Clustering and halo occupation of AGNs using a semi-analytic model of galaxy formation

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Oogi et al. in prep.

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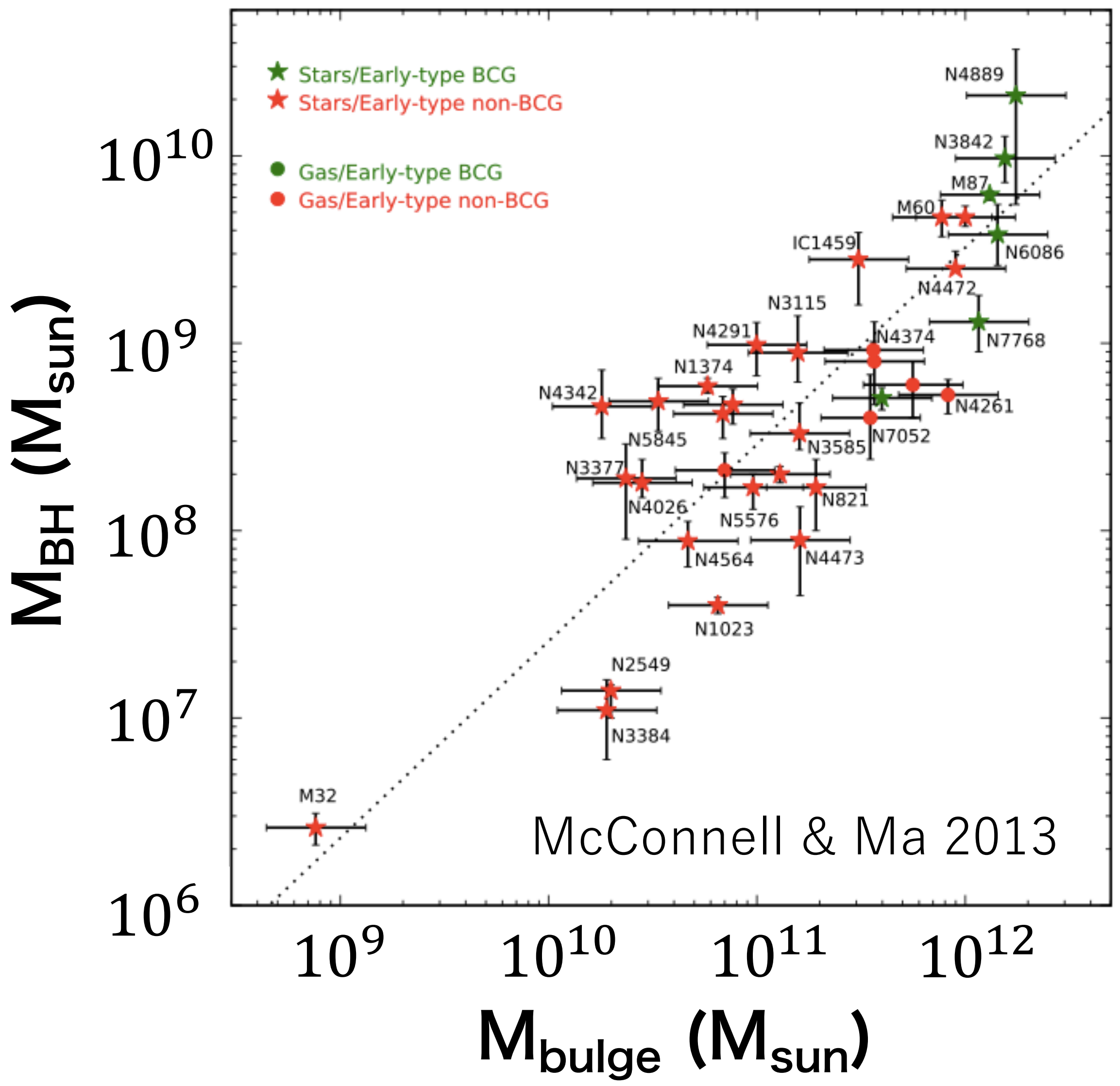
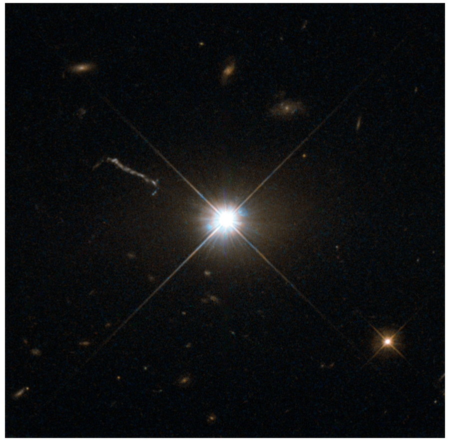
Outline

- Co-evolution of supermassive black holes and galaxies
- AGN host halo masses
- Previous work
- Model
  - AGN triggering mechanisms
- Results
  - Two-point correlation functions of AGNs
  - Redshift evolution of AGN host halo masses
  - AGN halo occupation distributions (HODs)
- Summary

M_{BH}-M_{bulge} relation



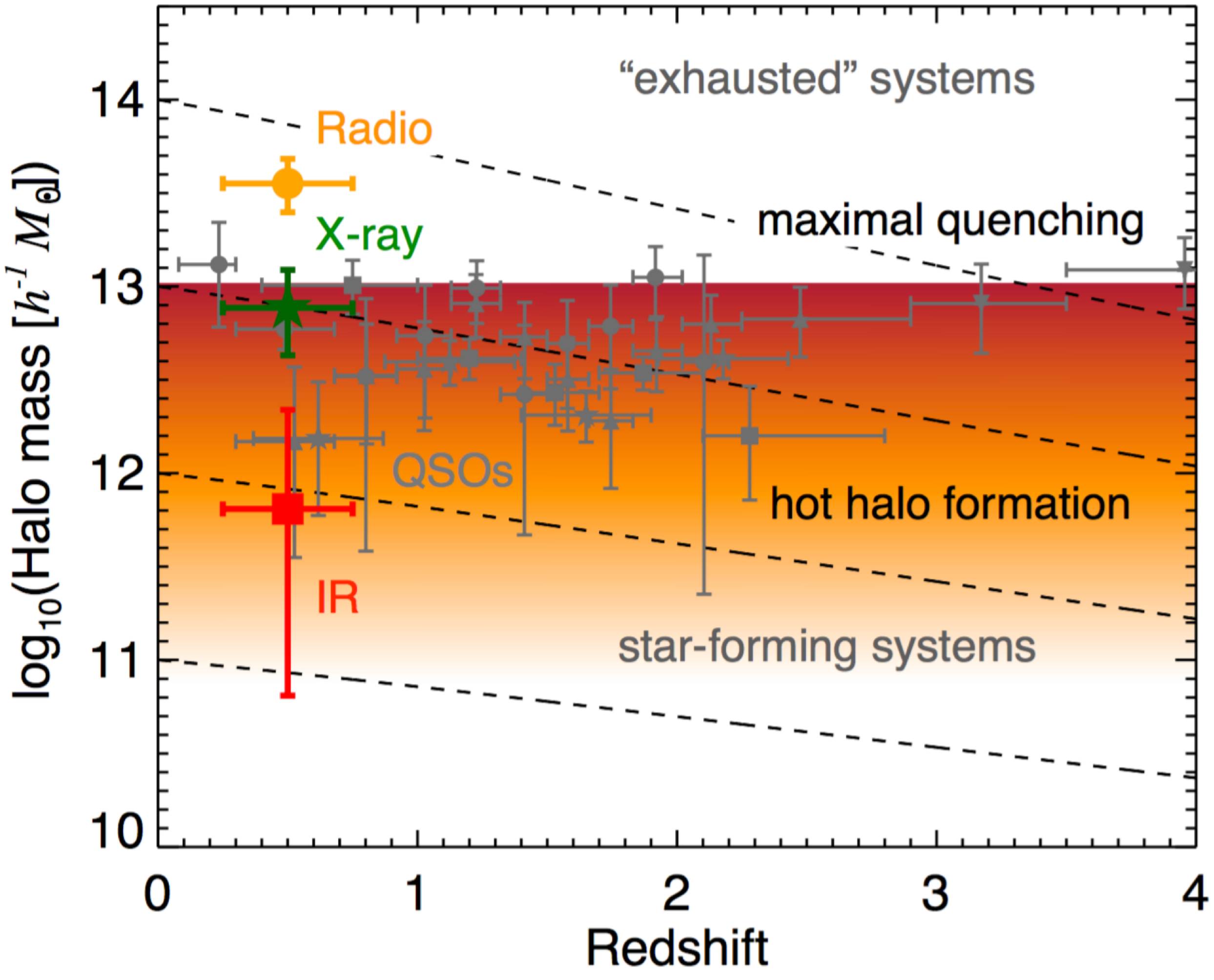


QSO 3C273
(ESA/Hubble & NASA)

- Implication for the co-evolution of SMBHs and galaxies.
- Statistical properties of active galactic nuclei (AGNs) are important for understanding the co-evolution.

AGN host dark matter (DM) halos

Redshift evolution of DM halo mass inferred from AGN clustering for AGN populations (Alexander & Hickox 2012)



AGN clustering and host halo mass can be constraints on the SMBH growth and AGN triggering mechanisms.

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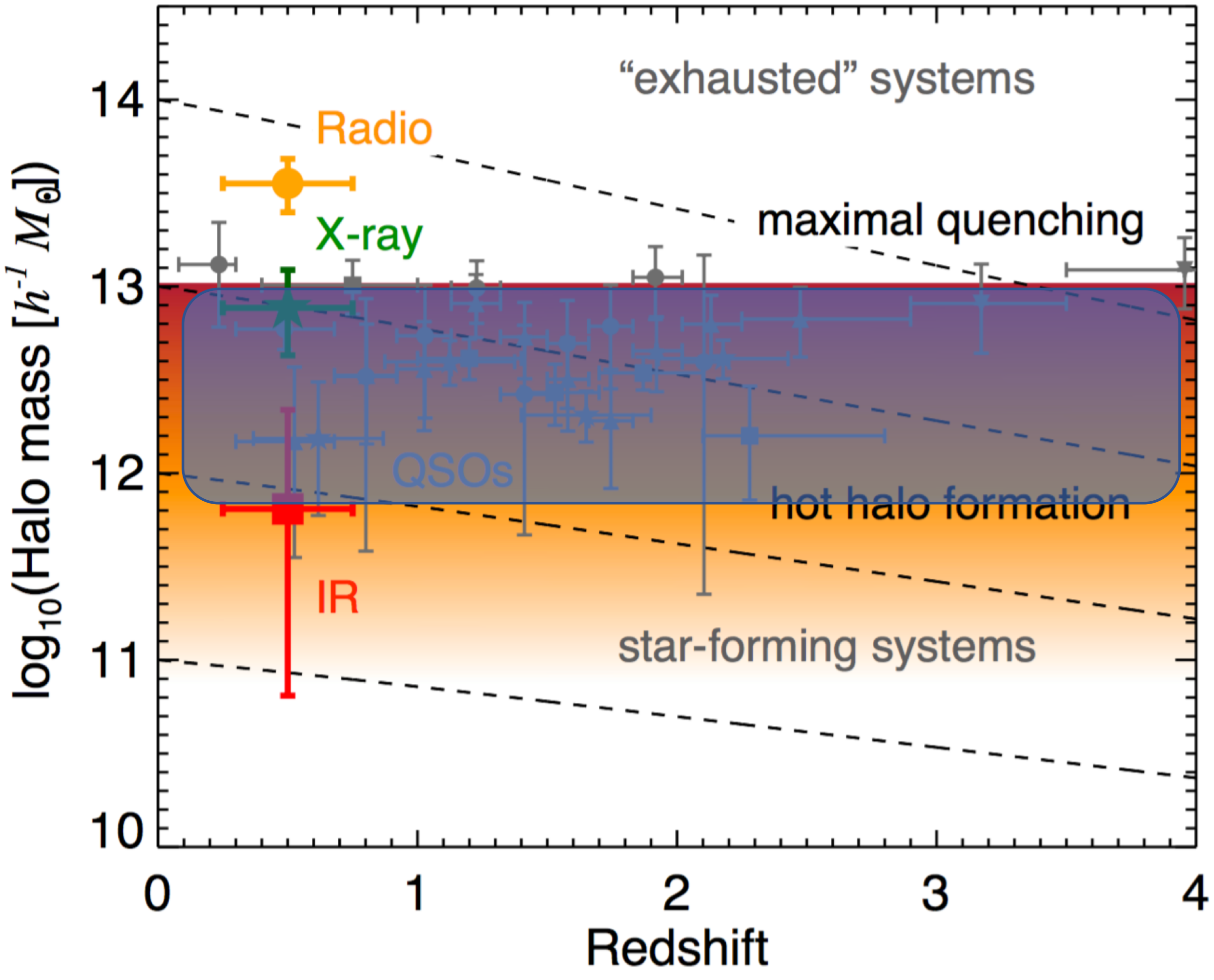
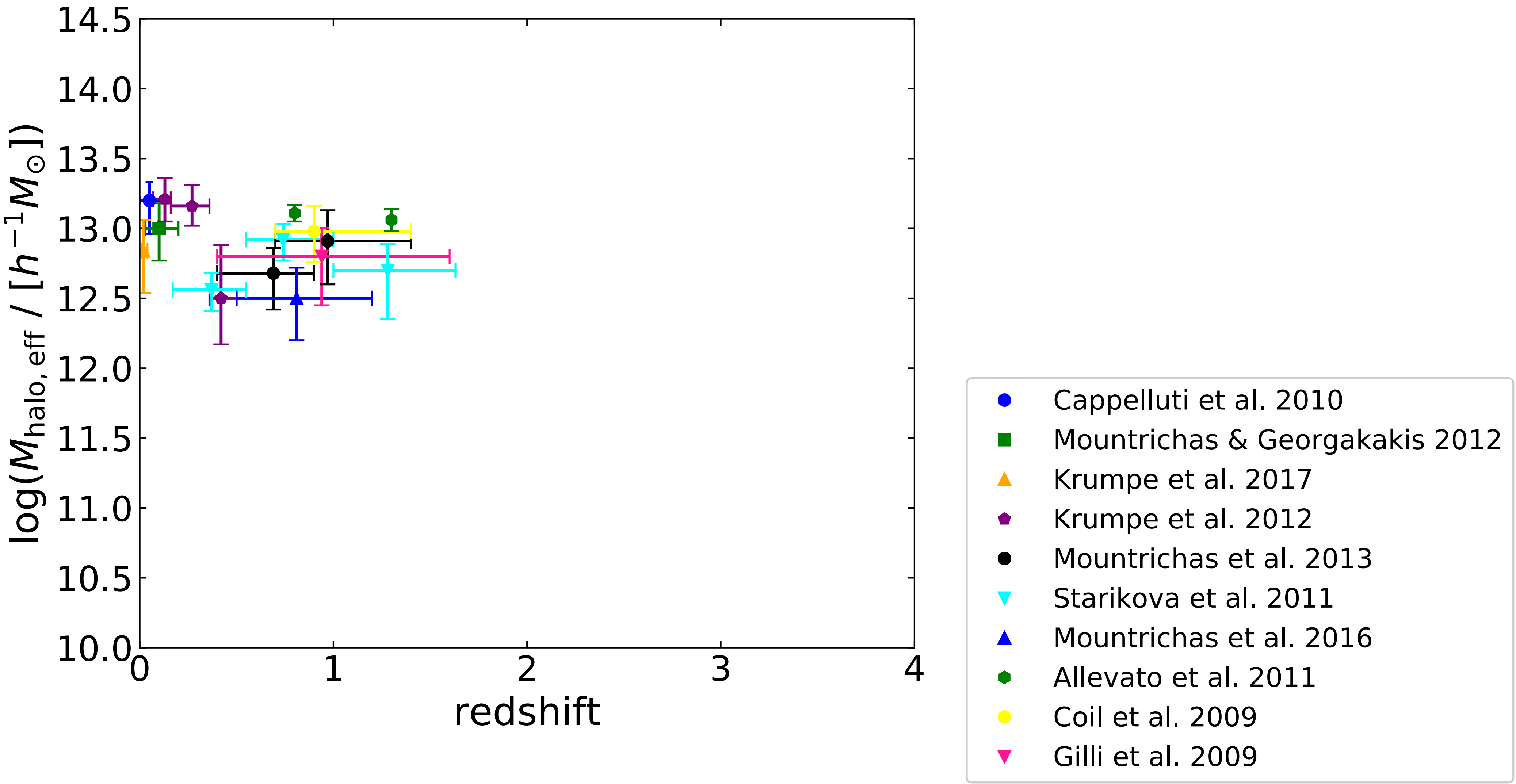


For optically luminous quasars, the host halo mass inferred from clustering is $\mathbf{2-3\times10^{12}}h^{-1}M_{\odot}$.

DM halo mass of X-ray AGNs

Redshift evolution of DM halo mass for moderate luminosity (X-ray) AGNs (compilation by Georgakakis et al. 2019)



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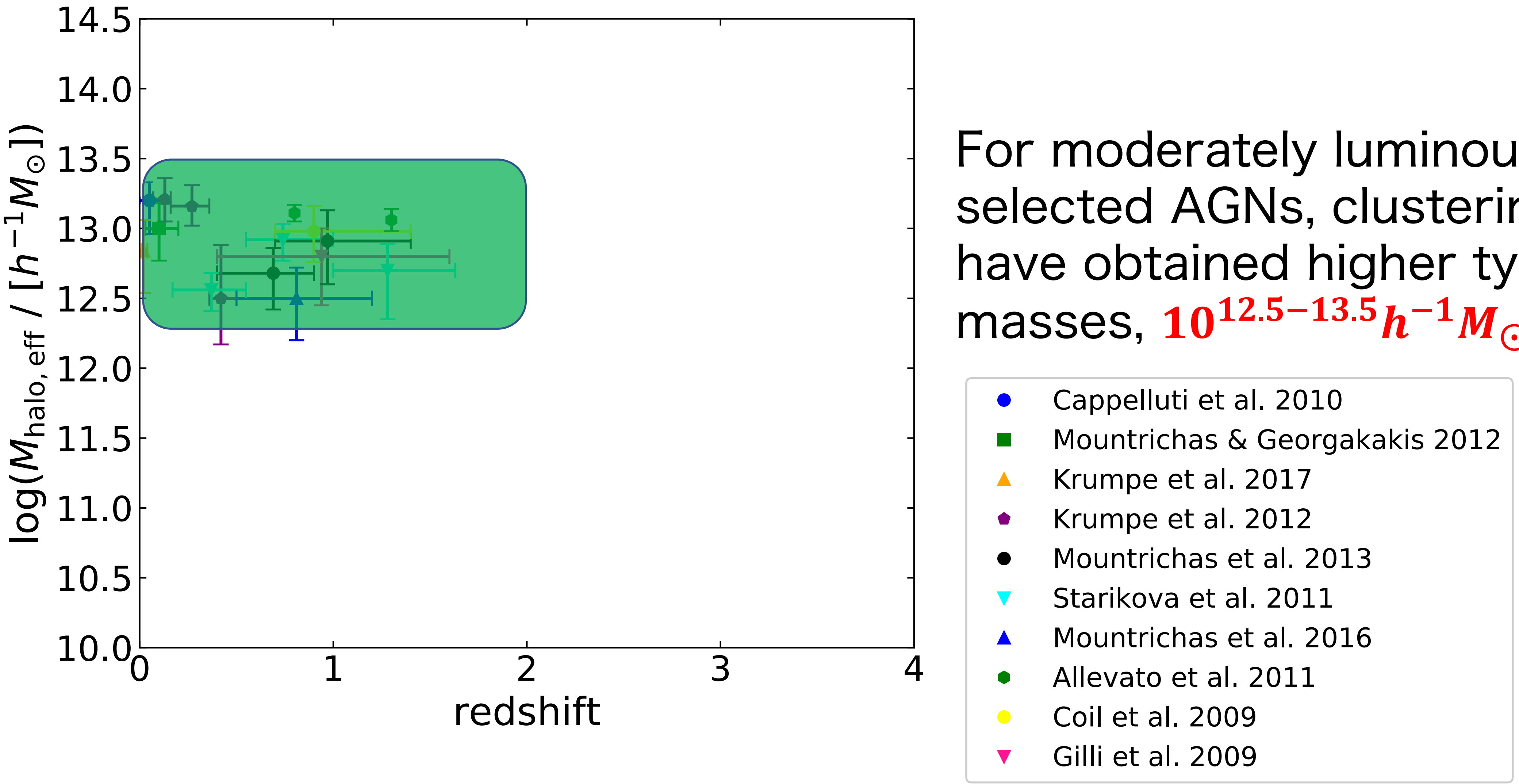

For moderately luminous X-ray-selected AGNs, clustering studies have obtained higher typical halo masses, $\mathbf{10^{12.5-13.5}} \boldsymbol{h^{-1} M_{\odot}}$.

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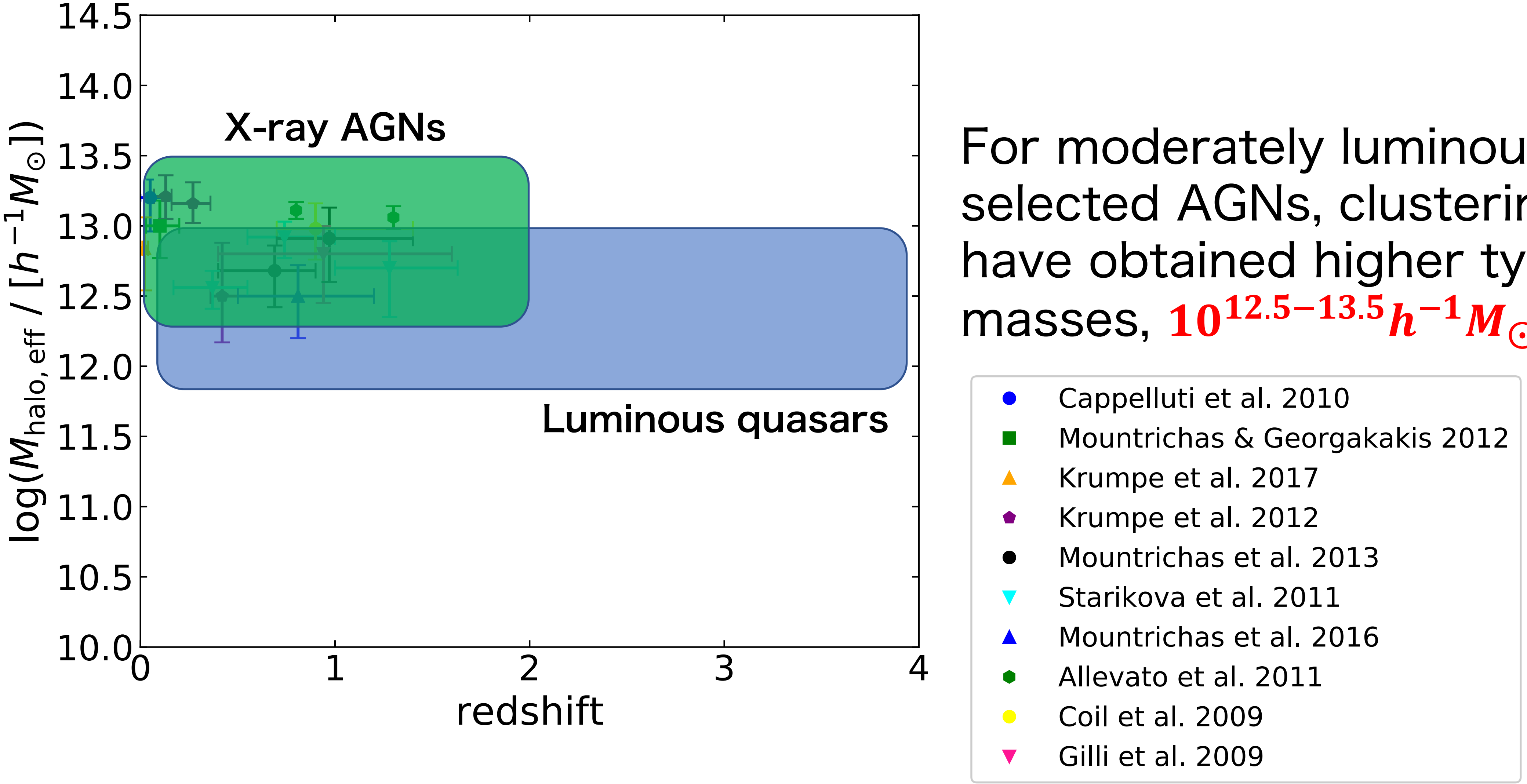

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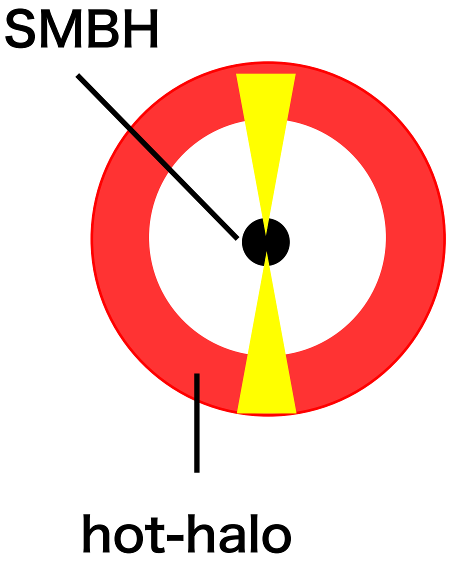
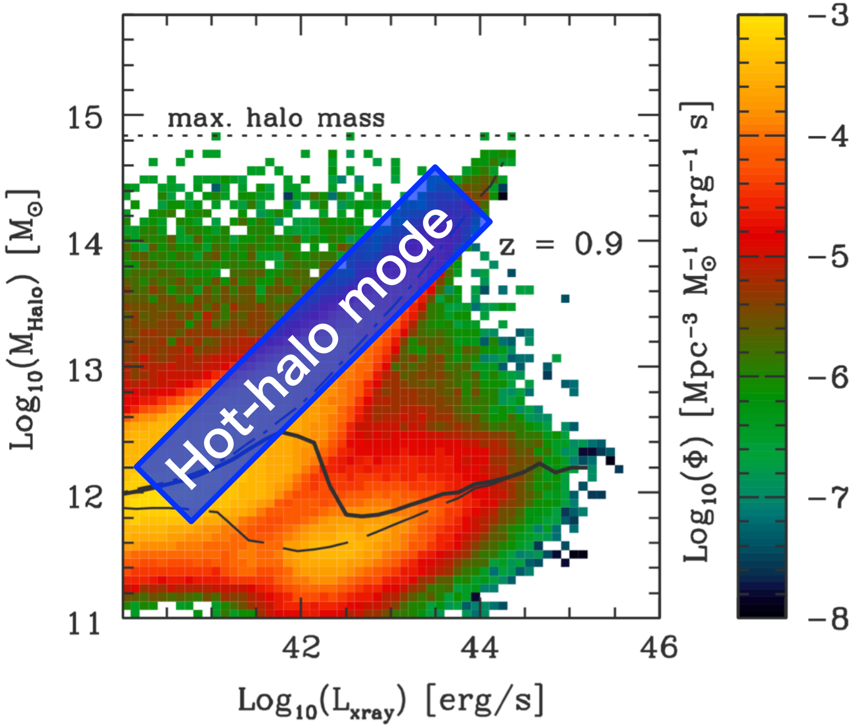
Previous work

- The DM halo mass of luminous quasars can be explained by models in which quasar activity is triggered by galaxy major mergers (at least $z \lesssim 2$).
- The X-ray AGN host halo can be explained by “hot-halo mode AGN” (Fanidakis et al. 2013).

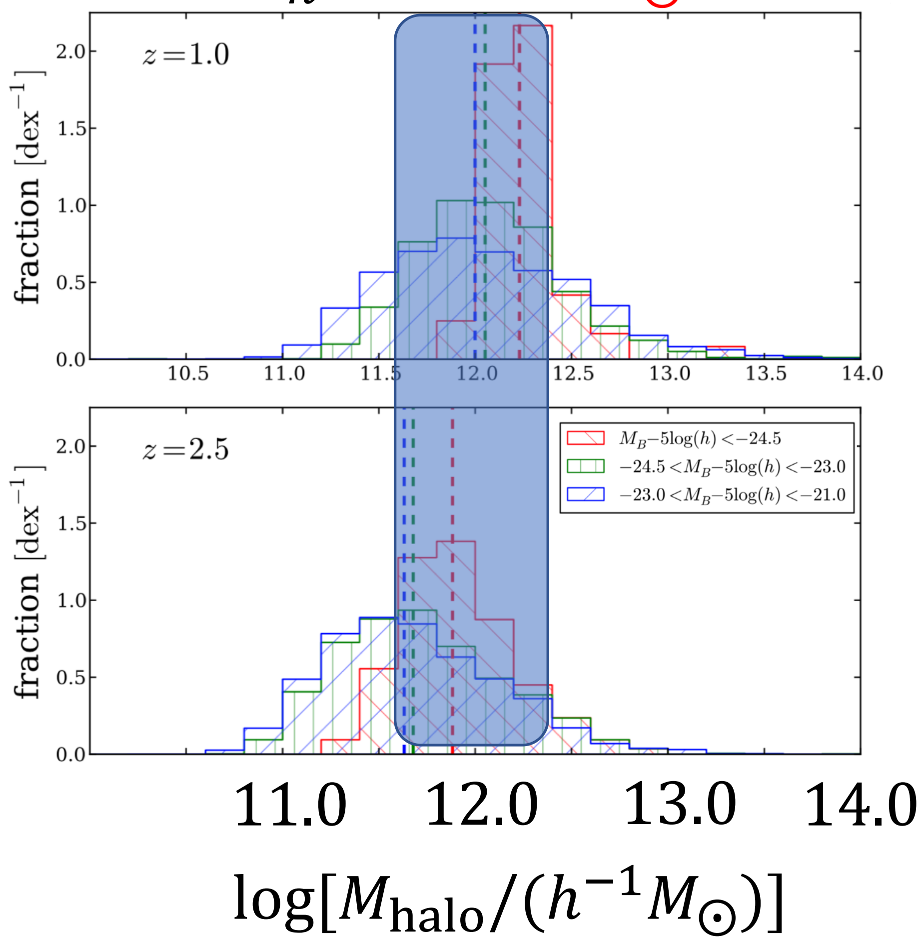




Fanidakis et al. 2013

DM halo mass distribution of quasars

$M_h \sim 10^{12} h^{-1} M_\odot$

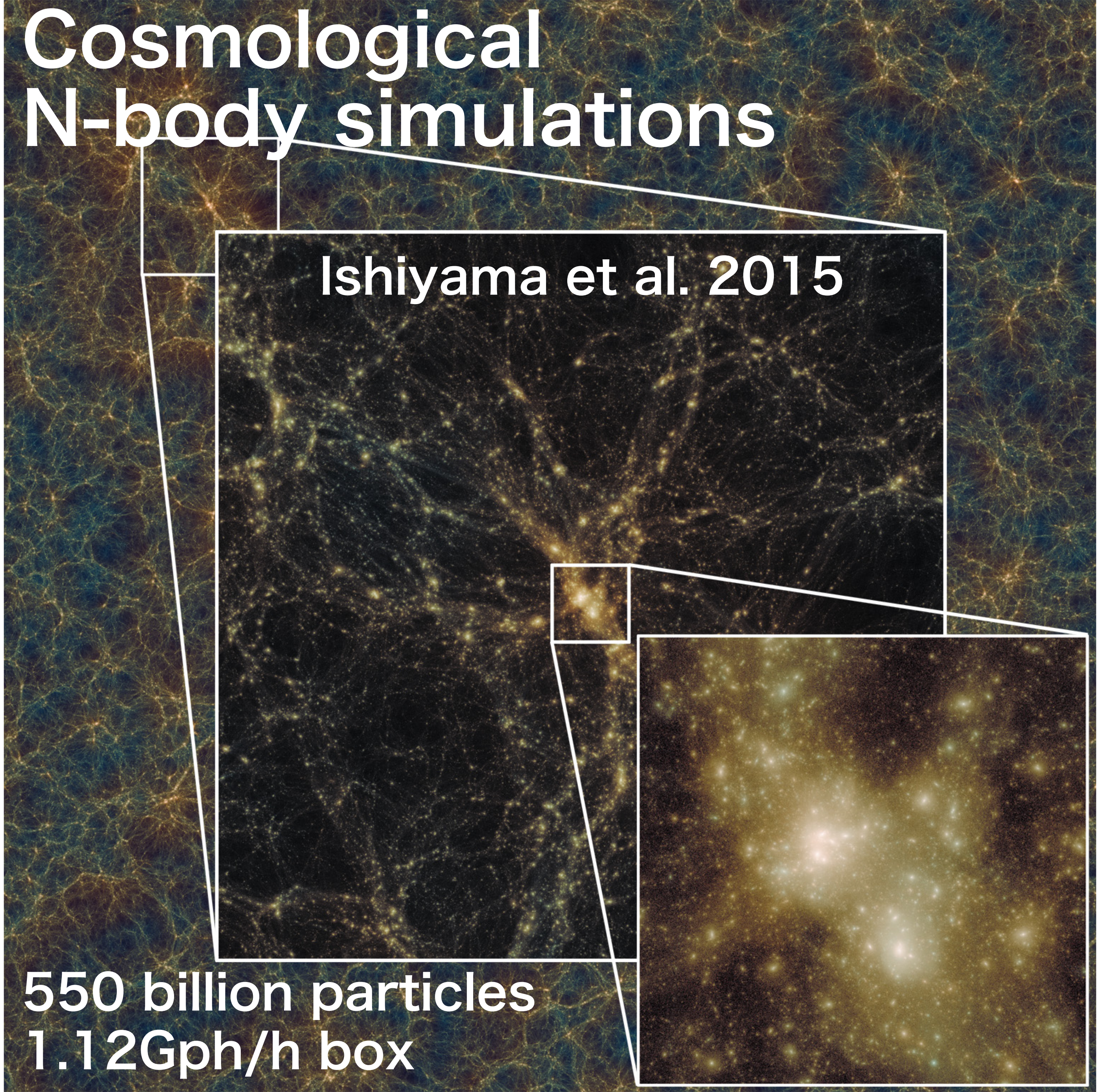


Oogi et al. 2016

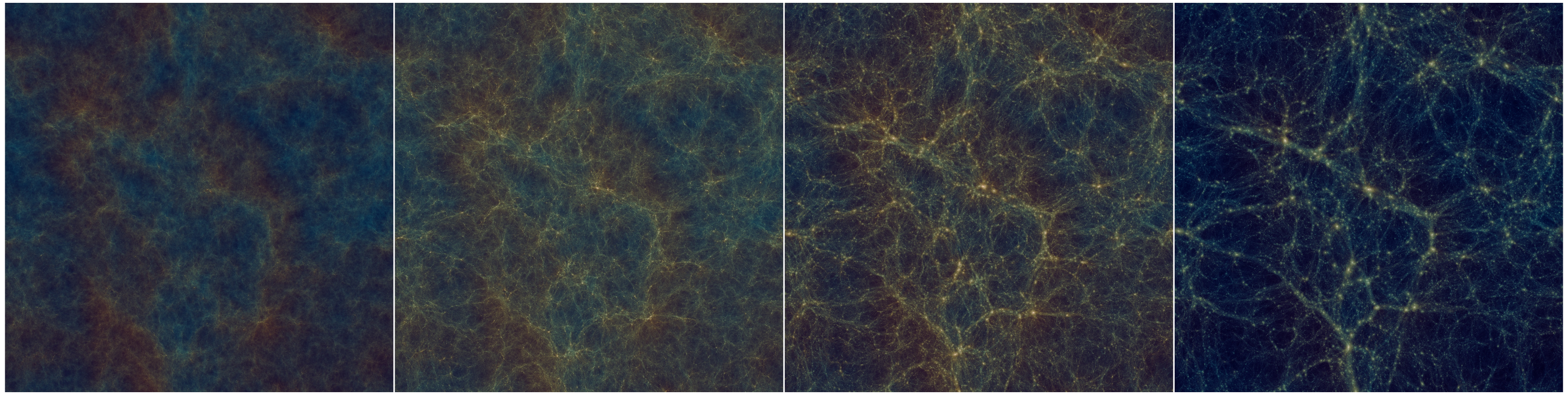
Aim of this study

We explore whether the galaxy major and minor mergers and disc instabilities as triggering mechanisms for AGNs are able to explain the host haloes of X-ray AGNs with $\sim 10^{13} h^{-1} M_{\odot}$ or not.

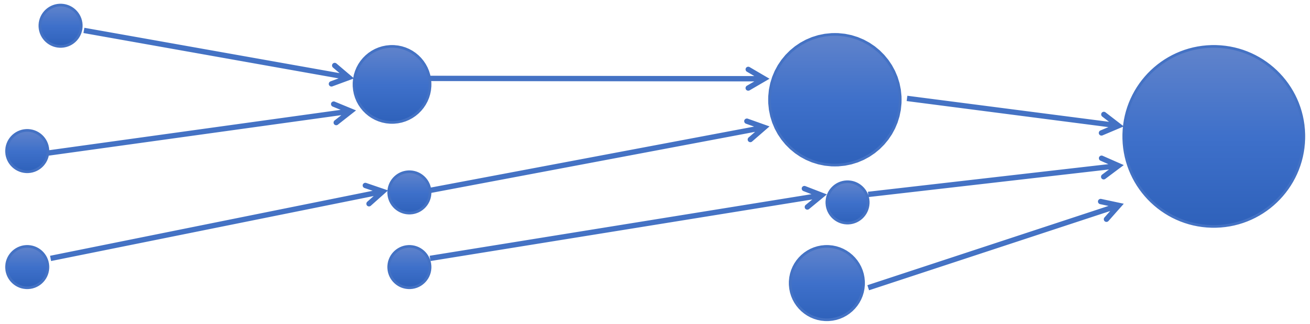
We investigate this issue with our semi-analytic model of galaxy and AGN formation, $\nu^2 GC$ (Shirakata et al. 2019)


Cosmological
N-body simulations
Ishiyama et al. 2015
550 billion particles
1.12Gph/h box

Merger trees of dark matter halos



Merger history of dark matter halos



Boxsize (Mpc/h)	N	m (M_{sun}/h)	ε (kpc/h)	M_{min} (M_{sun}/h)	Cosmology
1120.0	8192^3	2.20×10^8	4.27	8.79×10^9	Planck

Semi-analytic model ν^2GC

1. AGN triggering model

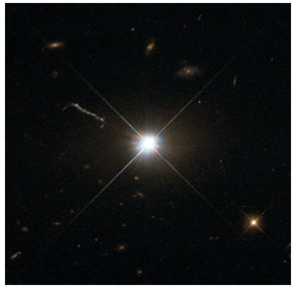
Assumption: a major/minor merger of galaxies and disk instability trigger cold gas accretion on to a SMBH and AGN activity.

The mass accretion rate:

$$\dot{M}_{\mathrm{BH}} = \frac{\Delta M_{\mathrm{acc}}}{t_{\mathrm{acc}}} \exp\left(-\frac{t - t_{\mathrm{start}}}{t_{\mathrm{acc}}}\right)$$

Galaxy mergers

Disk instability



QSO 3C273 (ESA/Hubble & NASA)

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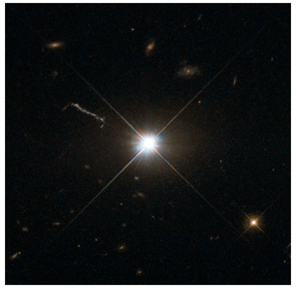

QSO 3C273 (ESA/Hubble & NASA)

2. Gas accretion timescales onto black holes

Assumption: the timescale of BH growth, i.e. gas accretion, is controlled by two timescales

- Dynamical timescale of the bulge, $t_{\rm dyn,bulge}$
- Timescale of angular momentum loss at < 100 pc, $t_{\rm loss}$

$$t_{\rm acc} = \alpha_{\rm bulge} t_{\rm dyn,bulge} + t_{\rm loss}$$

$$t_{\rm loss} \propto M_{\rm BH}^{3.5} \, \Delta M_{\rm acc}^{-4}$$

where $M_{\rm BH}$ is the SMBH mass and $\Delta M_{\rm acc}$ is the accreted gas mass.

Semi-analytic model ν^2GC

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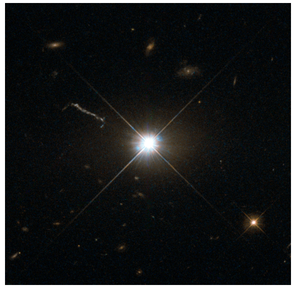

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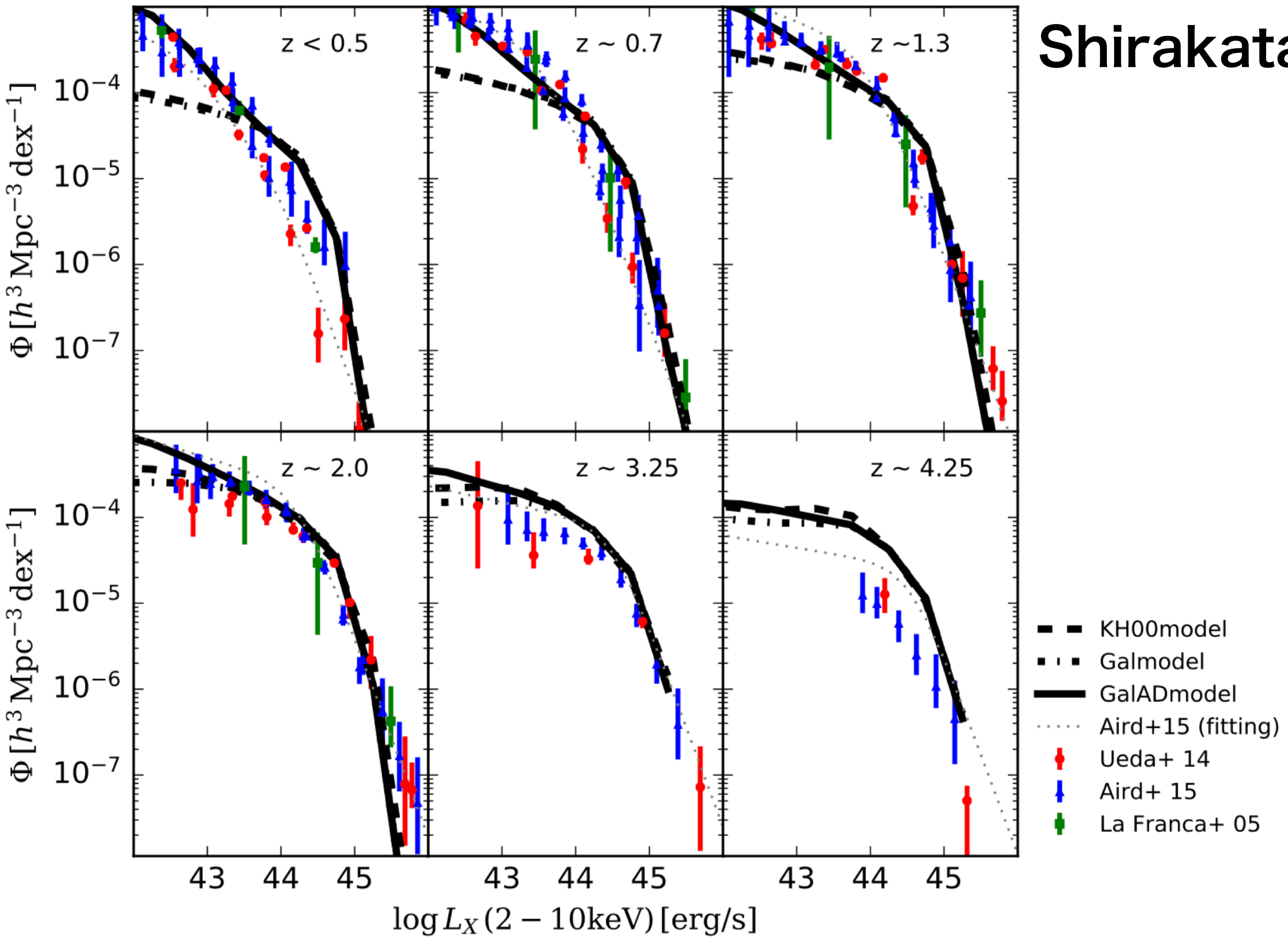
Two models

1. Model w/ $t_{\rm loss}$; $t_{\rm acc} = \alpha_{\rm bulge} t_{\rm dyn,bulge} + t_{\rm loss}$ (Fiducial model)
2. Model w/o $t_{\rm loss}$; $t_{\rm acc} = \alpha_{\rm bulge} t_{\rm dyn,bulge}$

where $M_{\rm BH}$ is

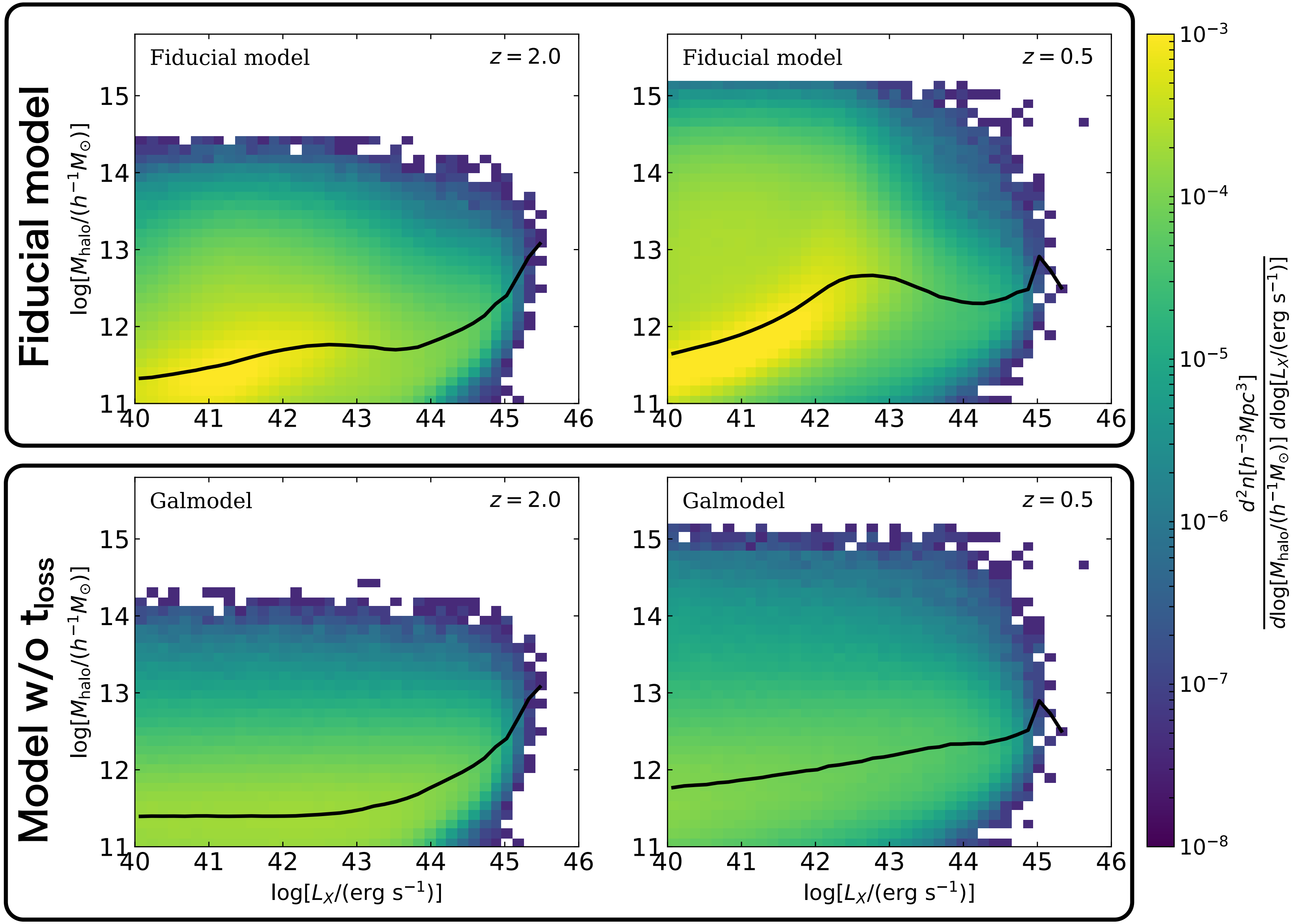
AGN luminosity functions



Shirakata et al. 2019

The model reproduces the observed AGN luminosity function at z<6.

L_x-M_{halo} relation



At z=2 and z=0.5, the halo mass depends on AGN luminosity.

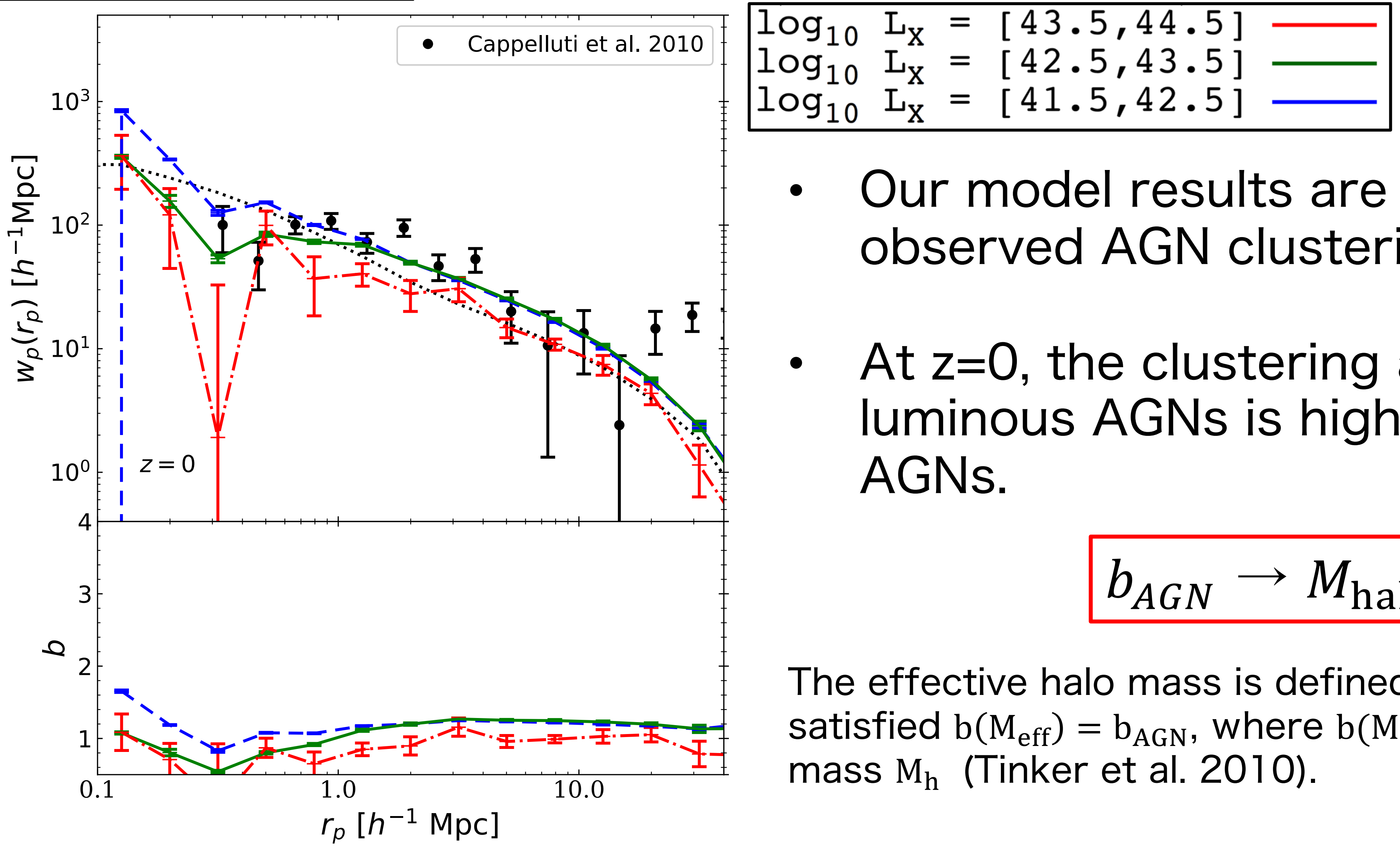
At z=0.5, the median increases and drops.

There are many faint AGNs in high mass halos ($M_{halo} \gtrsim 10^{13}h^{-1}M_\odot$).

These AGNs have long gas accretion timescales.

2PCF of X-ray AGN: comparison with Obs.

$$w_p(r_p) = 2\int_0^{\pi_{\max}} \xi(r_p, \pi)\mathrm{d}\pi.$$

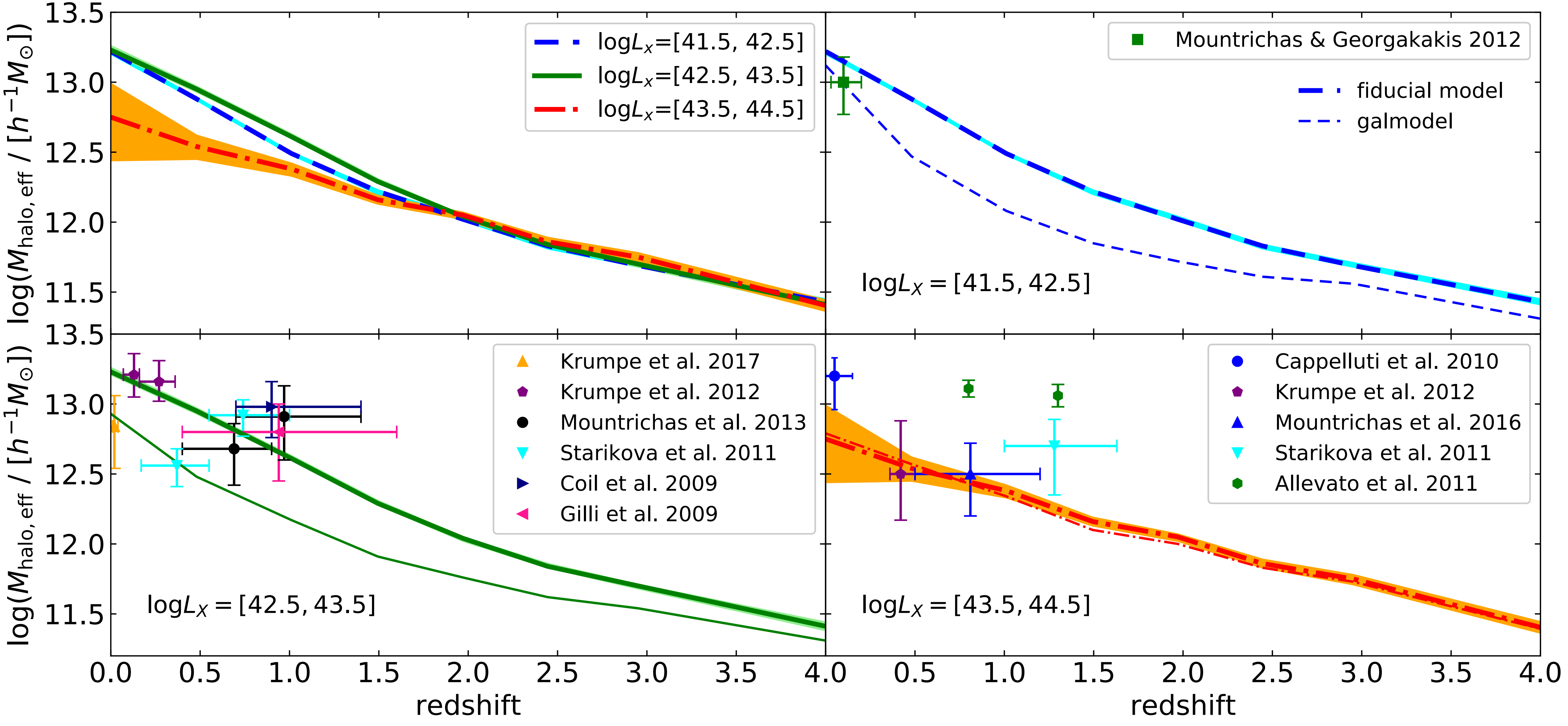


- Our model results are in agreement with observed AGN clustering.
- At z=0, the clustering amplitude of less luminous AGNs is higher than luminous AGNs.

$$b_{AGN} \rightarrow M_{\mathrm{halo,eff}}$$

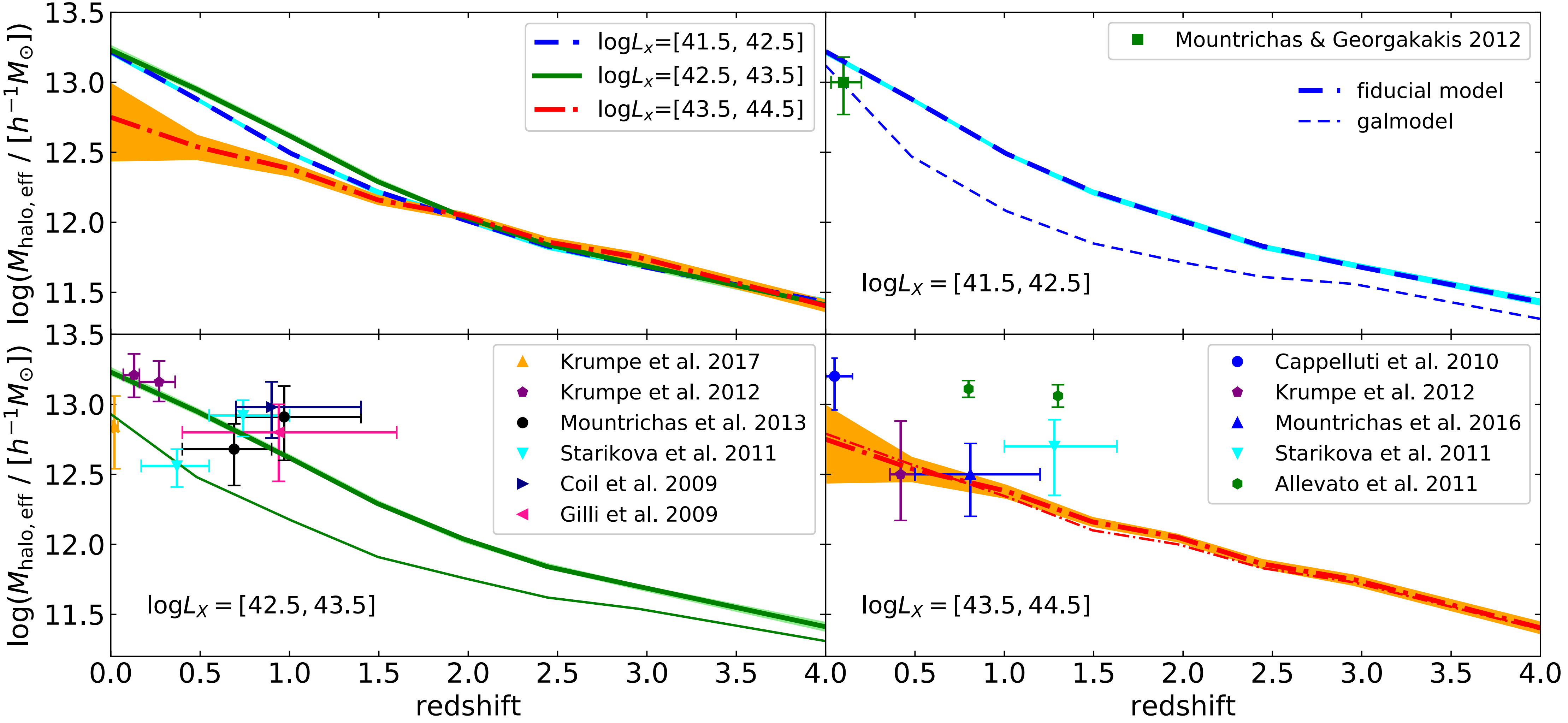
The effective halo mass is defined as the mass which satisfied $\mathrm{b(M_{eff}) = b_{AGN}}$, where $\mathrm{b(M_h)}$ is the halo bias of mass $\mathrm{M_h}$ (Tinker et al. 2010).

Redshift evolution of AGN host halo mass



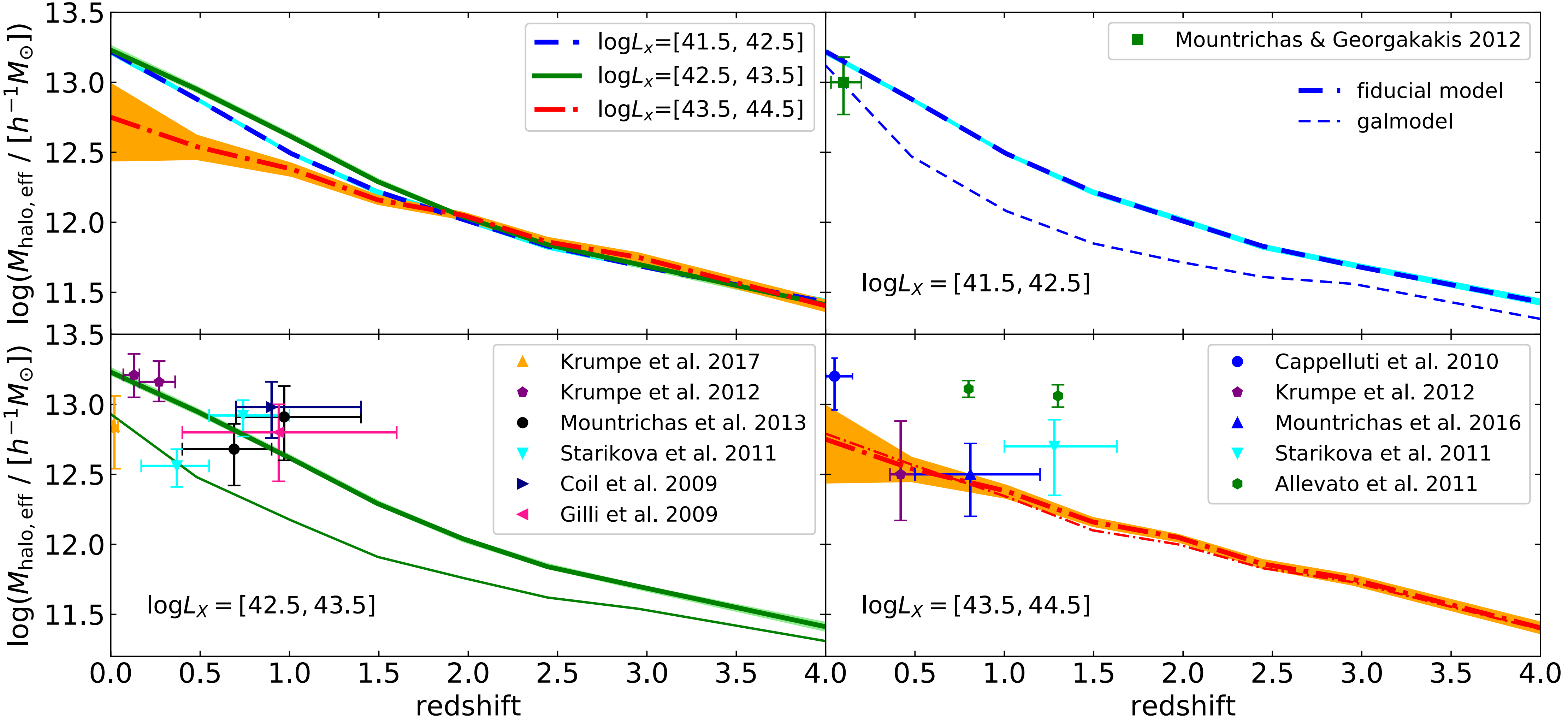
- The AGN host halo mass of low luminosity AGNs is higher than that of luminous AGNs at low-z.
- At high-z, there is no significant luminosity dependence.

Redshift evolution of AGN host halo mass



- Overall, our model is consistent with the current observations.
  - typical host halo mass, $10^{12.5-13.5} h^{-1} M_\odot$.
- There is a large scatter of the observationally estimated halo masses.
- The disagreement is seen for luminous AGNs.

Redshift evolution of AGN host halo mass



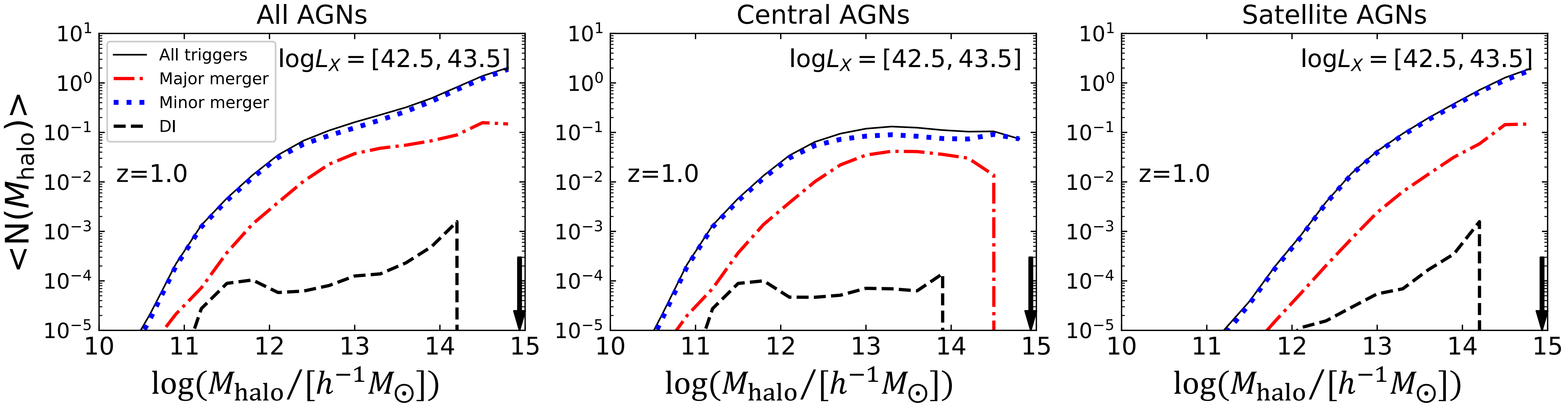
Thick lines: model with the accretion timescale t_{loss} (fiducial model).
Thin lines: model without t_{loss}

Further observations can constrain the models.

HOD for different triggering mechanisms

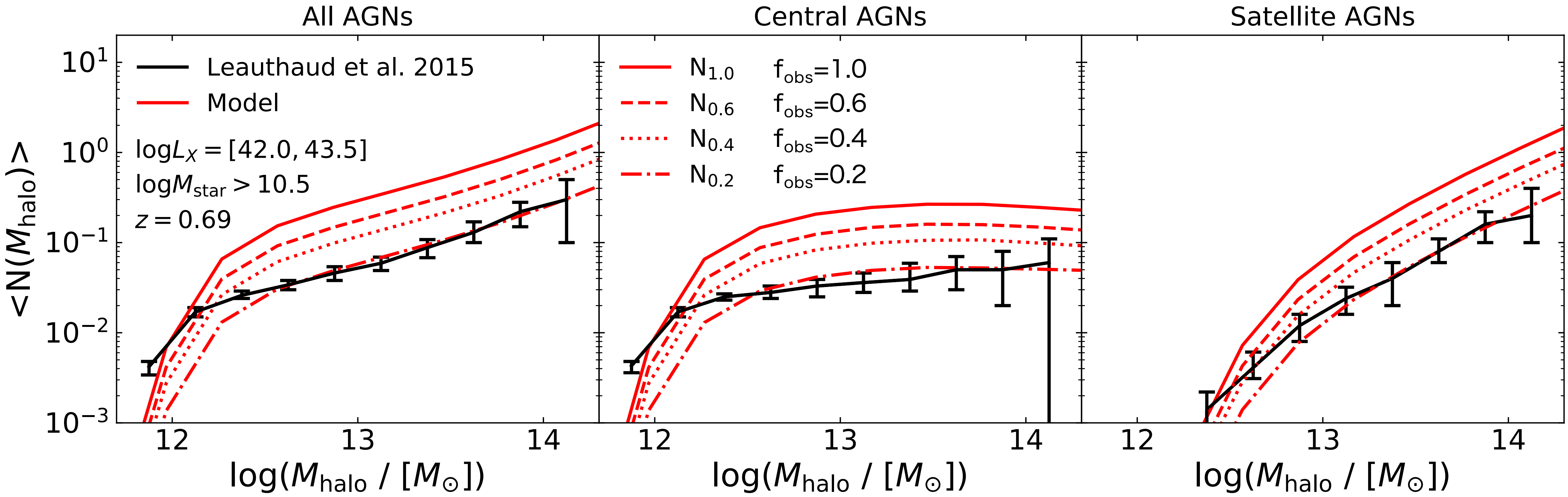
X-ray AGNs with 42.5 < log (L_X / erg s^{-1}) < 43.5

DI: Disc instability



- Minor mergers are the main triggering mechanism of AGN.
- The satellite fraction f_{sat}~0.12.
  - f_{sat} : the fraction of satellite AGNs to the total AGNs
- Satellite AGNs contribute the HOD.

HOD: comparison with observation



- Observation: Leauthaud et al. 2015
  - COSMOS X-ray AGN sample
  - $\log(M_{star})$ > 10.5
- The HOD of our model is qualitatively consistent with the observation.
- Uncertainties (Obscured fraction, sample incompleteness)

Summary

- We can predict the AGN host halo mass and clustering by using our latest semi-analytic model.
- Our model is consistent with the current observations.
  - Typical host halo mass, $\sim 10^{13} h^{-1} M_{\odot}$.
- The host halo mass of X-ray AGNs can be explained by the model in which galaxy mergers and disc instabilities trigger AGN activity.
- Minor mergers are the main triggering mechanism of AGNs.
- Halo occupation distributions of AGNs can be an additional constraint.