Halo-Galaxy-BH Co-Evolution

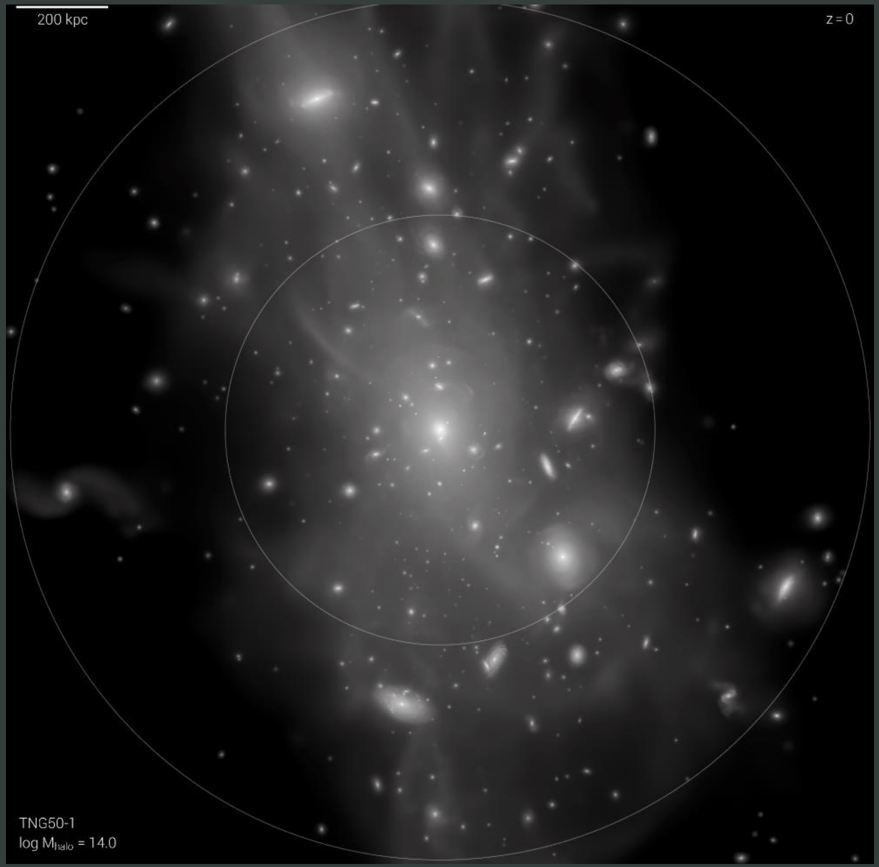
In simulation

A primary introduction!
Advice welcome!

Halo

Central

Satellite



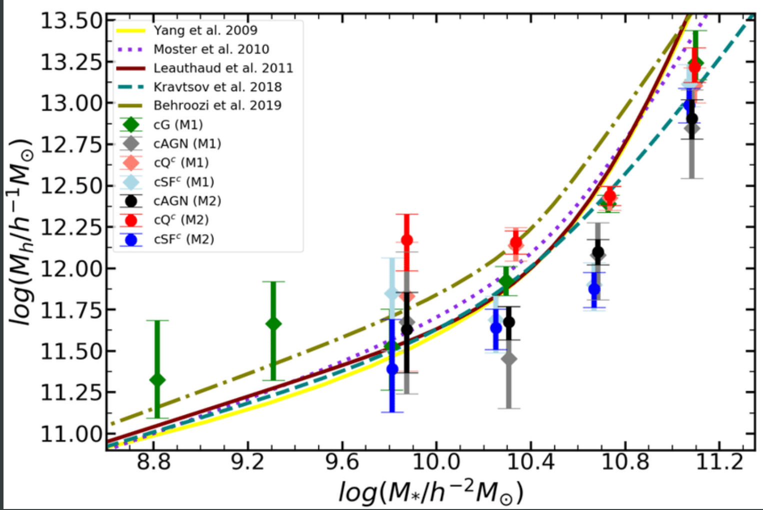
Blackhole

Blackhole

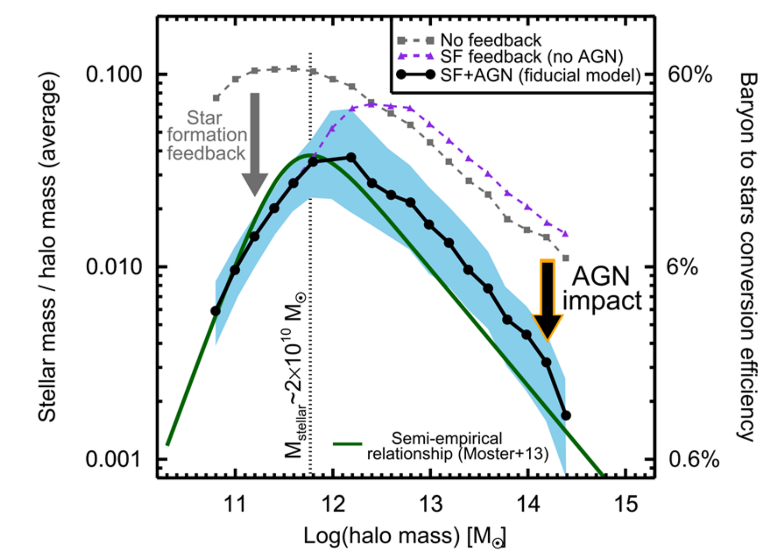
Halo

Central

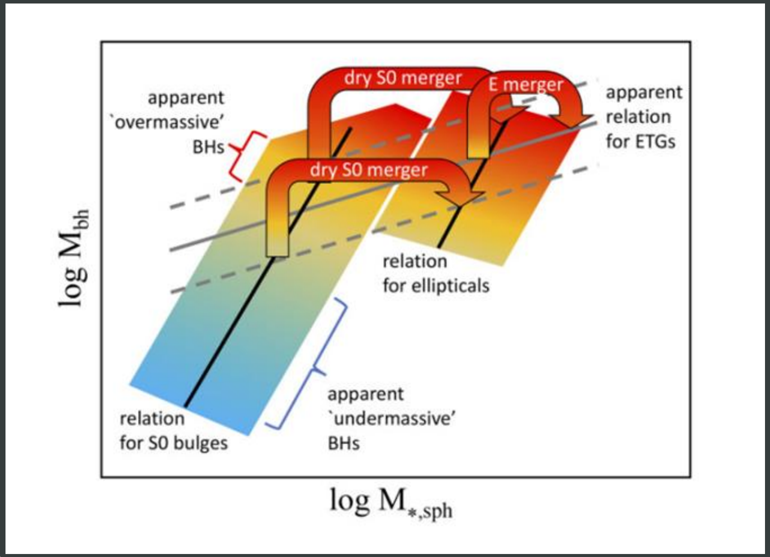
Blackhole



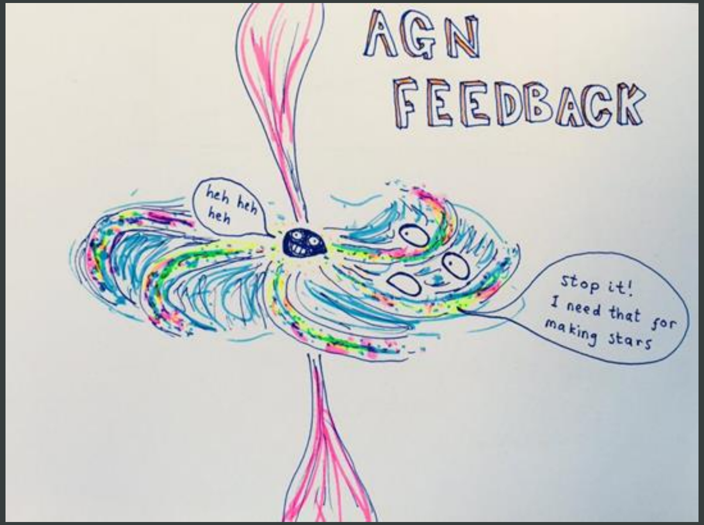
Zhang et al.2022



N. Werner et al.2018

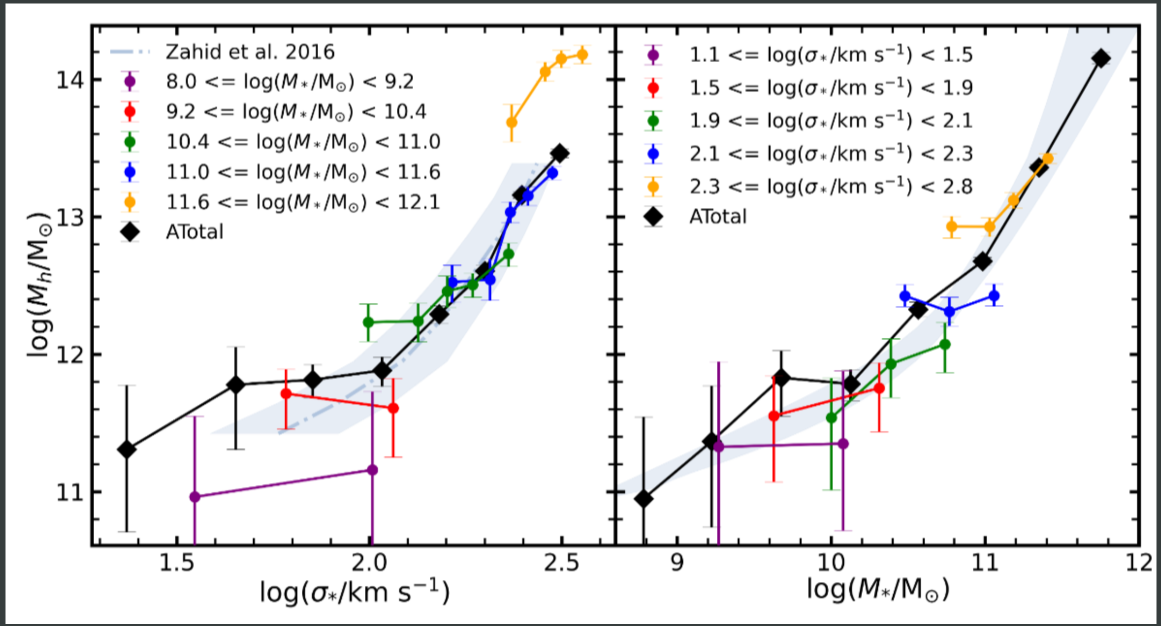


Graham & Sahu 2023

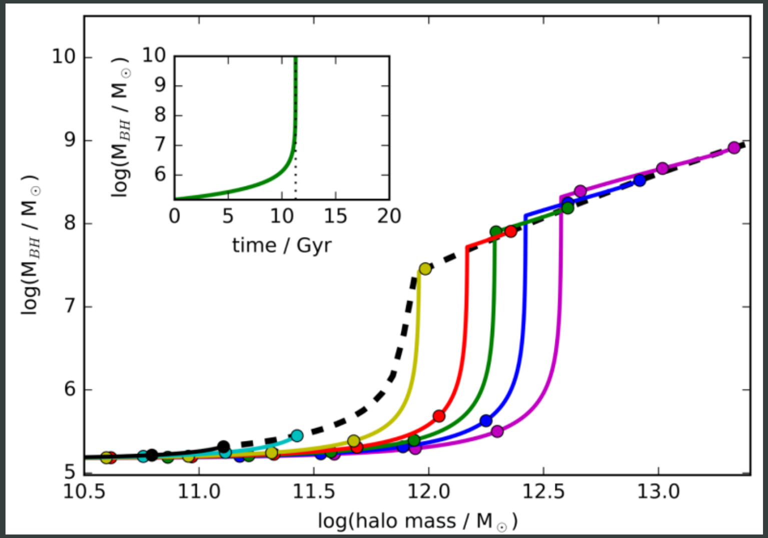


Halo-BH

- However, the detailed study finds that there might be some span BH will take the control power, and build a much tighter connections with Halo.
- And there is indeed some model trying to connect the black hole growth history with the halo's properties.

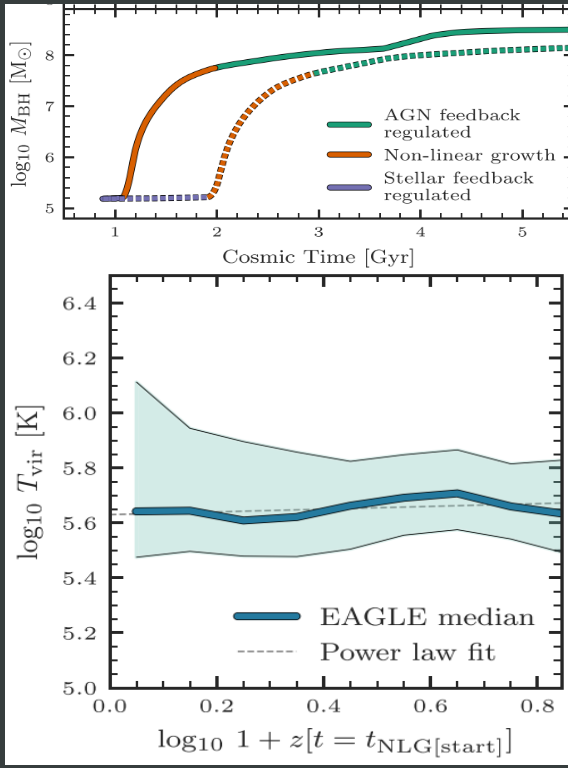


Zhang et.al.2023



Bower et.al.2017

Halo binding energy limits the M_{BH}



Stuart McAlpine et.al.2018

T_{vir} triggers the fast BH accretion

Scaling Relations and Evolution Path

Stellar mass Halo mass relation:

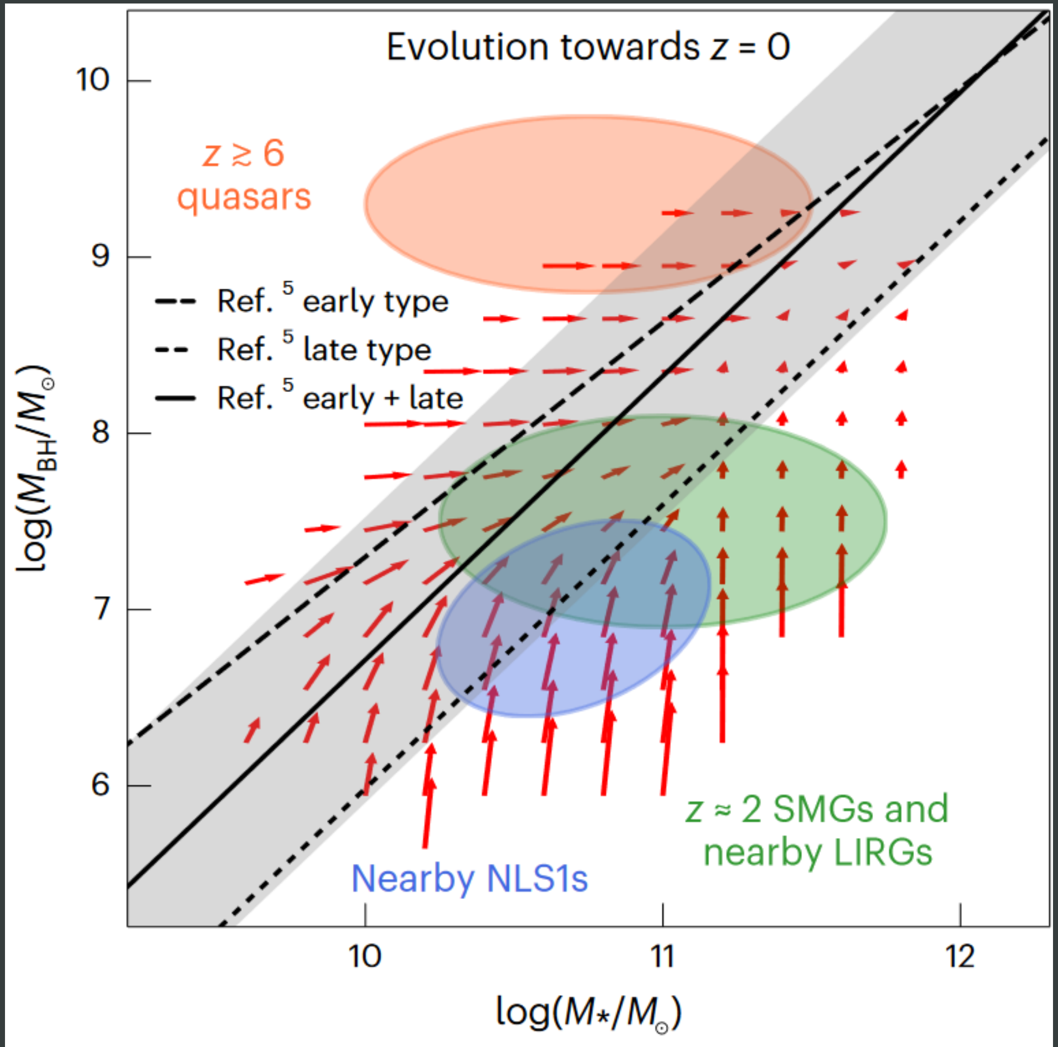
- There should be feedback to suppress the star formation and show different mass dependence after a critical mass or something.
- Stellar feedback will cause gas outflow to balance the cosmic inflow early but will fail at a certain time point.
- AGN feedback may be the other energy source but in debate.

Stellar mass BH mass relation:

- How does the relation arise? AGN feedback regulated? How?
- Relations for different types of galaxies differ from each other.

Halo mass BH mass relation:

- How does the relation arise? AGN feedback regulated? How?
- For halo and bh, it is hard to measure their mass, can we do some work here?



Evolutionary paths of active galactic nuclei and their host galaxies

Sample:

1. 11,474 $z \leq 0.35$ type 1 AGNs; SDSS DR7
2. AGN bolometric luminosity ($L_{bol} = 10^{41.9} – 104^{6.4}$ erg s^{-1})
3. BH mass ($M_{BH} = 10^{5.1} – 10^{10.0}$ $M_\odot$)
4. Eddington ratios ($\lambda_E = 10^{-3.5} – 10^{0.7}$)

$$\log(M_{BH}/M_\odot) = (1.88 \pm 0.05) \log(M_*/10^{11}M_\odot) + (7.89 \pm 0.40), \quad (1)$$

$$\log(M_{BH}/M_\odot) = (1.81 \pm 0.06) \log(M_*/10^{11}M_\odot) + (7.61 \pm 0.50), \quad (2)$$

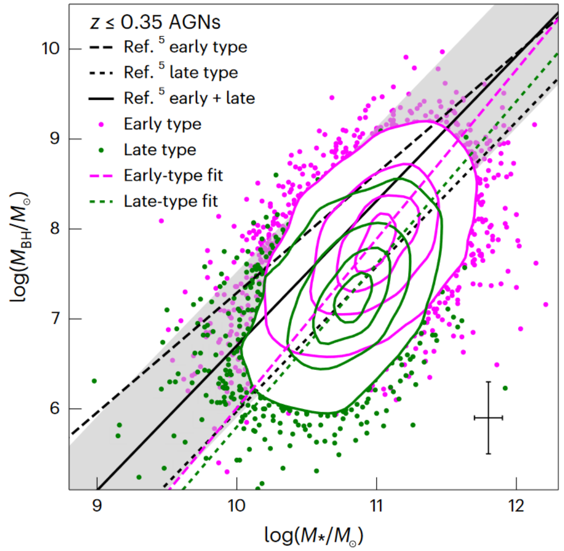


Fig. 1 | The relation between M_{BH} and M_* for $z \leq 0.35$ type 1 AGNs. Objects with late-type, disk-dominated and early-type, bulge-dominated host morphologies are shown in green and magenta, respectively. Best-fit relations from ref. 5 for local early-type galaxies (black dashed line), late-type galaxies (black dotted line) and both types combined (black solid line; intrinsic scatter of 0.81 dex indicated as shaded grey region). We plot the best-fit relation for the early-type AGNs as a magenta dashed line and for the late-type AGNs as a green dotted line. Data are presented as median values, and typical uncertainty is shown in the lower-right corner. Contours indicate the distribution of 10%, 30%, 60% and 90% of the entire sample, respectively. Dots are individual objects located outside the 90% contour.

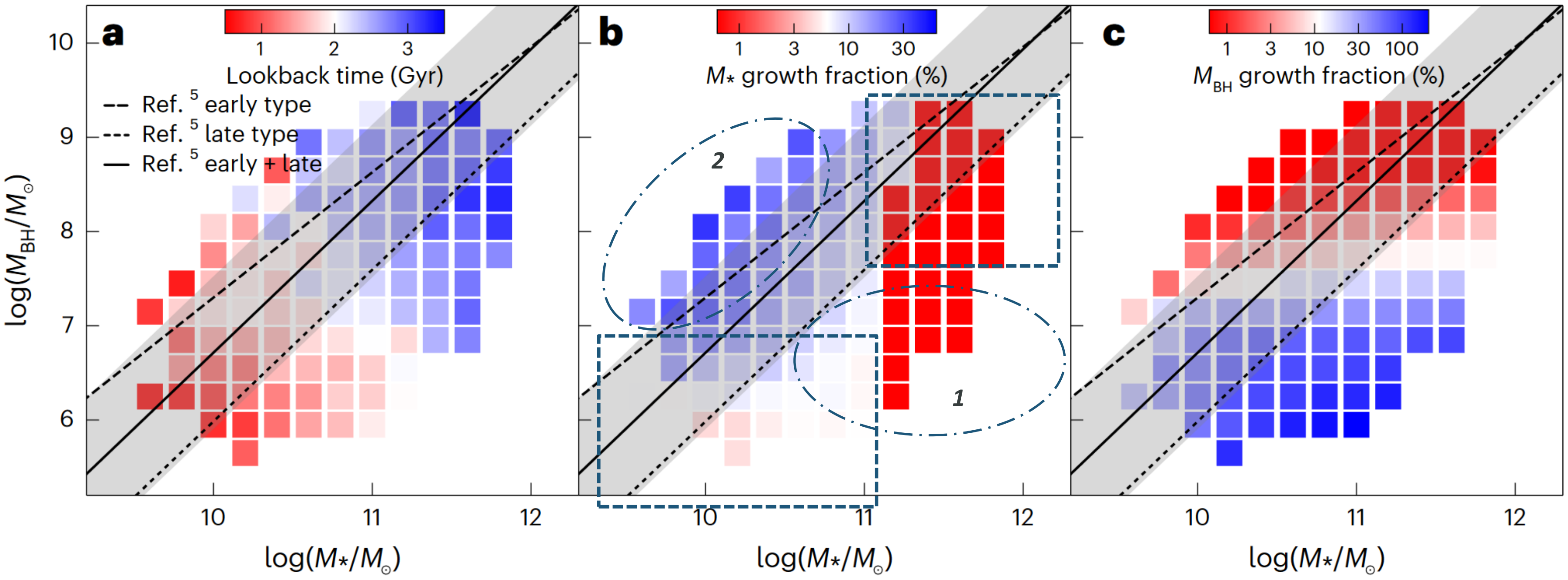


Fig. 3 | The relation between M_{BH} and M_* for $z \le 0.35$ AGNs. a–c, Colours represent median lookback time (**a**), growth fraction of M_* (**b**) and growth fraction of M_{BH} (**c**). The growth fraction is defined as $\Delta M/M$ at $z = 0$. The host galaxies are assumed to be able to sustain star formation at the current rate. M_{BH}-dependent duty cycle of the BH accretion is adopted to estimate the mass gain of BHs (Methods).

$$\log(\mathrm{sSFR}/\mathrm{yr}^{-1}) = -(2.98 \pm 0.06)(g' - r')_0 - (8.61 \pm 0.03), \qquad (5)$$

$$\dot{M}_{\mathrm{BH}} = 0.15\left(\frac{0.1}{\epsilon}\right)\left(\frac{L_{\mathrm{bol}}}{10^{45}\,\mathrm{erg\,s^{-1}}}\right) M_{\odot}\,\mathrm{yr}^{-1}, \qquad (6)$$

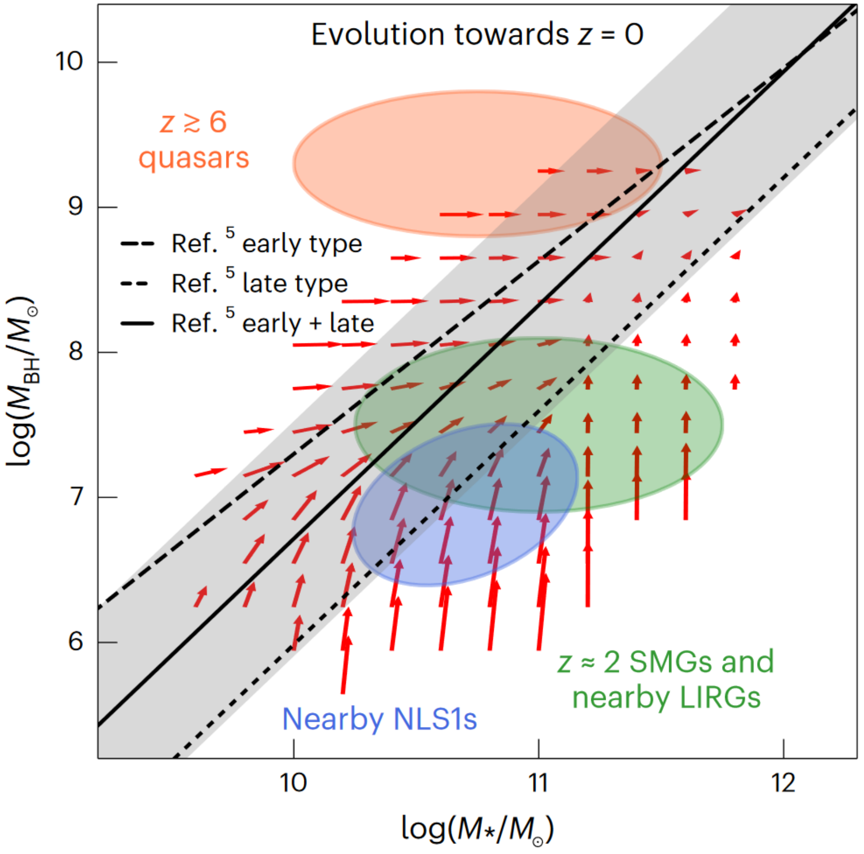


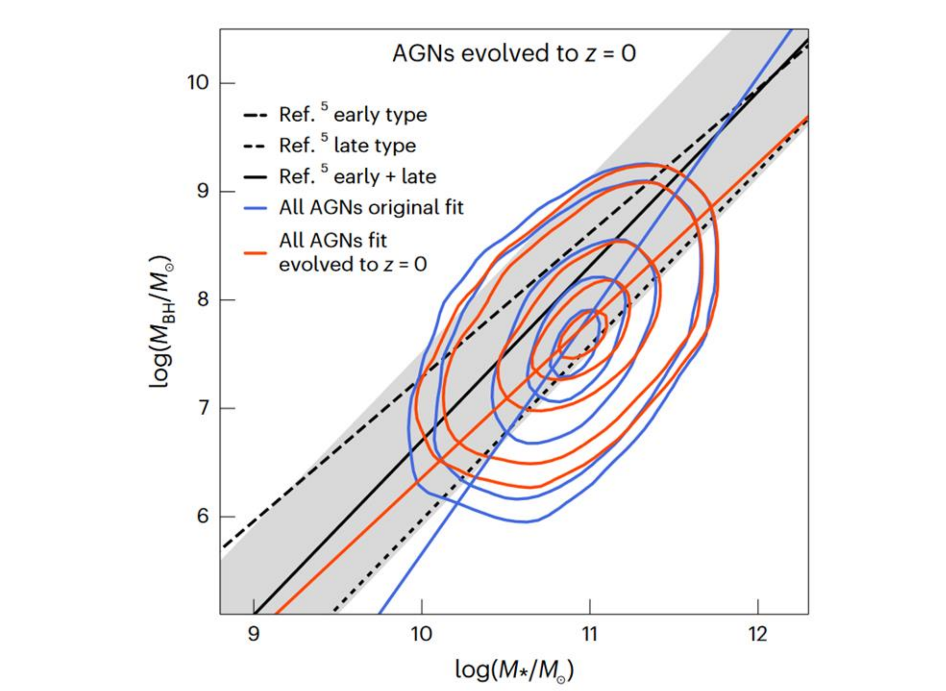
Fig. 4 | Evolutionary paths towards $z = 0$ of objects on the M_{BH}–M_* plane. Evolutionary paths are indicated by the direction and length of each arrow. The red, green and blue ellipses represent typical locations of $z \geq 6$ quasars[11,44], $z \approx 2$ submillimetre galaxies (SMGs) and nearby LIRGs[9,28,29] and nearby NLS1s[20,21]. Best-fit relations from ref. 5 are shown for local early-type galaxies (black dashed line), late-type galaxies (black dotted line) and both types combined (black solid line; intrinsic scatter of 0.81 dex indicated as shaded grey region).

Green and blue:

- Two population host under massive BH , they are gas-rich and late type. But the evolution path may be different.

The other:

- quasar-like, SF active, evolving to early type inactive galaxies. Secular evolution?

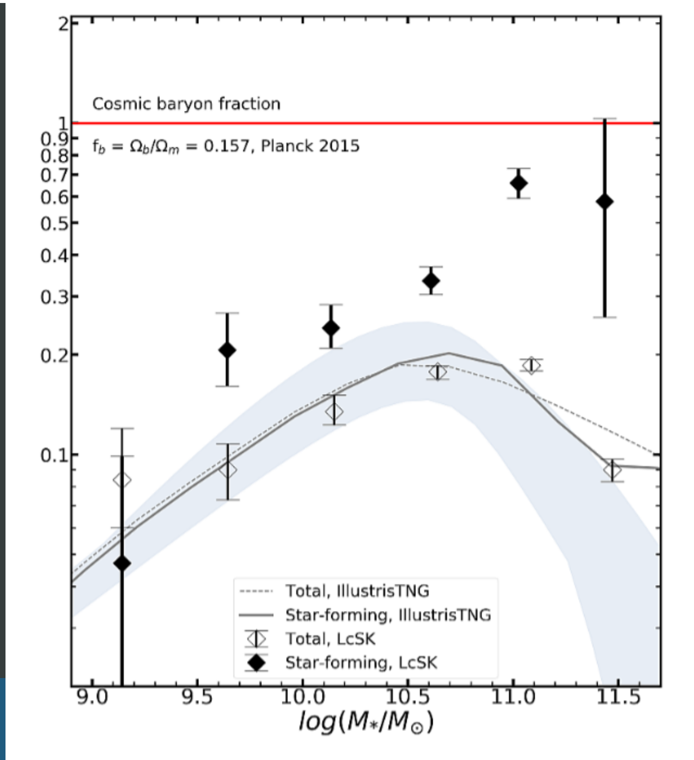


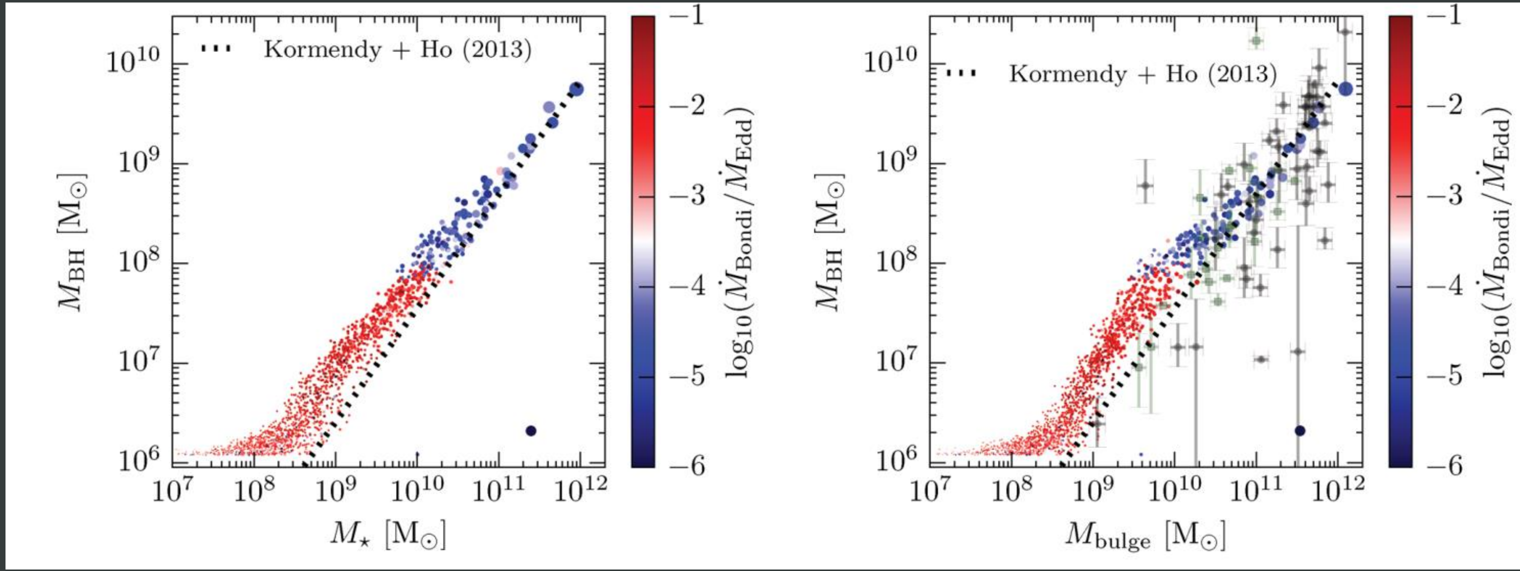
$$\log(M_{BH}/M_\odot) = (1.45 \pm 0.03)\log(M_*/10^{11}M_\odot) + (7.81 \pm 0.21). \quad (4)$$

In simulations

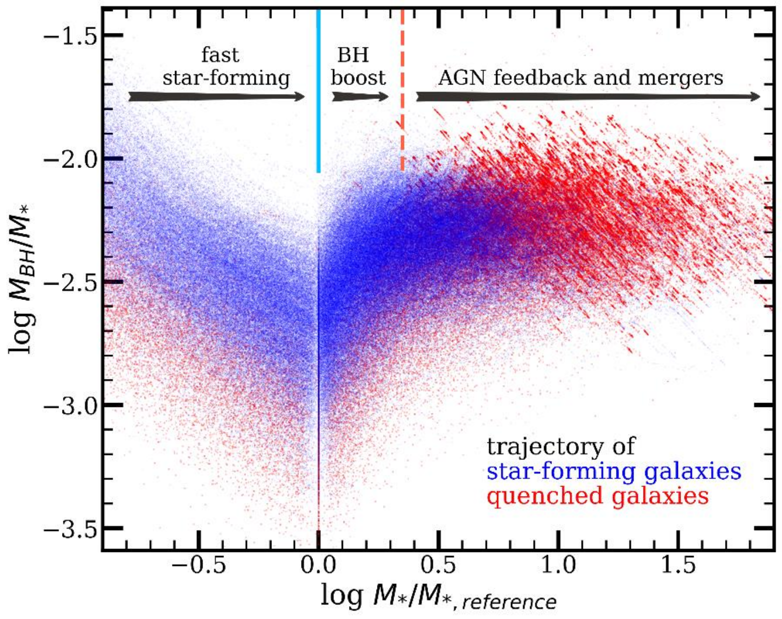
Table 1 Details of Simulations used for Illustrative Examples

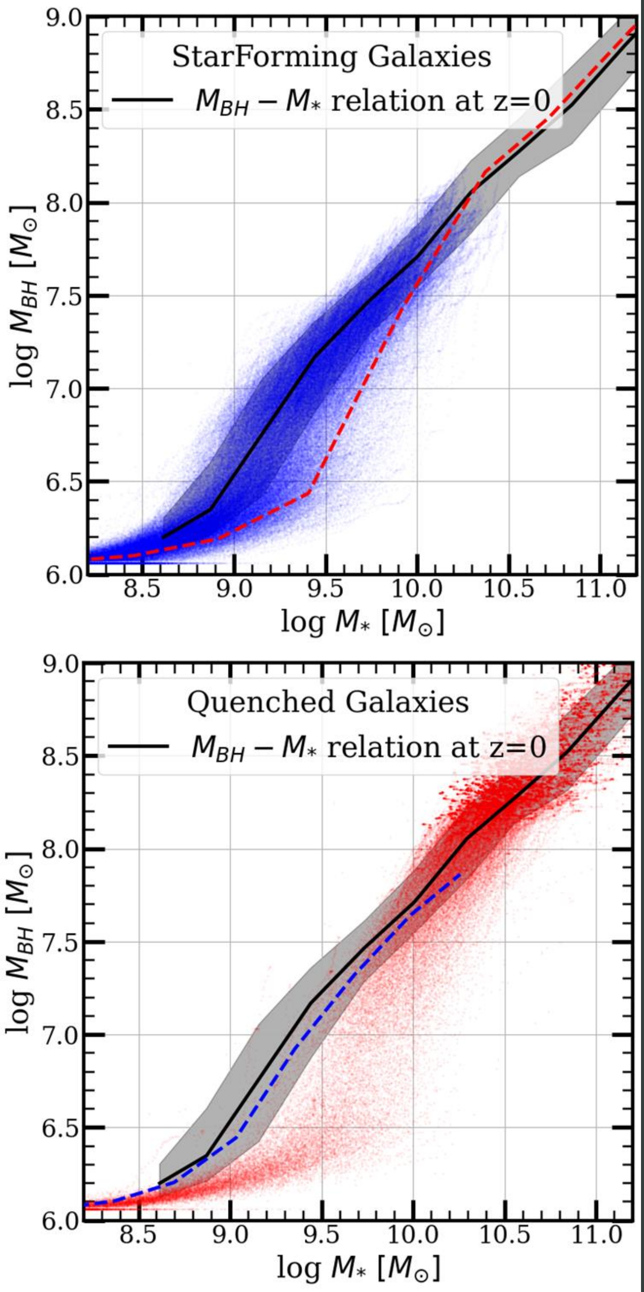
Simulation	Hydro method	Box size (cMpc)	DM particles per dimension	Baryonic mass resolution ($M_\odot$)	Baryonic spatial resolution[a] (pkpc)
EAGLE[b]	Modern SPH	100.0	1504	1.9×10^6	0.70
Horizon-AGN	AMR	142.0	1024	1.0×10^7	1.00
IllustrisTNG[c]	Moving mesh	110.7	1820	1.4×10^6	0.19
SIMBA[d]	MFM	147.0	1024	1.8×10^7	0.74





In simulations



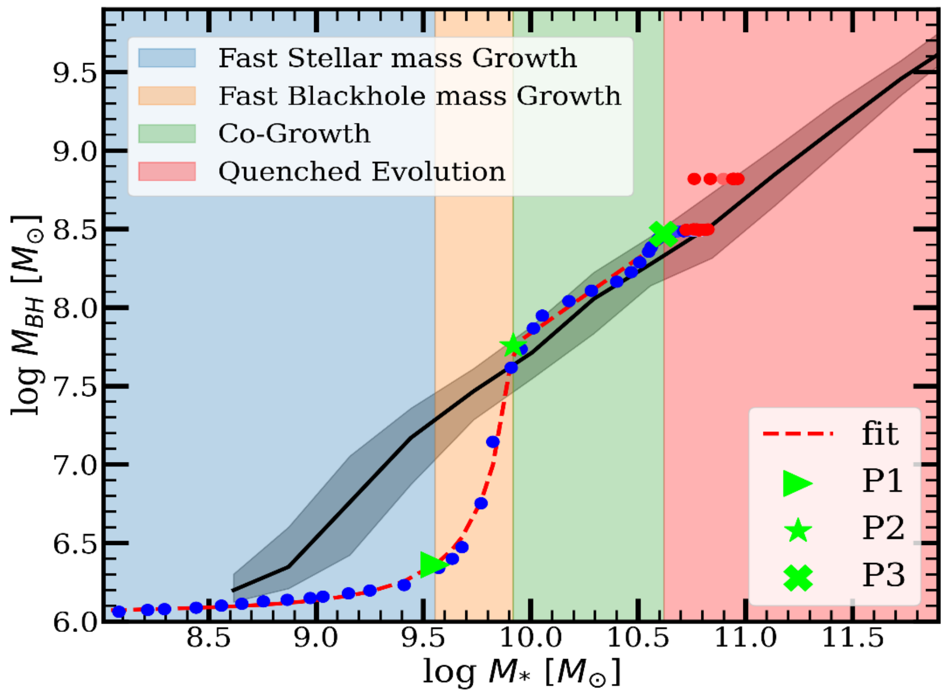


Usually：

- Galaxy will be in a fast star-forming phase early in the life of the object, during which stellar feedback will be the main feedback to balance the cosmic inflow.
- But to some time point when stellar mass is large enough, balance will be broken due to the relatively weaker feedback power, and the density at the vicinity of the BH will increase greatly to feed the BH boost.
- When stellar feedback (due to star-forming) fails, a further source of energy is required to keep or rebuild the balance and restore the quasi-equilibrium, which is commonly attributed to the feedback from the central supermassive black hole.
- Thus AGN feedback plays an important role in quenching the star-forming galaxies and transiting them into quiescent.

In simulations

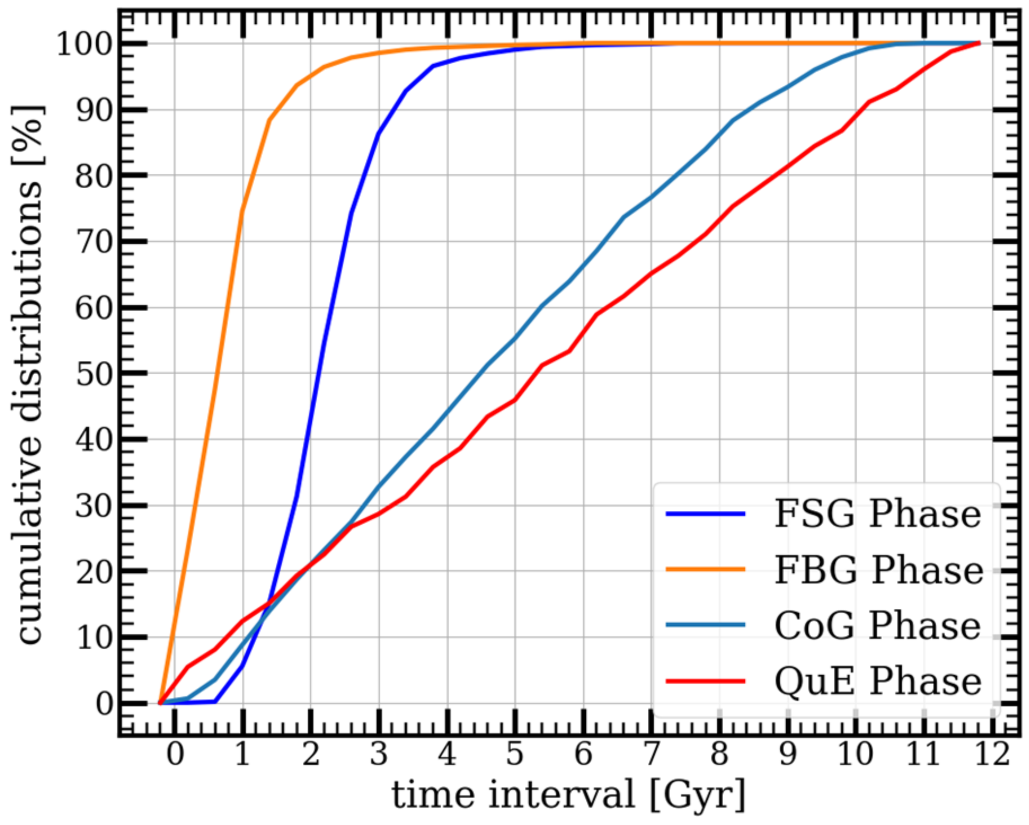
$$F(x) = \begin{cases} \frac{c}{[x-x_0+a)]^2} + y_0 - \frac{c}{a^2}, & if\ x \in [0, x_0) \\ k(x - x0) + y0, & if\ x \in [x_0, +\infty) \end{cases} \quad (1)$$



P1: the start point for BH boosting, so let us call it the "boost point".

P2: the starting point for Co-growth, some balance may built here so let us call it the "balance point".

P3: galaxies are going to be quiescent, so let us call it the "quench point"

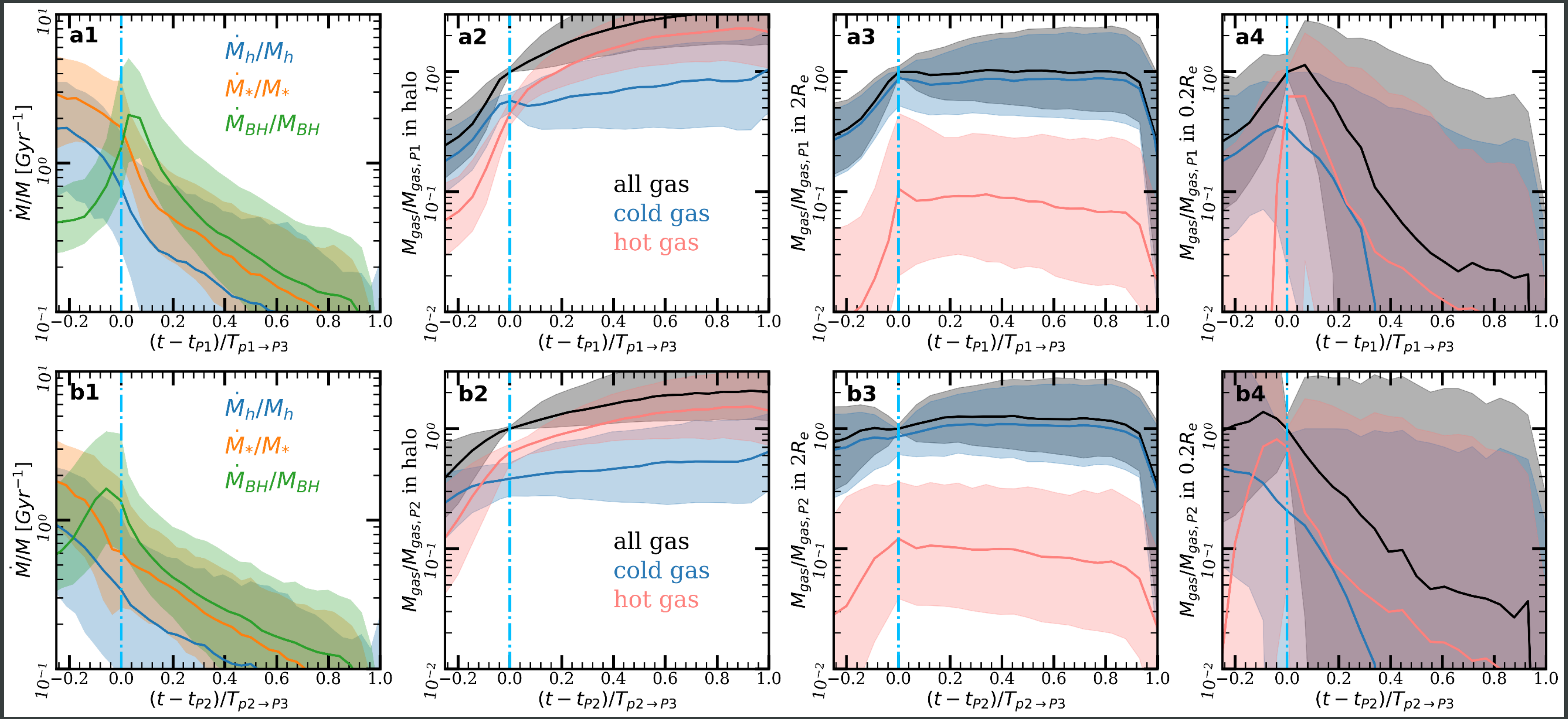


Fast Stellar mass Growth, FSG

Fast Blackhole mass Growth, FBG

Co-Growth, CoG

Quenched Evolution, QuE



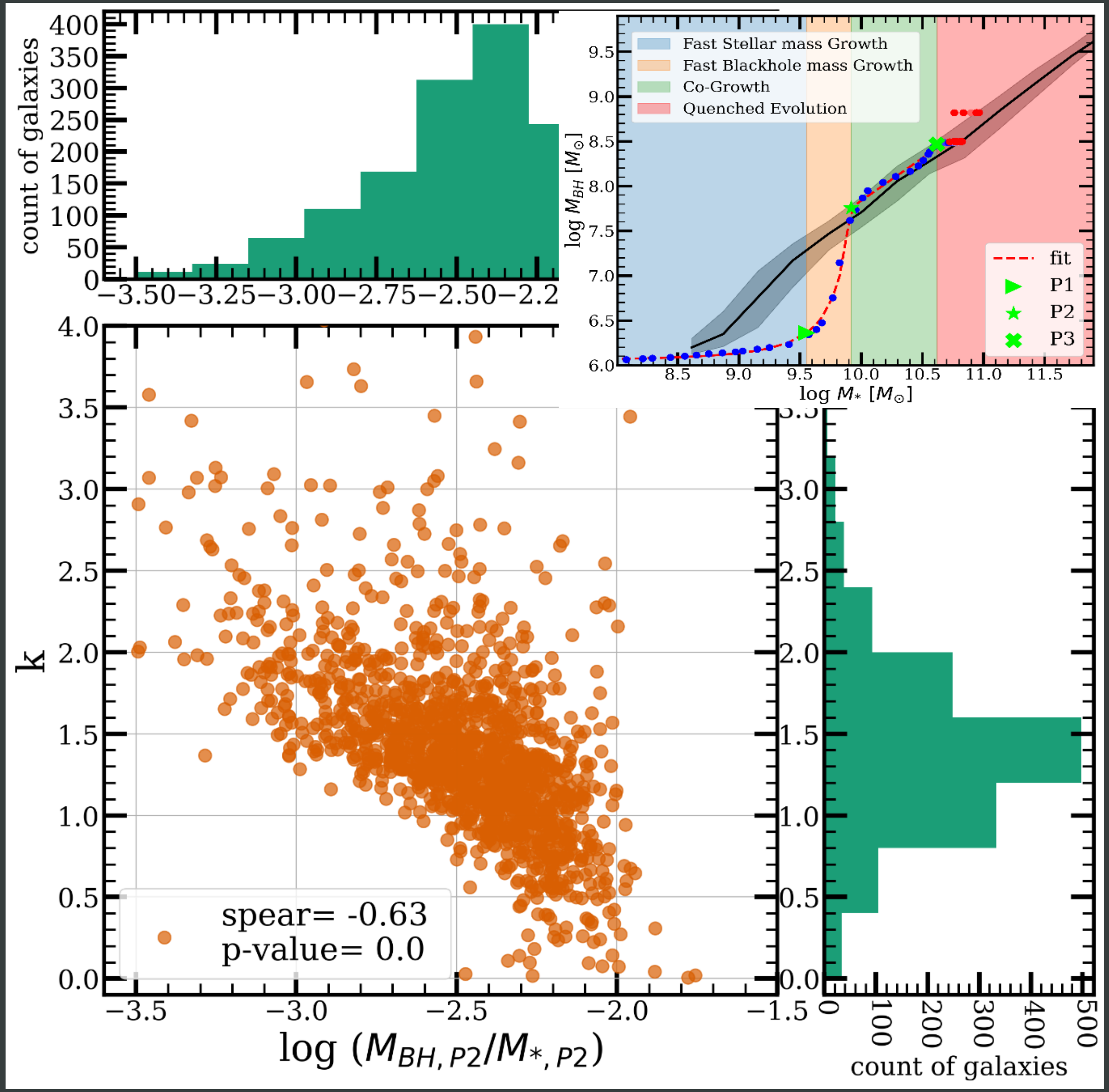
Series a: The properties as a function of the time since boost point P1. Time is scaled by the time interval from P1 to quench point P3.

Series b: The properties as a function of the time since boost point P2. Time is scaled by the time interval from P2 to quench point P3.

a1(b1) shows the specific mass growth rate, the different colors corresponding to sHAR(blue), sSFR(orange), and sBHAR(green).

the others show the gas mass scale by the all gas mass in the certain scale, the different colors show the cold and hot gas differed by 10^5K.

In simulations

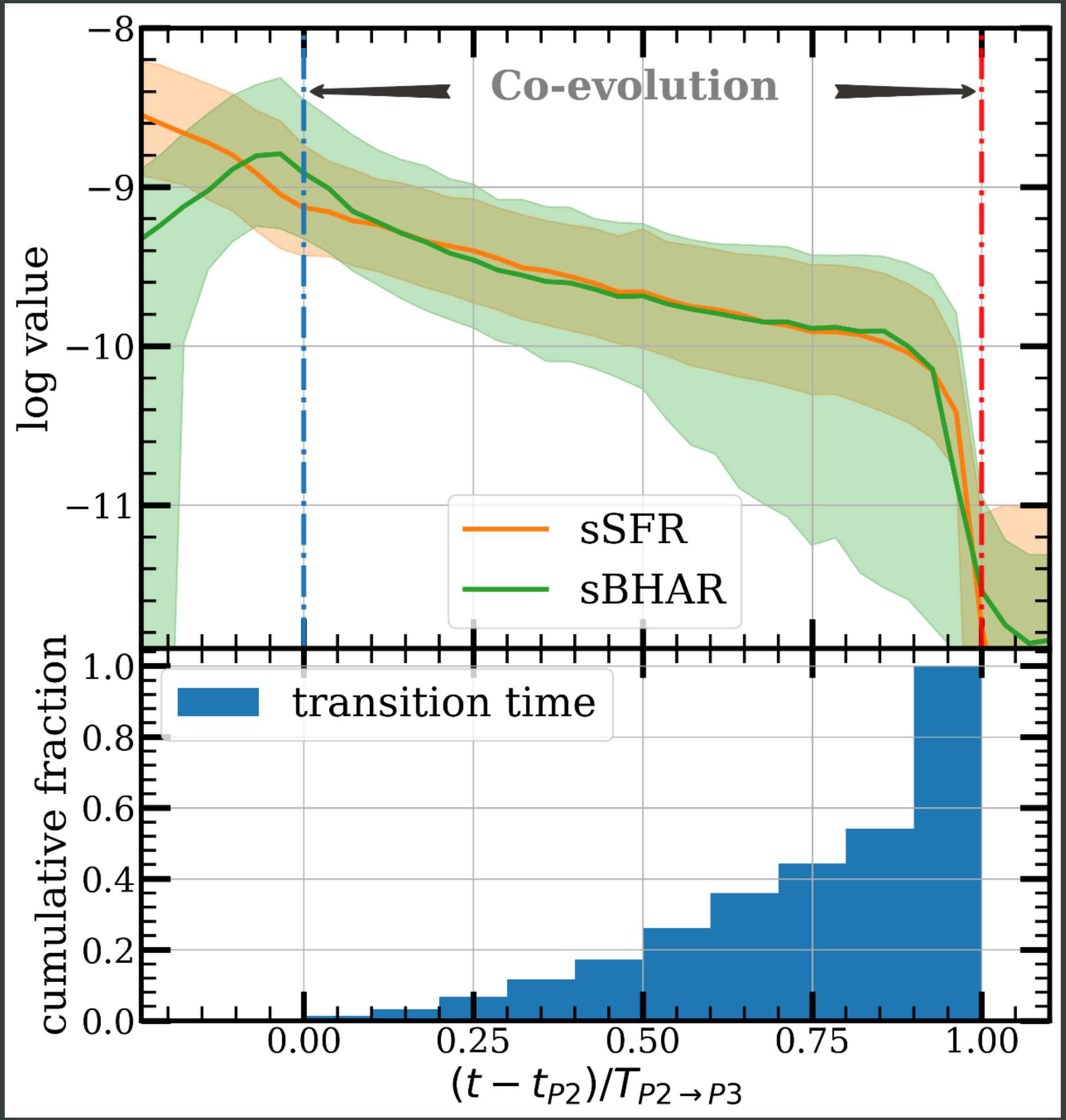


The coevolution slope is related to the position of point P_2 on the M_*-M_{BH} plane.

To be clear, there appear to be 3 populations:

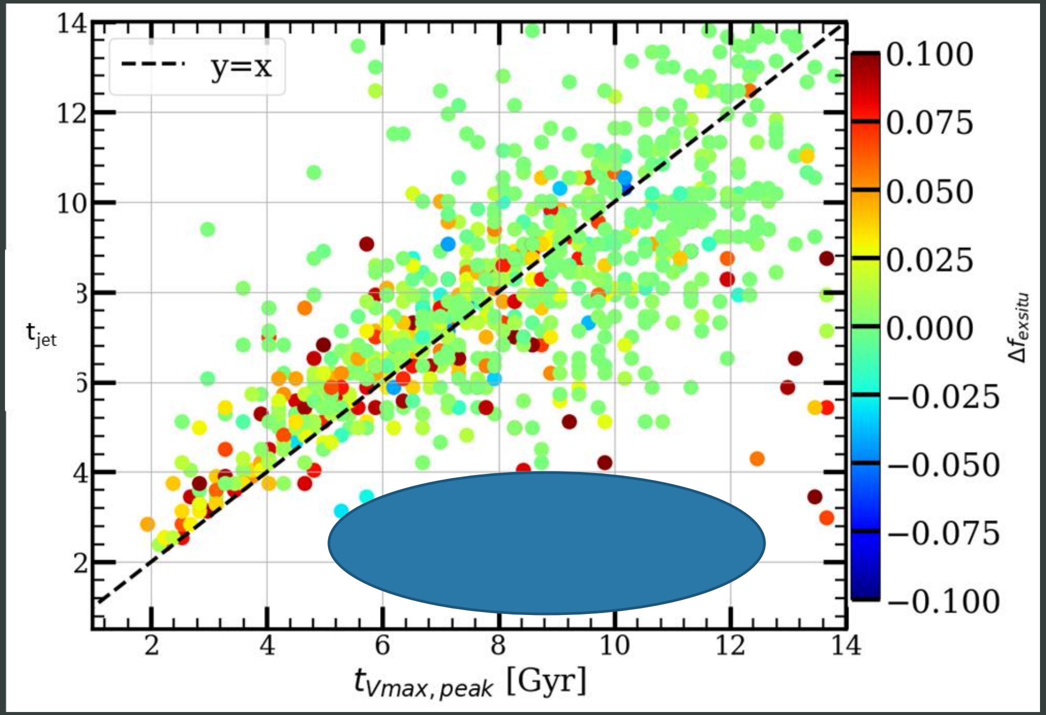
- First is the object whose liner point is located above the simulation z=0 relation, their star formation will go on at a relatively quicker speed than the BH accretion. AGN feedback on the inner region may be the reason. Most of the feedback from the central SMBH is in radiative mode, which has little influence on the galaxy's SF, but it appears to be effective in suppressing the BH accretion.
- Second is the object whose liner point is located near the relation. For them, just as mentioned in Zhuang & Ho 2023, they can grow along the relation, and it means that the relation can be built without the mergers at the beginning.
- The last is the object whose liner point is located under the relation. BH will still grow at a relatively larger rate, but what confuses us is that we can fit it with a linear function and it means that the ratio between the two growth rates is a fixed value.

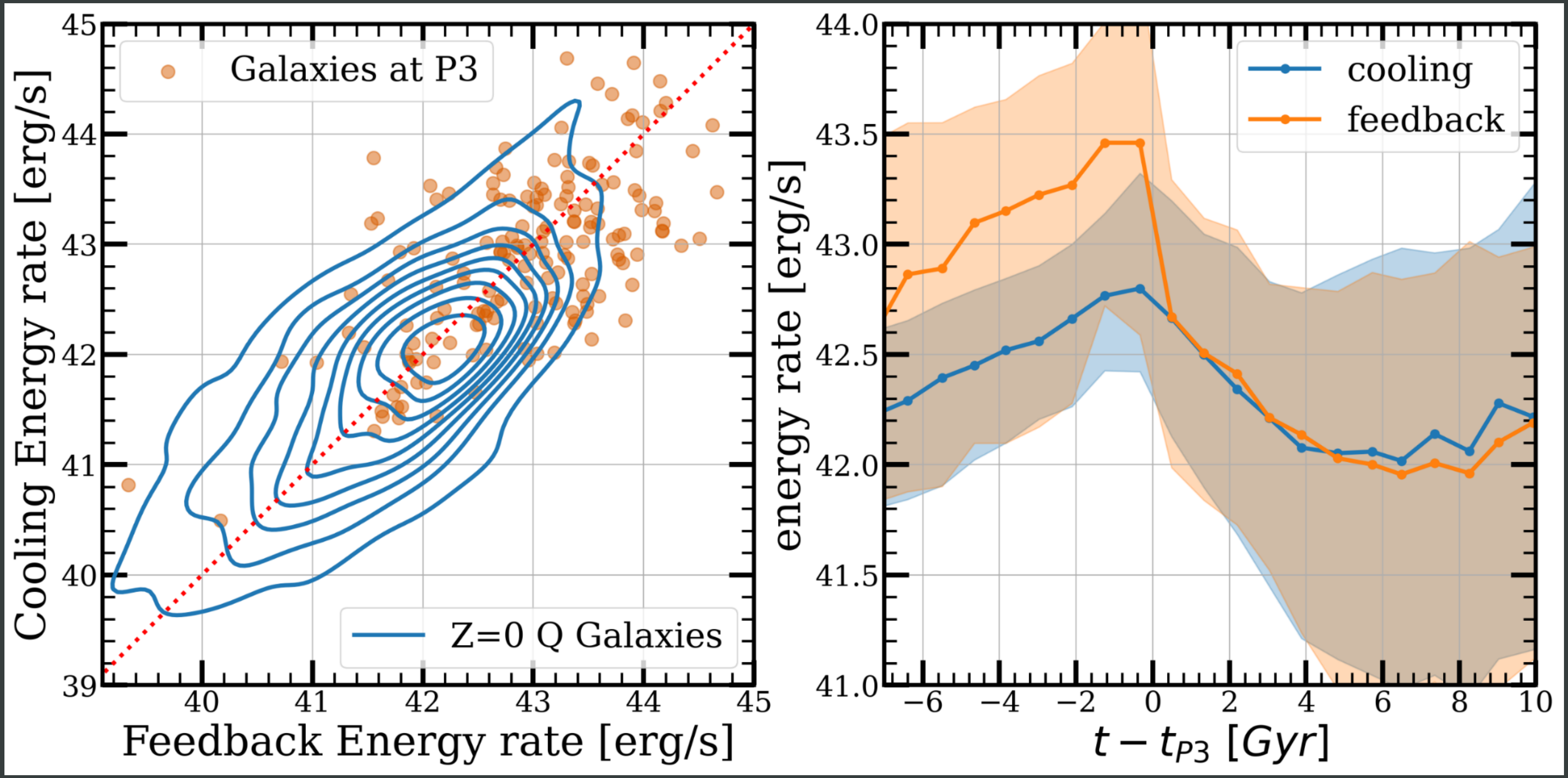
In simulations



The instantaneous sSFR and sBHAR

- The median value shows that the tight relation seems more likely built by the balance between the BH and the galaxies in the co-evolution phase. And sSFR changes its evolution pattern little, mostly the balance is built by adjusting the sBHAR.
- From the green shadow, we can find that when feedback transits to kinetic mode, the balance is actually destroyed gradually. In light of that, quasar mode may play a critical role in building and maintaining the weak balance to form a good linear relation in the log scale.

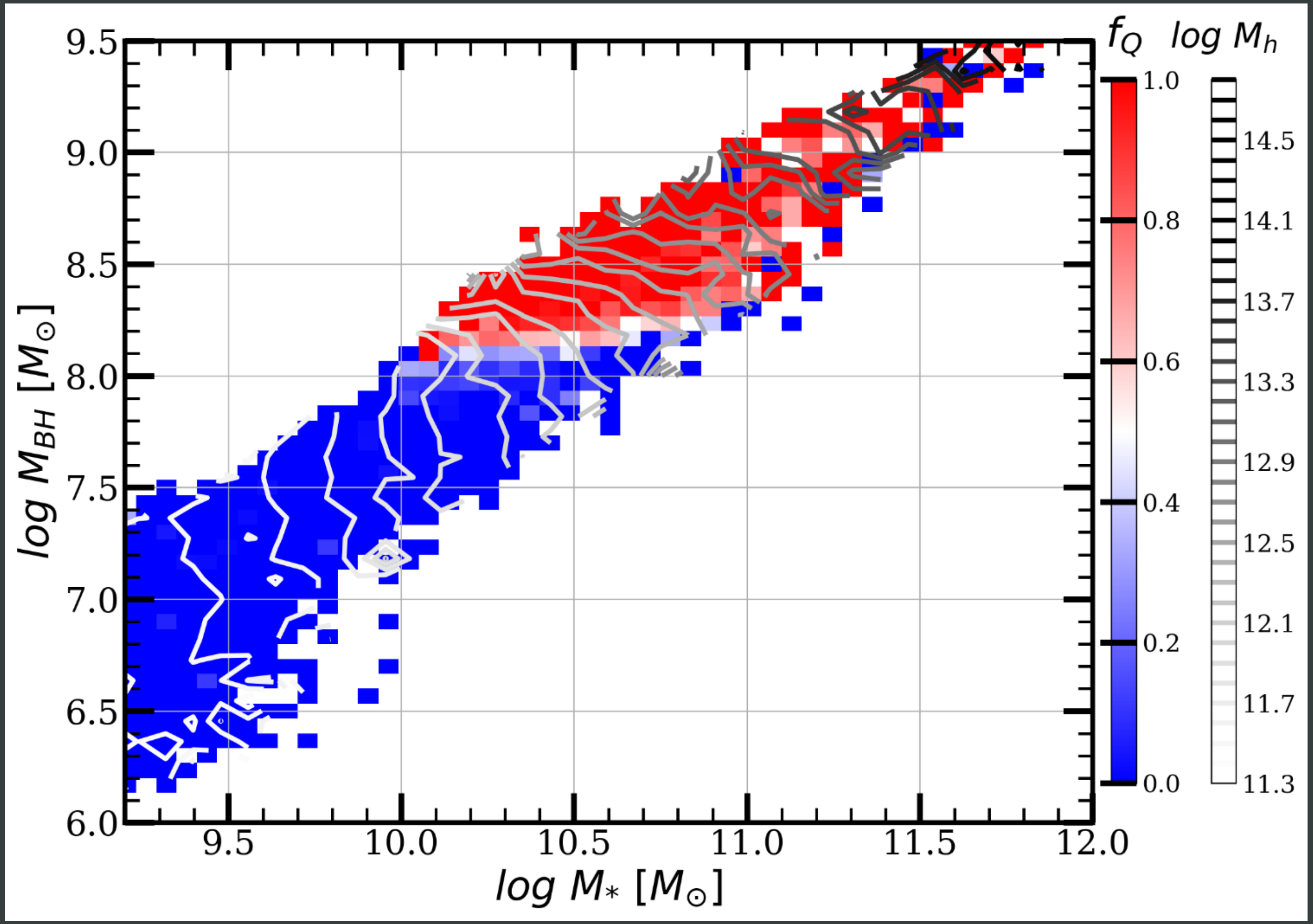




- When kinetic feedback is triggered, the galaxy host this SMBH will become quiescent soon after the time point.
- The detailed inspection shows that for the quiescent galaxy, its host halo will have a corresponding cooling rate with the feedback energy rate of the central SMBH hosted by the galaxy.

- We also noticed that even after the quenching point, the energy balance will be kept very well. This needs some corrective actions that are sensitive to the changes inside the halo or around the BH and can pass it to the other in a short time!

Halo-Galaxy-BH



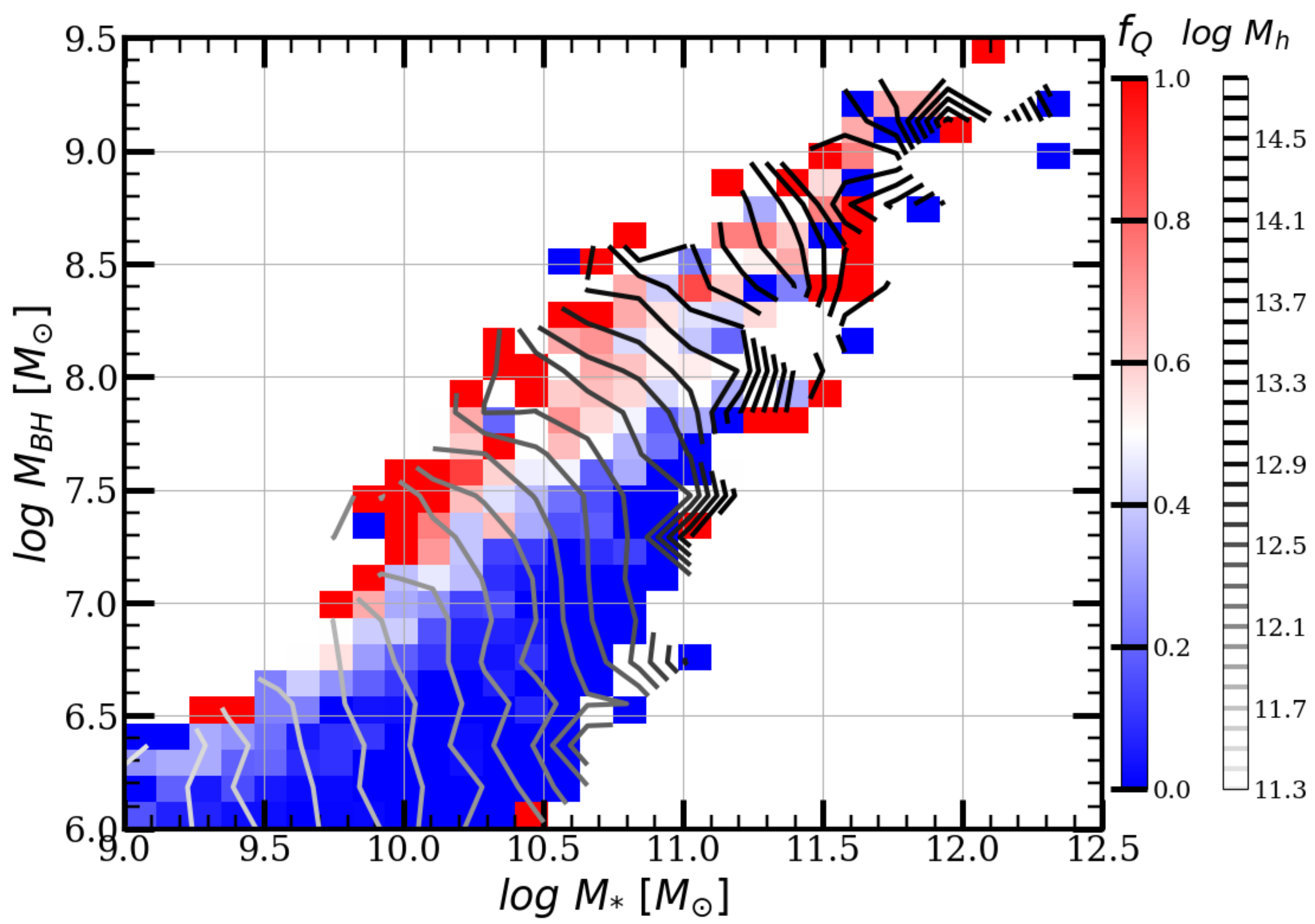
TNG100-1, central galaxies at z=0

Color map: quench fraction, SF -> Q
Greyscale: log M_h

- M_h related to M_*, at
  low mass, low quench fraction end

- M_h related to M_{BH}, at
  high mass, high quench fraction end

It shows a similar trend to the observation result shown above, thus we choose TNG simulation to search for reason.



EAGLE

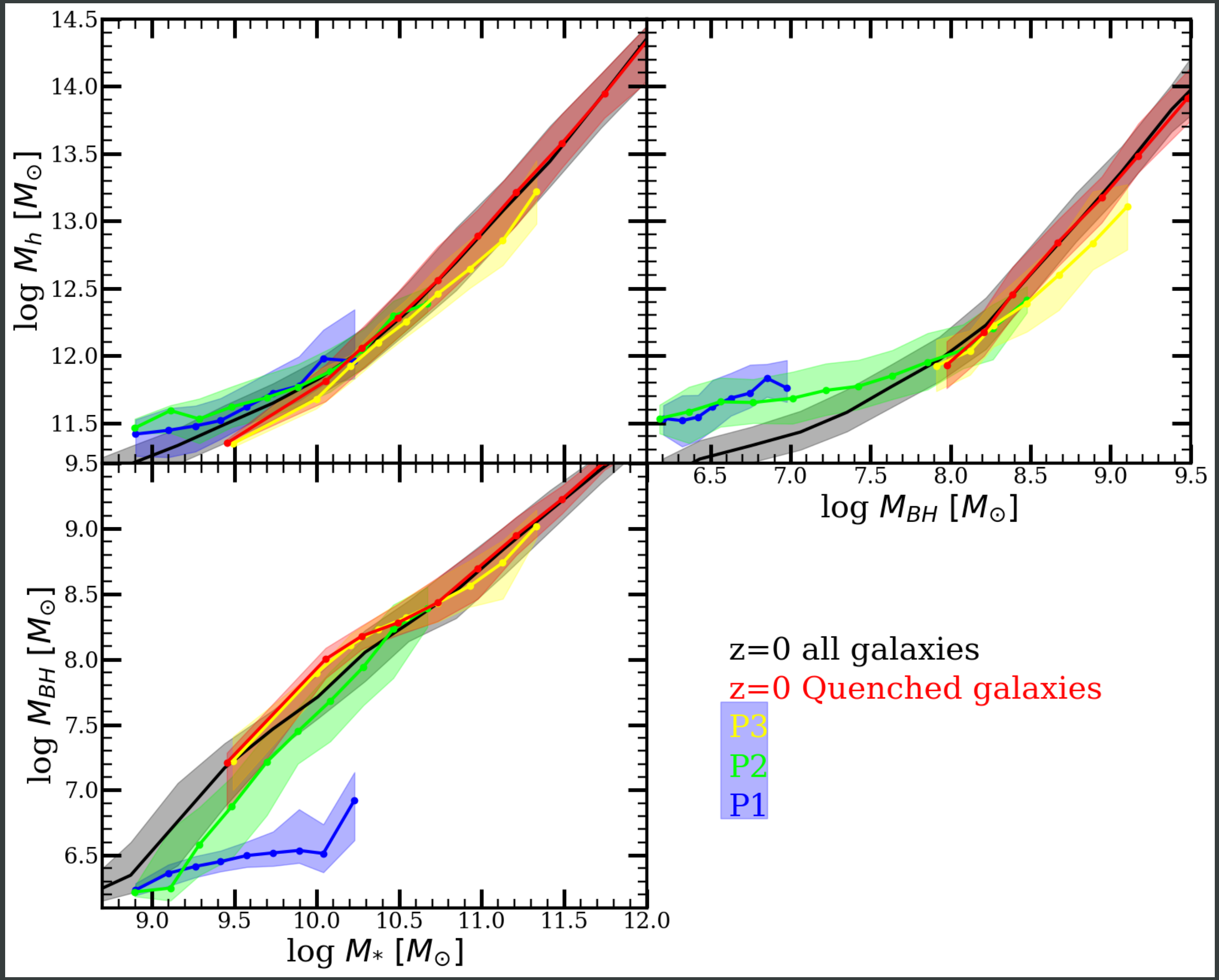
Show connection difference for quenched galaxies.

So, whether the fitting is good or not, there should be something both two models reach. Which might be the energy balance.

And for high mass end, it shows the same result as TNG, so merger is more likely to be the reason.

Name	L (cMpc)	N	m_g ($M_\odot$)	m_{dm} ($M_\odot$)	ϵ_{com} (ckpc)	ϵ_{prop} (pkpc)
RefL0025N0376	25	376^3	1.81×10^6	9.70×10^6	2.66	0.70
RecalL0025N0752	25	752^3	2.26×10^5	1.21×10^6	1.33	0.35
RefL0050N0752	50	752^3	1.81×10^6	9.70×10^6	2.66	0.70
RefL0100N1504	100	1504^3	1.81×10^6	9.70×10^6	2.66	0.70

Halo-Galaxy-BH – 3scaling relations

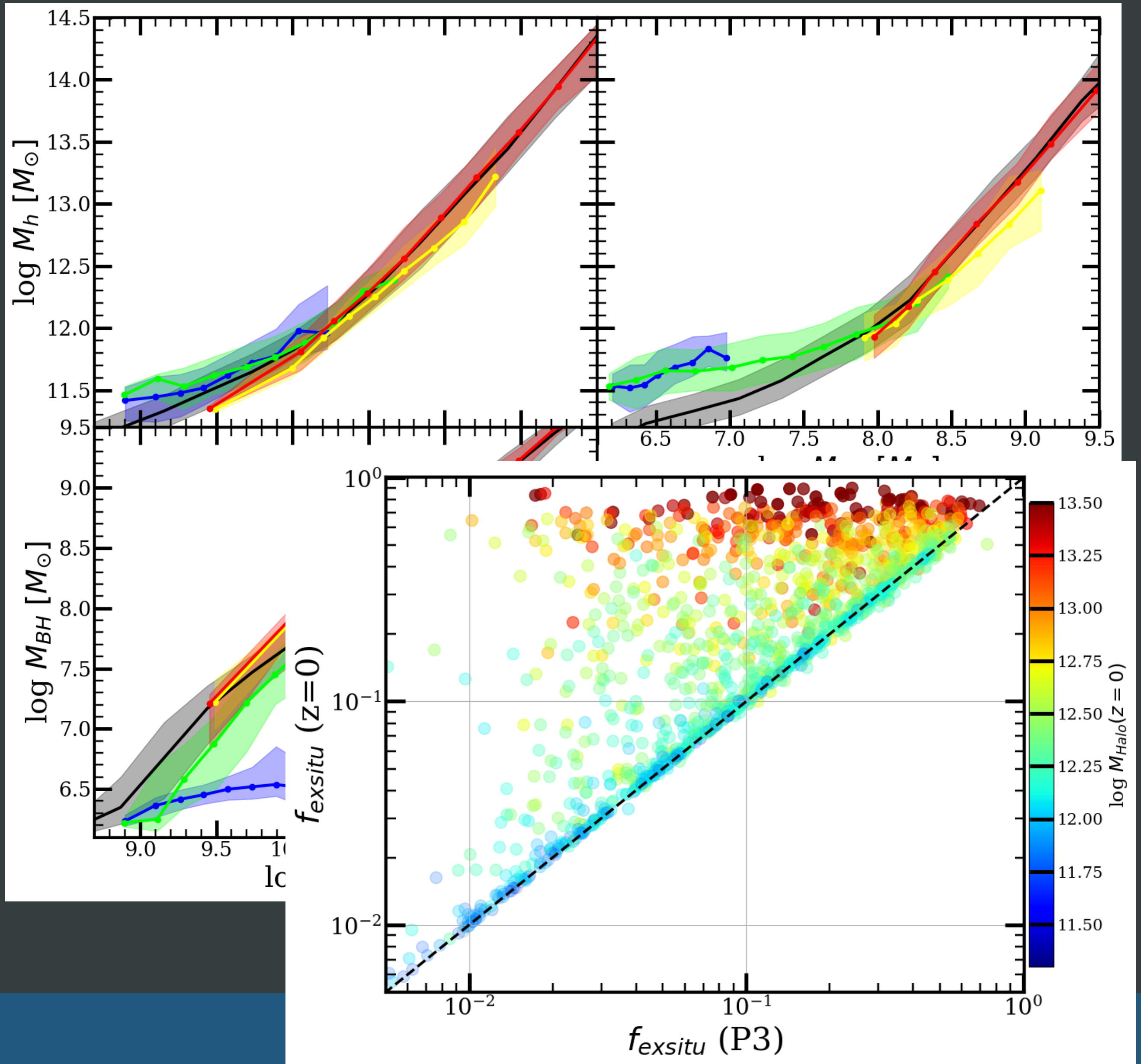


Top left: M_*-M_h relation Top right: M_{BH}-M_h relation

Bottom left: M_*-M_{BH} relation

- For P1 all relations involving M_{BH} are different from that at Z=0, but the SHMR is almost on the relation. It is the result of SN feedback which suppresses the BH growth. Thus BH is not important before P2.
- For P2 the two relation is evolving to the z=0 relation, AGN feedback is becoming important and until P3, it is balanced with halo cooling and build up the M_{BH}-M_h relation.
- However, at P3, all relations involve M_h have offset with Z=0 relations, and that is the result of merge events.

Halo-Galaxy-BH – 3scaling relations



Top left: M_*-M_h relation **Top right**: M_{BH}-M_h relation

Bottom left: M_*-M_{BH} relation

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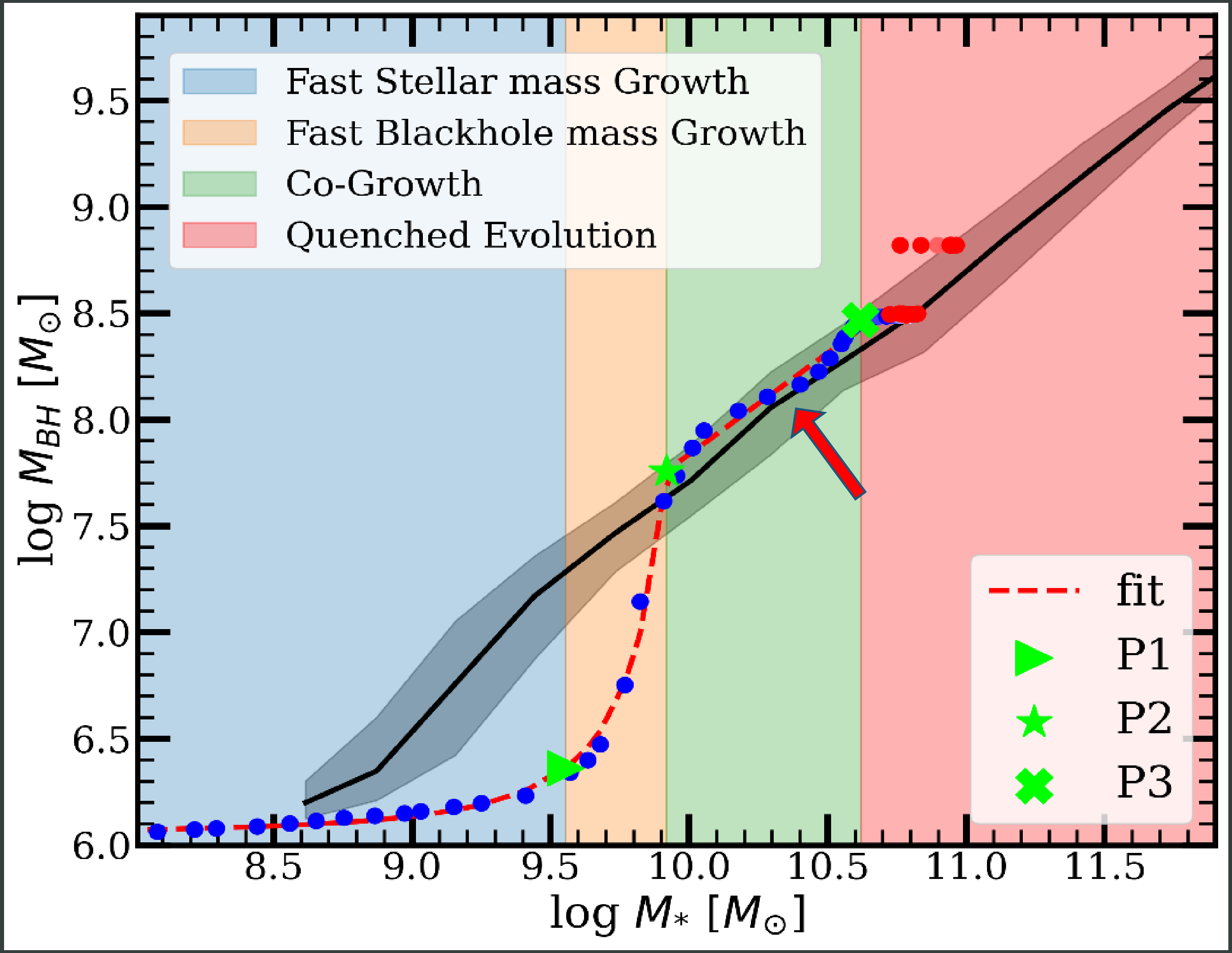

Fast Stellar mass Growth
Fast Blackhole mass Growth
Co-Growth
Quenched Evolution
fit
P1
P2
P3
log M_{BH} [$M_\odot$]
log M_* [$M_\odot$]
9.5
9.0
8.5
8.0
7.5
7.0
6.5
6.0
8.5
9.0
9.5
10.0
10.5
11.0
11.5