Anti-hierarchical evolution of the quasar space density in a hierarchical universe

Motohiro Enoki

東京経済大学
TOKYO KEIZAI UNIVERSITY

Tomoaki Ishiyama (Tsukuba Univ.)
Masakazu A. R. Kobayashi (Ehime Univ.)
Masahiro Nagashima (Nagasaki Univ.)
SWANS Theory Alliance

§1. Introduction

- QSO/AGN is fueled by accretion of gas onto Supermassive Black Holes (SMBH) in the nuclei of host galaxy.
- Many nearby galaxies have central SMBHs and their physical properties correlate with those of spheroids of their host galaxies.
  - $M_{\mathrm{BH}} / M_{\mathrm{bulge}} = 0.001 - 0.006$
  - $M_{\mathrm{BH}} \propto \sigma_{\mathrm{bulge}}{}^{n}$, $n = 3.7 - 5.3$

=> QSO/SMBHs formation physically link galaxy formation.

=> To study the evolution of QSO, it is necessary to construct a model that includes galaxy formation and QSO/SMBH formation.

- Hierarchical galaxy formation scenario

In the standard hierarchical clustering scenario in a cold dark matter (CDM) universe, dark halos cluster gravitationally and merge together.

In each dark halo, a galaxy formed. Galaxies in a merged dark halo sometimes merge together and a more massive galaxy is formed.

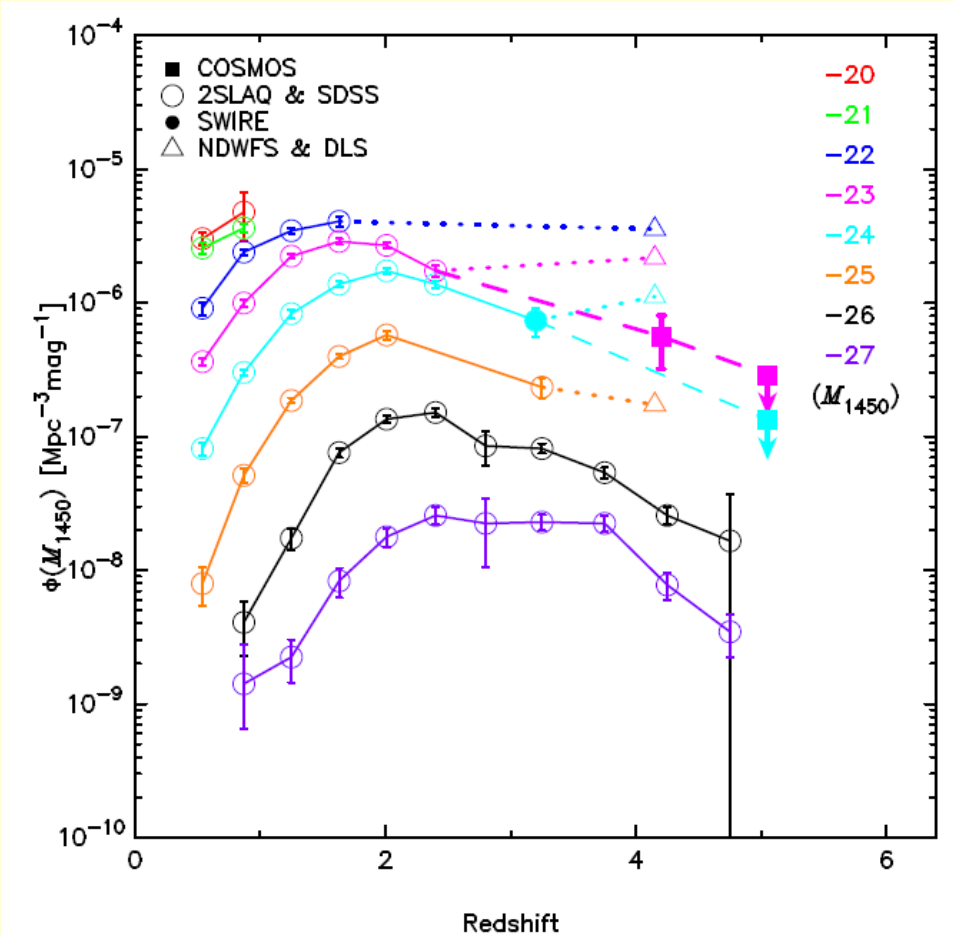
=> More massive galaxies formed at lower redshifts.

If the brighter QSOs have the more massive SMBHs, then brighter QSOs must form at lower redshifts because massive galaxies have massive SMBHs.

=> The space densities of luminous QSOs peak at lower redshifts than those of faint QSOs.

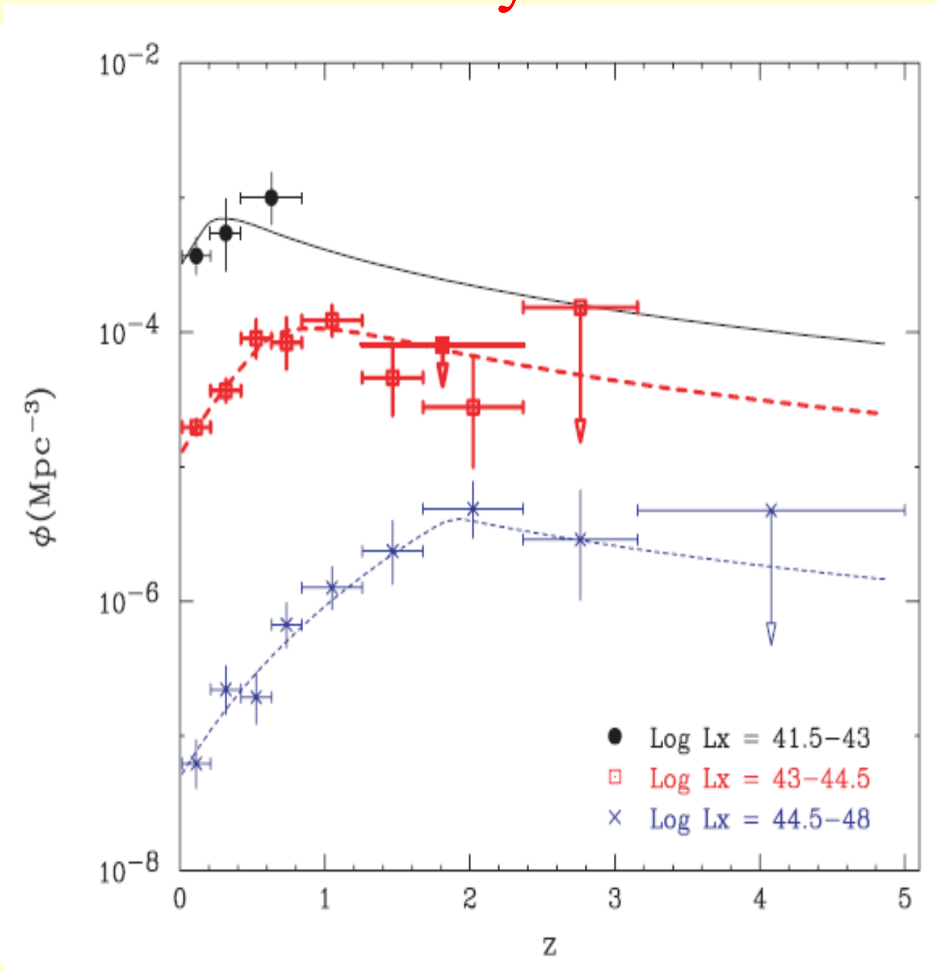
• Observed Evolution of QSO/AGN space density

optical



Ikeda et al. (2012)

X-ray



Ueda et al. (2003)

• Downsizing evolution of QSOs.

Observational results

=> The space densities of luminous QSOs peak at higher redshifts than those of faint QSOs.

=> *Downsizing* (or *Anti-hierarchical*) *evolution* of QSOs.

This downsizing evolution of QSO density seems to conflict with the hierarchical galaxy formation scenario.

In this study, we investigate whether the anti-hierarchical trend of QSO density evolution can be explained using a semi-analytic model of galaxy and SMBH/QSO formation based on a hierarchical clustering scenario (SA-model).

§2. Semi-analytical model of galaxy and SMBH/QSO formation **(SA-model)**

In order to compare enormous observational data with theoretical predictions, it is inevitable to show the statistical quantities.

- QSO number densities (luminosity functions)
- Spatial distributions of QSOs (QSO auto correlation functions, QSO-galaxy cross correlation functions).

SA-model approach enables us to study statistical properties of galaxies and QSOs.

*Nu*merical *G*alactic *C*atalog : νGC

Our SA model of galaxy formation model with cosmological *N*-body simulation : ***Nu**merical **G**alactic **C**atalog* : **νGC** (Nagashima, Yahagi, Enoki, Yoshii & Gouda 2005).

- Box size : 100 Mpc, 200 Mpc
- Number of particles : 512^3

• SMBH/QSO formation model (Enoki et al. 2003) included

Now, we have started to construct *New* **νGC**.

- Galaxy formation model updated
- Large box size *N*-body simulations (Ishiyama et al.)
  - Box size : 400 Mpc
  - Number of particles : 2048^3

QSO/SMBH Formation Model (Enoki et al. 2003)

Assumptions

1) When host galaxies merge, the pre-existing SMBHs in the progenitors immediately evolve to the gravitational wave emission regime and coalesce.

2) During a major merger of galaxies, a certain fraction of the cold gas that is proportional to the total mass of newly formed stars at starburst accretes onto the SMBH. This accretion process leads to a QSO activity.

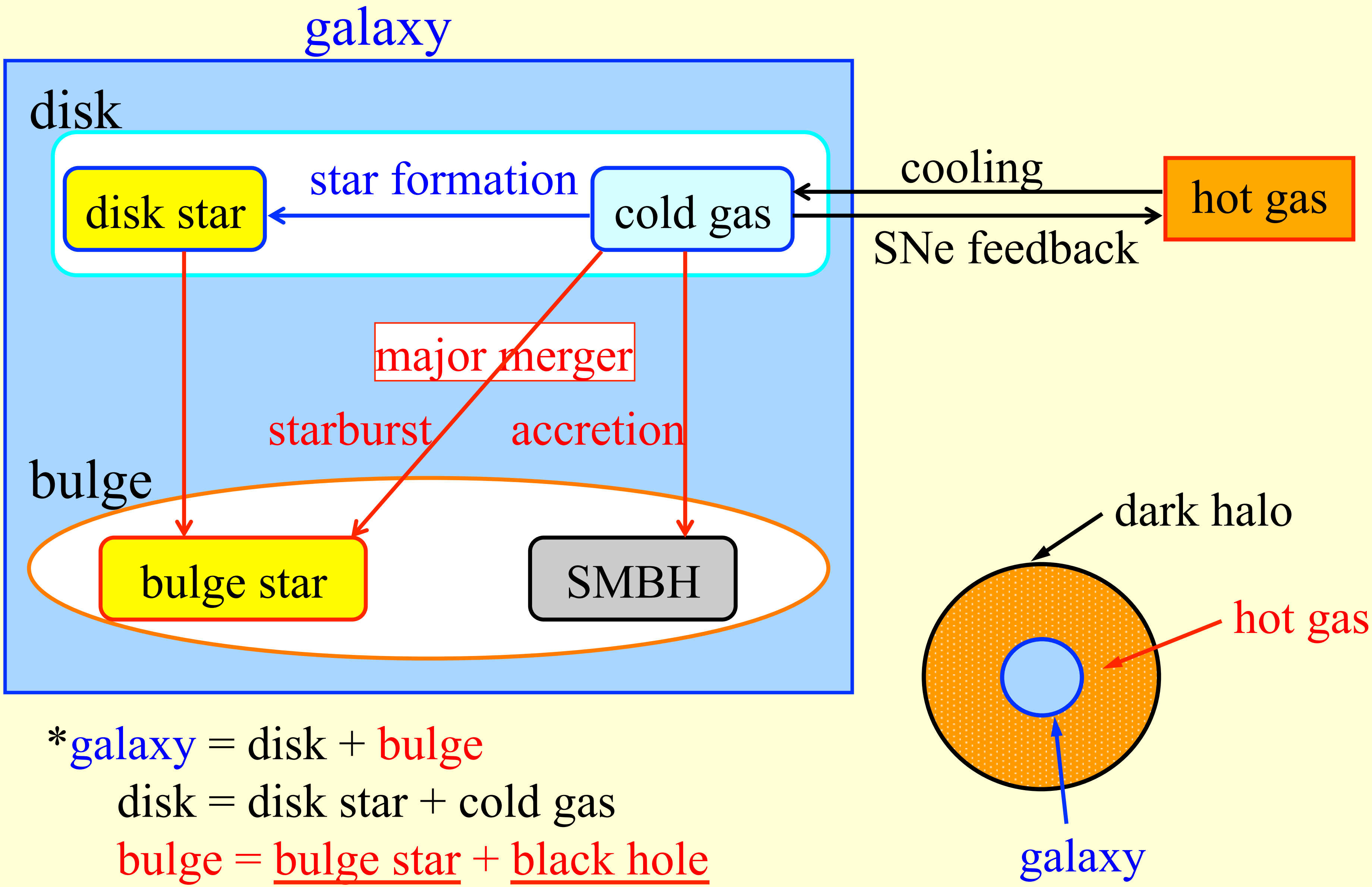
$$M_{acc} = f_{BH} \, M_{*,burst}$$

(cold gas => BH)

f_{BH}: fixed by matching the observed relation M_{bulge}-M_{BH}

We adopted f_{BH}=0.01

• Flow of baryons in the SA-model



*galaxy = disk + bulge

disk = disk star + cold gas

bulge = bulge star + black hole

* hot gas ; diffuse gas, virial temperature

- QSO/AGN light curve model

QSO *B*-band luminosity

$$L_B(t) = \frac{\varepsilon_B M_{\rm acc} c^2}{t_{\rm life}} \exp\left(-\frac{t}{t_{\rm life}}\right)$$

$\varepsilon_{\rm B}$: the radiative efficiency in the *B*-band

$t_{\rm life}$: QSO lifetime scale

$$t_{\rm life}(z) \propto t_{\rm dyn} \propto 1/\rho_{\rm vir}$$

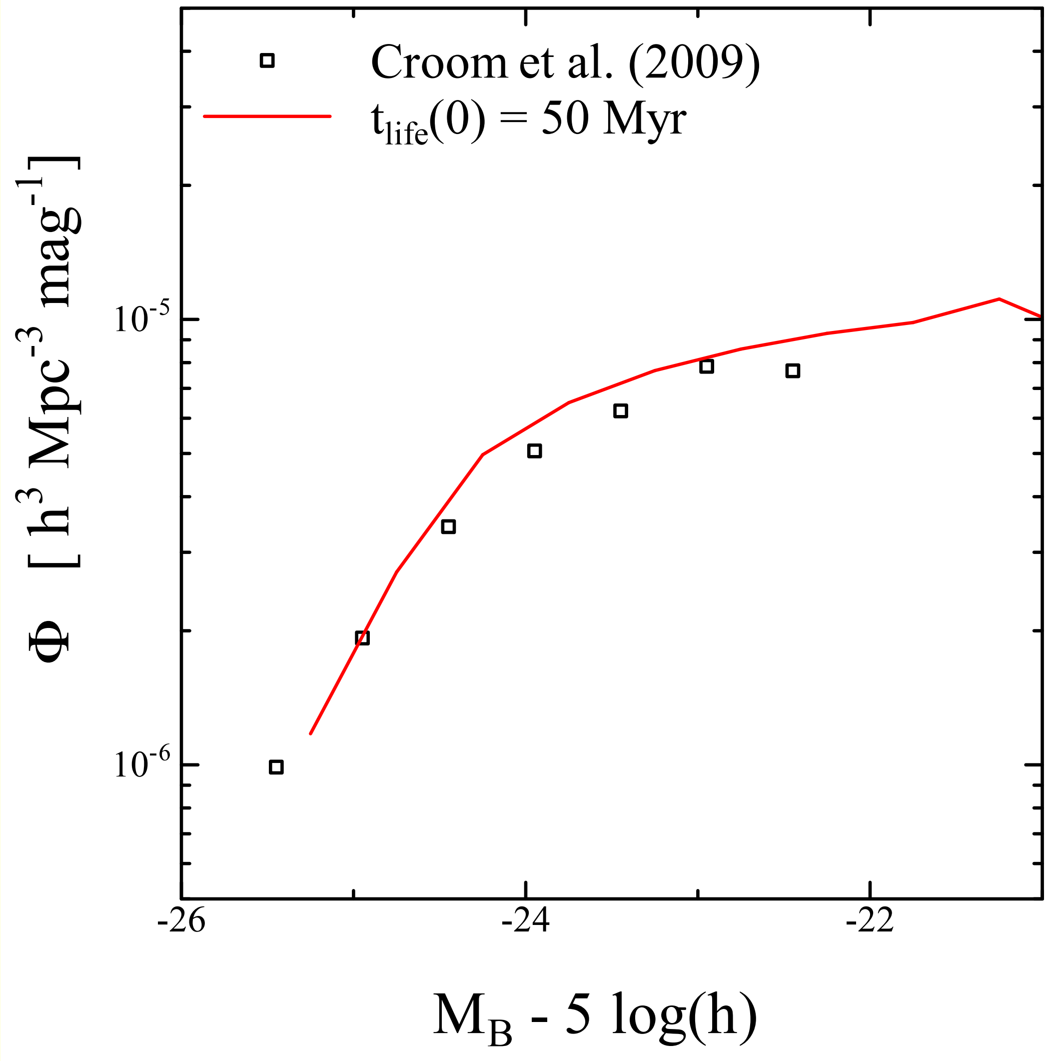
$t_{\rm life}$ scales with the dynamical time scale of the host galaxy

ε_B, $t_{\rm life}$ (z = 0); fixed by matching the observed *B*-band luminosity function of QSO at z = 2.

$\varepsilon_{\rm B}$, = 0.0055

$t_{\rm life}$ (z = 0) = 50 Myr

• QSO luminosity functions at z = 2

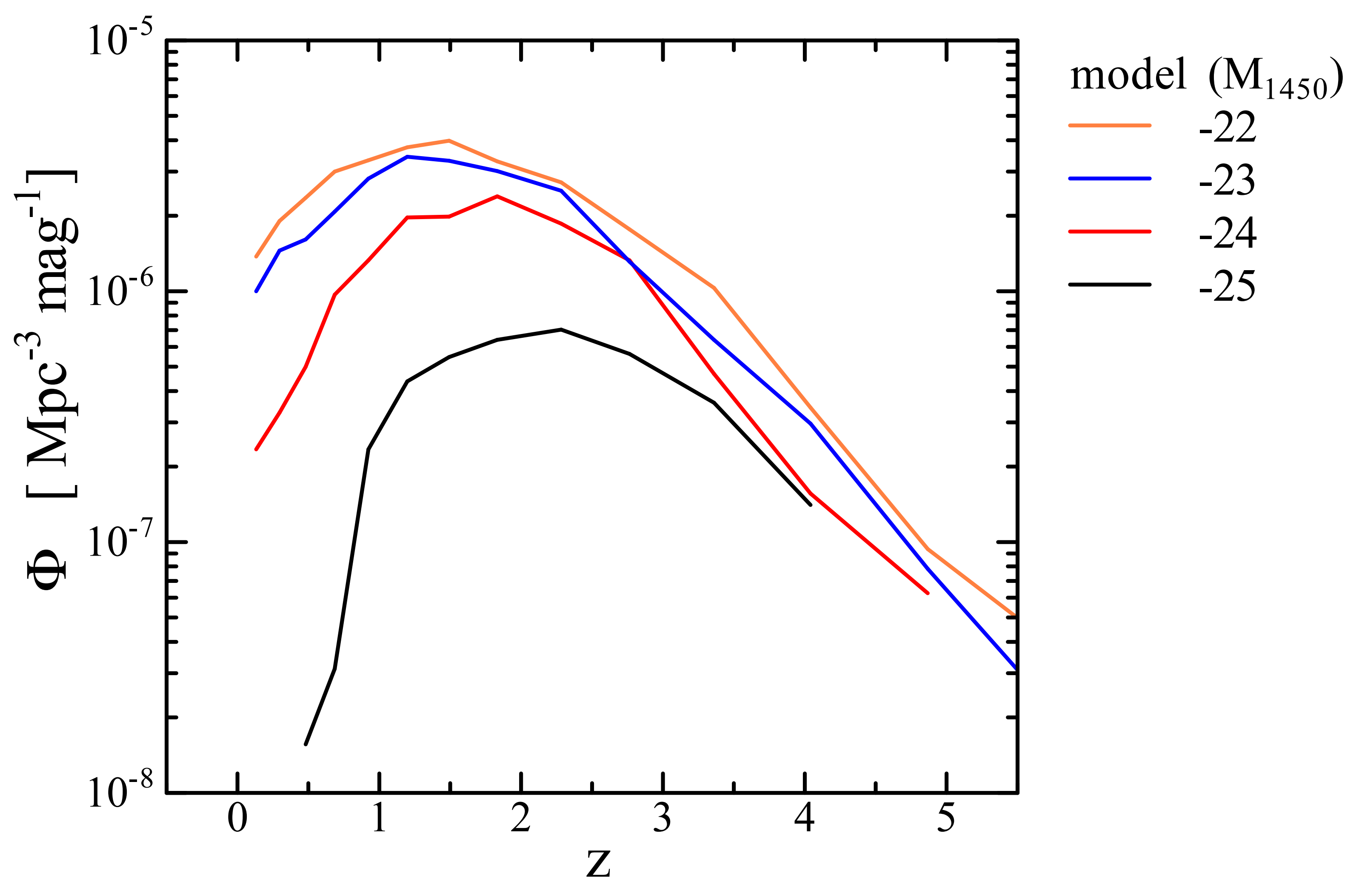


ε_B, = 0.0055,

$t_{\rm life}$ (z = 0) = 50 Myr

§3. QSO number density evolution

Our SA-model results.



The SA-model can reproduce downsizing trend.

- Why does the SA-model show down sizing trend ?

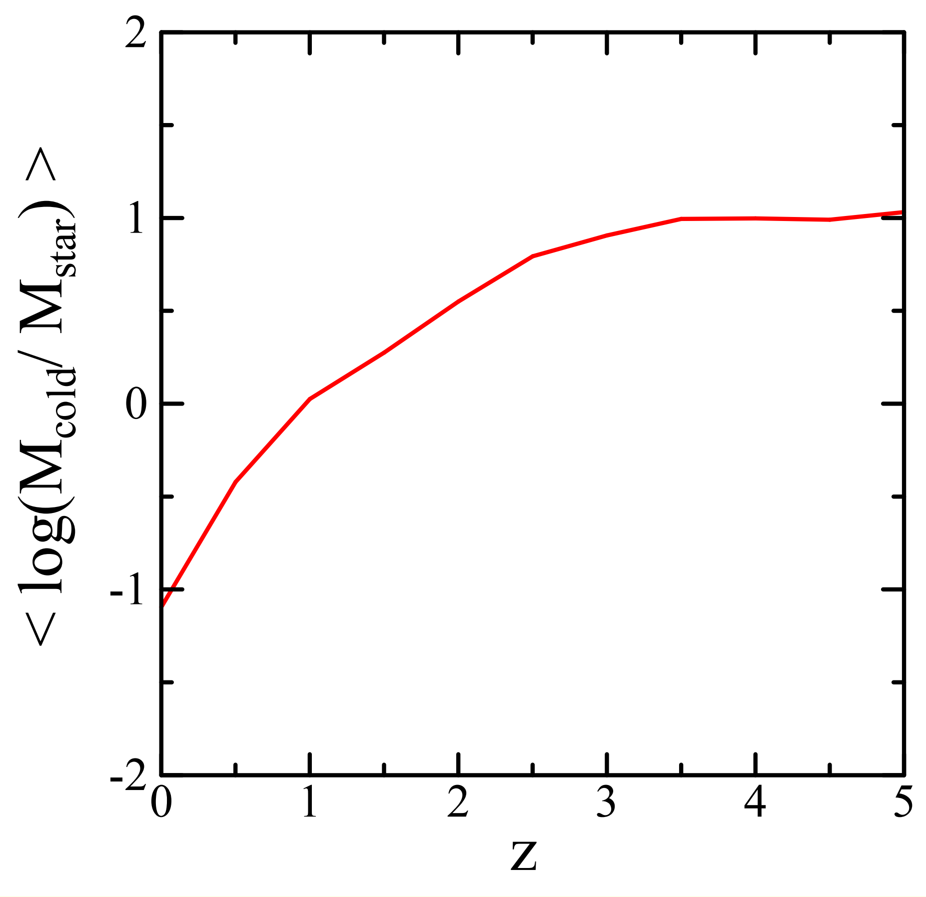
In our SA-model, the mass growth processes of SMBH are (1) cold gas accretion during starburst and (2) SMBHs coalescence.

At high redshifts, during major merger, SMBHs are fueled by much cold gas and become luminous QSOs because galaxies have much cold gas.

However, cold gas in galaxies depleted over time by star formation. The amounts of cold gas accreted onto SMBH decrease with time

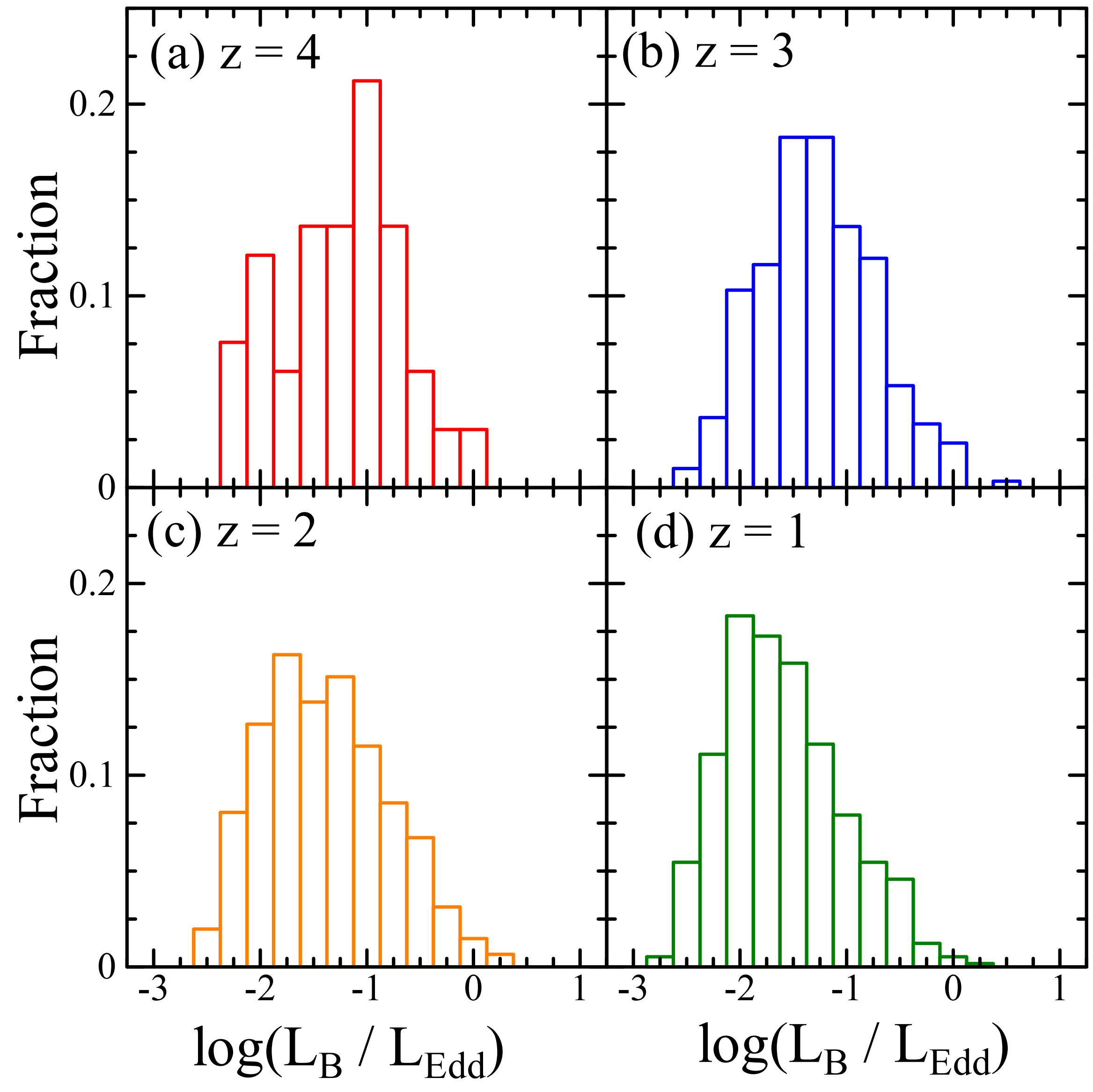
=> The space density of luminous QSOs decreases more quickly than those of faint QSOs.

• Redshift evolution of cold gas mass to stellar mass



The cold gas mass ratio in a galaxy decreases with time.
=> The amounts of cold gas accreted onto SMBH decrease with time.

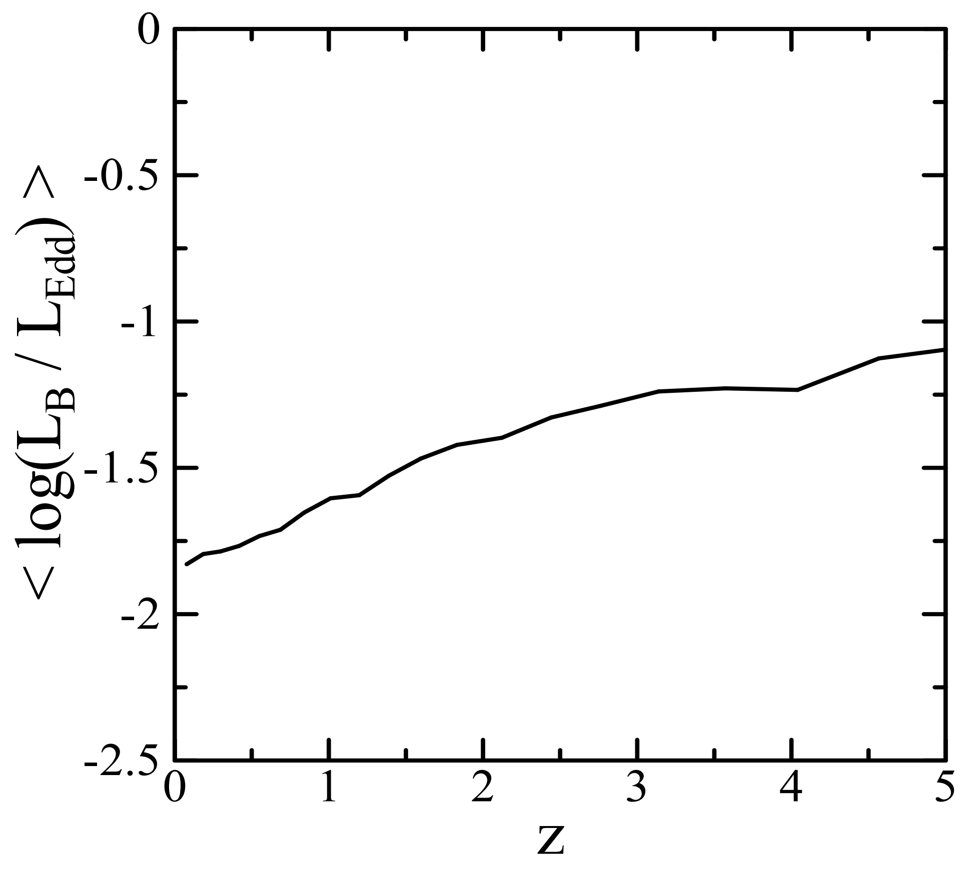
- *B*-band Eddington Ratio distributions



QSOs with M_B< -22

The fraction of high Eddington ratio QSOs (log [L_B / L_{Edd}] > -1) decreases with time.

- Redshift evolution of mean *B*-band Eddington Ratio



QSOs with $M_B < -22$

The mean of logarithm of the *B*-band Eddington ratio ($<\log[L_B / L_{Edd}]>$) decreases with time.

=> The ratio of M_{acc} to M_{BH} decreases with time.

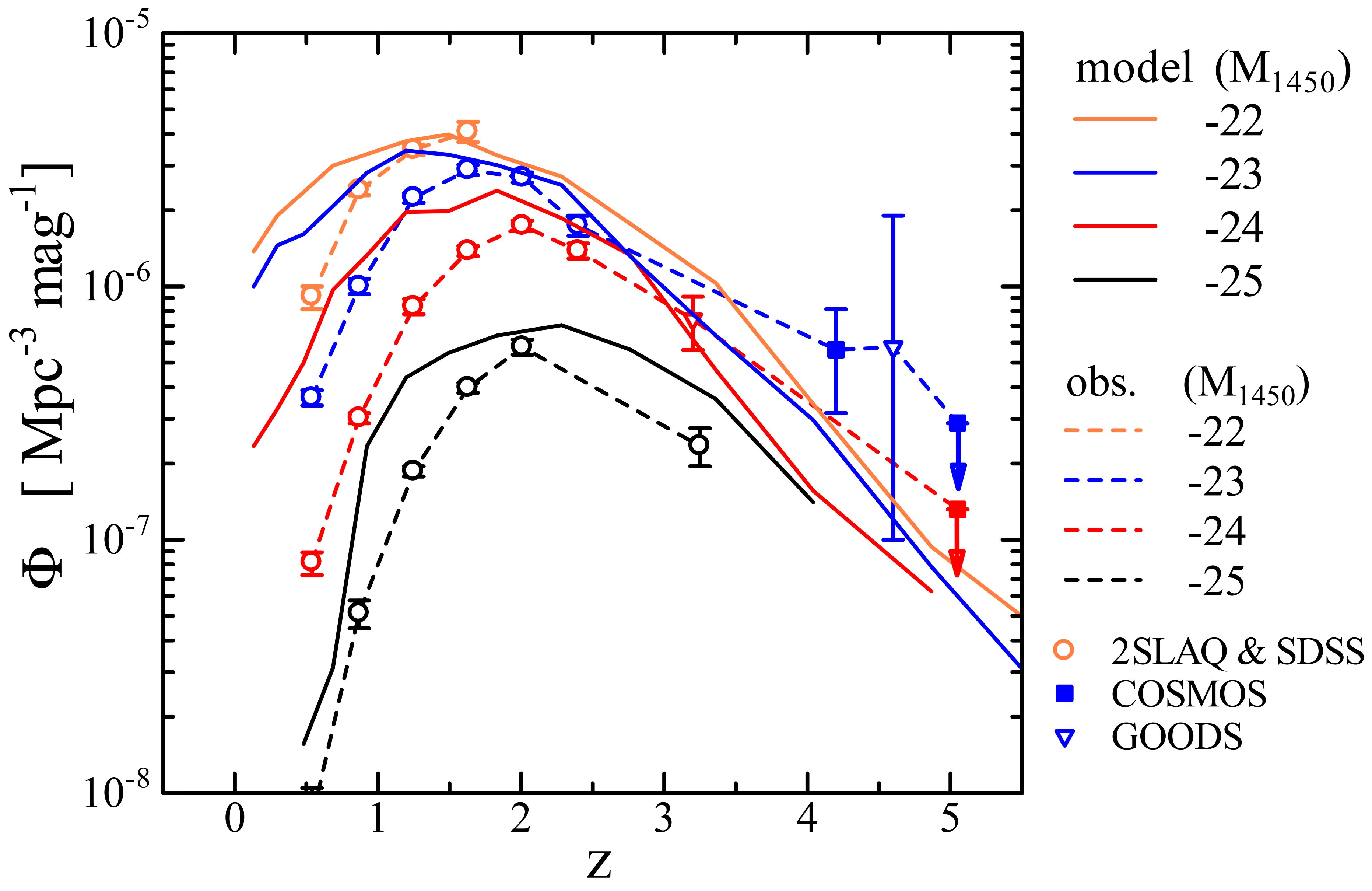
- Remark

We did not modify our model to reproduce the downsizing trend of QSOs number density evolution.

For our model, the downsizing trend of QSOs came about as a natural result.

Anti-hierarchical evolution of the QSO space density does not necessarily conflict with hierarchical structure formation scenarios.

§4. Comparison with observational data



- The space density of QSOs at $z < 1$

The faint QSO space density in our model is larger than observed faint QSO density.

=> This suggests that the cold gas mass accreted on a SMBH in our model is too large at $z < 1$.

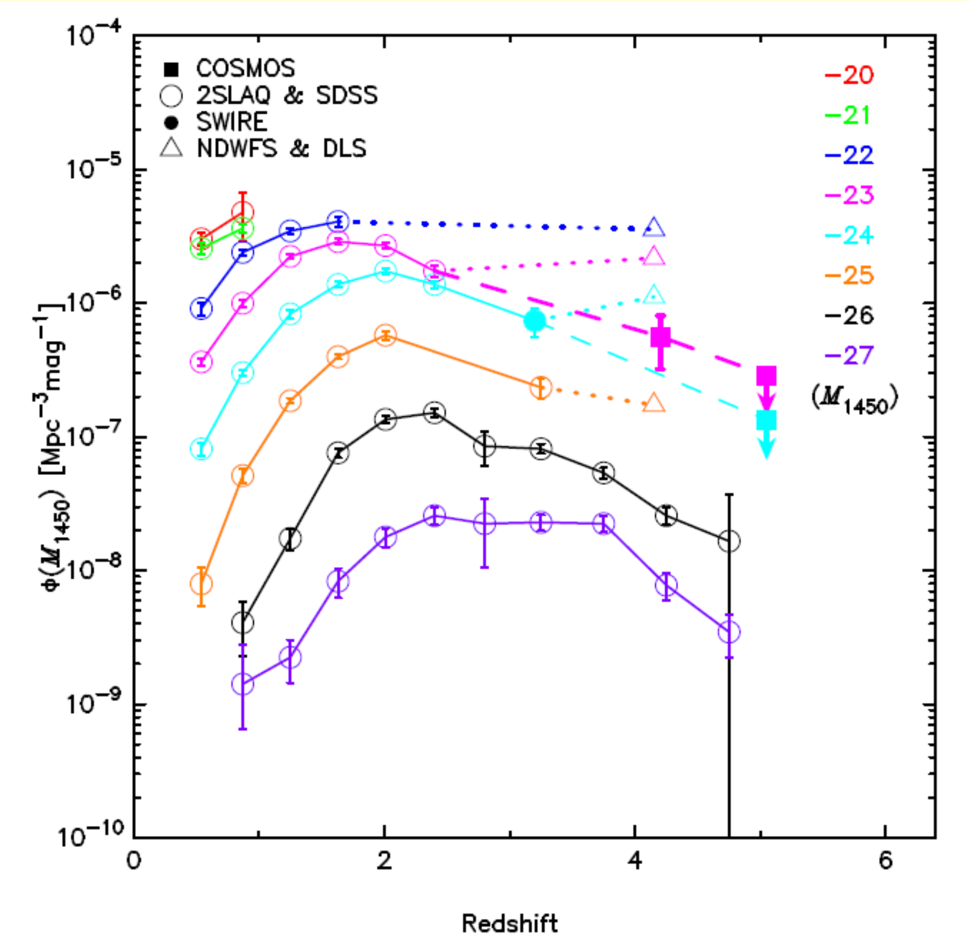
In our model, we assume that all the cold gas supplied from host galaxy accretes onto the SMBH.

⇔ The coevolution model of a SMBH and a circumnuclear disk proposed by Kawakatu & Wada (2008) .

In their model, not all the gas supplied from host galaxy accretes onto the SMBH because part of the gas is used to form stars in the circumnuclear disk.

• The space density of QSOs at z > 3

There is a discrepancy between observational results themselves of faint QSO space densities.



Ikeda et al. (2012)

=> Further observations of faint QSOs in a wider survey area are crucial to obtain QSO densities.

=> **HSC survey** will provide useful constraints on QSO & SMBH evolution model.

- Summary

In our semi-analytic model of galaxy and QSO formation based on a hierarchical structure formation scenario, the evolution of QSO space density shows downsizing trend.

=> We suggest that anti-hierarchical evolution of the QSO space density is not necessarily contradictory to hierarchical structure formation scenarios.

We plan to improve our SA-model to include the SMBHs and circumnuclear disks coevolution model of Kawakatu & Wada (2008).

=> Study of the clustering of QSOs and galaxies

§5. QSO clustering (in progress)

Cosmological *N*-body simulations enable us to study the clustering of QSOs and galaxies.

The number density of QSO is small : $n_{\rm qso} = 10^{-8} \sim 10^{-6}$ Mpc^{-3}

=> Large simulation boxes are required.

⇔ In the case of a large box size simulation, the mass resolution is low.

We plan to use 2 simulations.

* 400Mpc box size simulation
  => QSO-galaxy cross correlation

* 800Mpc box size simulation
  => QSO-QSO auto correlation

- Cosmological *N*-body simulations (Ishiyama et al.)

Number of particles : 2048^3

* 400Mpc box size simulation

Merging histories of dark halos are taken from *N*-body simulations.

=> *New* **νGC**

* 800Mpc box size simulation

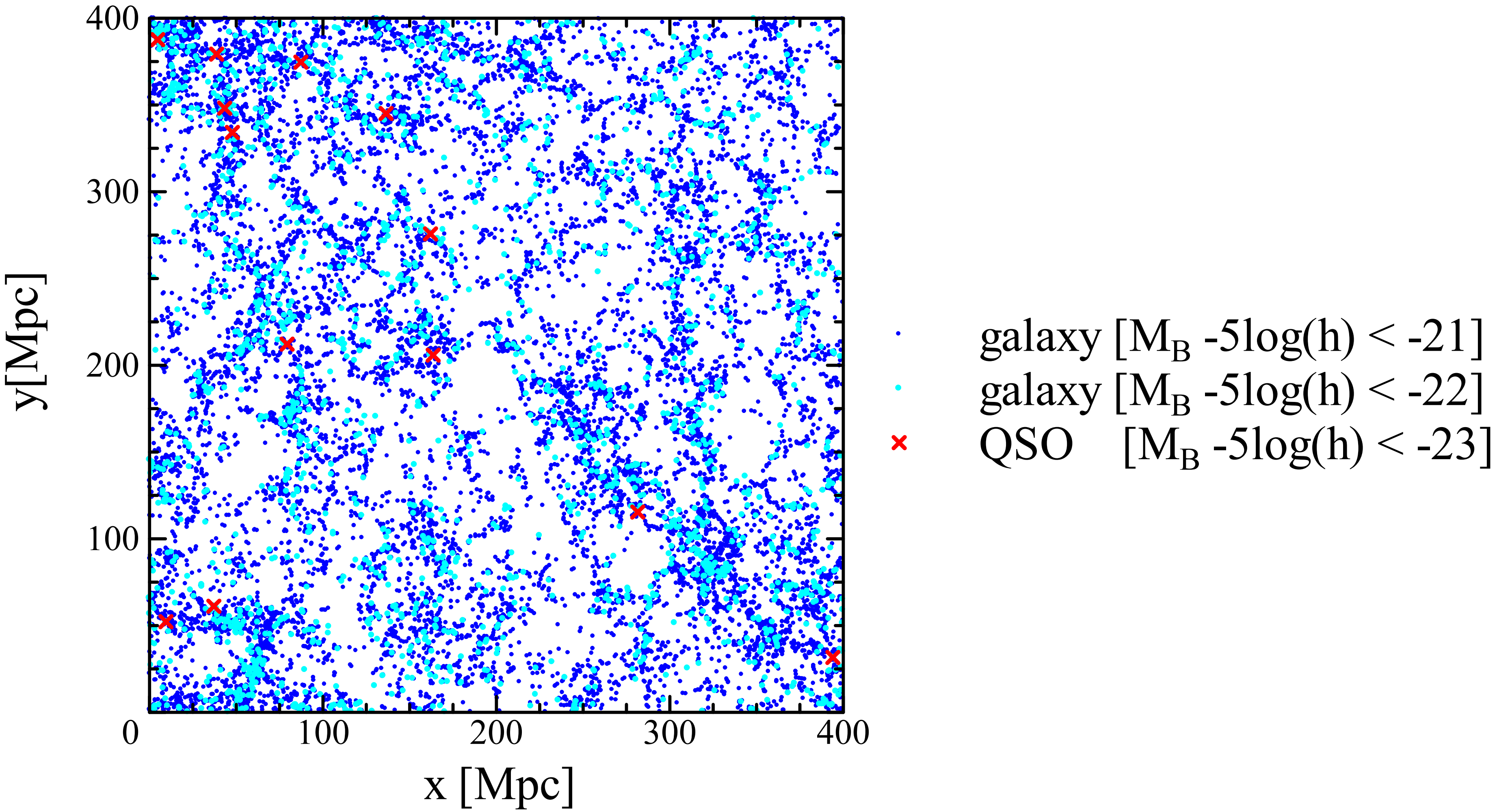
We use information on dark halo distribution from *N*-body simulations at output redshifts.

Merging histories of dark halos are realized using a Monte-Carlo algorithm.

=> Hybrid SA model

• QSO and galaxy distributions (preliminary)

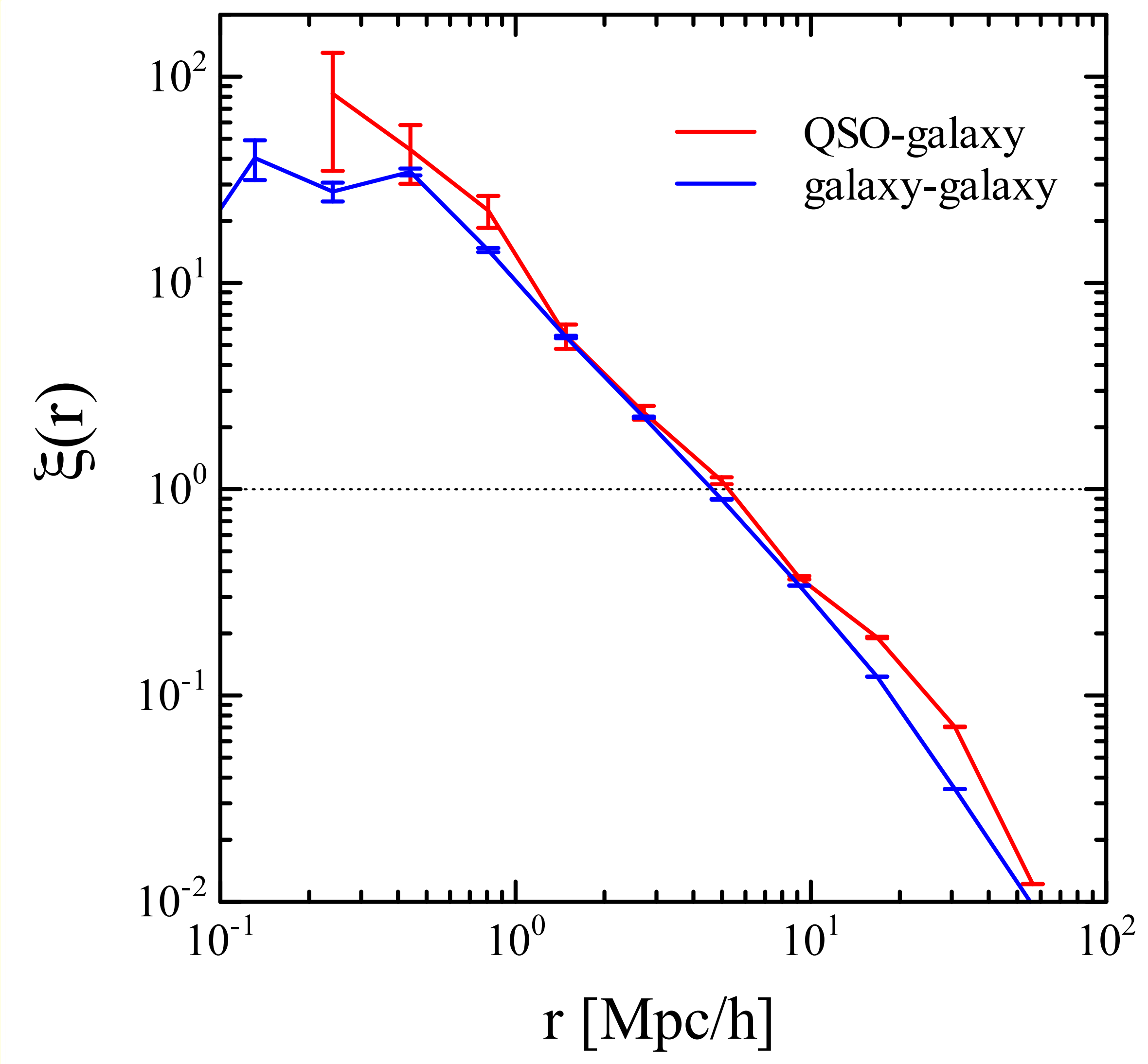
Current *New* **νGC** result at z = 3（400Mpc ⇔ 3.5 deg）



400 Mpc ×400Mpc× 20 Mpc

• QSO-galaxy cross correlation functions (preliminary)

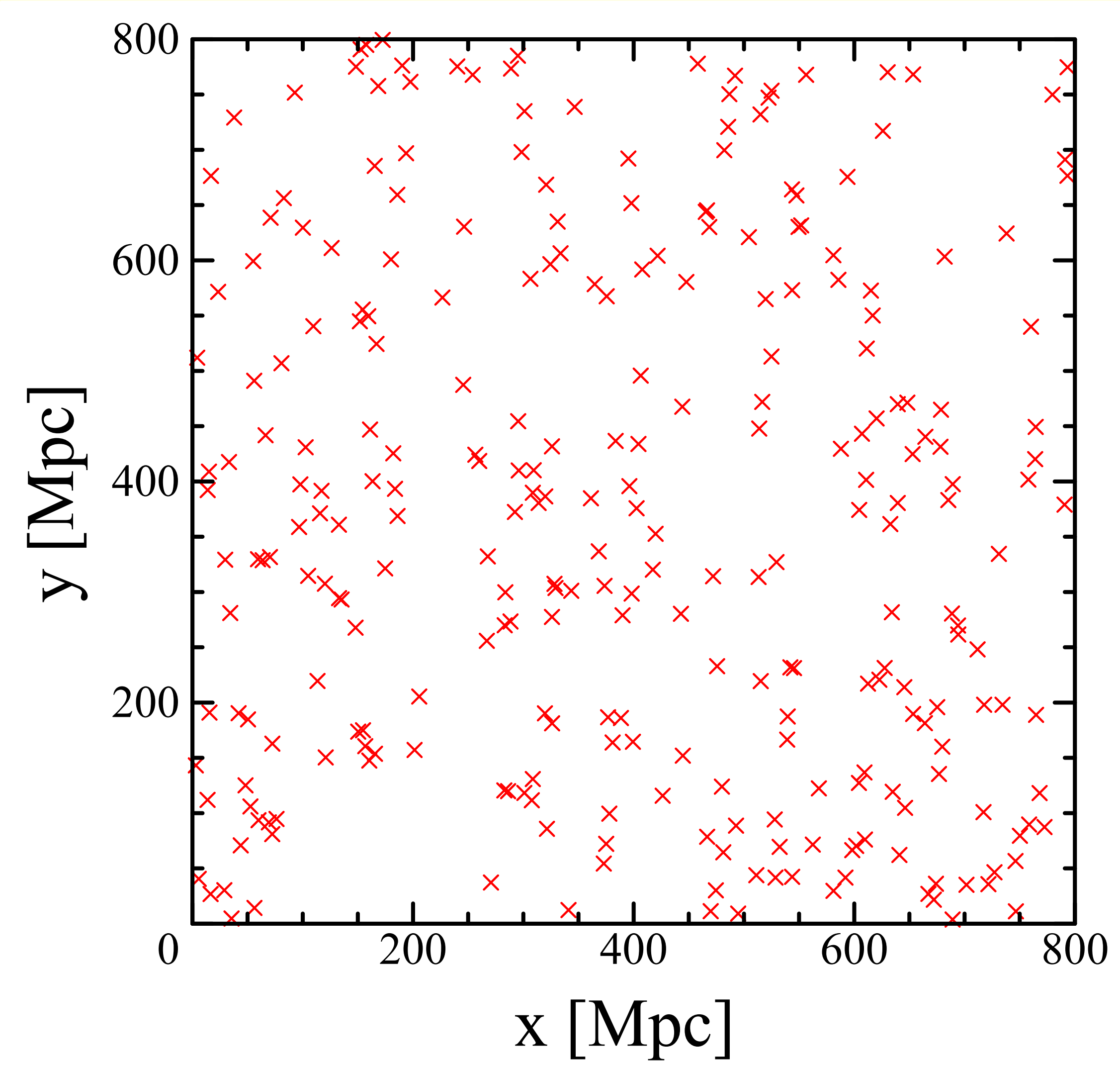
Current *New* **νGC** result at z = 3 (400Mpc box simulation)



$M_B - 5\log(h) < -22$

• QSO distribution (tentative)

A Hybrid SA-Model result at z = 3 （800Mpc ⇔ 7 deg）

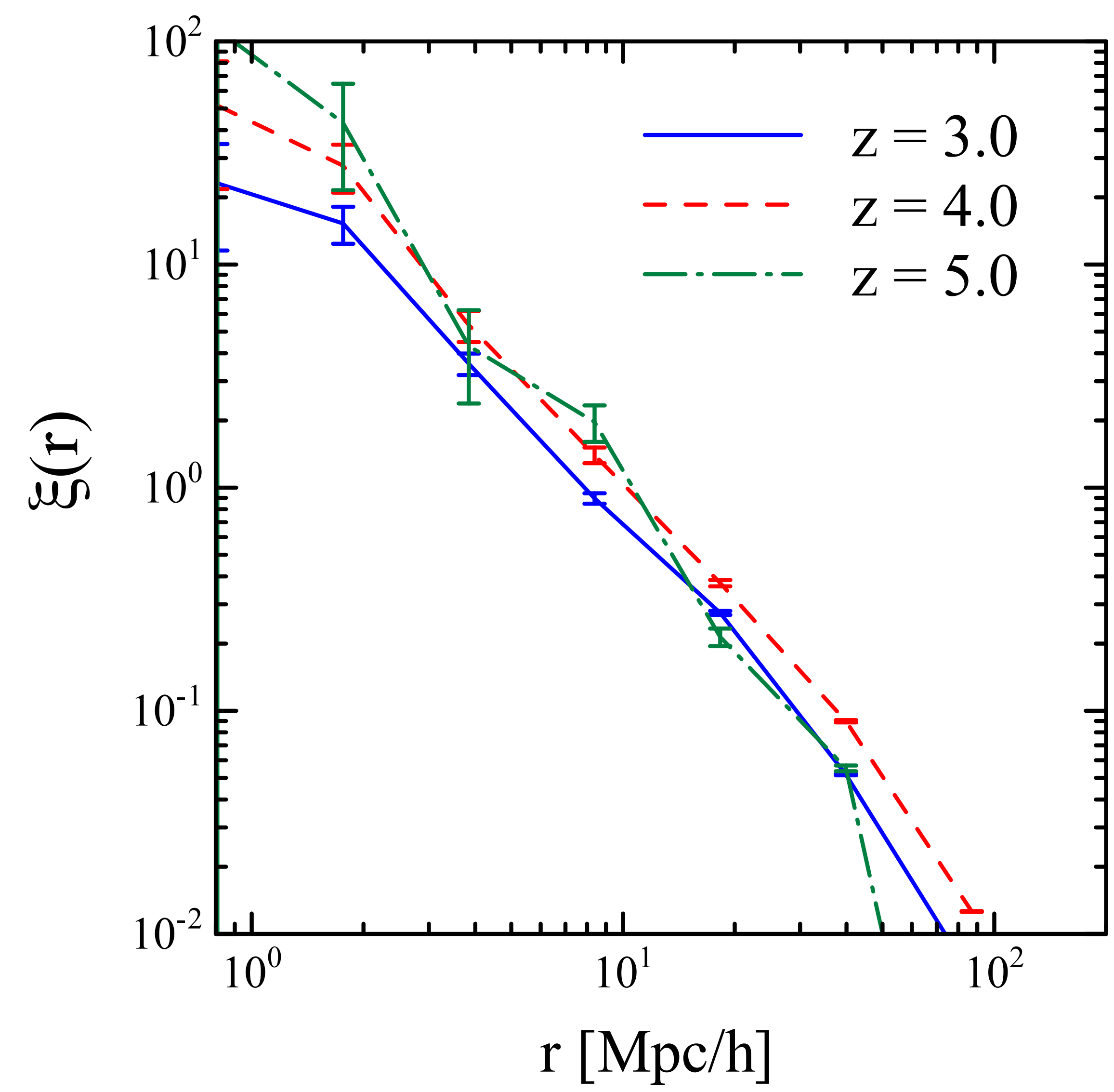


QSOs with
$M_B - 5\log(h) < -22$

800 Mpc ×800Mpc× 80 Mpc

• QSO auto correlation functions (tentative)

A Hybrid SA-Model results at z = 3, 4, 5



$M_B - 5\log(h) < -22$