Osservatorio Astronomico
di Trieste - INAF
SEMINAR

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Galaxy formation in SAMs and cosmological zoom simulations

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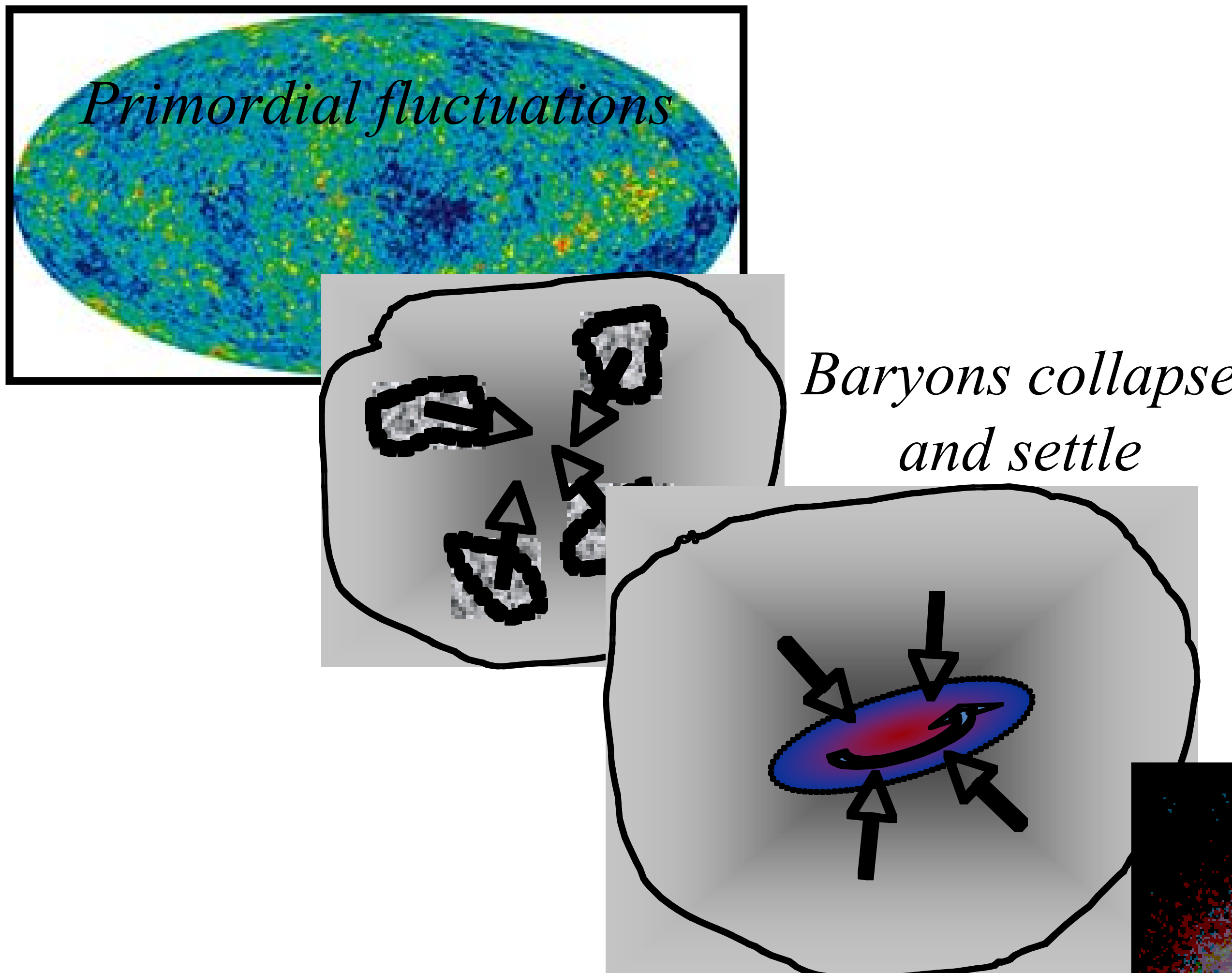
Current picture of galaxy formation



Dark matter structures start to form
Baryonic matter follows the evolution of DM halos

Galaxies assemble and take shape

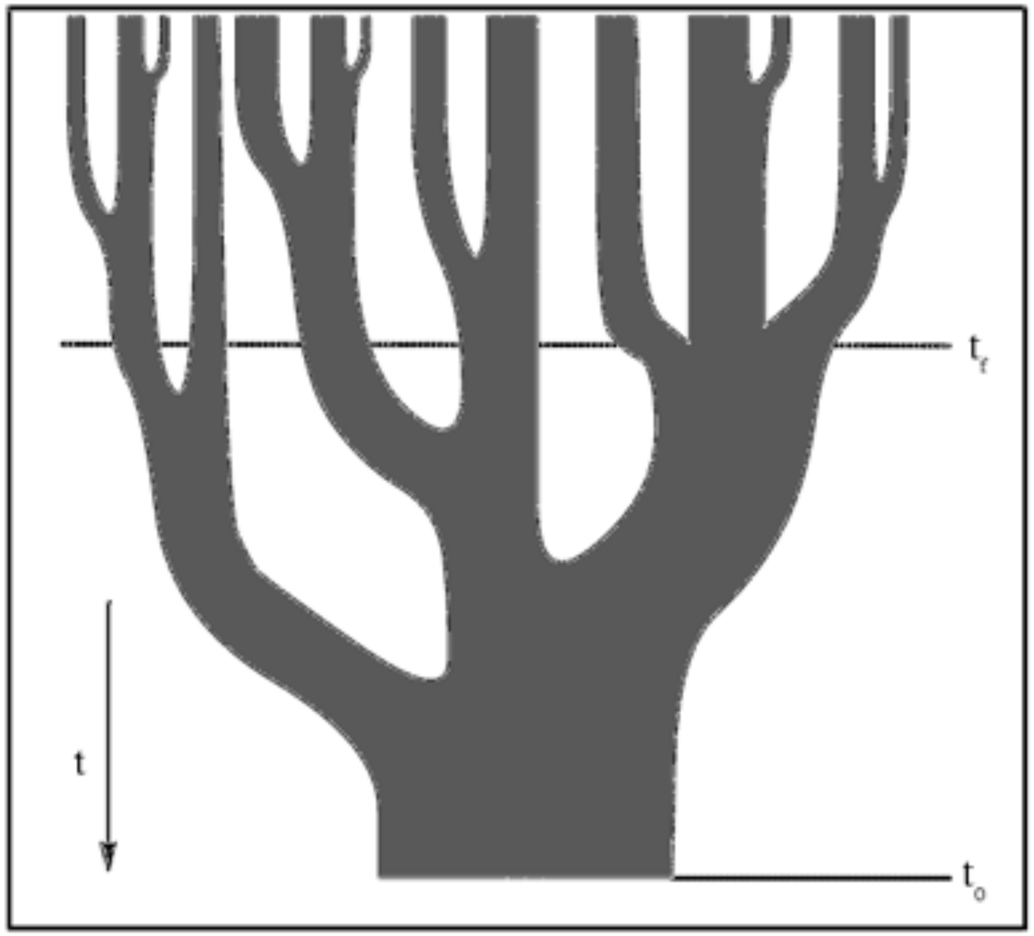
Gas is trapped in potential wells, is shock heated, cools and condenses at the center of the halos → galaxies form!!

Dynamical evolution of dark matter

Evolution of dark matter is only driven by gravitational forces

Dark matter halos assemble according to ***hierarchical clustering*** and they can be followed by ***merger trees***

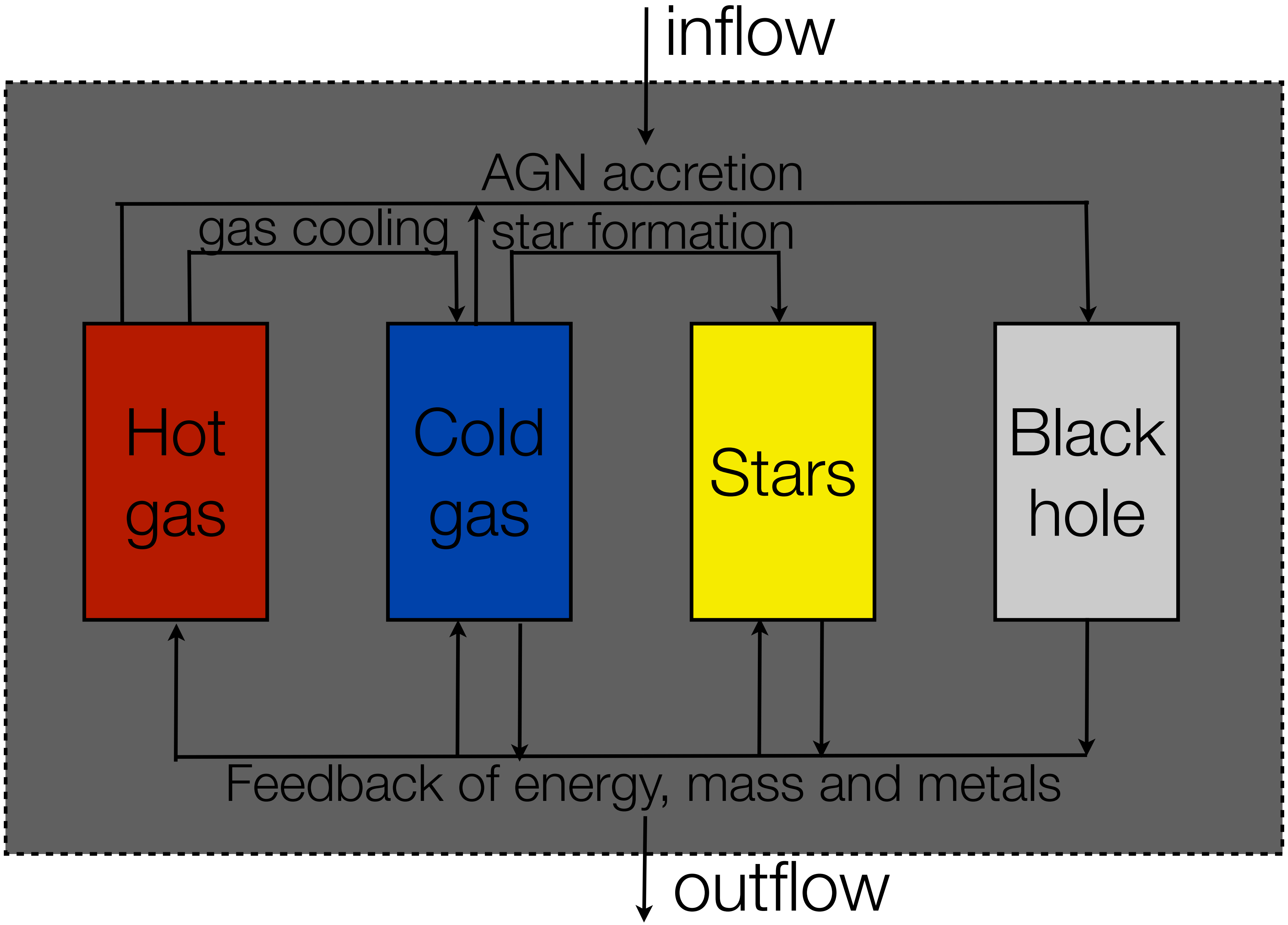
Analytic approaches
e.g. Monte-Carlo methods based on the extended Press-Schechter formalism (EPS, *Press & Schechter, 1974*)



Collisionless N-body simulations
Single dark matter halos have to be identified to construct merger trees (*Frenk et al., 1988*)

Modeling galaxy formation

Baryons follow the evolution of dark matter, but gas physical processes are more complicated



Aim of our study

Direct comparison of simulation and SAM

Understanding and overcoming respective model limitations

Previous studies:

- Large galaxy populations *(e.g. Helly et al. 2003, Cattaneo et al. 2007, Lu et al. 2010, Benson & Bower 2010)*
- Single objects: galaxy cluster *(Saro et al., 2010)*, disk galaxy *(Stringer et al., 2010)*

Modeling galaxy formation

How can we *model* galaxy formation??

Hydro-simulations ↔ **Semi-analytic models**

Hydro-simulations
Explicitly solving gas dynamical equations

Semi-analytic models
Approximation with physically motivated analytic laws

+ More correct treatment of underlying gas physics
+ Self-consistent galaxy formation from initial density fluctuations
- High computational costs
- Sub-resolution models for formation of stars and black holes

+ Main strength for statistical properties
+ Low computational costs
- Dynamics of the baryon component not directly followed
- Often too simplified models with a large free parameter space

Aim of our study

Direct comparison of simulation and SAM

Understanding and overcoming respective model limitations

OUR study:

48 individual, high-resolved resimulated halos GADGET2
(Oser et al., 2010)

↔

SAM based on same underlying dark matter evolution
(Somerville et al., 2008)

Focus on gas physics and stellar mass assembly

Methods

Cosmological zoom simulations

Modeling dark matter

(Oser et al., 2010)

1. Choose 48 halos from a 100 Mpc simulated box
2. Trace particles back in time within $2 \times r_{vir}$
3. Replace them with dark matter particles of higher resolution
   ($m_{DM} = 2.1 \times 10^7\ M_\odot$, $m_{gas} = 4.2 \times 10^6\ M_\odot$)

Modeling baryonic matter

Entropy conserving formulation of SPH *(Springel et al., 2005)*

- Radiative cooling for a primordial distribution of He & H *(Theuns et al., 1998)*
- Photo-ionizing background *(Haardt & Madau 1996)*

Multiphase hybrid model *(Springel & Hernquist, 2003)*

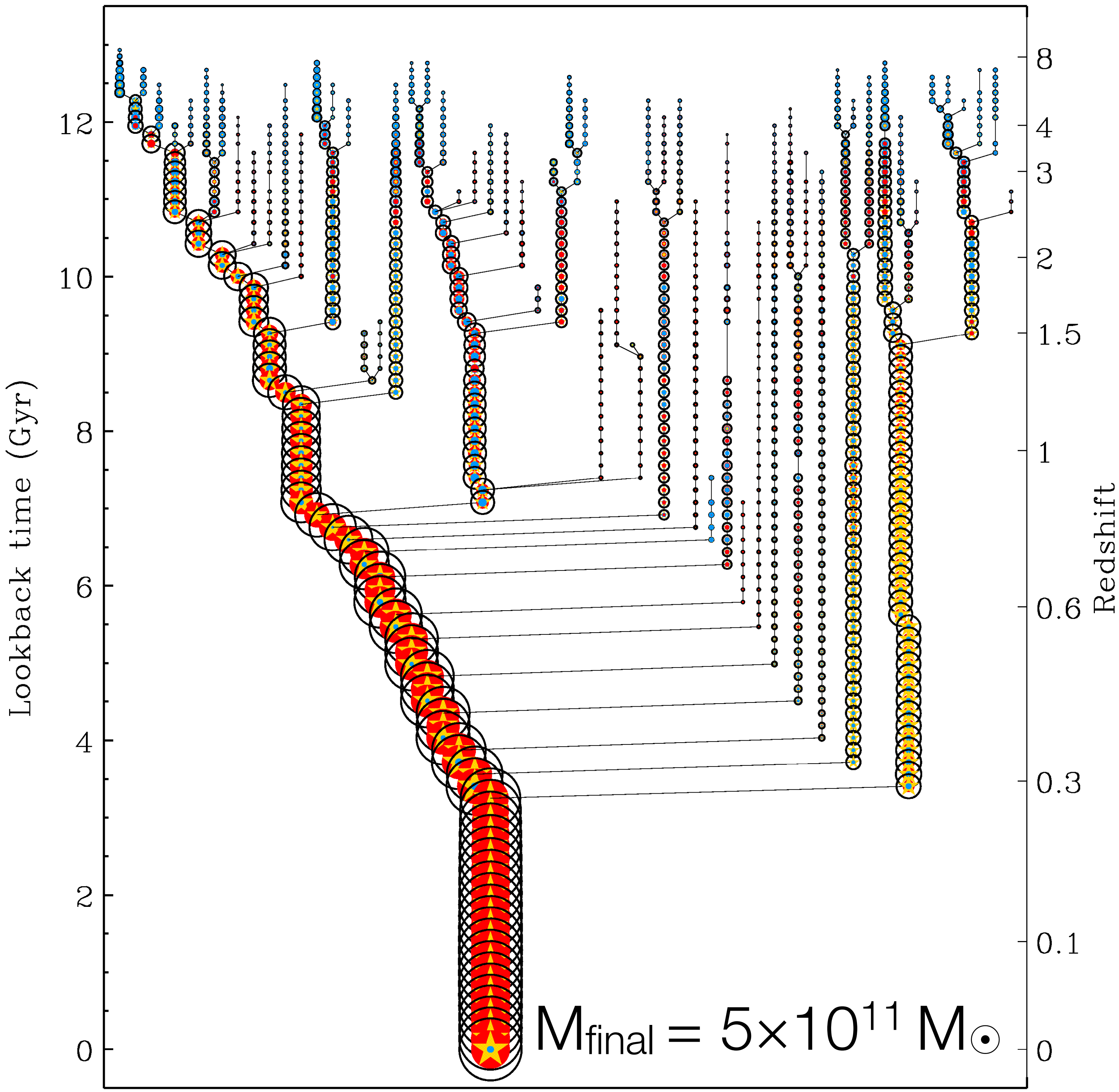
- Star formation out of cold gas clouds on a timescale $t_\star$

$$\frac{d\rho_*}{dt} = (1-\beta)\frac{\rho_c}{t_*} \quad \text{with} \quad t_* = t_*^0(\rho/\rho_{\rm th})^{-1/2}$$

- Thermal supernova feedback $\left.\frac{\mathrm{d}}{\mathrm{d}t}(\rho_{\rm h}u_{\rm h})\right|_{\rm SN} = \epsilon_{\rm SN}\frac{\mathrm{d}\rho_\star}{\mathrm{d}t}$:

Merger trees

- *Extract single halos* with halofinder FOF and Subfind
- *Connect halos* from timestep to timestep:
  1. Search for the most massive progenitors
  2. Connect the loose ends of the branches



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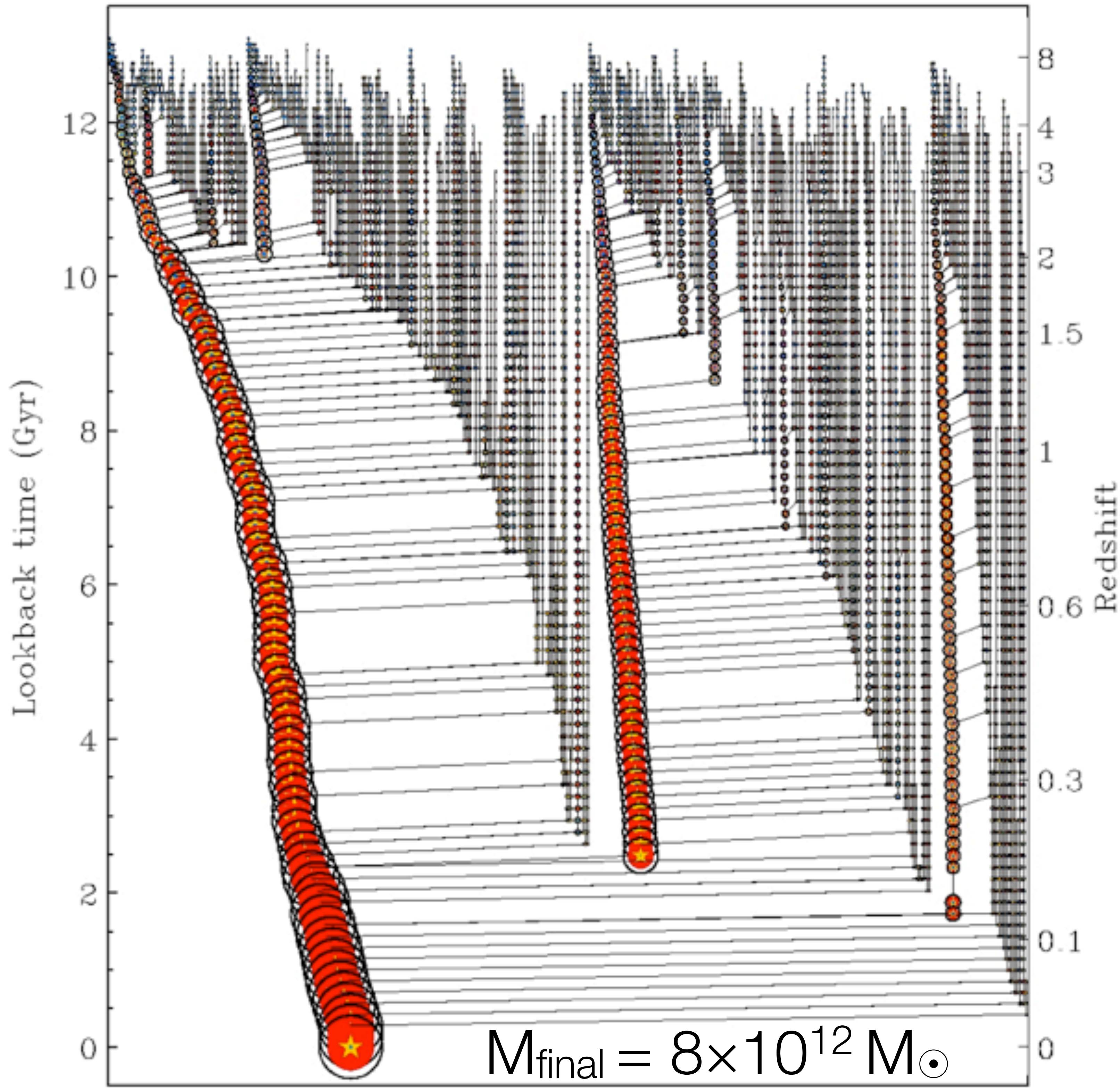


Semi-analytical model

Somerville et al., 2008

Radiative gas cooling

Photo-ionization: Suppression of gas collapsing into small mass halos

Quiescent star formation based on the empirical Schmidt-Kennicutt-law

Supernova feedback modeled as energy-driven winds

Merging history of the zoom simulations

Star formation during a burst (triggered by mergers)

Black hole growth: Radio and Quasar mode

Metal enrichment

Semi-analytical model

- *Gas cooling:*

  White & Frenk, 1991

$$\rho_g(r) = m_{\rm hot}/(4\pi r_{vir} r^2)$$

$$t_{\rm cool}(r) = \frac{3/2 \mu m_p k T}{\rho_g(r) \Lambda(T, Z_h)}$$

$r_{\rm cool}$ is defined as the point, where $t_{\rm cool} = t_{\rm dyn} = \frac{r_{\rm vir}}{v_{\rm vir}}$

$r_{\rm cool} < r_{\rm vir}$: 'hot mode' cooling: shock-heating

$$\frac{dm_{\rm cool}}{dt} = \frac{1}{2} m_{\rm hot} \frac{r_{\rm cool}}{r_{\rm vir}} \frac{1}{t_{\rm cool}}$$

$r_{\rm cool} > r_{\rm vir}$: 'cold mode' cooling, cooling rate limited by accretion rate

Semi-analytical model

- *Quiescent star formation:* Schmidt-Kennicutt-relation

$$\Sigma_{\rm SFR} = A_{\rm Kenn}\Sigma_{\rm gas}^{N_K}$$
$$A_{\rm Kenn} = 1.6 \times 10^{-4} M_\odot {\rm yr}^{-1}{\rm kpc}^{-2}$$
$$N_K = 1.4$$
$$\Sigma_{\rm thr} = 6\ M_\odot {\rm pc}^{-2}$$

- *Supernova feedback:* energy-driven winds

$$\dot{m}_{\rm rh} = \epsilon_0^{\rm SN} \left(\frac{V_{\rm disk}}{200\ {\rm km/s}}\right)^{-2} \dot{m}_*$$
$$f_{\rm eject}(V_{\rm vir}) = \left[1 + \left(\frac{V_{\rm vir}}{V_{\rm eject}}\right)^{\alpha_{\rm eject}}\right]^{-1}$$
$$\dot{m}_{\rm reinfall} = \chi_{\rm reinfall}\left(\frac{m_{\rm eject}}{t_{\rm dyn}}\right)$$

Semi-analytical model

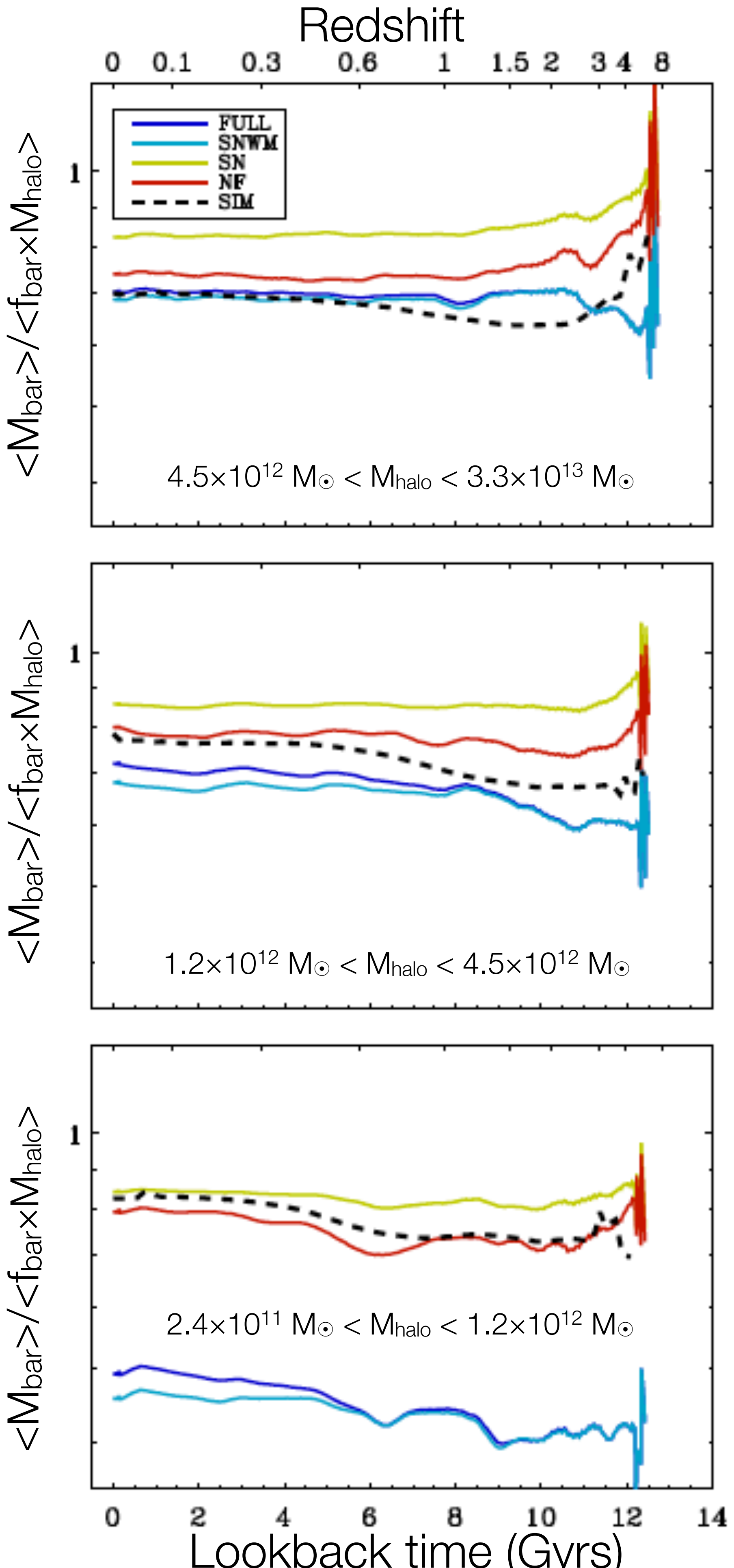
For a fair comparison we consider different SAM versions:

- **NF**: No feedback, no metals
- **SN**: Only thermal SN feedback (i.e. $f_{eject}=0$)

} Comparable to simulations

- **SNWM**: Thermal SN feedback & winds & metal cooling
- **FULL**: Full model, including AGN feedback

Results



Redshift evolution of the baryons

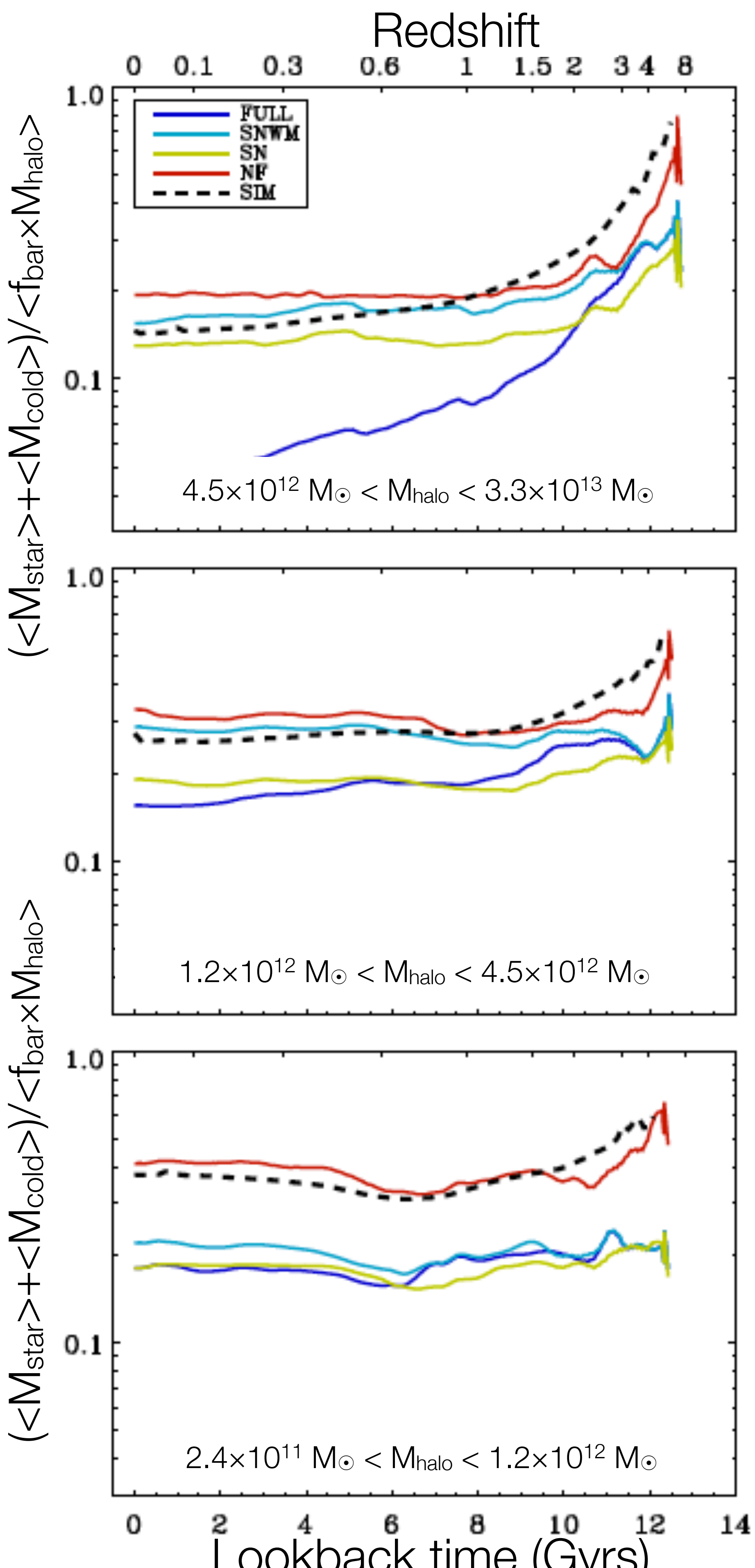
- In simulations and SAMs baryon fraction < 1:

  --stars and cold gas in the central galaxy (within 1/10 rvir)

  -- hot gas in the halo (within r_{vir})

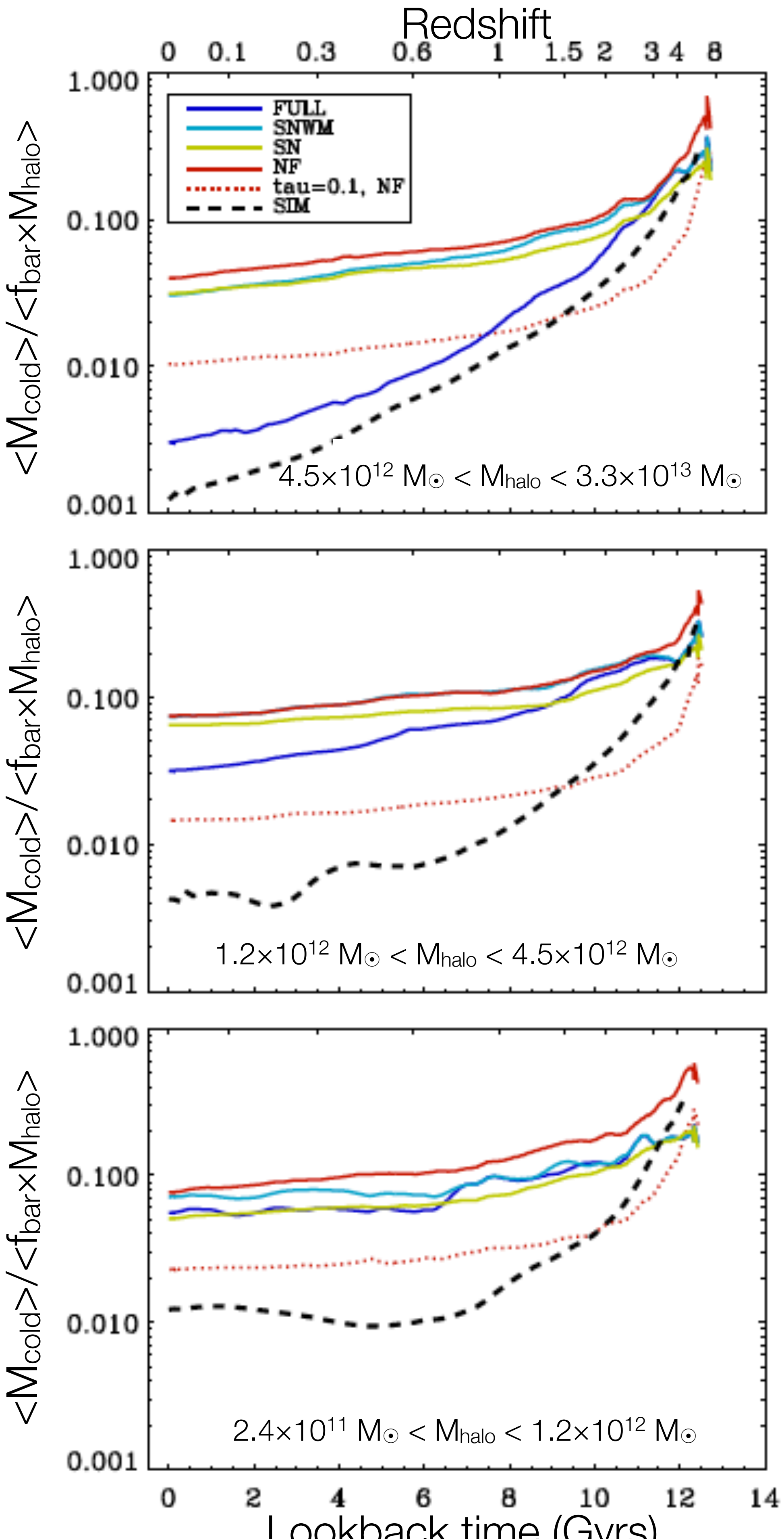
- High mass bin: agreement between simulations & FULL model

- Intermediate & low mass bin: agreement between simulations & NF model



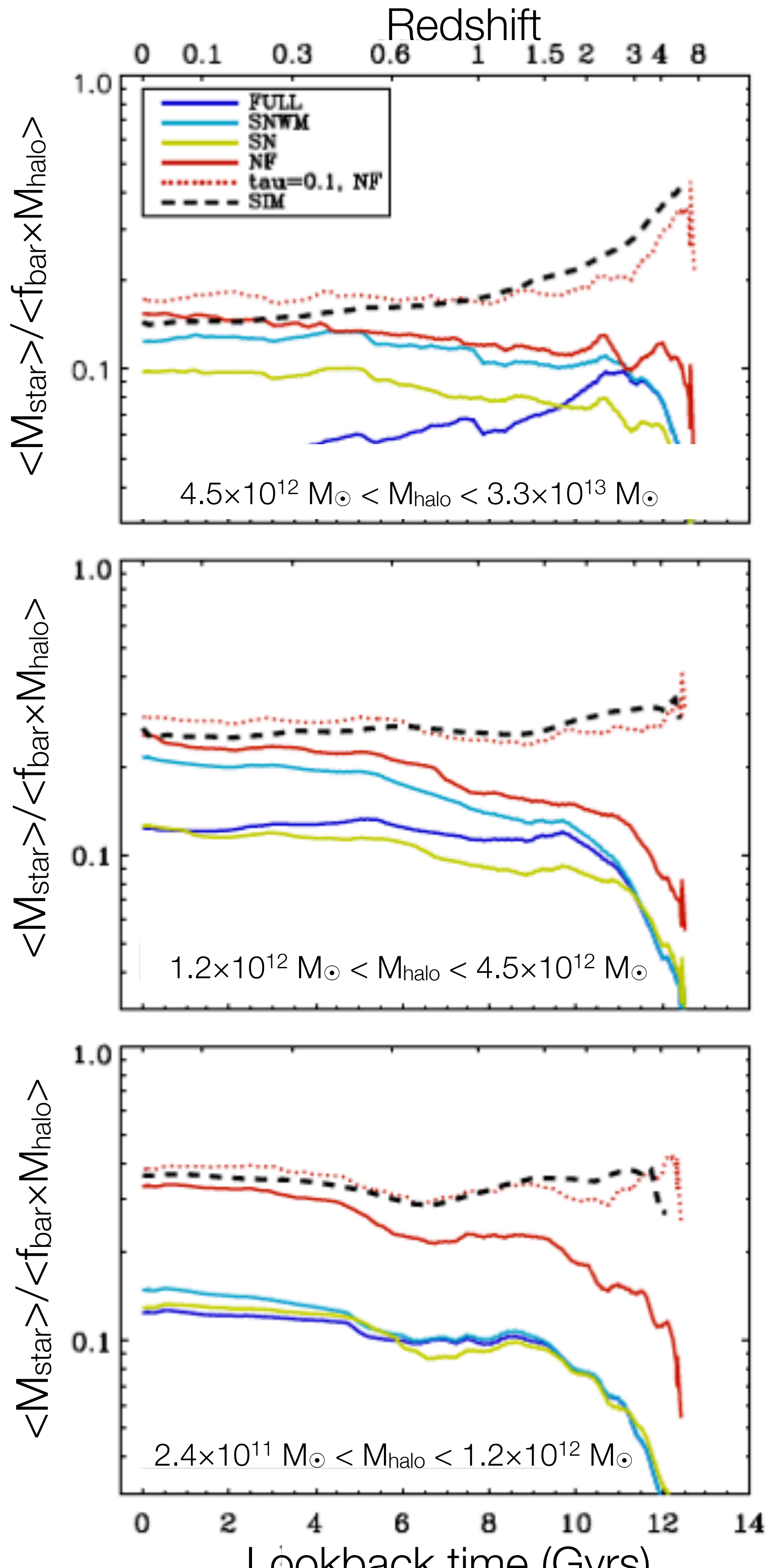
Redshift evolution of cold gas and stars

- Condensed baryons
- Decreasing fraction with decreasing time in simulations and SAMs
- For the whole redshift range: good match between simulations and NF model



Redshift evolution of cold gas

- For $z > 3$, relatively good agreement for SAMs and simulations
- *Rapid depletion* of cold gas in simulations due to more efficient conversion into stars

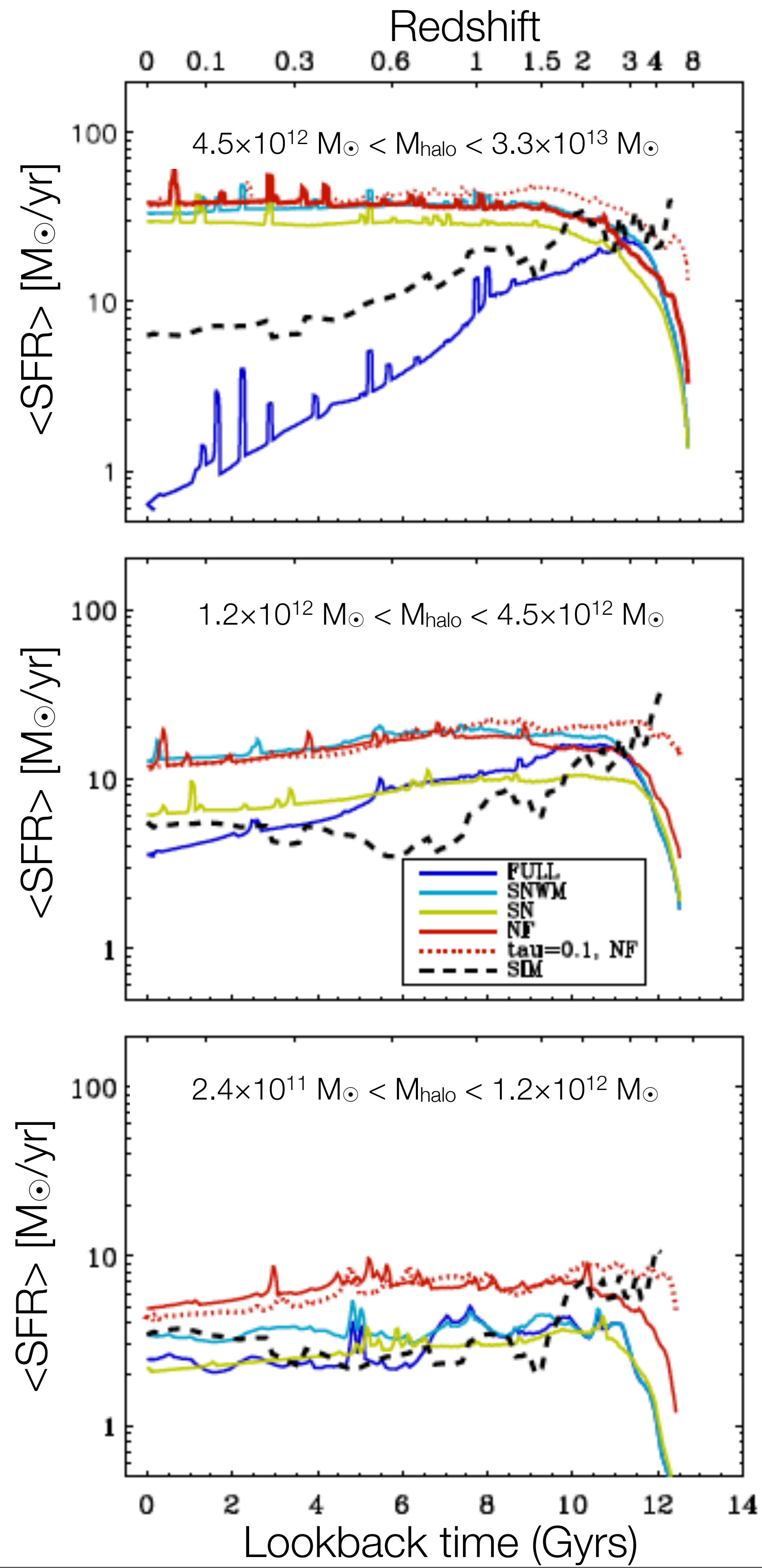


Redshift evolution of stars

- z < 0.6: good agreement between NF model & simulations
- *Efficient star formation* at z > 1 in simulations
- *Changing normalization* in SK-relation in SAMs

$$\Sigma_{\rm SFR} = A_{\rm Kenn}/\tau\ \Sigma_{\rm gas}^{N_K}$$

$$\tau = 0.1$$



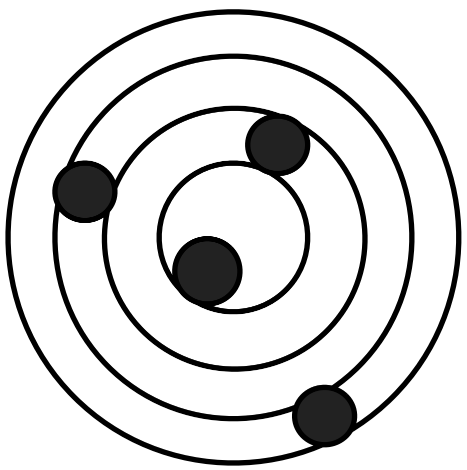
Redshift evolution of SFRs

- *Larger SFR* in simulations at z > 3 than in SAMs
- *Strong decrease* of SFR in simulations
- *Changing normalization* in SK-relation in SAMs matches simulations better at high z

Why efficient star formation in sims?

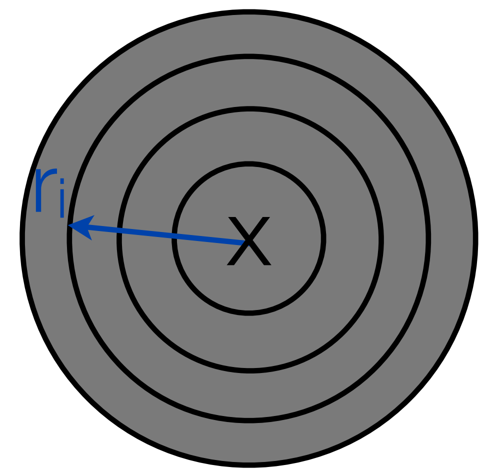
Simulations

clumpy cold gas structure



SAMs

smooth gas distribution



$i :=$ number of radial bin

$$M_i = M_{\rm cl}$$

$$r_i = 2 i r_{\rm cl}$$

$$r_{i+1}^2 - r_i^2 = 4 r_{\rm cl}^2 (2i+1)$$

Simulations:

$$\Sigma_{{\rm gas},i} = \frac{M_{\rm cl}}{\pi r_{\rm cl}^2}$$

$$\Sigma_{{\rm SFR},i} = A_{\rm KS} \times \left(\frac{M_{\rm cl}}{\pi r_{\rm cl}^2}\right)^{1.4}$$

$$SFR_i = A_{\rm KS} \times \left(\frac{M_{\rm cl}}{\pi r_{\rm cl}^2}\right)^{1.4} \times \pi r_{\rm cl}^2$$

SAMs:

$$\Sigma_{{\rm gas},i} = \left(\frac{M_{\rm i}}{\pi (r_{i+1}^2 - r_i^2)}\right)$$

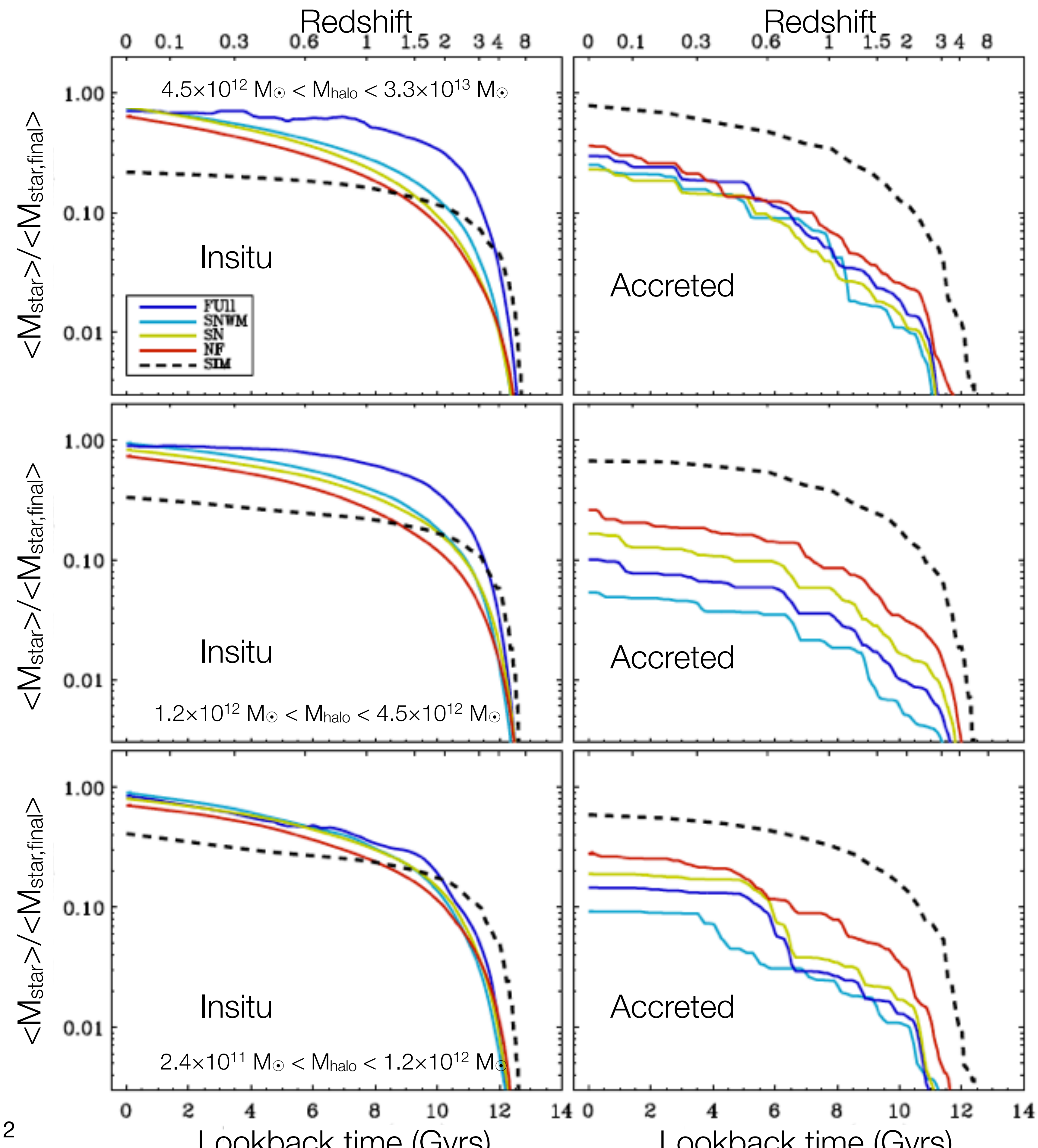
$$\Sigma_{{\rm SFR},i} = A_{\rm KS} \times \left(\frac{M_{\rm i}}{\pi (r_{i+1}^2 - r_i^2)}\right)^{1.4}$$

$$SFR_i = A_{\rm KS} \times \left(\frac{M_{\rm i}}{\pi (r_{i+1}^2 - r_i^2)}\right)^{1.4} \times \pi (r_{i+1}^2 - r_i^2)$$

$$= A_{\rm KS} \times \left(\frac{M_{\rm i}}{\pi r_{\rm cl}^2}\right)^{1.4} \times \pi r_{\rm cl}^2 \times \frac{4(2i+1)}{(4(2i+1))^{1.4}}$$

< 1

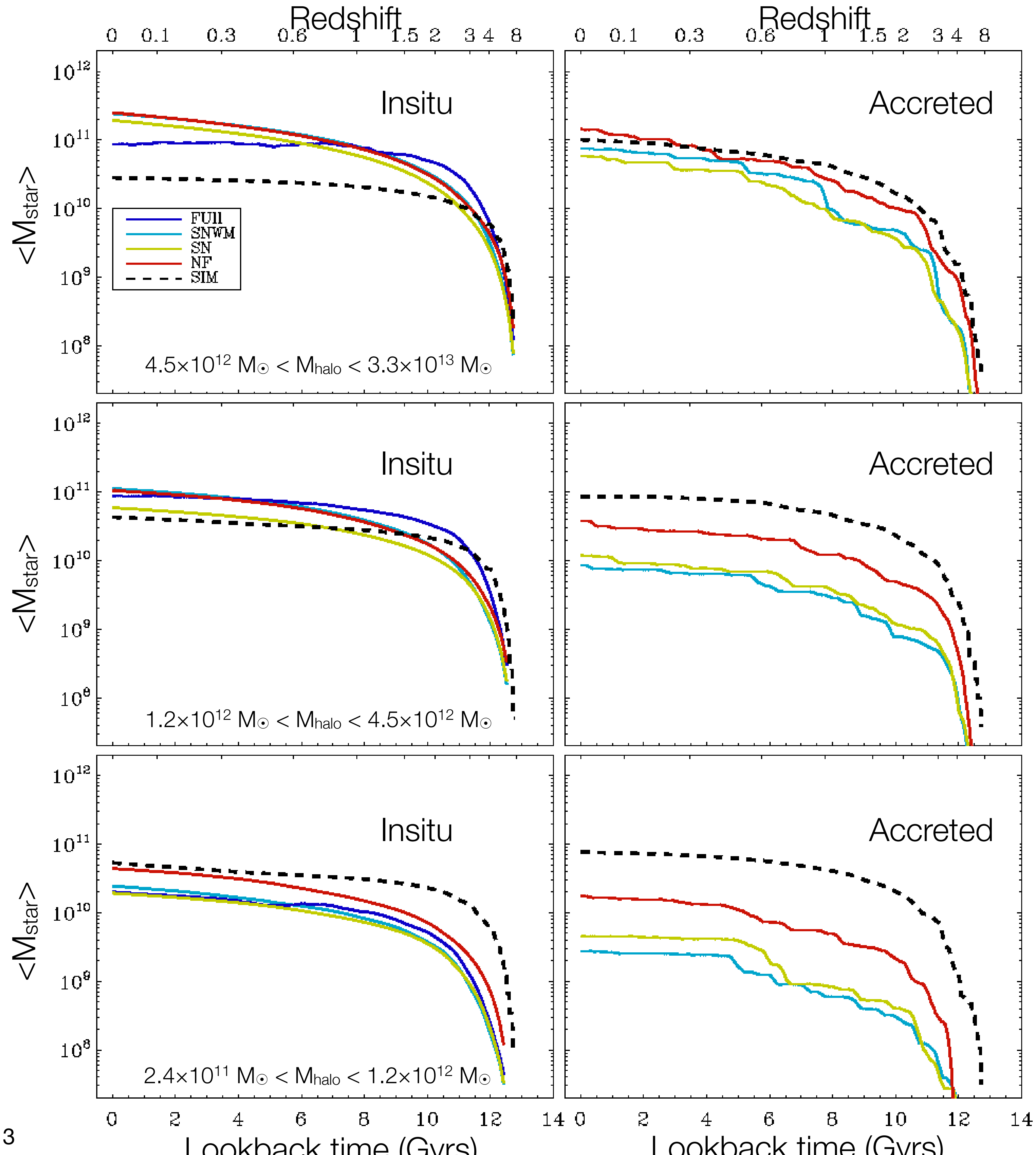
$\rightarrow$ $SFR_{\rm tot,clumpy} > SFR_{\rm tot,smooth}$



In-situ versus accreted star formation

Normalized to final star mass

- Simulations: at $z > 3$ insitu formed star fraction is dominating, at $z < 2$ accretion of stars becomes dominant
- SAMs: For *all* redshift, insitu star formation is dominating



In-situ versus accreted star formation

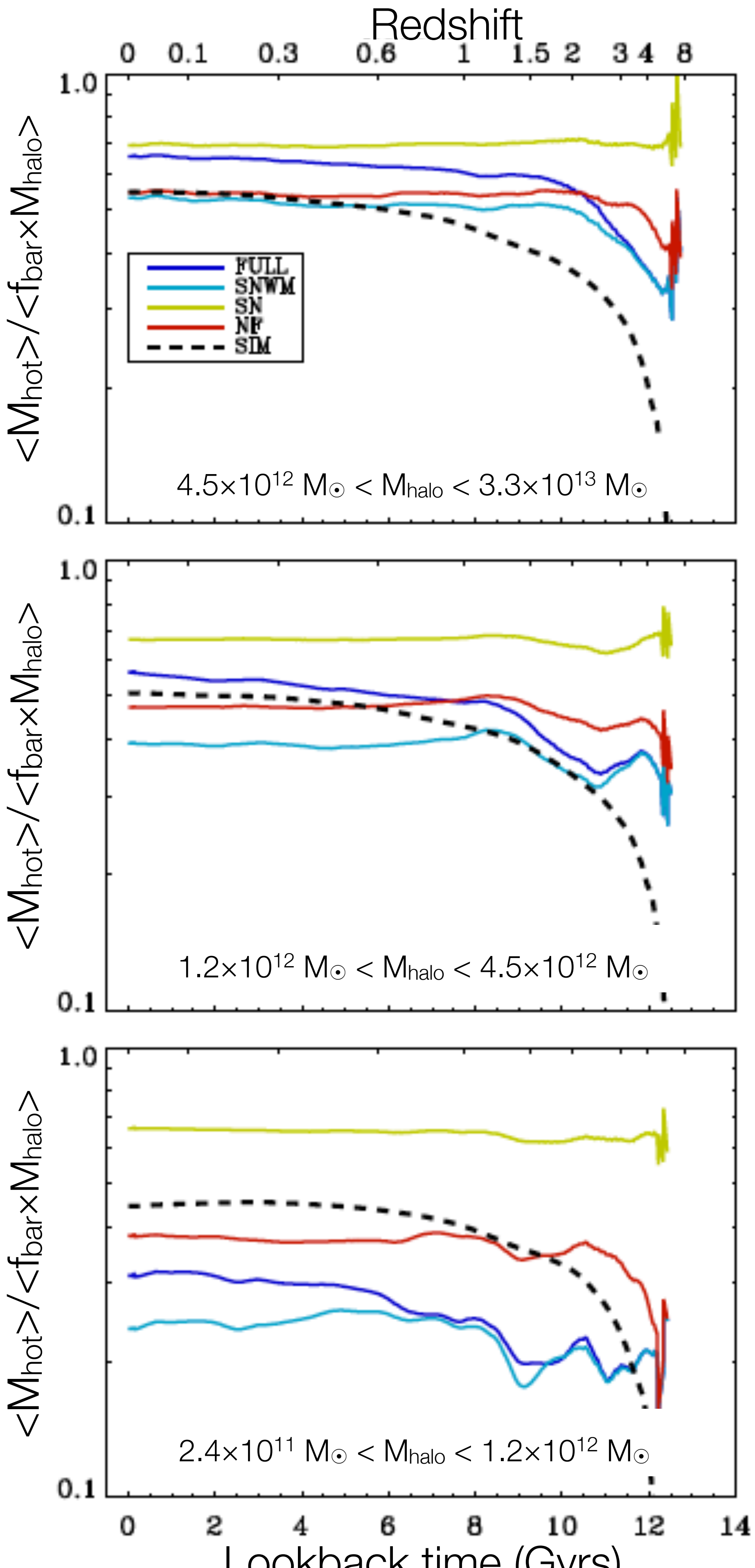
Absolute star masses

- SAMs: too much insitu star formation in high mass objects

⇒*Gravitational heating?*

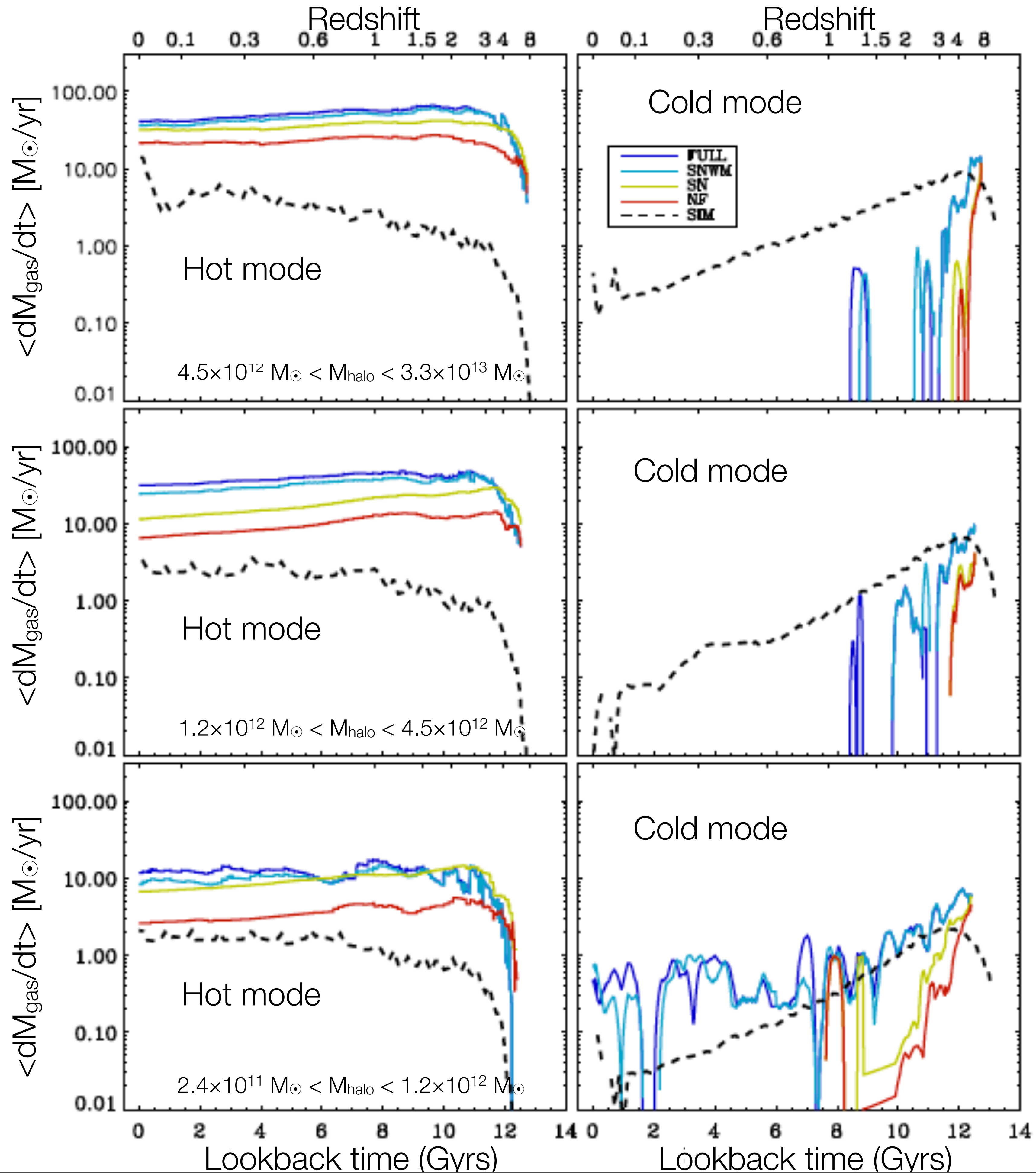
- SAMs: too less star formation in accreted systems onto low-mass galaxies

⇒*Delayed strangulation?*



Redshift evolution of hot gas

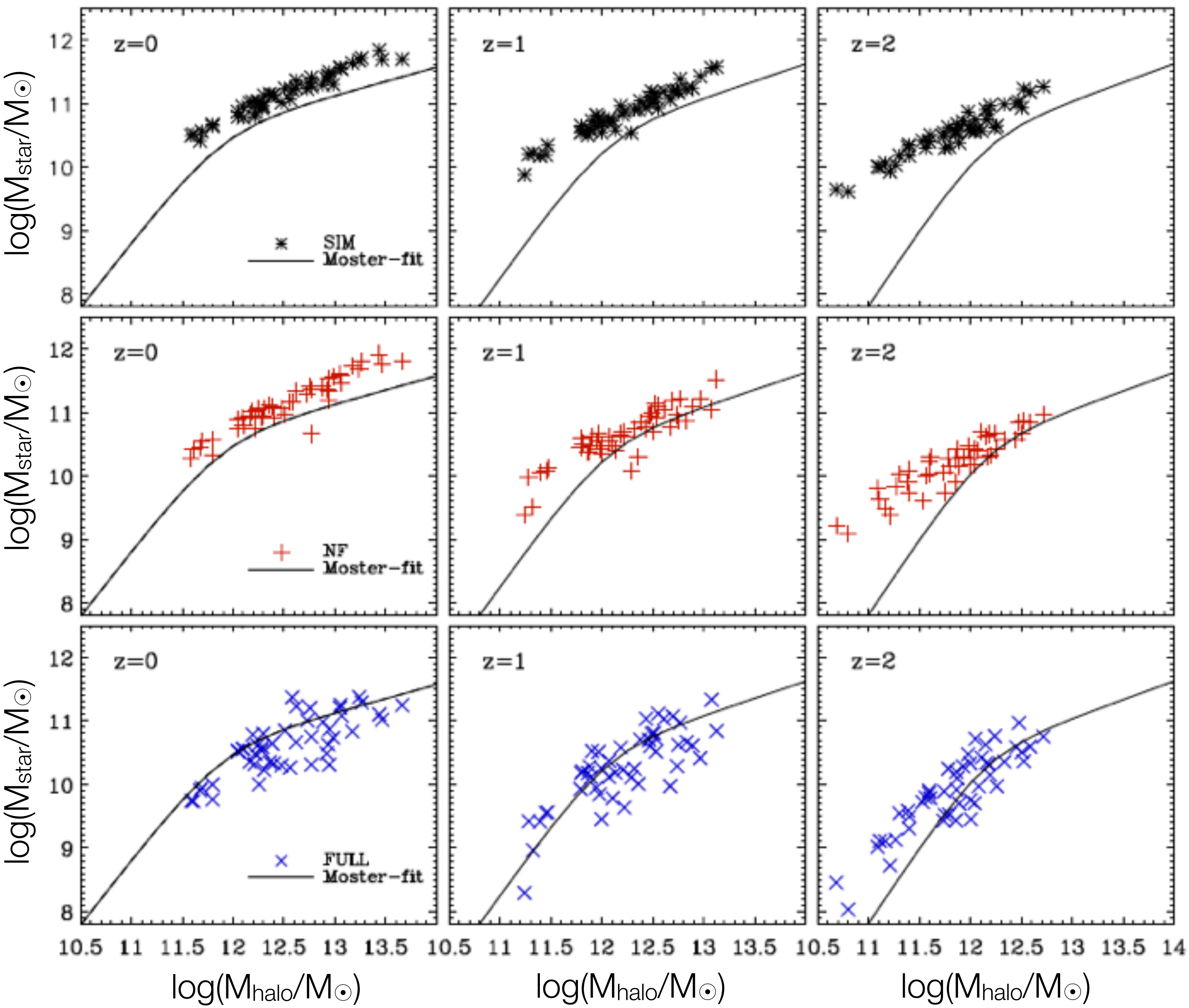
- Good agreement for $z < 1.5$ between simulations and NF model
- $z > 2$ & high mass halos: too large hot gas content in SAMs, in particular without metal cooling
- *Too inefficient cold flows* at high z in SAMs??



Hot & cold mode accre-tion

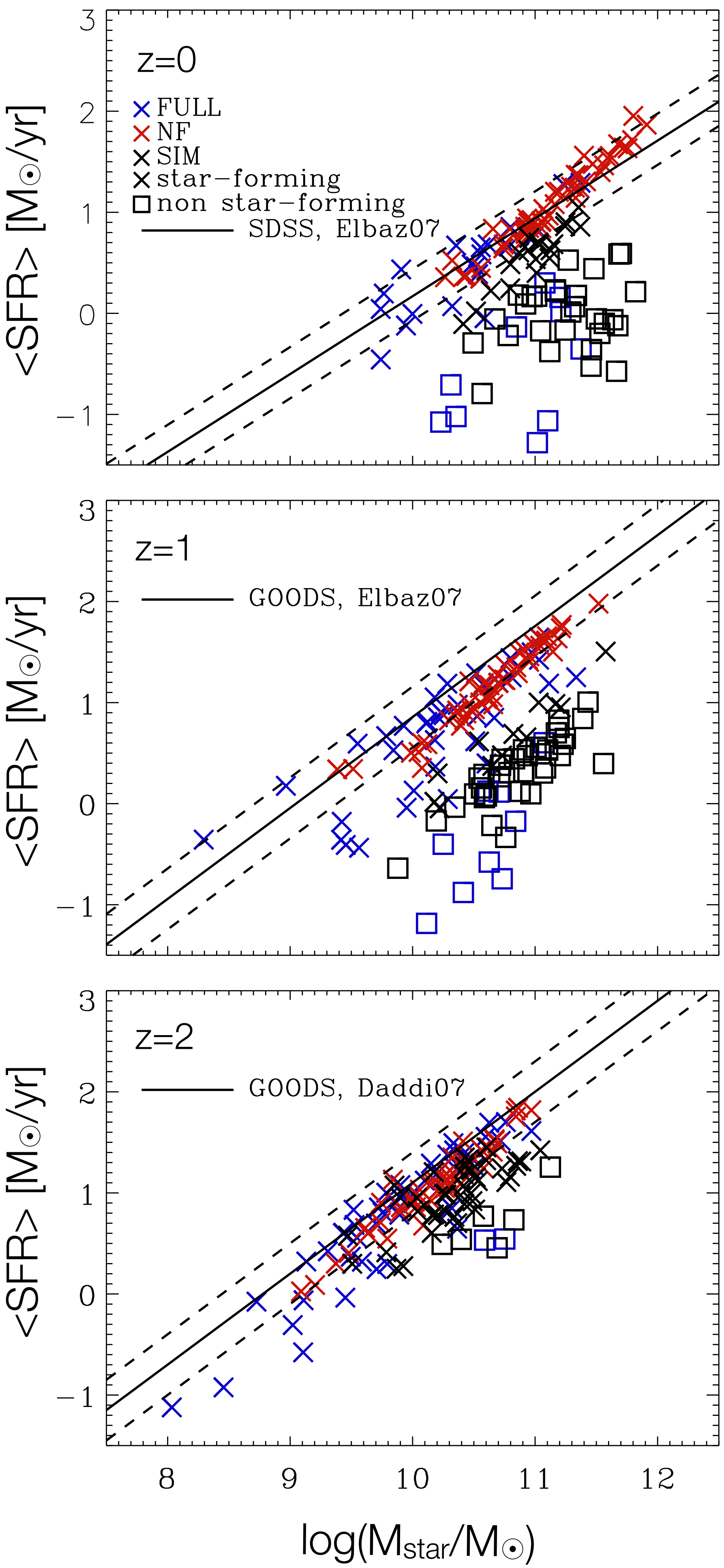
- Simulations: for z > 1 cold accretion is dominating
- SAMs: Too less cold accretion, in particular for models w/o metals
- *Too simplified recipe in SAMs*: No simultaneous cold and hot mode accretion

⇒*Gravitational heating?*



M⋆-Mhalo-relation

- SAMs: stronger SN fb at z>2?
- Simulations: AGN feedback for high-mass end
- Simulations: stronger SN feedback for low-mass end



SFR-M⋆-relation

- Star-forming galaxies: ✕

$$\frac{SFR}{M_{\rm star}} > 0.3 \times t^{-1}_{\rm Hubble}$$

- Non-star-forming galaxies: □

$$\frac{SFR}{M_{\rm star}} < 0.3 \times t^{-1}_{\rm Hubble}$$

Franx et al., 2008

- Simulations: too small SFRs
- *Only* SF galaxies in NF model
- *Best agreement* between FULL model & observations

Summary: Limitations of both approaches

Simulations ⟷ ***SAMs***

Best agreement for NF model

- Very *efficient star formation*,
  → clumpy cold gas structure
- *Less efficient star formation*
  → smooth gas distribution
- *Accretion of stars* is dominating at $z < 2$
- *In-situ star formation* is dominating at all z
- *Efficient cold flows* at high z
- *Inefficient cold flows* at all z
- *Too weak SN feedback* at all z
- *Too weak SN feedback* at high z
- *Missing AGN feedback*

Next steps???

Next steps...

High-resolved simulations including enhanced physics ⟷ Improving recipes in Semi-analytic models

- Perform re-simulations with a code including *SN-winds* and *metal cooling*, compare the effect to SAMs
- Study the effect of different types of *AGN feedback* in simulations, compare to SAMs

- *Cooling recipe:* Fitting the ratio of hot & cold mode accretion and implement it in SAM
- *Gravitational heating*
- Improve satellite physics: *Delayed strangulation* and dependence on the halo potential well

Effect of SN feedback & metals

Direct comparison of

Zoom simulations

- metal cooling
- SN driven winds
- stellar mass loss from SNII/Ia and AGB stars

e.g. Oppenheimer & Dave, 2008

↔

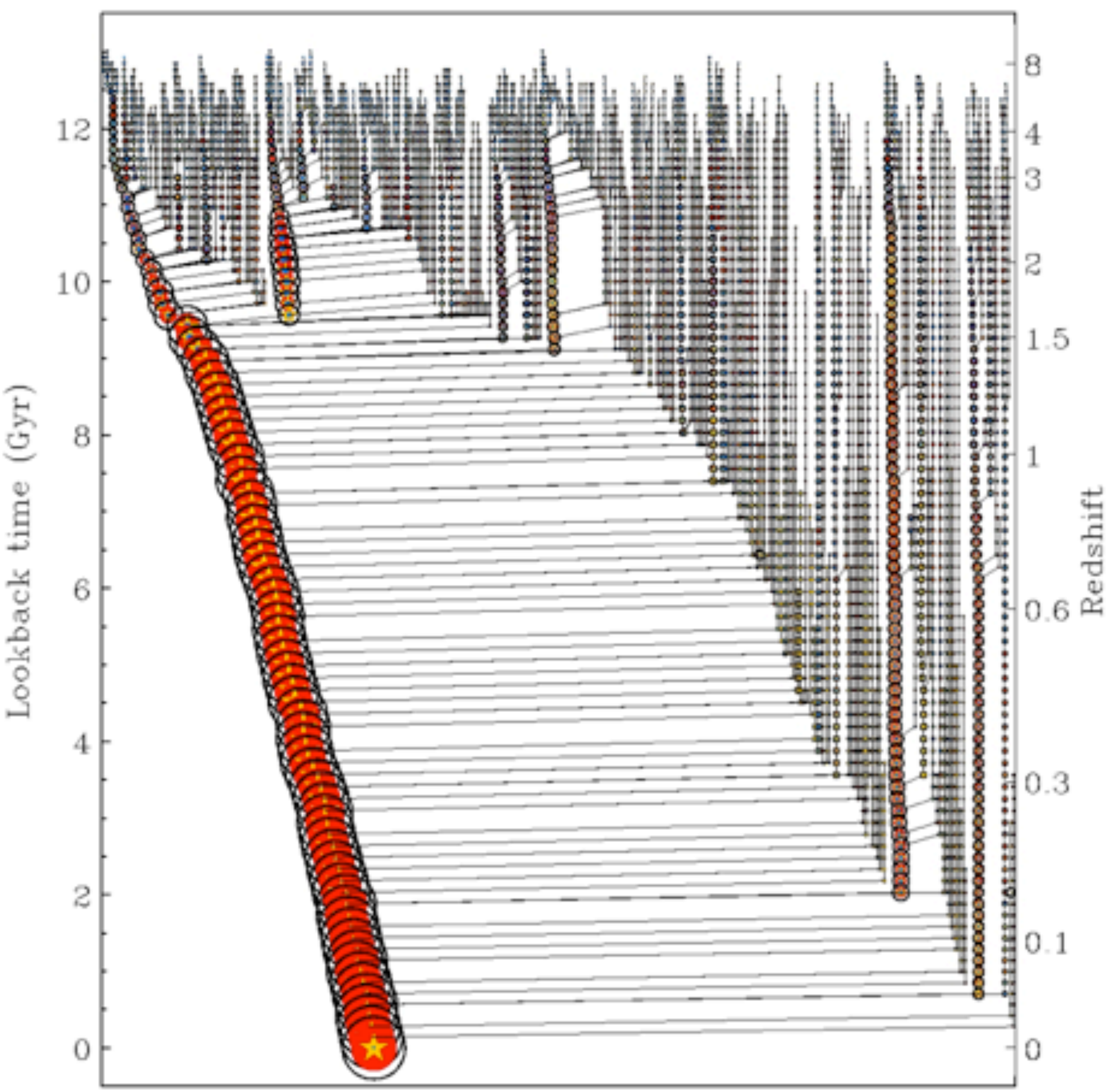
Semi-analytic models

based on the same merger history different stripped-down versions

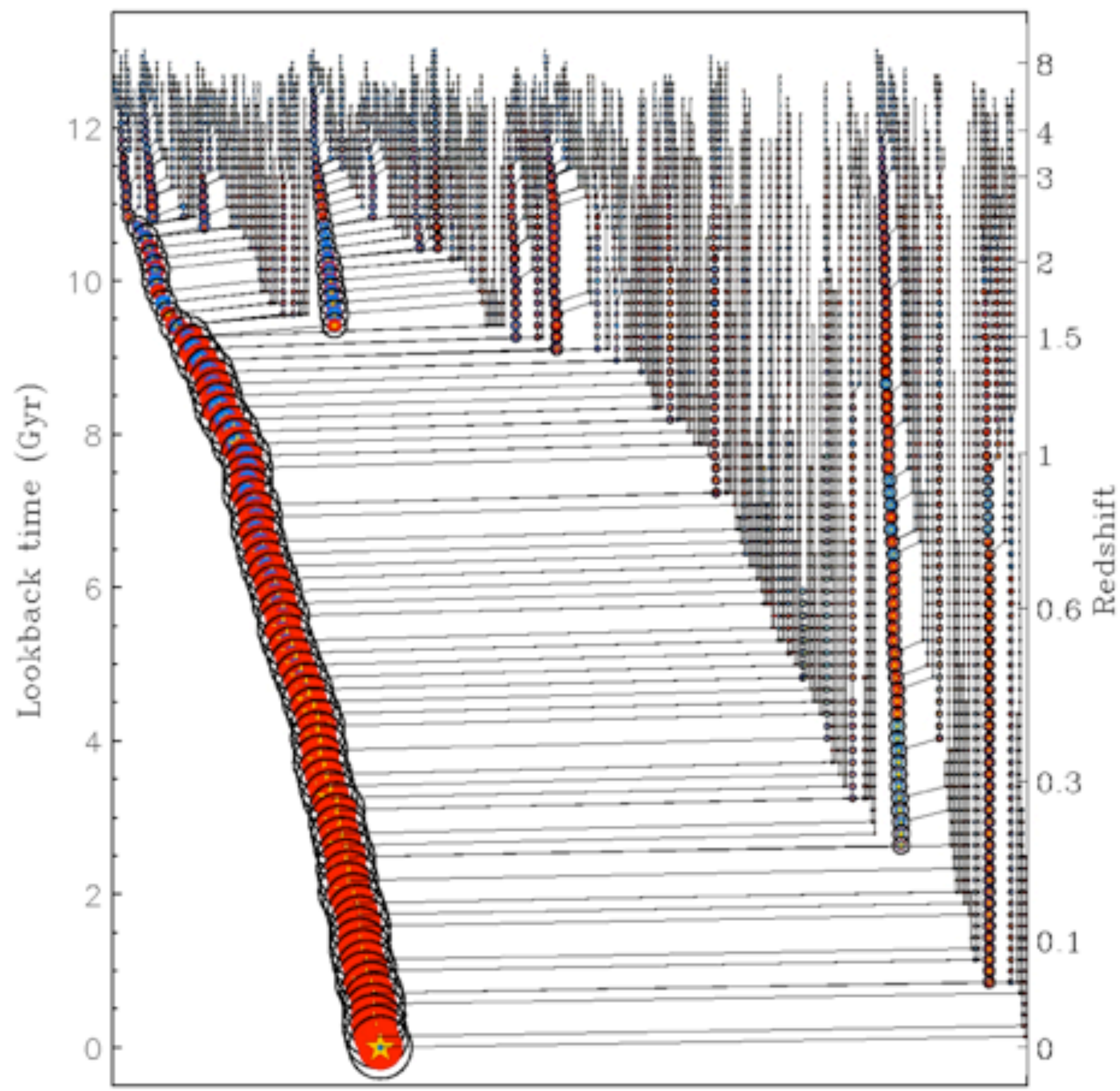
Assess the limitations of both methods concerning *metal cooling & SN-winds*

Preliminary results: winds & metals

Old



Winds & metals

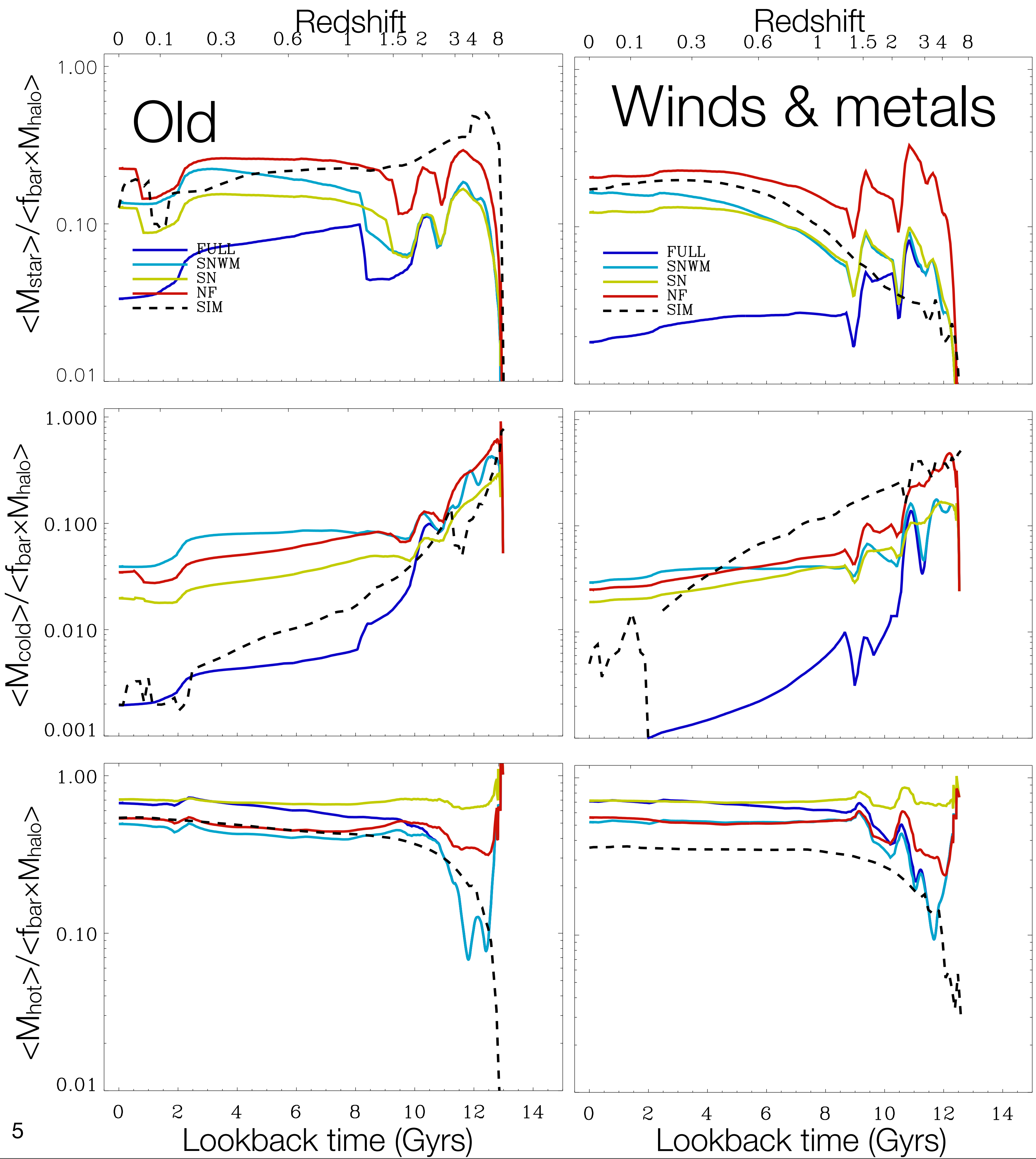


$M_{final} = 6\times10^{12}\, M_\odot$

Efficient star formation
rapid cold gas depletion

More cold gas
later star formation

Galaxy formation ins SAMs and sims



Preliminary results: winds & metals

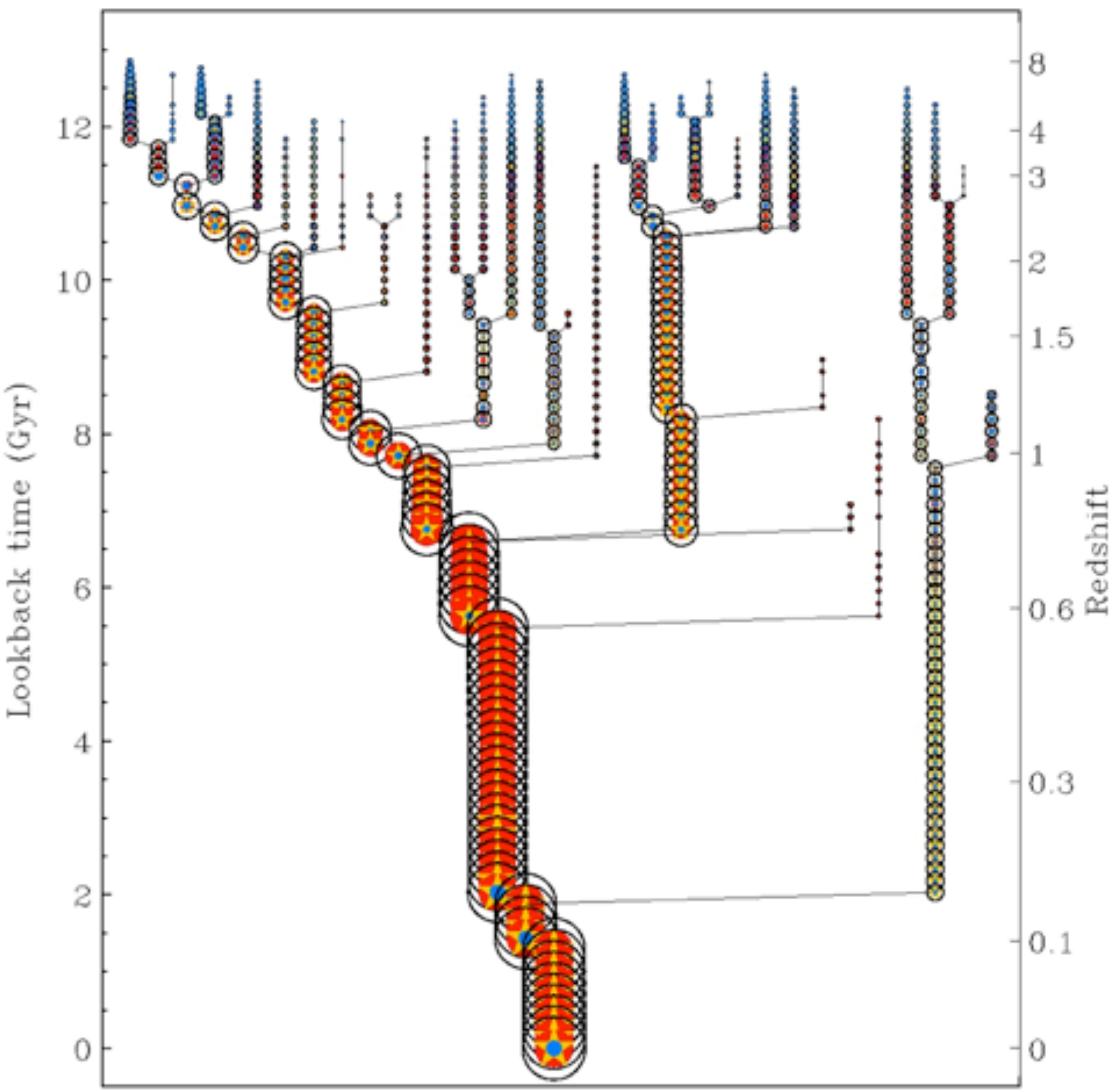
$M_{final} = 6\times10^{12}\,M_\odot$

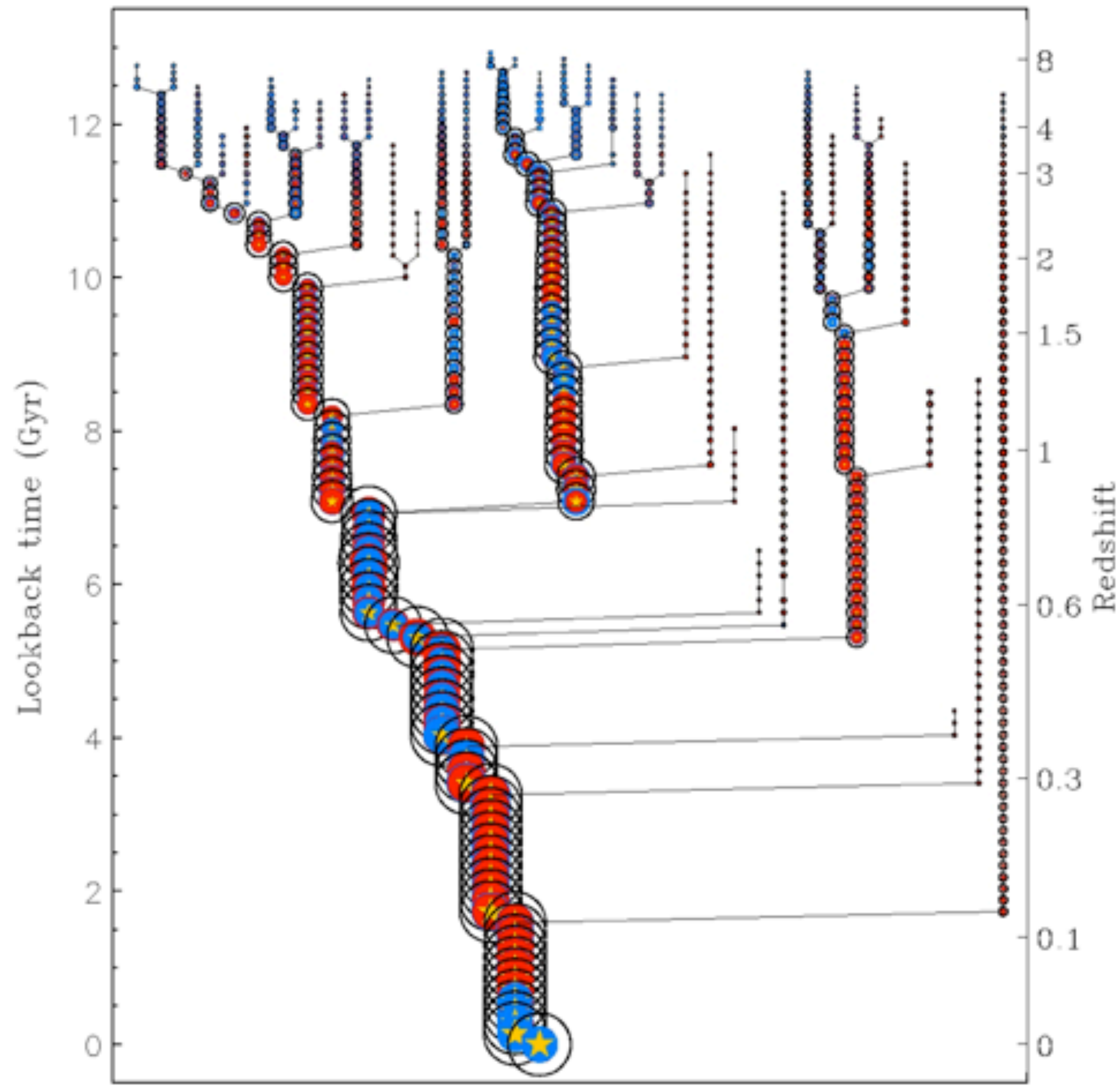
- *Stars:* less efficient star formation at high z
- *Cold gas:* weaker decrease
- *Hot gas:* smaller mass at $z < 1$

Preliminary results: winds & metals

Old

Winds & metals

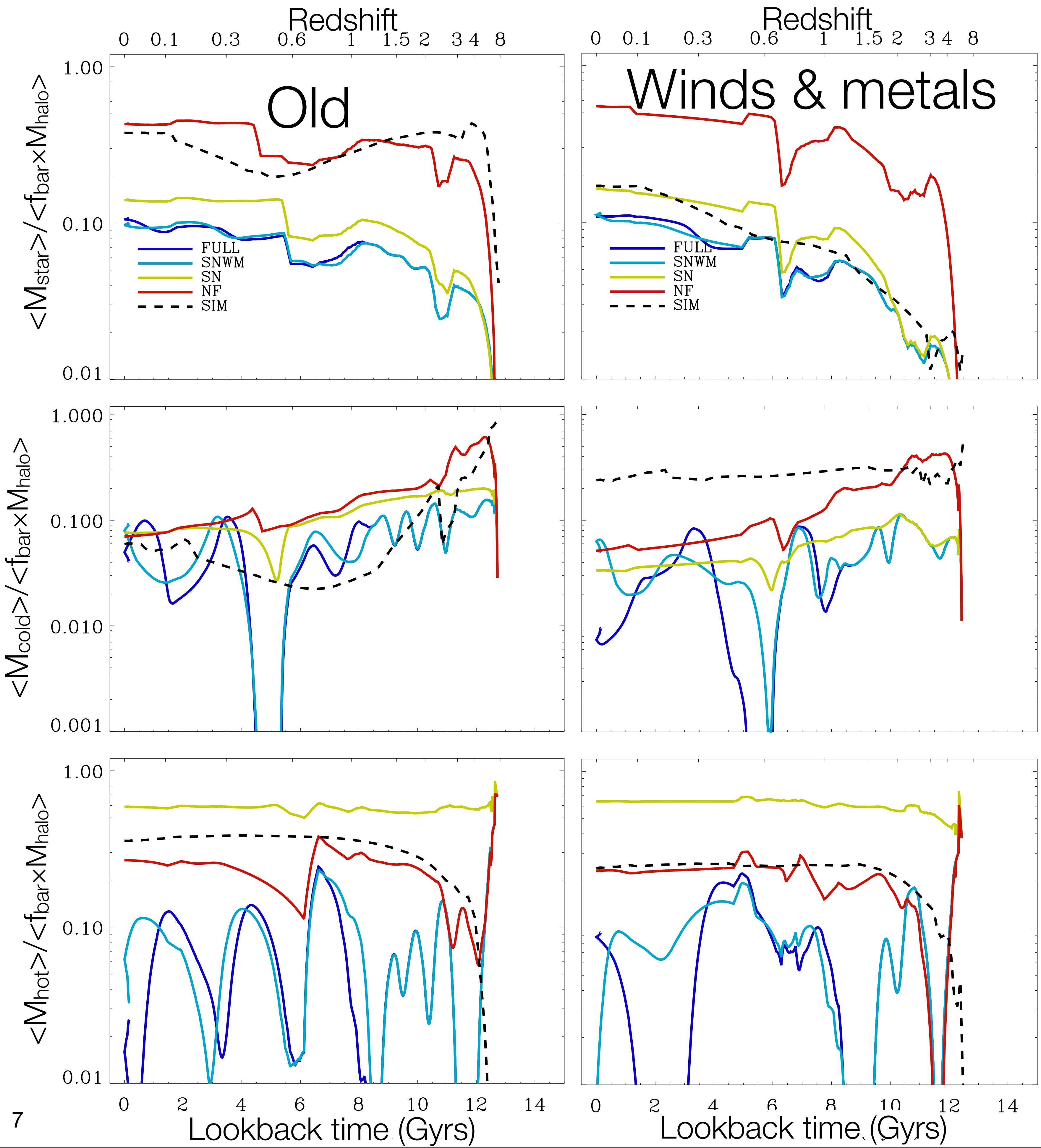




Efficient star formation
rapid cold gas depletion

$M_{final} = 3 \times 10^{11} M_{\odot}$

More cold gas
less star formation



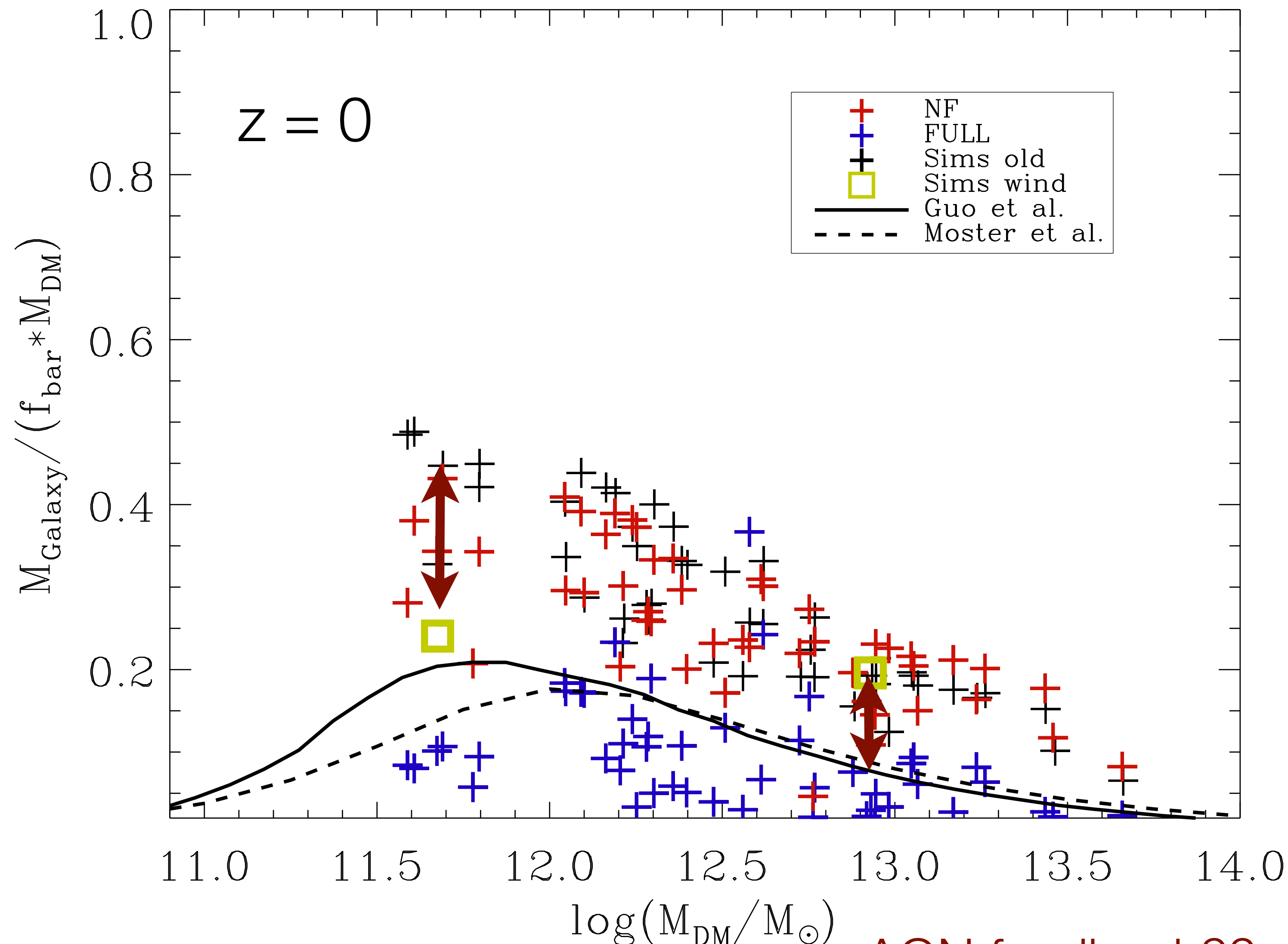
Preliminary results: winds & metals

$M_{final} = 3 \times 10^{11}\, M_{\odot}$

- *Stars:* less efficient star formation at all z
- *Cold gas:* almost constant evolution
- *Hot gas:* best agreement with NF model

Preliminary results: winds & metals

Baryon conversion efficiency



AGN feedback??

e.g. Wake et al. 2010:

Conversion efficiency for larger z (=1,2)

Shifting peak towards larger halo masses

"Halo downsizing"

Are current implementations in SAMs and Sims sufficient??

Tentative summary

- *SN-Winds* have a *significant influence on suppressing SF, in particular at high redshifts* (better match to SNWM/FULL models)
- *Metals increase the amount of the cold gas content*, but cold gas is probably blown out of the central, star-forming regions and thus, not available for star formation

But:

- *Larger number* of simulations has to be analysed
- More careful analysis of metals and winds *separately*
- *Additional implementation* of stellar mass loss from AGB and SNIa into SAMs

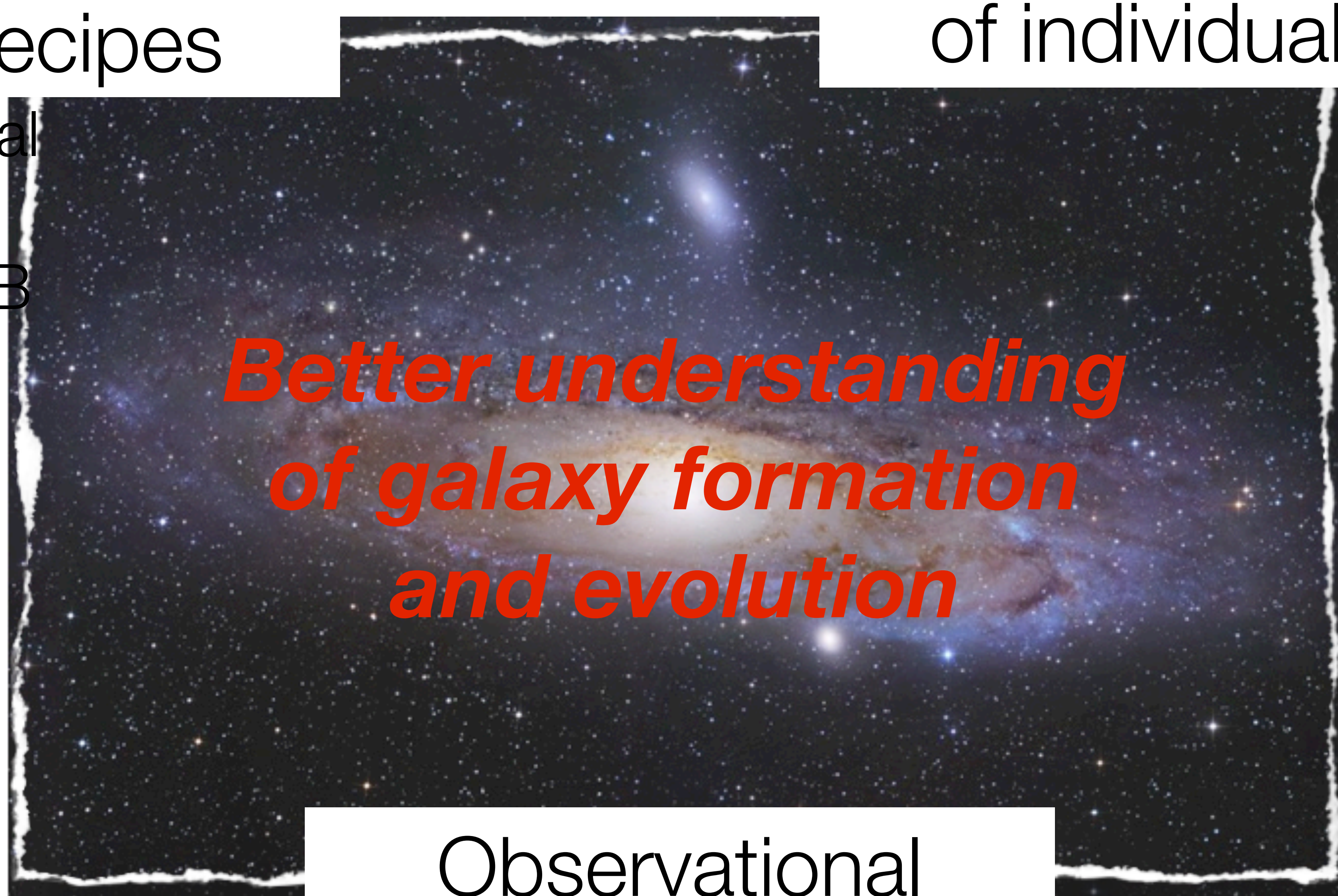
OUTLOOK...

SAMs including refined recipes

- gravitational heating
- SNIa &AGB stars
- Cooling recipe

High-res resimulations of individual halos

with enhanced physics



Observational studies