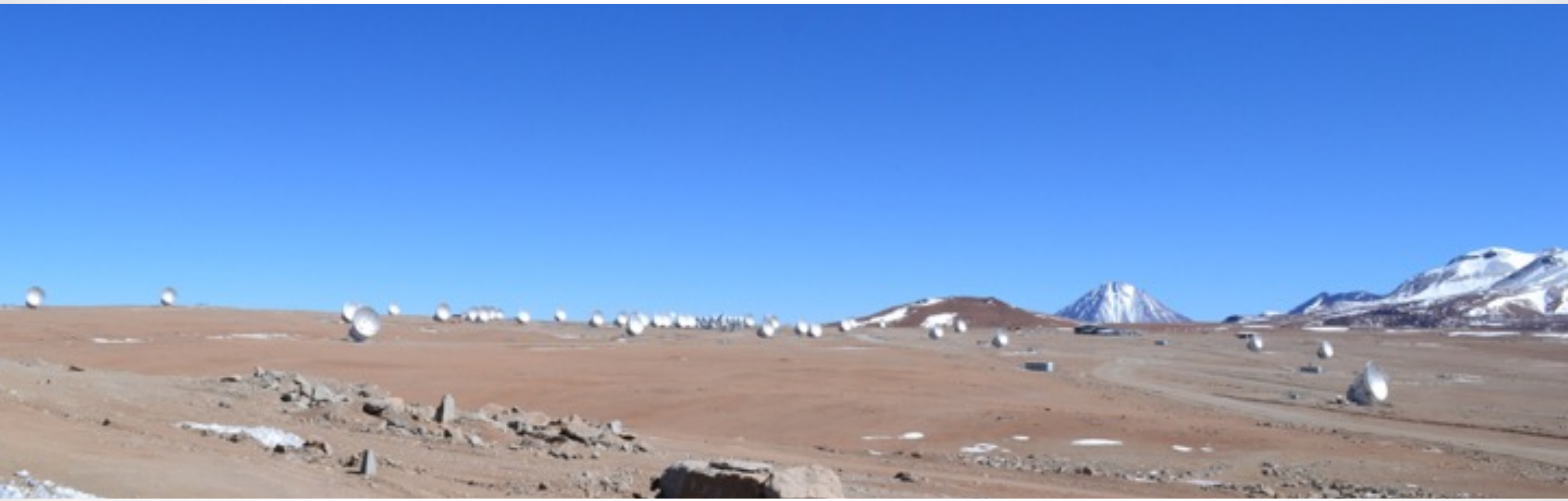
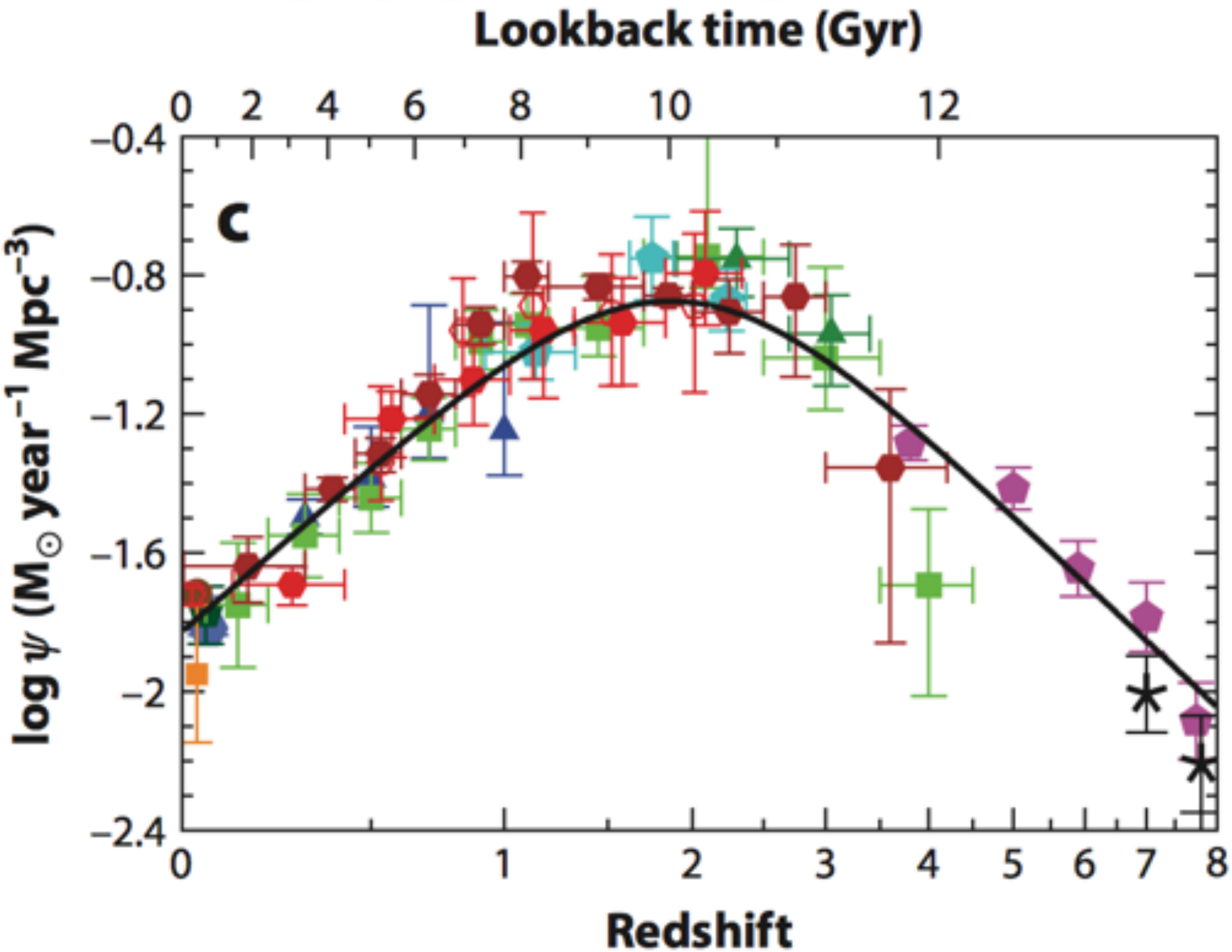
The gas content of galaxies over cosmic time



Gergö Popping (ESO fellow)

R.S. Somerville, P.S. Behroozi, S.C. Trager, K.I. Caputi, E. van Kampen, R. Decarli, M. Spaans, M.S. Peeples

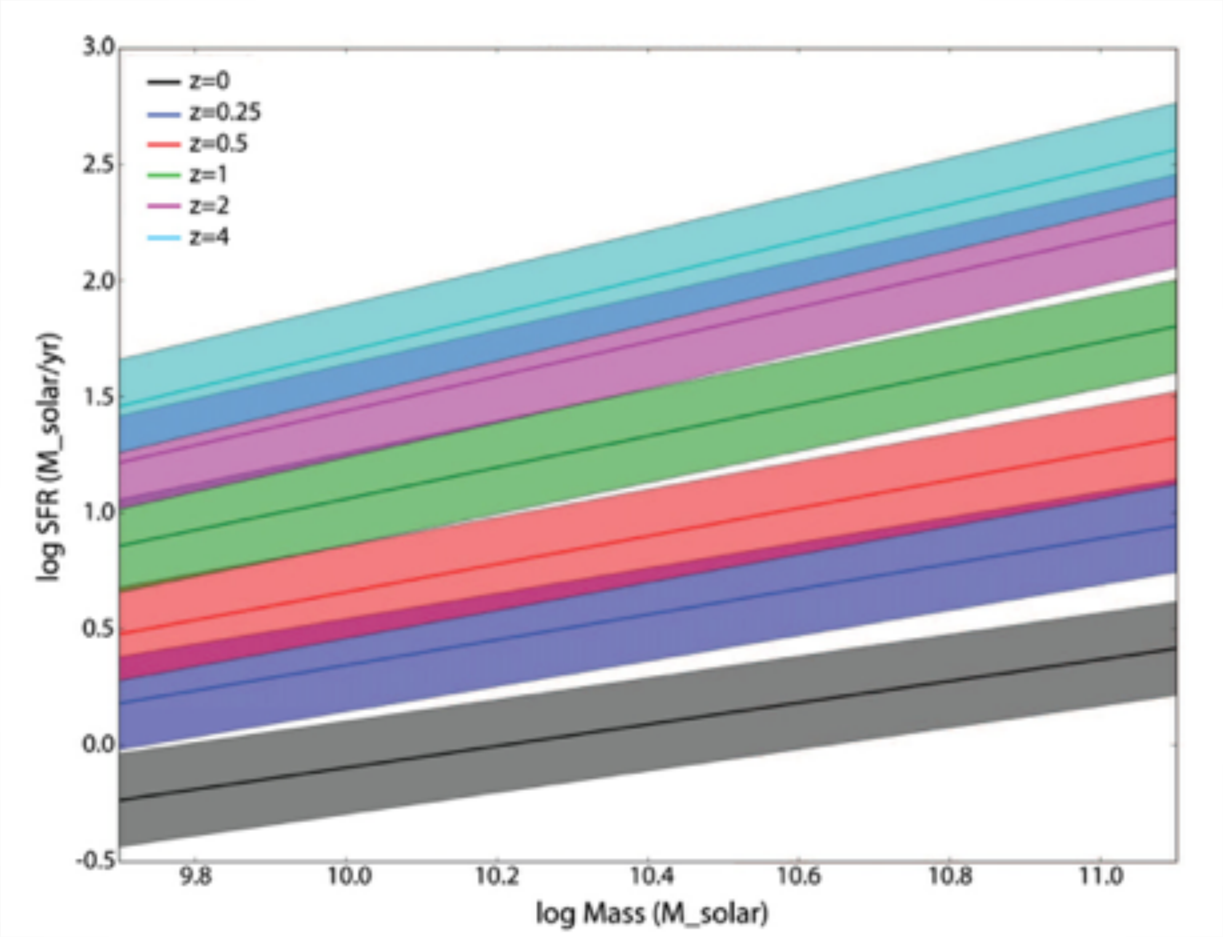
Cosmic SFR



What are the gas properties of galaxies that support this SFR density?

Star formation

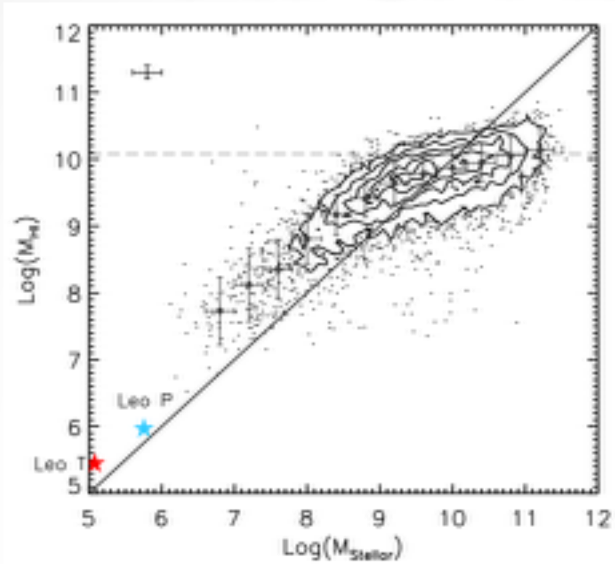
SFR

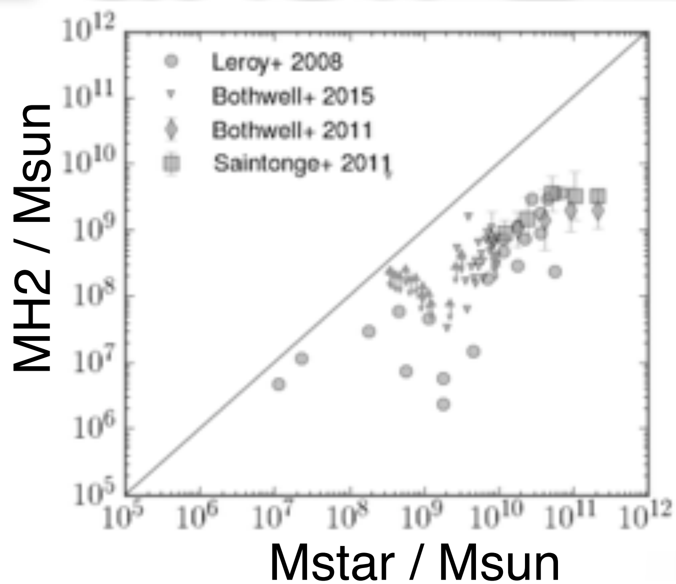


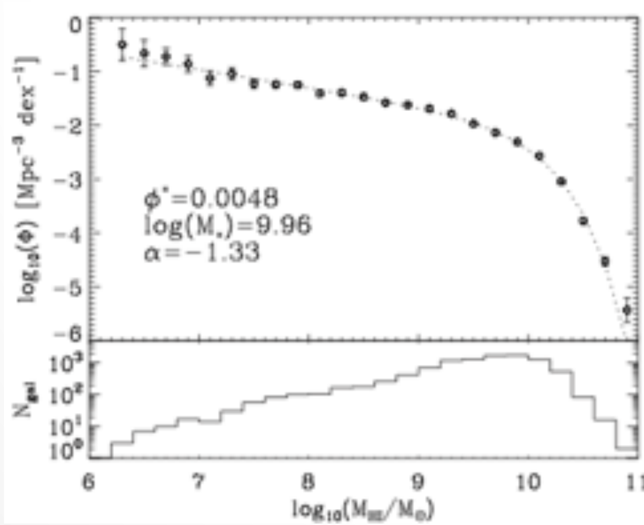
Stellar mass

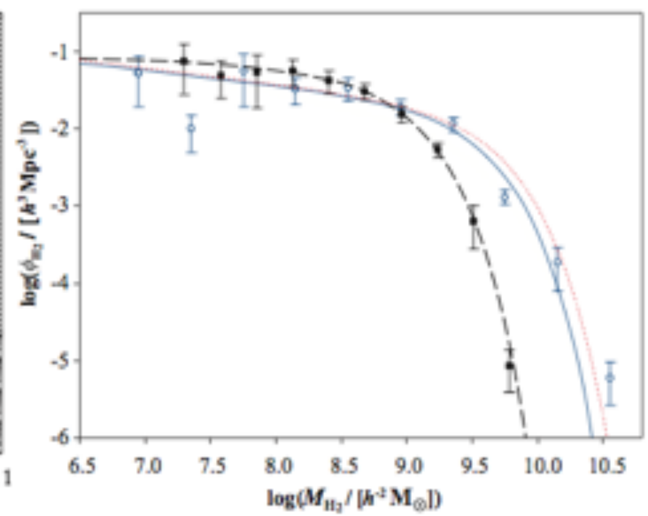
What are the gas properties of galaxies that support this behaviour?

HI & H2 at low-z



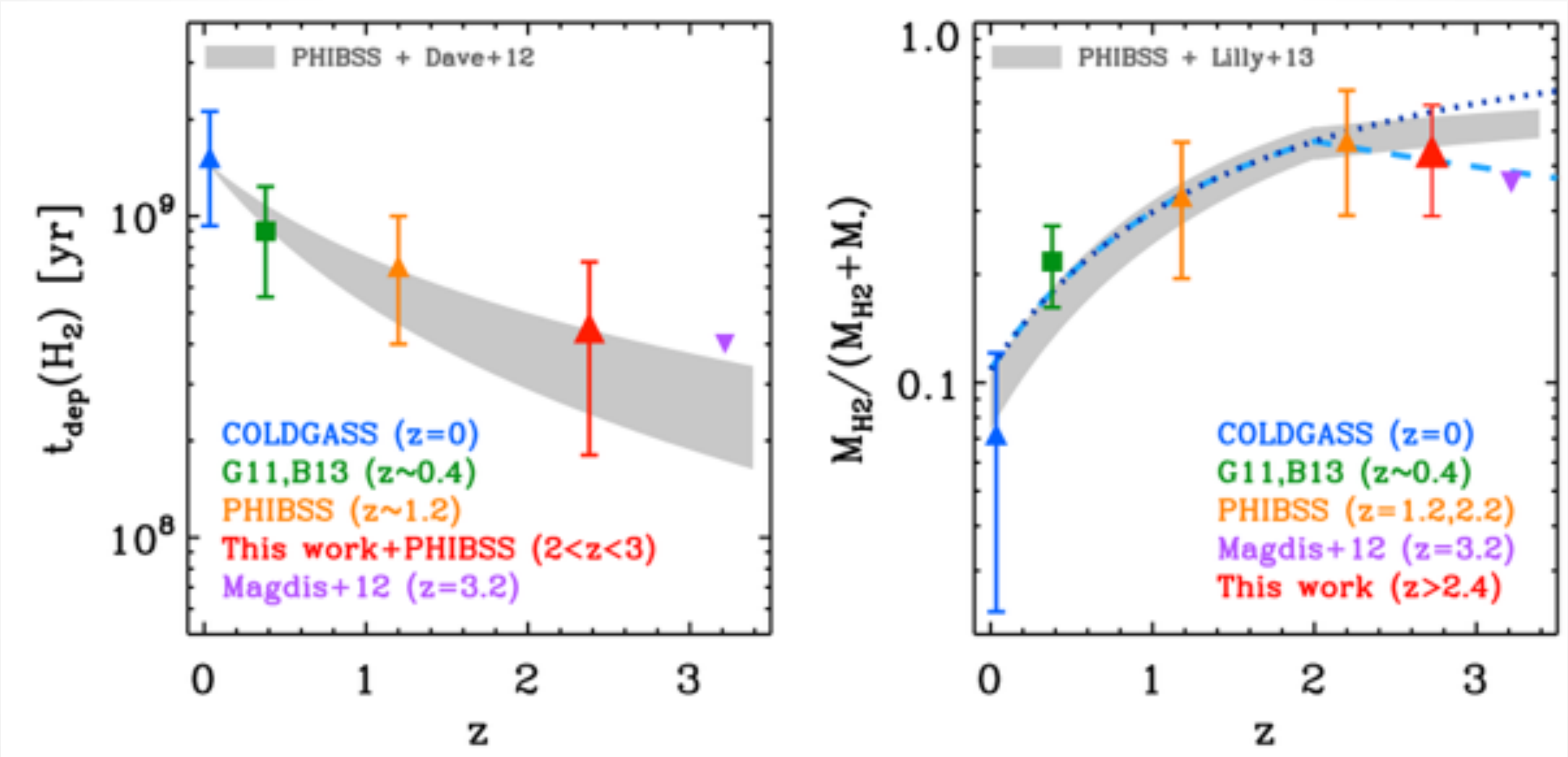






ALFALFA, Maddox et al. 2015, Compilation of COLD GASS, HERACLES, ALLSMOG, Martin 2010, Zwaan 2005, Keres 2003, Obreschkow 2009

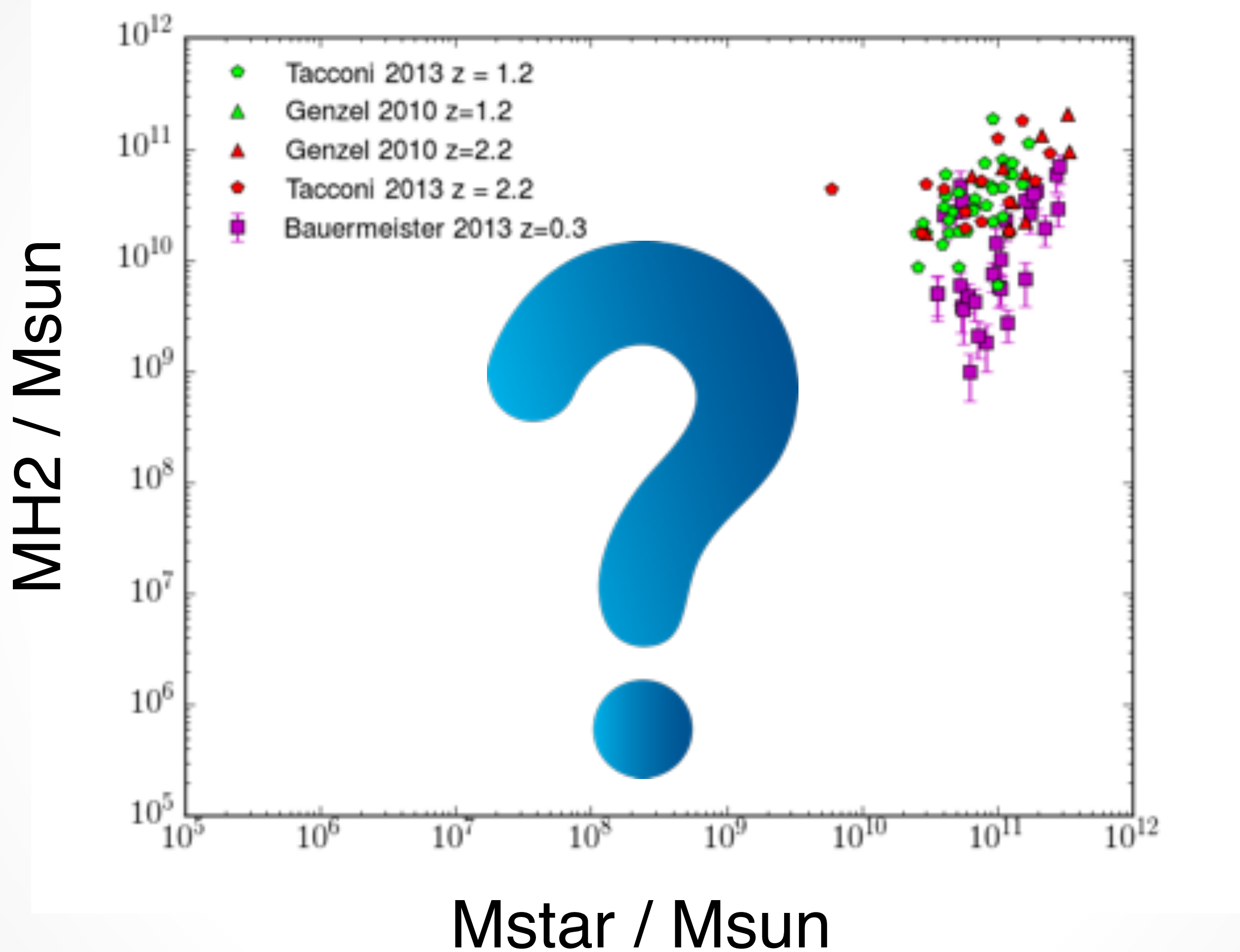
Gas properties of galaxies at z>0



Gas fractions in high-z galaxies are higher; Depletion times are shorter

Tacconi+2010, Magdis+2012,Saintonge+2013, Tacconi+2013, Bethermin+2015, Scoville+2014, 2016

What have we observed?



We have only probed a small region of parameter space

Compilation from Genzel 2010, Bauermeister 2013, Tacconi 2013

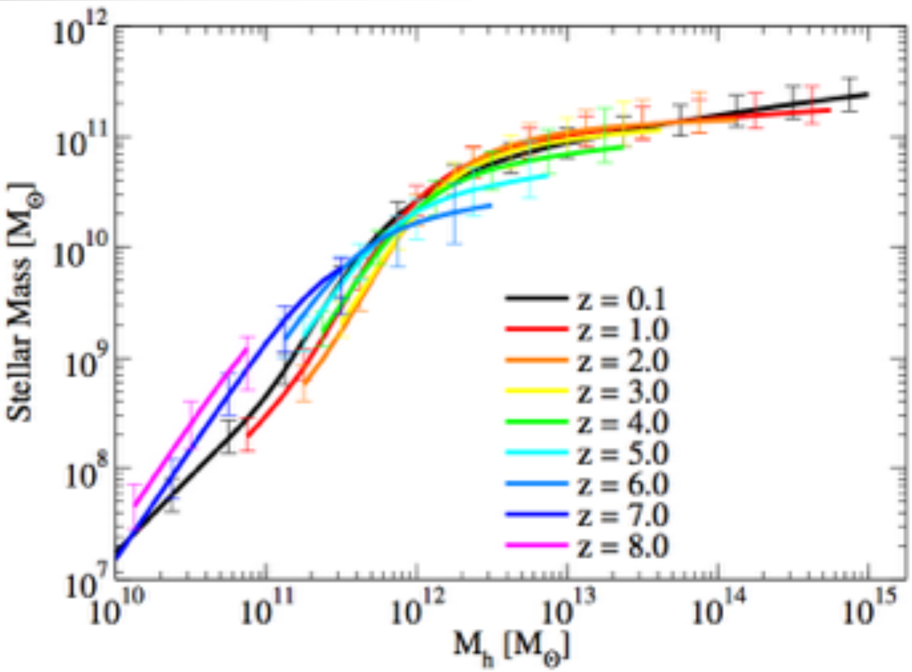
Newest generation of radio and sub-mm instruments

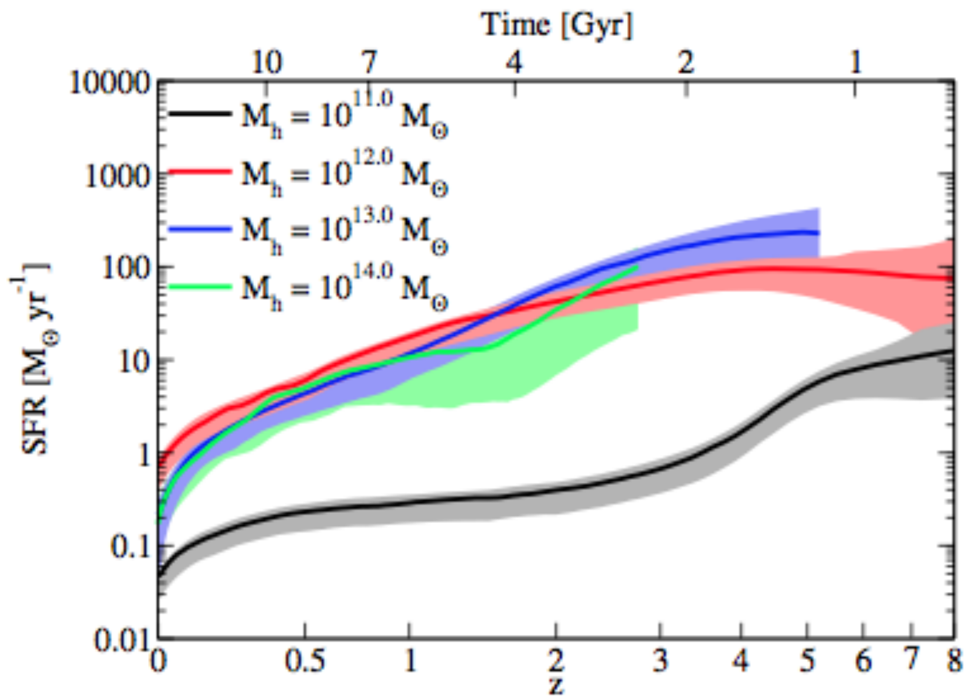
New facilities will provide huge amounts of information on multiphase gas in galaxies over cosmic time

Gergö Popping

gpopping@eso.org

Abundance matching

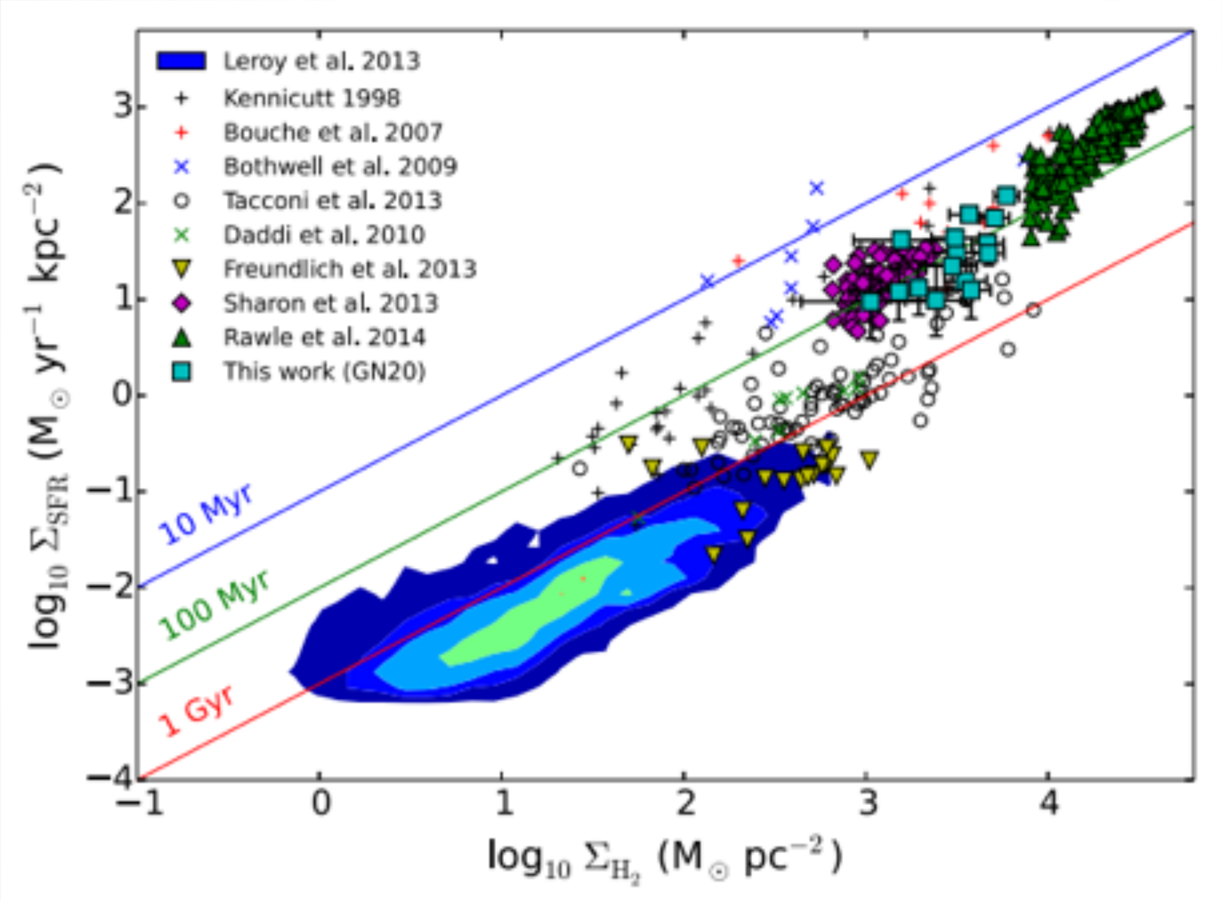




Observationally driven model for stellar mass and SFR as a function of halo mass and redshift

Behroozi et al. 2013a, 2013b

H_2 based star-formation relation

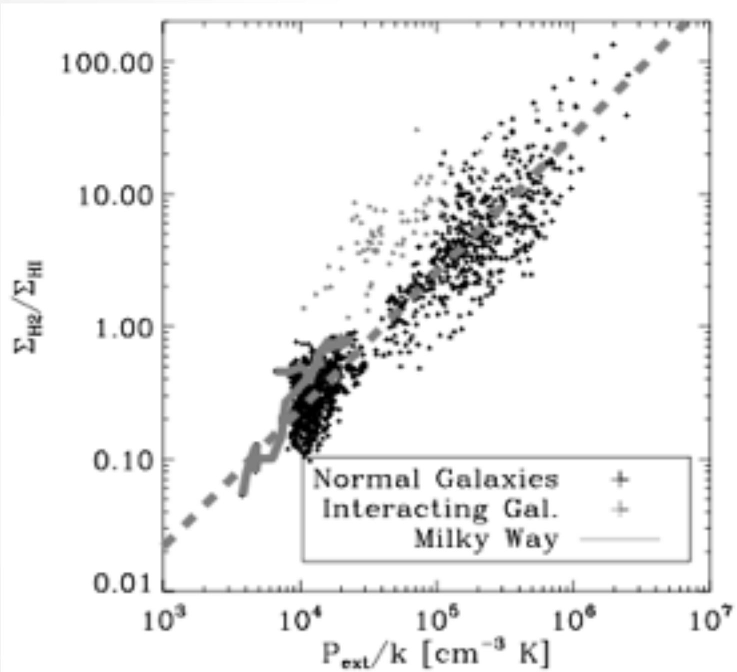


$$\Sigma_{\rm SFR} = \frac{A_{\rm SF}}{10}(1 + \frac{\Sigma_{\rm gas}}{\Sigma_{\rm crit}})^{N_{\rm SF}} f_{H2} \Sigma_{\rm gas}$$

Hodge+2015, Bigiel+ 2008, Leroy+2008, Bigiel 2012

Calculating H2 fractions

Pressure based (BR)



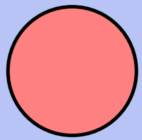
$$R_{H_2} = \left(\frac{\Sigma_{H_2}}{\Sigma_{H\,I}}\right) = \left(\frac{P_m}{P_0}\right)^{\alpha}$$

$$P_m \sim \frac{\pi}{2} G \Sigma_{gas} \left(\Sigma_{gas} + \Sigma_* \frac{\sigma_{gas}}{\sigma_*}\right)$$

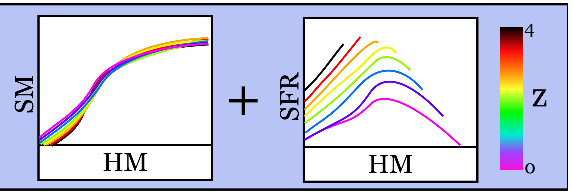
Molecular hydrogen fraction as a function of mid-plane pressure

How to calculate gas masses?

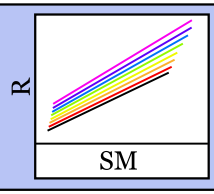
1. Pick a halo from the simulation, which will have a halo mass (HM) and redshift (z).



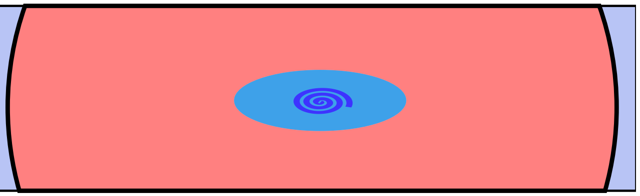
2. Assign a galaxy stellar mass and SFR to halo using relations in Behroozi et al. (2013).



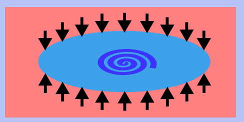
3. Use size-stellar mass relation in van der Wel et al. (2014), scaled by 2.6, to assign gas disc size.



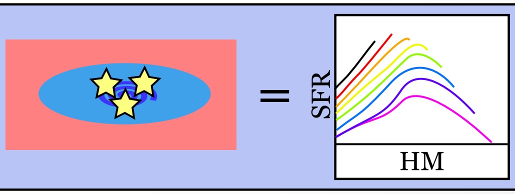
4. Assuming that the gas+stars are distributed exponentially, choose a total cold gas mass.



5. The mass gives a midplane pressure, setting the HI/H_2 fraction (Blitz & Rosolowsky 2006). The H_2 density implies an SFR (Bigiel et al. 2008).

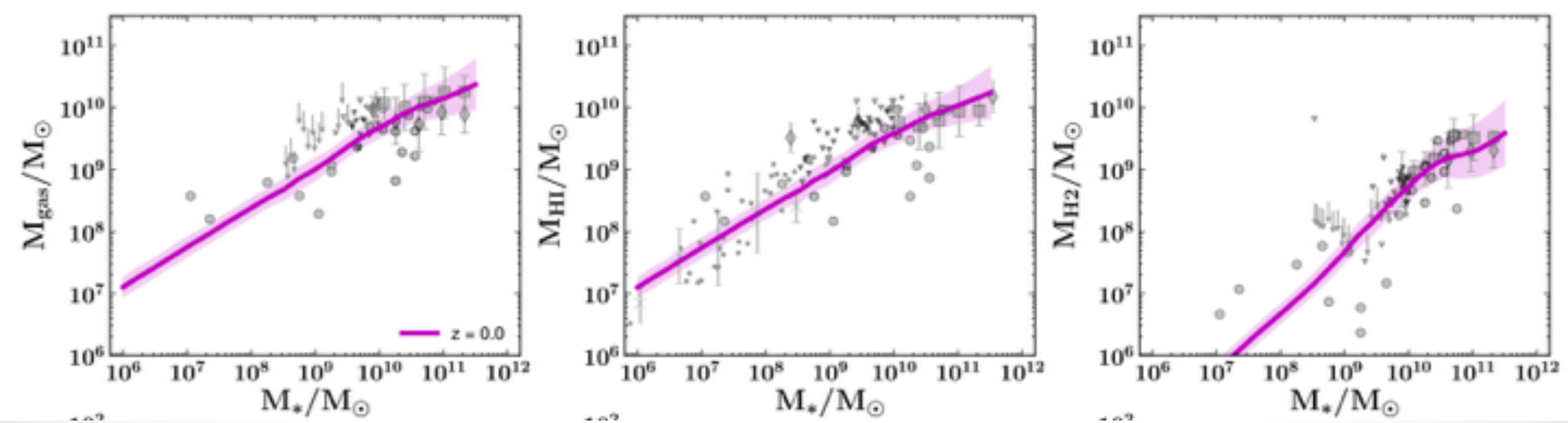


6. Compare implied SFR with Behroozi et al. (2013); keep iterating gas masses until the two SFRs match.



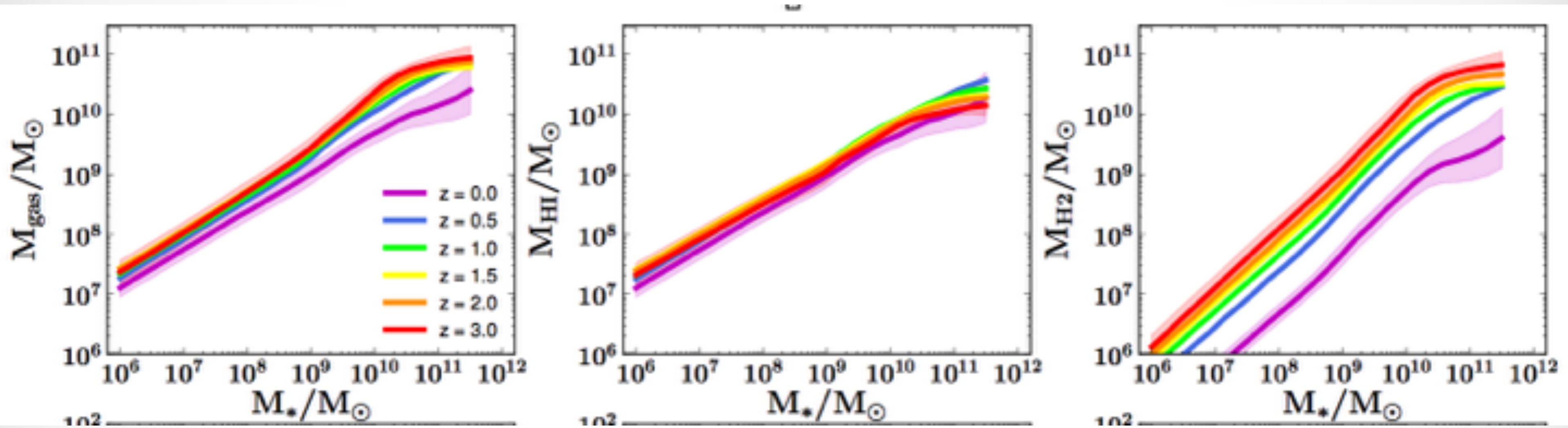
Popping, Behroozi, and Peeples 2015

SHAM + inferred gas masses



Inferring the gas, H2, and HI mass of galaxies with abundance matching

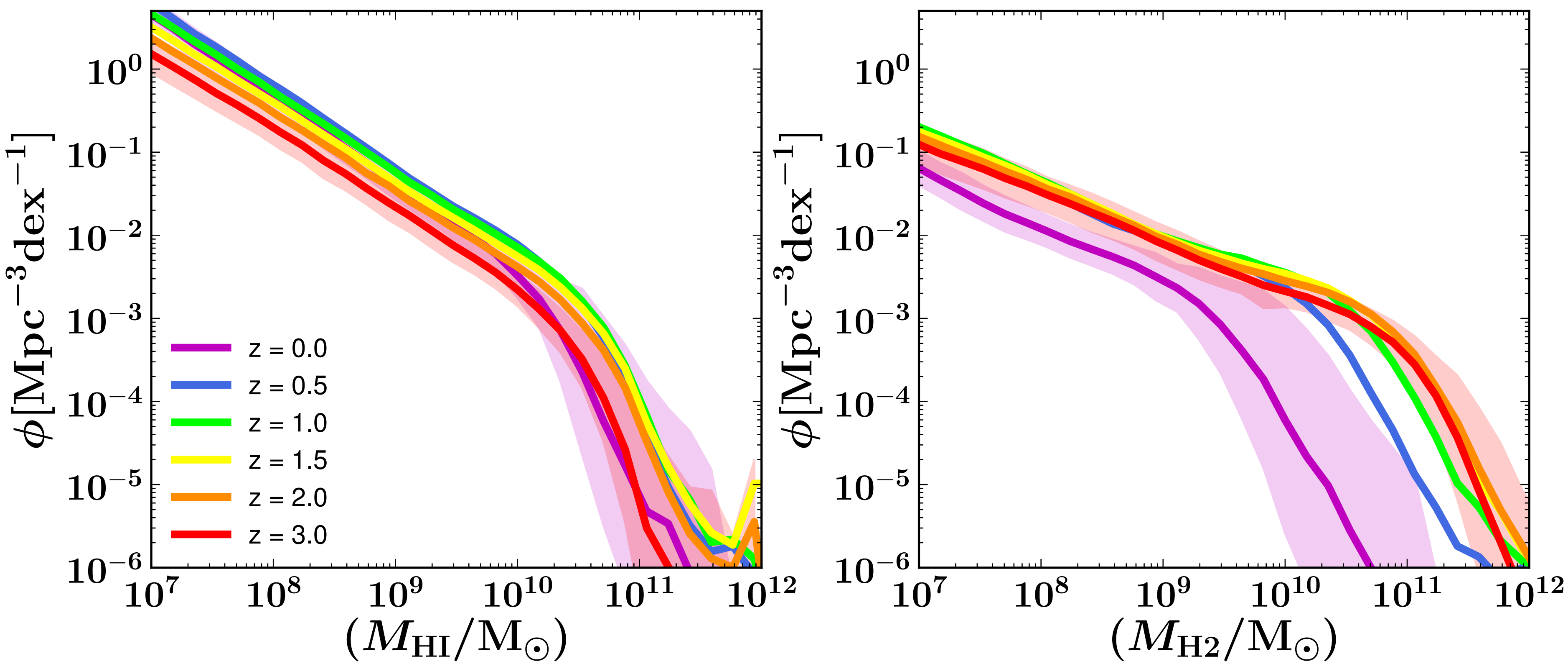
SHAM + inferred gas masses



Some evolution in Mgas, little evolution in HI, strong evolution in H2

Popping, Behroozi, and Peeples 2015

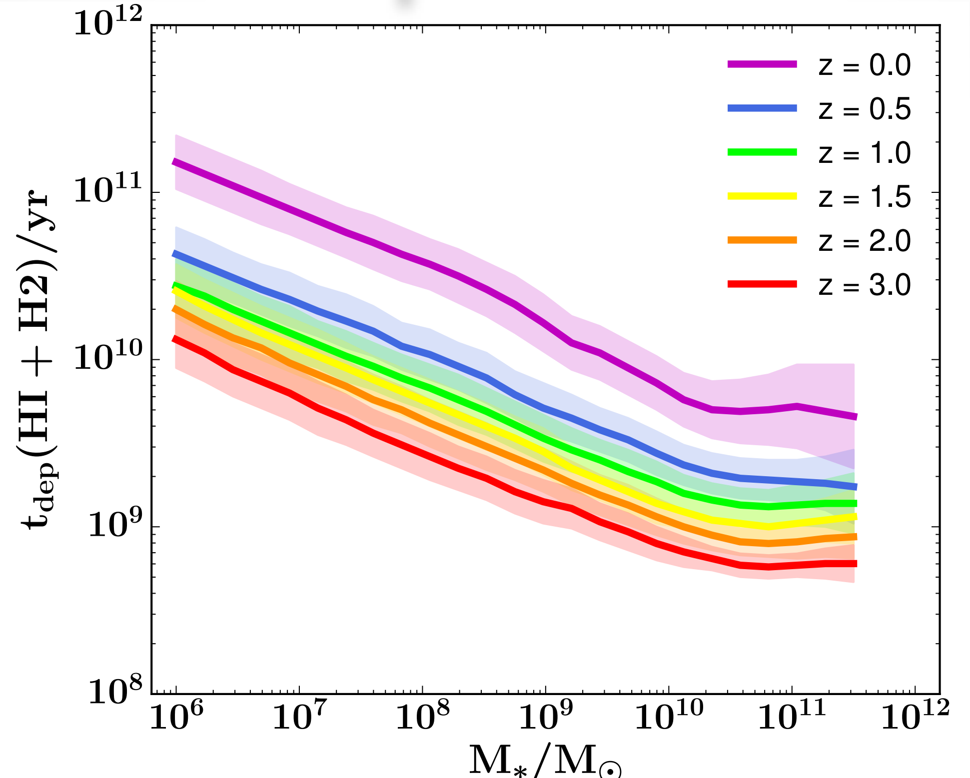
SHAM + inferred gas masses



Little evolution in HI mass function, strong evolution in H2 mass function

Popping, Behroozi, and Peeples 2015

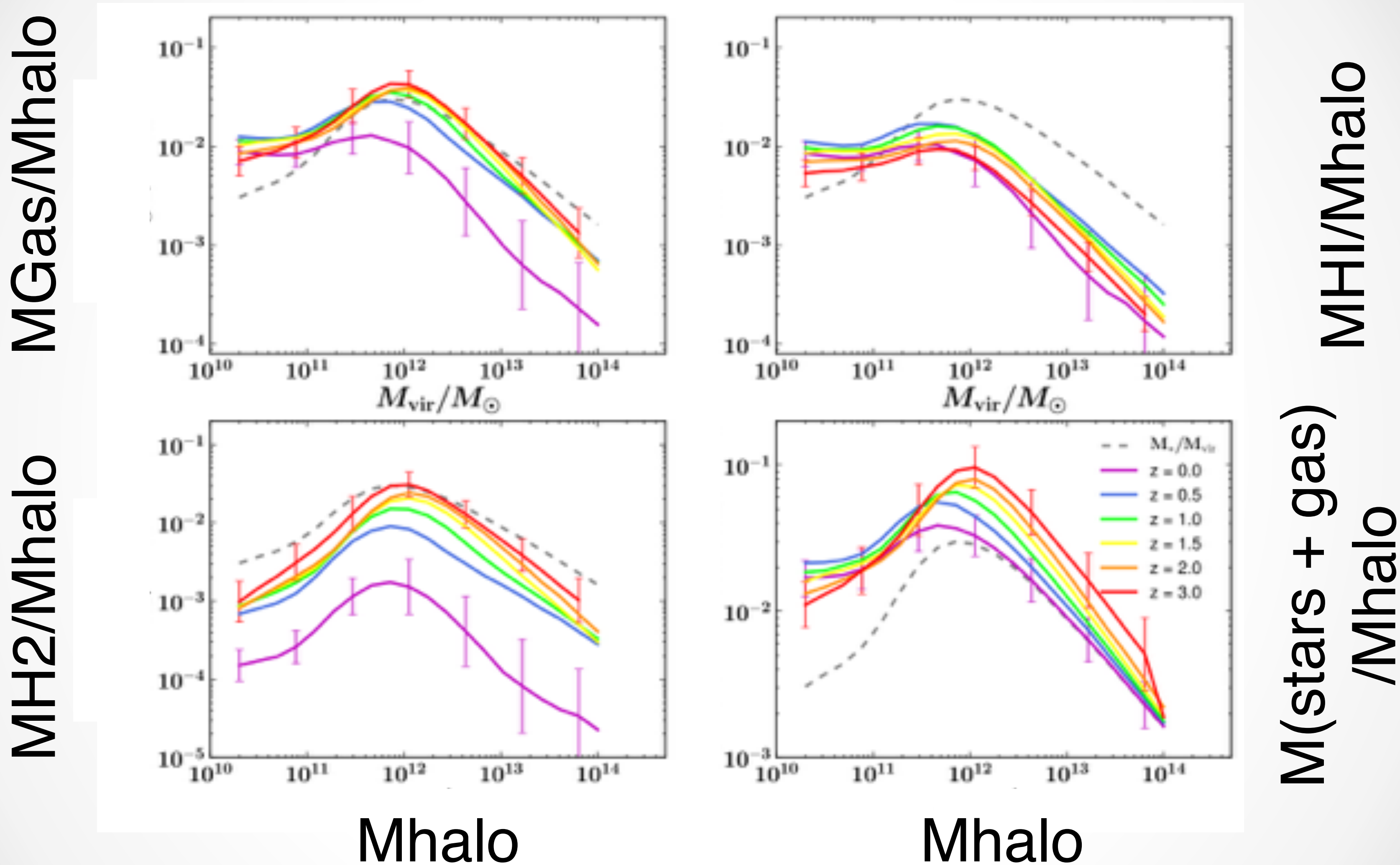
Gas depletion time



Depletion time increases with redshift and decreases with stellar mass

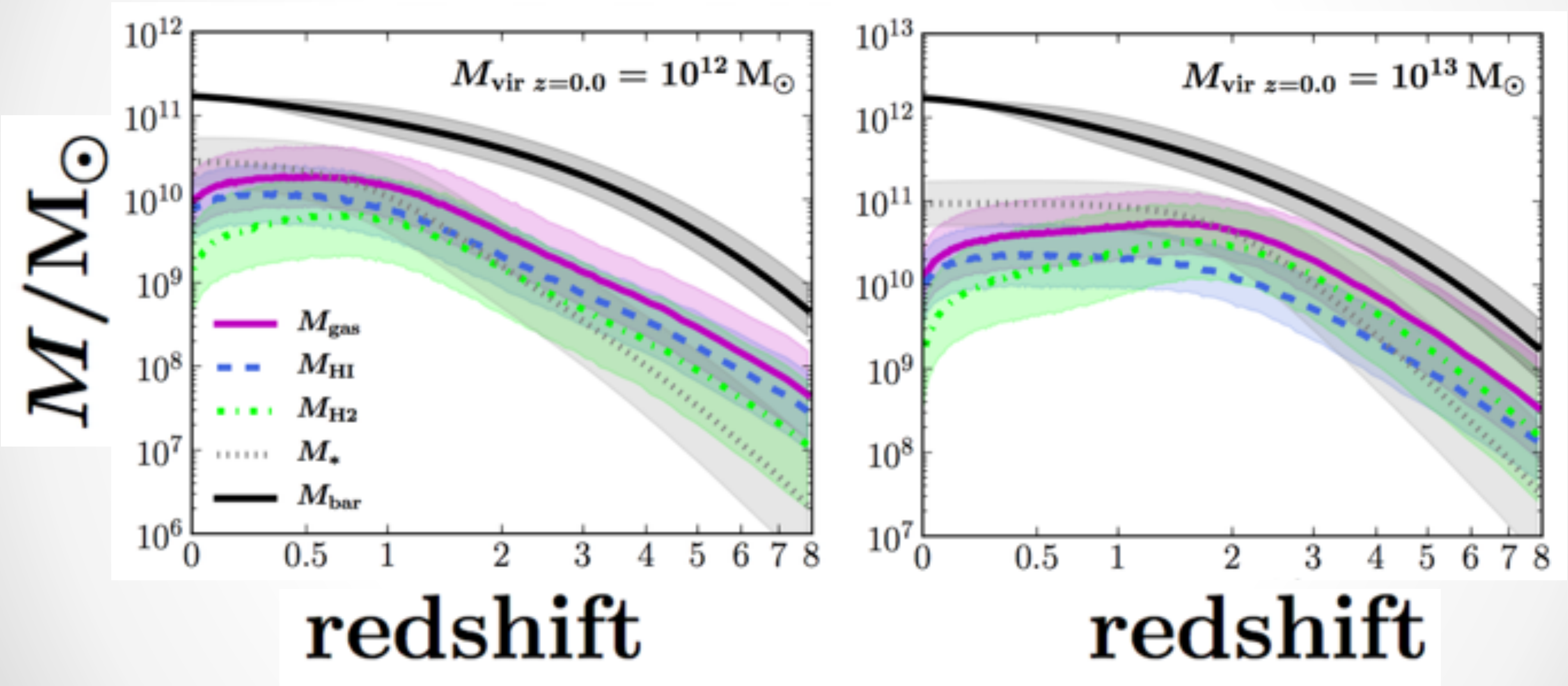
Especially big difference between z=0 & z>= 1

Gas evolution in DM haloes



Gas masses as a function of dark matter halo mass

Gas evolution in DM haloes



The inferred evolution of gas in individual galaxies

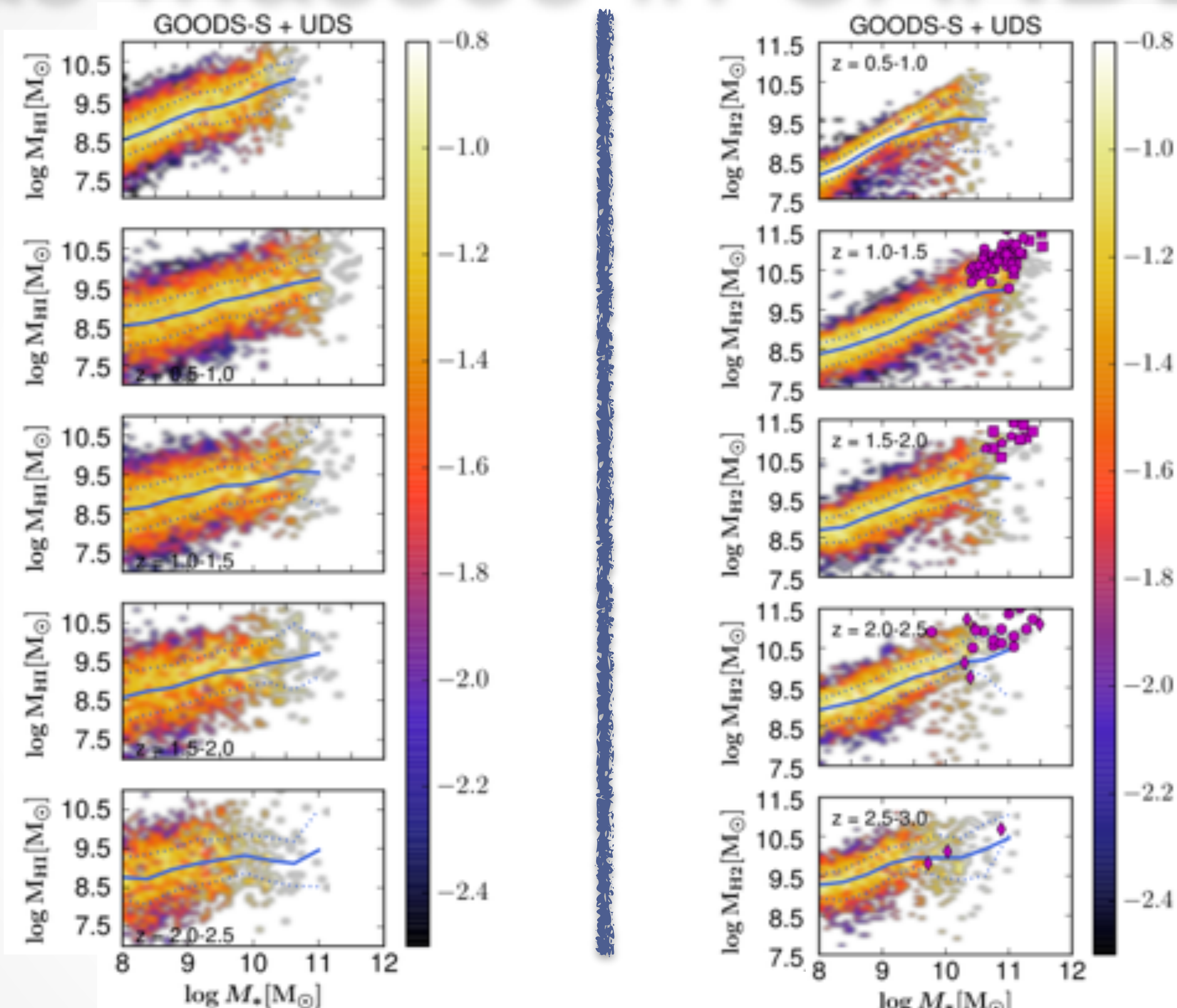
Gas masses in CANDELS

Now with real galaxies

24.000 galaxies from $z = 0.5$ to $z = 3.0$

Gas masses in CANDELS

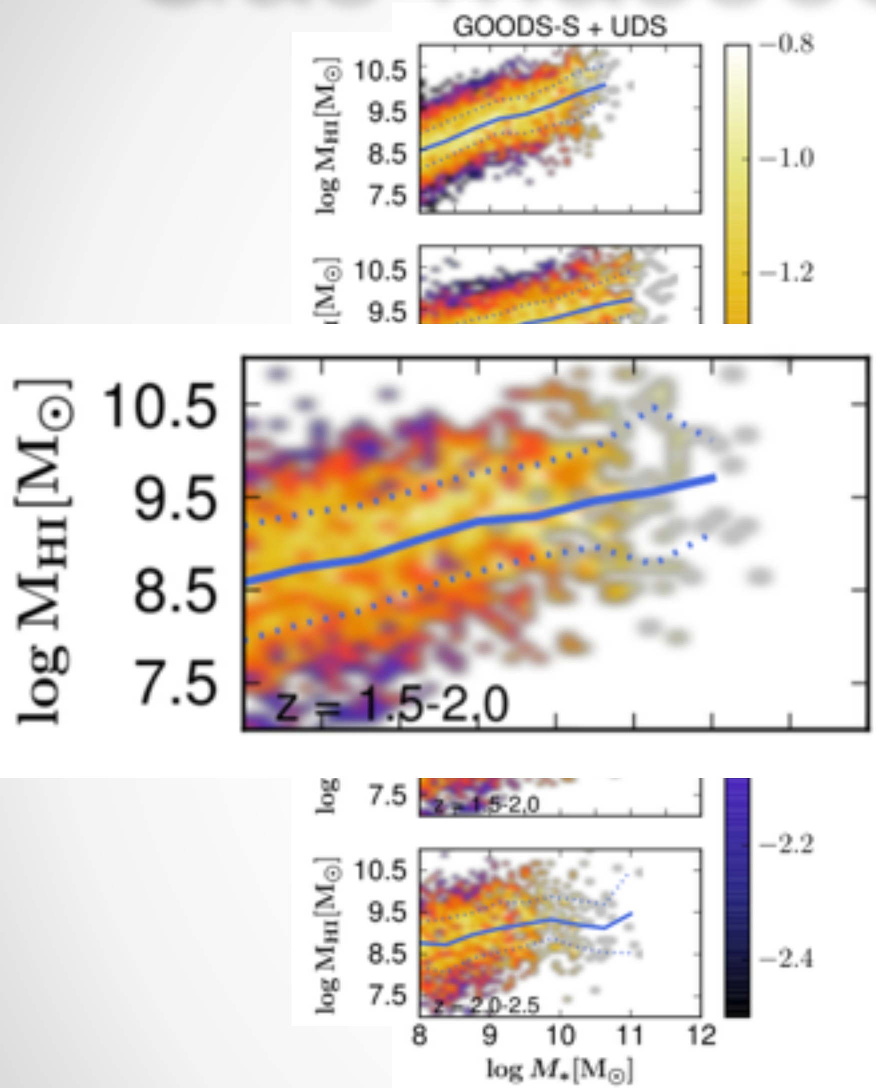
HI

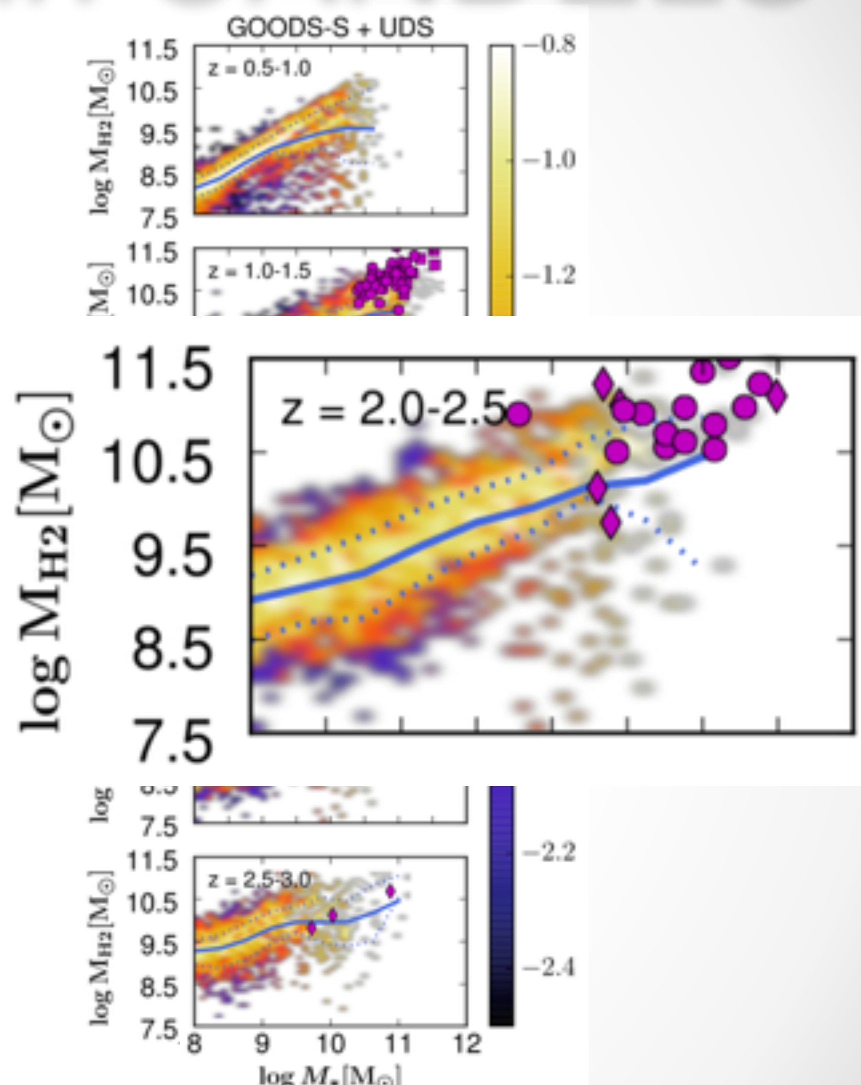


H2

24.000 galaxies from z = 0.5 to z = 3.0

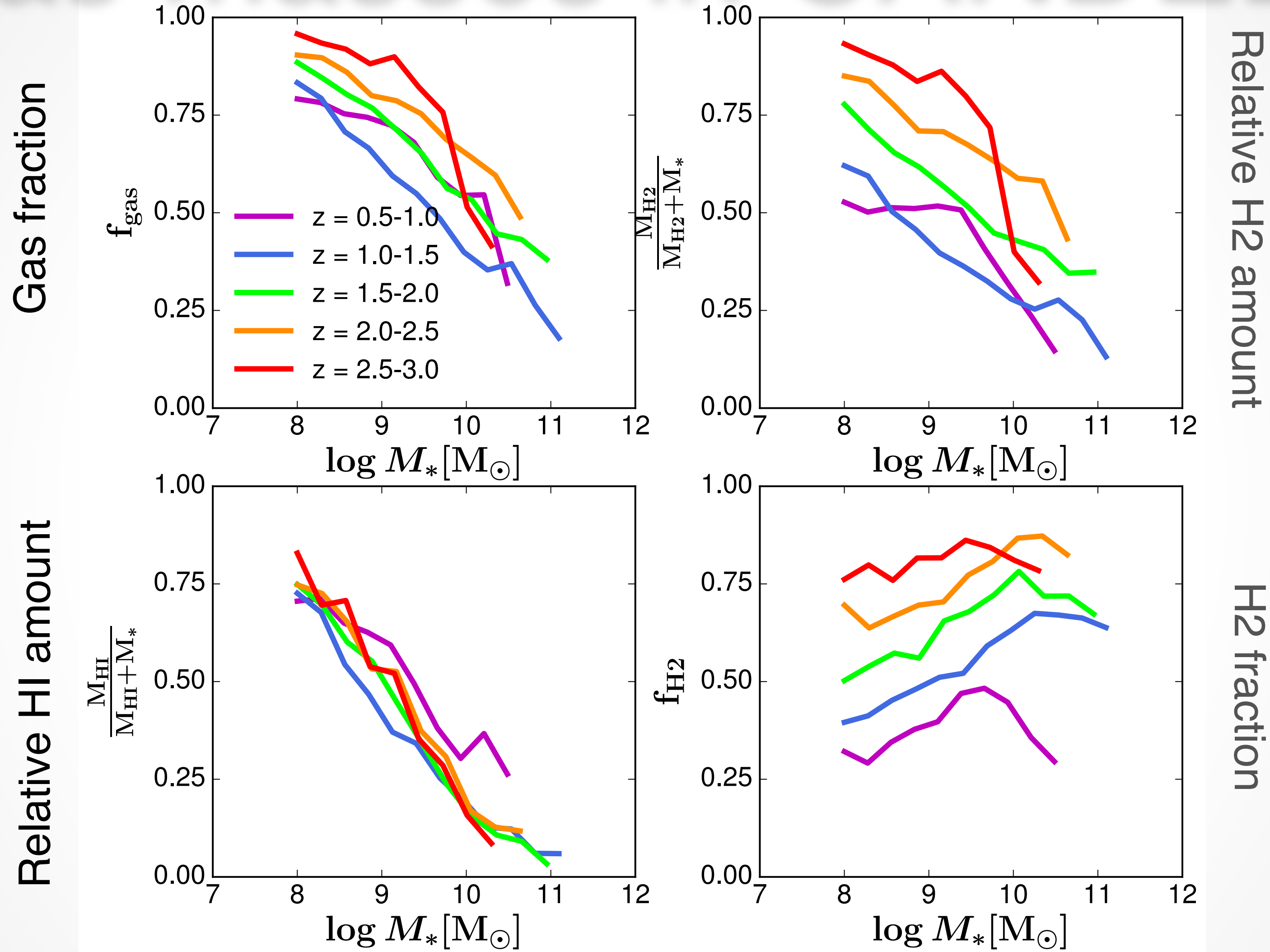
Gas masses in CANDELS





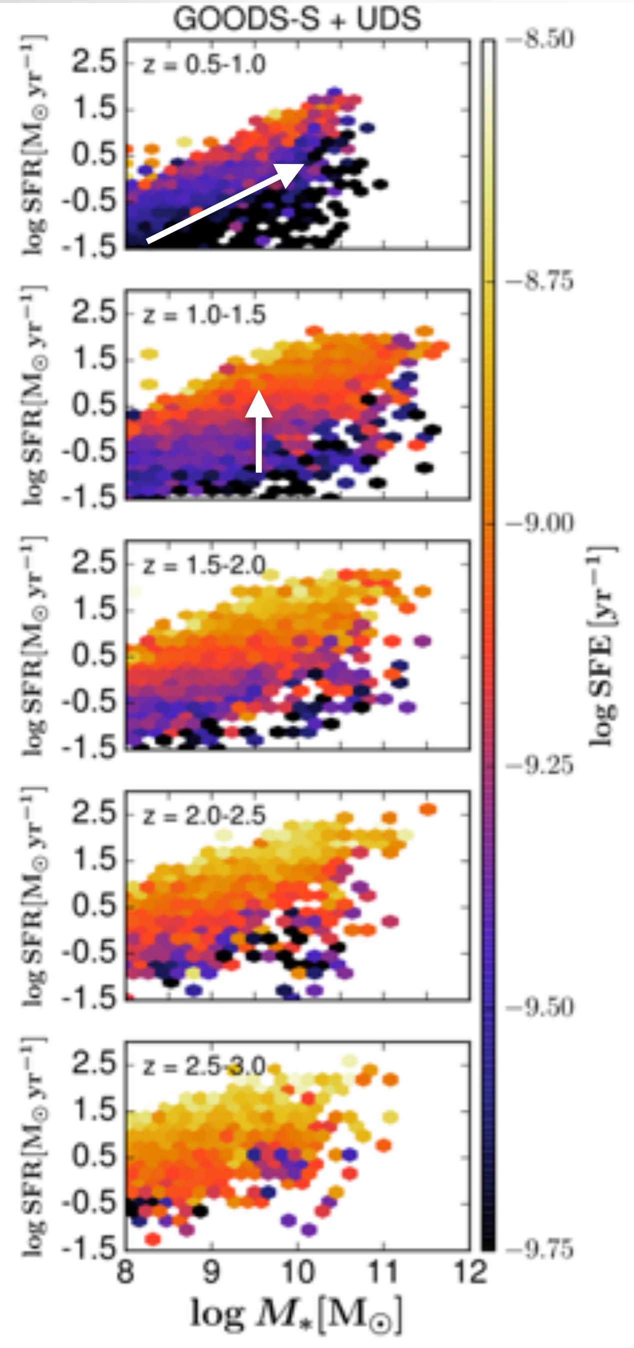
24.000 galaxies from z = 0.5 to z = 3.0

Gas masses in CANDELS



24.000 galaxies from z = 0.5 to z = 3.0

Popping et al. 2015



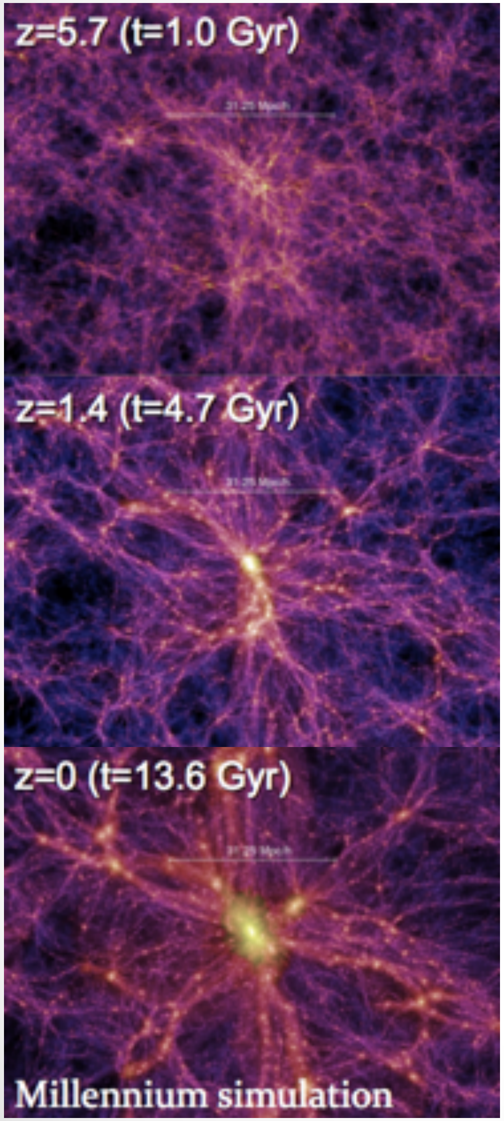
SFE in CANDELS

SFE = SFR/(MHI + MH2)

Star-formation efficiency evolves along the main-sequence of star formation and redshift

Popping et al. 2015

Semi-Analytic Model



- Gravitationally bound structures (halos) form as predicted by ΛCDM
- Gravity causes gas to accrete into halos and galaxies
- Accretion may be suppressed by presence of photoionizing background
- Stars formed out of cold, molecular gas
- Sizes are determined based on angular momentum conservation
- Cold gas is heated and removed from galaxy by SN
- Metals produced by stars enrich cold gas

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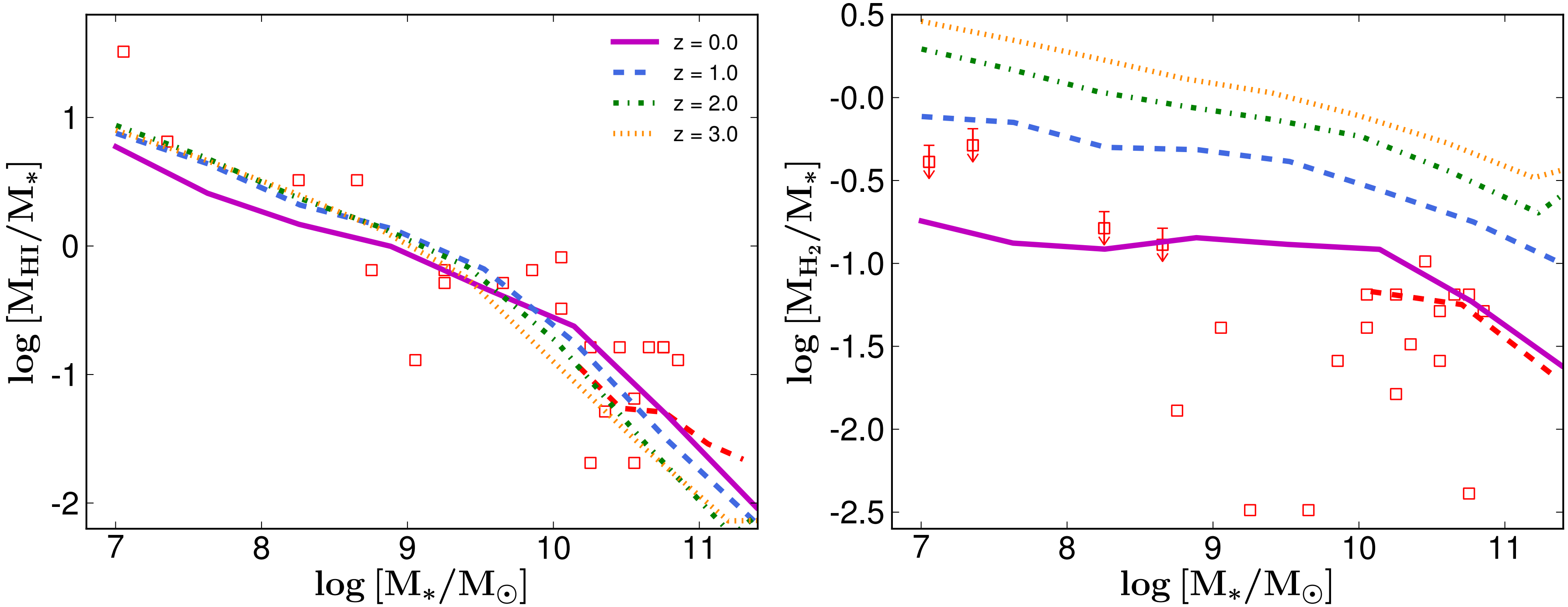
Gas fractions



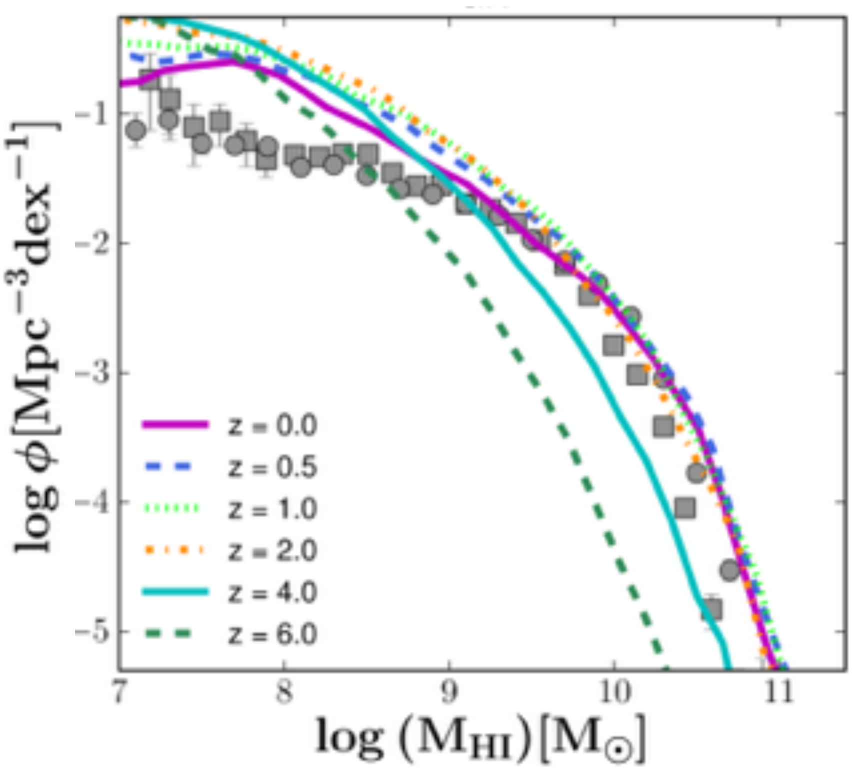
- Relative H2 content of galaxies decreases with time
- HI content remains roughly constant

Popping 2014a

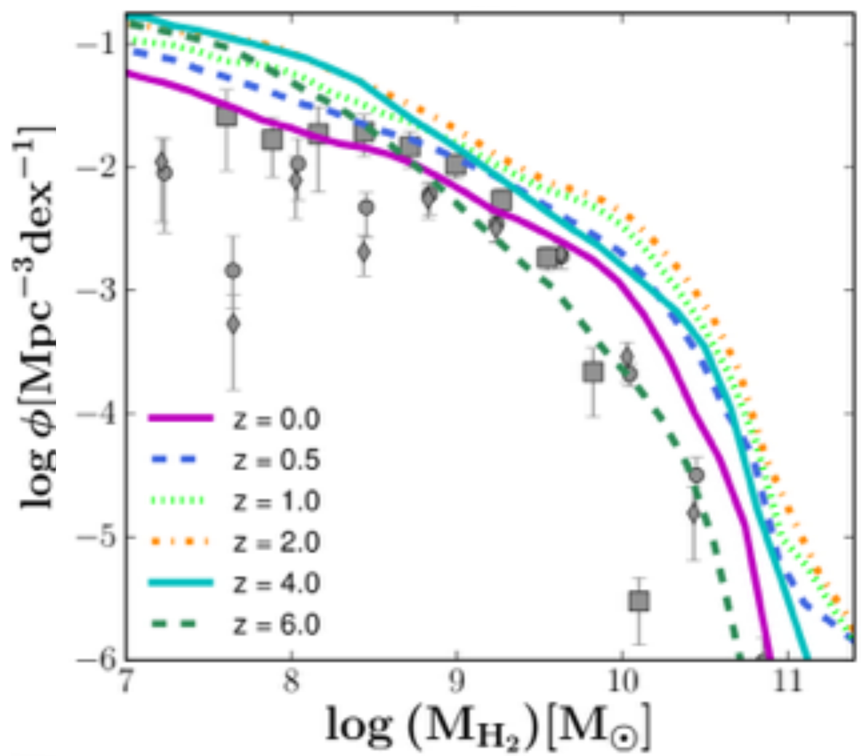
Gas mass functions

Nearly constant HI mass function at z<2.0
H2 mass function evolves strongly

HI

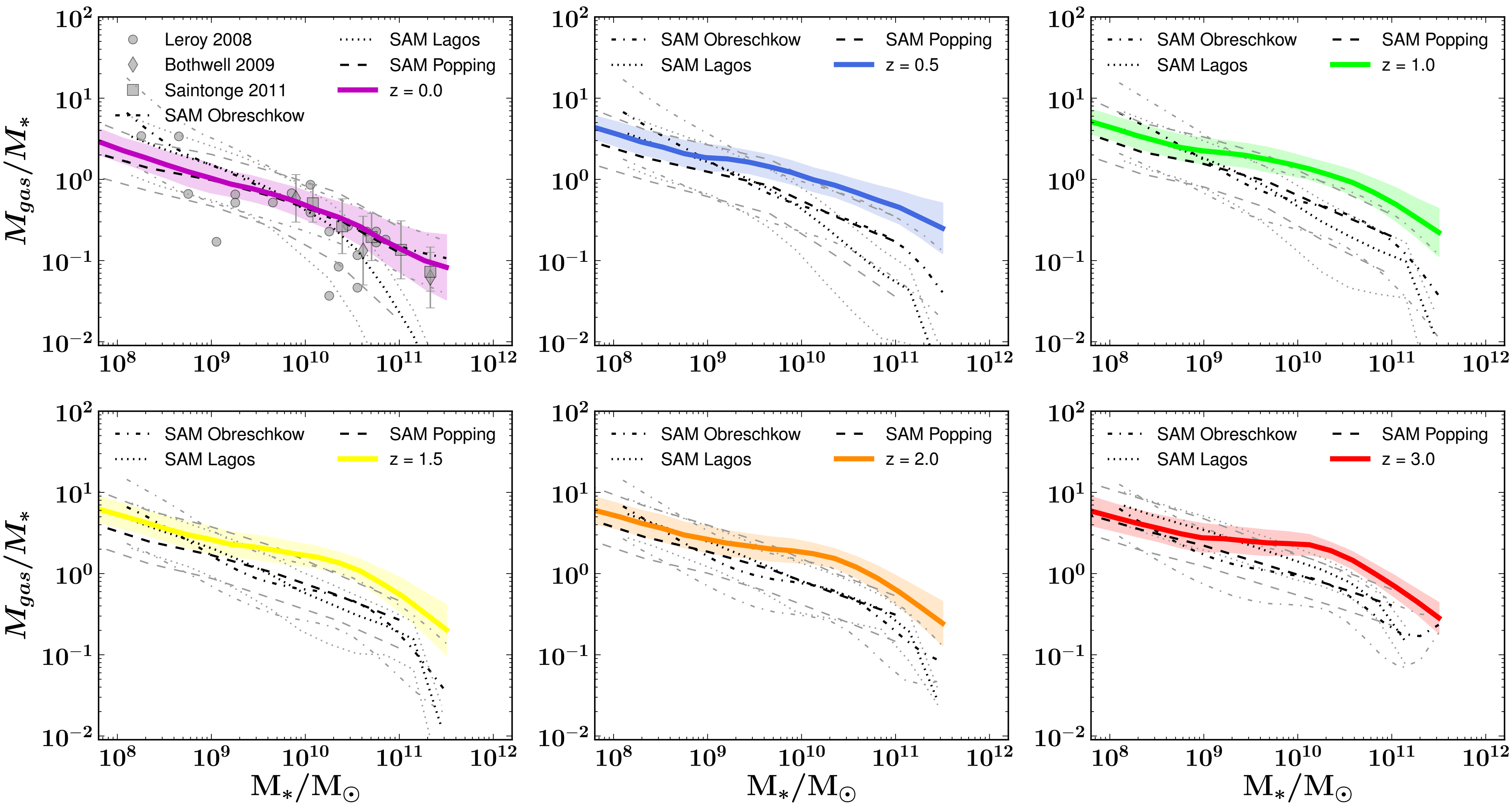


H2



Popping 2014a

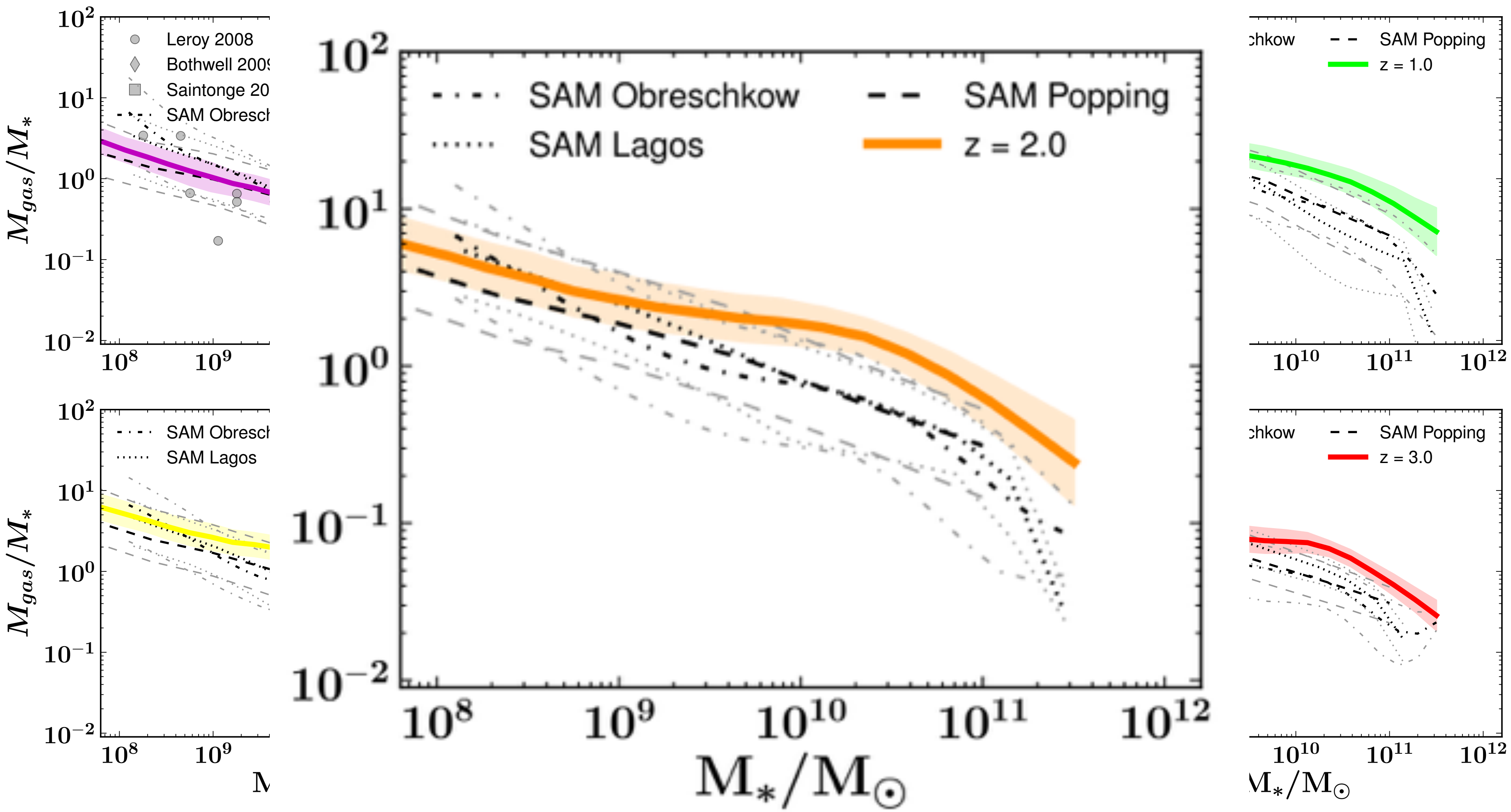
SAM vs. inferred gas masses



Models do not predict enough gas in galaxies at z~2

Popping, Behroozi, and Peeples 2015

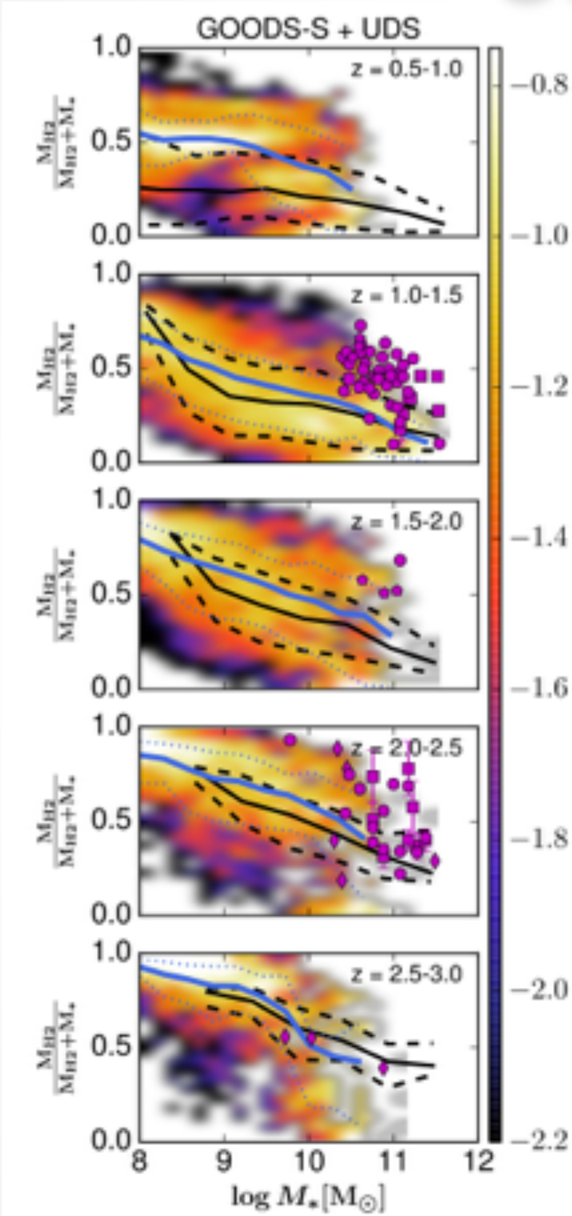
SAM vs. inferred gas masses



Galaxy formation models do not predict enough gas in galaxies at z~2

Popping, Behroozi, and Peeples 2015

same

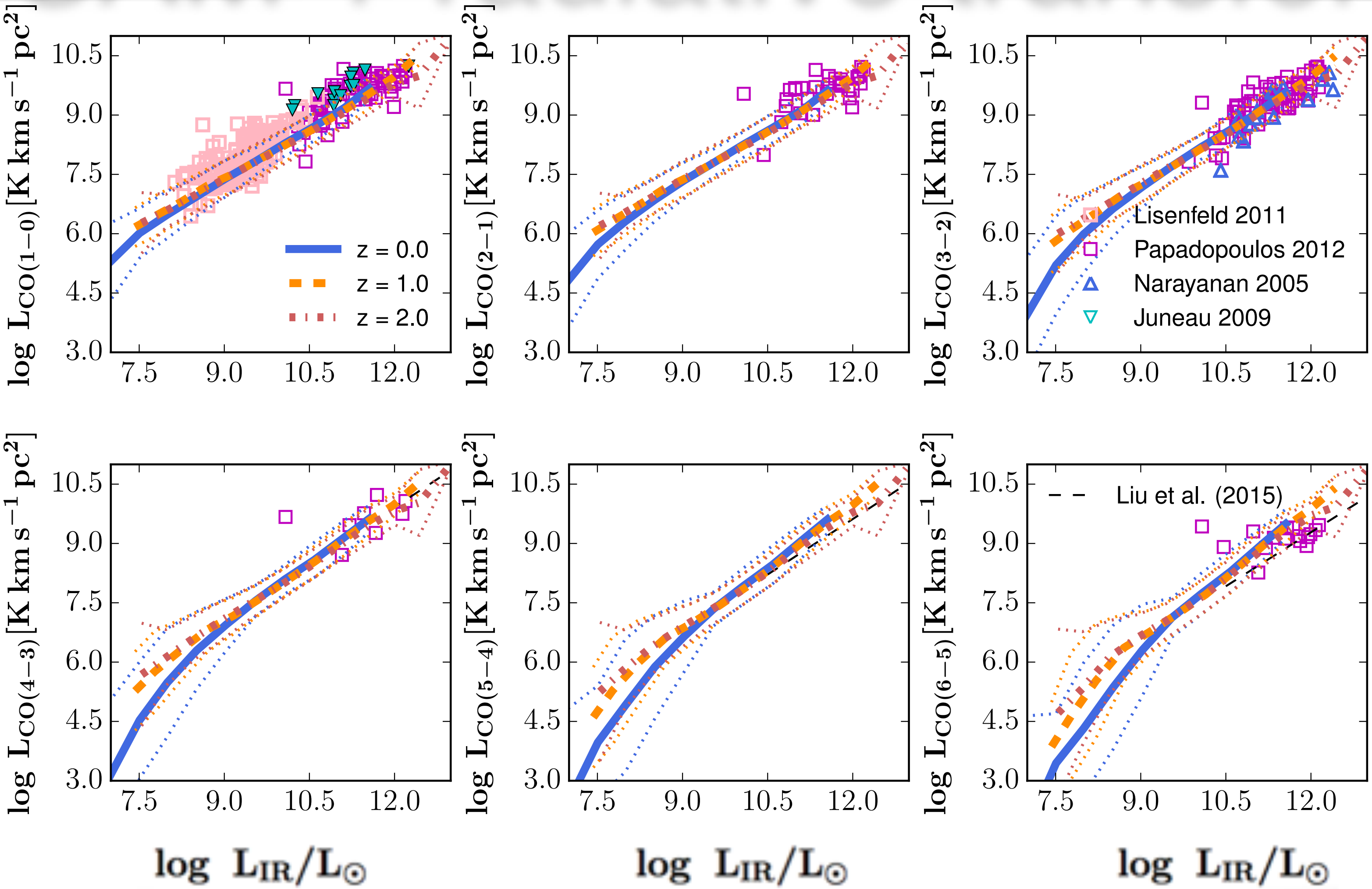


Black line: SAM

BLUE LINE: CANDELS

~ 0.3 dex too little gas in galaxies at z~2.0

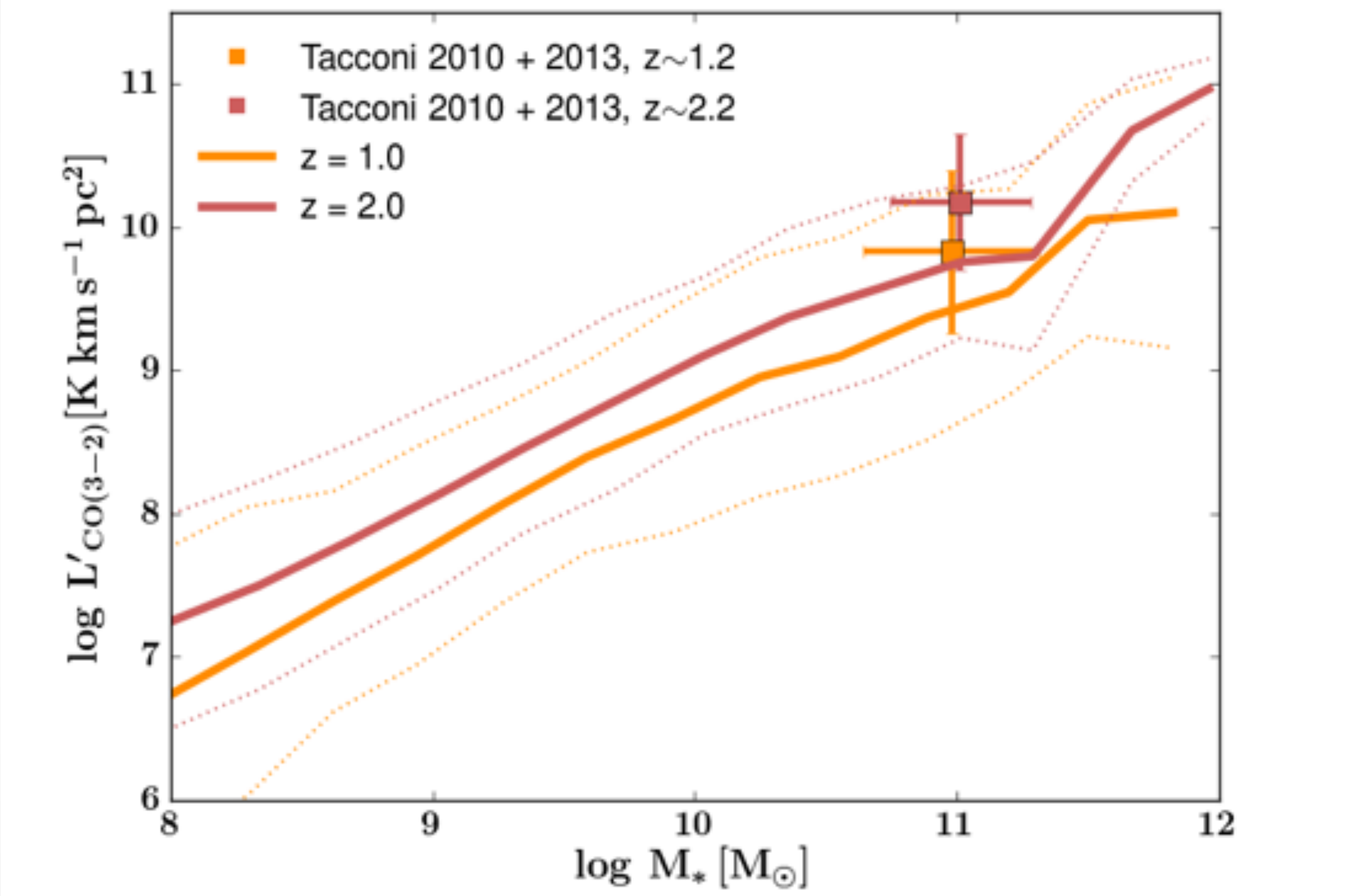
SAM + radiative transfer



Semi-analytic models can now make predictions for sub-mm line emission as well!!!

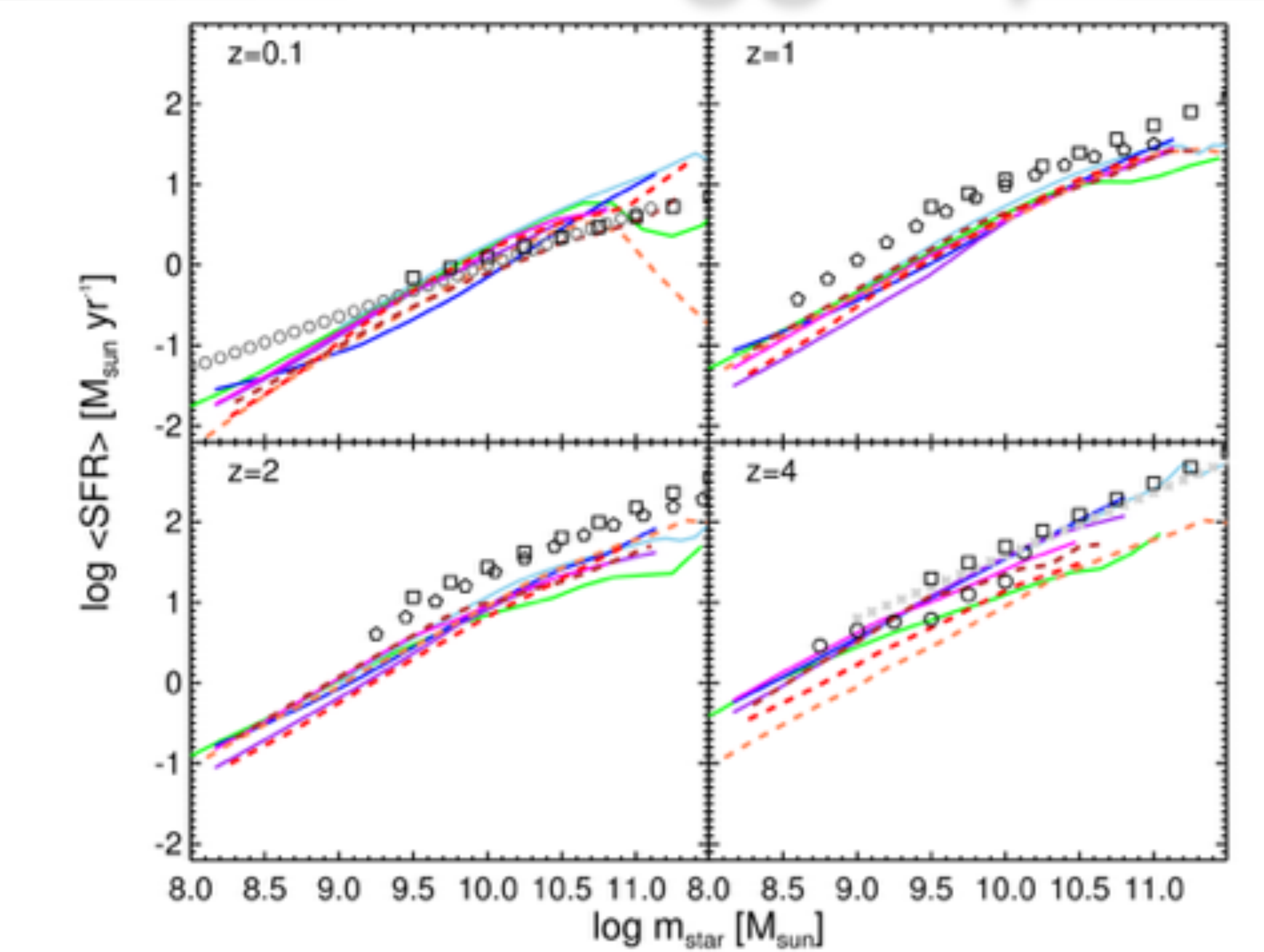
Popping et al. 2014b, Popping et al. 2016

Problems in galaxy theory



Galaxy formation models do not predict enough CO at z~1 & 2

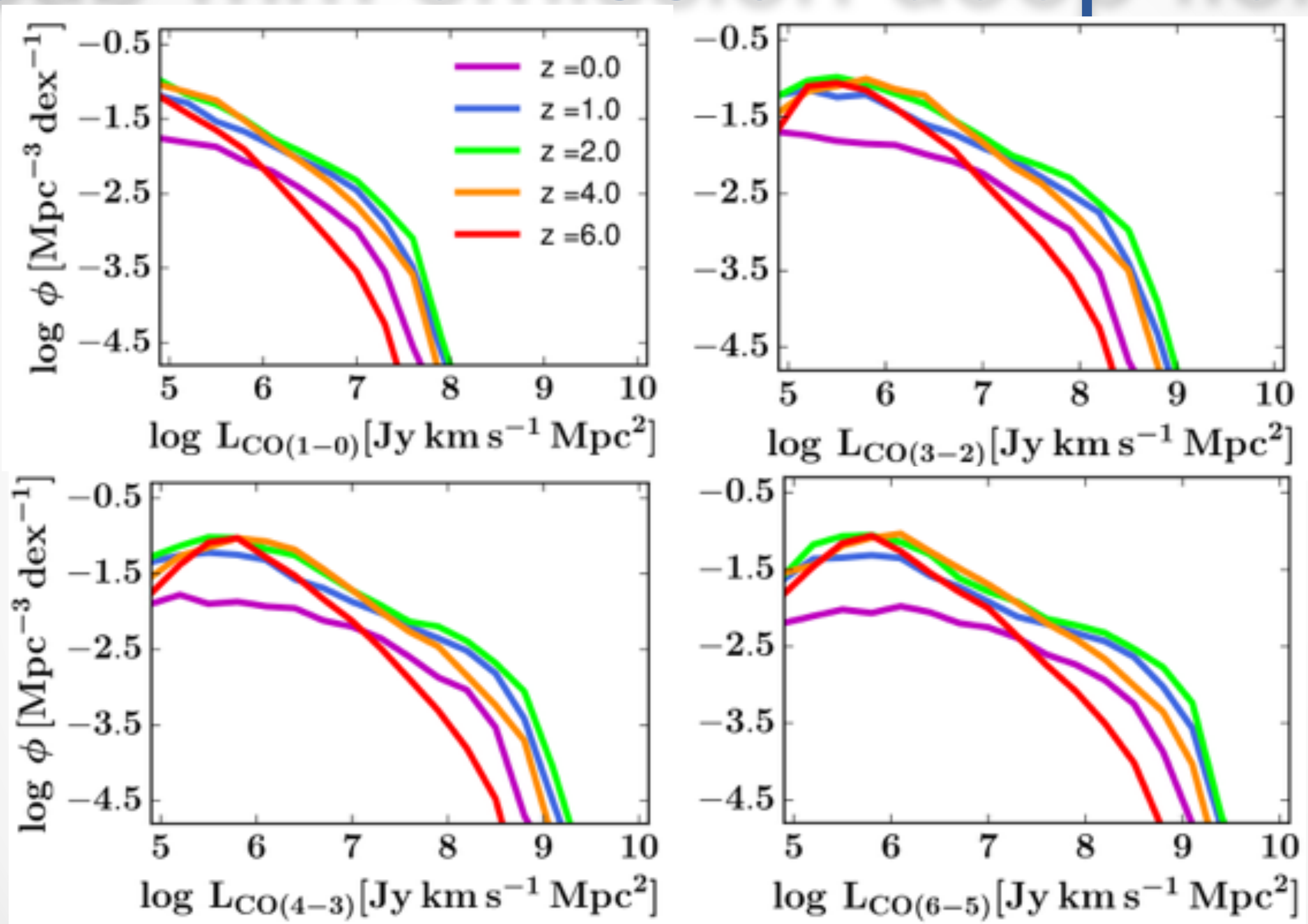
Part of one bigger problem?



from semi-analytic models: SAGE (Croton et al. in prep, dark blue), Y. Lu SAM (Lu et al. 2013, magenta), GALFORM (Gonzalez-Perez et al. 2014, green), the Santa Cruz SAM (Porter et al. 2014, purple), and the MPA Millennium SAM (Henriques et al. 2013). The dotted light blue line shows the Henriques et al. (2013) SAM with observational errors convolved (see text). Colored dashed lines show predictions from numerical hydrodynamic simulations: EAGLE simulations (Schaye et al. 2014, dark red), ezw simulations of Davé and collaborators (Davé et al. 2013, bright red) and the Illustris simulations (Vogelsberger et al. 2014b, orange).

Somerville & Davé 2015

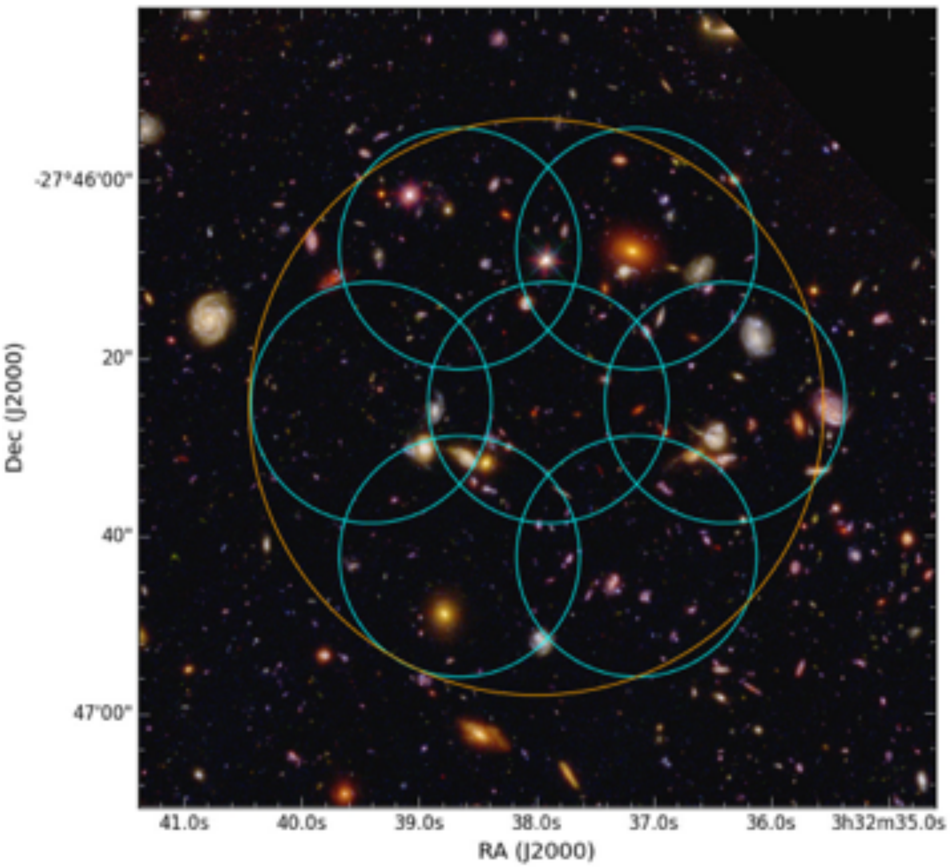
sub-mm emission deep fields

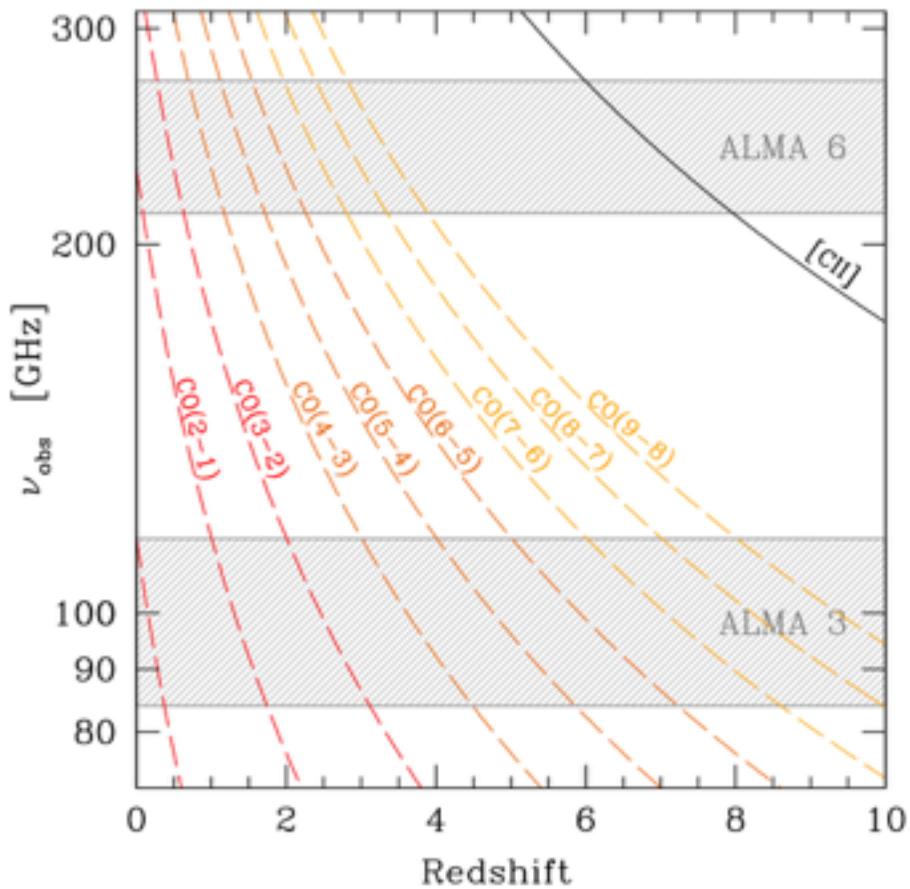


Predictions for deep fields with PdBI/NOEMA, ALMA and (ng)VLA

Popping et al. 2016

ASPECS

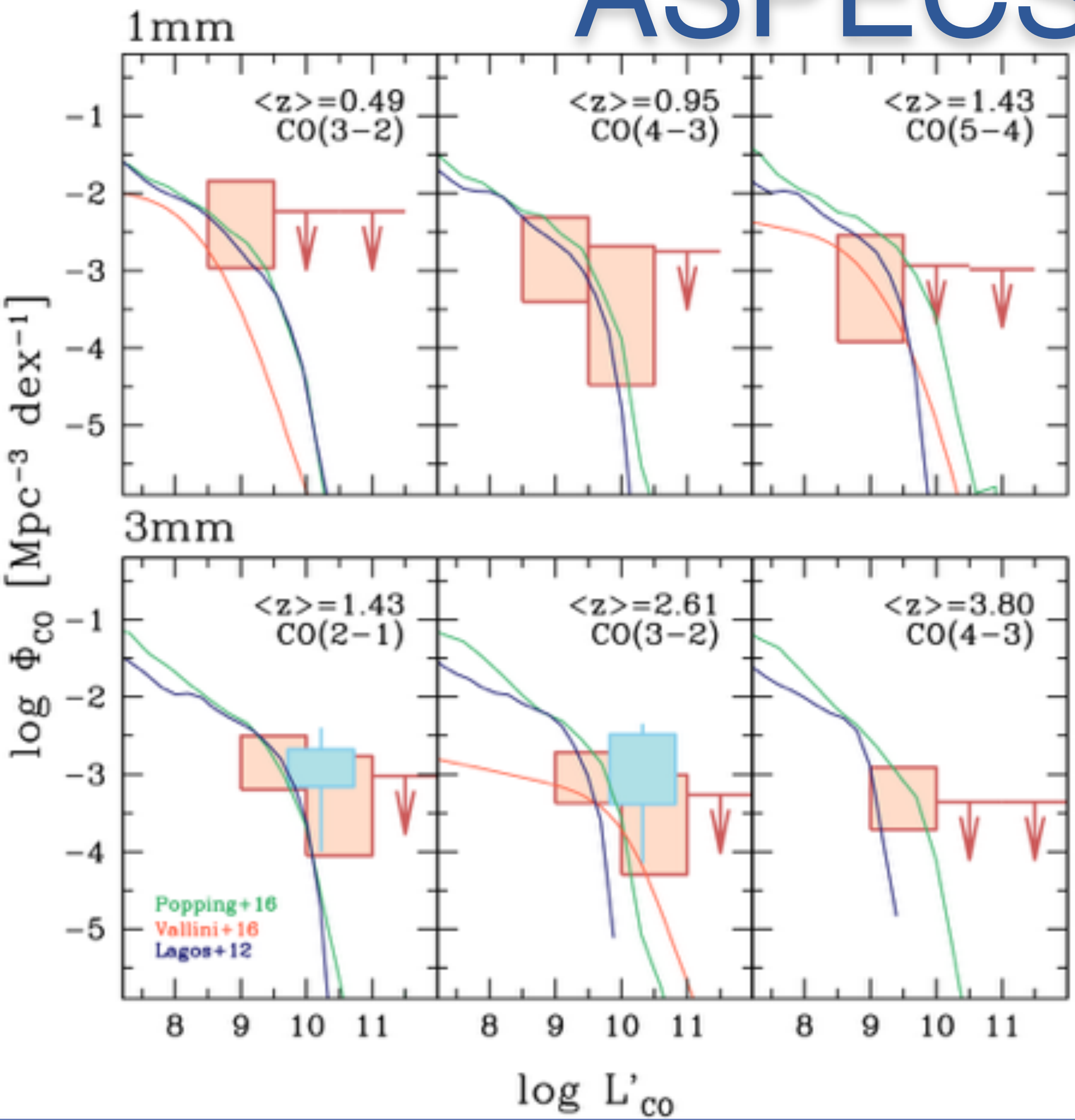




A spectroscopic deep field in the UDF with ALMA band 3 and band 6. Looking for CO, [CII], and continuum

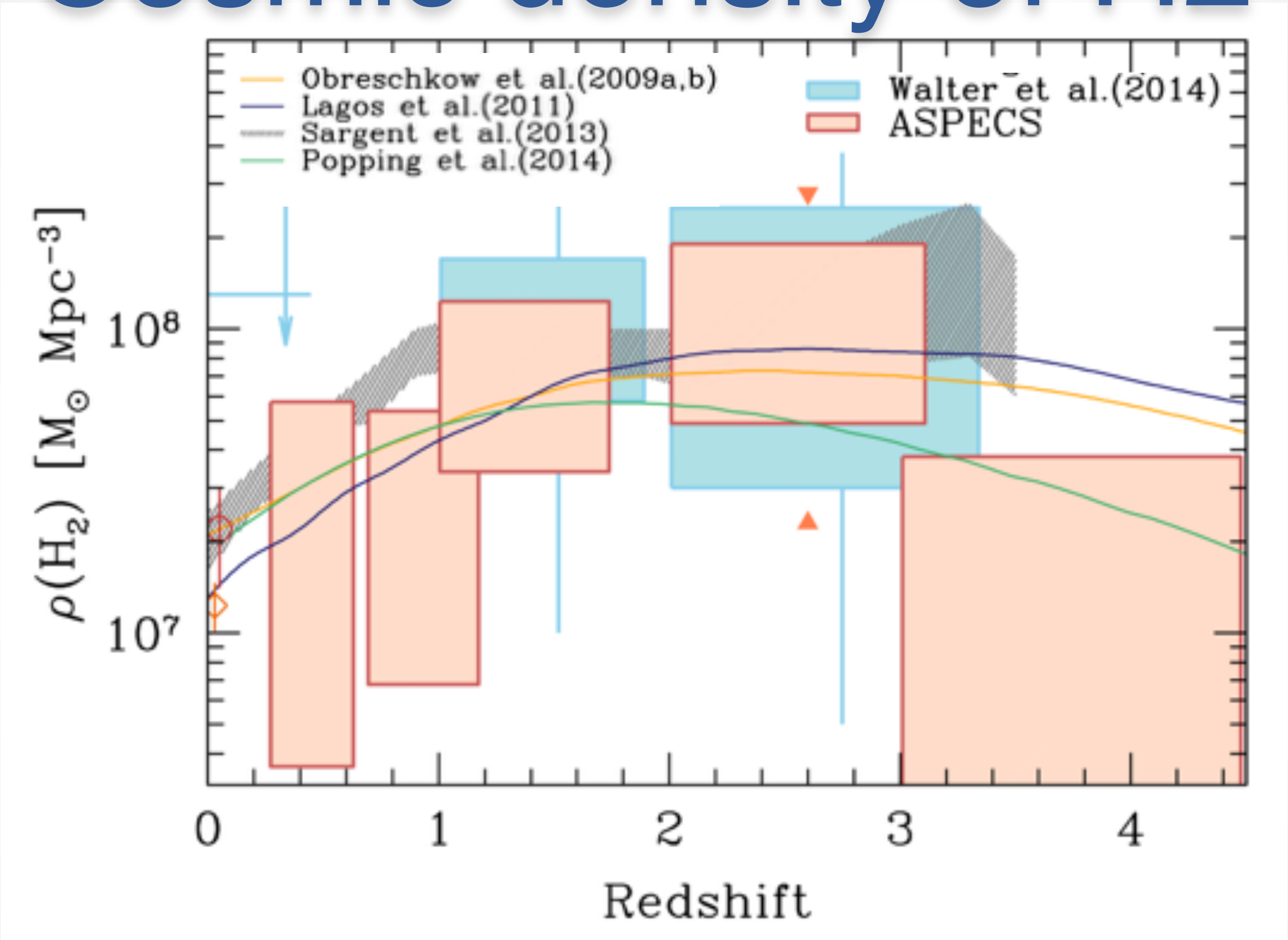
Walter, Decarli, Aravena, …, GP,… (2016)

ASPECS



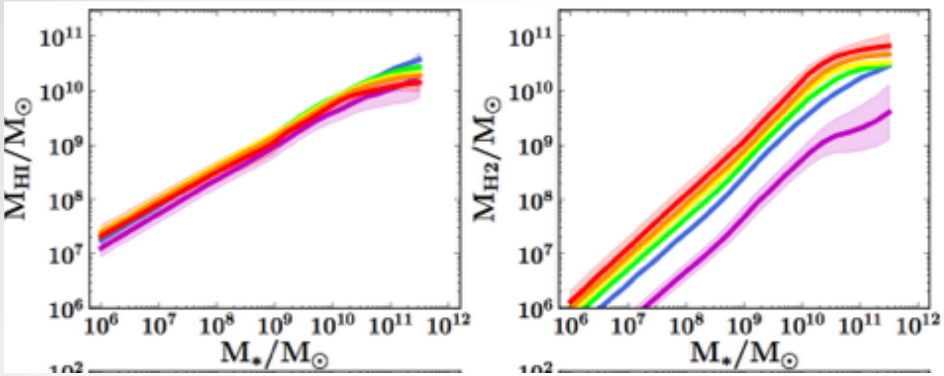
ALMA blind deep field to observe first CO luminosity functions up to z~4

Cosmic density of H2



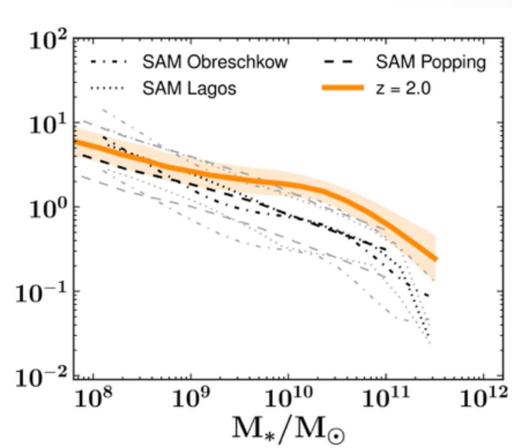
First constraint on cosmic density of H2 up to z~4. H2 density peaks at z~2.5, similar to SFR

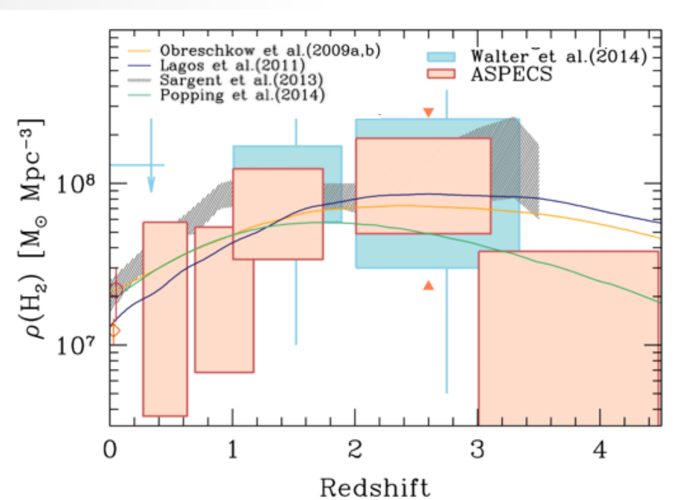
Conclusions



Models predict hardly any evolution in galaxy HI content. Strong evolution in H2 content and depletion time

Theoretical models predict too little gas at intermediate redshifts





First constraints on cosmic density of H2 up to z~4. Similar to Lilly-Madau plot

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