Semi-analytical model of galaxy formation based on high-resolution N-body simulations

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XI KANG ET AL. IN PREPARATION

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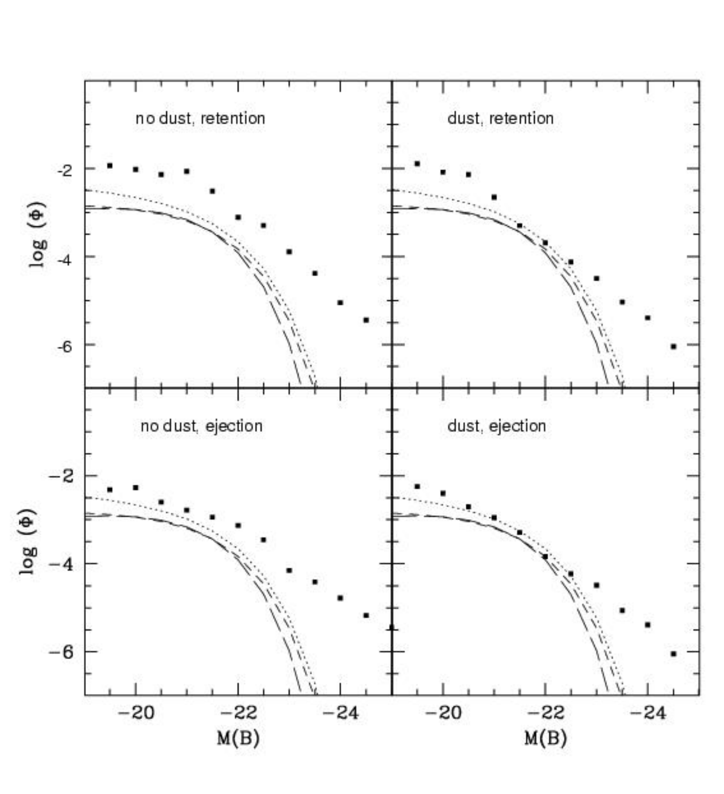
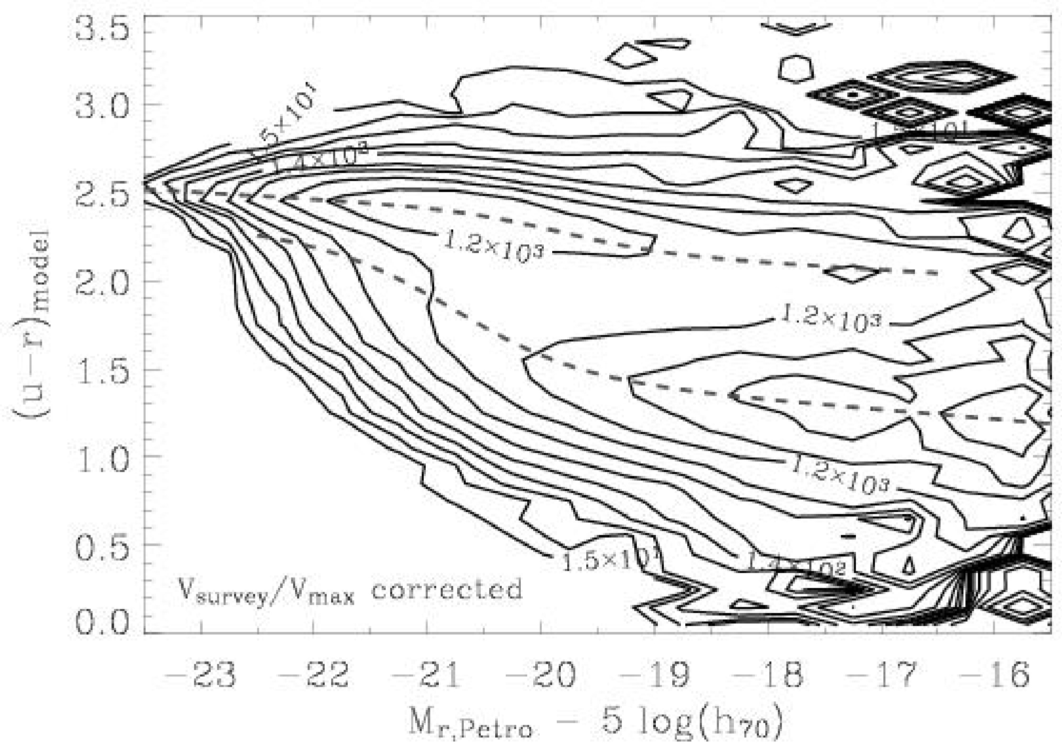
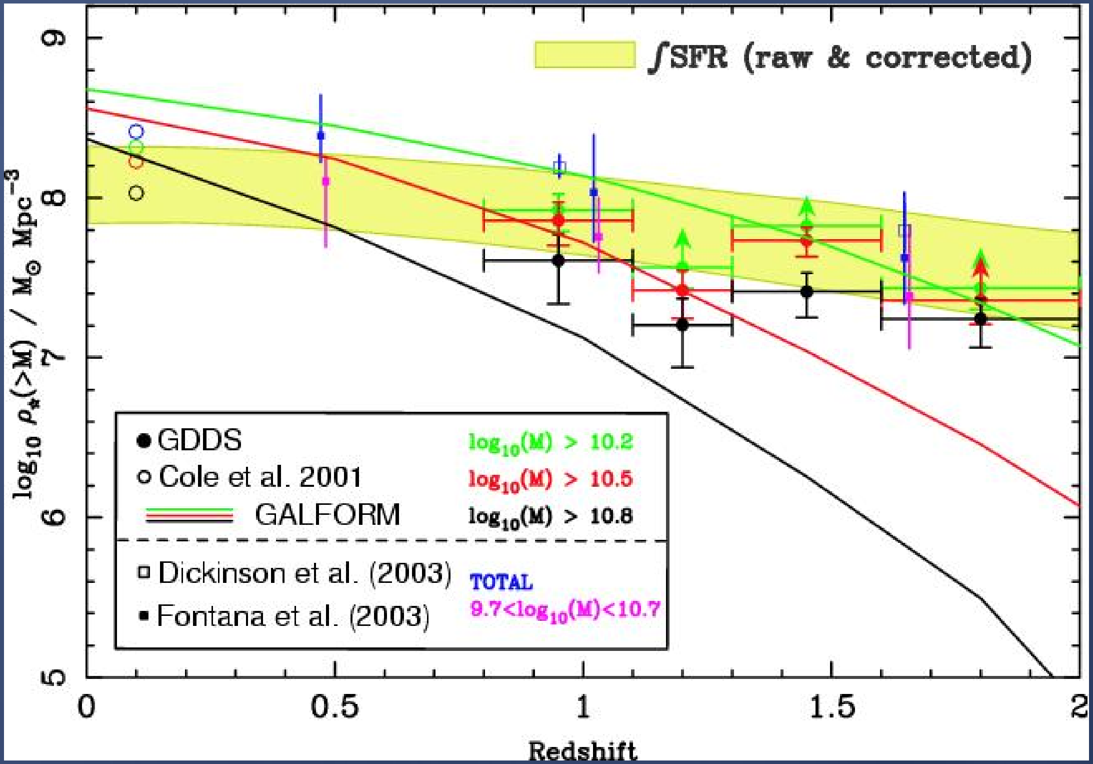
Difficulty 1 — Luminosity function is power law at high-mass end in semi-analytical modeling (e.g. Kauffmann et al. 1999, ApJ, 303, 188), in contrast to the Shechter function (exponential) in observations



Difficulty 2 — The bimodal distribution of galaxies in the color-magnitude diagram (e.g. Baldry et al. 2004, ApJ, 600, 681) cannot be easily predicted in hierarchical theory (cf. recent talks by J. Primack), because the star formation is continuous and the distribution of galaxies in many models. We need to cut star formation for ellipticals



Difficulty 3 — The hierarchical theories underpredict the abundance of RED (e.g. $I - K > 4$) massive galaxies at $z = 1 \sim 1.5$ (e.g. Glazebrook 2004, Nature, 430,181)



1. Motivations

- We want to examine the failures of the current theories mentioned above and others (like the luminosity dependence of galaxy clustering);
- All above problems are related to the formation of high mass galaxies;
- Merging and cooling are crucial for formation of massive galaxies,

Merging Merging is determined by the dynamical time in the previous semi-analytical models (Munich, Durhram, Santa Cruz);

Cooling Cooling is switched off for massive halos (say circular velocity $v_c > 390\,\mathrm{km\,s^{-1}}$

- High-resolution N-body simulations which can follow the merging precisely;
- Investigate other recipes for cutting cooling in massive halos;
- An independent semi-analytical model with different parameters;
- investigate which are the fundamental difficulties for LCDM models and what may be just the consequences of inaccurate description of the galaxy formation models

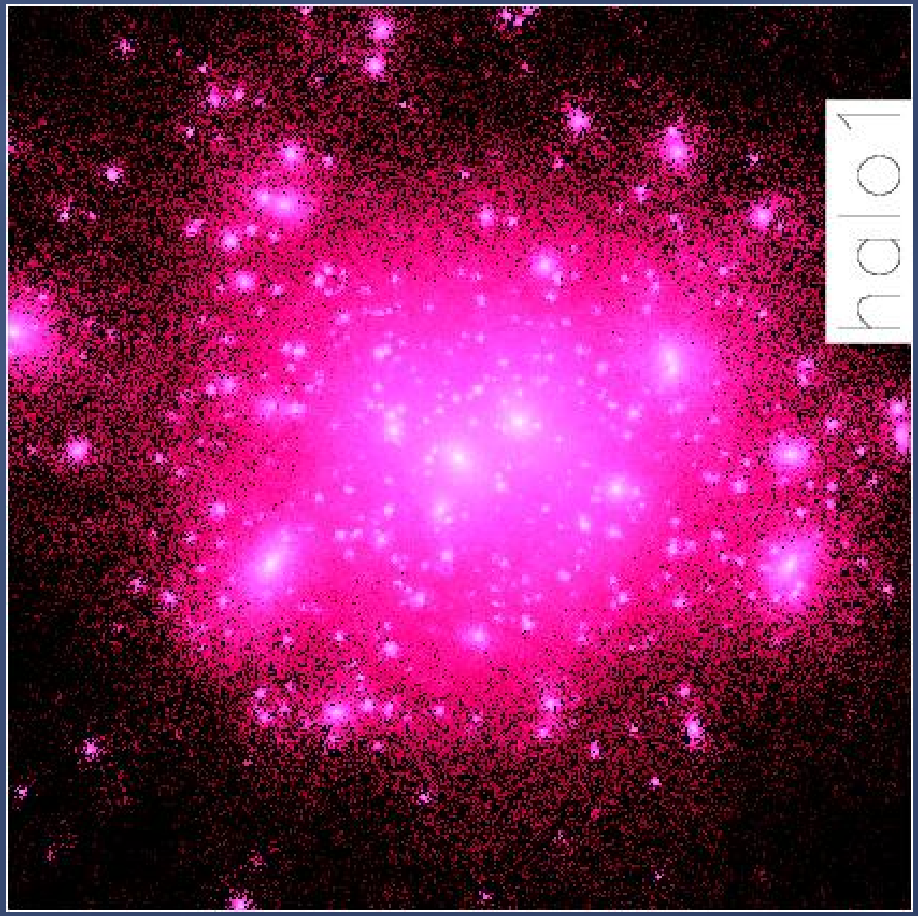
2. Cosmological Model

- Concordance LCDM Model: $\Omega_{\mathrm{m},0} = 0.3$ and $\Omega_{\Lambda,0} = 0.7$; CDM dominated;
- Primordial Spectrum: $P(k) \propto k$ with the amplitude $\sigma_8 = 0.9$;
- Baryon Density: $\Omega_{\mathrm{b},0} = 0.045$;
- Hubble Constant: $H_0 = 71\,\mathrm{km\,s^{-1}Mpc^{-1}}$

3. N-body simulations

- **Main simulation L100:** P^3M cosmological simulation of 512^3 particles in $L = 100\,h^{-1}\mathrm{Mpc}$; 5000 time steps; $z_i = 72$; softening $\eta_f = 10\,h^{-1}\mathrm{kpc}$ (S2); particle mass $m_p = 6.2 \times 10^8 \mathrm{M}_\odot$ (Jing & Suto 2002)
- Supplemented by
  - **Re-simulations of 20 massive halos:** mass $M = 1 \sim 3 \times 10^{15}\,h^{-1}\mathrm{M}_\odot$; 2×10^6 particles within R_{vir}; $m_p = (0.5 \sim 1) \times 10^9\,h^{-1}\mathrm{M}_\odot$; the nested-grid P^3M code (Jing & Suto 2000);
  - **Cosmological simulation L25:** 256^3 particles in $L = 25\,h^{-1}\mathrm{Mpc}$; $\eta_f = 5\,h^{-1}\mathrm{kpc}$; others similar to L100. Higher mass resolution ($8\times$) and force resolutions for a smaller box

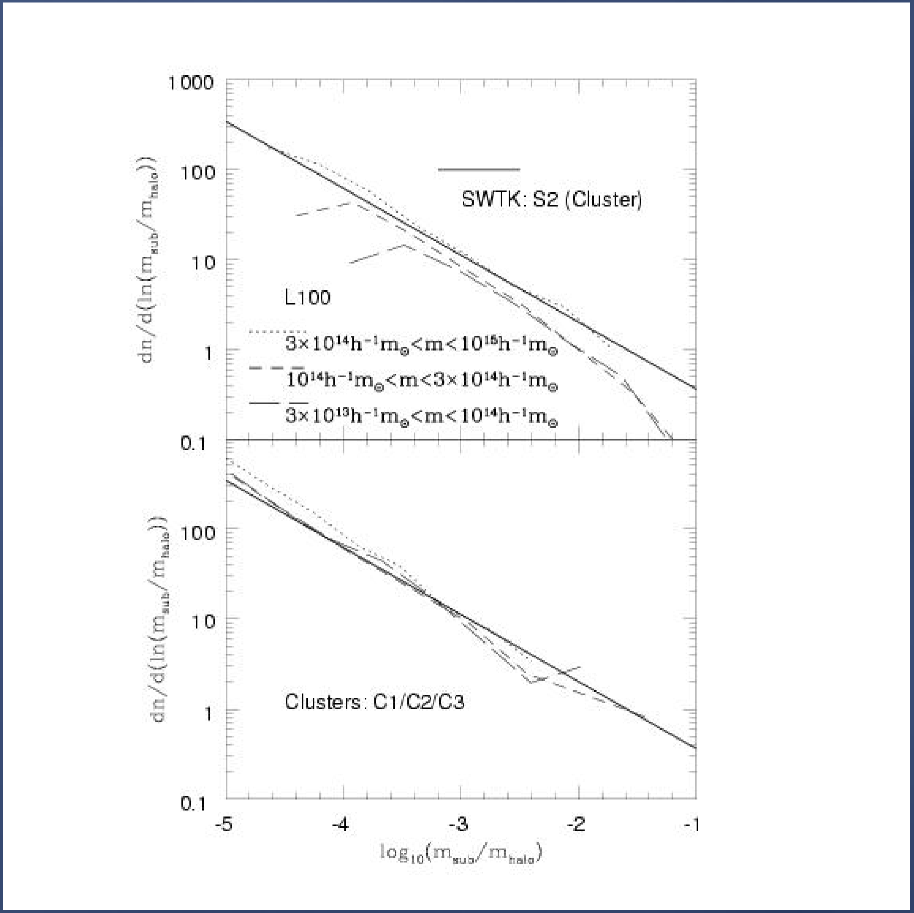
— A massive halo in L100



Subhalos and galaxy populations

- Halo identification: using FOF with $b = 0.2$;
- Subhalo identification: using SUBFIND of Volker Springel for identifying self-bound subhalos;
- Galaxy populations according to their relation to subhalos:
  - Central Galaxy: at the center of halo
  - Halo Galaxy: at the center of a subhalo halo
  - Satellite Galaxy: otherwise

Resolution test — subhalos are resolved to 50 particles, i.e. $3 \times 10^{10} M_{\odot}$ in L100



The mass function of subhalos as a function of the mass ratio of the subhalo to the host halo.

4. Physical Processes

- Cooling of hot gas:

$$t_{\rm cool}(r) = \frac{3}{2} \frac{kT \rho_{\rm g}(r)}{\overline{\mu} m_{\rm p} n_{\rm e}^2(r)\, \Lambda(T,Z)} \,, \qquad (1)$$

with $t_{\rm cool} = t_{\rm age}$

- Star formation: The star formation rate ψ :

$$\psi = \alpha m_{\rm cold}/t_{\rm d} \,. \qquad (2)$$

with

$$\alpha = \alpha_0 \left(\frac{V_{\rm vir}}{220\,{\rm km\,s^{-1}}} \right)^n \,. \qquad (3)$$

$n = 2.2$: cold gas is converted slowly to stars in low mass galaxies

- **Supernova Feedback**: With an amount of $\Delta m_\star$ of newly formed stars, the amount of cold gas that can be reheated can be expressed as,

$$\Delta m_{\rm eject} = \frac{4}{3}\epsilon\frac{\eta_{\rm SN} E_{\rm SN}}{V_{\rm vir}^2}\Delta m_\star\,, \tag{4}$$

and added to the hot gas of the halo

- **Chemical evolution**:
  - Stellar mass change in each galaxy

$$\dot{m}_\star = (1-{\rm R})\psi\,. \tag{5}$$

  - Cold gas change in each galaxy

$$\dot{m}_{\rm cold} = \dot{m}_{\rm cool} - (1-{\rm R})\psi - \dot{m}_{\rm eject}\,. \tag{6}$$

  - Hot gas change in the main halo

$$\dot{m}_{\rm hot} = -\dot{m}_{\rm cool} + \sum_i \dot{m}_{\rm eject}^{(i)}\,, \tag{7}$$

– the mass changes in heavy elements in the the components

$$\dot{m}_\star^Z = (1-R)Z_{\rm cold}\psi\,, \qquad (8)$$

$$\dot{m}_{\rm cold}^Z = \dot{m}_{\rm cool}Z_{\rm hot} + {\rm p}\psi - (1-{\rm R}){\rm Z}_{\rm cold}\psi - \dot{\rm m}_{\rm eject}{\rm Z}_{\rm cold}\,, \qquad (9)$$

and

$$\dot{m}_{\rm hot}^Z = -\dot{m}_{\rm cool}Z_{\rm hot} + \sum_i \dot{m}_{\rm eject}^{(i)} Z_{\rm cold}^{(i)}\,, \qquad (10)$$

- Halo mergers and galaxy mergers
  - Halo merges: given by N-body simulation
  - galaxy merges: For halo galaxies, given by subhalo merge tree. For satellites, merge with central or halo galaxy after a dynamical friction time scale τ,

$$\tau = 0.5\frac{f(\epsilon)V_c r_c^2}{CGm_{\rm sat}\ln\Lambda}\,, \qquad (11)$$

  - Merge Remnants:
    * Minor merge: $M_1^\star/M_2^\star < 0.3$; cold gas of smaller galaxy added to the bigger one; stars of smaller galaxy added to the bulge of bigger one;
    * Major merge: $M_1^\star/M_2^\star > 0.3$; all cold gas converted to stars in a new bulge

- # Photometric evolution of galaxies
  - The spectral energy distribution of a galaxy,

$$S_\nu = \int_0^t F_\nu(t-t')\dot{m}_\star(t')dt' \ , \qquad (12)$$

where F_ν is the SED for a single age population, depending on the IMF, metallicity and age (Bruzual & Charlot 2000 Library)

- # Dust extinction
  - The optical depth in the B-band scales with luminosity as

$$\tau_{\rm B} = \tau_{{\rm B},\star}\left(\frac{L_{\rm B}}{L_{{\rm B},\star}}\right)^{\beta} \qquad (13)$$

with $\tau_{{\rm B},\star} = 0.8$, $L_{{\rm B},\star} = 1.3\times 10^{10}L_\odot$ and $\beta = 0.5$ (Wang & Heckman 1996).

  - The model of Cardelli et al. (1989) to derive the ratio $\tau_\lambda/\tau_{\rm B}$.
  - the total galactic extinction (Tully & Fouqué 1985) for thin disk:

$$A_\lambda = -2.5\log_{10}\left(\frac{1-e^{-\tau_\lambda\sec\theta}}{\tau_\lambda\sec\theta}\right) \ , \qquad (14)$$

  - Only for disk, not for bulge component

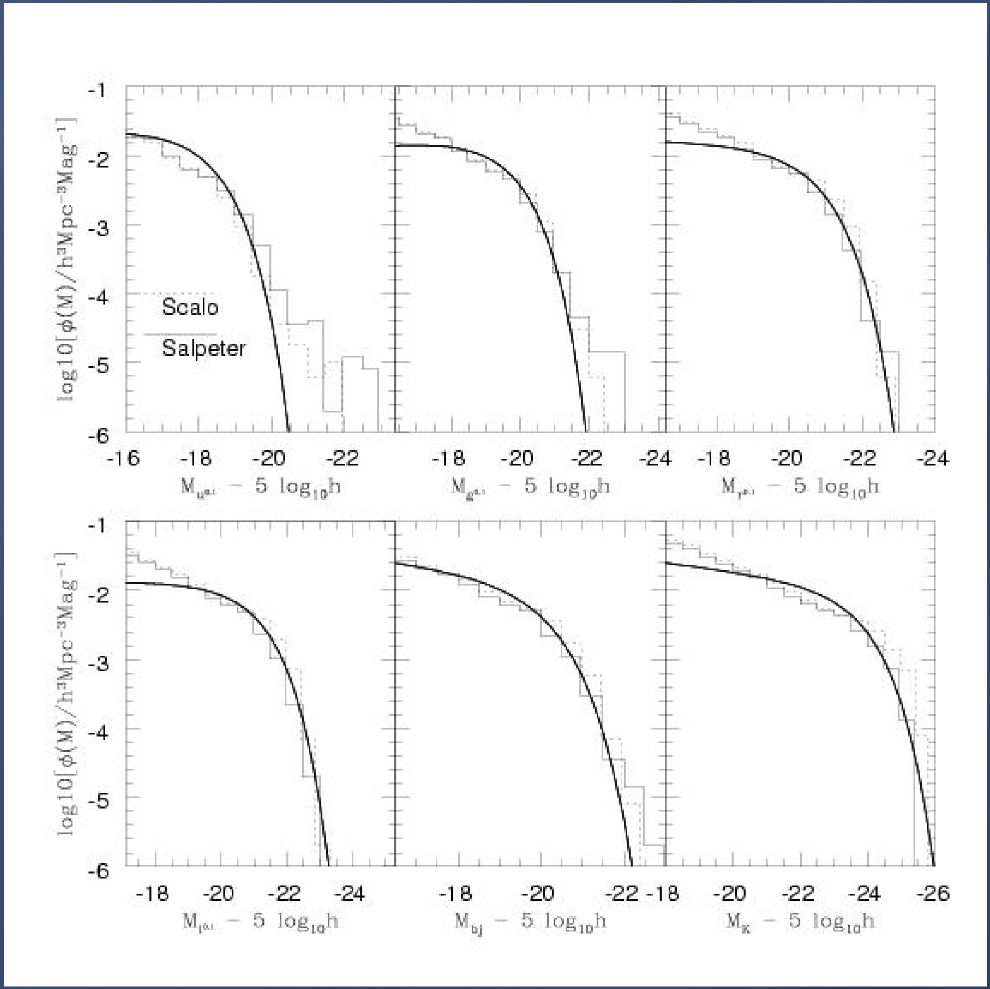
- Model parameters
  - IMF: the initial stellar mass function: Salpeter IMF, but Scalo IMF for a comparison;
  - p: the yield of metals from a unit mass of newly formed stars; 0.032 (from CMR of cluster ellipticals);
  - R: the fraction of mass recycled into the cold gas by evolved stars; $R = 0.35$ from stellar evolution theory
  - α_0: the amplitude of the power-law star formation efficiency; $\alpha_0 = 0.1$ from i-band LF
  - n: the slope of the power-law star formation efficiency; $n = 2.2$ from the cold gas of MW
  - ϵ: the feedback efficiency; ϵ from i-band LF and cold gas of Milky Way.

Comparison with Previous works

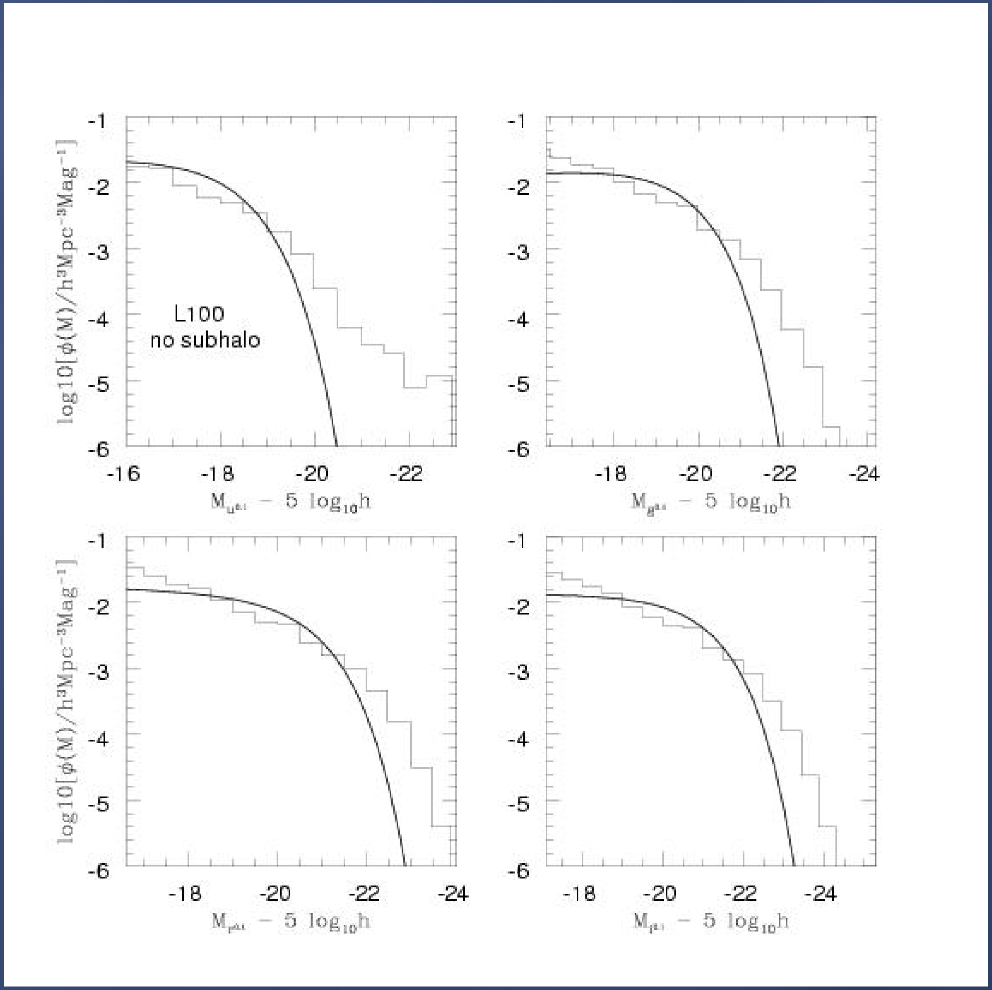
Our modeling follows the works of Munich group, but has the following features,

- Using simulations with subhalos resolved (cf. Kauffman et al 1999)
- A cosmological volume (cf. Springel et al. 2001 for a single cluster)
- Use $t_{\mathrm{cool}} = t_{\mathrm{age}}$ for the cooling time
- Attempted to include most of the important physical processes
- An independent implementation of SAM

The multi-waveband luminosity functions of galax-ies



The multi-waveband luminosity functions of galaxies without resolving subhalos



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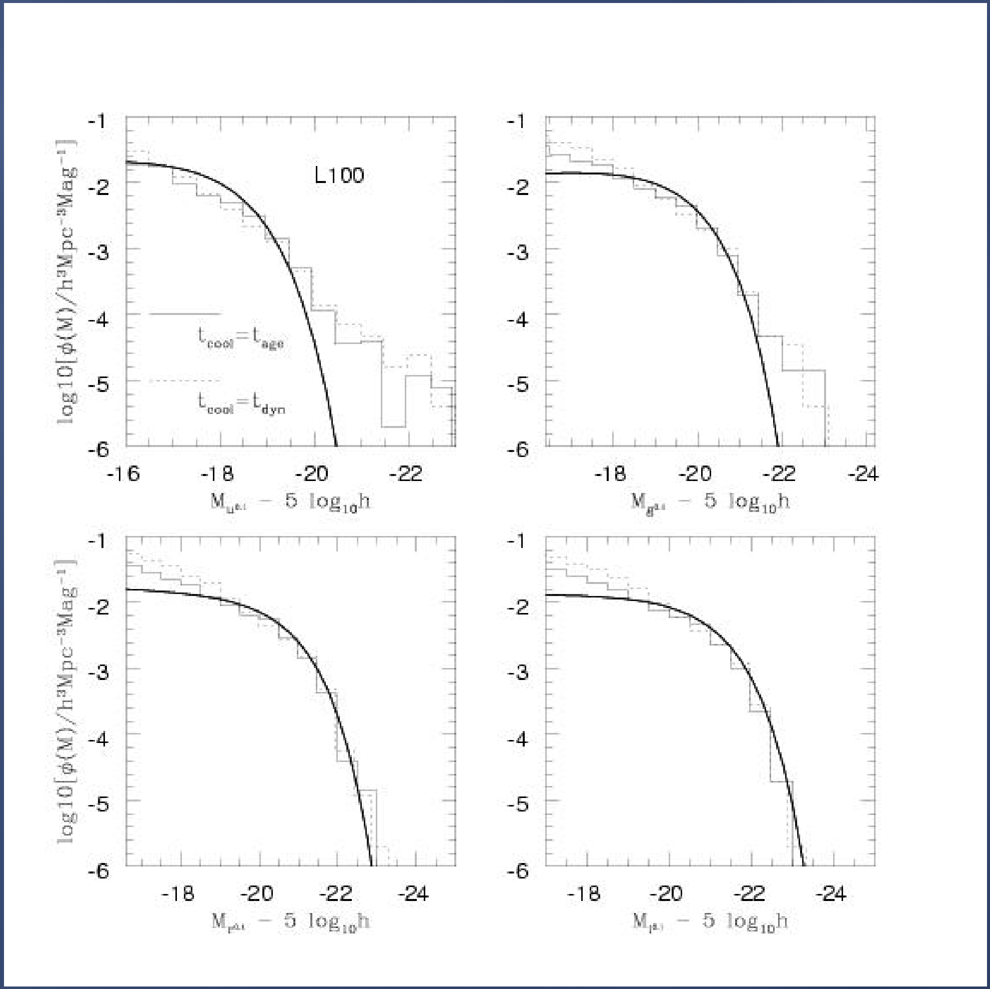
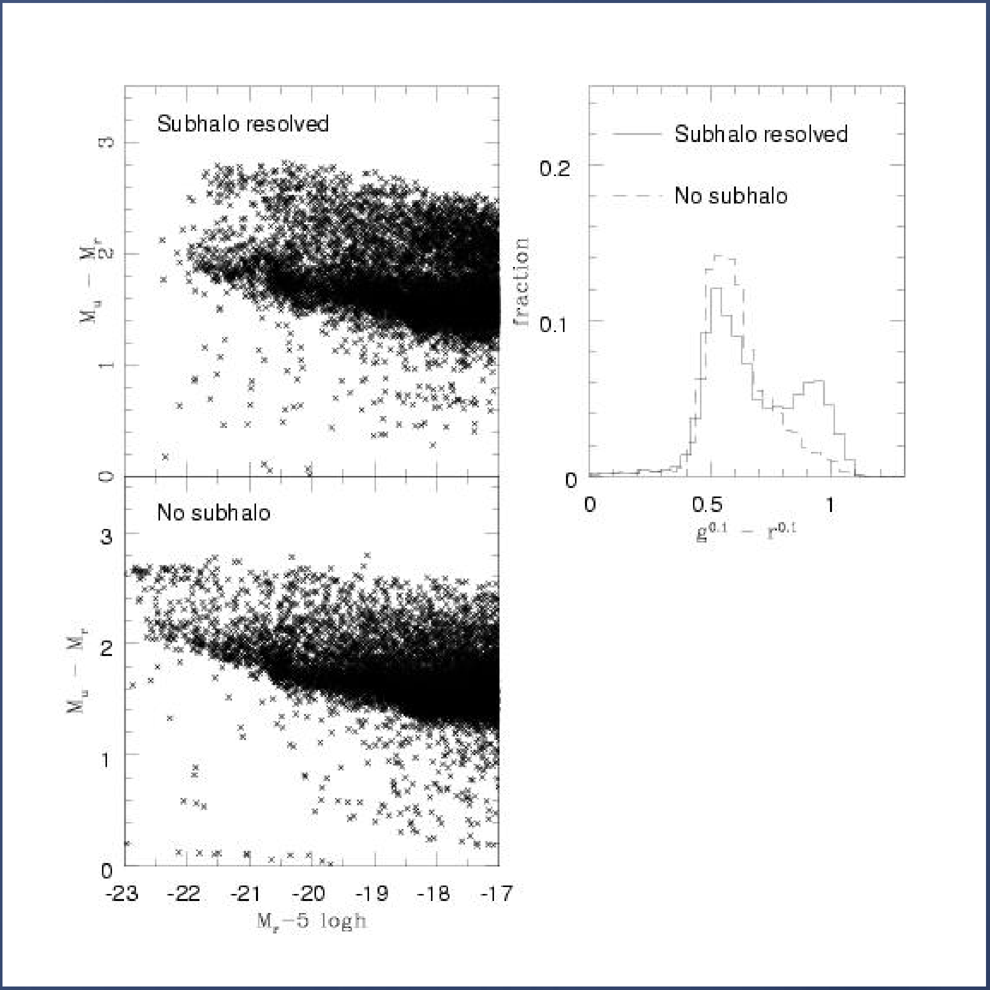
The multi-waveband luminosity functions of galaxies with the change of cooling time scale



What we learned from the LF

- The exponential form of the LF at the bright end reproduced in the subhalo scheme (but not at the u-band)
- Main reason: the merging of bright satellite galaxies with the central galaxies is slower than the simple friction dynamical estimate (cf. Springel et al. 2001 for the cluster LF)
- The LF at the faint end is improved if $t_{\rm cool} = t_{\rm age}$ used for the cooling time
- In u-band: too many $> L_\star$ galaxies and too few $<\sim L_\star$ (about a factor of 2) galaxies: cooling cut-off? dust model? SF history and minor bursts? Top heavy IMF?

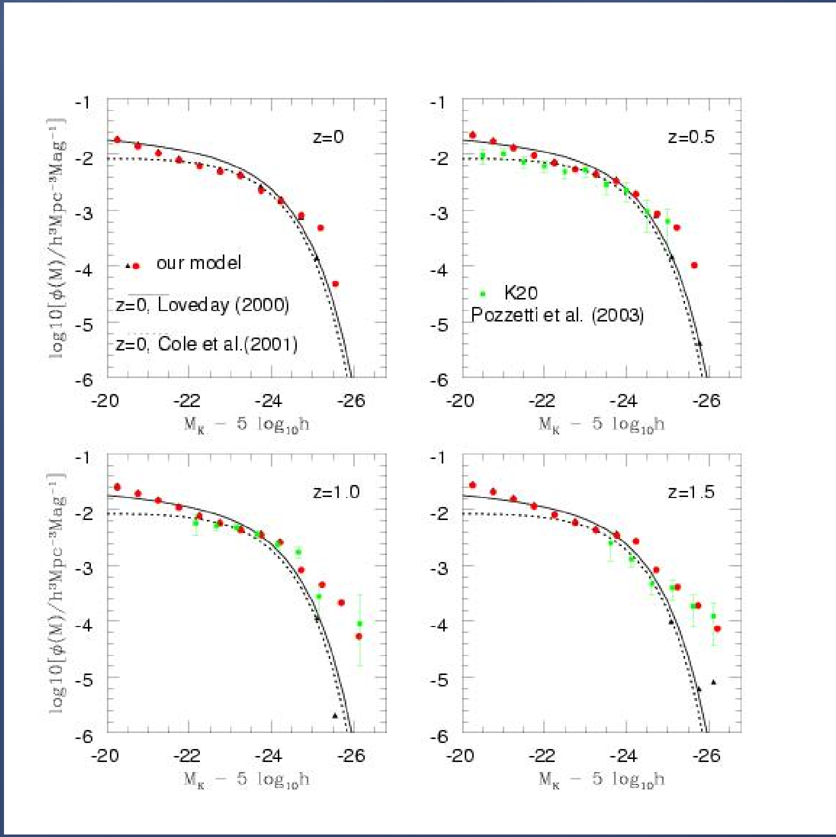
The bimodal distribution of galaxies in the color-magnitude diagram and the color distribution



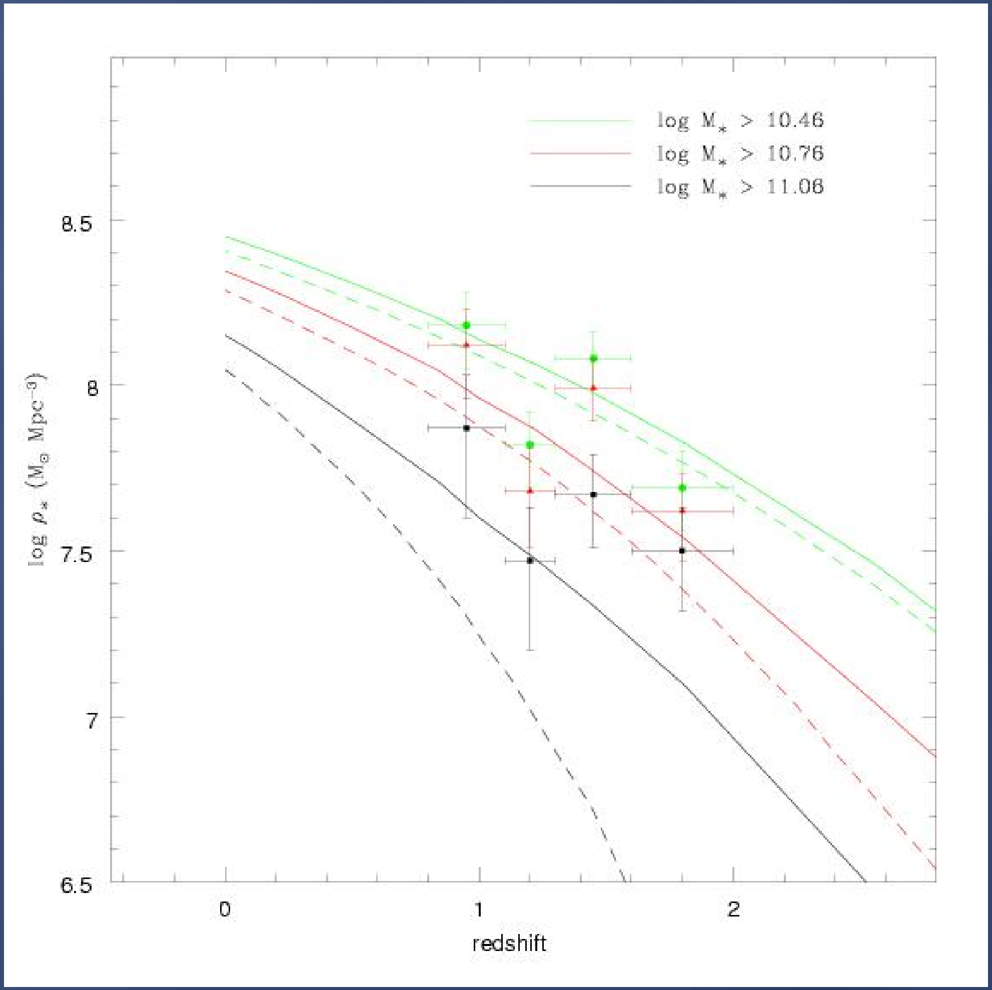
What we learned from the color distribution

- The bimodal distribution can be better explained in the subhalo scheme
- Main reason: red bright satellite galaxies can stay longer in the subhalo scheme

Changing the prescription for the cooling cut-off can dramatically change the abundance of massive galaxies (Kang et al. in preparation): New model (cutoff according to the halo mass) vs. old model (halo circular velocity).

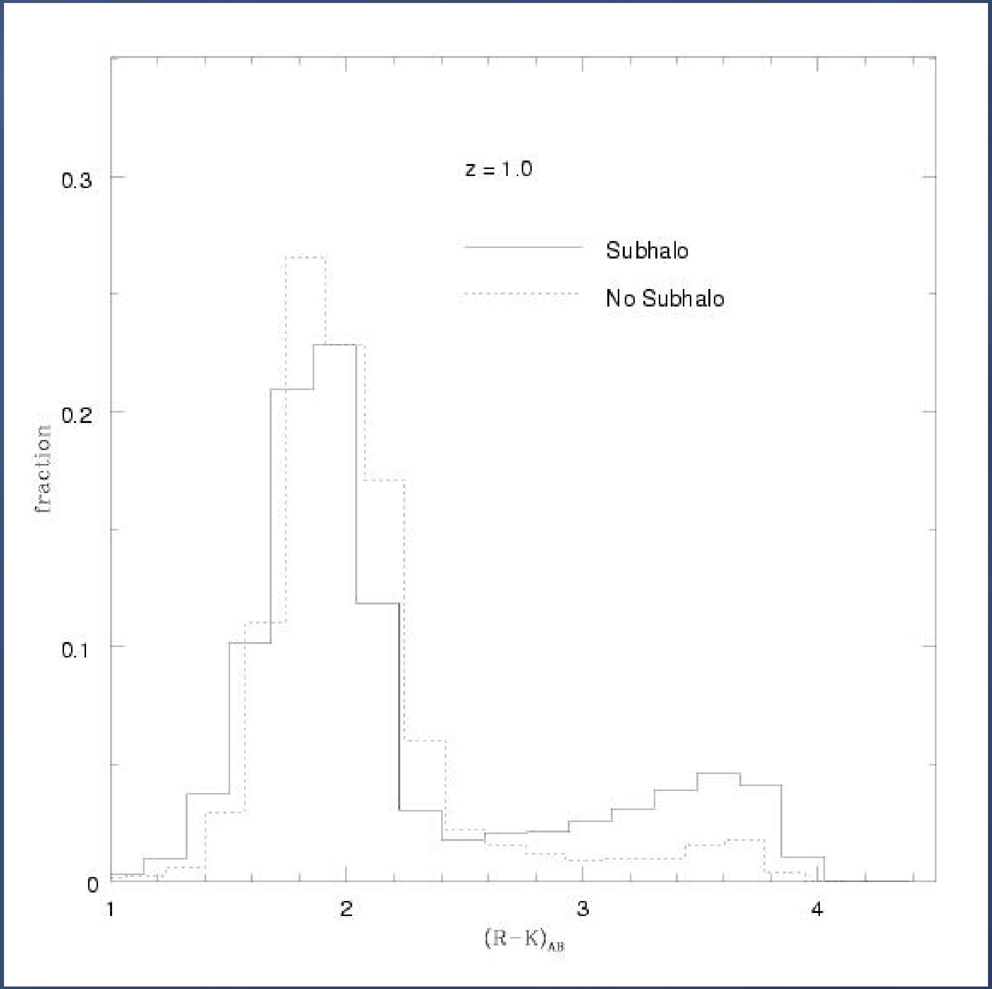


Triangles: velocity cutoff; circles: mass cutoff;



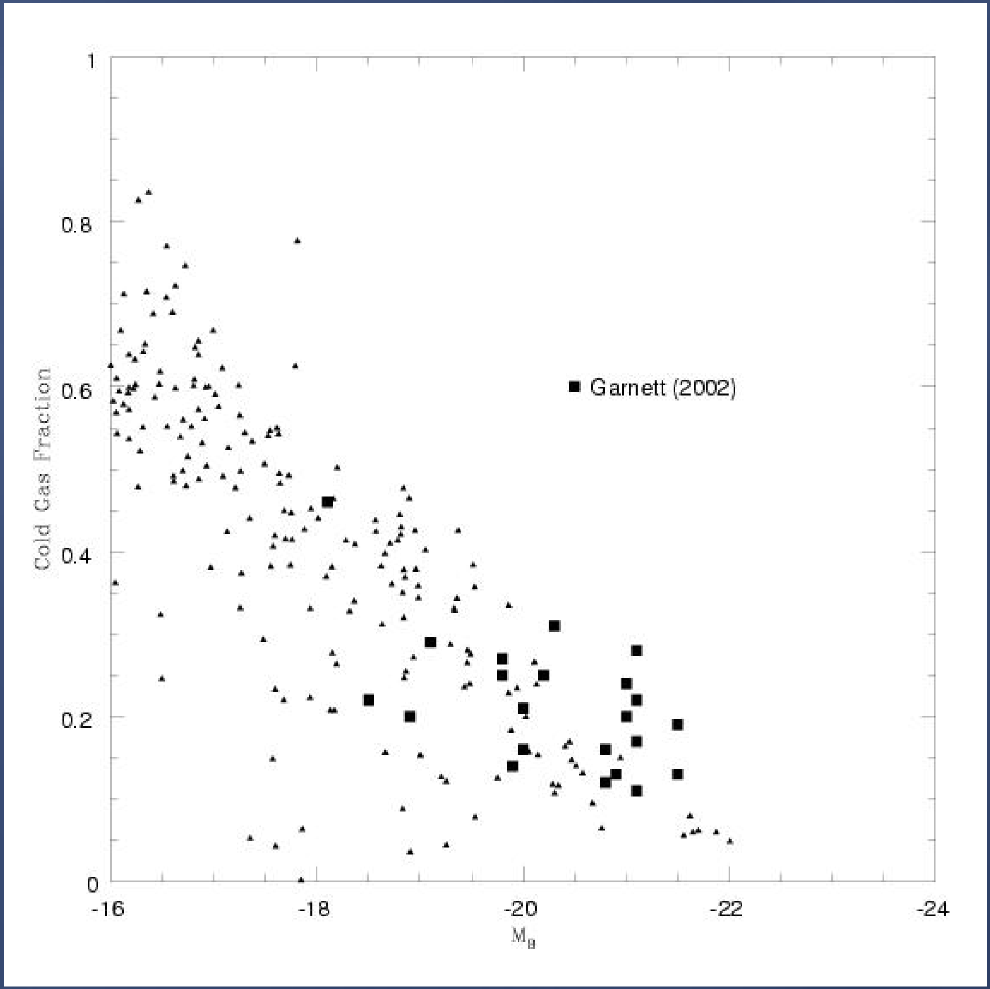
dashed lines: velocity cutoff; solid lines: mass cutoff; squares with errors: observations of GDDS (Glazebrook et al. 2004)

Abundance of massive red galaxies at z=1. The distribution of $(R-K)$ color for bright galaxies with $M_K \leq -23.2$ at $z=1$ (velocity cutoff).

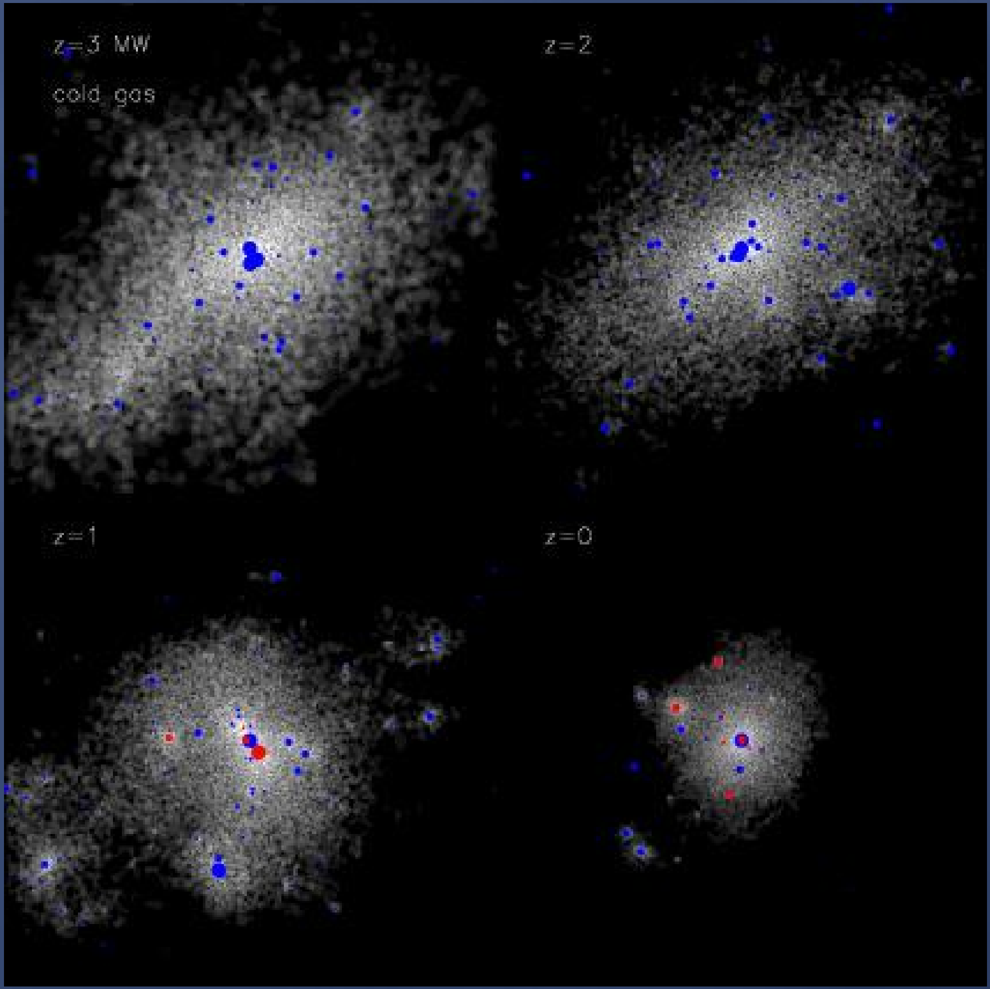


Abundance of red massive galaxies at z=1 not a fundamental problem for hierarchical theories! Rather it is very sensitive to the feedback mechanism that also closely influences the cold gas fraction

The cold gas fraction as a function of the B-band luminosity.



The cold gas distribution in Milky-Way halos at different redshifts.



5. Main Conclusions

- We have modeled galaxy formation in high-resolution N-body simulations which well resolve subhalos;
- Our semi-analytical model can match well LF of bright galaxies $M < M^{\star} + 1.5$ in various wave-bands;
- With subhalos, better reproduce the bimodal distribution of galaxies in CMD;
- the abundance of massive red galaxies at $z = 1$ not a fundamental problem; could be a good constraint on the AGN feedback
- The model can also match the observed Z-L relation and Z-v_{rot} relation of S galaxies, the f_{gas} in $z = 0$ S galaxies, and the color-magnitude re-

6. Unsolved Problems for Future

- Too many blue bright galaxies: might be related to the simplified assumption of cooling switch off for $v_c < 390\,\mathrm{km\,s^{-1}}$. More physical model needed; also dust model?;
- insufficient number of blue galaxies with intermediate luminosities; Dust model?
- Faint-end slope of LF: $t_{cool} = t_{age}$ instead of high feedback efficiency. Why?
- the predicted Tully-Fisher zero point is too low, unless there are some processes that can significantly flatten CDM halos. $v^g_{rot,max} = 1.15 v^h_{cir}$?