Black Hole Mass Scaling Relations and their Scatter

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University of Michigan

- Measured the most up-to-date M-σ and M-L relations.
- Measured the intrinsic scatter of the relations.
- Infer Black Hole Density. Worry about bias.
- Radio and X-ray measurements.

Black Holes have mass, spin, and charge.

- Mass: M_{BH}
- Spin: a (talks by Volonteri, Reynolds, Jon Miller?)
- Charge: q

Black Holes have mass and spin.

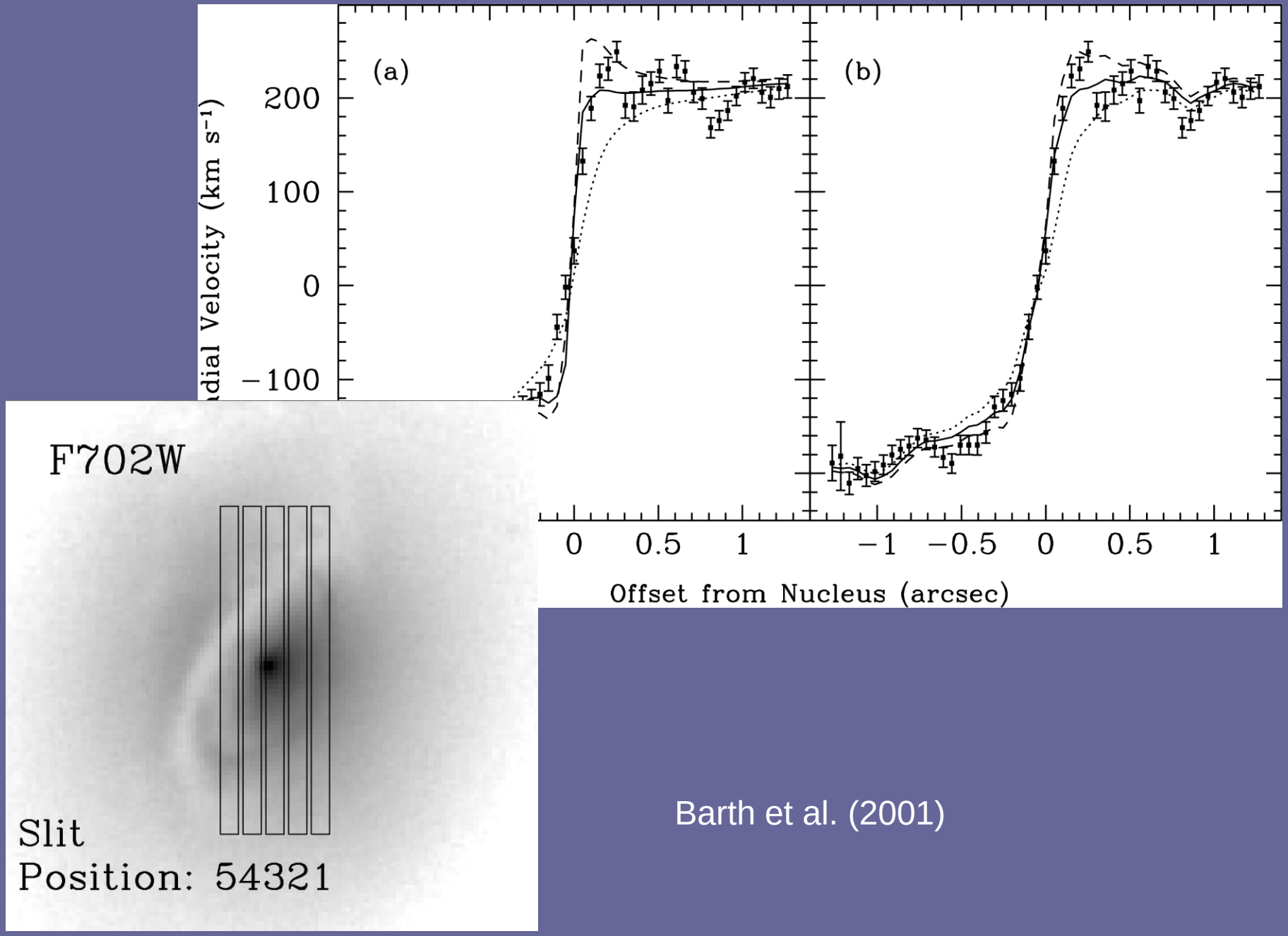
- Mass: $M_{\rm BH}$
- Spin: a (talks by Reynolds, Jon Miller?)
- How do you measure the mass?

$$v^2 = \frac{GM_{BH}}{r}$$

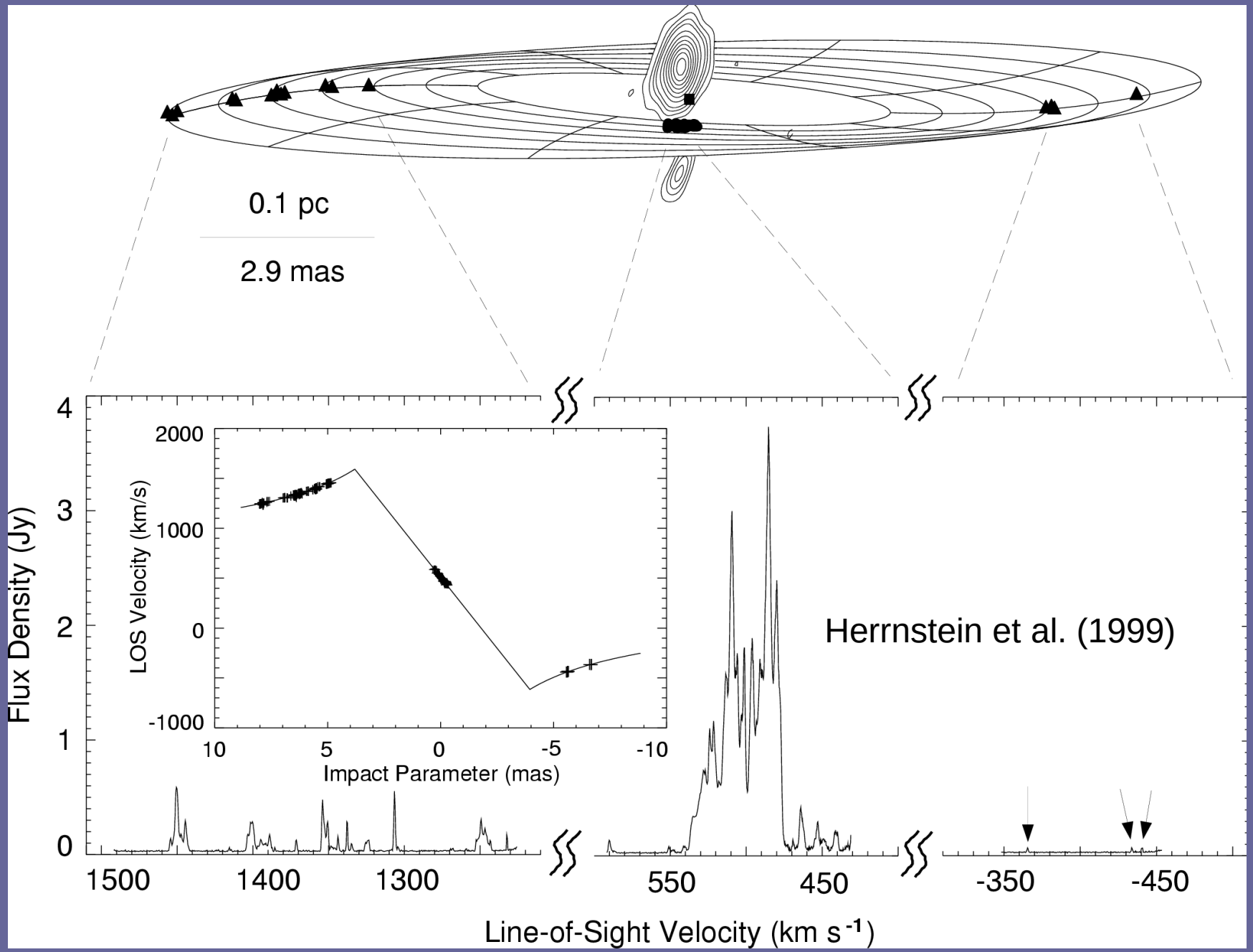
$$M_{BH} = \frac{v^2 r}{G}$$

Primary, direct measurements.

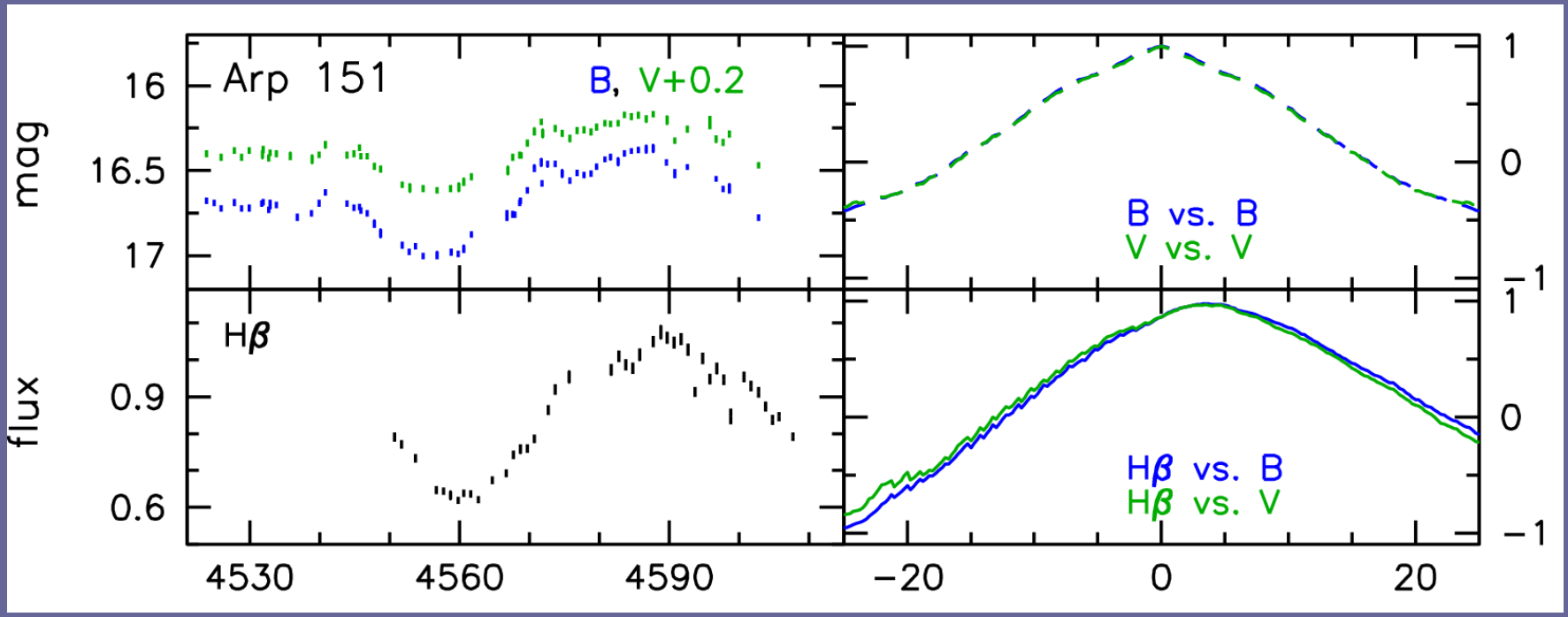
- Gas dynamical.
- Maser dynamical.
- Reverberation mapping (secondary).
- Stellar dynamical.



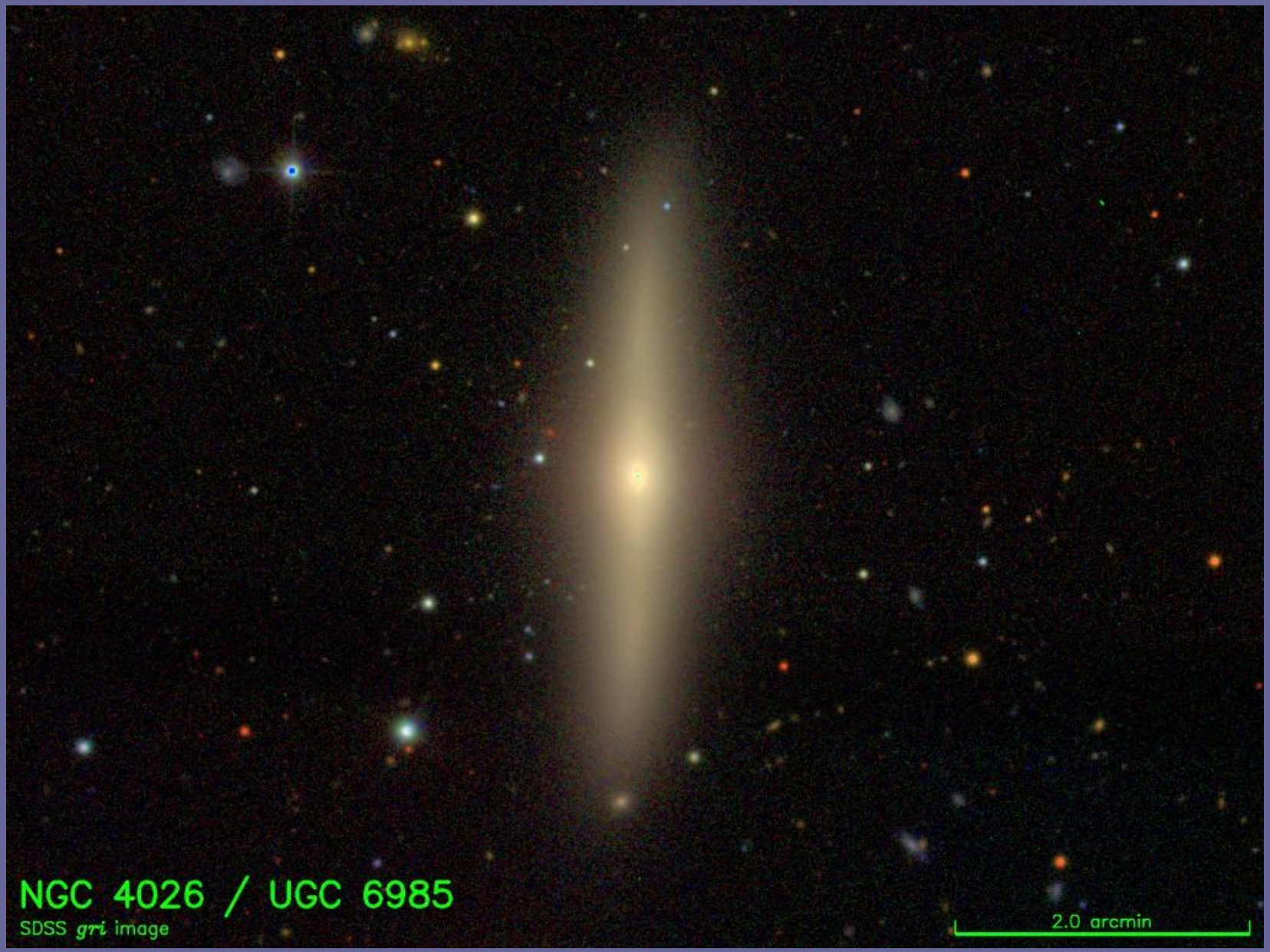
Barth et al. (2001)


0.1 pc
2.9 mas
Flux Density (Jy)
LOS Velocity (km/s)
Impact Parameter (mas)
Herrnstein et al. (1999)
Line-of-Sight Velocity (km s-1)

$$M_{BH} = f \frac{v^2 c \tau}{G}$$



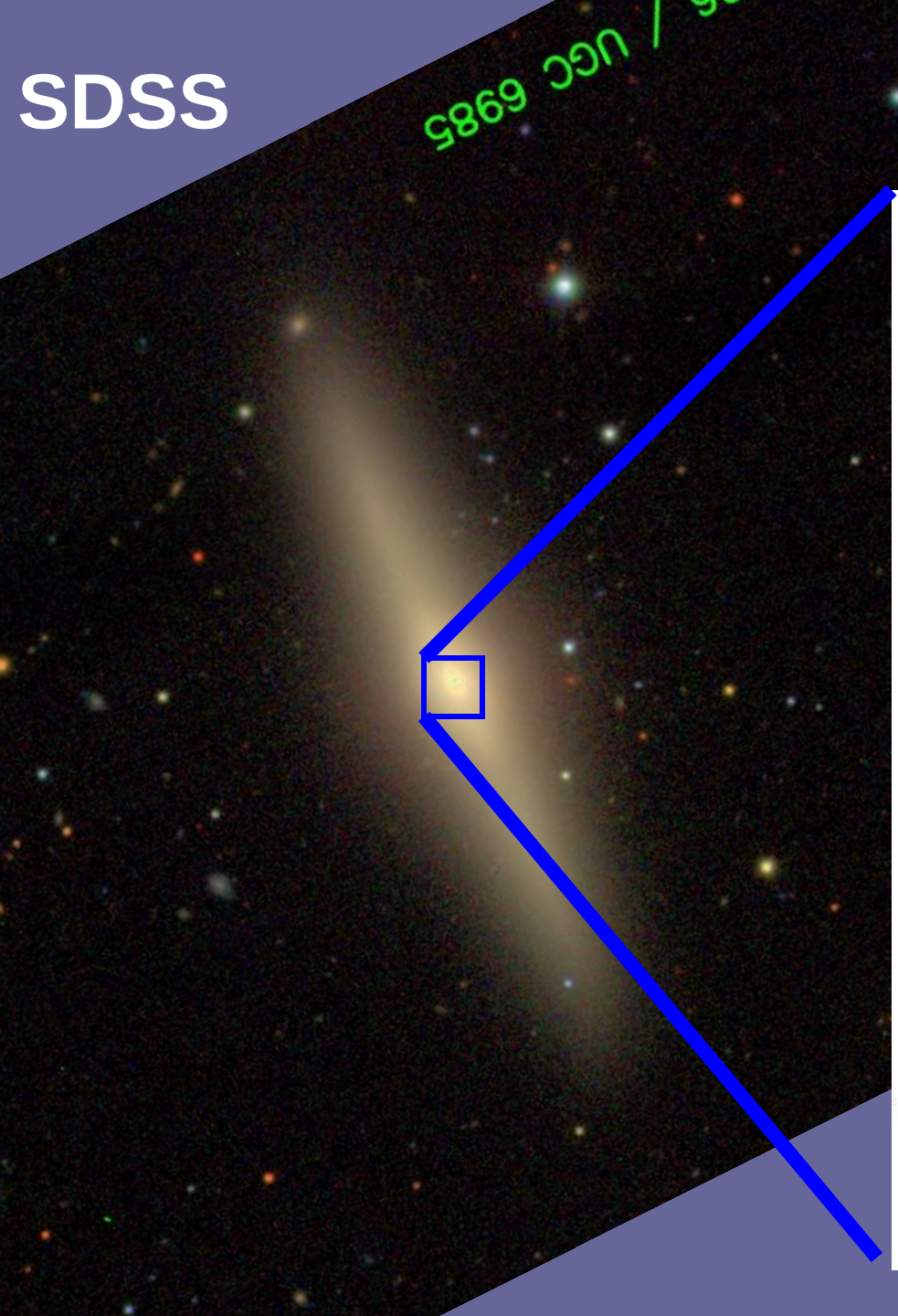
Bentz et al. (2009)

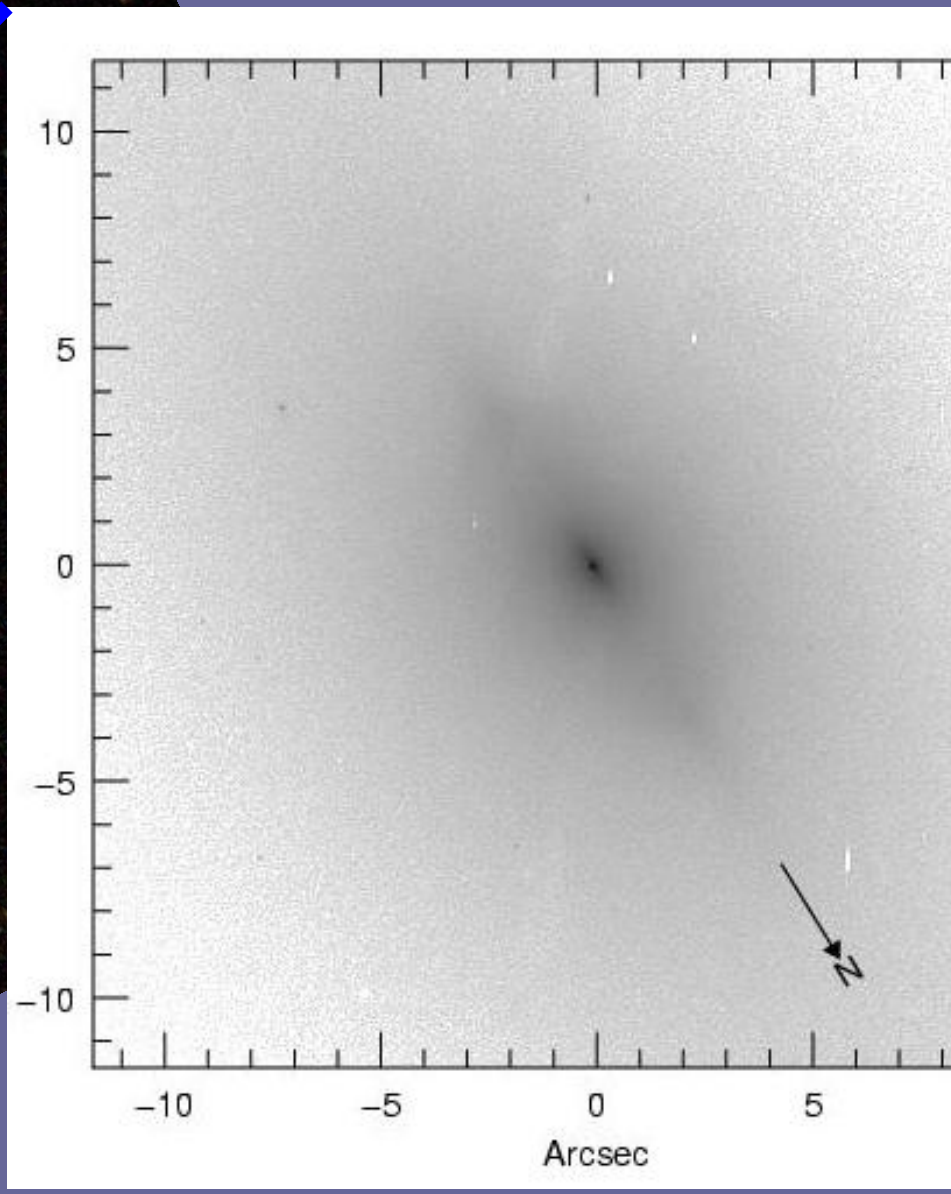


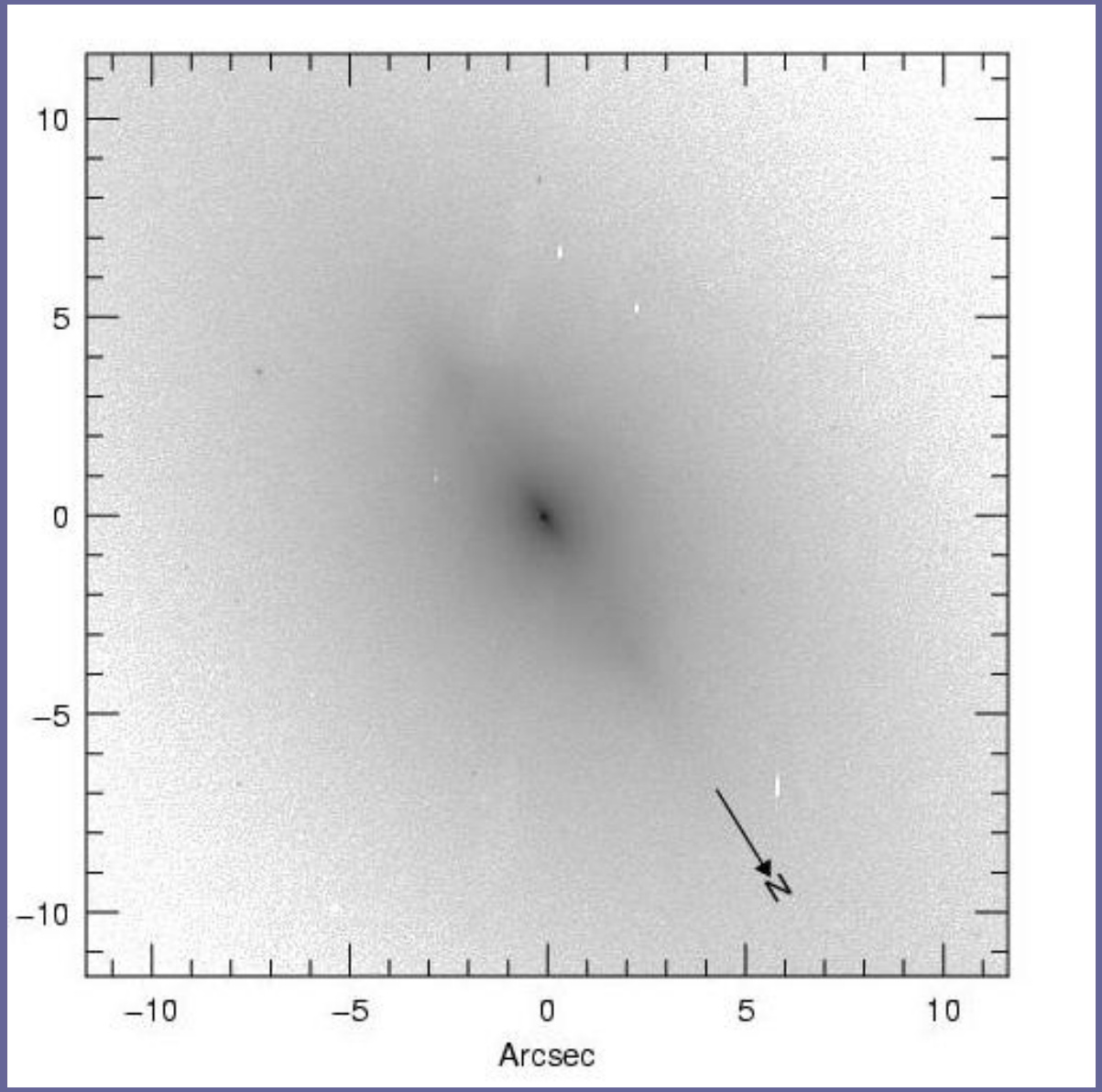
Hogg, Blanton, & SDSS

SDSS

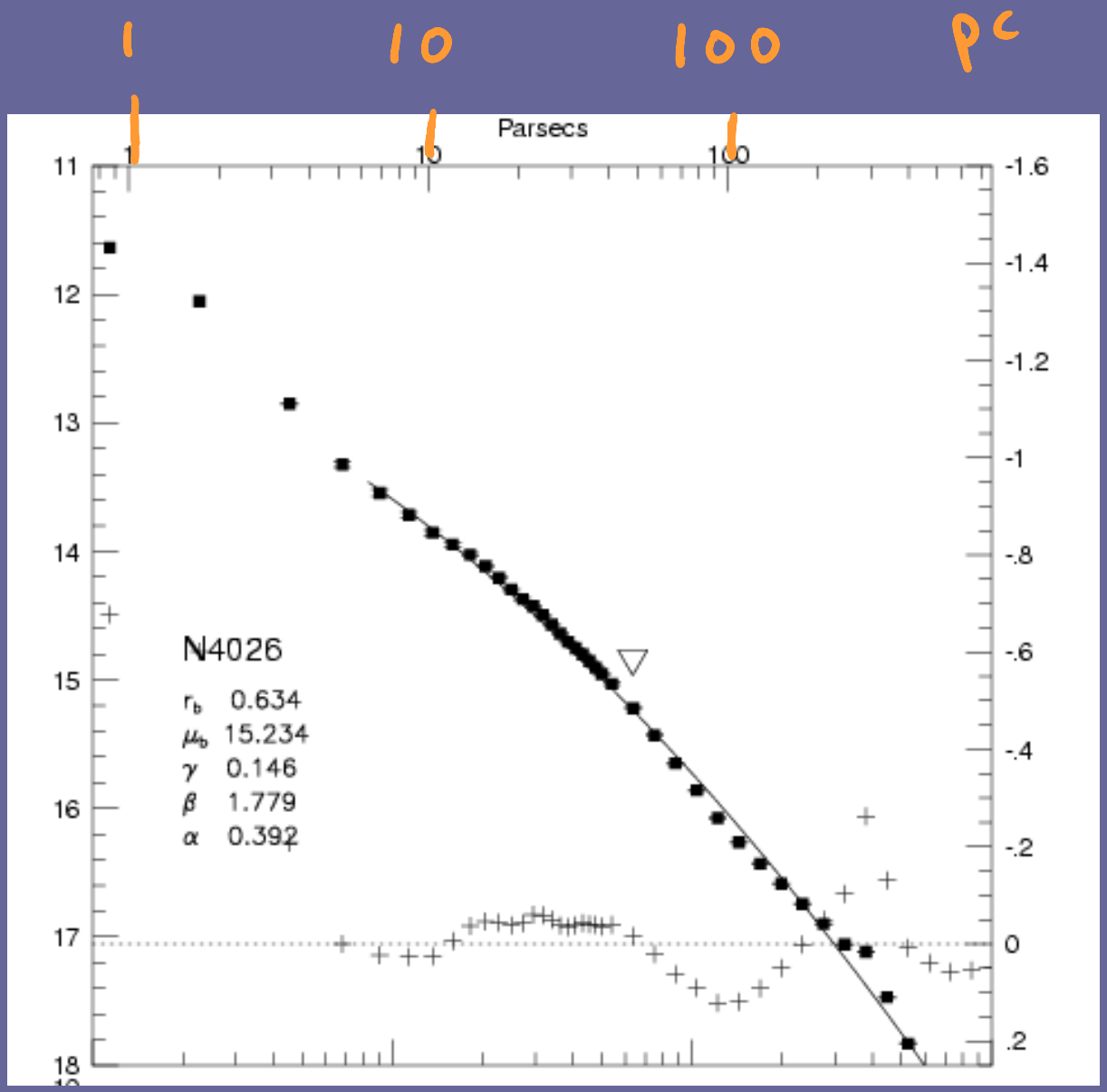
WFPC2






10
5
0
−5
−10
−10
−5
0
5
10
Arcsec
N

Surface Brightness



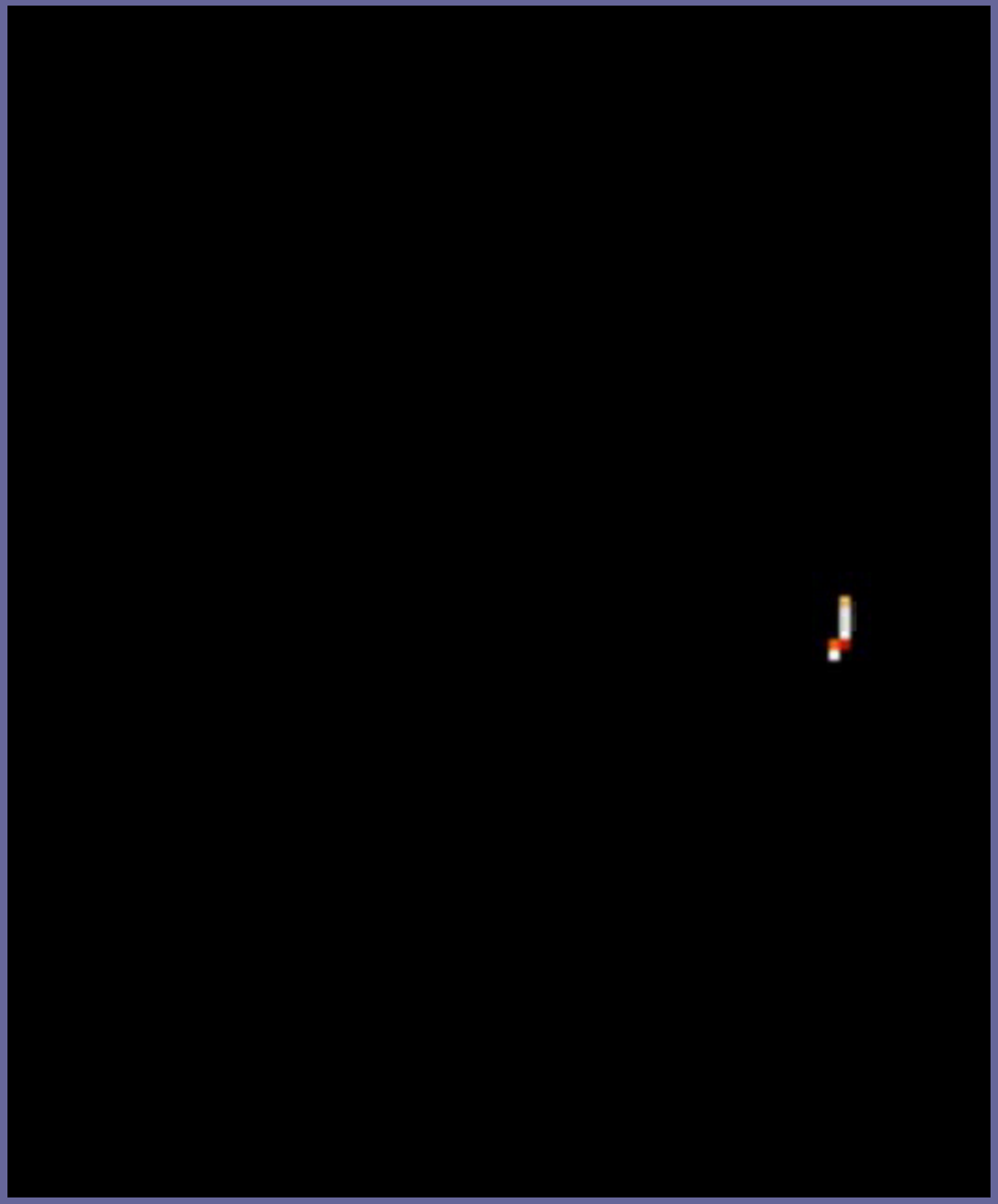
log (r)

Turn Surface Brightness into Φ

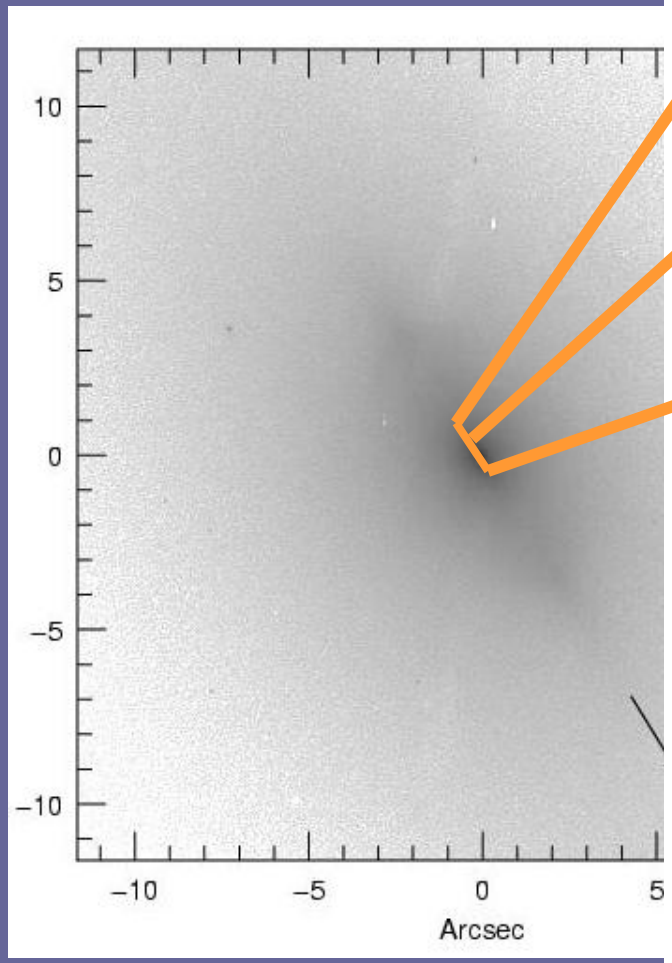
1. Pick an inclination: i.
2. Assume axisymmetry.
3. Invert to get luminosity density: $j(r, \theta)$.
4. Pick a Mass-to-Light Ratio: Υ.
5. Calculate mass density: $\rho(r, \theta) = \Upsilon\, j(r, \theta)$.
6. To get the potential: $\Phi(r, \theta)$.
7. Pick $M_{\rm BH}$ and add to potential.

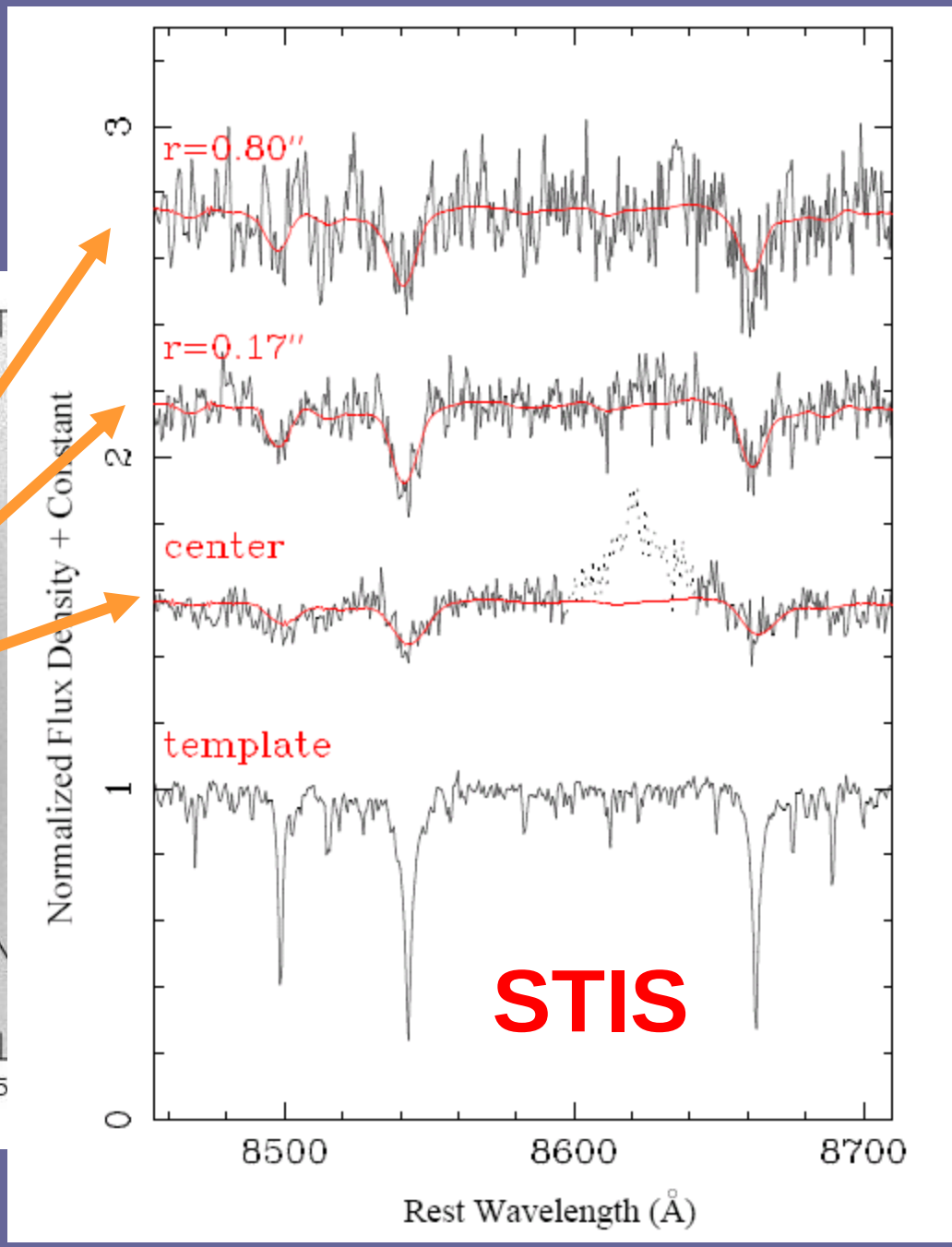
Calculate orbits of representative stars: Schwarzschild orbit library

van den Bosch et al. (2008)

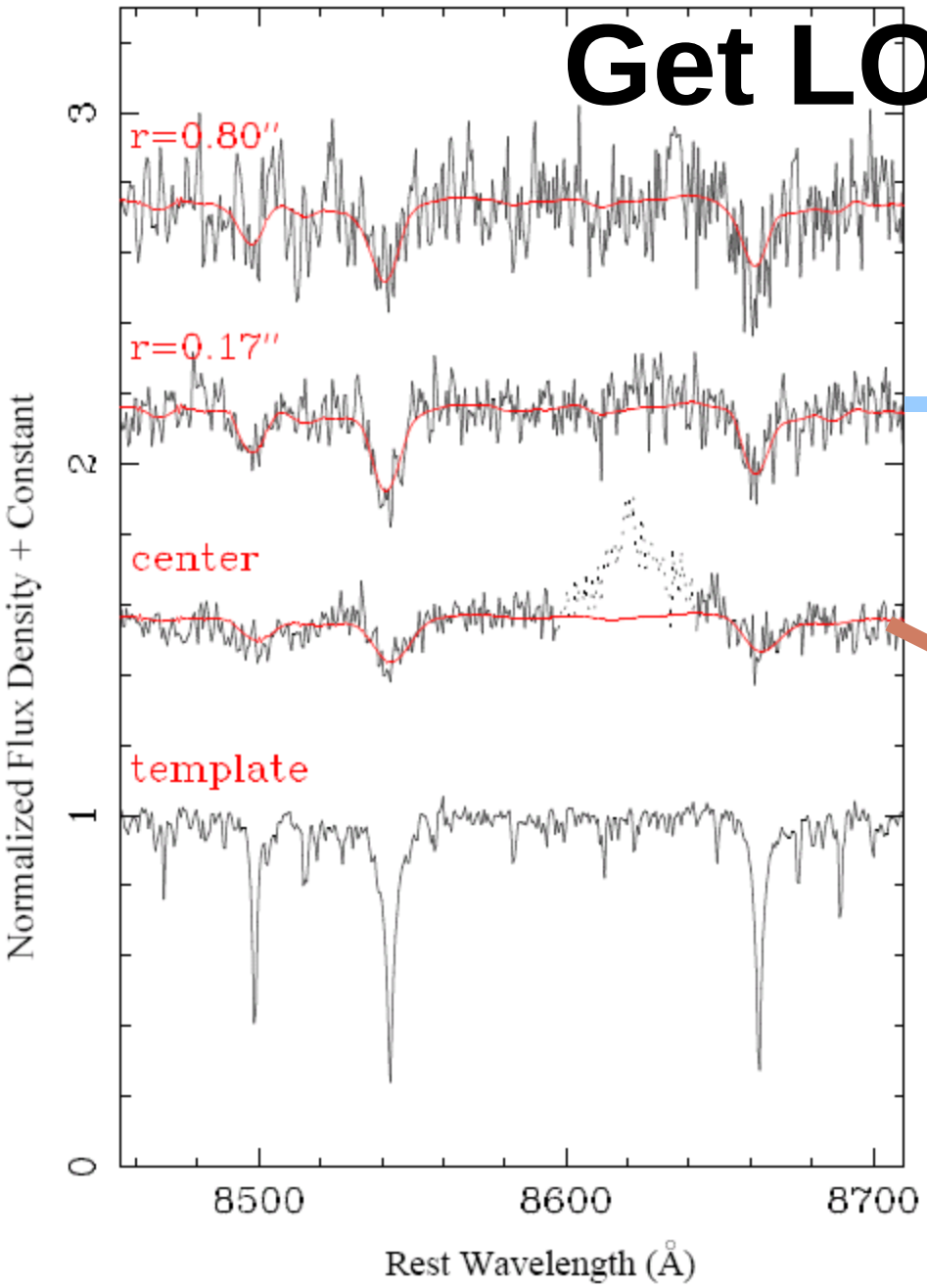


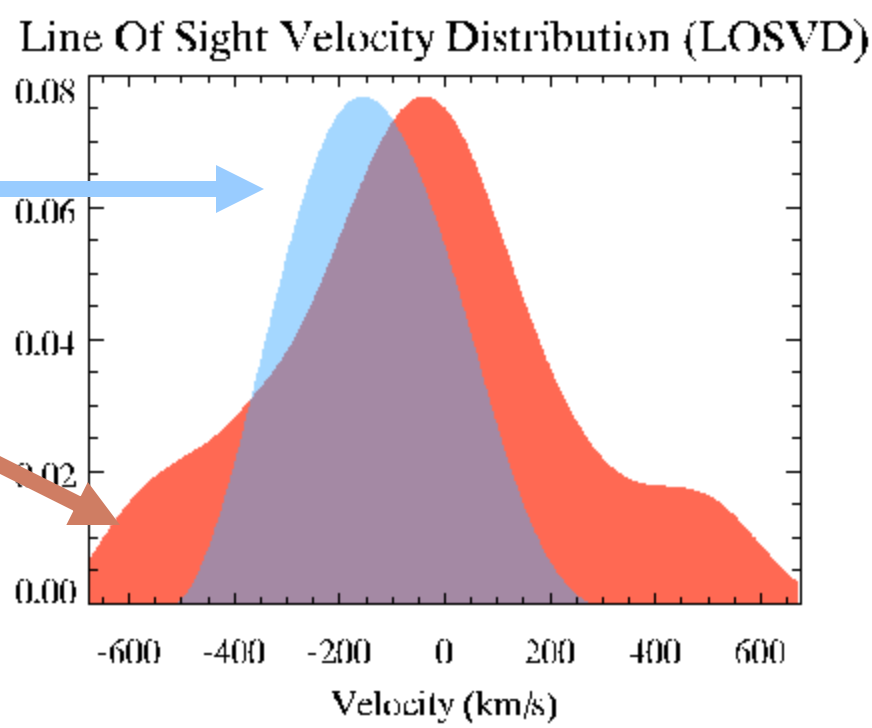
Take spectrum

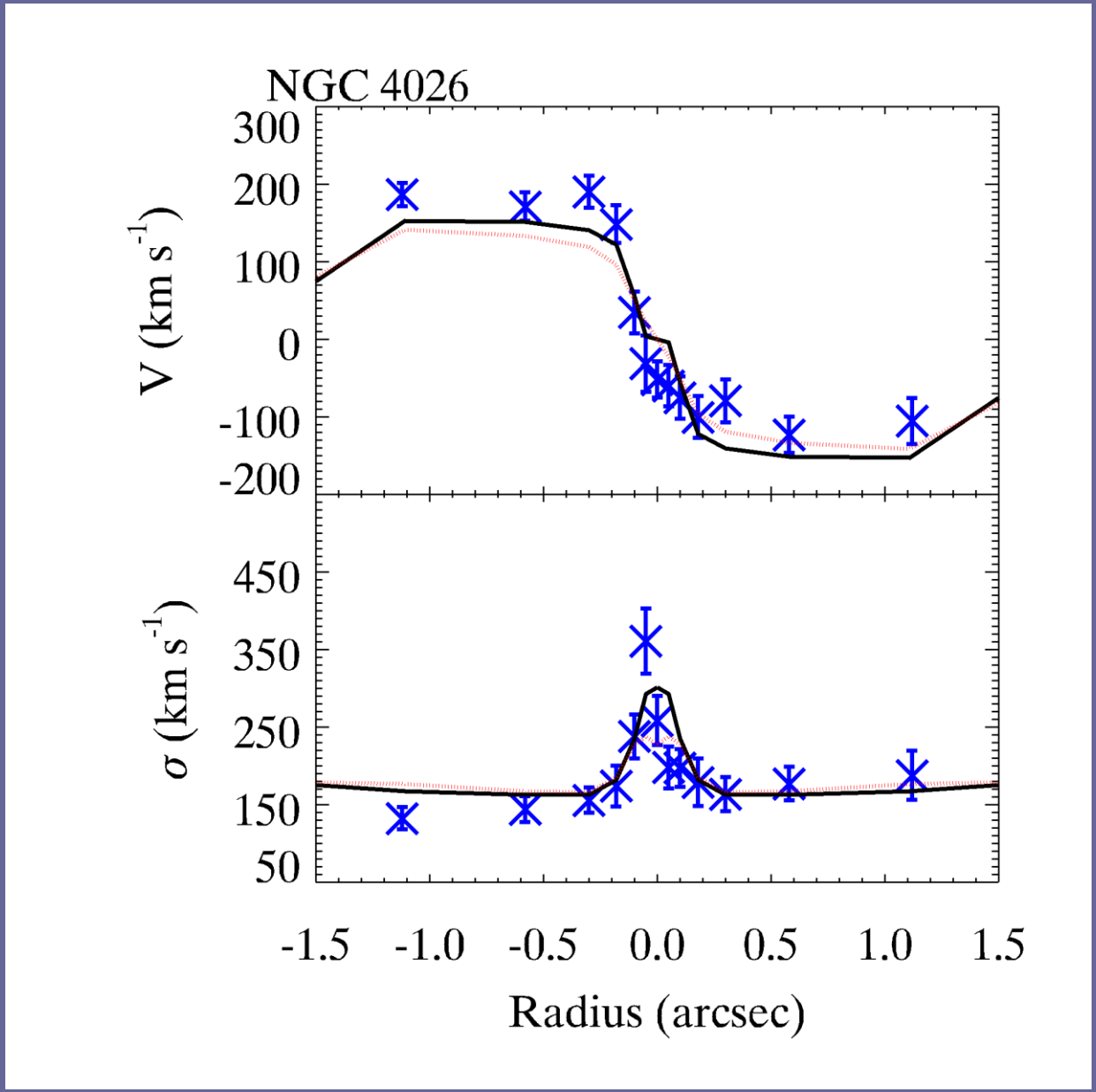




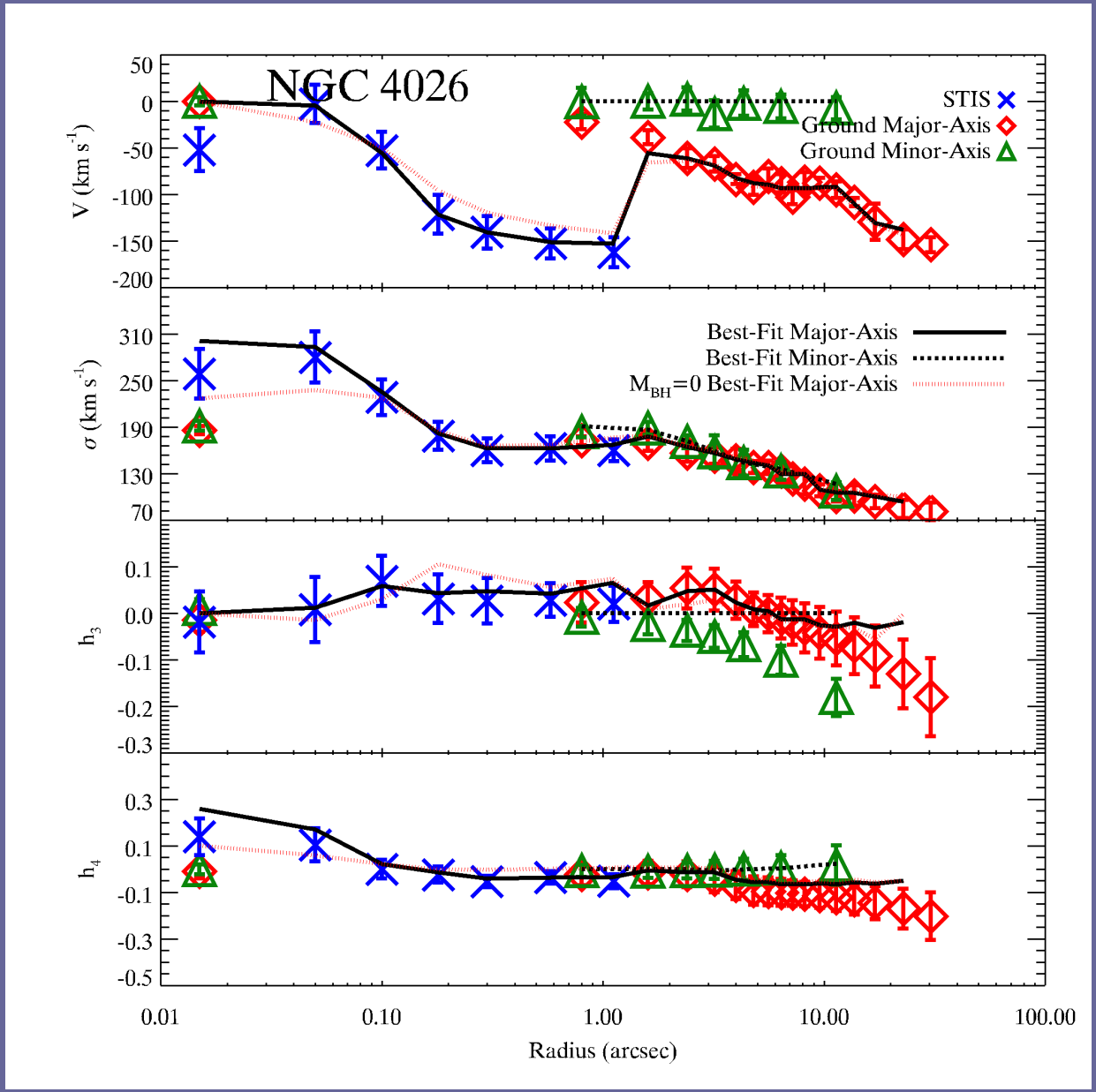
Get LOSVDs


r=0.80″
r=0.17″
center
template
Normalized Flux Density + Constant
0
1
2
3
8500
8600
8700
Rest Wavelength (Å)

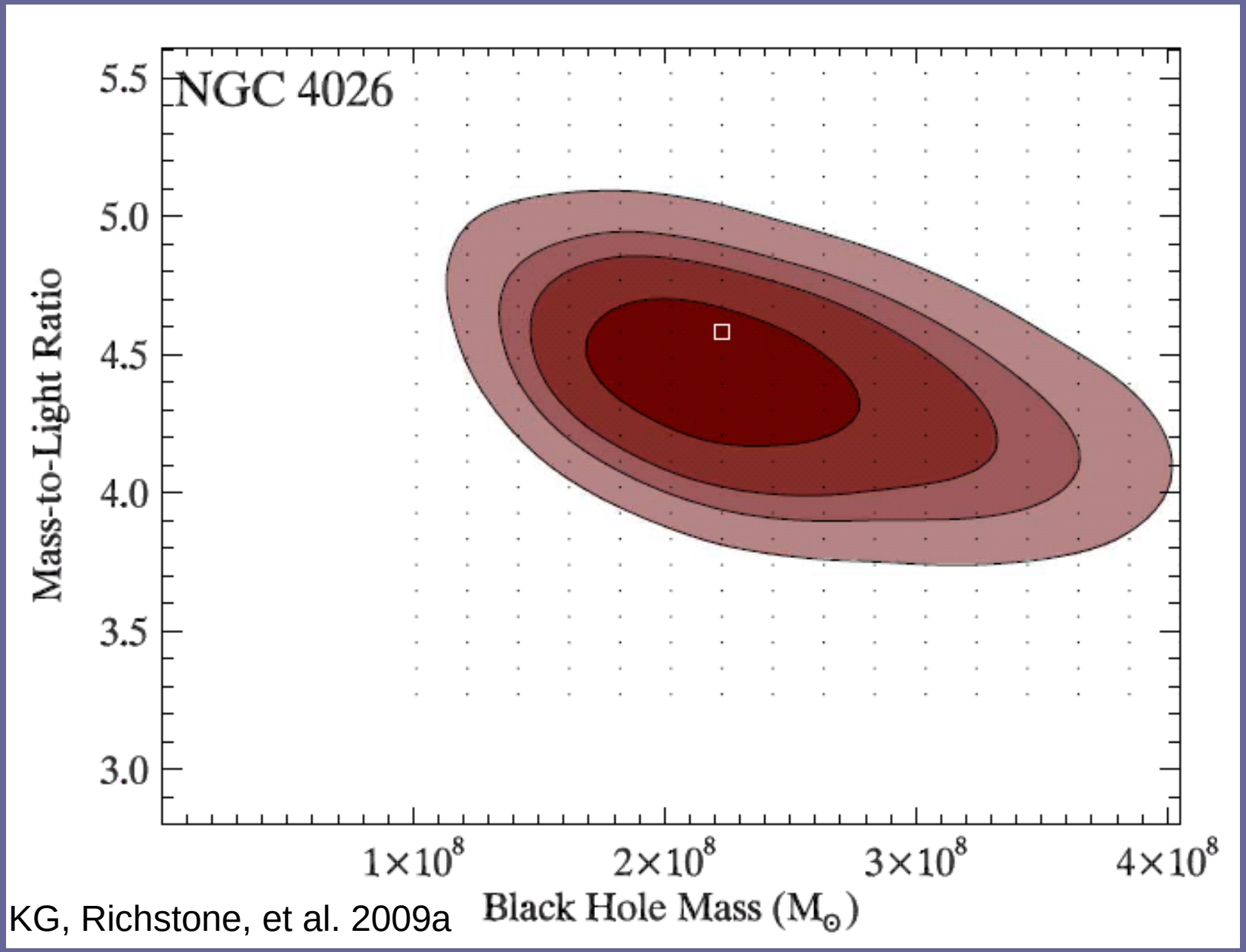

Line Of Sight Velocity Distribution (LOSVD)
0.08
0.06
0.04
0.00
-600
-400
-200
0
200
400
600
Velocity (km/s)



KG, Richstone, et al. 2009a



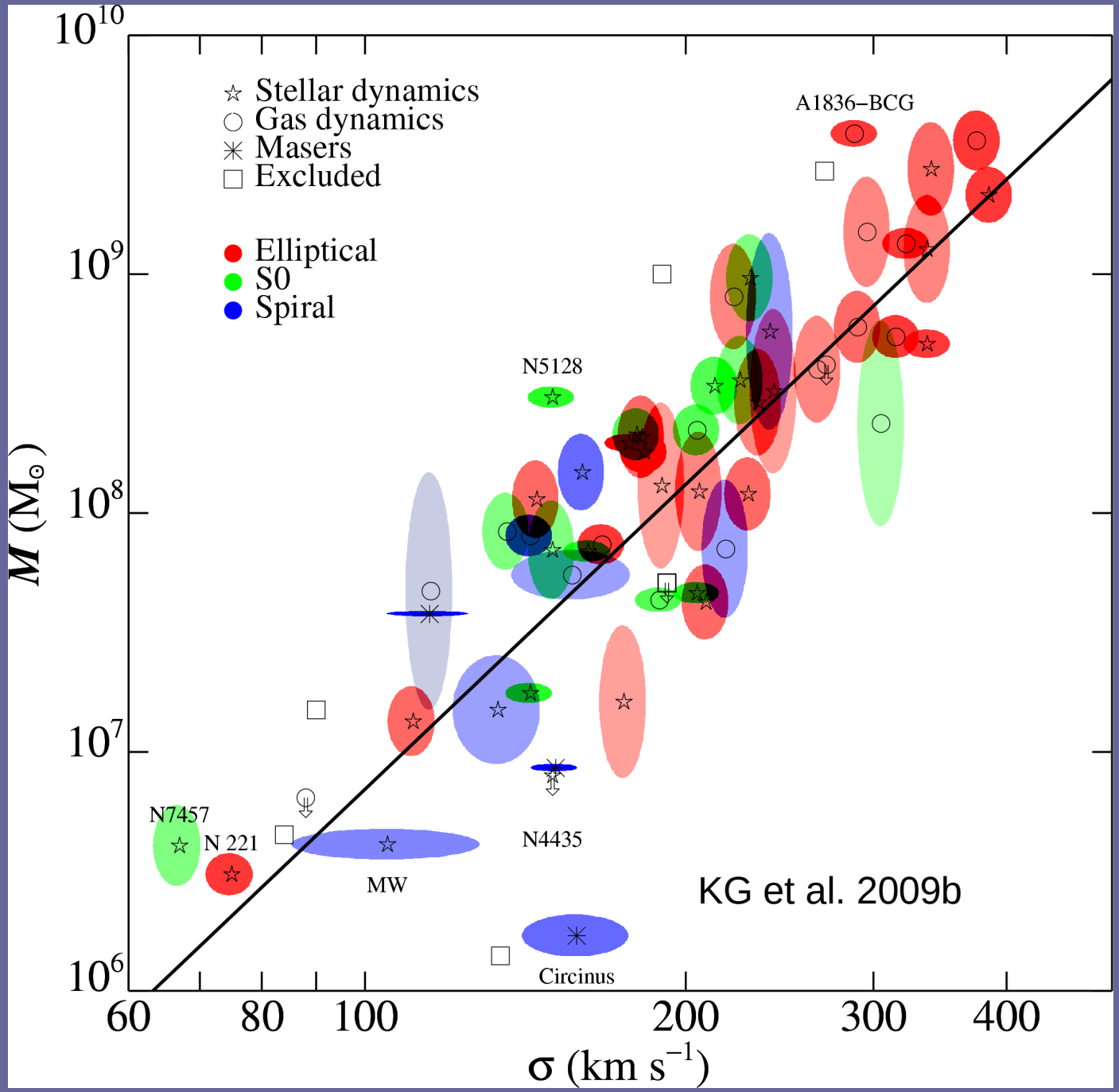
KG, Richstone, et al. 2009a



KG, Richstone, et al. 2009a

Black hole masses correlate with galaxy properties!

- Velocity dispersion.
- Bulge luminosity / mass.
- Lots of other parameters. . . .
  - Sersic index (not really)
  - $(M_{*}\sigma^{2})$
  - M_{bulge}
  - R_{e}


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

M-σ is a substitute for measuring M

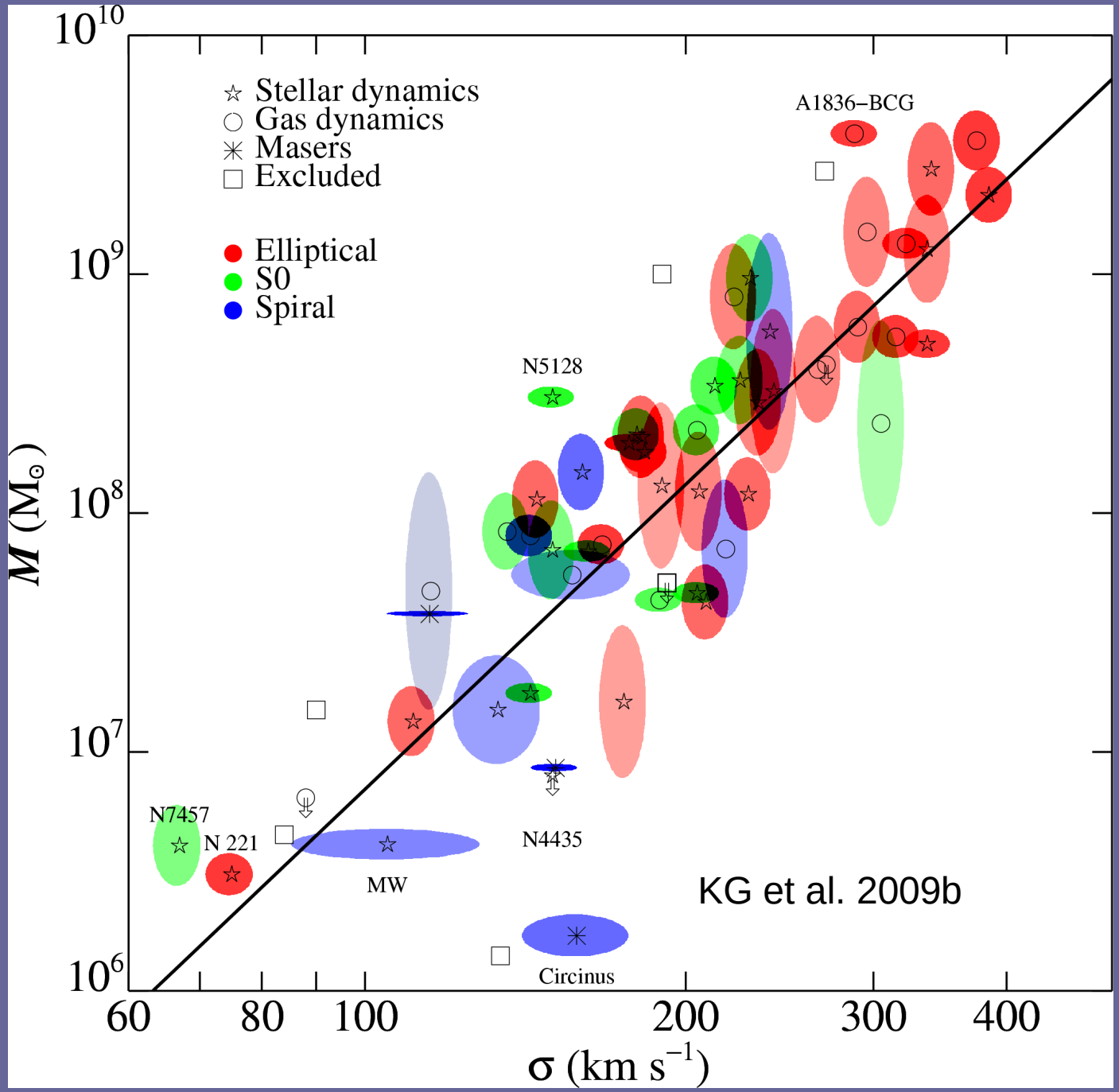
- Reverberation mapping is calibrated to M-σ
  - Maybe M-L in the future (Bentz et al. in prep.)
- AGN line-widths are normalized to Reverb. Map
- 48 “real” measurements and lots of extrapolation

M-σ relates to galaxy formation

- Black Holes are small. Velocity dispersion comes from large-scale physics.
- What does it tell us, though?

Some ideas:

- Energy conservation $M \sim \sigma^5$.
  - Silk & Rees (1998); Haenhelt, Natarajan, & Rees (1998); Wyithe & Loeb (2003)
- Momentum conservation $M \sim \sigma^4$.
  - Wind (mechanical): Fabian (1999).
  - Radiation: Fabian, Wilman & Crawford (2002); King (2003); Murray, Quatert, & Thompson (2005).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60
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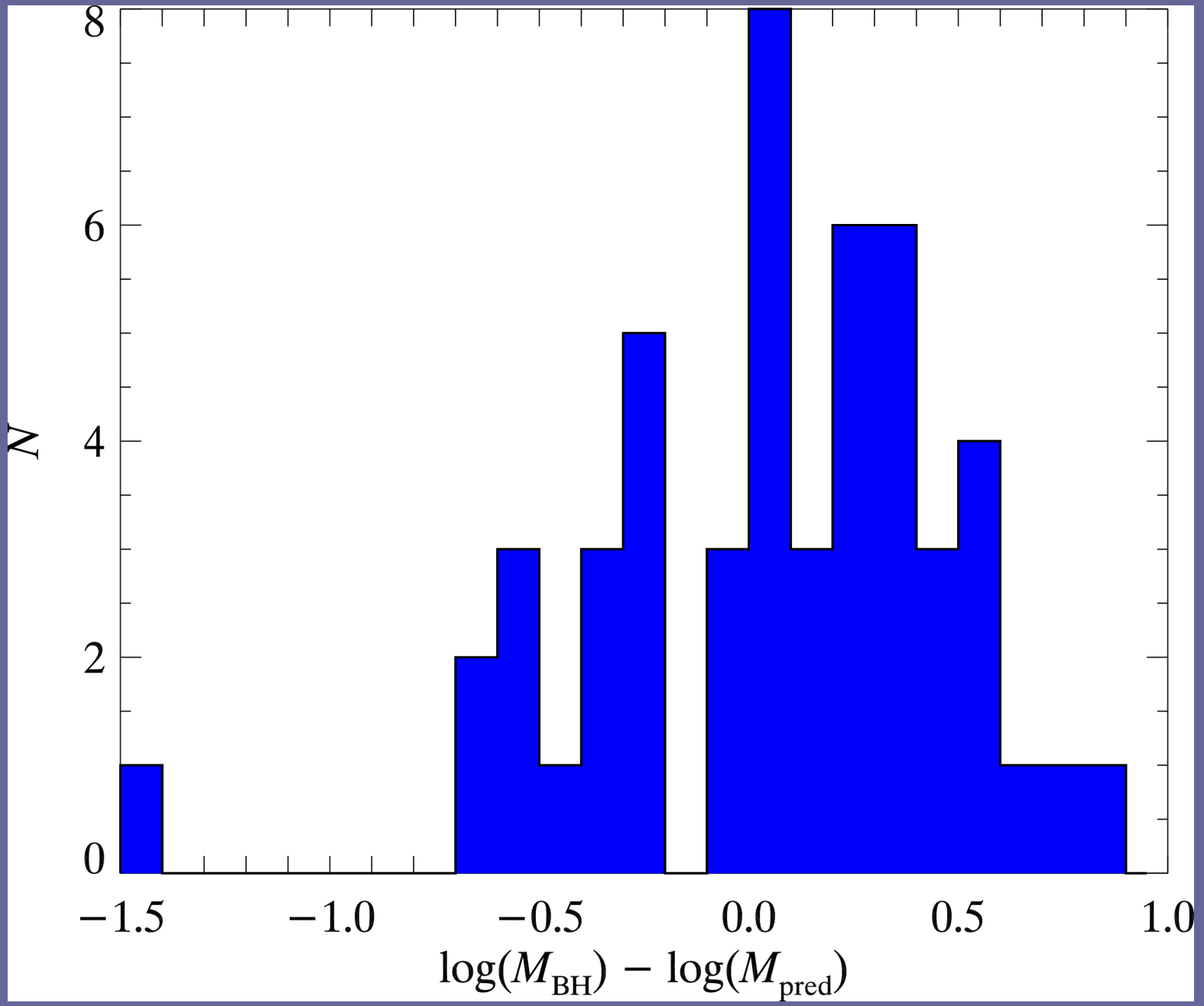
σ (km s^{-1})

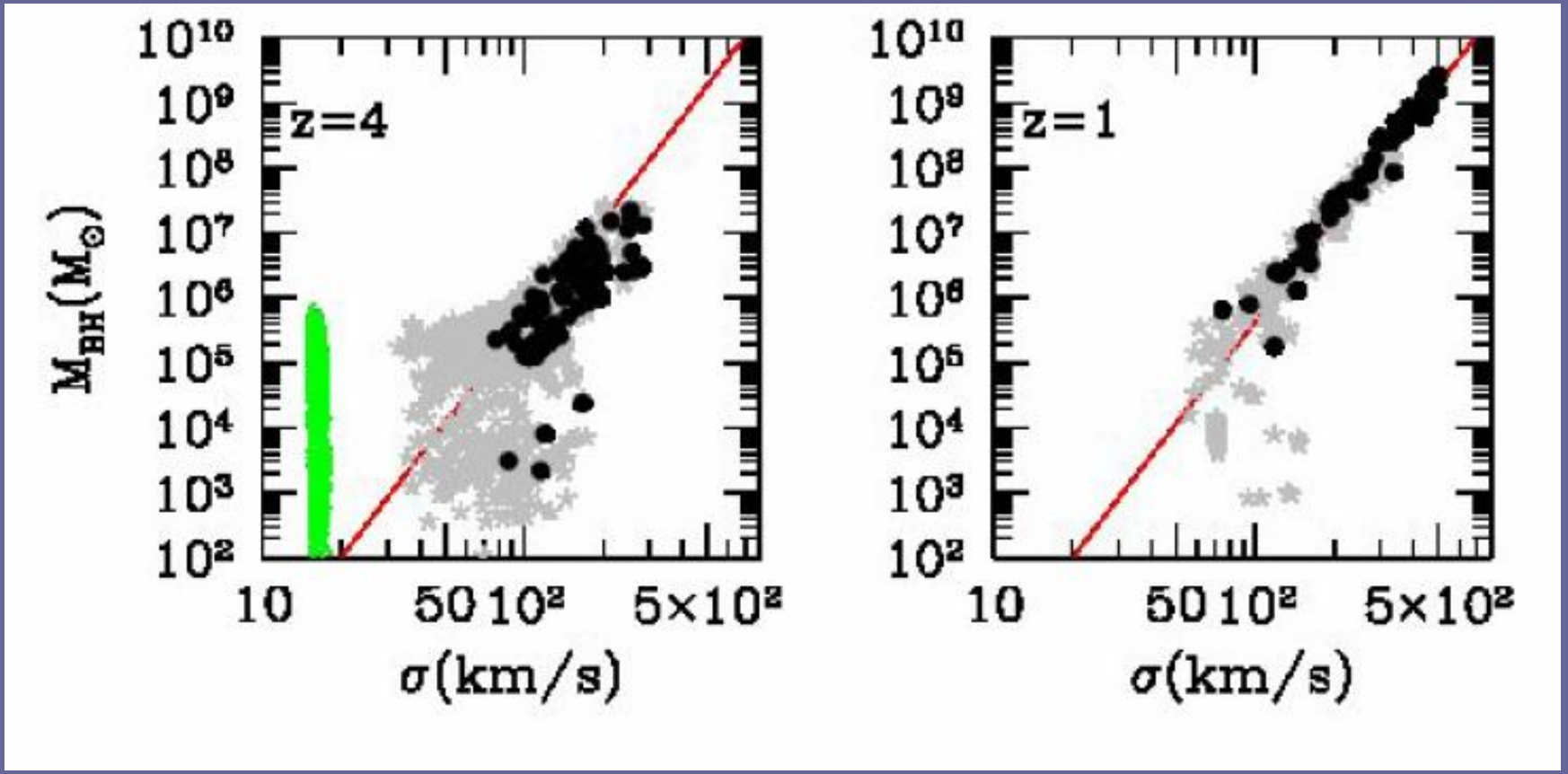
The scatter in M-sigma is not insignificant.

- 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.

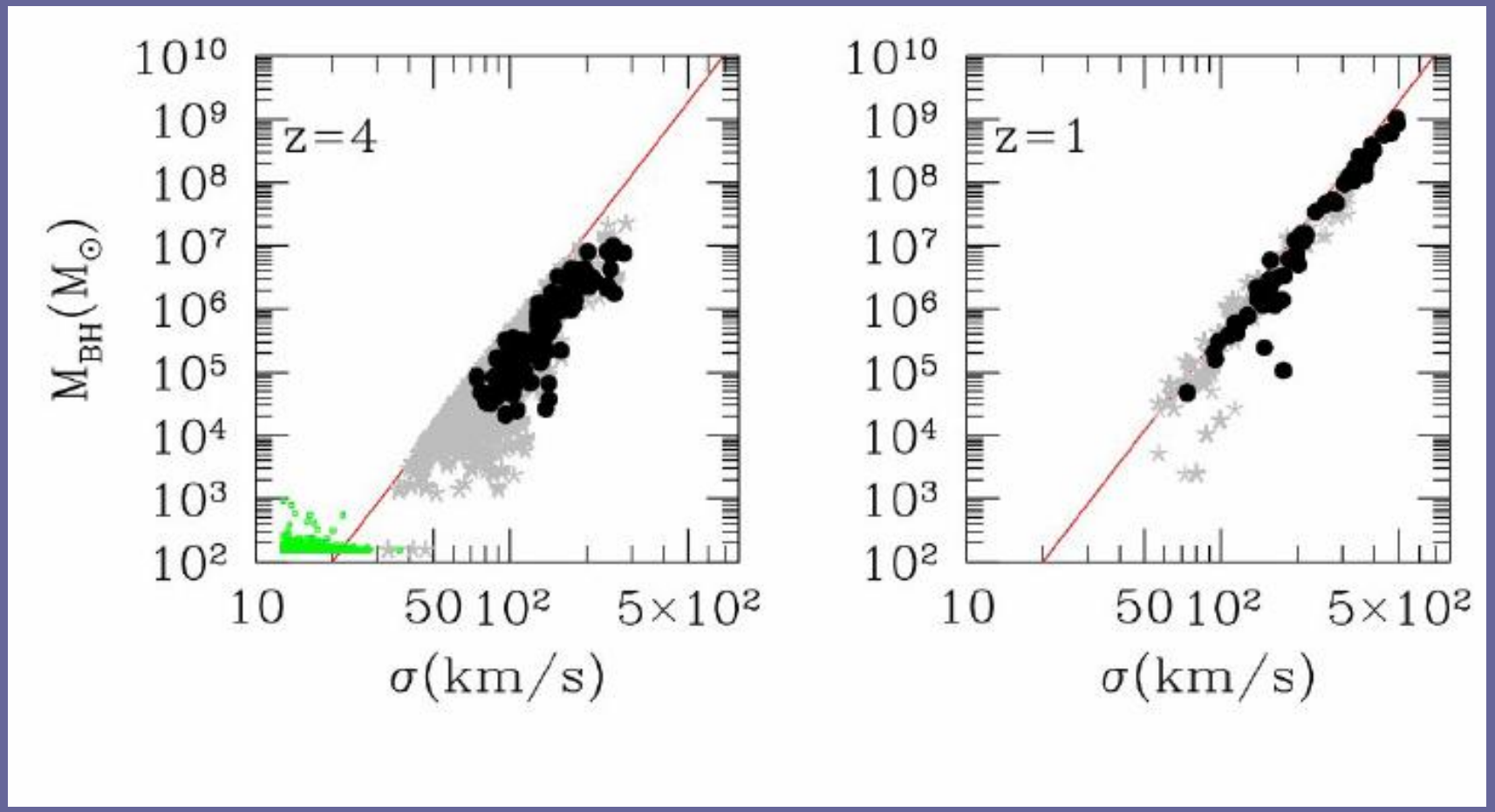

8
6
4
2
0
N
−1.5
−1.0
−0.5
0.0
0.5
1.0
log(M_BH) − log(M_pred)

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.

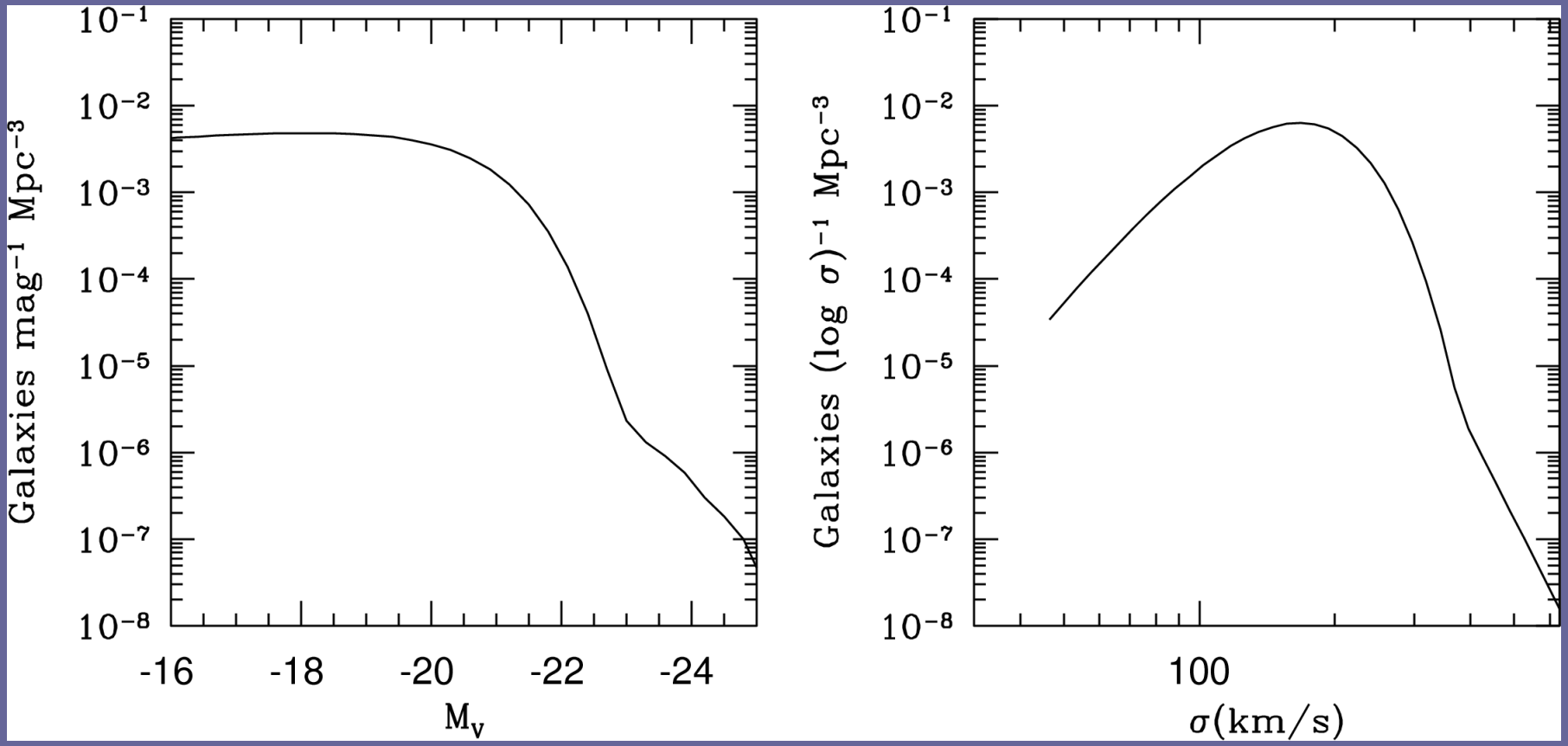


Volonteri & Natarajan (2009)



Volonteri & Natarajan (2009)

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



Lauer et al. 2007c

[Blanton 2003 + Postman & Lauer 1995; Sheth et al. 2003 + Bernardi et al. 2006

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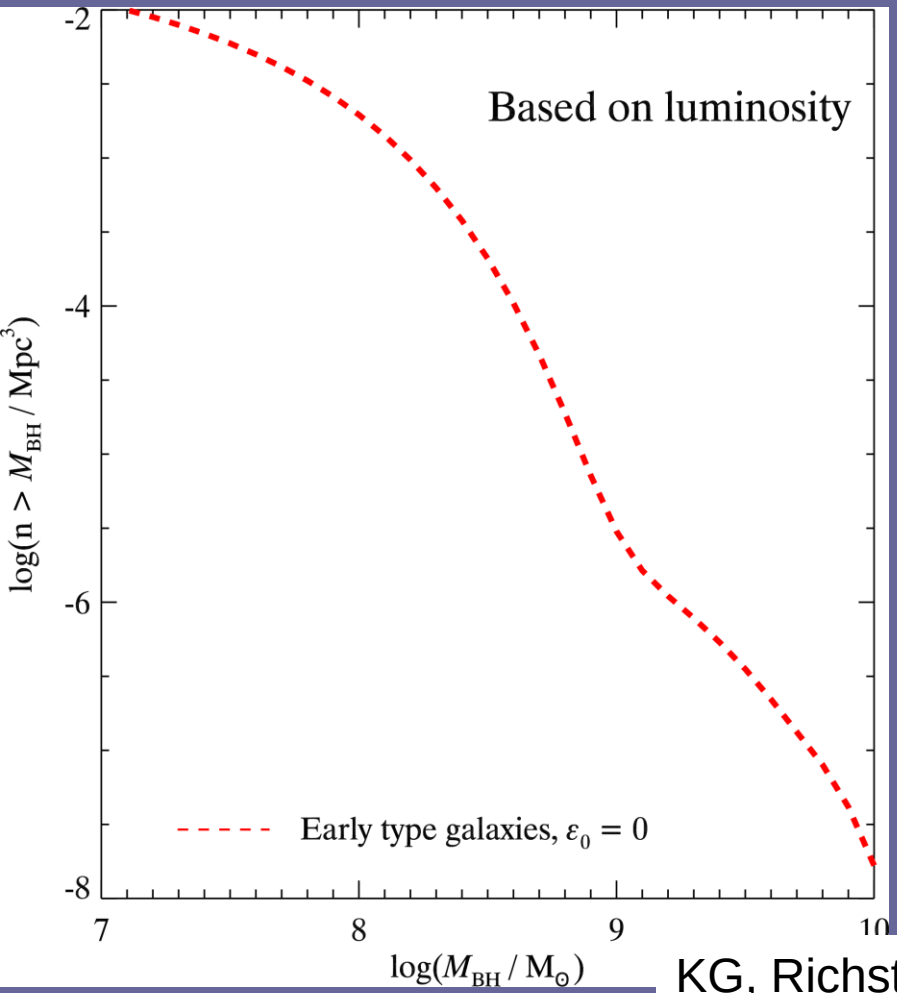

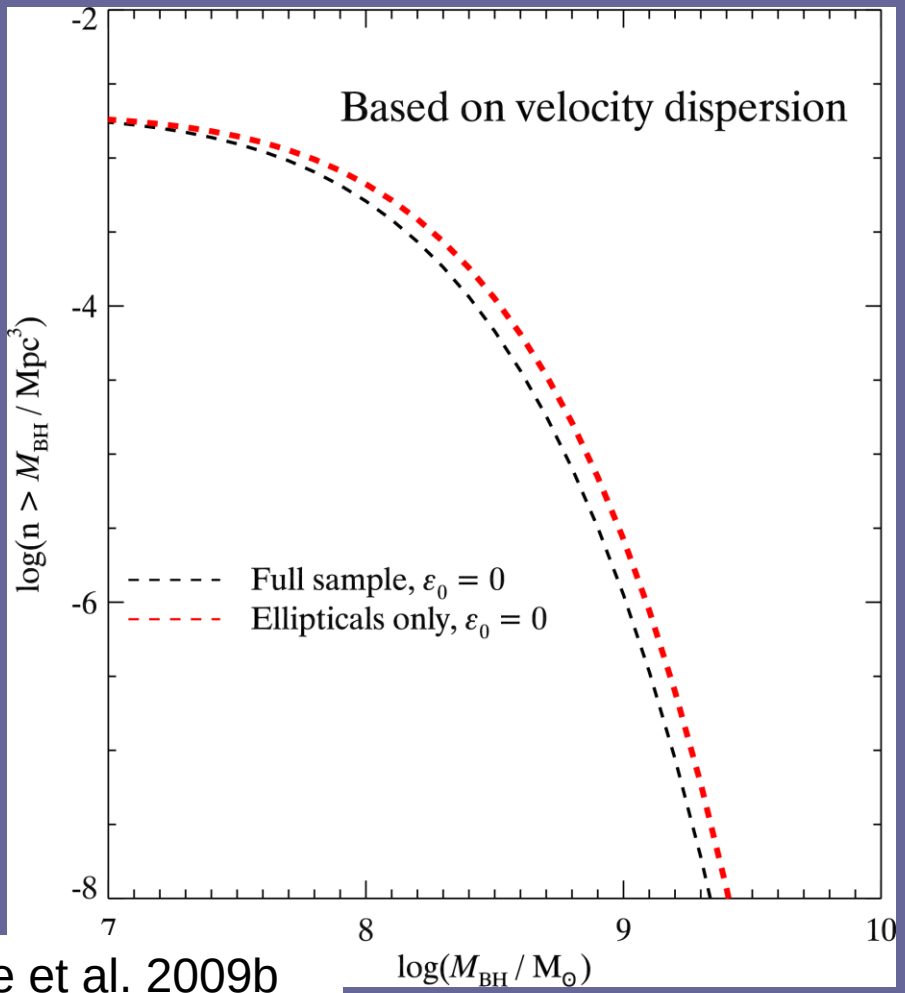

KG, Richstone et al. 2009b

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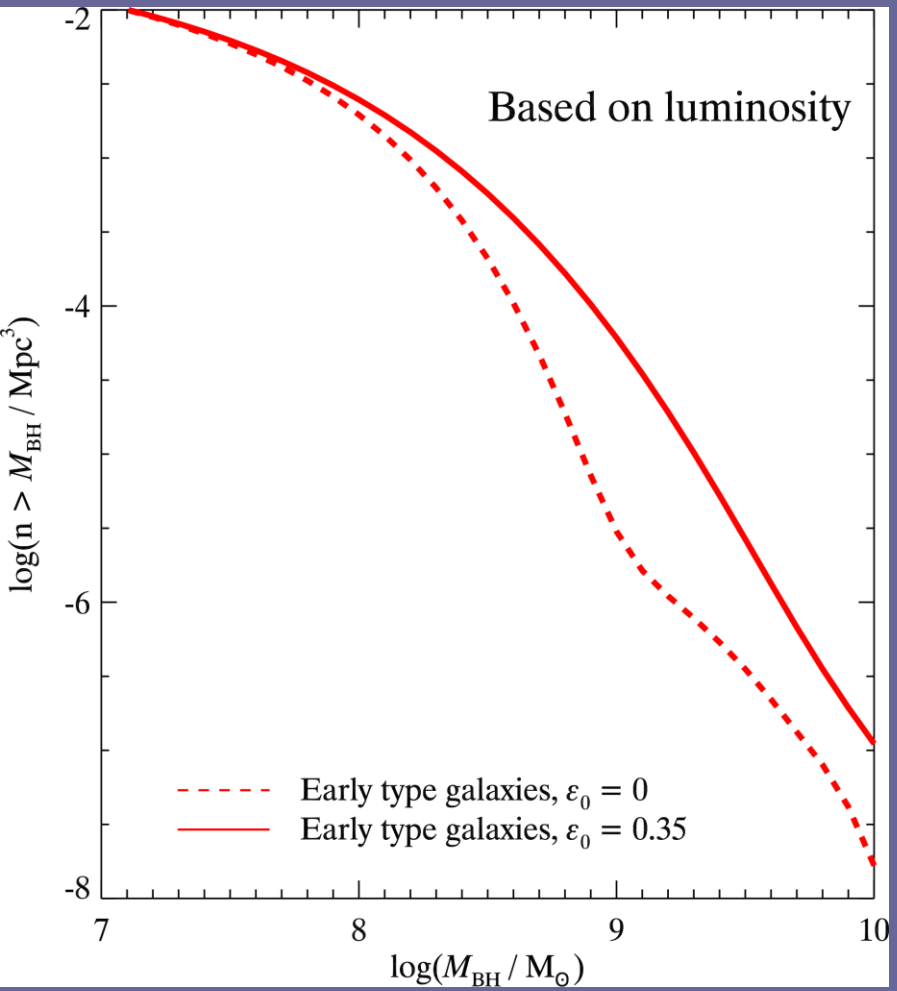

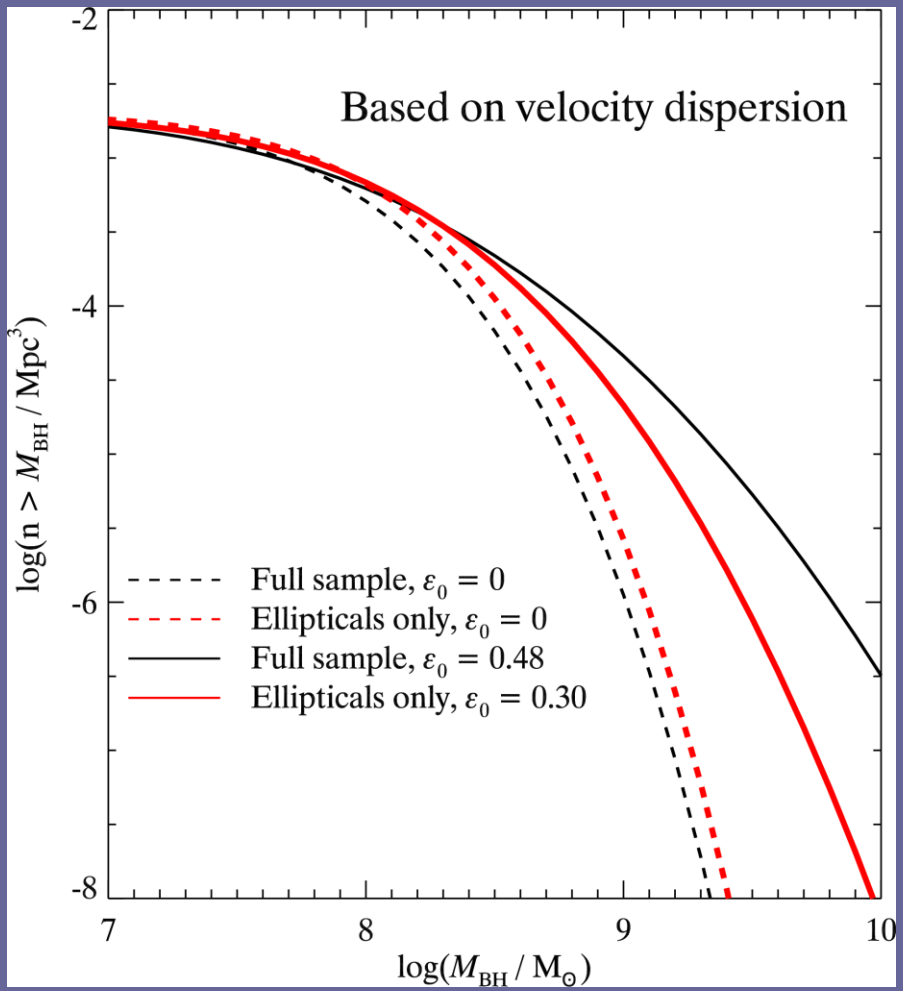

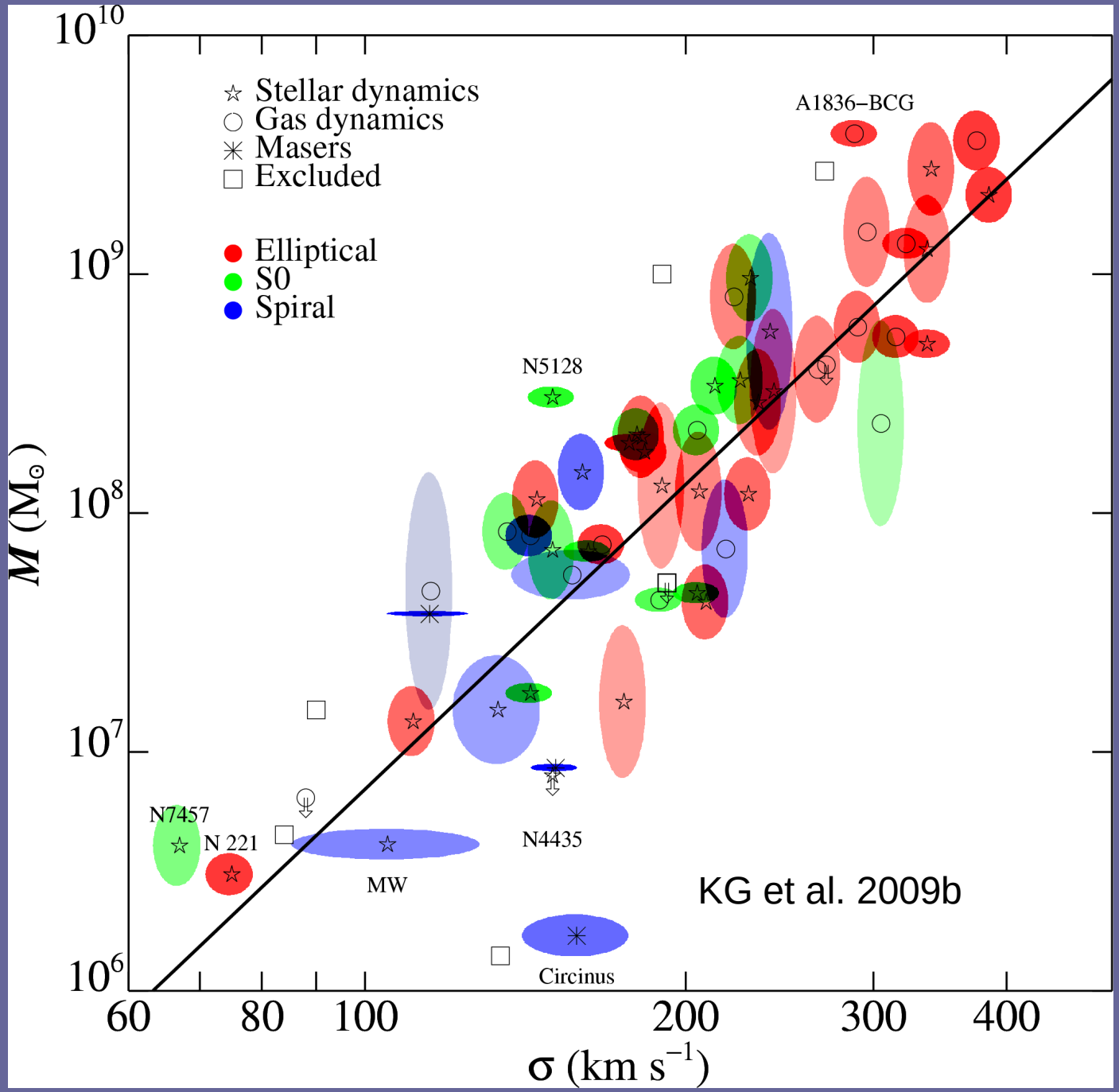
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10^{10}
10^{9}
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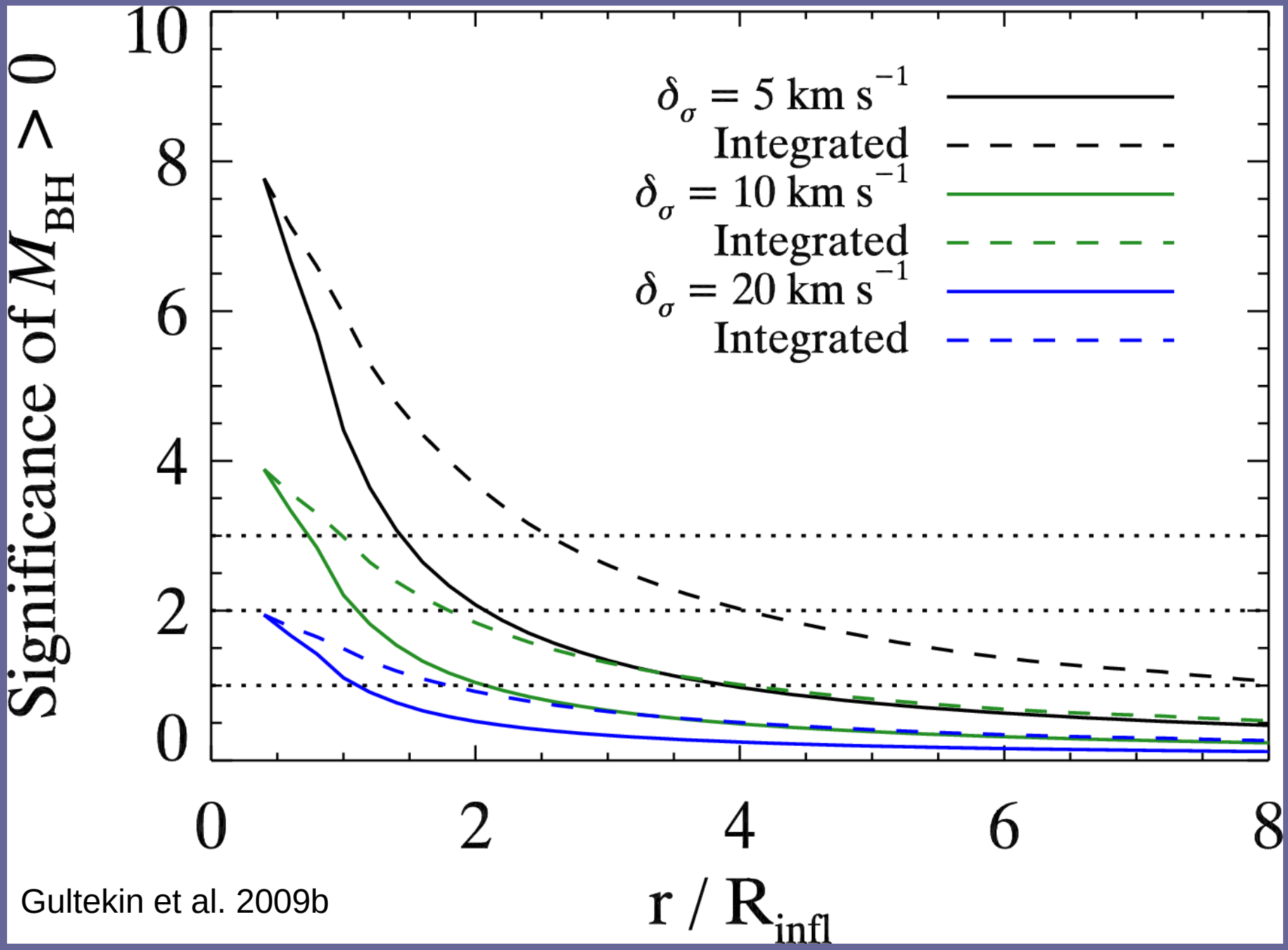
10^{6}
M ($M_\odot$)
60
80
100
200
300
400
σ (km s^{-1})

The *intrinsic* scatter in M-σ relation.

- Another “answer in the back of the book” for galaxy-formation 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.
- Where does the scatter come from?

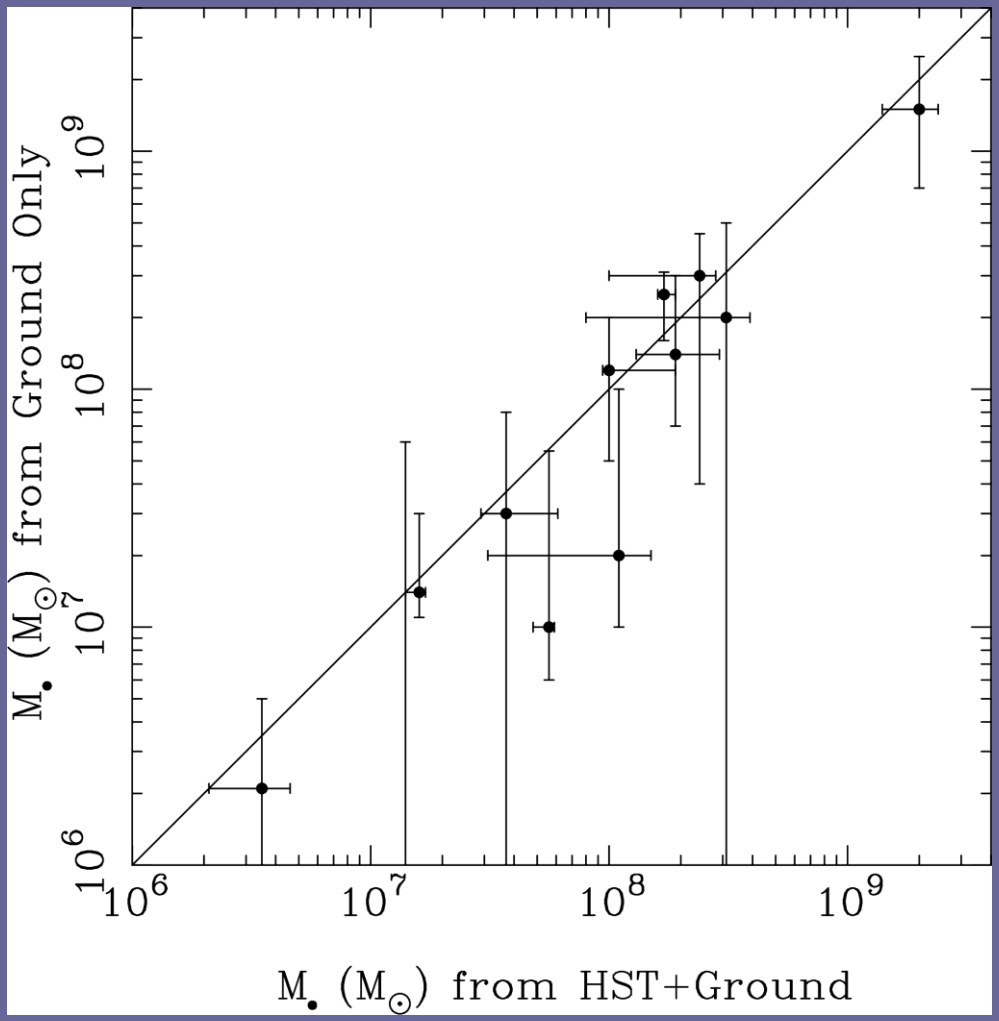
Resolving the sphere of influence of a BH is not a necessary or sufficient condition for measuring BH mass.

- $R_{\mathrm{infl}} = G\, M_{\mathrm{BH}} / \sigma^2$
- S.O.I. does not encode any information about, e.g., spectral resolution.
- Most of the information is inside S.O.I., but not all.



Gultekin et al. 2009b

Better spatial resolution gives better error bars, but not a bias!

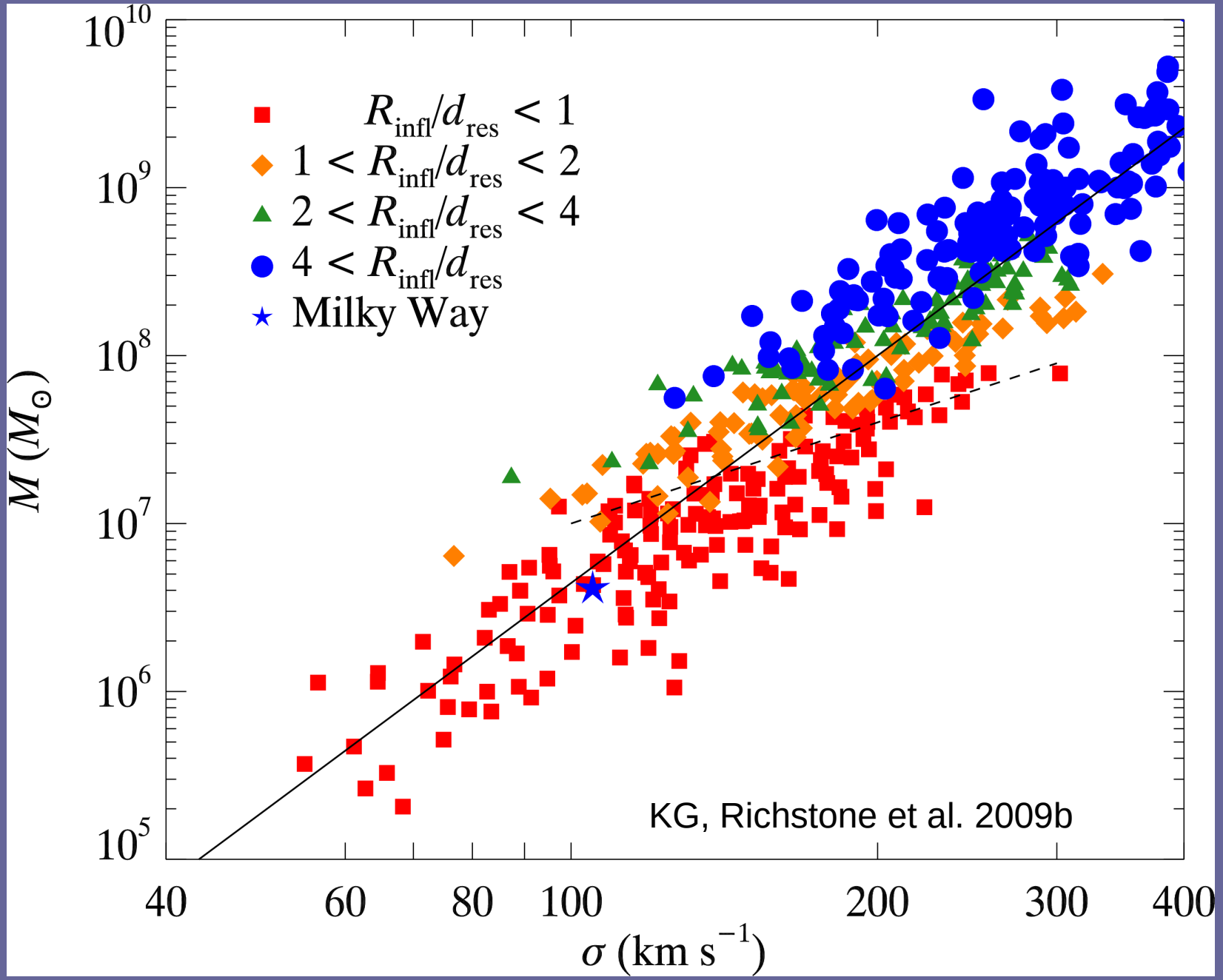


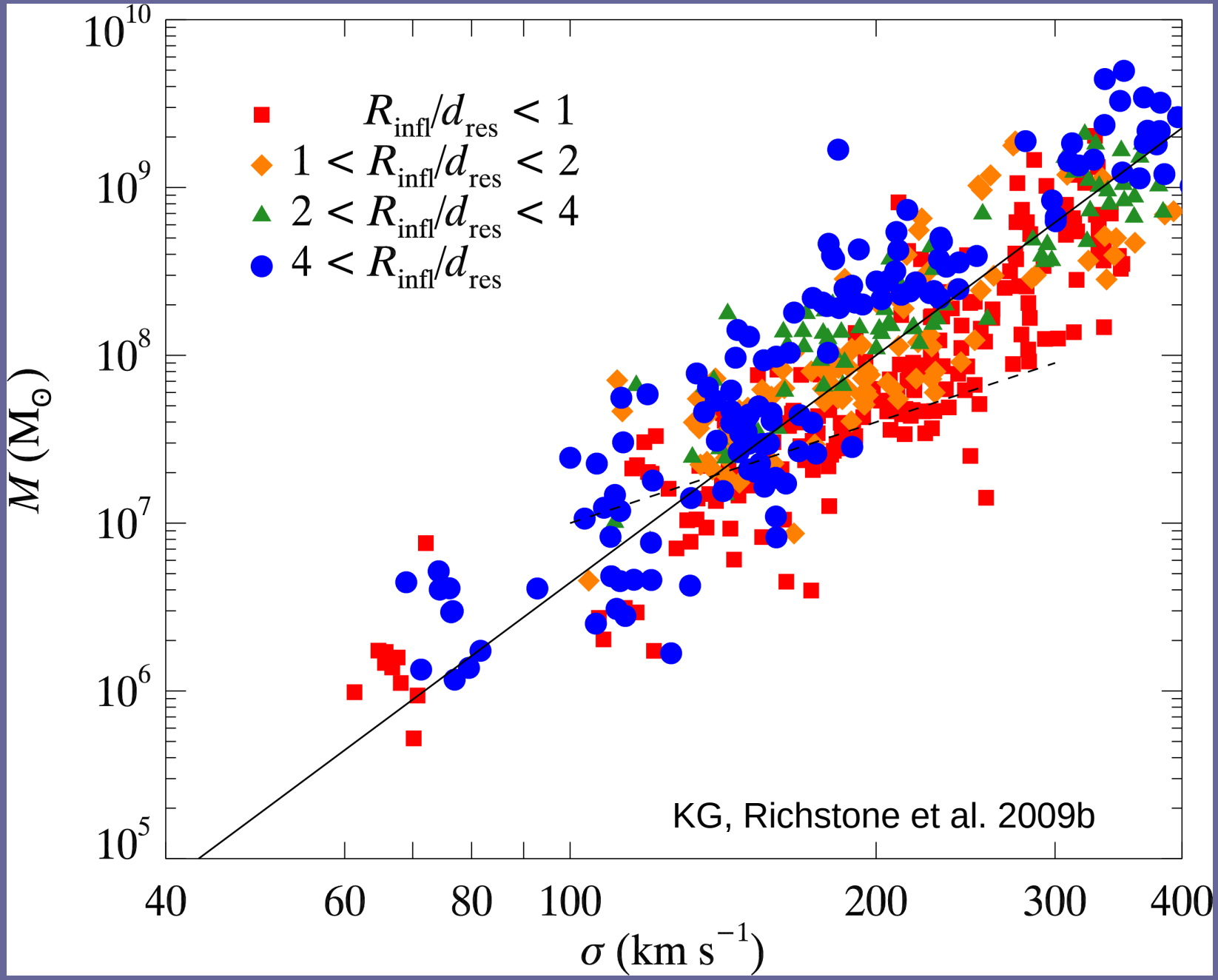
Gebhardt et al. 2003

Rejecting MBH values based on the sphere of influence *does* introduce a bias

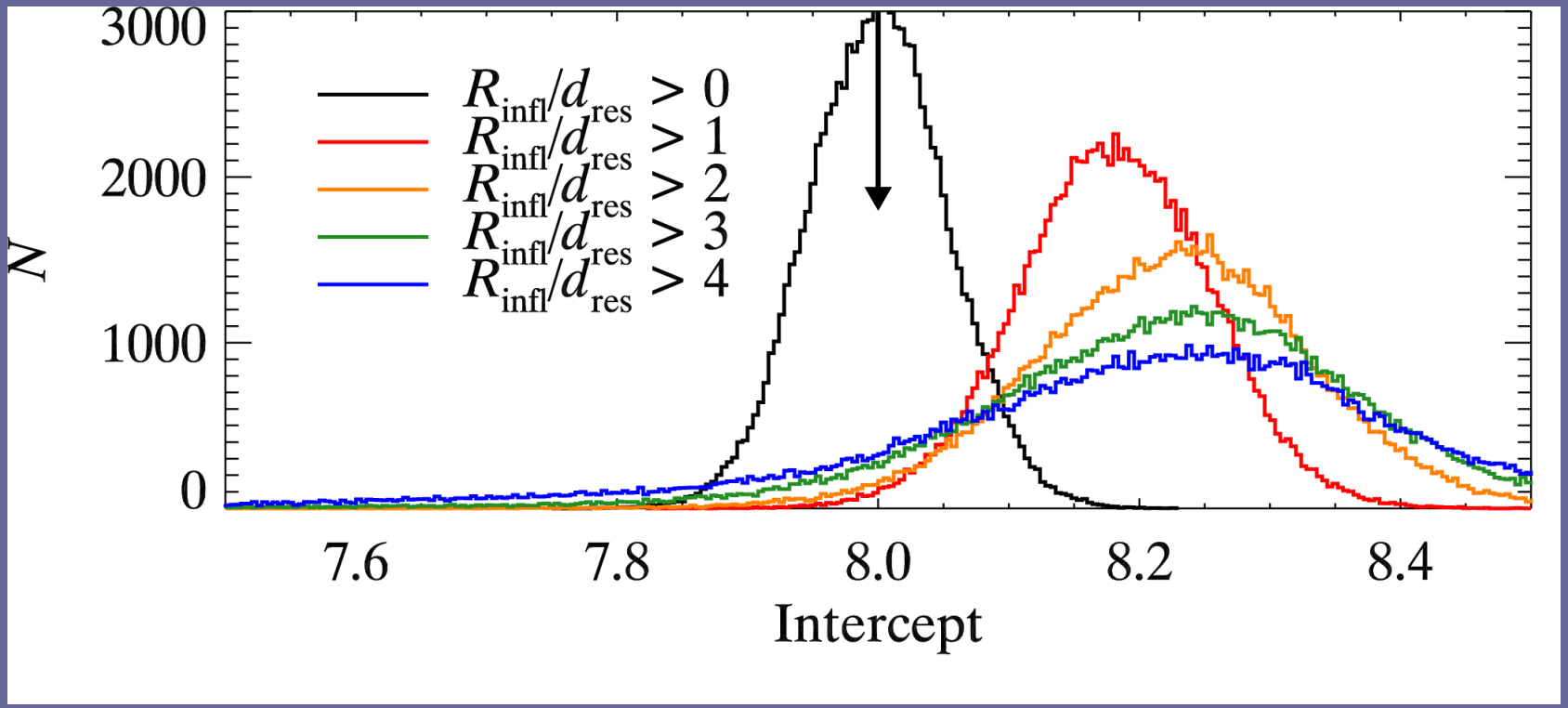
- $R_{infl} \sim M_{BH}\ \sigma^{-2}$
- $M_{BH} \sim \sigma^{\beta}$
- So cuts in R_{infl} fall on lines of

$$R_{infl} \sim \sigma^{(\beta - 2)}$$


10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
$M\ (M_\odot)$
$R_{\rm infl}/d_{\rm res} < 1$
$1 < R_{\rm infl}/d_{\rm res} < 2$
$2 < R_{\rm infl}/d_{\rm res} < 4$
$4 < R_{\rm infl}/d_{\rm res}$
Milky Way
KG, Richstone et al. 2009b
40
60
80
100
200
300
400
σ (km s^{-1})

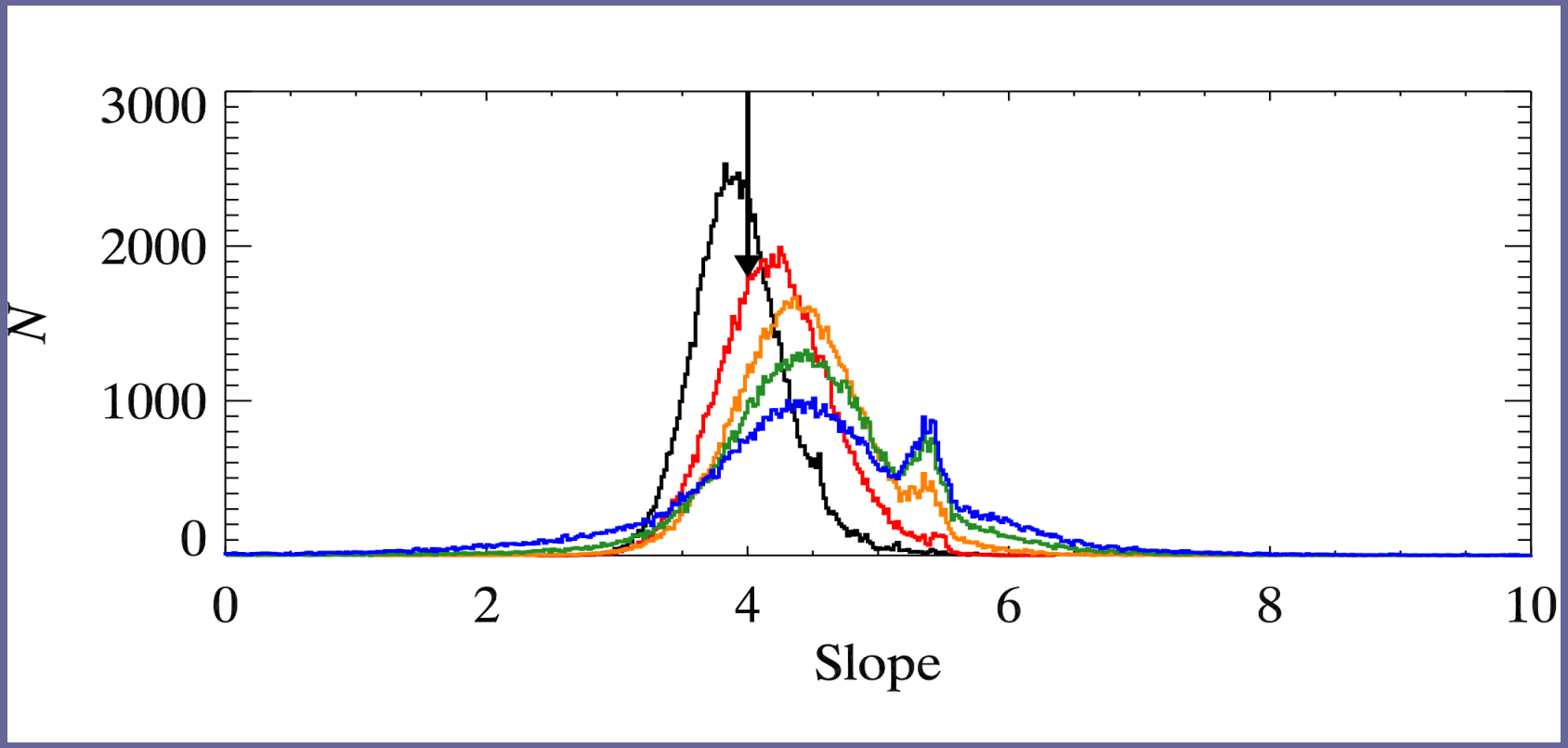

10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
$M\ (M_\odot)$
$R_{\rm infl}/d_{\rm res} < 1$
$1 < R_{\rm infl}/d_{\rm res} < 2$
$2 < R_{\rm infl}/d_{\rm res} < 4$
$4 < R_{\rm infl}/d_{\rm res}$
KG, Richstone et al. 2009b
40
60
80
100
200
300
400
$\sigma\ (\mathrm{km\ s^{-1}})$

Bias to high intercept.



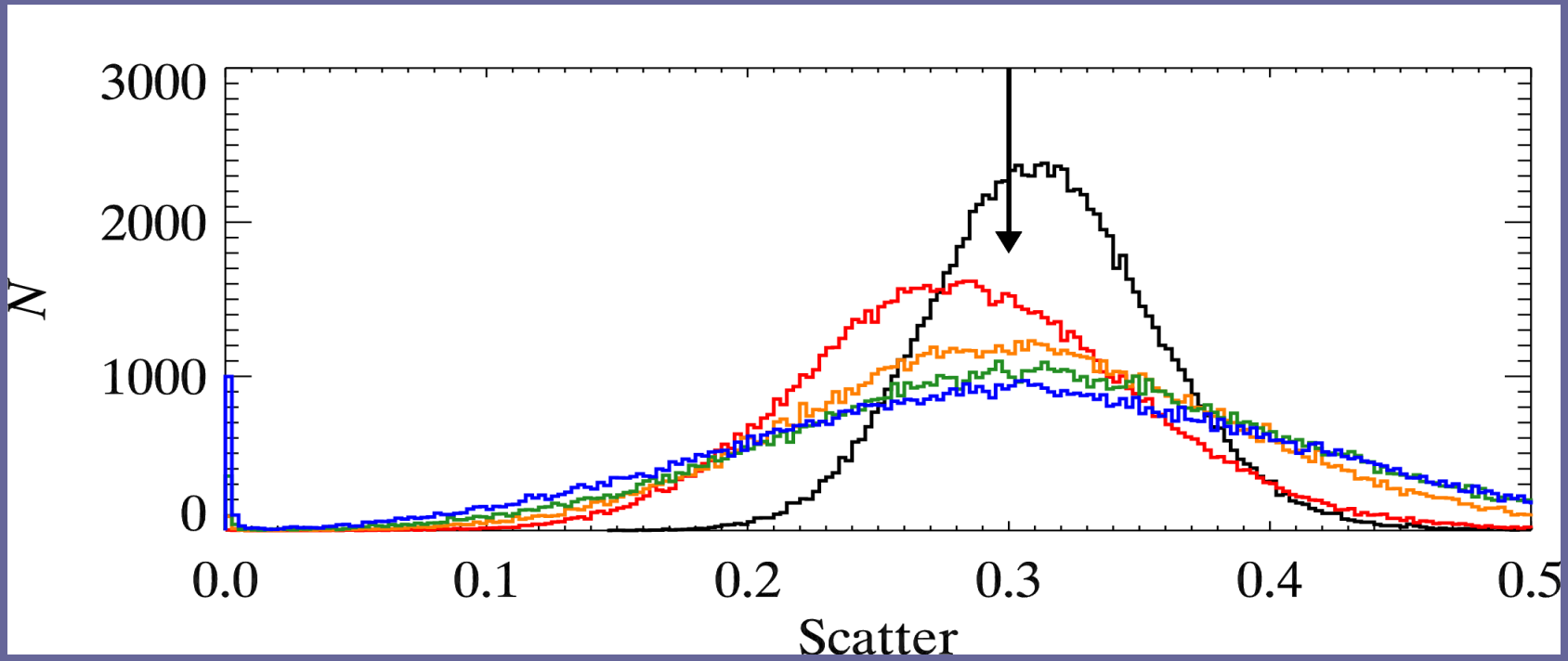
KG, Richstone et al. 2009b

Bias to high slope.

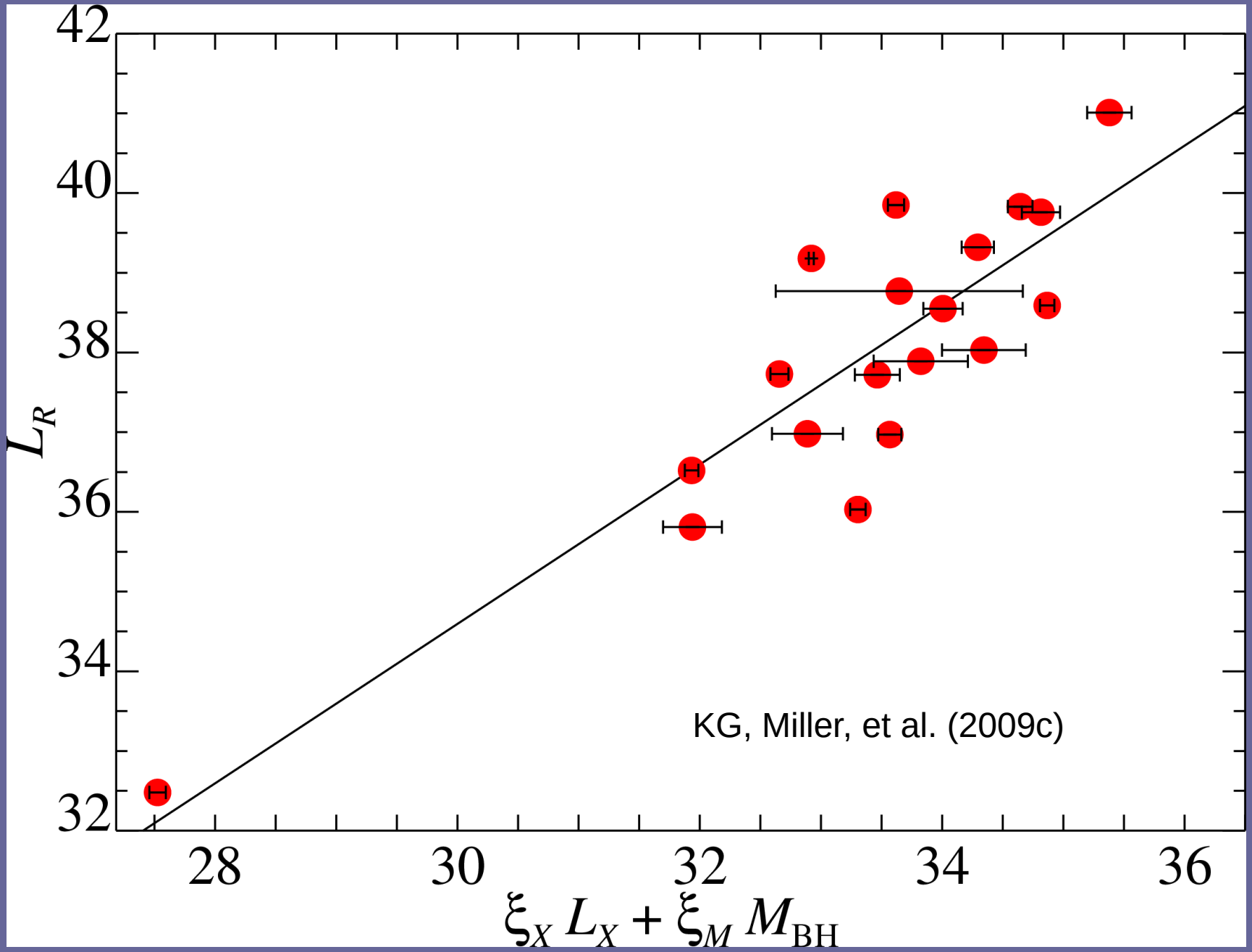


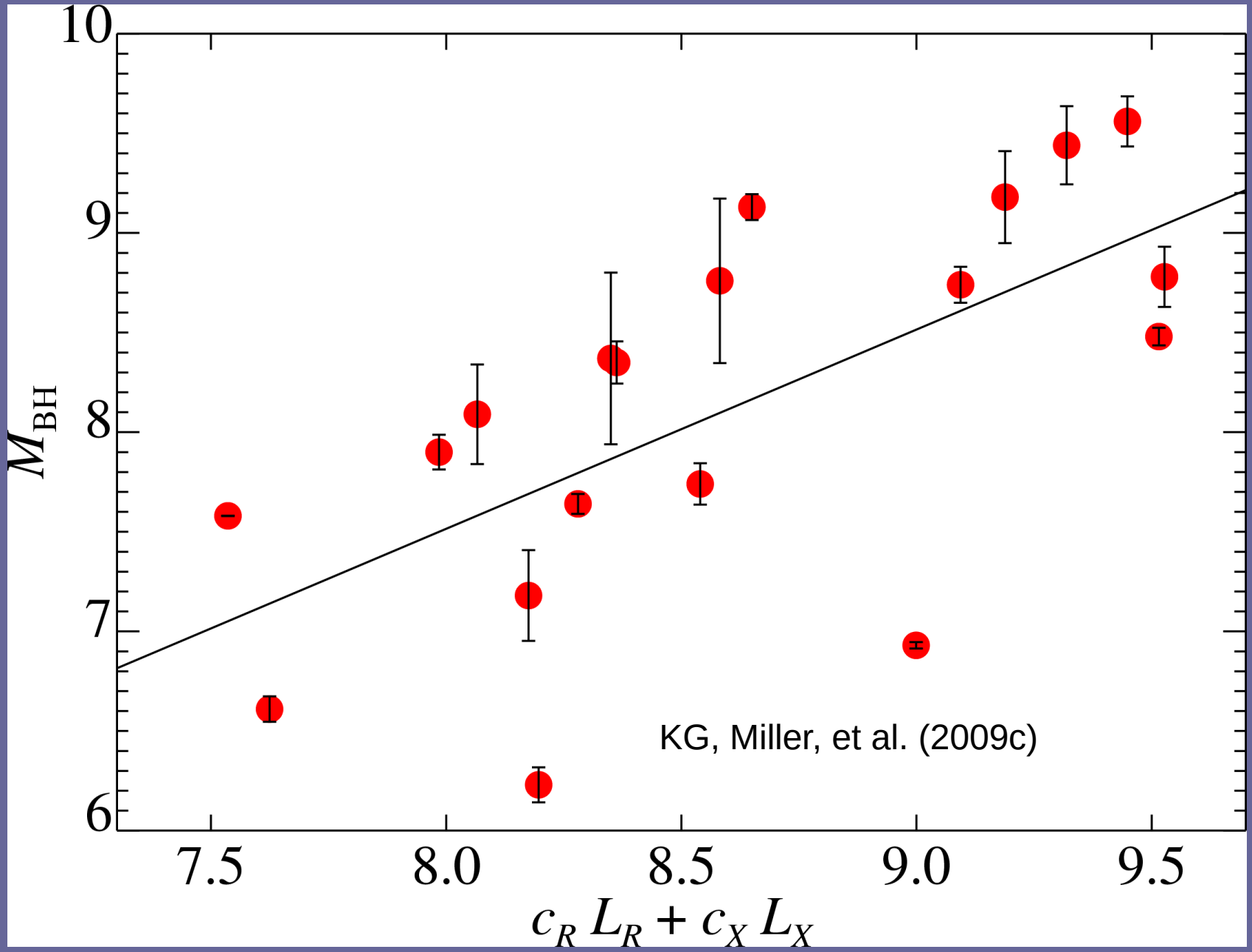
KG, Richstone et al. 2009b

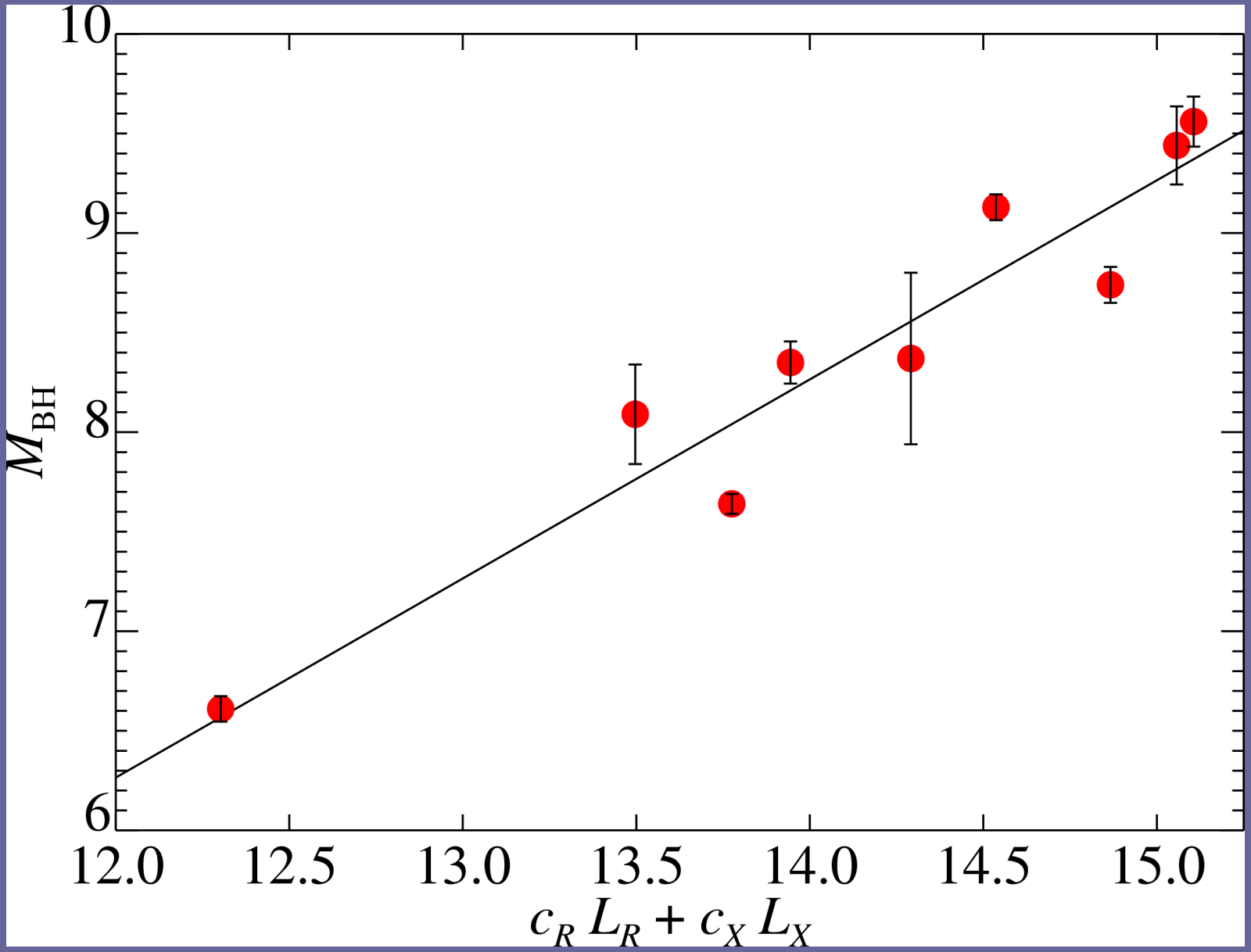
Bias to low scatter.

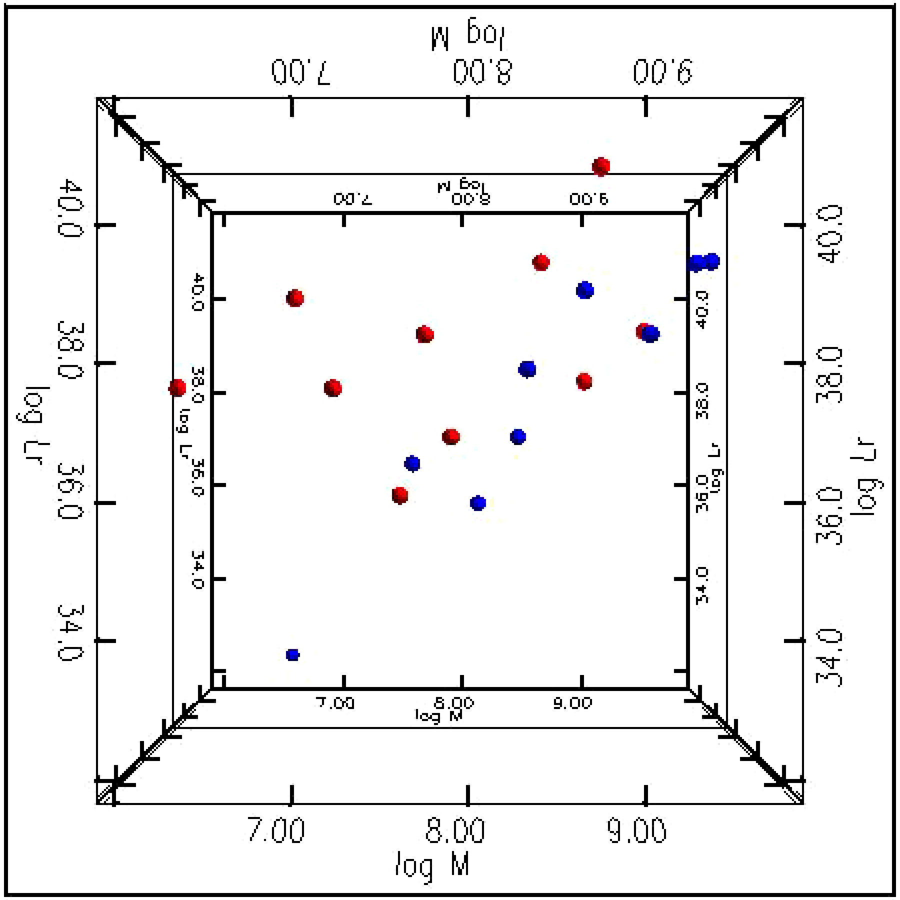


KG, Richstone et al. 2009b


42
40
38
36
34
32
L_R
28
30
32
34
36
$\xi_X L_X + \xi_M M_{\rm BH}$
KG, Miller, et al. (2009c)


10
9
8
7
6
$M_{\rm BH}$
7.5
8.0
8.5
9.0
9.5
$c_R\,L_R + c_X\,L_X$
KG, Miller, 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
$c_R\,L_R + c_X\,L_X$



log M
7.00
8.00
9.00
log Lr
34.0
36.0
38.0
40.0

- M-σ and M-L relations have been updated, and we measured their scatter.
- Ellipticals follow M-σ more tightly.
- Scatter is important for knowing number density of BHs.
- Scatter implies selection issues for studying evolution of the scaling relations.
- Censoring “under-resolved” BHs is bad.
- L_R, L_X, M fundamental plane.