The coevolution of galaxies and black holes in the past 10Gyrs

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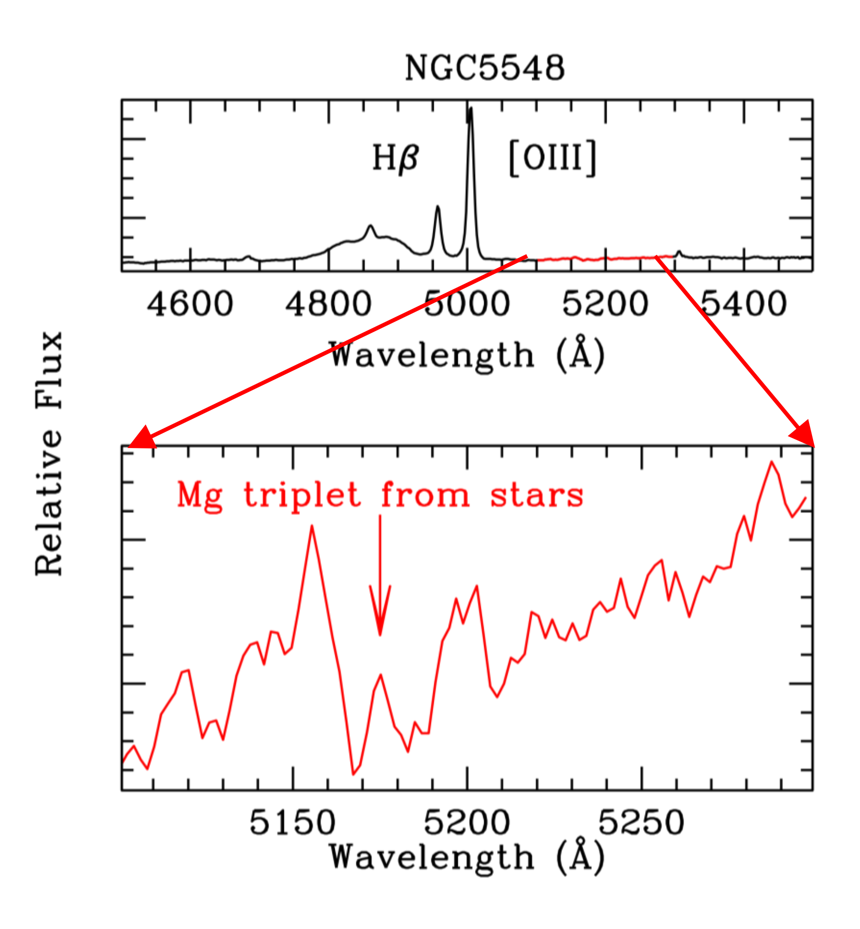
Many thanks to:

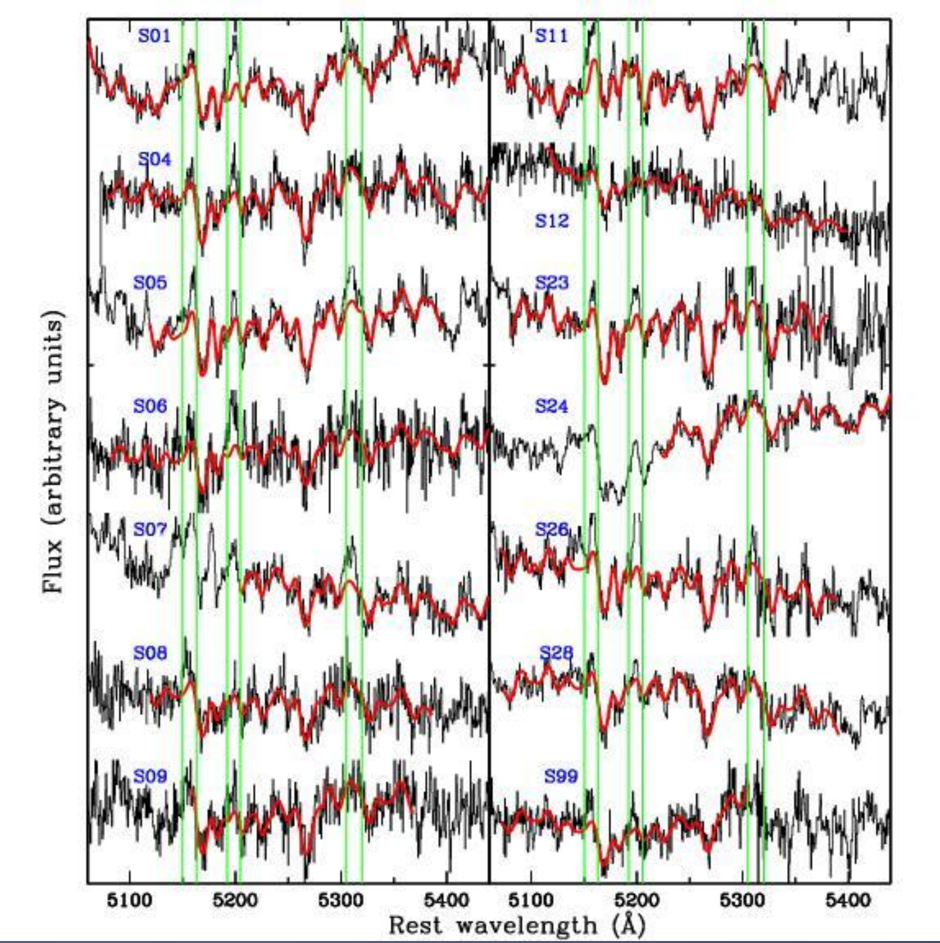
- **Matthew Auger (IoA)**
- Aaron Barth (UCI)
- **Vardha Bennert (CalPoly)**
- Roger Blandford (Stanford)
- **Brendon Brewer (Aukland)**
- **Chelsea Harris (Berkeley)**
- Matthew Malkan (UCLA)
- **Phil Marshall (Oxford)**
- **Anna Pancoast (UCSB)**
- **Jonghak Woo (SNU)**

How do black-holes and spheroids know about each other?

- The local MBH-sigma/M* relation are remarkable
- Black hole and galaxies evolve over cosmic time, in different ways. If you establish the correlations at one time they are not trivially preserved!!
- Probing its evolution is a key measurement to test bh formation scenarios as well as the role of AGN feeback in galaxy formation

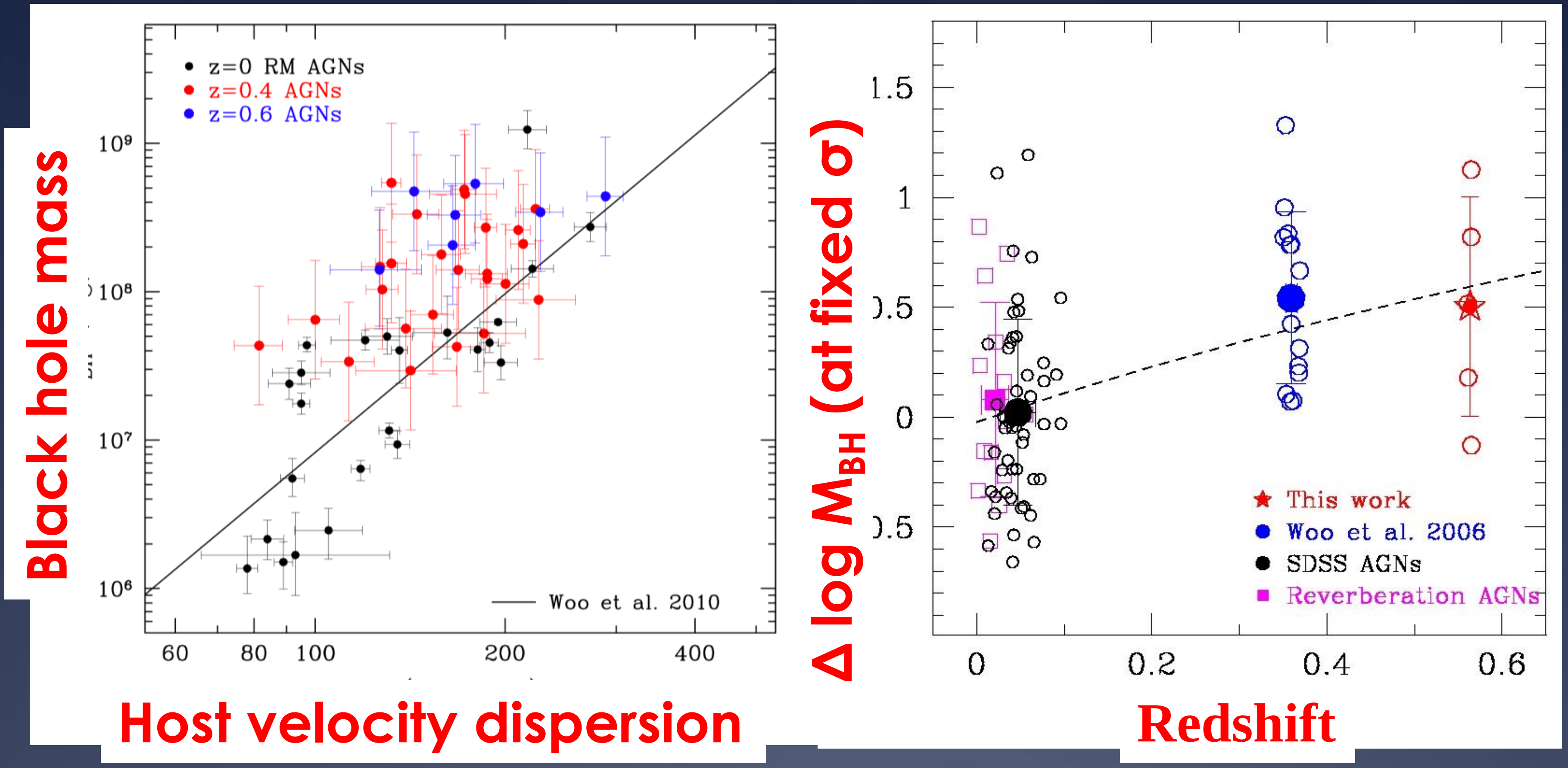
Measuring velocity dispersion





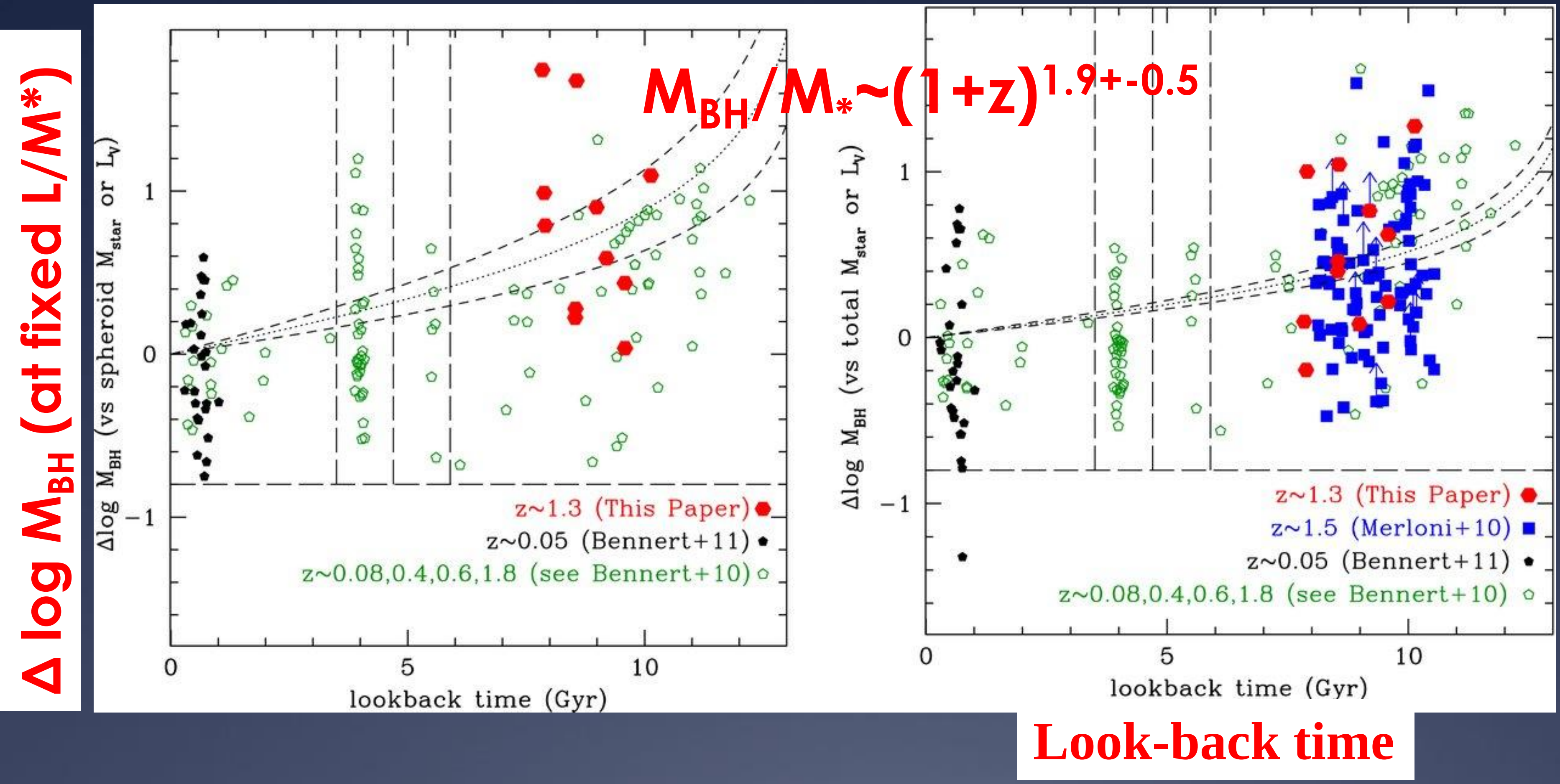
Treu et al. 2004; Woo et al. 2006

Evolution of the M_{BH}-σ relation



Treu et al. 2004; Woo et al. 2006, 2008, 2010, 2013

Evolution of the M-L/M* relation



Treu et al. 2007; Bennert et al 2010, 2011

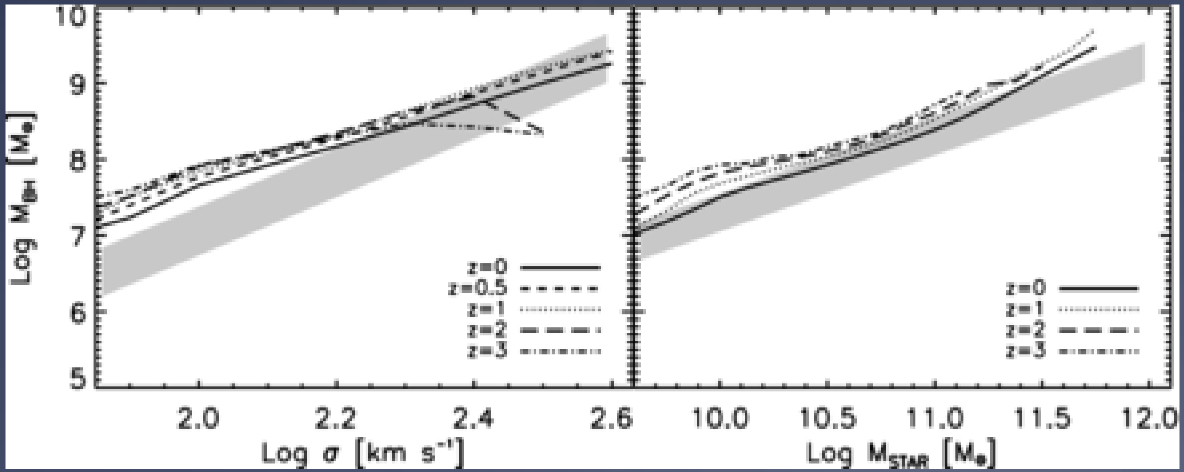
The three possible explanations of every astronomical observation

- Something interesting is happening
- Selection effects
- Measurement errors

Something interesting

A scenario and a conjecture

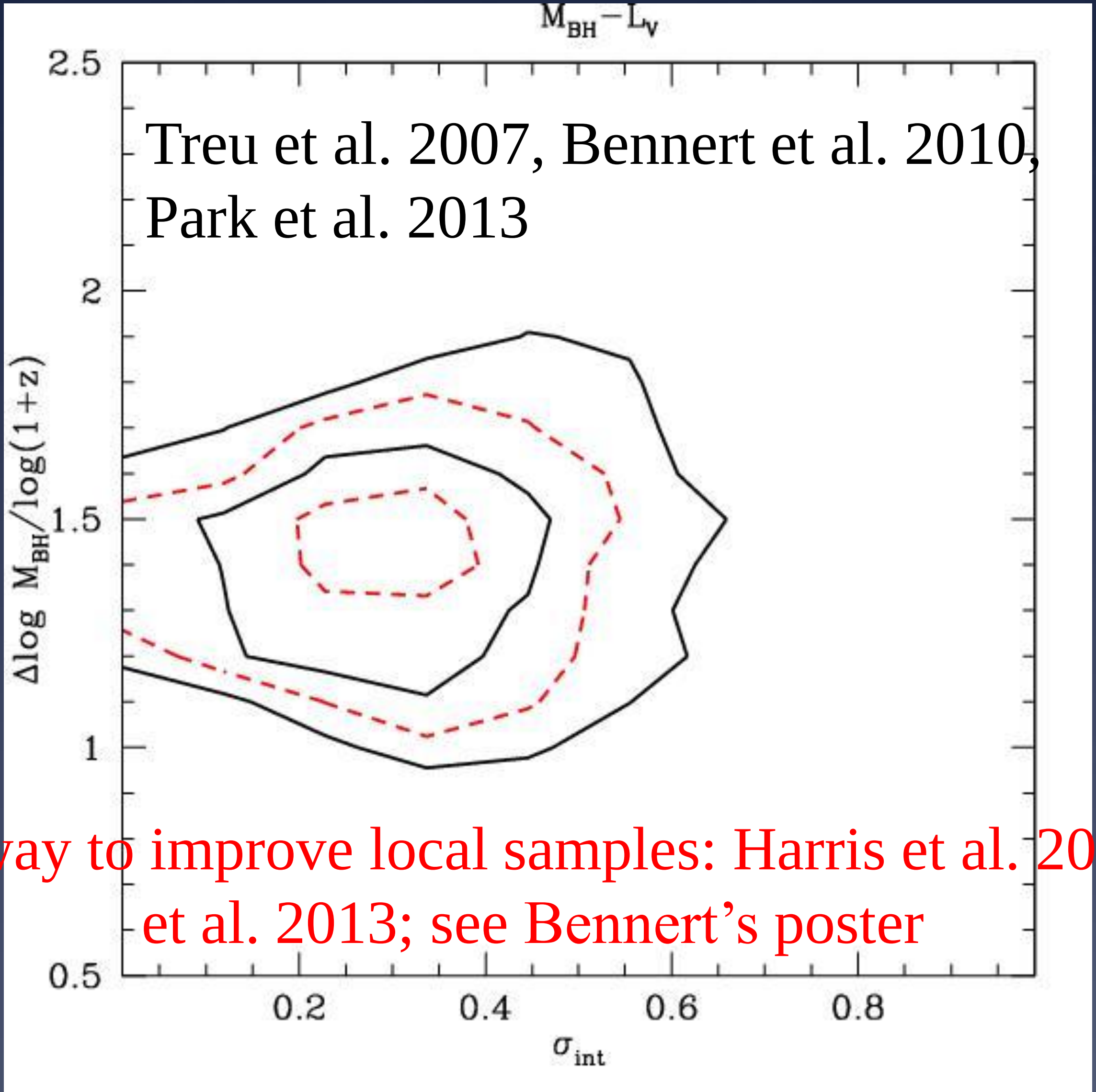
- Co-evolution is mass dependent.
- For the more massive ellipticals ($M_* > 10^{11}\ M_{sun}$):
  - Most of the mass is assembled by z~1.5-2
  - Black hole accretion is also completed early-on (z~2)
- At smaller masses (including bulges of spirals) process is delayed and significant activity lingers to z~0.5
- ***Slope of M_{BH}-M_* and M_{BH}-σ should evolve with time***



Shankar et al. 2013
Croton et al. 2006

Selection effects?

Evolution is not a selection effect



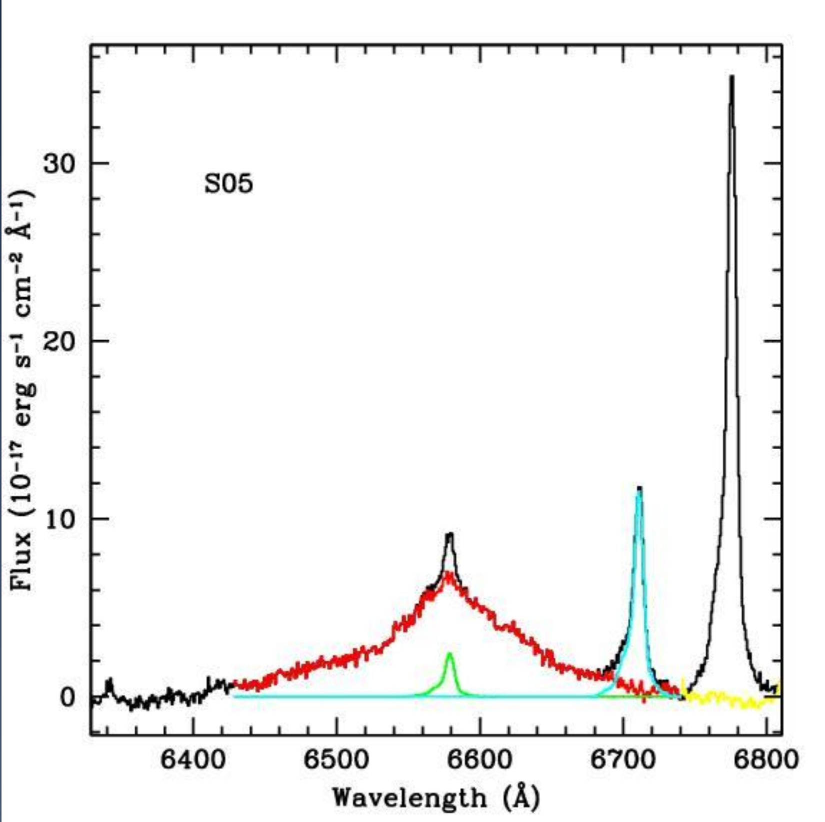
Treu et al. 2007, Bennert et al. 2010, Park et al. 2013

Work underway to improve local samples: Harris et al. 2012; Bennert et al. 2013; see Bennert's poster

Measurement errors?

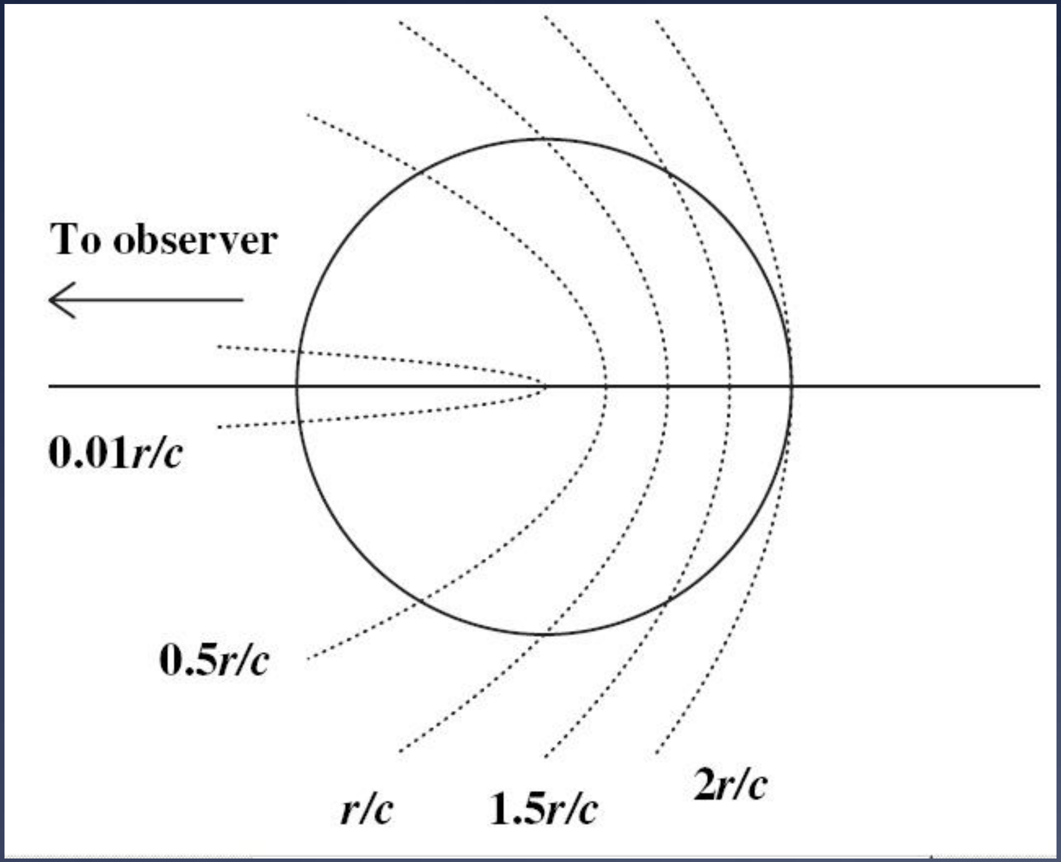
Measuring black hole masses at z>0

- Broad Hβ width measures the kinematics of the gas orbiting the black hole
- Size from L
- **Overall uncertainty on BH mass ~0.4-0.5 dex**



$$M_{BH} = 10^{8.58} \left(\frac{\sigma_{H\beta}}{3000 \mathrm{km\,s^{-1}}} \right)^2 \left(\frac{\lambda L_{5100}}{10^{44} \mathrm{erg\,s^{-1}}} \right)^{0.518}$$

Reverberation Mapping



Ring of gas with radius *r*

Gas along line of sight to observer will appear to respond with no delay

Gas that is furthest from observer will appear to have response delayed by 2*r*/*c*

Mean lag time is *r*/*c*

Blandford & McKee 1982

Example of traditional results

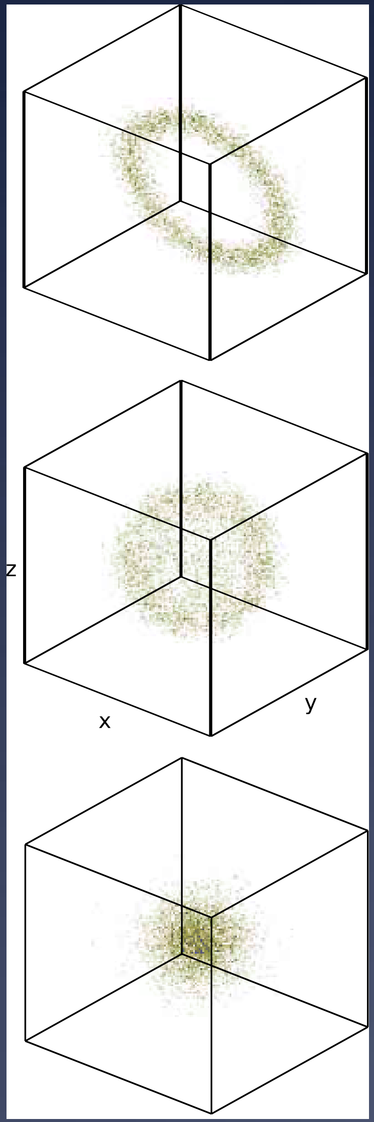
Table 13. Virial Products and Derived Black Hole Masses

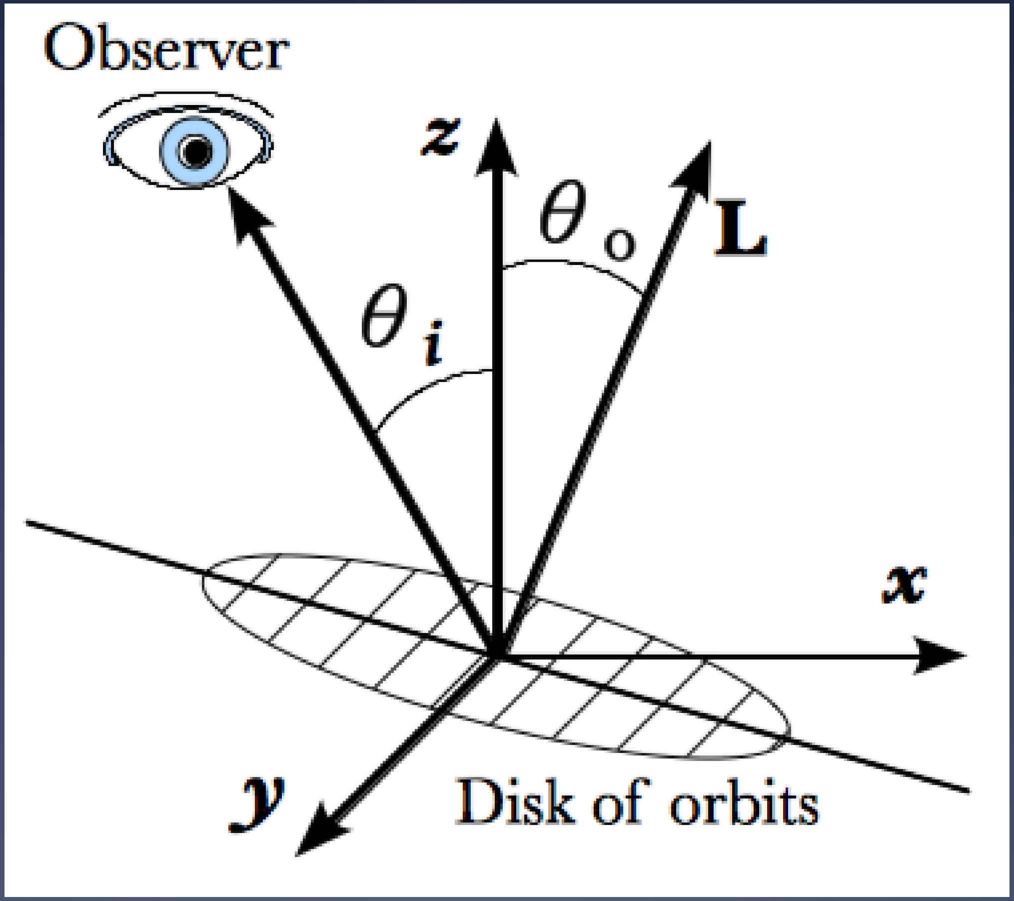
Object	$c\tau_{cent}\sigma^2_{line}/G$ (10^6 $M_\odot$)	M_{BH}[a] (10^6 $M_\odot$)
Mrk 142	$0.40^{+0.12}_{-0.14}$	$2.17^{+0.68}_{-0.75}$
SBS 1116+583A	$1.05^{+0.33}_{-0.29}$	$5.80^{+1.84}_{-1.58}$
Arp 151	$1.22^{+0.16}_{-0.22}$	$6.72^{+0.89}_{-1.19}$
Mrk 1310	$0.41^{+0.12}_{-0.13}$	$2.24^{+0.68}_{-0.69}$
Mrk 202	$0.26^{+0.15}_{-0.10}$	$1.42^{+0.83}_{-0.56}$
NGC 4253	$0.32^{+0.21}_{-0.20}$	$1.76^{+1.15}_{-1.11}$
NGC 4748	$0.47^{+0.16}_{-0.21}$	$2.57^{+0.90}_{-1.14}$
NGC 5548	$14.9^{+3.4}_{-4.9}$	82^{+19}_{-27}
NGC 6814	$3.36^{+0.54}_{-0.56}$	$18.5^{+3.0}_{-3.1}$

[a]Assuming $f = 5.5$.

Bentz et al. 2009

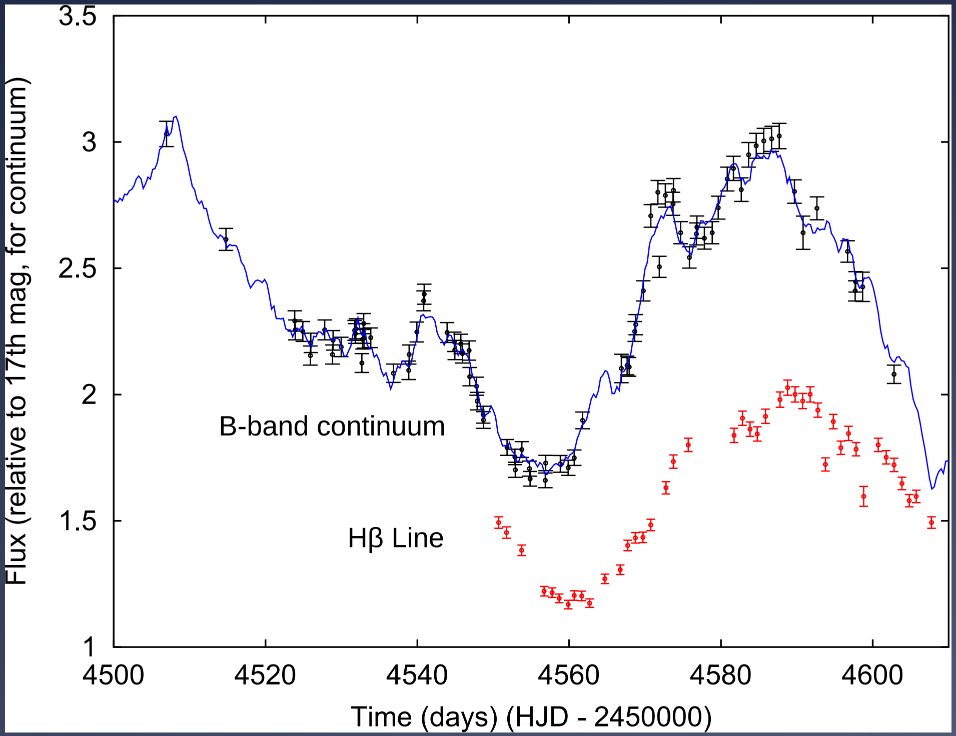
A new approach: Geometric and dynamical models

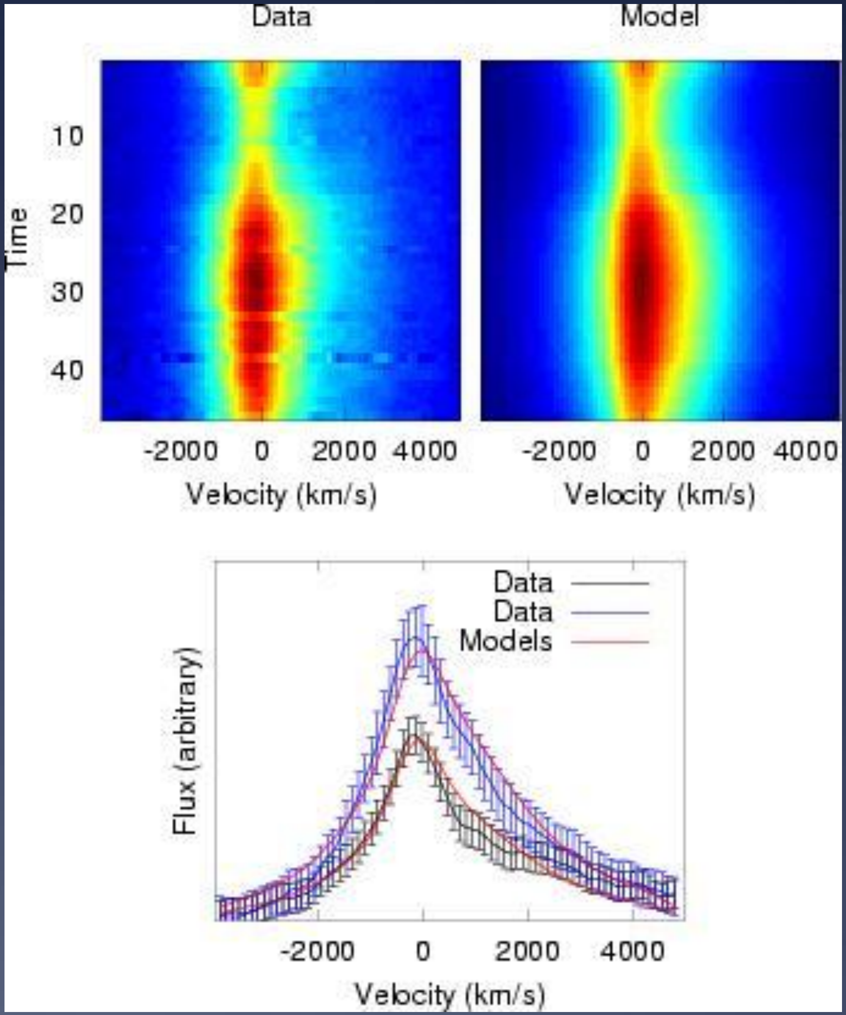




Pancoast, Brewer & Treu, 2011

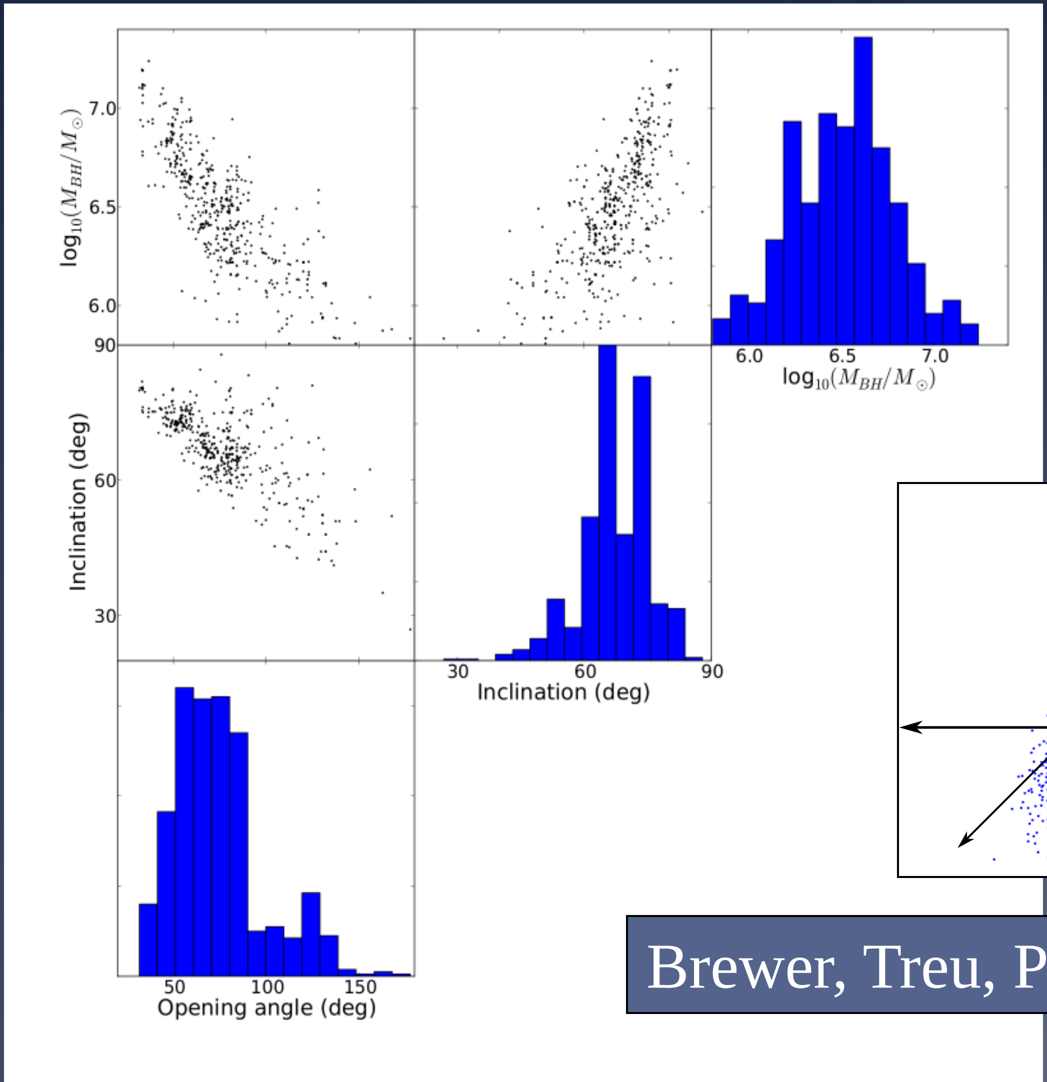
Geometric and dynamical models: Application to Arp 151



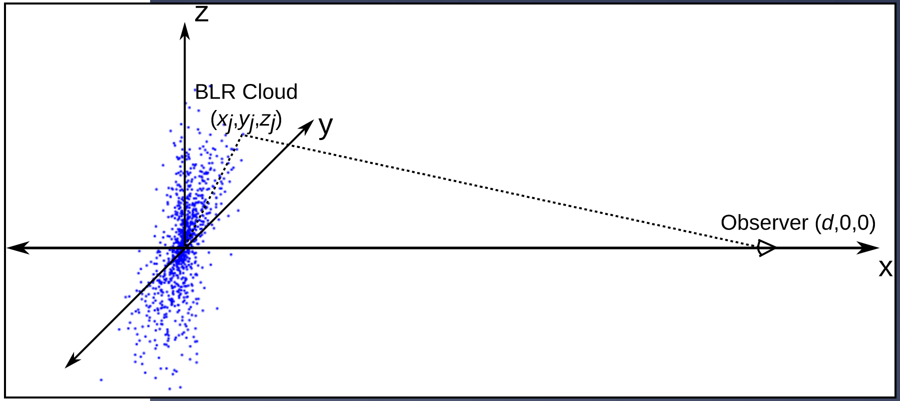


Brewer, Treu, Pancoast et al 2011

Geometric and dynamical models: Application to Arp 151



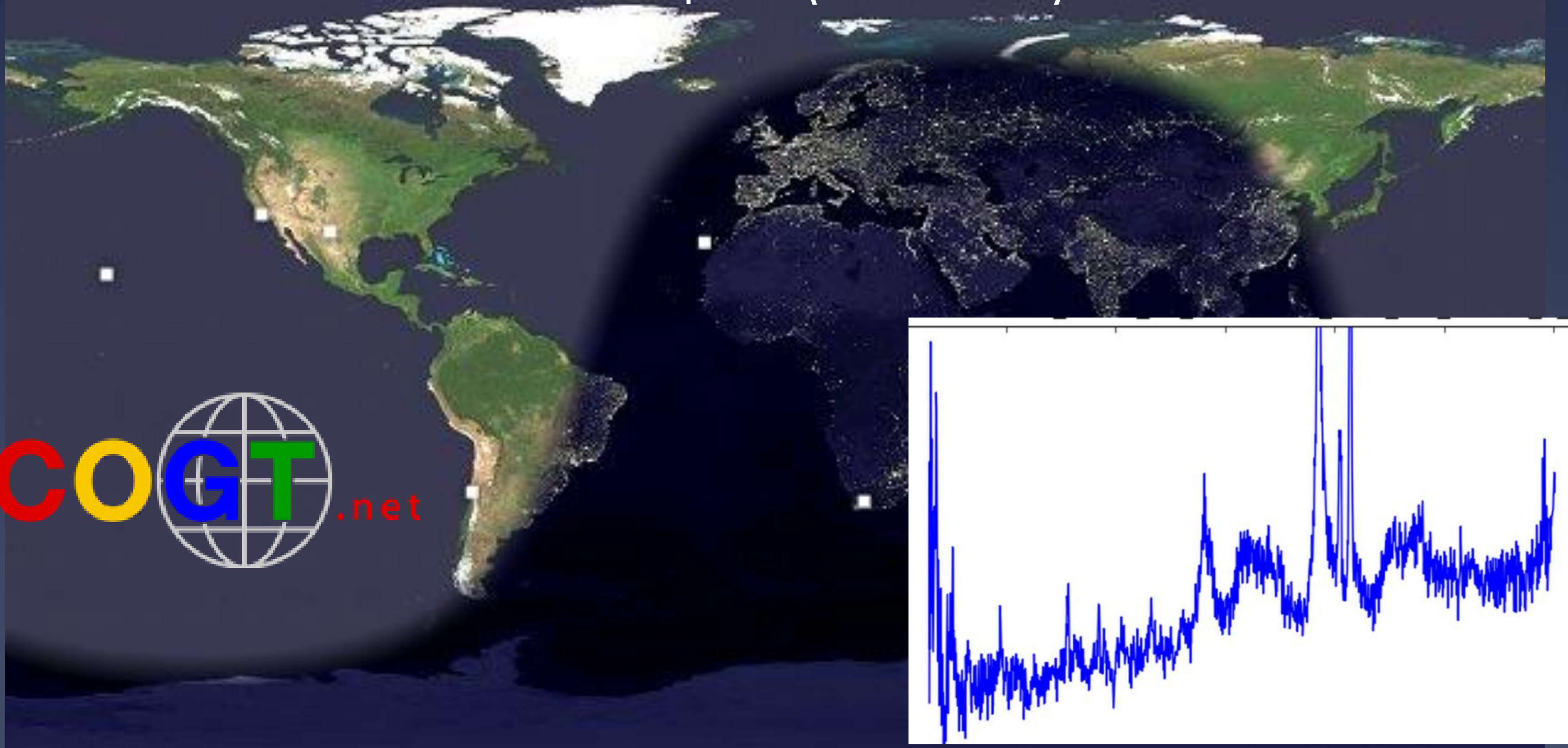
See Pancoast's poster for more systems and details



Brewer, Treu, Pancoast et al 2011

Reverberation mapping

- At z~0, several objects have been studied with sufficient quality (LAMP08/11 and Peterson Group)
- At z>0, very hard with traditional telescopes (e.g. Woo et al. 2007). Large program under way with LCOGT robotic telescopes (PI: Sand).



Summary

- The correlations between host galaxy properties and black hole mass evolve with cosmic time
- Black holes growth predate galaxy assembly
- Much work is under way to improve mass determinations at high-z via reverberation mapping and improve local samples

The end