Evolution of the Galaxy Main Sequence in Semi-Analytic Galaxy Formation Models

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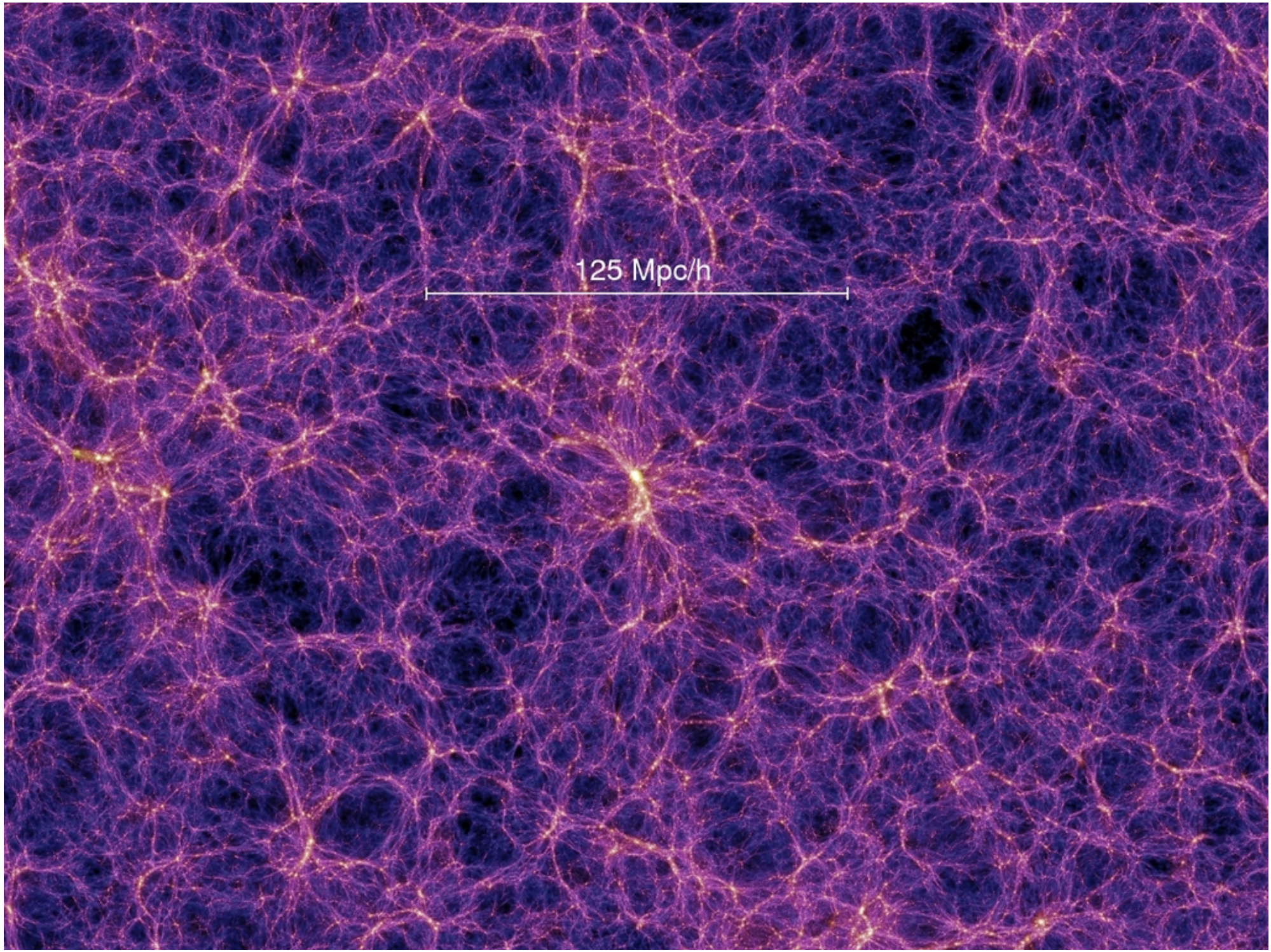
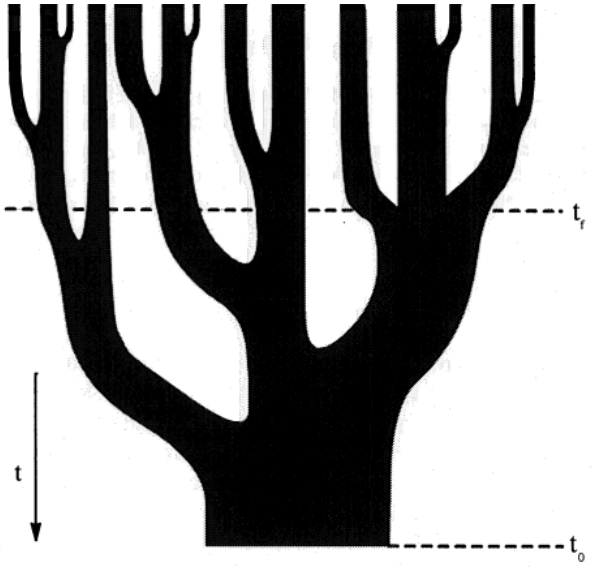
Mitchell et al., 2014, MNRAS, 444, 2637

Outline

- Semi-analytic modelling and stellar mass assembly
- The star forming sequence
- Disagreement in predicted/observed sSFR evolution for star forming galaxies
- The star formation histories of star forming galaxies
- Connection to halo assembly


125 Mpc/h



$f_B \dot{M}_{Halo}$

Hot (Halo) Gas

M_{Hot}

$\dot{M}_{cool}$

Cold (Disk) Gas

M_{Cold}

$\beta\psi$

$\dot{M}_{ret}$

$R\psi$

ψ

Ejected Gas

M_{Res}

Stars

M_*

Traditional semi-analytic galaxy formation modelling

Star formation/feedback

Infall

Accretion

$$\begin{pmatrix} \dot{M}_{Hot} \\ \dot{M}_{Cold} \\ \dot{M}_{Res} \\ \dot{M}_{*} \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1/\tau_{ret} & 0 \\ 0 & \frac{-(1-R+\beta)}{\tau_{*}} & 0 & 0 \\ 0 & \beta/\tau_{*} & -1/\tau_{ret} & 0 \\ 0 & (1-R)/\tau_{*} & 0 & 0 \end{pmatrix} \begin{pmatrix} M_{Hot} \\ M_{Cold} \\ M_{Res} \\ M_{*} \end{pmatrix} + \begin{pmatrix} -\dot{M}_{cool} \\ \dot{M}_{cool} \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} f_B \dot{M}_{Halo} \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

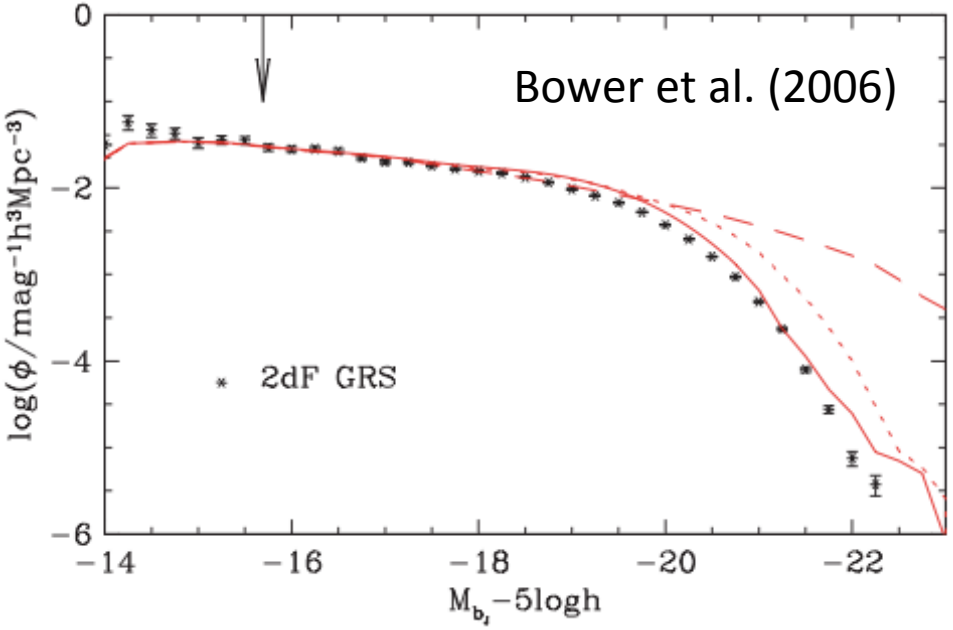
Mass loading factor: $\beta \equiv \frac{\dot{M}_{eject}}{SFR}$

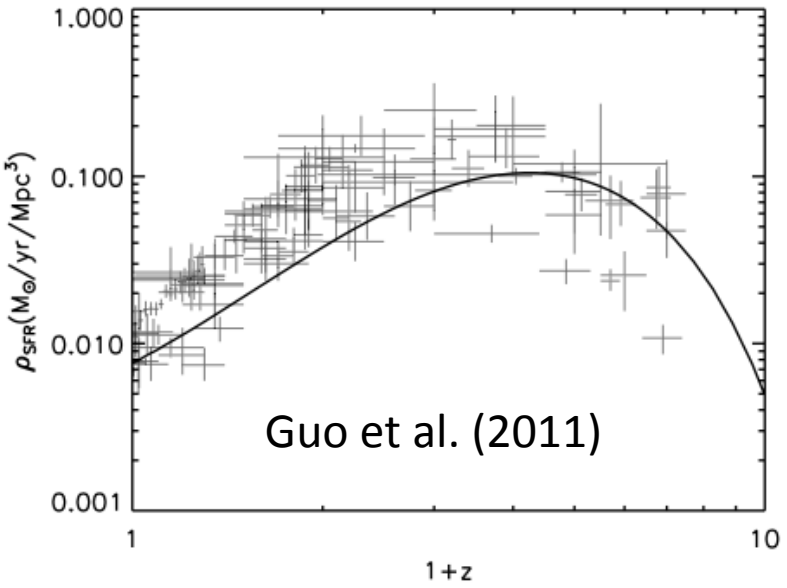
Reincorporation timescale: τ_{ret}

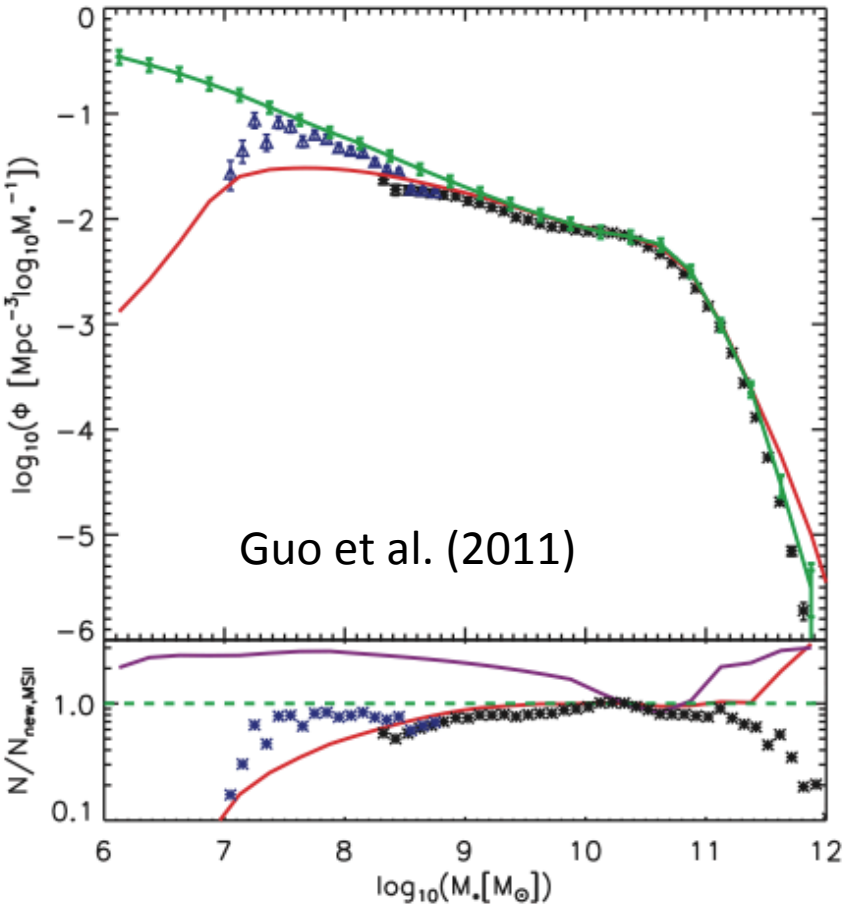
$$\beta \propto V_{disk}^{-3.2}$$

$$\tau_{ret} \propto \tau_{dyn} \propto \frac{M_{Halo}}{V_{Halo}^3}$$

Standard diagnostics for stellar mass assembly

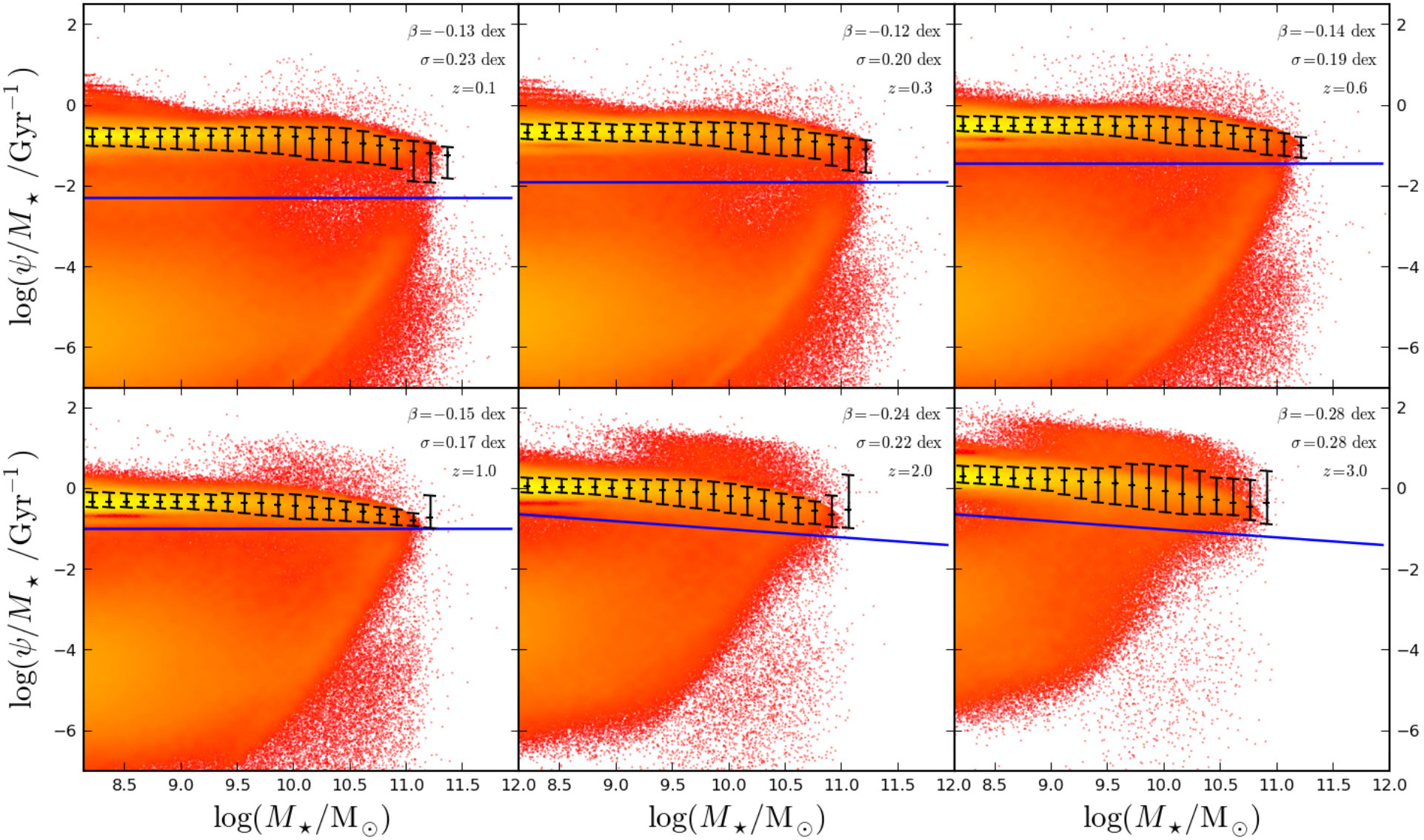




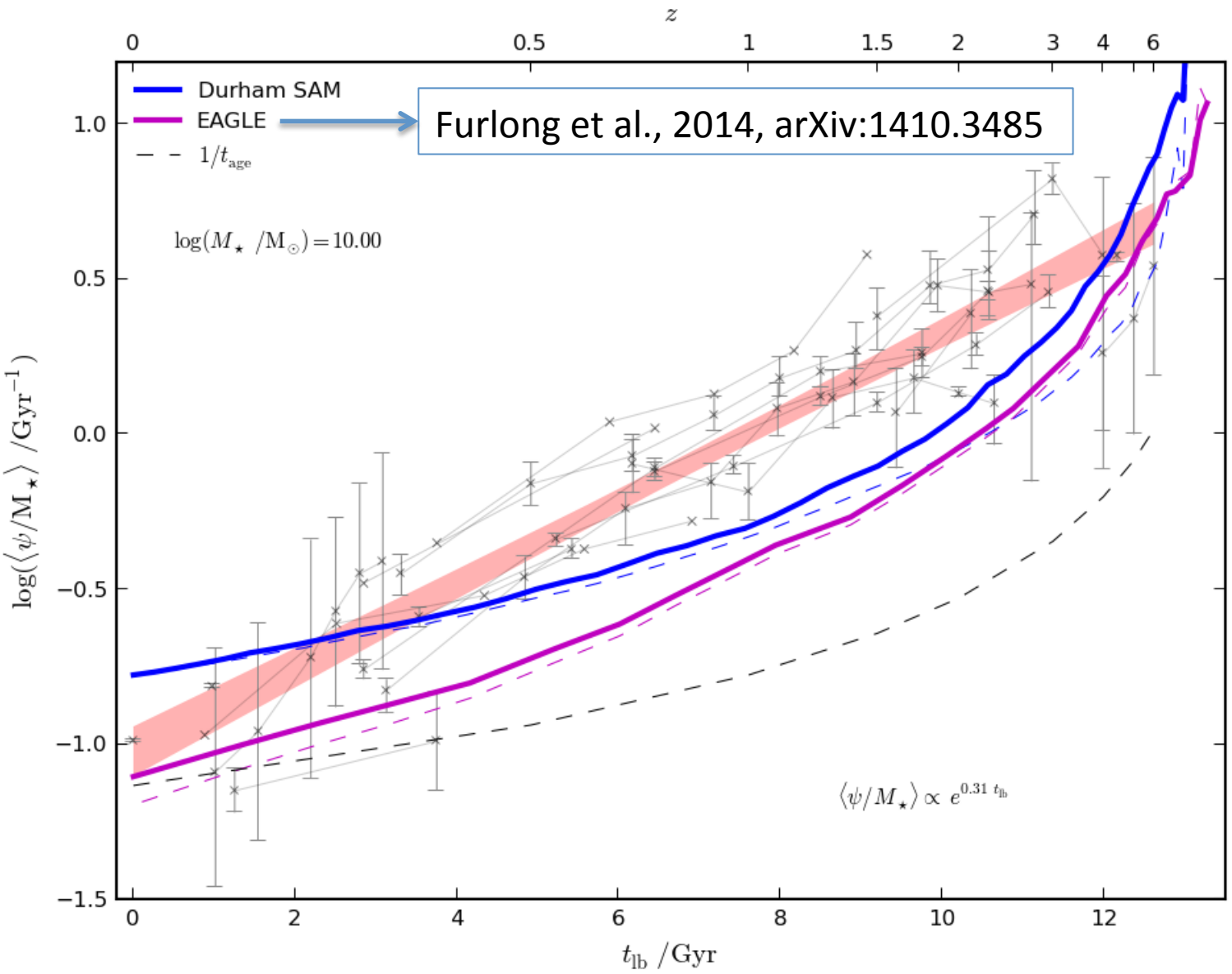


These diagnostics are sensitive to all the physics input into a given galaxy formation model

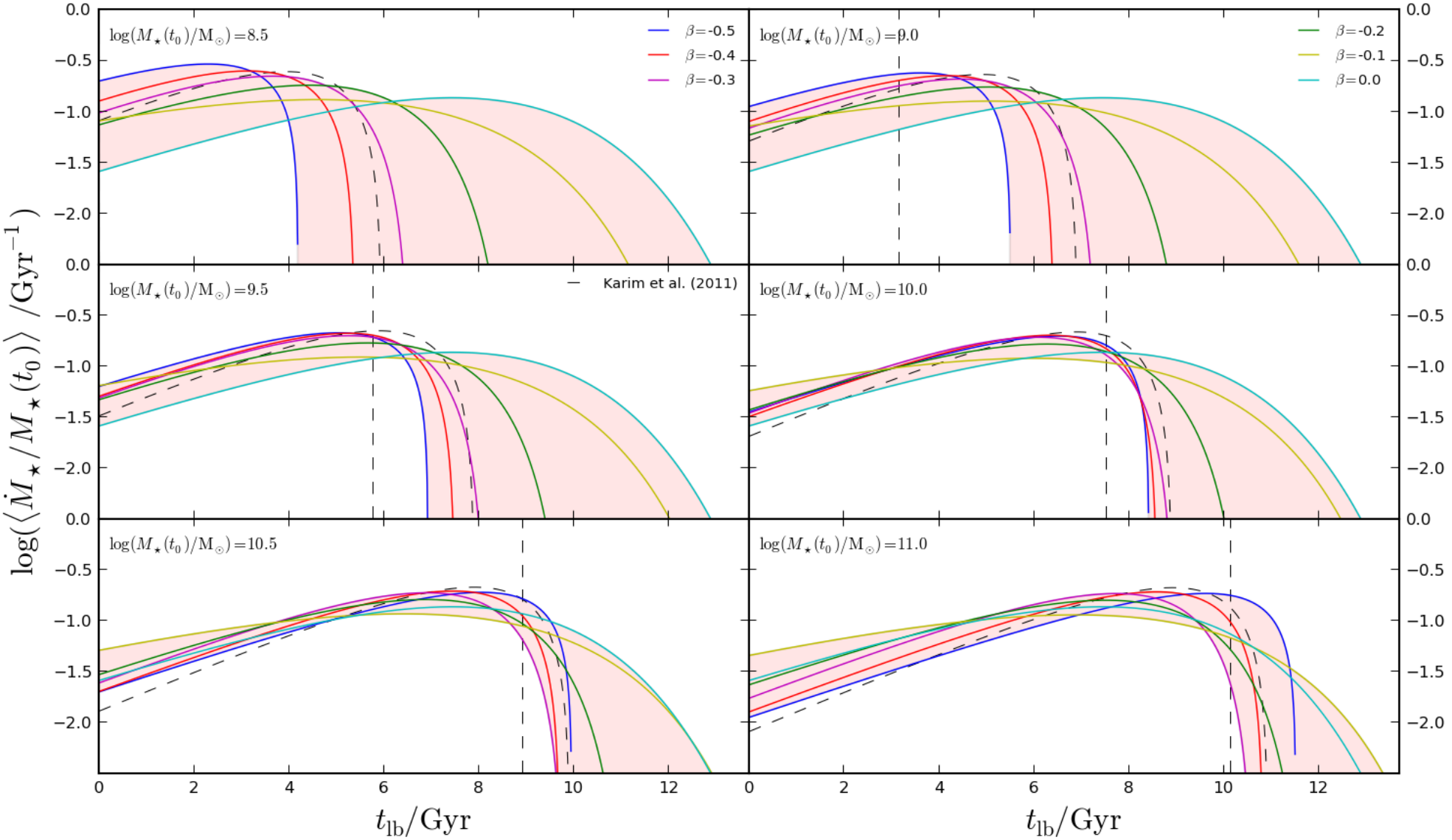
The star forming sequence as a starting point?



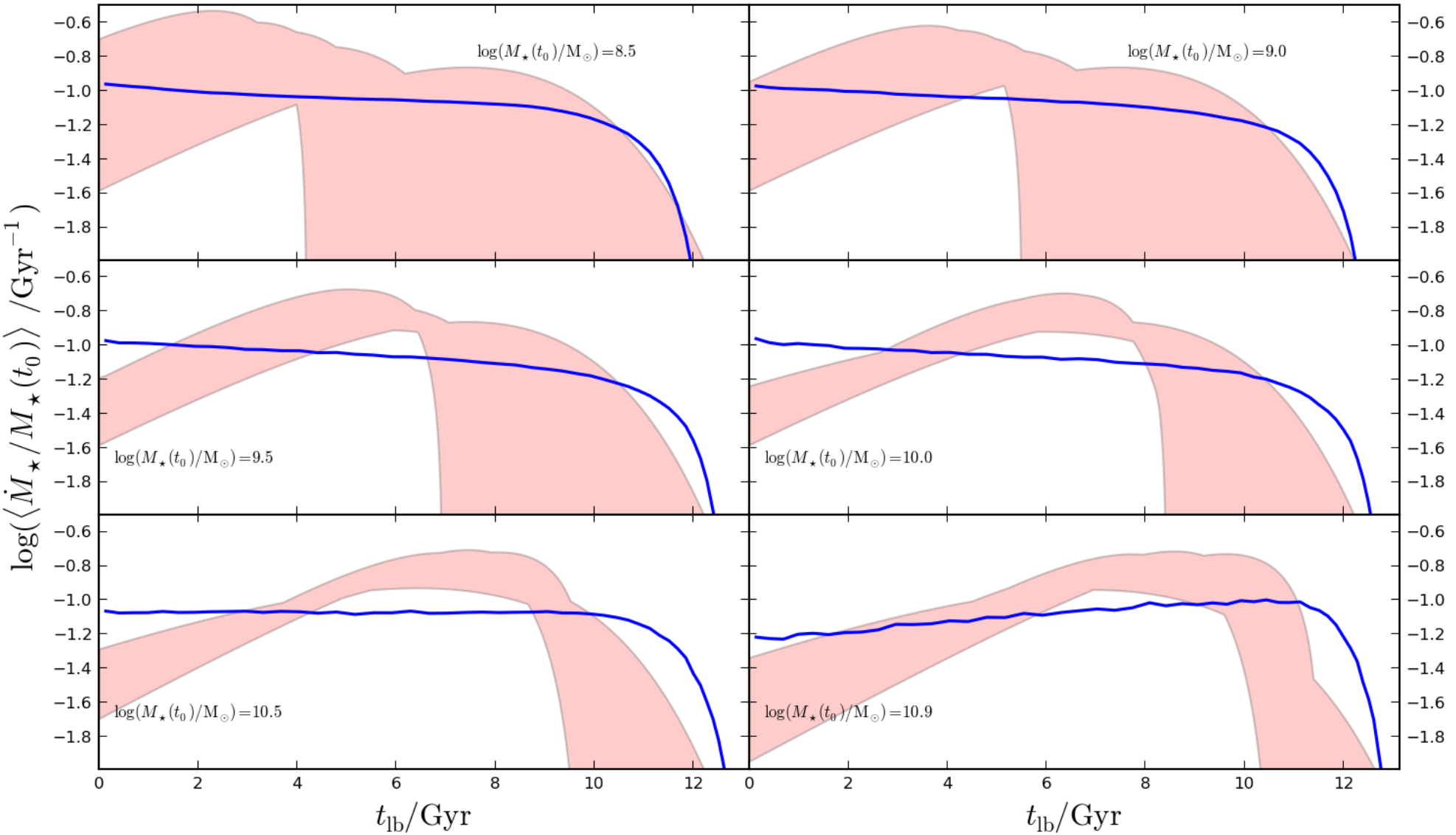
Evolution in sSFRs of star forming galaxies



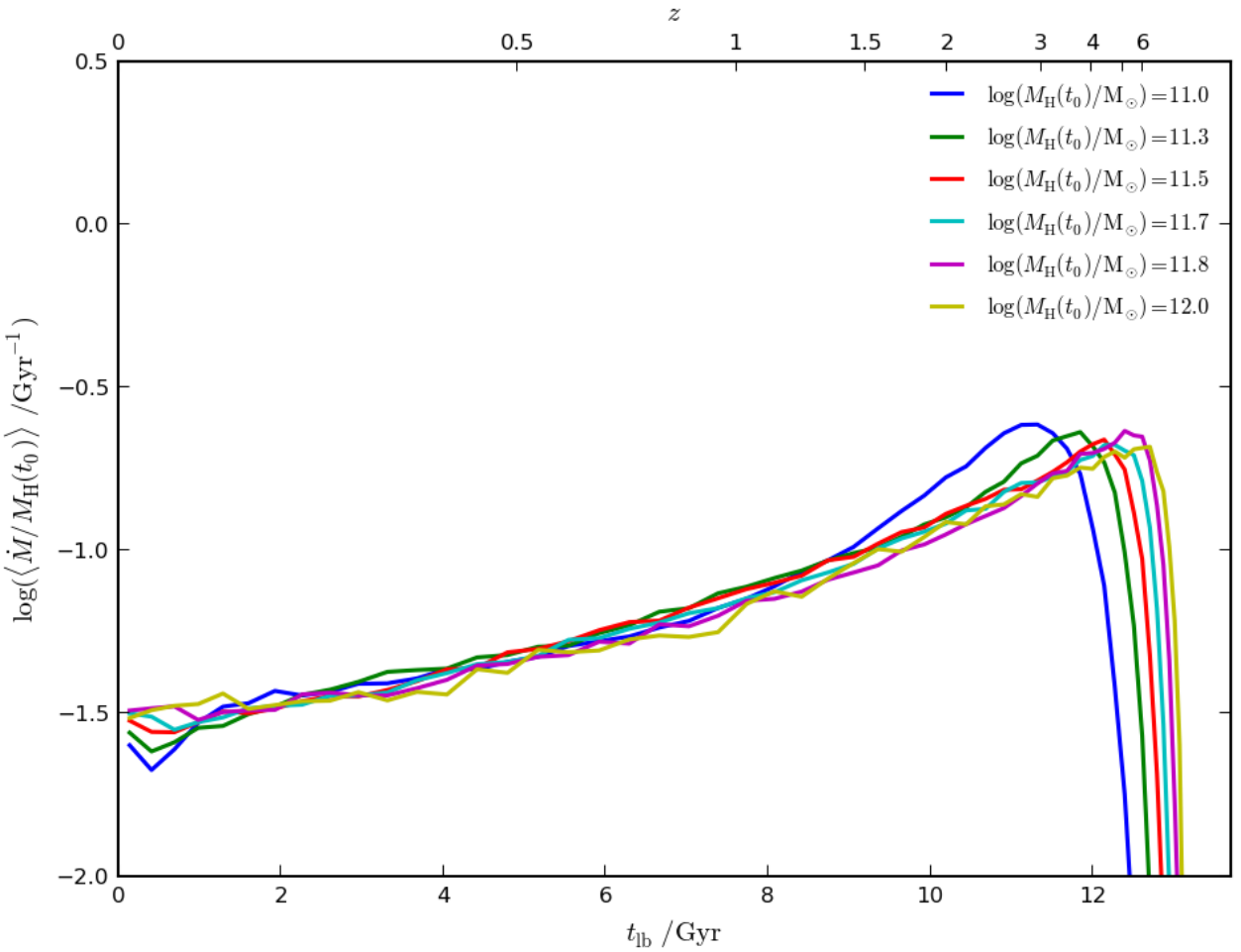
Inferred SFHs of star forming galaxies



Peaked vrs Flat/Rising SFHs



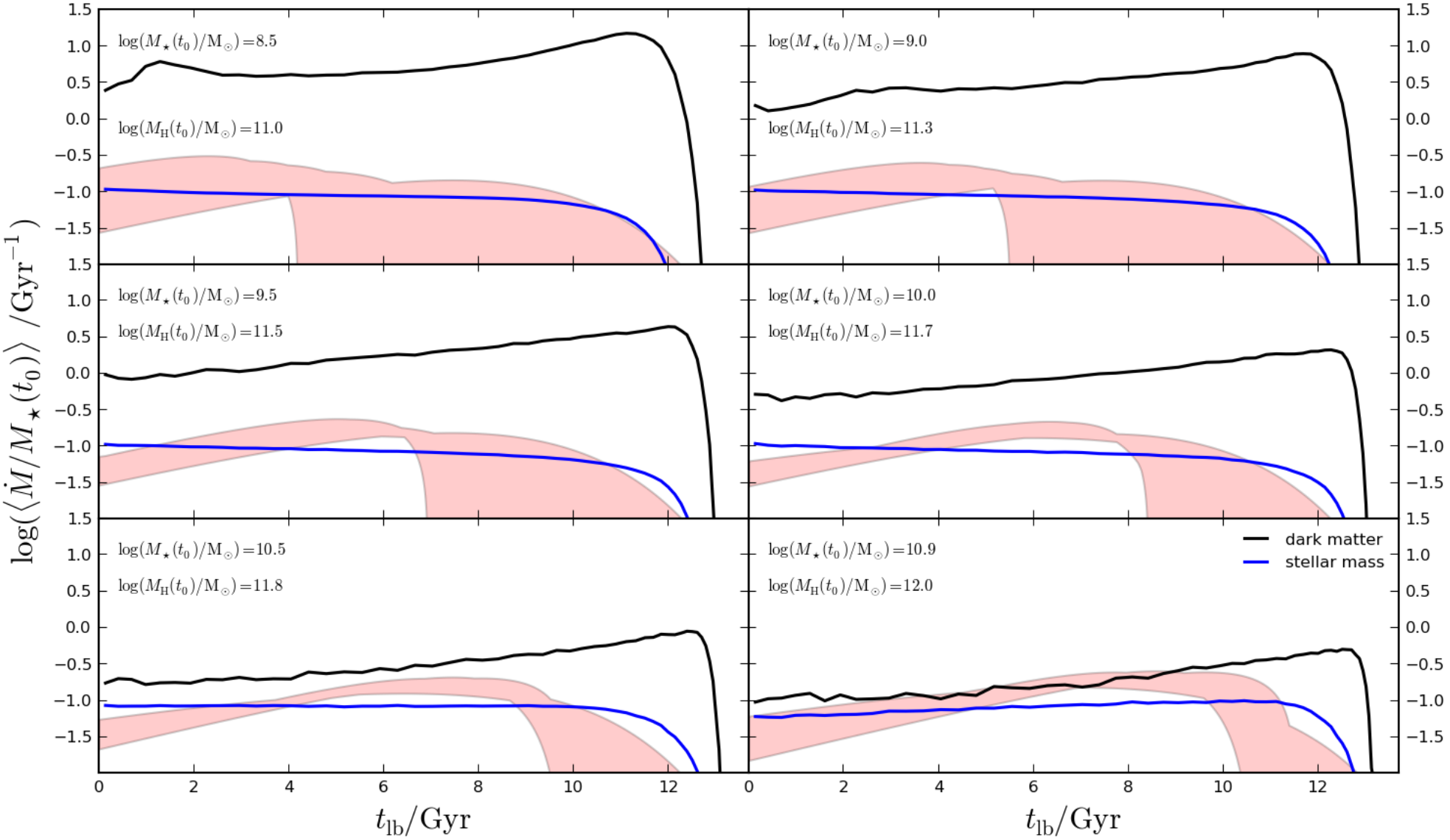
Dark matter halo assembly



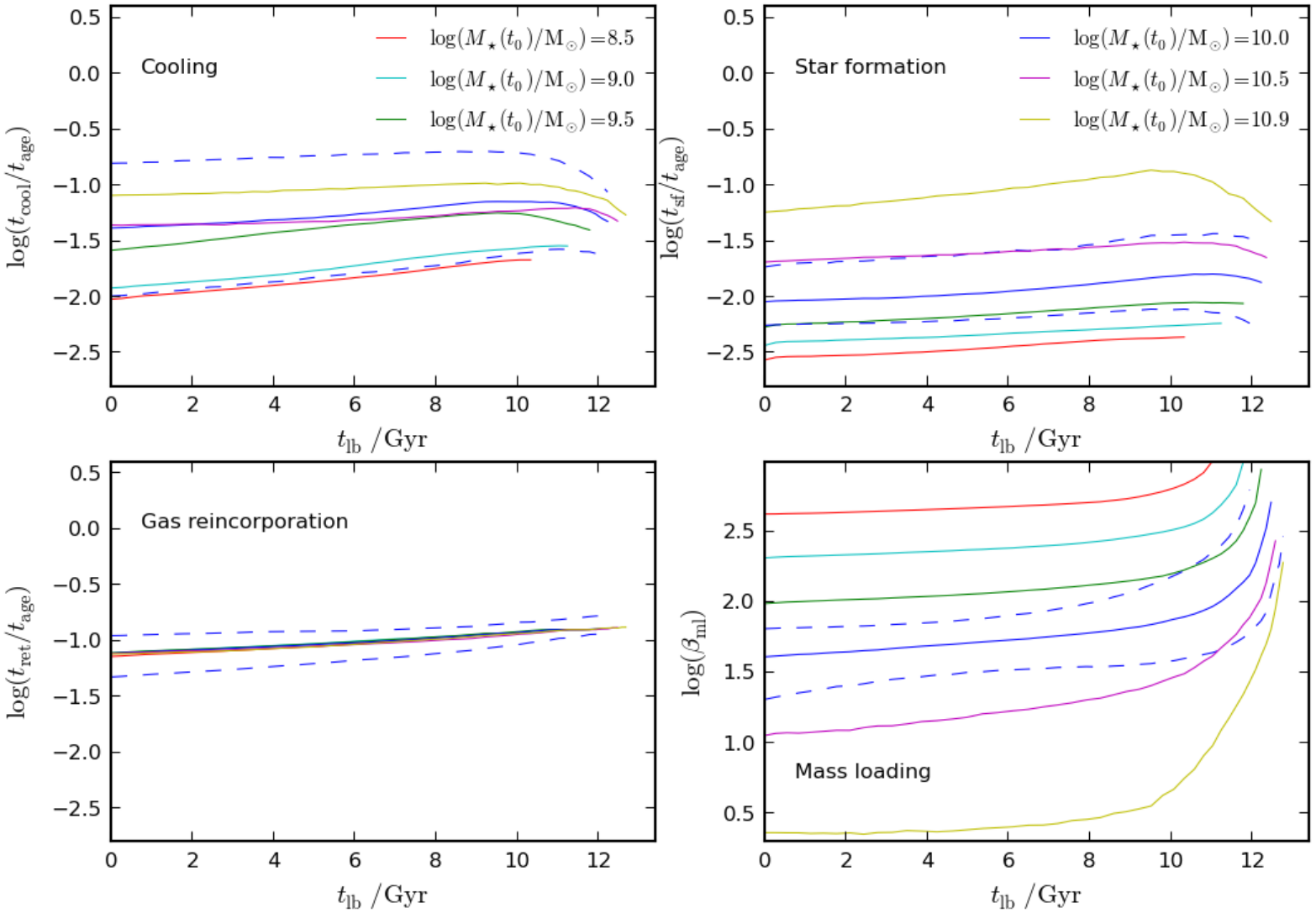
$$\langle \dot{M} \rangle_{\rm mean} = 46.1\ {\rm M}_\odot\ {\rm yr}^{-1} \left(\frac{M}{10^{12}\,{\rm M}_\odot} \right)^{1.1} \times (1+1.11z)\sqrt{\Omega_{\rm m}(1+z)^3+\Omega_\Lambda}$$

Fakhouri et al. (2010)

Connection to Halo Assembly



Why flat predicted SFHs?

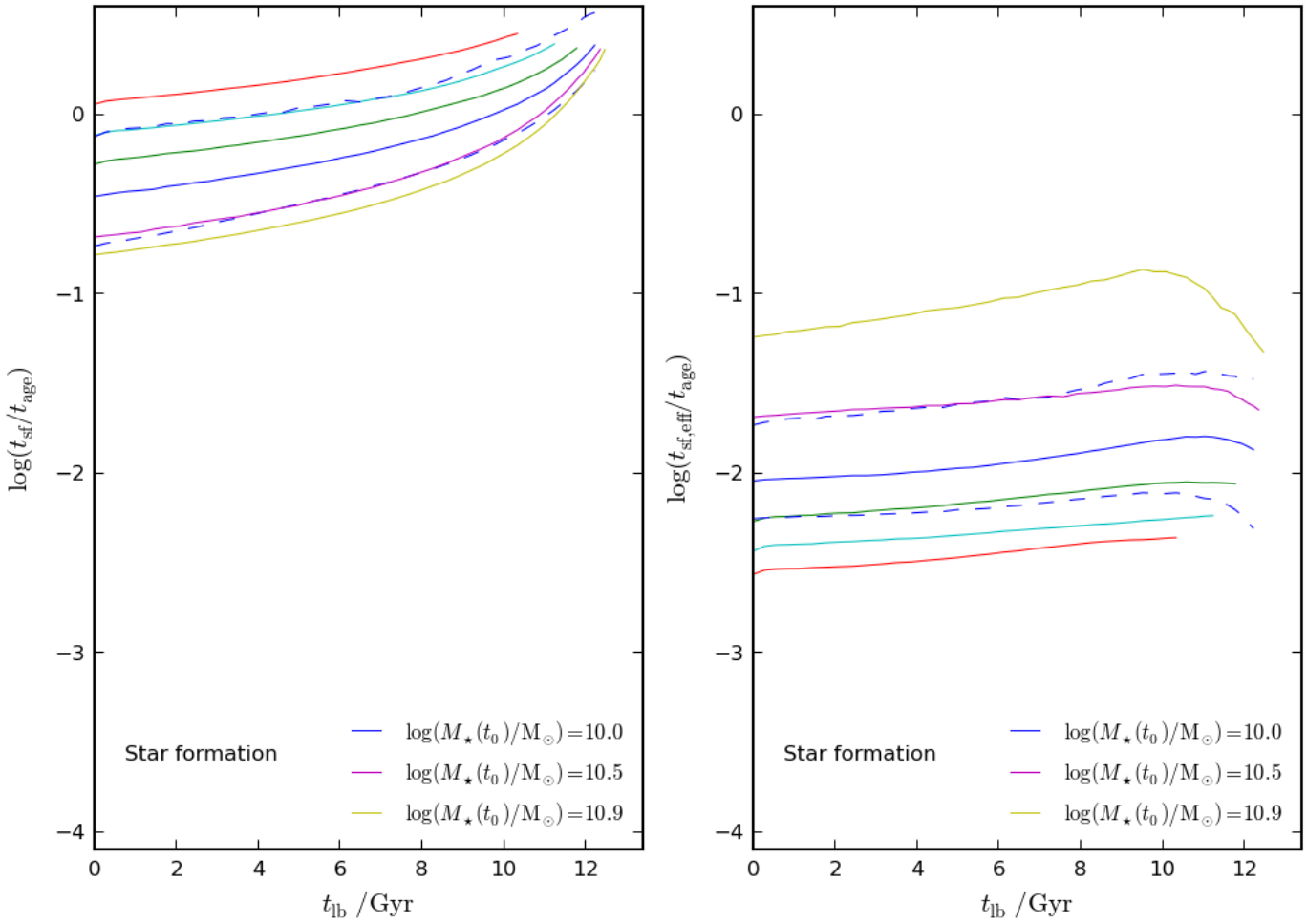


$$t_{ret} \propto t_{dyn} \propto \frac{M_{Halo}}{V_{Halo}^3}$$

$$\beta \propto V_{disk}^{-3.2}$$

Effective star formation timescale

$$\tau_* \equiv \frac{M_{gas}}{SFR} \qquad \tau_{*,eff} \equiv \frac{\tau_*}{(1 - R + \beta)}$$



Solution: Mass loading?

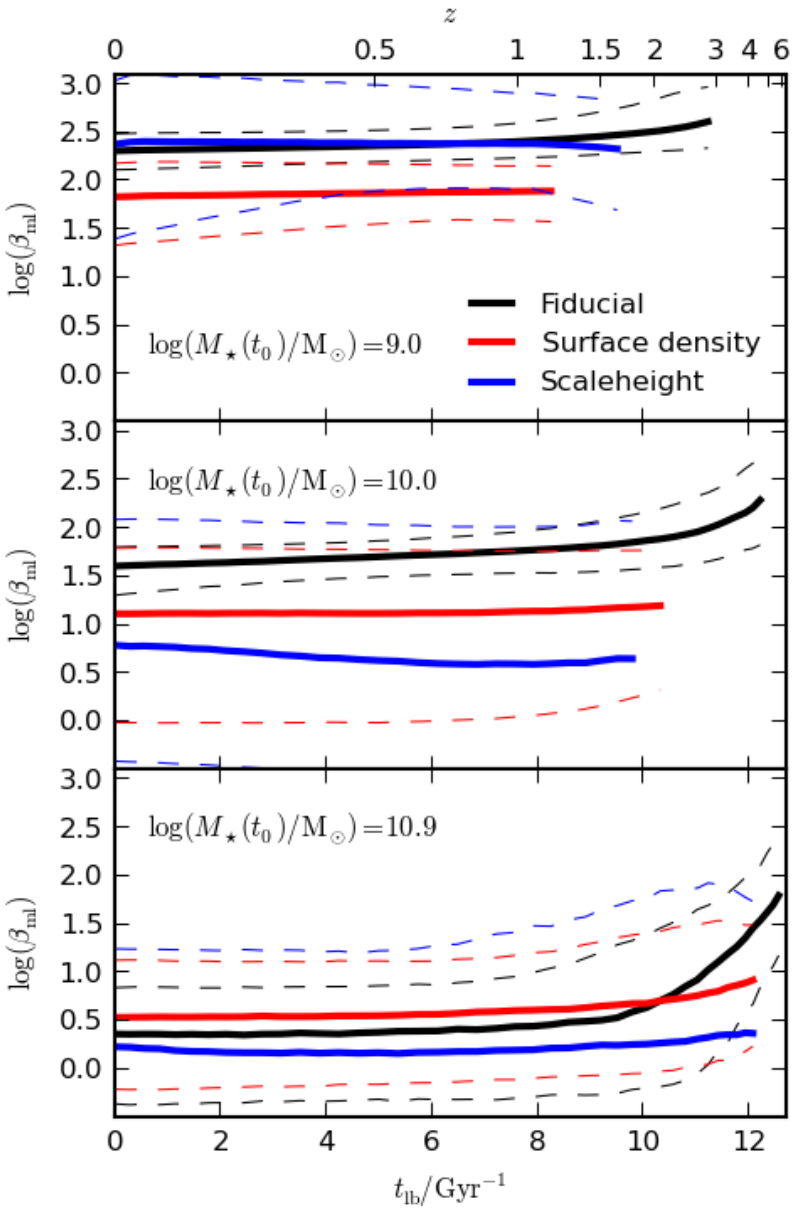
Traditional

$$\beta \propto V_{disk}^{-3.2} \quad \text{or} \quad \beta = f(V_{Halo})$$

Simplified modelling: Lagos et al. (2013)

$$\beta \propto \frac{f_{gas}^{0.8}}{\Sigma_{gas}^{0.6}}$$

- Mass loading is expected to scale (in an integrated sense) with galaxy disk sizes.
- Disk size evolution is not well reproduced by semi-analytic modelling



Solution: Gas reincorporation timescale?

- Traditional:

$$t_{ret} \propto t_{dyn} \propto \frac{M_{Halo}}{V_{Halo}^3}$$

- Henriques et al. (2013) suggestion to reconcile model with stellar mass function

$$t_{ret} \propto \frac{1}{M_{halo}}$$

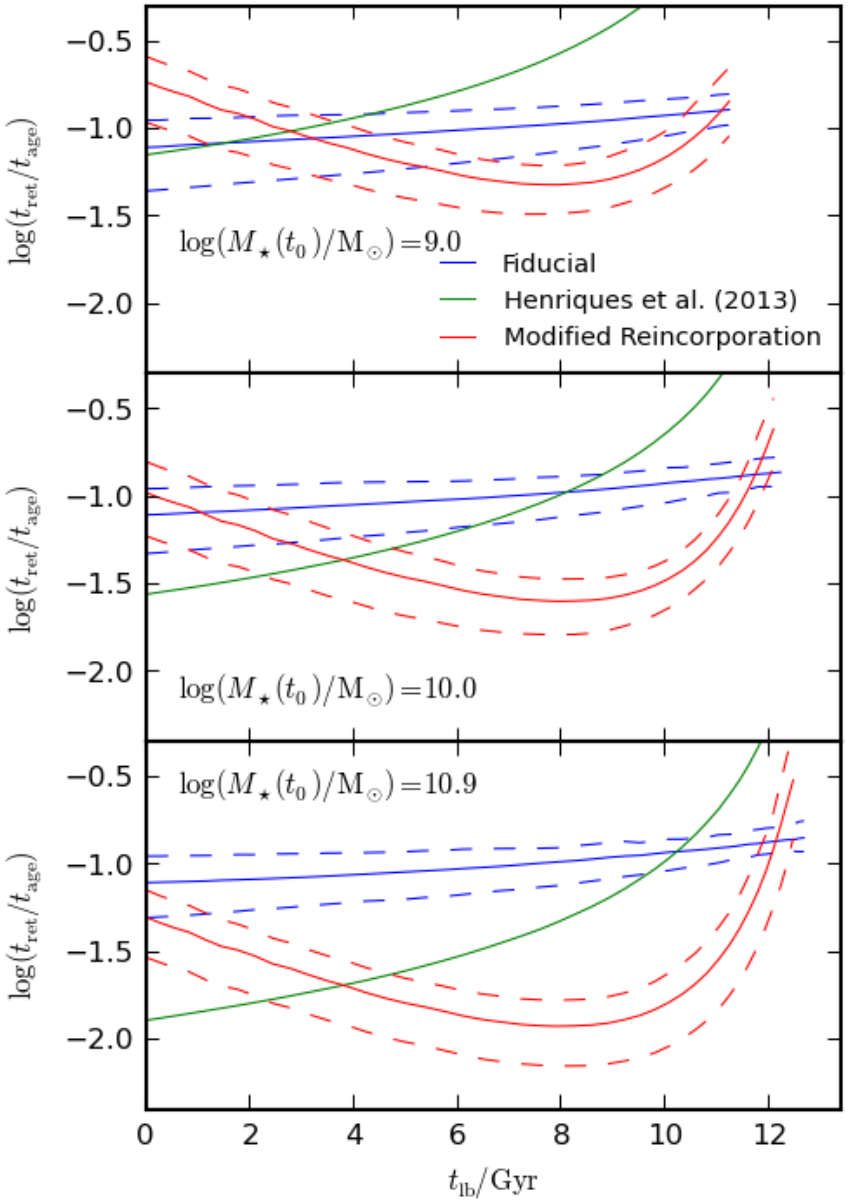
  - Their suggestion works well in Durham model for stellar mass functions but works poorly for sSFR evolution

- Mitchell et al. (2014) extremely ad hoc modification to force the model to agree with sSFR data

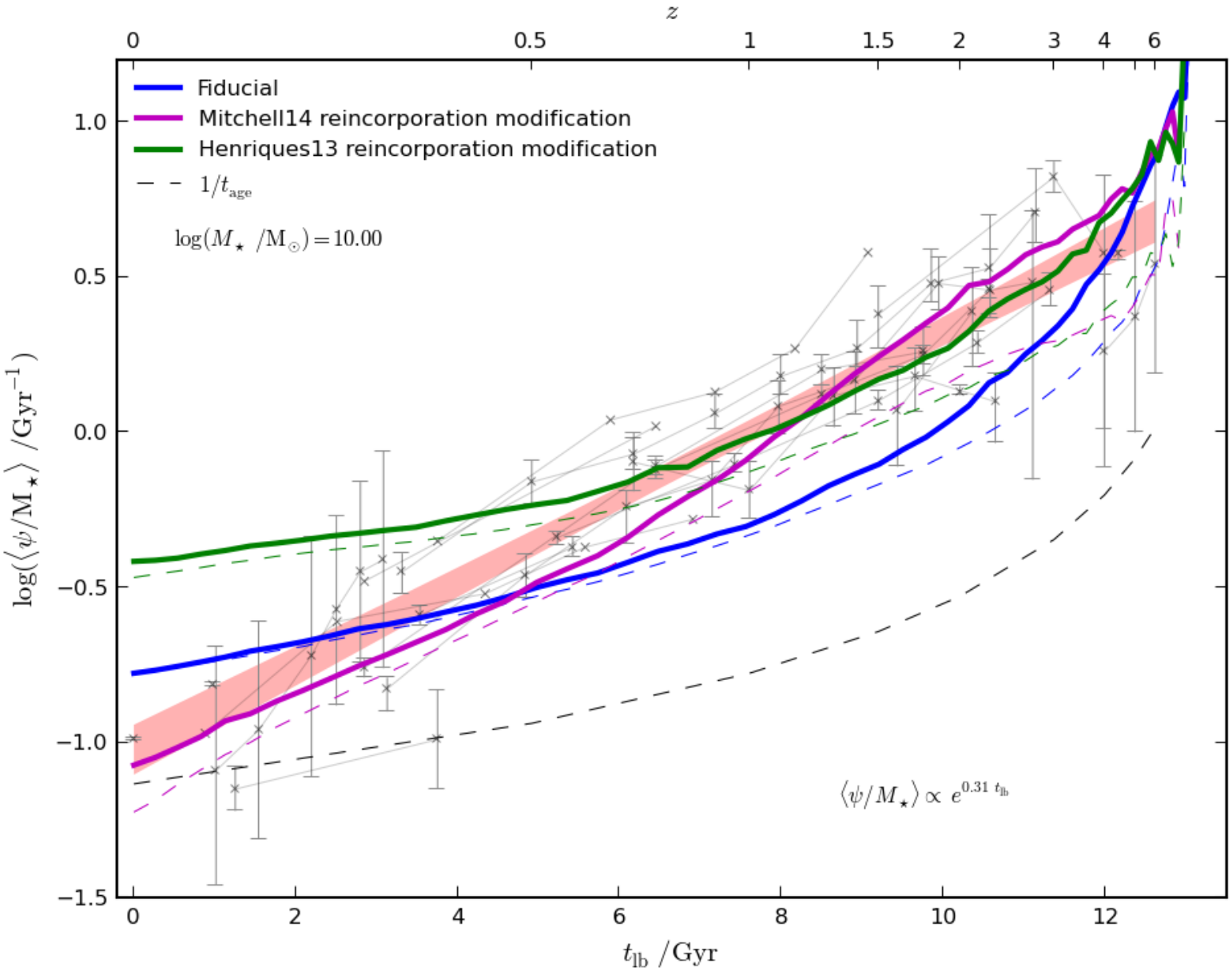
$$t_{ret} \propto \frac{t_{dyn}}{M_{halo}} f(z)$$

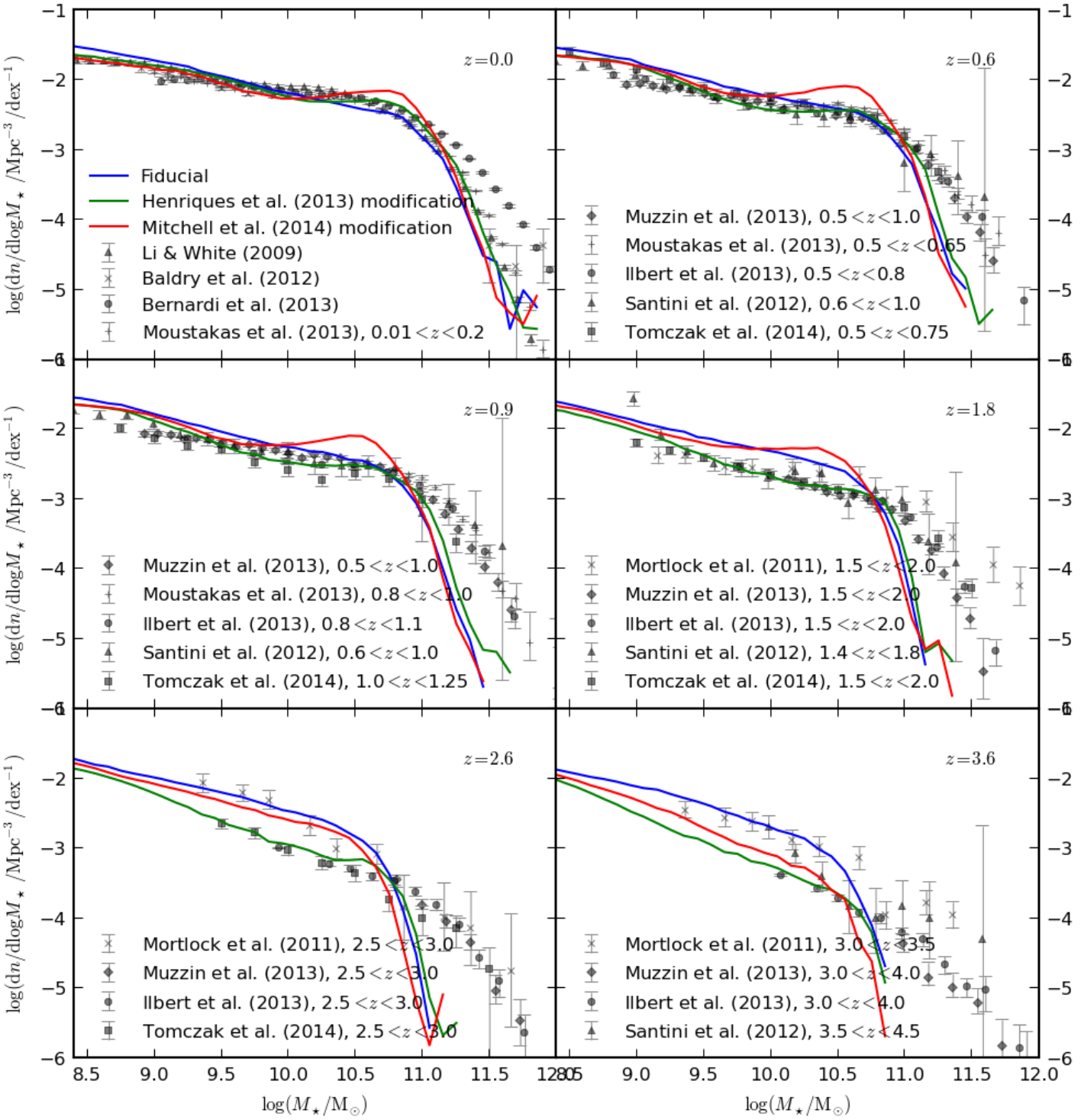
  - Works poorly for stellar mass function evolution

- Data inconsistency? Leja et al. (2014) arXiv: 1407.1842



sSFR evolution with modified models




$z=0.0$
Fiducial
Henriques et al. (2013) modification
Mitchell et al. (2014) modification
Li & White (2009)
Baldry et al. (2012)
Bernardi et al. (2013)
Moustakas et al. (2013), 0.01 < z < 0.2
$z=0.6$
Muzzin et al. (2013), 0.5 < z < 1.0
Moustakas et al. (2013), 0.5 < z < 0.65
Ilbert et al. (2013), 0.5 < z < 0.8
Santini et al. (2012), 0.6 < z < 1.0
Tomczak et al. (2014), 0.5 < z < 0.75
$z=0.9$
Muzzin et al. (2013), 0.5 < z < 1.0
Moustakas et al. (2013), 0.8 < z < 1.0
Ilbert et al. (2013), 0.8 < z < 1.1
Santini et al. (2012), 0.6 < z < 1.0
Tomczak et al. (2014), 1.0 < z < 1.25
$z=1.8$
Mortlock et al. (2011), 1.5 < z < 2.0
Muzzin et al. (2013), 1.5 < z < 2.0
Ilbert et al. (2013), 1.5 < z < 2.0
Santini et al. (2012), 1.4 < z < 1.8
Tomczak et al. (2014), 1.5 < z < 2.0
$z=2.6$
Mortlock et al. (2011), 2.5 < z < 3.0
Muzzin et al. (2013), 2.5 < z < 3.0
Ilbert et al. (2013), 2.5 < z < 3.0
Tomczak et al. (2014), 2.5 < z < 3.0
$z=3.6$
Mortlock et al. (2011), 3.0 < z < 3.5
Muzzin et al. (2013), 3.0 < z < 4.0
Ilbert et al. (2013), 3.0 < z < 4.0
Santini et al. (2012), 3.5 < z < 4.5
$\log(\mathrm{d}n/\mathrm{dlog}M_\star\ /\mathrm{Mpc}^{-3}\ /\mathrm{dex}^{-1})$
$\log(M_\star/\mathrm{M}_\odot)$
−1
−2
−3
−4
−5
−6
8.5
9.0
9.5
10.0
10.5
11.0
11.5
12.0

Is the star forming sequence evolution a constraint on feedback?

- Yes – but only if the basic picture of star formation and feedback is correct in semi-analytic models (questionable!)
  - Key constraint on evolution in relative fb efficiency for a common population of star forming galaxies tracked over cosmic time.
  - Star forming sequence normalisation does not (necessarily) change with change in global feedback efficiency. Galaxies move up/down main sequence with change of global efficiency.

$$sfr \propto \dot{M}_{\mathrm{inf}\,low} \frac{t}{\tau_{ret}(t)(1+\beta(t))}$$

Conclusions

- SAMs/cosmological hydrodynamic simulations have problems reproducing the observed evolution in the normalisation of the galaxy main sequence.

- Models naturally predict flat/rising SFHs for star forming galaxies that are closely related to underlying halo mass assembly.

- The current sSFR data implies that real SFHs are peaked for star forming galaxies.
  - The time of this peak is delayed with respect to the time of peak halo accretion.