The Cycle of Stars, Gas and Metals in Models of Galaxy Formation

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with thanks to Matias Arrigoni, Mike Berry, Cathy Caviglia, Ari Maller, Gergo Popping & Scott Trager

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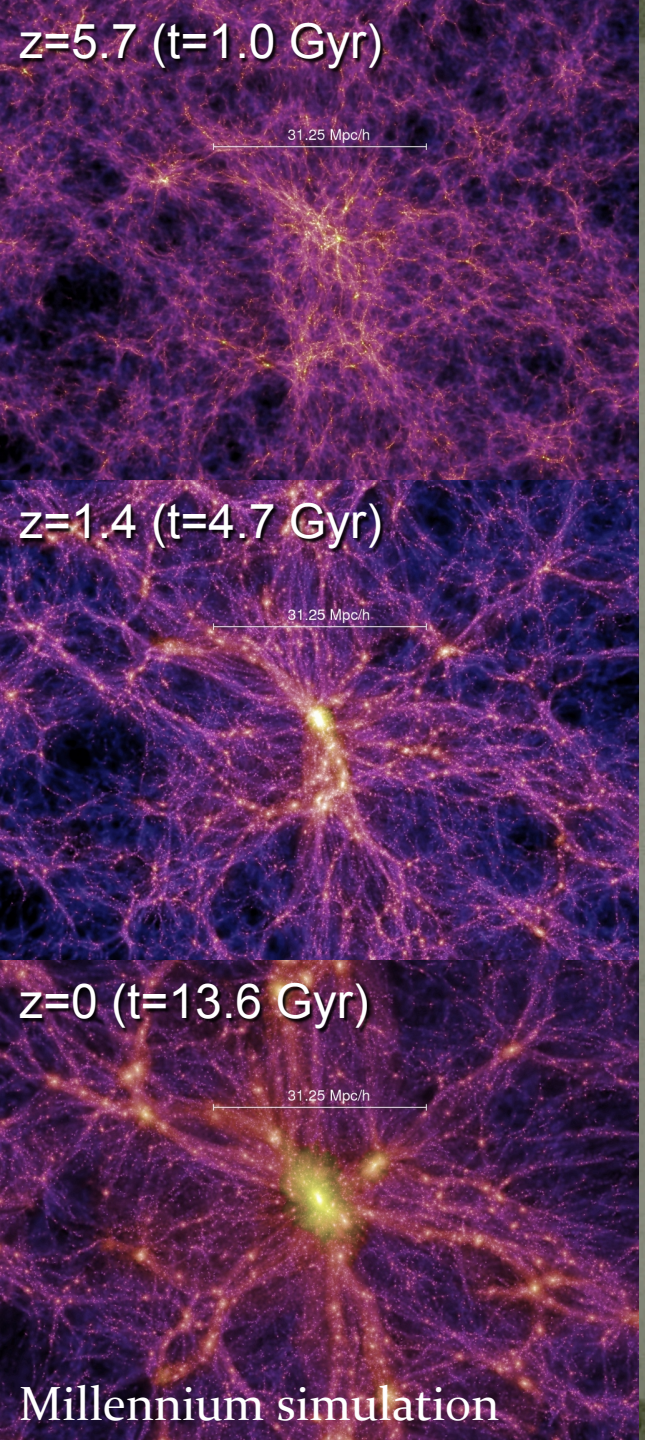
motivation for this talk

- we hear a lot about these “missing baryons”. we all want to know: where are they, and how did they get there?
- if we can build a [physically motivated] model that reproduces the properties of the baryons we *can* see, maybe it can provide some clues to these questions
- unfortunately, this is not as easy as it sounds…



Millennium simulation

Standard ingredients in a galaxy formation model

- gravitationally bound structures (halos) form as predicted by LCDM
- gravity also causes gas to accrete into halos and galaxies
- accretion may be suppressed in halos below the “filtering mass” by the presence of a photoionizing background
- cold dense gas can form stars (Kennicutt relation)
- cold gas is heated and removed from galaxies by stellar & SNae-driven winds
- metals produced by stars enrich cold gas and blown around by winds

large scale galactic outflows

- energy from SNae and massive stars assumed to drive large-scale outflows which remove cold gas from the disk, thus making it (temporarily) unavailable for SF

$$\dot{m}_{out} = \eta \dot{m}_*$$

$$\eta = \varepsilon (V_0 / V_c)^{\alpha}$$

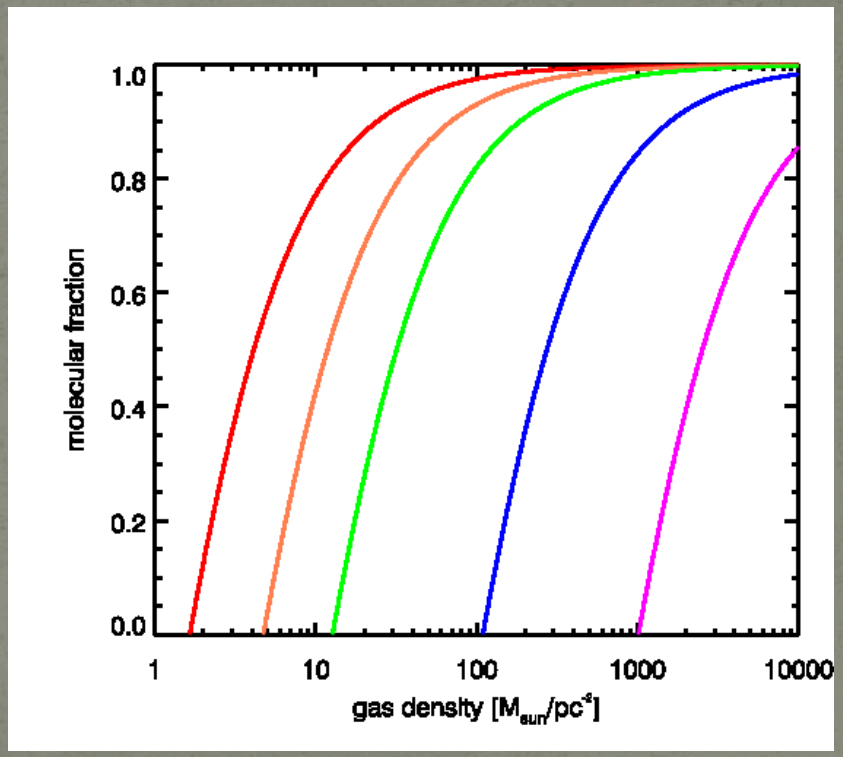
α=1 "momentum driven"
α=2 "energy driven"

typically ε~1-2
V_0~200 km/s

Kauffmann et al. 1994; rss & Primack 1998
Murray, Quataert & Thompson 2005
Oppenheimer & Dave' 2007

Tracking molecular hydrogen

- H_2 fraction depends on gas density, amount of dust (metallicity) and intensity of UV radiation



Z=1.0
0.3
0.1
0.01
0.001

see also
Gnedin & Kravtsov 2010;
Robertson & Kravtsov 2009

Krumholz, McKee & Tumlinson 2008a,b, 2009
McKee & Krumholz 2010; Krumholz & Dekel 2011

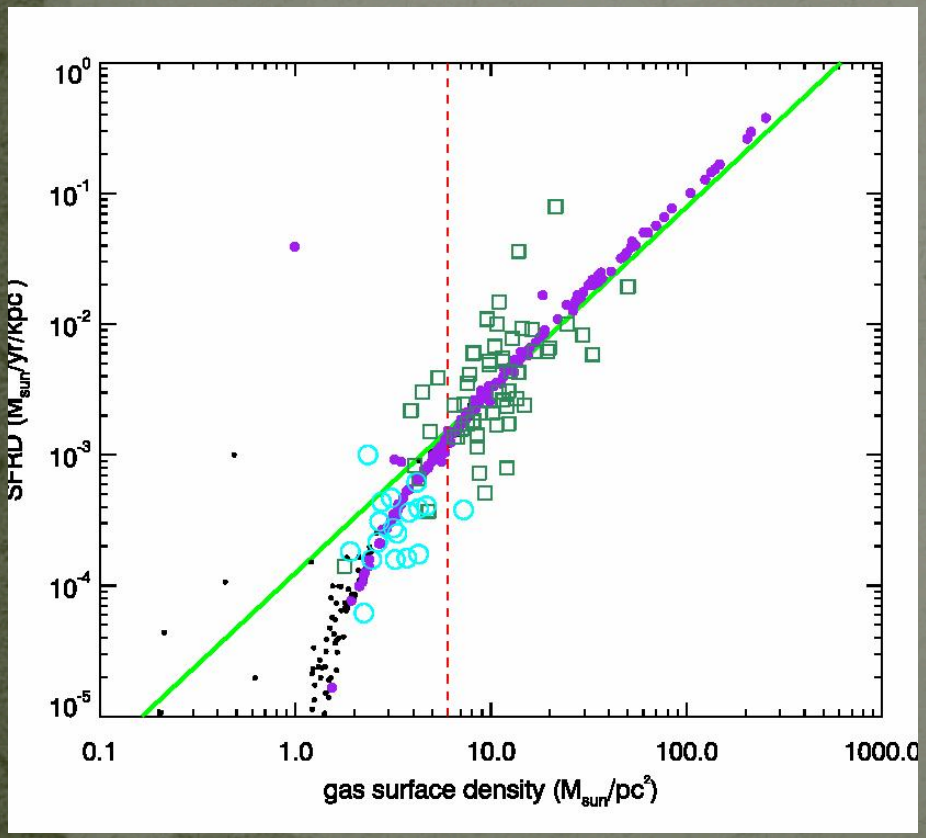
Implementation in SAM

- disk sizes modelled using standard angular momentum conservation arguments + adiabatic contraction
- assume that total gas radial density distribution within each disk is described by an exponential
- dust-to-gas propto cold-phase metallicity; IGM "pre-enriched" to 10^{-3} Z_{sun} by Pop III stars
- compute $f(H_2)$ and corresponding SFRD at each timestep (do not track formation/consumption/destruction)
- stars form in H2 with ~constant efficiency/timescale (Bigiel et al. 2008)

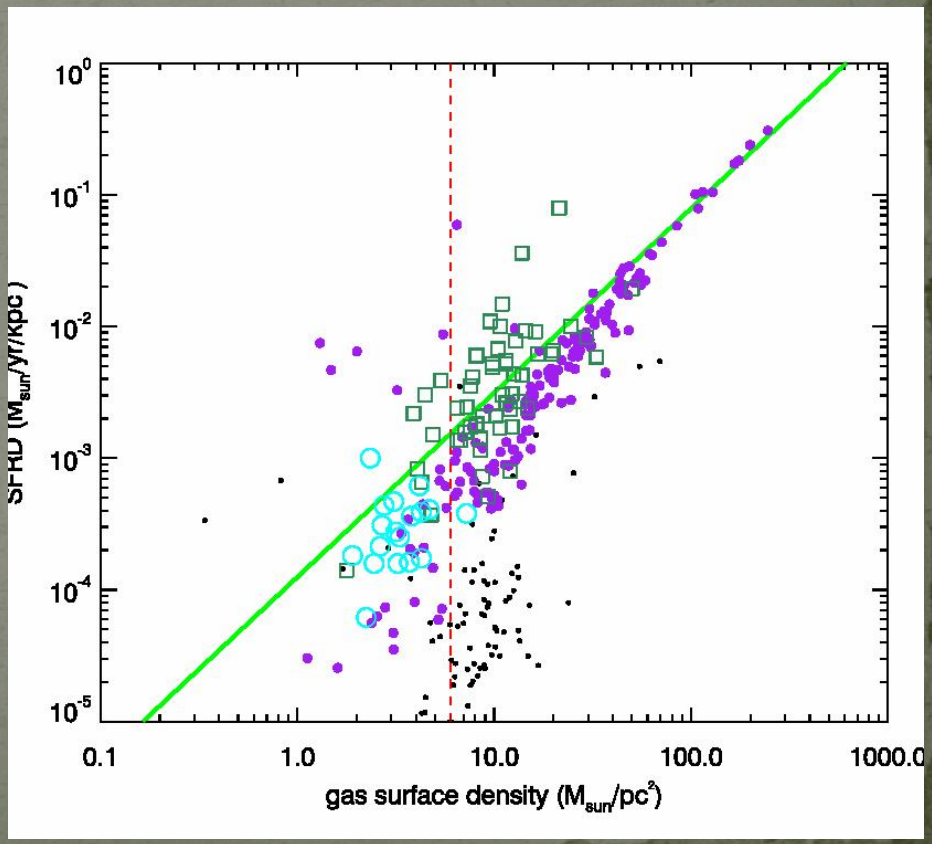
rss, Popping & Trager; Popping, rss & Trager in prep

KENNICUTT-SCHMIDT RELATION

Kennicutt + threshold

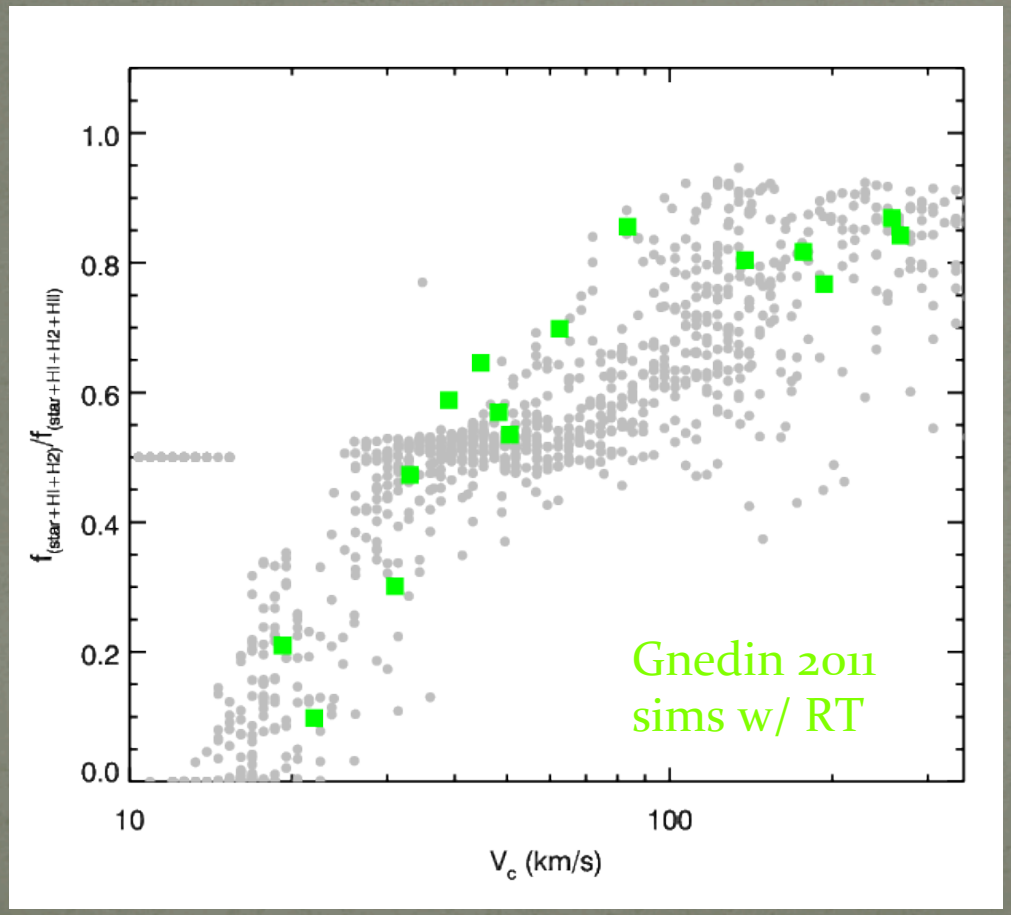


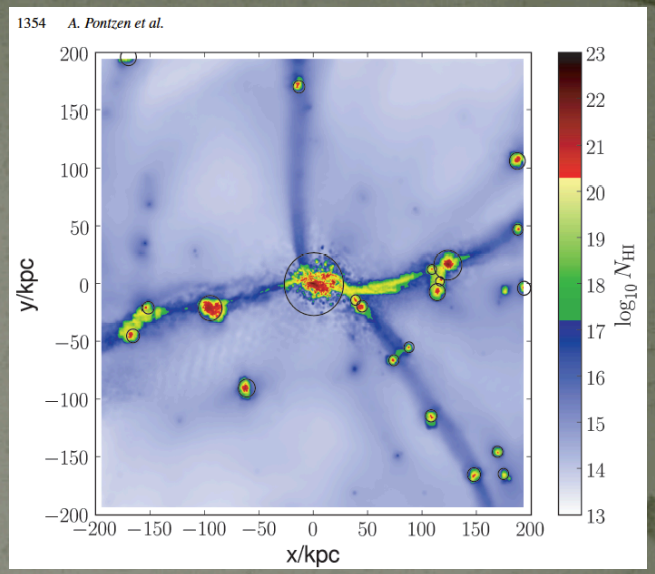
Z-dependent H2-based recipe



What about ionized gas within halos/galaxies?

(stars+HI+H2)/(stars+HI+H2+HII)





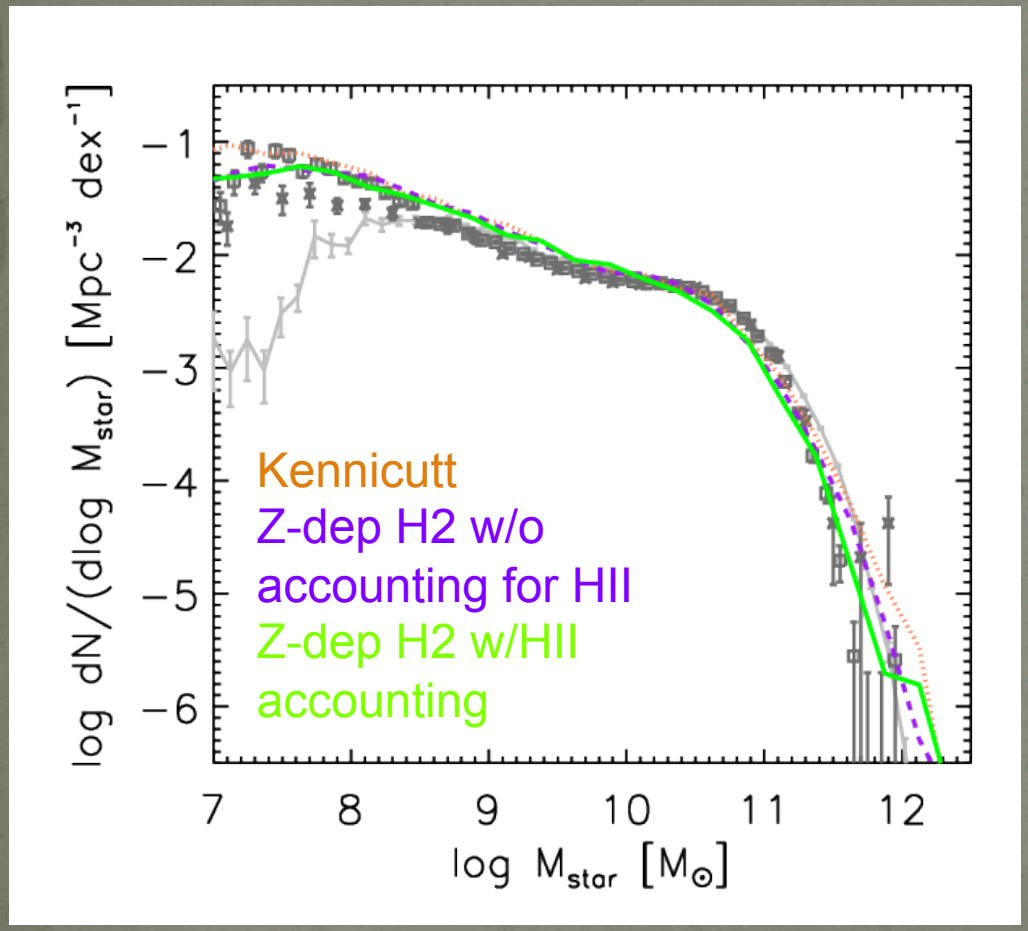
Pontzen et al. 2008

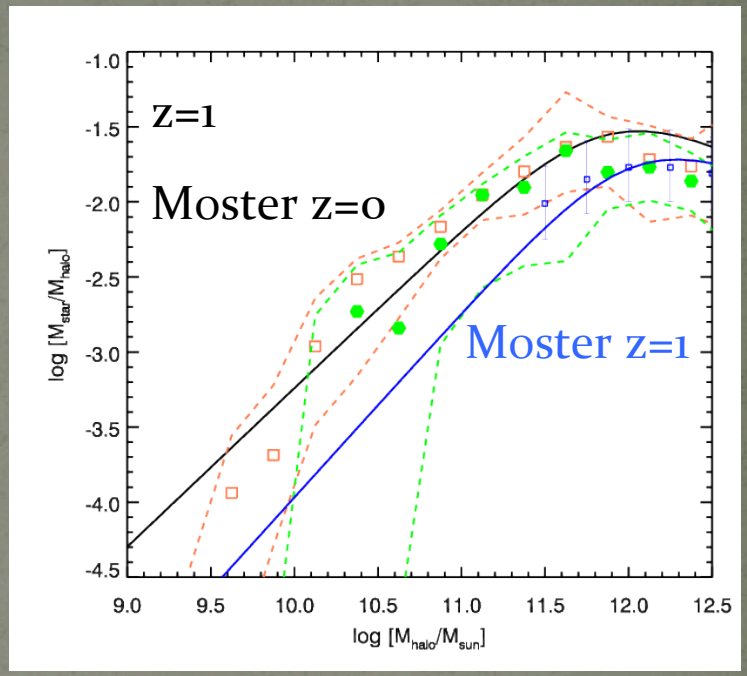
simple model: all gas below a critical surface density (above & below disk, and in outer disk) is ionized by the external background +constant fraction is ionized by internal sources

observational targets

- stellar fraction vs. halo mass (SMF/LF)
- gas fractions vs. stellar mass
- SSFR vs stellar mass ("star forming main sequence")
- mass-metallicity relation (MZR)
- all of the above, as function of cosmic time…

SHMF basically unchanged (due to self-regulated SF)
-still require very strong stellar-driven outflows to match stellar mass function
-still overproduce stellar fractions/numbers of low mass galaxies @ high-z



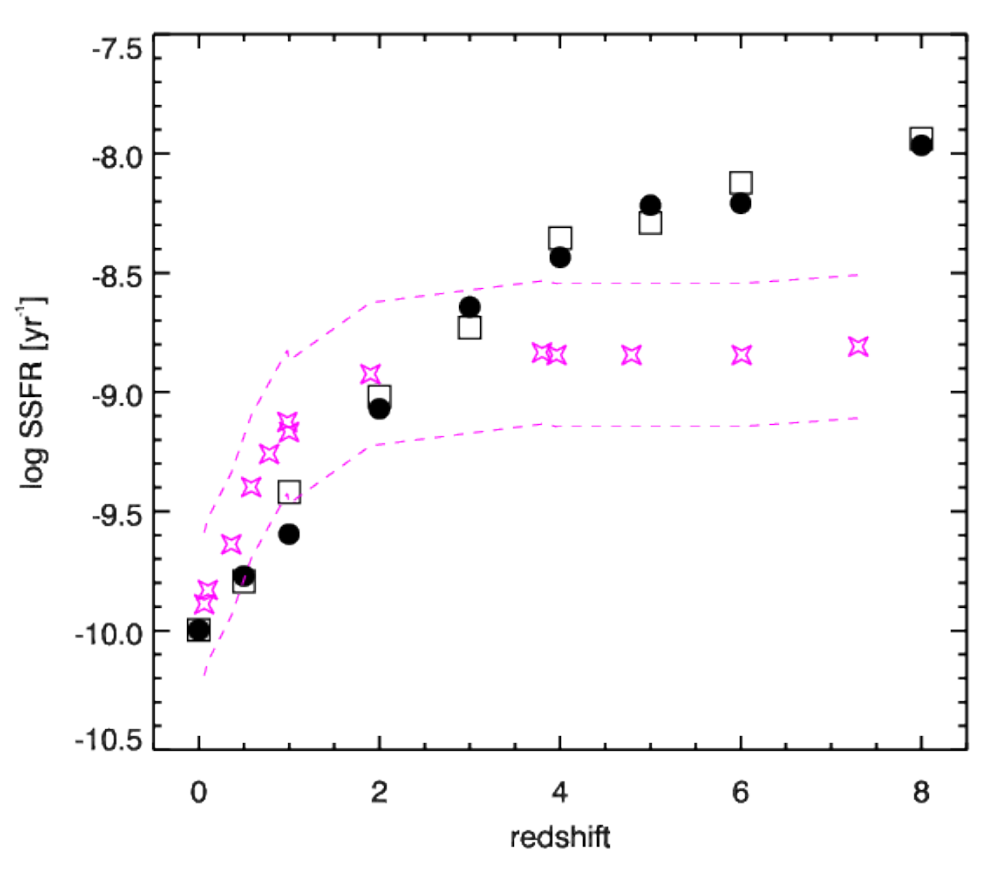


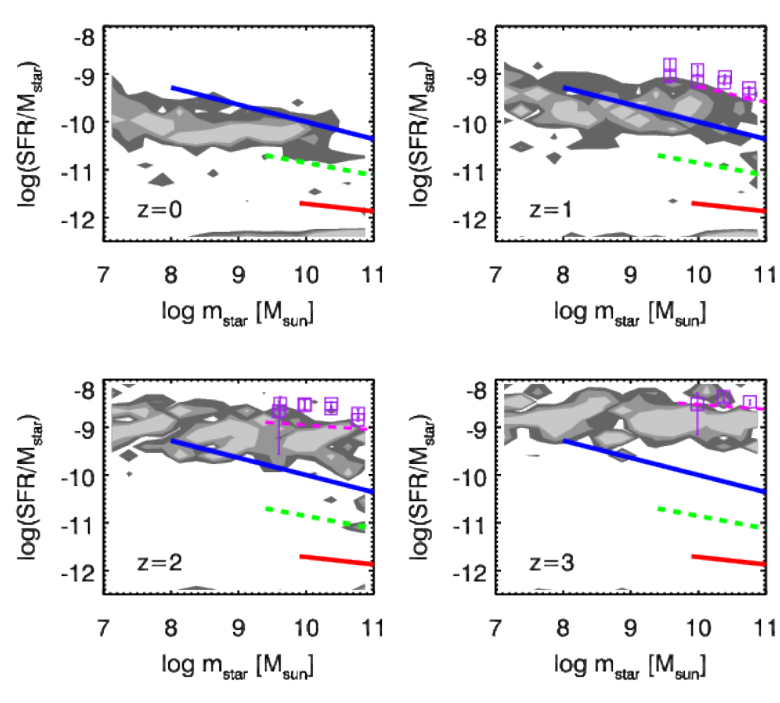
see also Fontanot et al. 2009
Santini et al. 2011
Guo et al. 2011
Fu, Kauffmann et al. 2012
Caviglia, rss et al. in prep

n.b. "root halo" mass limit 5.0E08 M_{sun}, followed down to 5.0E06 M_{sun}

rss, Popping & Trager in prep

sSFR's too low at low z and too high at high z...sSFR vs. mass relation too flat at all redshifts...





Z-dep H2 model with HII accounting

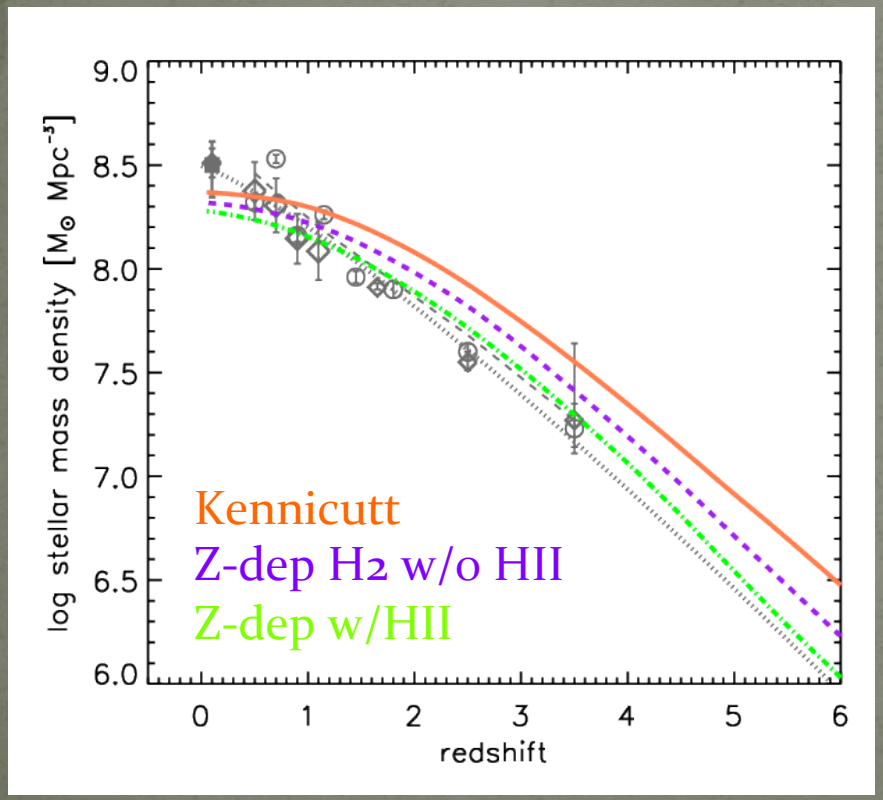
slope ~traces specific gas accretion rate

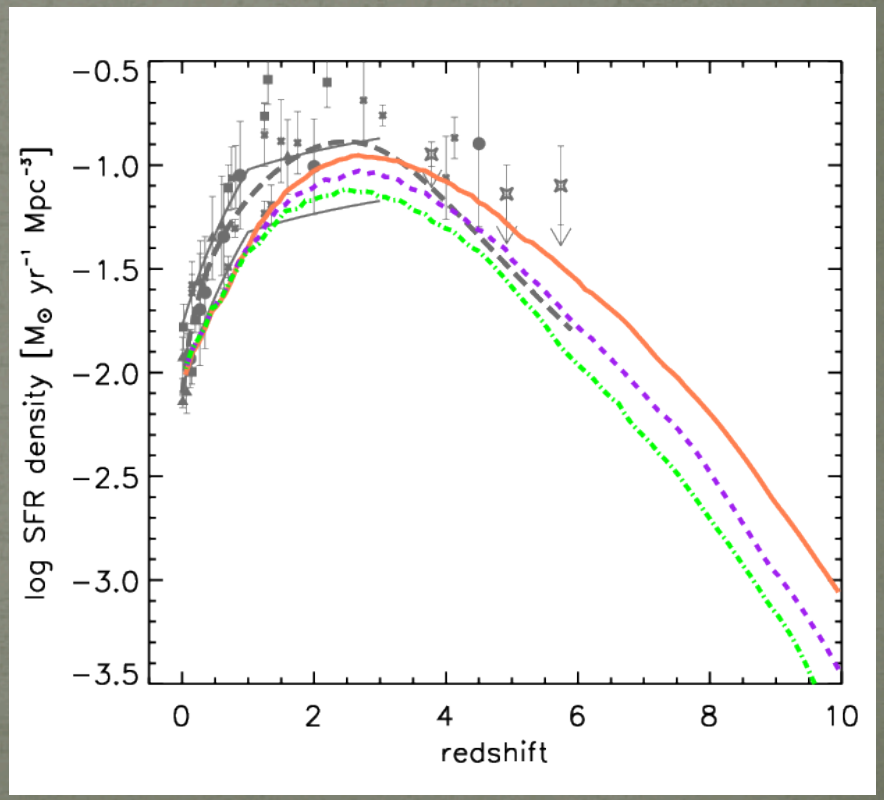
see also
Dutton et al. 2008
Weinmann et al. 2011
contrast Krumholz & Dekel 2011

rss, Popping & Trager in prep

global stellar mass assembly and star formation history

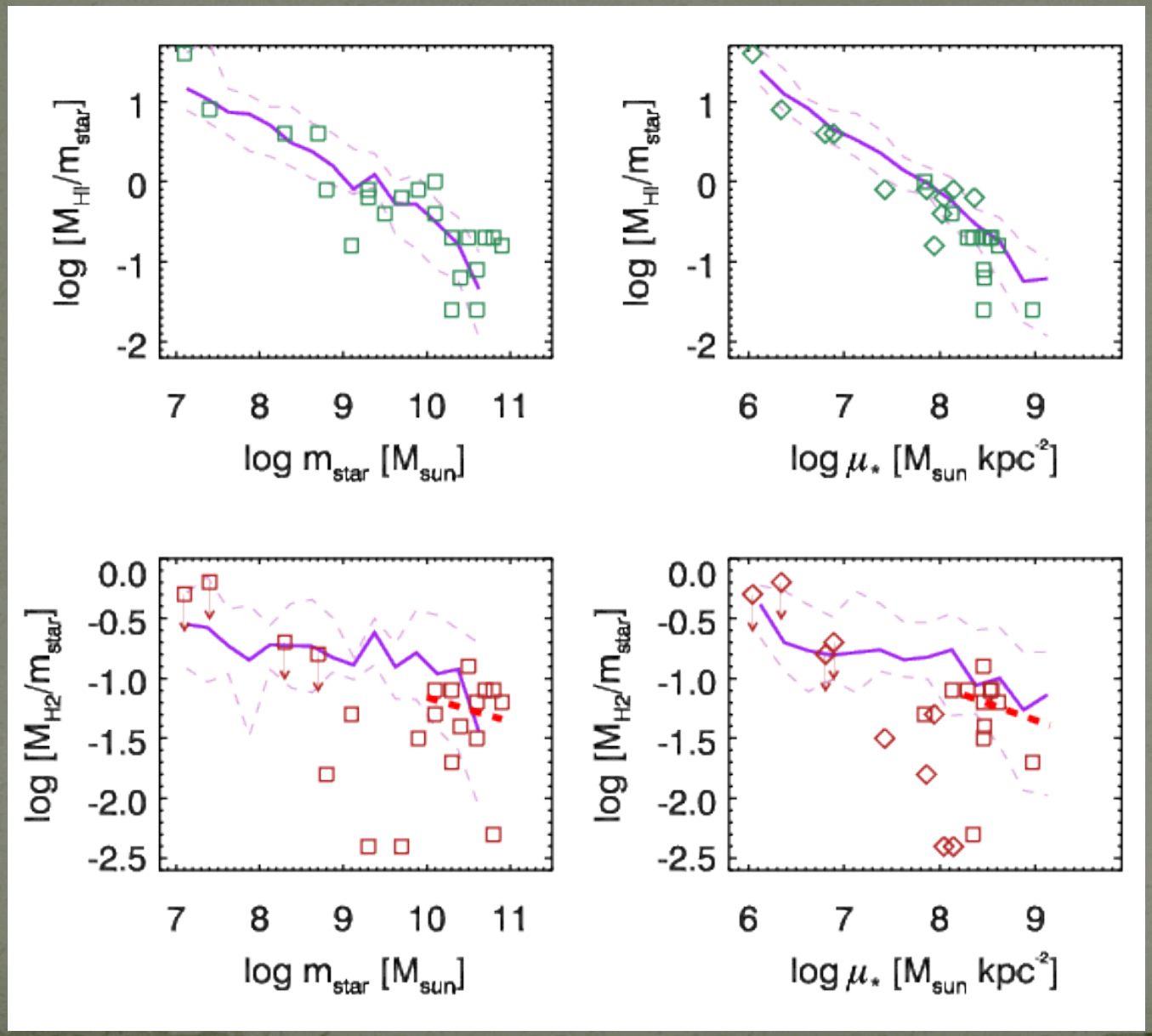
new models appear better...but misleading because we have actually reduced the number of high mass galaxies at high redshift, in conflict with observations





rss, Popping & Trager in prep

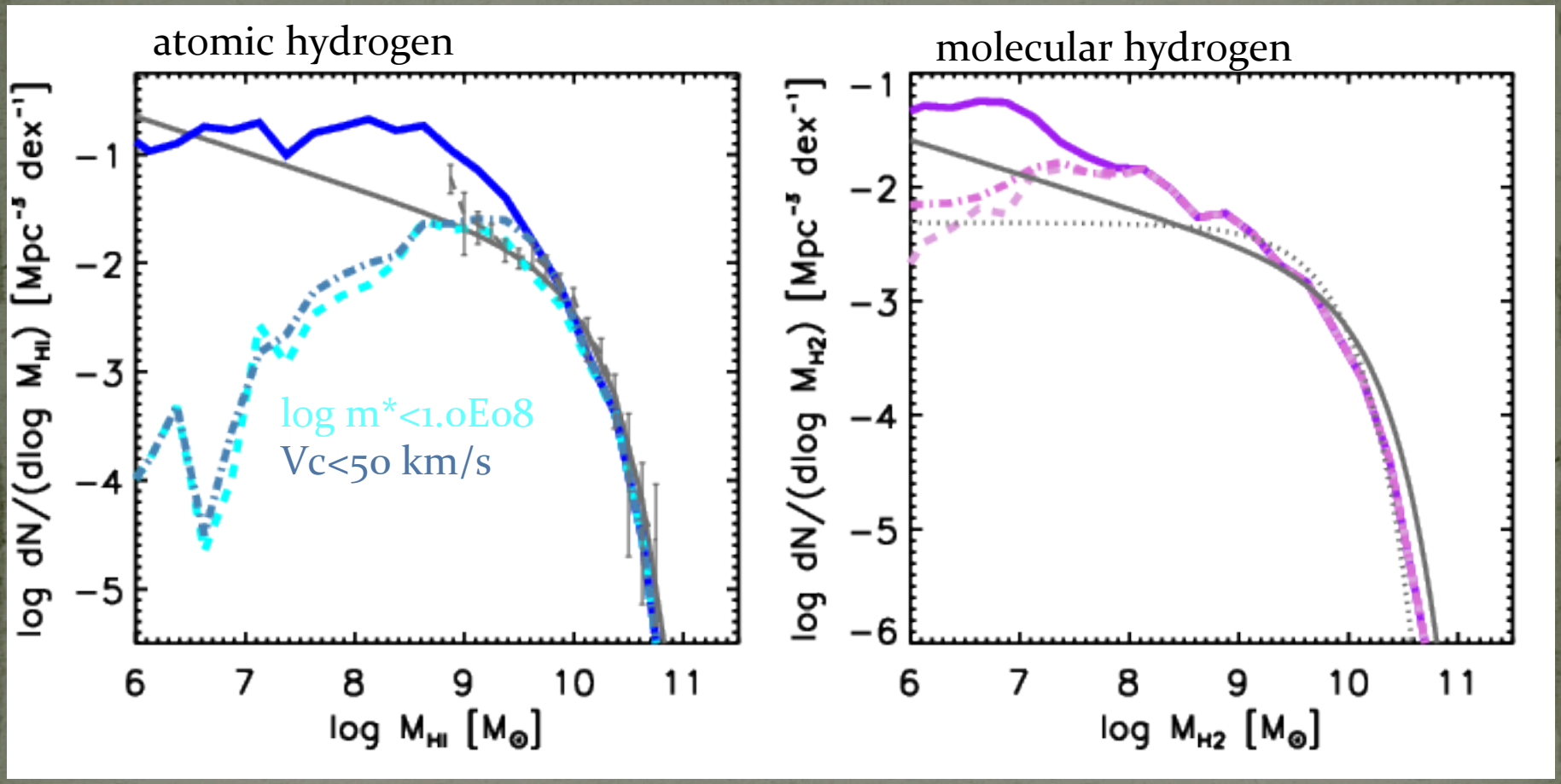
match scaling relations for HI and H2 at z=0



Popping, rss
& Trager in prep

observations
from THINGS
and COLDGASS

cold gas mass functions z=0

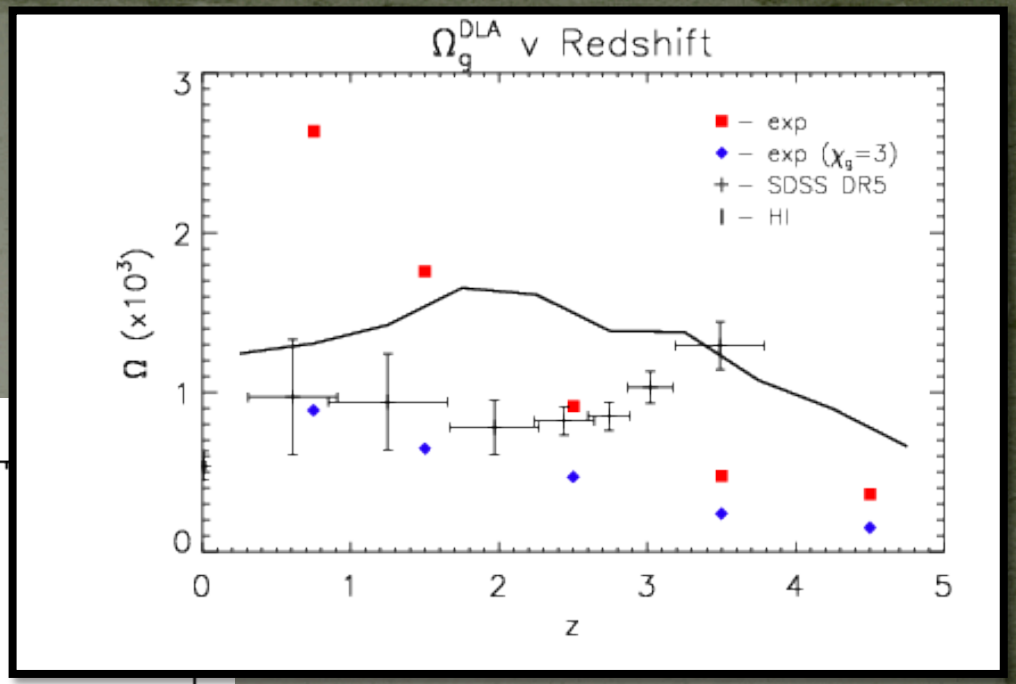


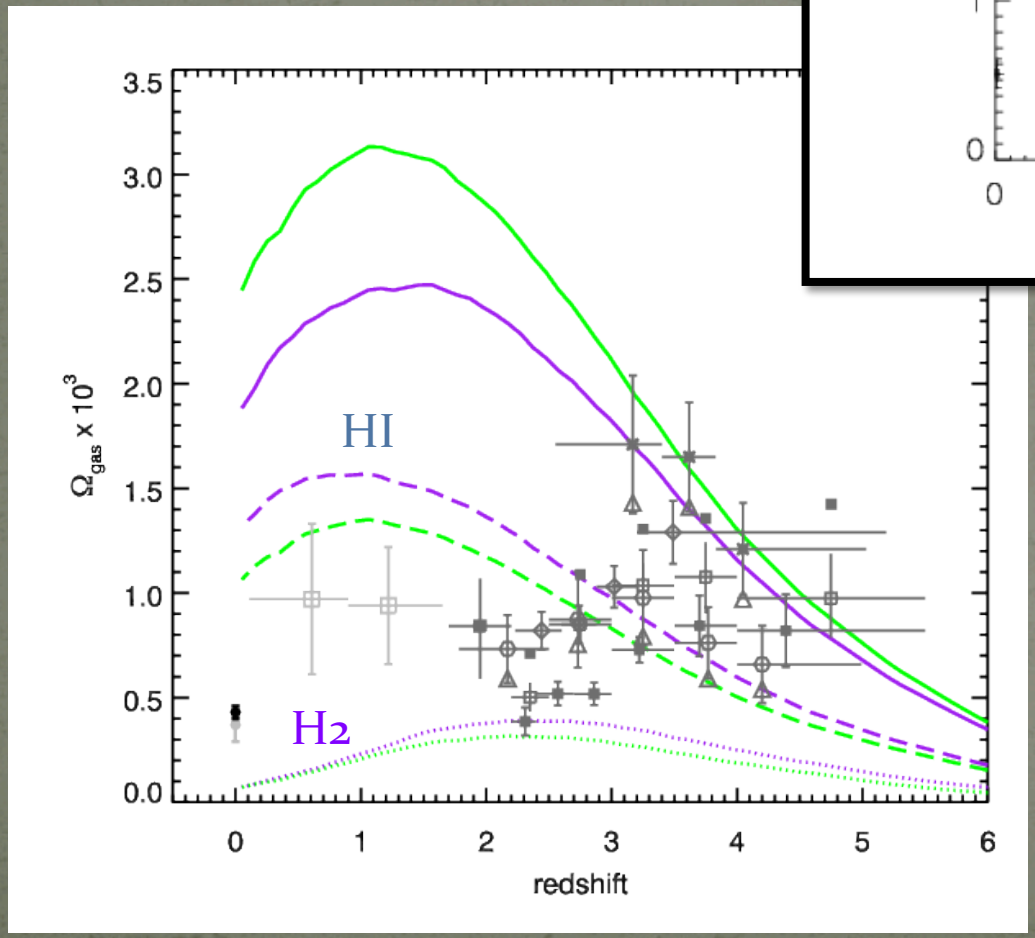
observations: Martin et al. 2010 (ALFALFA); Keres et al. 2003

Popping, rss & Trager in prep

models appear to consume or expel too much gas at high redshift

"goddess"-eye view of cold gas



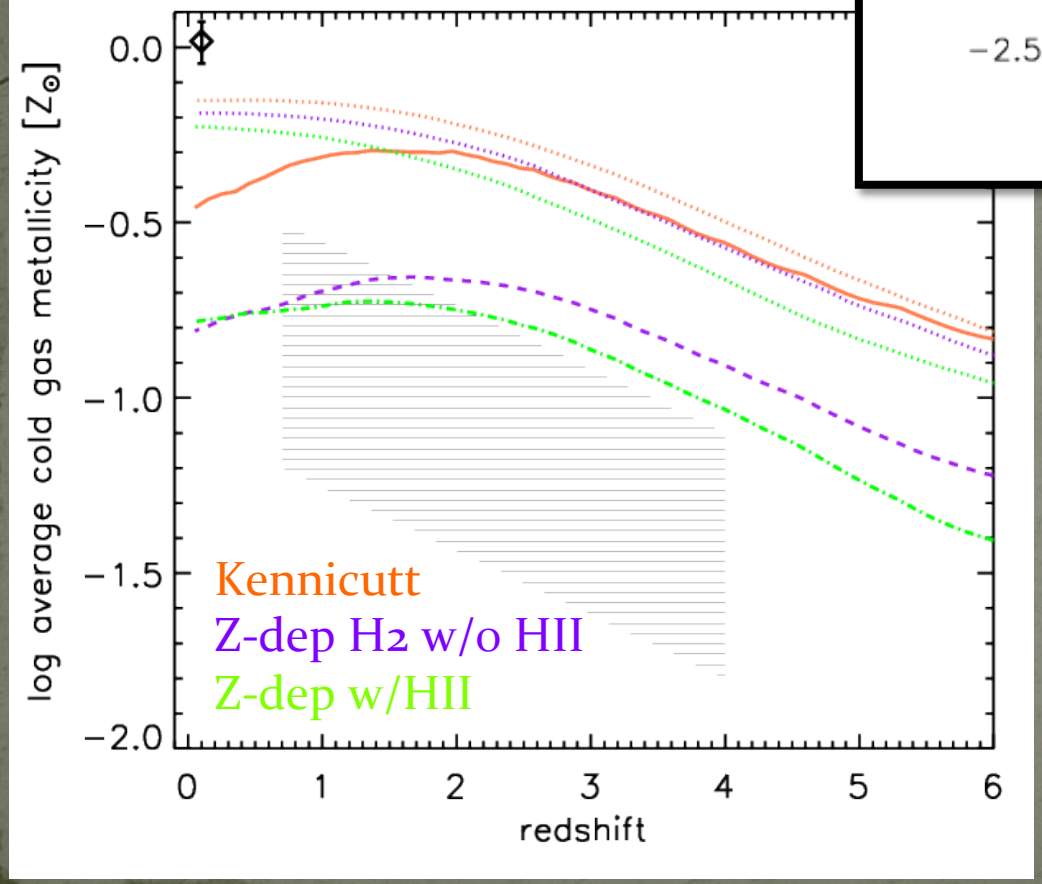


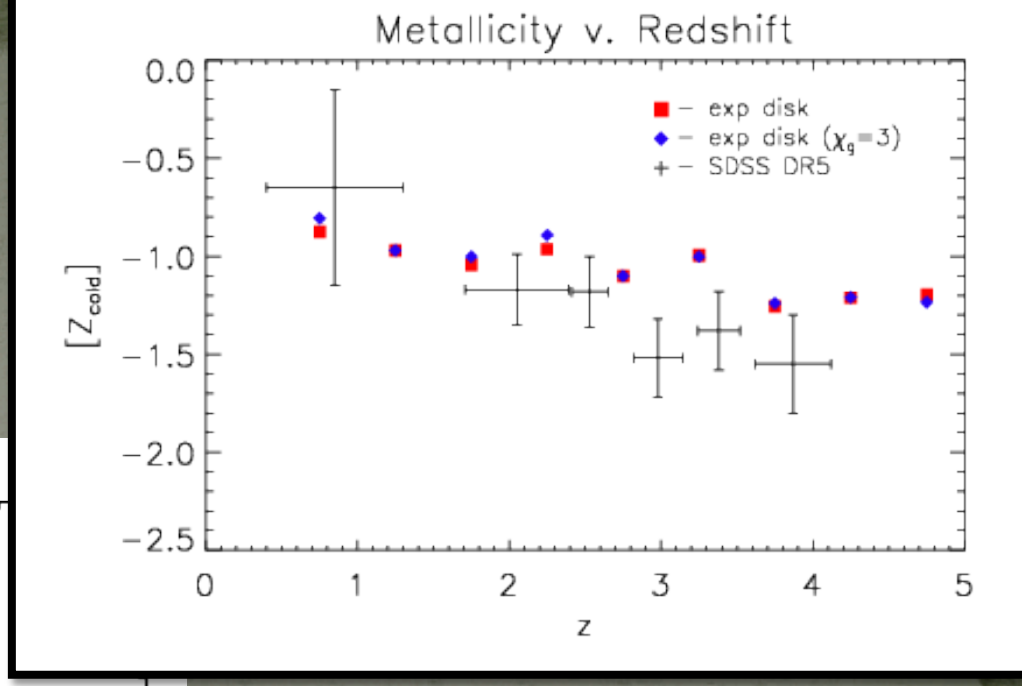
gas from mock DLA "observations"
Berry, rss, Maller & Gawiser in prep

Z-dep SF
Z-dep SF w/ HII accounting

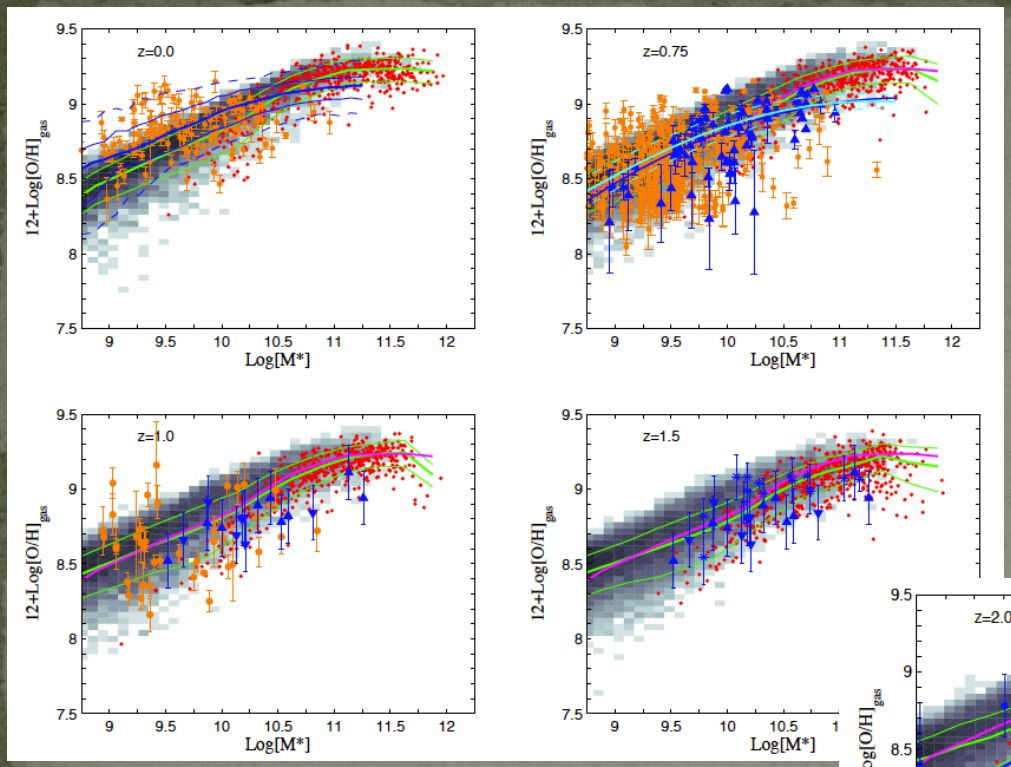
gas appears to get enriched too early--this is alleviated in new models with Z-dep H2-based SF recipe and by doing mock DLA-selection

goddess-eye view



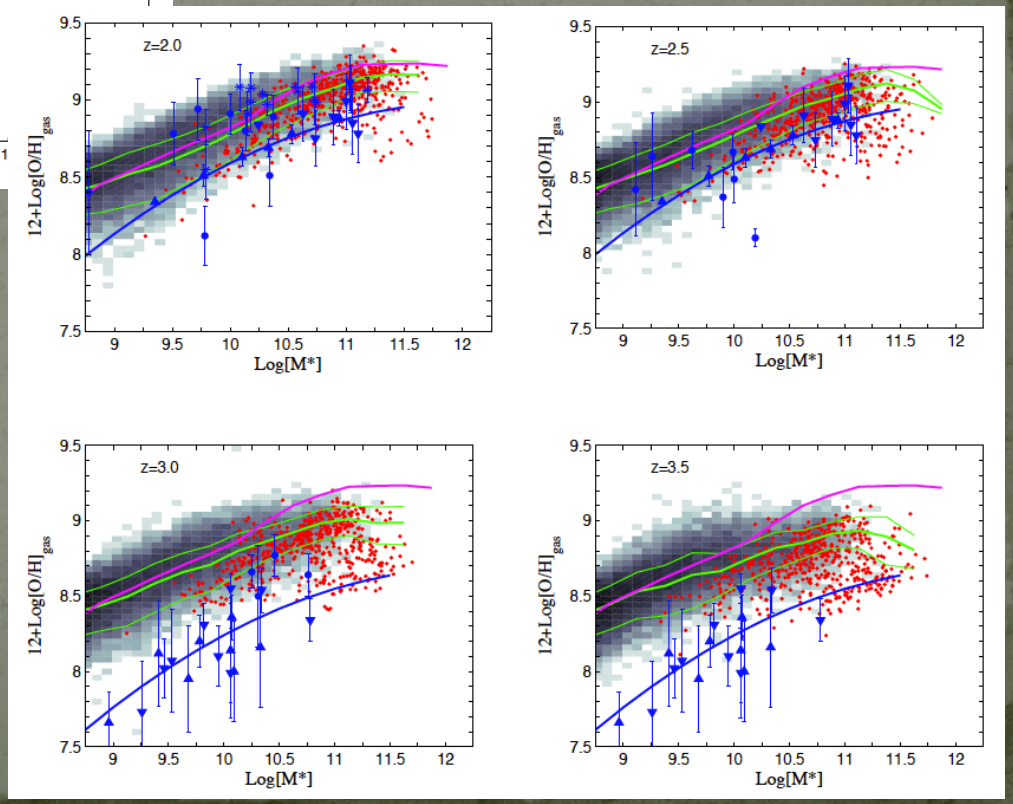


DLA-selected view
Berry, rss et al. in prep



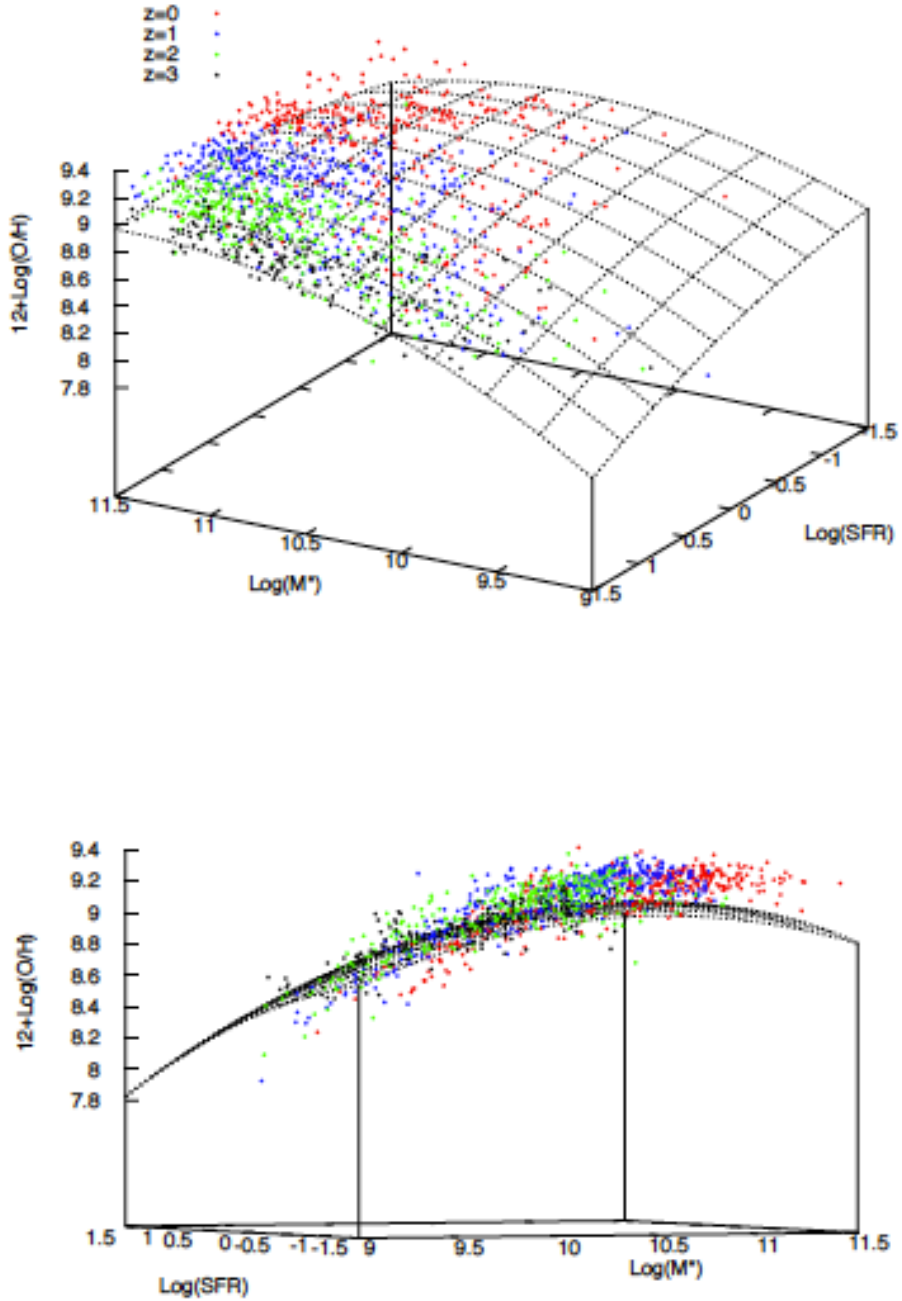
Galactic Chemical Enrichment models (SNae II & Ia) coupled with SAM

(low mass) model galaxies appear to be too enriched at high redshift



(these results are for the "classical Kennicutt" model)

Arrigoni, Trager, rss & Popping 2012

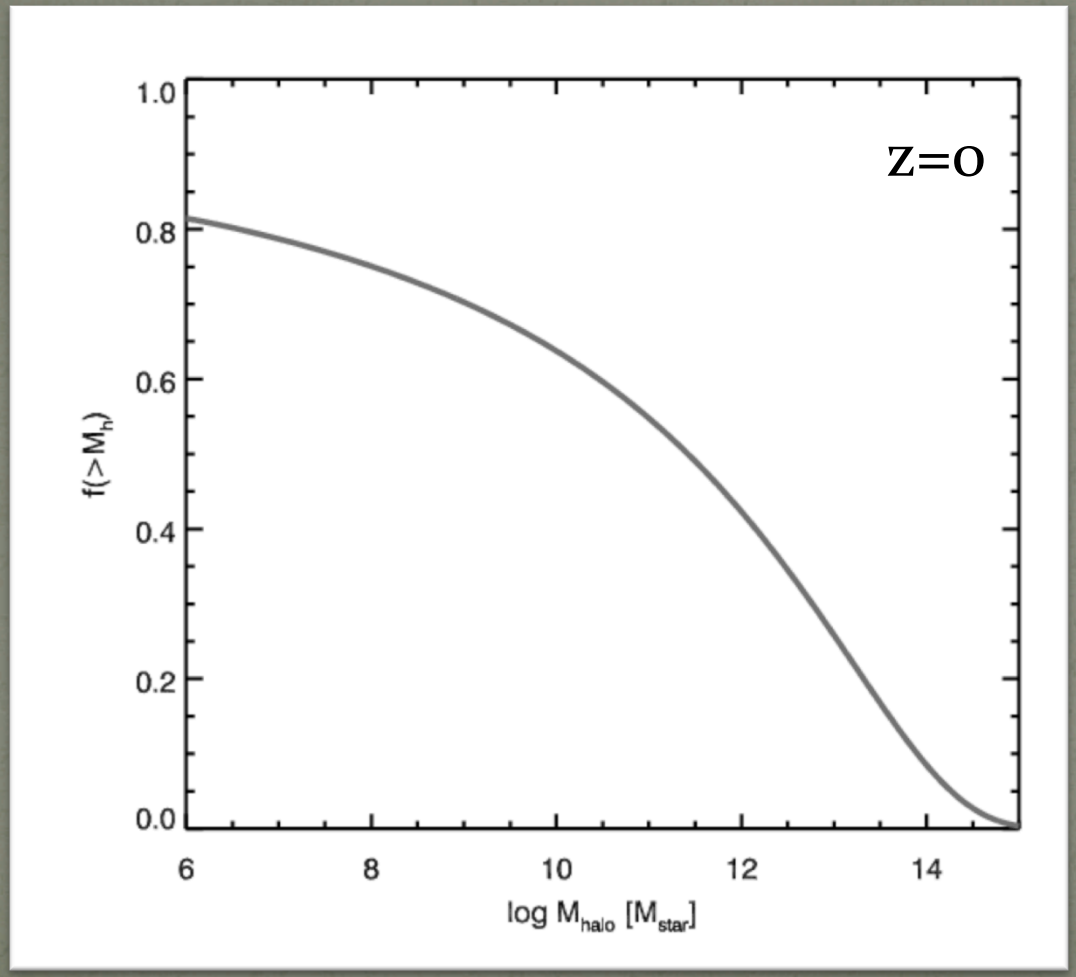


but interestingly, the model galaxies *do* seem to lie on (and evolve along) the "Fundamental M-Z-SFR Plane" (Mannucci et al. 2010)!

Arrigoni, Trager, rss & Popping 2012

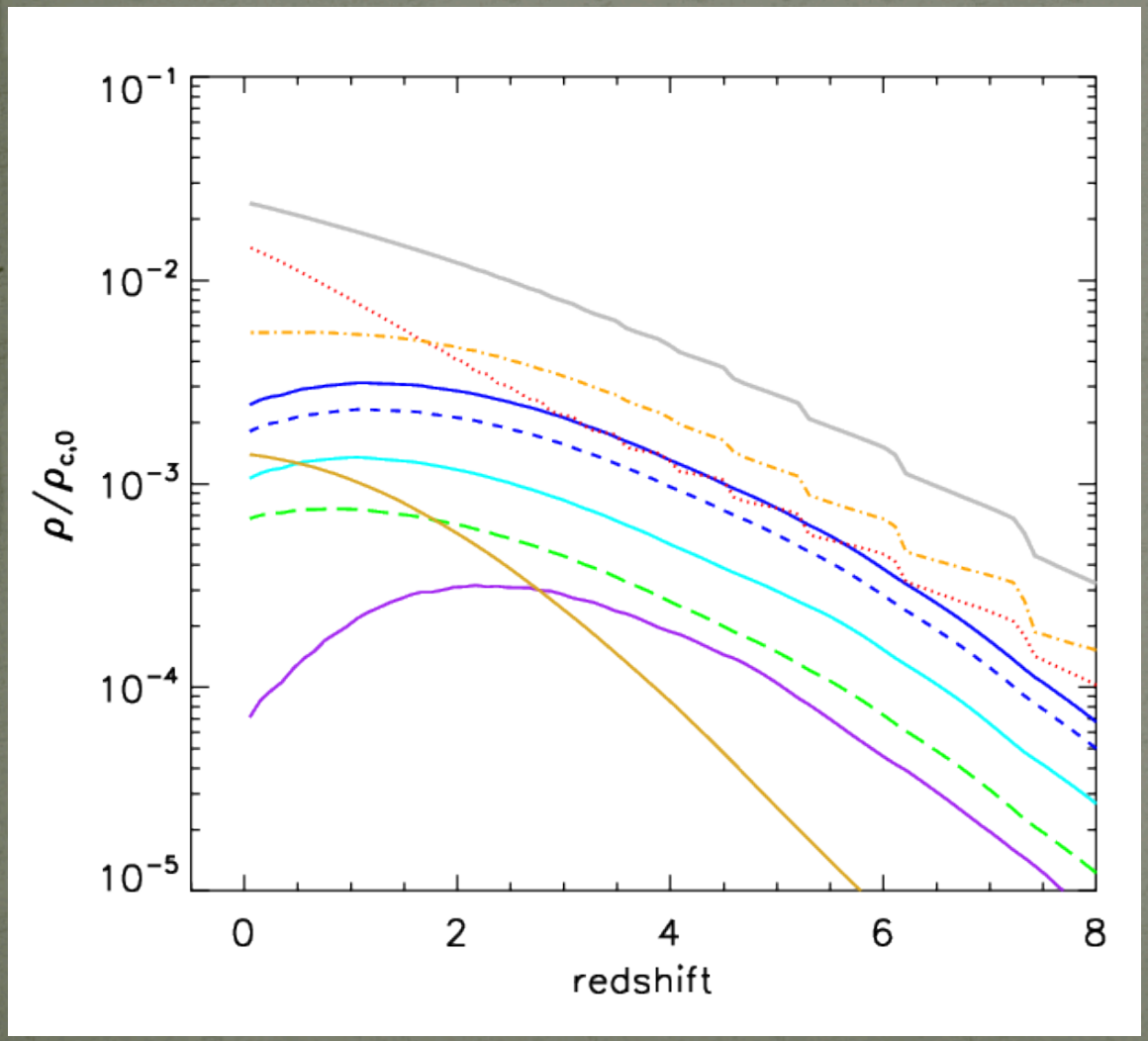
where are the baryons?

fraction of mass in halos



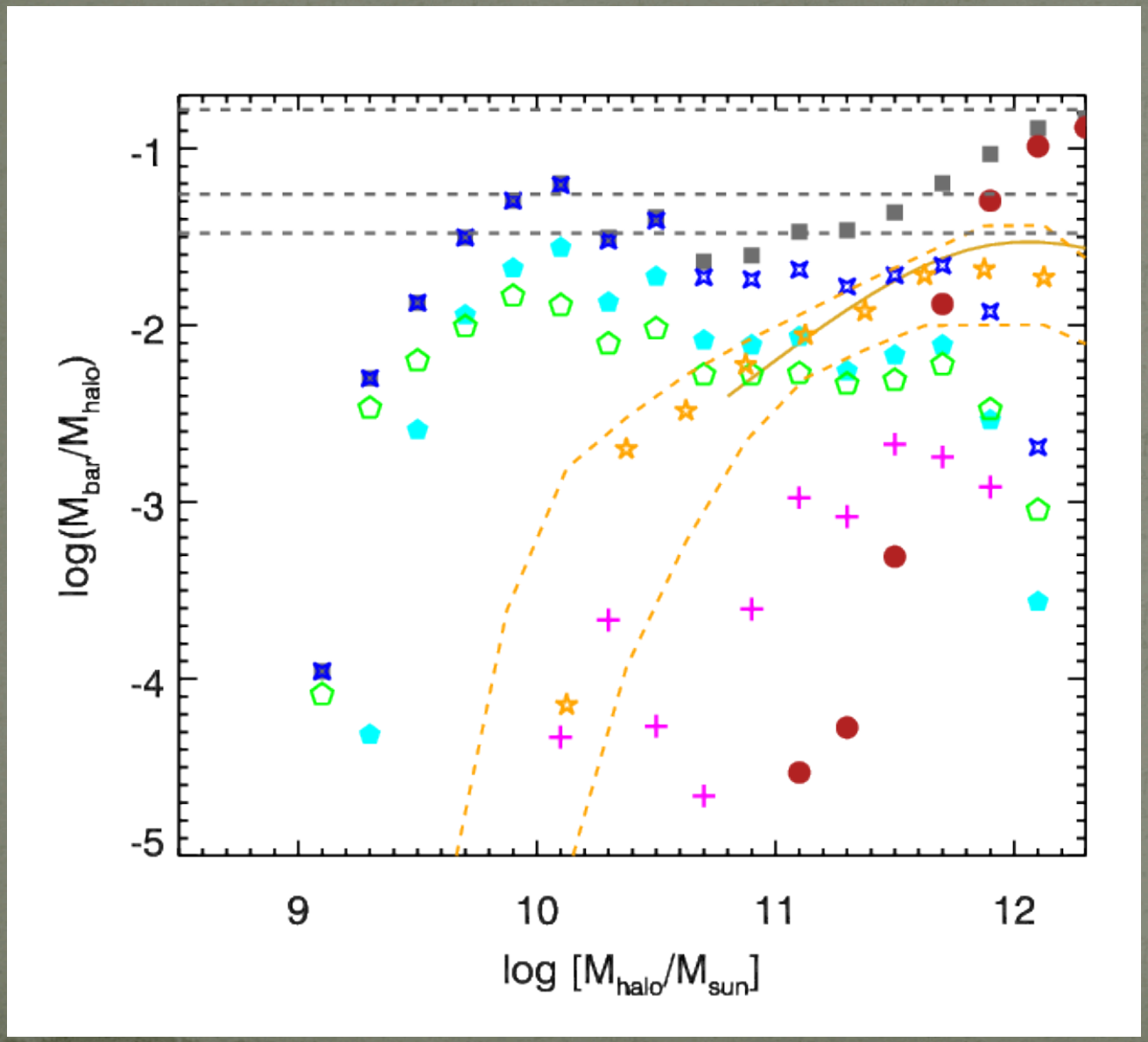
about 30-40% of baryons have never collapsed into halos – "IGM"

new models track baryons in different phases,
allow more detailed comparison with observations



f_b*mass in halos
ejected gas
hot halo gas
all cold H+He
all cold H
cold HI
ionized gas
H2
stars

where are the baryons, as a function of halo mass?

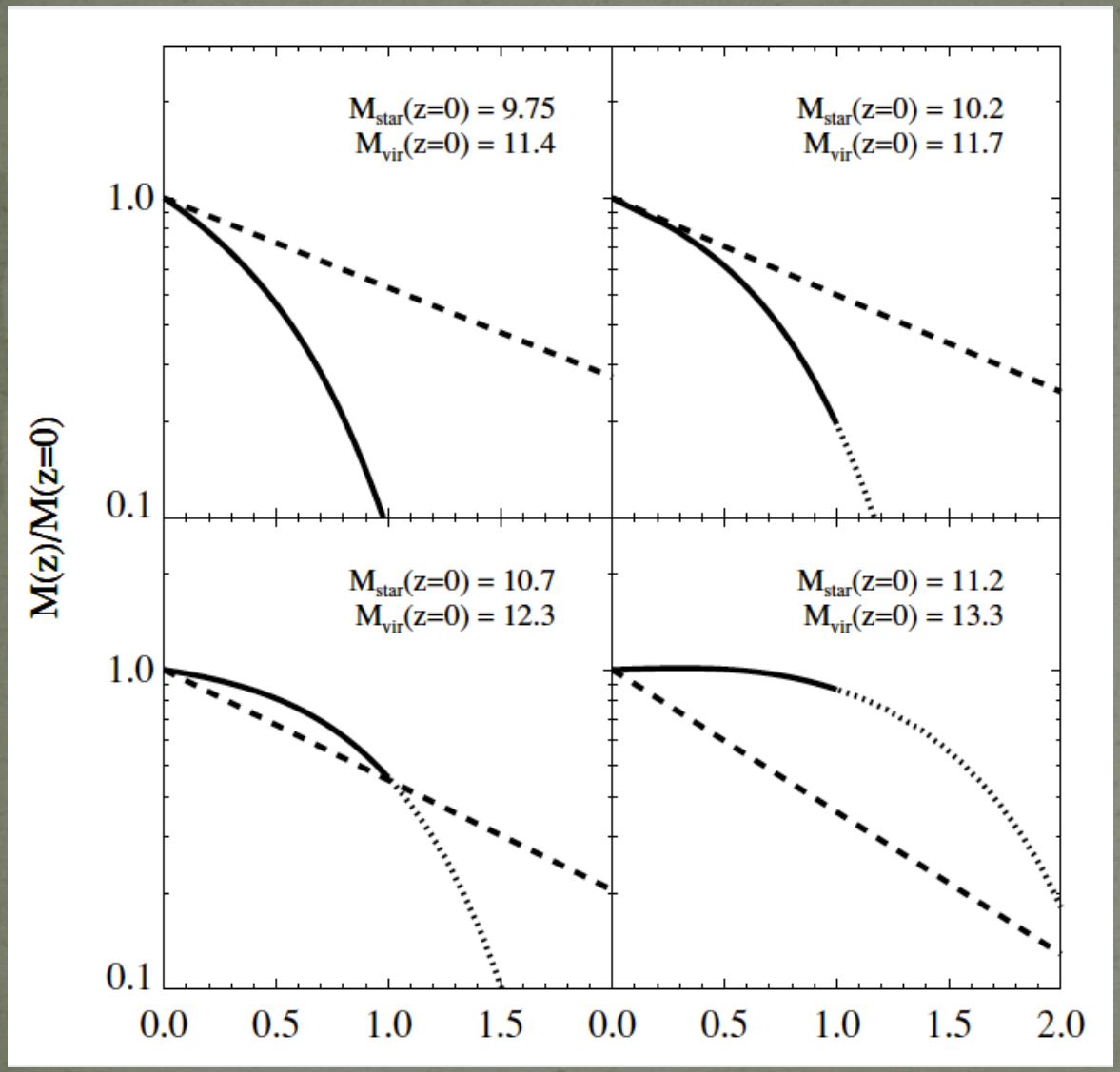


all baryons
hot halo gas
all cold H+He
cold HI
ionized gas
H_2
stars

summary of problems with the current paradigm

- no model simultaneously reproduces $f_*(M_h)$, $f_{gas}(m_*)$, and $sSFR(m_*)$ at any redshift
- stellar population ages at z=0 too old for low mass galaxies (rss et al. 2008; Fontanot et al. 2009)
- low mass galaxies too numerous at high-z; low-mass halos at high-z have stellar fractions that are too high
- specific star formation rates too low at low z and too high at high z; no sSFR plateau at high z
- low mass galaxies become chemically enriched too early
- not enough cold gas at high redshift (z>3) – gas being consumed or expelled too efficiently?

the root of the problem: star formation histories



halo Mass Accretion Histories are nearly self-similar; massive halos form slightly later than low-mass halos

galaxies appear to show a much stronger trend of formation history with mass; in the opposite sense (downsizing)

no physical model of galaxy formation has been shown to reproduce this trend.

Conroy & Wechsler 2009; Moster et al. in prep; Behroozi et al. in prep.

Summary

- current paradigm of galaxy formation does not correctly reproduce the observationally implied trend of galaxy SF history with stellar/halo mass, leading to a series of conflicts with observations
- an improved metallicity dependent, molecular hydrogen based star formation recipe, and accounting for ionized gas, alleviates some problems but mostly does not help
- should we be adopting ‘preventative’ measures rather than ‘curative’ (keep gas out rather than accreting then blowing out)? if so what is the physics?