On the cosmological evolution of the black hole-host relation in quasars

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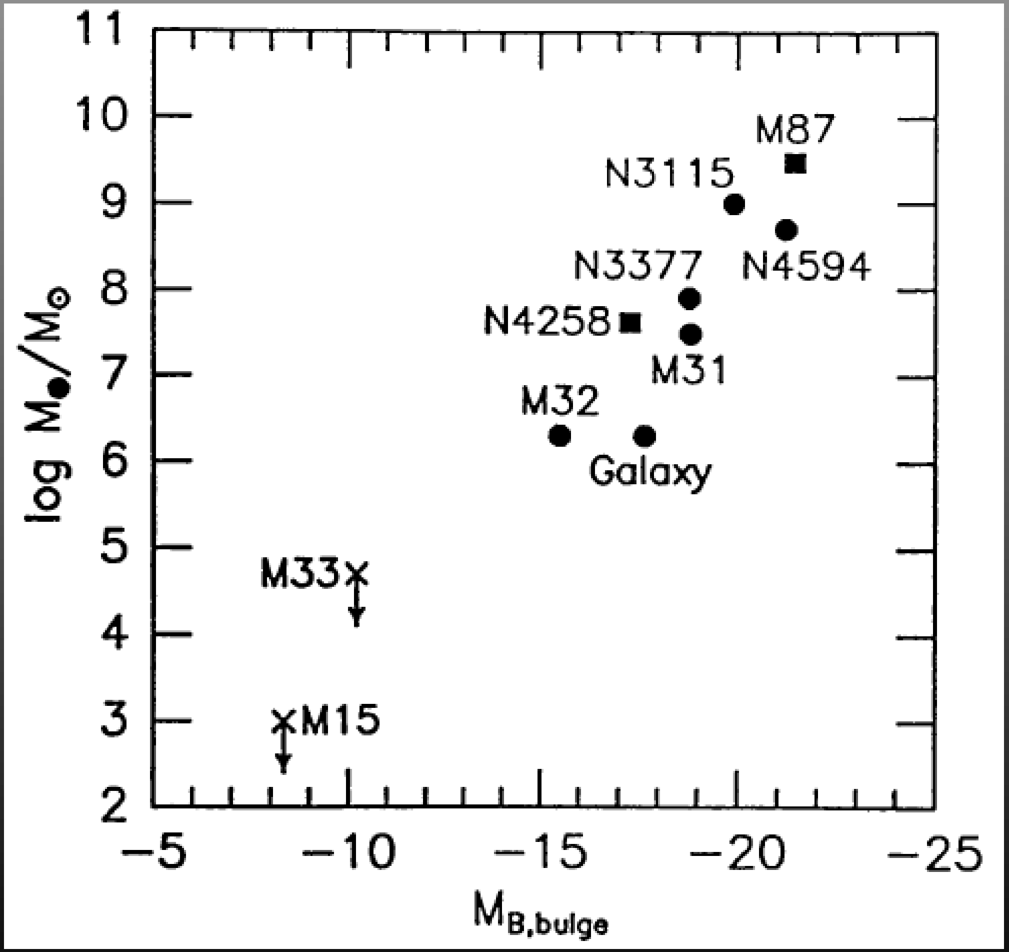
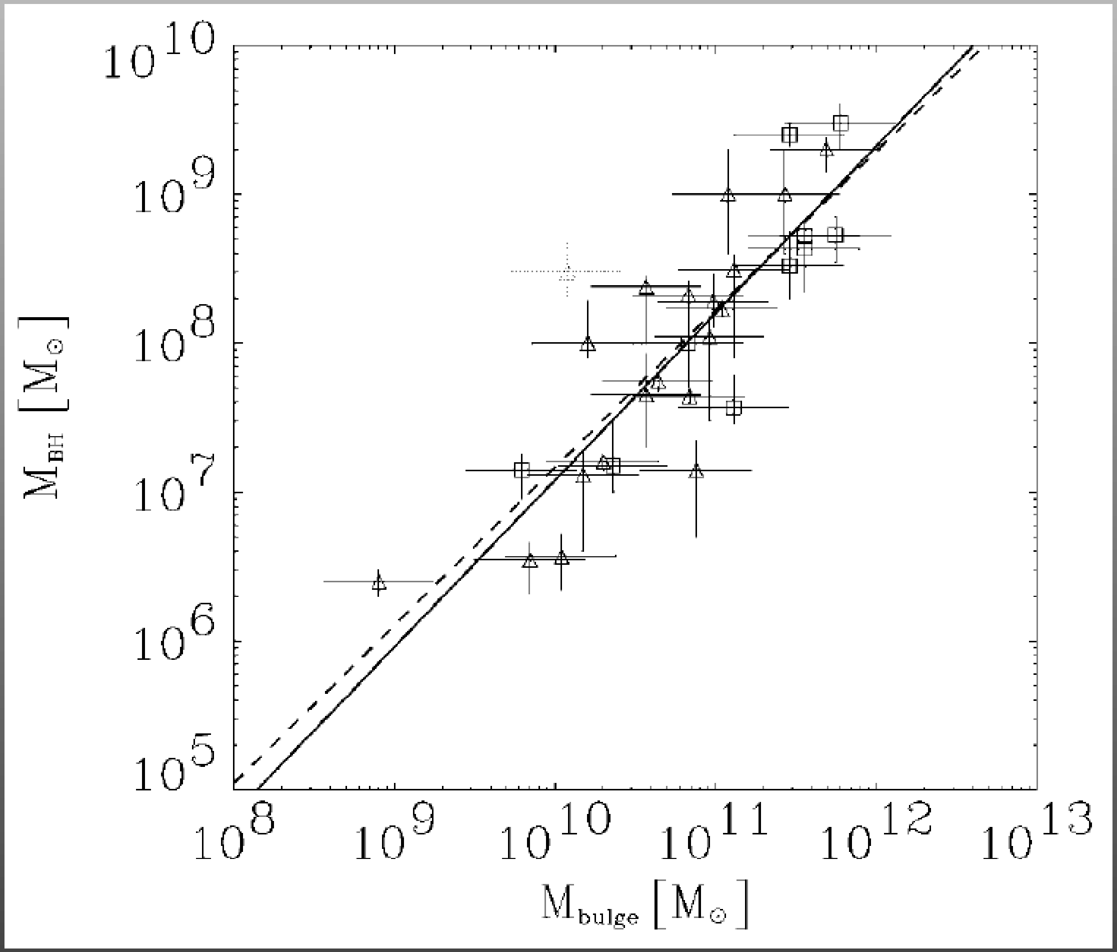
Super-Massive Black Holes are common in the centers of galaxies, and their mass is correlated with the properties of the host spheroid (bulge or elliptical): luminosity, stellar mass, velocity dispersion, concentration...



(Kormendy & Richstone 1995)

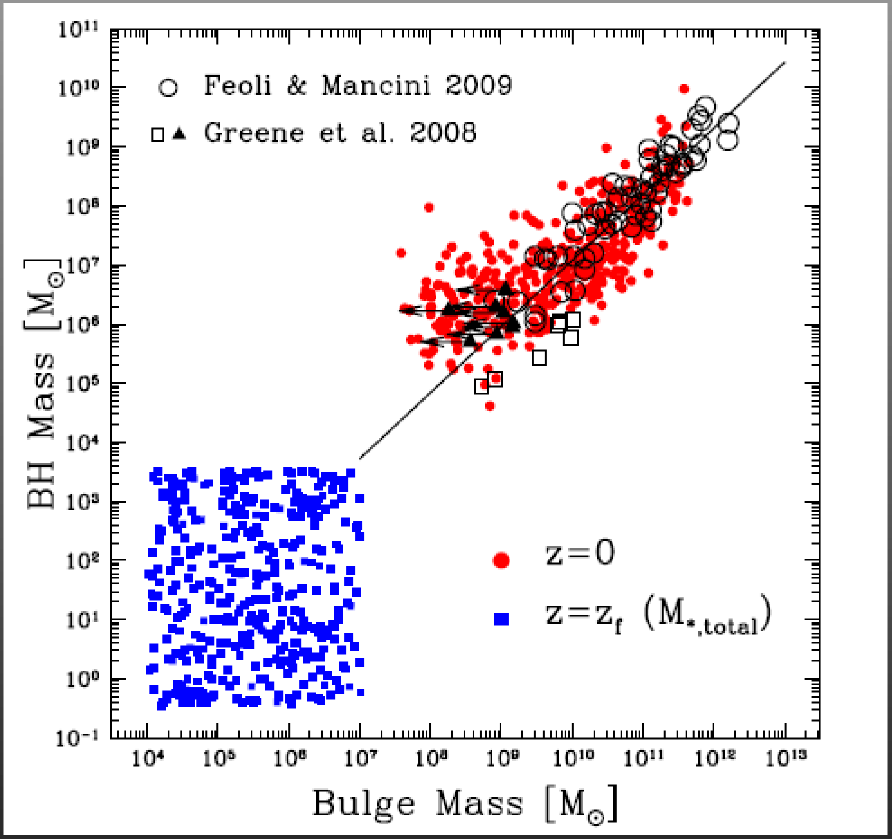


M_{BH}-M_{bulge} relation at z=0:
Marconi & Hunt (2003)
Häring & Rix (2004)

$$\Gamma = \frac{M_{BH}}{M_{bulge}} \simeq 0.002$$

→ co-evolution of black holes and spheroids

In the hierarchical scenario, mergers are responsible for the formation of spheroids and for feeding the central BH (Kauffmann & Haehnelt 2000).



Extreme version : no intrinsic physical association needed between bulge and BH; the 1:1 relation is just a statistical outcome of the stochastic merger process. In presence of additional internal effects, mergers help to tighten the relation around a 1:1 slope and minimize the scatter for the most massive galaxies (Peng 2007; Jahnke & Macciò 2010)

Processes responsible for the co-evolution (in SAM):

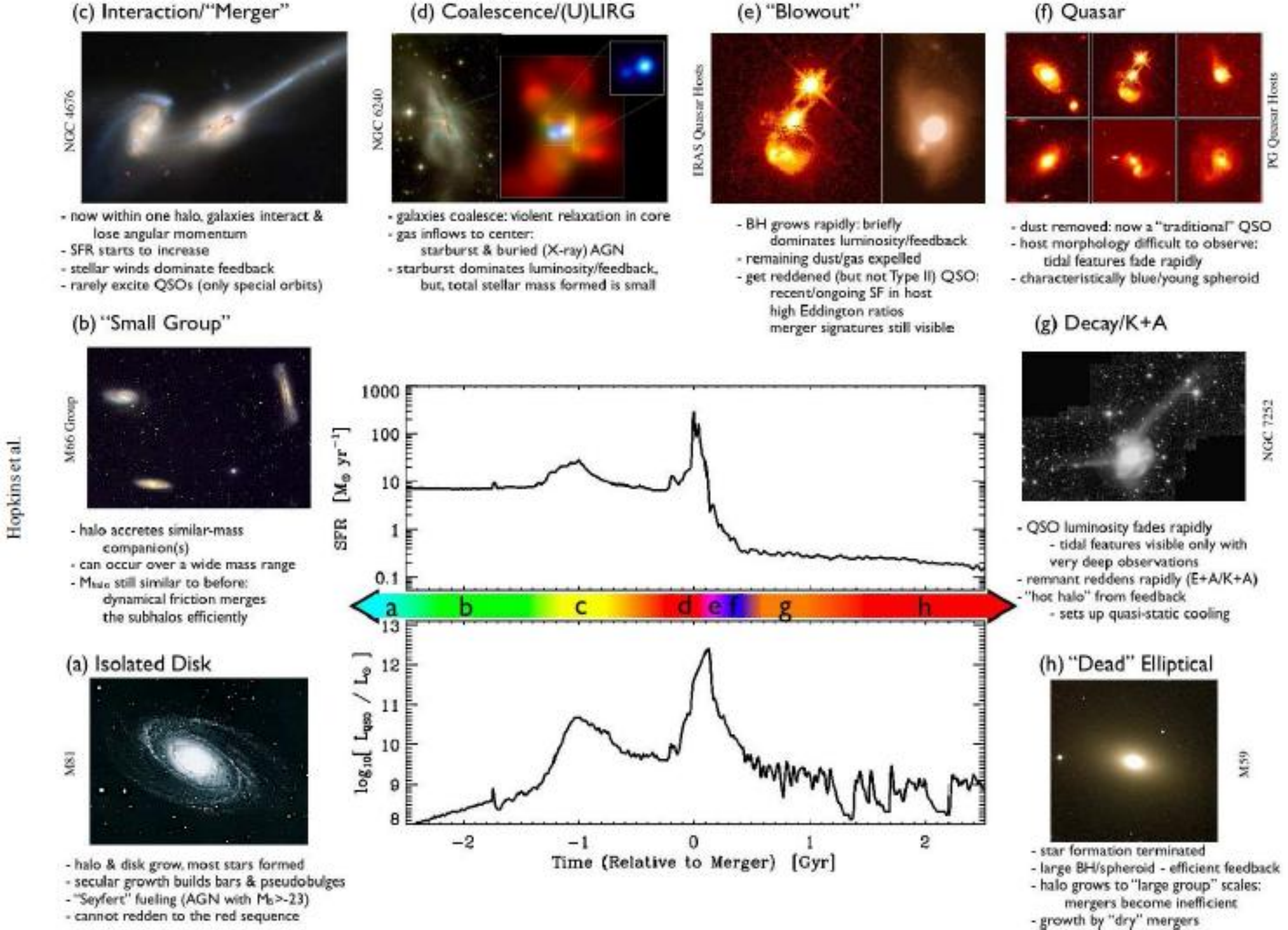
1. **Joint origin** of Bulges and Black Holes:

- mergers (Kauffmann & Haehnelt 2000; Wyithe & Loeb 2003; Cattaneo et al. 2005; Croton et al. 2006; Hopkins et al. 200x; Menci et al. 2006; Malbon et al. 2007; Somerville et al. 2008; Marulli et al. 2008; Jahnke & Macciò 2010)
- BH growth directly connected with the Star Formation Rate in the host (radiation drag; works also in monolithic scenario) (Granato et al. 2001, 2004; Fontanot et al. 2006) or intrinsic morphological transformation disc → bulge (Bower et al. 2006)

2. **Joint end** of Bulge and Black Hole growth:

- exhaustion of available cold gas (Kauffmann & Haehnelt 2000; Croton et al. 2006; Bower 2006)
- feedback from the QSO and galactic wind (Granato et al. 2001, 2004; Fontanot et al. 2006; Menci et al. 2006; Somerville et al. 2008)

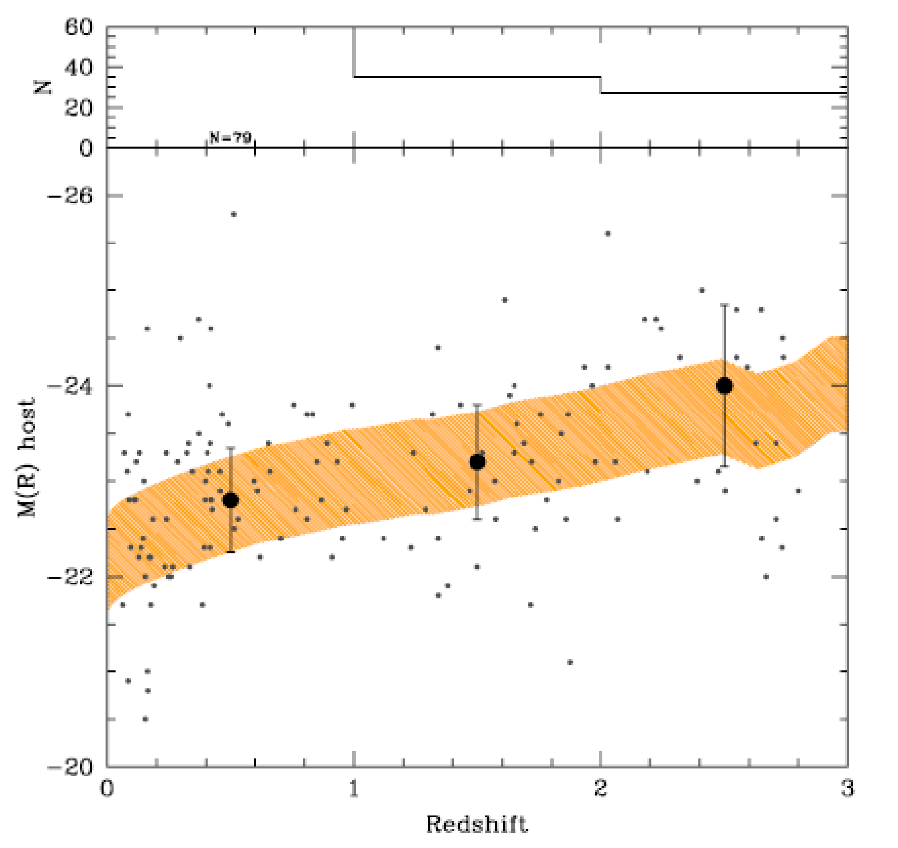
Common scenario : a quasar host is a young spheroid



Hopkins et al. (2008)

What do observations say ?

The luminosity of quasar hosts increases at increasing redshift compatibly with passive evolution: very different from the ”recent merger” scenario.



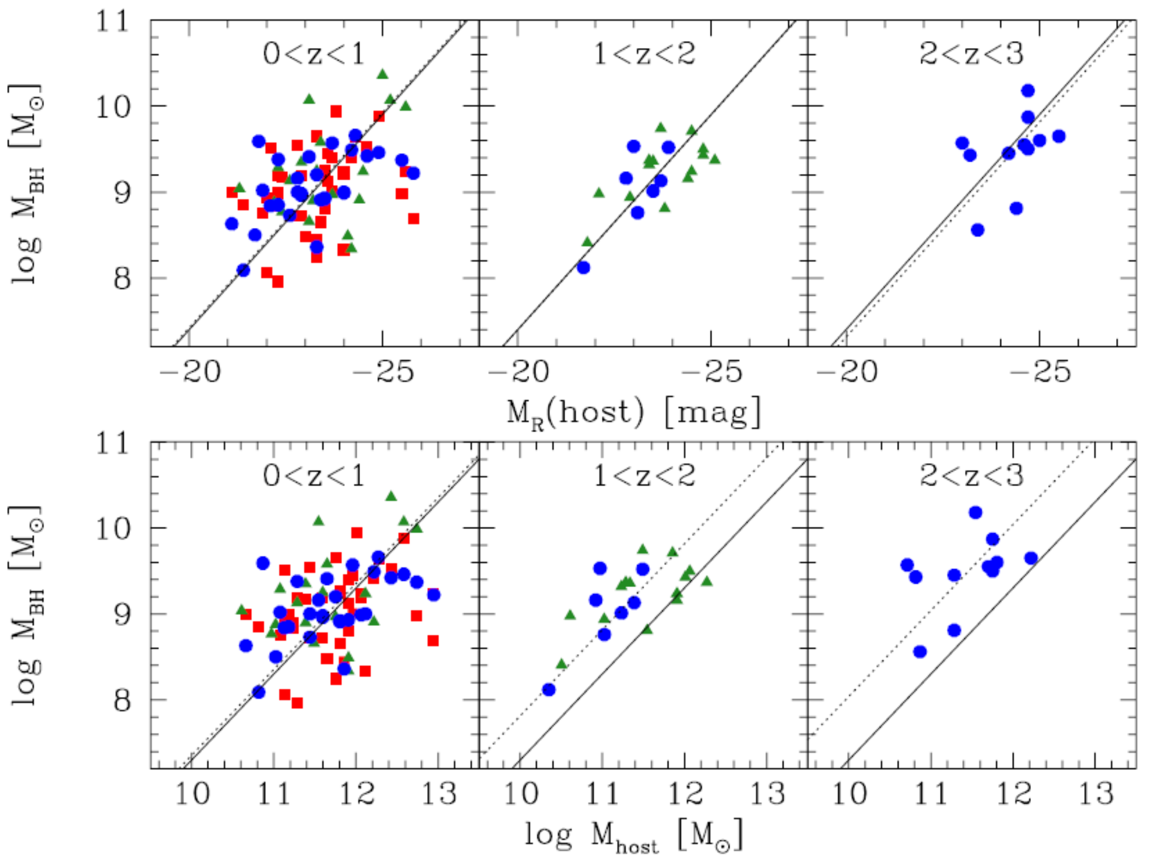
(Kotilainen et al. 2009)

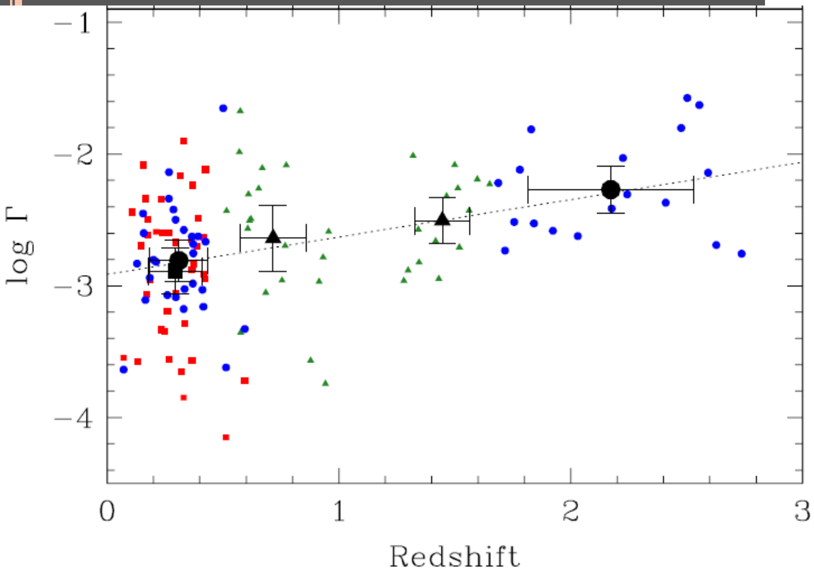
BH mass vs. host luminosity: no evolution wrt local relation

DIRECTLY OBSERVED

BH mass vs. host stellar mass: host masses at high z were smaller (at given BH mass) → the growth of BHs was faster than that of host galaxies

INFERRED assuming PASSIVE EVOLUTION





$$\log \Gamma = (0.28 \pm 0.06)\, z - (2.91 \pm 0.06)$$

Decarli et al. (2010)

Comparison of observational results to Semi-Analytical Models:
Millennium database

Millennium Cold Dark Matter cosmological simulation
+ semi-analytical galaxy catalogue by De Lucia & Blaizot (2007)
(grand-grandchild of Kauffmann & Haehnelt 2000).

Co-evolution of BH and bulges due to:

joint origin : mergers

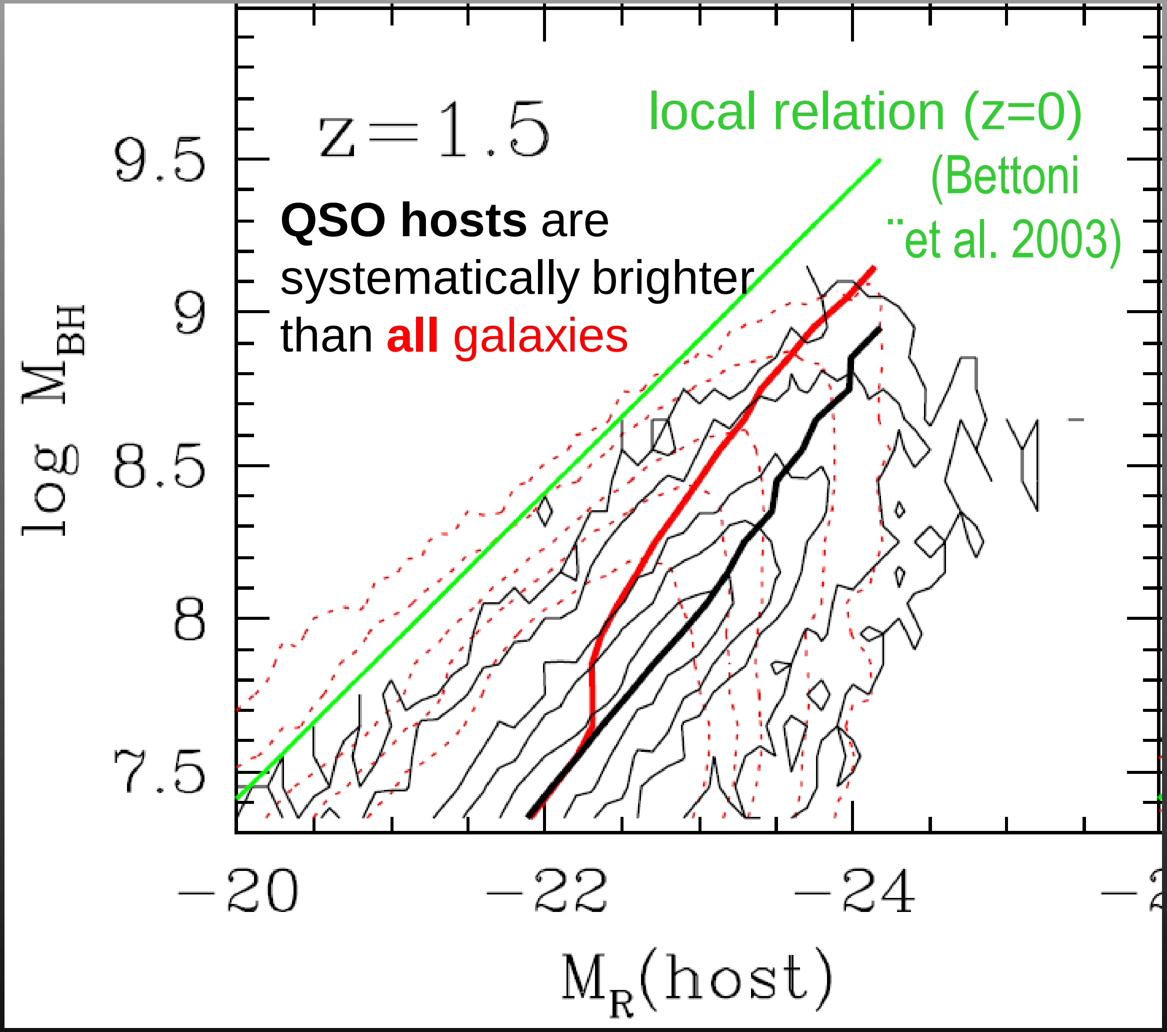
joint end: exhaustion of cold gas (no quasar feedback)

Seletion of quasar hosts:

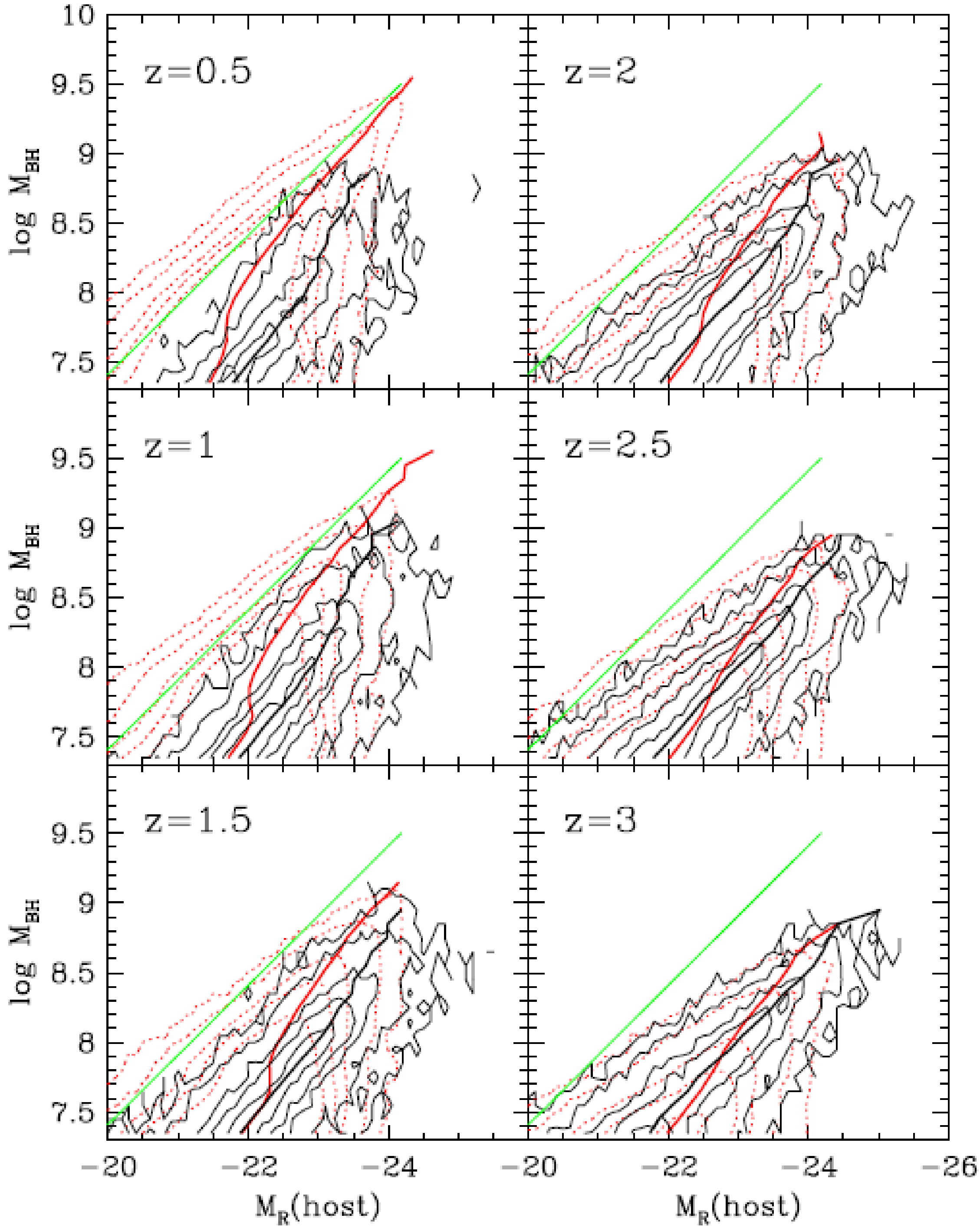
1. Galaxies that have suffered a recent merger, since the previous snapshot (1-3 x10^8 yrs)
2. $M_{BH} > 2 \times 10^7 M_\odot$ (minimum mass of active quasars)
3. Significant BH accretion (related to QSO activity): the M_{BH} has grown by >50% wrt the original seed BHs.

The BH mass-host luminosity relation

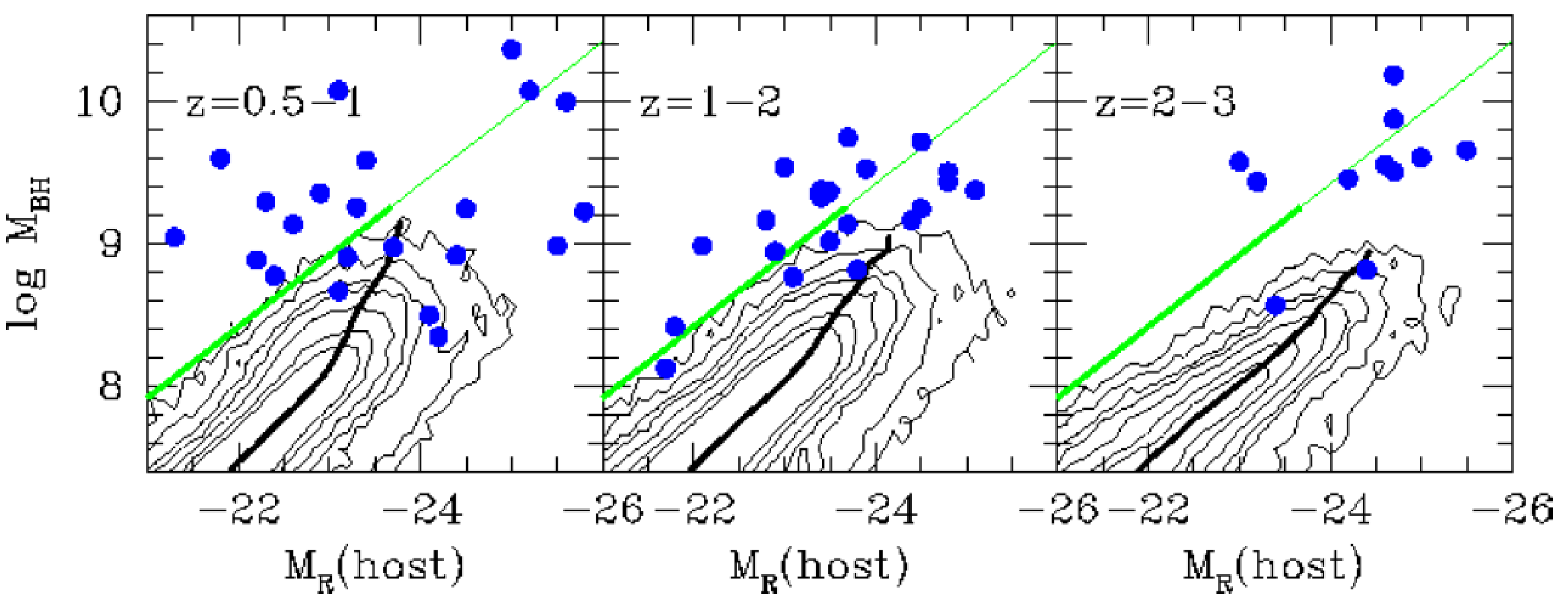
This is the most direct comparison between models and data, as luminosity is directly observed (while stellar mass is deduced)



N.B.: $R_{Johnson} \rightarrow R_{Cousins}$

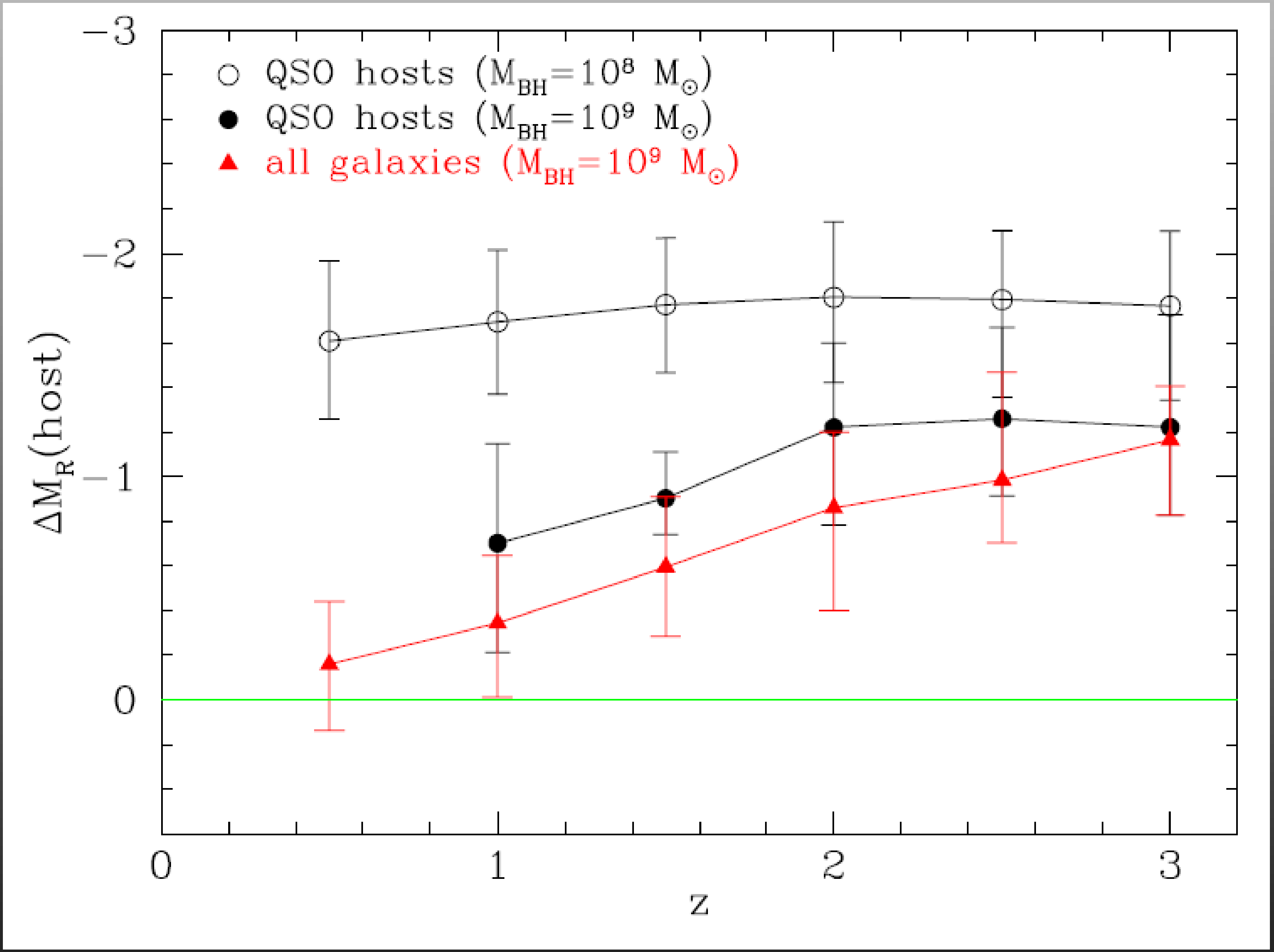


In the SAM, QSO host galaxies are systematically brighter than the local relation, at odds with observational datasets



Direct comparison between observed data points, clustering around the local relation out to high redshift (Decarli et al. 2010) and the luminosity of quasar hosts expected from the SAM. The models are offset in luminosity by 1.5-2 mag; and/or in BH mass by about 0.7 dex (= factor of 5)

Beware: the normalization of the observed M_{BH} is somewhat arbitrary (depending on the assumed geometry of the BLR) but not even (unlikely) isotropic case would reconcile models and data.

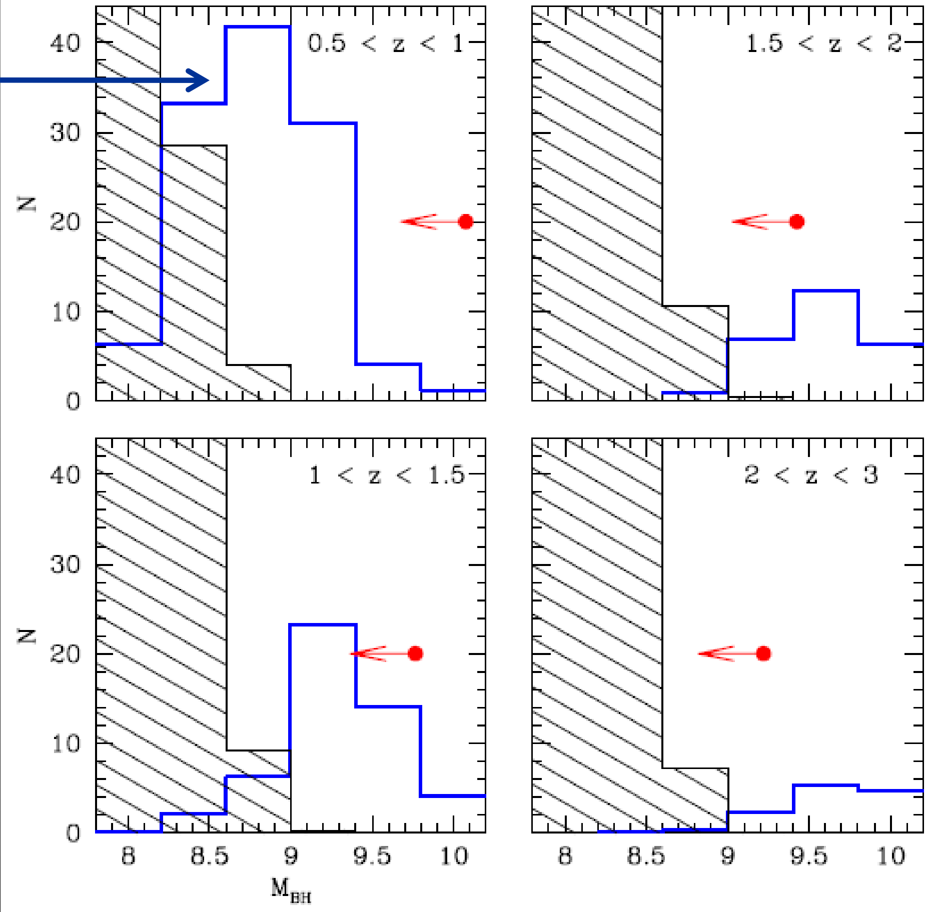


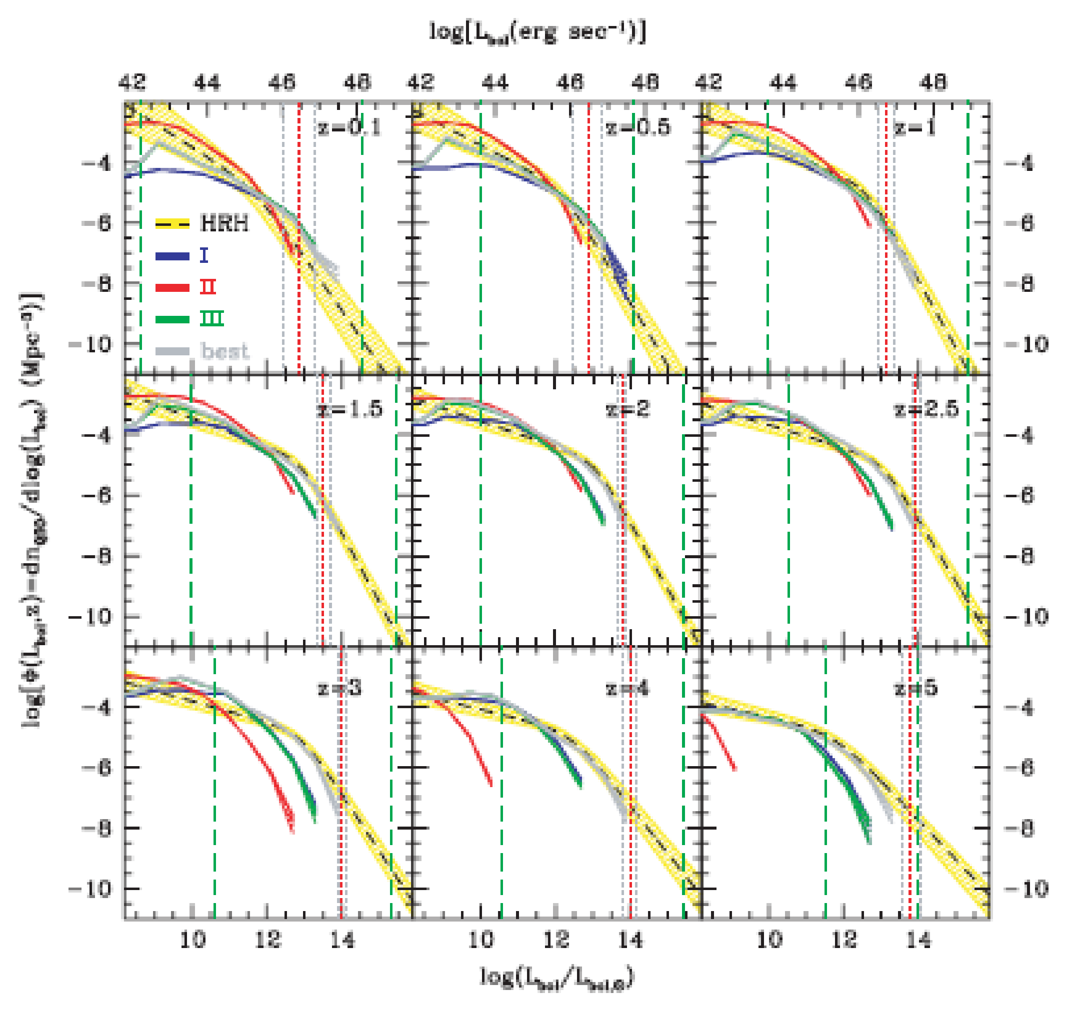
Evolution of the offset ΔM_R with respect to the local relation.

The offset can indicate:

1) overluminous hosts: due to the recent merger/starburst? Abrupt halt of star formation due to AGN feedback + extended luminosity curve of the QSO may help.
2) Undermassive black holes : more efficient recipes to form massive BH at high redshift

According to the empirical mass function of high-z QSOs (Vestergaard & Osmer 2009), in the Millennium volume (box of 500 h^{-1} Mpc) we should find, between 2<z<3, ~10 active QSO's with $M_{BH}=10^{9.5}$ — 10^{10} $M_{\odot}$. None is predicted in the SAM. Even considering the global galaxy population, no BH with $M_{BH}>10^{9.5}$ $M_{\odot}$ is yet formed in the SAM by z=2.





An analogous problem (lack of bright AGNs at high z) in the Munich SAM had been noticed also by Marulli et al. (2008).
→ Need for new recipes (increased accretion efficiency?) or new mechanisms (Mayer et al. 2010) to ease the formation of massive BH at high z

Conclusions (1) : the M_{BH} – L relation

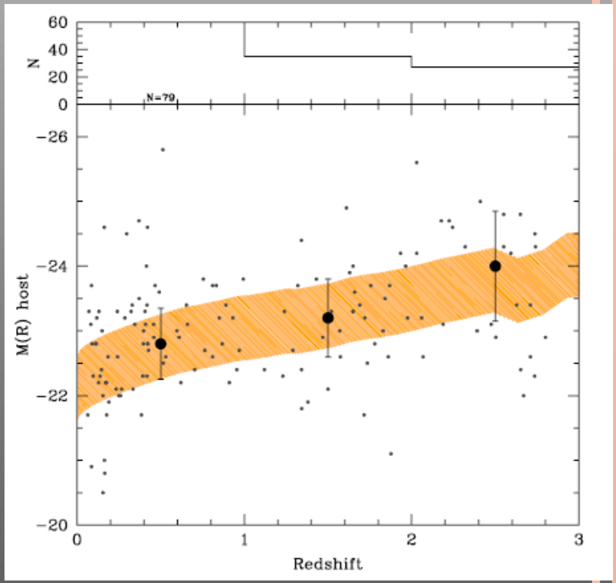
✓ The most direct and fair comparison to the data is in the M_{BH} – luminosity plane

✓Observed QSO hosts lie on the local relation up to z=3, while in the SAM they are systematically brighter/have systematically undermassive BH

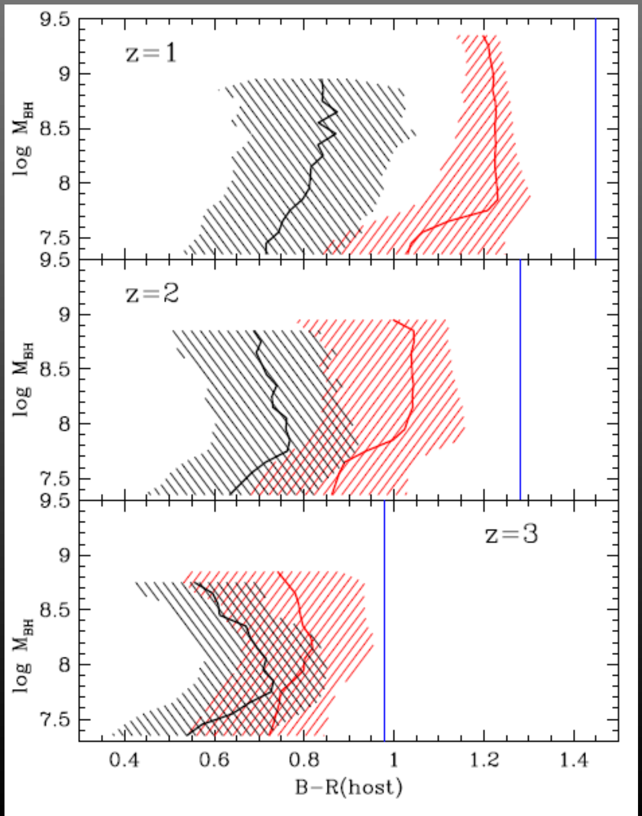
⟶ overluminosity problems with the "recent merger/starburst" scenario? Quasar feedback to halt SF+extended lightcurve?

⟶ problems with undermassive BH at high z : need for different mechanisms to form the most massive BH (c.f. Mayer et al. 2010)

From luminosities to stellar masses : colour and M/L evolution

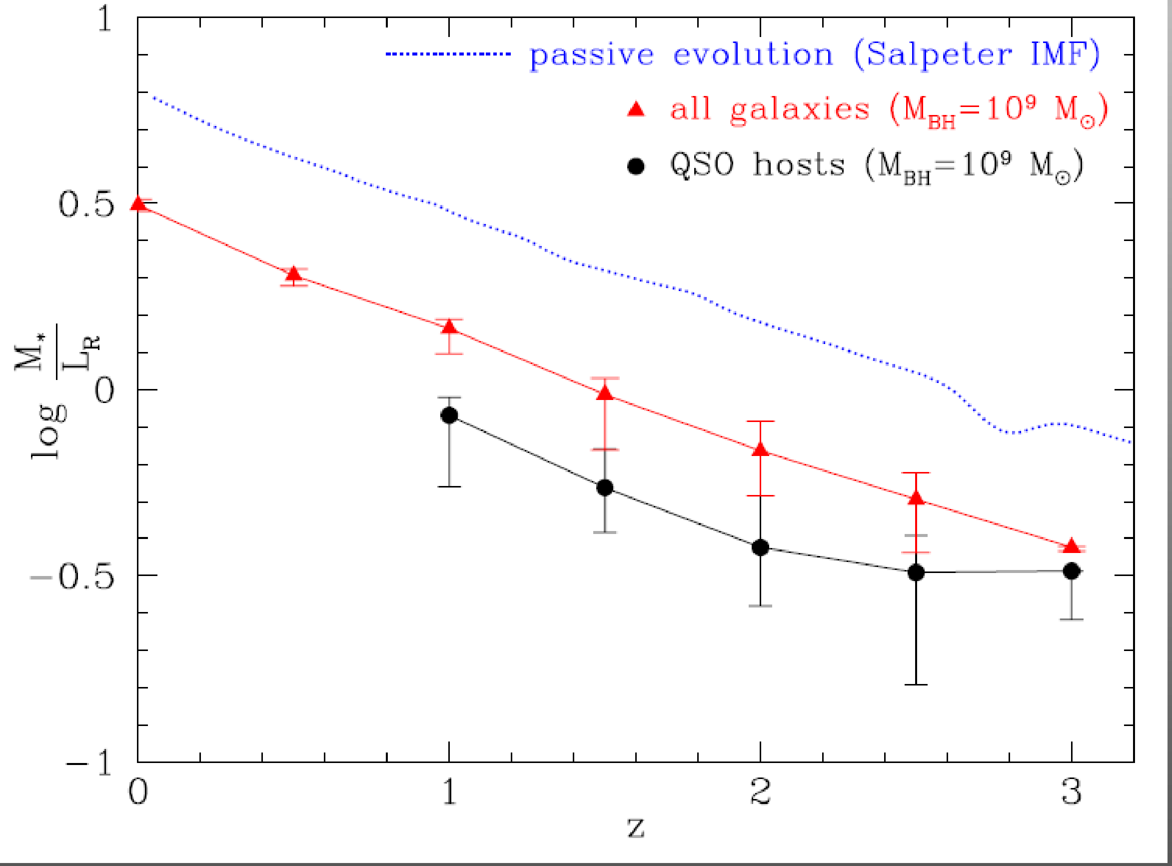


While luminosity is directly observed, the stellar mass of the host is an inferred quantity, typically assuming passive evolution with $z_{for}=5$ (Kotilainen et al. 2009; Decarli et al. 2010)



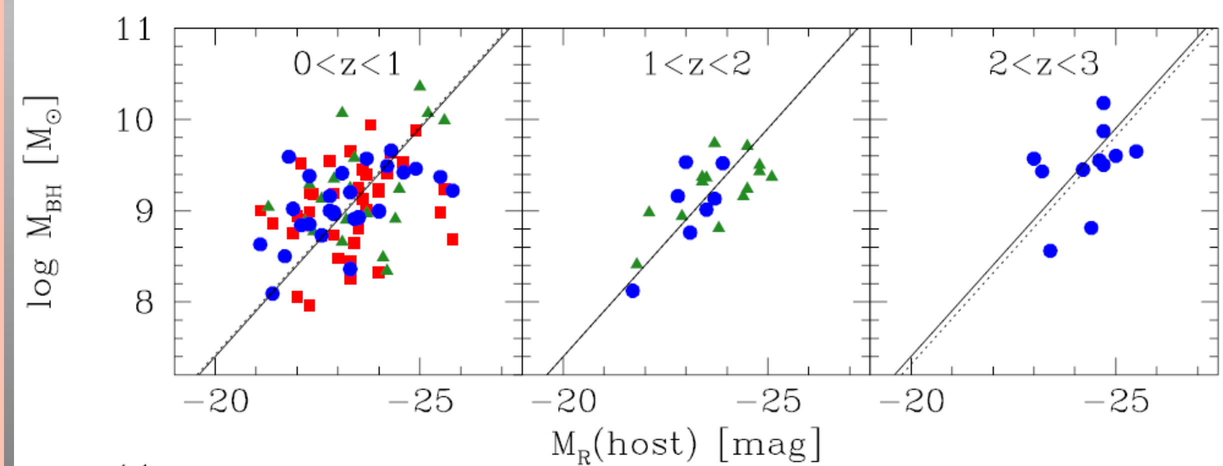
In the hierarchical scenario:

1) Galaxies build up progressively → bluer colours and lower M_{*}/L ratios than in the monolithic scenario
2) QSO hosts, being recent mergers/ young spheroids, deviate even more from the passively evolving case

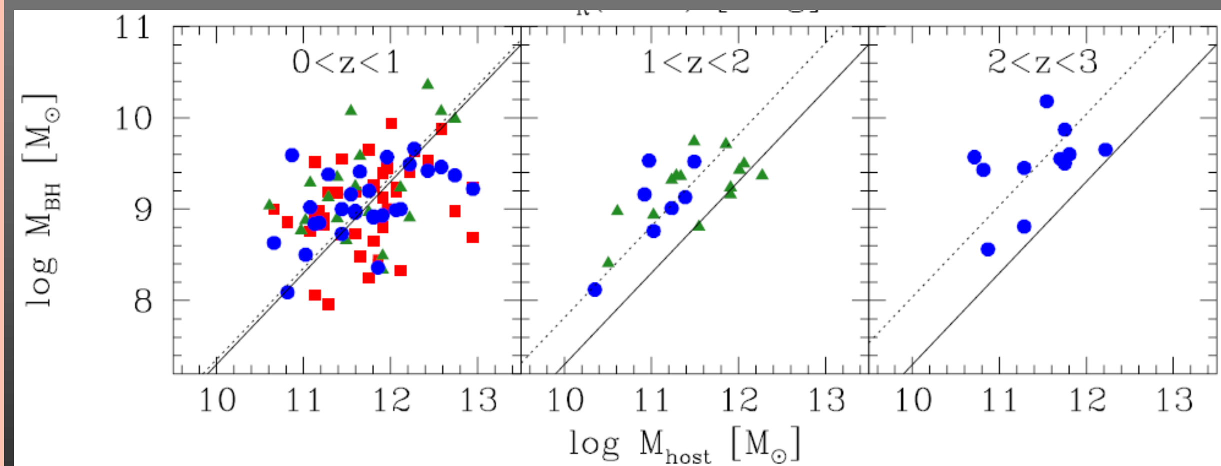


The offset (0.3 dex) in M/L between passive evolution and SAM galaxies is partly due to the different IMF adopted (Salpeter vs. Chabrier) and partly due to the different star formation history. But the rate of the M/L evolution is the same! Even for QSO hosts, characterized by recent starbursts and even further offset from passove evolution, the rate is not very different.

Decarli et al. (2010)



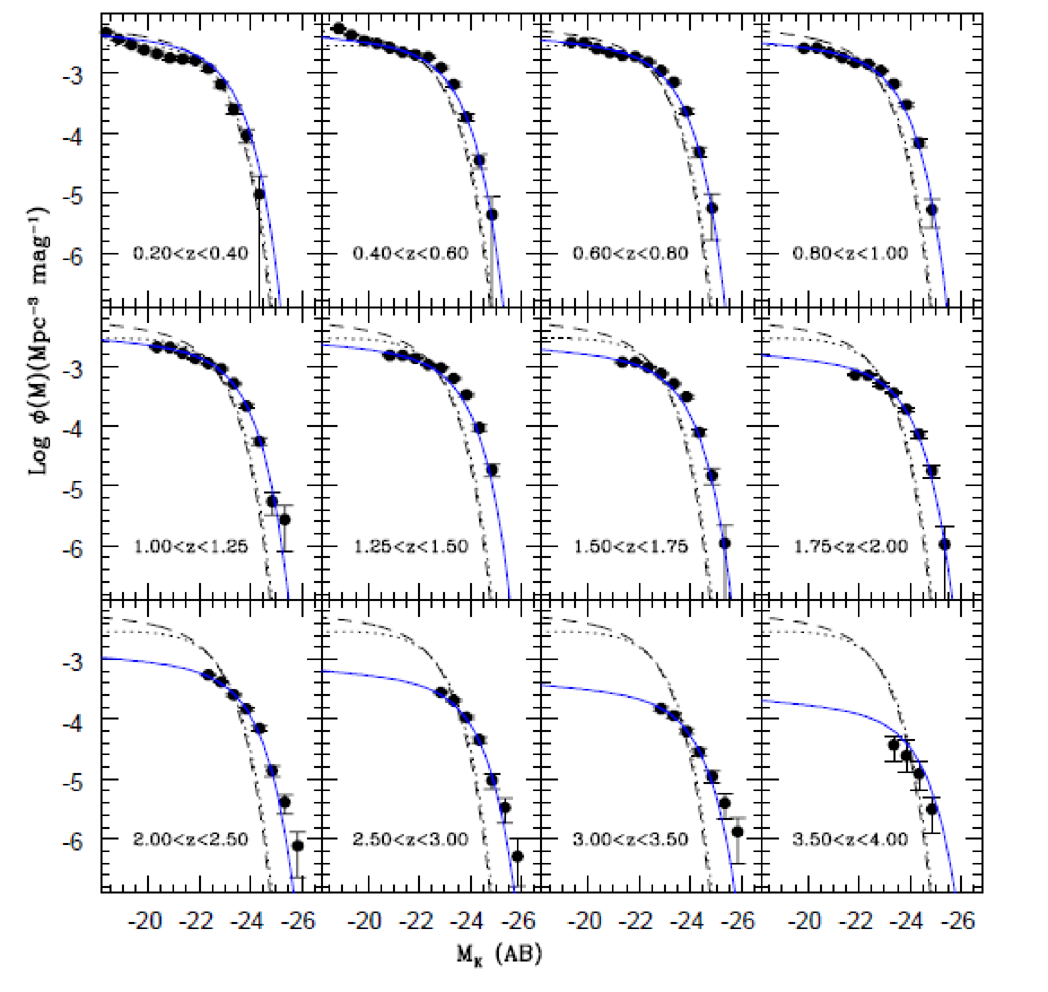
passive evolution

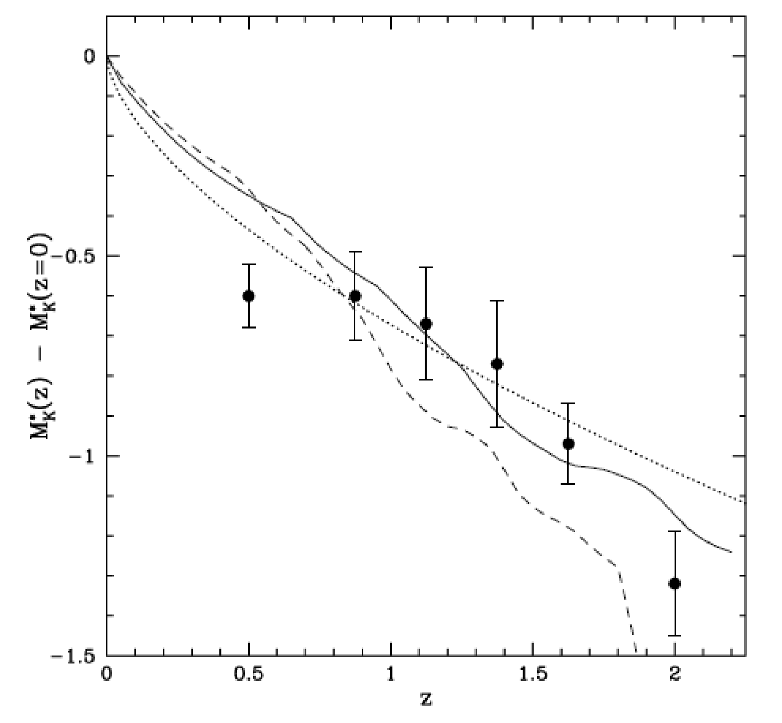


Adopting $M_{ж}$/L ratios from the SAM rather than from passive evolution, the conclusion about host masses being much smaller at high z (= strong evolution of the M_{BH}-M relation) would be reinforced.

An evolutionary *rate* resembling passive evolution in a monochromatic band is not a strong indication of actual monolithic formation and passive evolution.

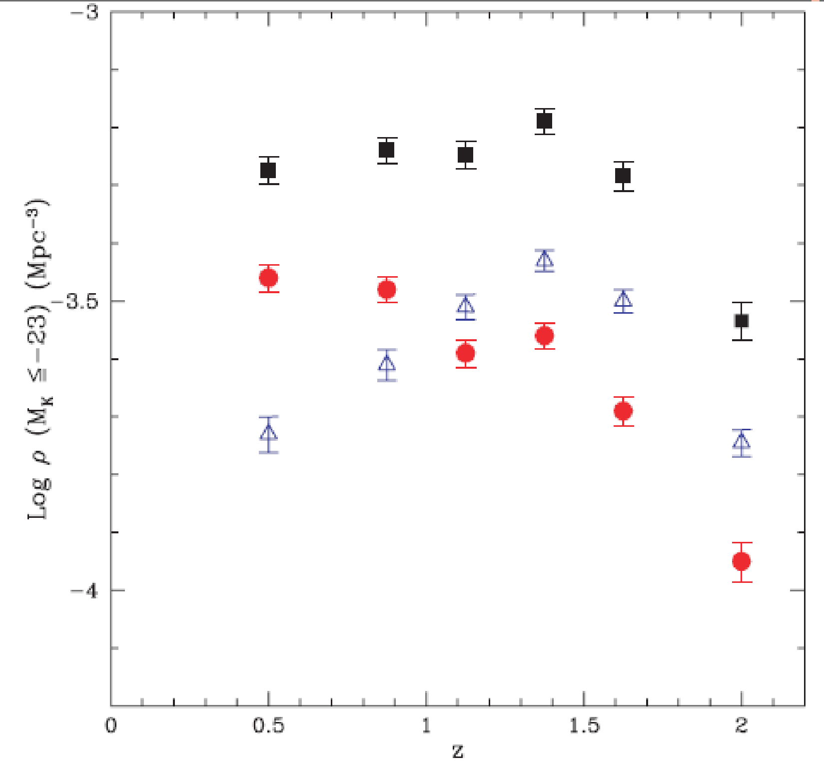
An example of this is the evolution of the K-band luminosity function (Cirasuolo et al. 2007, 2008)

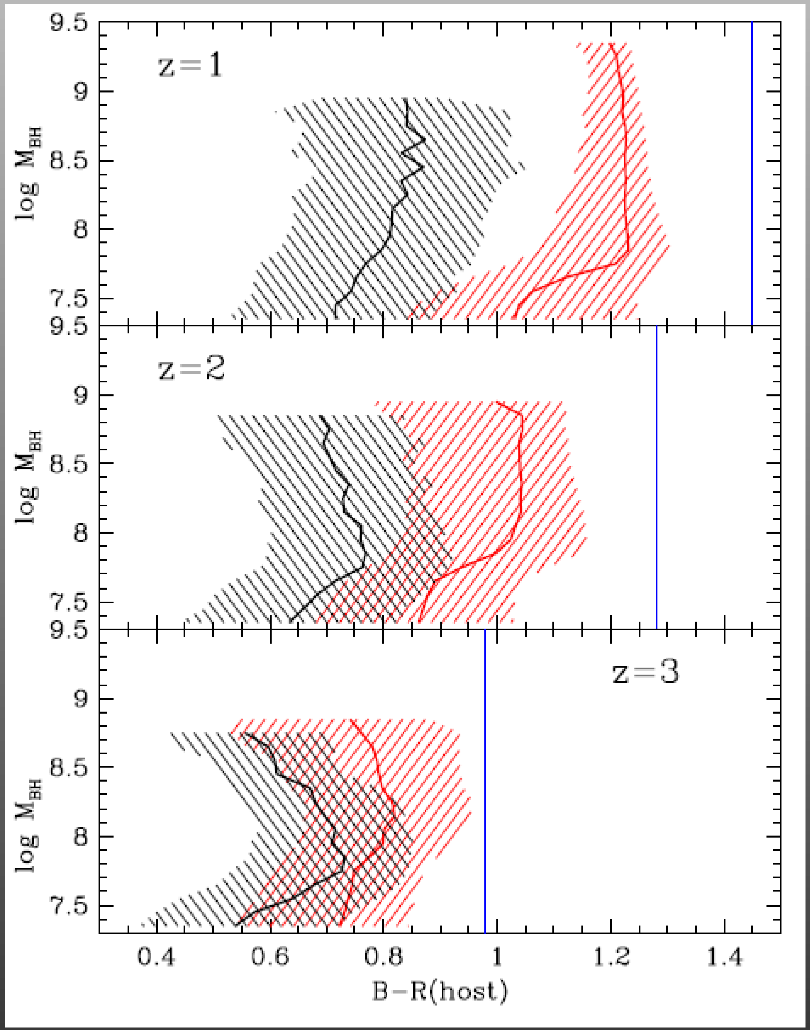




The characteristic magnitude M_K*(z) of the Schechter LF, apparently follows passive evolution: is the typical L* galaxy an elliptical galaxy formed at z=3-6, and passively evolving ever after ?

NO: the number density is not constant with redshift, and the separating blue and red objects in the sample reveals a much more complex evolution.



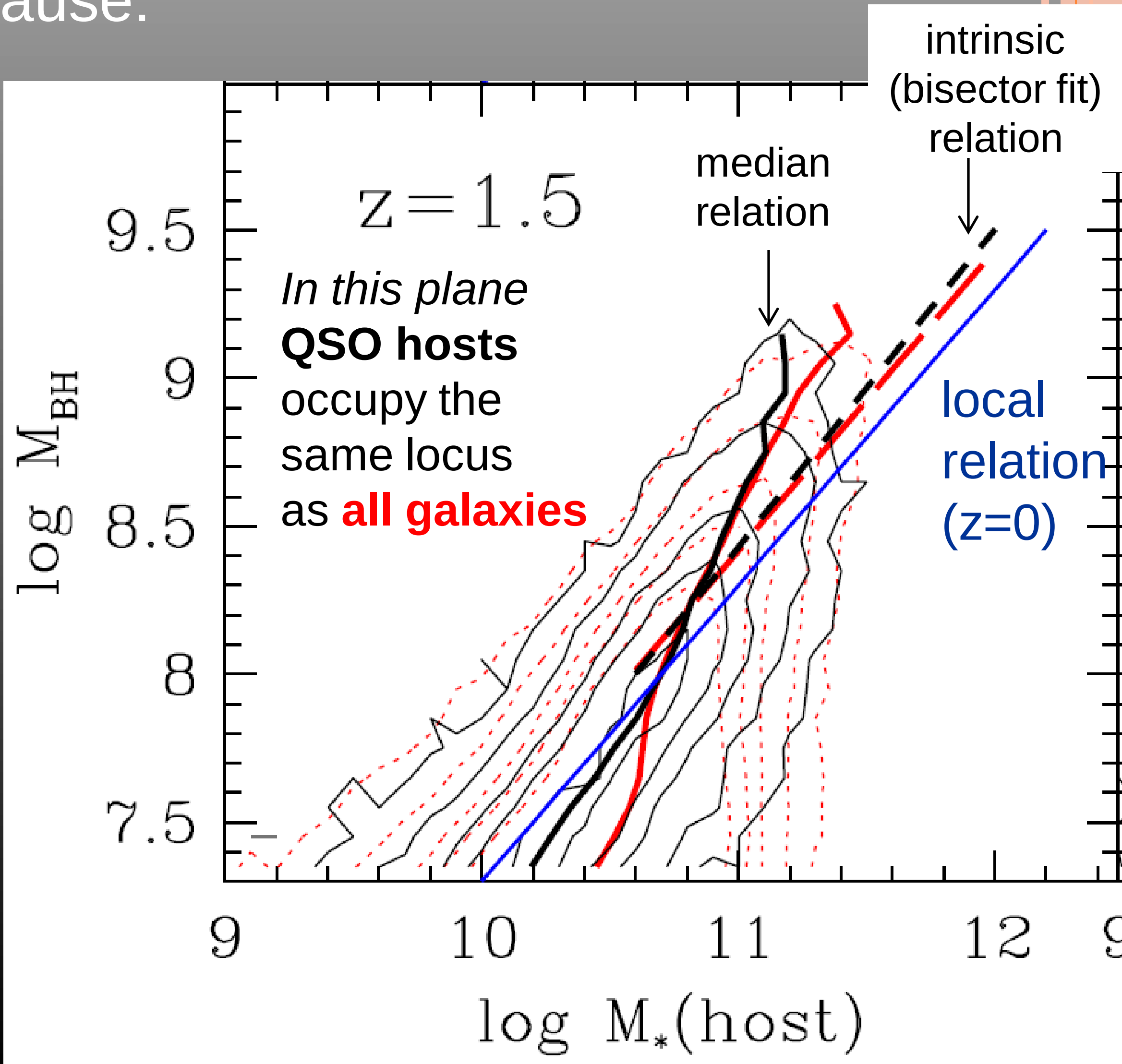


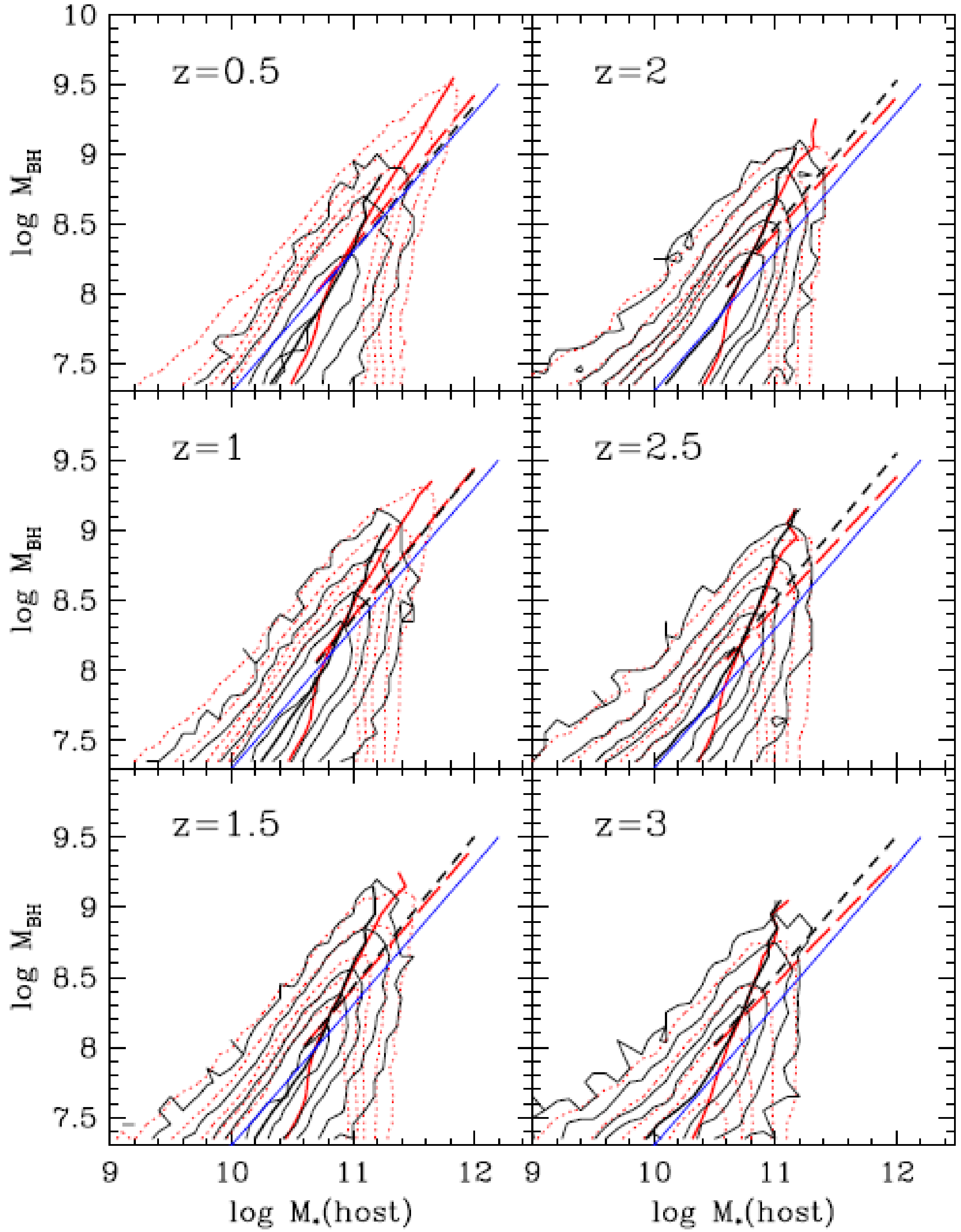
In principle one can use colours to discriminate between passive evolution vs. merger scenario; in practice, this is presently at the borderline of the precision achievable on the colours (0.3 dex in each magnitude band)

The BH mass-host mass relation

Although the M_{BH}-L relation provides the fairest comparison to the direct observations, we discuss also the M_{BH}-$M_{ж}$ relation (taken at face value) because:

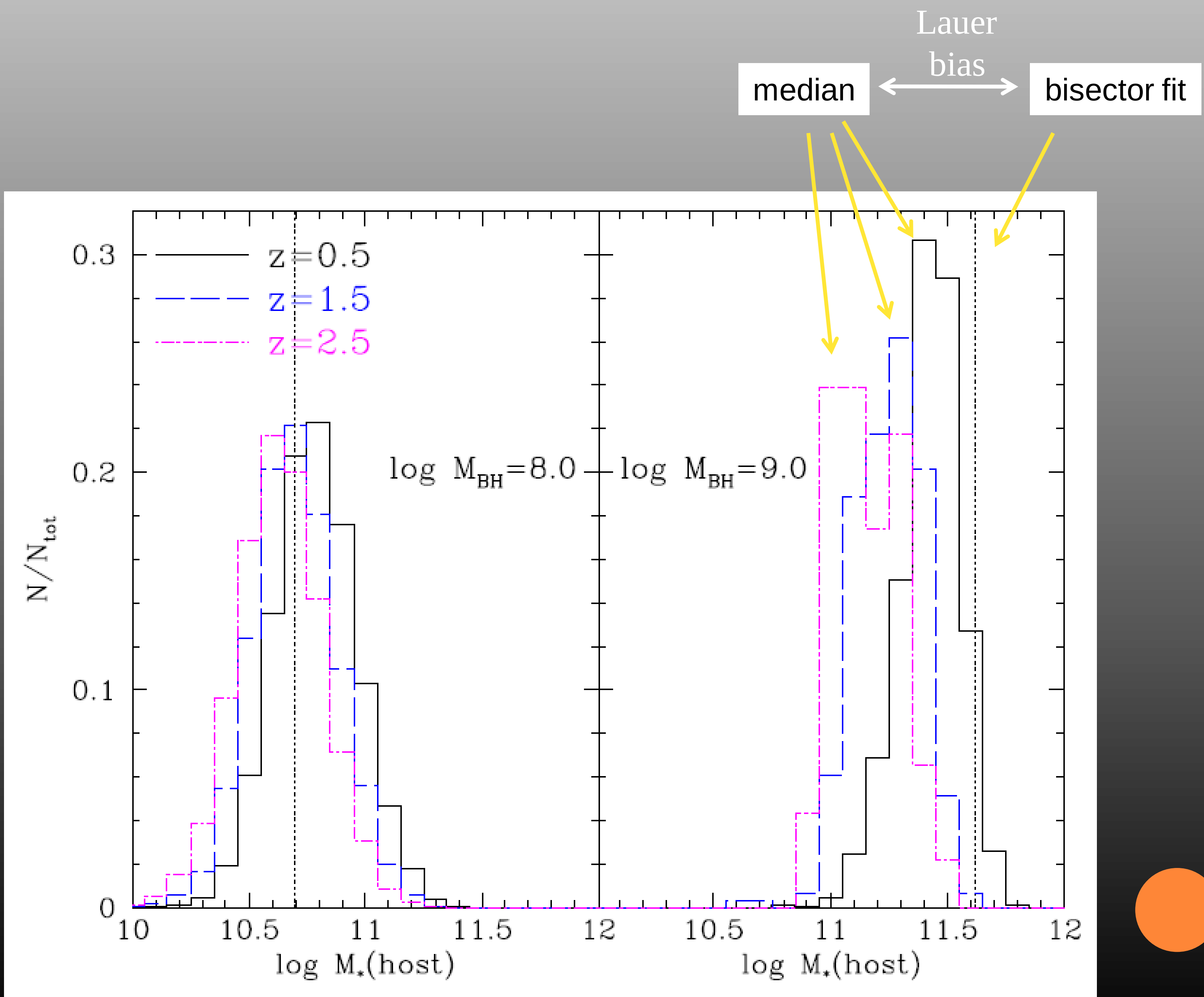
- this is what everybody does ! (comparison to other models)
- the luminosity of model galaxies (especially in post--starburst phase) may be less robust than their stellar mass
- we will have the chance to discuss selection biases





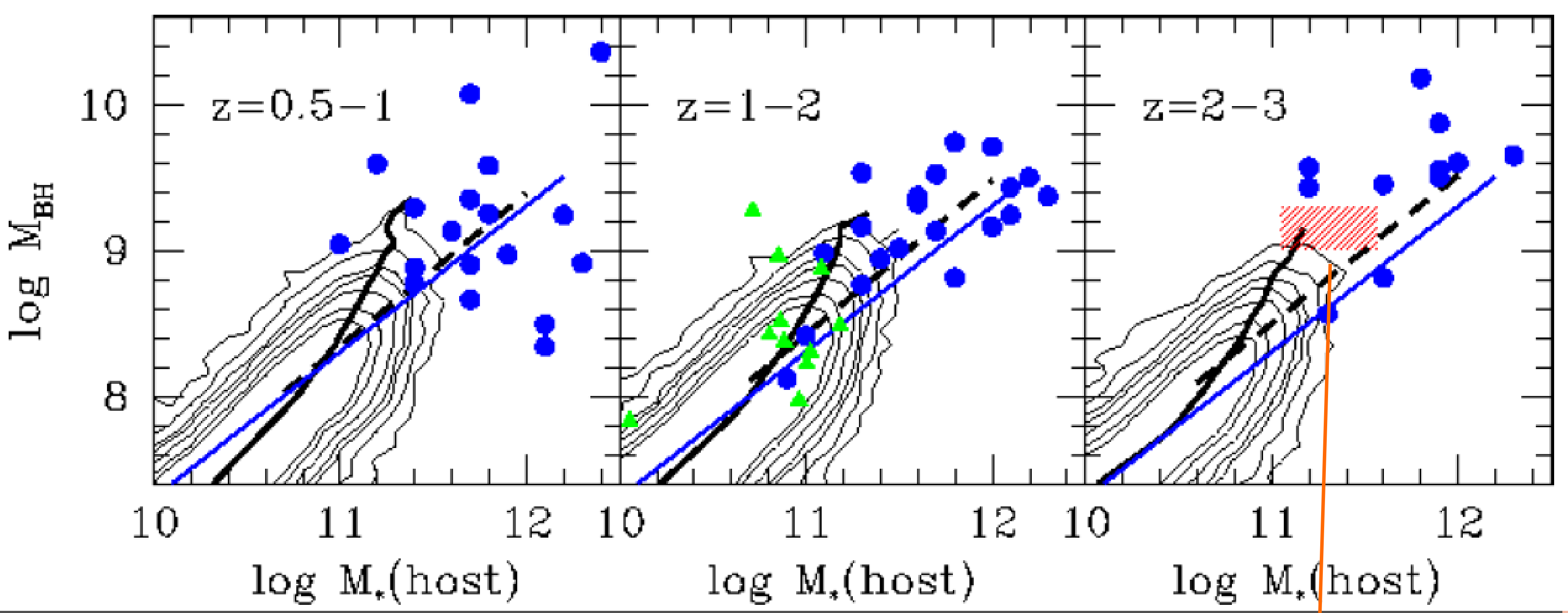
Bisector fit (intrinsic) relation: agrees with the observed one at low z, shows little evolution.

The median relation, for $M_{BH}>10^{8.5}$ $M_{\odot}$, traces systematically under-massive hosts → Lauer bias (Lauer et al. 2007)



Lauer bias
median
bisector fit
z=0.5
z=1.5
z=2.5
log M_BH=8.0
log M_BH=9.0
N/N_tot
log M*(host)
log M*(host)
0.3
0.2
0.1
0
10
10.5
11
11.5
12
10.5
11
11.5
12

In spite of negligible evolution, the models can still match the data thanks to the Lauer bias at the high mass end.



lack of massive BH at high z in the SAM

locus of the most massive BH in the SAM at z=3

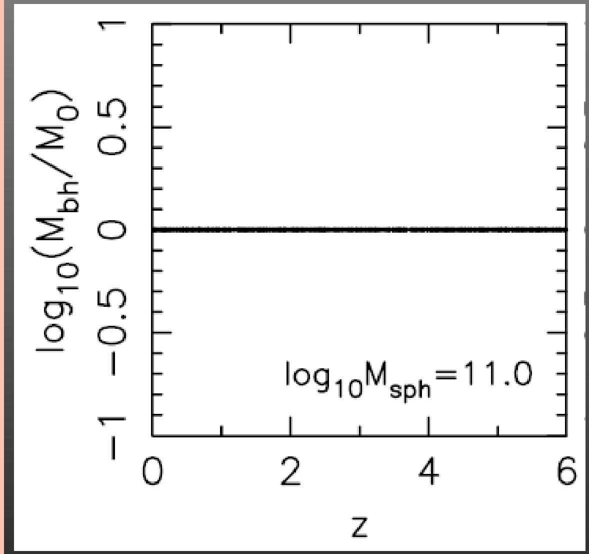
enhancement of the Lauer bias (that is more pronounced for more rare objects)

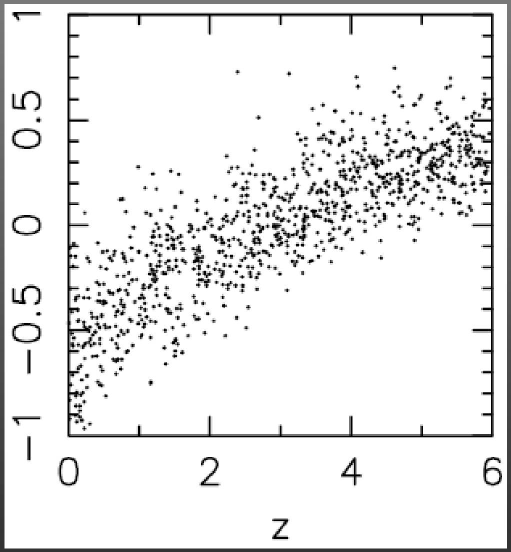
The evolution of $\Gamma=M_{BH}/M_{**}$

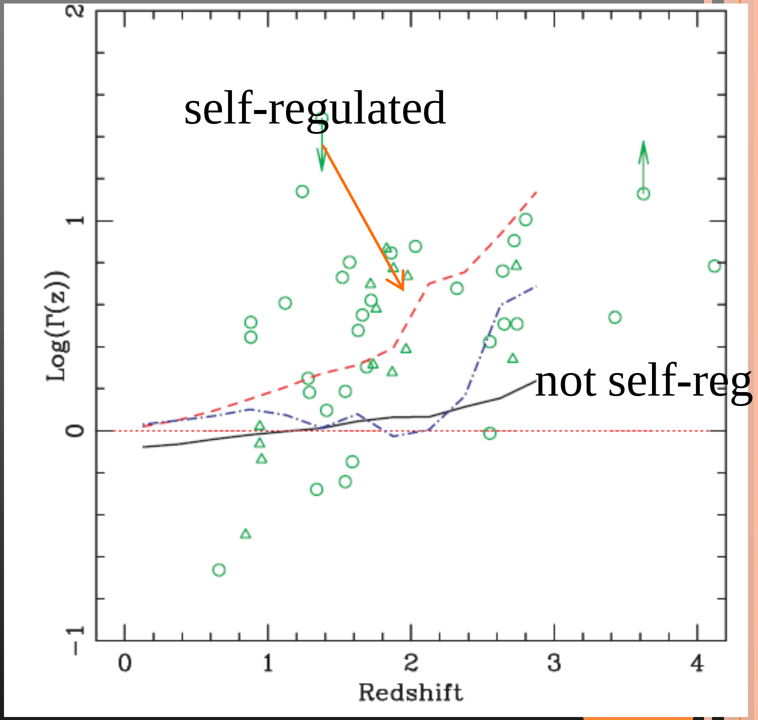
The evolution of the ratio $\Gamma=M_{BH}/M_{bulge}$ can discriminate between models including quasar feedback → strong evolution or not → mild or no evolution

Wyithe & Loeb (2005)

Fontanot et al. (2006)

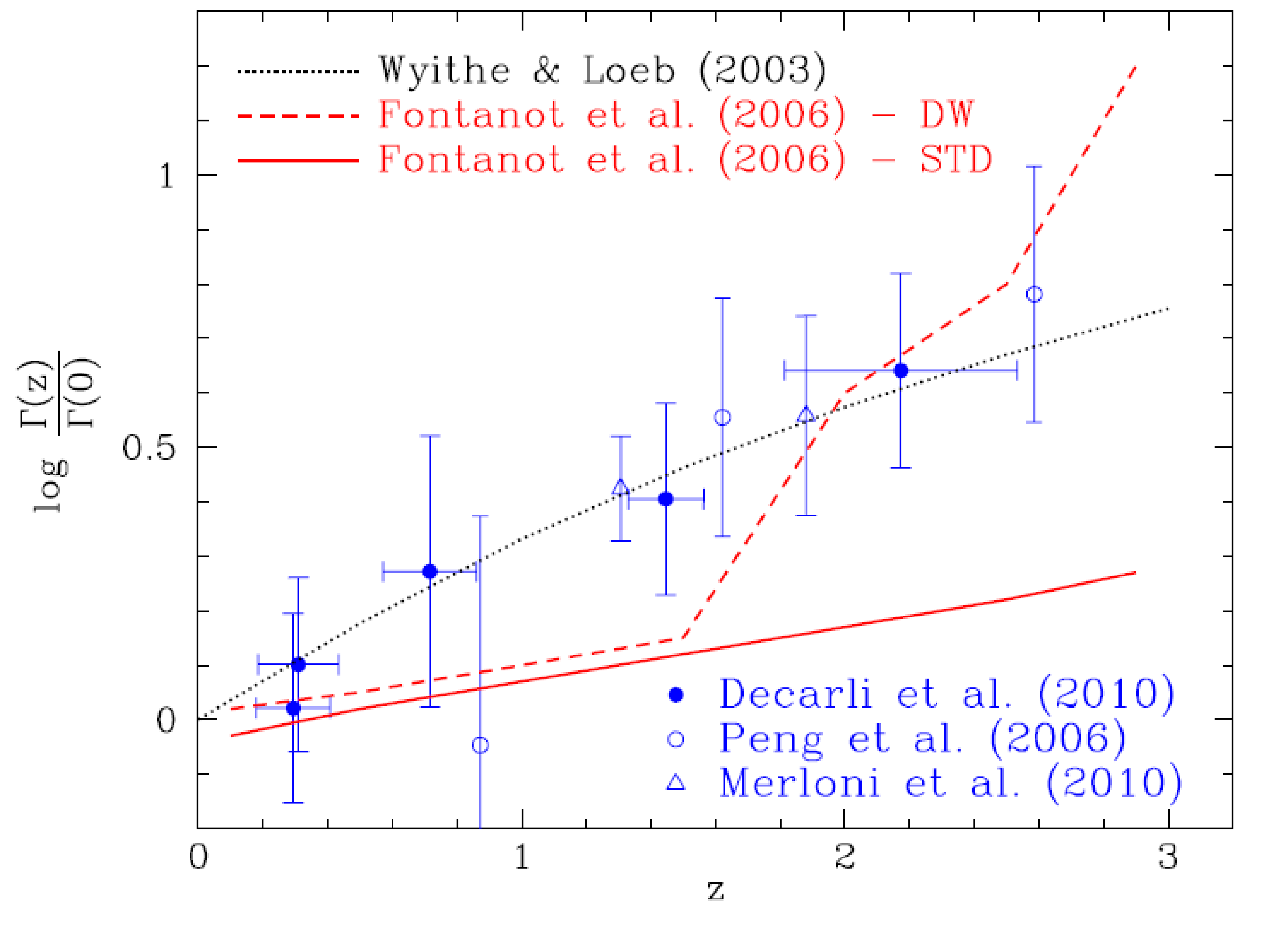






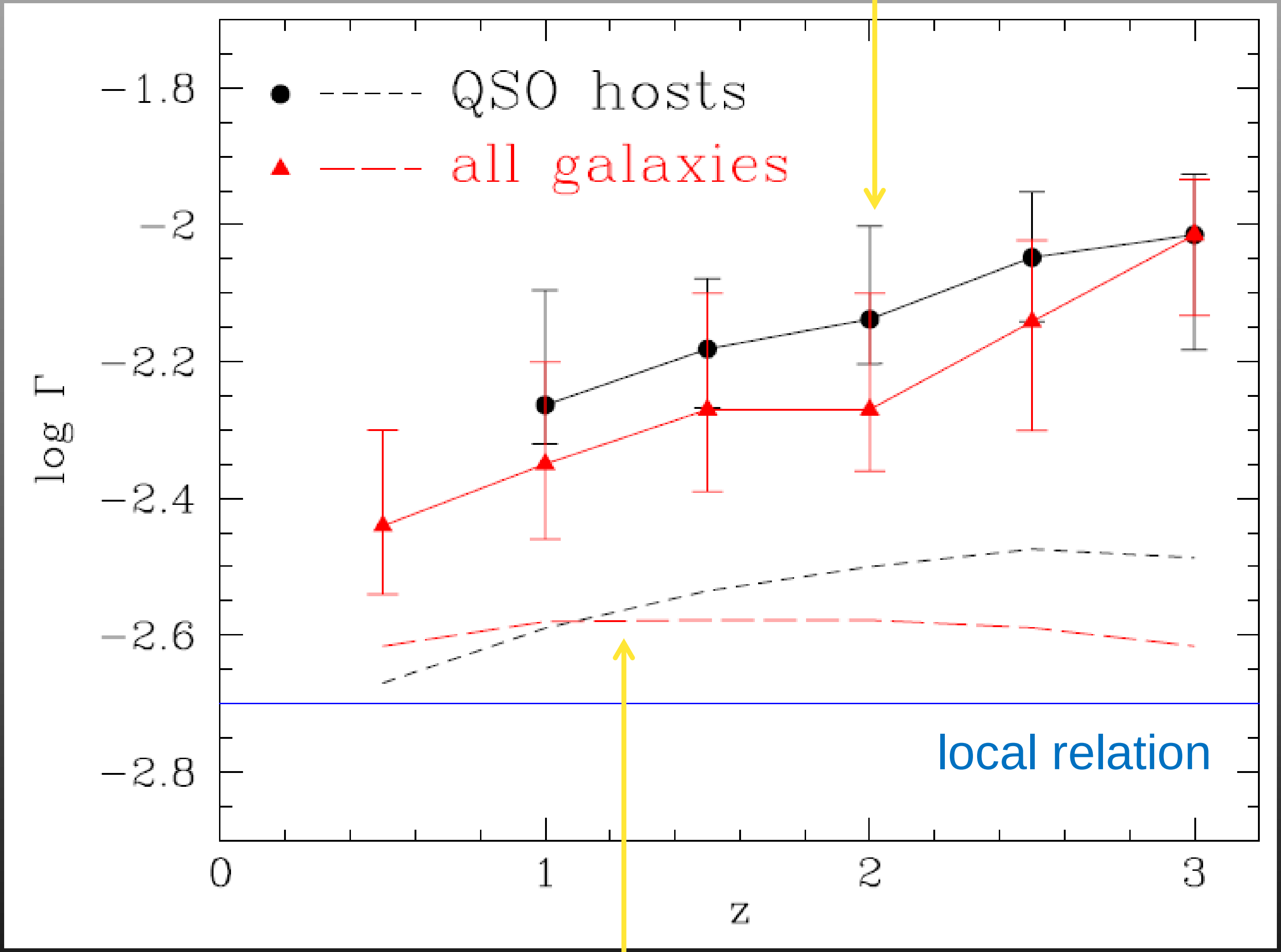
no feedback

feedback



It’s very tempting just to plot the observed evolution of Γ, overplot the models and decide the best feedback recipe. But things are more complicated than that....

median relation : some evolution
(0.2-0.3 dex at z=1→3);
systematic offset at $M_{BH} = 10^9 M_{\odot}$



bisector fit relation: no or mild evolution
(expected for models with no quasar feedback)

Conclusions (2) : $M_{BH} - M_{ж}$ relation and Γ ratio

- ✓ The observed evolution of the $M_{BH} - M_{ж}$ relation and of the Γ ratio should favour SAM including effective QSO feedback …
- ✓... but the Lauer bias could still reconcile observations with SAM with no feedback.
- ✓ The Lauer bias depends on the statistical properties of the galaxy & QSO population (Lauer et al. 2007): the intrinsic scatter in the relation, the luminosity function of galaxies and of BHs (at various z)

  ⟶ requires a ”global” approach, i.e. SAM that reproduce the QSO mass function etc.

Datasets on QSO hosts at high z are improving (VLT, HST; in perspective: ELT, NGST).

If we believe that the QSO phase is a crucial phase of galaxy evolution, these data are worthwhile confronting to

BIAS ?

Local relation (z=0)	⟷	**High z QSO hosts**
quiescent galaxies		in a peculiar phase of evolution (post-merger, post-starburst)
tightest between BH and host bulge		global host galaxy (hard to decompose bulge/disc)
few $10^6 < M_{BH} <$ few $10^9 M_{\odot}$		QSOs trace systematically more massive BHs at high z: Lauer bias (Lauer et al. 2007)

Wishlist for modellers

- Predict the relation(s) for QSO hosts: galaxies at the moment the quasar shines are a special beast!
  (cf. also Lamastra et al. 2010)

- Discuss separately the ”intrinsic relation” from the median relation (Lauer bias)

- Consider the comparison in the M_{BH} – luminosity plane: it’s a more direct and self-consistent comparison to observations.