準解析的モデルで探る宇宙初期の銀河とブラックホールの共進化

ブラックホール大研究会

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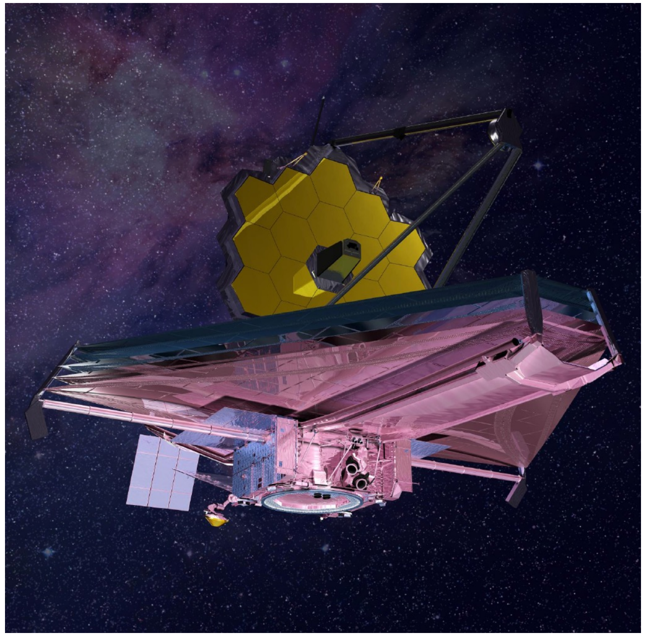
Outline

- Properties of AGN at $z>4$ for JWST observations and some highlights of the faint/low-mass BH population in our model

- Stochastic gravitational wave background and our model prediction

JWST observations are ongoing

- It seems difficult to detect faint quasars with JWST, given the result of our semi-analytical model.
- However, JWST has found faint AGN having broad permitted lines (H_{α} etc.) in their host galaxies.



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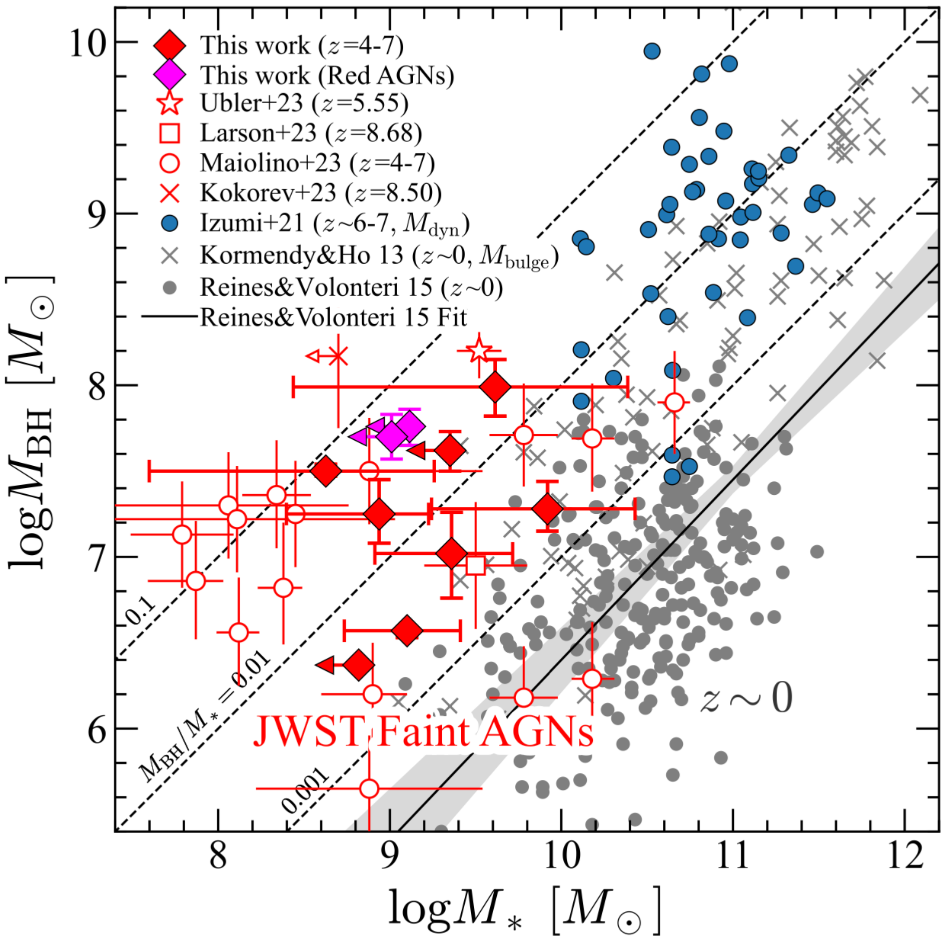
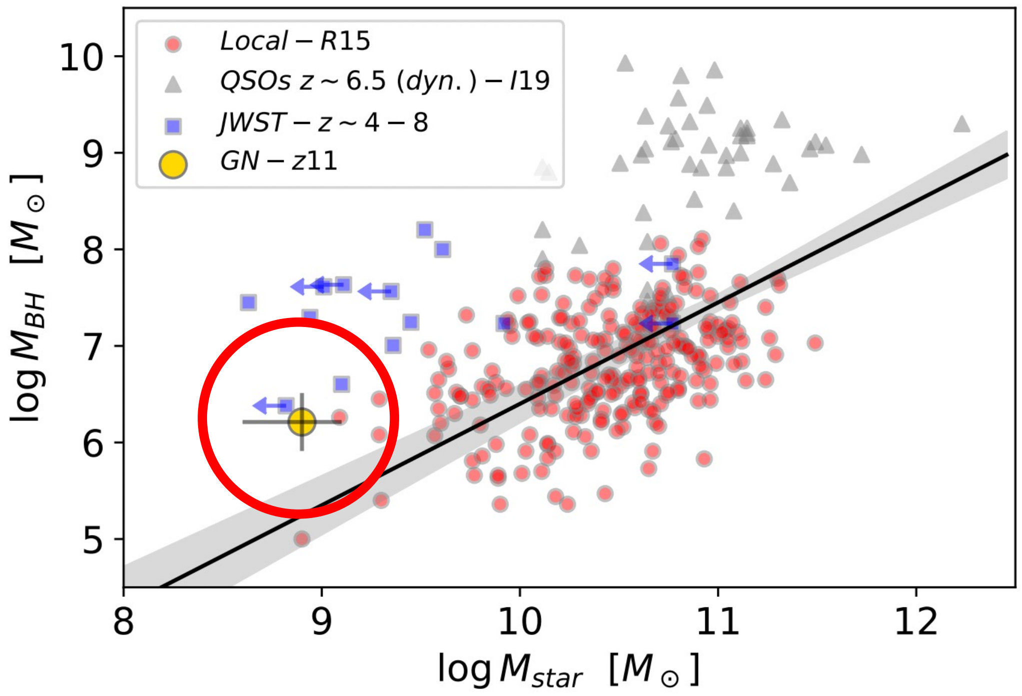
M_{BH} – M_{star} relation from JWST

4 < z < 7



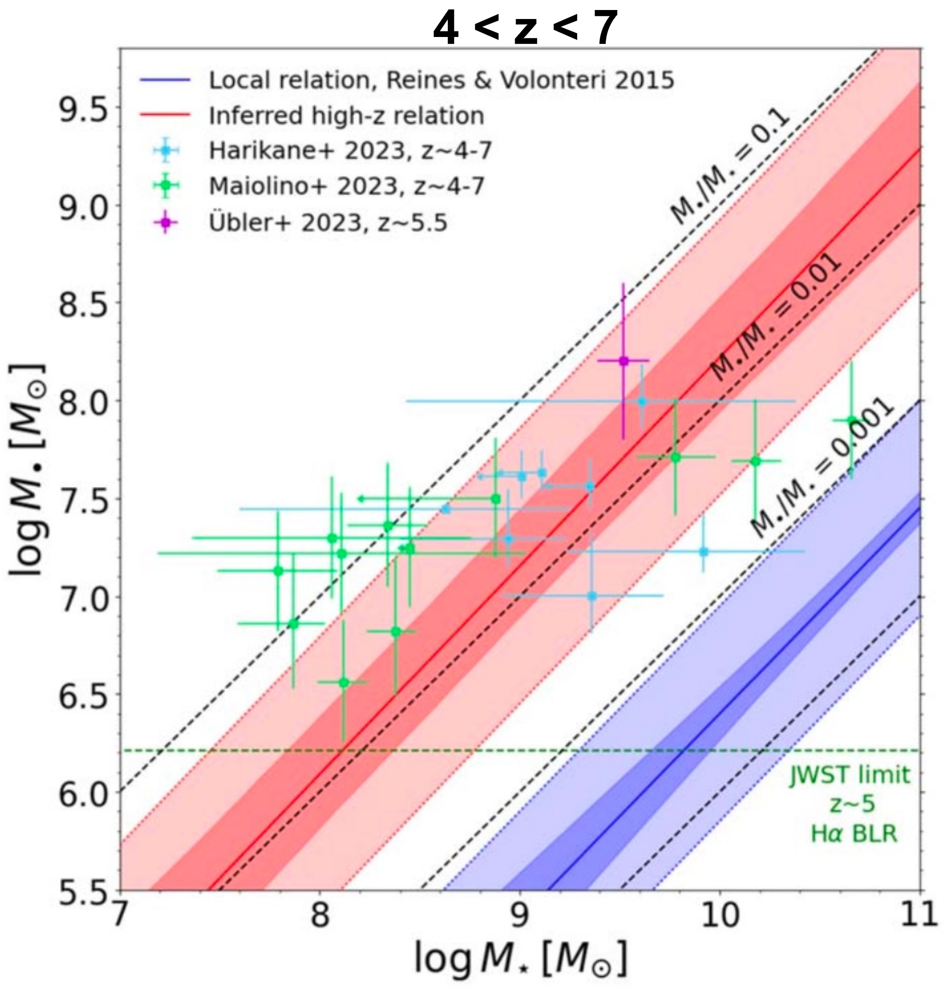
Harikane et al. 2023

z >10



Maiolino et al. 2023

M_{BH} – M_{star} relation from JWST



Pacucci et al. 2023

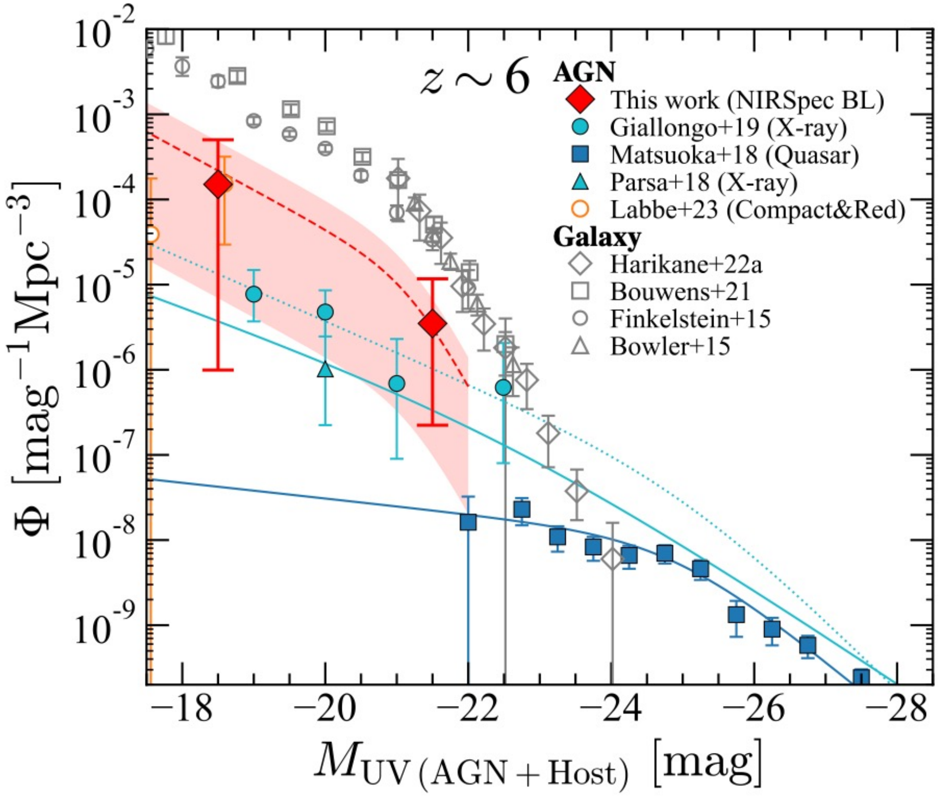
$$\log\left(\frac{M_\bullet}{M_\odot}\right) = -2.43^{+0.83}_{-0.83} + 1.06^{+0.09}_{-0.09}\log\left(\frac{M_\star}{M_\odot}\right)$$

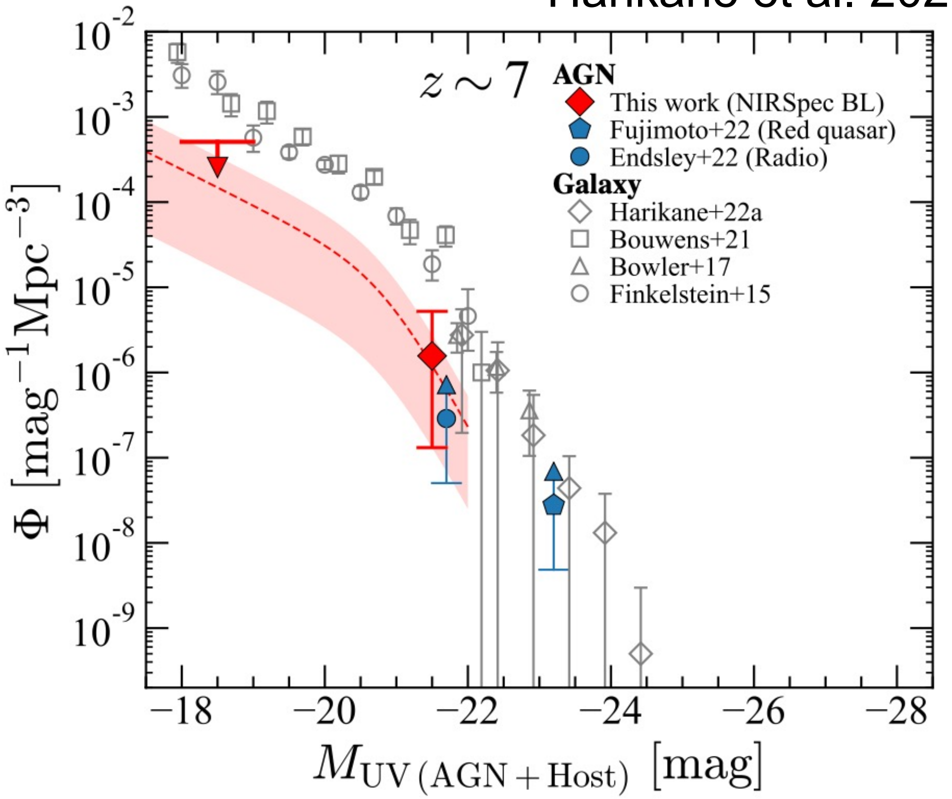
The high-z relation differs significantly from the local relation by ~2 orders of magnitude.

A clue to the early coevolution of BHs and galaxies

UV luminosity functions of broad-line AGN at z>4 from JWST NIRSpec

Harikane et al. 2023





Note: The UV emission of the sample is a composite of the AGN and the host galaxies.

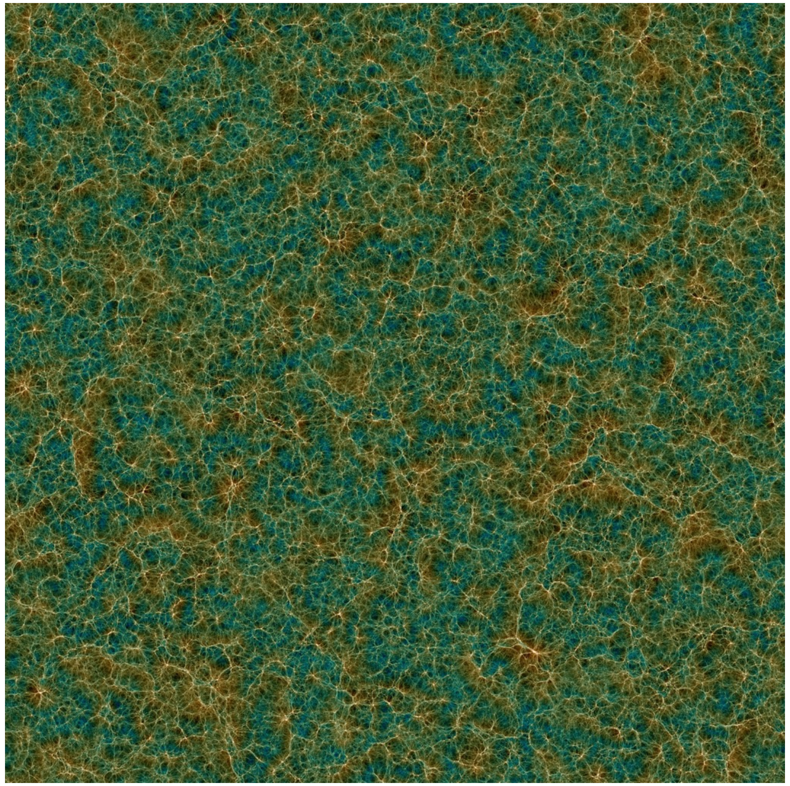
Aim of this study

We investigate the physical properties of AGN and their host galaxies at high redshifts using a semi-analytic model of galaxy and AGN formation, ν^2GC, based on the Uchuu cosmological N-body simulation (**Uchuu-$\boldsymbol{\nu^2}$GC**) and Monte Carlo-based merger trees (**MCtree-$\boldsymbol{\nu^2}$GC**).

Semi-analytic model Uchuu-ν^2GC

Makiya et al. 2016; Shirakata et al. 2019; Oogi et al. 2022

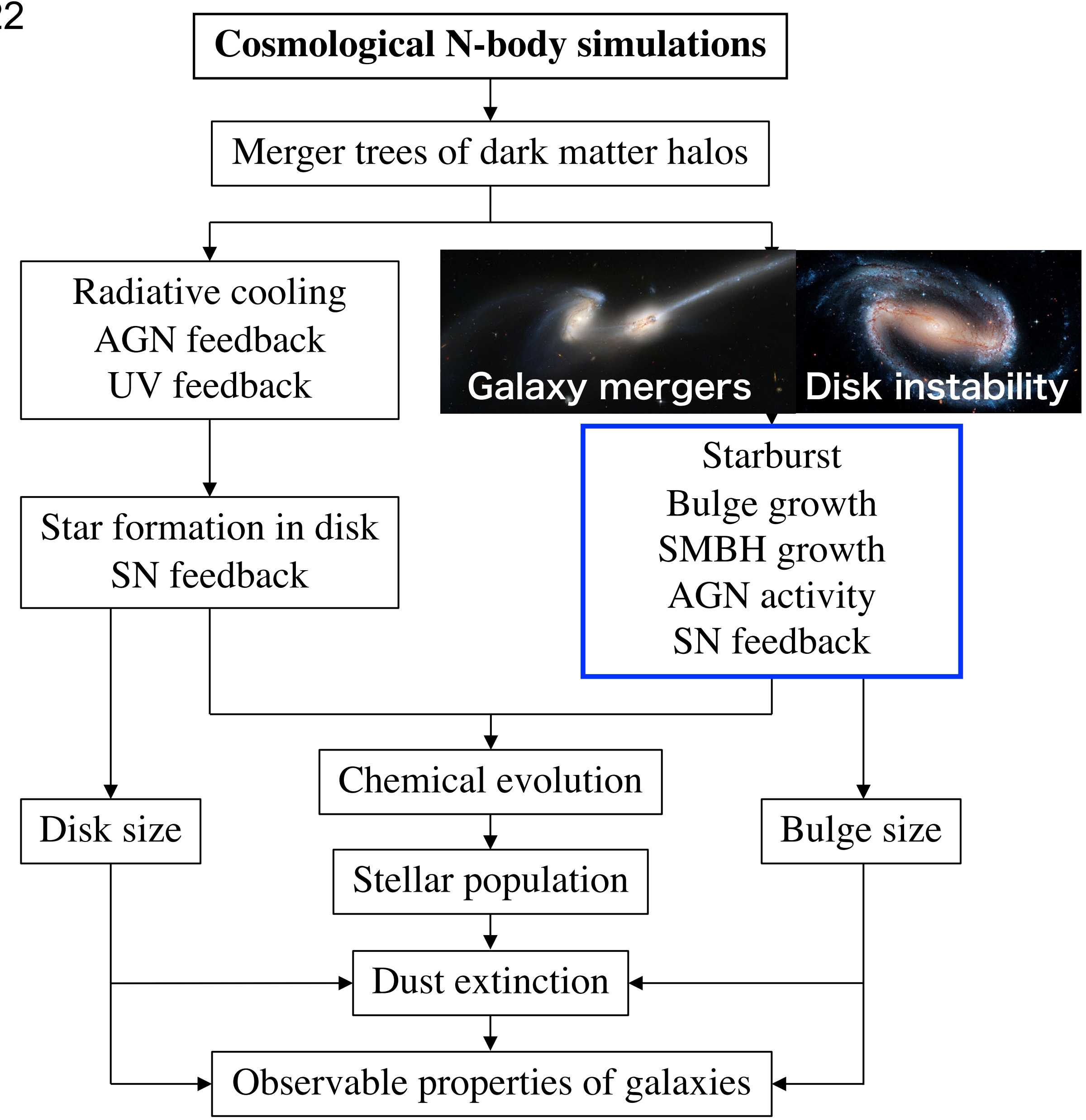
Uchuu simulation (Ishiyama et al. 2021)



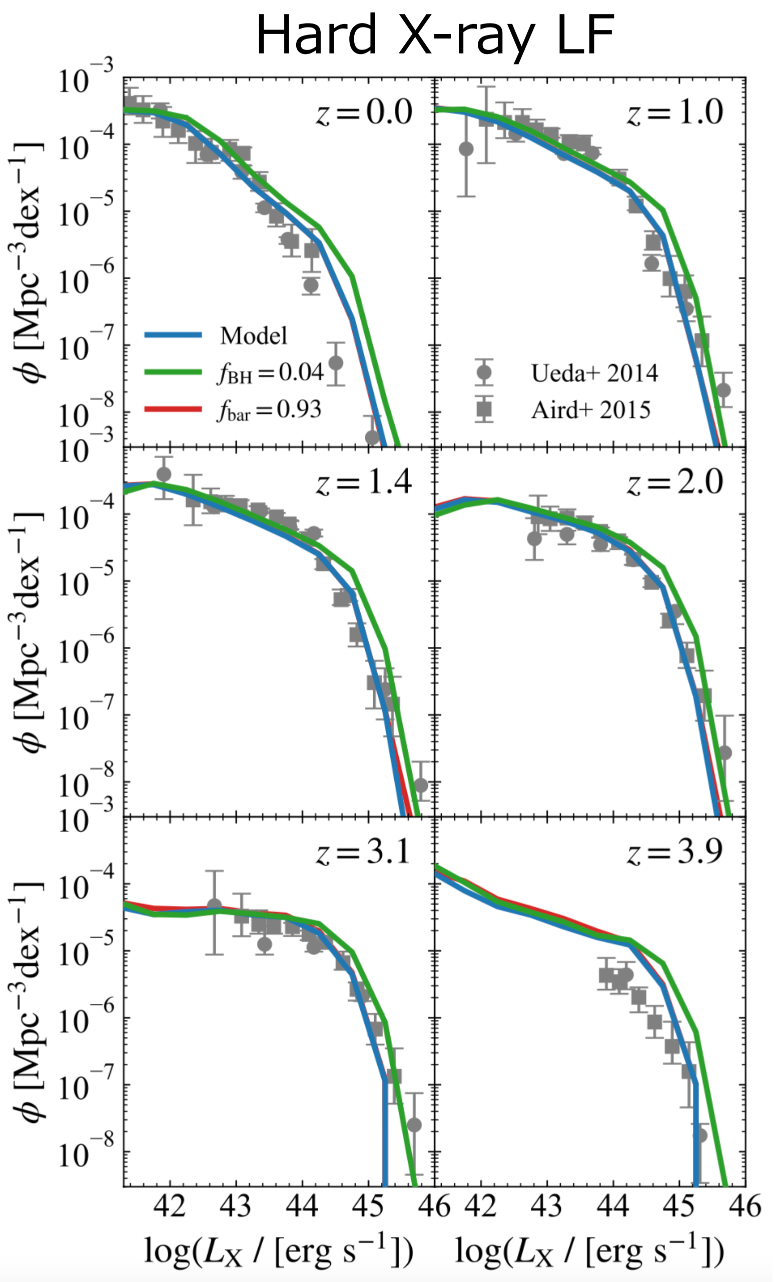
2.0 h^{-1} Gpc Box

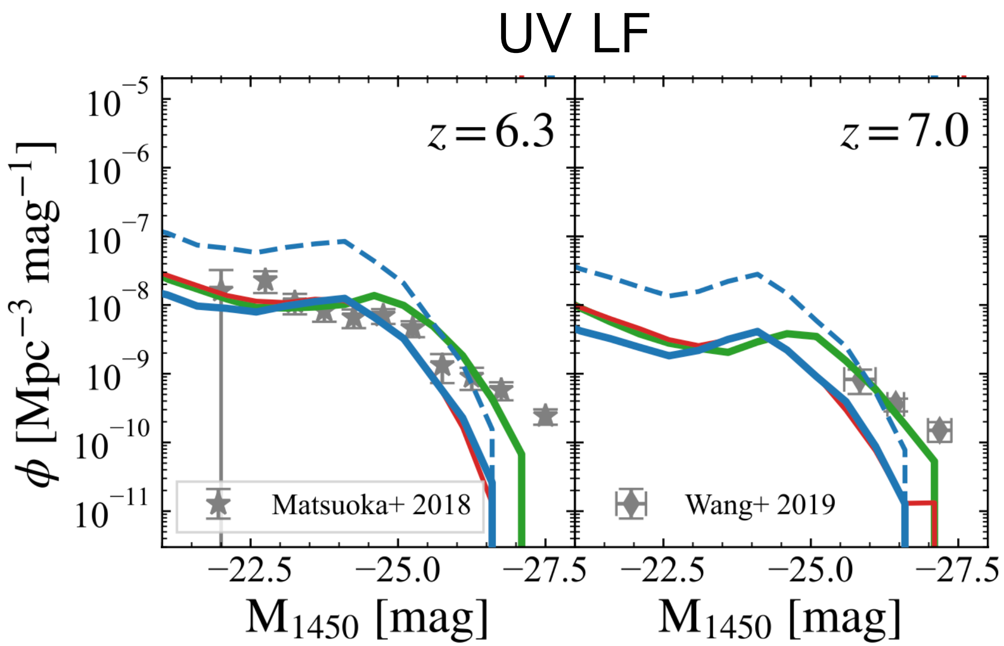
Minimum halo mass: 1.93×10^{10} M_{sun}

12800^3 = 2.1 trillion particles



AGN hard X-ray and UV luminosity functions



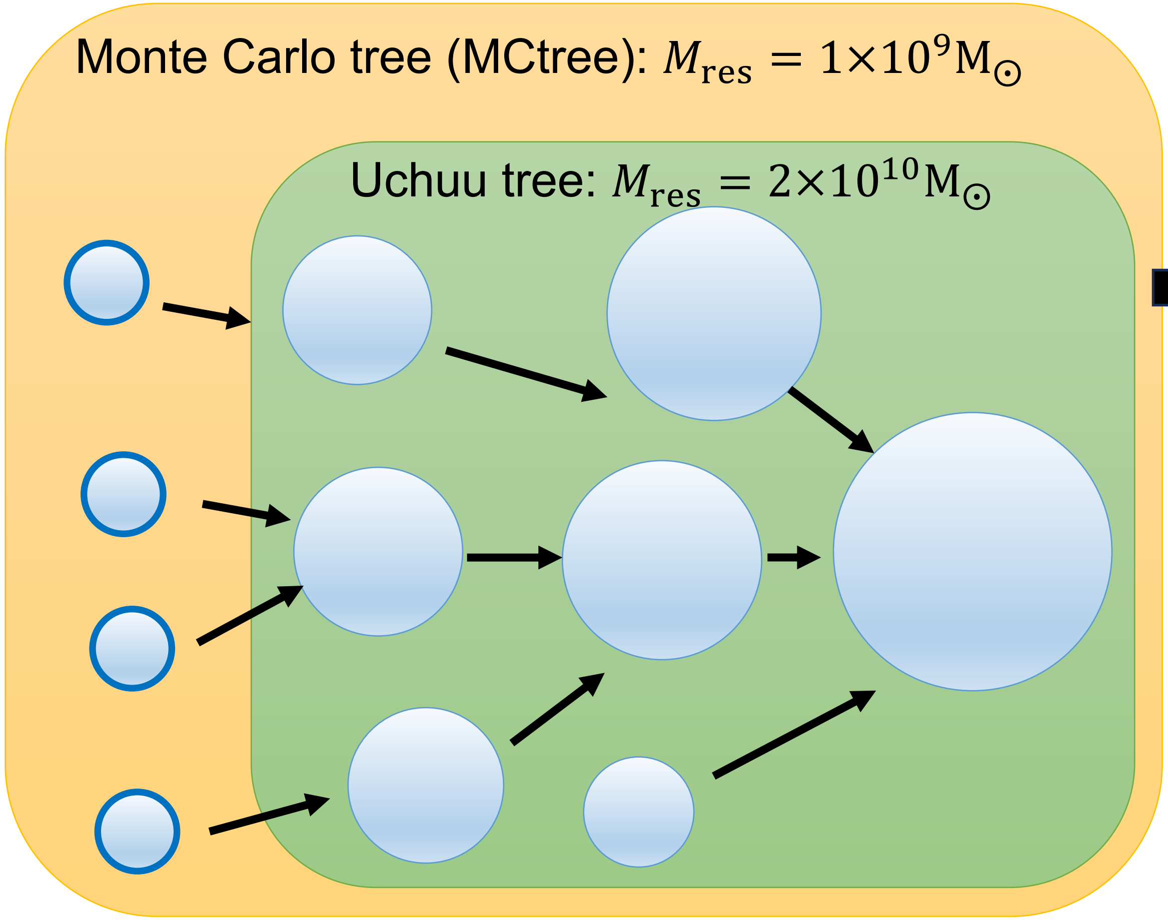


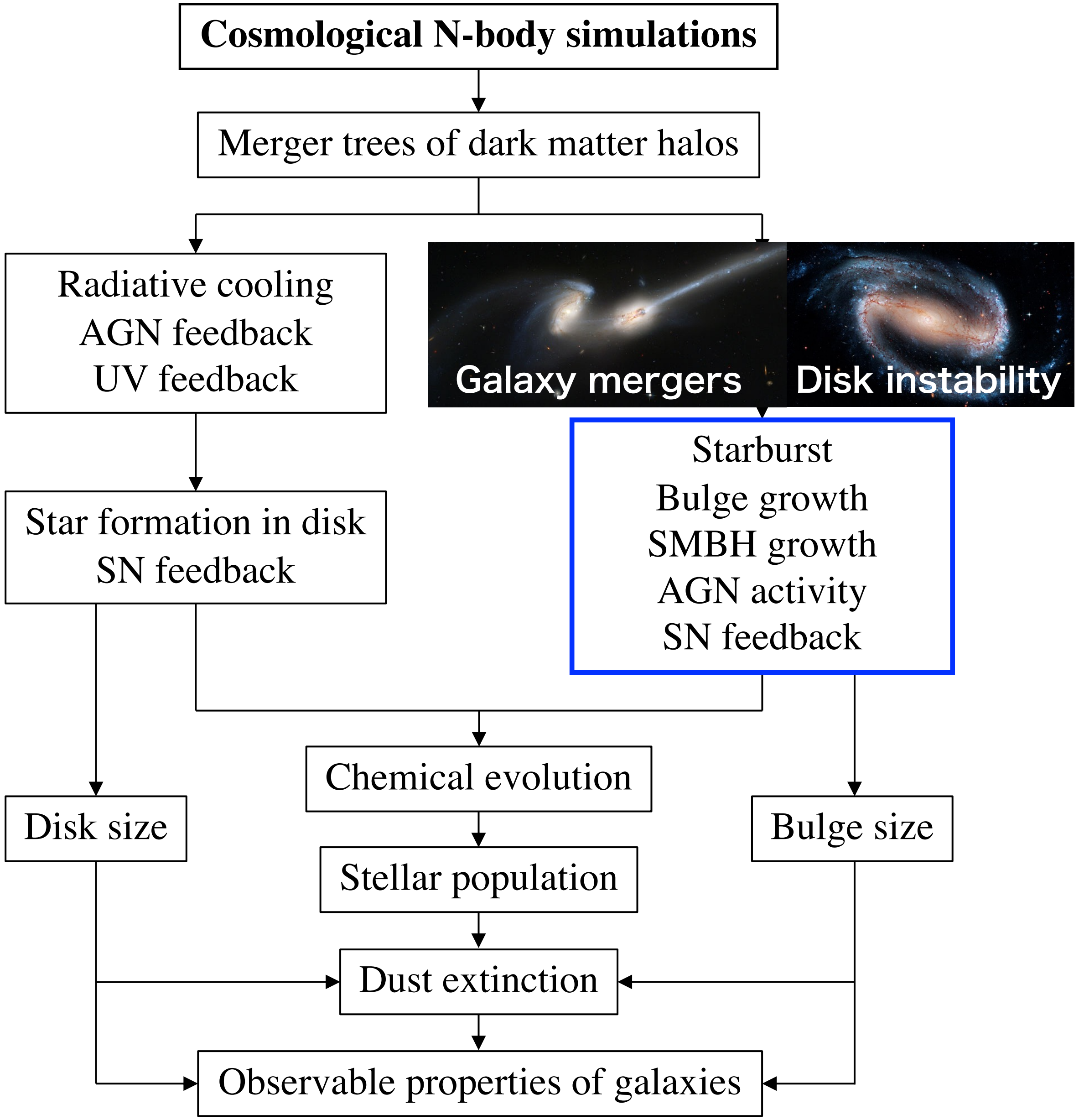
Oogi et al. 2023

- Our model reproduces the observed hard X-ray LF of AGNs over a wide redshift range, 0<=z<=4.
- Also reproduces the observed AGN UV LF, assuming high black hole accretion rates.

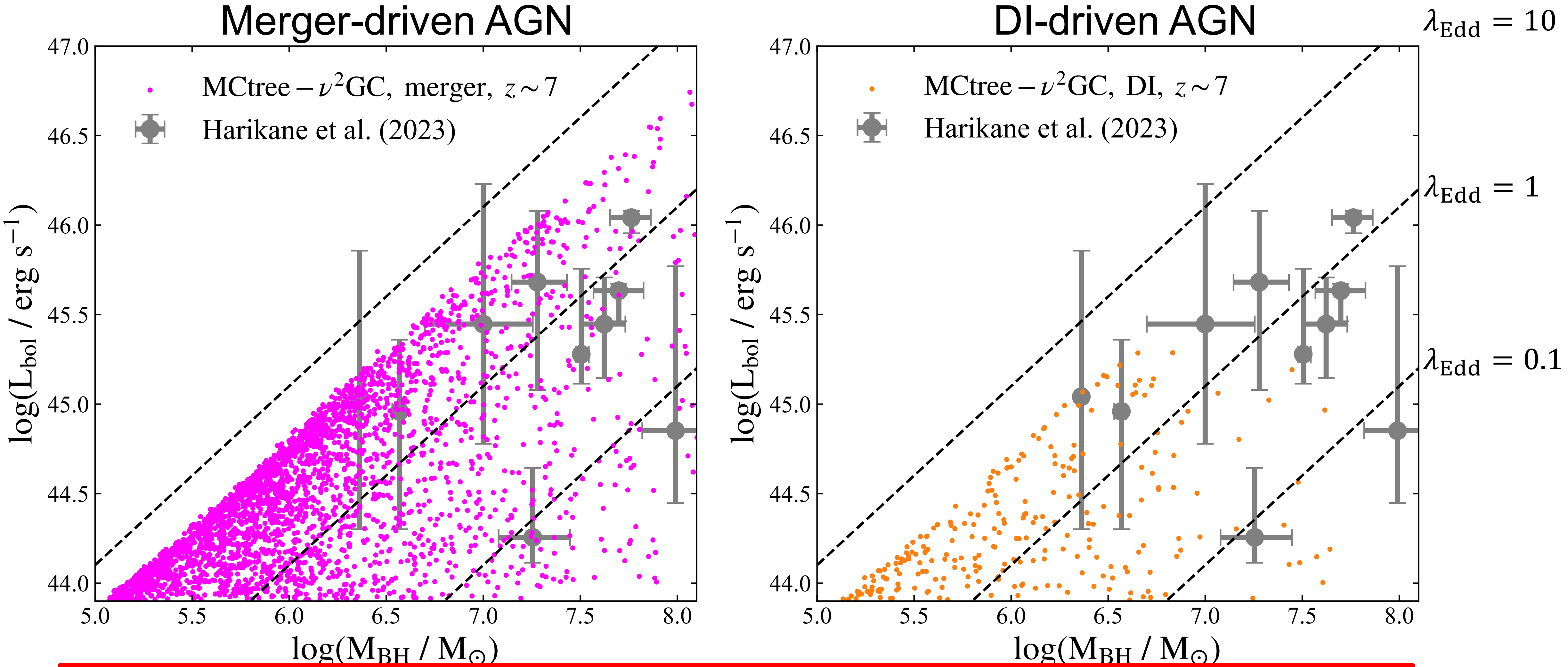
Construction of MCtree-ν^2GC model

- Constructing Monte Carlo-based merger trees of dark matter halos by using the Parkinson et al. (2008) model.
- Mass resolution: $10^9 \mathrm{M}_\odot$
- Effective volume: $(\sim 500\ \mathrm{Mpc}/h)^3$



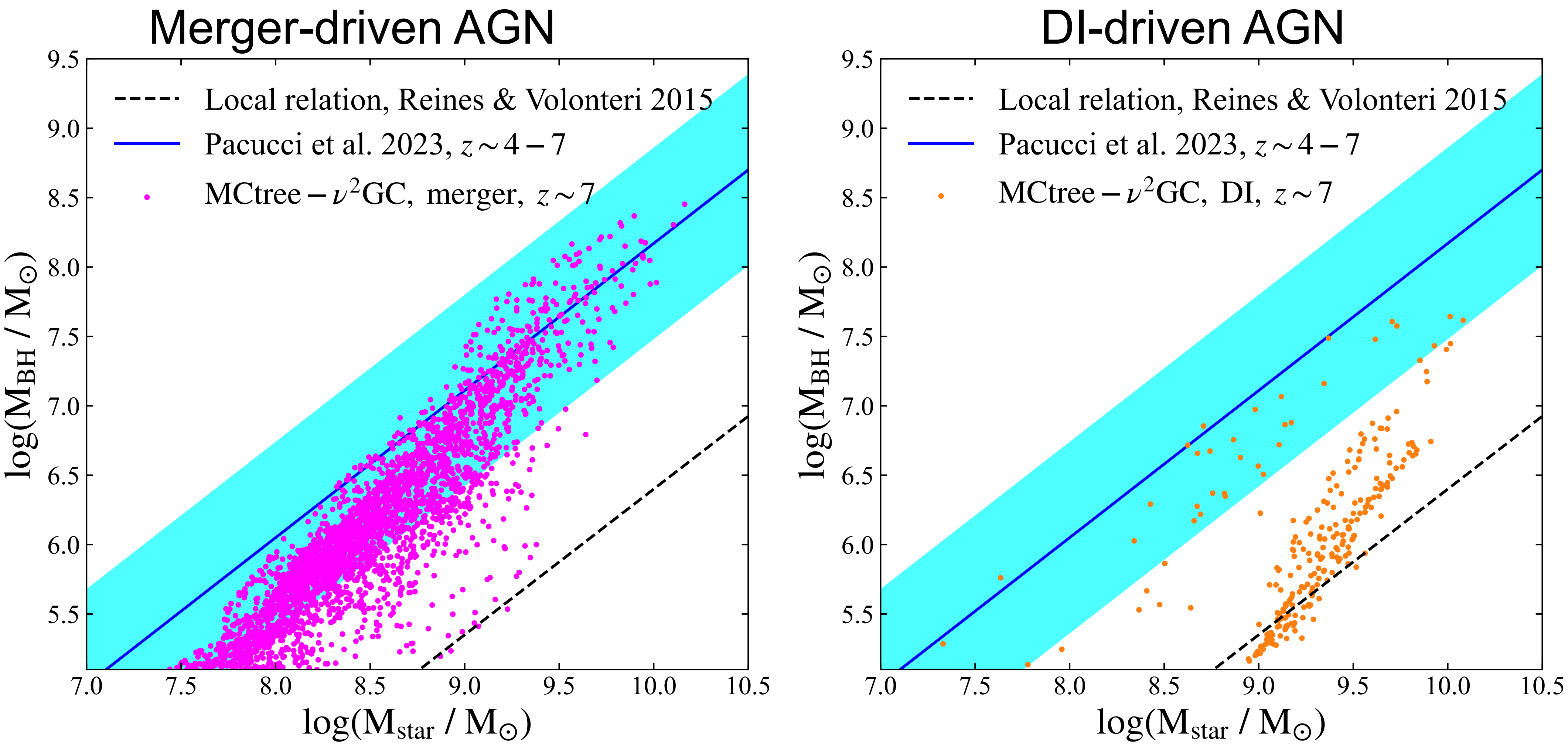


M_{BH} – L_{bol} relation from MCtree-ν^2GC



Our model results are consistent with the observed AGN sample derived from JWST.

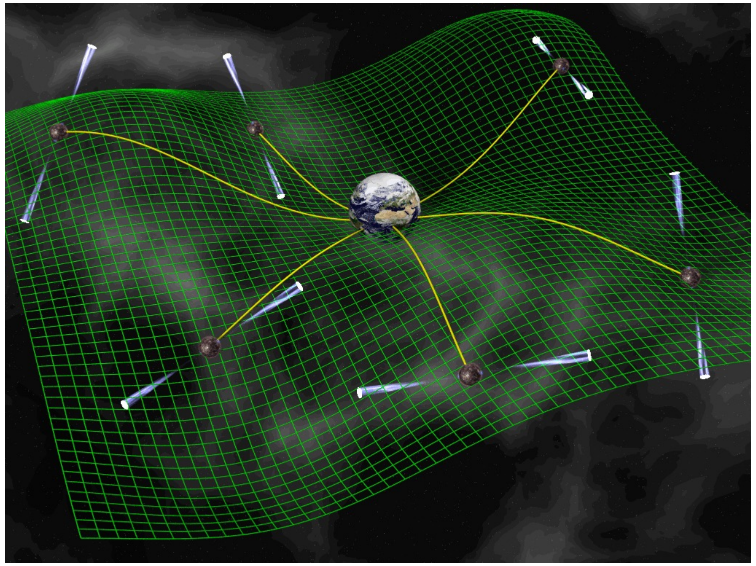
M_{BH} – M_{star} relation from MCtree-ν^2GC



Our model results are consistent with the observed AGN sample derived from JWST.

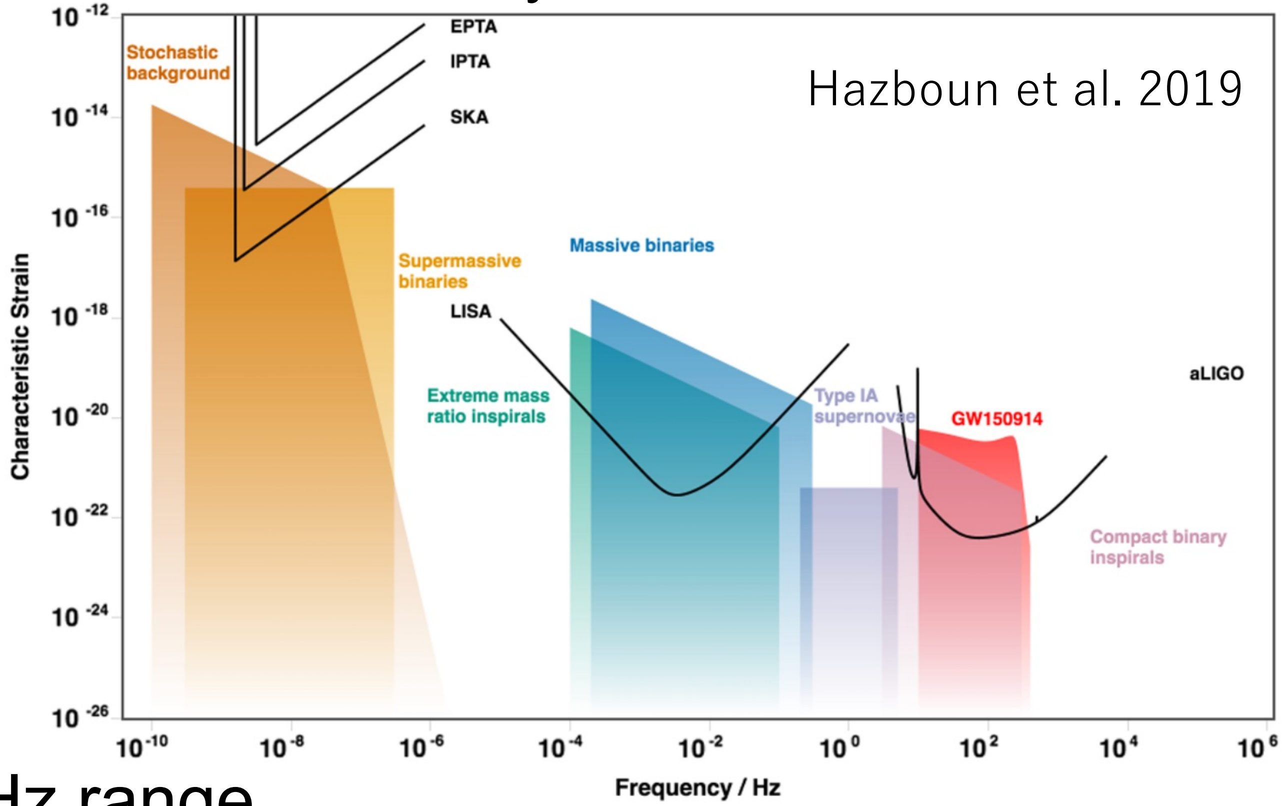
Stochastic Gravitational Wave Background

Pulser timing



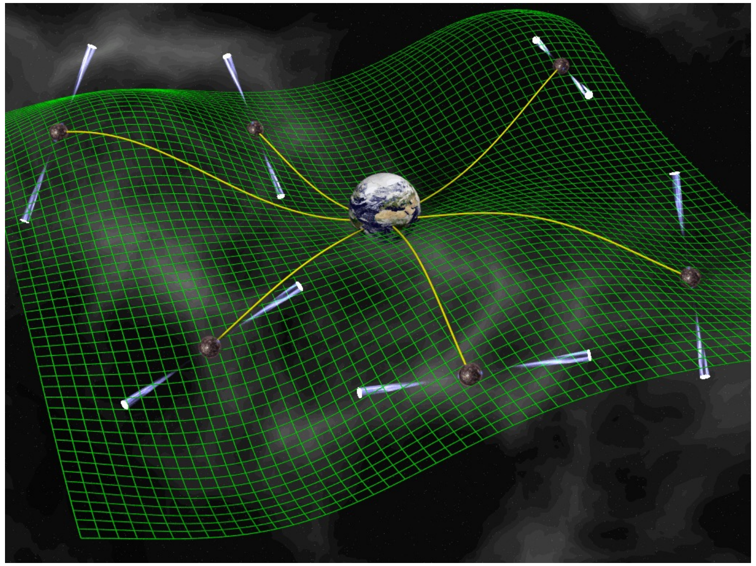
credit: David J. Champion

Sensitivity curves for GW obs.



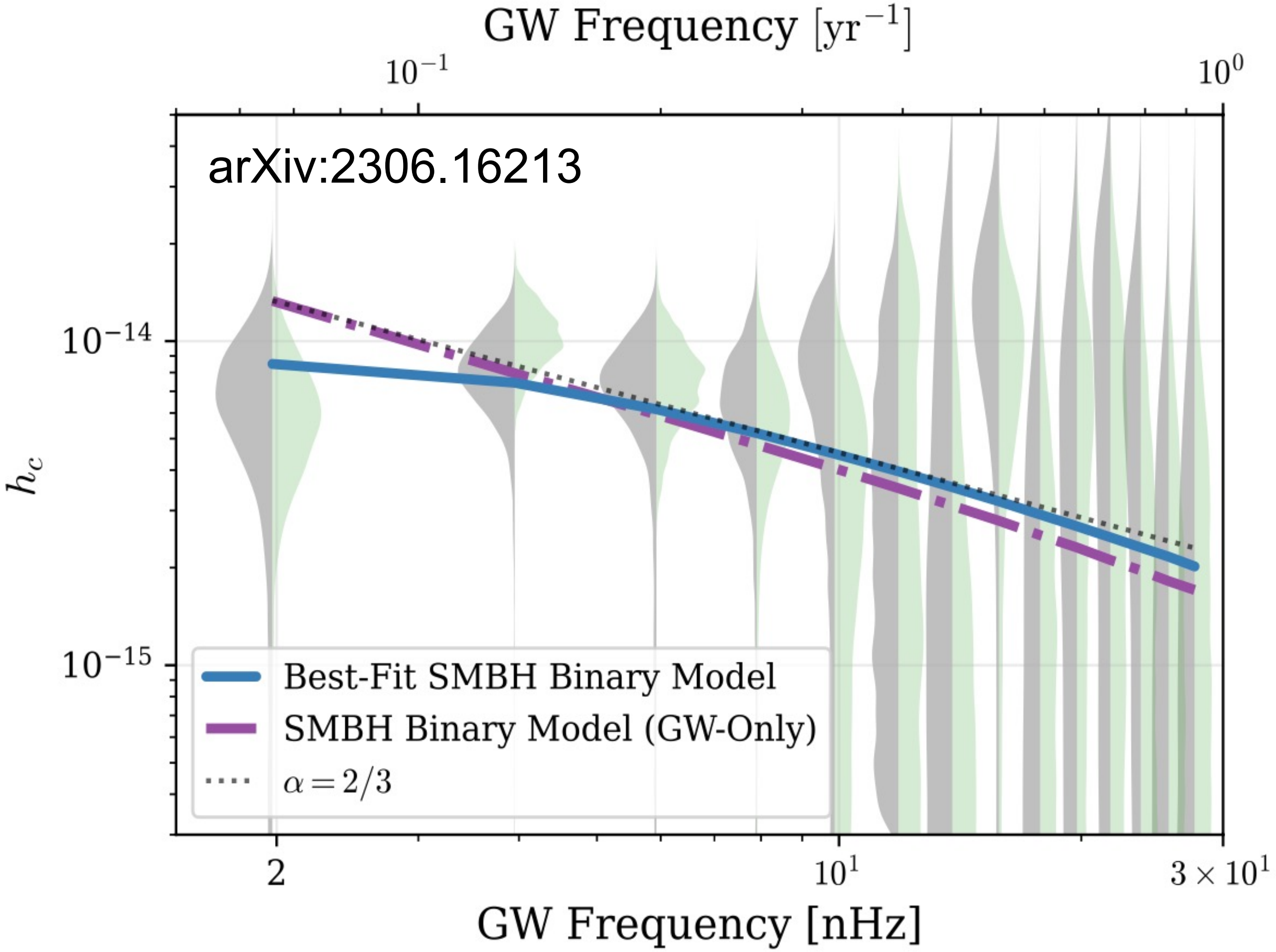
- Detect GW background at ~1nHz range
  - Obs. for ~1yr, f ~ 30 nHz
- Candidate sources: SMBH binary, cosmological origin, etc.
- An independent constraint on the SMBH growth
- Basic observables：Time residuals

Pulser timing



credit: David J. Champion

NANOGrav 15-year result



- Detect GW background at ~
  - Obs. for ~1yr, f ~ 30 nHz
- Candidate sources: SMBH binary, cosmological origin, etc.
- An independent constraint on the SMBH growth
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Stochastic Gravitational wave background (SGWB)

The amplitude of gravitational wave from a binary is given by

$$h_s(z, f, M_1, M_2) = 4\sqrt{\frac{2}{5}}\frac{\left(GM_{chirp}\right)^{5/3}}{c^4 D(z)}\left(2\pi f_p\right)^{2/3} = 3.5\times10^{-17}\left(\frac{M_{chirp}}{10^8 M_{sun}}\right)^{5/3}\left(\frac{D(z)}{1Gpc}\right)^{-1}\left(\frac{f(1+z)}{10^{-7}Hz}\right)^{2/3}$$

The spectrum of the gravitational wave background is

$\nu(M_1, M_2, z)$: number of SMBH binaries

$\tau_{GW,obs}$: timescale of the gravitational waves

f_{max}: the maximum frequency

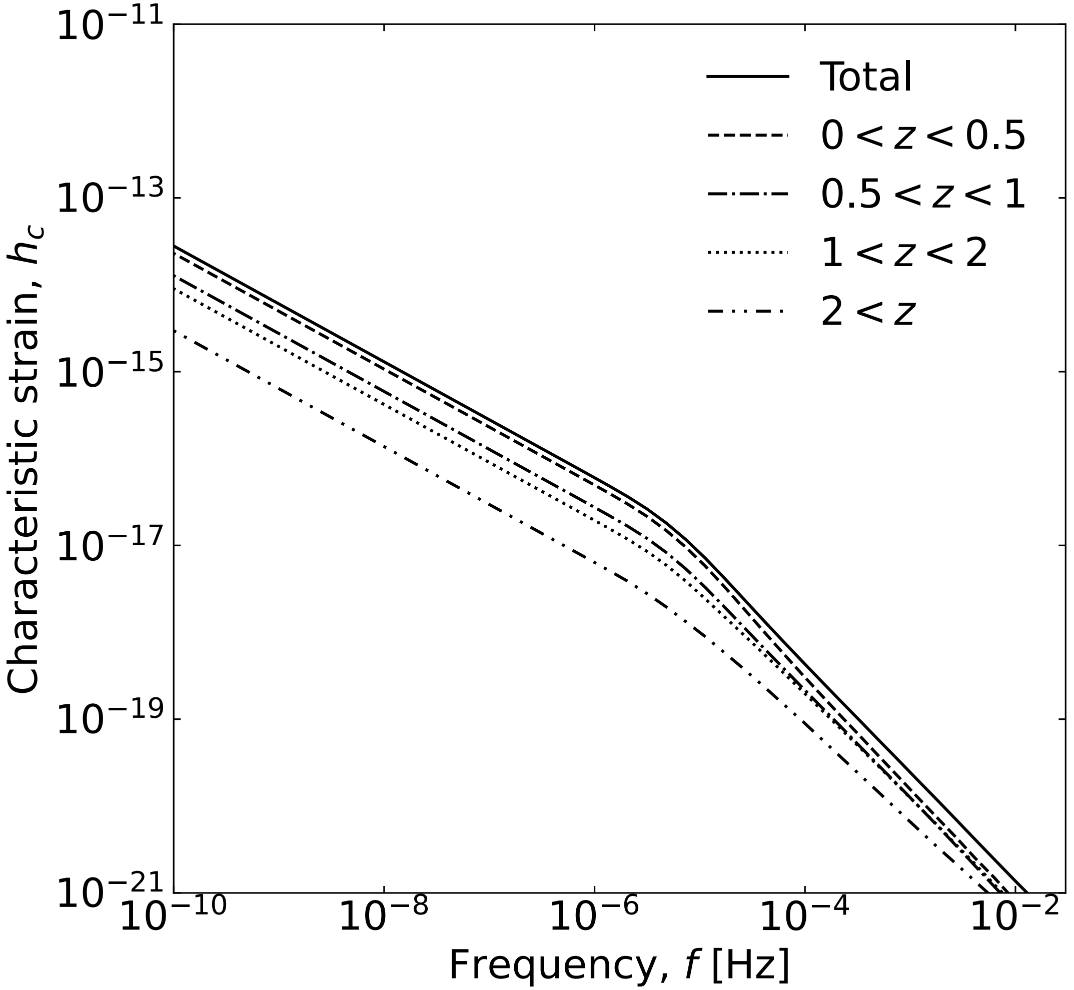
$$h_c^2(f) = \int dz dM_1 dM_2\, h_s^2\ \nu(M_1, M_2, z)\, \tau_{GW,obs}\, \theta(f_{max} - f)$$

$$= \int dz dM_1 dM_2 \frac{4\pi c^3}{3}\left(\frac{GM_{chirp}}{c^3}\right)^{5/3}(\pi f)^{-4/3}(1+z)^{-1/3}\, \underline{n_c(M_1, M_2, z)}\,\theta(f_{max} - f)$$

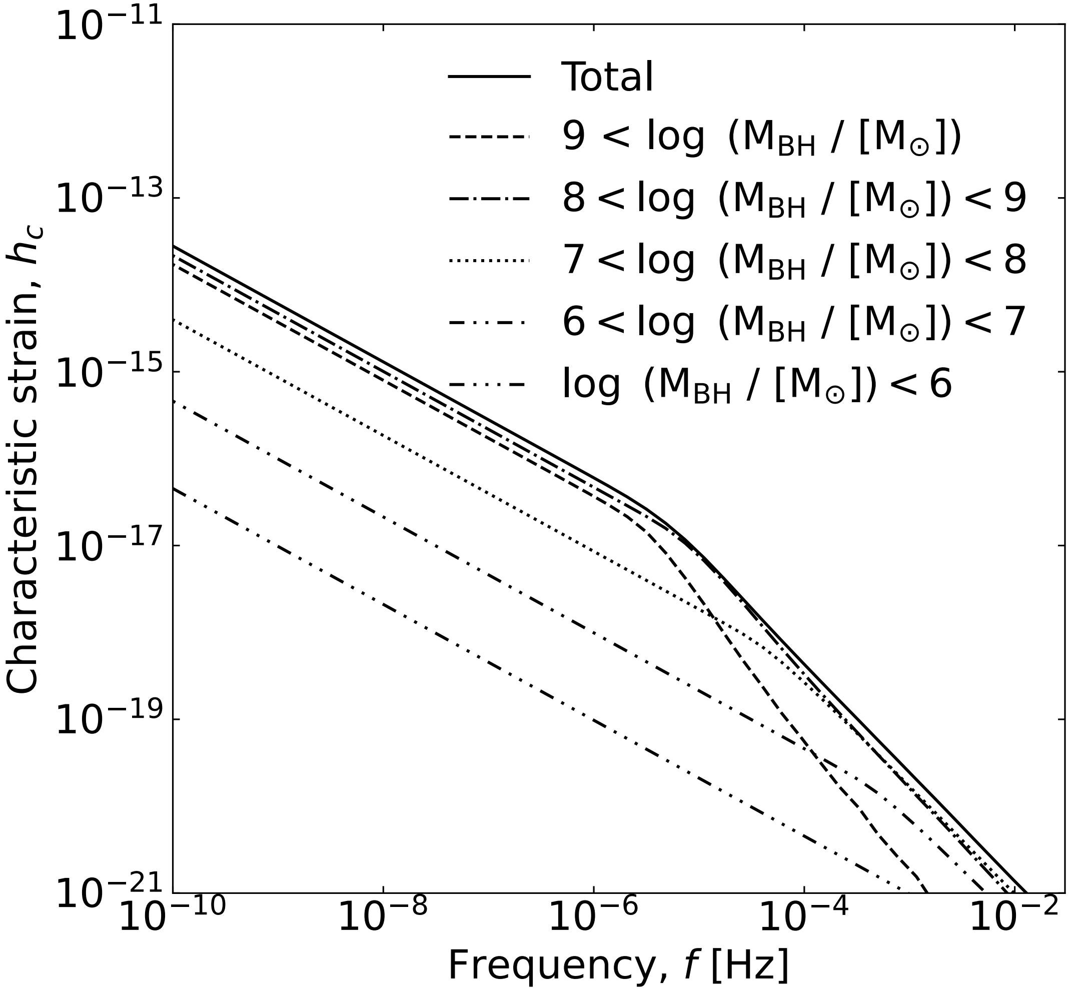
taken from semi-analytic models

(Phinney 2001; Enoki et al. 2004)

SGWB: Result

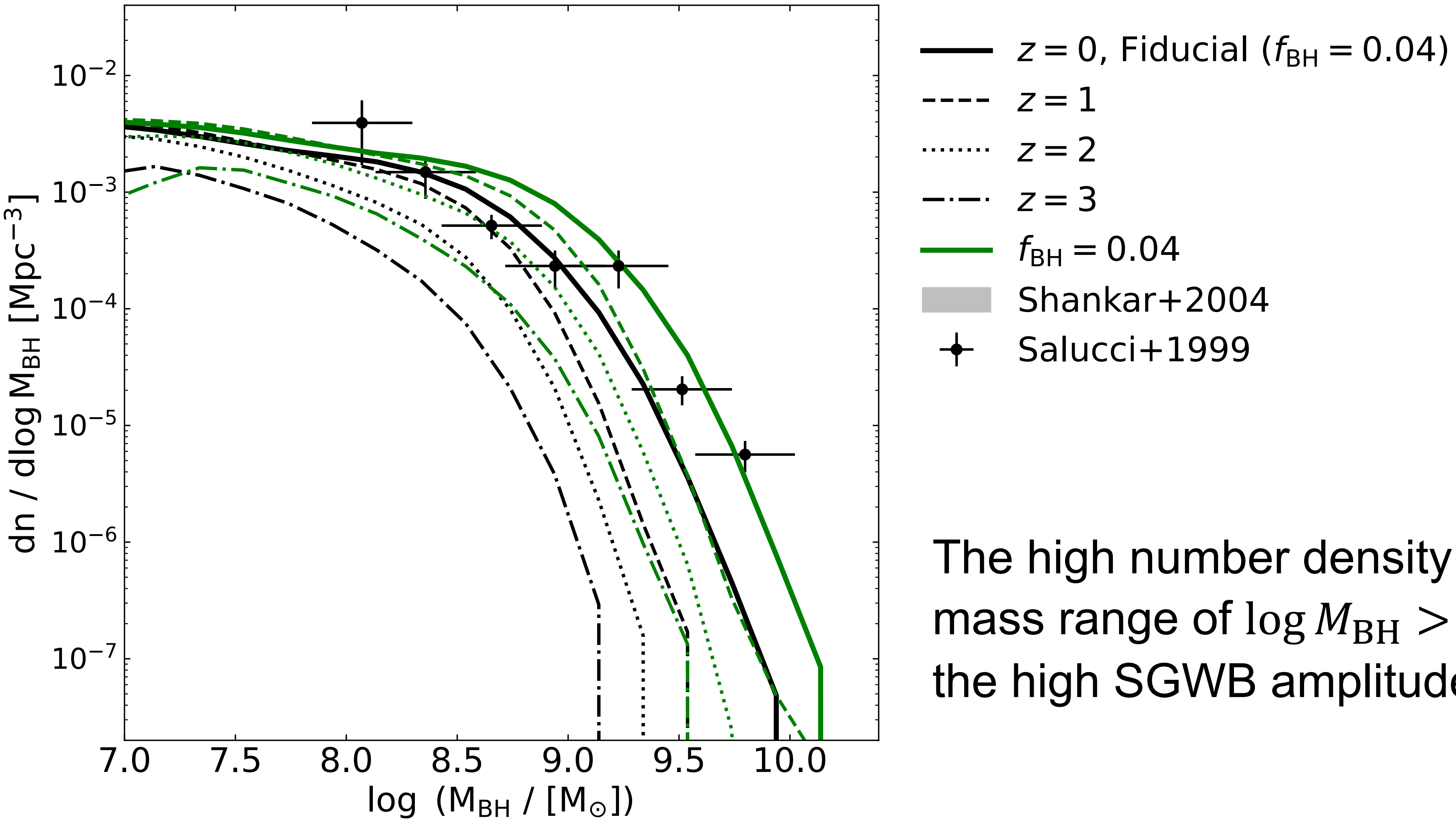


Total
$0 < z < 0.5$
$0.5 < z < 1$
$1 < z < 2$
$2 < z$
Characteristic strain, h_c
Frequency, f [Hz]
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}



Total
$9 < \log\ (M_{BH}\ /\ [M_\odot])$
$8 < \log\ (M_{BH}\ /\ [M_\odot]) < 9$
$7 < \log\ (M_{BH}\ /\ [M_\odot]) < 8$
$6 < \log\ (M_{BH}\ /\ [M_\odot]) < 7$
$\log\ (M_{BH}\ /\ [M_\odot]) < 6$
Characteristic strain, h_c
Frequency, f [Hz]
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}

Black hole mass function



The high number density in the mass range of $\log M_{\rm BH} > 8$ leads to the high SGWB amplitude.

Summary

- MCtree-ν^2GC model is consistent with the physical properties of AGN recently observed with JWST.
- Our model underestimates the SGWB compared to the recent PTA results.
- The combination of the AGN surveys and the black hole observations (BHMF, SGWB) is important for the formation and evolution of SMBH.