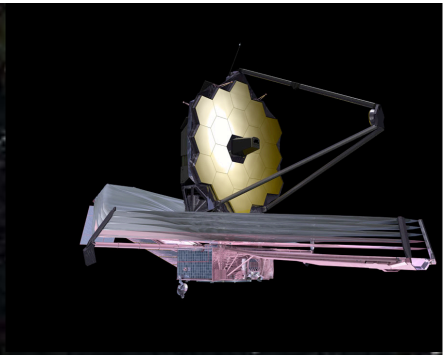
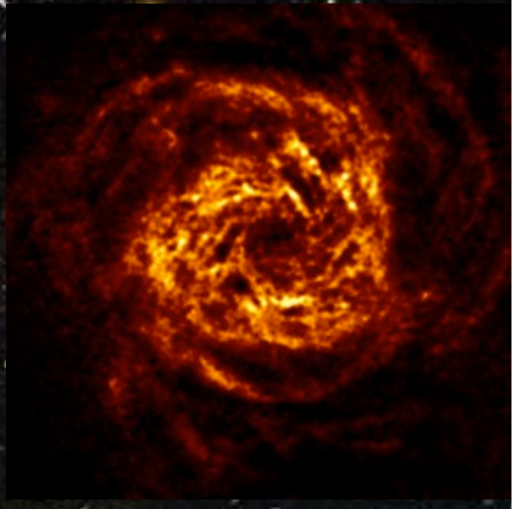


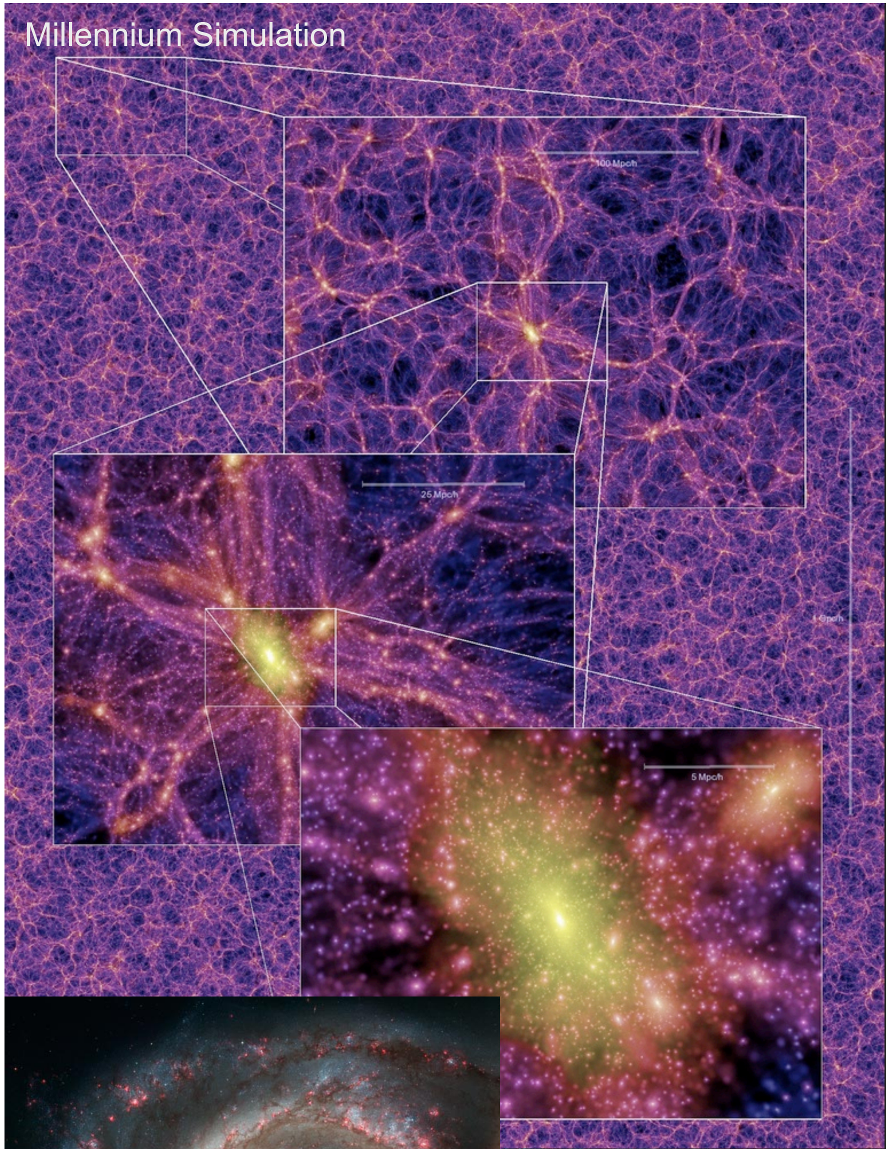
Star formation and feedback in cosmological simulations

rachel somerville

STScI/JHU

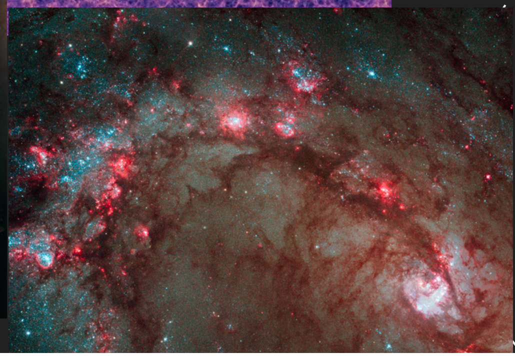
→Rutgers

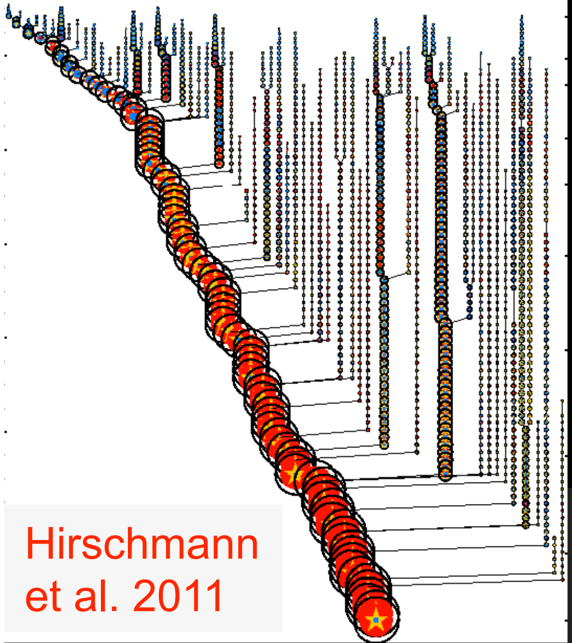




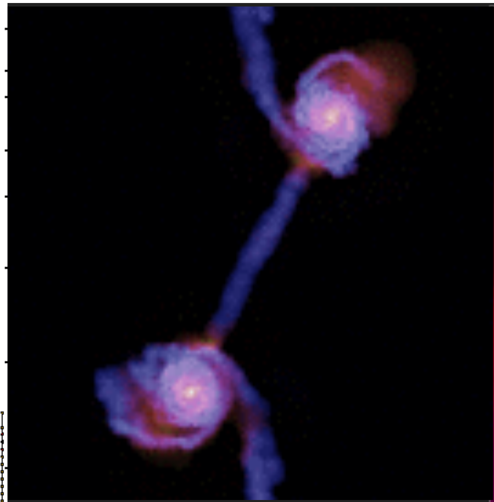
The challenge: dynamic range

- large-scale structure: 100's of Mpc
- galaxy environment: ~1-3 Mpc
- galaxy internal structure ~0.1-1 kpc
- GMC's: ~10's of pc
- star clusters/SNae: pc/ sub-pc

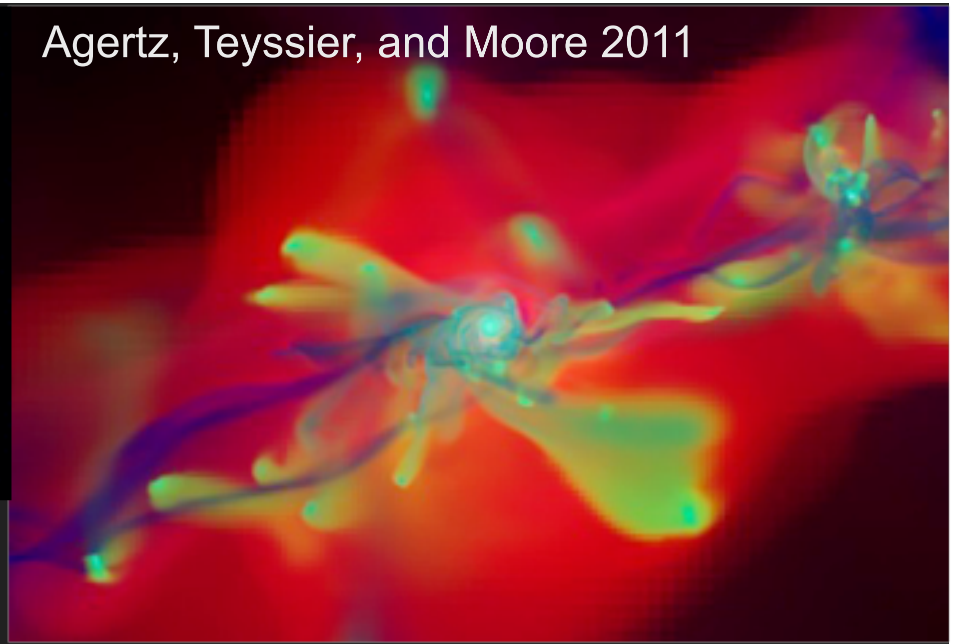




Hirschmann et al. 2011



Springel et al. 2005



Agertz, Teyssier, and Moore 2011

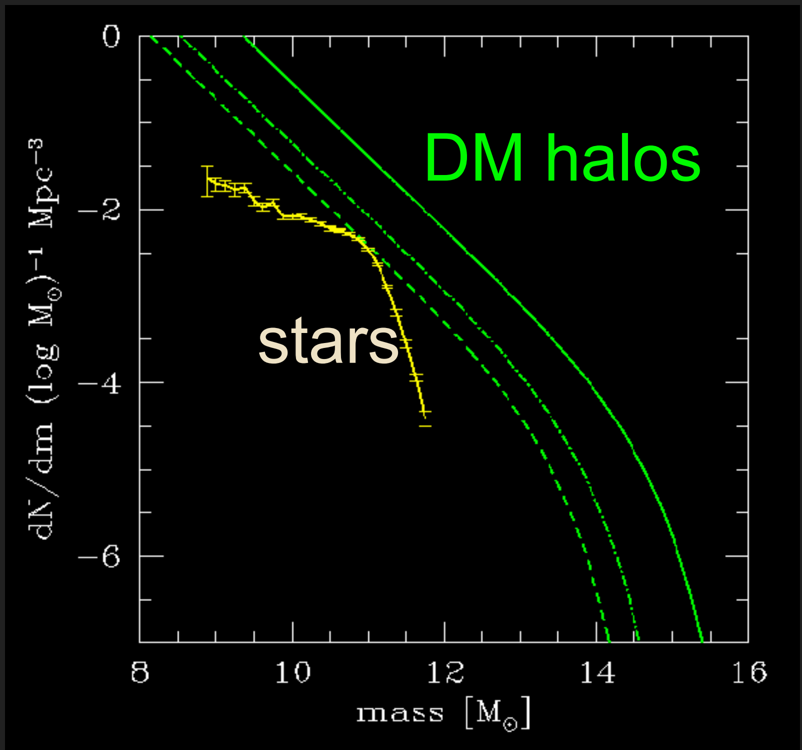
- merger trees + semi-analytics (rss; Croton/de Lucia/Kauffmann; Bower & Benson; Lagos, Baugh, Lacey, & coll.)
- hydro + sub-grid for 'non-cosmological' sims (e.g. isolated galaxies, mergers – Springel & Hernquist; Cox et al.; Robertson et al.)
- cosmological hydro + sub-grid (e.g. Dave', Oppenheimer & Finlator 2011; Schaye et al.; de Rossi, Tissera et al. 2010)
- cosmo initial conditions + zoom + sub-grid (Governato & coll.; Ceverino & Klypin 2009; Guedes et al. 2011; Bournaud et al.)

Problems feedback invoked to solve

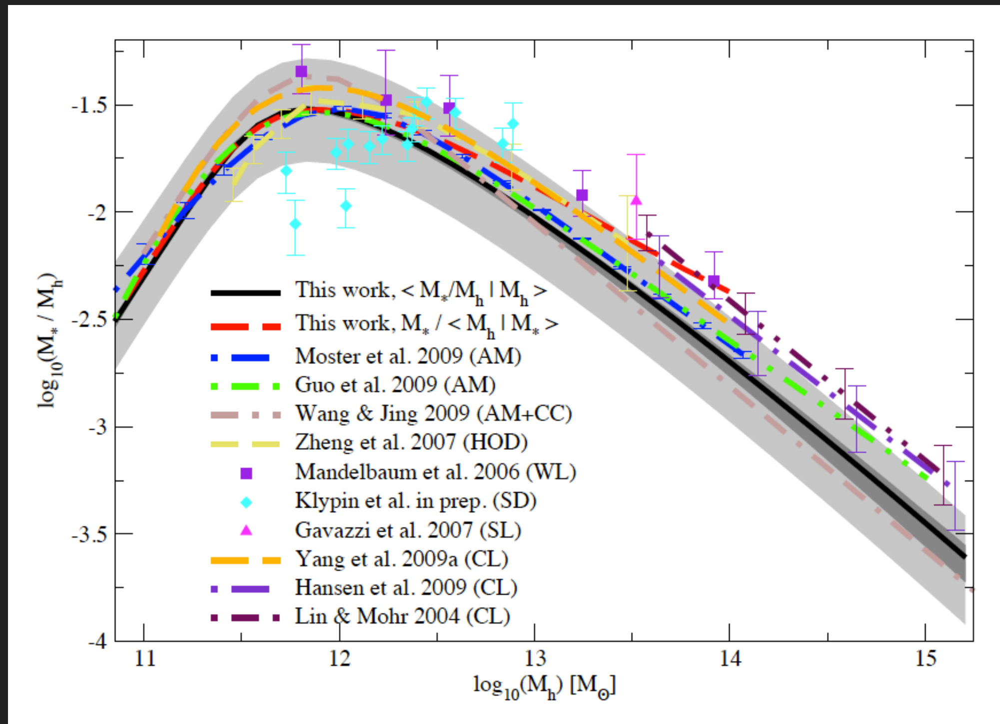
- Mismatch between predicted & observed LF/MF faint end slope
- MW substructure/satellite problem
- Pollution of IGM/mass-Z relationship
- Quenching of SF in massive galaxies
- Overcooling problem
- group & cluster entropy floors, L_X-T_X
- Angular momentum catastrophe/rotation curves/cores in dwarf galaxies, etc.

WHY IS THERE A 'SPECIAL SCALE' FOR GALAXY FORMATION?

- abundance matching & other techniques indicate stellar fractions decline sharply both above and below halo mass $M_h \sim 10^{12}\ M_{sun}$

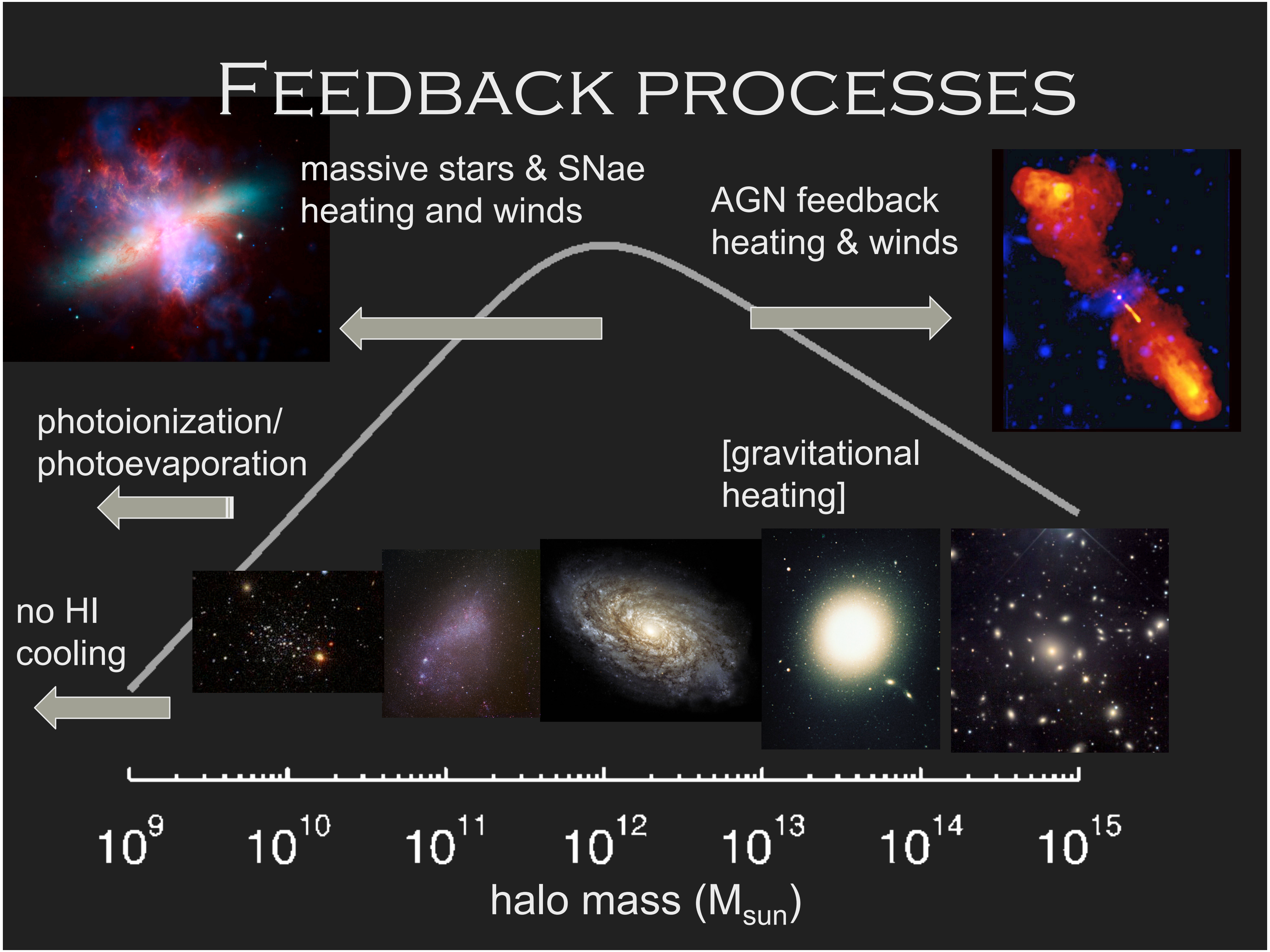


fraction of mass in stars



log halo mass

Moster, rss et al. 2009, Behroozi et al. 2010


FEEDBACK PROCESSES
massive stars & SNae
heating and winds
AGN feedback
heating & winds
photoionization/
photoevaporation
[gravitational
heating]
no HI
cooling
10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15}
halo mass (M_{sun})

STELLAR FEEDBACK: IMPLEMENTATION

- ‘thermal’ : add thermal energy from massive stars and SNae to gas. hot bubbles should create pressure-driven outflow – *requires very high resolution*
- ‘kinetic/momentum driven’: add kinetic energy (e.g. give kicks to particles), according to an input scaling law (radiation pressure sometimes invoked)

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"

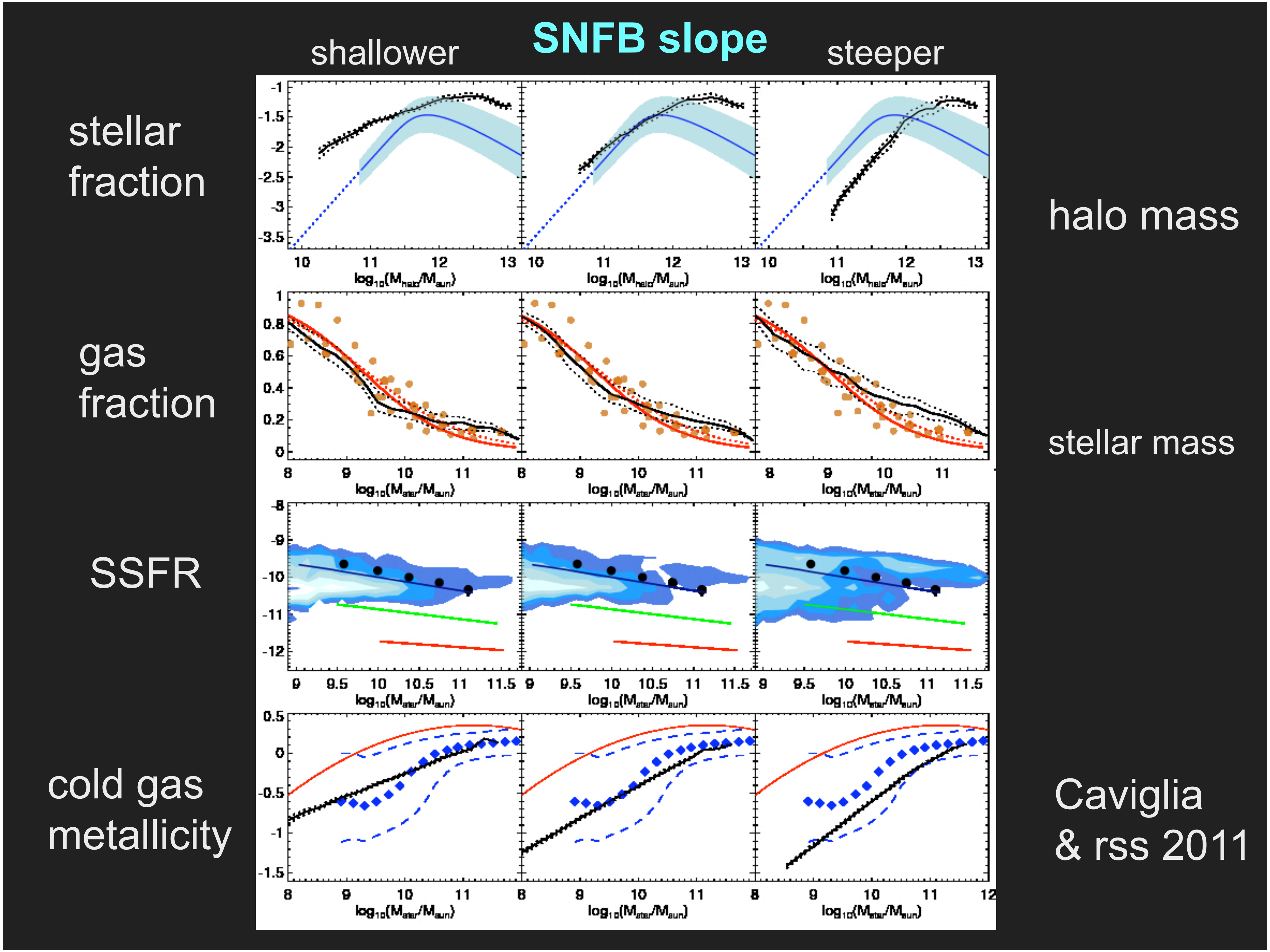
STAR FORMATION RECIPE

- Kennicutt relation with surface density cutoff:

$$\dot{\Sigma}_* \propto \Sigma_g^N$$

$$\dot{m}_* = \frac{K}{\tau_*} \int_0^{r_{crit}} \Sigma_g^N(r) 2\pi r d r$$

- S08: fixed surface density Σ_{crit} ~ 3-6 M_{sun}/pc^2
- Croton et al./de Lucia et al.: radially dependent Σ_{crit} based on Toomre Q; $\Sigma_{crit} \sim V_c/r$ for flat rotation curve



SNFB slope
shallower
steeper
stellar fraction
gas fraction
SSFR
cold gas metallicity
halo mass
stellar mass
Caviglia & rss 2011
$\log_{10}(M_{halo}/M_{sun})$
$\log_{10}(M_{star}/M_{sun})$

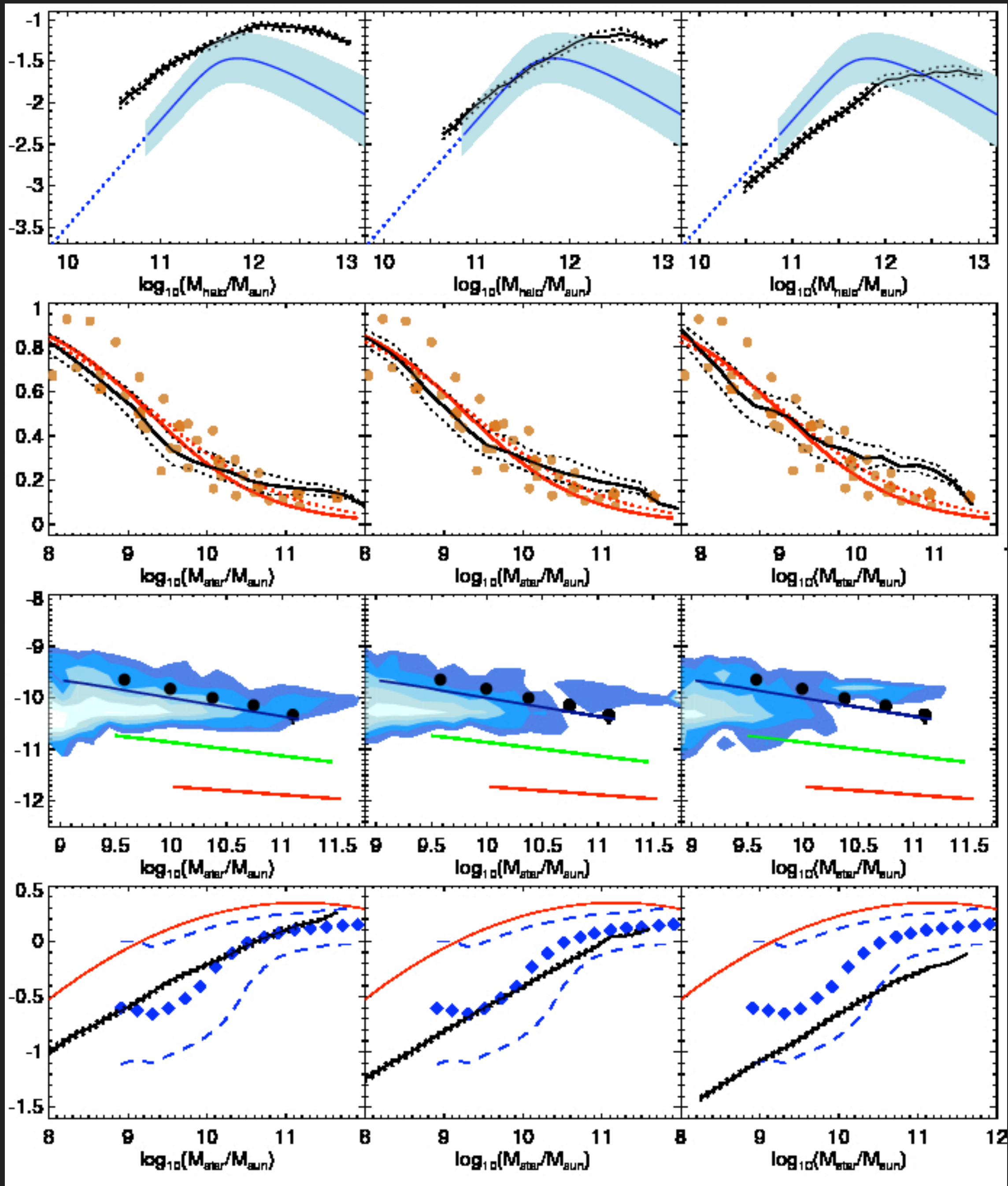
smaller **SNFB norm** larger

stellar fraction

gas fraction

SSFR

cold gas metallicity



halo mass

stellar mass

Caviglia & rss 2011

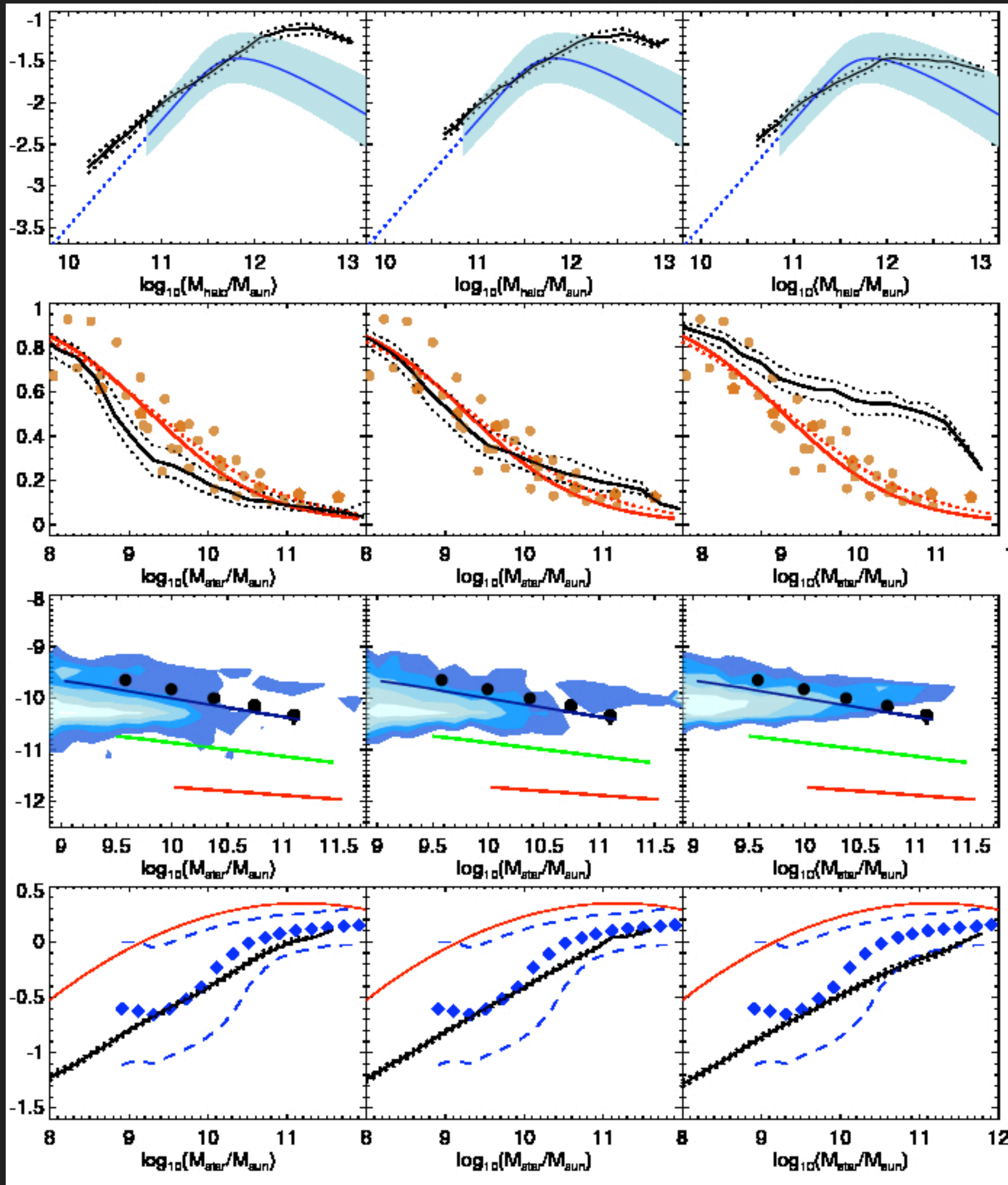
smaller **SF timescale** larger

stellar fraction

gas fraction

SSFR

cold gas metallicity

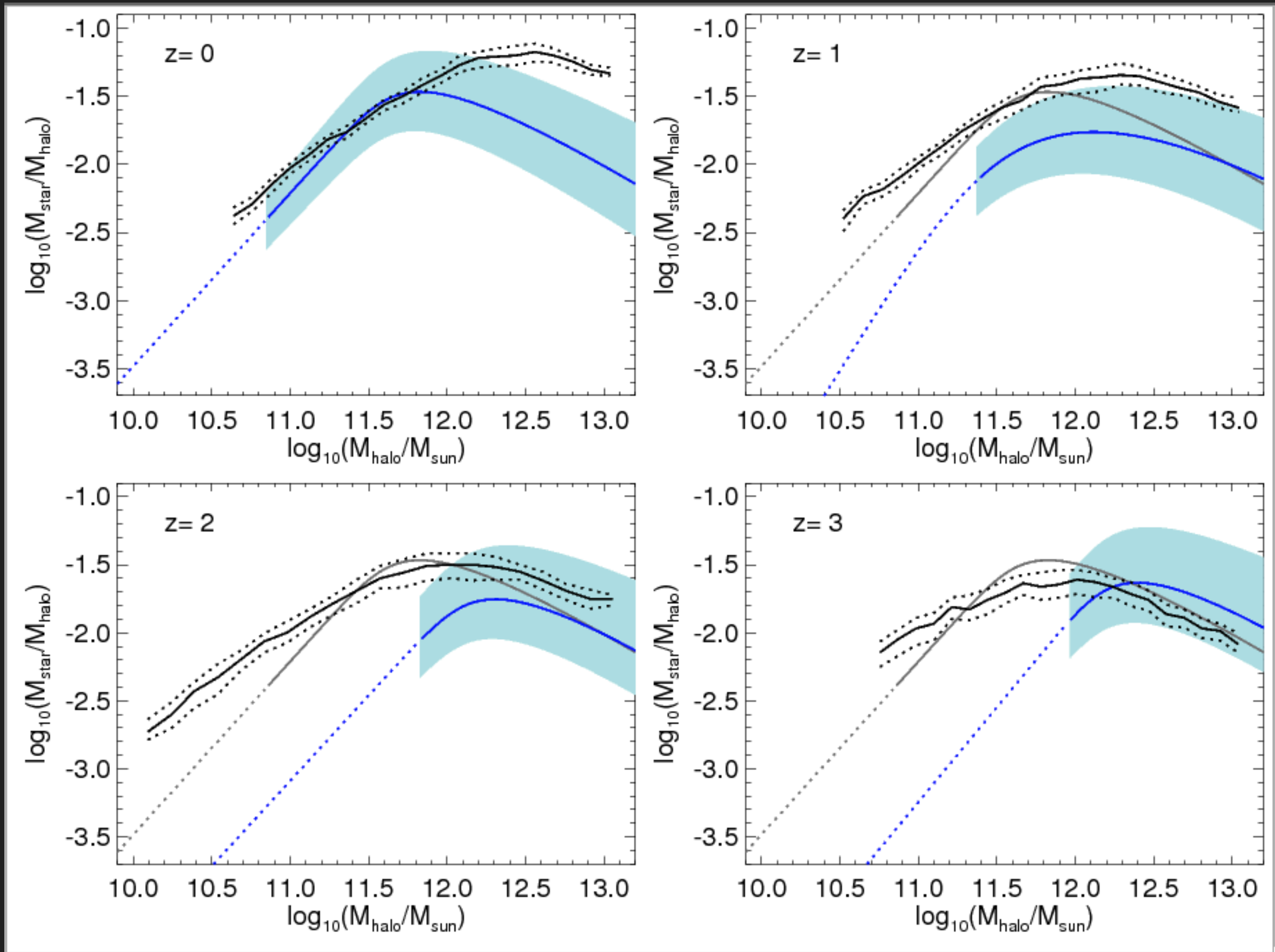


halo mass

stellar mass

Caviglia & rss 2011

problem: low mass galaxies form too early (stellar fractions are too high, LF & MF too steep at high-z)

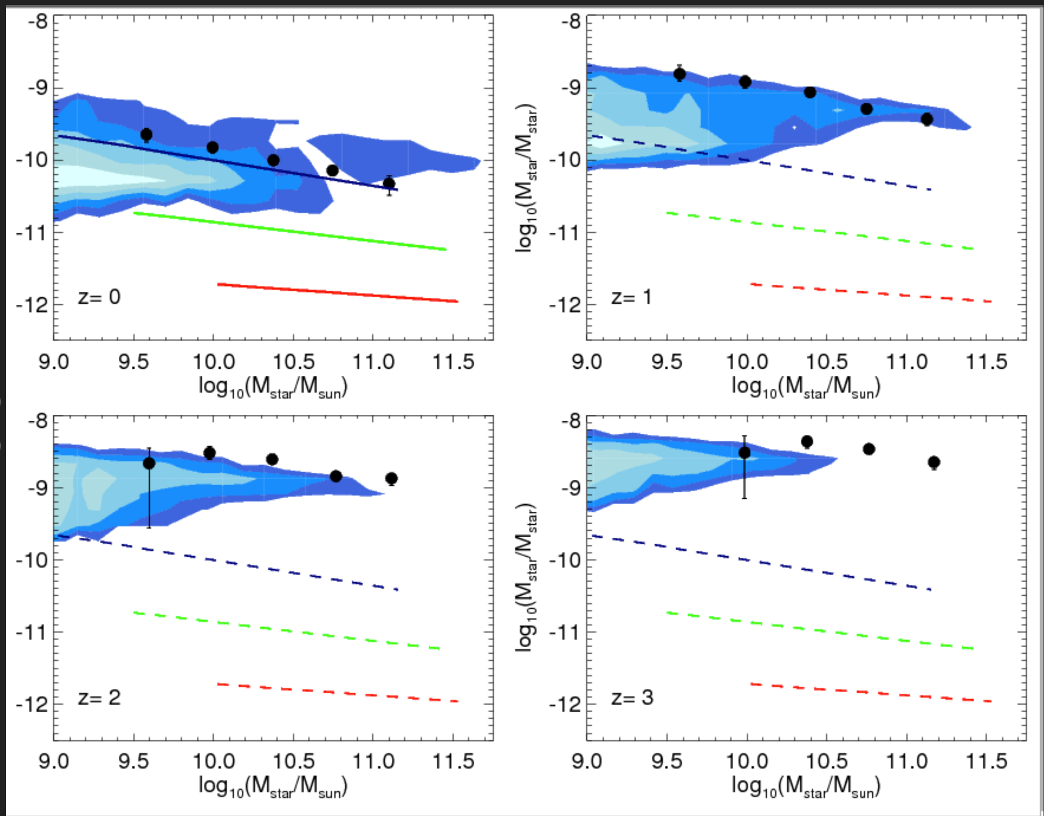


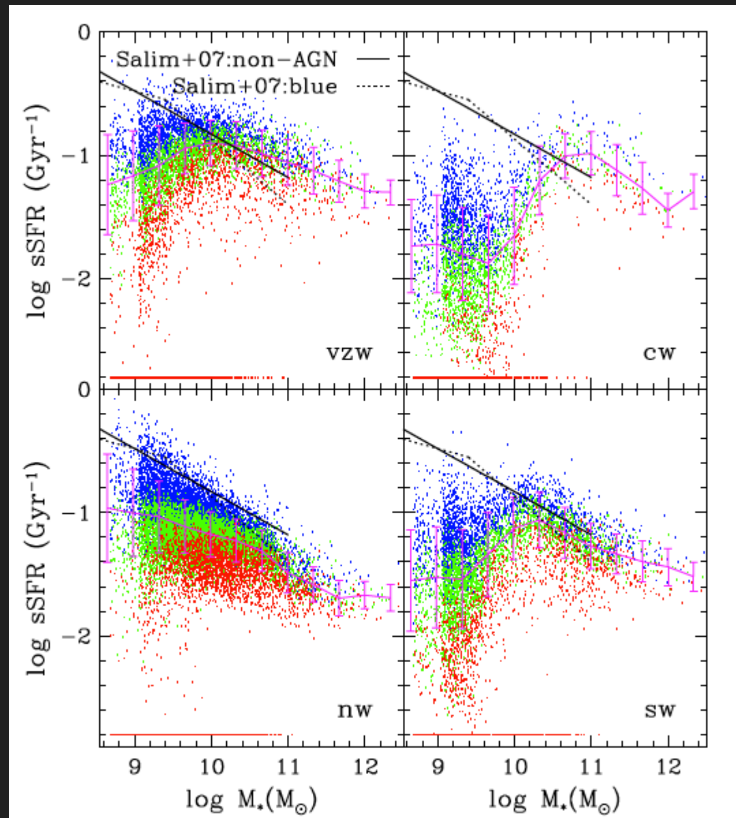
Caviglia & rss in prep; see also Fontanot et al. 2009, Dave' et al. 2011

low mass galaxies are ‘too quiescent’, at least at z<2

z=0

SSFR





log stellar mass

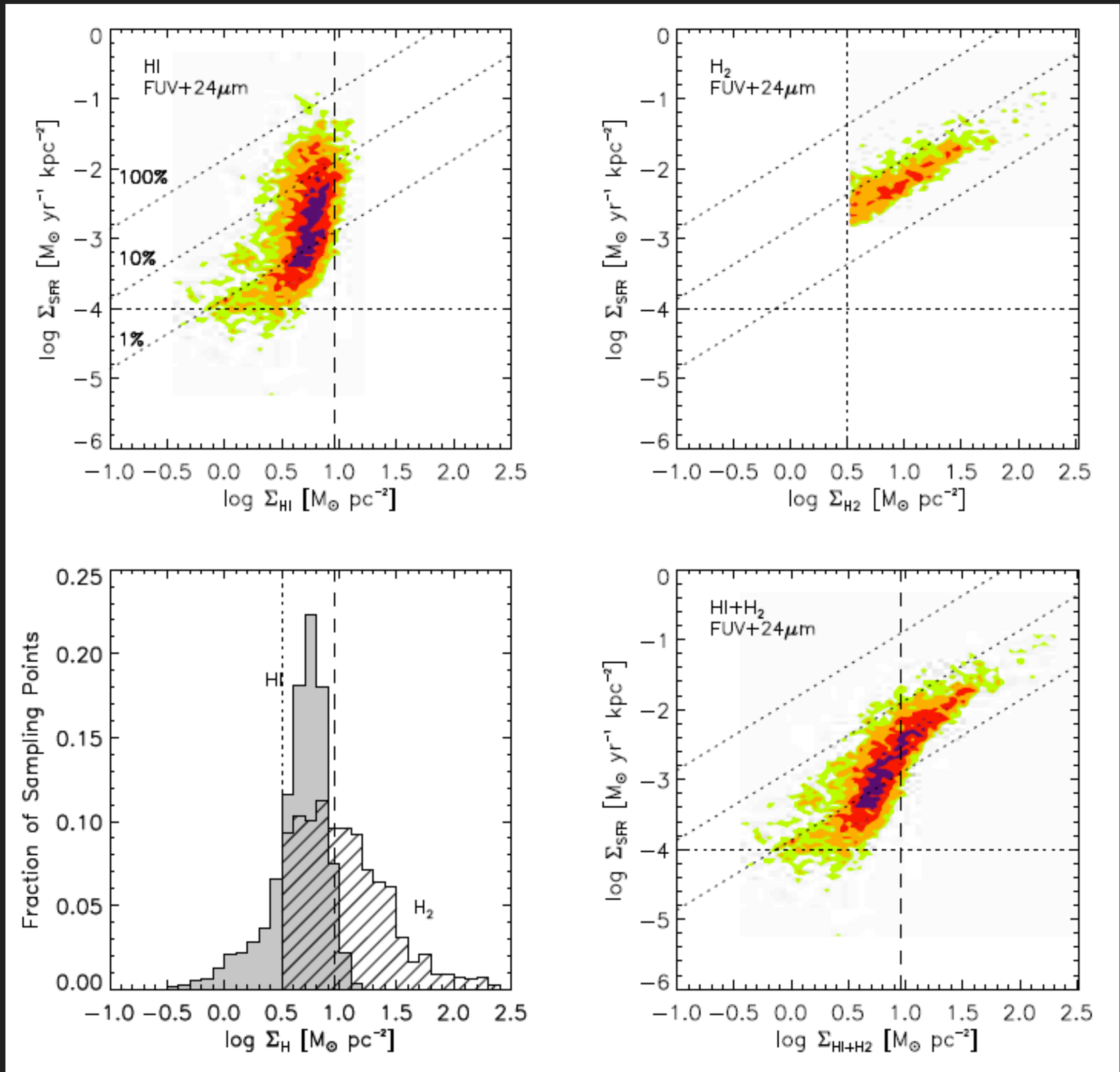
Caviglia & rss

Dave’ et al. 2011

SUMMARY OF PROBLEMS WITH 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 all redshifts where we can measure them
- stellar population ages at z=0 too old
- become chemically enriched too early (Arrigoni, Trager & rss 2011)
- *same problem is seen in many (all?) SAMs (Fontanot et al. 2009; Santini et al. 2011), and in cosmological hydrodynamic simulations with similar 'sub-grid' recipes for SF & SN-driven winds (see e.g. Dave' et al. 2011)*

BEYOND KENNICUTT

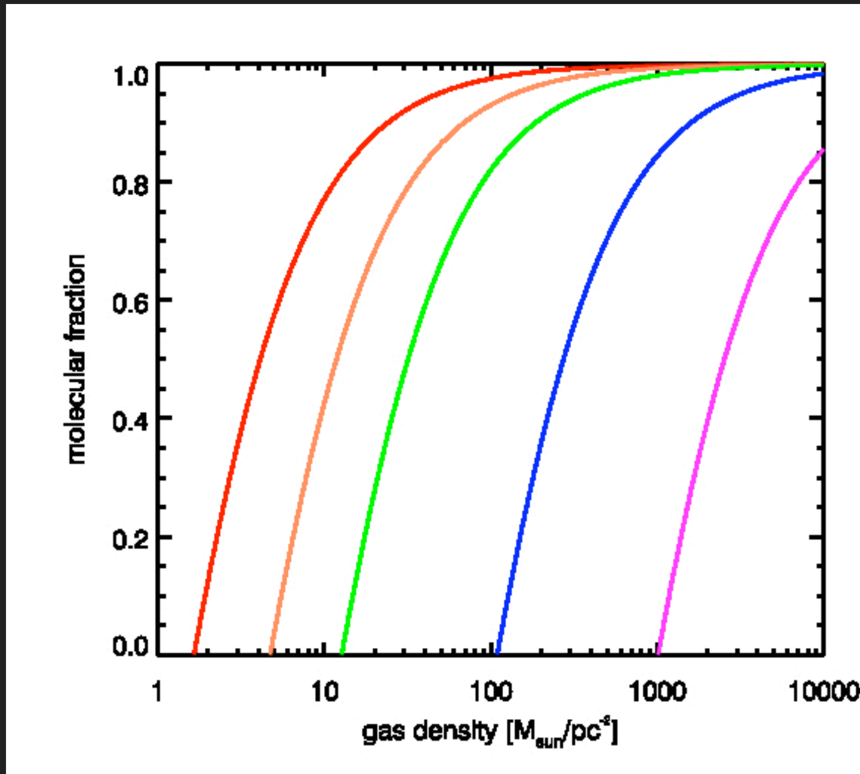


star formation correlated with density of *molecular* hydrogen; almost no correlation with HI

Bigiel et al. 2008; see also Leroy et al. 2008, Leroy talk

Molecular hydrogen formation

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



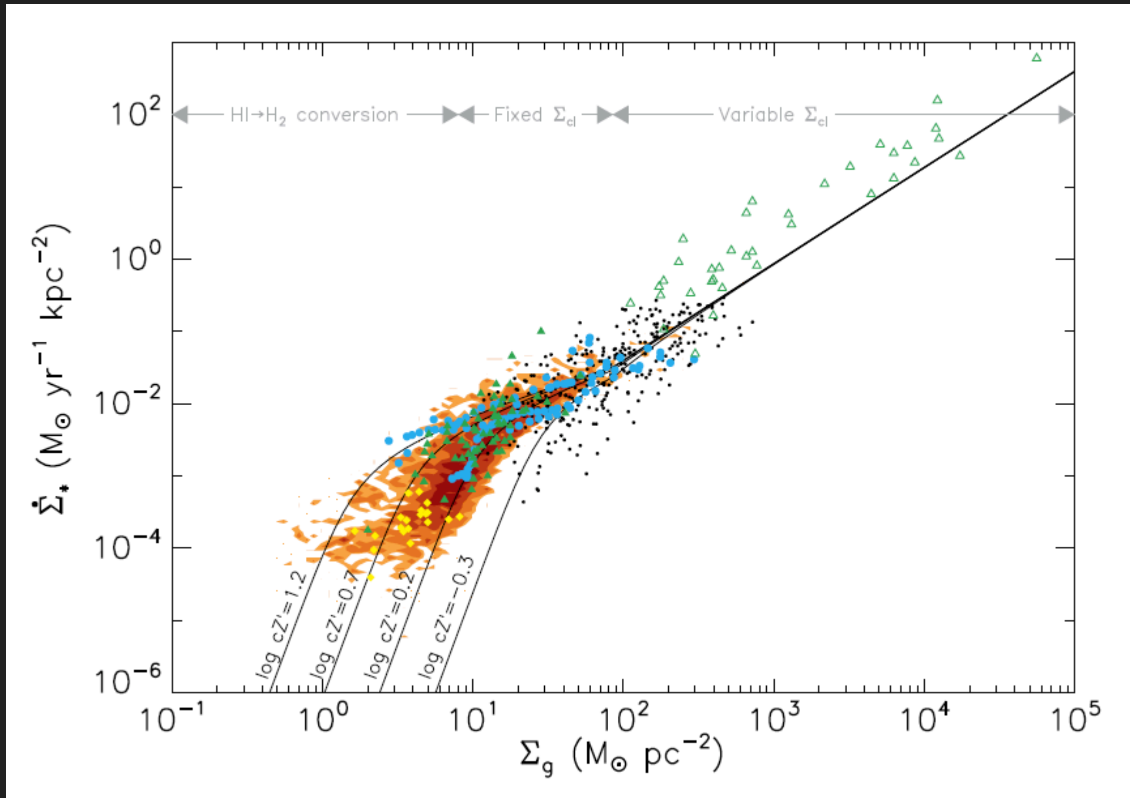
Z=1.0
0.3
0.1
0.01
0.001

see also
Gnedin & Kravtsov 2010;
Robertson & Kravtsov 2009
Kuhlen et al. 2011

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

Molecular hydrogen based SF recipe

- stars form from H_2 with nearly constant efficiency below Σ_g~100 M_{sun}/pc^2
- Possibly steeper slope for "starbursts"?

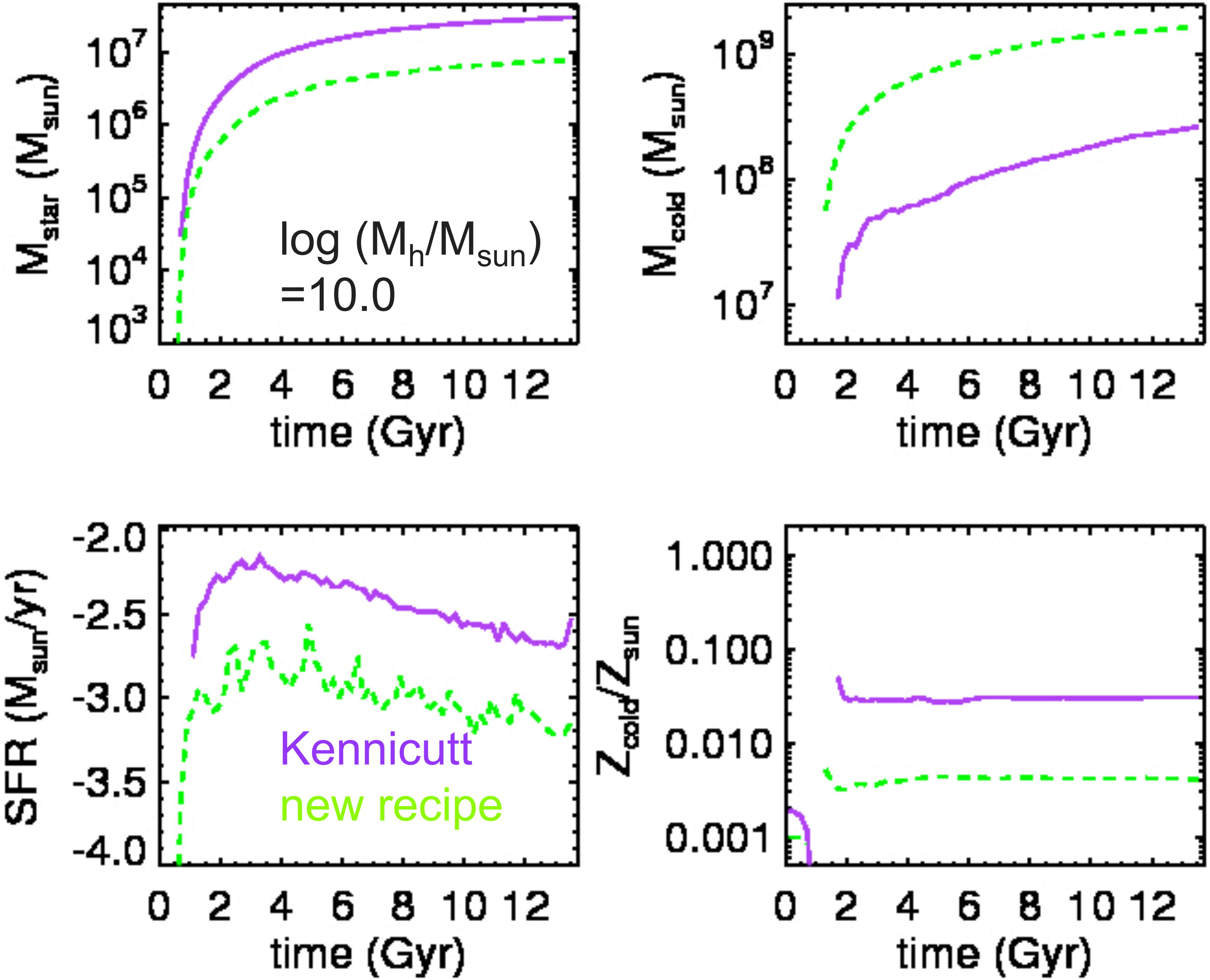


Krumholz, McKee & Tumlinson 2009

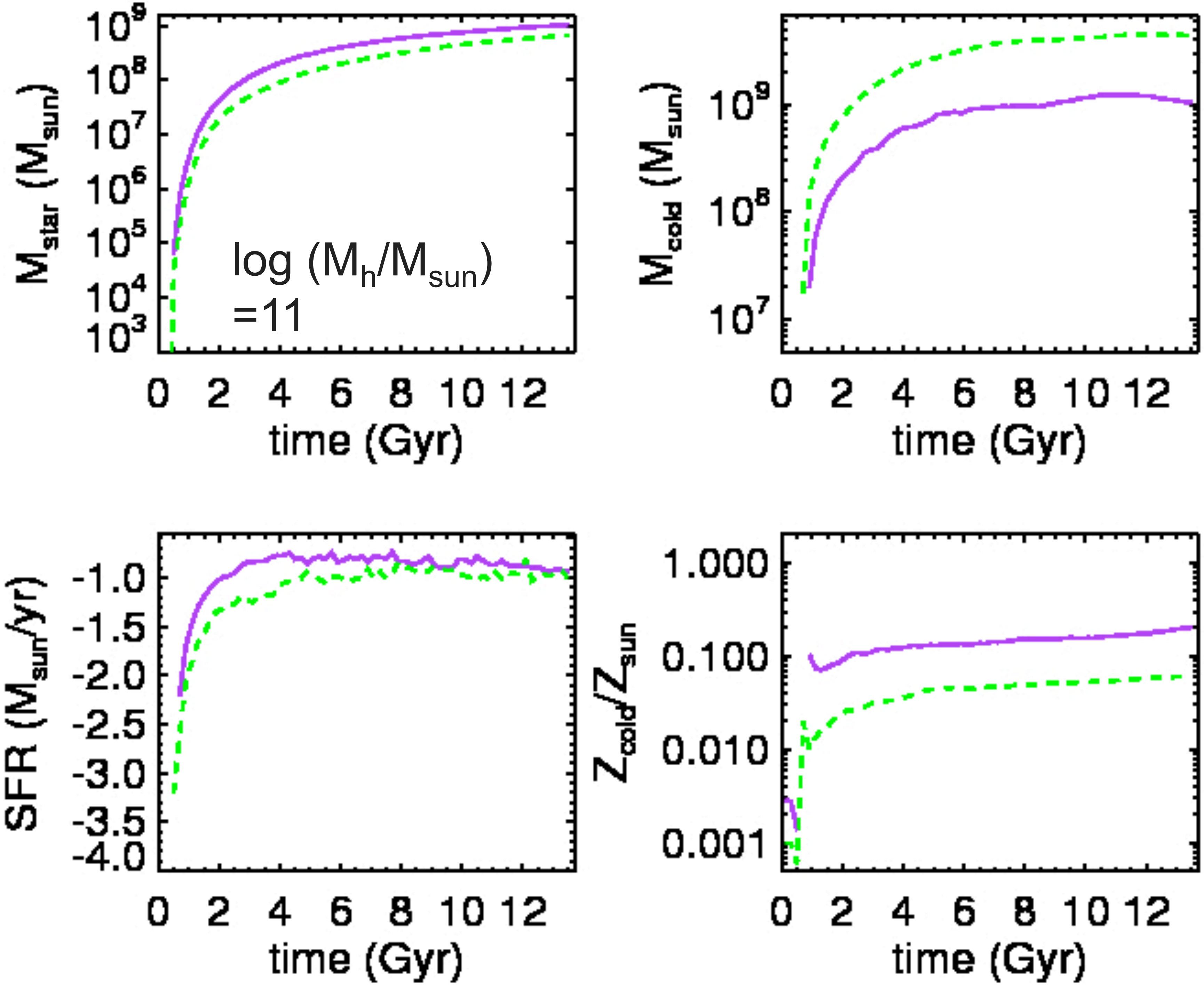
IMPLEMENTATION IN SAM

- assume that total gas radial density distribution within each disk is described by an exponential; r_{gas} propto r_{star}
- 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)

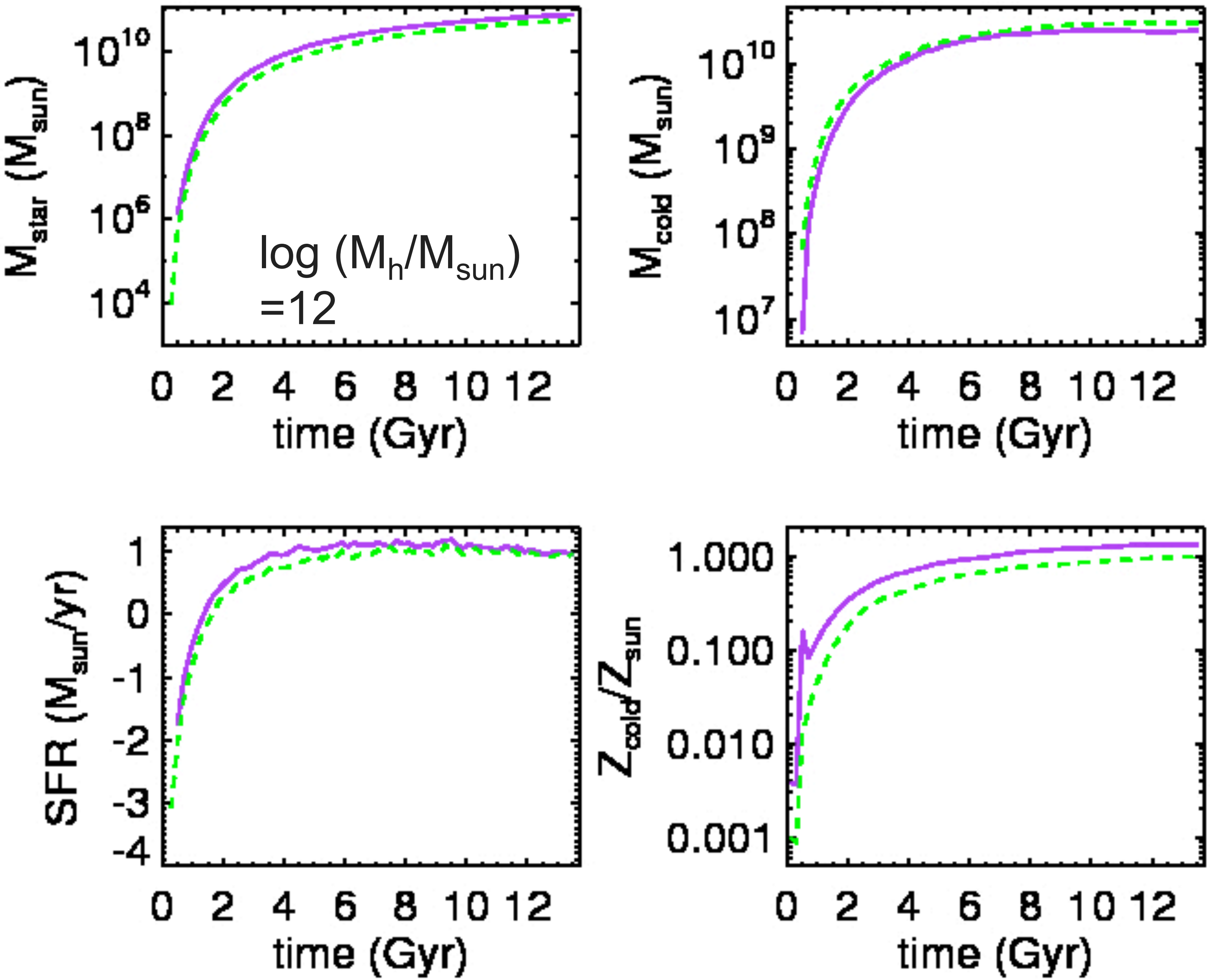
rss, Popping & Trager, in prep; Krumholz & Dekel 2011
Lagos et al. 2010; 2011; Fu et al. 2010



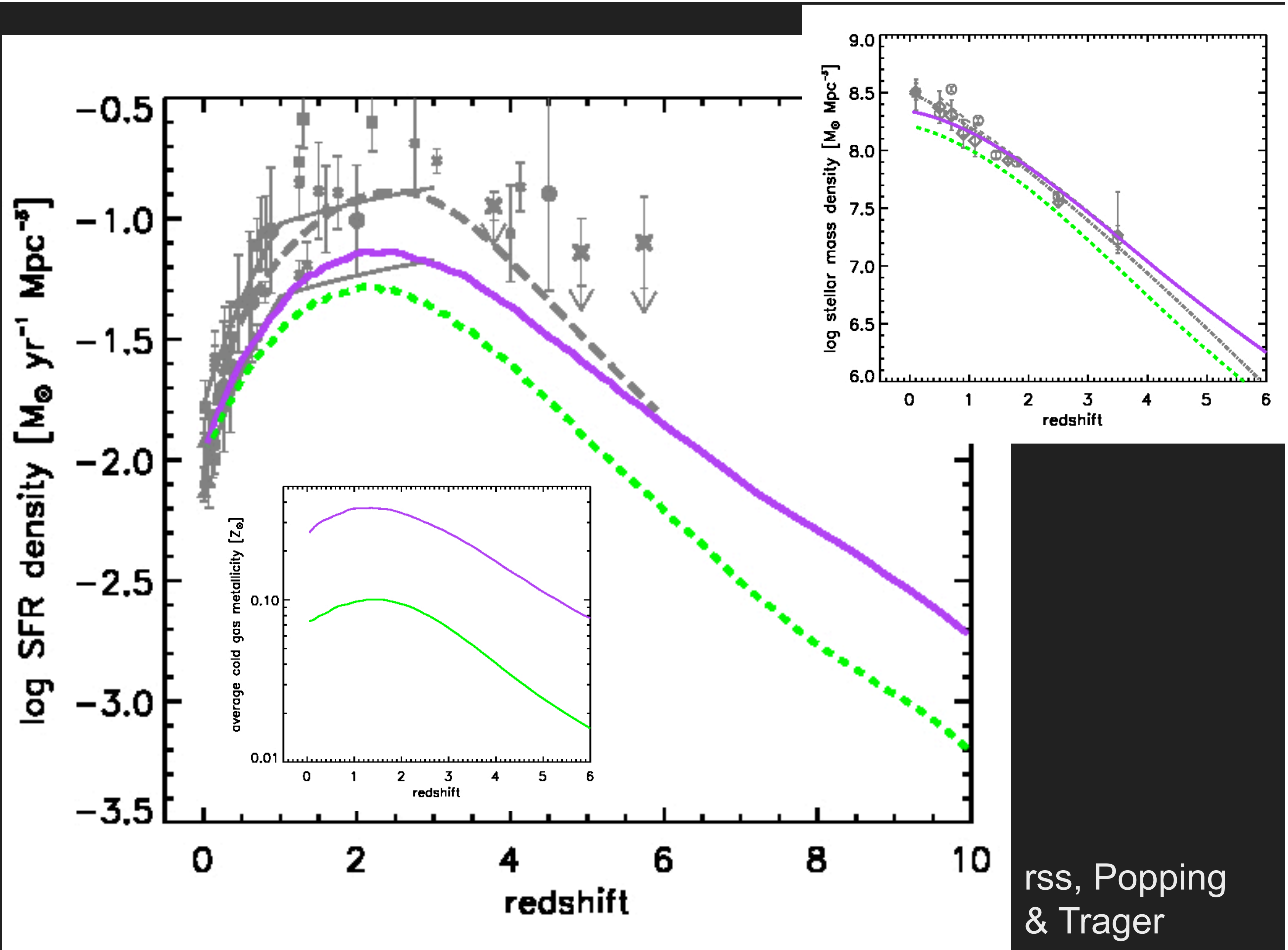
log (M_h/M_{sun}) =10.0
M_{star} (M_{sun})
M_{cold} (M_{sun})
SFR (M_{sun}/yr)
Z_{cold}/Z_{sun}
time (Gyr)
Kennicutt
new recipe



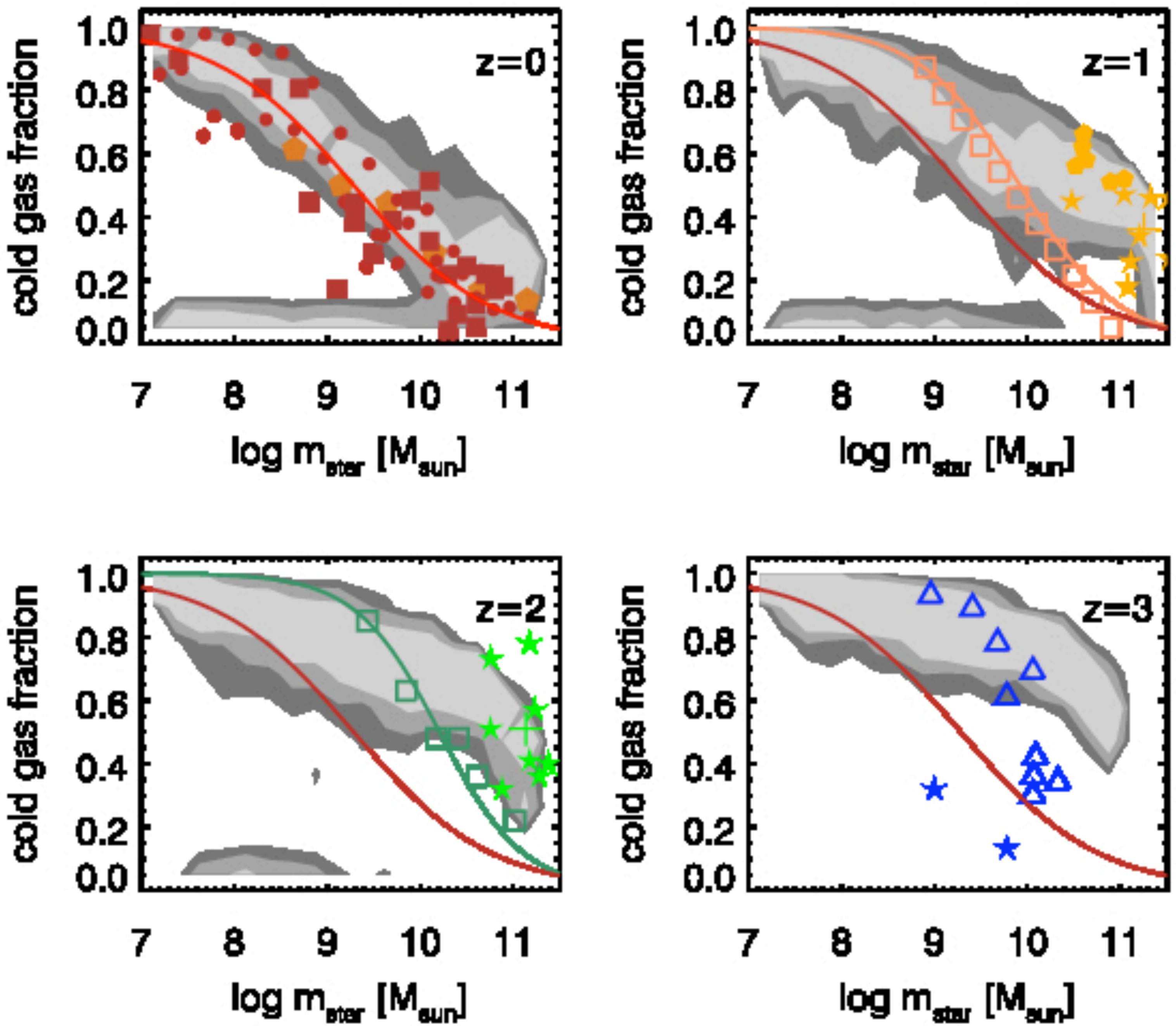
M_{star} (M_{sun})
10^3
10^4
10^5
10^6
10^7
10^8
10^9
log (M_h/M_{sun})
=11
M_{cold} (M_{sun})
10^7
10^8
10^9
SFR (M_{sun}/yr)
-1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
Z_{cold}/Z_{sun}
1.000
0.100
0.010
0.001
0 2 4 6 8 10 12
time (Gyr)



log (M_h/M_sun) =12
M_star (M_sun)
M_cold (M_sun)
SFR (M_sun/yr)
Z_cold/Z_sun
time (Gyr)
time (Gyr)
time (Gyr)
time (Gyr)



rss, Popping & Trager



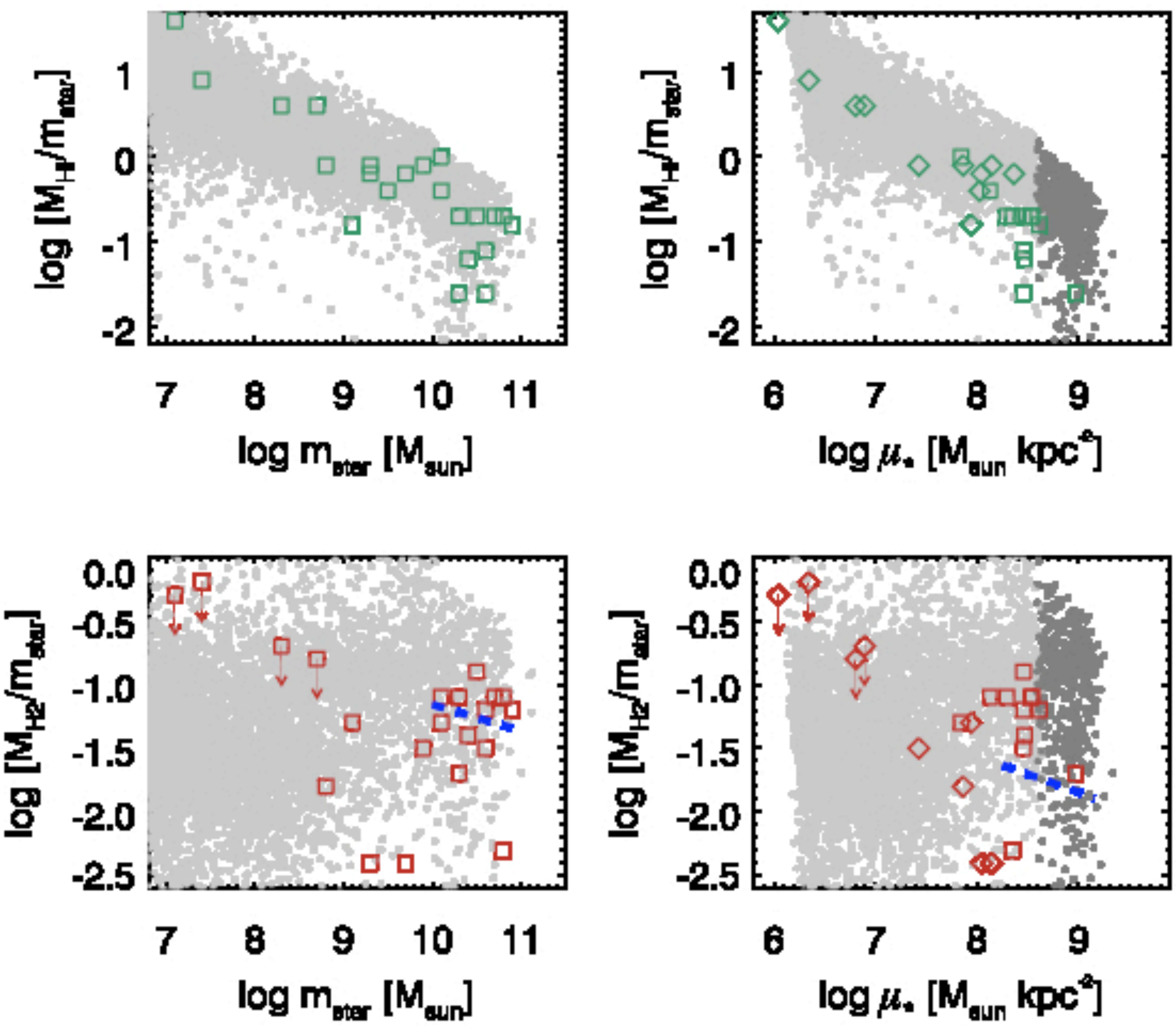
z=0
z=1
z=2
z=3
cold gas fraction
0.0
0.2
0.4
0.6
0.8
1.0
7
8
9
10
11
log m_star [M_sun]

z=0

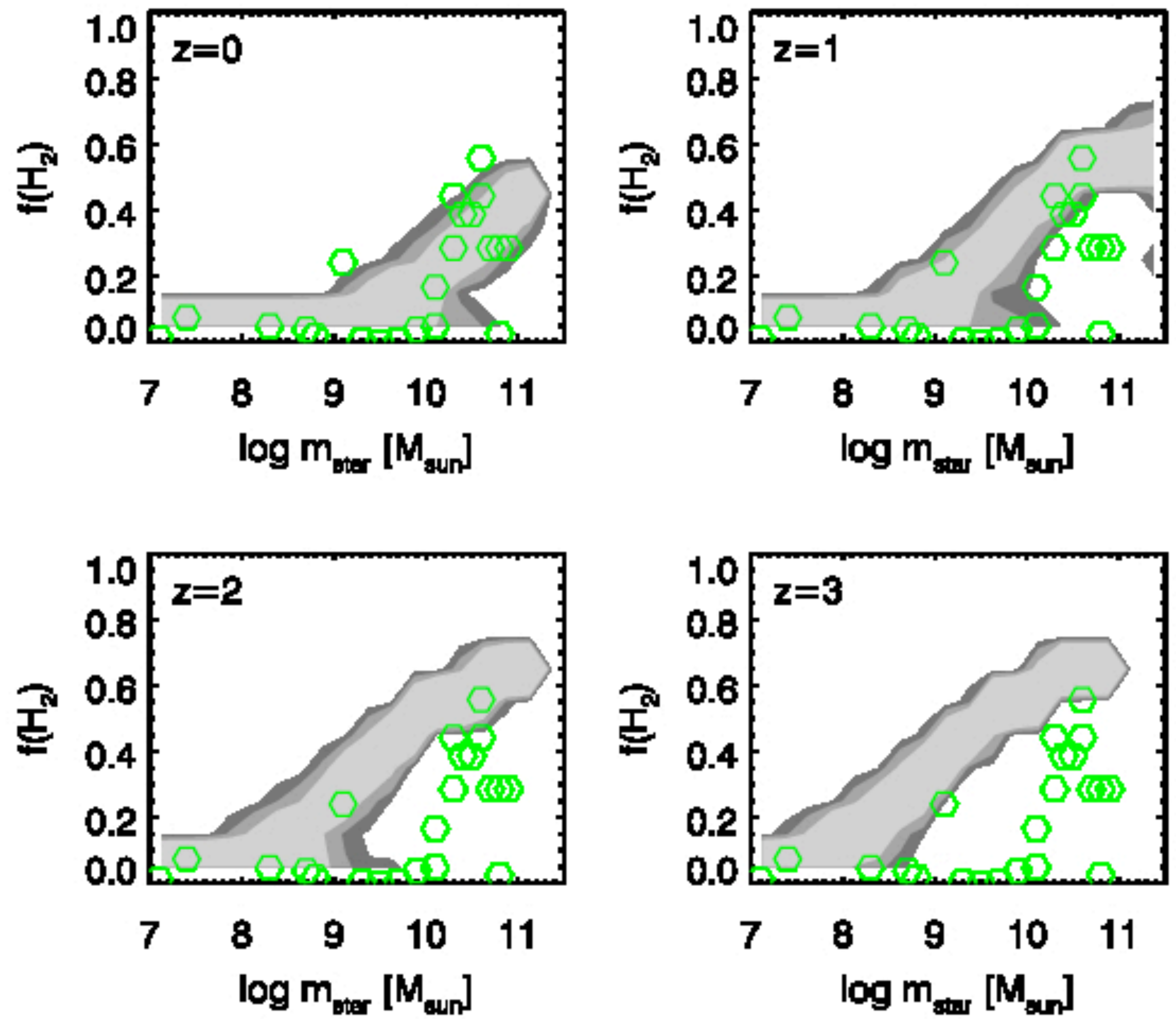
atomic fraction

molecular fraction

observations From THINGS, COLDGASS



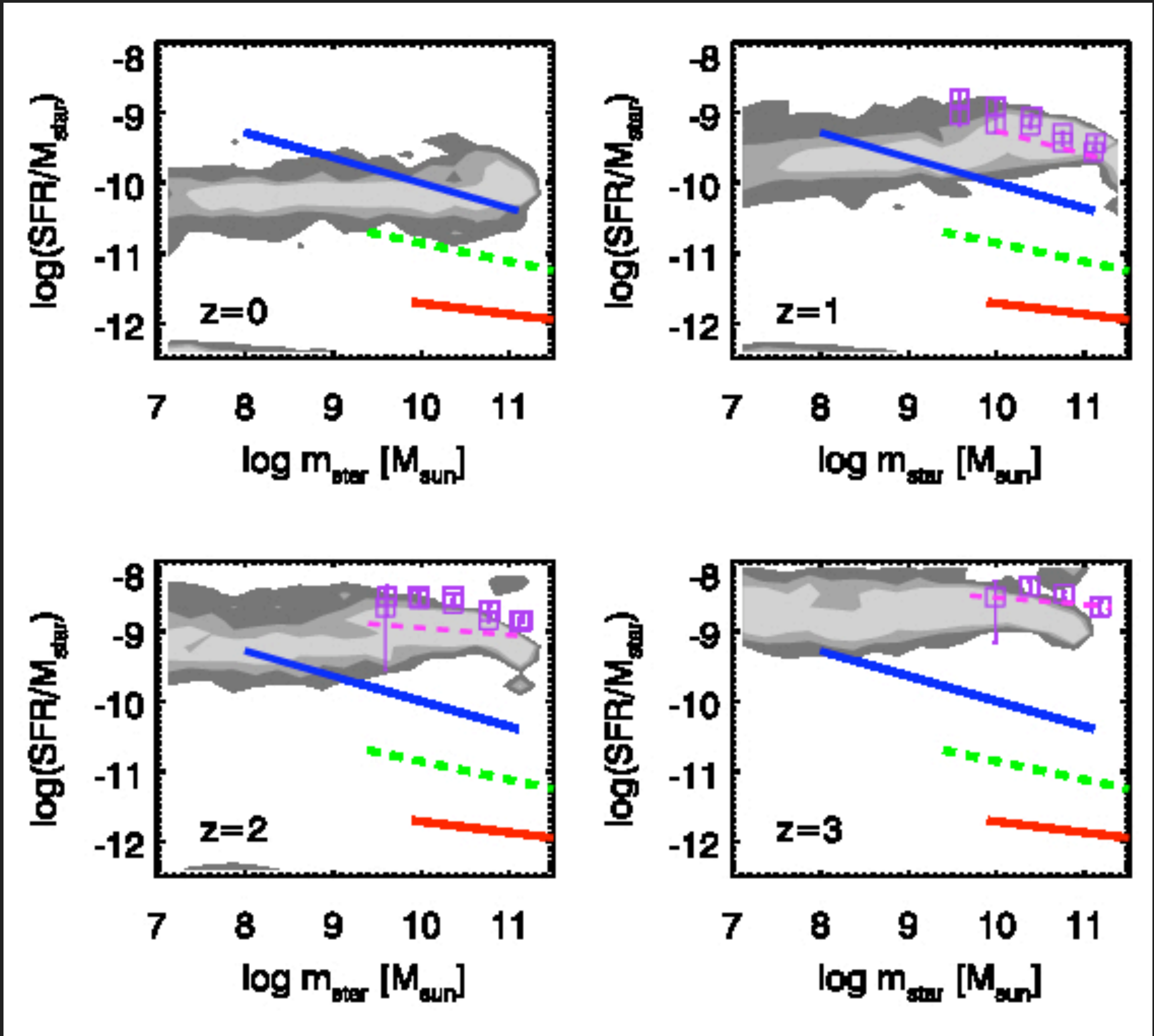
molecular fraction



observations from THINGS (z=0)

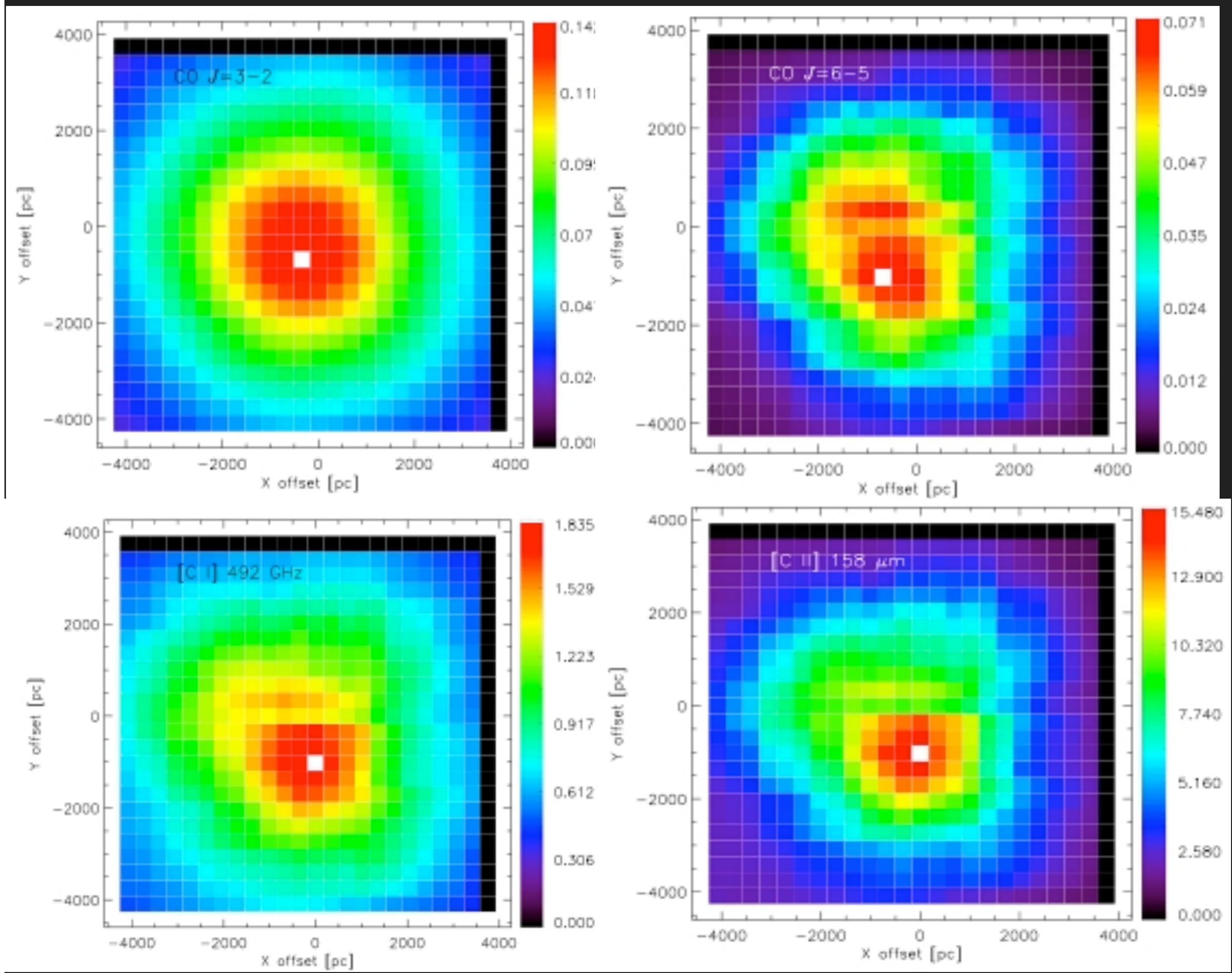
metallicity-dependent H2-based SF model

new SF recipe does NOT solve the 'downsizing' problem!



‘QUIESCENT’ GALAXY AT Z=2:
WHAT ALMA WILL SEE

CO J=3-2 CO J=6-5



[C I] 492 GHz [C II] 158 μm

G. Popping, S. Trager,
J.P. Perez-Beaupuits,
M. Spaans, rss:

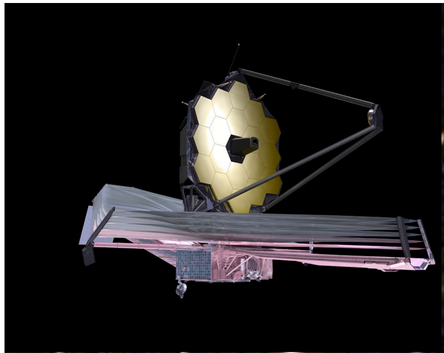
combine SAM predictions with
PDR chemical model,
(Meijerink & Spaans 2005)
3D radiative transfer
and line tracing
(see P.-B. et al. 2011)

SUMMARY

- measuring the gas content of galaxies at high redshift can help break degeneracies between uncertainties in SF and SN FB recipes in cosmological simulations
- ‘sub-grid’ scaling recipes implemented in lower-resolution cosmological simulations or SAMs show many successes – but still some problems (e.g. ‘downsizing’ of low-mass galaxies)
- several groups are implementing new H_2-based star formation recipes in cosmological simulations, which will enable predictions for ALMA and other upcoming facilities – caution: new SF recipes may have even stronger ‘coupling’ between SF & SN FB

Problems feedback invoked to solve

- LF/MF faint end slope -- *stellar-driven winds*
- MW satellites – *photo-ionization + SN FB*
- Pollution of IGM/mass-Z relationship *– stellar-driven winds*
- Quenching in massive galaxies – *AGN FB, gravitational heating?*
- Overcooling problem – *stellar-driven winds + AGN FB/gravitational heating*
- Angular momentum catastrophe/rotation curves/cores in dwarf galaxies – *SN FB*

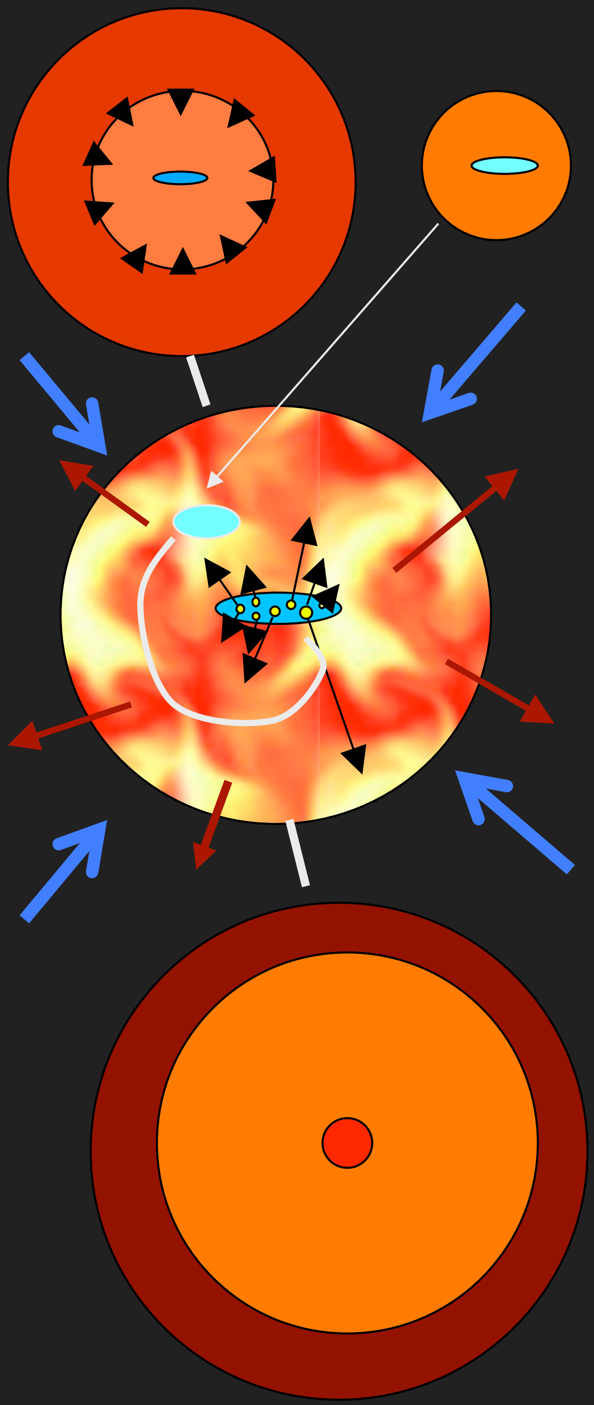


MOTIVATION

- Improved constraints on HI and H_2 content of nearby galaxies (THINGS, GASS, COLDGASS, ALFALFA, HIPASS)
- Theoretical insights into how cold gas is converted into stars
- Upcoming facilities that will measure HI and H_2 content of large samples of galaxies at high redshift (ALMA, LMT, MeerKAT, ASKAP, SKA)
- Large samples with HST/WFC3 imaging to z~8 (e.g. CANDELS; PIs: Faber & Ferguson)
- looking forward to JWST…

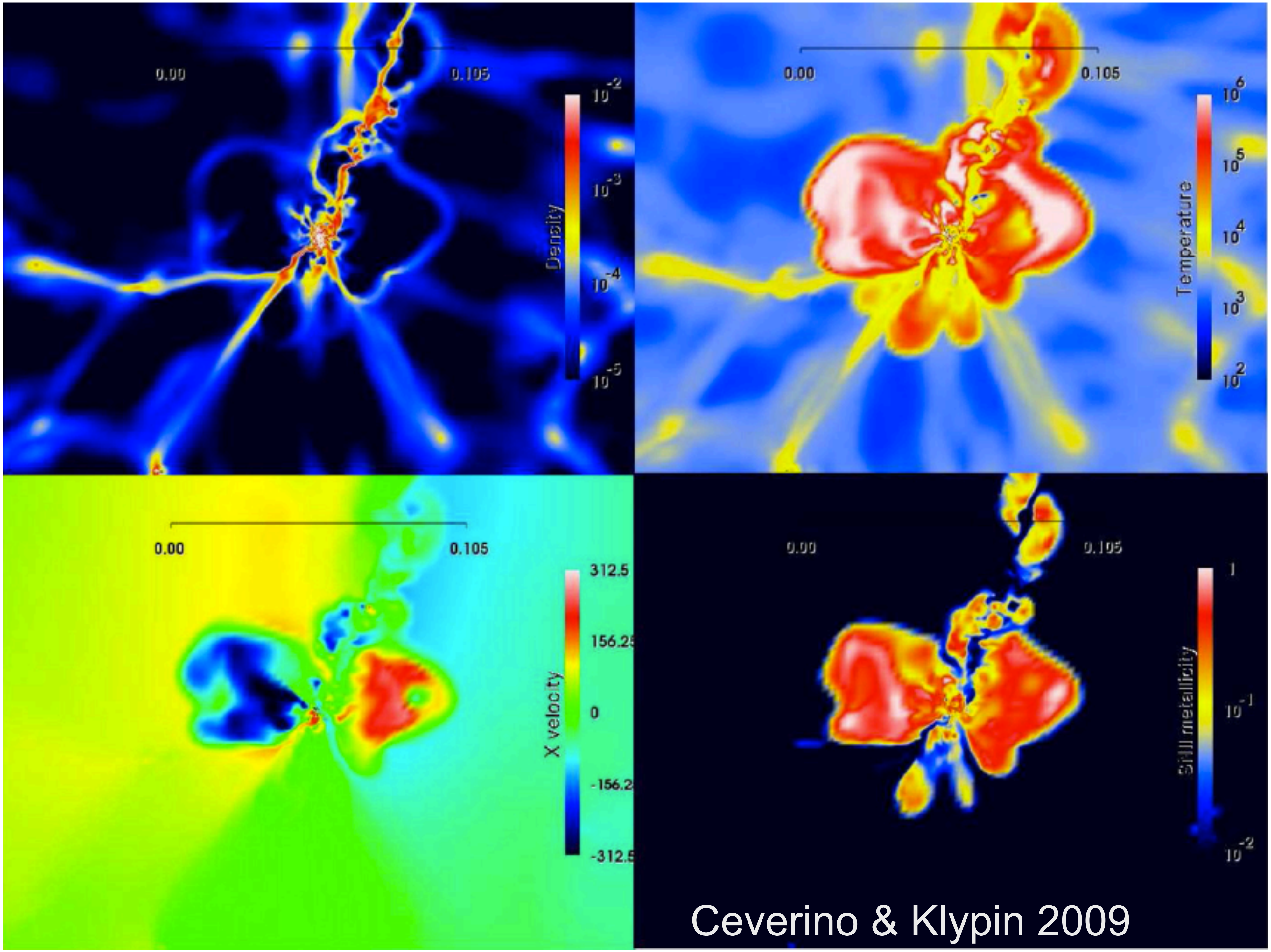
background: CANDELS image (Koekemoer et al. 2011)

GALAXY FORMATION IN A CDM UNIVERSE

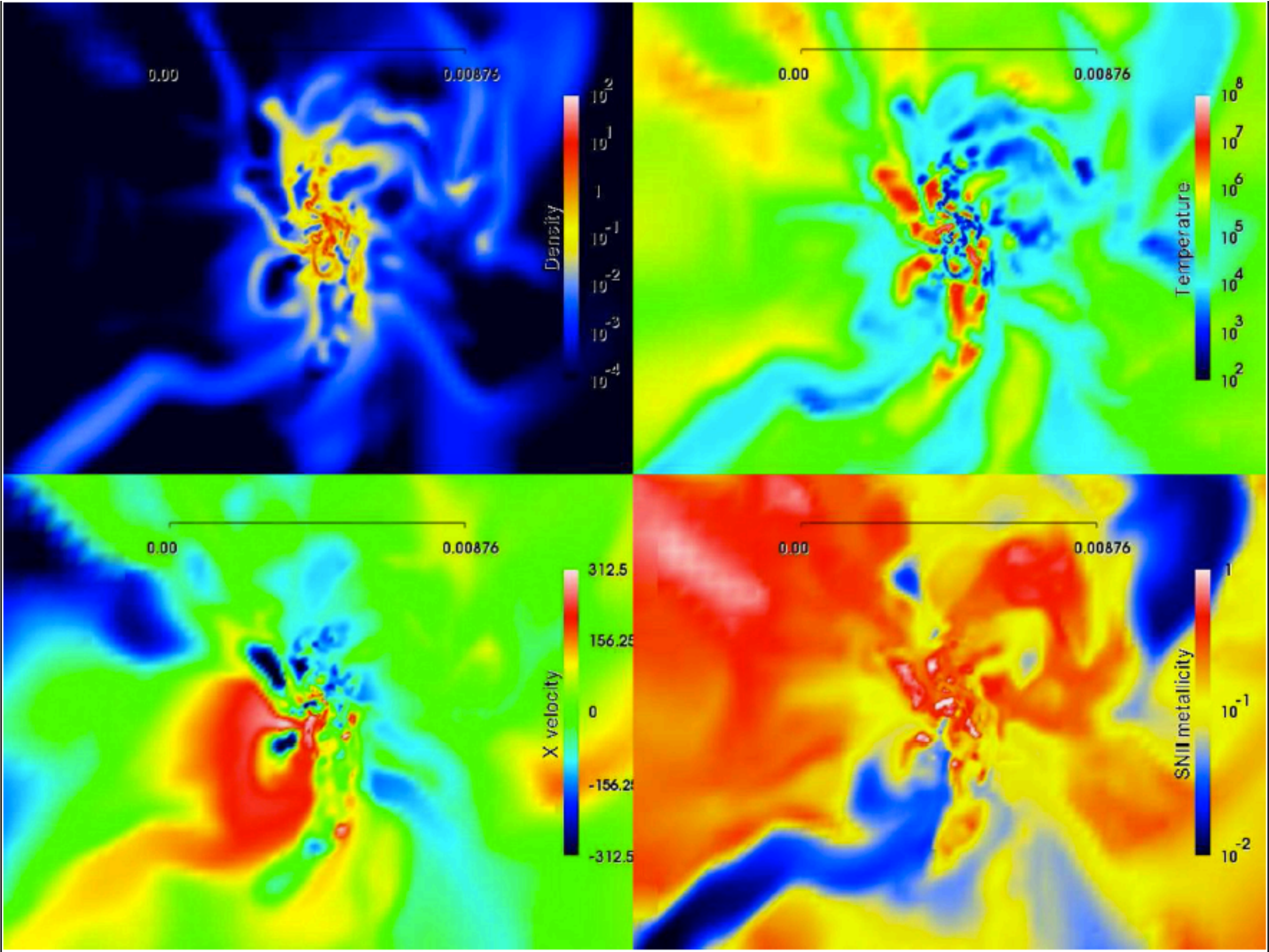


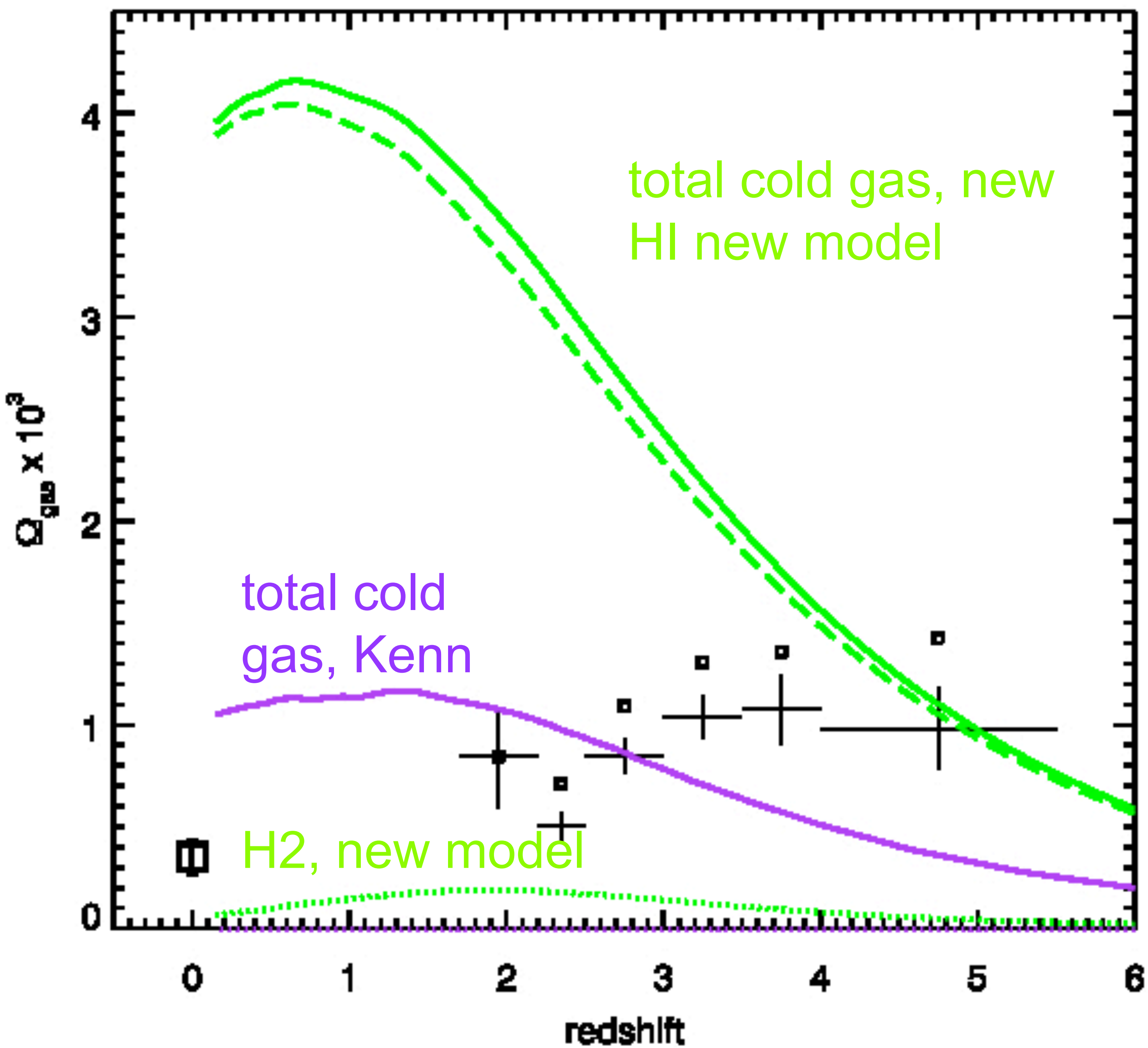
- gas is collisionally heated when perturbations 'turn around' and collapse to form gravitationally bound structures
- gas in halos cools via atomic line transitions (depends on density, temperature, and metallicity)
- cooled gas collapses to form a rotationally supported disk
- cold gas forms stars, with efficiency a function of gas density (e.g. Schmidt-Kennicutt Law)
- massive stars and SNae reheat (and expel?) cold gas

White & Rees 1978; Blumenthal et al. 1984; White & Frenk 1991



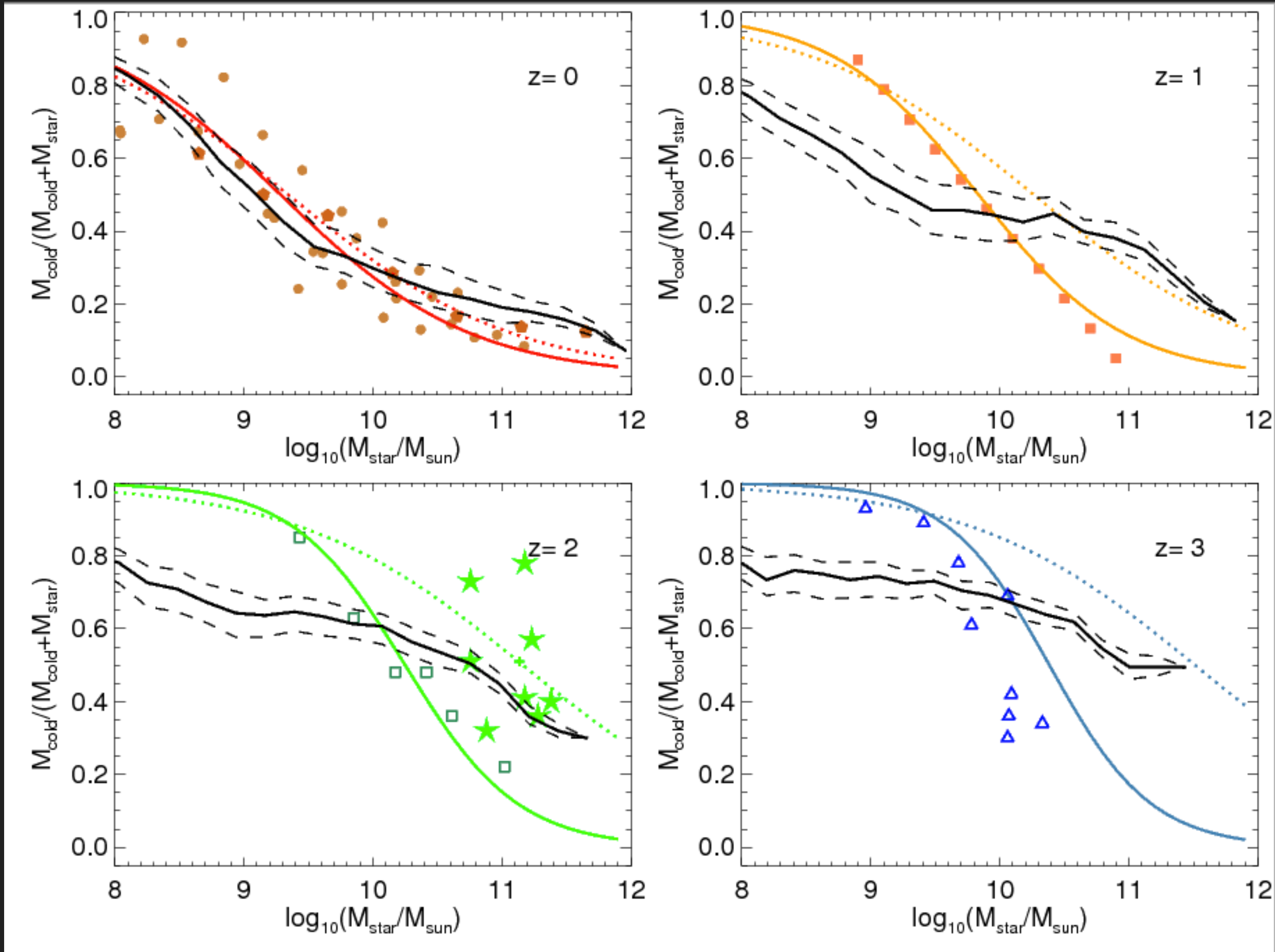
Ceverino & Klypin 2009


0.00
0.00876
Density
10^{2}
10^{1}
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.00
0.00876
Temperature
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
0.00
0.00876
X velocity
312.5
156.25
0
-156.25
-312.5
0.00
0.00876
SNII metallicity
1
10^{-1}
10^{-2}


total cold gas, new
HI new model
total cold
gas, Kenn
H2, new model
Ω_gas x 10^3
redshift
0
1
2
3
4
5
6

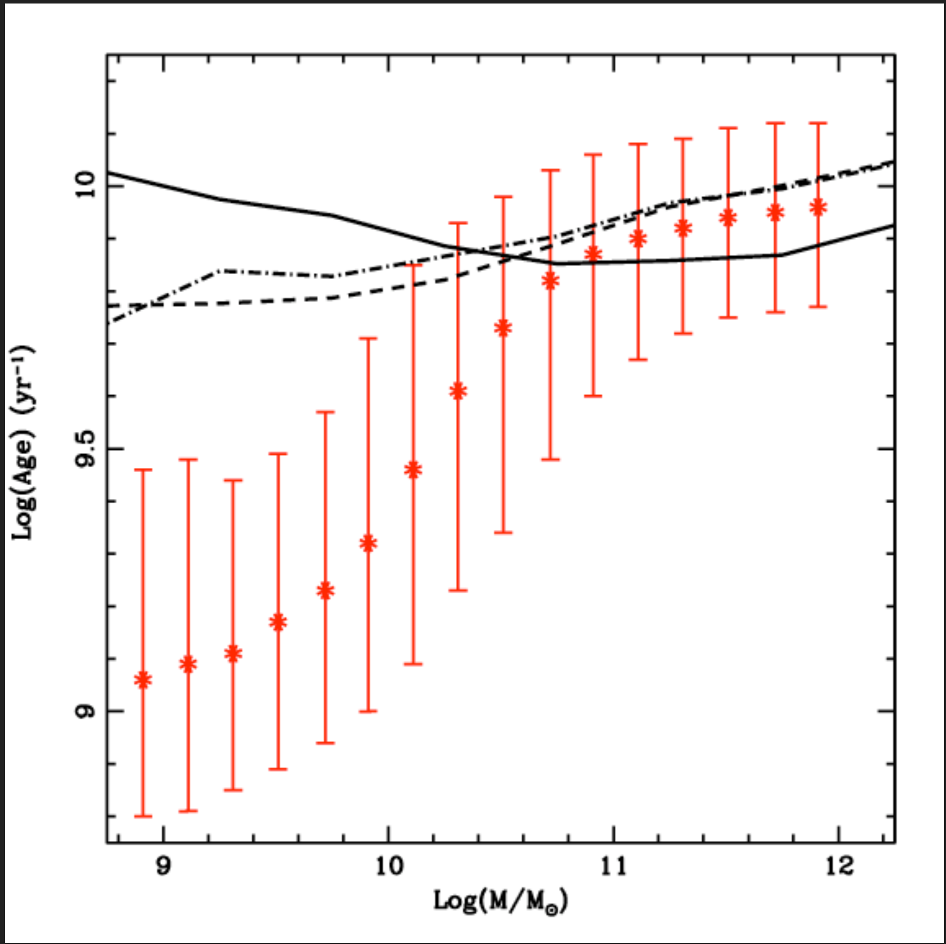
Fiducial

low mass galaxies gas fractions don't evolve much



ARCHEOLOGICAL DOWNSIZING

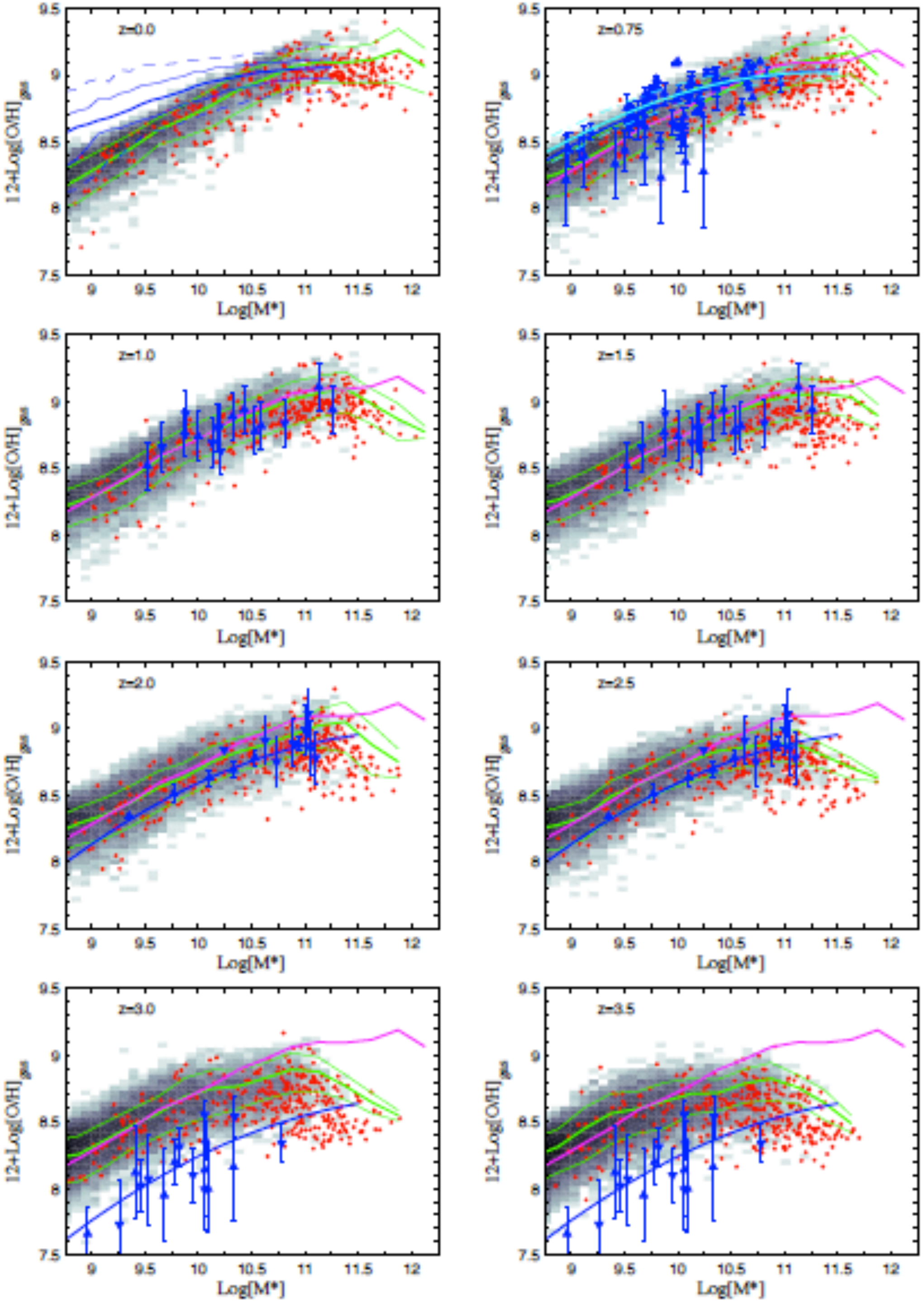
data: Gallazzi et al. 2007



- stellar populations in low mass model galaxies are too old, downsizing is too weak
- partly, but not wholly, due to biases intrinsic to age estimates from Balmer lines (see Trager & rss 2008)

Fontanot et al. 2009

gas phase Oxygen abundance

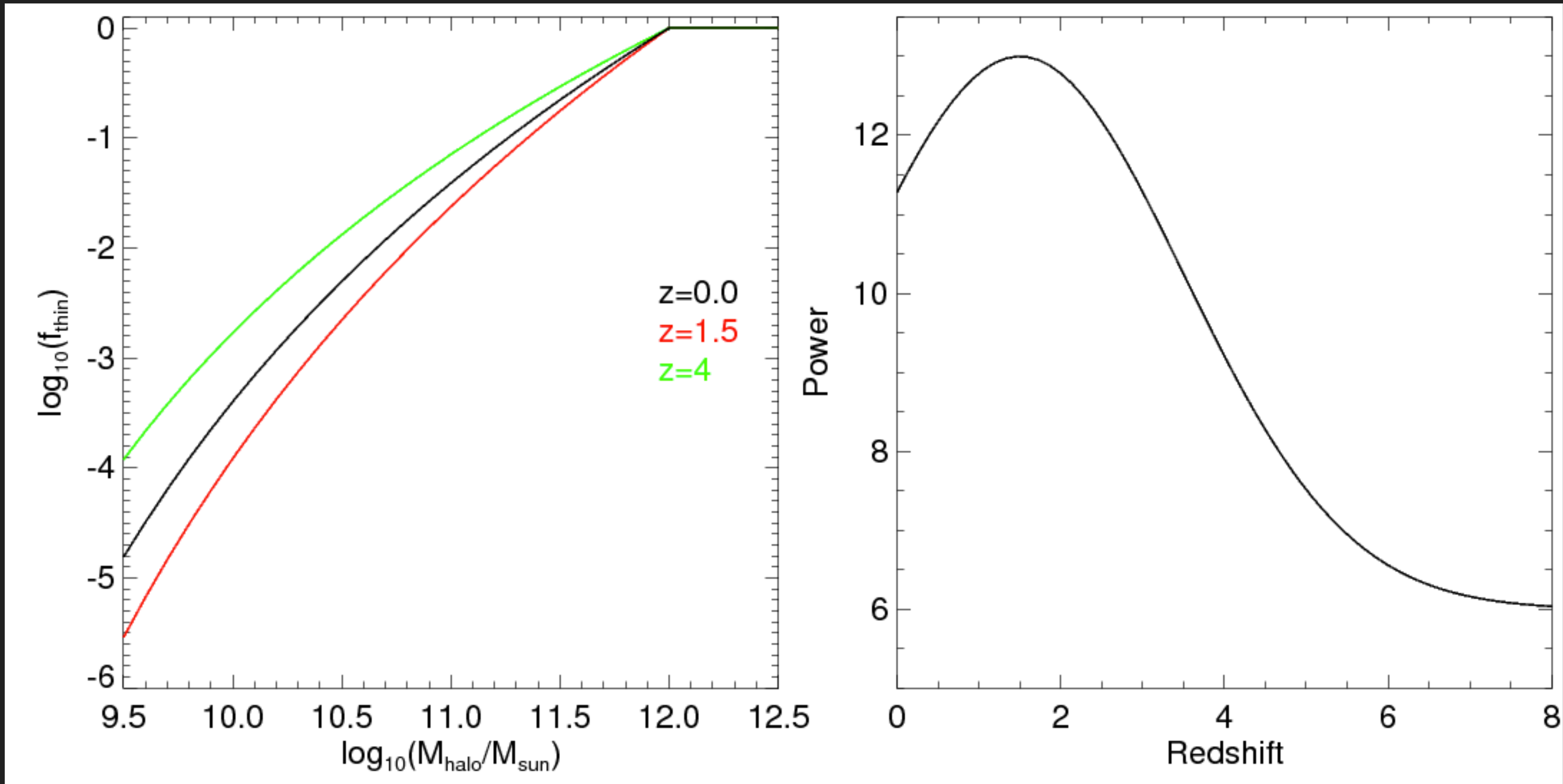


low mass galaxies become enriched too early

blue lines: z=0 relation from Tremonti et al. 2004
blue symbols: observations at various redshifts
red dots: central model galaxies
gray: all model galaxies
green: median for model galaxies
magenta: model galaxies z=0

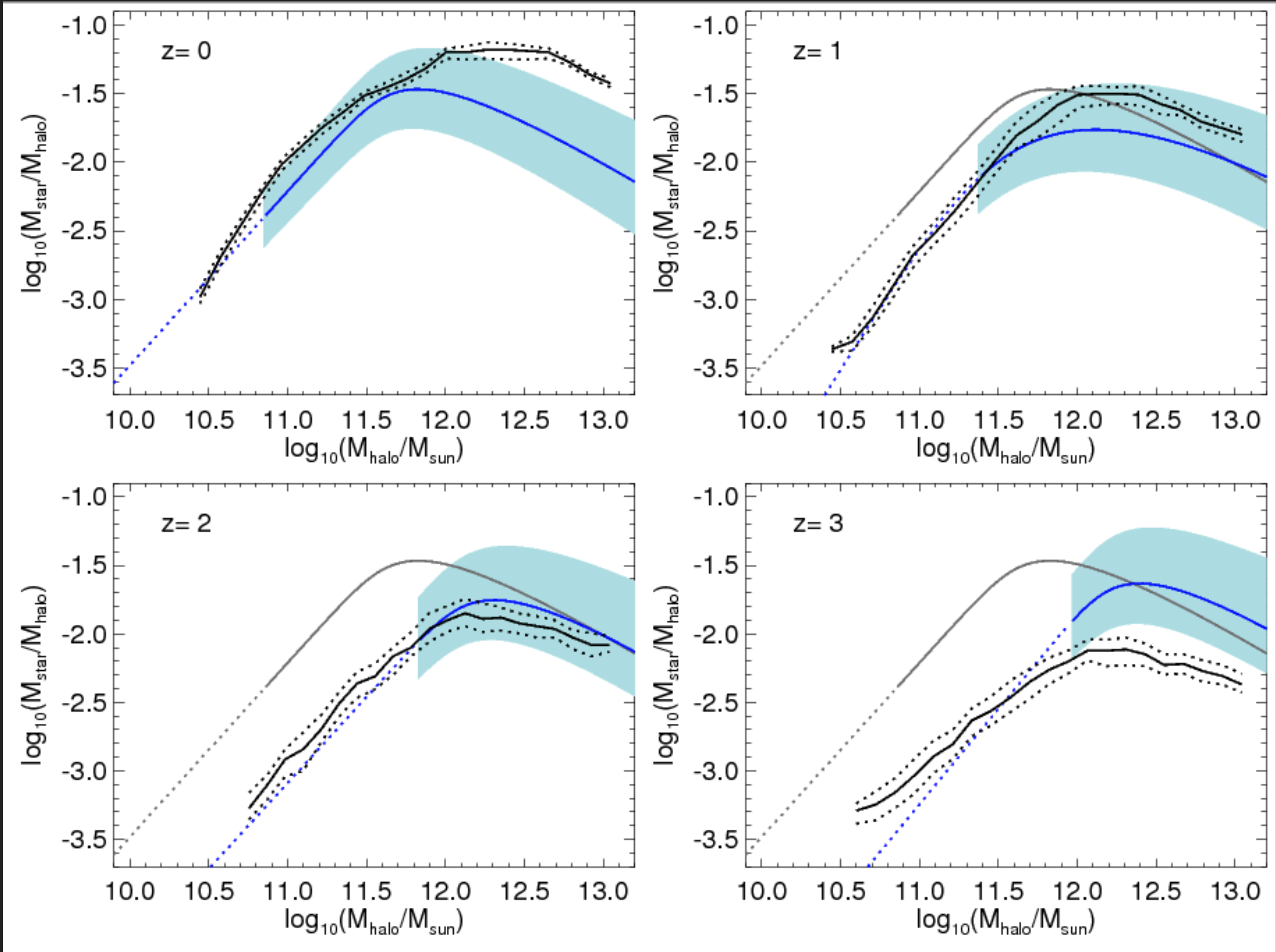
Arrigoni, Trager & rss 2011

what if we make the fraction of gas that is eligible for SF an arbitrary function of halo mass and redshift?

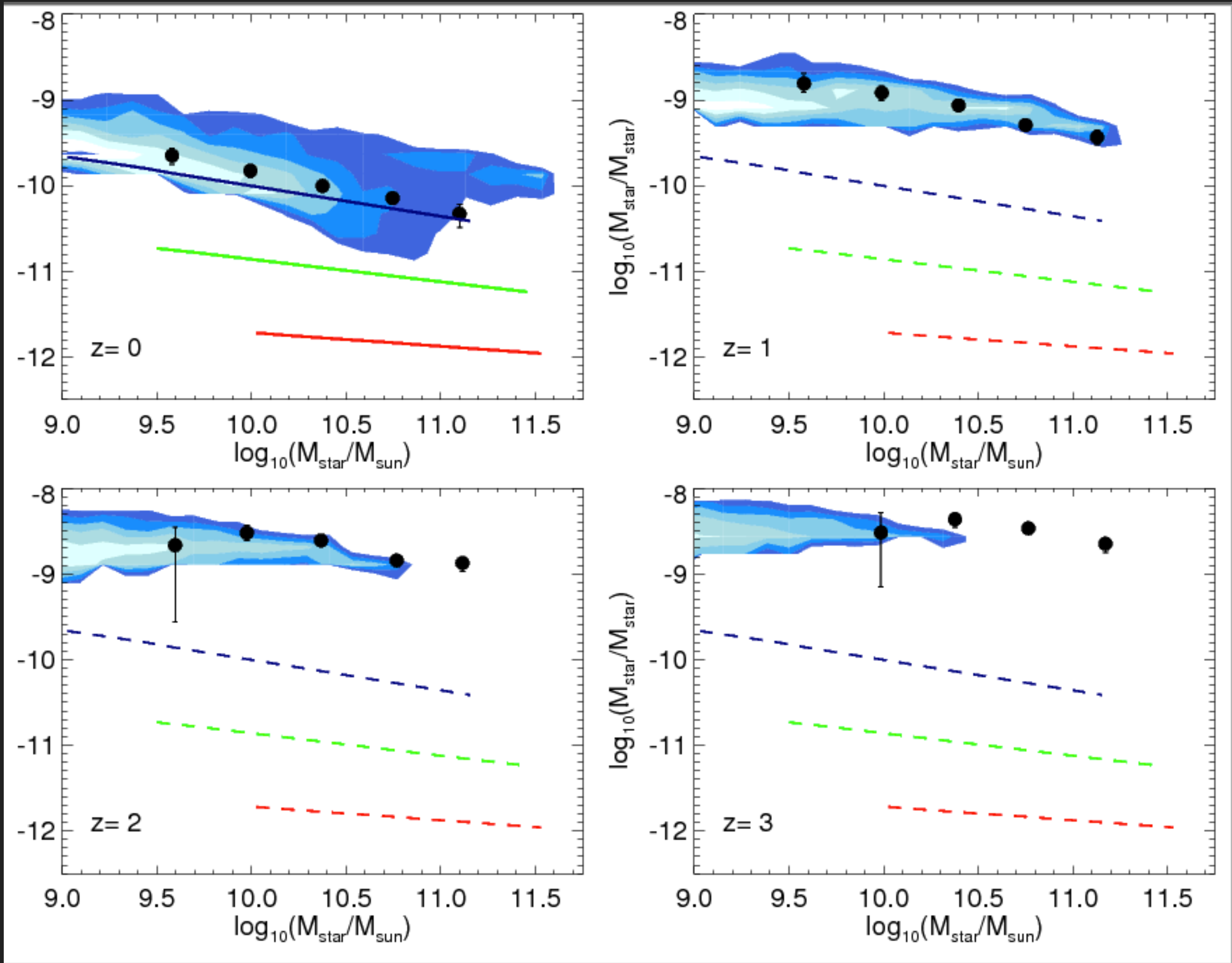


Caviglia & rss 2011

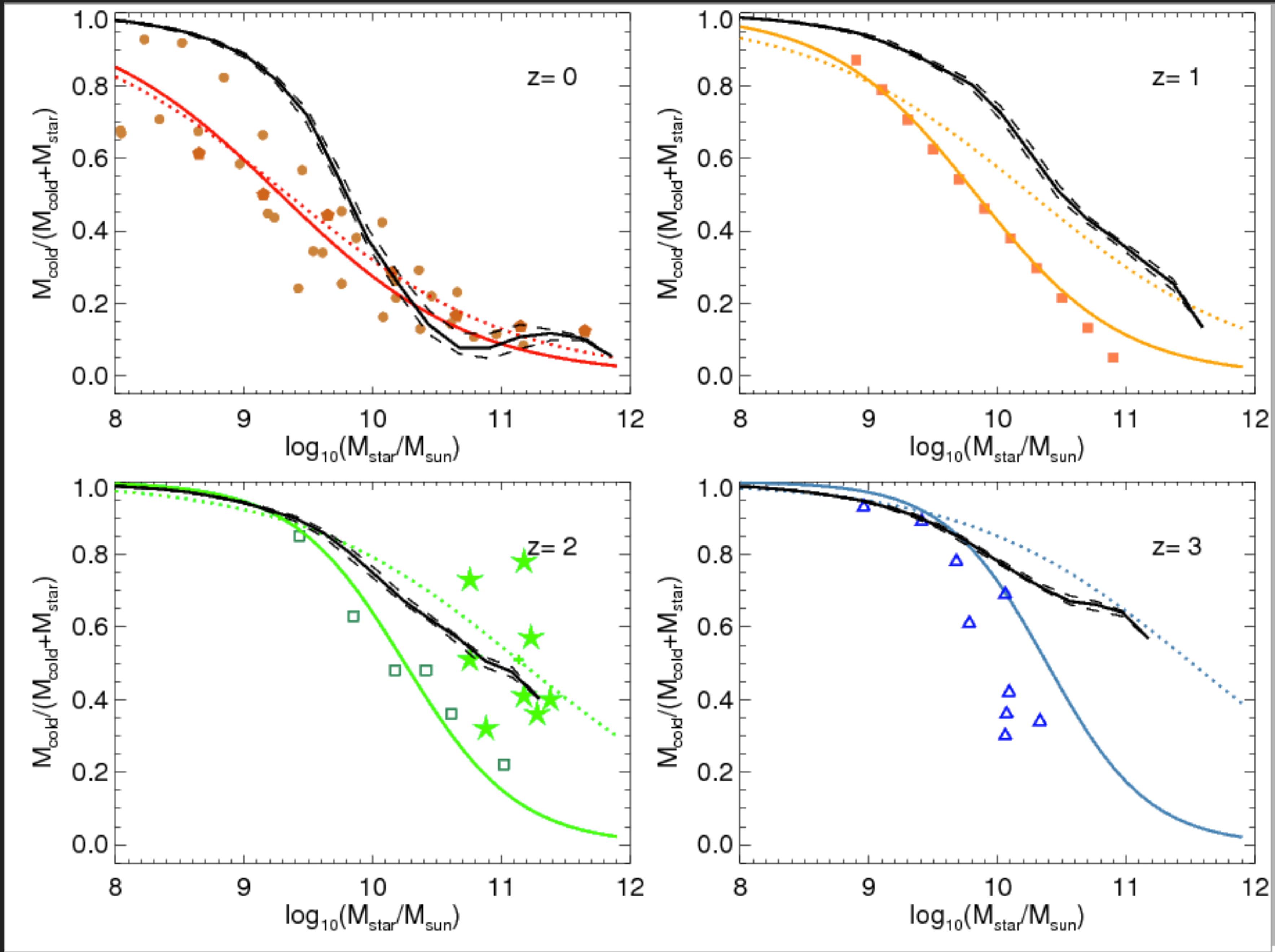
“thinning” model

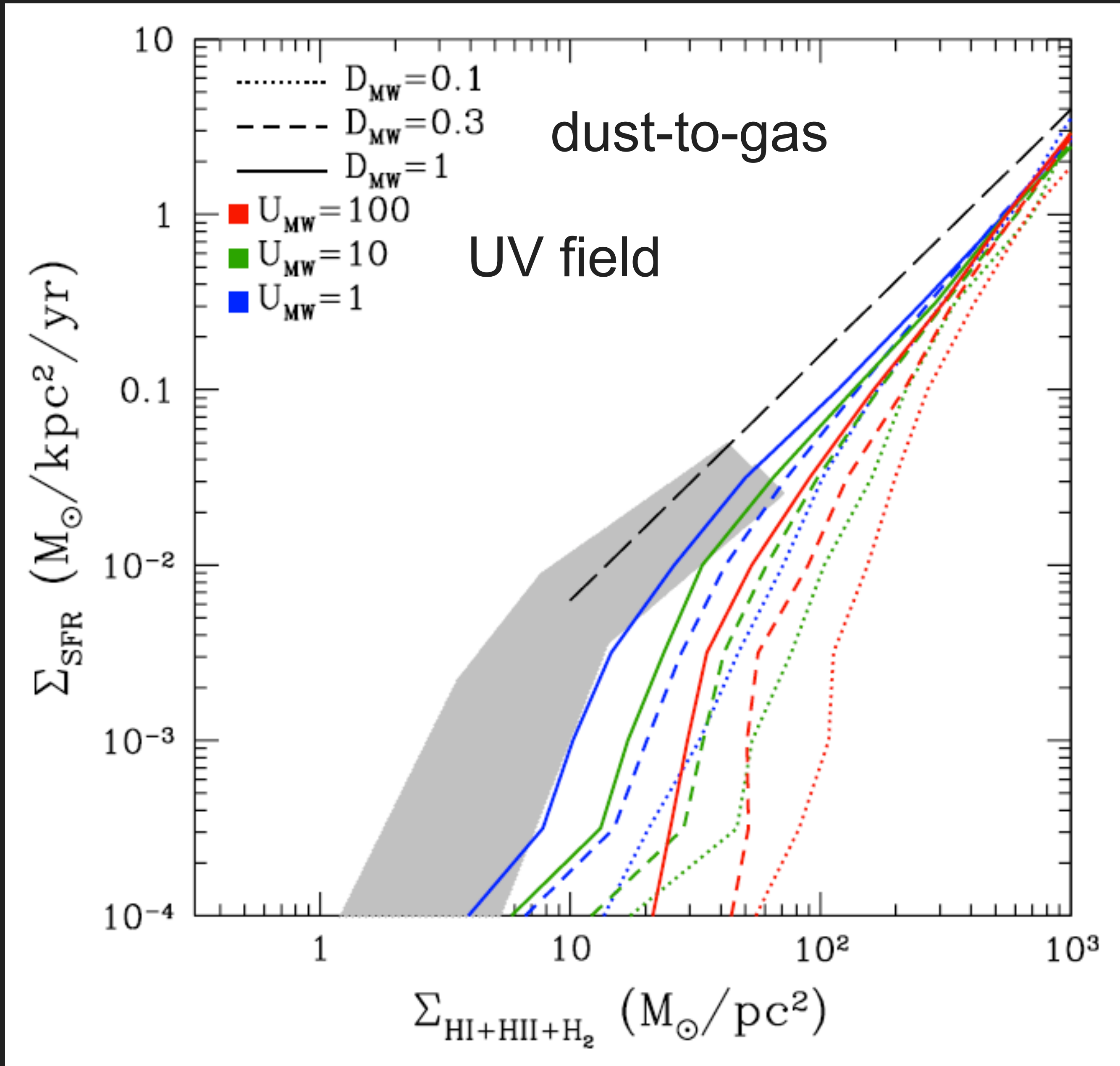


“thinning” model – simultaneously solves all ‘downsizing’ problems!



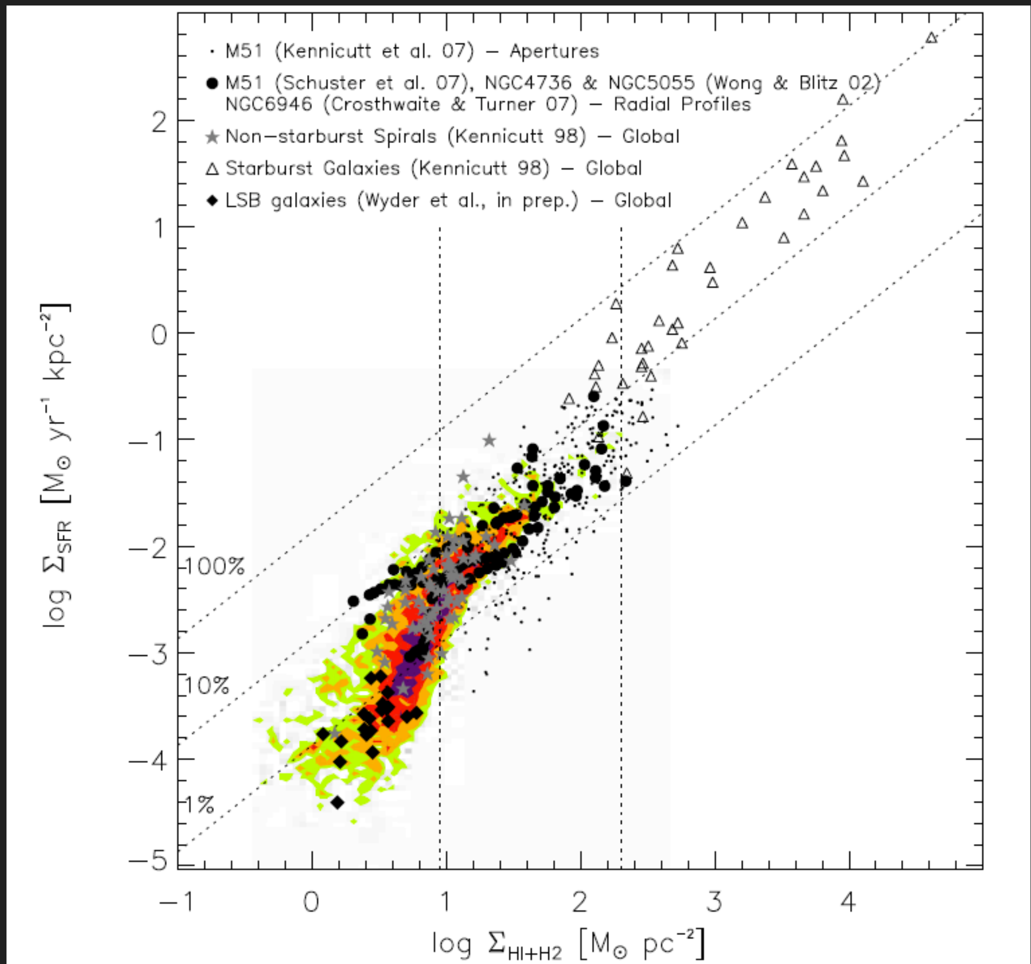
except…too much gas left over at z=0?





Gnedin & Kravtsov 2010; see also Robertson & Kravtsov 2008

BEYOND KENNICUTT: NEW INSIGHTS ON RELATIONSHIP BETWEEN SF AND GAS DENSITY



Bigiel et al. 2008; see also Leroy et al. 2008