A Modified star formation law in semi-analytic models

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Outline

- Introduction
  - semi-analytic models of galaxy formation
  - star formation law
- Modified star formation law
  - quiescent mode in disks
  - burst mode during mergers
- Results
- Conclusion

Galaxy formation models

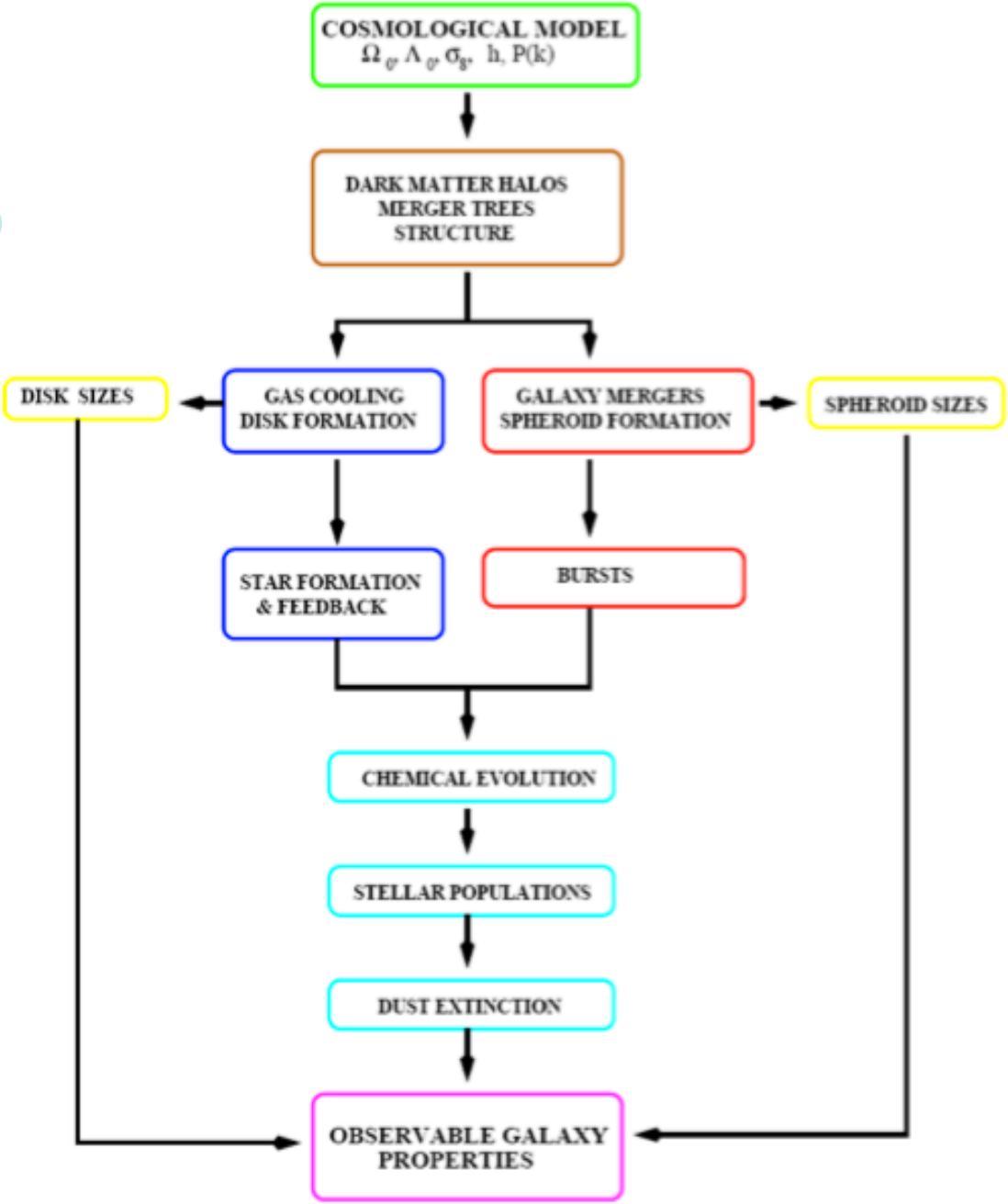
- Two stages: *White & Rees 1978*
  - Dark matter haloes form through gravitational collapse
  - Galaxies form through cooling of baryonic component in dark matter haloes
- Linking galaxy properties to DM halos:
  - Hydrodynamic Simulation

    e.g. *White, Hernquist & Springel 2001*
  - Semi-analytic models

    De Lucia & Blaizot 2007
  - Halo Occupation Distribution models (HOD)

    Berlind & Weinberg 2002

Semi-analytic



Bower et al. 2006

Semi-analytic models: Yes & No

- SAMs (*White & Frenk 1991*) have been successfully used to study how different physical processes determine the formation and evolution of galaxies

- Still have problems in reproducing:
  - low mass end of the stellar mass function at z~0
  - stellar mass functions at high redshifts
  - the 2-point auto-correlation function of galaxies
  - the SSFR - stellar mass relation

e.g. Somerville et al. 2008; Fontanot et al. 2009 ; Marchesini et al. 2009; Guo et al. 2011

Discrepancies- Why?

- Possible reasons:
  - inaccurate physical modeling/ fixed functional form of physical processes that govern galaxy formation
    - SNe feedback *Guo et al. 2011*
    - star formation law
  - technical problems in tuning the model against a large set of observational constraints
  - wrong cosmological model adopted in the simulations

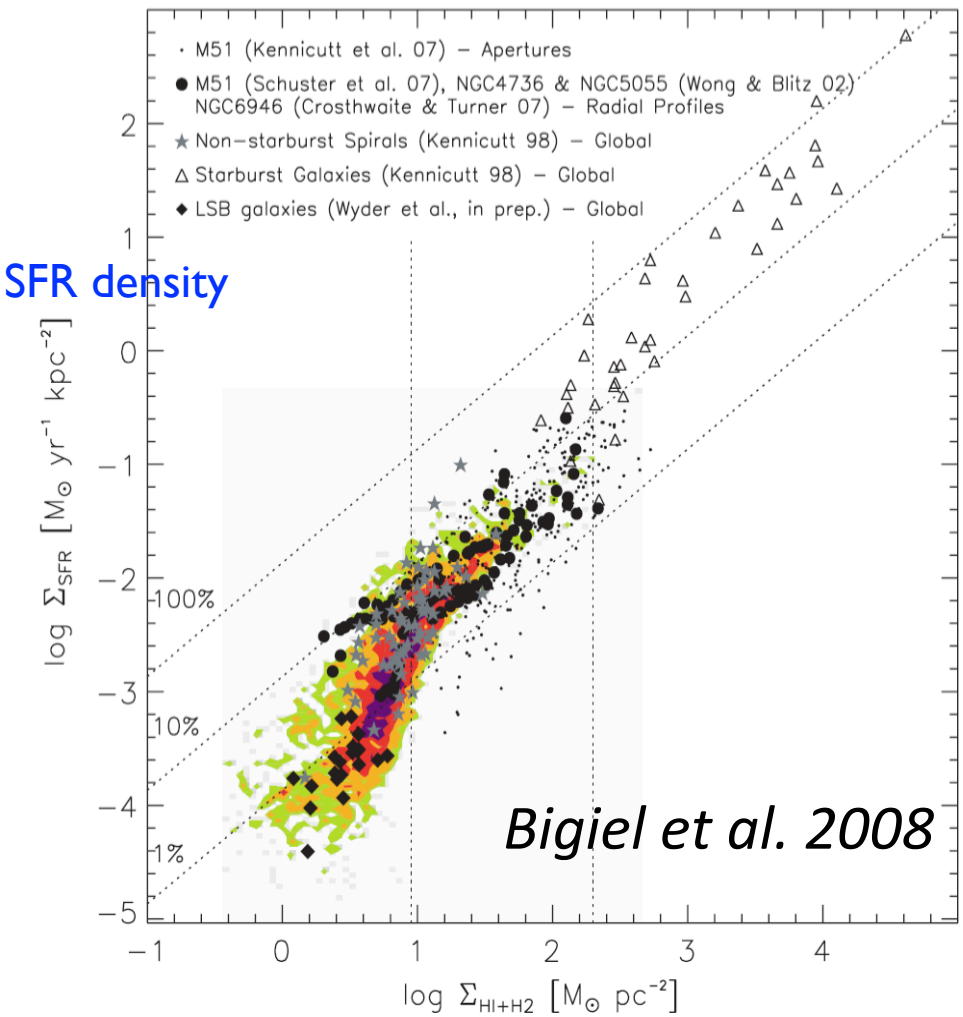
Star formation law: obs *vs.* modeling

- Most of the current SAMs: an analogue to the empirical Kennicutt–Schmidt law:

$$\dot{M}_{\rm star} = \alpha(M_{\rm cold} - M_{\rm crit})/t_{\rm dyn}$$

- Recent observations:
  - the threshold for SF at low mass densities is not sharp. *(Kennicutt et al. 2007; Bigiel et al. 2008; Wyder et al. 2009)*
  - the SF rate is correlated more strongly with the mass of molecular gas (H2) *(Bigiel et al. 2008; Leroy et al. 2008*)
  - the normalization of the SF law might be lower at high redshift than locally *(e.g. Wolfe & Chen 2006; Gnedin & Kravtsov 2010; Krumholz & Dekel 2011).*

Modify the SF recipe



- Our modifications: suppressing the total SFR (M_{cold}, t, M_{halo}) in low mass haloes, constrained by the observed SMF
- Millennium (- II) simulations:

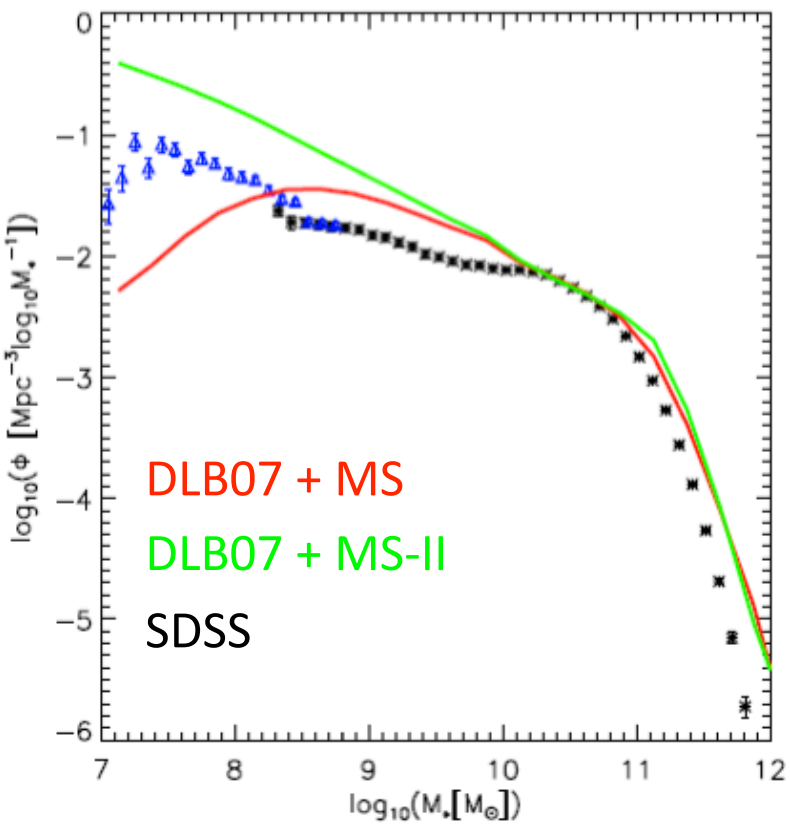
$$N = 2160^3, L = 500(100)h^{-1}Mpc$$

$$M_p = 8.6\times10^8(6.89\times10^6)h^{-1}M_\odot$$

Fiducial model

- *De Lucia & Blaizot 2007*
  - SMF over-predicted

- *Neistein & Weinmann 2010:* semi-analytic model with efficiencies depending on halo mass and cosmic time



Guo et al. 2011

Modified star formation laws

- Quiescent mode
  - Standard model

$$\dot{M}_{\rm star} = f_s (M_{\rm cold} - M_{\rm crit})$$

model 1): $f_s = 2.04\, M_{12}^{0.094} 10^{-0.039[\log M_{12}]^2} t^{-0.82}$

$$M_{\rm crit} = 0.355\, f_s^{-1} M_{12}^{0.68} t^{-0.515}$$

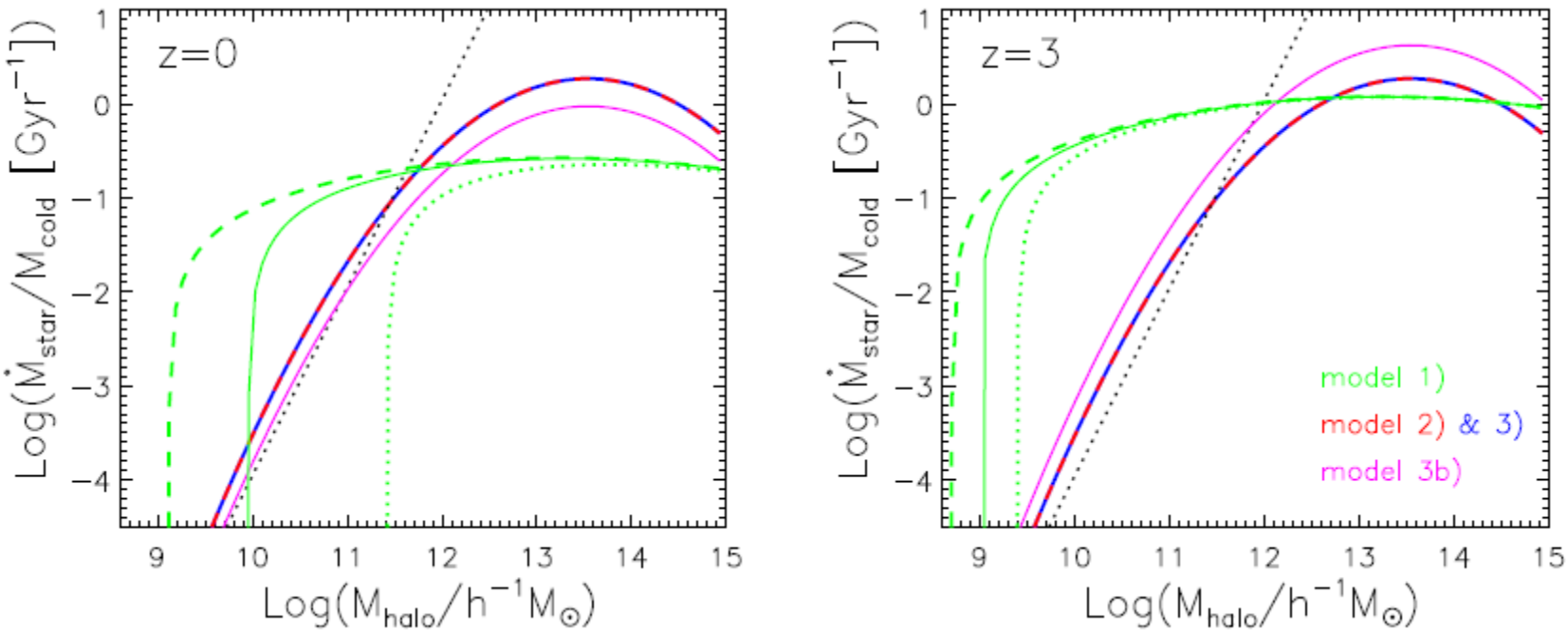
  - Modified model

$$M_{\rm crit} = 0$$

model 2) & 3): $f_s = 0.41\, M_{12}^{0.94} 10^{-0.30[\log M_{12}]^2}$

model 3b): $f_s = 1.74\, M_{12}^{0.94} 10^{-0.30[\log M_{12}]^2} t^{-0.82}$

Modified quiescent star formation



- For galaxies within low mass halos, SF efficiency depends on halo mass, roughly corresponding to a power law of index 2 (black dotted lines)
- SFE dependent of time or not? -similar results

Modified star formation laws

- Burst mode
  - Standard model: model 1) & 2)

$$\dot{M}_{\rm star,burst} = \alpha_{\rm burst}(M_{1,\rm cold} + M_{2,\rm cold})$$

$$\alpha_{\rm burst} = 0.56(M_1/M_2)^{0.7}$$

  - Modified model: model 3) & 3b)

for haloes less massive than $M_0 = 10^{11.5} h^{-1} \mathrm{M}_\odot$

$$\alpha_{\rm burst} = 0.56(M_1/M_2)^{0.7} \times (M_{\rm halo}/M_0)$$

Results: Stellar mass function

- Suppressing SF in low mass galaxies help to fit the stellar mass function, for both MS and MS-II

model 1) - standard SF

model 2)

- modified quiescent SF

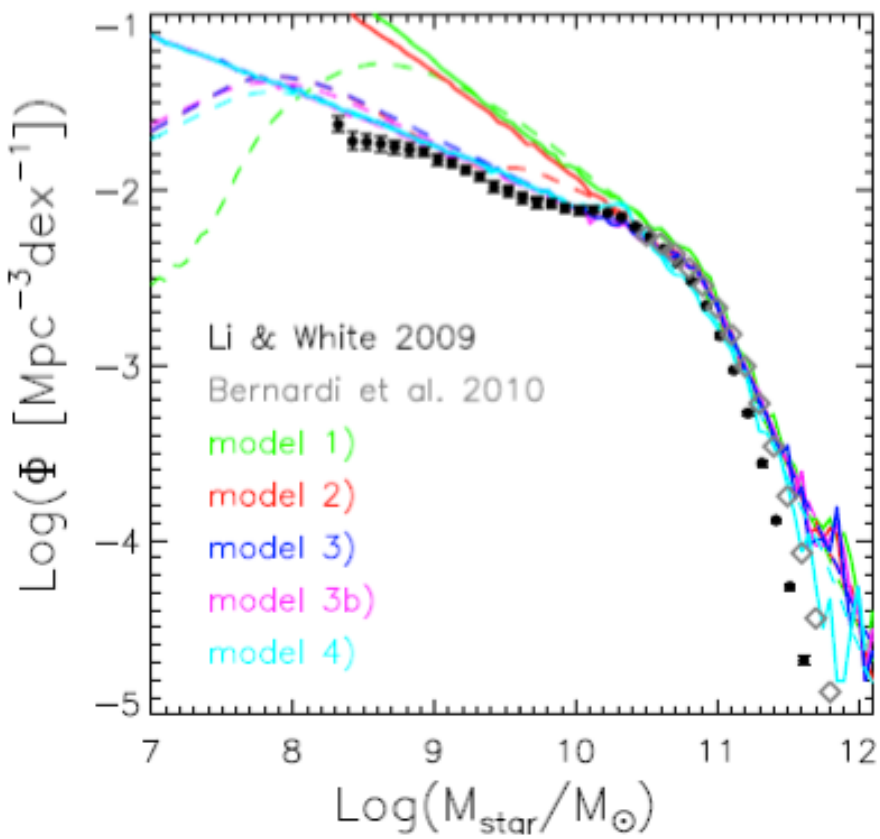
model 3)

- modified quiescent SF & burst SF

model 3b)

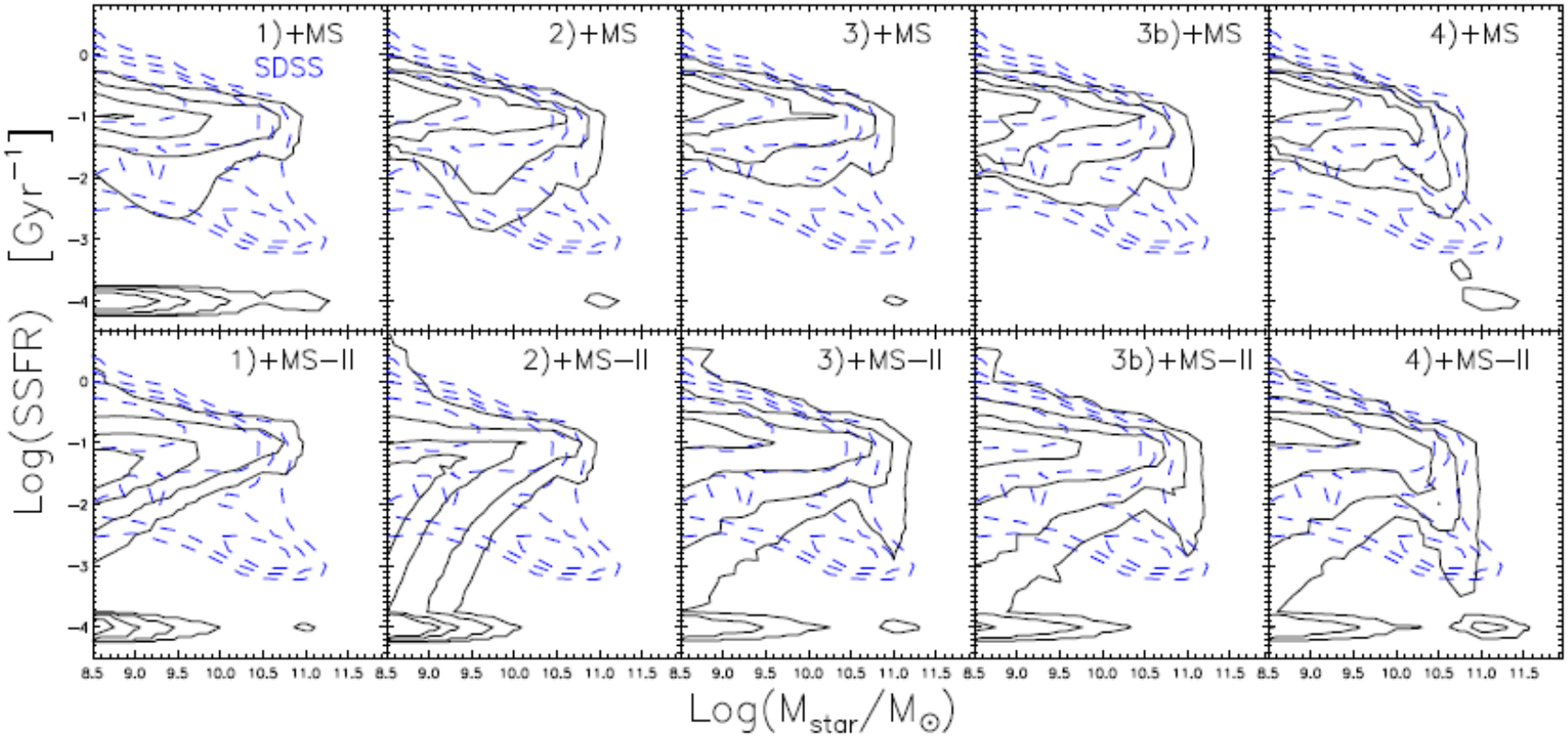
- SFE dependent of time

model 4) - further changes for massive galaxies based on 3)



SSFR-Mstar relation

- Observation: two distinct sequences
- Models: modified SF laws make the passive fraction lower and active sequence higher



Median SSFR - Mstar

model 1) - standard SF

model 2)

- modified quiescent SF

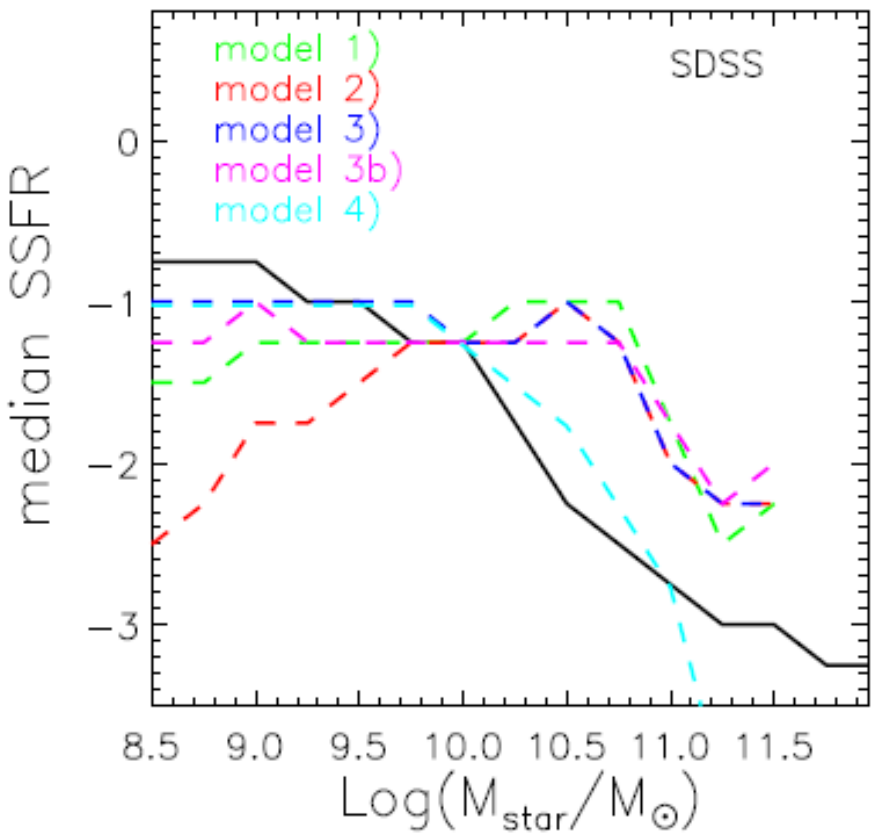
model 3)

- modified quiescent SF & burst SF

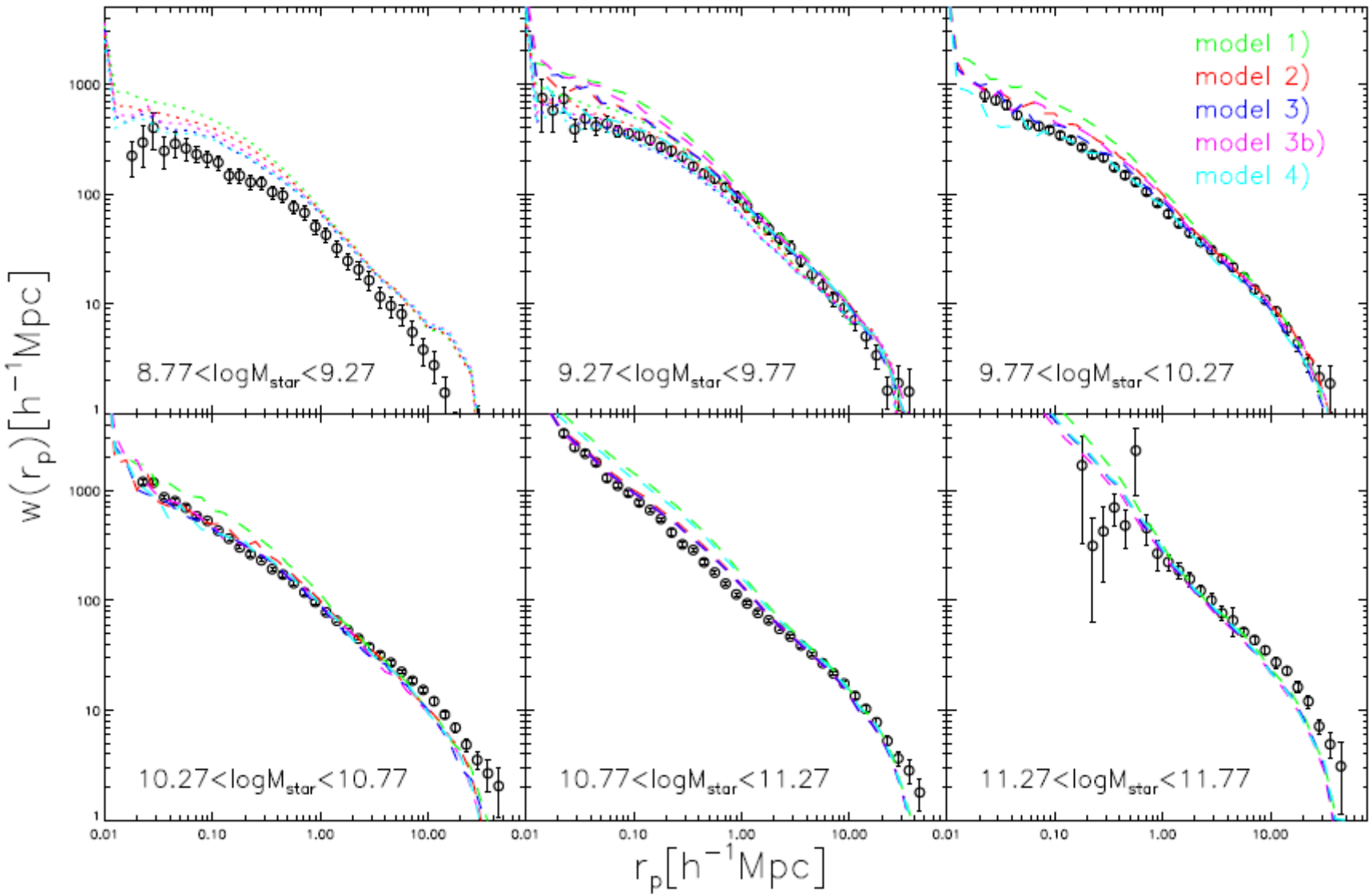
model 3b)

- SFE dependent of time

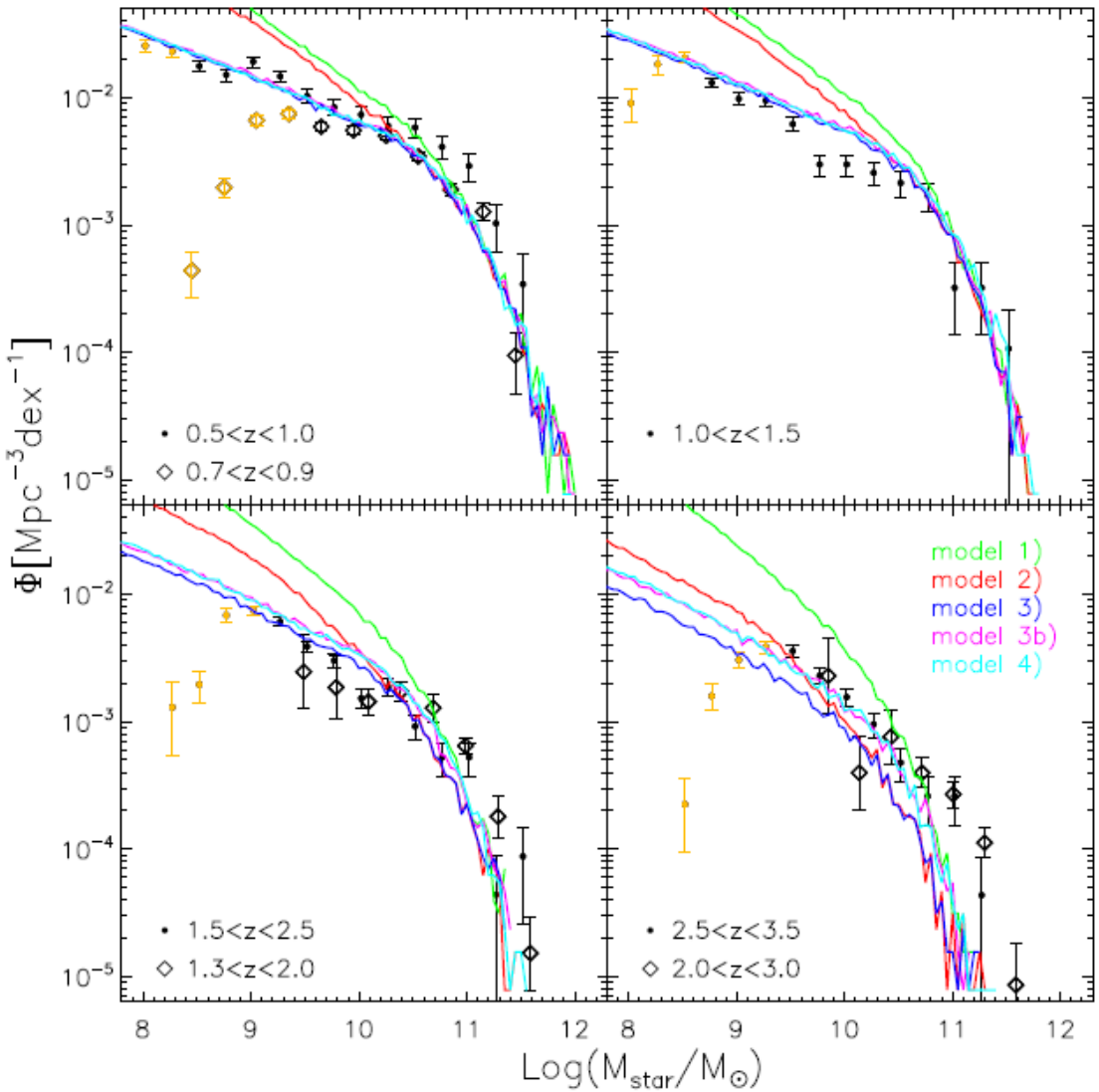
model 4) - further changes for massive galaxies



Correlation functions



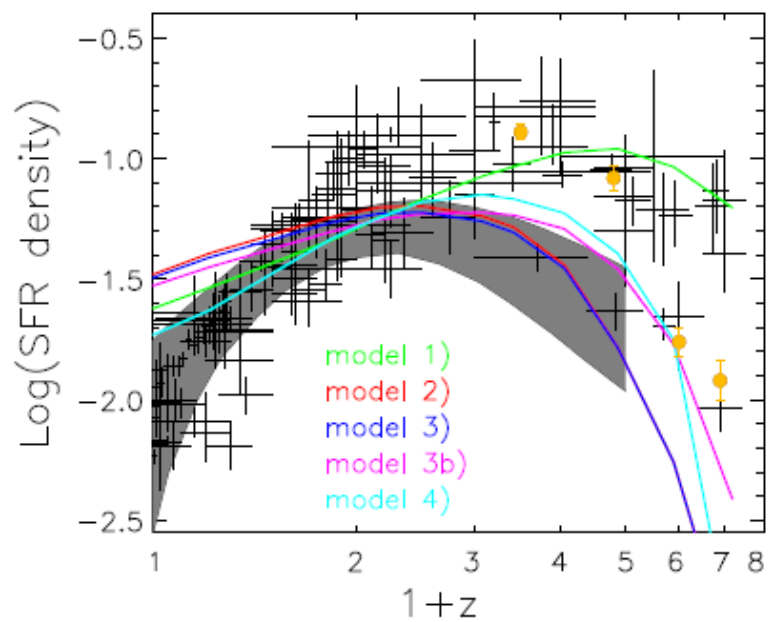
High z SMFs & SFR density



model 1) - standard SF

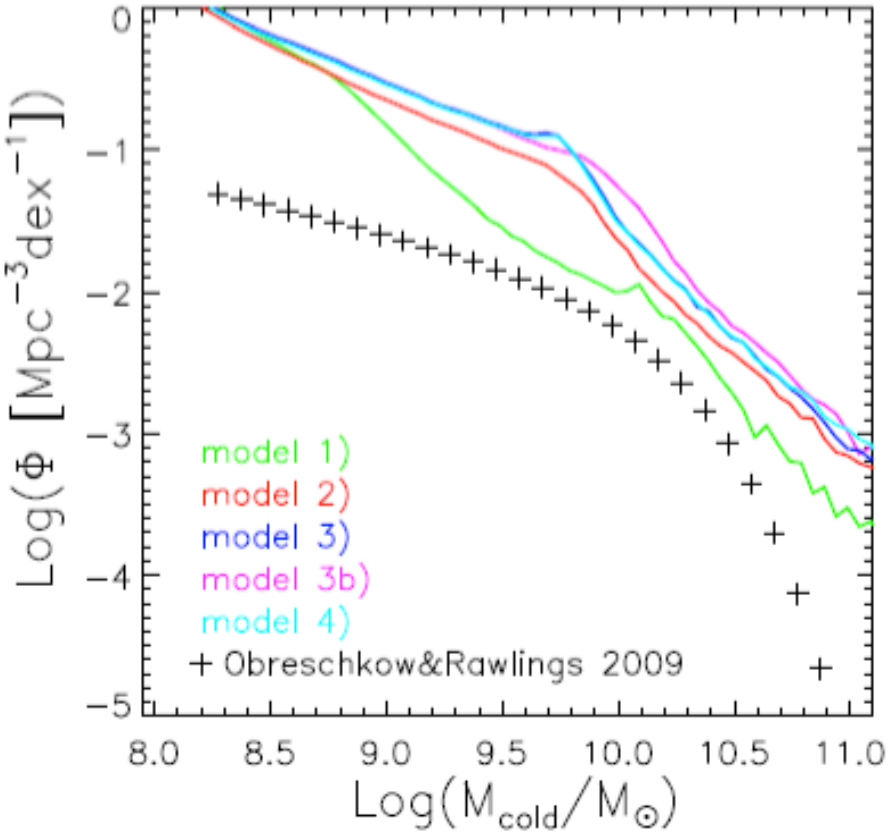
model 2) - modified quiescent SF

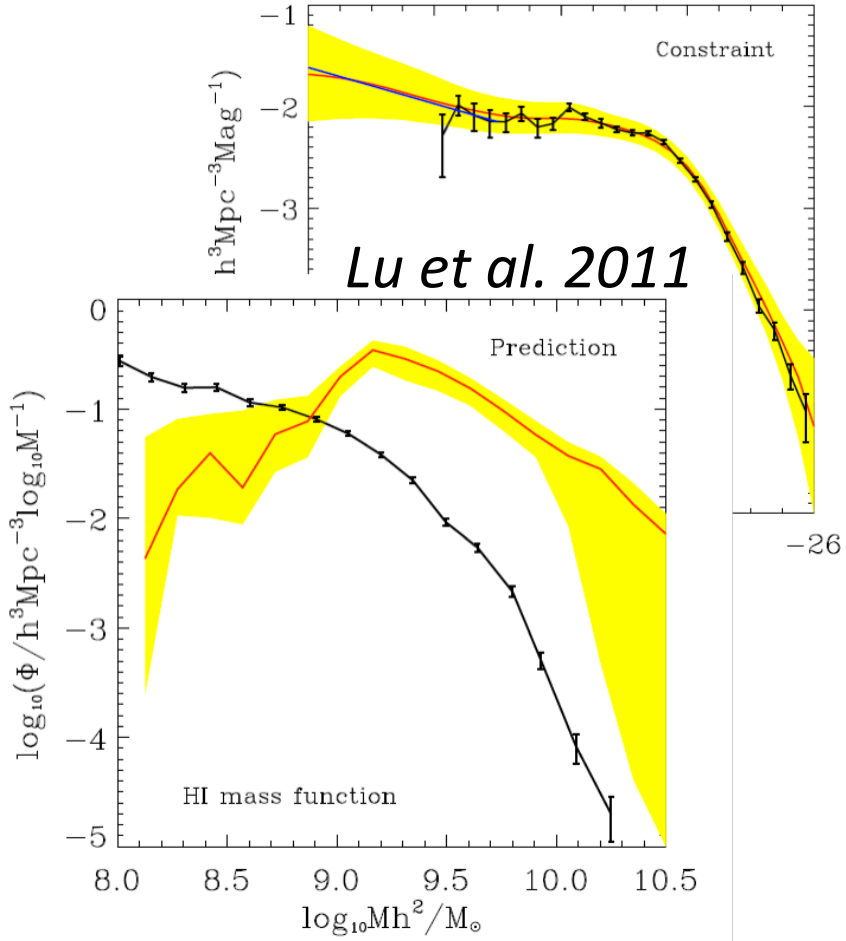
model 3) - modified quiescent & burst SF



Cold gas mass function

- Cold gas mass function is over-predicted

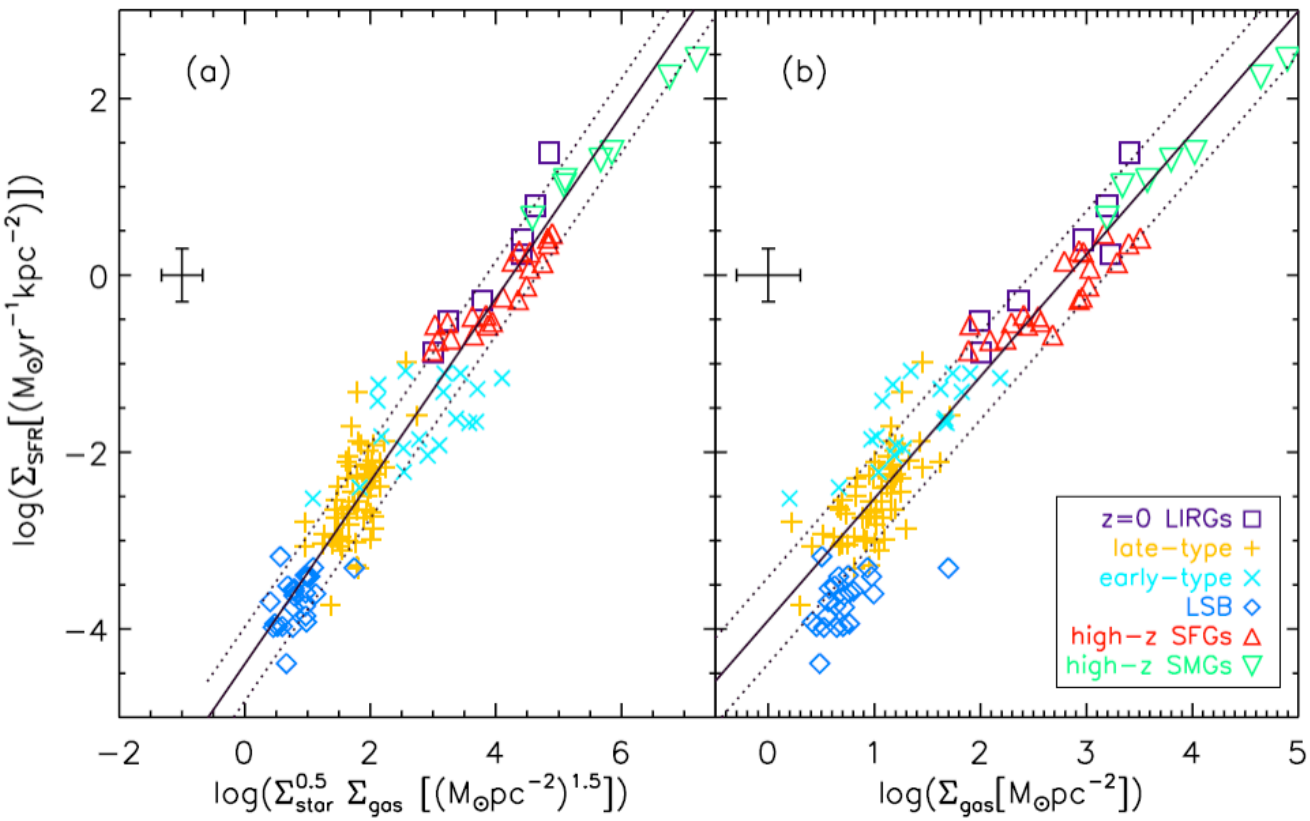




The observed 'extended Schmidt law'

$$\frac{\mathrm{SFE}}{\mathrm{yr}^{-1}} = 10^{-10.28} \left(\frac{\Sigma_{\mathrm{star}}}{M_\odot\,\mathrm{pc}^{-2}} \right)^{0.48}$$

Shi et al. 2011



vs. The extended Schmidt law

$$\frac{\mathrm{SFE}}{\mathrm{yr}^{-1}} = 10^{-10.28}\left(\frac{\Sigma_{\mathrm{star}}}{M_\odot\,\mathrm{pc}^{-2}}\right)^{0.48}$$

Shi et al. 2011

at low masses:

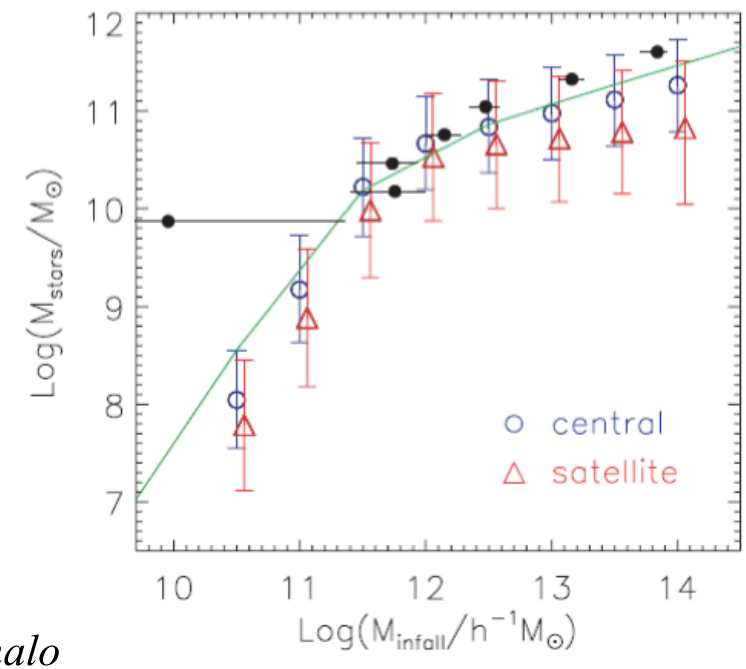
$$M_{star} \propto M_{halo}^{2.87}$$

$$\longrightarrow \quad SFE \propto M_{halo}^{1.4}$$

- quiescent mode:

$$SFE \propto M_{halo}^{2}$$

- burst mode: $SFE \propto M_{halo}^{1}$



Wang et al. 2006

Summary: how SF law is modified

- No sharp threshold in the cold gas mass for SF
- The SF efficiency in the quiescent mode depend on host halo mass
- A lower star burst efficiency in low mass haloes
- No dependence of the star formation rate on cosmic time
- Additional modifications of cooling and SF in massive haloes can match the properties of high mass galaxies.

Conclusion

- Suppression of star formation in both quiescent and burst modes are required to fit the low mass end of the SMF
- Better statistics are obtained with the modified SF law, including: high z SMFs, SSFR-M_{star} relation, correlation functions
- However, cold gas mass function is over-predicted
- Not a final solution: Cooling? modify both SF and SNe feedback? missing processes?

Thank you !

Test model 4)

- model 4) - further changes for massive galaxies
  - lower cooling efficiencies for haloes more massive than $10^{11.75} h^{-1} \mathrm{M}_{\odot}$
  - SF stopped completely in haloes more massive than $5 \times 10^{12} h^{-1} \mathrm{M}_{\odot}$ at z<1.3
  - dynamical friction time dependent on time, being shorter at higher z (*Weinmann et al. 2011*): due to the more radial orbits of high z satellite galaxies (*Dekel et al. 2009; Hopkins et al. 2010*)

SFR *vs*. HI mass

- While over-predicting the cold gas MF, the SFE in our model is much lower than in reality