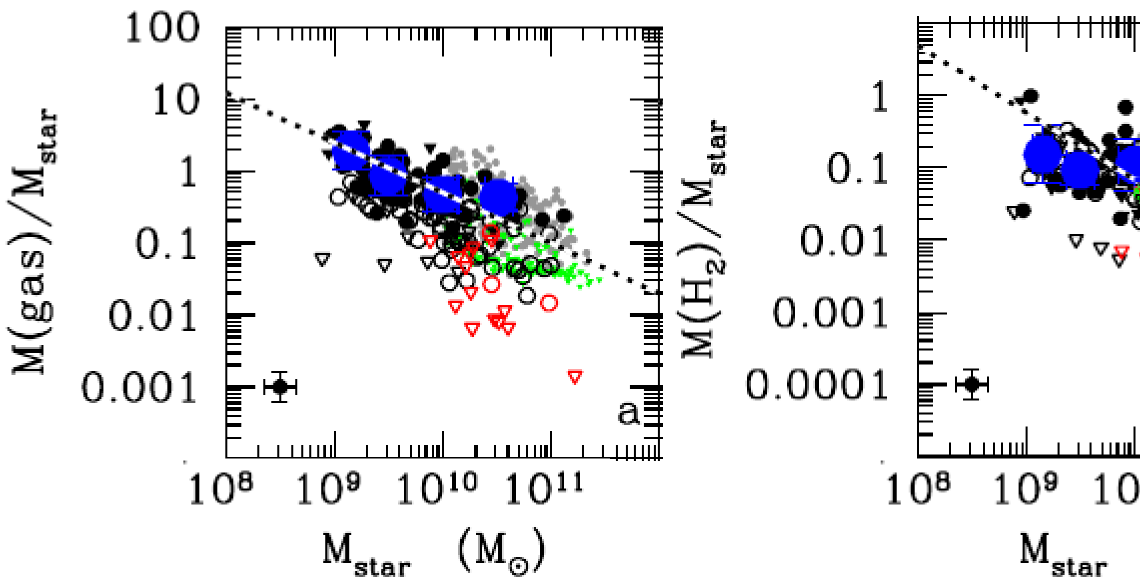
The University of Western Australia

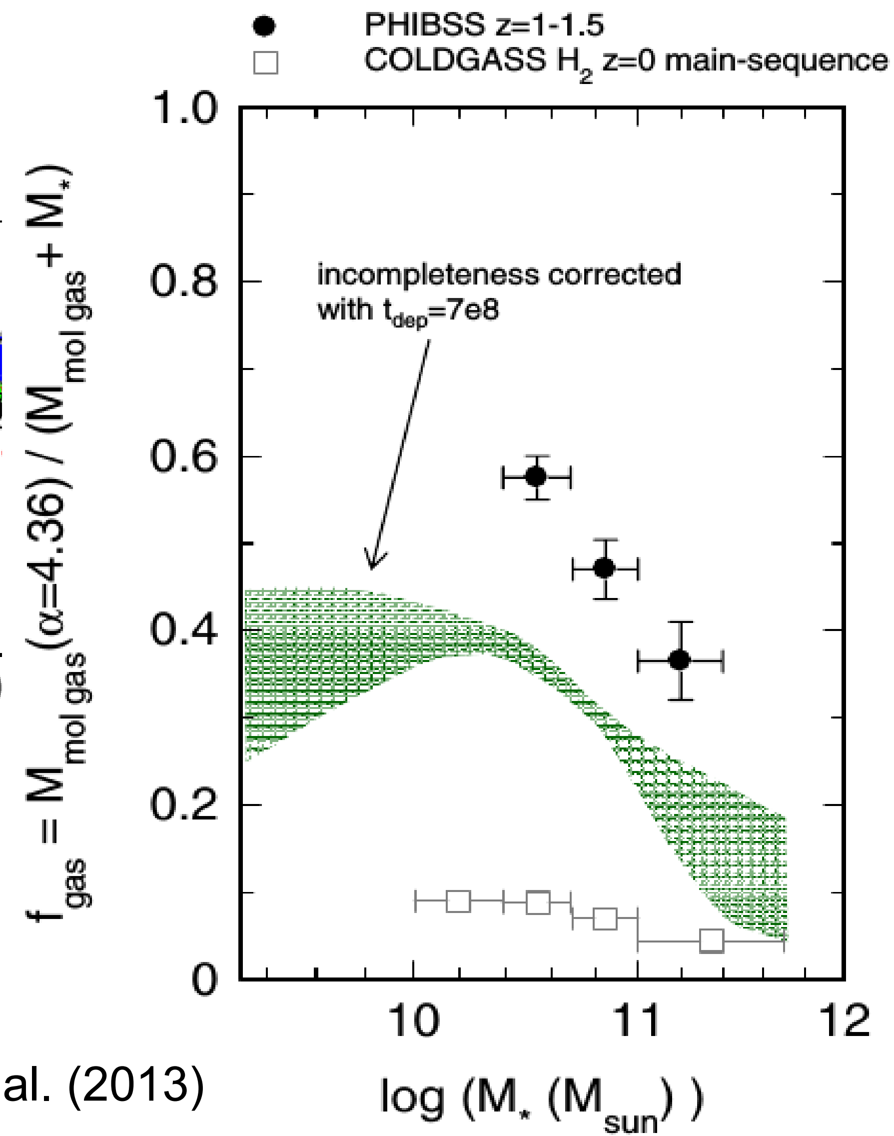
Scaling relations of gas in galaxies

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; more recently stacking)
- **Volume limited** ($ATLAS^{3D}$; HRS)

Boselli et al. (2014)



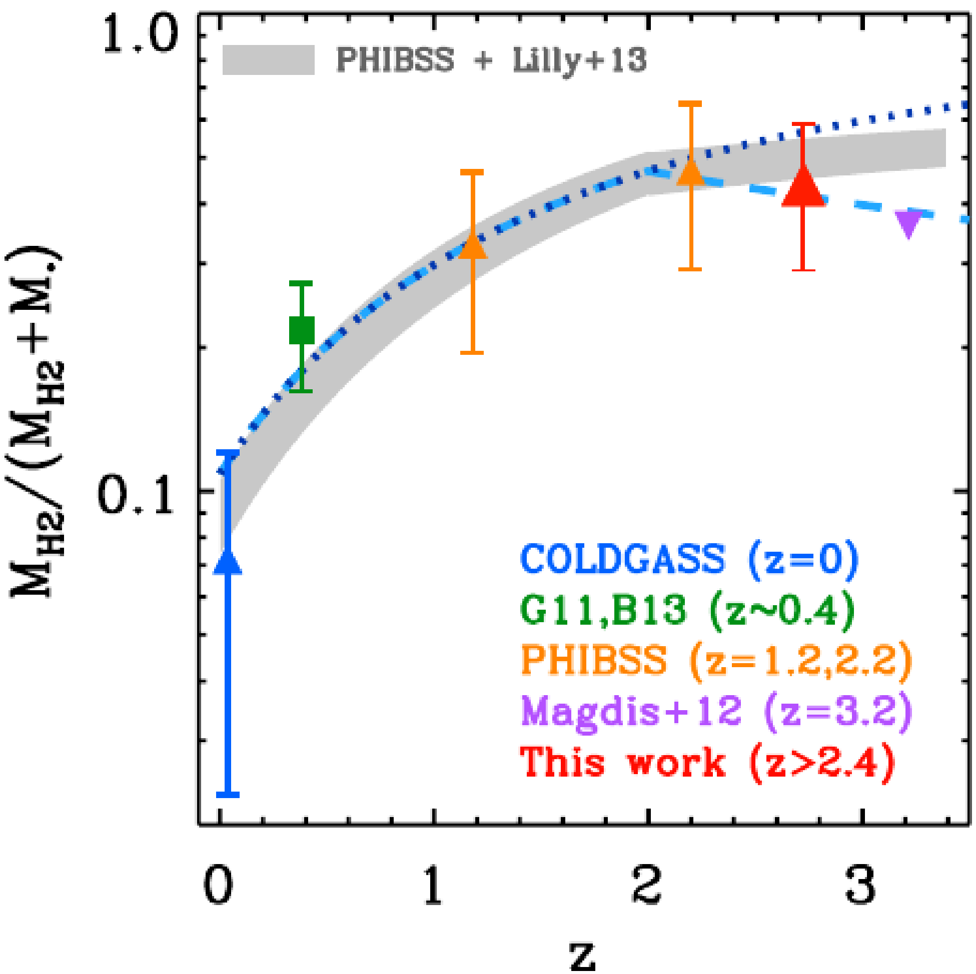


Cold gas content of galaxies evolves by 2-4 times to z=1.5

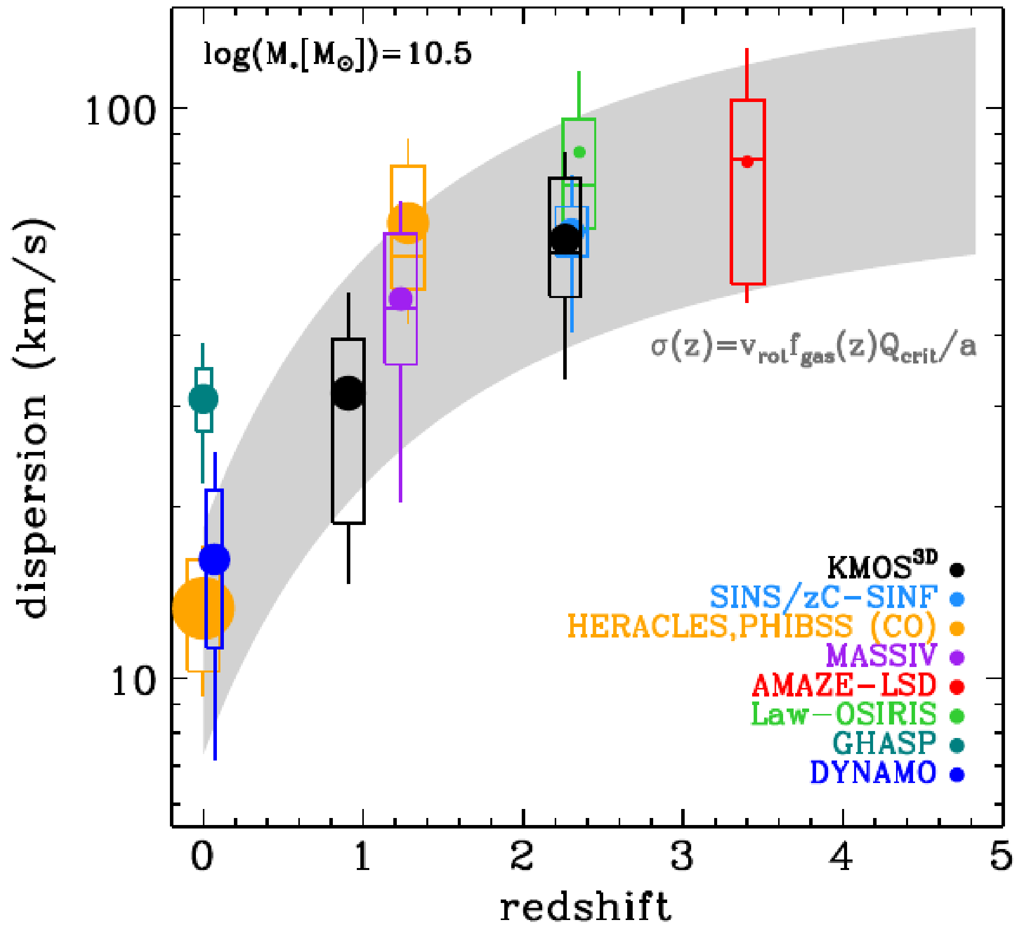
Tacconi et al. (2013)

Gas content and dynamics of galaxies

Saintonge et al. (2013)



Wisnioski et al. (2015)



Although these scaling relations provide valuable insight, they cannot distinguish cause/effect → use simulations!

Observations described well by Q=1
Connection between gas fraction and stability of disks? (also see Obreschkow et al. 2016)

Use EAGLE to:

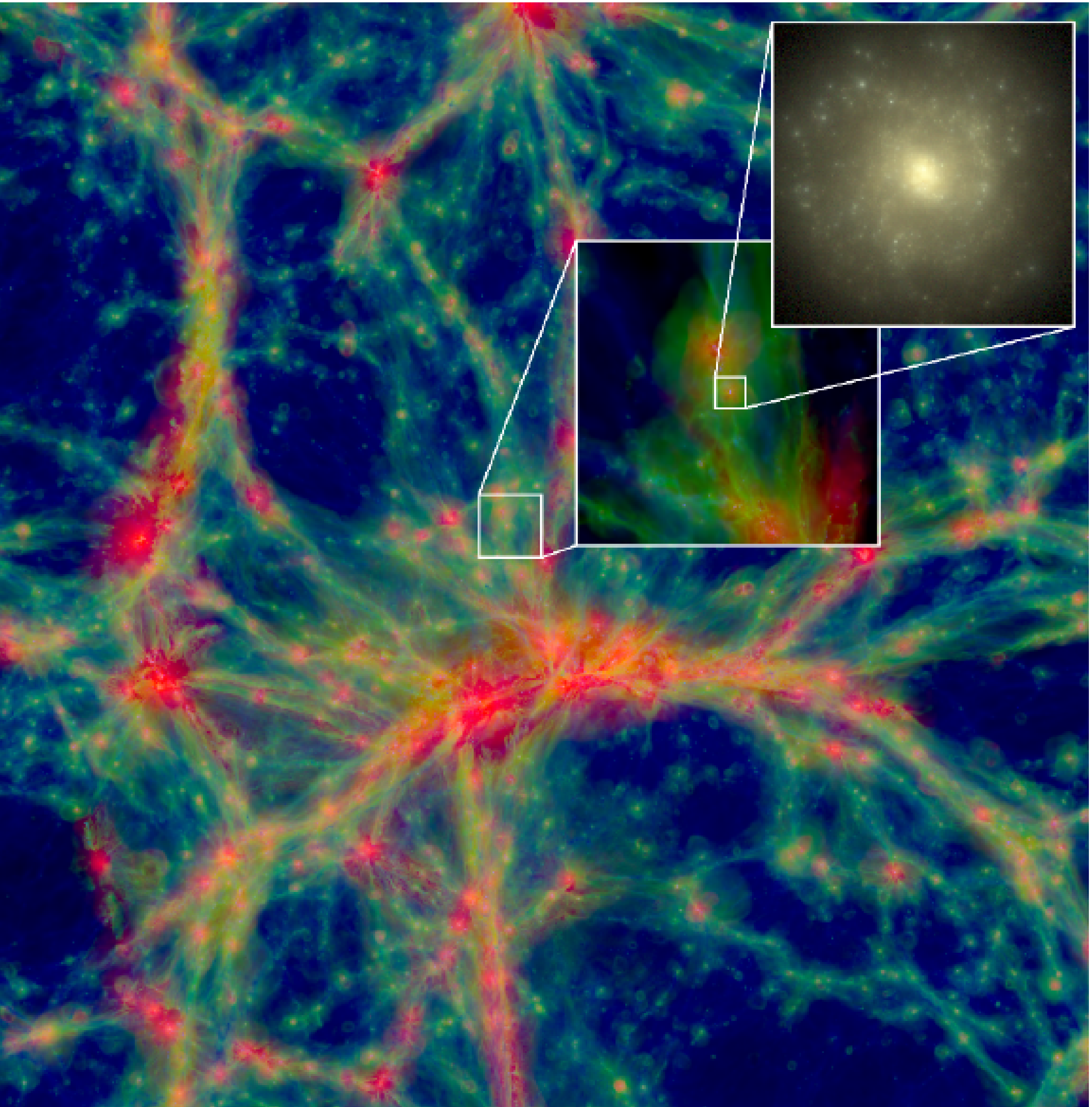
(1) Implement gas phases (HII, HI, H_2) and explore scaling relations

(2) Determine which relations are most fundamental and explore causality

(3) Connect dynamics to integrated galaxy properties

Lagos et al. (2015b, 2016ab), Bahe et al. (2016), Crain et al. (2016), Marasco et al. (2016), Stevens et al. (2016b), Rahmati et al. (2015,2016)

The EAGLE Simulation



Improved hydrodynamics
("Anarchy")

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

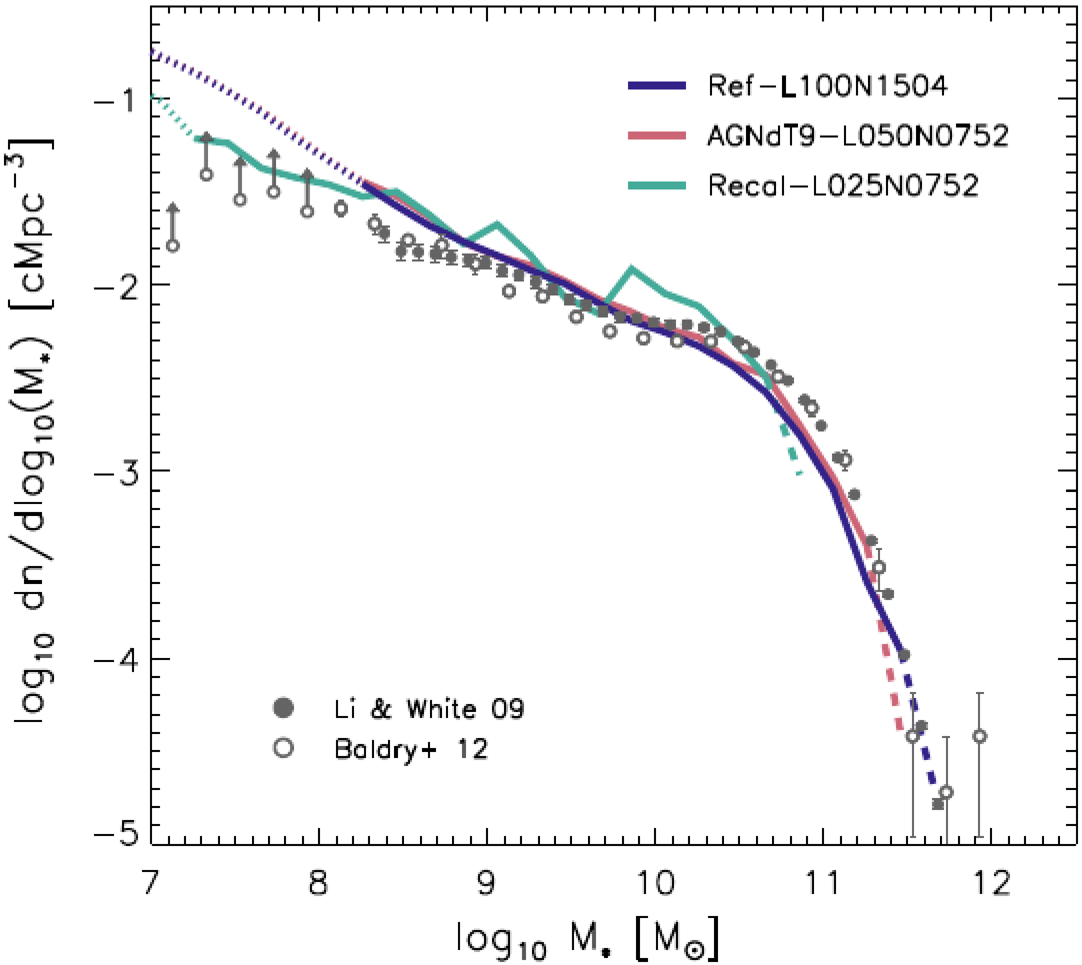
(~700pc resolution, 1e6Msun, 100Mpc box size)

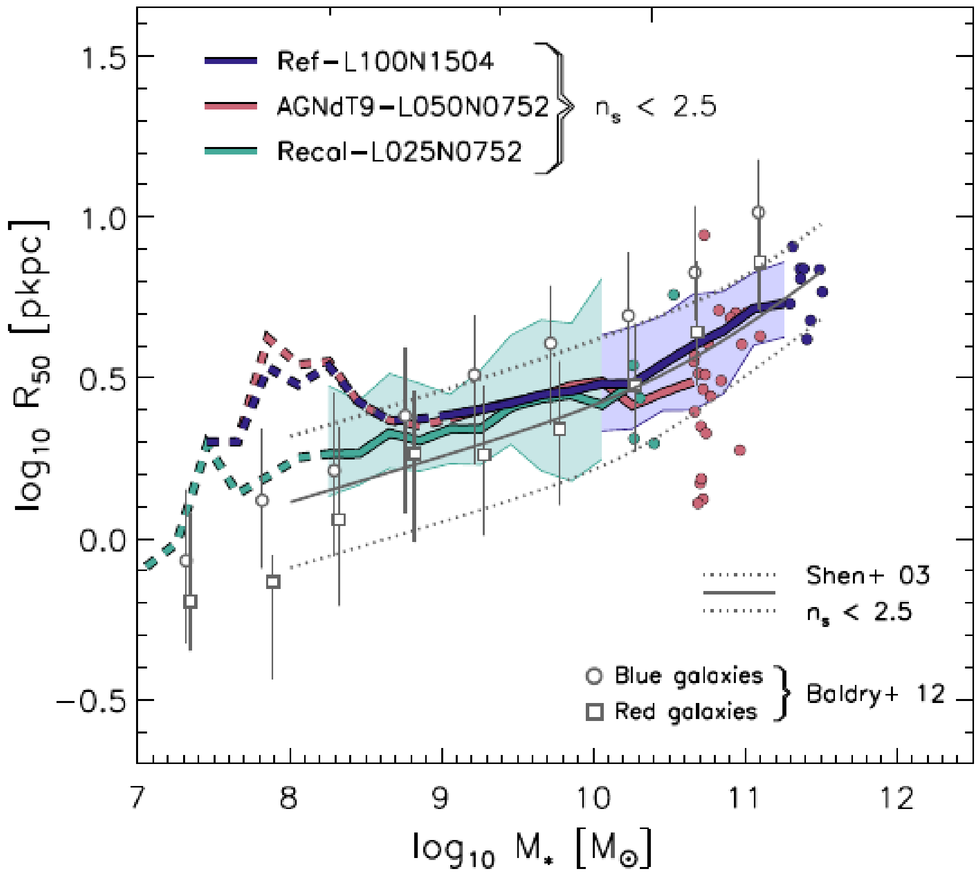
Schaye et al.(2015); Furlong et al. (2015); Crain et al. (2015); Lagos et al. (2015); Bahe et al. (2016)…

More details in Rob Crain's talk

The EAGLE Simulation: parameter tunning

Schaye et al. (2015)





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

This means that gas properties are mostly an independent test of the simulation...

Use EAGLE to:

(1) Implement gas phases (HII, HI, H_2) and explore scaling relations

Lagos et al. (2015b, 2016a,b), Bahe et al. (2016), Crain et al. (2016), Marasco et al. (2016), Stevens et al. (2016b), Rahmati et al. (2015,2016)

Implementing gas phase transitions

Lagos et al. (2015b): description of multiphase ISM in EAGLE in post-processing

HII, HI, H_2

HII

Neutral H
$HI+H_2$

Molecular H
H_2

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

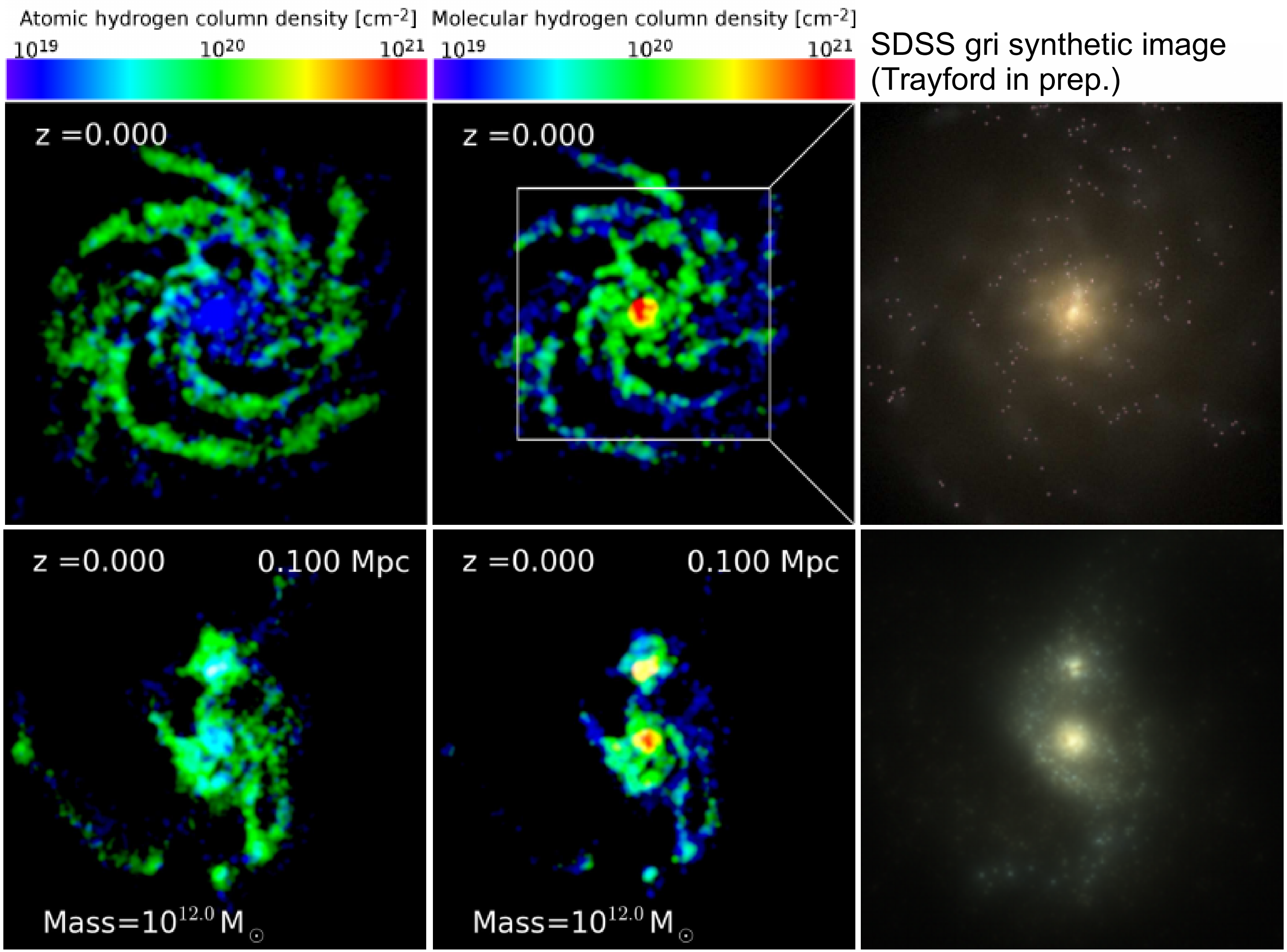
$f_{neutral} = \eta(\Gamma_{TOT}, T, n_H)$: Ionisation equilibirum

Gnedin & Kravtsov (2011)
Krumholz (2013)
Blitz & Rosolowsky (2006)

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

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

Illustrating the power of EAGLE…
HI and H_2 maps

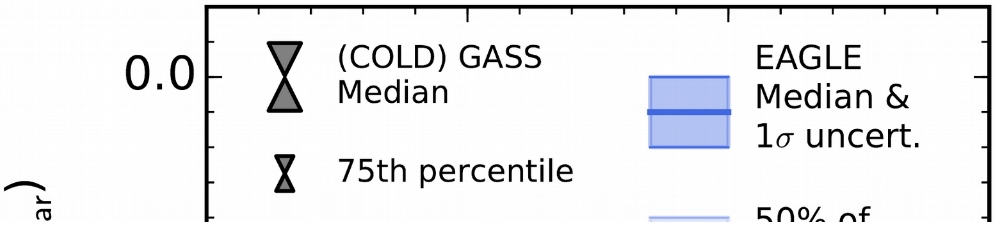


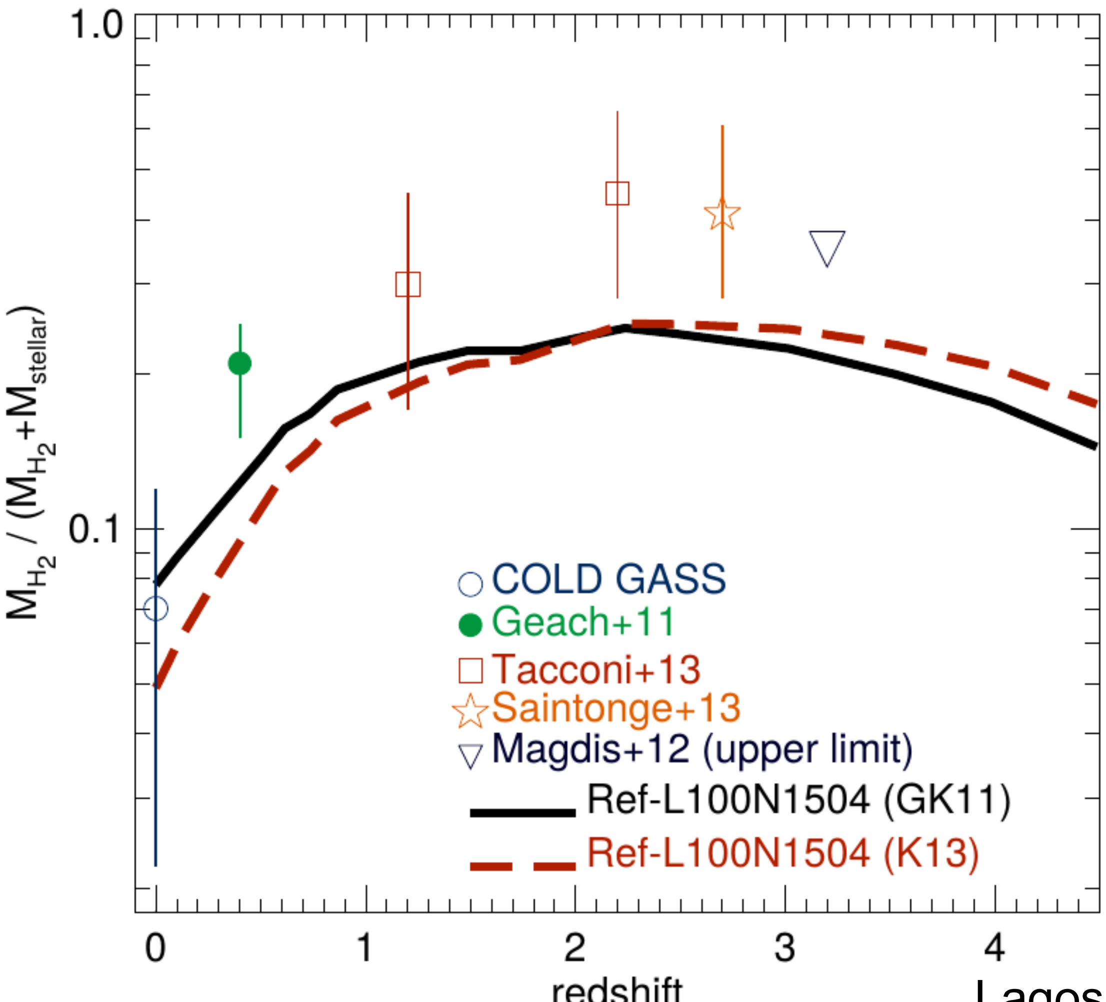
Nice rotating disk at z=0

Gas-rich merging systems

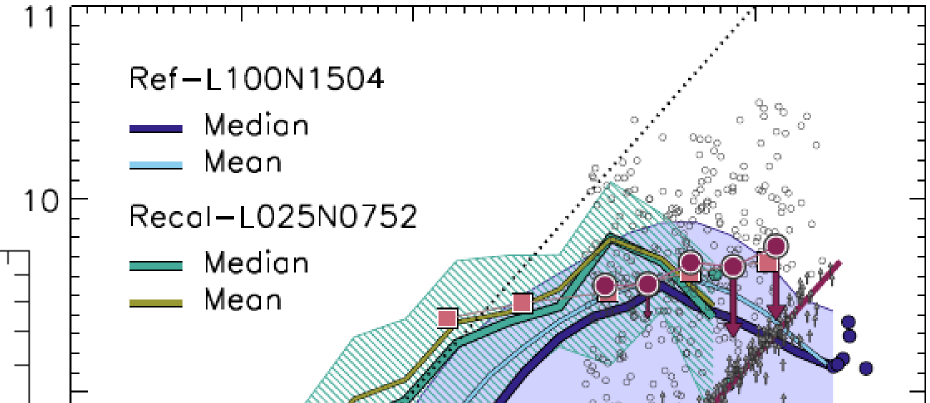
EAGLE's scaling relations: gas fractions

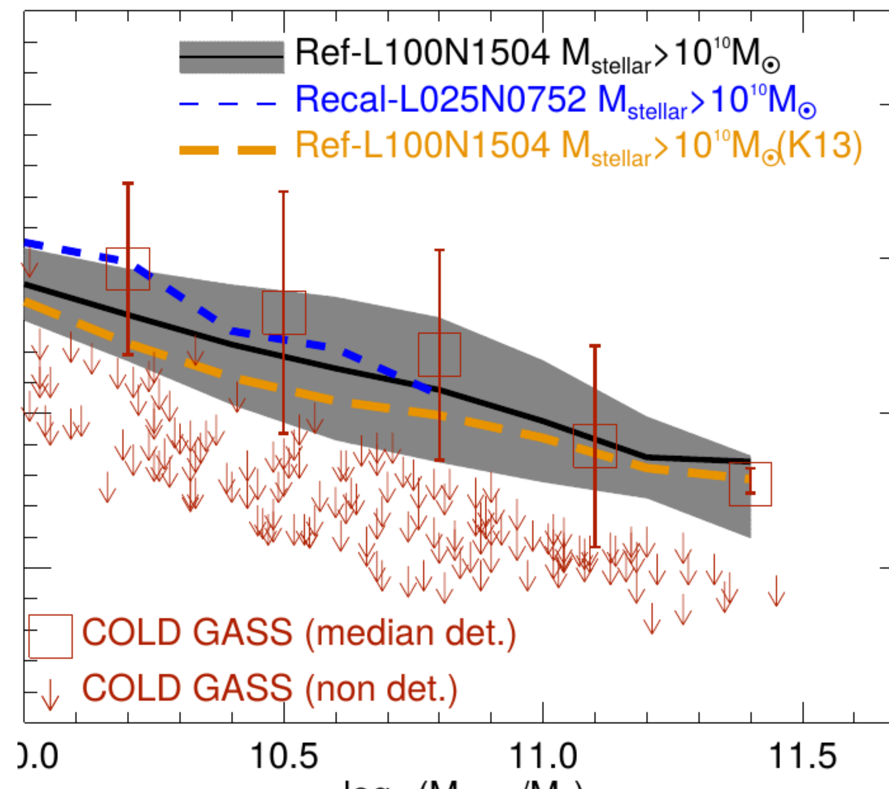
Bahe et al. (2015):
total neutral gas fraction





Crain et al. (2016):
HI gas fraction

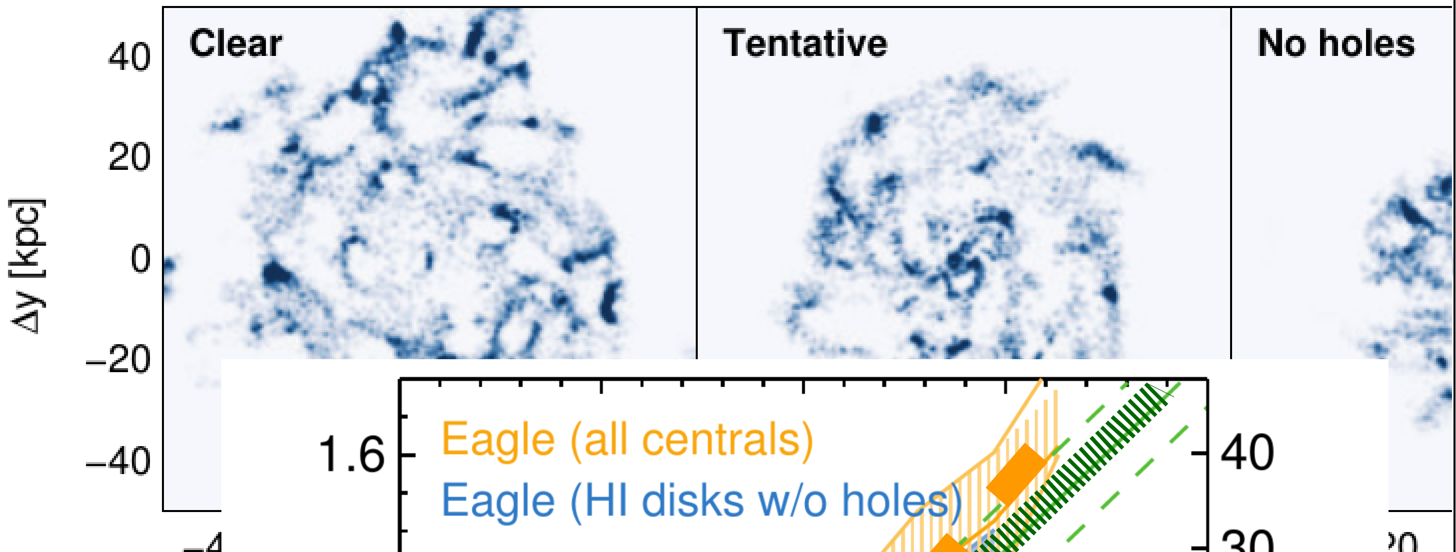


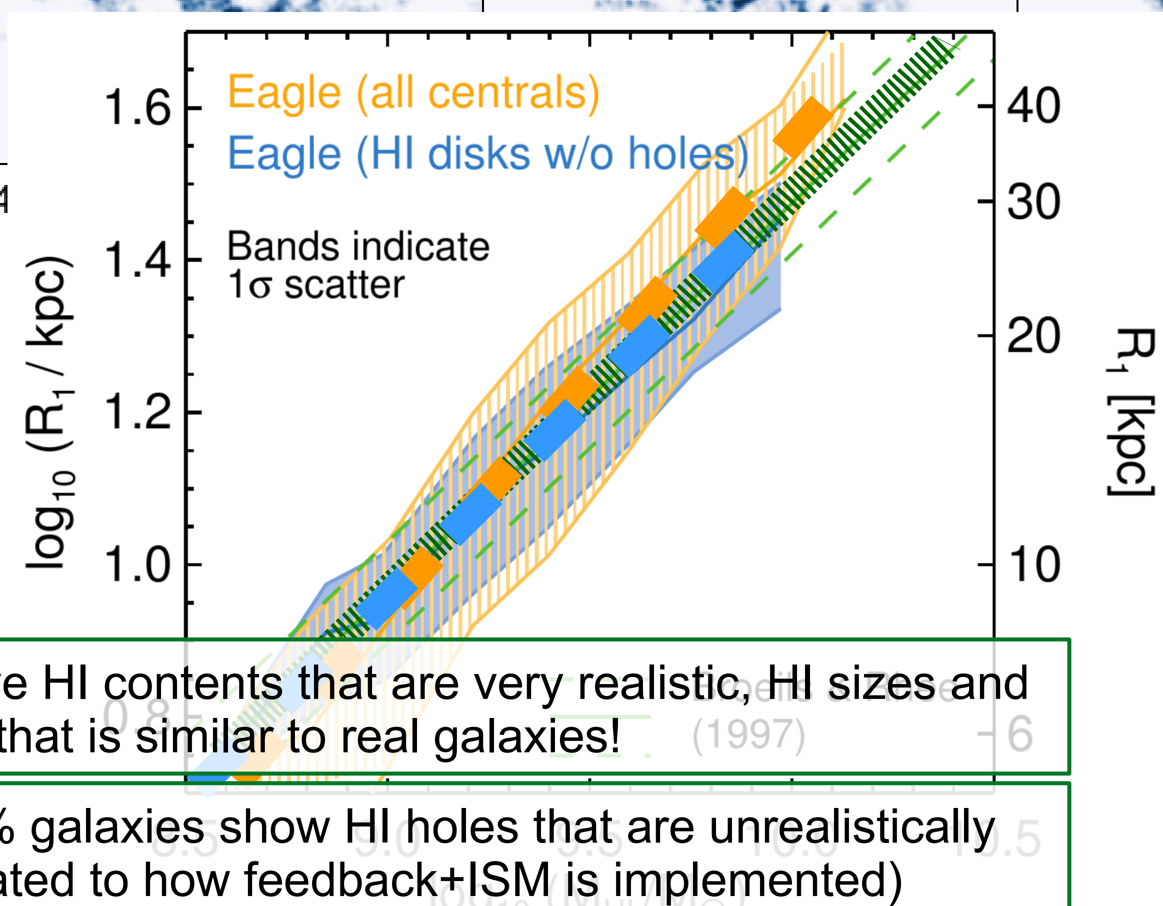


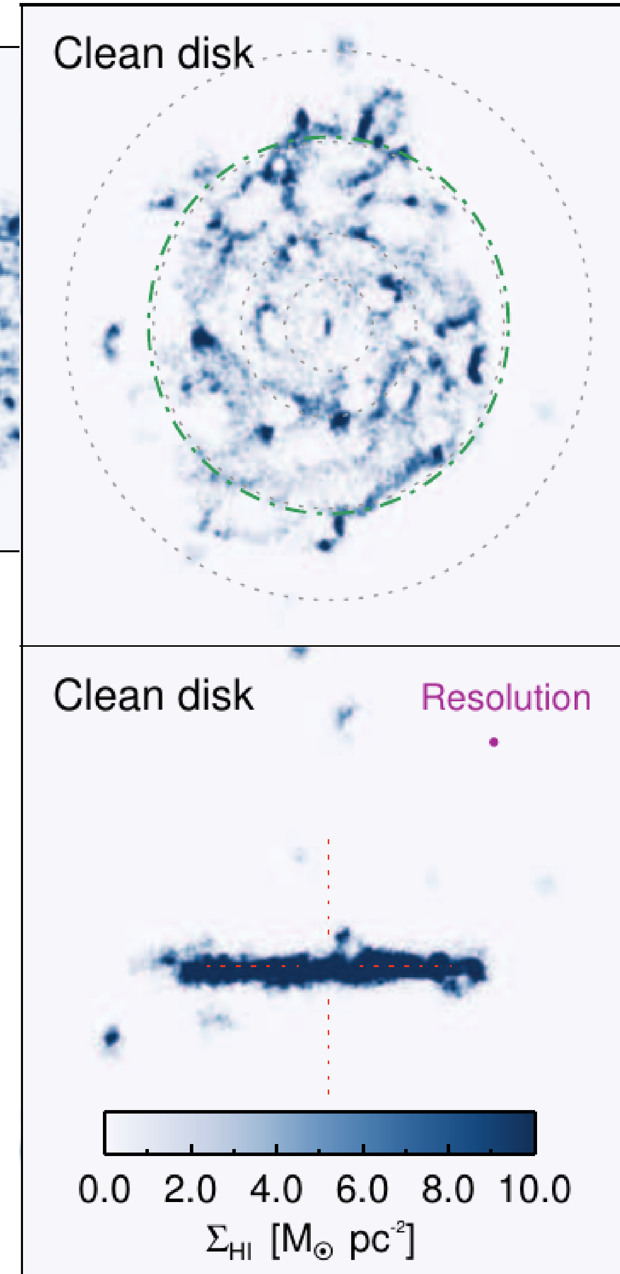
Lagos et al. (2015b)

Spatial distribution of the HI gas

Bahe et al. (2015)







Disks have HI contents that are very realistic, HI sizes and structure that is similar to real galaxies!

But, ~30% galaxies show HI holes that are unrealistically large (related to how feedback+ISM is implemented)

Use EAGLE to:

(2) Determine which relations are most fundamental and explore causality

Lagos et al. (2015b, 2016ab), Bahe et al. (2016), Crain et al. (2016), Marasco et al. (2016), Stevens et al. (2016b), Rahmati et al. (2015,2016)

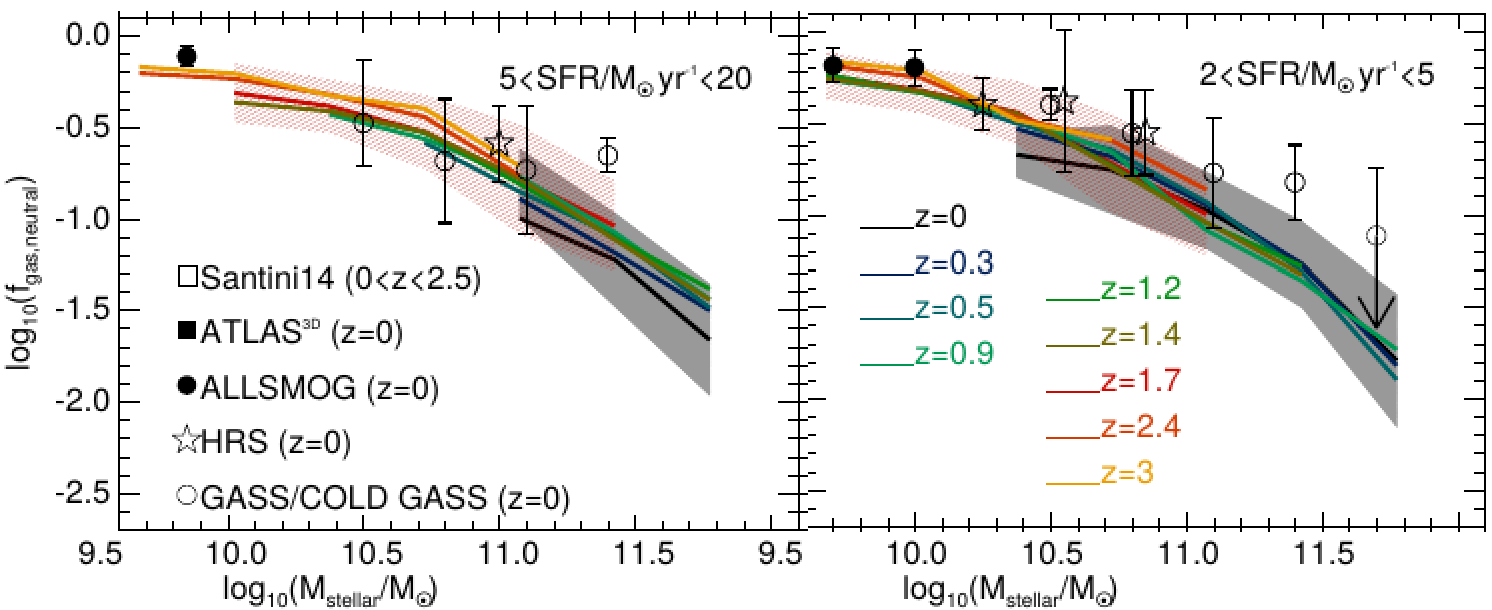
The fundamental plane of star formation

Lagos et al. (2016a): We asked which combinations of galaxy properties are most fundamental? (PCA over 10 galaxy properties)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
comp.	$\hat{x}_1$	$\hat{x}_2$	$\hat{x}_3$	$\hat{x}_4$	$\hat{x}_5$	$\hat{x}_6$	$\hat{x}_7$
Prop.	$\log_{10}\left(\frac{M_{stellar}}{M_\odot}\right)$	$\log_{10}\left(\frac{SFR}{M_\odot\,yr^{-1}}\right)$	$\log_{10}\left(\frac{Z_{SF,gas}}{Z_\odot}\right)$	$\log_{10}\left(\frac{M_{H_2}}{M_\odot}\right)$	$\log_{10}\left(\frac{M_{HI}}{M_\odot}\right)$	$\log_{10}\left(\frac{M_{neutral}}{M_\odot}\right)$	$\log_{10}\left(\frac{r_{50,\star}}{kpc}\right)$
PC1	$\boxed{0.31}$	$\boxed{-0.57}$	−0.19	−0.15	0.4	$\boxed{0.6}$	0.06
PC2	0.46	0.04	−0.31	−0.51	0.22	−0.61	0.09
PC3	−0.19	−0.68	−0.14	0.33	−0.33	−0.51	0.002

55% of the variance contained in the relation between *Mstellar-SFR-Mneutral (HI+H_2)*

25% of the variance contained in the Mstellar-SFR-Metallicity relation



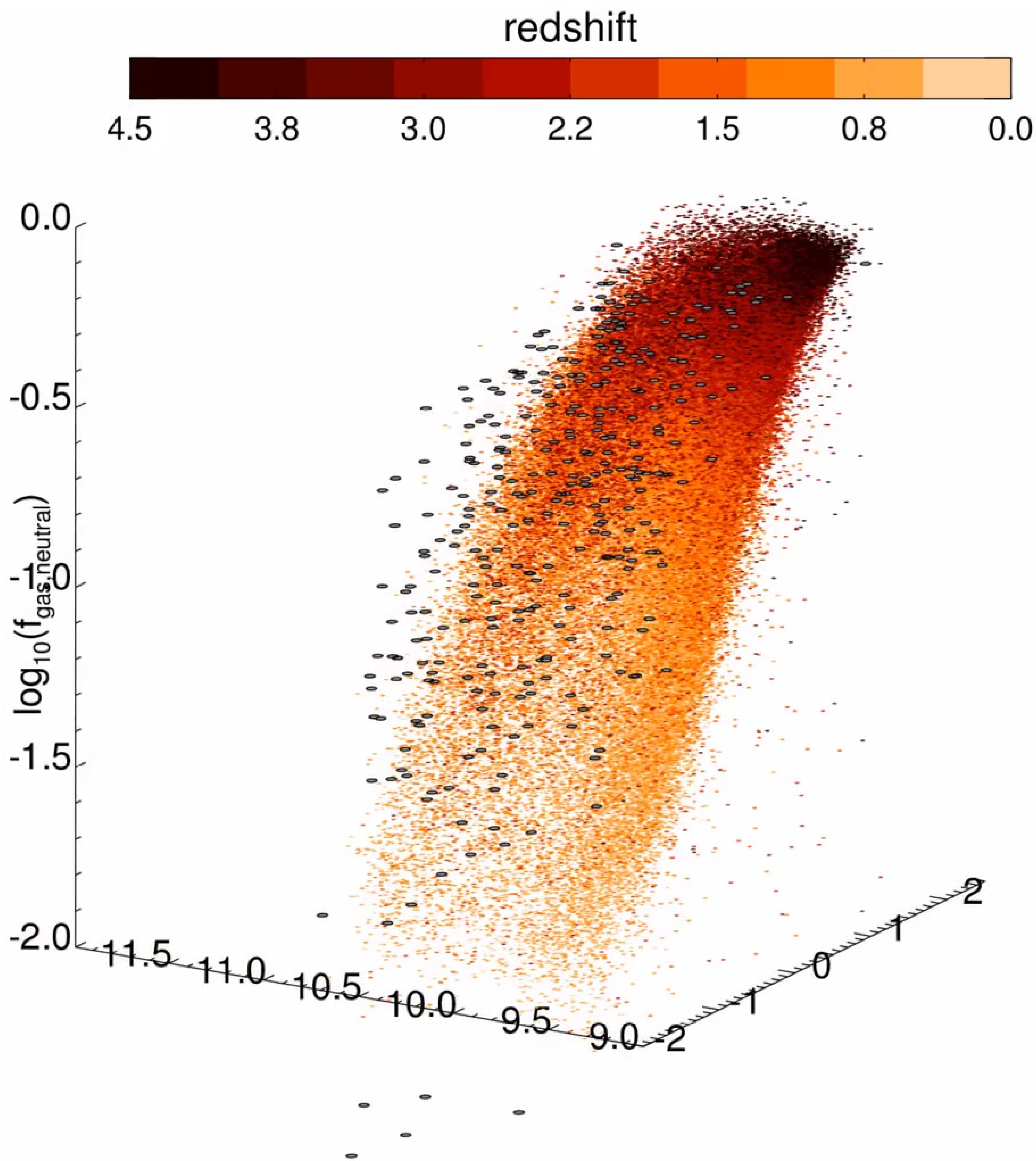
Lagos et al. (2016a)
The Fundamental Plane of Star Formation

Comparison with observations of the neutral hydrogen content of galaxies

ALLSMOG
GASS/COLD GASS
HRS
ATLAS[3D]

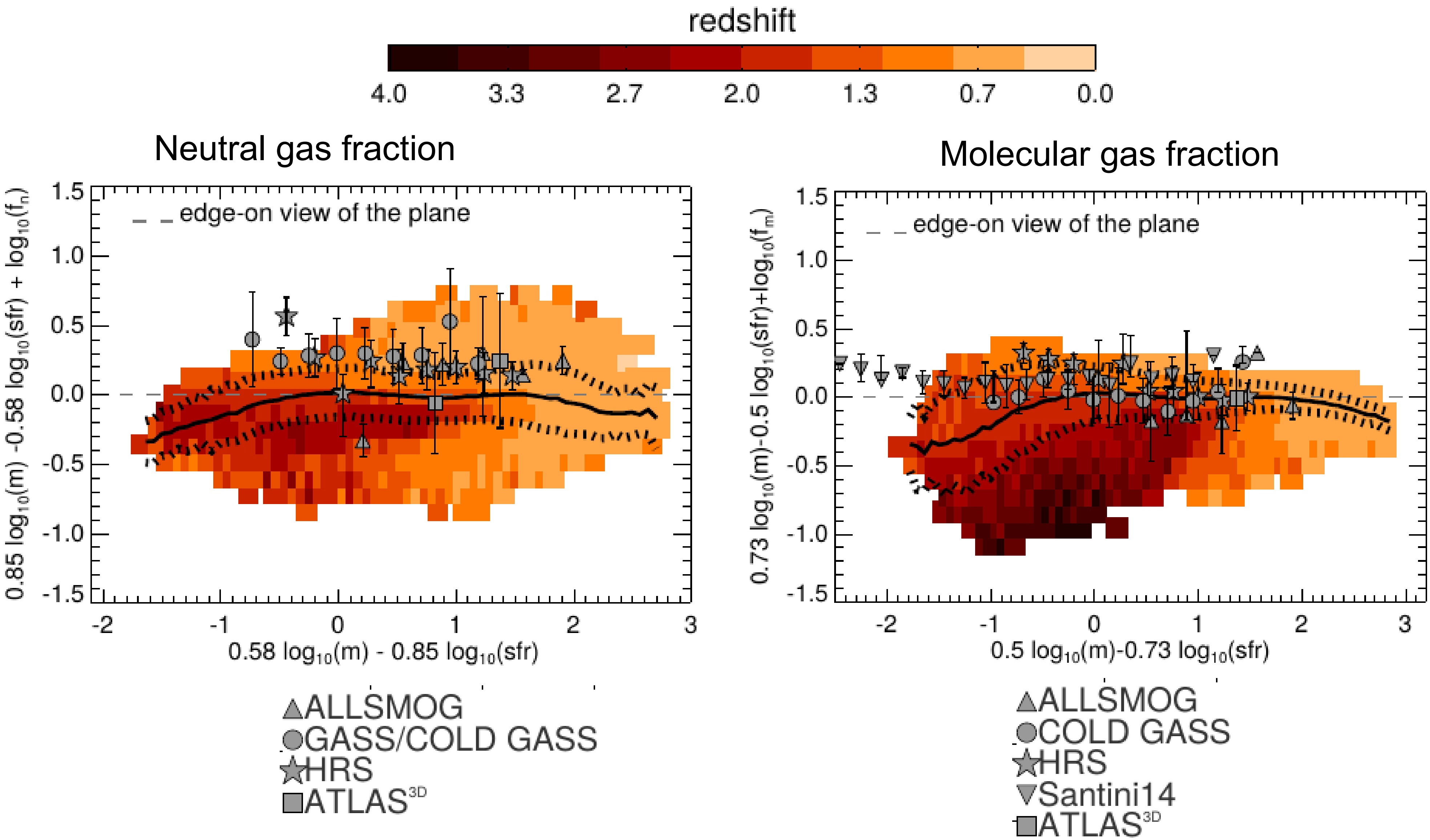
Accounts for 55% of all the variance of the galaxy population!

Note that the FPoSF is followed by active AND passive galaxies!



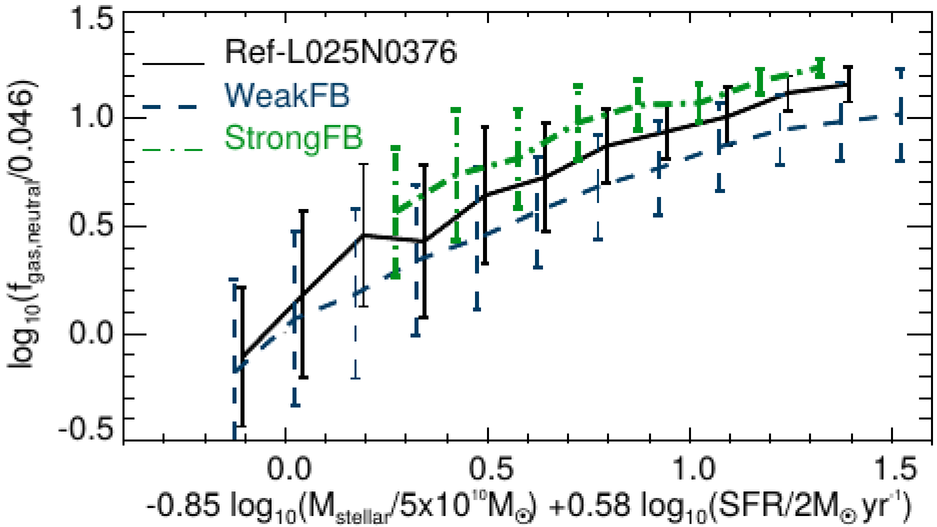
The FPoSF in observations: the edge-on view

Lagos et al. (2016a): Observations follow a very similar plane!



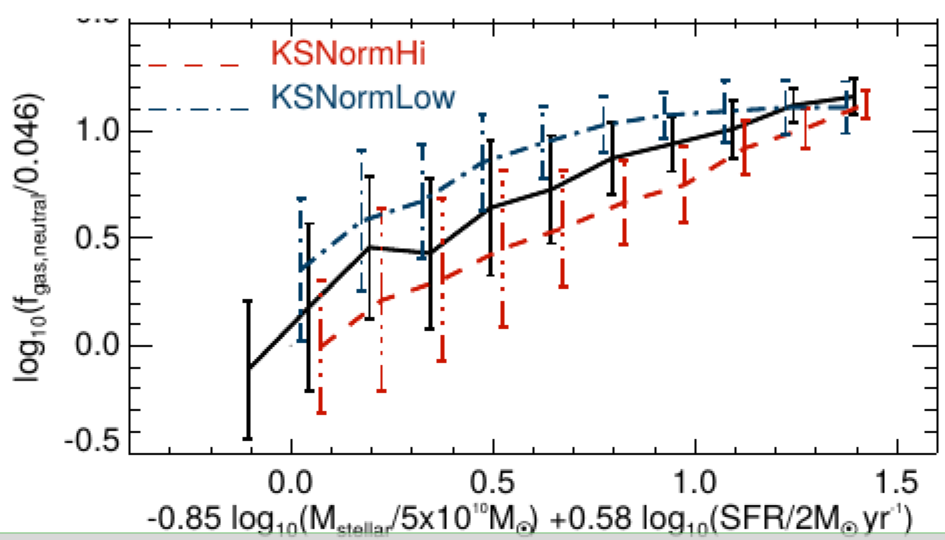
The physics behind the FPoSF

(1) Why does the FPoSF exists? Tests using different EAGLE models

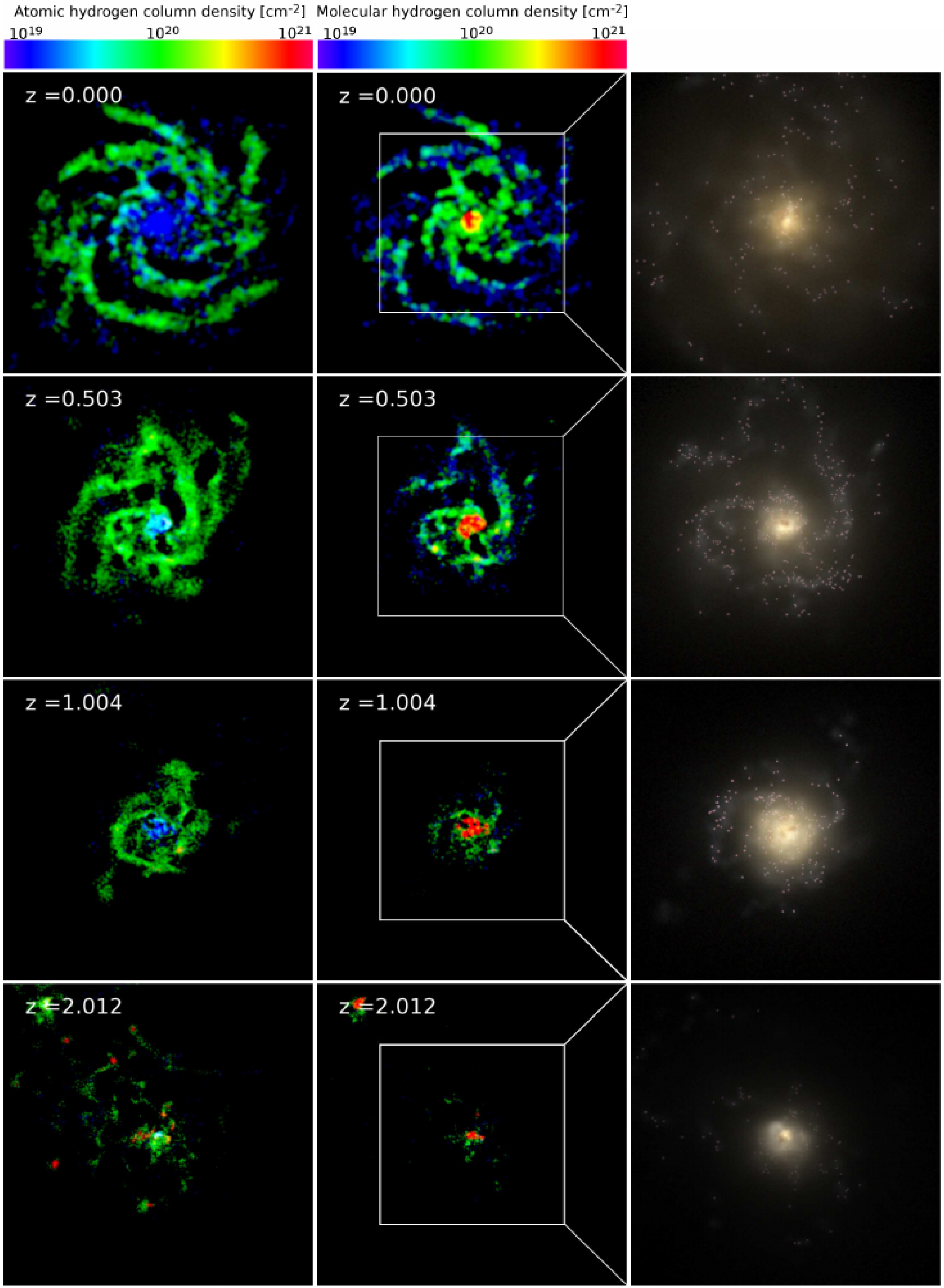


Existence of FPoSF is due to self-regulation of star formation in galaxies.

(2) What sets the curvature of the FPoSF?



Curvature of FPoSF set by how gas gets converted into stars and the gas density PDF (in the ISM) evolution.



Galaxies with the same stellar mass, SFR, HI and H2 masses but at different redshifts

Sizes/angular momentum extremely sensitive to accretion flows/compactness of galaxies (Lagos et al. 2016b)

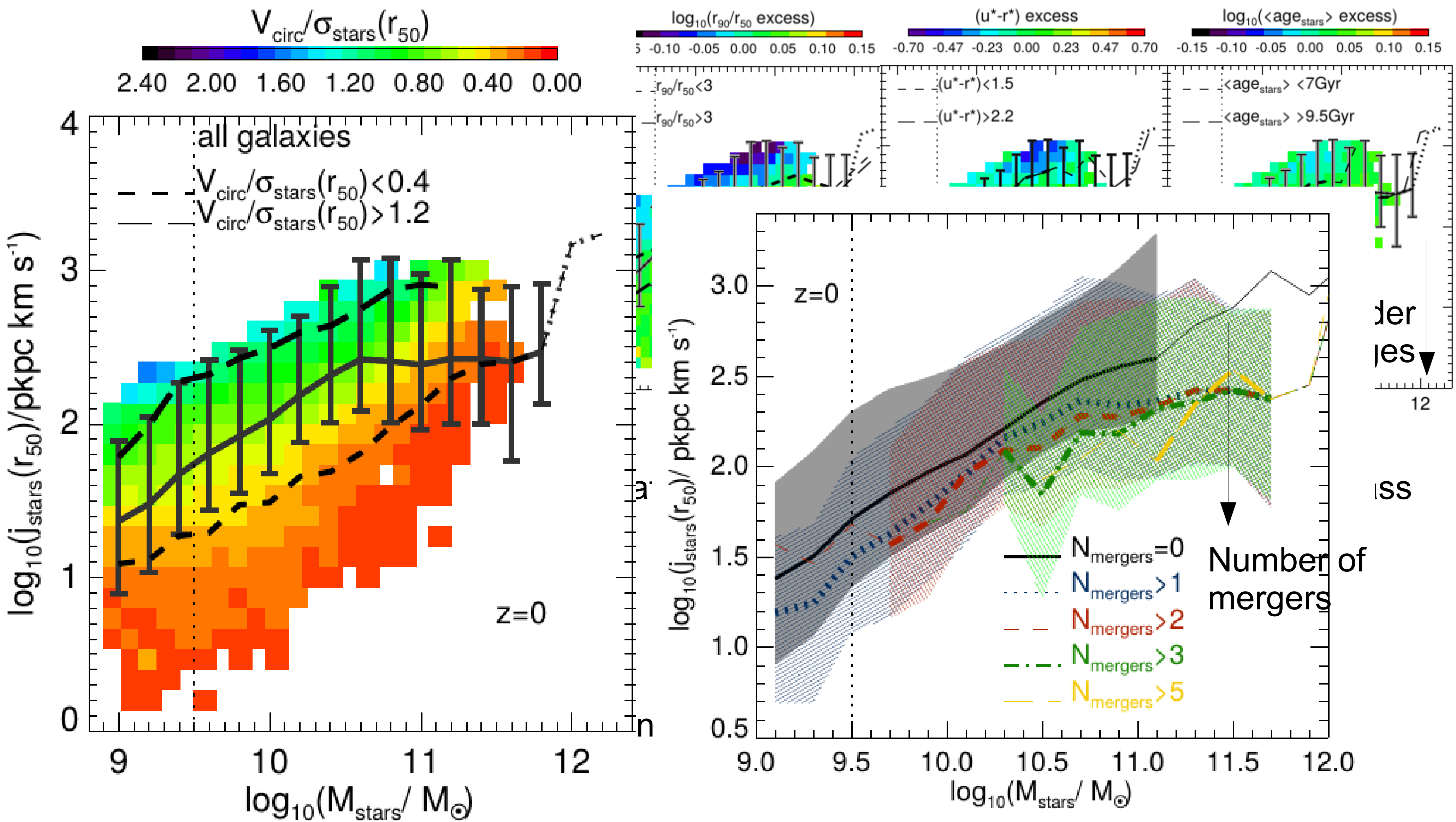
Use EAGLE to:

(3) Connect dynamics to integrated galaxy properties

Lagos et al. (2015b, 2016ab), Bahe et al. (2016), Crain et al. (2016), Marasco et al. (2016), Stevens et al. (2016b), Rahmati et al. (2015,2016)

Angular momentum of galaxies in EAGLE

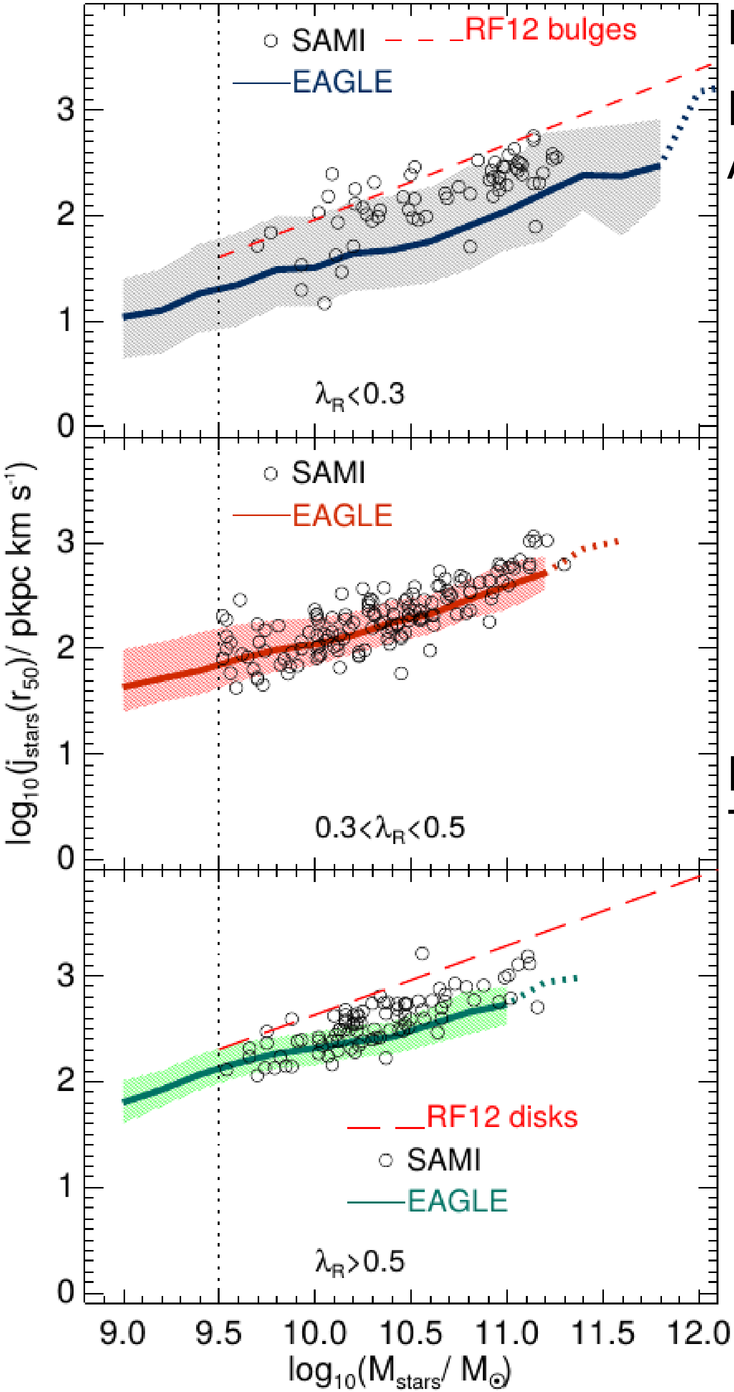
Exhaustive study of j in EAGLE galaxies: **Lagos et al. (2016b)**, Stevens et al. (2016b), Contreras et al. (in prep.), Zavala et al. (2016)



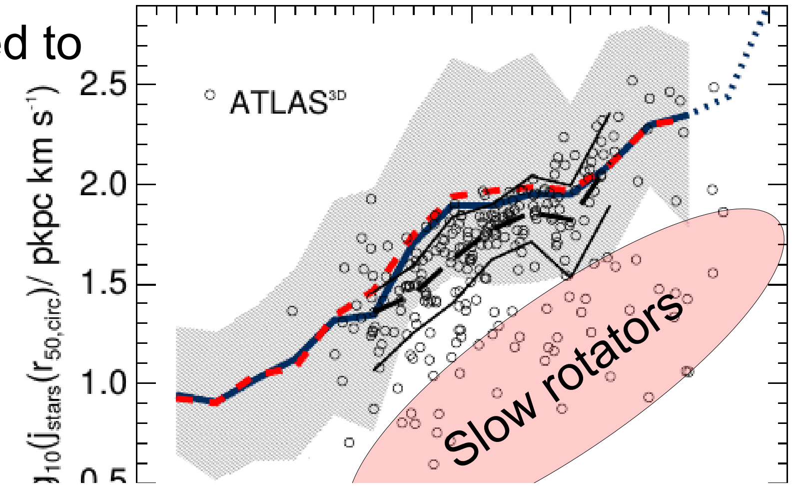
See also Teklu+15, Pedrosa+15, Genel+15

Angular momentum compared to obs.

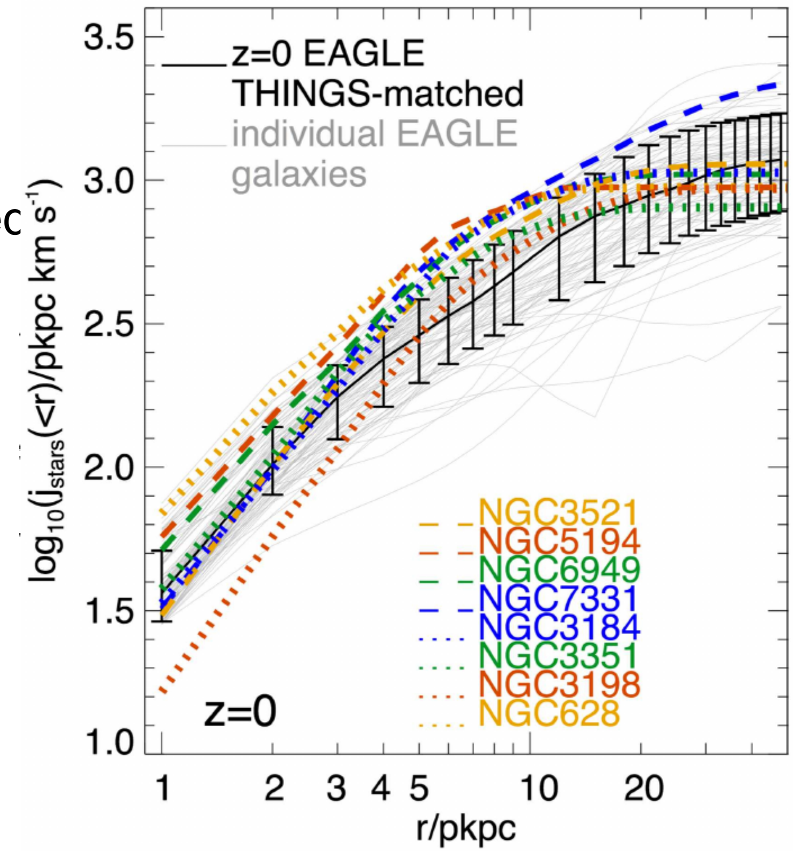
EAGLE compared to SAMI (Cortese+16)



EAGLE compared to ATLAS3D



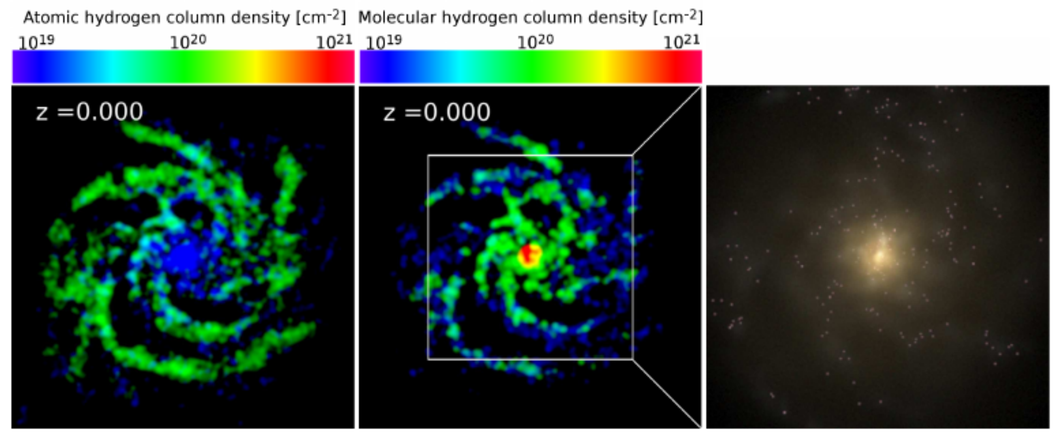
EAGLE compared to THINGS

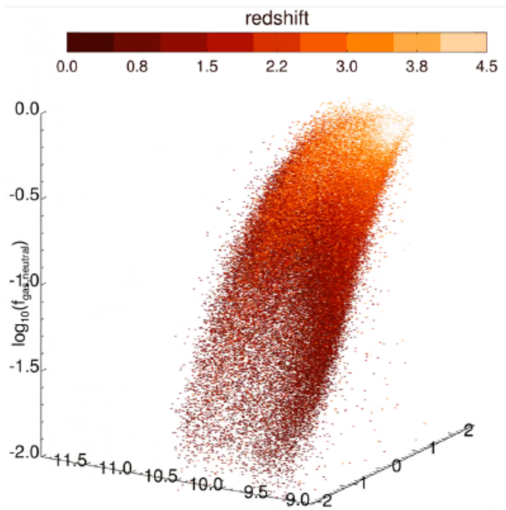


Lagos et al. (in prep.)

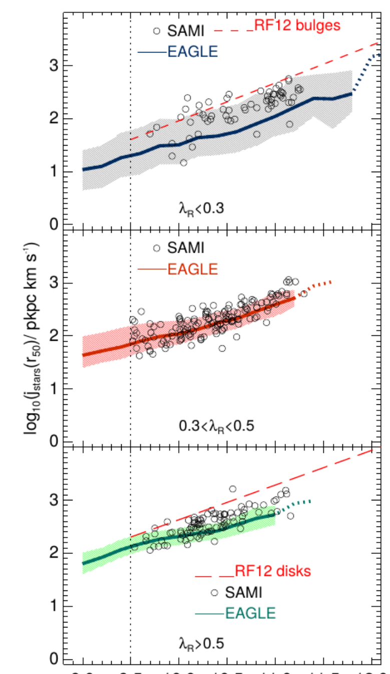
Conclusions

(1) Successfully implemented gas phase transitions in EAGLE in postprocessing: HI/H2 scaling relations mostly agree with observations



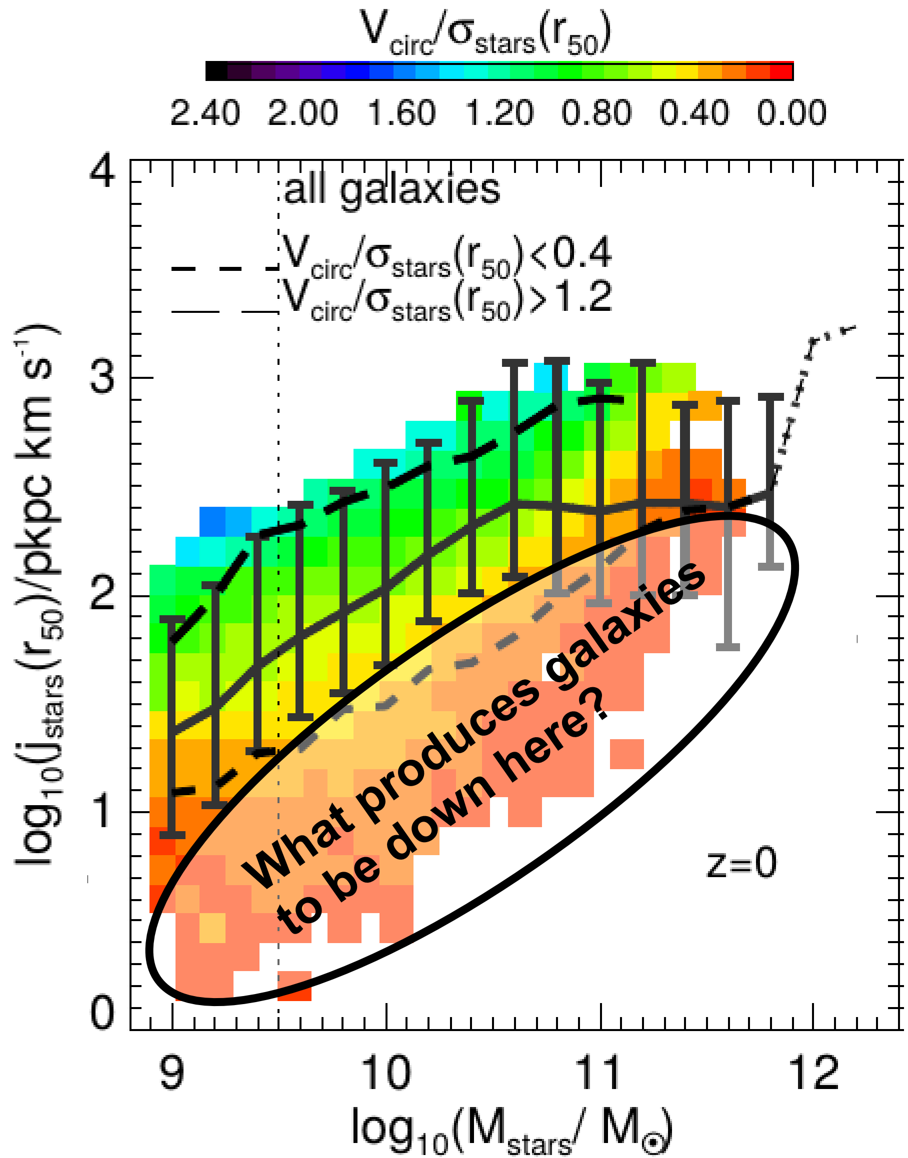


(2) *FPoSF: responsible for most of the variance* seen in the galaxy population in EAGLE. NEUTRAL gas fraction is the relevant quantity (connected to accretion/outflows/SF). Followed by star-forming AND passive galaxies. Physics set by self-regulation and how gas gets converted into stars.



(3) *Angular momentum lower in gas-poor, low V/sigma, highly concentrated, red and old. Great agreement with observations.* Two channels of low jstars: galaxy mergers, and early quenching of star formation, with mergers not only decreasing j, but also changing its distribution.

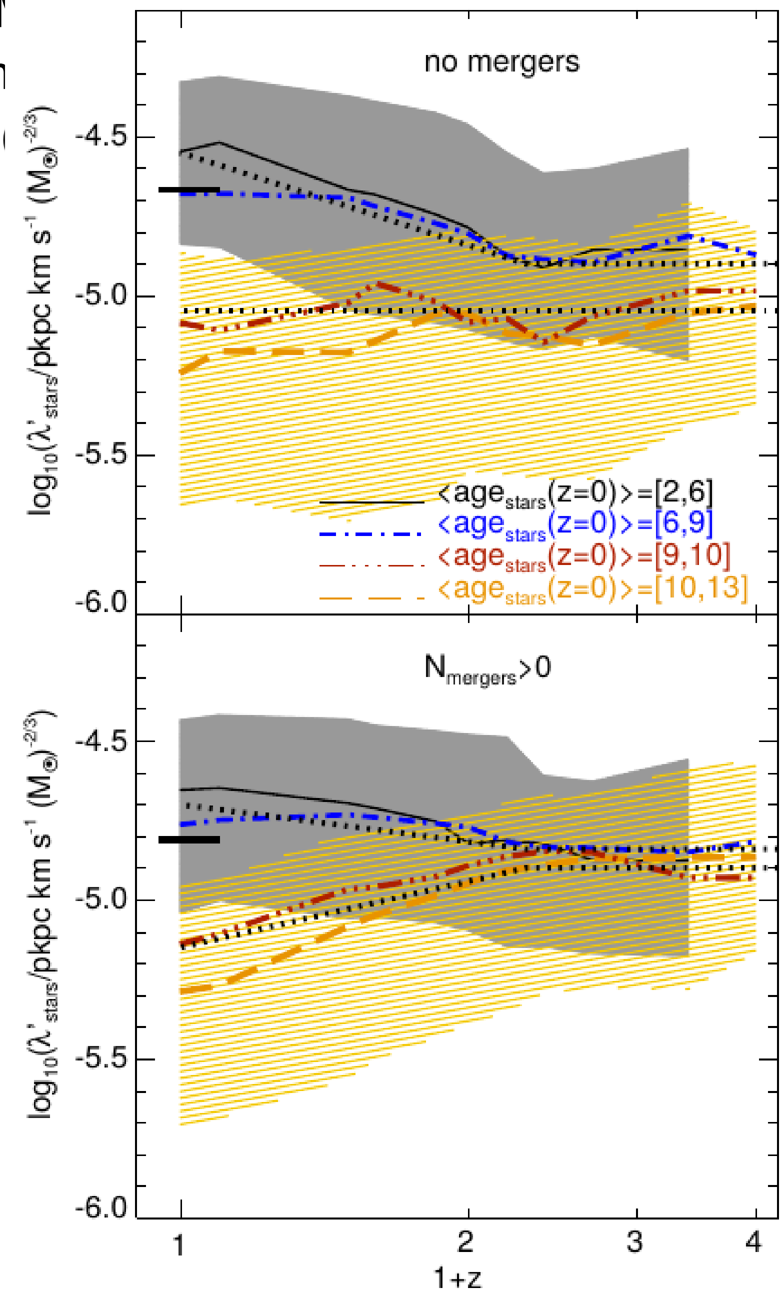
What drives the range of j?



Mergers (Fall+83): main cause of low j in galaxies with M

merger very in

$\lambda'_{\rm stars} \equiv j_{\rm stars}$

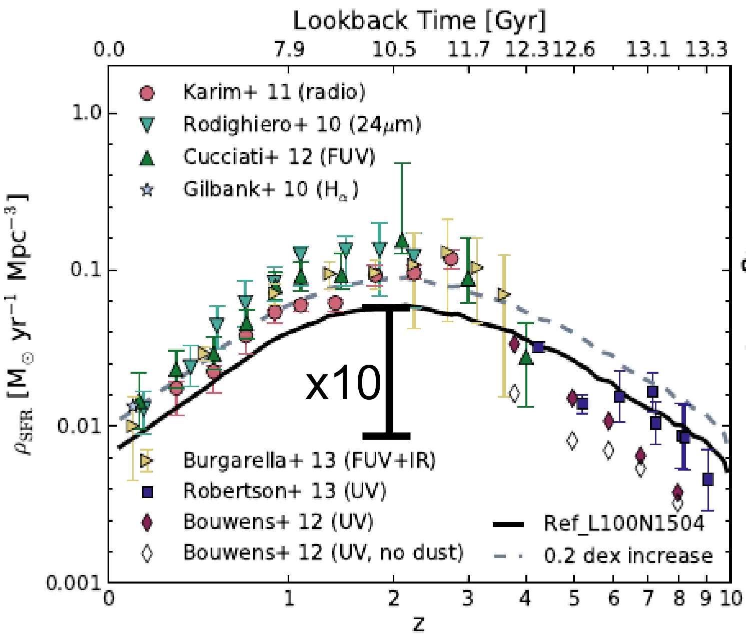


Two channels of low j:
(1) galaxy mergers (but accompanied with quenching)
(2) early quenching of star formation (AGN feedback)

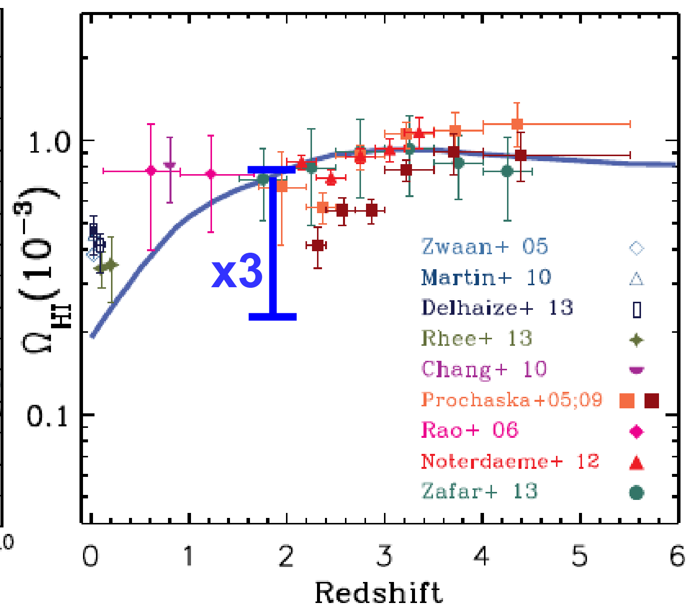
Omega HI and H_2 in the EAGLE simulations

Connecting the SFR evolution with different gas phases...

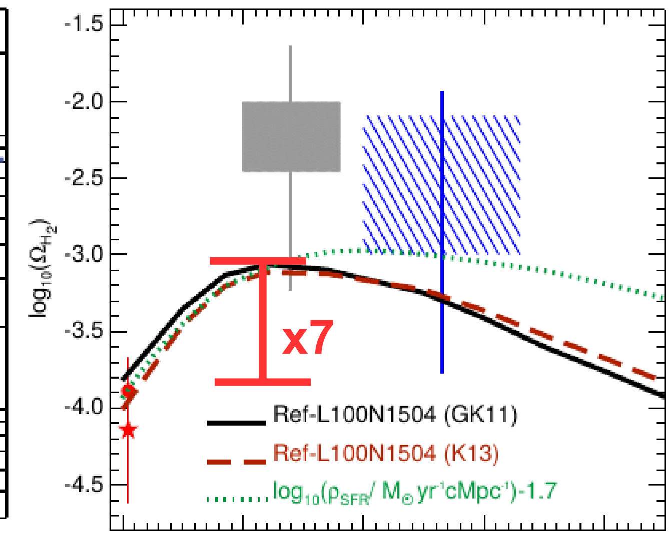
Furlong et al. (2015)

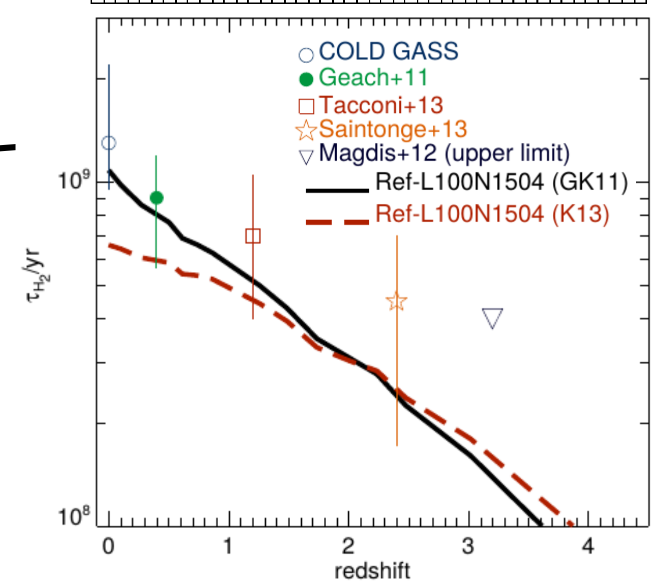


Rahmati et al. (2015)



Lagos et al. (2015b)

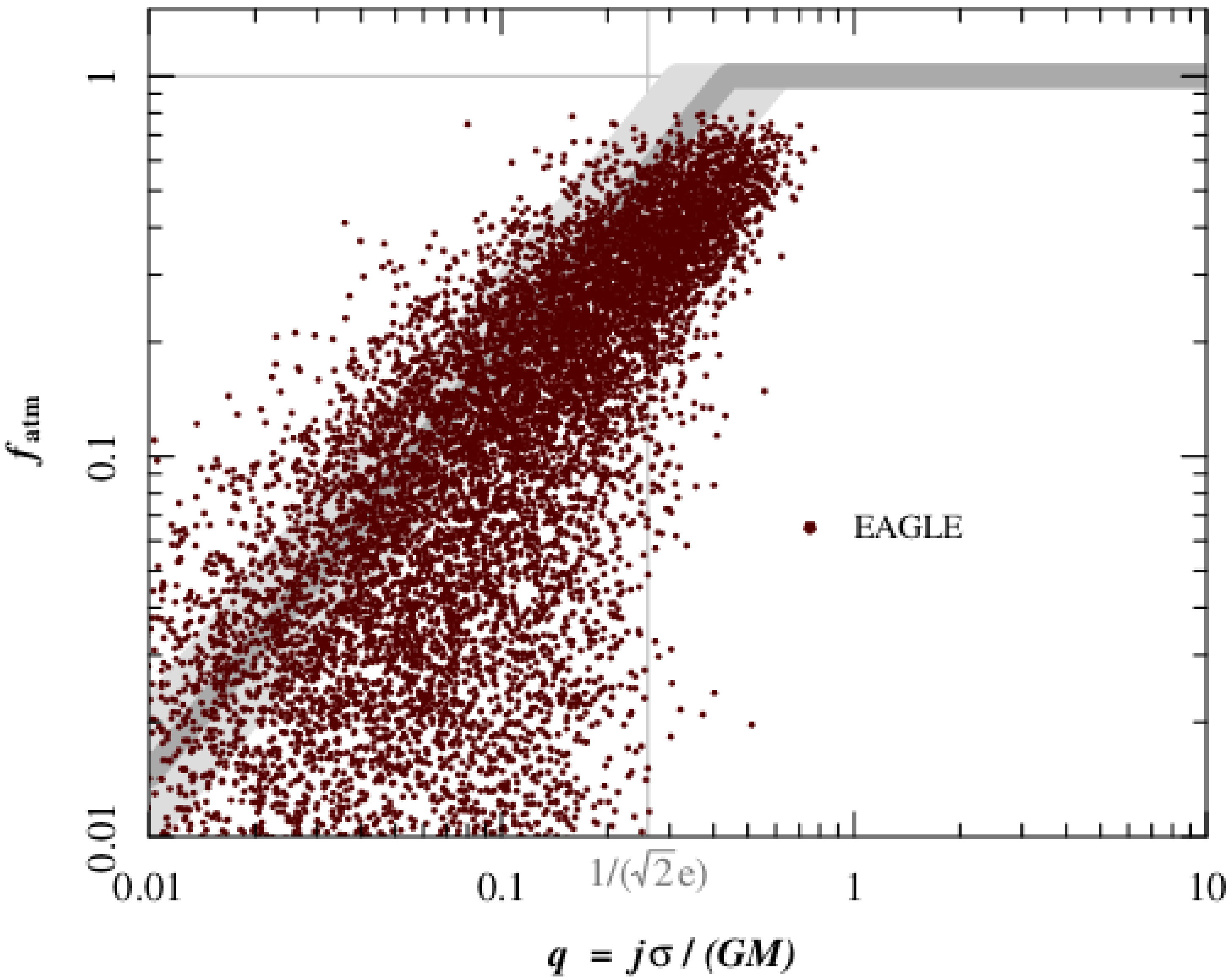




Increase of dense gas content + star formation efficiency (due to the 1.4 power-law index)

Connecting j with galaxy properties

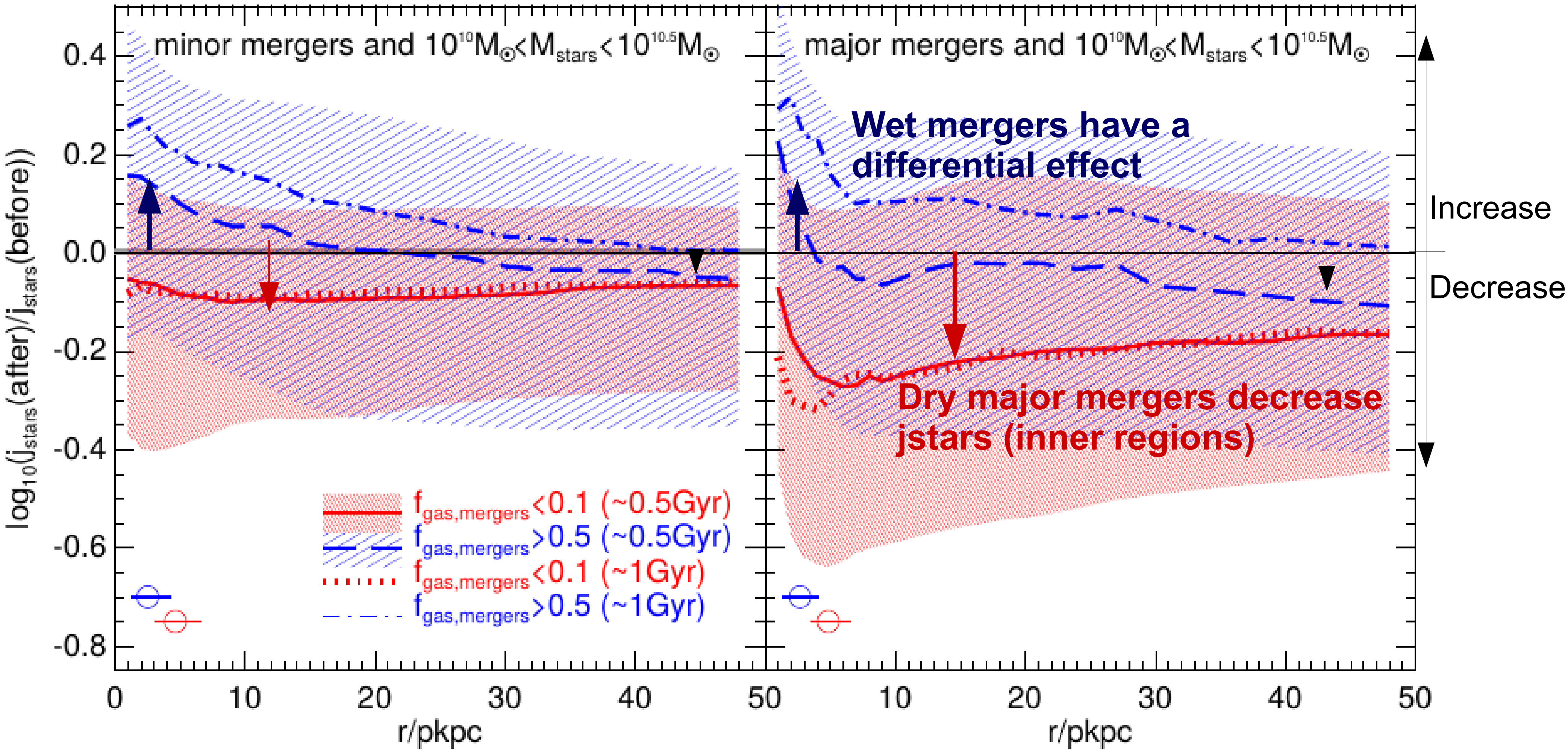
Is j defining the stability and thus the gas fraction of galaxies?



Obreschkow+16

Mergers and their catastrophic effect on j

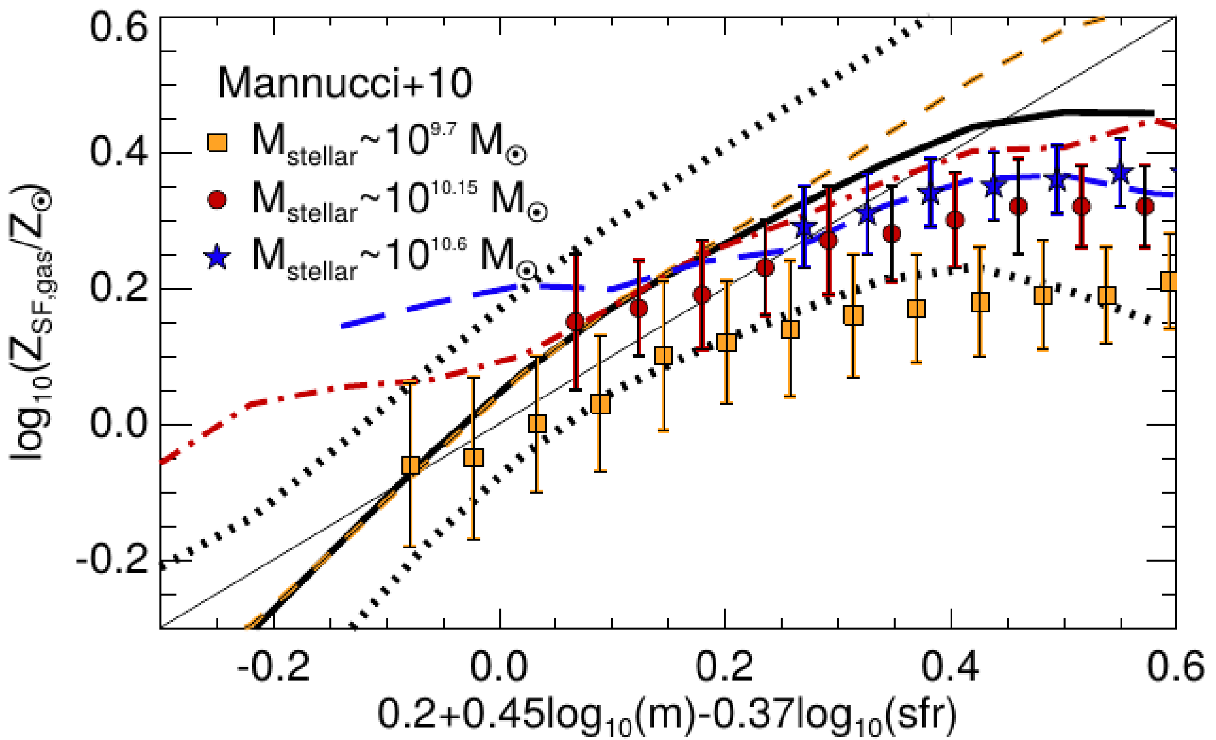
Lagos et al. (in prep.): Very preliminary results

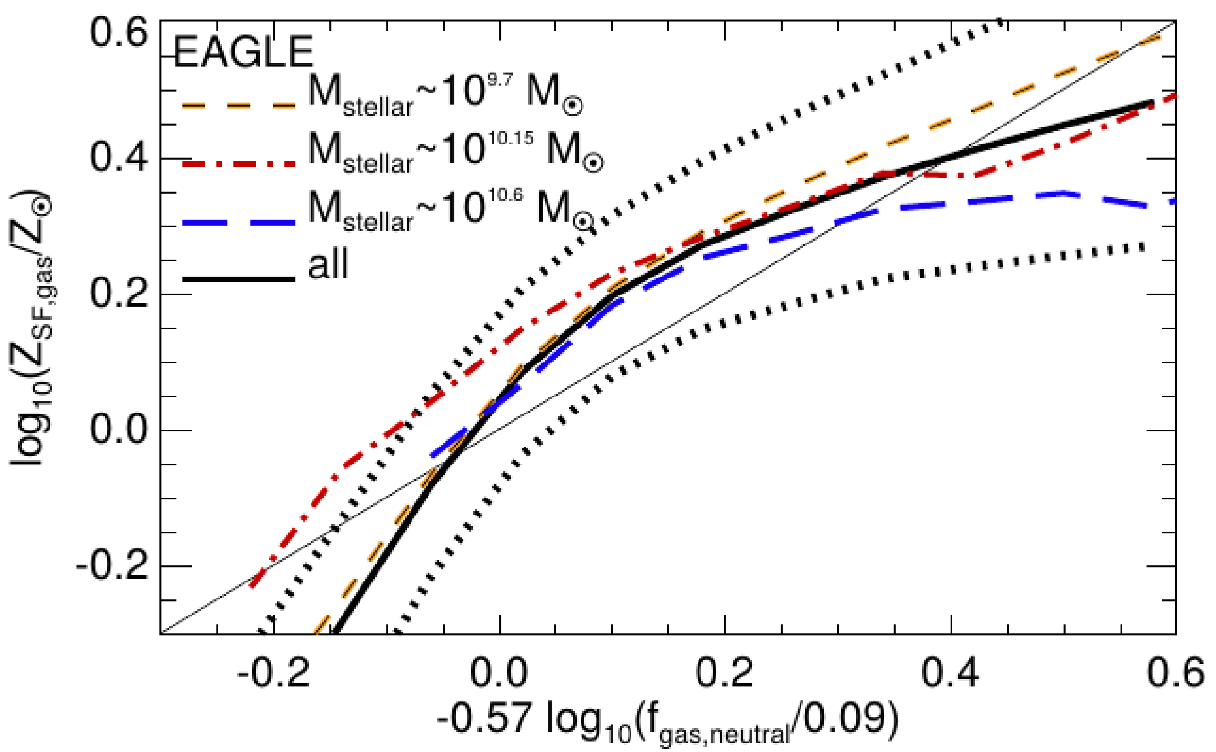


Mergers change the radial distribution of j in galaxies, but not always lead to a decrease in jtot

Metallicity in the FPoSF

Scatter in the MZ relation: strongly correlated with SFR and with neutral gas fraction



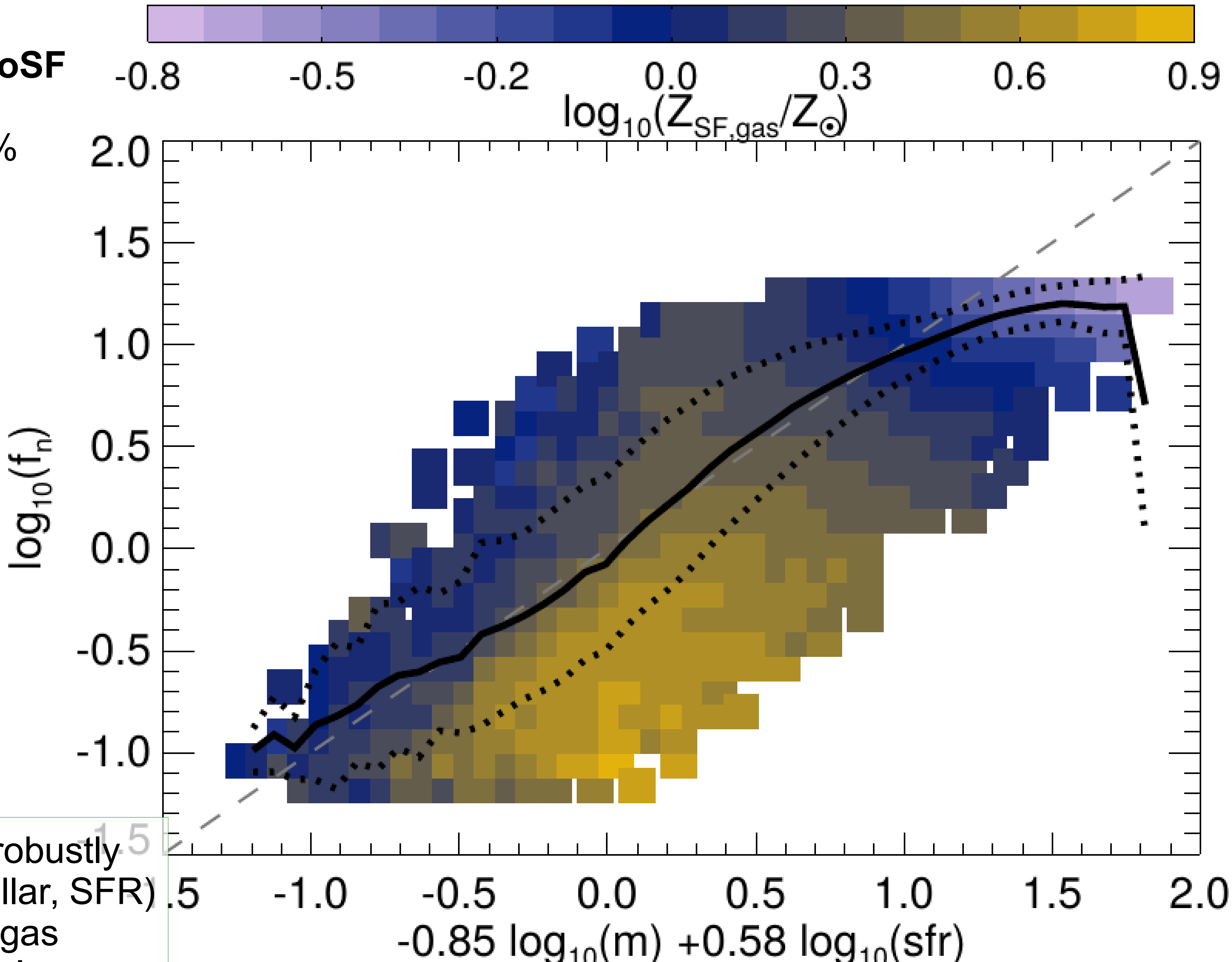


Metallicity can be robustly predicted from (Mstellar, SFR) or from neutral gas fraction alone!

The mass-metallicity relation

Lagos et al. (2016a)
Metallicity in the FpoSF

Contains another 25% of the variance of the galaxy population!

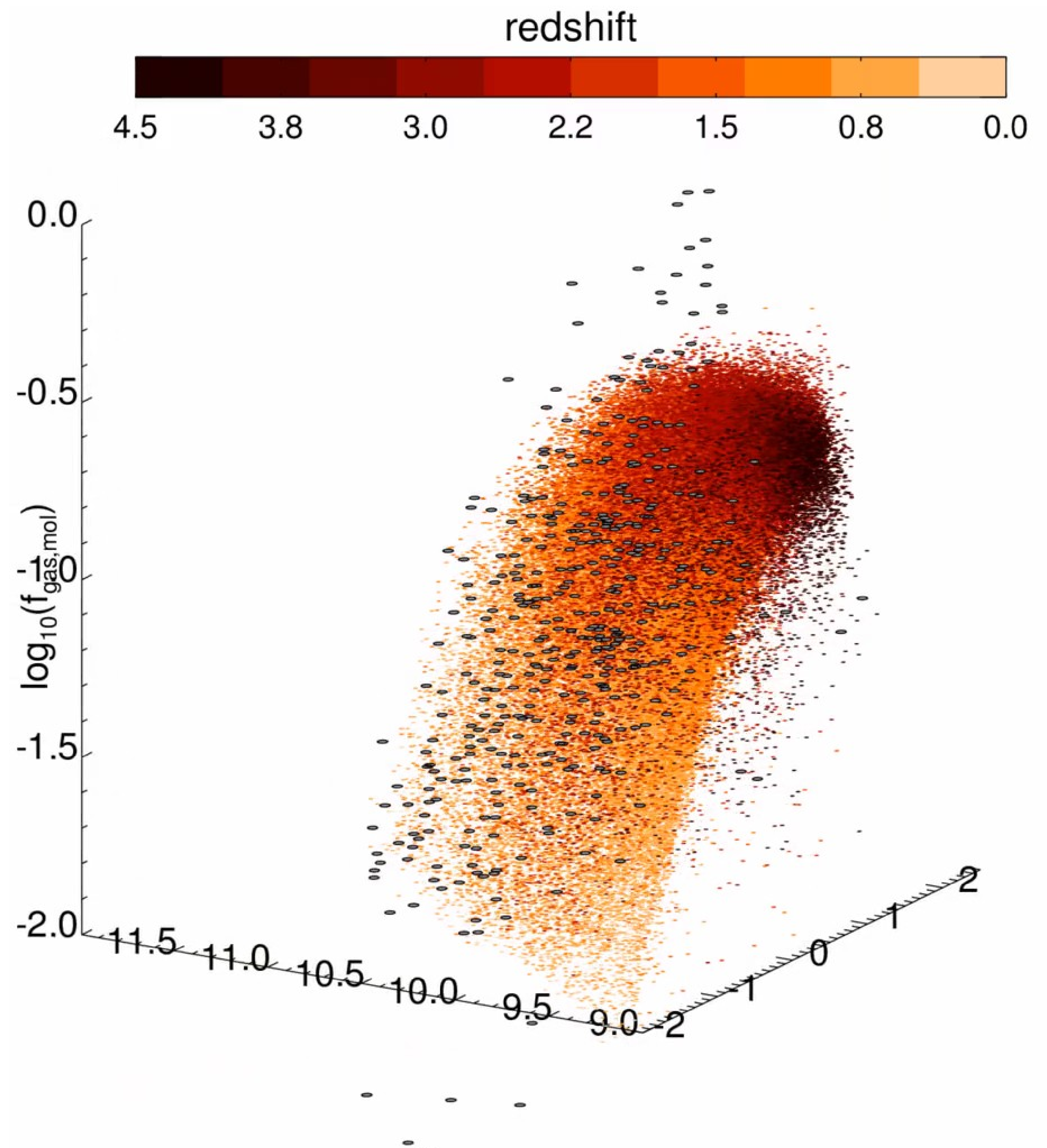


Metallicity can be robustly predicted from (Mstellar, SFR) or from neutral gas fraction alone!

Lagos et al. (2016a)
The Fundamental Plane of Star Formation

Comparison with observations of the molecular hydrogen content of galaxies

ALLSMOG
COLD GASS
HRS
Santini14
ATLAS^{3D}



Note that the FPoSF is followed by active AND passive galaxies!