Black Hole Growth, Baryon Lifting, Star Formation, and IllustrisTNG

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Abstract

Quenching of star formation in the central galaxies of cosmological halos is thought to result from energy released as gas accretes onto a supermassive black hole. The same energy source also appears to lower the central density and raise the cooling time of baryonic atmospheres in massive halos, thereby limiting both star formation and black hole growth, by lifting the baryons in those halos to greater altitudes. One predicted signature of that feedback mechanism is a nearly linear relationship between the central black hole's mass ($M_{\rm BH}$) and the original binding energy of the halo's baryons. We present the increasingly strong observational evidence supporting a such a relationship, showing that it extends up to halos of mass $M_{\rm halo} \sim 10^{14} M_\odot$. We then compare current observational constraints on the $M_{\rm BH}$–$M_{\rm halo}$ relation with numerical simulations, finding that black hole masses in IllustrisTNG appear to exceed those constraints at $M_{\rm halo} < 10^{13} M_\odot$ and that black hole masses in EAGLE fall short of observations at $M_{\rm halo} \sim 10^{14} M_\odot$. A closer look at IllustrisTNG shows that quenching of star formation and suppression of black hole growth do indeed coincide with black hole energy input that lifts the halo's baryons. However, IllustrisTNG does not reproduce the observed $M_{\rm BH}$–$M_{\rm halo}$ relation because its black holes gain mass primarily through accretion that does not contribute to baryon lifting. We suggest adjustments to some of the parameters in the IllustrisTNG feedback algorithm that may allow the resulting black hole masses to reflect the inherent links between black hole growth, baryon lifting, and star formation among the massive galaxies in those simulations.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Circumgalactic medium (1879); Supermassive black holes (1663); Active galaxies (17)

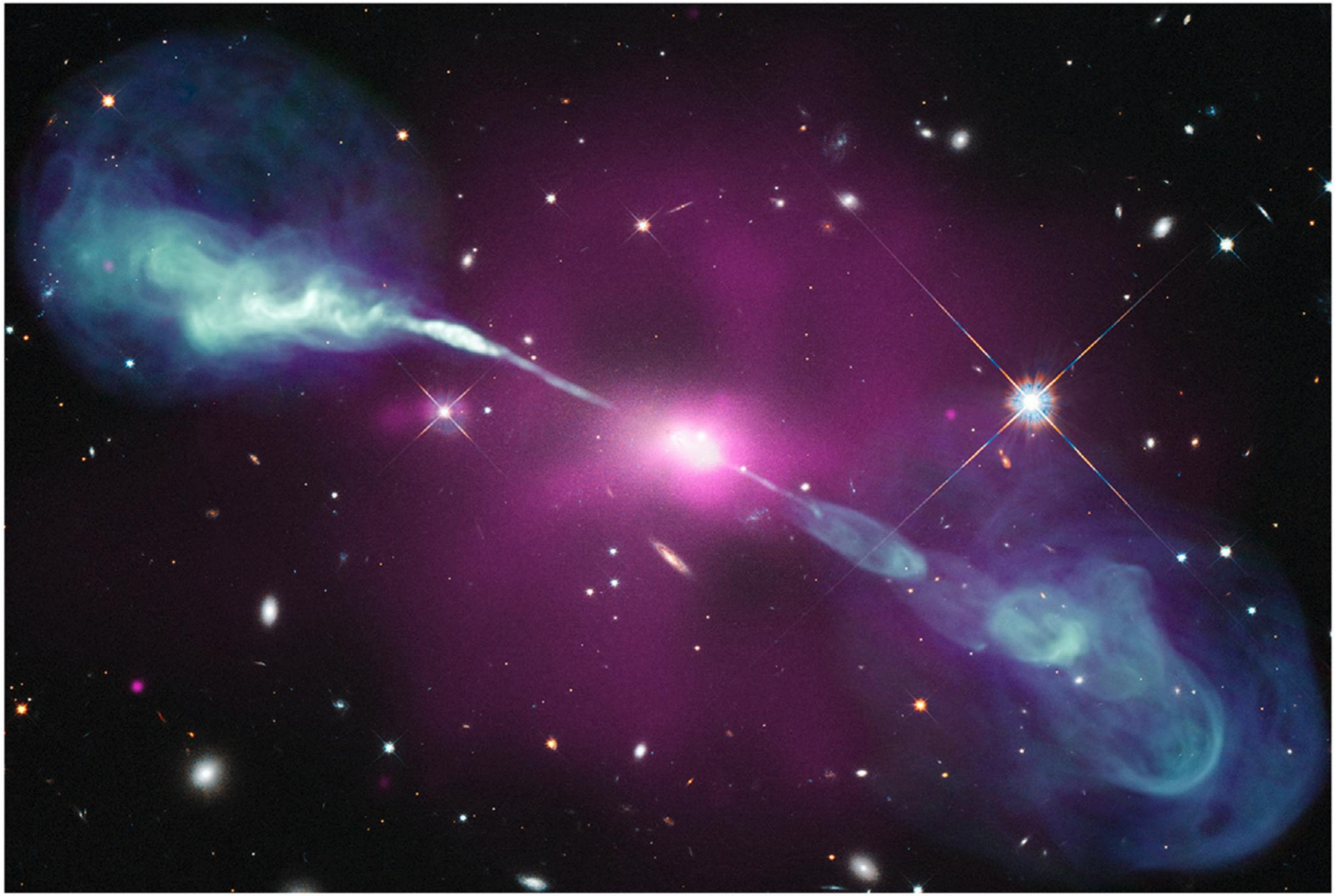
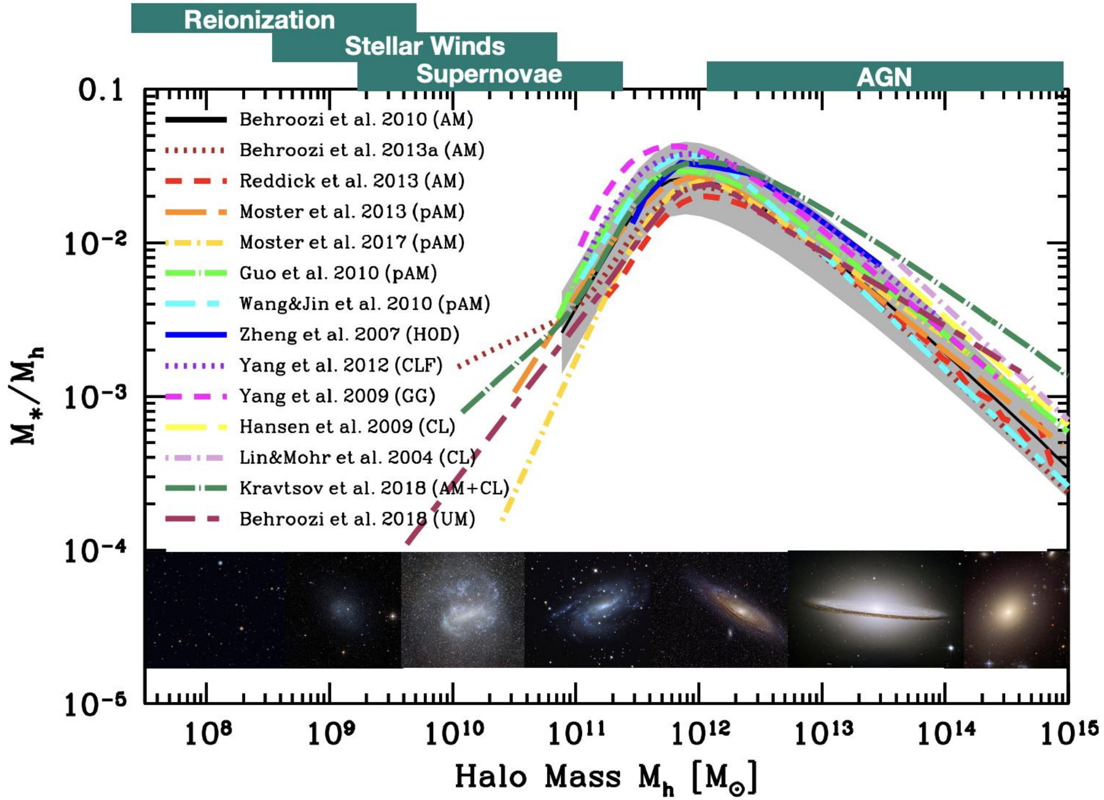


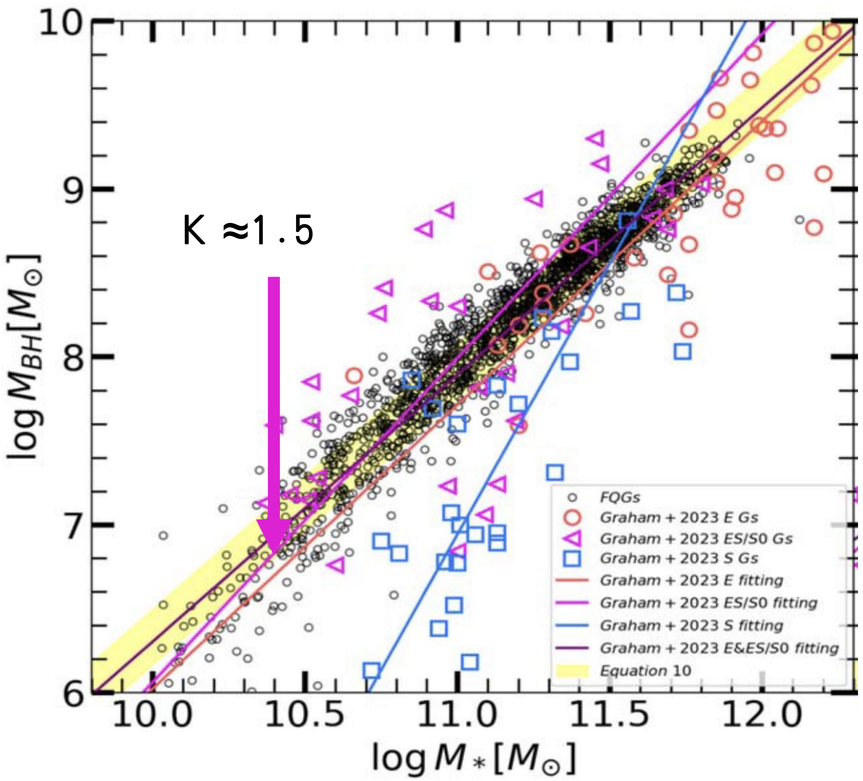
Fig. 21. Energetic bipolar outflows from the galaxy Hercules A. Radio observations (blue) show synchrotron emission from relativistic electrons. X-ray observations (purple) reveal the surrounding atmosphere. The outflows emerge from the galaxy as narrow jets which then broaden into lobes filled with relativistic plasma as they push against the galaxy's atmosphere.

Donahue & Voit 2022

Scaling relations ——How to build them

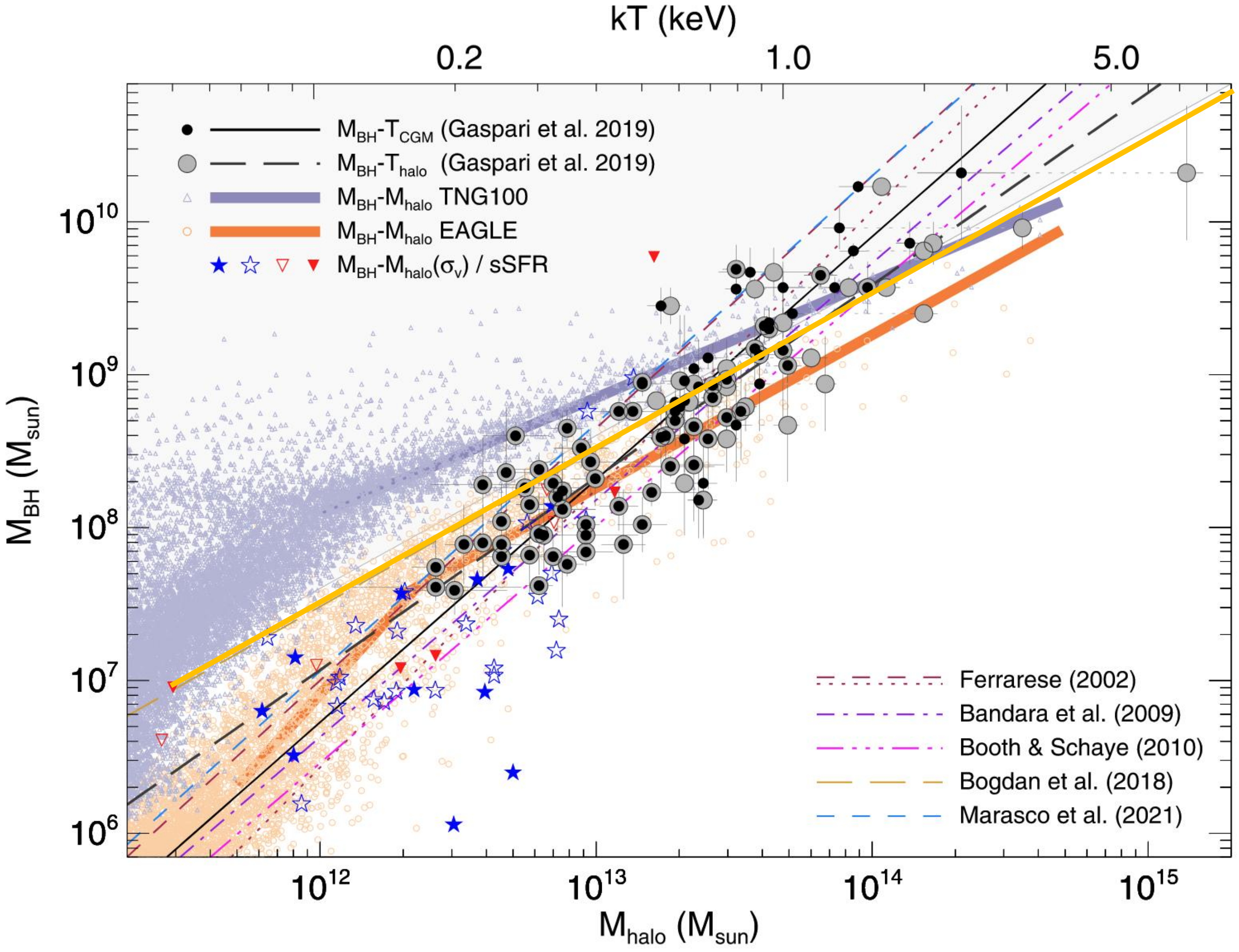


Stellar–Halo Mass Relation, **Wechsler and Tinker 2018**

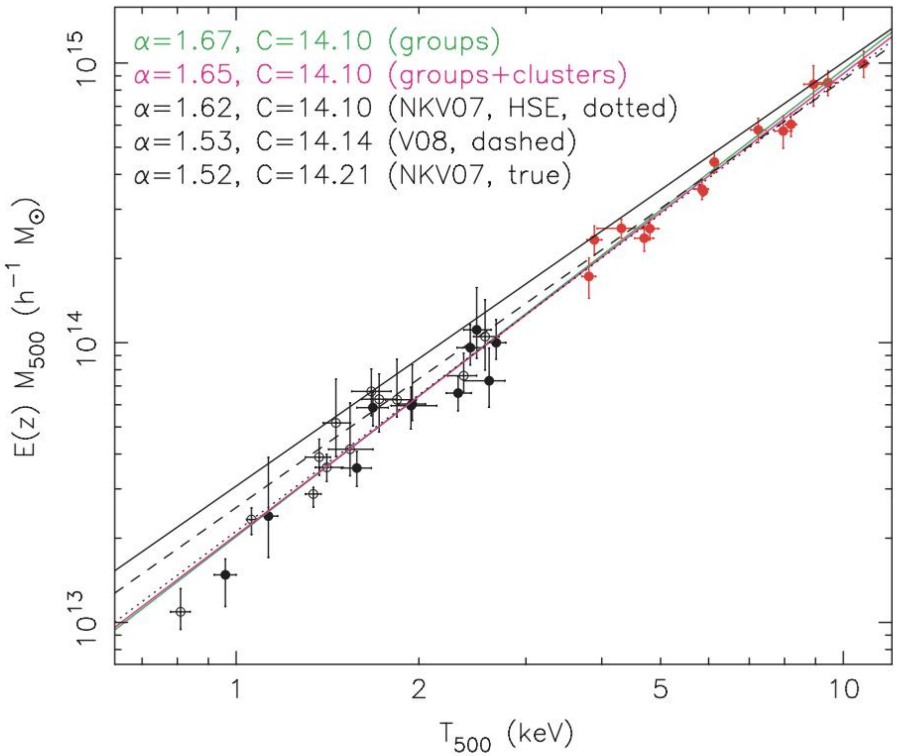


Stellar–BH Mass Relation, **Hong et al. 2023**

So what about the link between the M_{BH} and M_h?



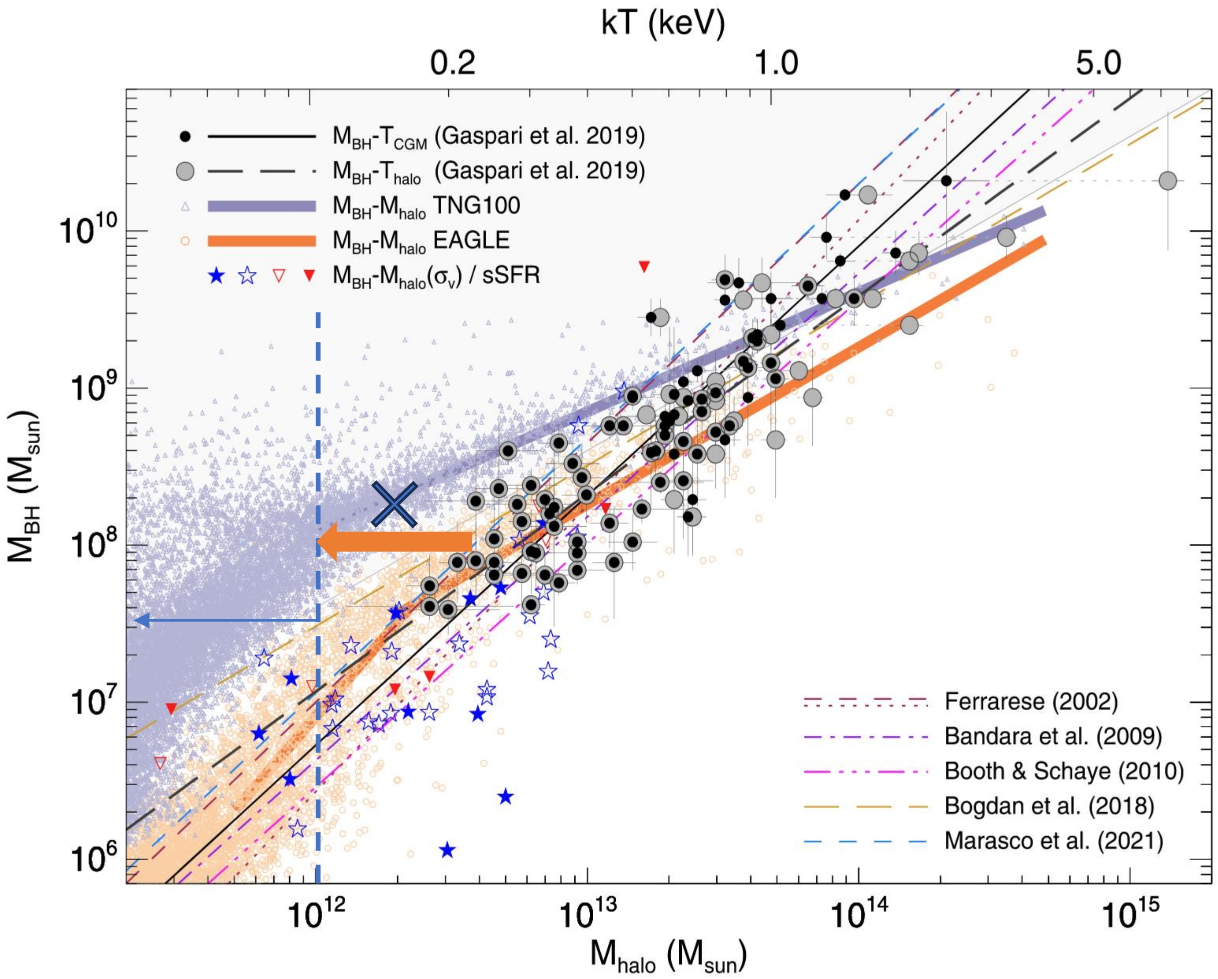
$$M_{200c} = 10^{15} M_\odot \left(\frac{kT_X}{6\ \mathrm{keV}} \right)^{1.7}$$



Sun et al.2009

$$M_{BH} \propto \sigma_v^5 \propto M_{halo}^{5/3}.$$

$$M_{BH} = 10^{8.3} M_\odot \left(\frac{M_{halo}}{10^{13} M_\odot} \right)^{1.6}$$



Due to the large uncertainty in BH mass measurement, the power law index ranges from 0.9 to 1.67 in weak-lensing results.

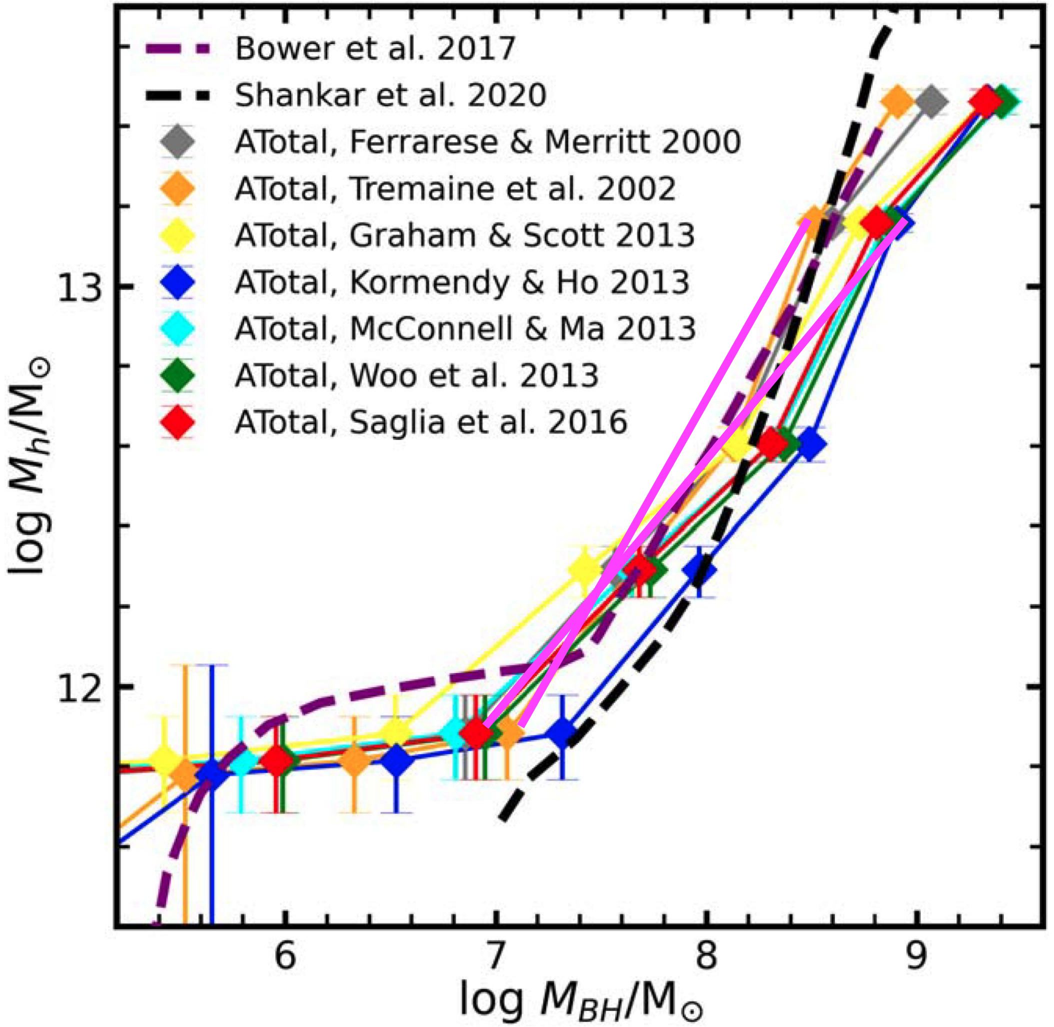
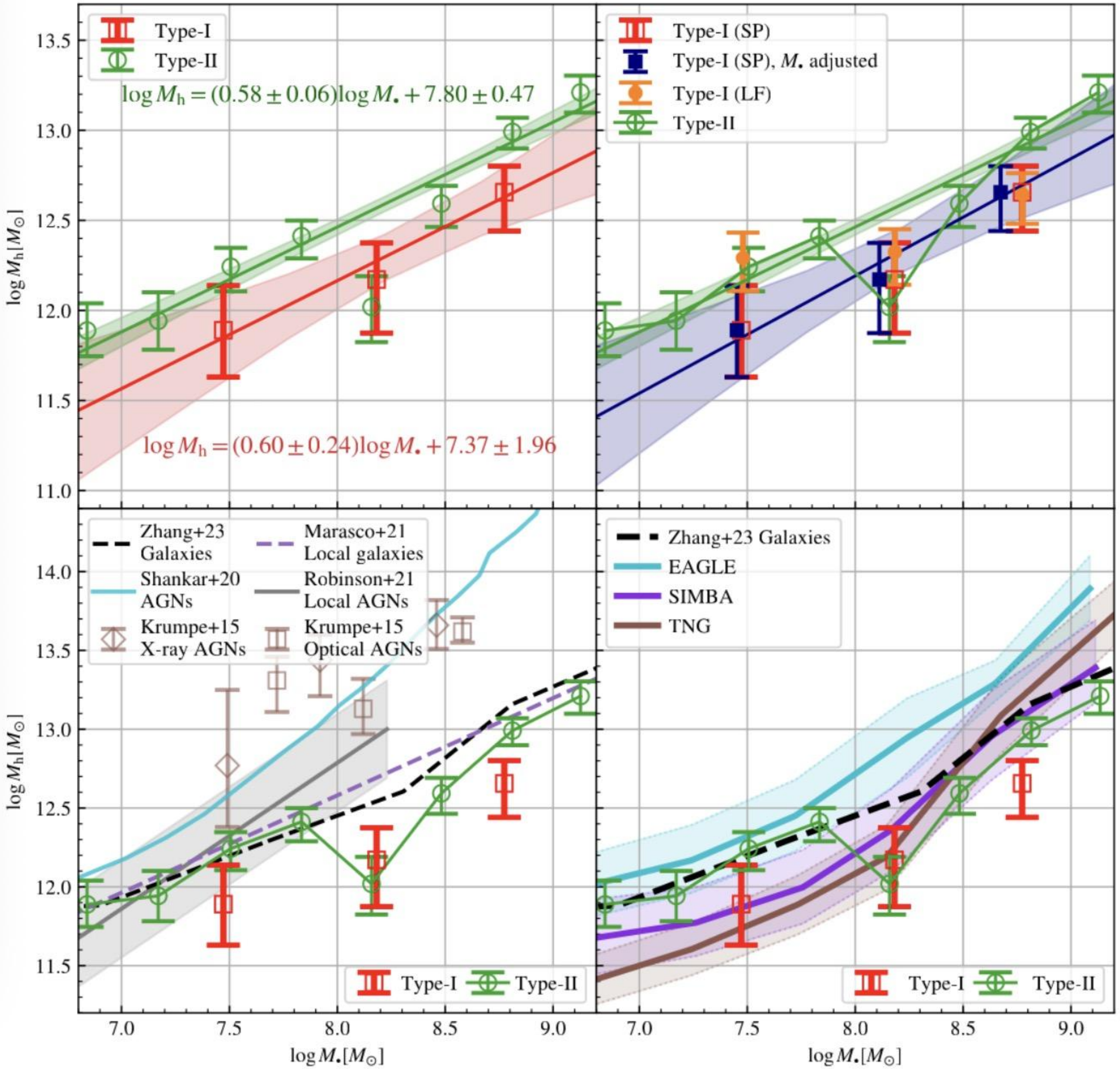


Figure 6. M_h–M_{BH} relations. We apply seven M_{BH}–σ_* relations from the literature, as indicated, to convert the M_h–σ_* relation into M_h–M_{BH} relations. For comparison, we show the model result of Bower et al. (2017) with a purple dashed line and the observational result of Shankar et al. (2020) with a black dashed line.

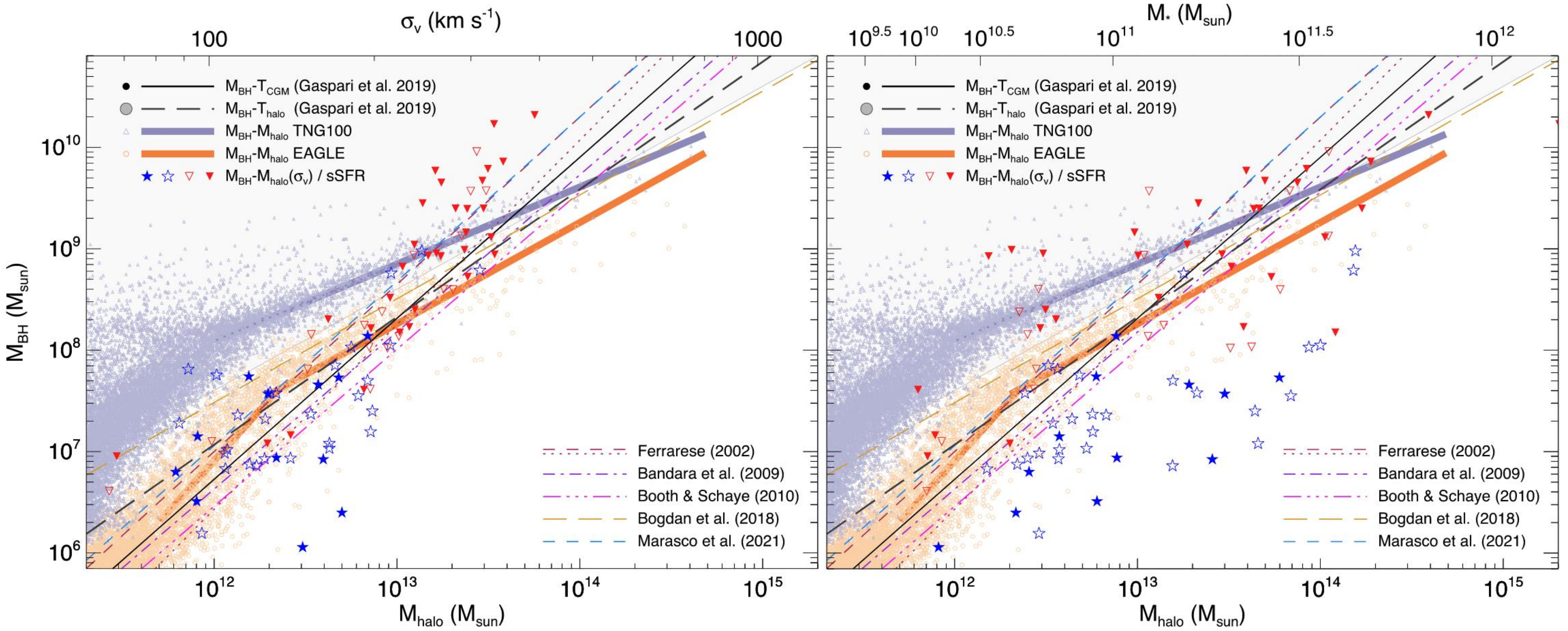
Ziwen Zhang et al. 2024



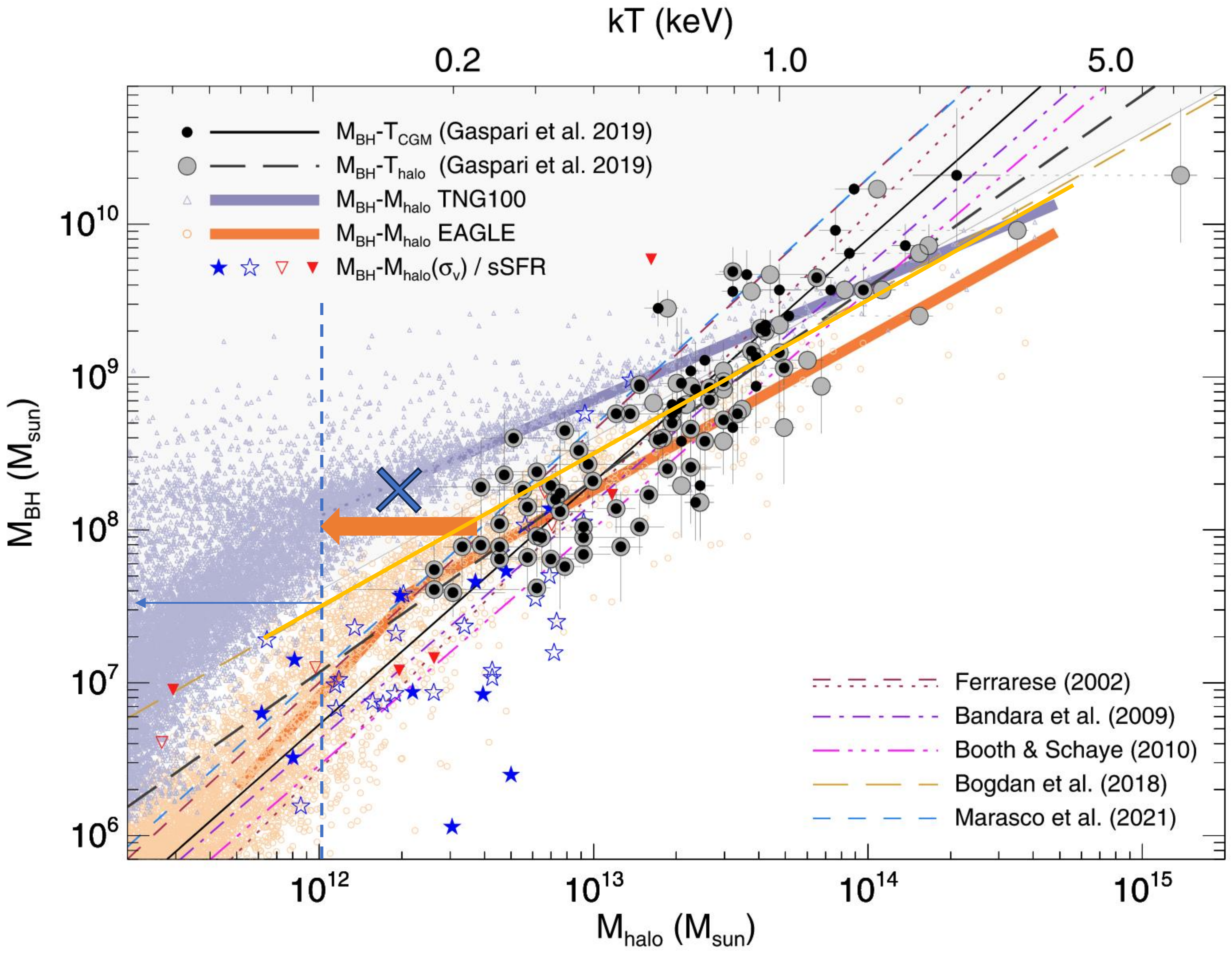
continuum luminosity) for their estimates. Here, we adopt their black hole masses based on $H\beta$. The mean statistical error in $\log M_\bullet$ is much smaller than the systematic error of the virial black hole mass ($\sim$0.4 dex; see Shen 2013).

As a complement to Wu & Shen (2022) at low black hole masses, we use the AGN catalog from Liu et al. (2019), a complete AGN sample including both quasars and Seyfert galaxies from SDSS Data Release 7. Black hole masses are measured with Hα and Hβ, and we adopt the $H\beta$ mass. This catalog contains 14,584 AGNs at $z < 0.35$.

Qinxun Li et al.2024

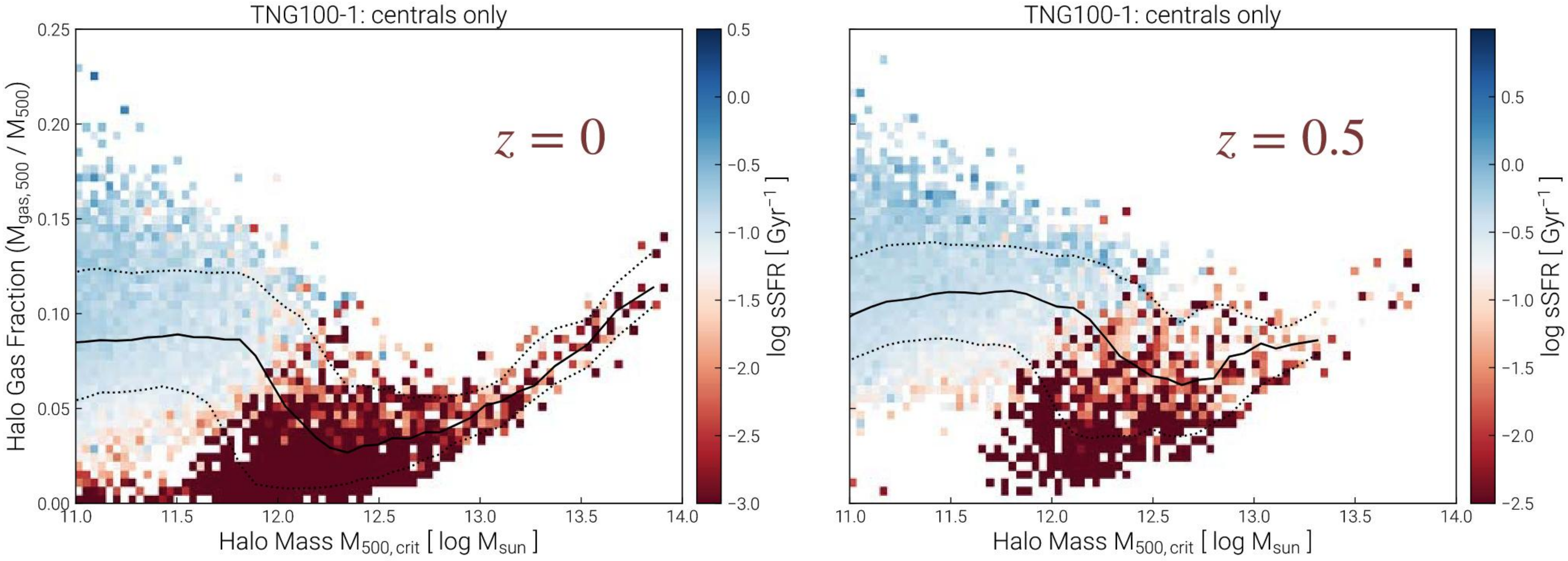


1. The upturn at $M_{BH}=10^9$, indicates that there should be some physical process prevent the rising of the velocity dispertion at high mass end.
2. The mass relation near the critical mass for quenching has a large disperation.



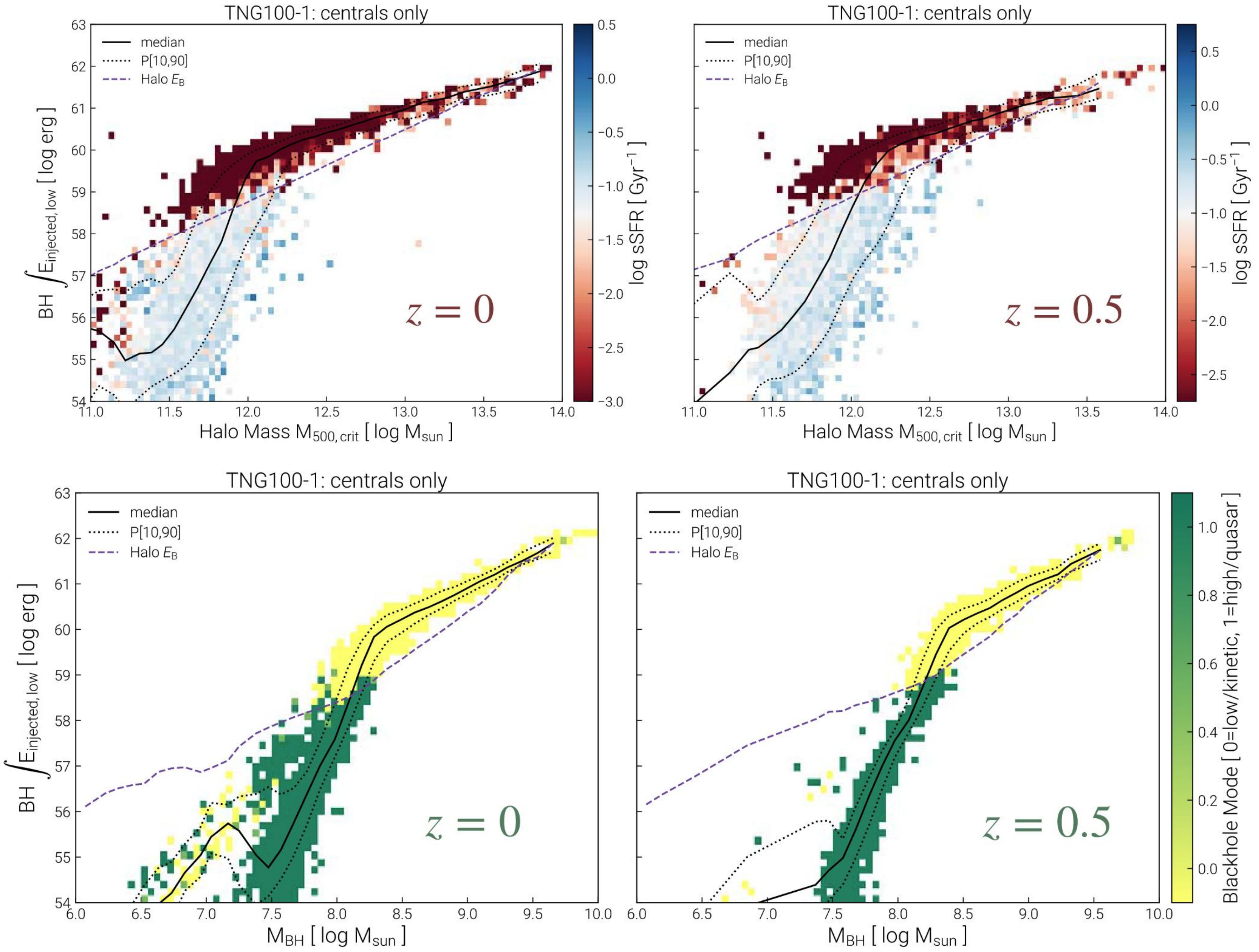
kT (keV)
0.2
1.0
5.0
M_BH-T_CGM (Gaspari et al. 2019)
M_BH-T_halo (Gaspari et al. 2019)
M_BH-M_halo TNG100
M_BH-M_halo EAGLE
M_BH-M_halo(σ_v) / sSFR
Ferrarese (2002)
Bandara et al. (2009)
Booth & Schaye (2010)
Bogdan et al. (2018)
Marasco et al. (2021)
M_BH (M_sun)
M_halo (M_sun)
10^6
10^7
10^8
10^9
10^10
10^12
10^13
10^14
10^15

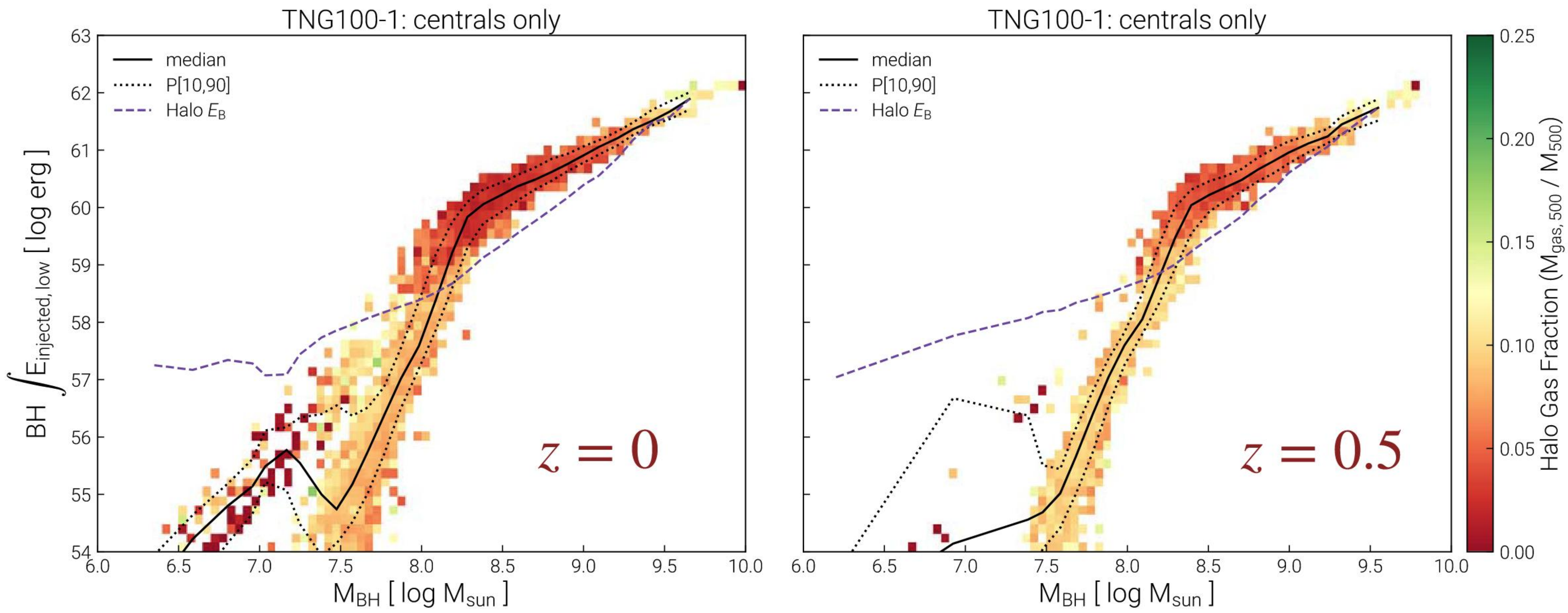
We therefore conclude that the IllustrisTNG $M_{\rm BH}$–$M_{\rm halo}$ relation is in strong tension with the available observational constraints. Those simulations consequently seem to be inconsistent with the proposed three-way link between black hole growth, baryon lifting, and quenching of star formation, but they are not. The rest of the paper looks more closely at IllustrisTNG and shows that both black hole growth and quenching of star formation are indeed linked to baryon lifting, despite the anomalous $M_{\rm BH}$–$M_{\rm halo}$ relation. Sections 3 and 4



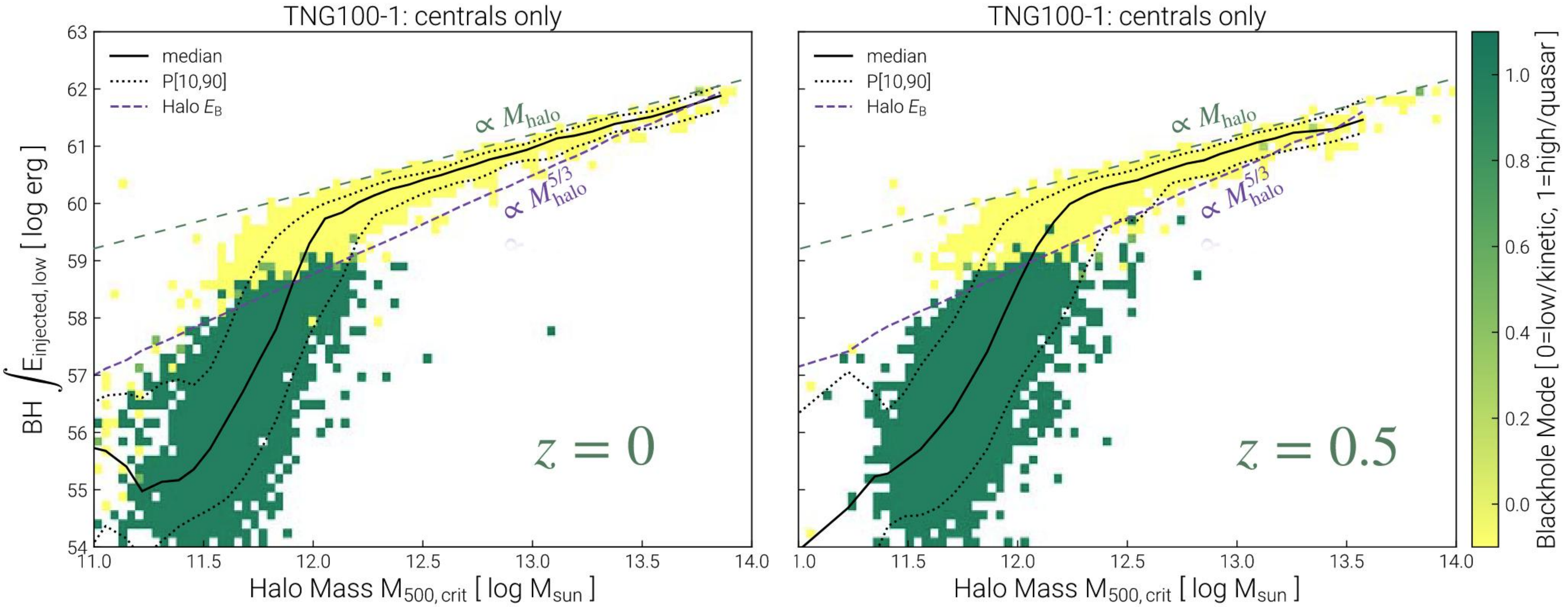
TNG100-1: centrals only
$z = 0$
Halo Gas Fraction ($M_{gas,\,500}$ / M_{500})
Halo Mass $M_{500,\,crit}$ [log M_{sun}]
log sSFR [Gyr^{-1}]
TNG100-1: centrals only
$z = 0.5$
Halo Mass $M_{500,\,crit}$ [log M_{sun}]
log sSFR [Gyr^{-1}]

$$E_{\rm B} \equiv \frac{3}{5}\frac{GM_{200c}^2}{r_{200}} f_{\rm b} \,,$$





The halo gas fraction drops at the same condition that the cumulative kinetic energy exceed the estimated energy for baryon lifting. A reasonable explaination is that the energy exceeding leads to the baryon lifting which is important for quenching.



$\sim 10^{14}\,M_\odot$. In IllustrisTNG, black hole mergers preserve the sum of cumulative kinetic energy injection, and so $E_{\rm kin}$ reflects the entire history of kinetic energy injection associated with a particular halo. The upper edge of the relation between $E_{\rm kin}$ and halo mass therefore reflects the kinetic energy requirements for quenching at $M_{\rm halo} \sim 10^{12-12.5}\,M_\odot$.

on the price of feedback. Assuming that baryon lifting is necessary for long-term quenching implies that a central black hole must inject an amount of energy at least as great as the halo's baryonic binding energy (E_B) into the CGM. The

$$\Delta M_{BH} \sim 10^8 M_\odot + 10^{5.5} M_\odot \left(\frac{M_{halo}}{10^{12} M_\odot} \right)^{5/3}, \qquad (20)$$

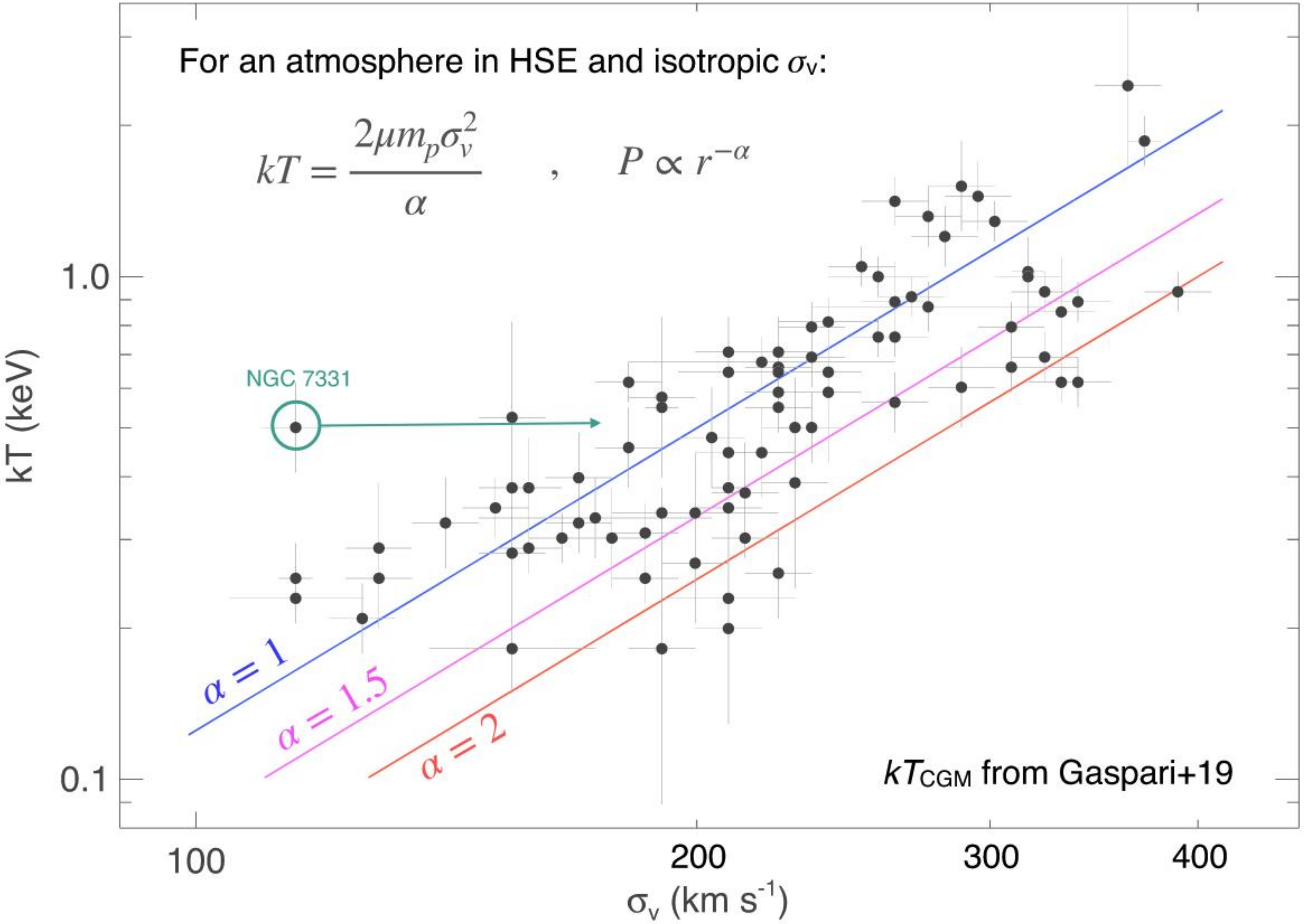
$$\frac{\dot{M}_{BH}}{\dot{M}_{Edd}} > \min \left[0.002 \left(\frac{M_{BH}}{10^8 \, M_\odot} \right)^2, 0.1 \right].$$

$$\Delta M_{BH} \gtrsim \frac{E_B}{\epsilon_{kin} c^2} \qquad (13)$$

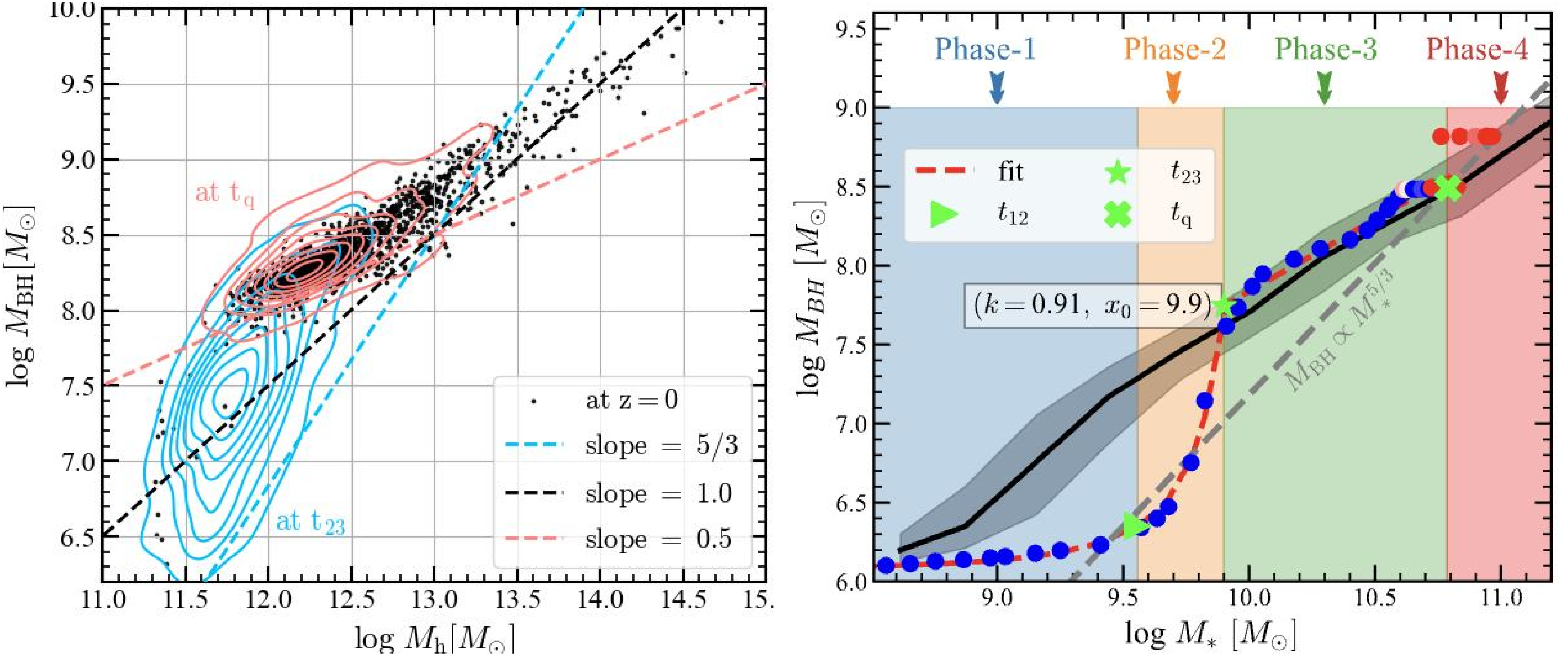
in which ϵ_{kin} is the conversion efficiency of accreted rest-mass energy into kinetic feedback energy and c is the speed of light. In IllustrisTNG, this relationship results in

$$\Delta M_{BH} \gtrsim \boxed{3 \times 10^5 \, M_\odot} \left(\frac{E_B}{10^{59} \text{ erg}} \right), \qquad (14)$$

Simultaneously implementing $\epsilon_{kin} \approx 0.015$ and $M_{piv} \approx 10^7 \, M_\odot$ in IllustrisTNG could potentially result in black hole masses that agree with M_{BH}–M_{halo} observations at both the low- and high-mass ends. However, a large potential downside could be a



For an atmosphere in HSE and isotropic σ_v:
$kT = \frac{2\mu m_p \sigma_v^2}{\alpha}$, $P \propto r^{-\alpha}$
NGC 7331
$\alpha = 1$
$\alpha = 1.5$
$\alpha = 2$
kT_{CGM} from Gaspari+19
kT (keV)
1.0
0.1
100
200
300
400
σ_v (km s^{-1})



at t_q
at t_23
at z = 0
slope = 5/3
slope = 1.0
slope = 0.5
log M_BH [M_⊙]
log M_h [M_⊙]
Phase-1
Phase-2
Phase-3
Phase-4
fit
t_12
t_23
t_q
(k = 0.91, x_0 = 9.9)
M_BH ∝ M_*^{5/3}
log M_BH [M_⊙]
log M_* [M_⊙]

1. Observation：
    - Weak lensing result (Blackhole mass measurements).
    - The low mass end.
    - High redshift.
2. Physical：
    - Why will the baryon lifting be a necessary requirement for long-time quenching?
    - Quench timescale or kinetic feedback alive time scale as a function of the kinetic feedback energy.
3. ??