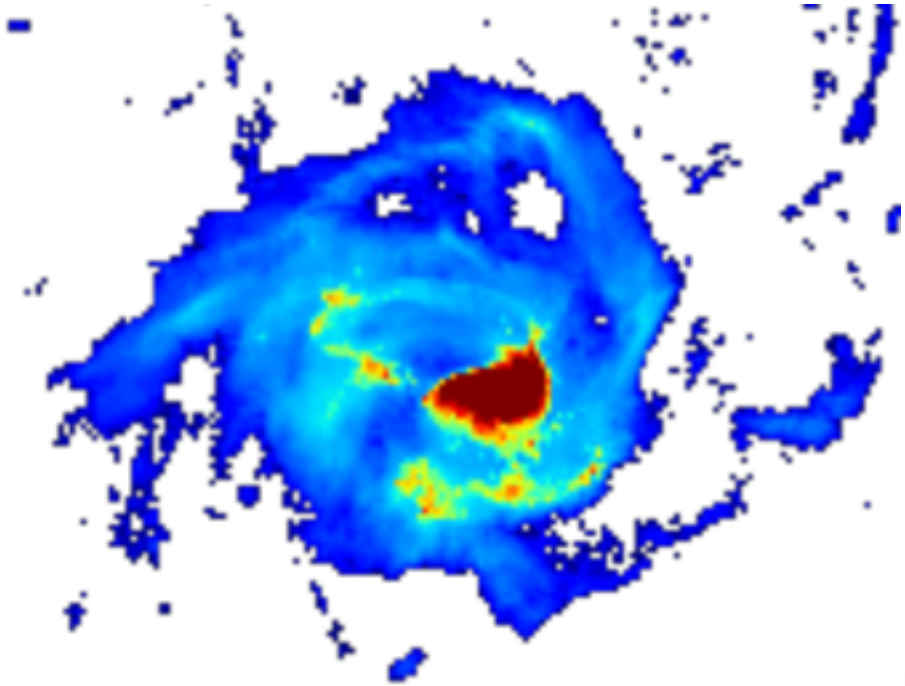
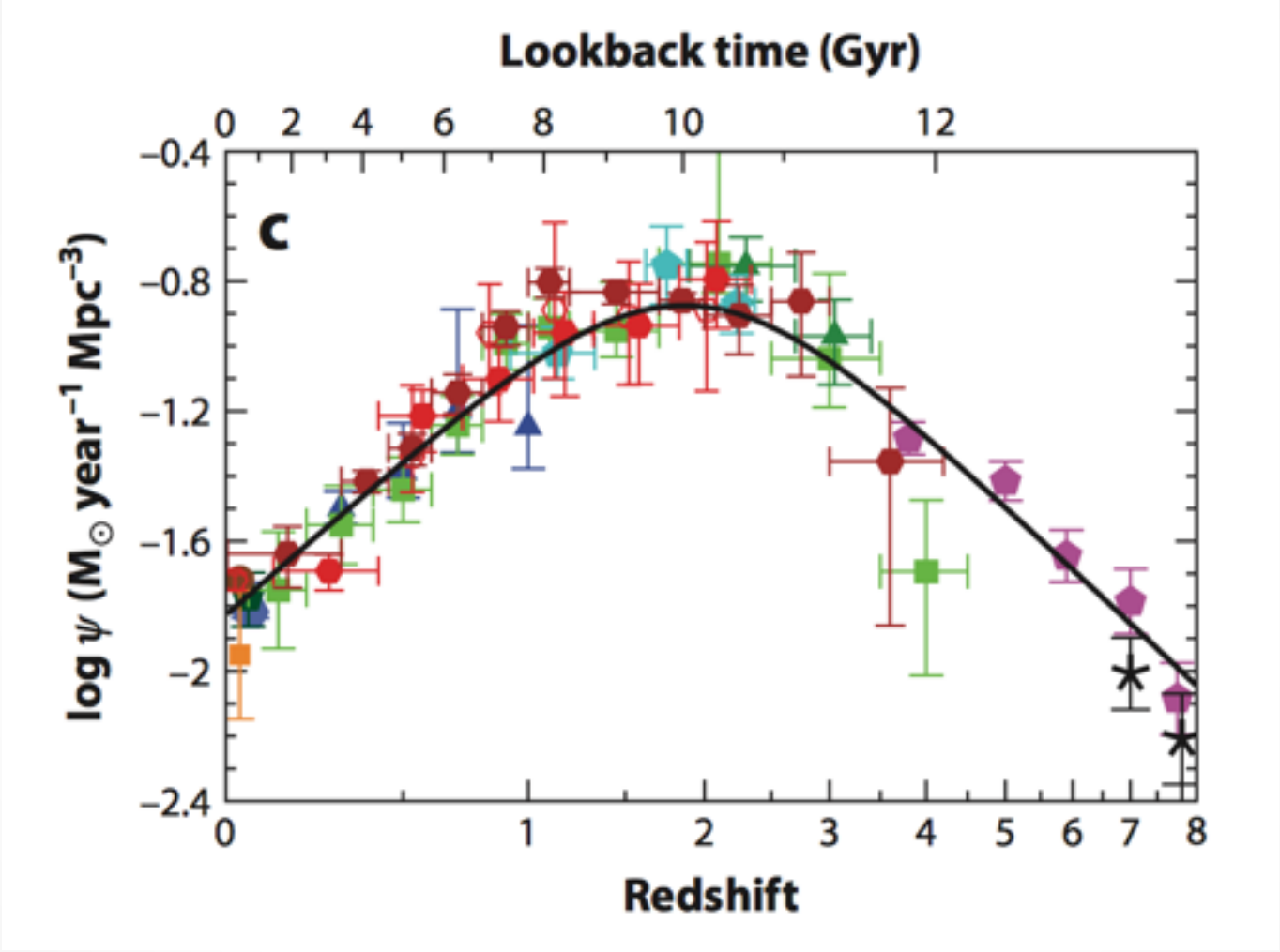
# The HI and H2 content and sub-mm emission of galaxies over cosmic time



Gergö Popping (ESO)

P.S. Behroozi, R.S. Somerville, S.C. Trager, M. Spaans, M.S. Peeples, J.P Pérez-Beaupuits,

# Cosmic SFR



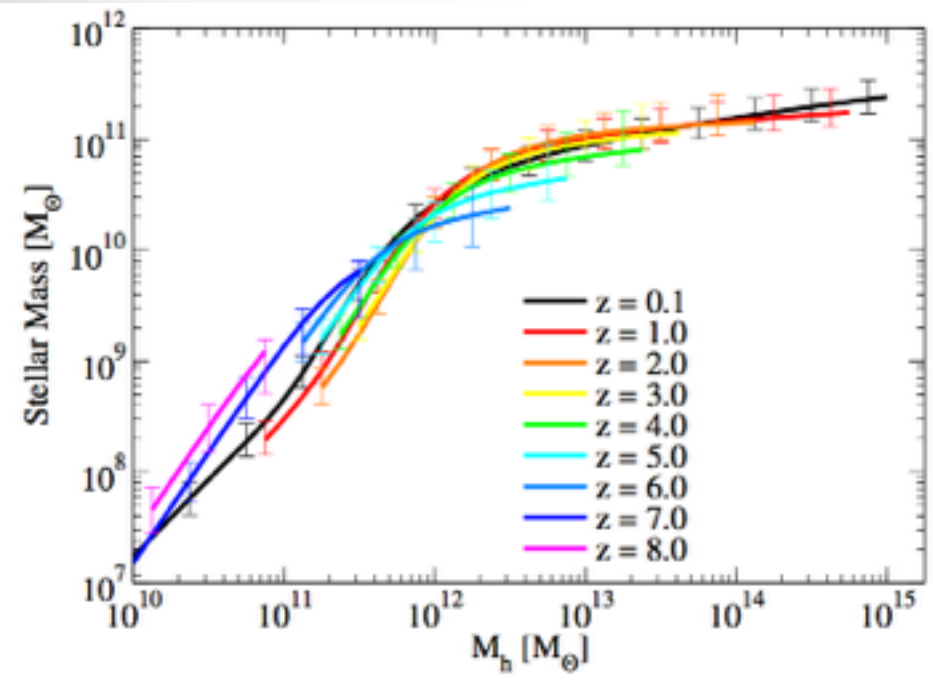

What are the gas properties of galaxies that support this SFR density?

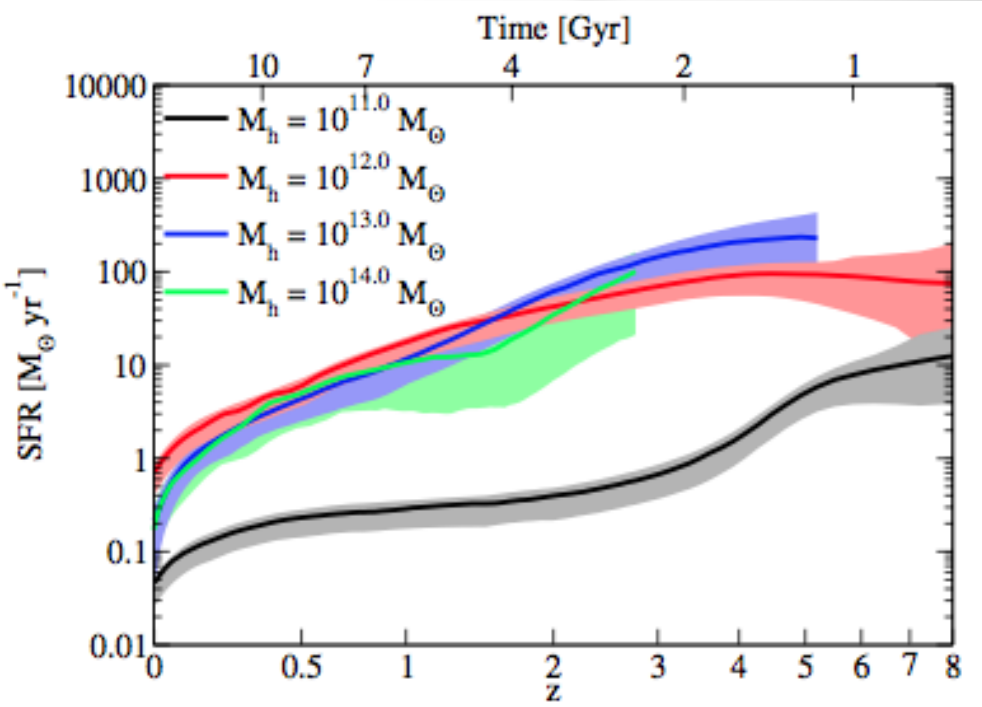
Madau & Dickinson 2014

# Newest generation of radio and sub-mm instruments

- Newest and upcoming facilities will provide huge amounts of multiphase gas information

# Abundance matching

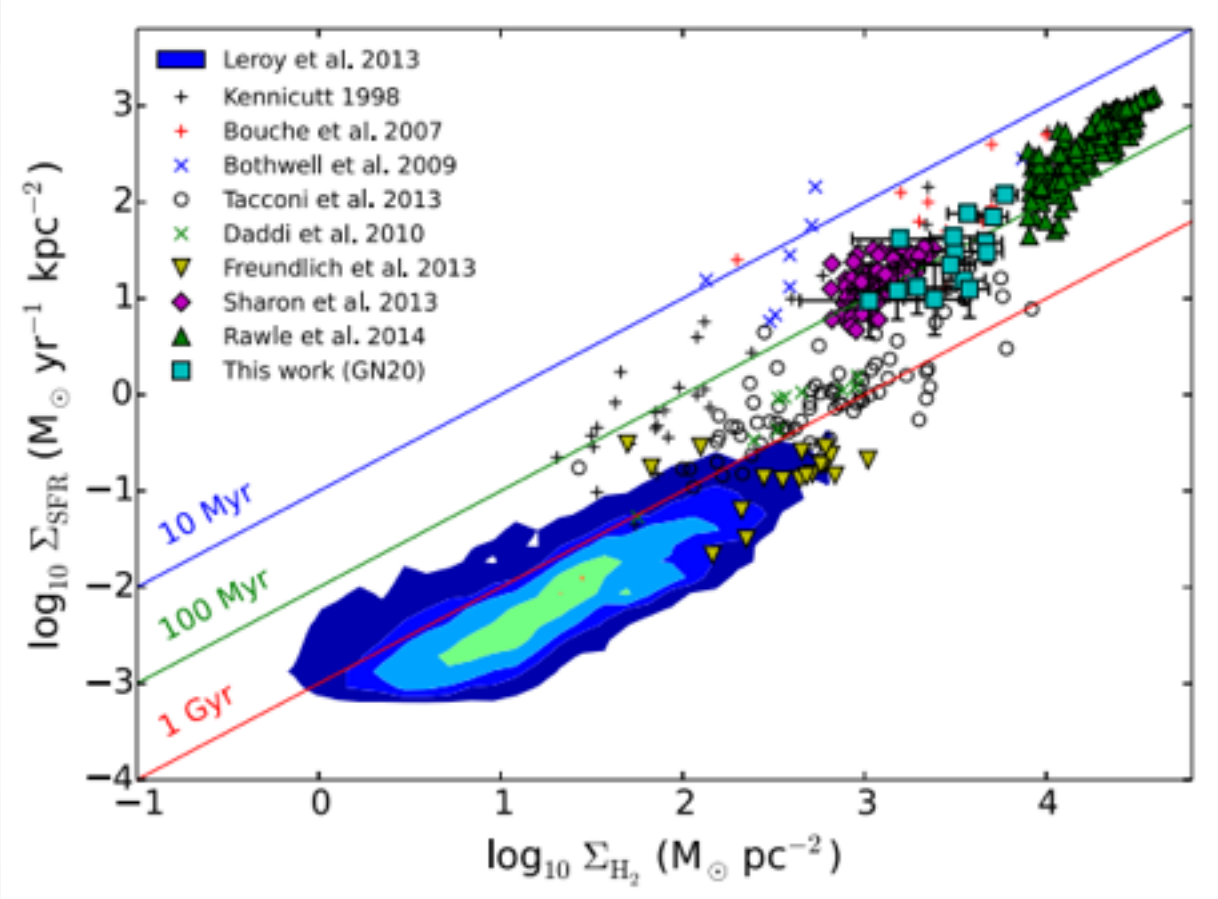



Observationally driven model for stellar mass and SFR as a function of halo mass and redshift

Behroozi et al. 2013a, 2013b

# $H_2$ based star-formation relation

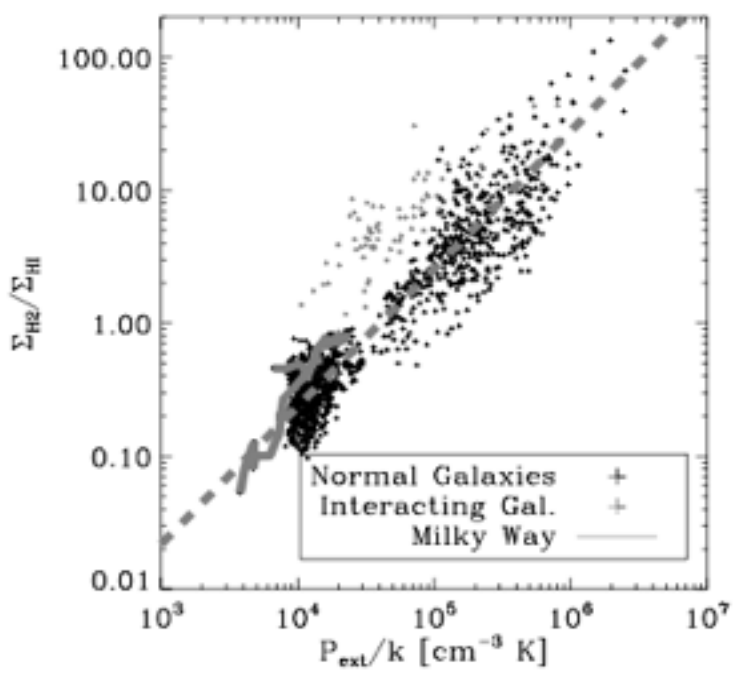



$$\Sigma_{\rm SFR} = \frac{A_{\rm SF}}{10}\left(1+\frac{\Sigma_{\rm gas}}{\Sigma_{\rm crit}}\right)^{N_{\rm SF}} f_{H2}\,\Sigma_{\rm gas}$$

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

# Calculating H2 fractions

Pressure based (BR)

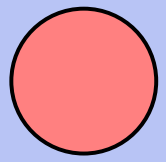



$$R_{H_2} = \left(\frac{\Sigma_{H_2}}{\Sigma_{HI}}\right) = \left(\frac{P_m}{P_0}\right)^{\alpha}$$

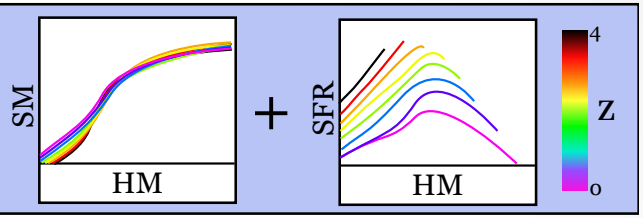
$$P_m \sim \frac{\pi}{2} G \Sigma_{gas} \left(\Sigma_{gas} + \Sigma_* \frac{\sigma_{gas}}{\sigma_*}\right)$$

Gnedin & Kravtsov 2011, Krumholz, McKee & Tumlinson 2008, 2009 Wong & Blitz 2003 Blitz & Rosolowsky 2006, Leroy 2008

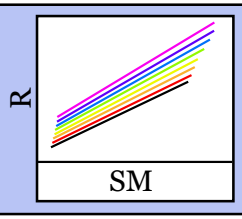
1. Pick a halo from the simulation, which will have a halo mass (HM) and redshift (z).



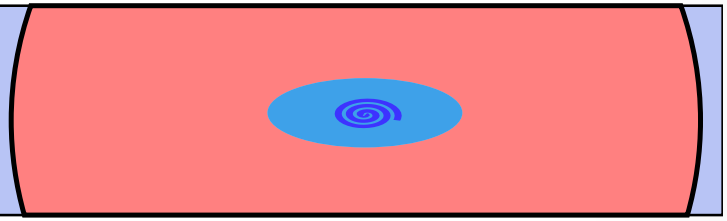
2. Assign a galaxy stellar mass and SFR to halo using relations in Behroozi et al. (2013).



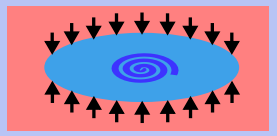

3. Use size-stellar mass relation in van der Wel et al. (2014), scaled by 2.6, to assign gas disc size.



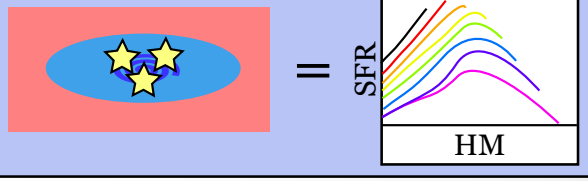

4. Assuming that the gas+stars are distributed exponentially, choose a total cold gas mass.



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).

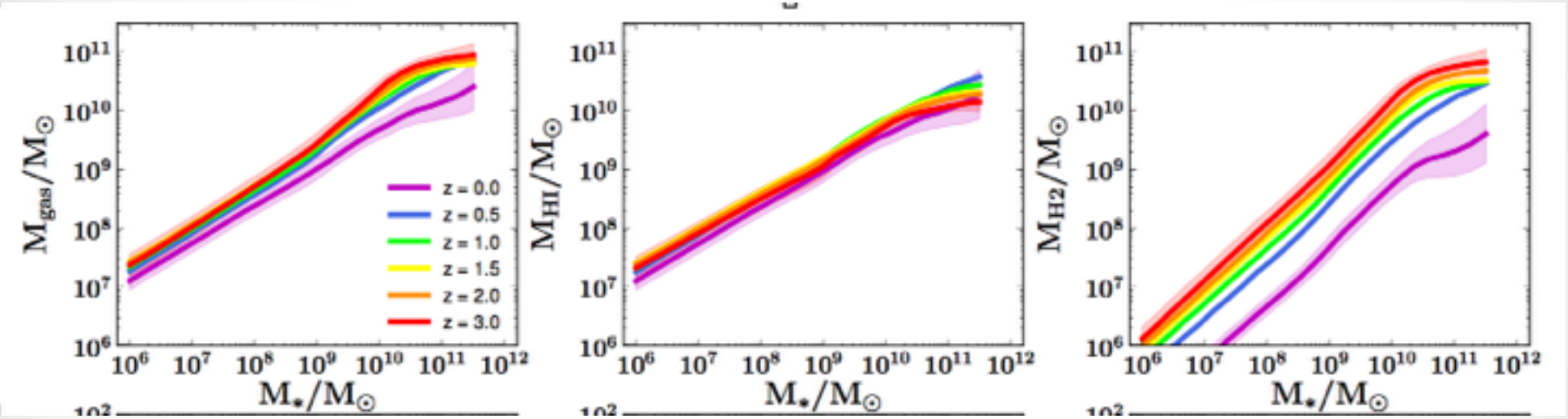


6. Compare implied SFR with Behroozi et al. (2013); keep iterating gas masses until the two SFRs match.




Popping, Behroozi, and Peeples 2015

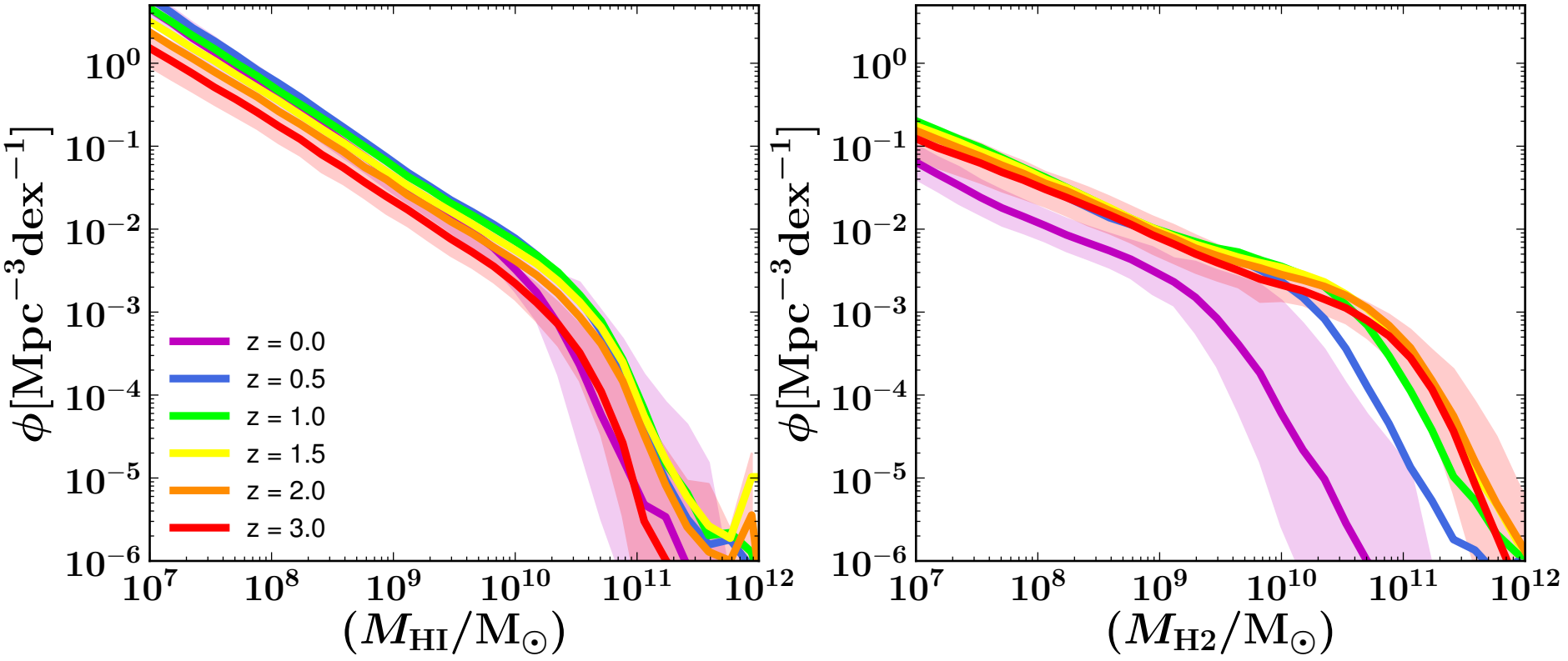
# SHAM + inferred gas masses




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

Popping, Behroozi, and Peeples 2015

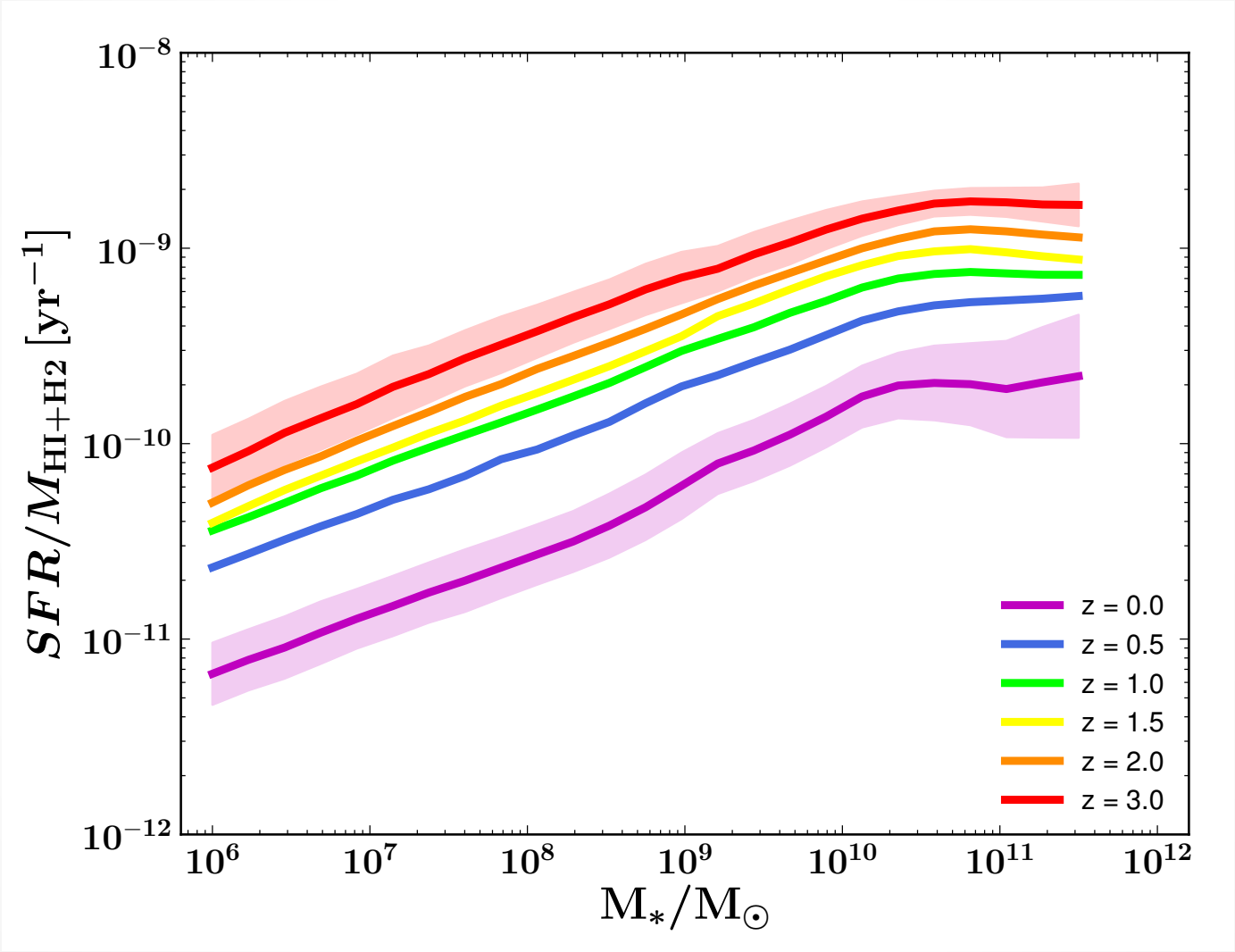
# SHAM + inferred gas masses




Little evolution in HI, strong evolution in H2

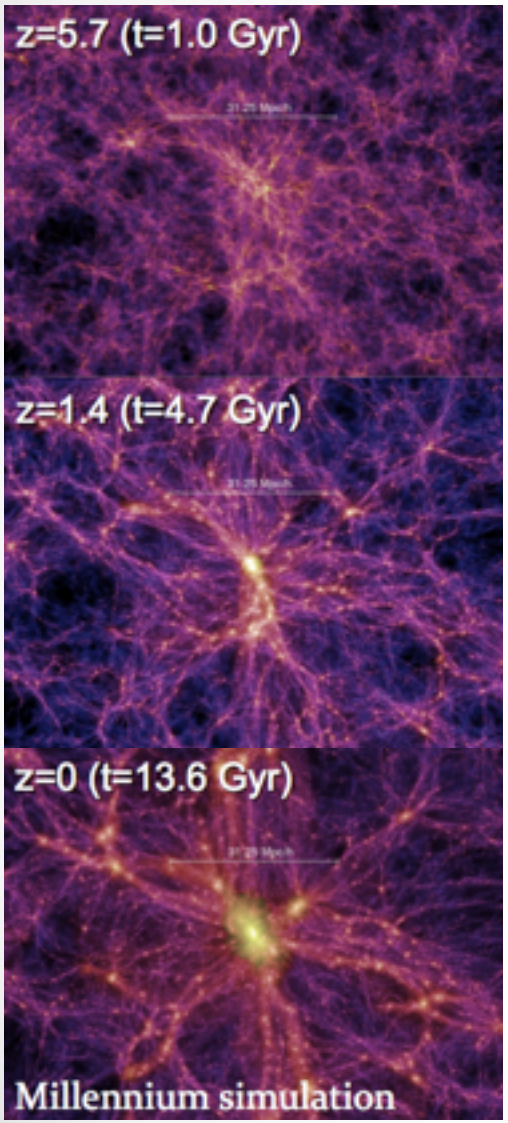
Popping, Behroozi, and Peeples 2015

# Star-formation efficiency



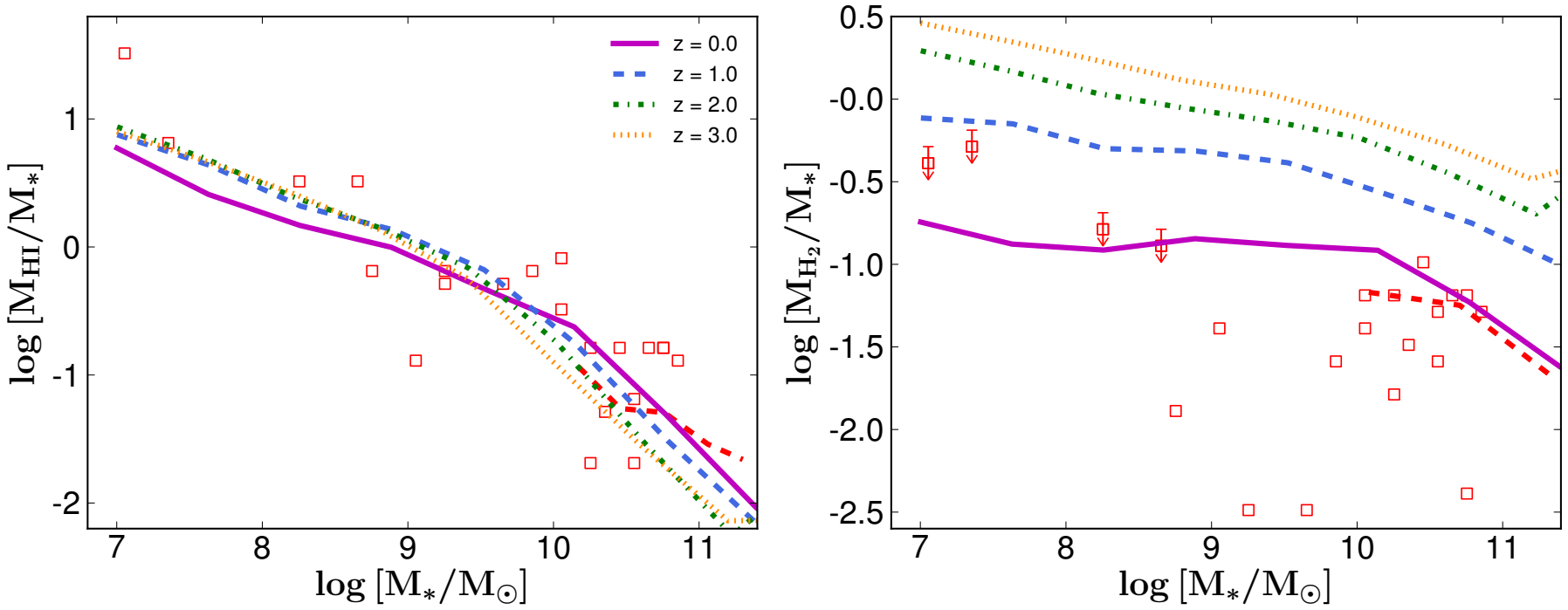

Popping, Behroozi, and Peeples 2015

# 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 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

# Gas fractions




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

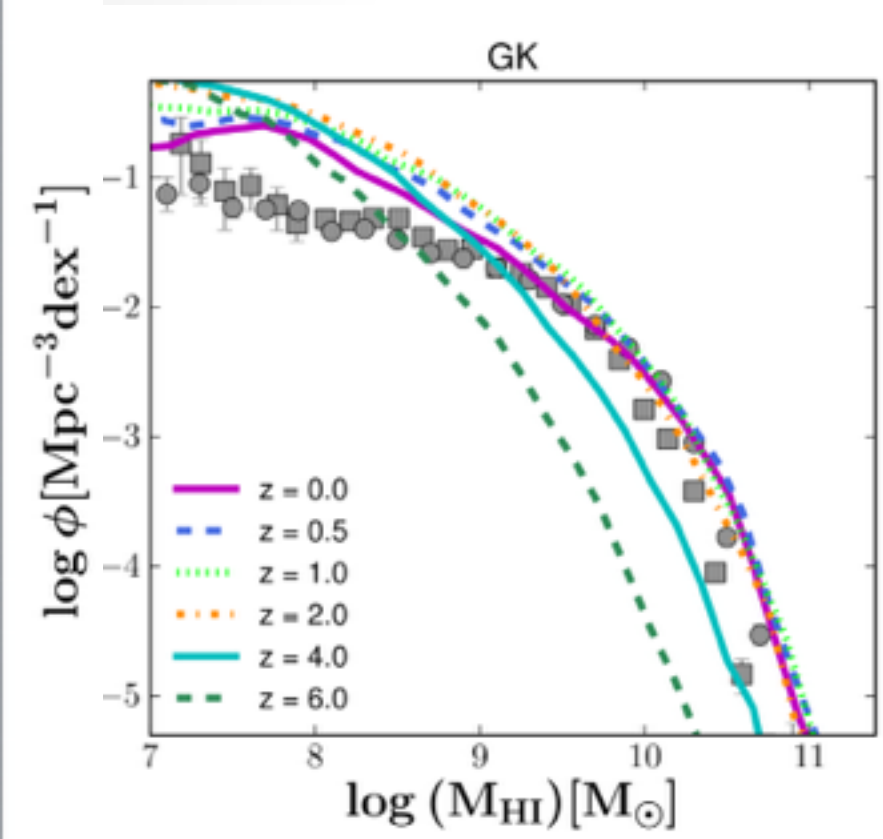
Popping 2014a

# Gas mass functions

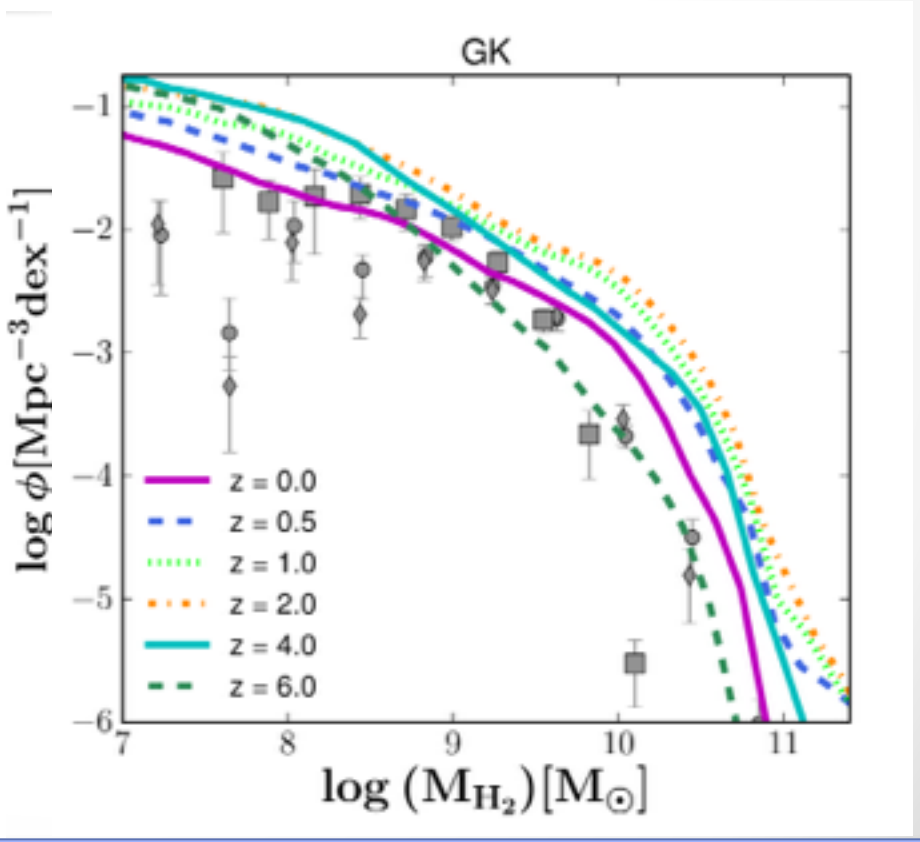
Nearly constant HI mass function at z<2.0

H2 mass function evolves strongly

HI

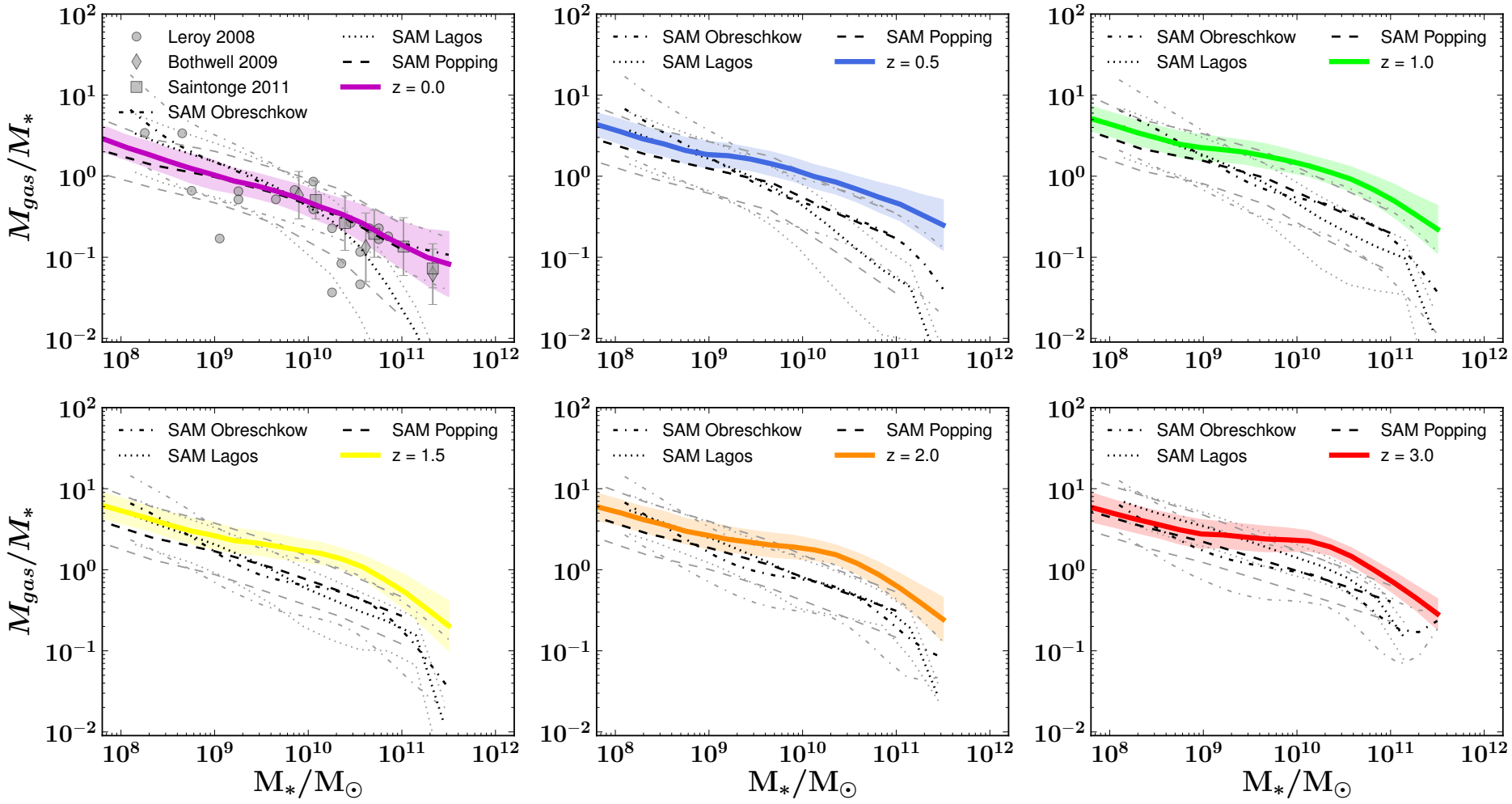



H2



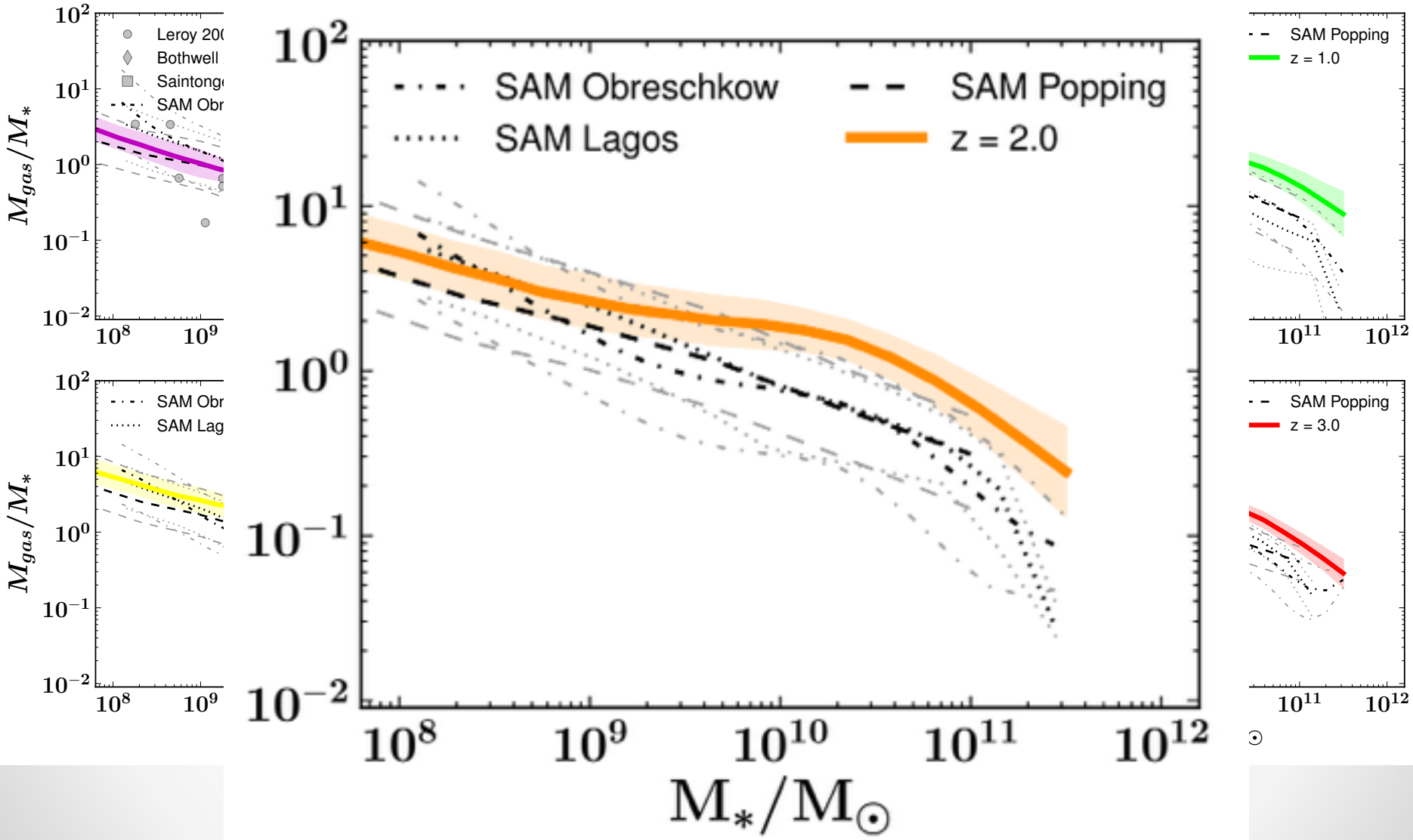

Popping 2014a

# Model vs. inferred gas masses



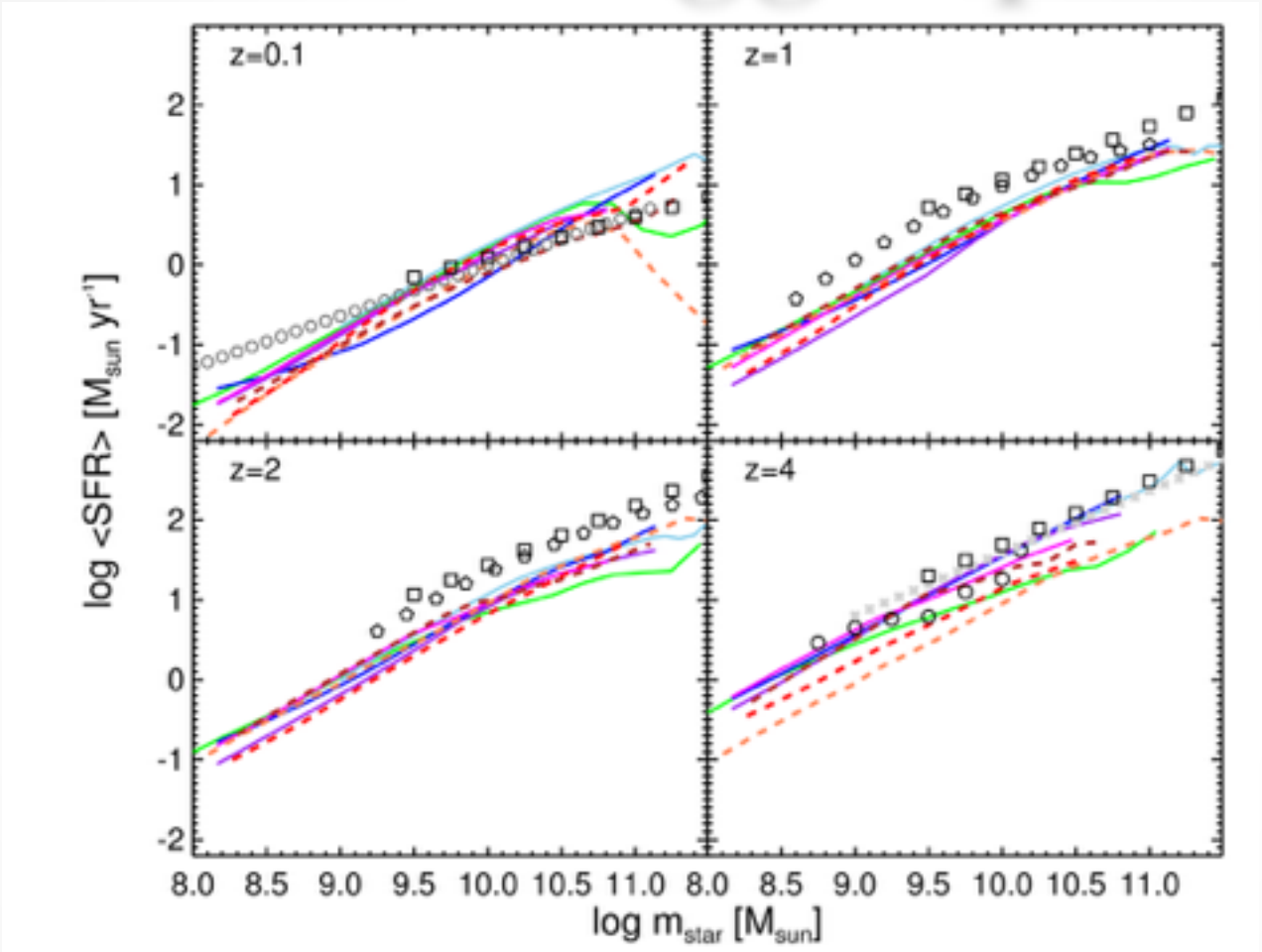

Popping, Behroozi, and Peeples 2015

# SAM vs. inferred gas masses




Popping, Behroozi, and Peeples 2015

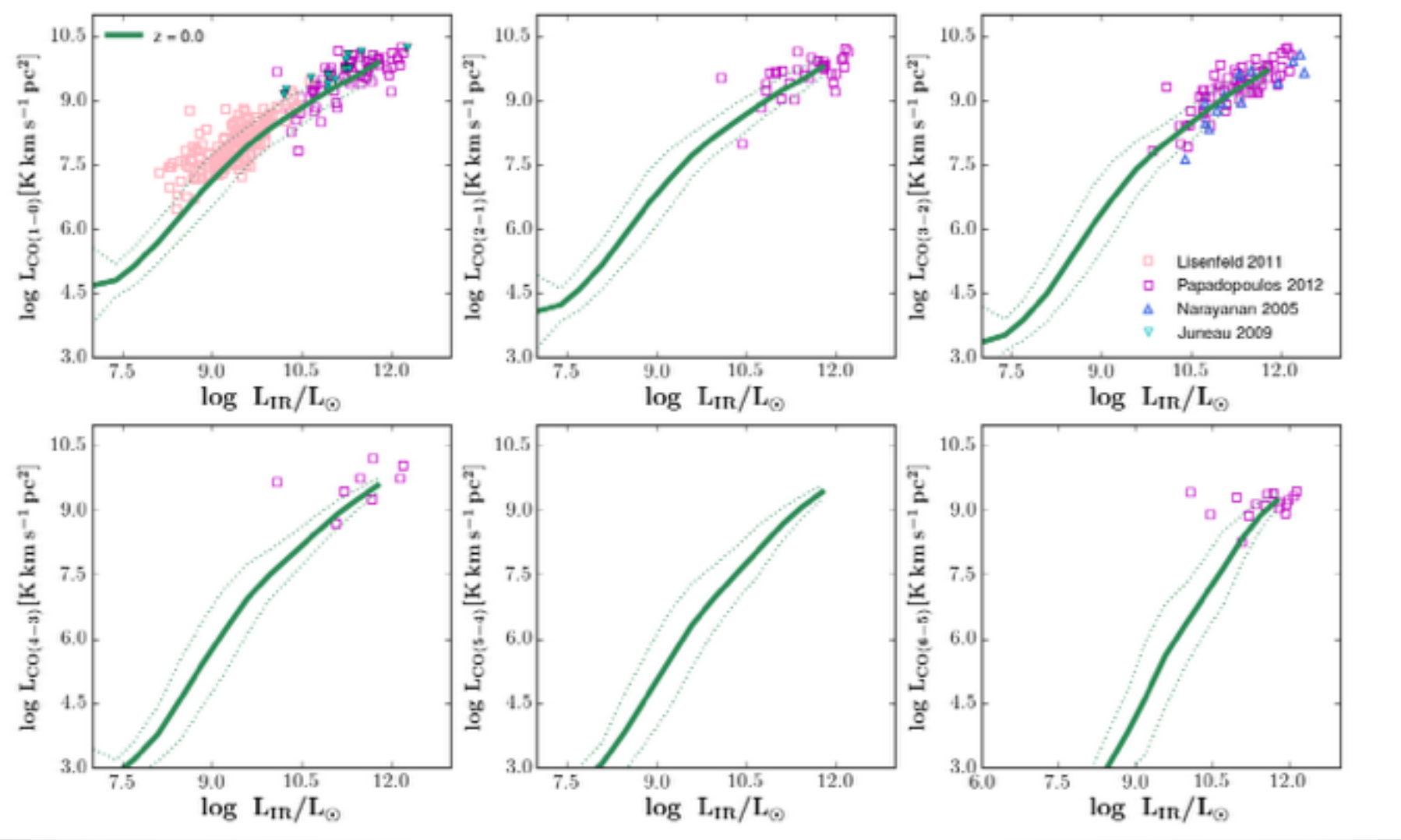
# Part of one bigger problem?




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 2014

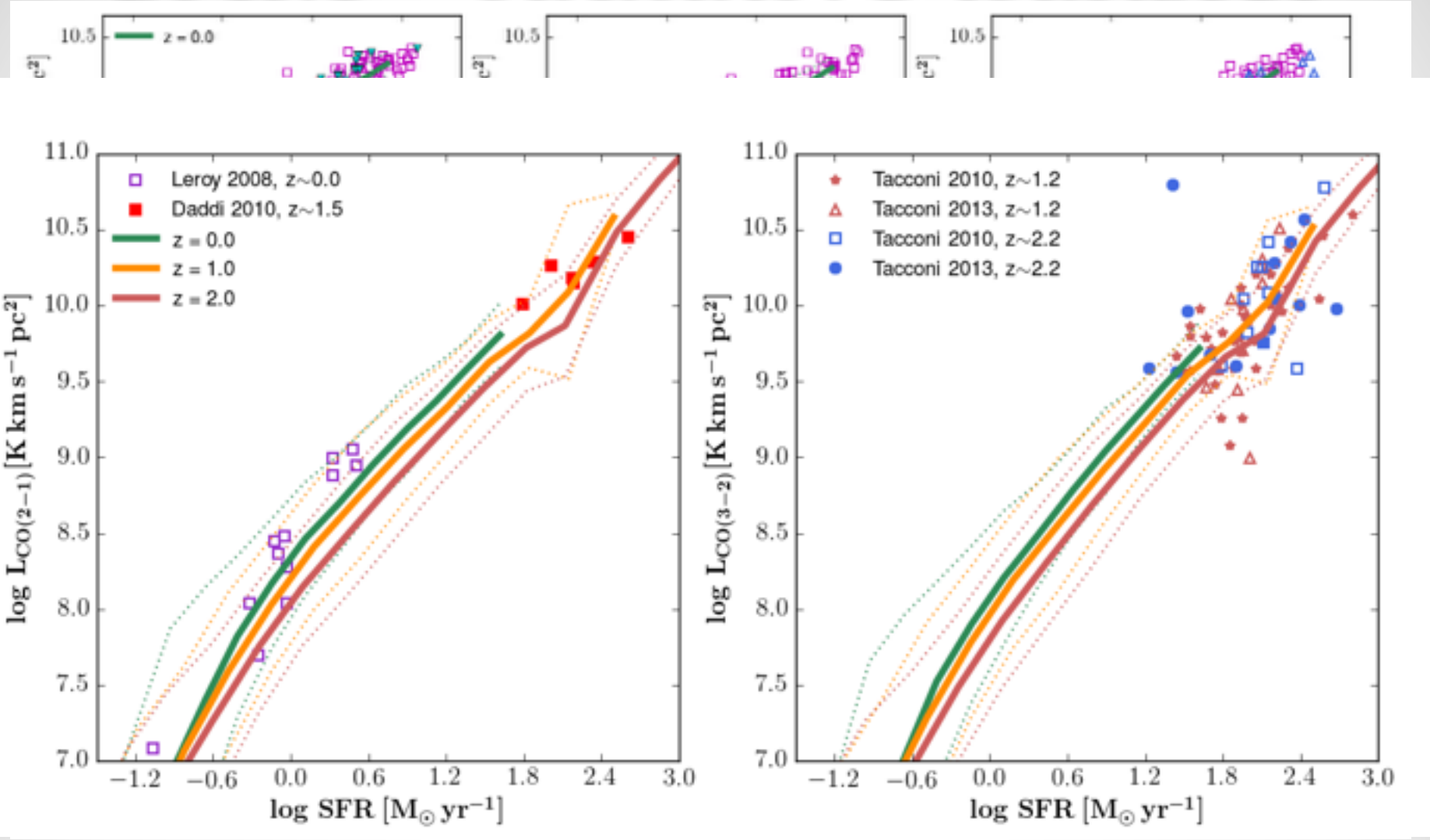
# SAM + radiative transfer




- Emission arising in regions with densities ranging from 10^3 to 10^5 $cm^{-3}$

Popping et al. 2014b

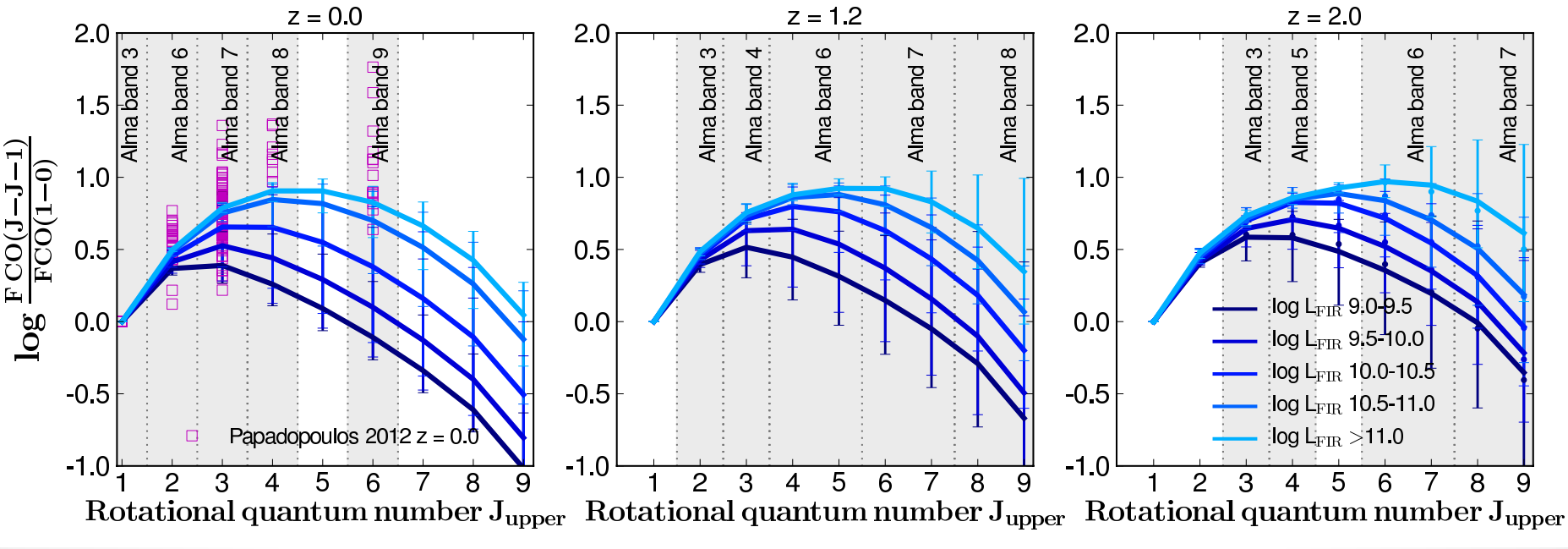
# SAM + radiative transfer




- Emission arising in regions with densities ranging from 10^3 to 10^5 cm$^{-3}$

Popping et al. 2014b

# CO SLEDs

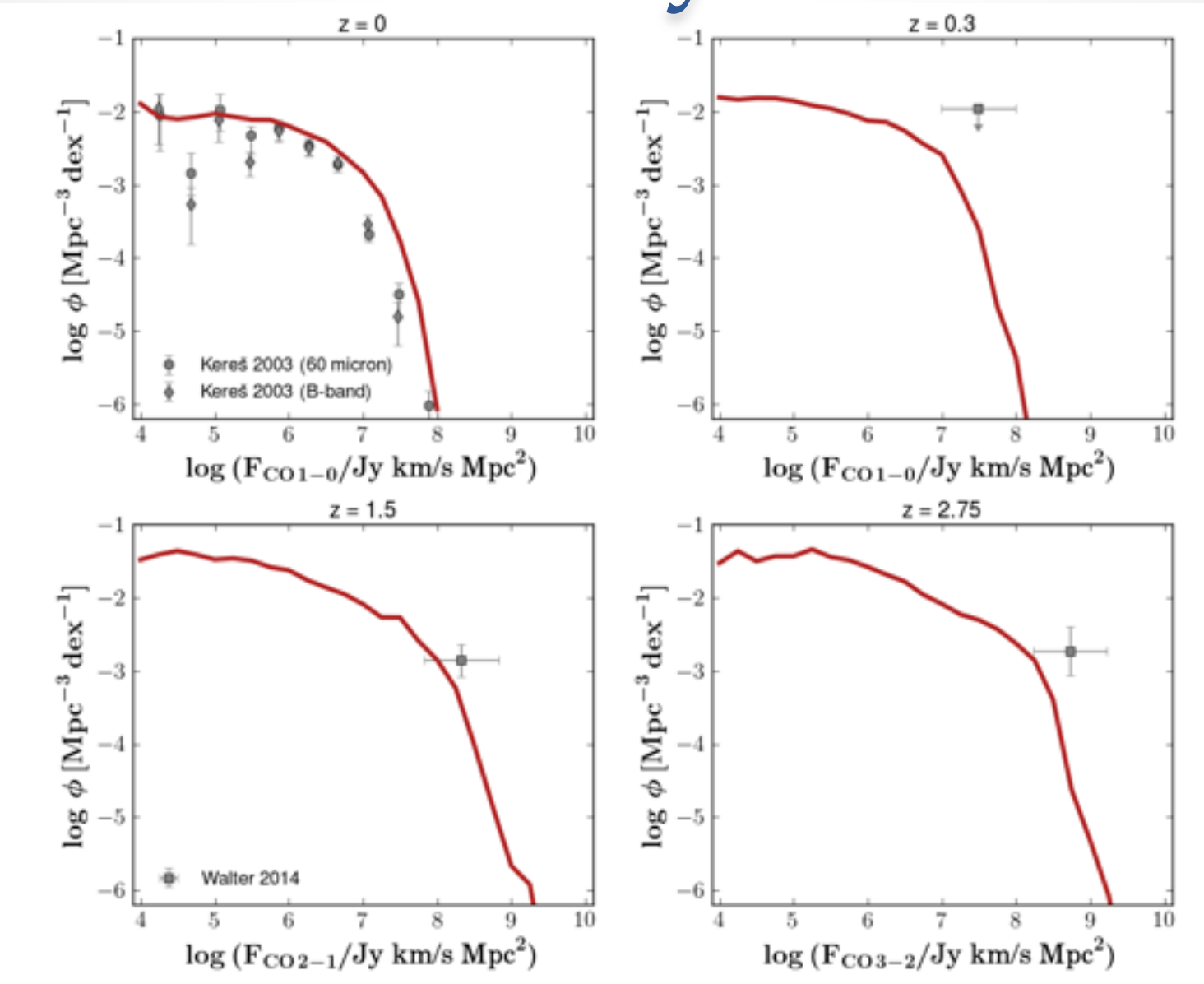



SLEDs peak at higher J-transitions: indicative of *denser* and *warmer* ISM (See also Daddi+ 2014)

To observe this go to high (CO J=5-4 and up) transitions

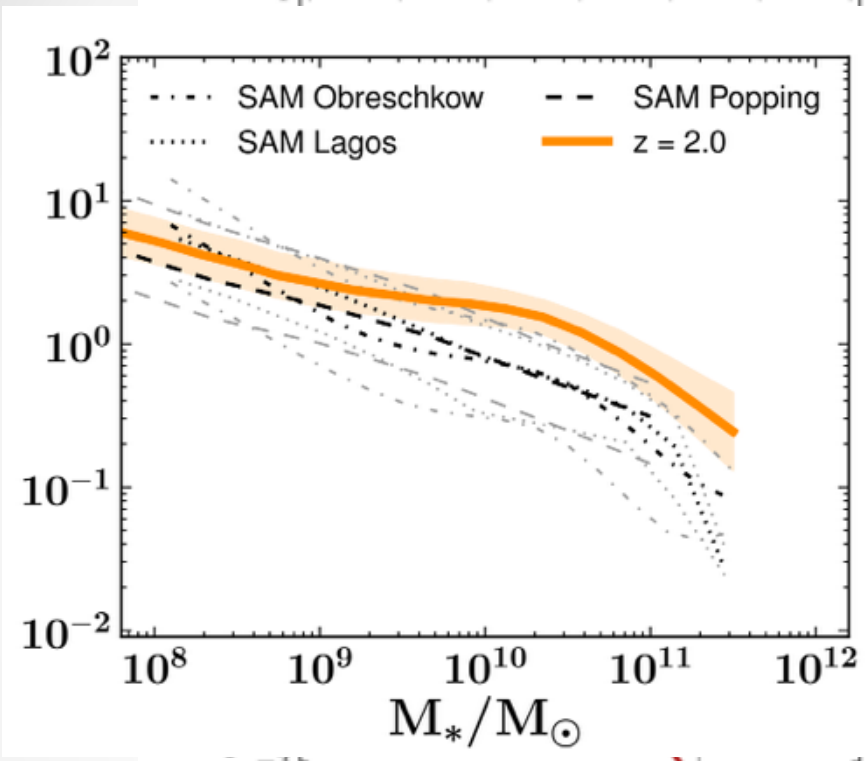
Popping et al. 2014b

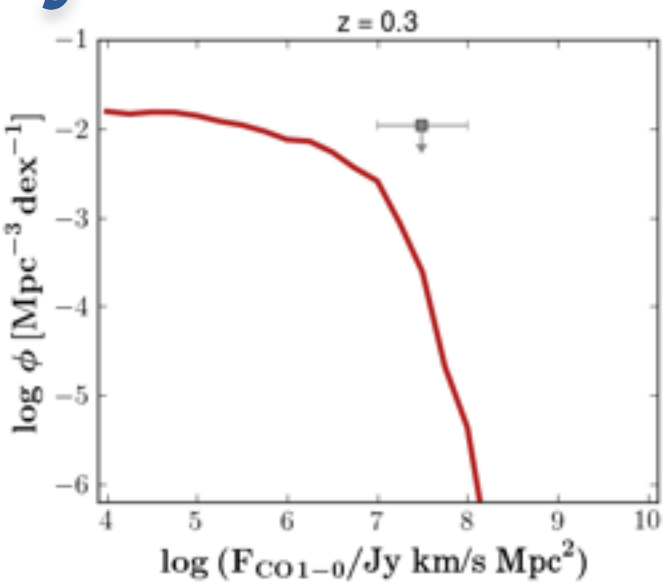
# CO luminosity functions

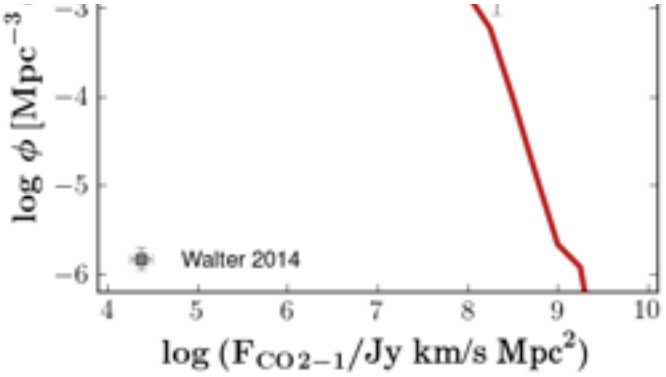


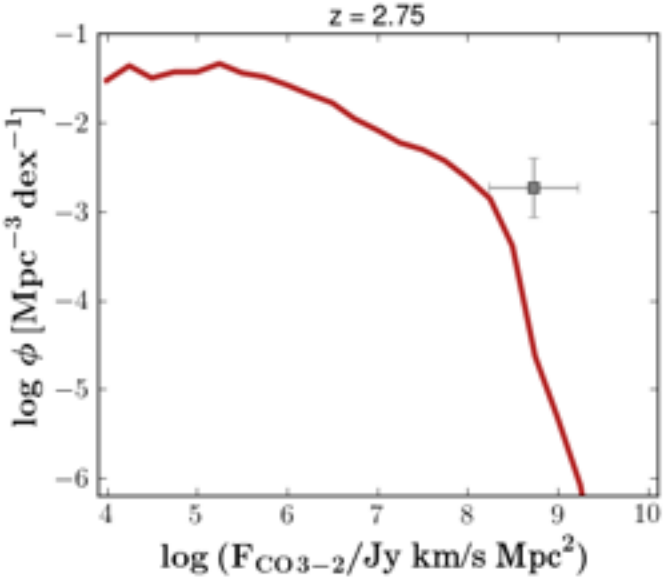

Popping in prep.

# CO luminosity functions



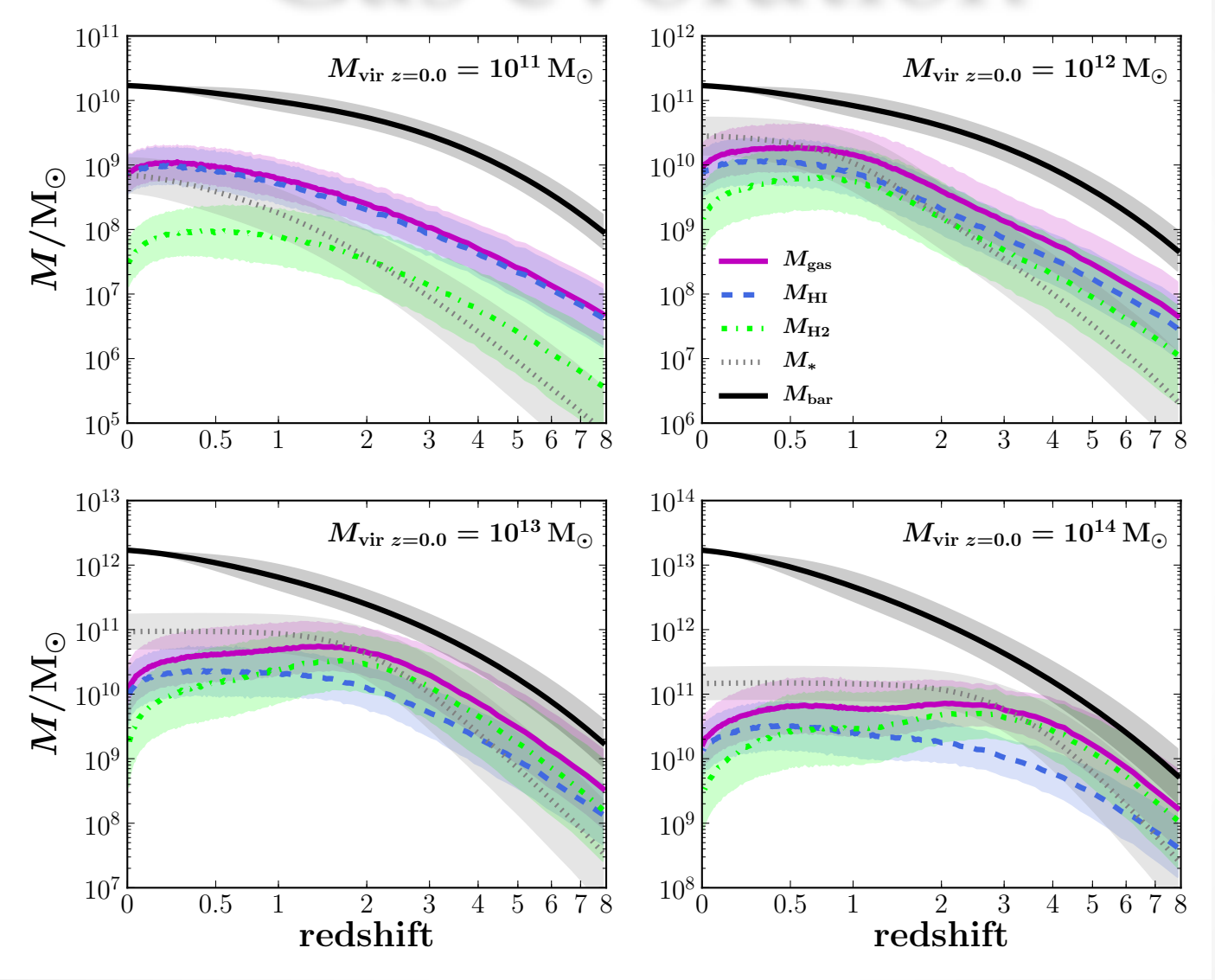

Popping in prep.

# Summary

- The HI mass of galaxies and HI mass function remain relatively constant at $z < 2$
- The H2 mass and mass function decrease by over an order of magnitude during the same epoch.
- The CO SLED of galaxies evolves with FIR brightness and cosmic time. Need to focus on high-density tracers
- Models successfully reproduce CO luminosities and luminosity functions
- Models do not predict enough gas at intermediate redshifts

# Thank you

# Gas evolution

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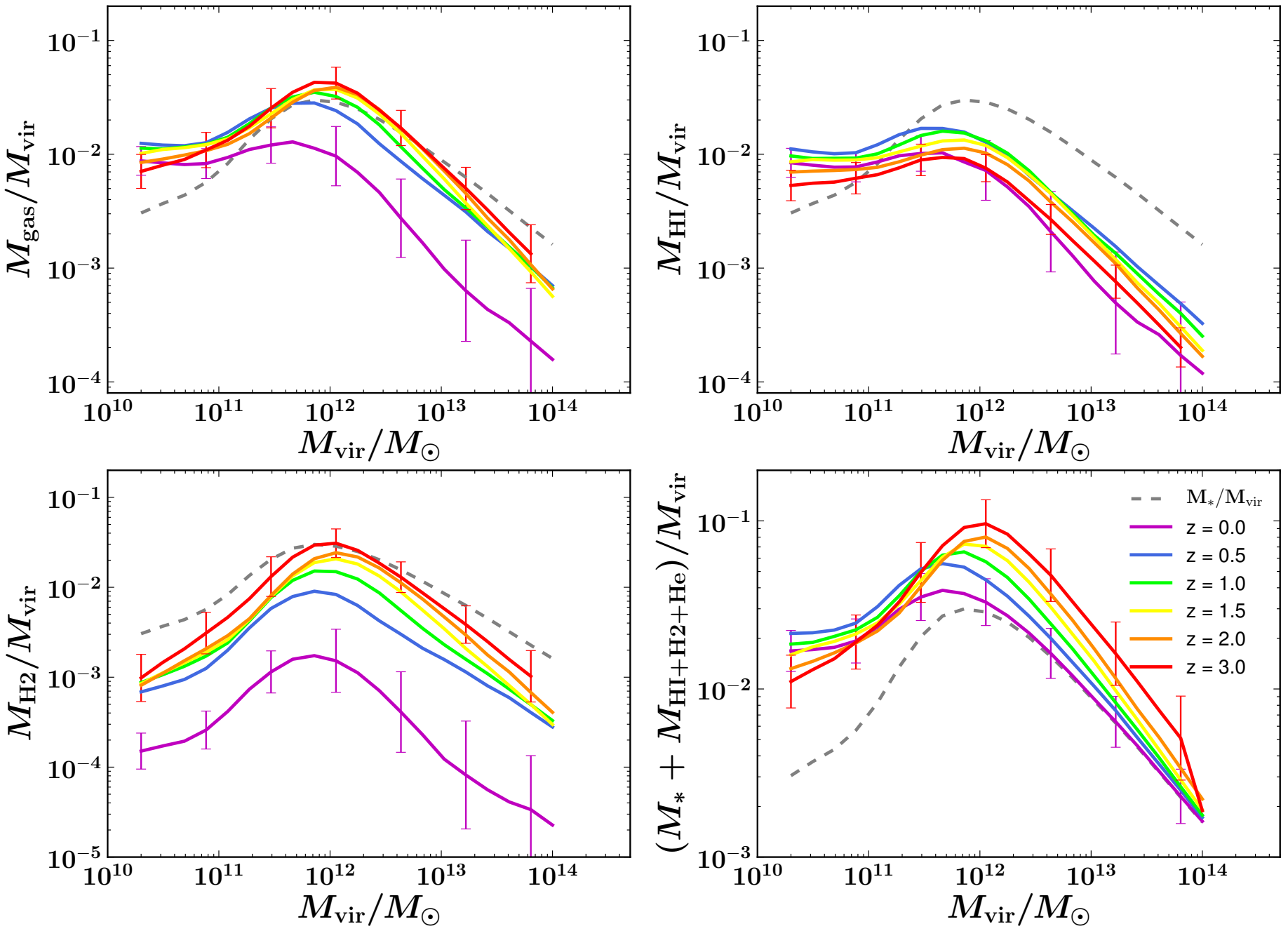
$M_{\rm gas}/M_{\rm vir}$
$M_{\rm HI}/M_{\rm vir}$
$M_{\rm H2}/M_{\rm vir}$
$(M_* + M_{\rm HI+H2+He})/M_{\rm vir}$
$M_{\rm vir}/M_\odot$
$M_*/M_{\rm vir}$
z = 0.0
z = 0.5
z = 1.0
z = 1.5
z = 2.0
z = 3.0