Black Hole Mass Scaling Relations and their Possible Evolution

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- Why care? Deep insights about evolution of galaxies and black holes. Gives us a way to guess BH mass in other galaxies.
- Brief History of BH Scaling Relations. (M-L, M-sigma, and friends.)
- Current status and open questions regarding the relations.
- Evolution of scaling relations and troubles of such inferences therein.

Black hole masses correlate with galaxy properties.

This may mean their growth/evolution are intimately connected.

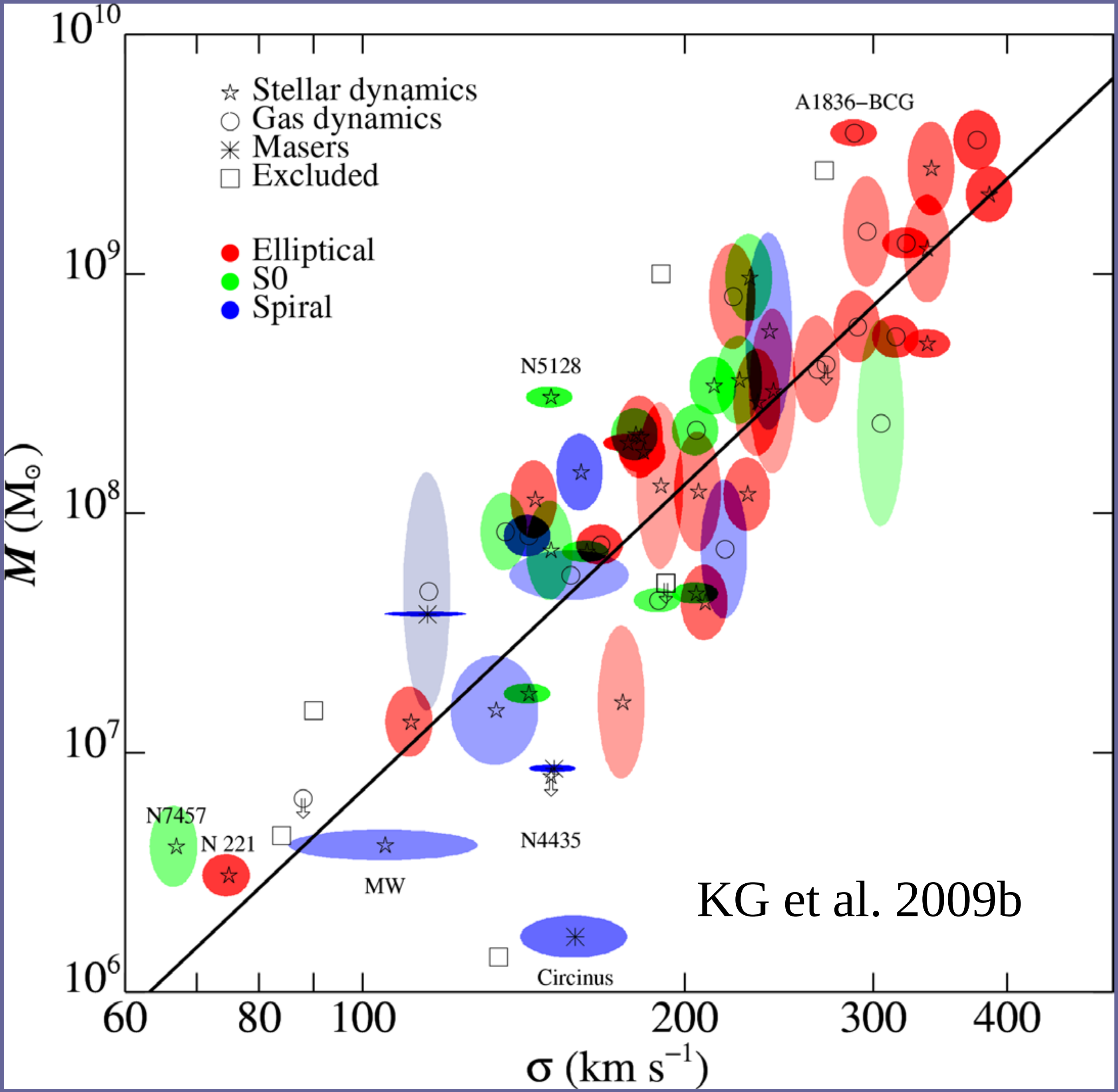
Prevailing paradigm is one where galaxy mergers drive cold gas to the center of a galaxy where a black hole can accrete and grow.

The feedback from outflows resulting from the accretion can expel gas and halt star formation.

Black hole masses correlate with galaxy properties.

This means we can guess BH mass by measuring something else.

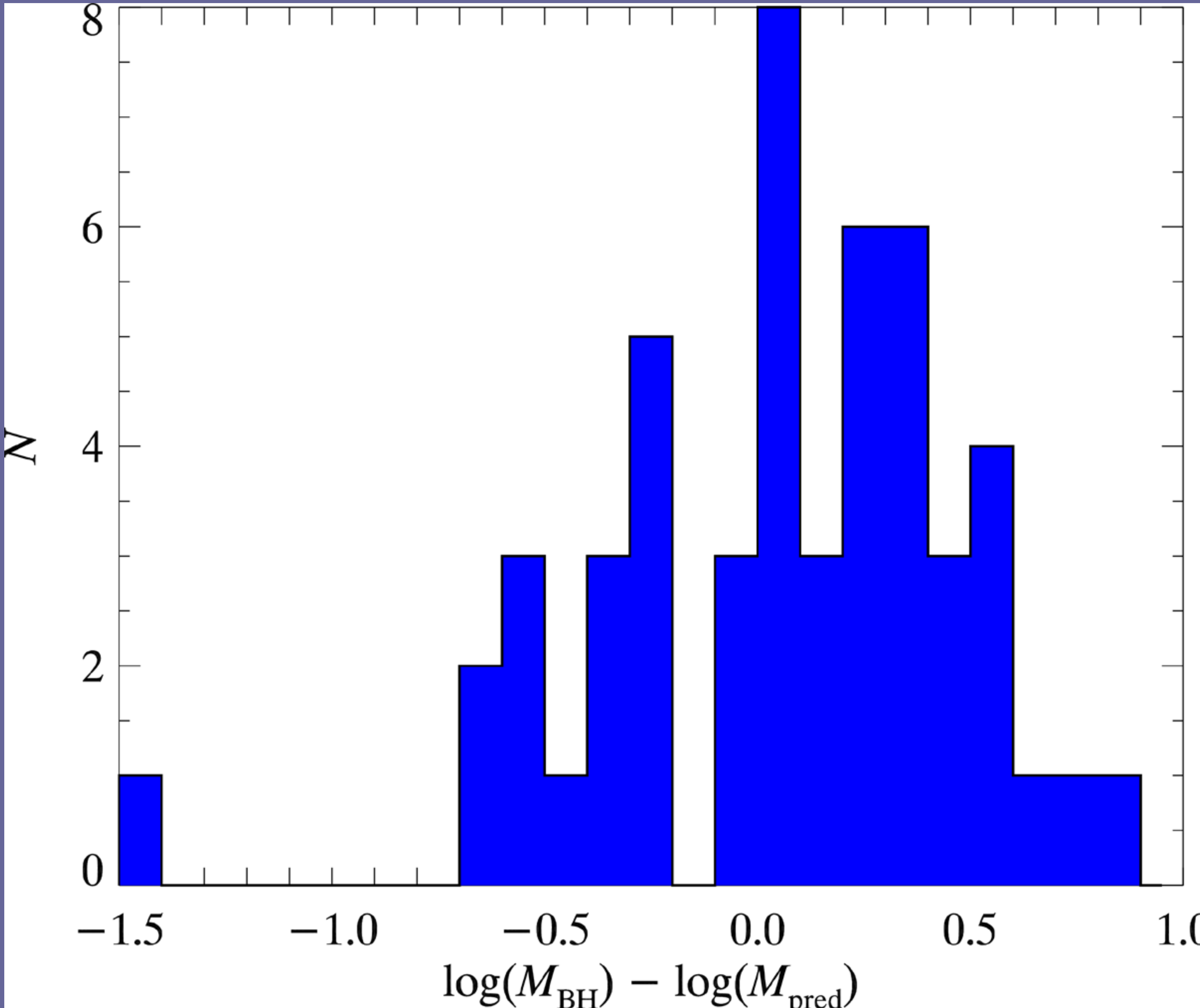
- Galaxy bulge luminosity.
  - Kormendy ('93); Kormendy & Richstone ('95)
- Galaxy bulge mass.
  - Dressler (1989); Magorrian (1998)
- Velocity dispersion.
  - Gebhardt et al. (2000)
- Multi-parameter relations (sigma-Re)
  - Hopkins et al. (2006)
- Etc. (Mass deficit, Sersic index, $M_*\sigma^2$, total light, number of globular clusters, spiral arm pitch angle, NGC#)



Stellar dynamics
Gas dynamics
Masers
Excluded
Elliptical
S0
Spiral
A1836–BCG
N5128
N7457
N 221
MW
N4435
Circinus
KG et al. 2009b
M ($M_\odot$)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
60
80
100
200
300
400
σ (km s^{-1})

The scatter in M-sigma is not insignificant.

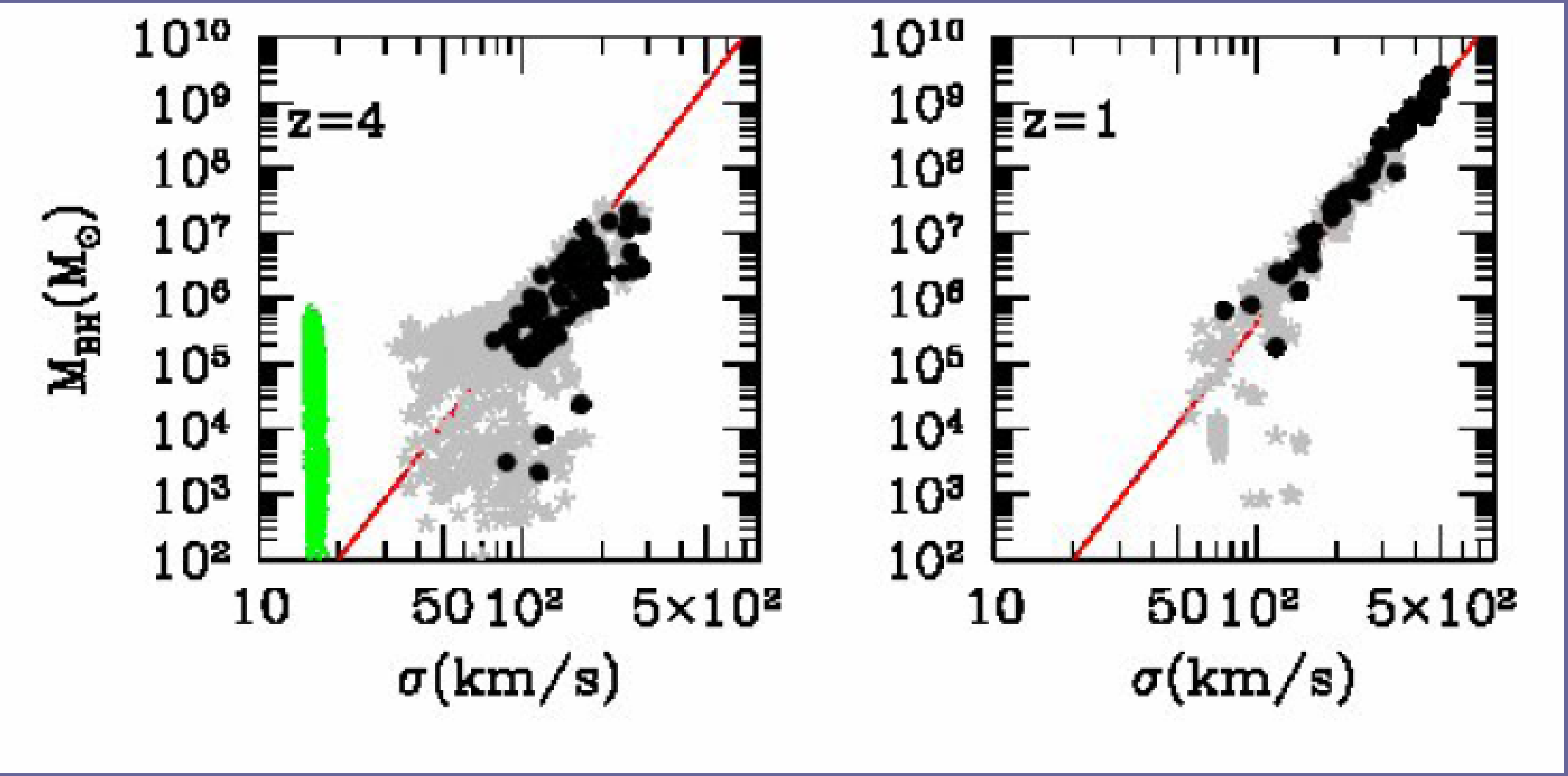
- M-sigma
  - Slope = 4.24 +/- 0.41; Scatter = 0.44 +/- 0.06.
  - Restricting to just Ellipticals reduces the scatter to 0.31 +/- 0.06.
- M-L (early-type only)
  - Slope = 1.11 +/- 0.18; Scatter = 0.38 +/- 0.09.
- The *distribution* of the residuals is Gaussian in logarithmic mass.



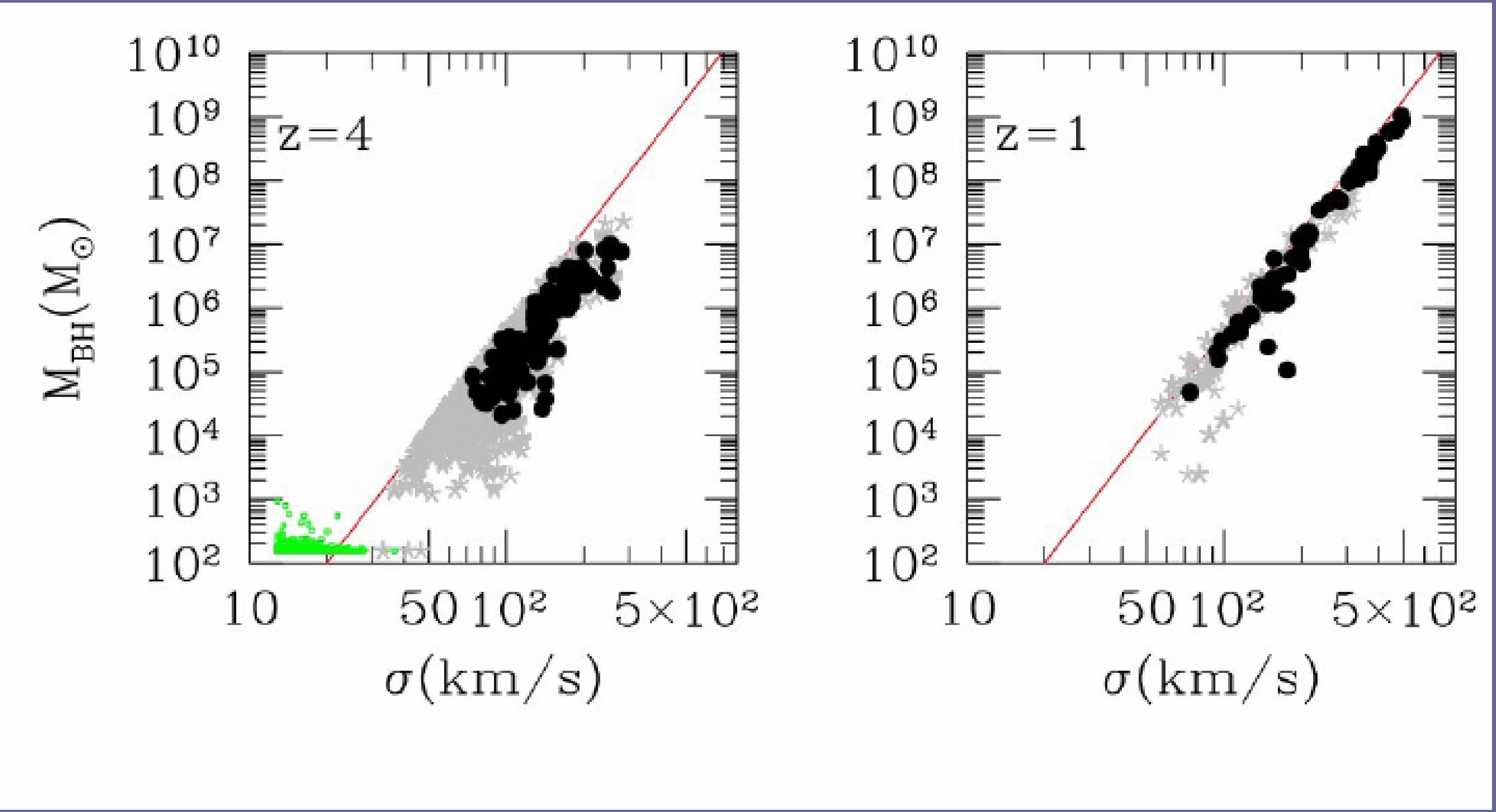
8
6
4
2
0
N
−1.5
−1.0
−0.5
0.0
0.5
1.0
log(M_{BH}) − log(M_{pred})

The *intrinsic* scatter in M-σ relation.

- Another “answer in the back of the book” for theorists.
- Studies of evolution of M-σ relation are biased by the scatter.
- The density of the BIGGEST black holes is dominated by the intrinsic scatter.

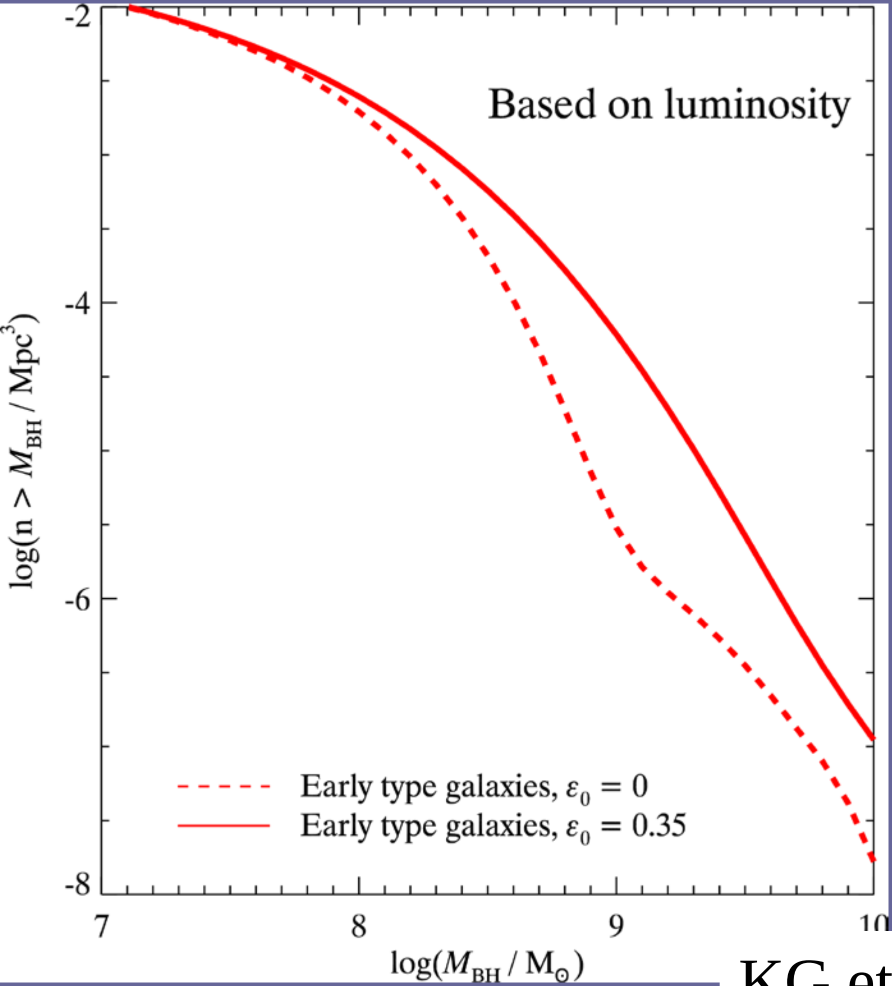


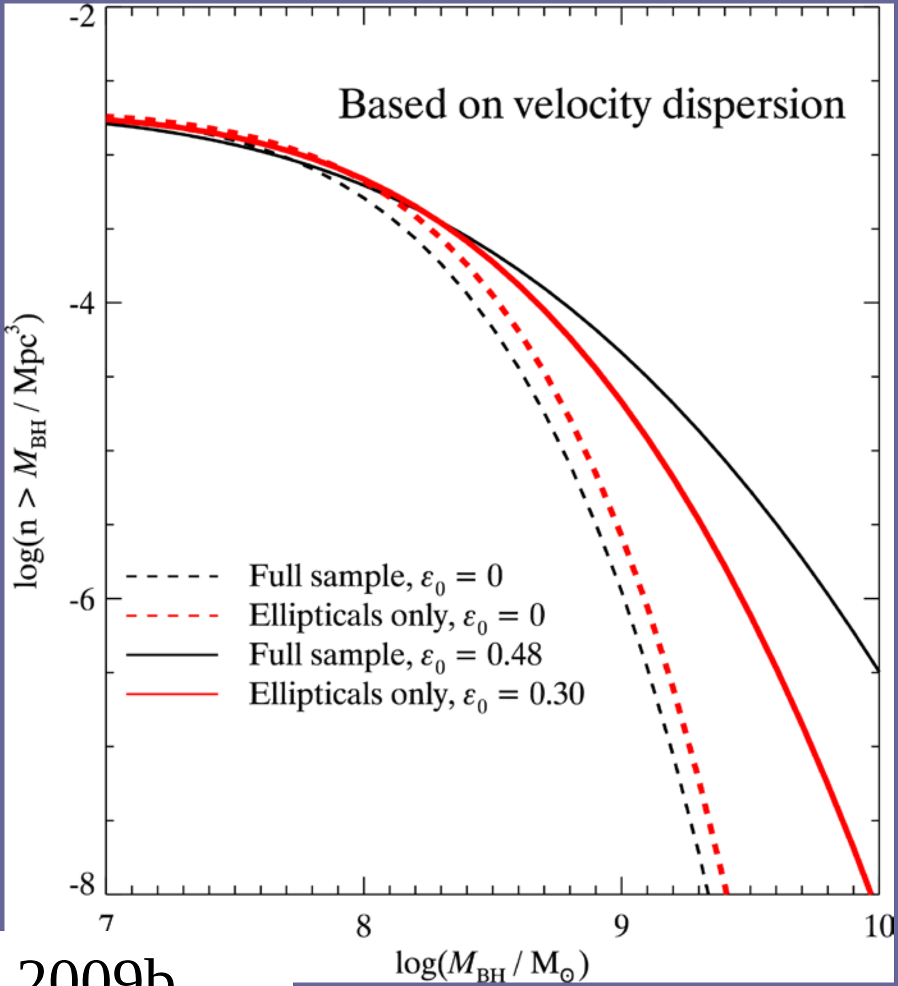
Volonteri & Natarajan (2009)



Volonteri & Natarajan (2009)

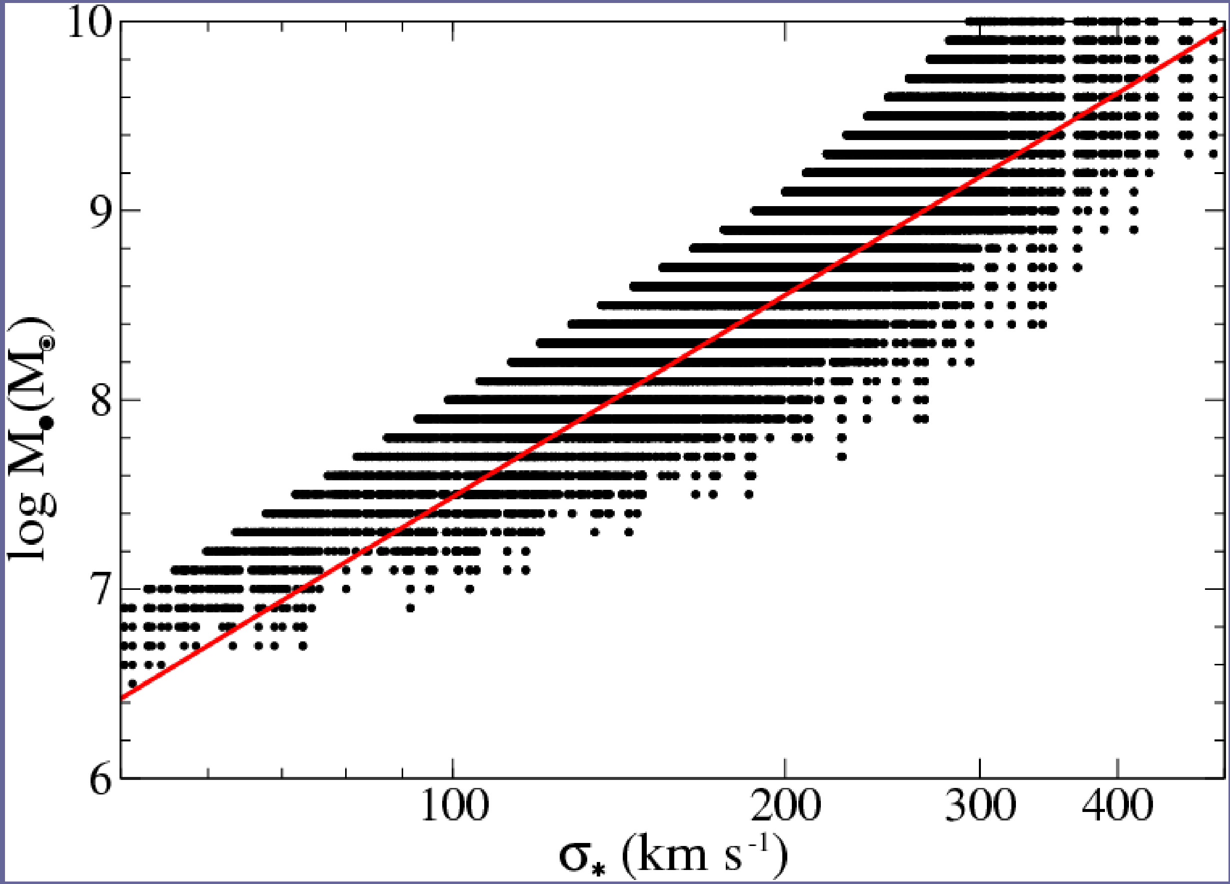
Nonzero scatter implies more BHs at the high-mass end.





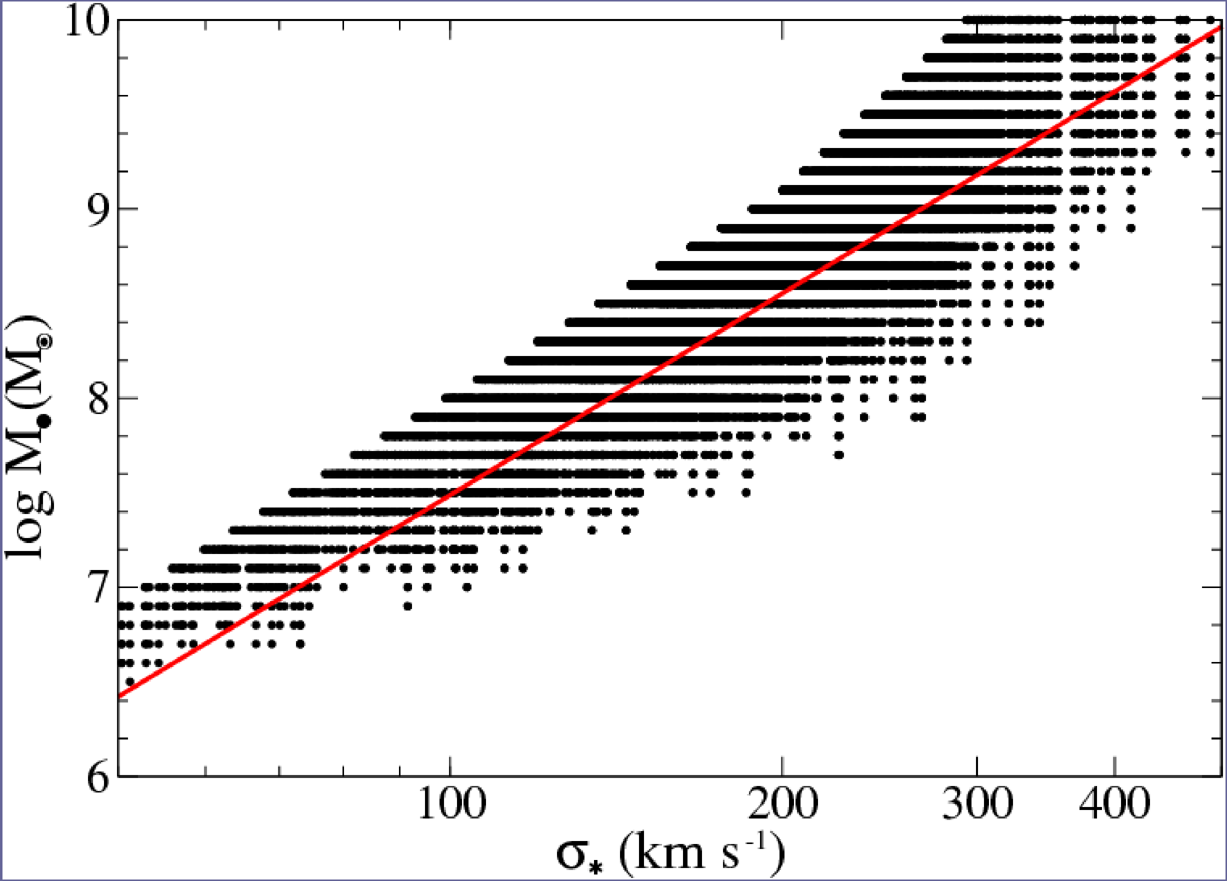
KG et al. 2009b

Is the M-sigma ridgeline actually an upper limit relation plus selection effects?



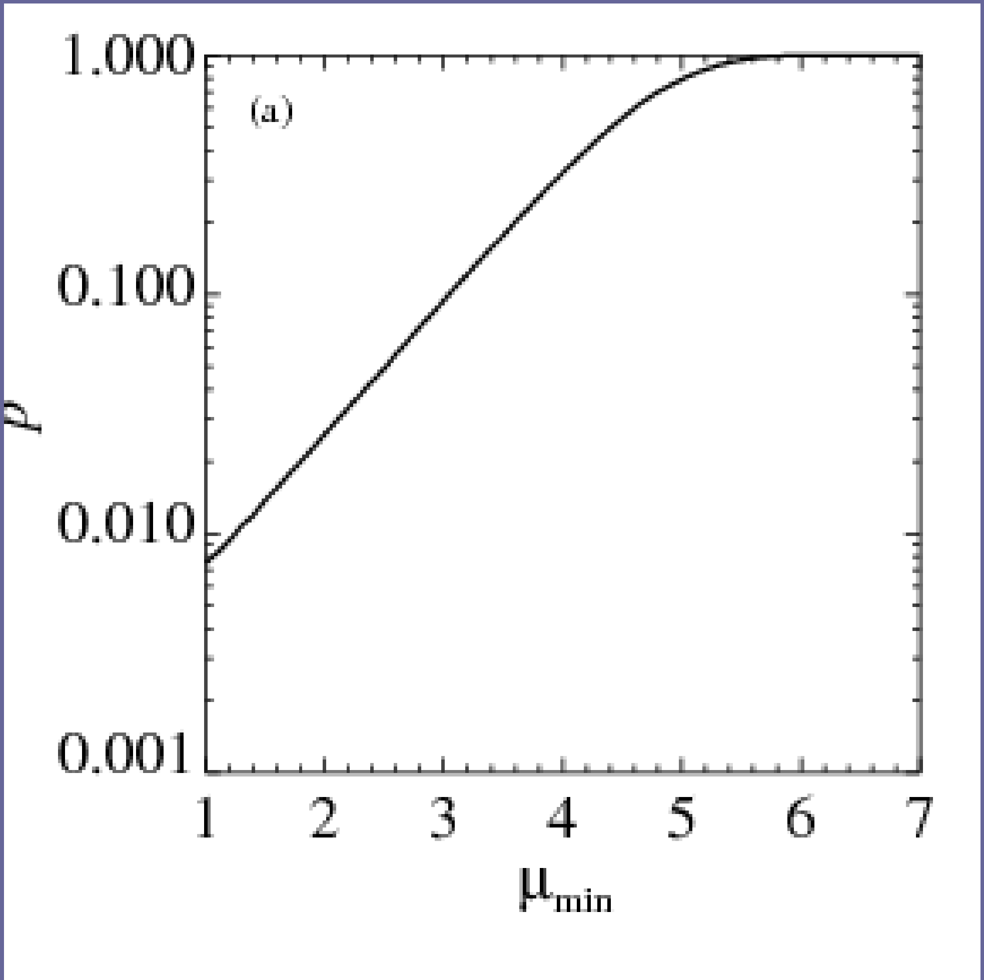
Batcheldor (2010)

No! There would be many more upper limits than measurements.



Batcheldor (2010)

We quantified this with generous assumptions and can rule out upper limit model at 99.9%.



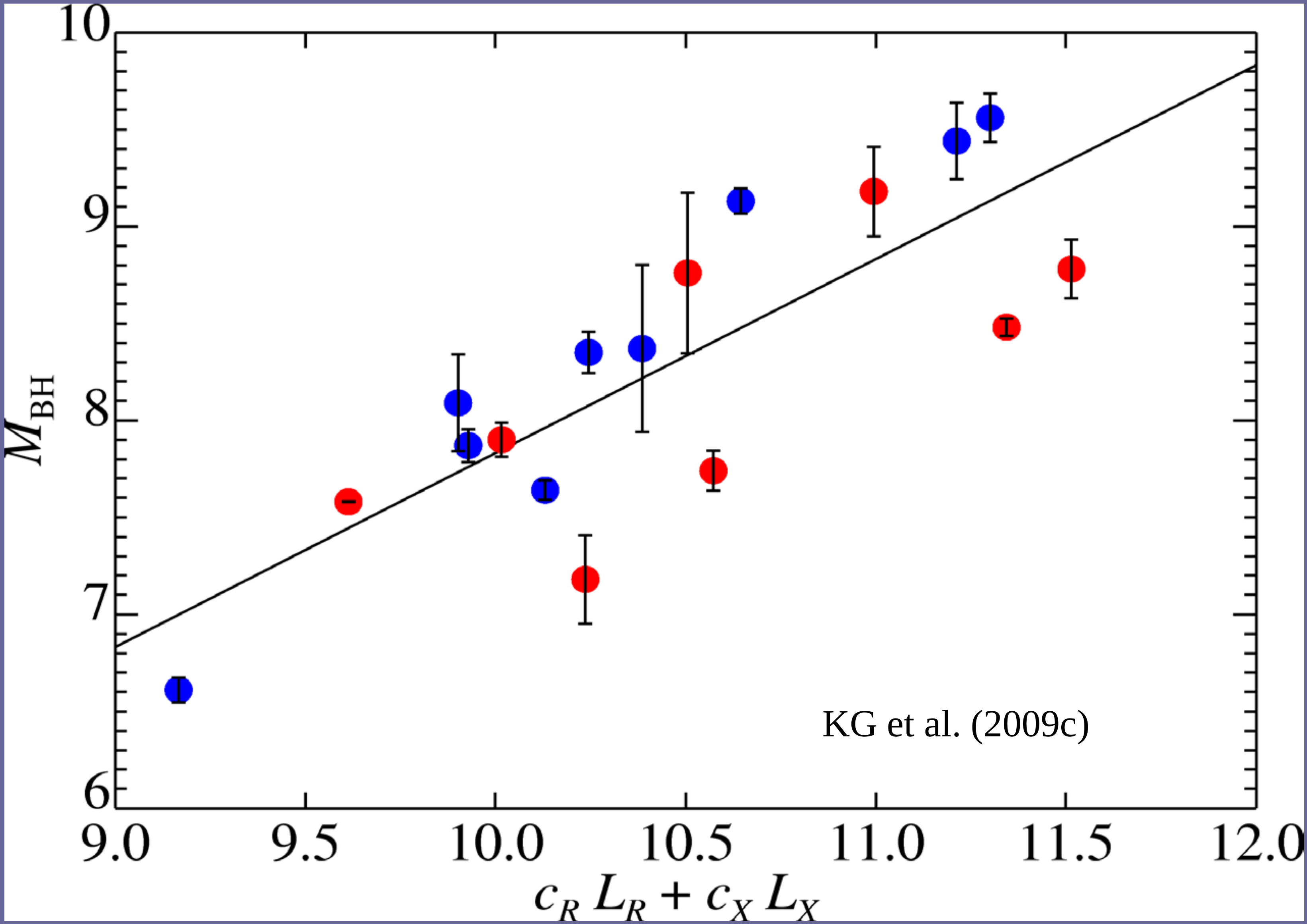
KG et al. (2011)

The “colors” of black holes correlate with mass.

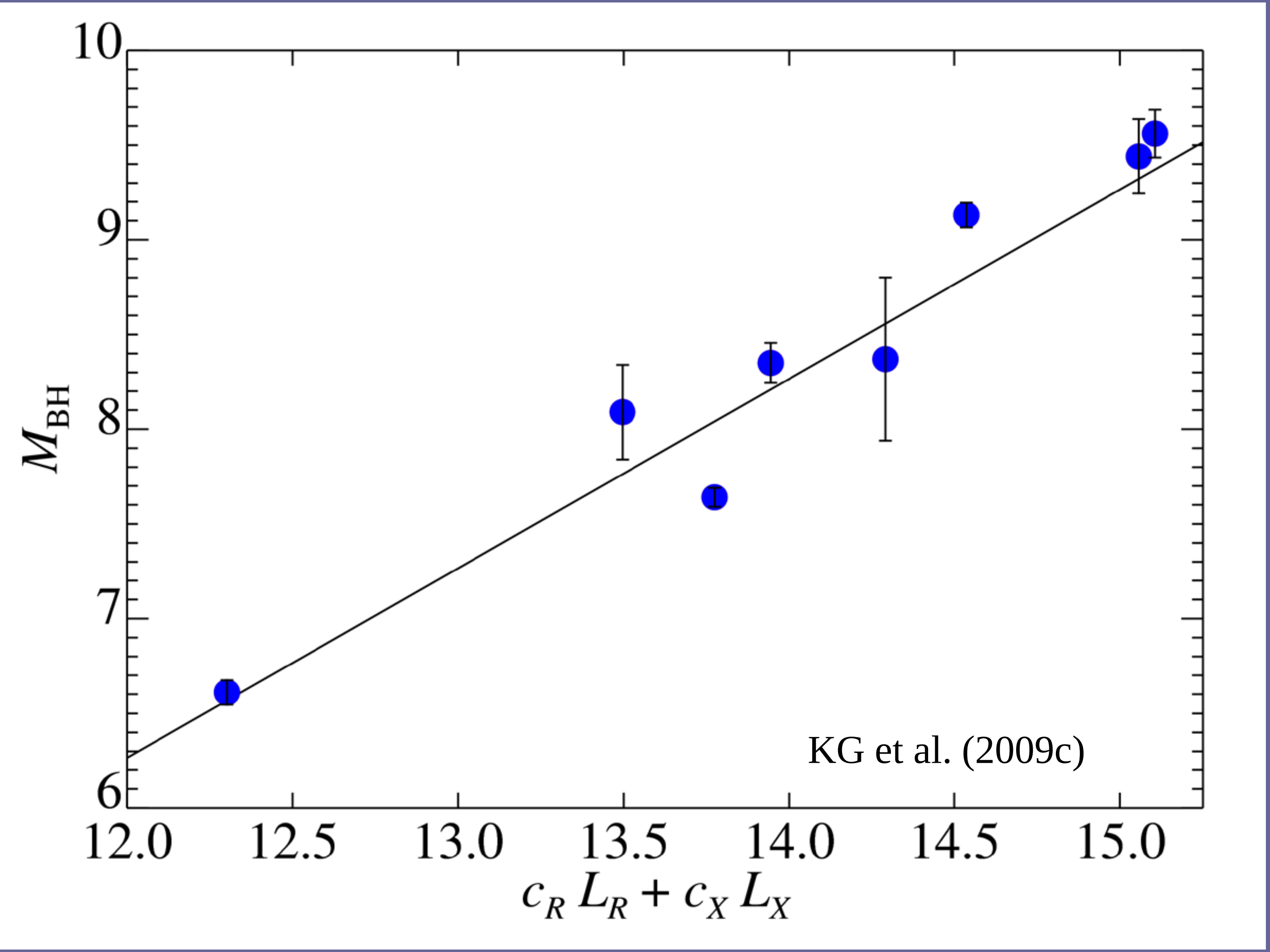
Measure X-ray (probe of accretion) and Radio (probe of outflow) luminosities.

Find: $M \sim L_R^{1.3} L_X^{-0.9}$

Physics is not completely understood. (Also important!)



10
9
8
7
6
M_{BH}
9.0
9.5
10.0
10.5
11.0
11.5
12.0
$c_R L_R + c_X L_X$
KG et al. (2009c)


10
9
8
7
6
$M_{\rm BH}$
12.0
12.5
13.0
13.5
14.0
14.5
15.0
$c_R\, L_R + c_X\, L_X$
KG et al. (2009c)

Cleary more observations are needed! And we have them!

Data taken. Analysis ongoing.

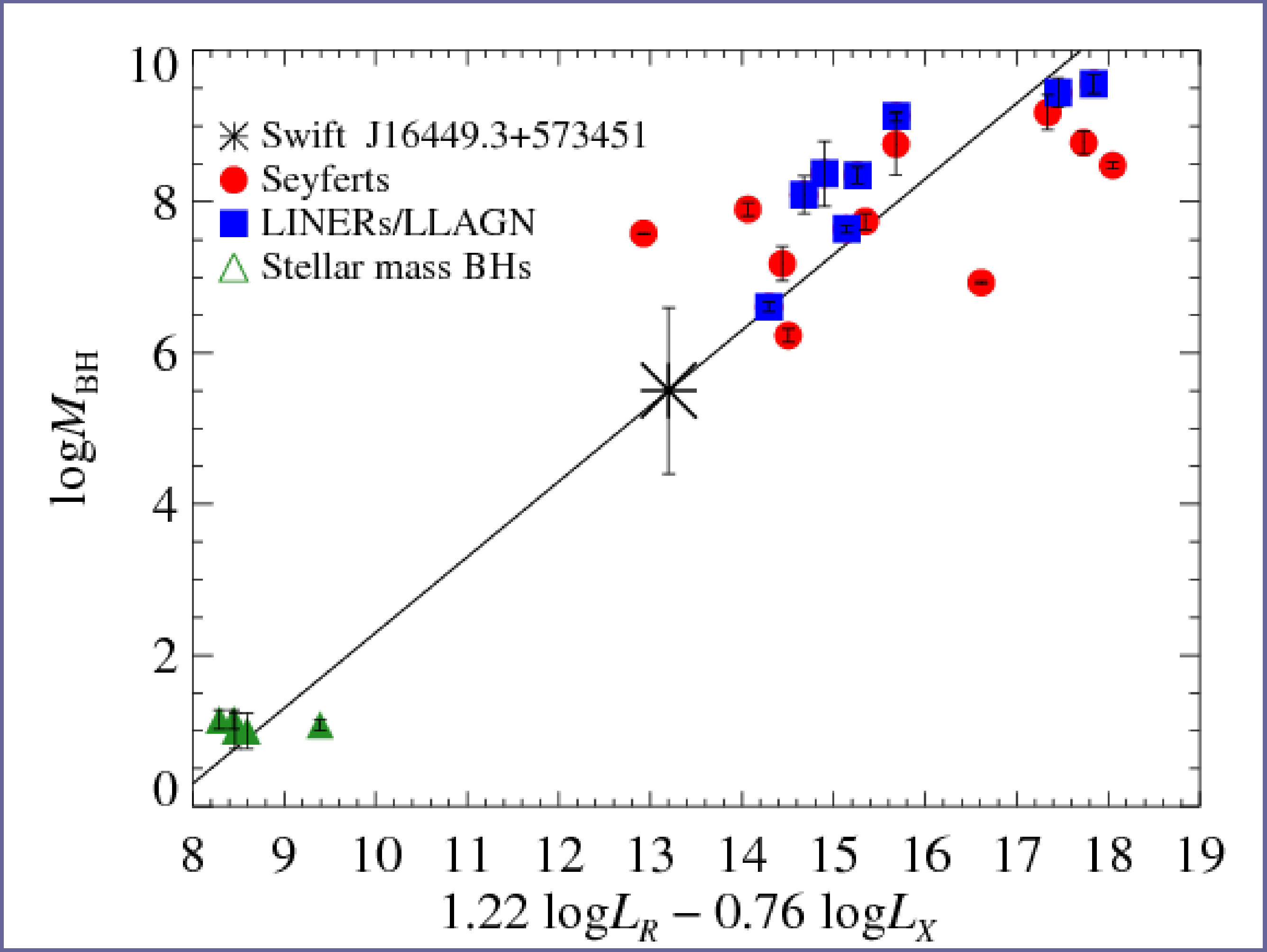
X-ray analysis for 12 more primary sources about to be submitted.

Radio analysis ongoing.

Previously, we had 18 data points, in the next few weeks we will have 30. In the next few months, we will have 45-50.

Still useful in its current form. (e.g., Reines+10, Heinze2-10)

Swift J164449.3+573451



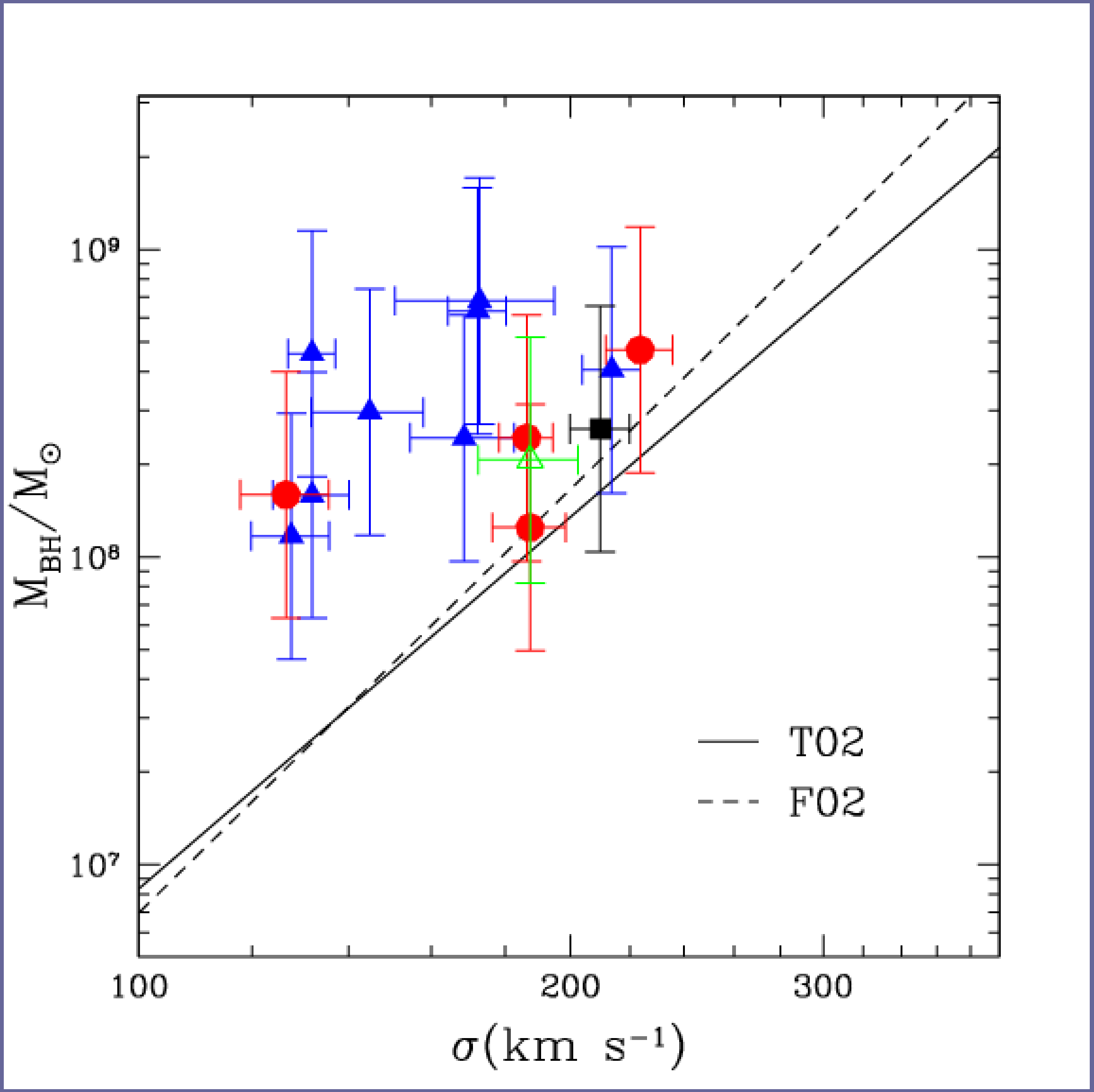
Miller & KG (2011)

The study of scaling relations is not over!

1. M-sigma vs. M-L? [Tod Lauer]
2. Scatter of the relations.
   - KG+09 optimized for “middle of the road”
   - Is it constant? Scatter in small/big galaxies?
3. Disk/Total/Bulge/Pseudobulge scalings
   - Kormendy+(2010a)
4. DM Halo vs Bulge baryons
   - Kormendy+(2010b) vs. Volonteri+(2010)

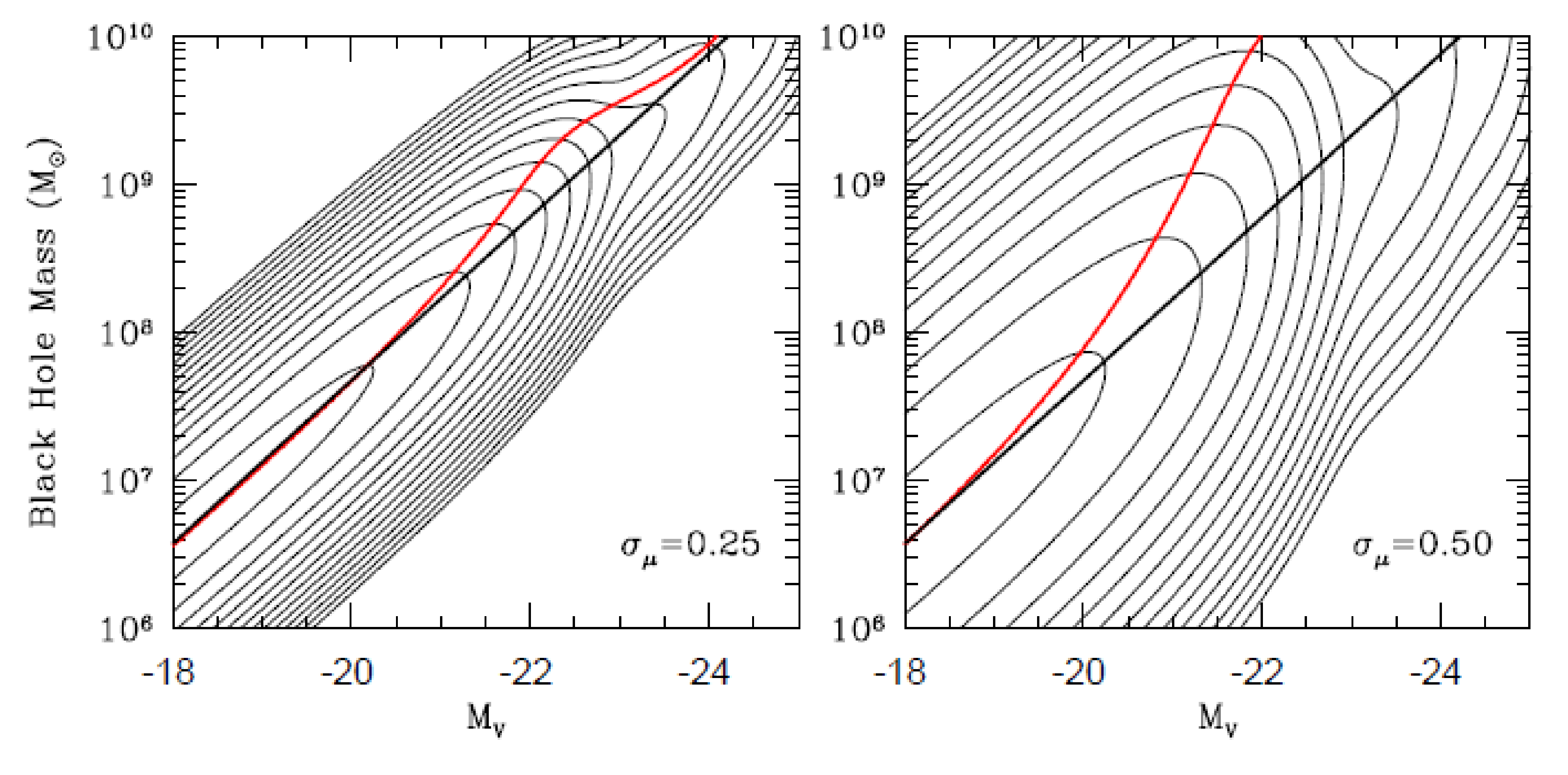
Evolution of Scaling Relations

- Measure BH masses (by secondary or tertiary methods) in high redshift galaxies ($z = 0.3 – 2$).
- Measure host galaxy bulge luminosity or stellar velocity dispersion (sometimes by secondary methods).
- Compare to present epoch. (Woo+, Treu+, Shields+, Salviander+, Bennert+, Merloni+)

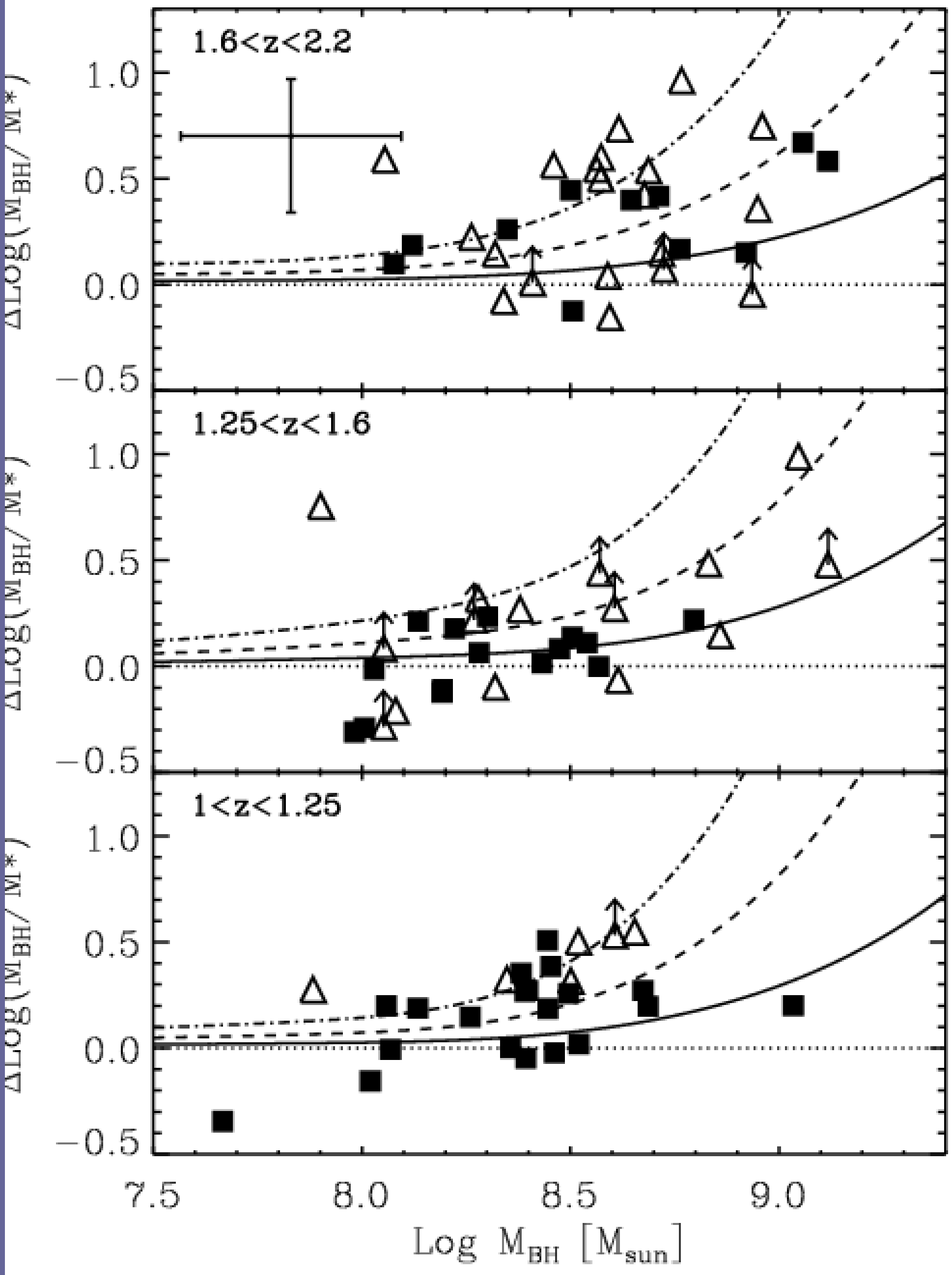


Woo+ (2006)

Are we comparing samples as well as possible? Have we seen evolution?



Lauer+ (2007)



Merloni+ (2010)

We may never be able to distinguish intercept evolution vs. scatter evolution.

- Or intercept, slope, and scatter evolution (Volonteri+11)

We know black hole masses scale with galaxy properties. Do we really know why? (Feedback or central limit?)

What is going on at the low end? (this afternoon)

What is going on at the high end? (M-sigma / M-L)

Is the scatter constant across galaxy mass or changing? What does that tell us about seed masses or coevolution?

Can we disentangle selection effects to know what is evolving in the scaling relations?