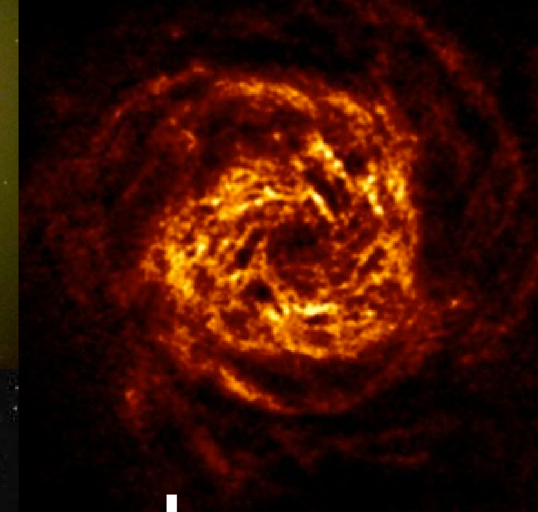
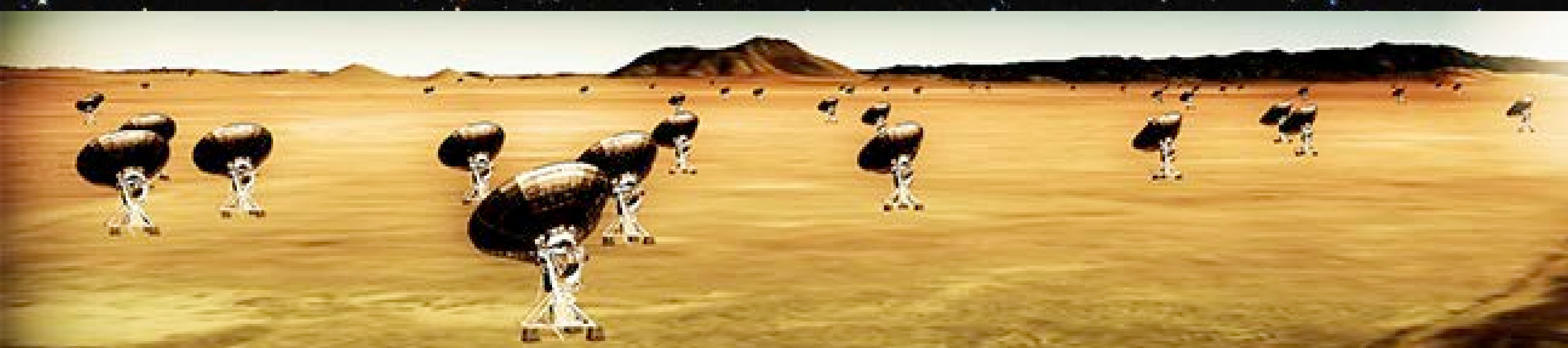


galaxy formation and ngVLA

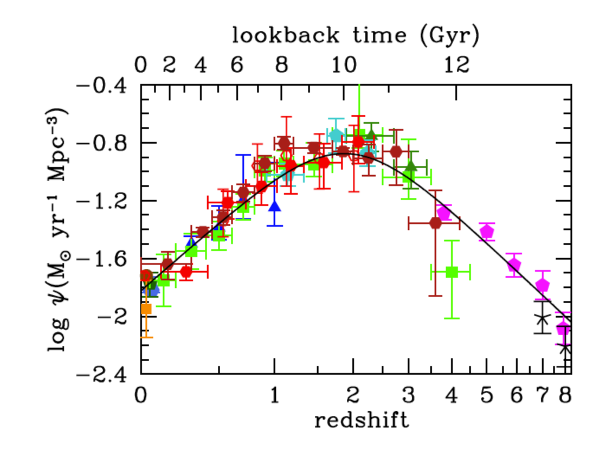
rachel somerville
Rutgers University



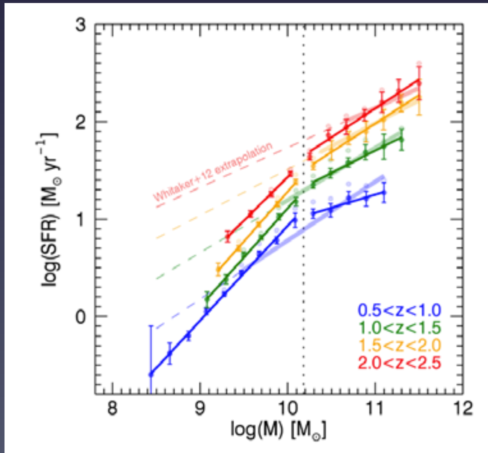
galaxy evolution: the UVOIR view

- star formation and stellar mass assembly history
- evolution of star forming main sequence & downsizing
- quenching of star formation, build up of quiescent population accompanied by structural and morphological transformation

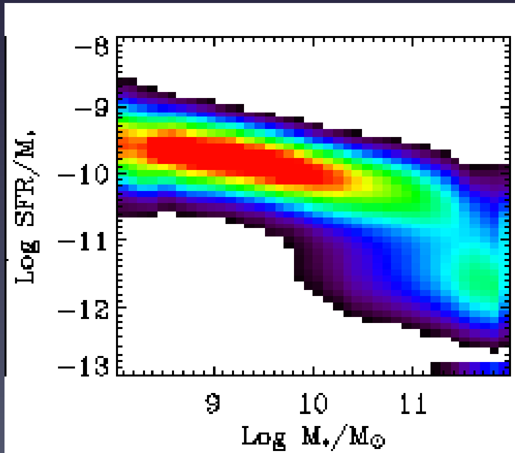
Madau & Dickinson 2014

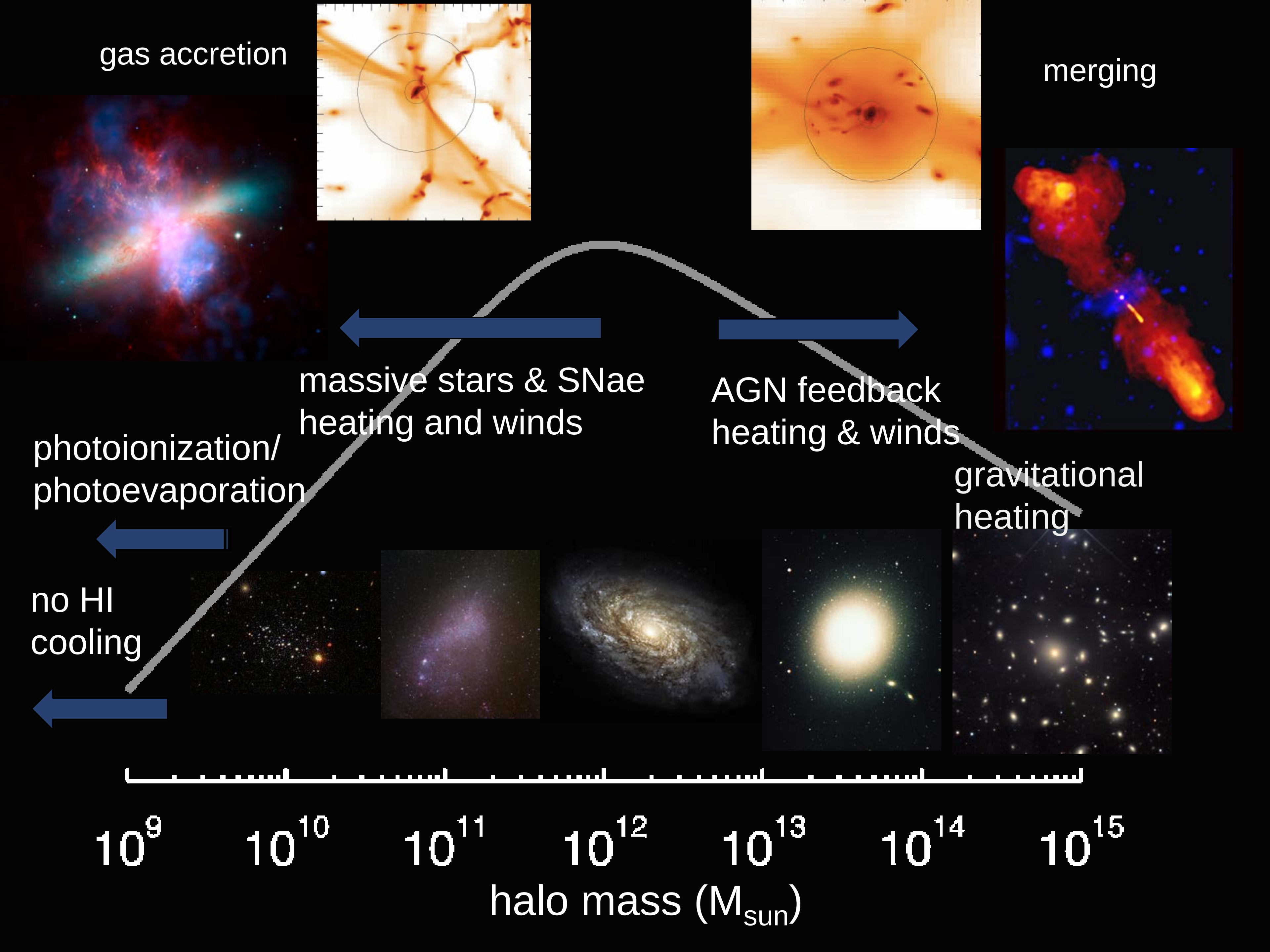


Whitaker et al. 2014

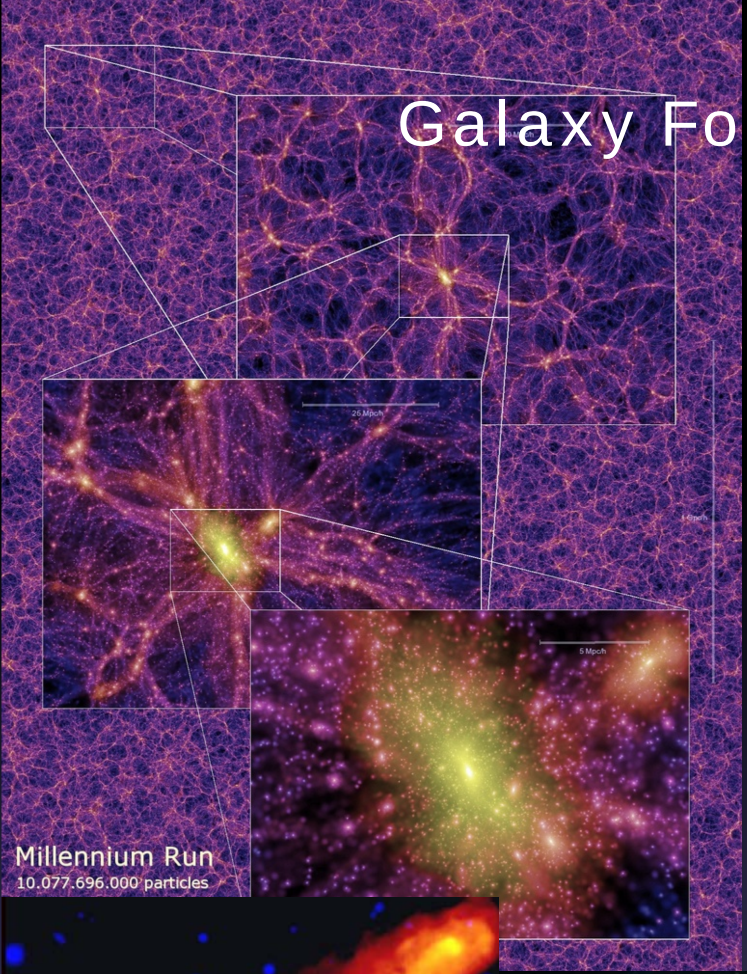


Brinchmann et al. 2003




gas accretion
merging
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})

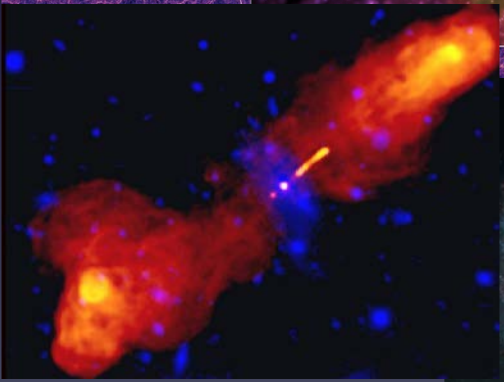
Galaxy Formation: The Grand Challenge

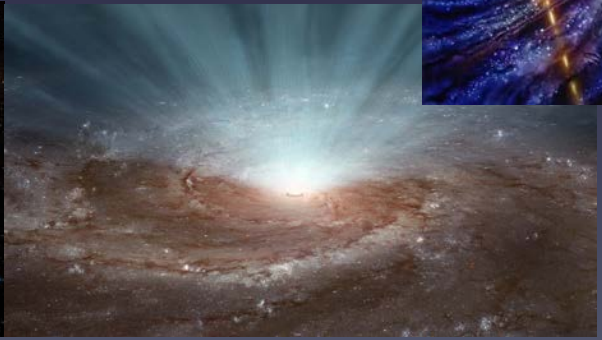


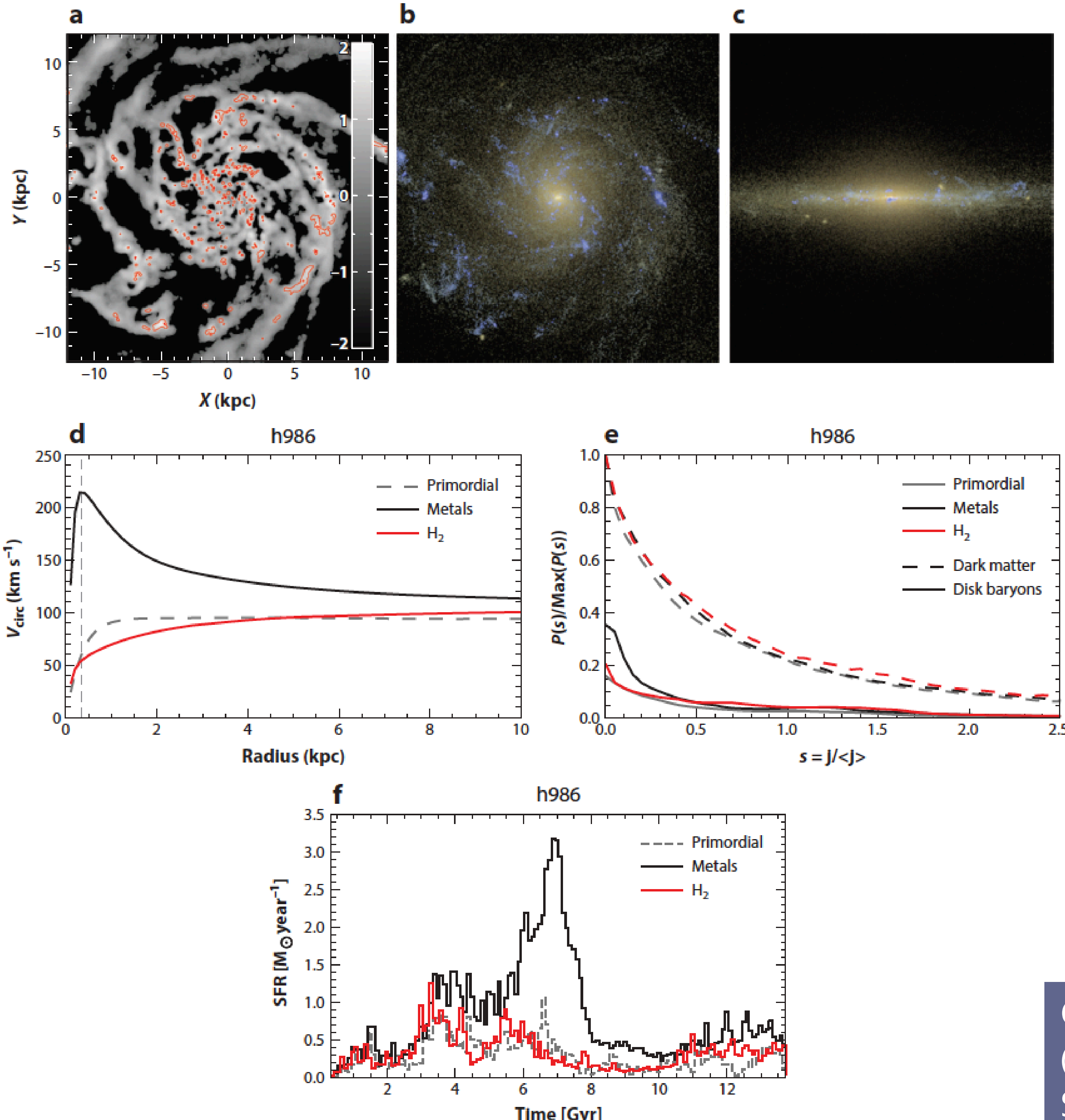
large-scale structure: 100's of Mpc
galaxy environment: ~1-8 Mpc
galaxy internal structure ~0.1-1 kpc
Giant Molecular clouds: ~10's of pc
star clusters/SNae: pc/sub-pc
structures associated with supermassive BH: pc/sub-pc

+ diverse array of physical processes

all cosmological simulations currently use phenomenological 'sub-grid' recipes – the challenge is to replace these with fundamental physics







predicted structural,
kinematic,
& morphological properties as well as SF history of galaxies highly sensitive to details of implementation of 'sub-grid' physics (multi-phase ISM, chemistry, stellar & BH feedback, etc)

Christensen et al. 2012 (as reproduced in Somerville & Davé 2015)

constraining the gas content in all phases is crucial for constraining the physical processes that drive galaxy evolution

- what determines the efficiency of converting [cold, dense] gas into stars? [how] does it depend on environment or other variables?
- what are the relative roles of radiative, thermal, & kinetic feedback processes? how does this depend on spatial scale & conditions?
- is stellar feedback primarily ‘ejective’ or ‘preventative’?
- how important are turbulence, magnetic fields, cosmic rays etc?

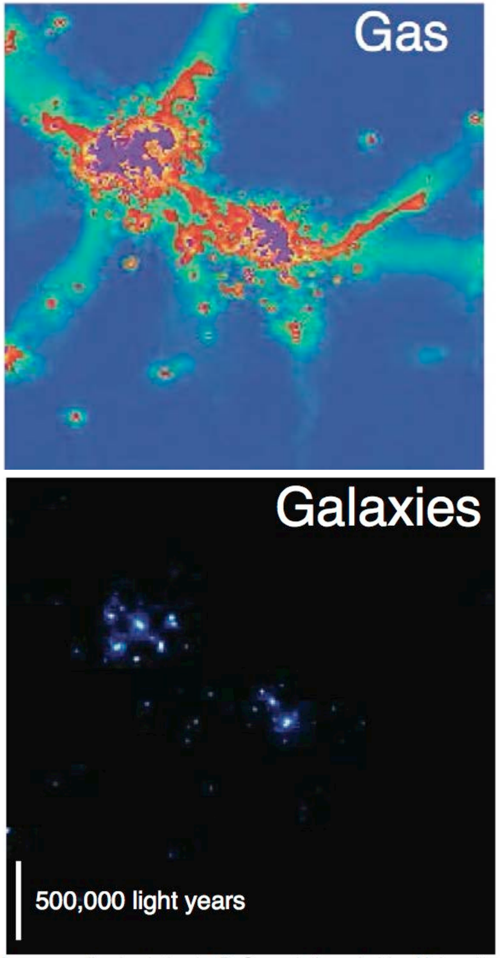


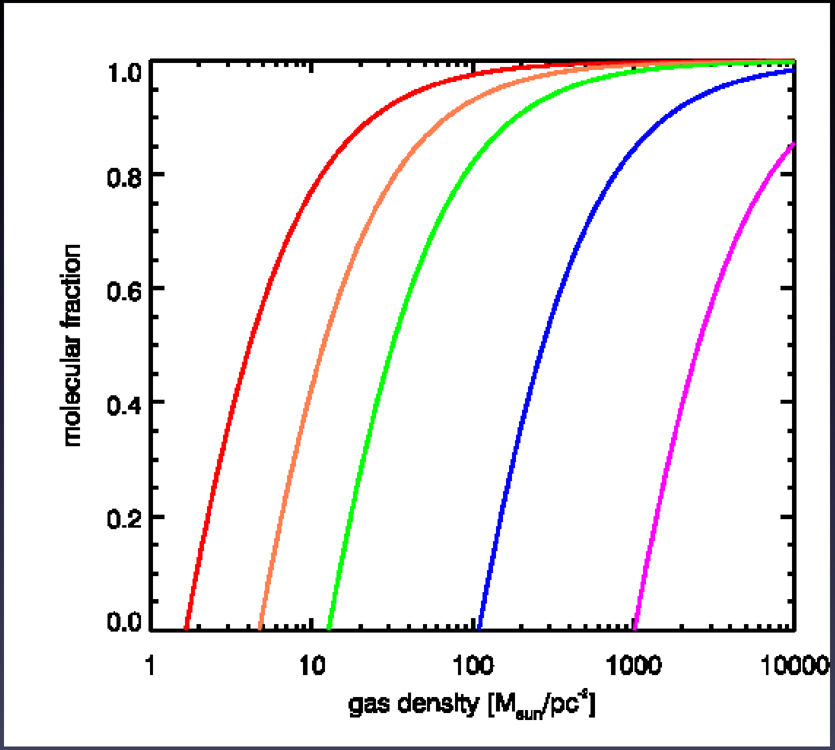
Image credit: simulation by B. Oppenheimer, Leiden University

Modeling multi-phase gas in cosmological simulations

rss, Popping & Trager 2015; Popping, rss & Trager 2014; Berry, rss et al. 2014; 2015
see also Fu & Kauffmann 2010, 2011; Lagos et al. 2011 a,b; Obreschkow et al. 2009

two main approaches used:

1) H_2 fraction depends on gas density, dust-to-gas (metallicity) and intensity of local UV radiation field - OR
2) H_2 fraction depends on disk midplane pressure



Z=1.0
0.3
0.1
0.01
0.001

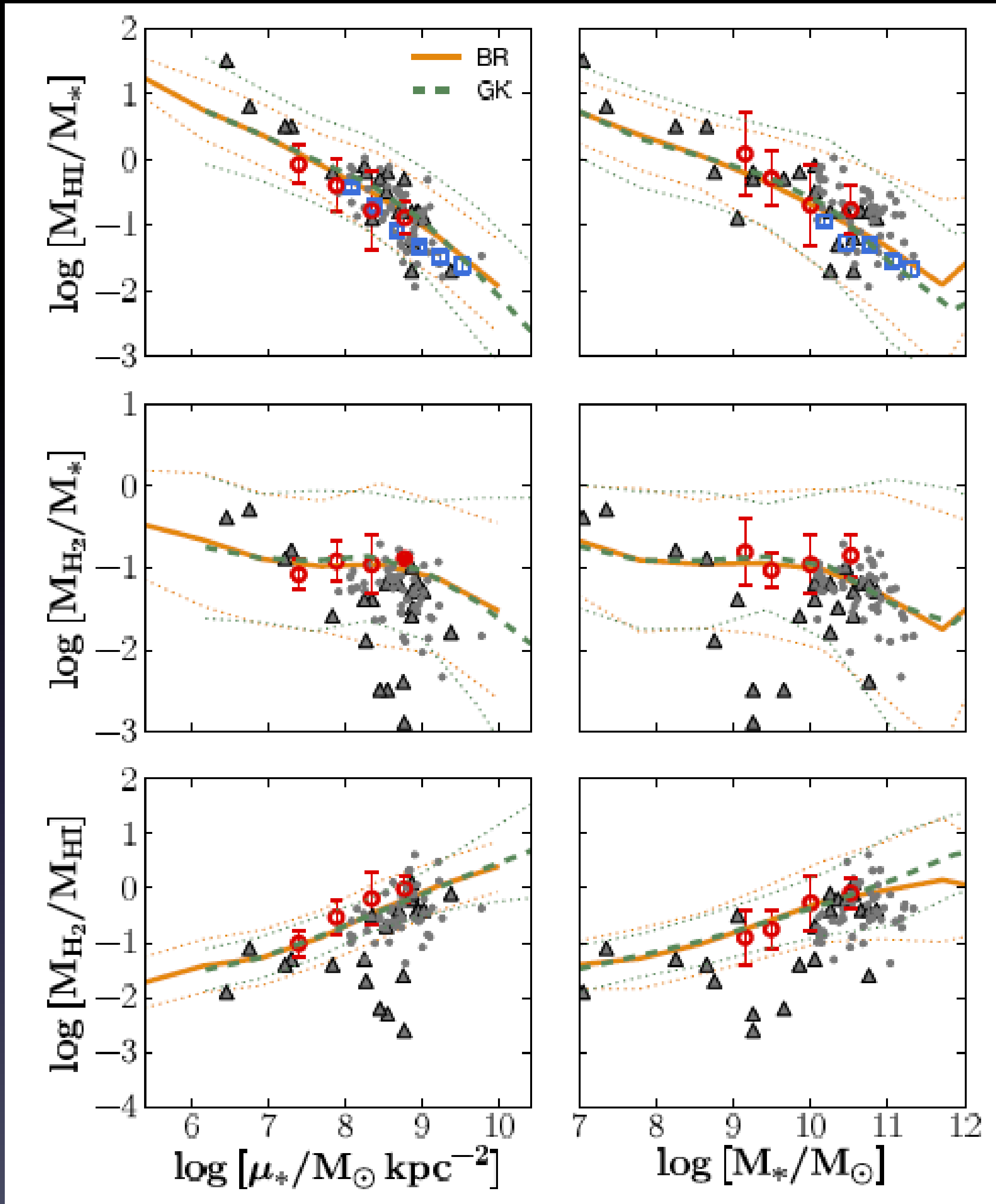
see also Robertson & Kravtsov 2009; Krumholz, McKee & Tumlinson 2008a,b, 2009
Gnedin & Kravtsov (2010, 2011); Christensen et al. 2012; 2014; Lagos et al. 2015

multi-phase gas scaling relations for disks at z=0

HI/stars

H2/stars

H2/HI



stellar density

stellar mass

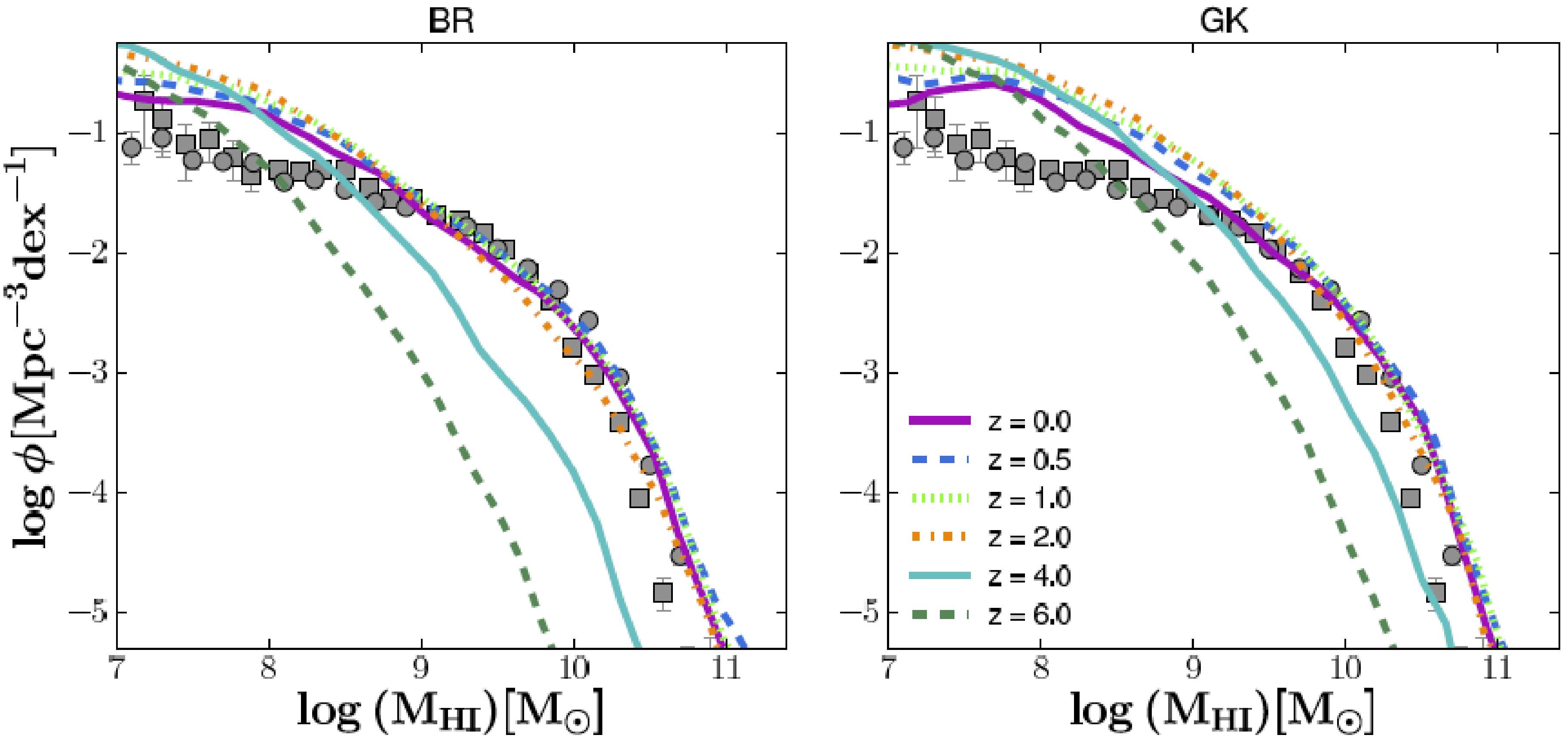
both the pressure & metallicity based recipes reproduce observed H2/HI fractions at z=0

dots=observations from
Leroy et al. 2008 (THINGS)
Saintonge et al. 2011 (COLD GASS)

Popping, rss & Trager '14

evolution of HI mass function with cosmic time

models predict very weak/no evolution since z~2

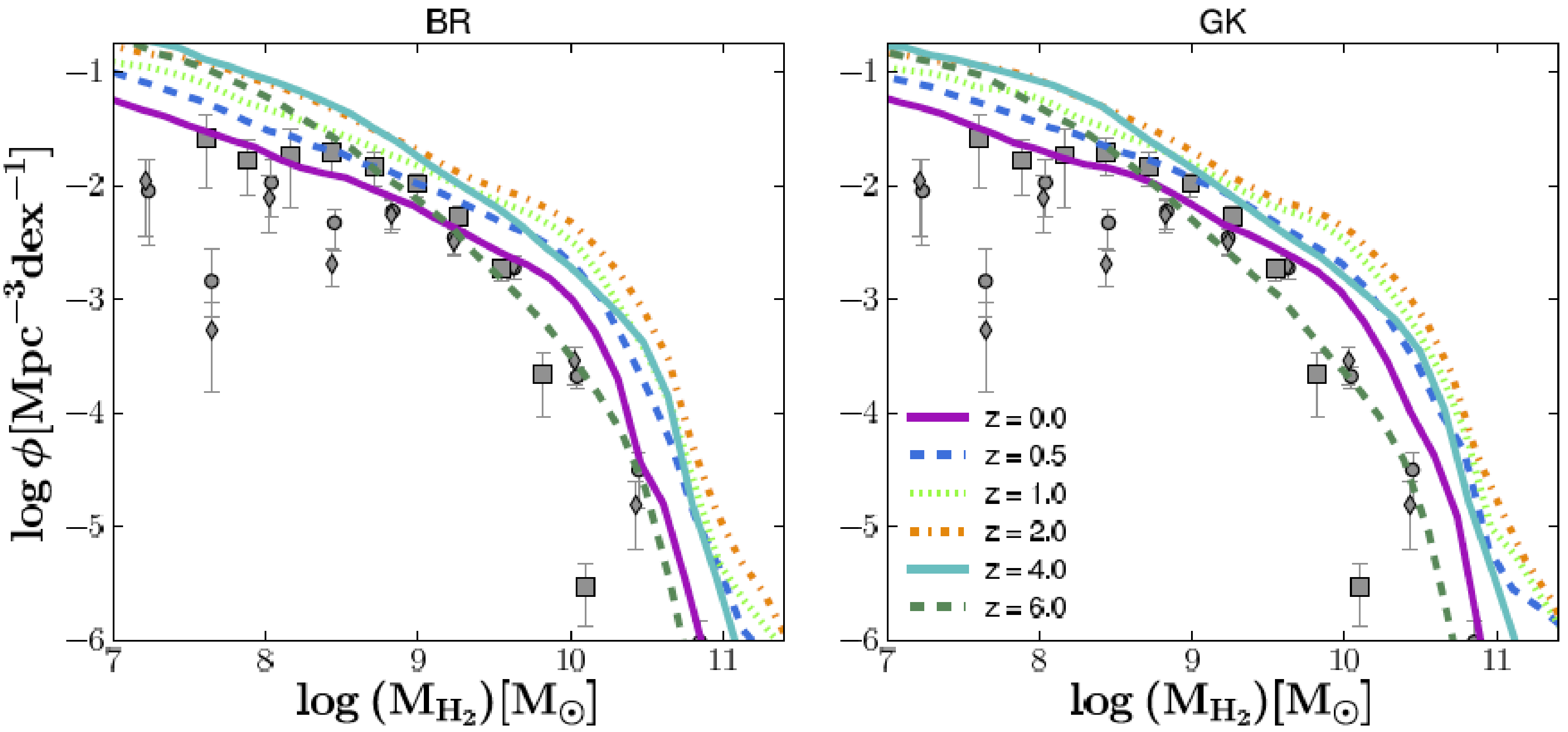


(observations are at z=0)

Popping, rss & Trager '14

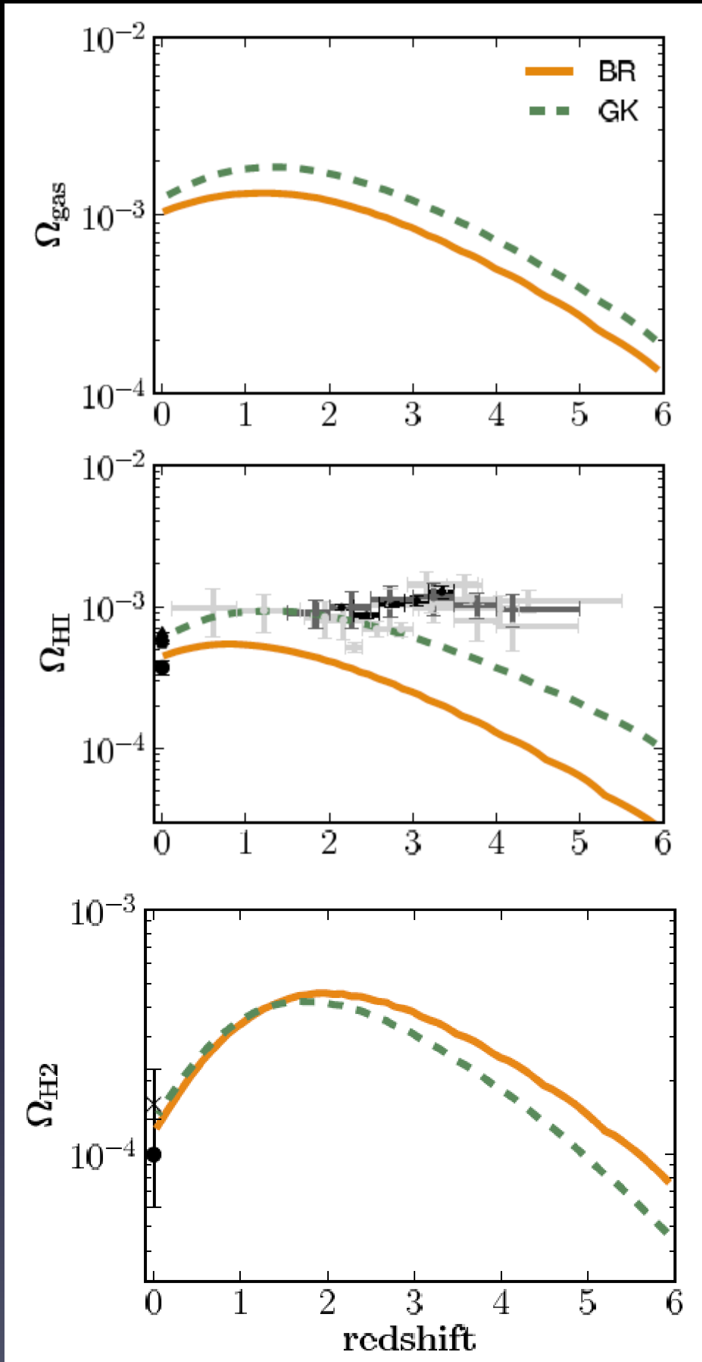
evolution of H2 mass function with cosmic time

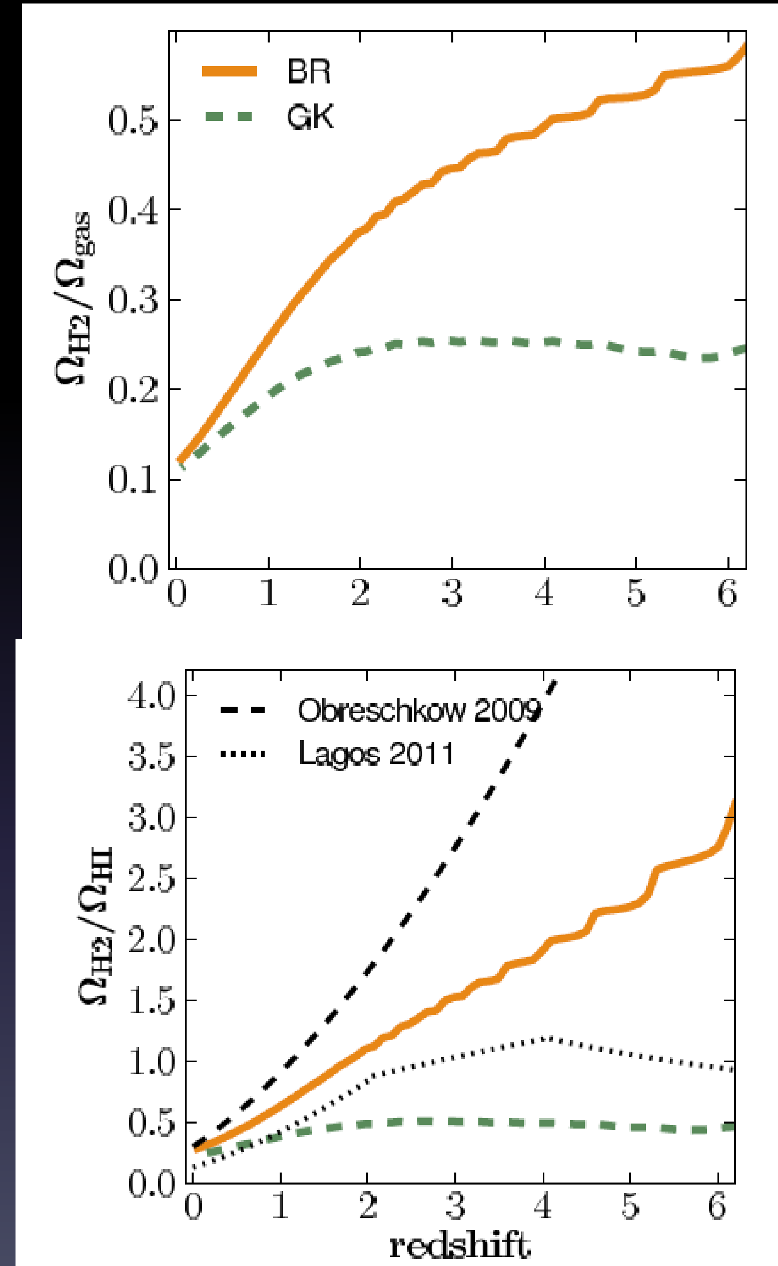
models predict relatively weak evolution to z~6 compared with stellar mass function



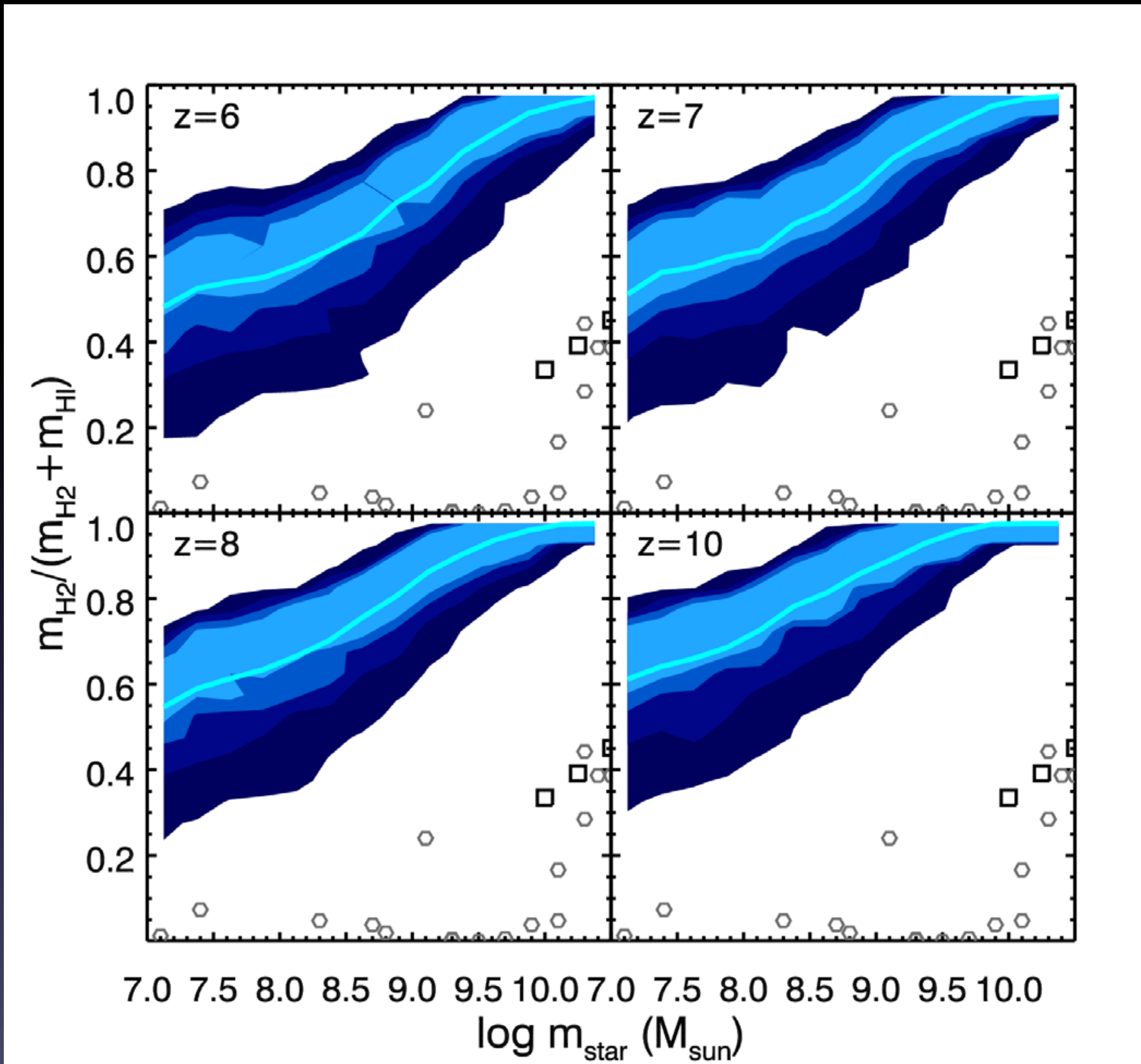
observations are shown at z=0

Popping, rss & Trager '14





Popping, rss & Trager '14
see also Berry et al. 2014

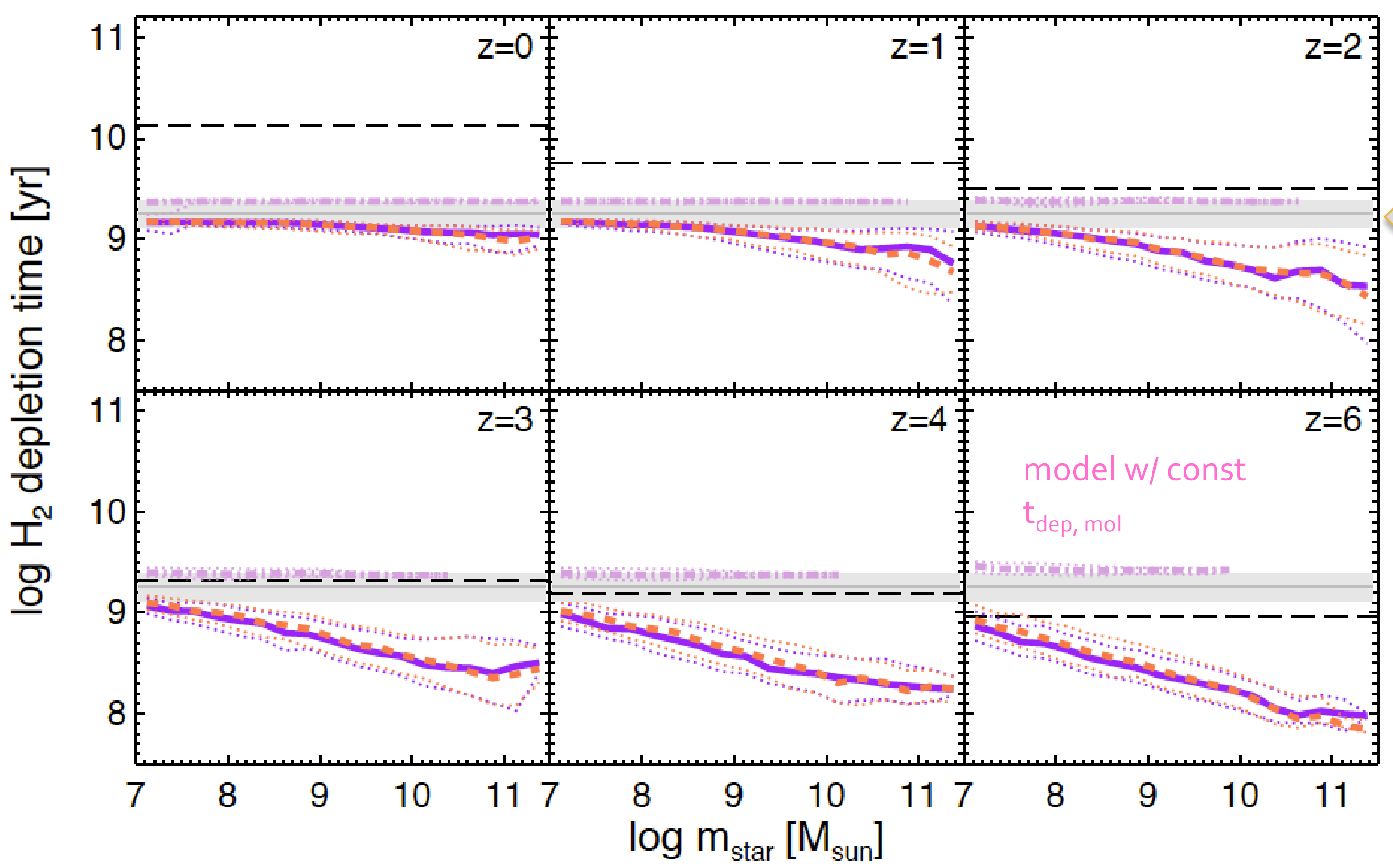


naïve expectation: low mass galaxies at v. high redshift will have difficulty forming molecular hydrogen due to their low Zs

model prediction: galaxies have very high gas surface densities and enrich quickly. → H_2 fractions are higher than in nearby galaxies.

same models presented in SPT15

molecular gas depletion times



mol. depletion times in nearby spirals (Leroy et al. 2013)

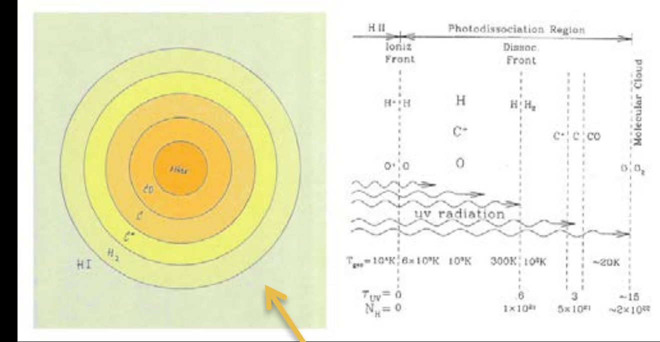
model w/ density dep. $t_{dep, mol}$

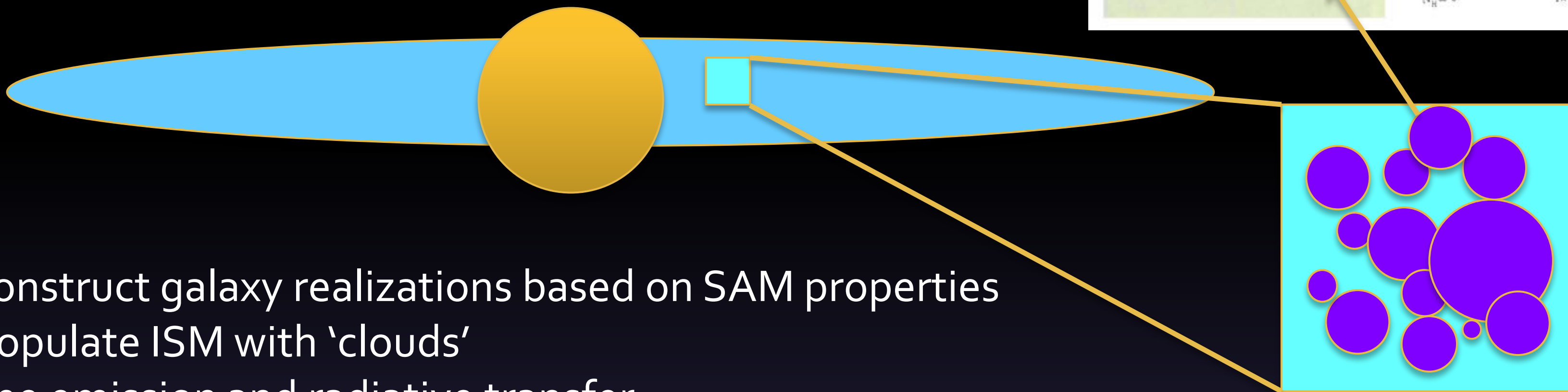
horizontal dashed line= age of universe

SPT15

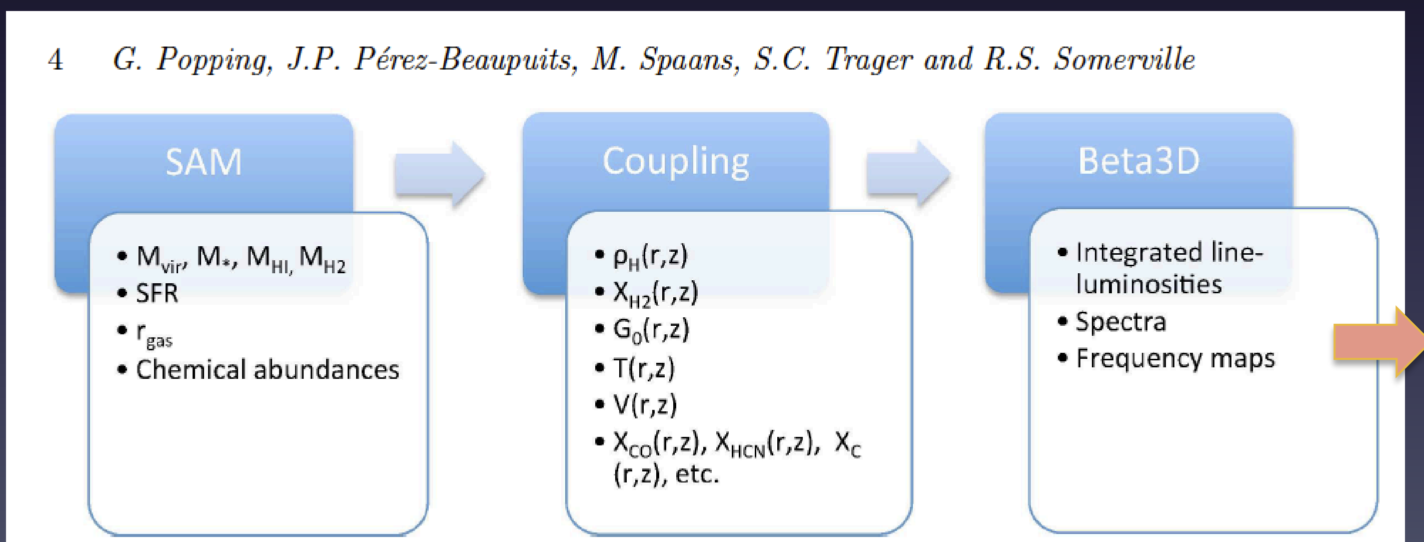
Combining multi-phase SAM with PDR+RT modeling

PhD thesis of Gergö Popping (w/ rss, S. Trager & M. Spaans)





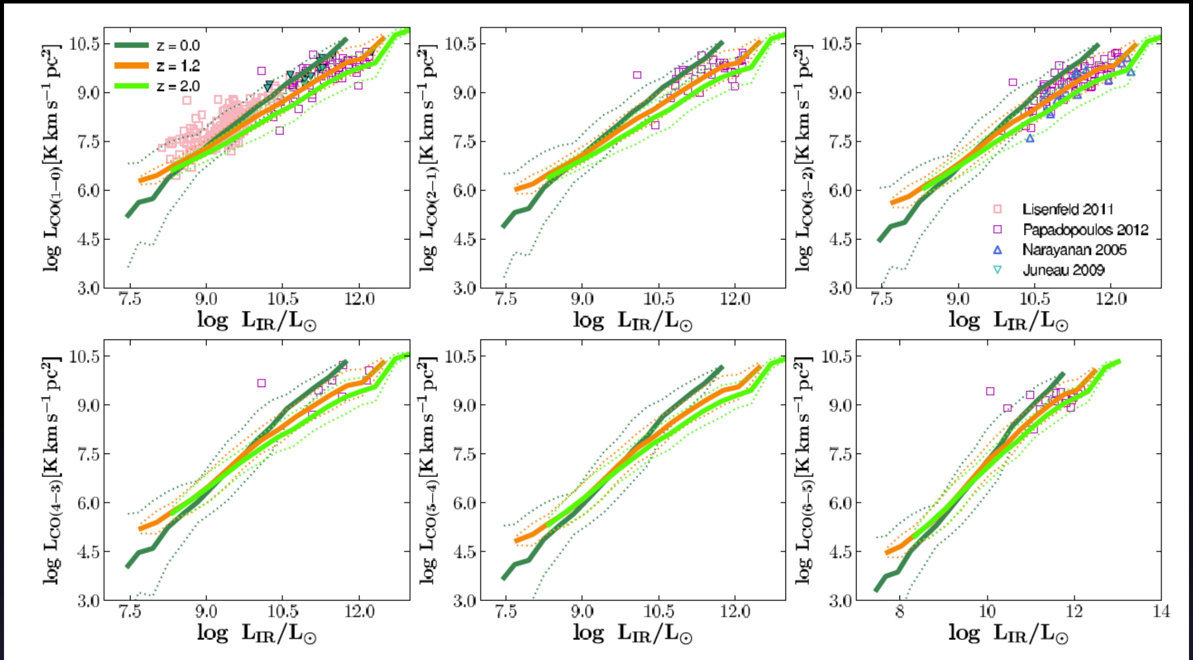
-construct galaxy realizations based on SAM properties
-populate ISM with 'clouds'
-line emission and radiative transfer

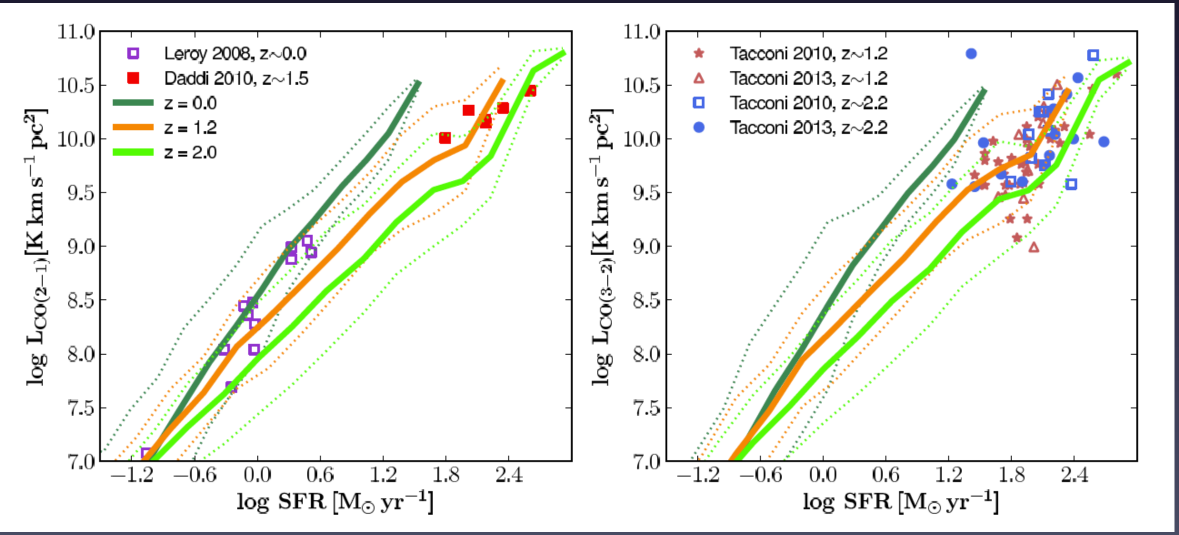


4 *G. Popping, J.P. Pérez-Beaupuits, M. Spaans, S.C. Trager and R.S. Somerville*

CO, HCN, C, C+, [OI]

CO(1-0)
CO(2-1)
CO(3-2)
CO(4-3)
CO(5-4)
CO(6-5)

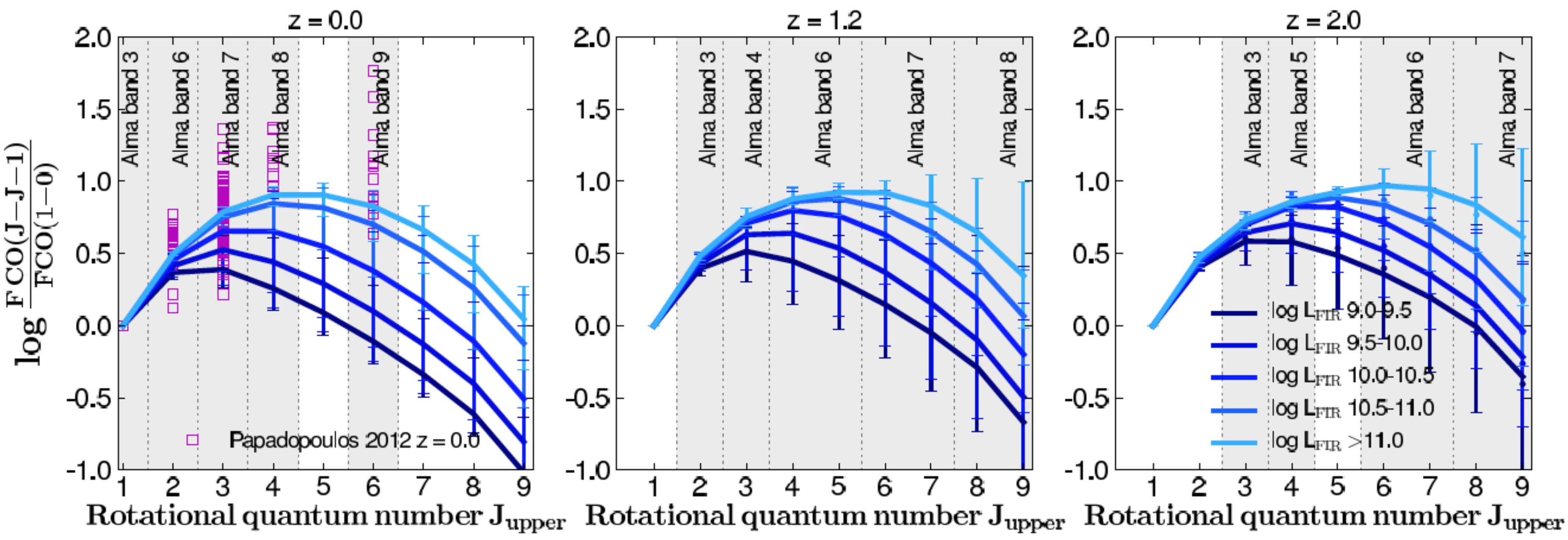




Popping et al. 2014

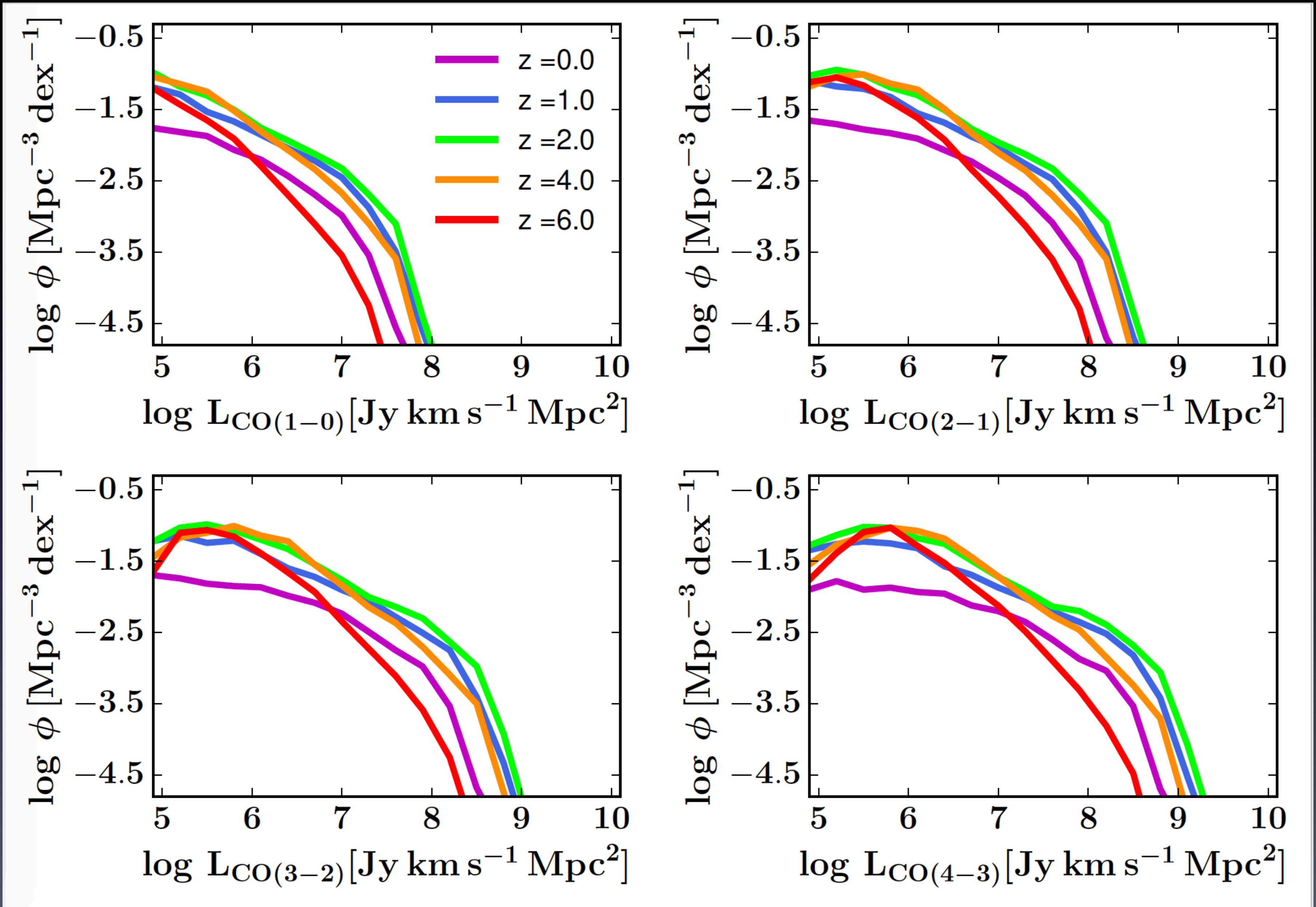
CO SLED for typical “main sequence” galaxies from z=0-2

ISM was warmer and denser at high redshift, leading to more ‘high-J’ emission



Popping et al. 2014

detailed predictions for CO LF evolution to z~6 based on SAM+GCE+PDR+RT
G. Popping et al. in prep



Summary

- the ‘grand challenge’ of galaxy formation theory is to replace phenomenological recipes with detailed physics – but this problem is too hard to do without help from observations
- ngVLA will provide unique constraints on key physical processes (star formation, stellar feedback, black hole growth, outflows, etc) in nearby and distant galaxies -- crucial for progress in theoretical modeling
- exciting synergy with other proposed facilities at other wavelengths