Models of galaxy formation and evolution: recent progress and open questions – the view from GAEA

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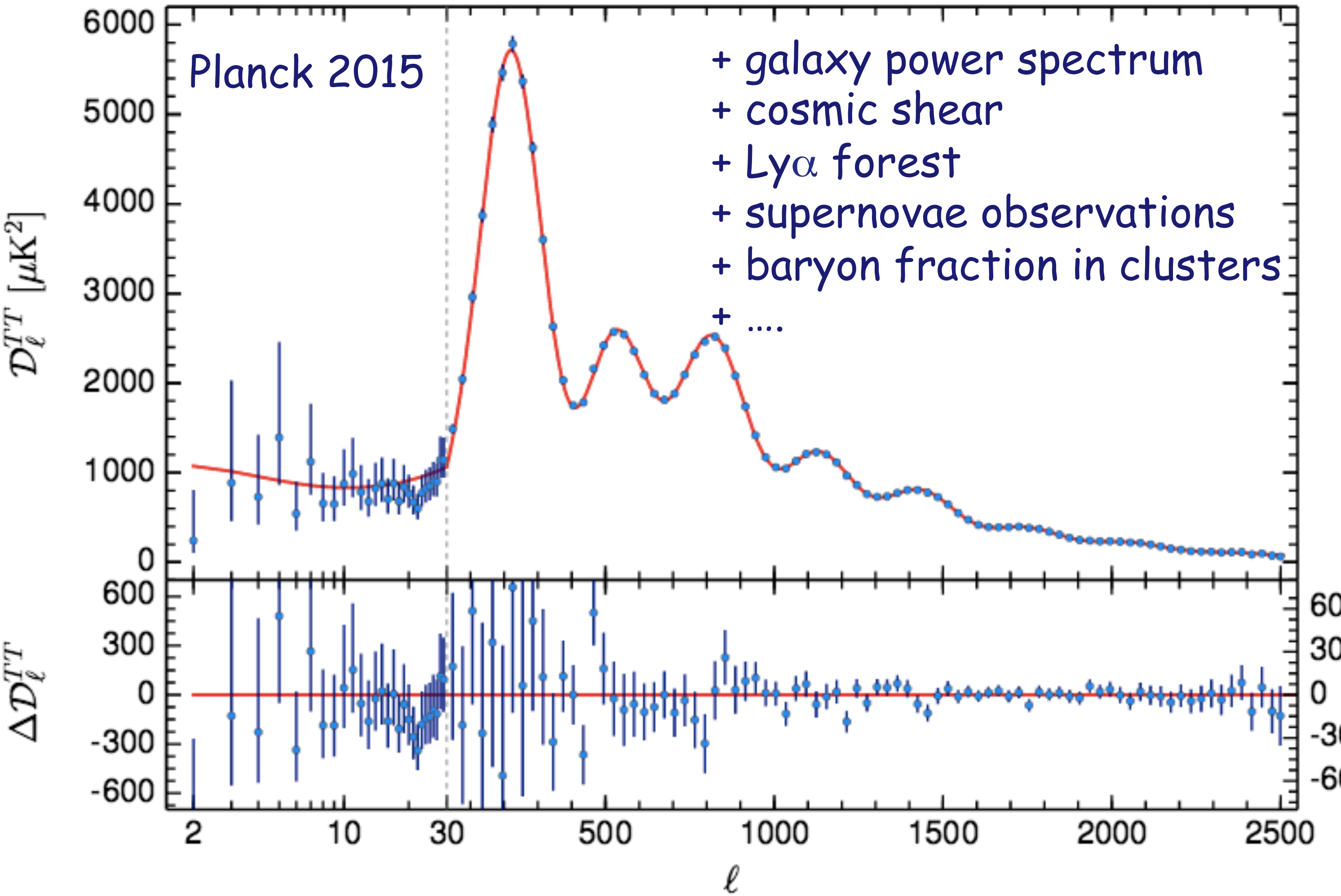
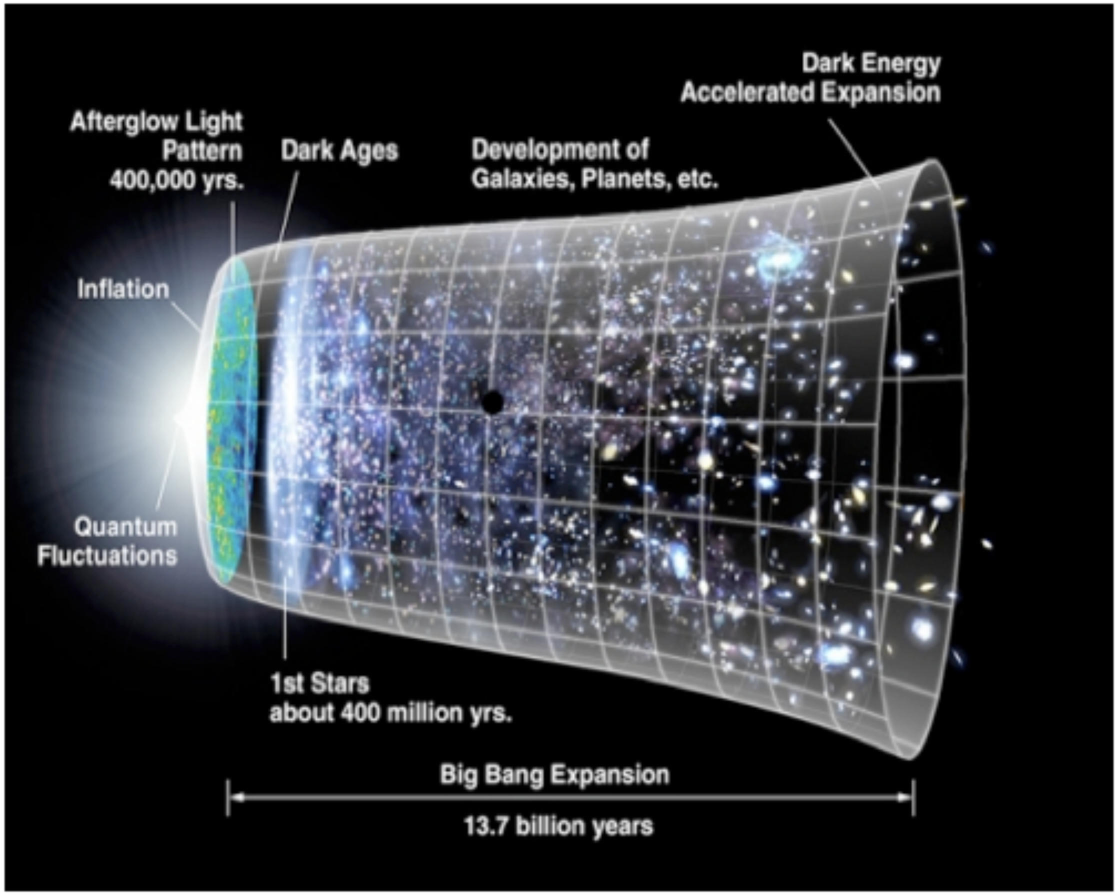
The framework

An era of `precision cosmology'



And an era of multi-wavelength, multi-epoch, high resolution, spatially resolved data. More is behind the corner…

Galaxy formation



A subject of great complexity involving physical processes that cover ~23 orders of magnitude in physical size and ~4 orders of magnitudes in time-scales.

Physical processes are entangled in a complex network of actions, back-reactions and self-regulations.

Galaxies are not only interesting in their own right, but also play a crucial role in cosmological studies: virtually all cosmological probes use baryons as tracers.

Cooling
(metallicity, halo structure, conductivity)

Star formation
(threshold, efficiency, initial mass function)

Dust
(formation,distribution, heating and cooling)

GALAXY FORMATION

Mergers and Galaxy interactions
(morphological transformations, induced star formation)

SN Feedback
(IGM heating, IGM enrichment, efficiency, winds)

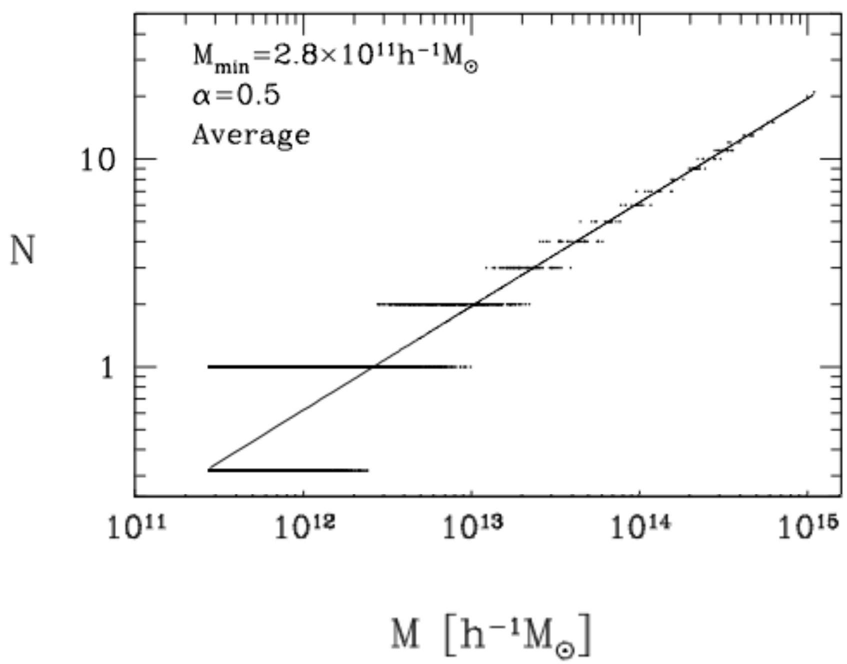
Stellar evolution
(spectro-photometric evolution, yields,feedback)

BHs and AGNs
(BH growth, quasar winds, radio bubbles)

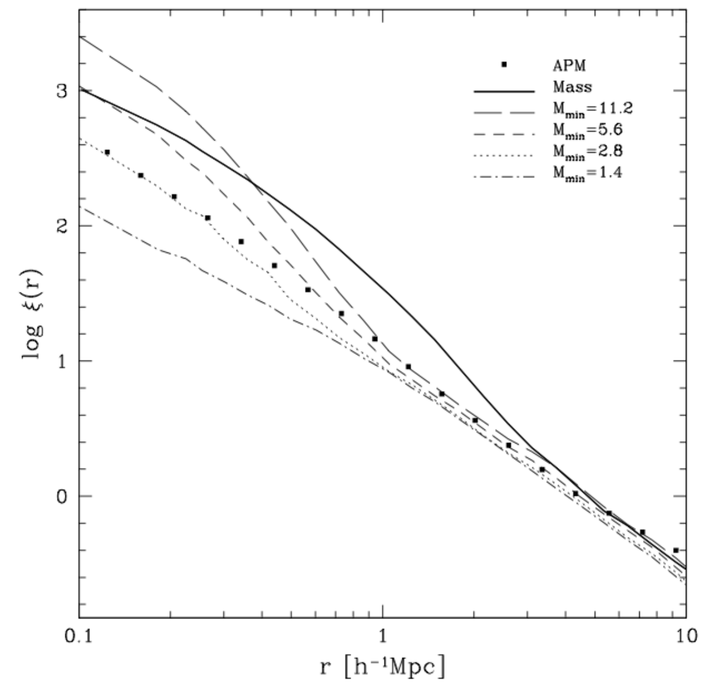
Halo occupation distribution approach

Bypasses explicit modeling of physical processes, and provides a statistical characterization of the link between DM and galaxies

P(N|M) + spatial distribution



Berlind et al., 2002



Assumption: galaxy content of a halo is statistically independent of its larger environment (depends only on halo mass).

HOD and conditional luminosity function

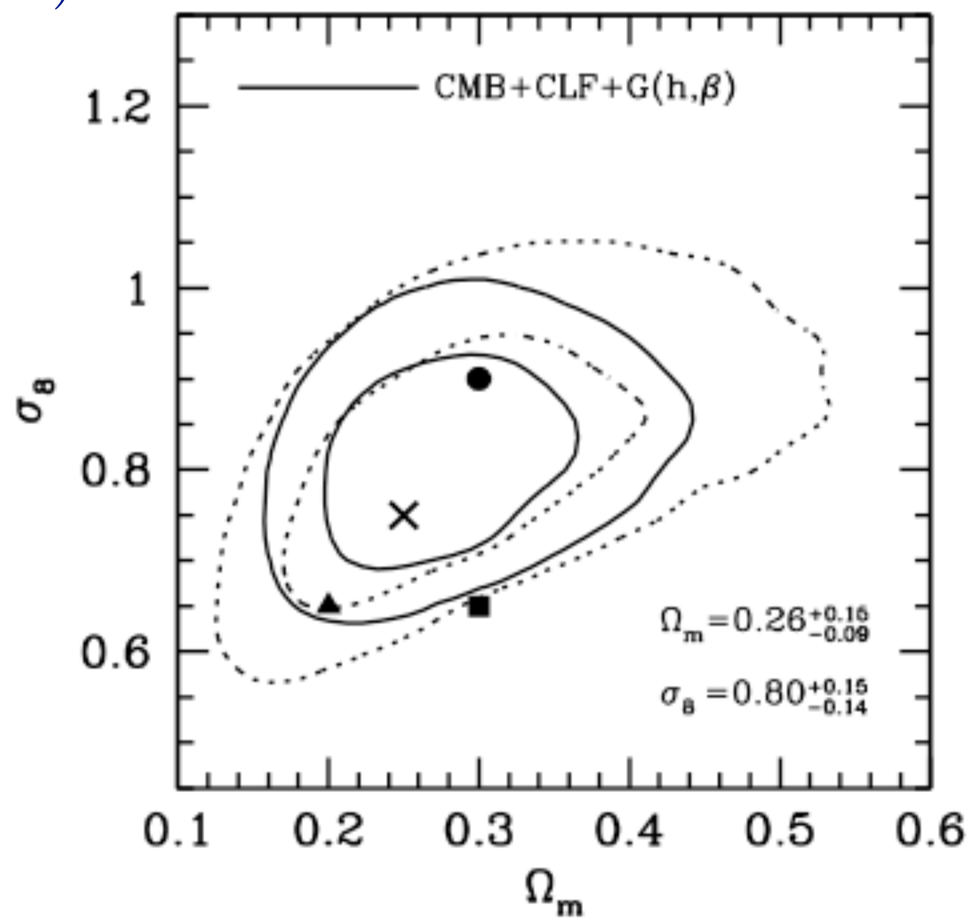
$$\Phi(L) = \int_0^\infty \Phi(L|M)n(M)dM$$

$$< L > (M) = \int_0^\infty \Phi(L|M)LdL$$

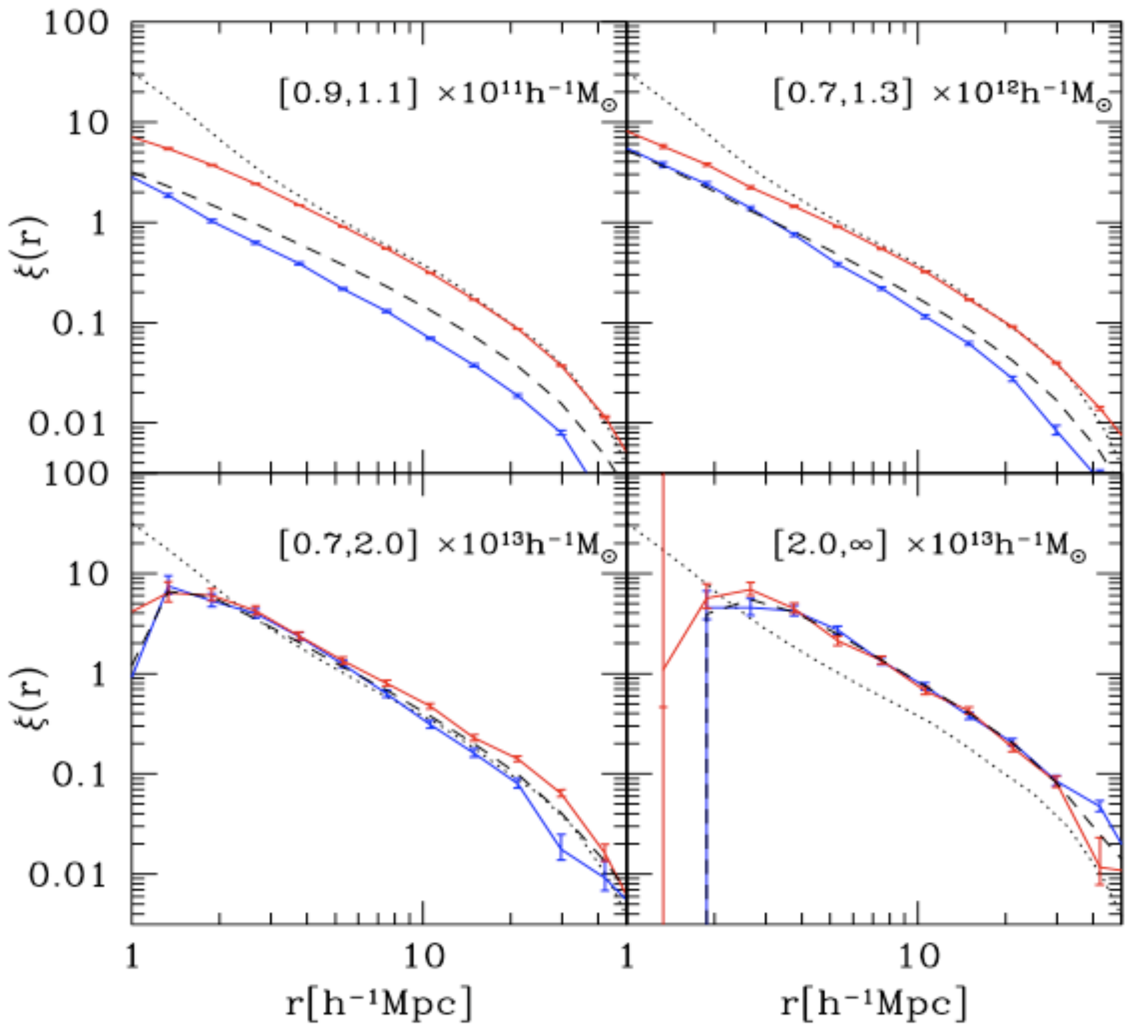
van den Bosch et al. 2003

The conditional LF can be constrained by using the observed galaxy luminosity function, the measurements of the galaxy-galaxy two-point correlation function as a function of luminosity and of the average mass-to-light ratio for haloes of different mass.

It is possible to use this approach to put constrain on cosmological parameters



Assembly bias



Halo properties (e.g. spin, concentration, shape) depend on the environment: haloes in over-dense regions form earlier and merge more rapidly than haloes in regions with average density.

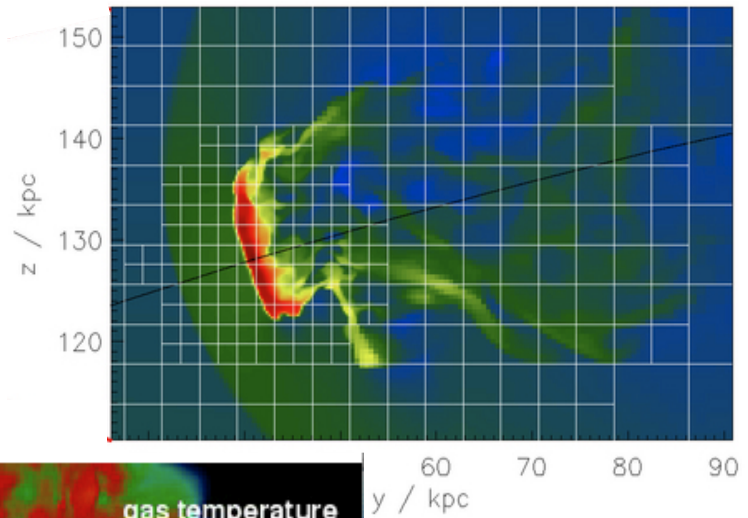
At face value, these results invalidate the assumption that the galaxy content of a halo depends only on its mass (basic for HOD approach).

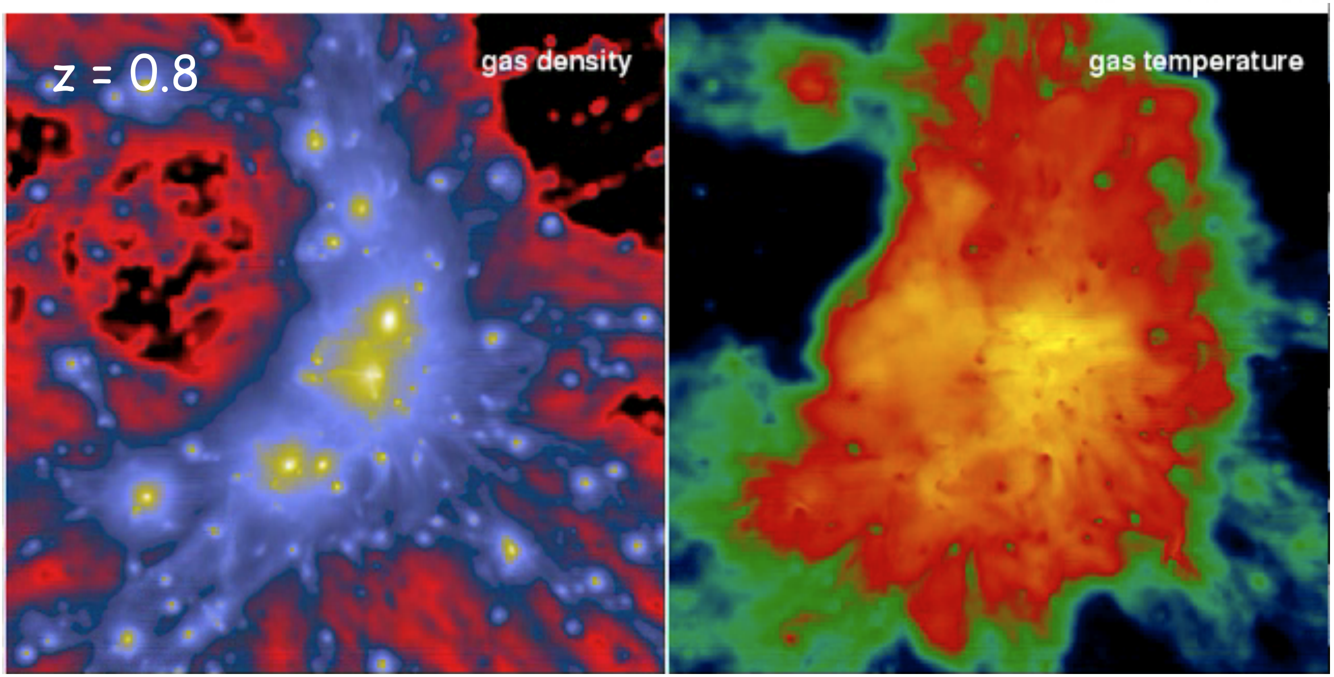
Gao et al. 2005

Hydrodynamical simulations

Provide an explicit description of gas dynamics. Still limited, however, by relatively low mass and spatial resolution (cosmological simulations), require significant computational time, and need to resort to “sub-grid” physics to account for many (all?) physical processes.

Roediger & Brueggen 2007

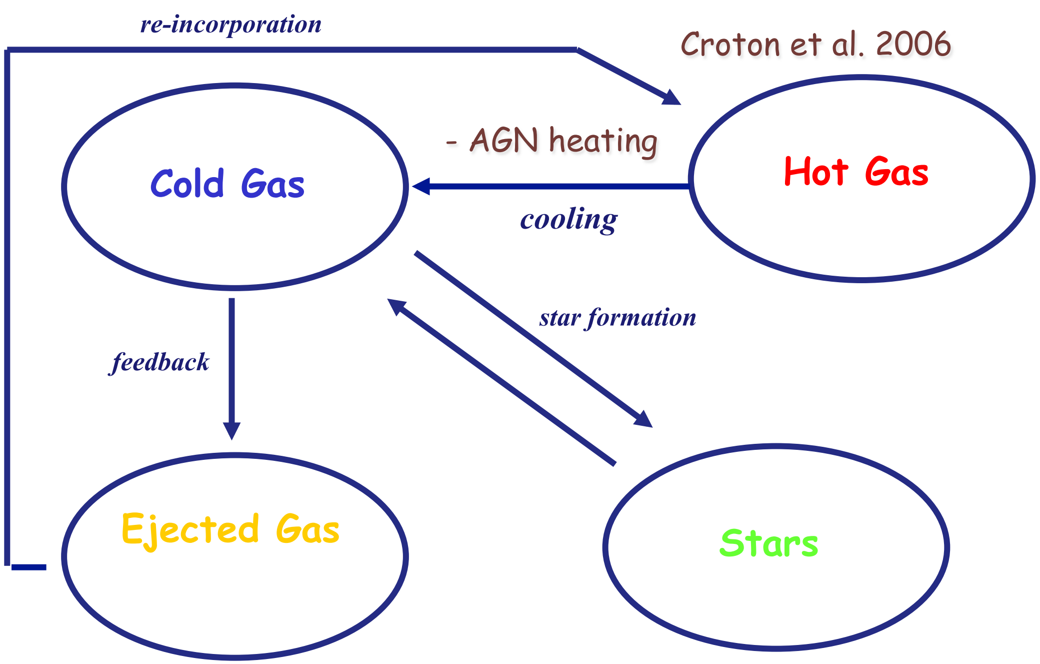




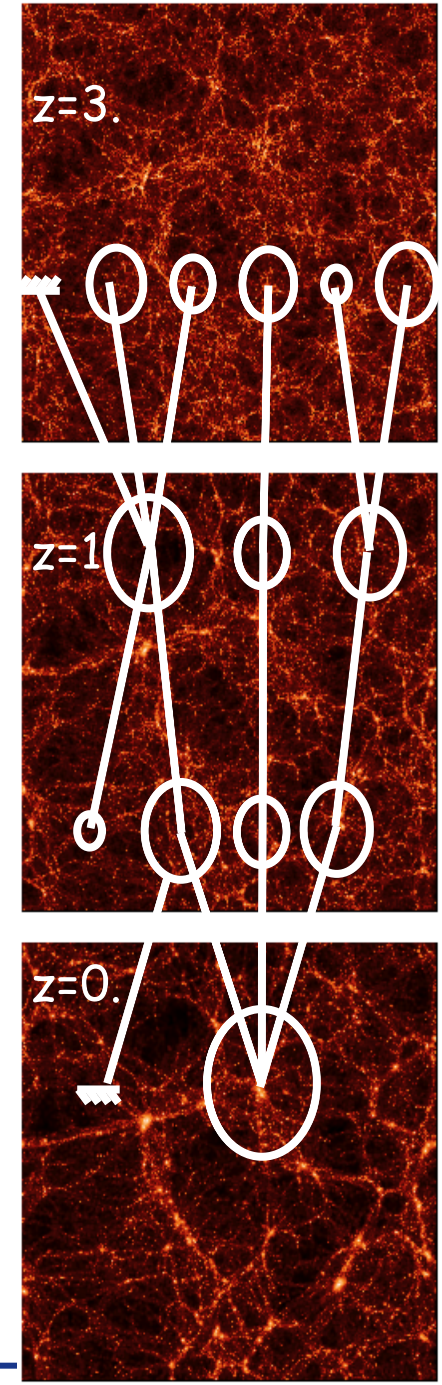
Courtesy: Volker Springel

Semi-analytic models

Rely on simple, yet physically and/or theoretically motivated prescriptions to model the evolution of the baryons. Coupled to dark matter simulations that are used to specify the location and evolution of dark matter haloes. Limited computational times. But no explicit description of the gas dynamics.



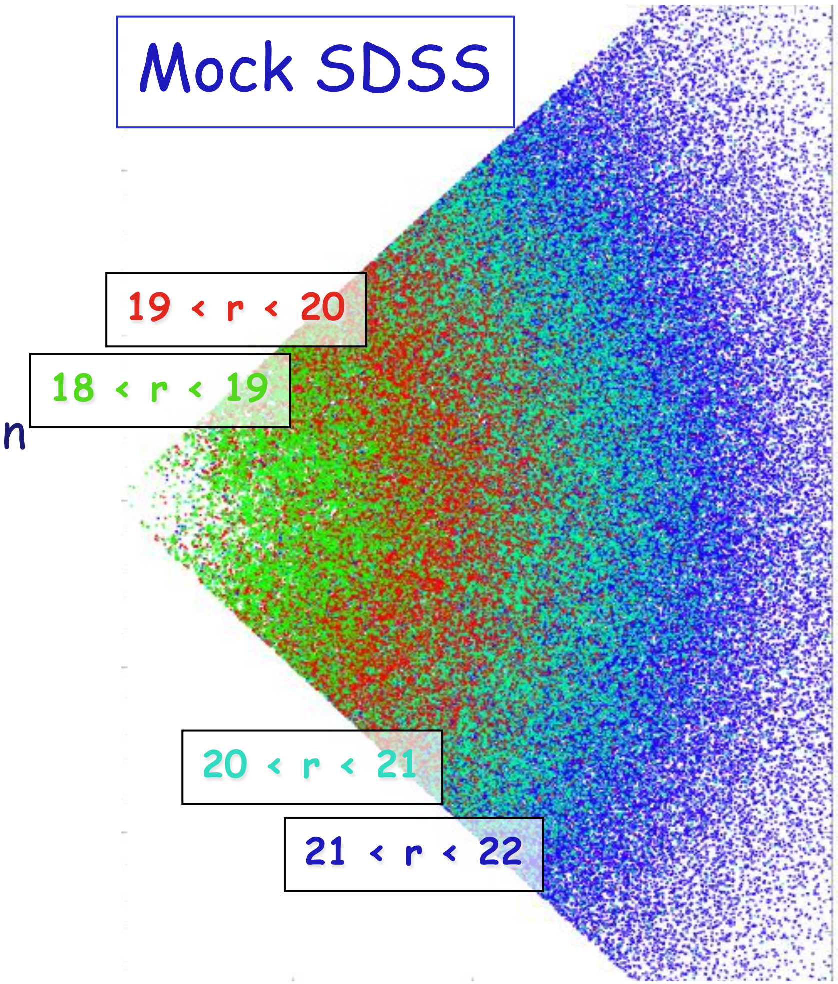
De Lucia, Kauffmann & White, 2004



Kauffmann et al., 1999

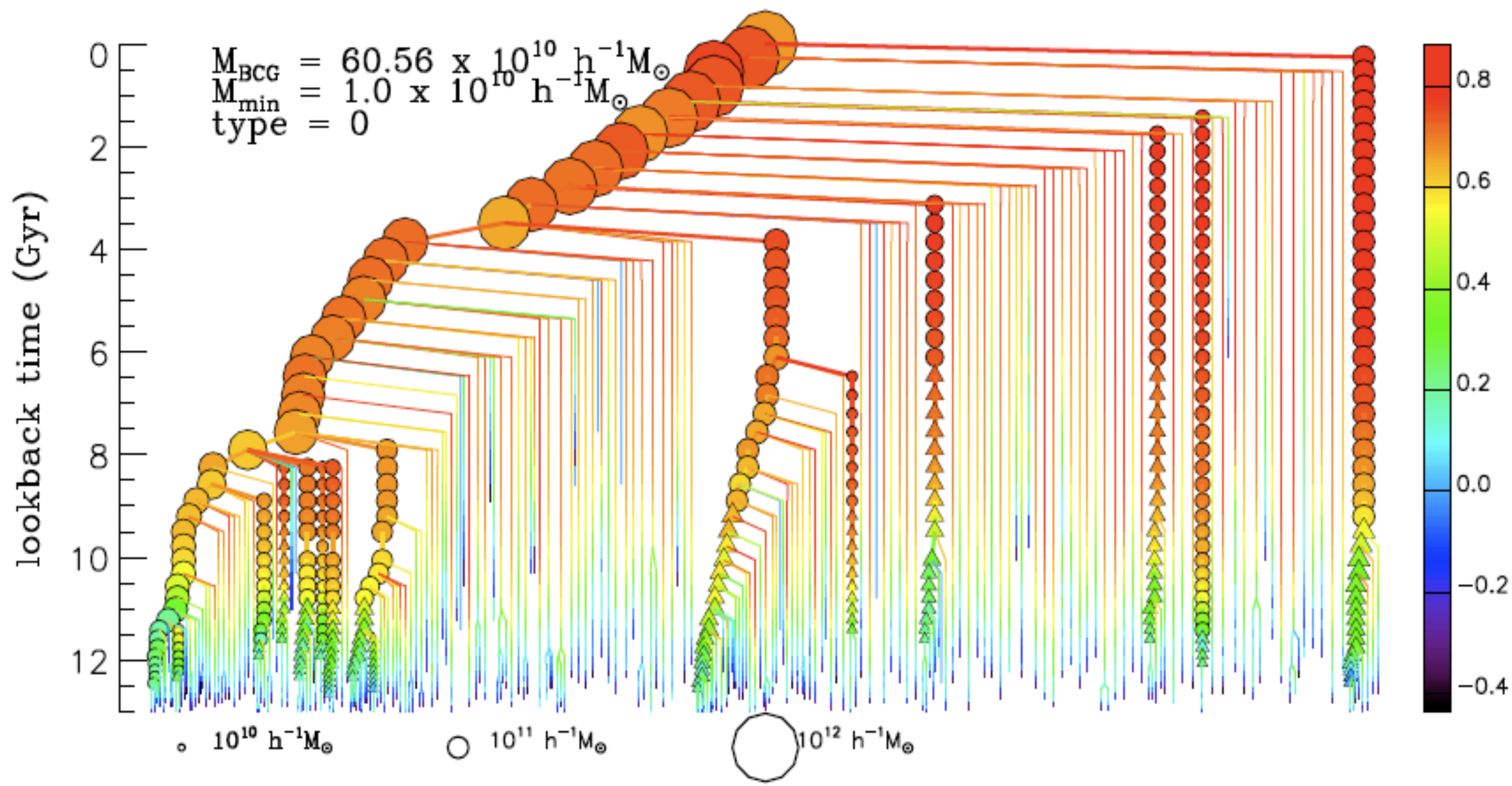
Pro and con of the SAM approach

- ☑ follows the evolution of DM in its full geometrical complexity
- ☑ follows explicitly the assembly history of each halo
- ☑ provides full dynamical information about model galaxies (catalogues including physical properties + redshifts + positions on the sky)
- ☐ no explicit description of the gas dynamics and no internal "spatial" resolution
- ☐ limited mass resolution (this also translates in a "history resolution")



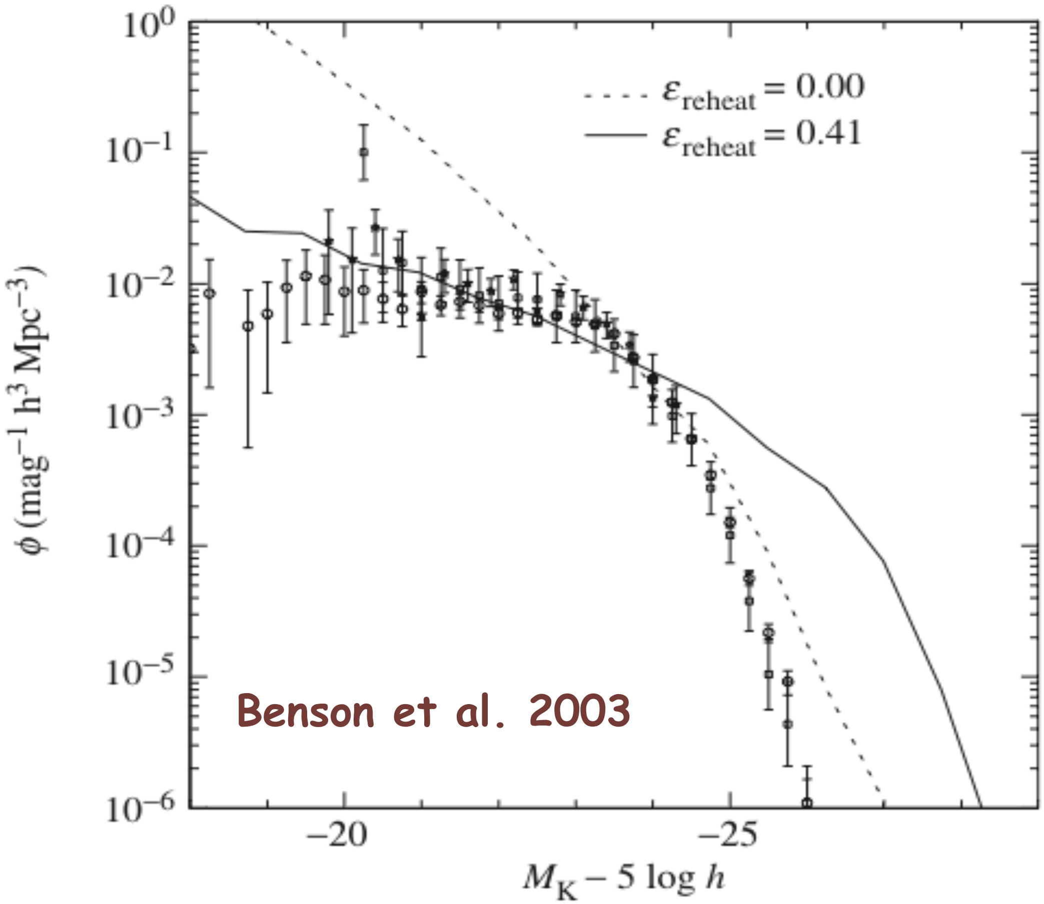
Courtesy of Jérémy Blaizot

The output of a semi-analytic model



De Lucia & Blaizot 2007

The galaxy LF and the feedback



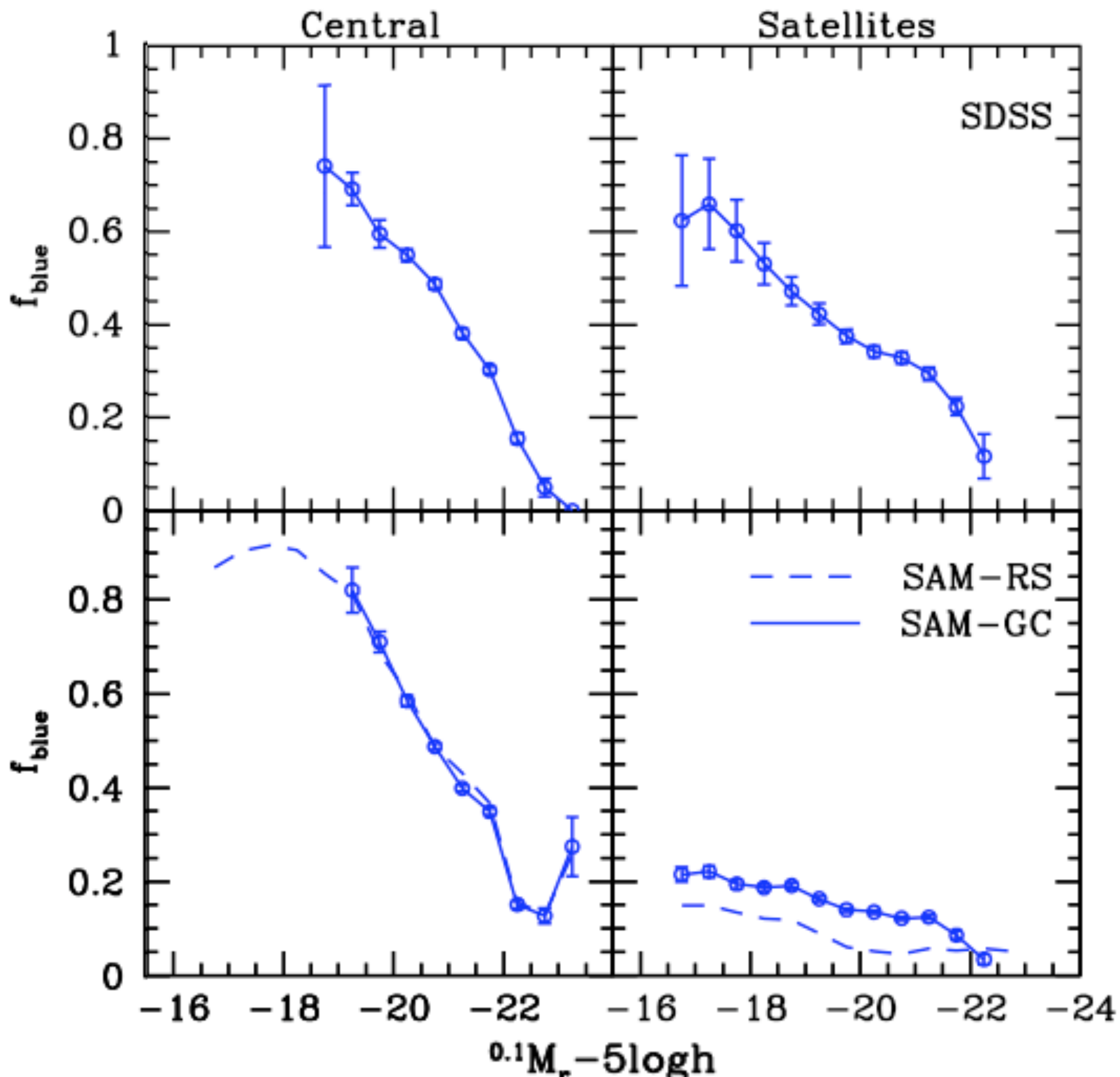
Stellar feedback is necessary to reduce the number of faint galaxies (re-ionization plays a role but only for the faintest galaxies).

Note that this success comes at the expenses of now producing <u>too many bright galaxies</u>

This problem already noted in the seminal paper by White & Frenk (1991) and is now “solved” invoking energetic feedback from AGN.

N.B. Excess of luminous galaxies is exacerbated in later models due to an increase of Ω_b (doubled).

Over-quenching of satellite galaxies



Weinmann et al. 2006

The fraction of blue (satellite) galaxies in the models is below the observational data, more so in low-mass haloes.

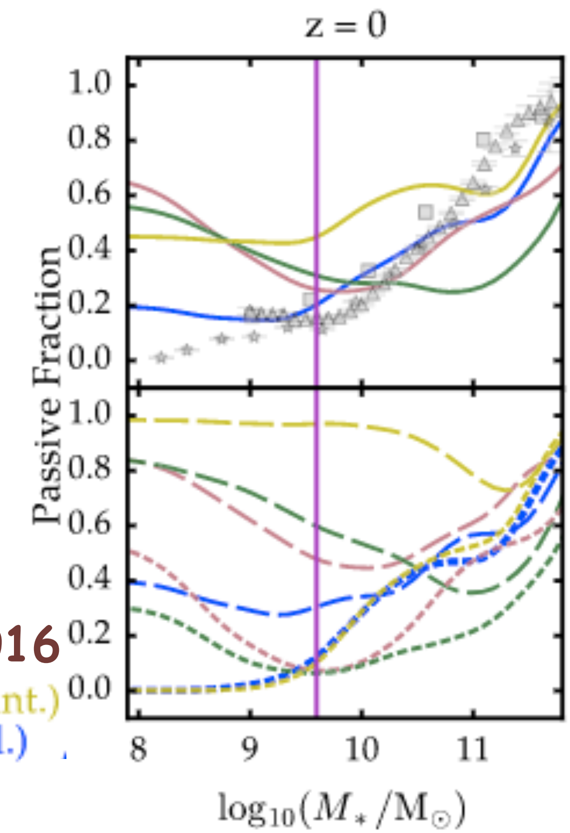
This problem is shared by all models published in those years (see e.g. Fontanot et al. 2009).

Is this due to an over-simplified treatment of the "strangulation"?

Better but still not that good

Modified treatment of satellites (a more gradual stripping of the hot gas) improves the agreement with data.

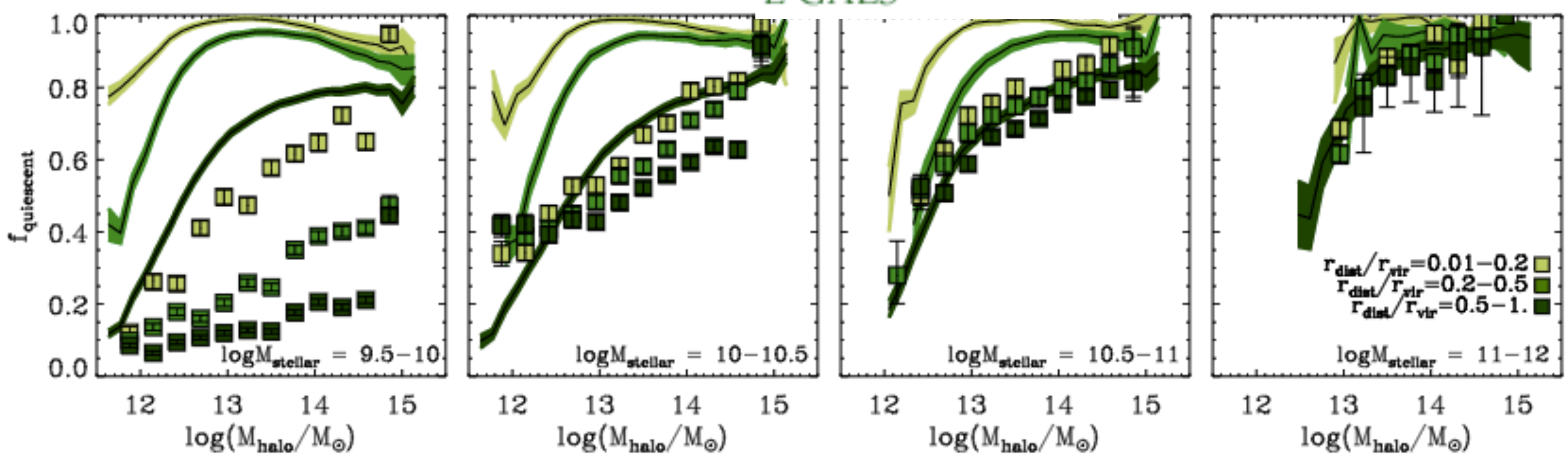
Most models (including simulations) however, still over-predict the fraction of quiescent satellites with the problem becoming worse for low stellar masses.



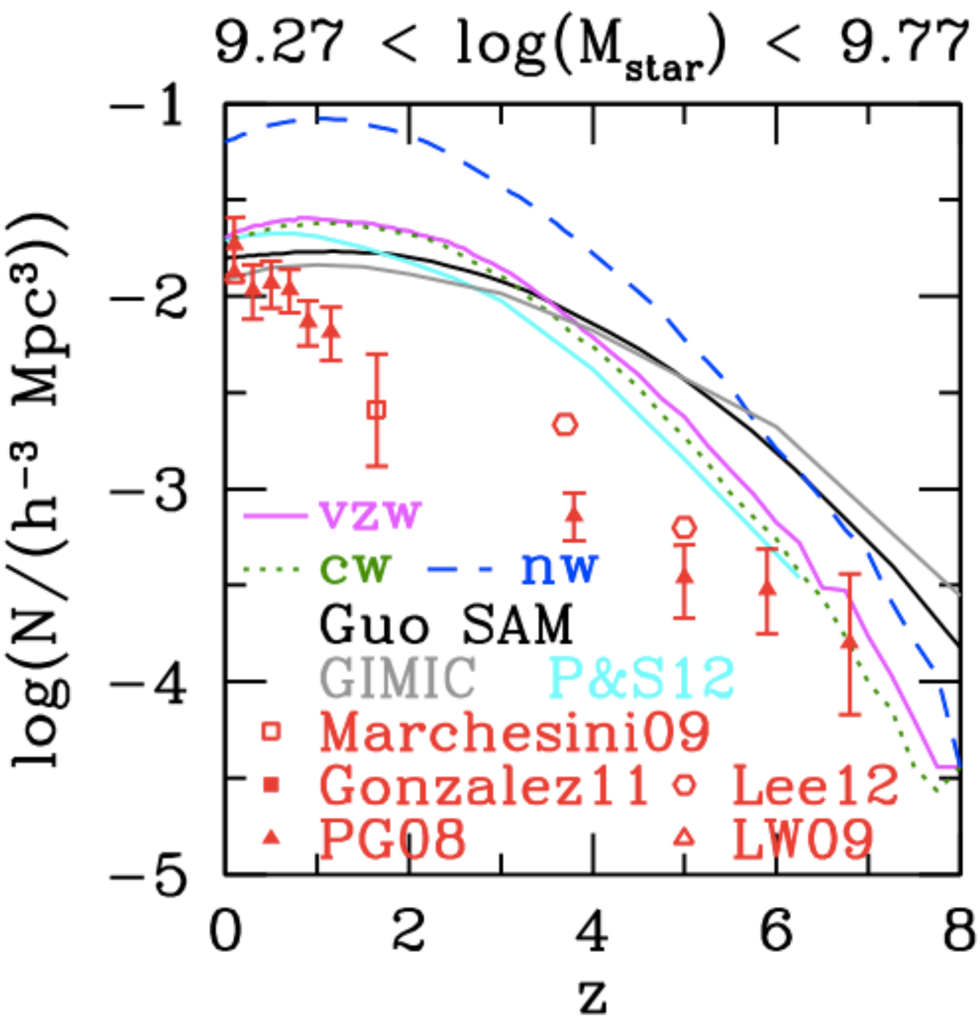
Guo et al. 2016

GALFORM (Instant.)
GALFORM (Grad.)
EAGLE
L-GALS

Hirschmann et al. 2014



An excess of low-mass galaxies:

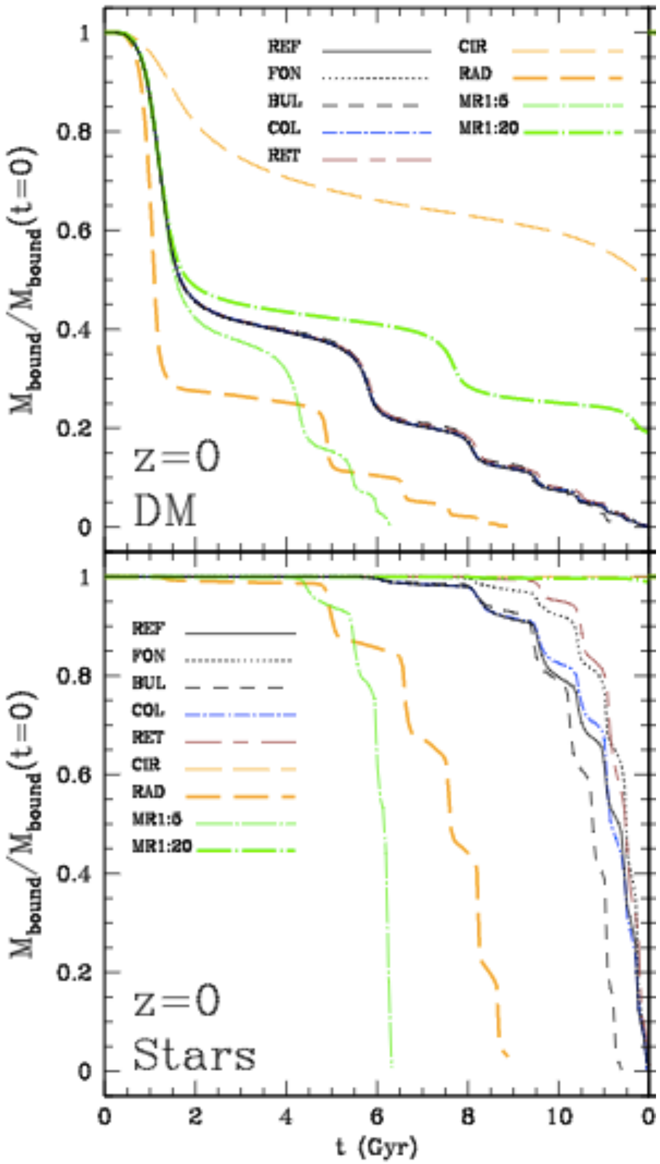


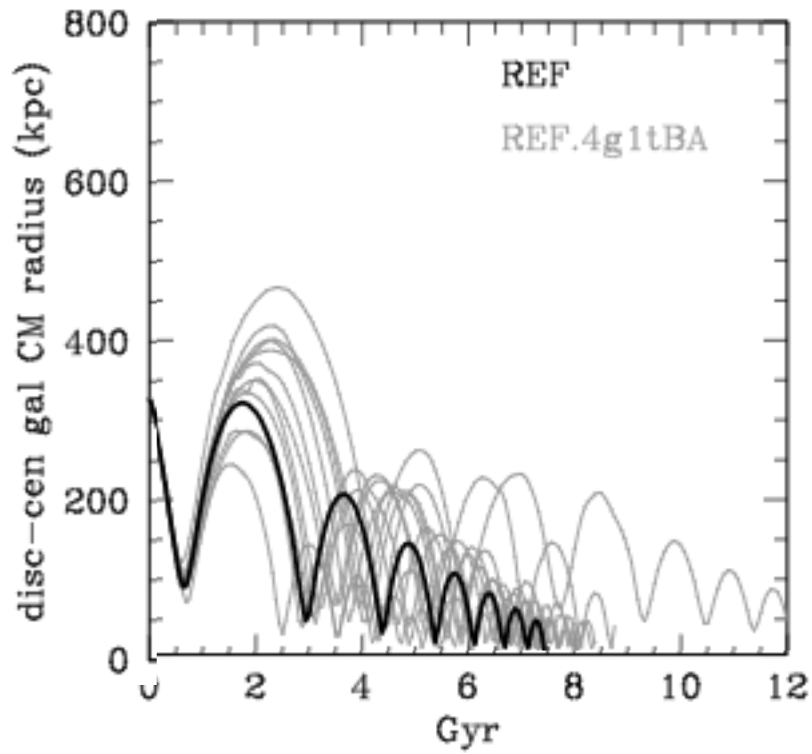
Weinmann et al. 2012

Number density of low-mass galaxies predicted by different models (and hydro-sims) with different implementations of stellar feedback is larger than observational estimates at z>0 (z=0 point is often "fine-tuned").

In this mass range, the mass growth of galaxies follow the growth of their parent haloes closely. A mechanism is required (Feedback? But not as currently modeled) to break this parallelism.

Stripping (disruption) and merging times





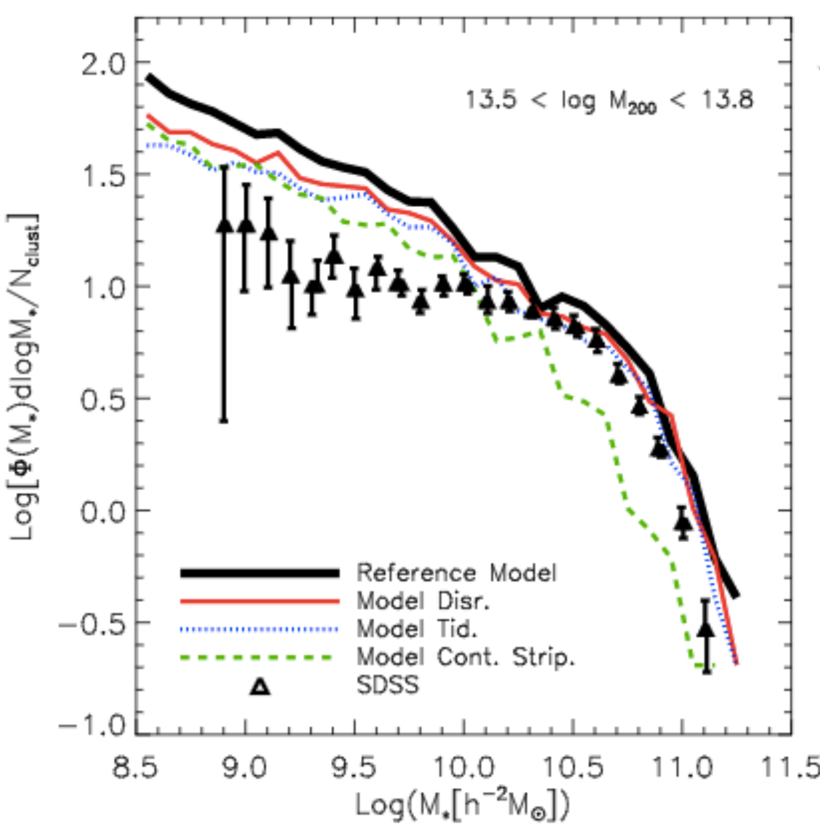
Stellar stripping starts only after dark matter has been significantly reduced; depends strongly on the orbit of the satellite (unsurprising) and on presence of other galaxies (often neglected).

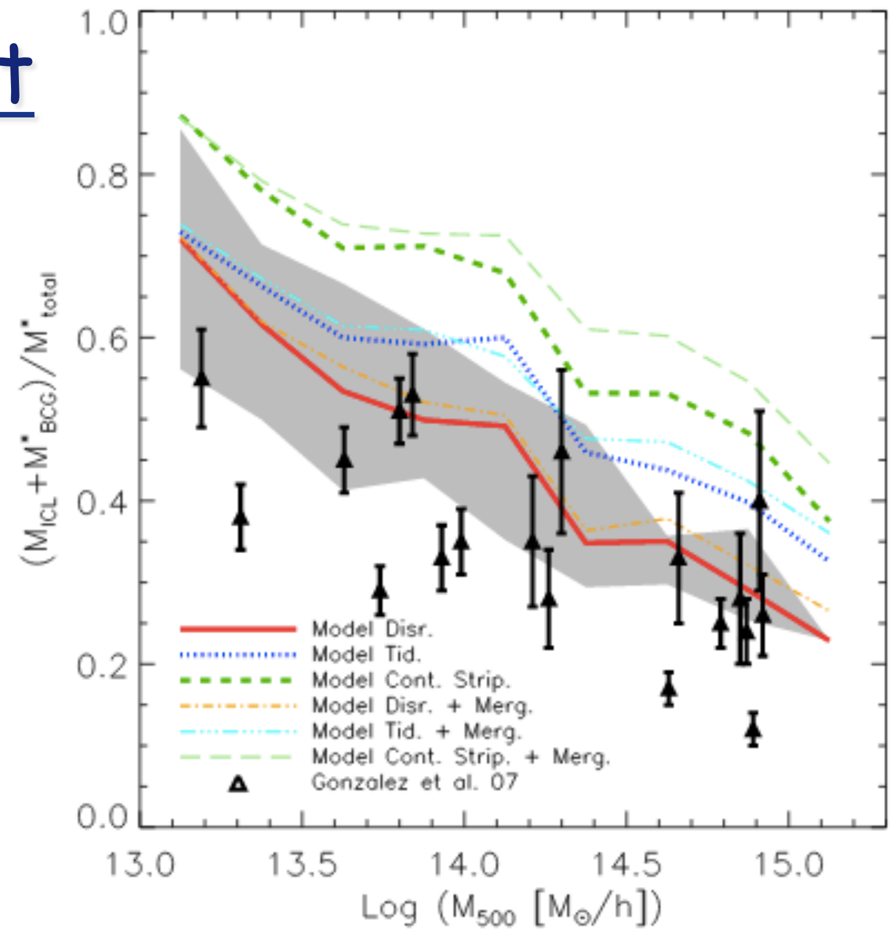
Villalobos et al. 2012, 2014

Diffuse stellar component

A merger channel plus tidal stripping of stars associated with satellites. Qualitative agreement with observational data.

Contini et al. 2014





Only a moderate influence on the stellar mass/abundance of intermediate to low mass galaxies that are still over-abundant with respect to data..

The development of GAEA

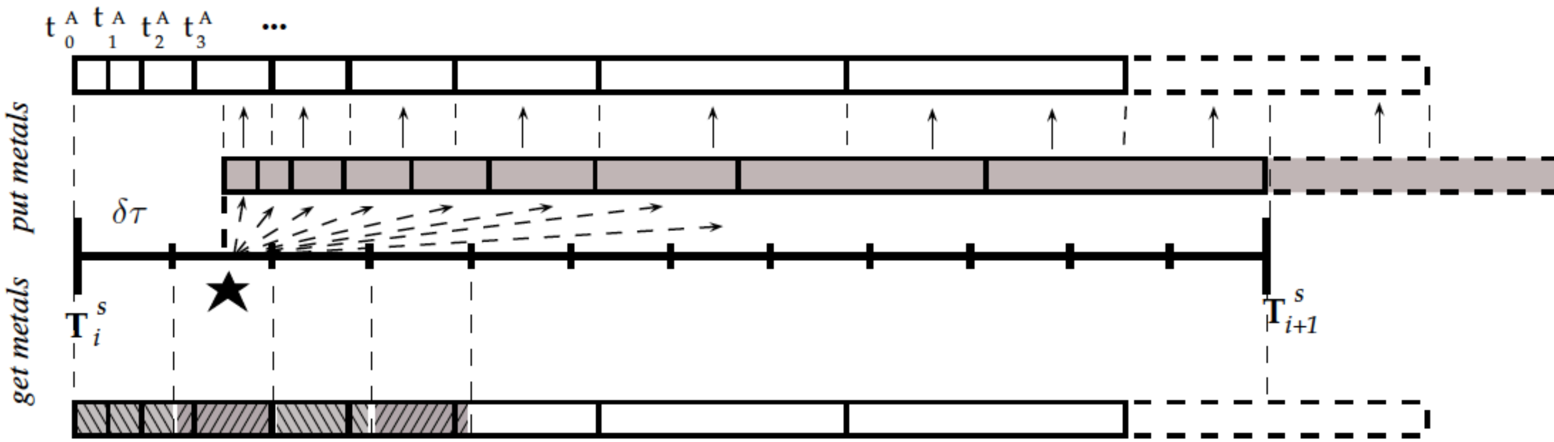
✓ Two "fundamental" problems with satellites (wrong properties, wrong number densities). No "easy" solution with modifying the treatment of satellites. The overall treatment of star formation-feedback cycle can (and need) to be improved.

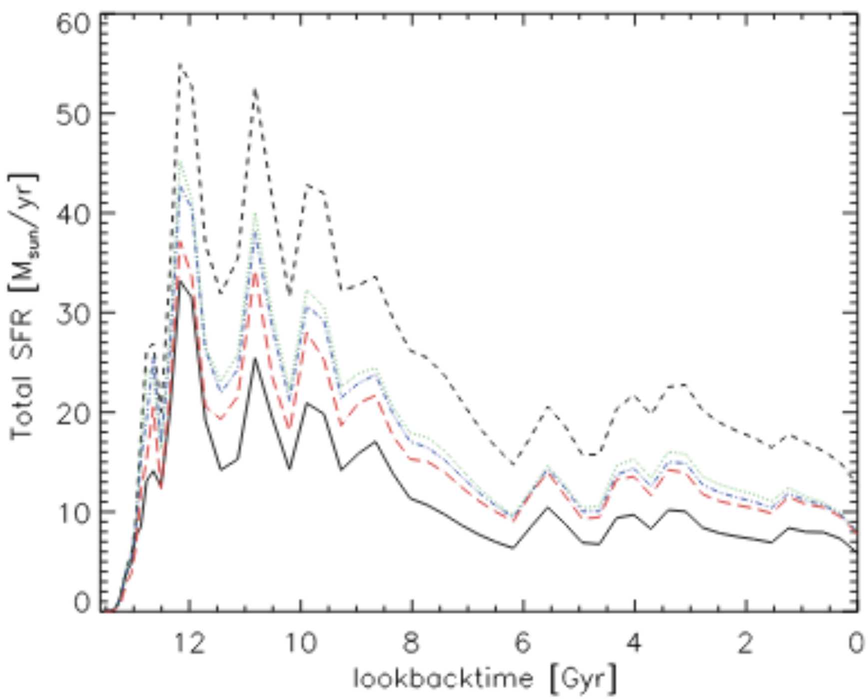
✓ Models still assume an instantaneous recycling approximation ...

✓ Gas is treated as a single phase component ...

✓ Both these limitations can influence significantly the behaviour of star formation and stellar feedback.

Non instantaneous approximation:



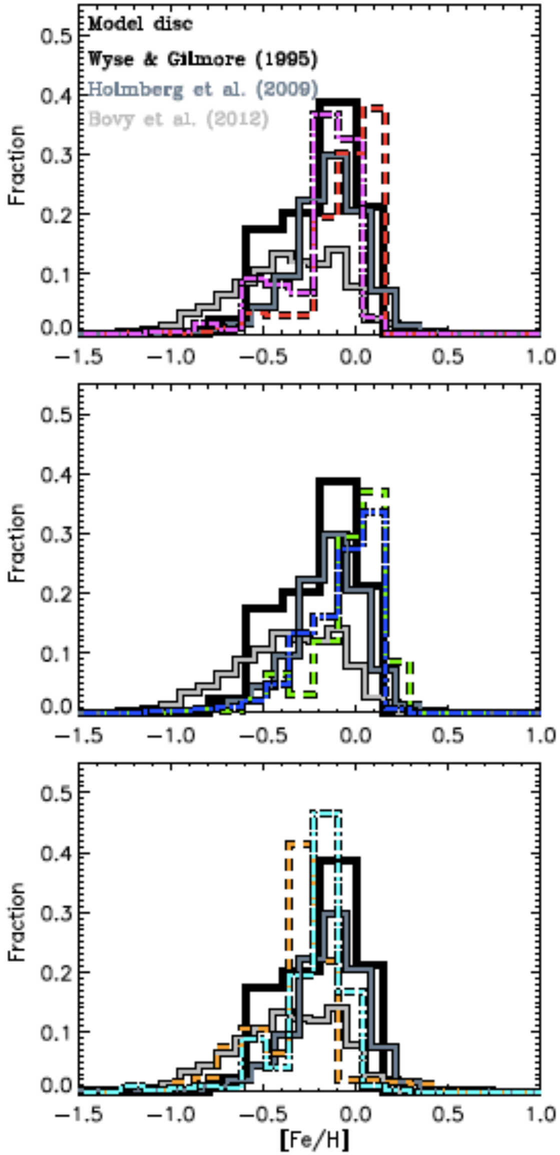


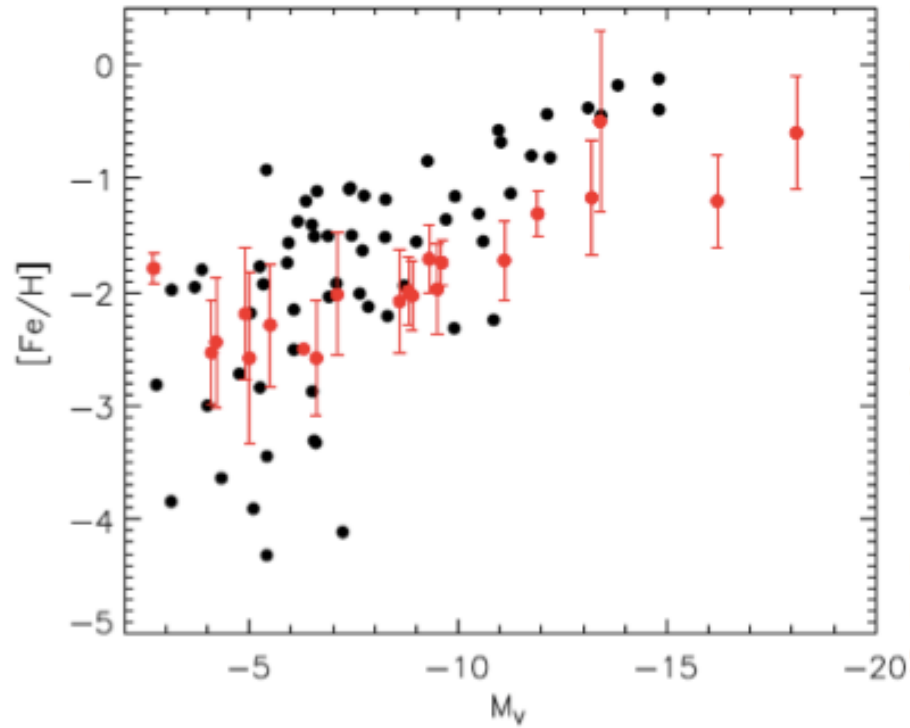
Instead of storing information about the past star formation history, we `project' the metals (and the gas and the energy) in the future.

Important consequences on the predicted star formation histories of galaxies (plus the chemical yield is no longer a free parameter)

De Lucia et al. 2014

Metals in MW stars





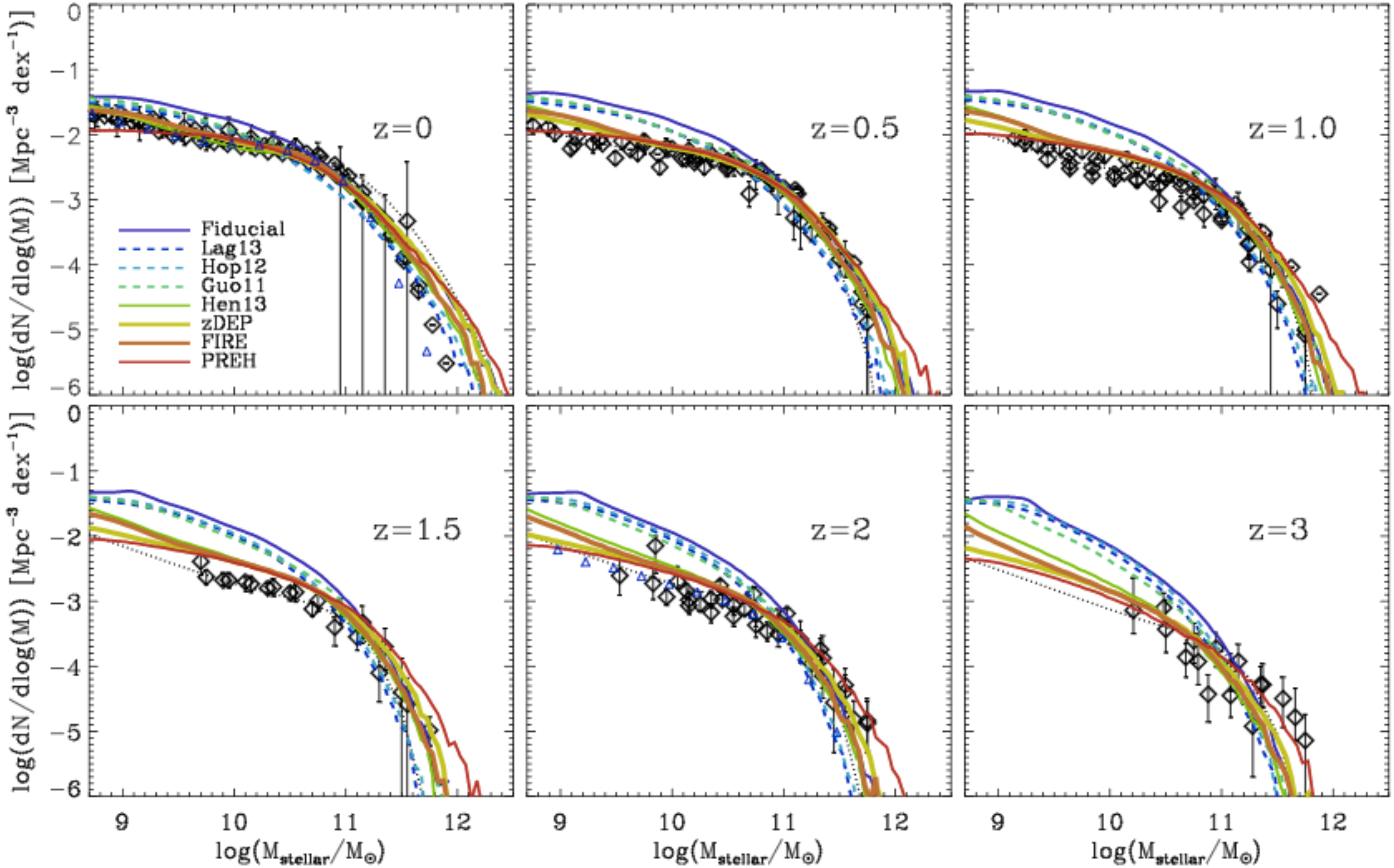
Non instantaneous chemical enrichment scheme has been tuned using the Aquarius simulations.

Our GAEA reference model reproduces relatively well the metallicity distribution of disk stars in the MW and the mass-metallicity relation measured for dwarf satellites.

De Lucia et al. 2014

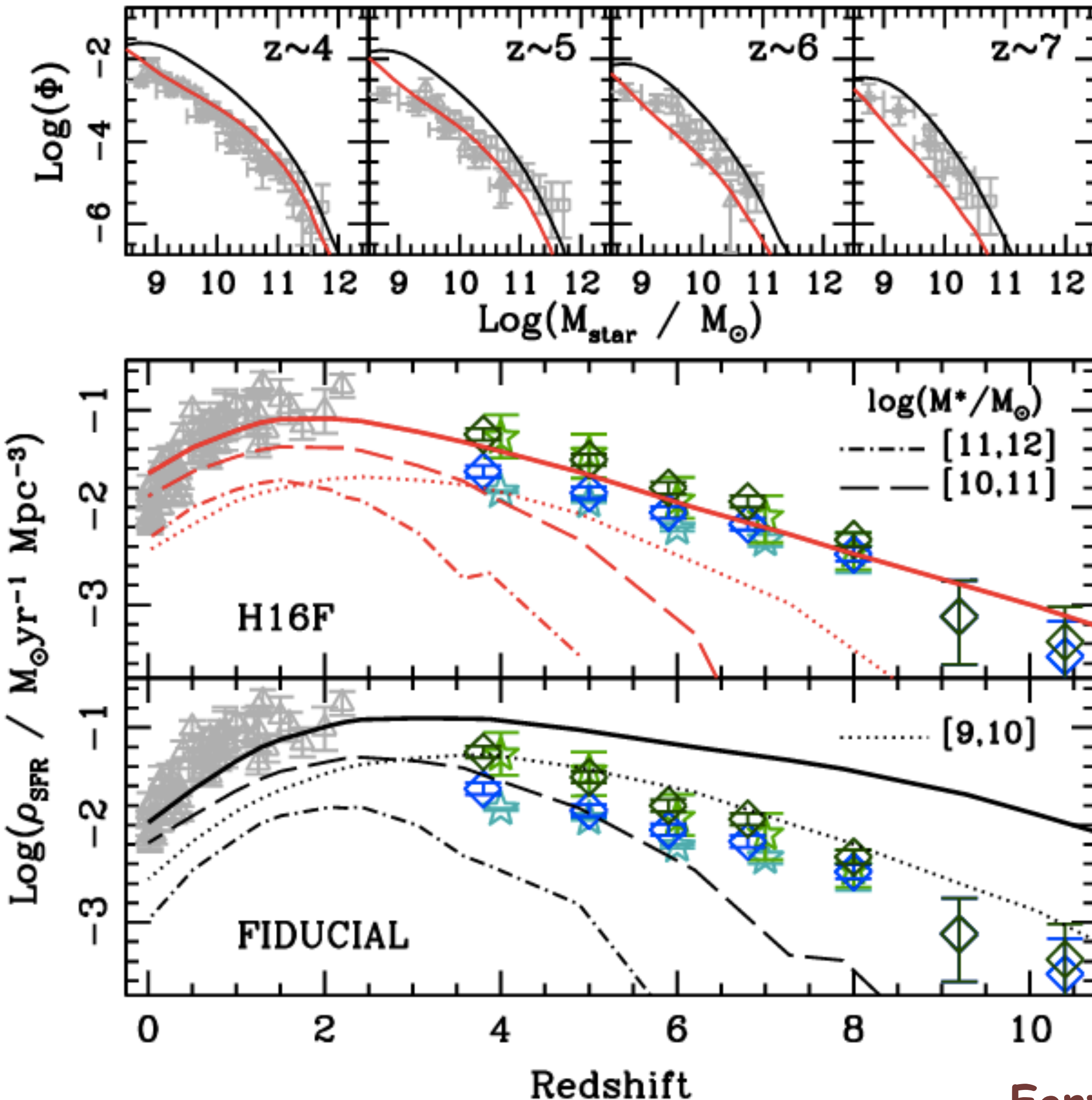
A different feedback scheme

*Hirschmann, De Lucia & Fontanot 2016



* Available at : https://apps.sciserver.org (contact me!)

Out to the cosmic dawn



Our reference model reproduces nicely the measured galaxy mass function out to z~7 and the cosmic SFR out to z~10 (these data have NOT been used to `tune' the model).

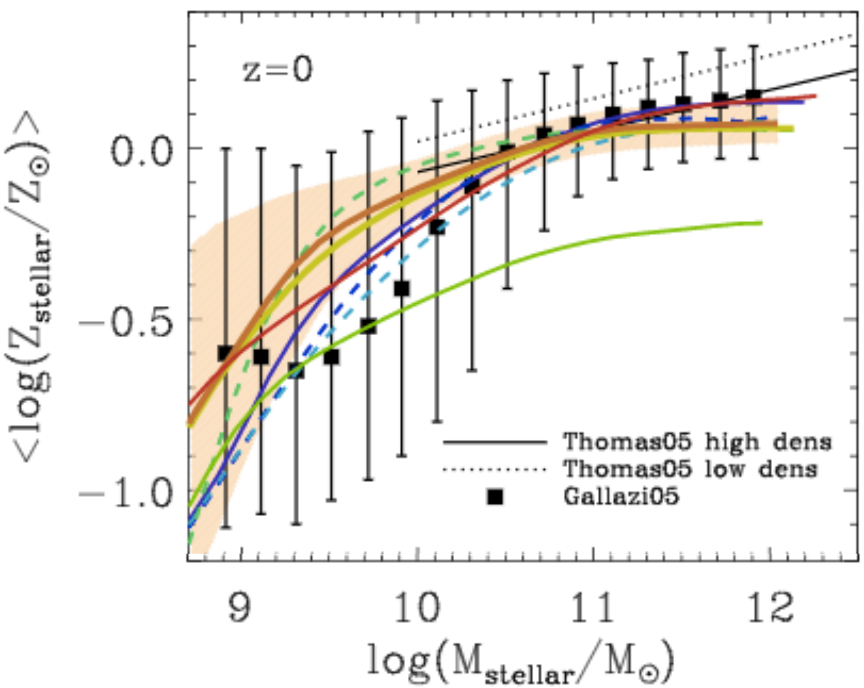
A decreasing importance of dust attenuation is required to reproduce the measured UV luminosity functions

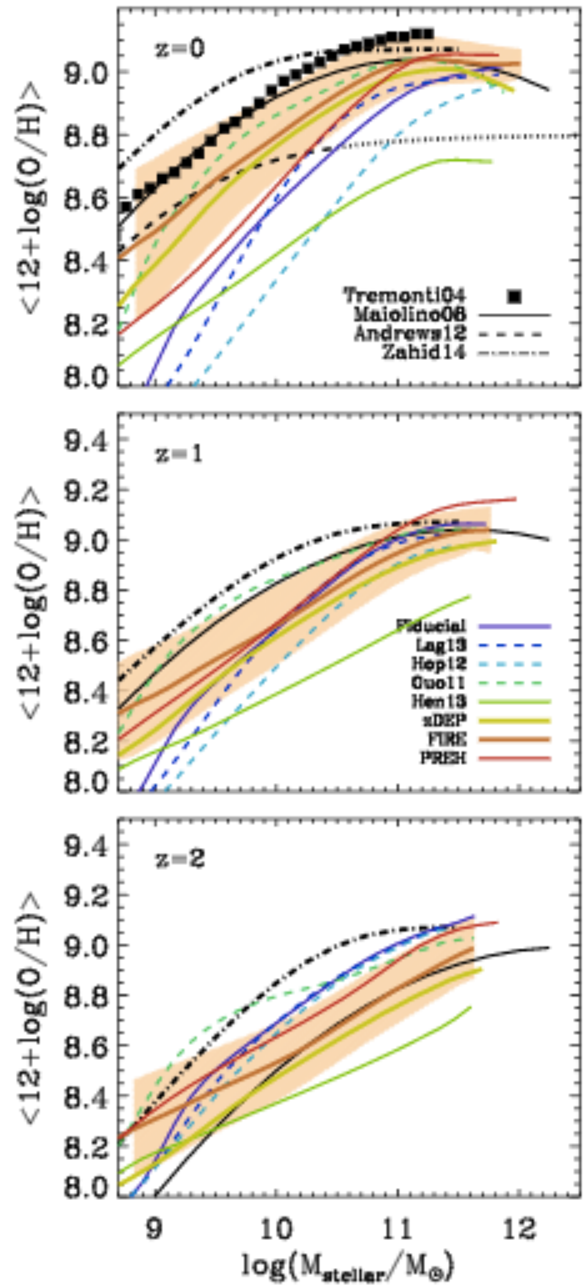
Fontanot et al. 2017

Metals in stars and gas

GAEA reproduces the observed mass-metallicity relations at z=0 and predicts an evolution of these as a function of z (qualitative agreement with data)

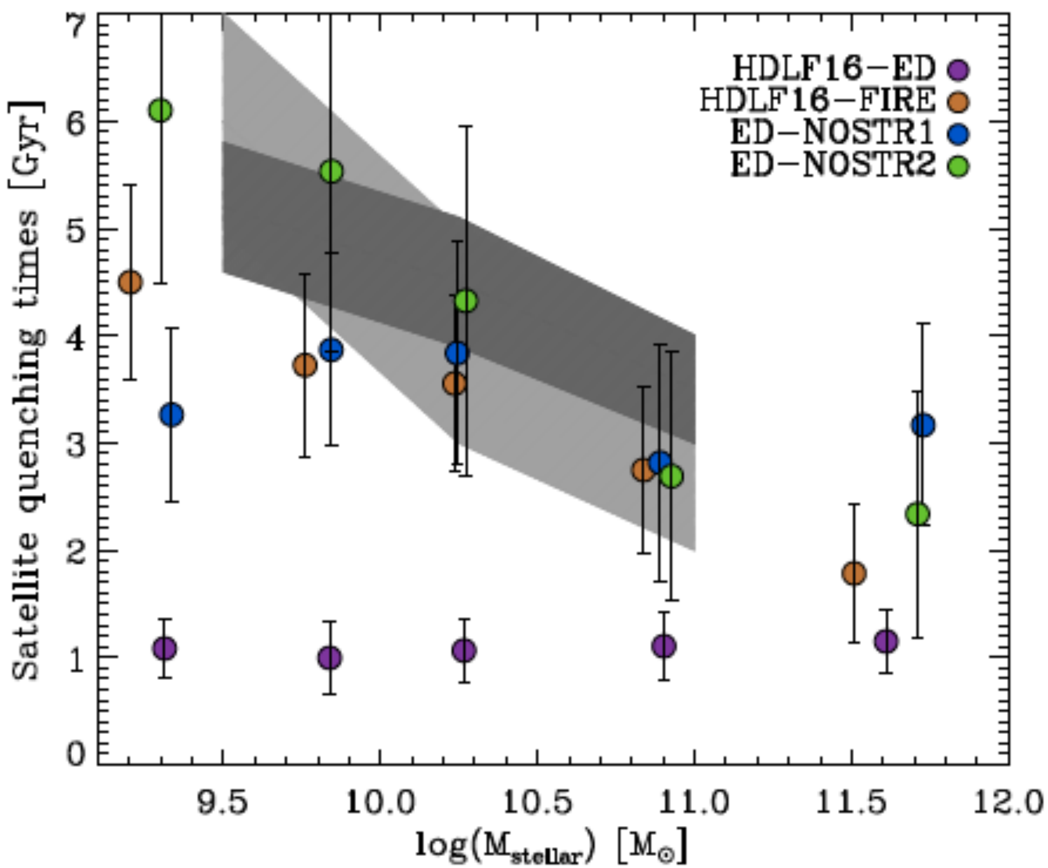
Results are robust against modifications of the chemical parameters (elemental yields, DTD of SNIa, IMF, etc.)





Hirschmann, De Lucia & Fontanot 2016

Quenching time-scale



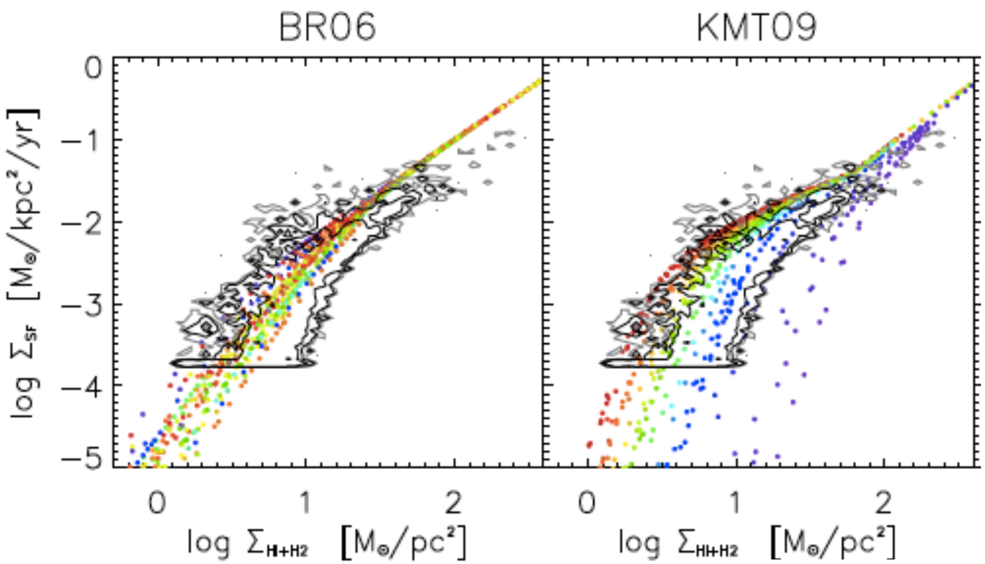
De Lucia et al. 2019

Modifications of the "internal processes" can affect strongly the evolution of the satellite galaxies.

Old "fiducial" model gives very short quenching time-scales although it includes only "strangulation".

No specific environmental process is needed other than strangulation (this is ok for at least the most massive galaxies)?

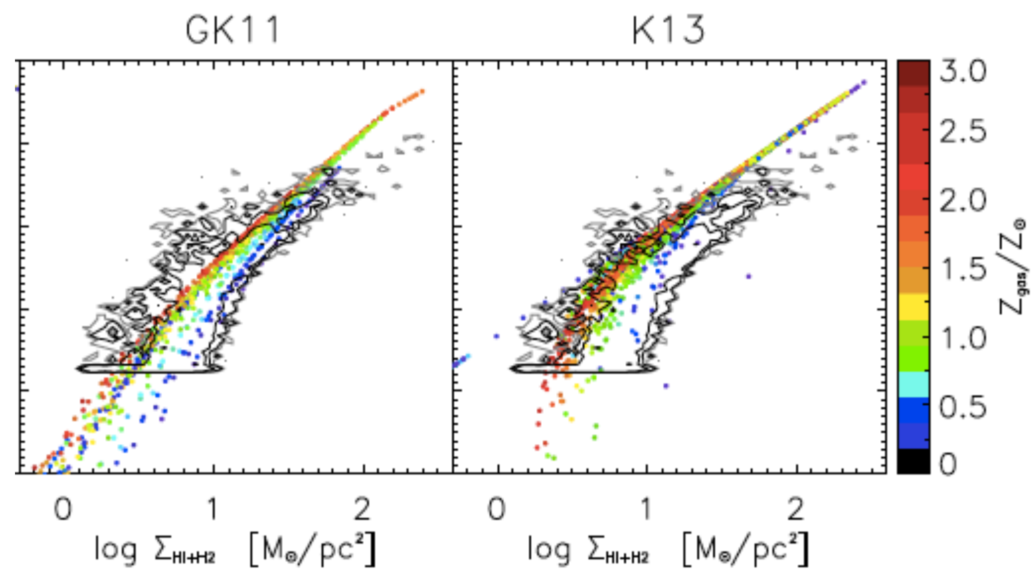
Molecular and atomic hydrogen



Different prescriptions to model the partition of the cold gas in its molecular and atomic components

Explicit tracing of the angular momentum evolution and an H_2 based star formation law

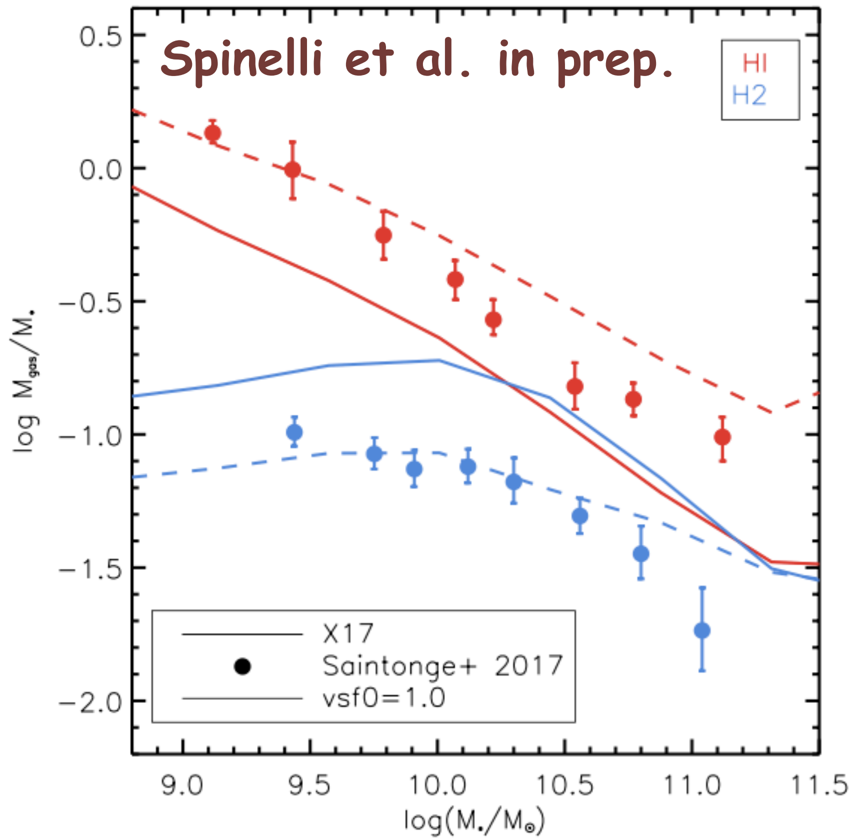
Our reference model is calibrated mainly on the HI and H_2 local mass functions.

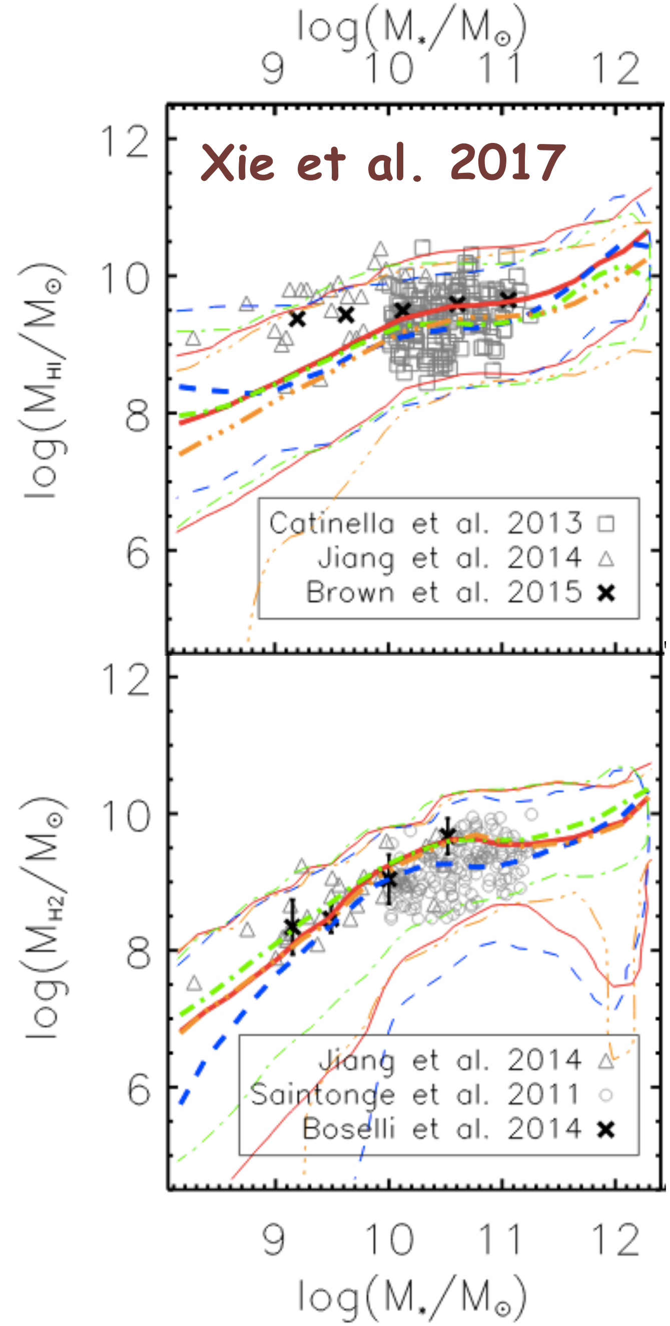


Xie et al. 2017
Zoldan et al. 2017

Gas scaling relations

Our reference model also reproduces well the scaling relations measured in the local Universe.

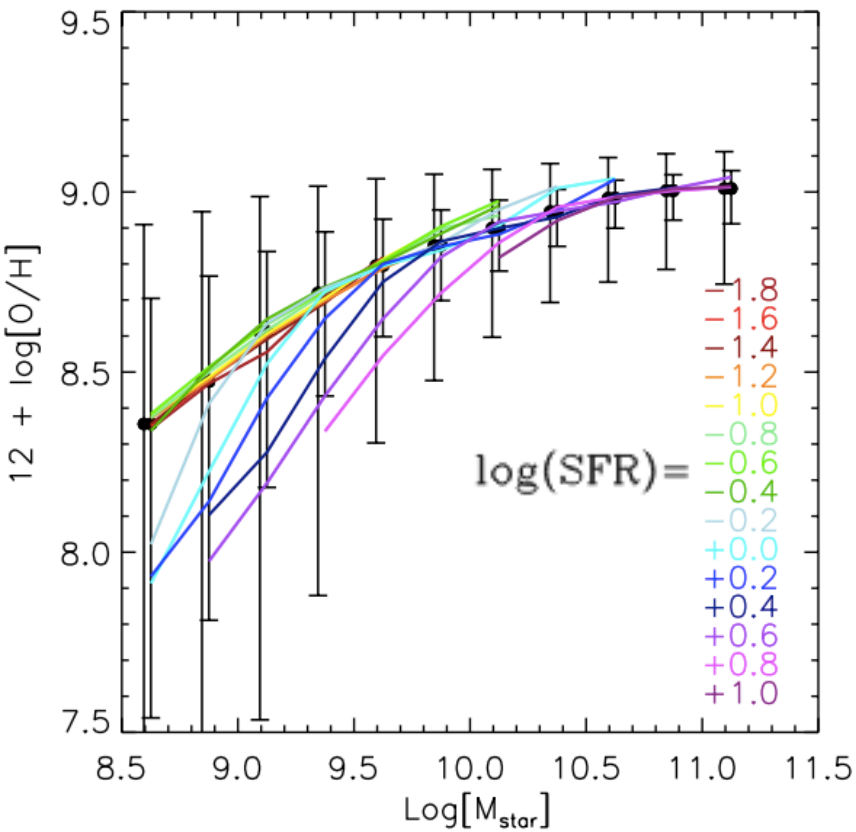


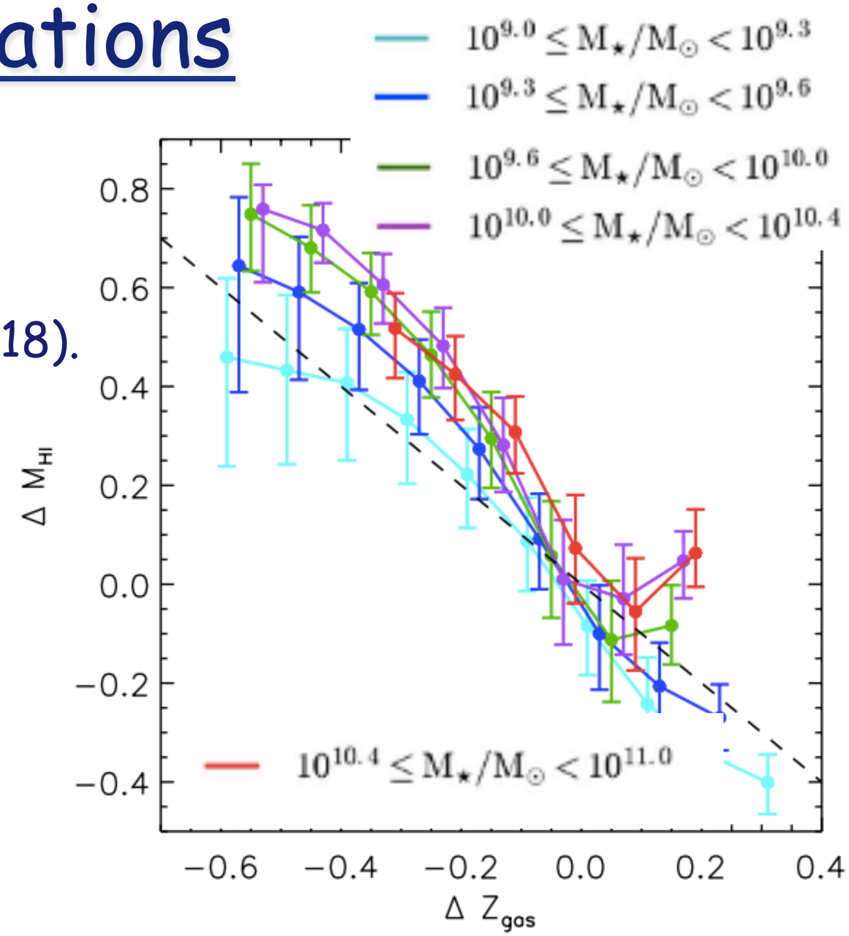


Gas and metals scaling relations

A secondary dependence in the mass-metallicity relation, in qualitative agreement with observational results (Mannucci et al. 2010; Brown et al. 2018).

De Lucia et al. in preparation





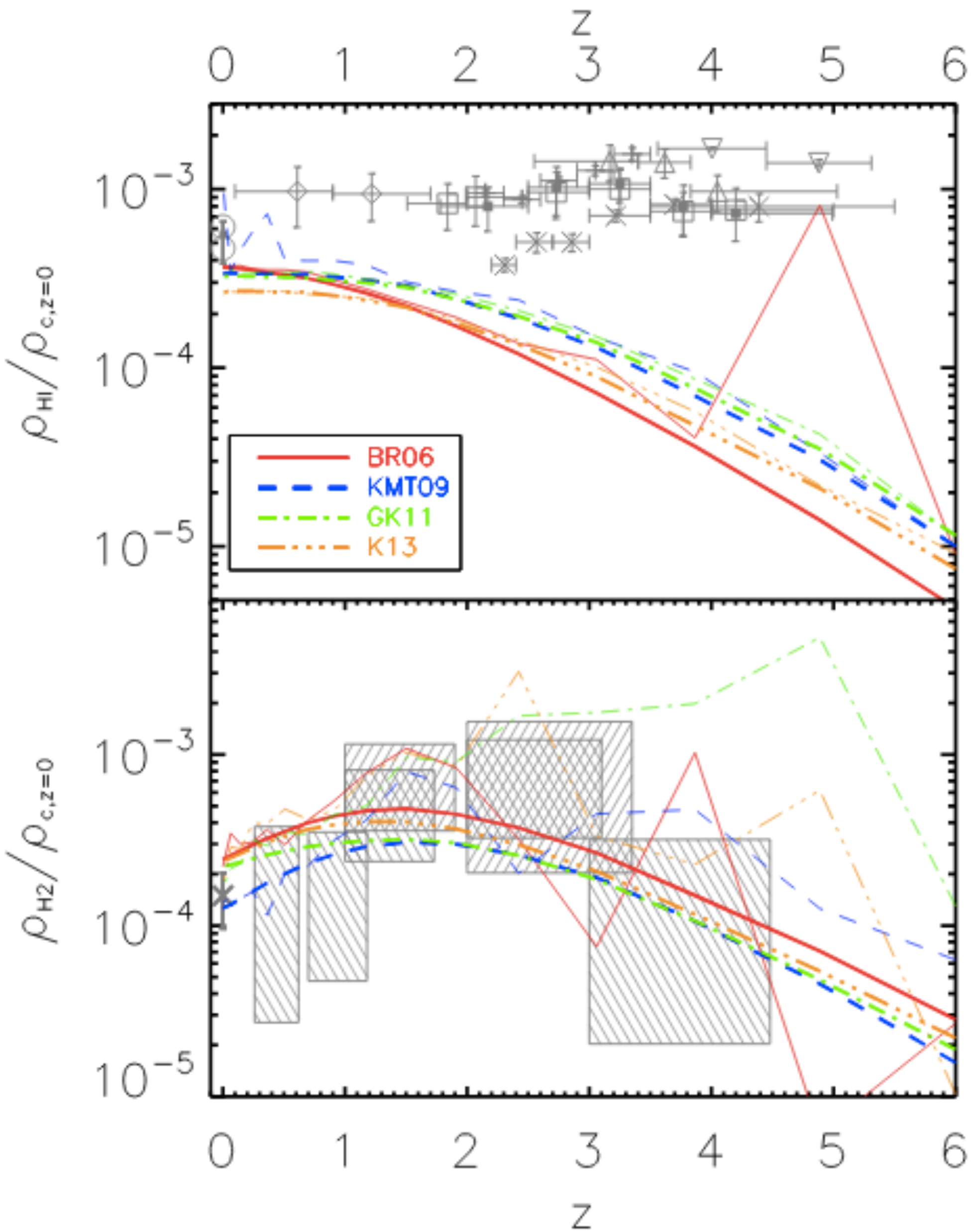
In our model, deviations below the median M-Z relation are driven by late accretion of (pristine?) cold gas, while deviations below are due to primarily to star formation (work ongoing. . . .)

Evolution to high-z

Reproduces relatively well the cosmic density of H_2 (and estimated scaling relations at higher-z), but incorrect evolution for the HI cosmic density.

This is in part (currently estimating) a problem of resolution.

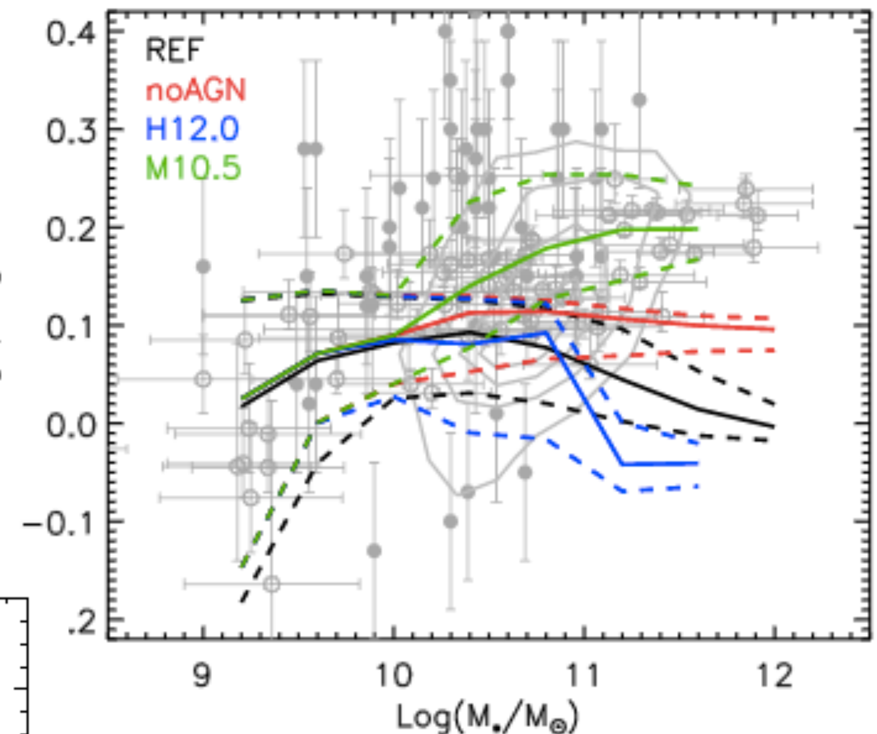
Ratio between H_2 and HI cosmic density is sensitive to the different star formation laws adopted. Unfortunately, this is also very sensitive to different prescriptions for other processes.

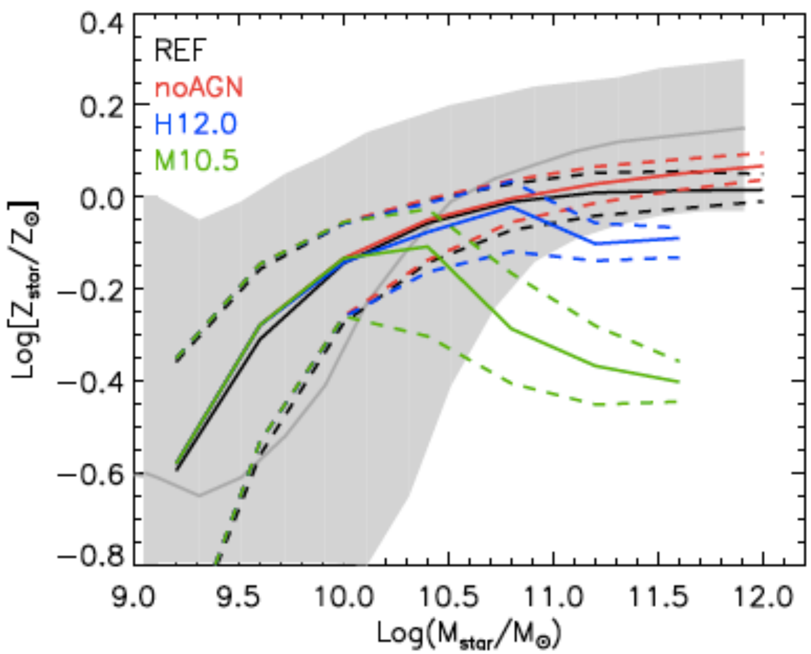


[α/Fe] - stellar mass

H12.0 = cooling suppressed in haloes more massive than ~10^12 Msun

M10.5 SF suppressed in galaxies more massive than ~10^10.5 Msun





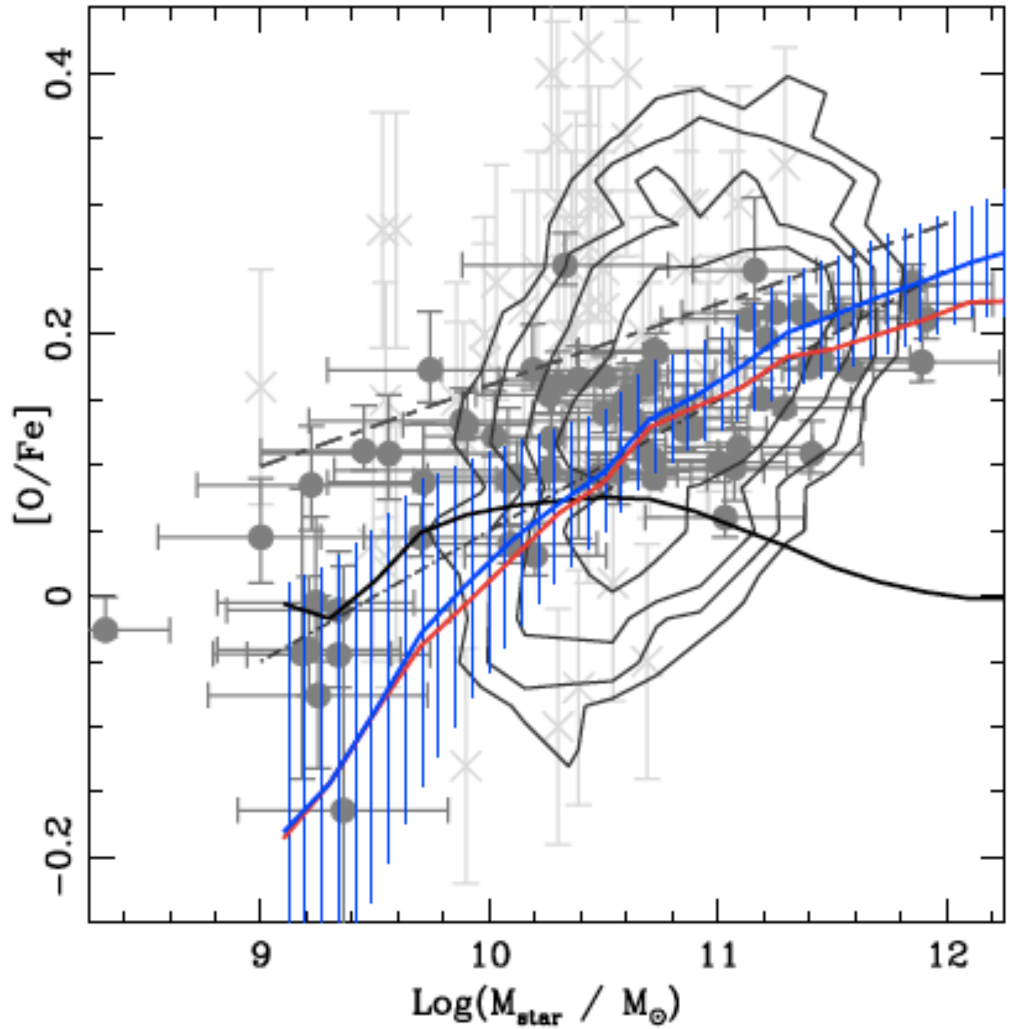
In GAEA, AGN feedback (as implemented) is not “the solution” to get a positive slope for the alpha/Fe vs stellar mass relation (as suggested in other recent studies work).

De Lucia et al. 2017

A variable Initial Mass Function?

A variable IMF (e.g. the IGIMF theory by Kroupa and collaborators) helps (in our framework) to get a positive slope in the alpha/Fe versus mass relation.

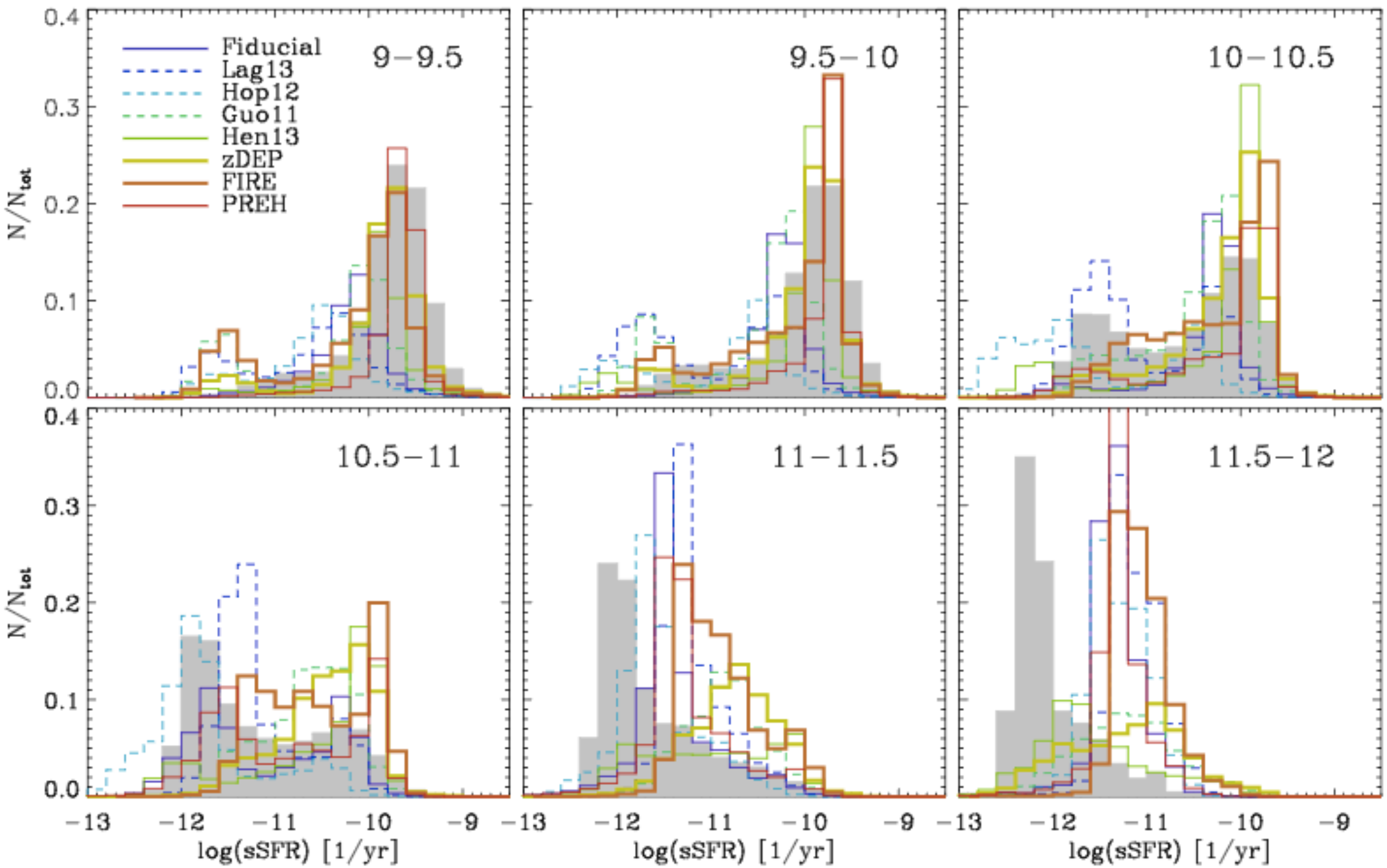
The same model predicts stellar masses and M/L larger than those estimated from synthetic photometry using a universal IMF, in agreement with recent results.



Fontanot et al. 2017, 2018

Distribution of sSFR (colours)

Hirschmann, De Lucia & Fontanot 2016



Massive galaxies are too active; bimodality not well pronounced.

Final remarks

✓ Semi-analytic models are arguably the most efficient method to build statistical predictions to be compared with modern surveys and test the influence of different physical processes.

✓ Only very recently models have overcome ~10-years old problems. Somewhat surprisingly, solution is not in a better treatment of satellite galaxies. It remains to be shown that proposed schemes are realistic.

✓ GAEA is a state-of-the-art semi-analytic model that reproduces nicely a large number of observations. Work is ongoing to test our more recent developments (gas partition, IMF variations, etc.). Model predictions are public (contact us!)

✓ Problems remain - colour/SFR bimodality is a difficult one. It likely requires a significant revision of the AGN feedback model used (lack of `quasar mode' and associated winds).