Credit: ESO/Kornmesser

Investigating the Growth of Supermassive Black Holes with the Quasar Black Hole Mass Function

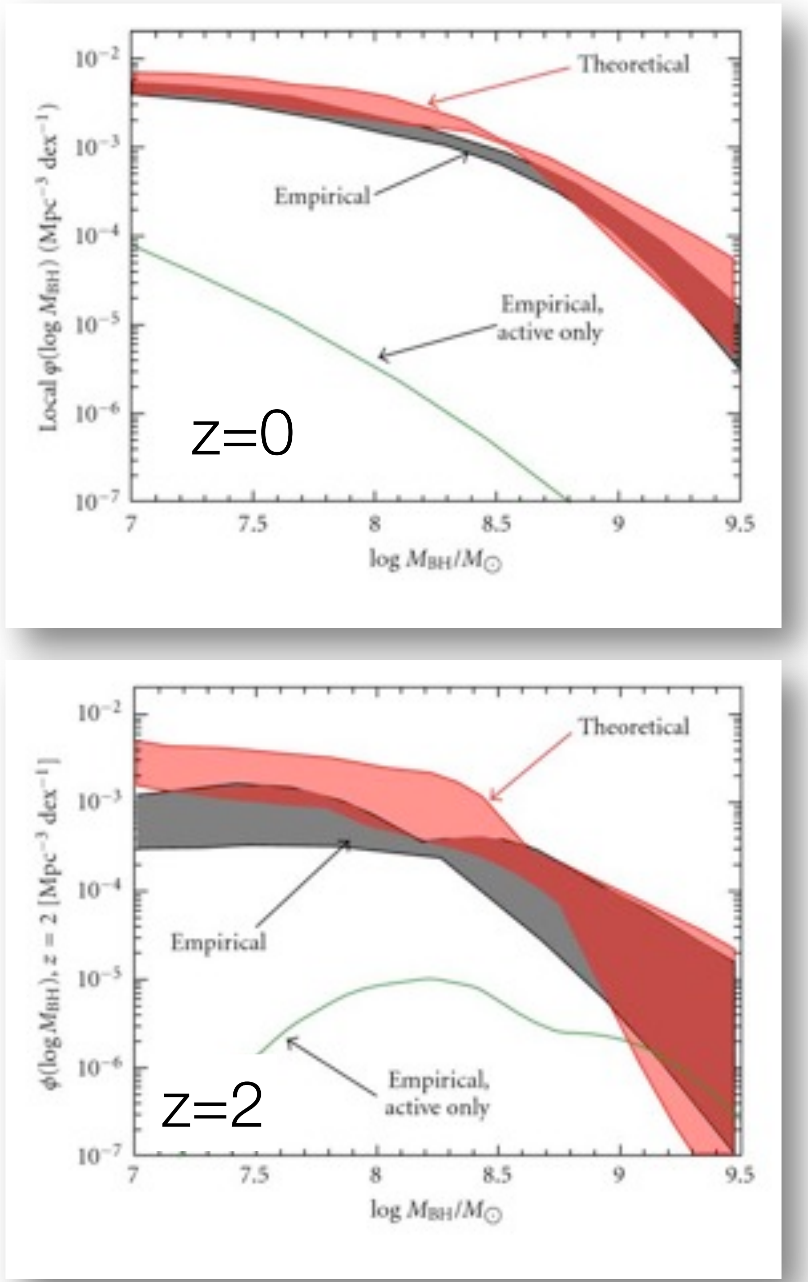
Brandon C. Kelly (UCSB, CGE Fellow, bckelly@physics.ucsb.edu)

Yue Shen (Carnegie), Tommaso Treu (UCSB), Matthew Malkan (UCLA), Anna Pancoast (UCSB), Jong-Hak Woo (SNU), Marianne Vestergaard (DARK), Xiaohui Fan (Arizona)

What does the Black Hole Mass Function (BHMF) give us?

- Probes build-up of supermassive black hole population, duty cycle of black hole activity
- Constrains black hole seeding models (e.g., Natarajan & Volonteri 2012)
- Mass function + luminosity function provides Eddington ratio distribution, constrains BH growth rates and time scales
- Important for planning surveys used to study AGN physics, gravitational waves, etc.

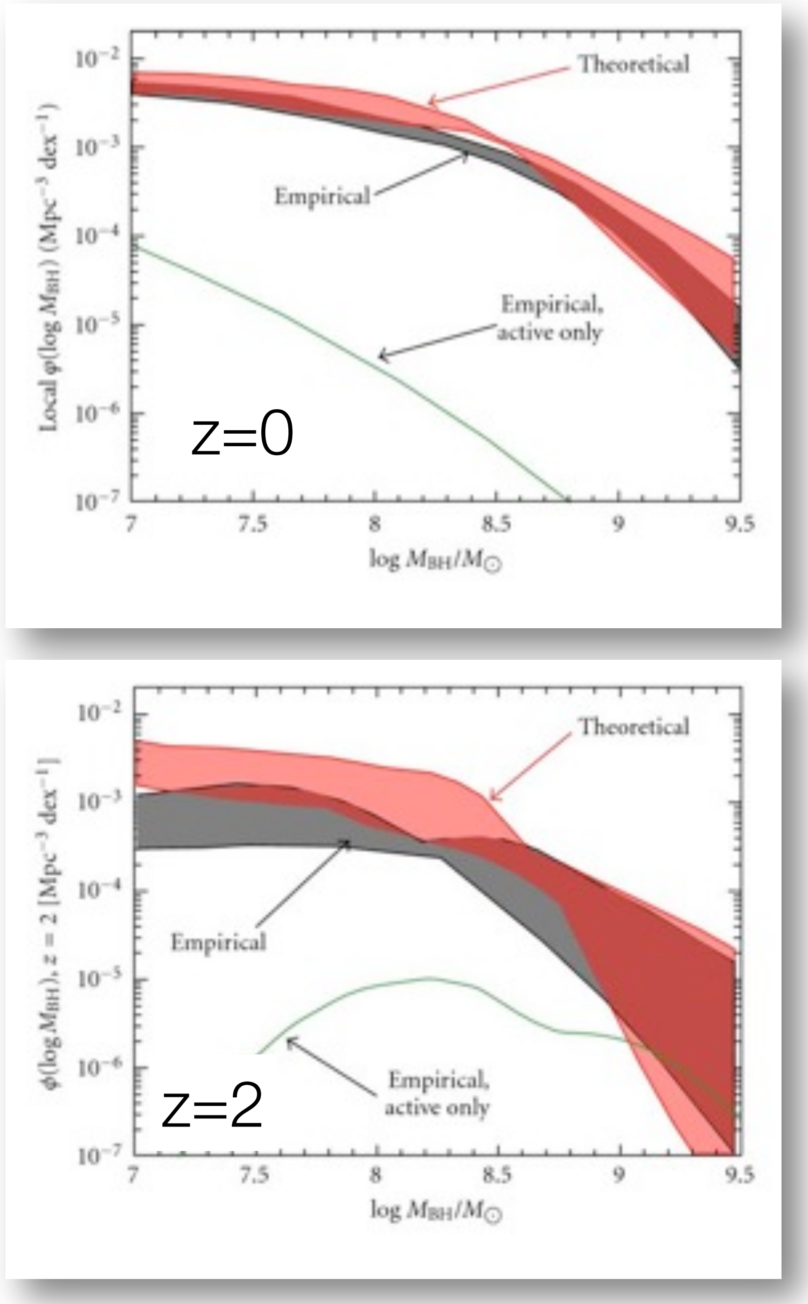
Estimating the BH Mass Function



Kelly & Merloni (2012)

Estimating the BH Mass Function

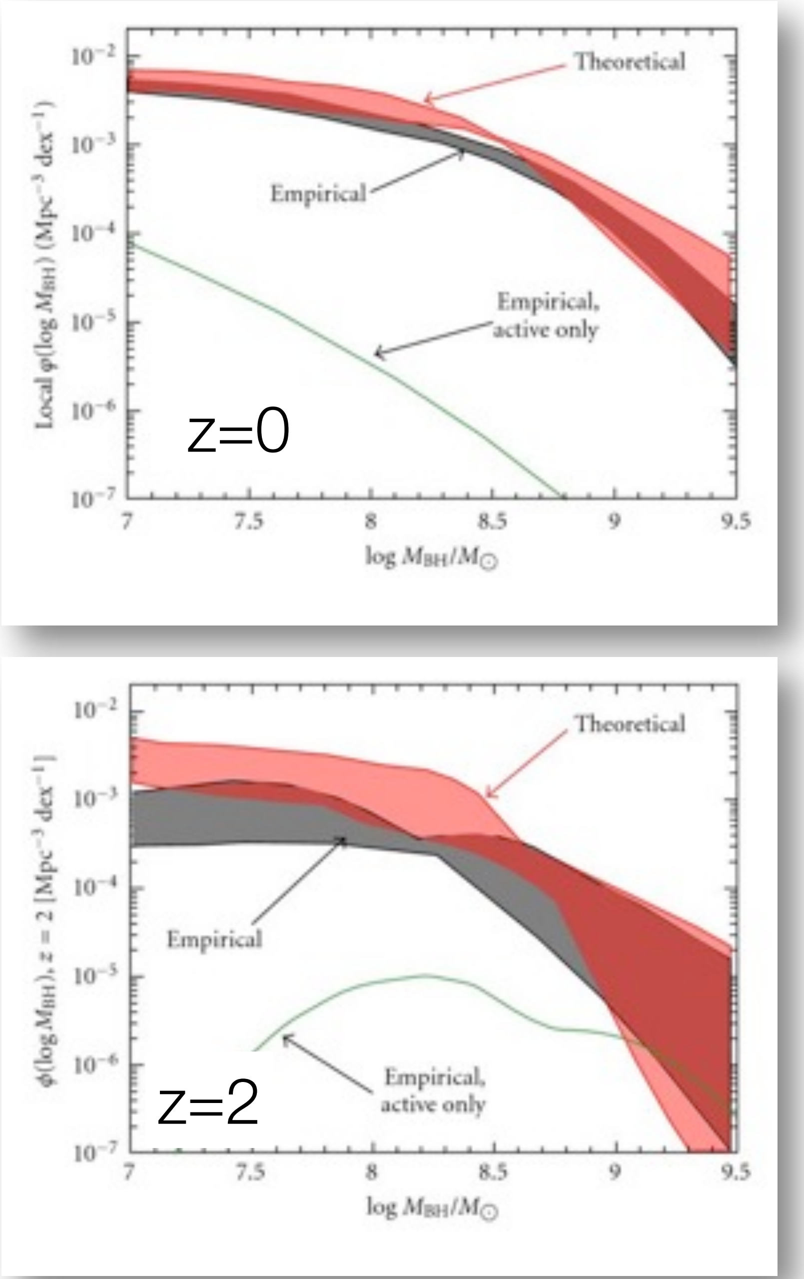
- From Scaling Relationships:
  - Estimate M_{BH} from observables for each source
  - Derive MF from these BH mass estimates
  - Primarily used beyond the local universe for Type 1 Quasars only (e.g., Greene & Ho 2007; Vestergaard +2008,2009; Schulze 2010; Kelly+2011,2013; Shen & Kelly 2012)



Kelly & Merloni (2012)

Estimating the BH Mass Function

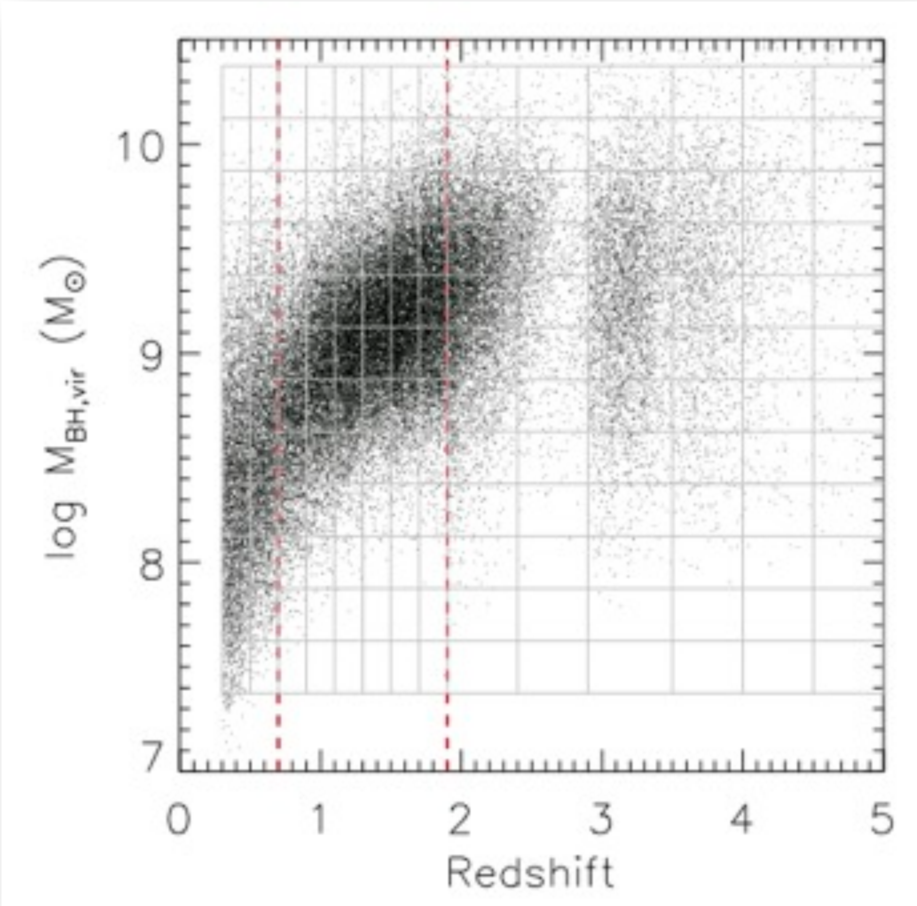
- From Scaling Relationships:
    - Estimate M_{BH} from observables for each source
    - Derive MF from these BH mass estimates
    - Primarily used beyond the local universe for Type 1 Quasars only (e.g., Greene & Ho 2007; Vestergaard +2008,2009; Schulze 2010; Kelly+2011,2013; Shen & Kelly 2012)
- From continuity equation methods (e.g., Marconi+2004, Merloni & Heinz 2008, Shankar+2009)
    - Use AGN luminosity function to estimate BH growth rate as a function of z, provides rate of change of BHMF
    - Start at local MF and work backwards to reconstruct MF as a function of z
    - Provides MF for all SMBHs (not just AGN), but less direct and more model-dependent



Kelly & Merloni (2012)

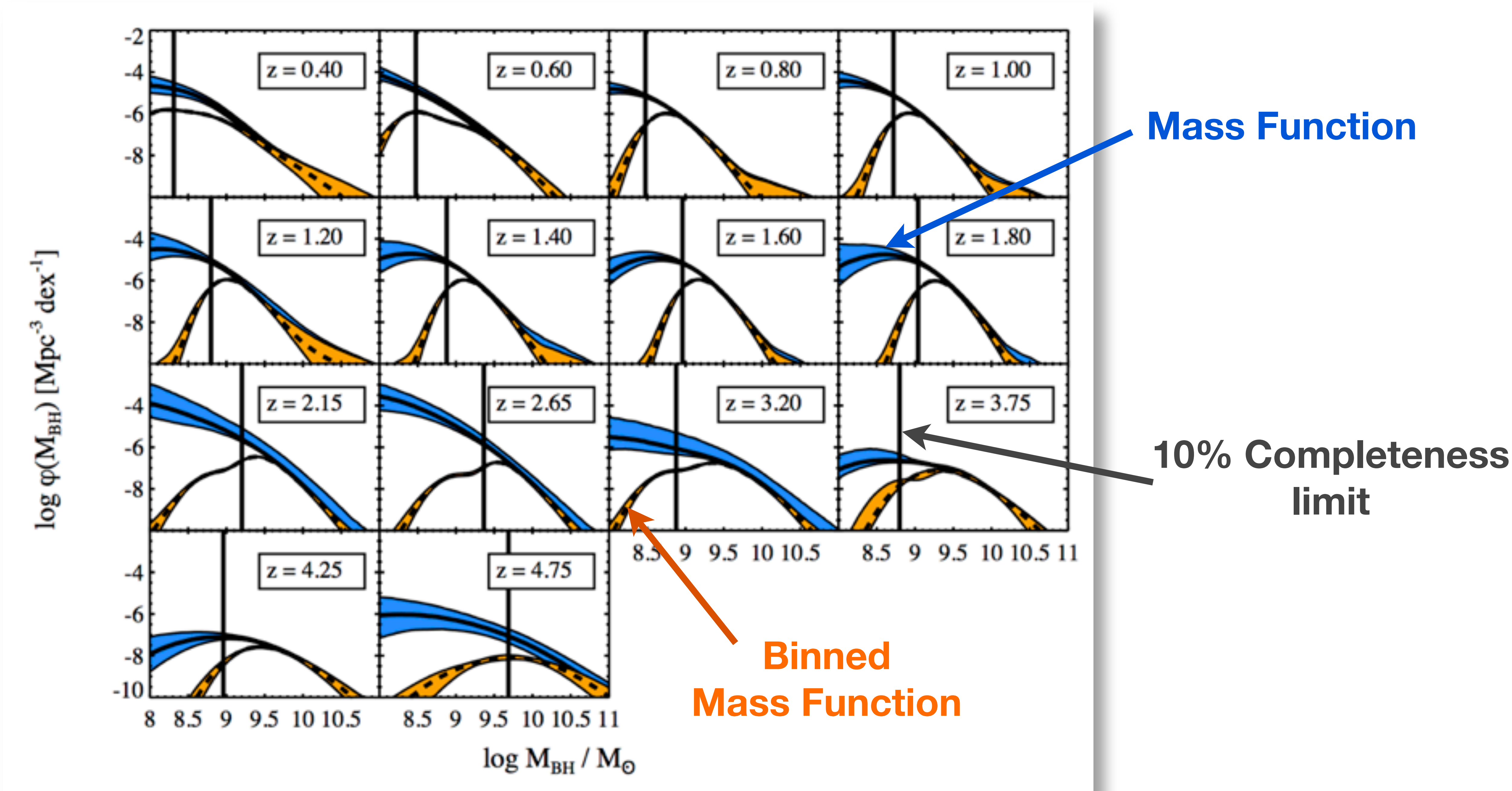
Our Sample: SDSS DR7 Quasar Catalogue (Shen +2011)

- Sample of 57,959 Type 1 quasars over $0.3 < z < 5.0$
    - Sky coverage of 6248 deg^2
- Uniformly selected, selection function given by Richards+(2006)
- Flux limits:
    - $i < 19.1$ at $z < 2.9$
    - $i < 20.2$ at $z > 2.9$
- Mass estimates derived by Shen+(2011) using FWHM:
    - Hβ: $0.3 < z < 0.7$
    - MgII: $0.7 < z < 1.9$
    - CIV: $z > 1.9$
- Used Bayesian technique (Kelly+2009) to correct for incompleteness and statistical error in mass estimates



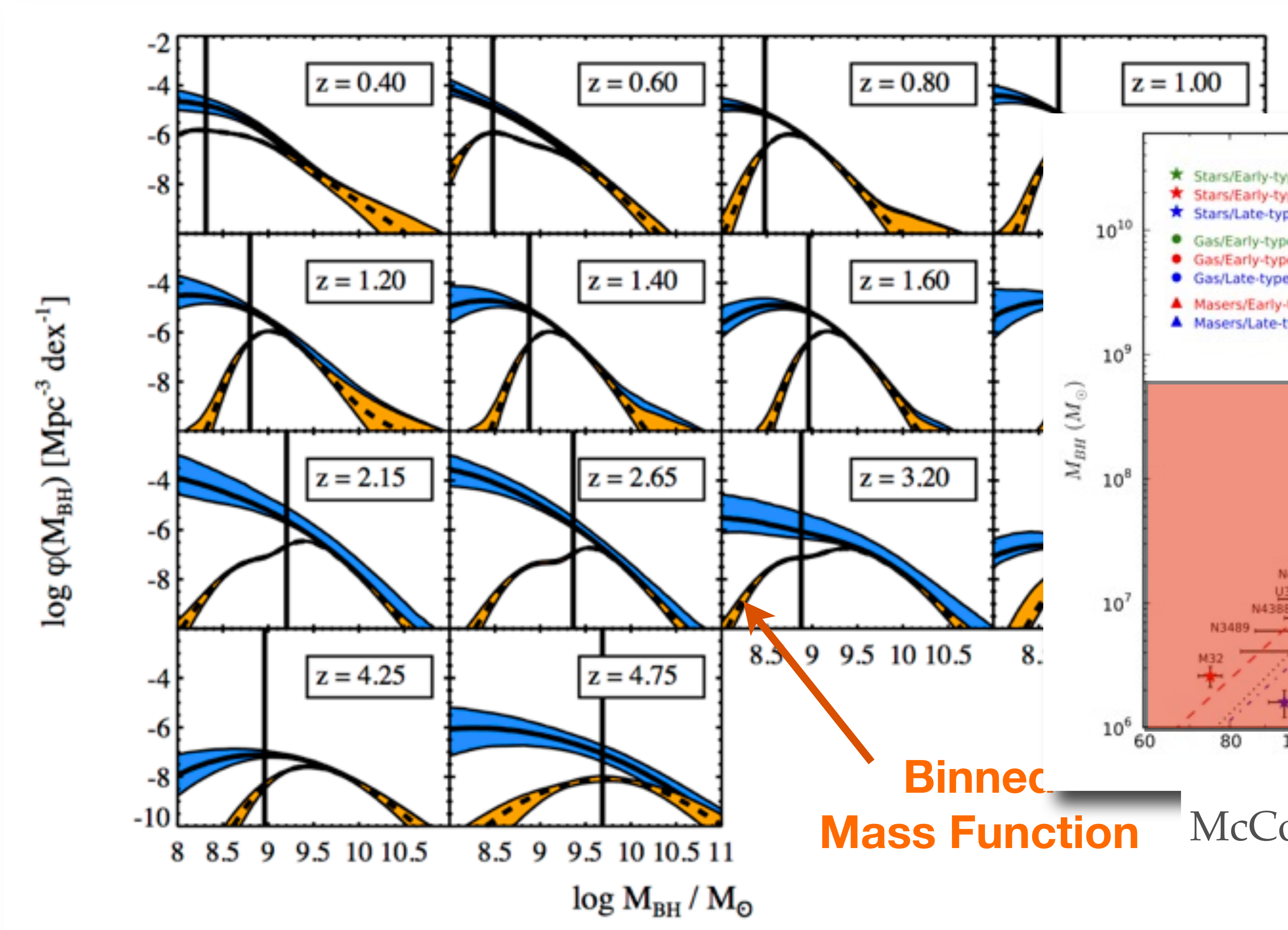
Shen & Kelly (2012)

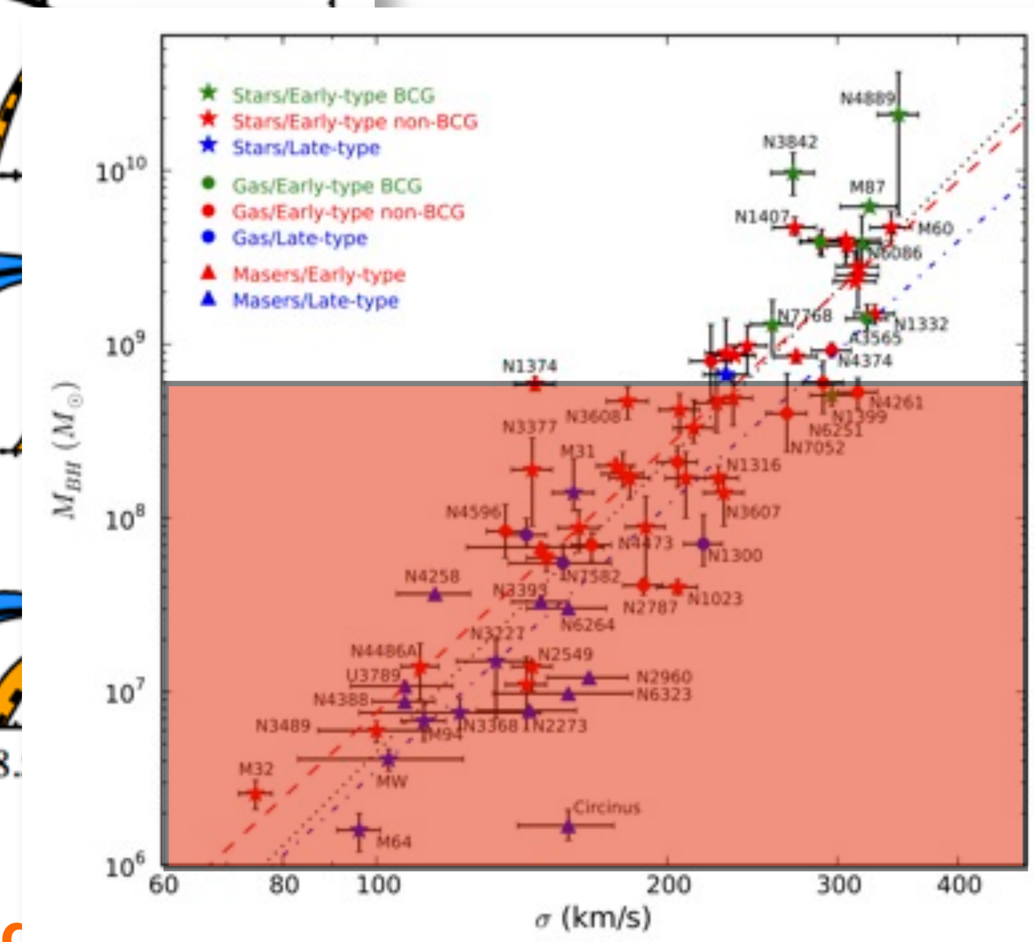
Type 1 Quasar Black Hole Mass Function



Kelly & Shen 2013, see also Kelly+(2010), Shen & Kelly (2012)

Type 1 Quasar Black Hole Mass Function



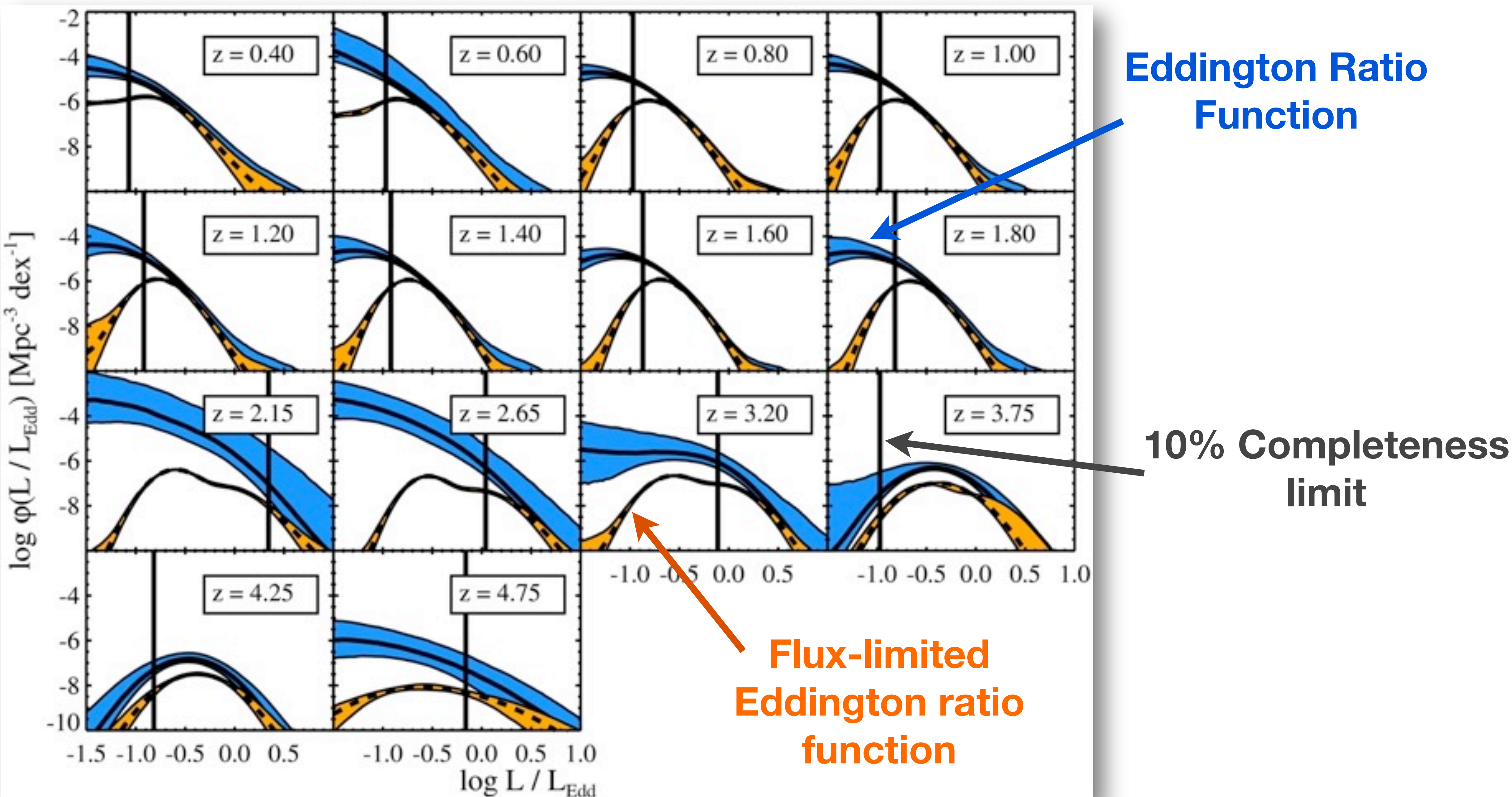


Binned Mass Function

McConnell & Ma (2013)

Kelly & Shen 2013, see also Kelly+(2010), Shen & Kelly (2012)

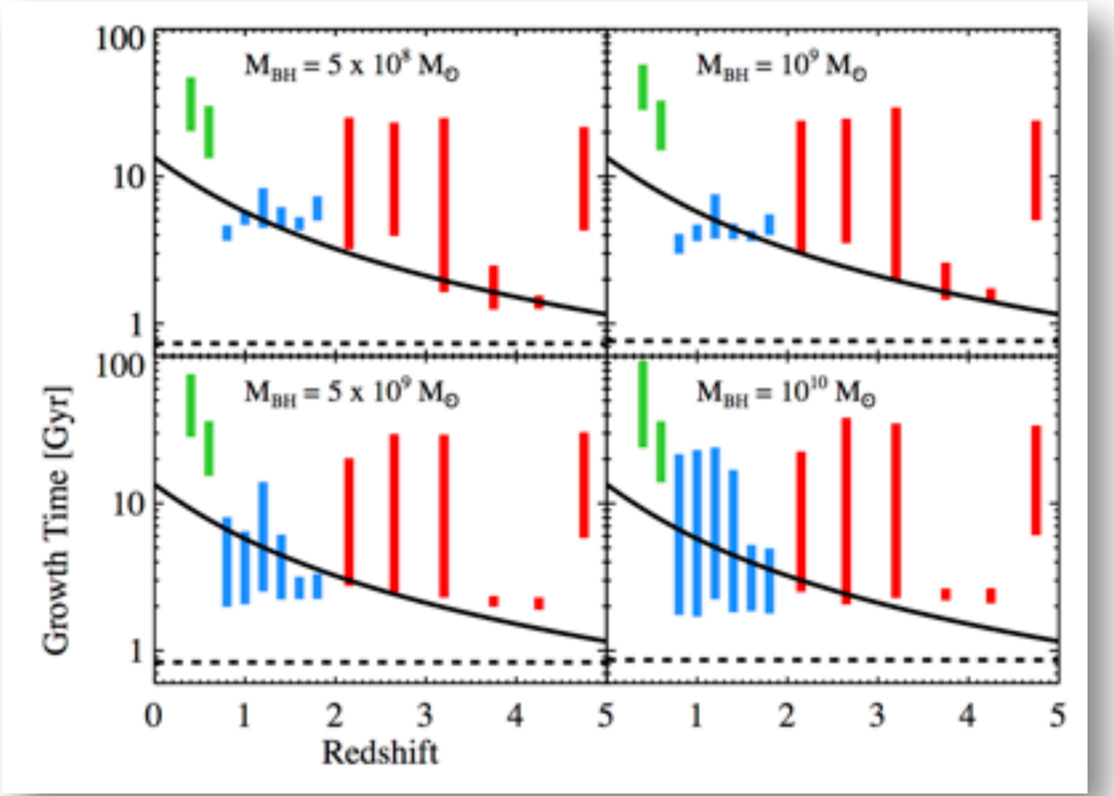
Type 1 Quasar Black Hole Eddington Ratio Function



Kelly & Shen 2013

Implied typical BH growth times

- Typical growth time at z > 2 comparable to or longer than Hubble time
- Implies earlier stage of (obscured?) accelerated growth
- z < 0.8: Long growth times reflect low Eddington ratio, re-ignition of BH activity (see also Heckman+2004, Kauffmann & Heckman 2009)



Kelly & Shen (2013)

See also Kelly+(2010), Trakhtenbrot+2011, this conference

Alternative methods for estimating mass: X-ray variability

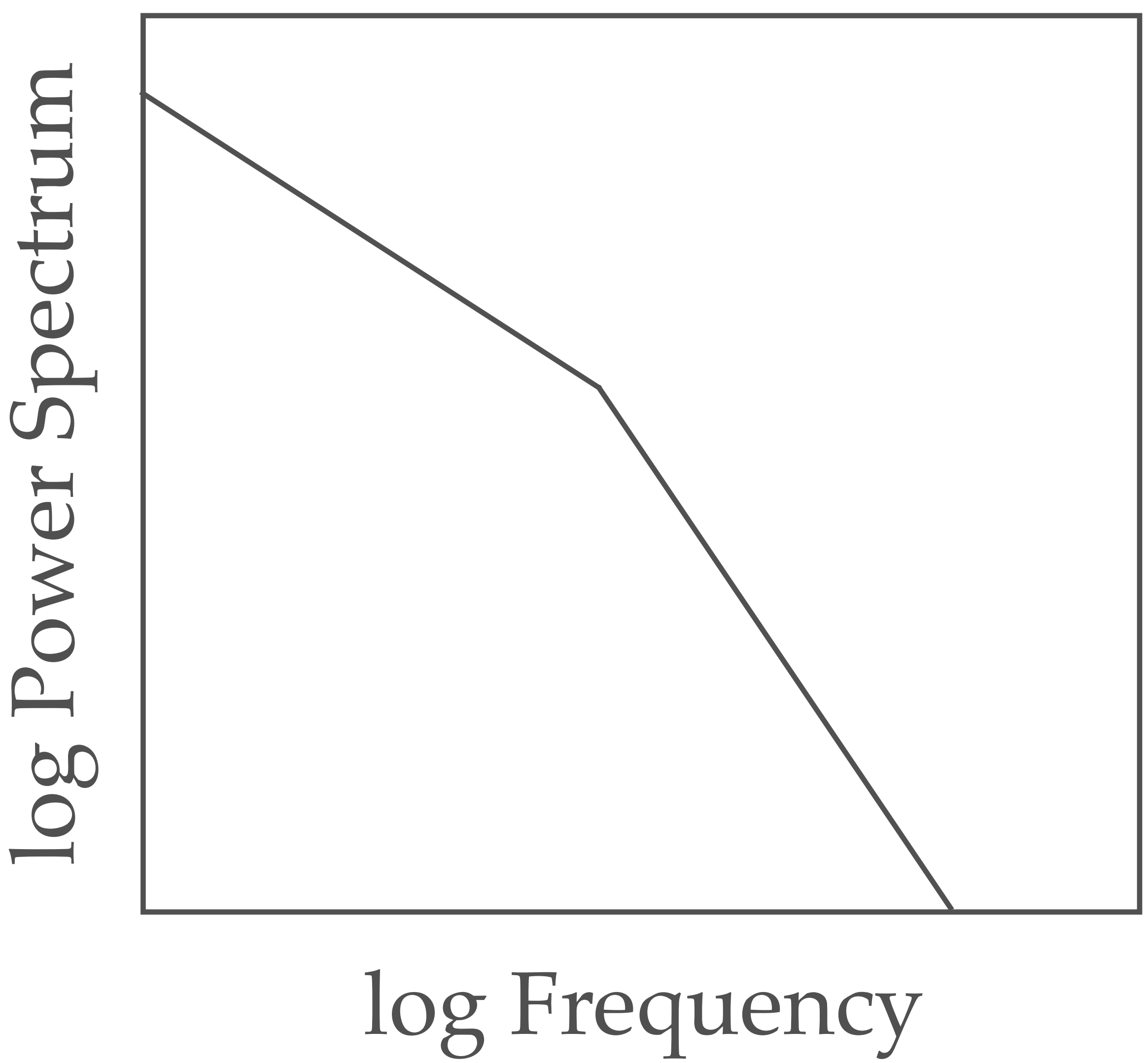
Alternative methods for estimating mass: X-ray variability

- Broad line scaling relationships may exhibit systematics:
  - Difficult to measure FWHM in low S/N spectra
  - Distribution of high-z/luminous quasars imply smaller statistical scatter in mass estimates compared to calibration (reverberation mapping) sample (e.g., Kollmeier+2006, Shen+2008, Steinhardt & Elvis 2010, Shen & Kelly 2012, Kelly & Shen 2013)
  - Extrapolation beyond emission line properties of calibration sample

Alternative methods for estimating mass: X-ray variability

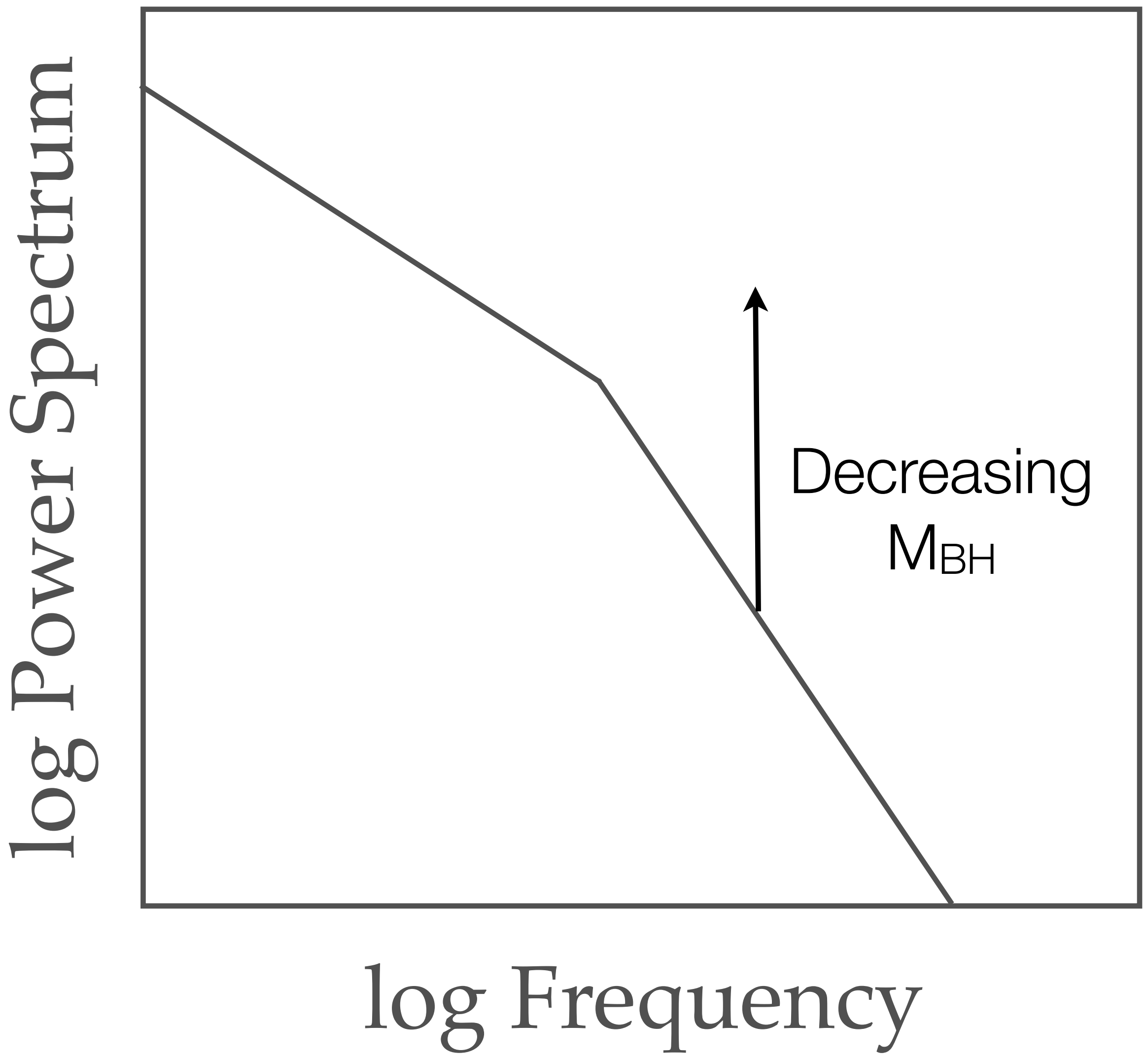
- Broad line scaling relationships may exhibit systematics:
  - Difficult to measure FWHM in low S/N spectra
  - Distribution of high-z/luminous quasars imply smaller statistical scatter in mass estimates compared to calibration (reverberation mapping) sample (e.g., Kollmeier+2006, Shen+2008, Steinhardt & Elvis 2010, Shen & Kelly 2012, Kelly & Shen 2013)
  - Extrapolation beyond emission line properties of calibration sample
- Mass estimates derived from X-ray variability:
  - Help balance out systematics (unknown unknowns)
  - In principle a clean measurement, no modeling of ‘nuisance’ components
  - In reality, is difficult measurement for noisy and/or irregularly sampled lightcurves

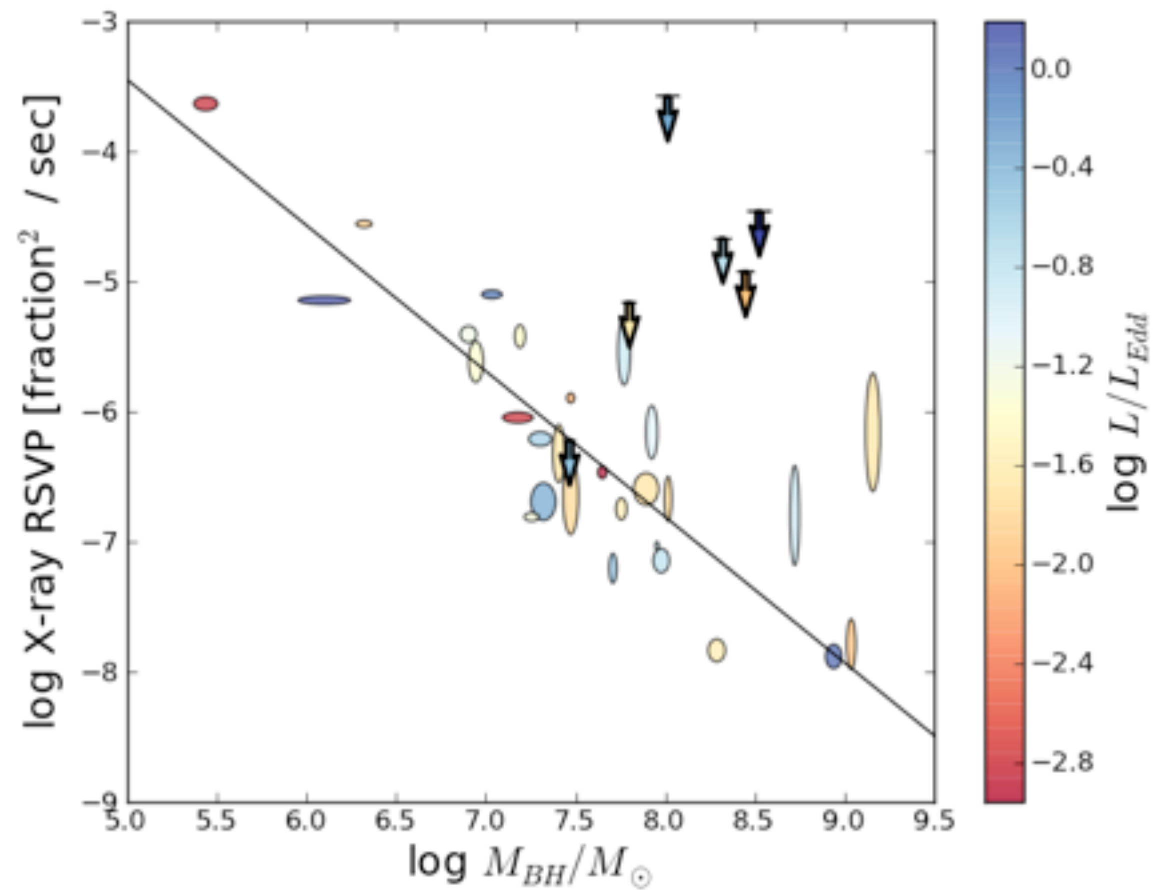
Amplitude of high-frequency X-ray variability scales with BH mass



See also, e.g., Yu & Lu (2001), Nikolajuk+(2004), Papadakis (2004), O'Neill+(2005), Miniutti+(2009), Caballero-Garcia+(2012)

Amplitude of high-frequency X-ray variability scales with BH mass





Kelly+(2013)

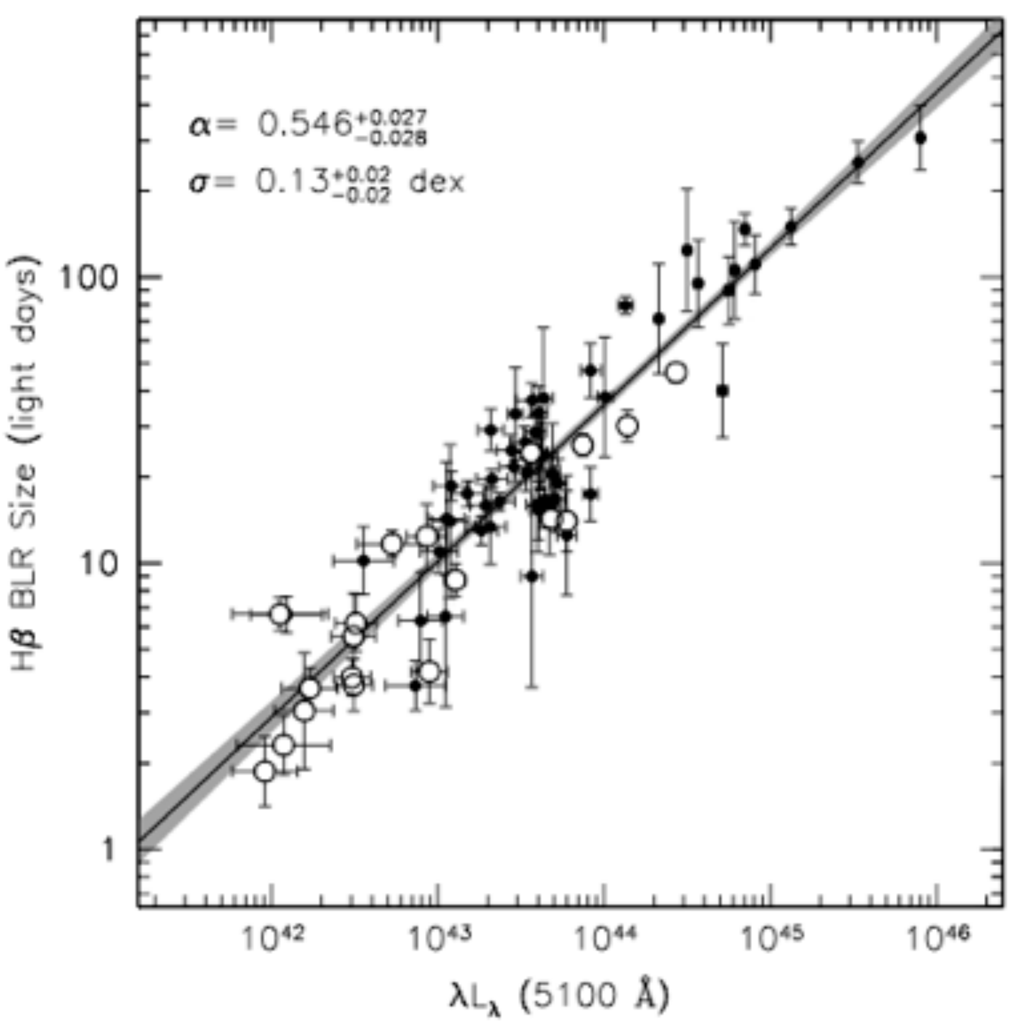
See also, e.g., Yu & Lu (2001), Nikolajuk+(2004), Papadakis (2004), O'Neill+(2005), Miniutti+(2009), Caballero-Garcia+(2012)

Summary

- SDSS incomplete at $M_{BH} < 5 \times 10^8 M_{Sun}$ and $L / L_{Edd} < 0.1$
- No evidence for a turnover in BH mass or Eddington ratio distribution down to incompleteness limits
- Typical growth times of most massive BHs comparable to Hubble time at $z > 2$
    - Earlier stage of accelerated obscured growth?
- X-ray variability provides a competitive method for estimating BH mass
    - May enable BH mass function estimation from several-epoch X-ray surveys

How do we estimate black hole mass for (Type 1) quasars?

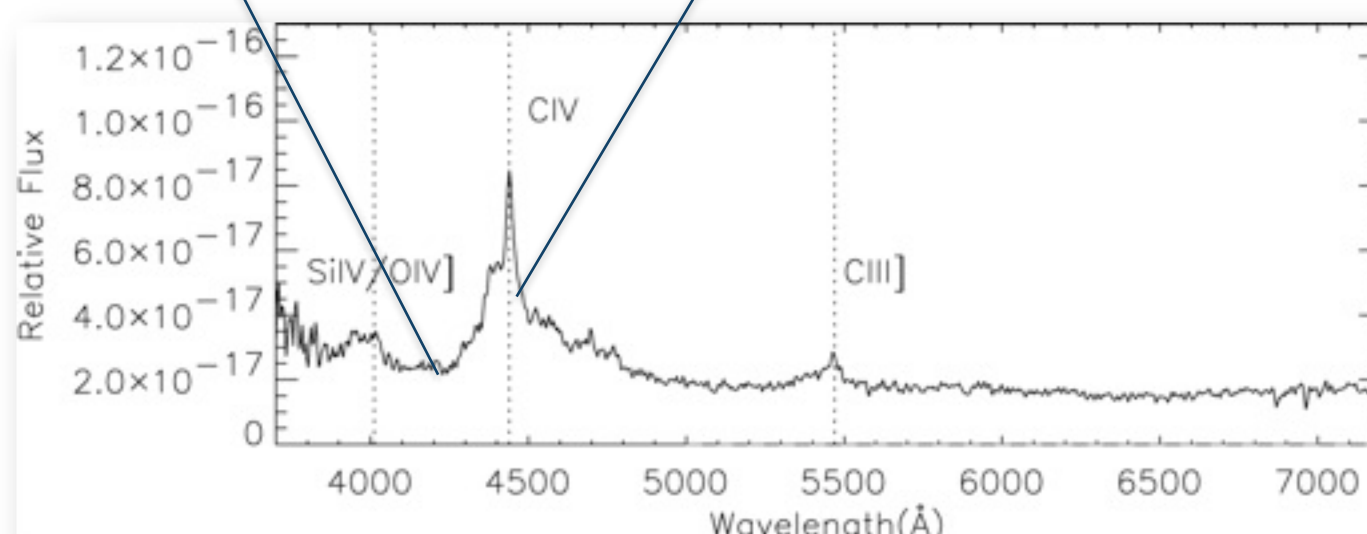
Bentz+(2013)



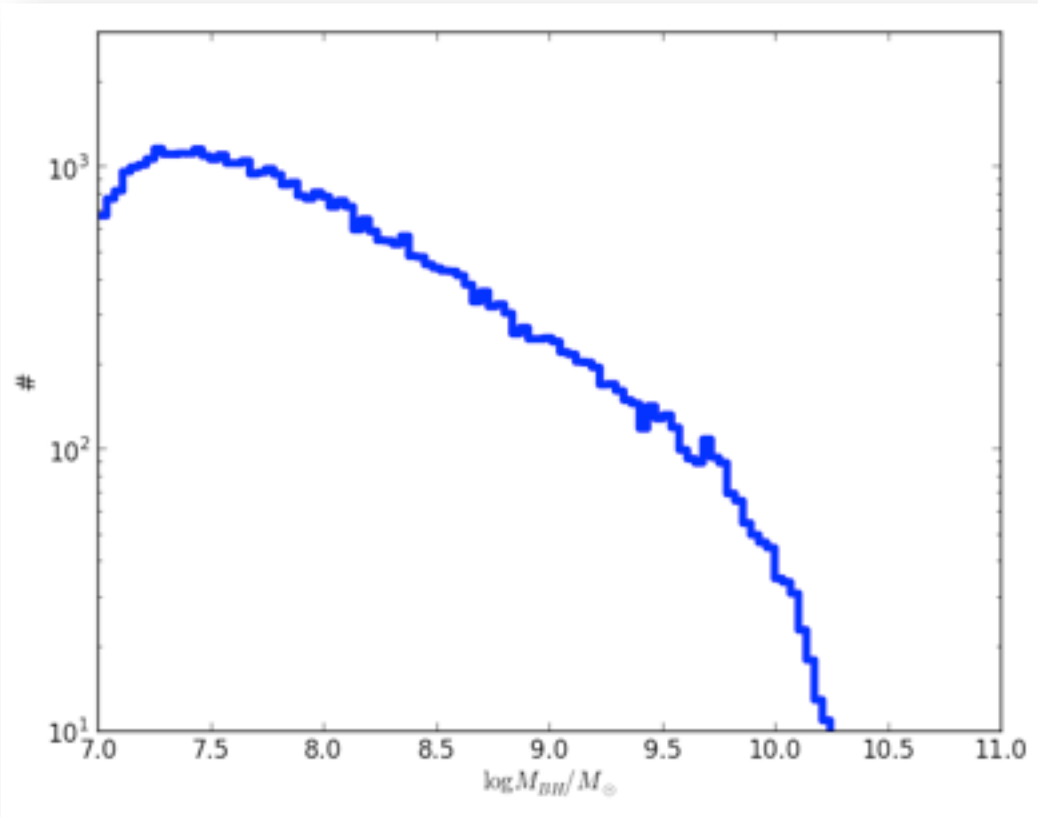
$$\hat{M}_{BH} \propto L_\lambda^{1/2} FWHM^2$$

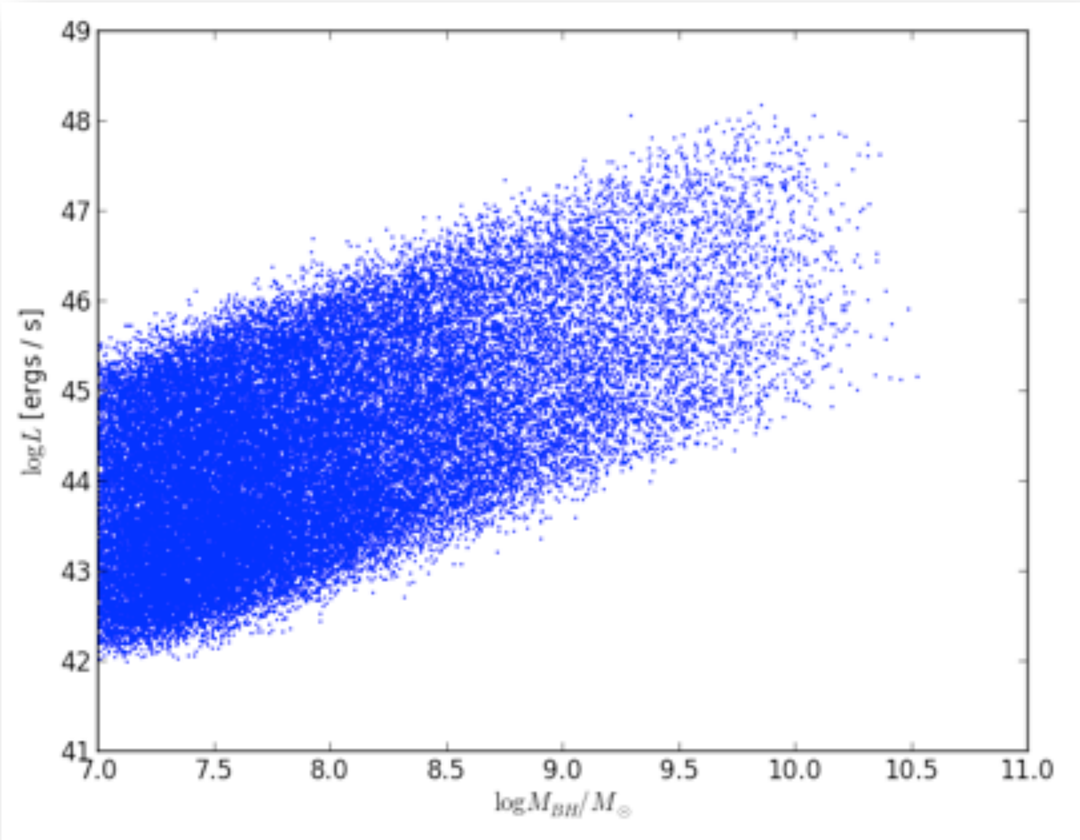
$$M_{BH} \propto RV^2$$

$$L_\lambda^{1/2} \propto R \qquad FWHM \propto V$$

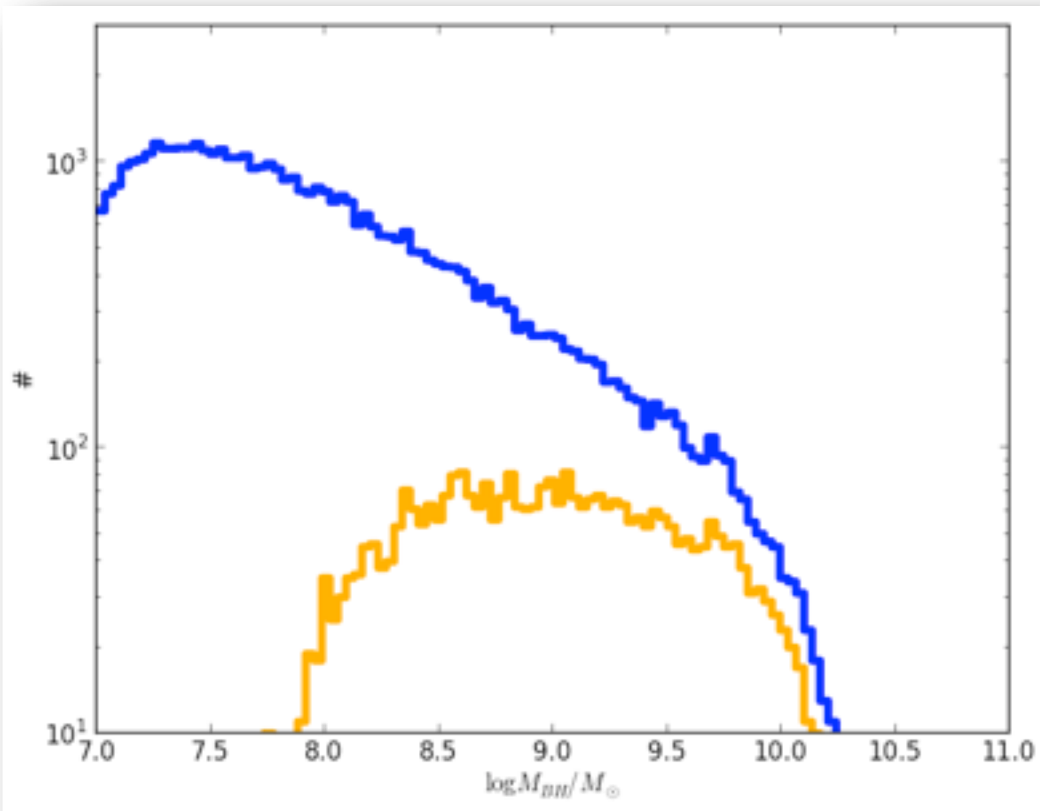


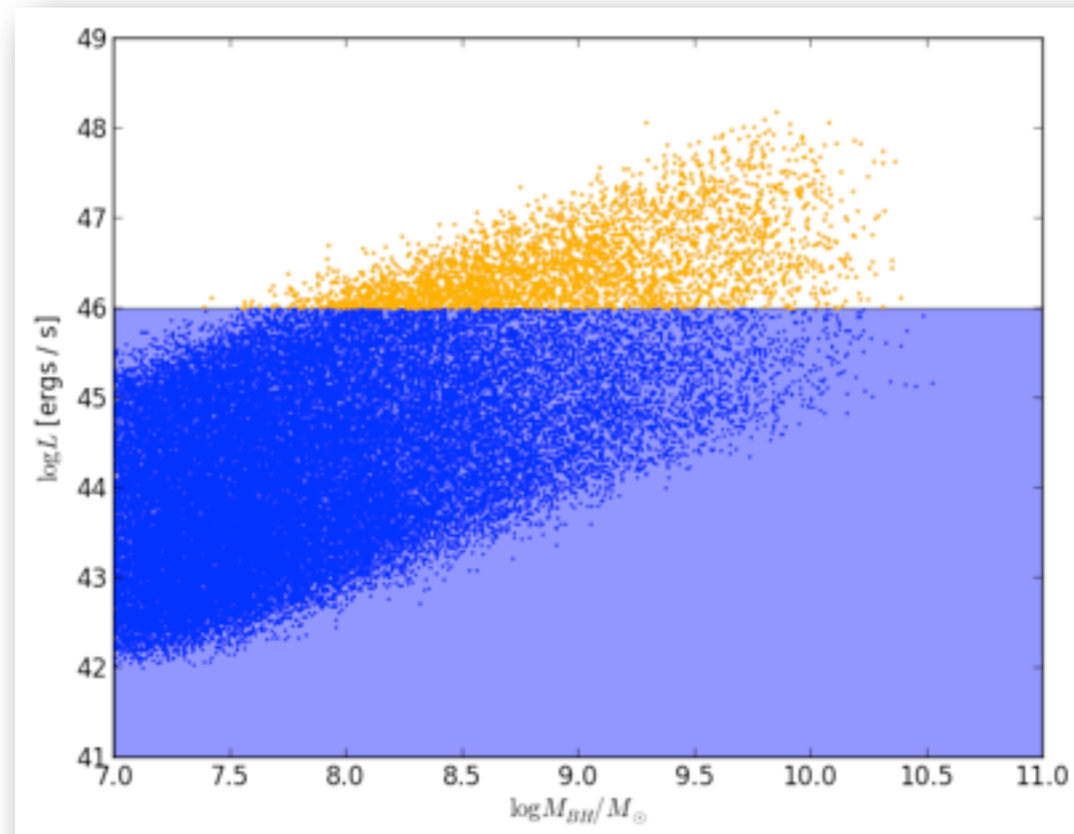
Two Problems: Incompleteness and Uncertainties in the Mass Estimates



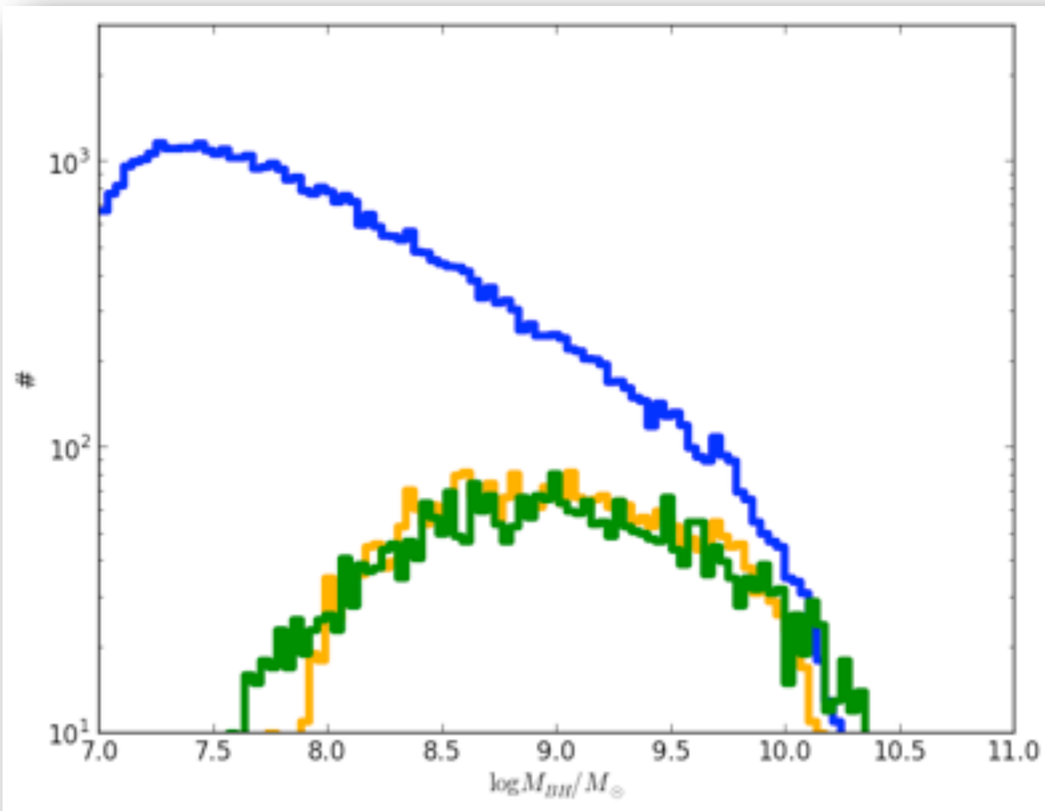


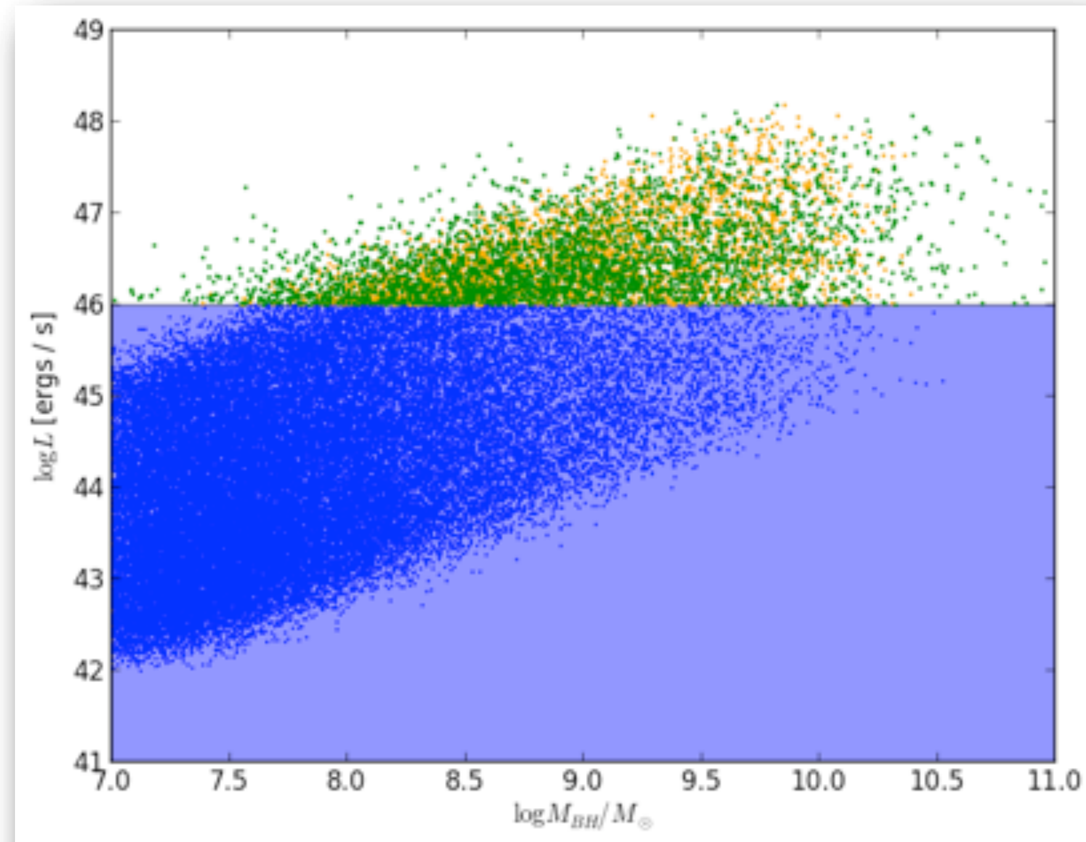
Two Problems: Incompleteness and Uncertainties in the Mass Estimates



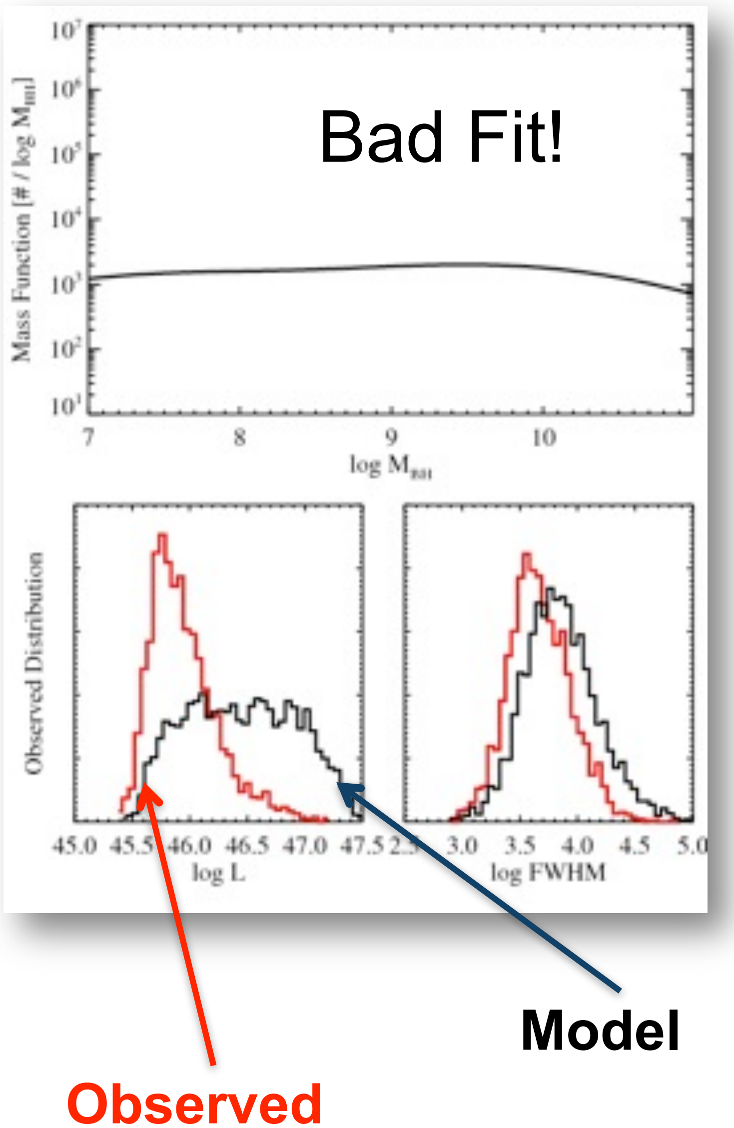


Two Problems: Incompleteness and Uncertainties in the Mass Estimates

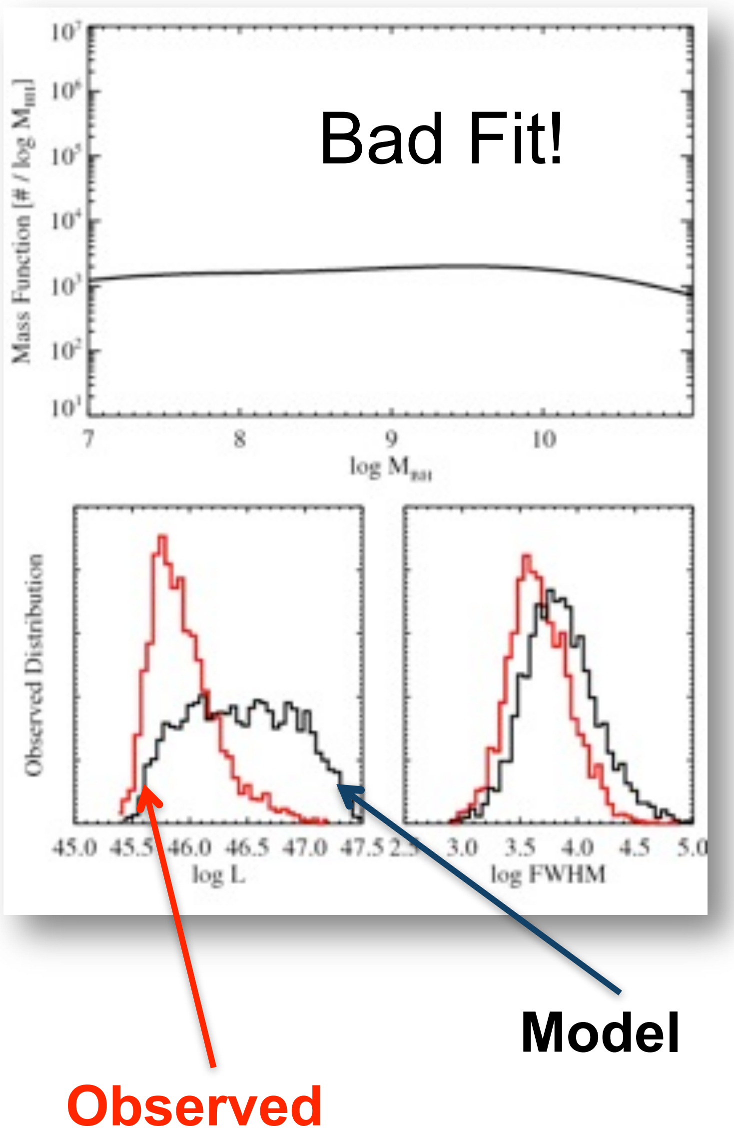


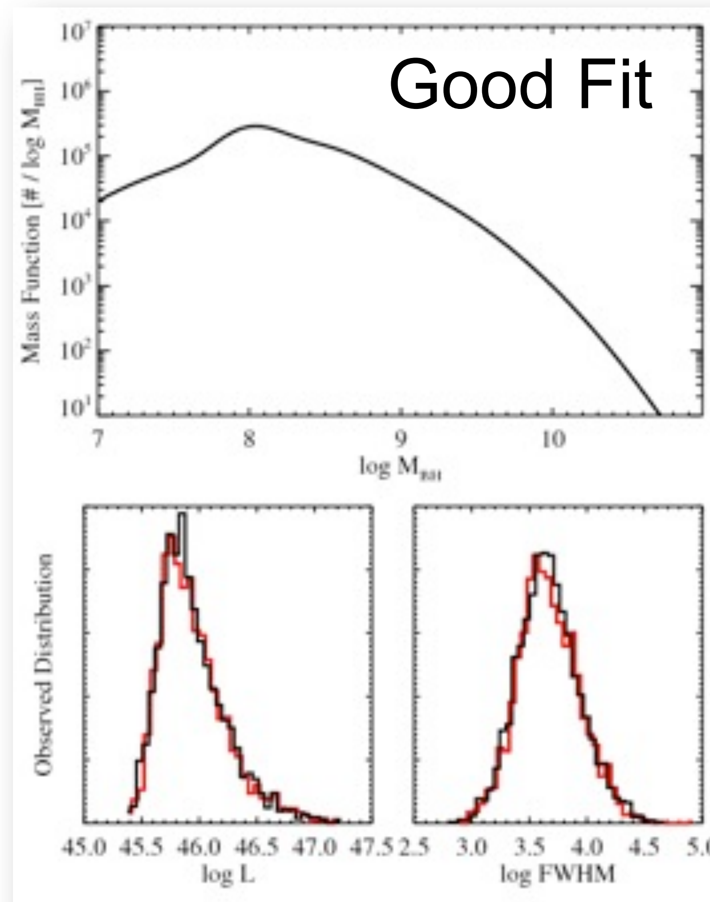


Correcting for biases: A Bayesian approach (Kelly, Vestergaard, & Fan 2009)

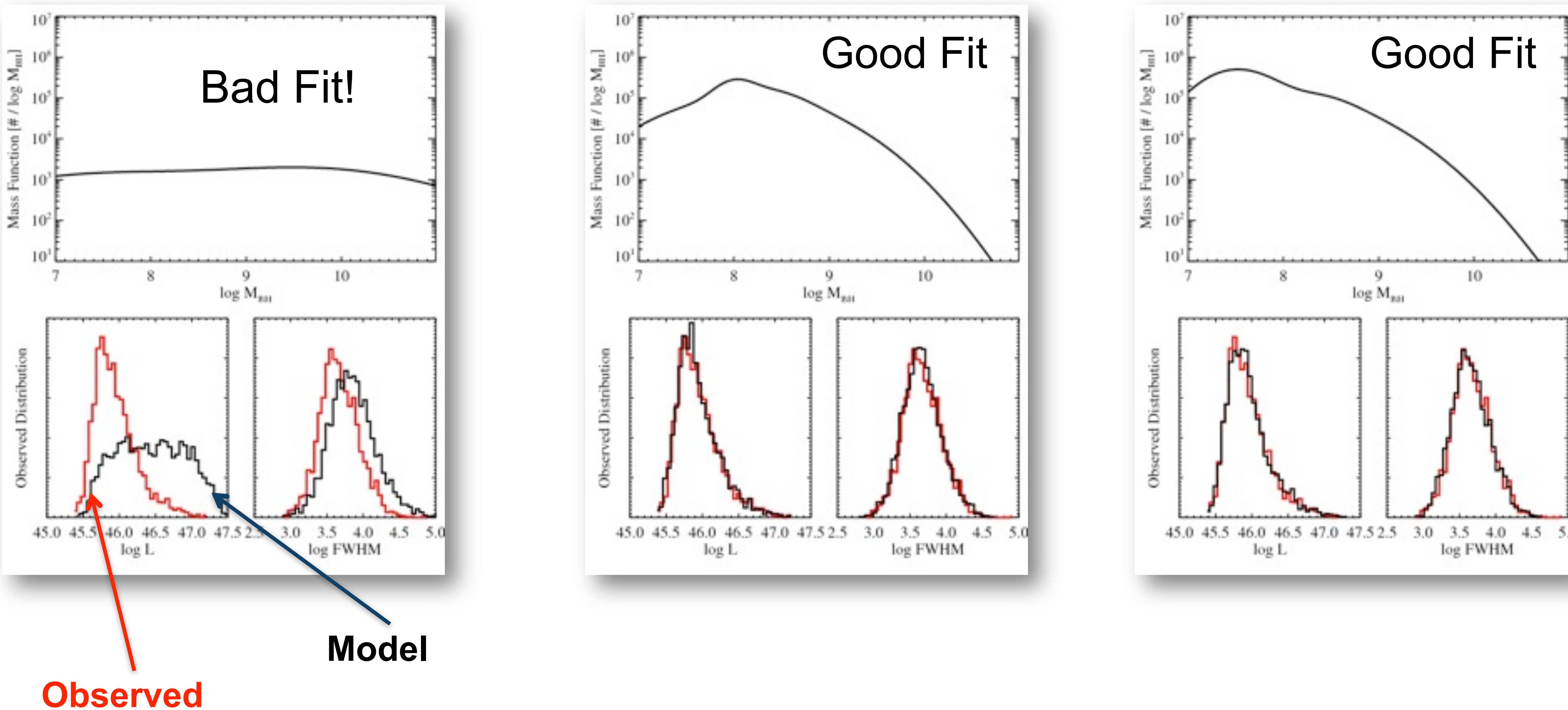


Correcting for biases: A Bayesian approach (Kelly, Vestergaard, & Fan 2009)

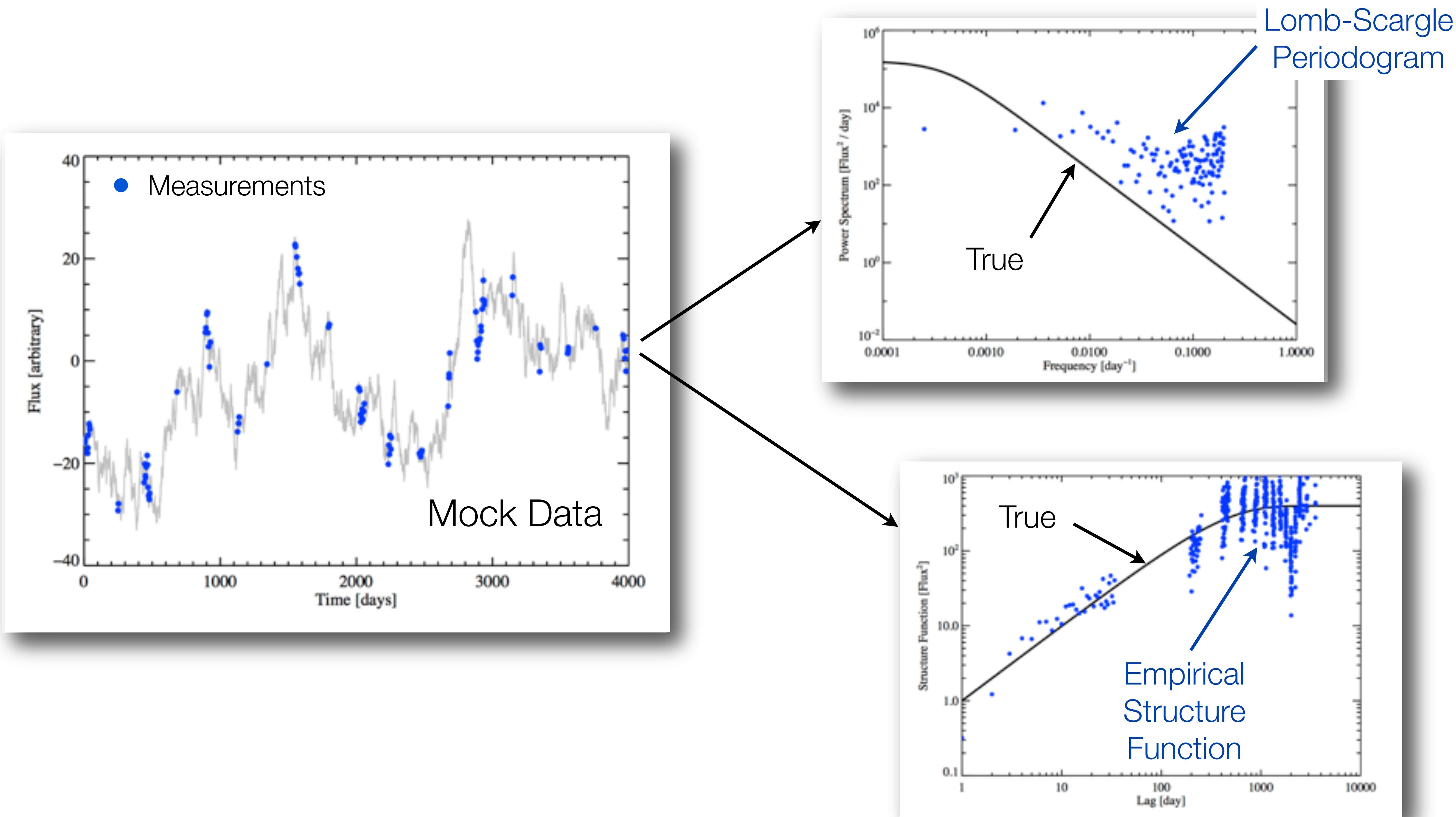




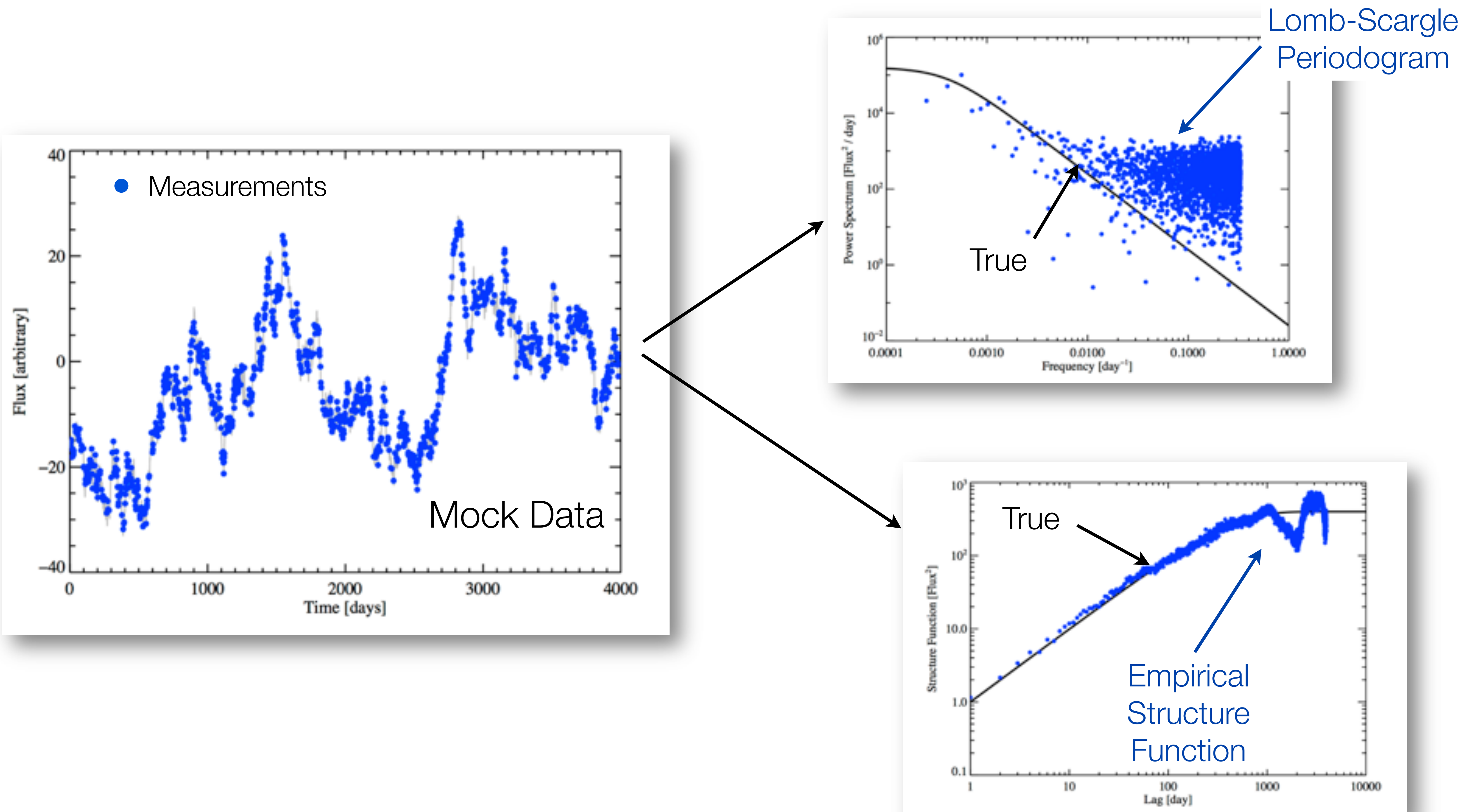
Correcting for biases: A Bayesian approach (Kelly, Vestergaard, & Fan 2009)



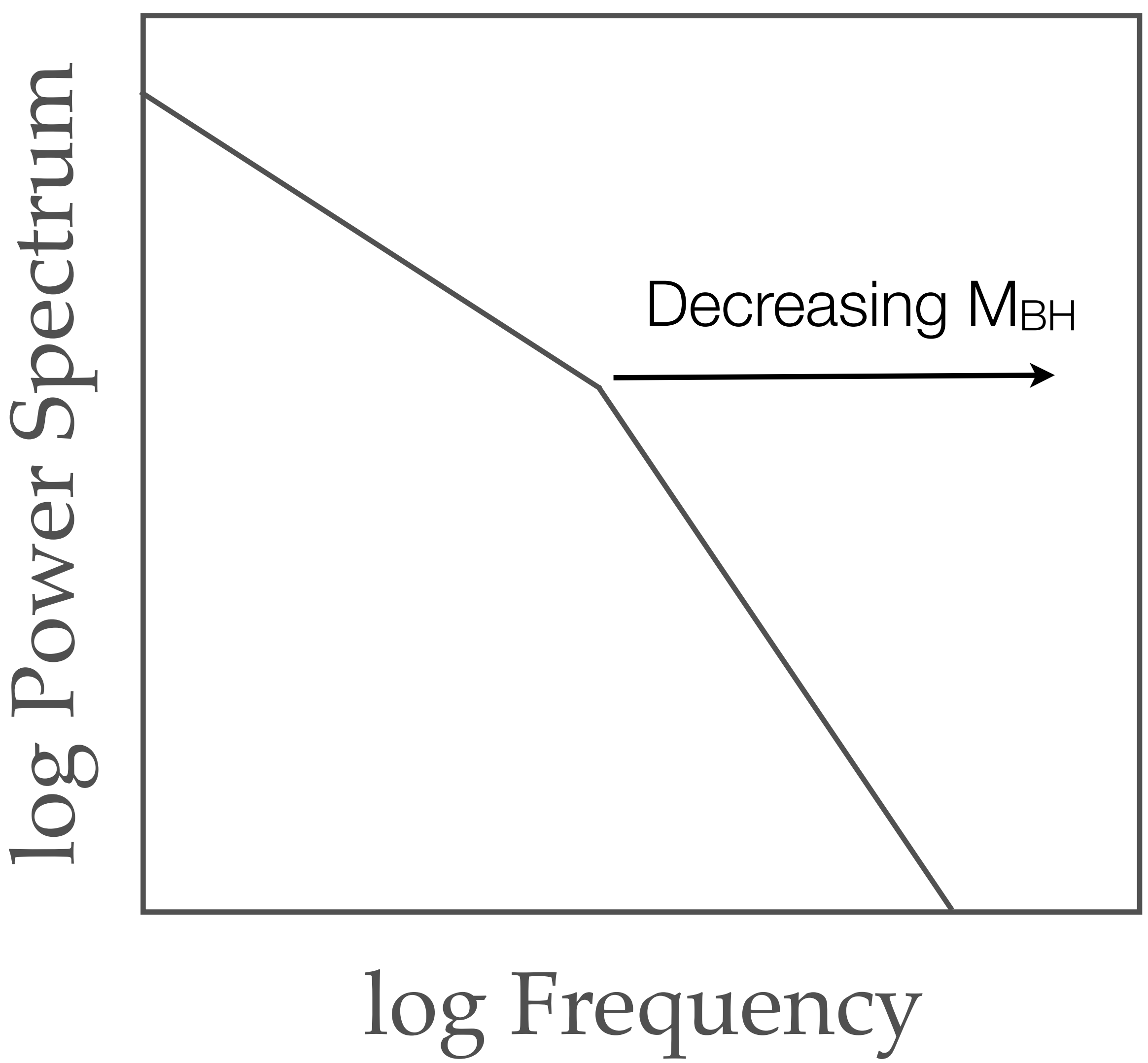
Disadvantages of Traditional Non-parameteric Tools for Quantifying Aperiodic Variability

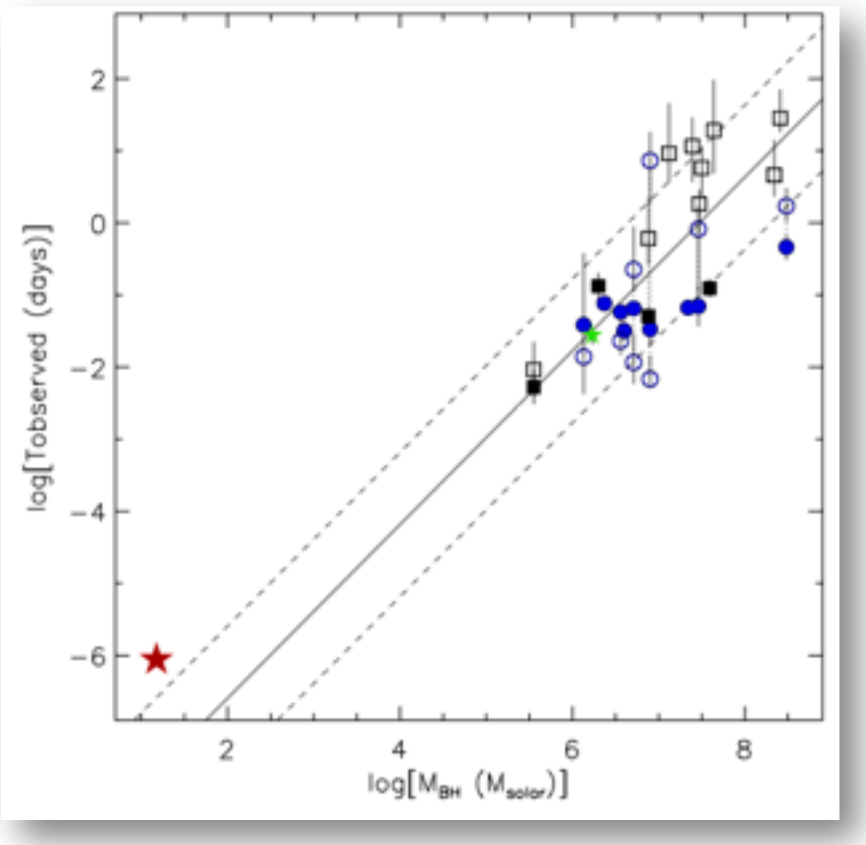


Disadvantages of Traditional Non-parameteric Tools for Quantifying Aperiodic Variability



X-ray variability features scale with black hole mass

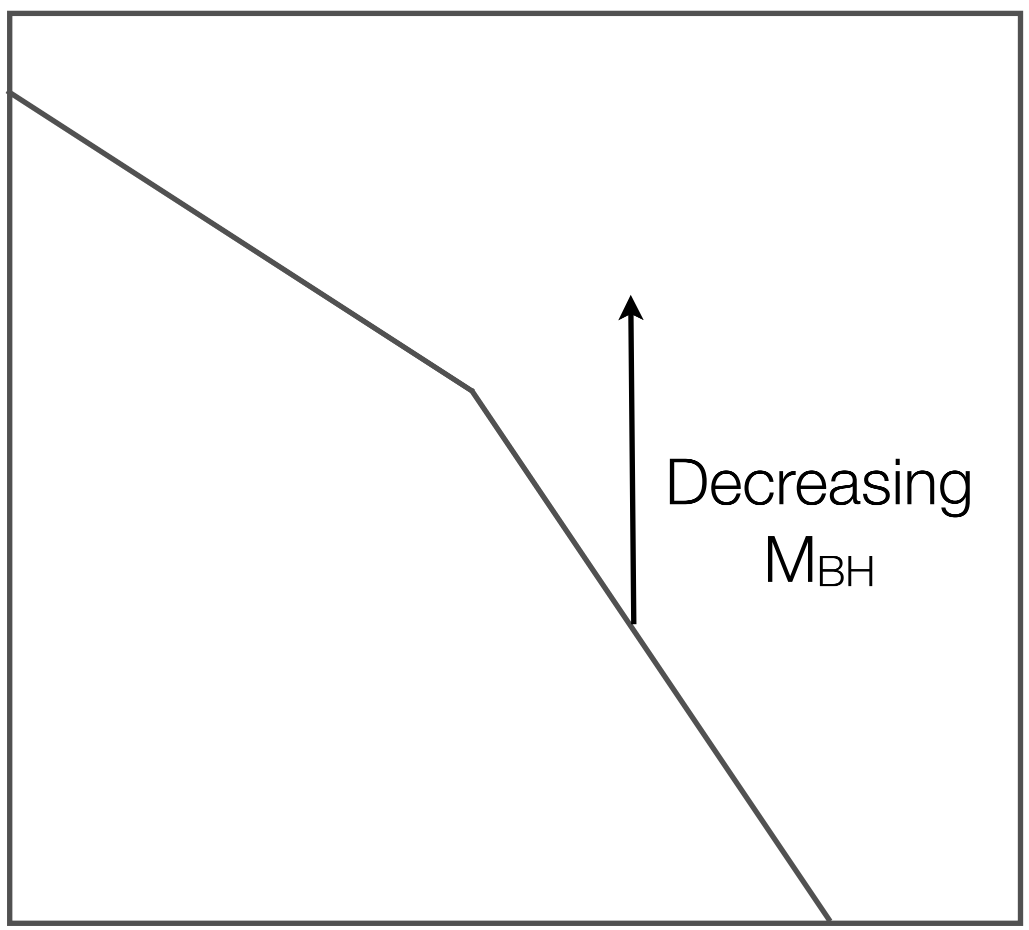




Gonzalez-Martin & Vaughan (2012)

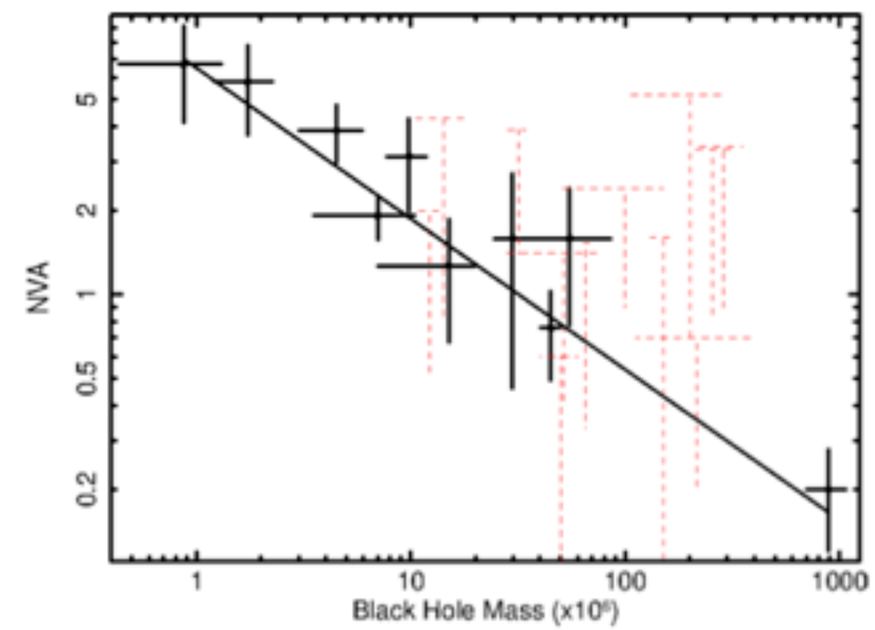
See also, e.g., Yu & Lu (2001), Nikolajuk+(2004), Papadakis (2004), O'Neill+(2005), Miniutti+(2009), Caballero-Garcia+(2012)

X-ray variability features scale with black hole mass



log Power Spectrum

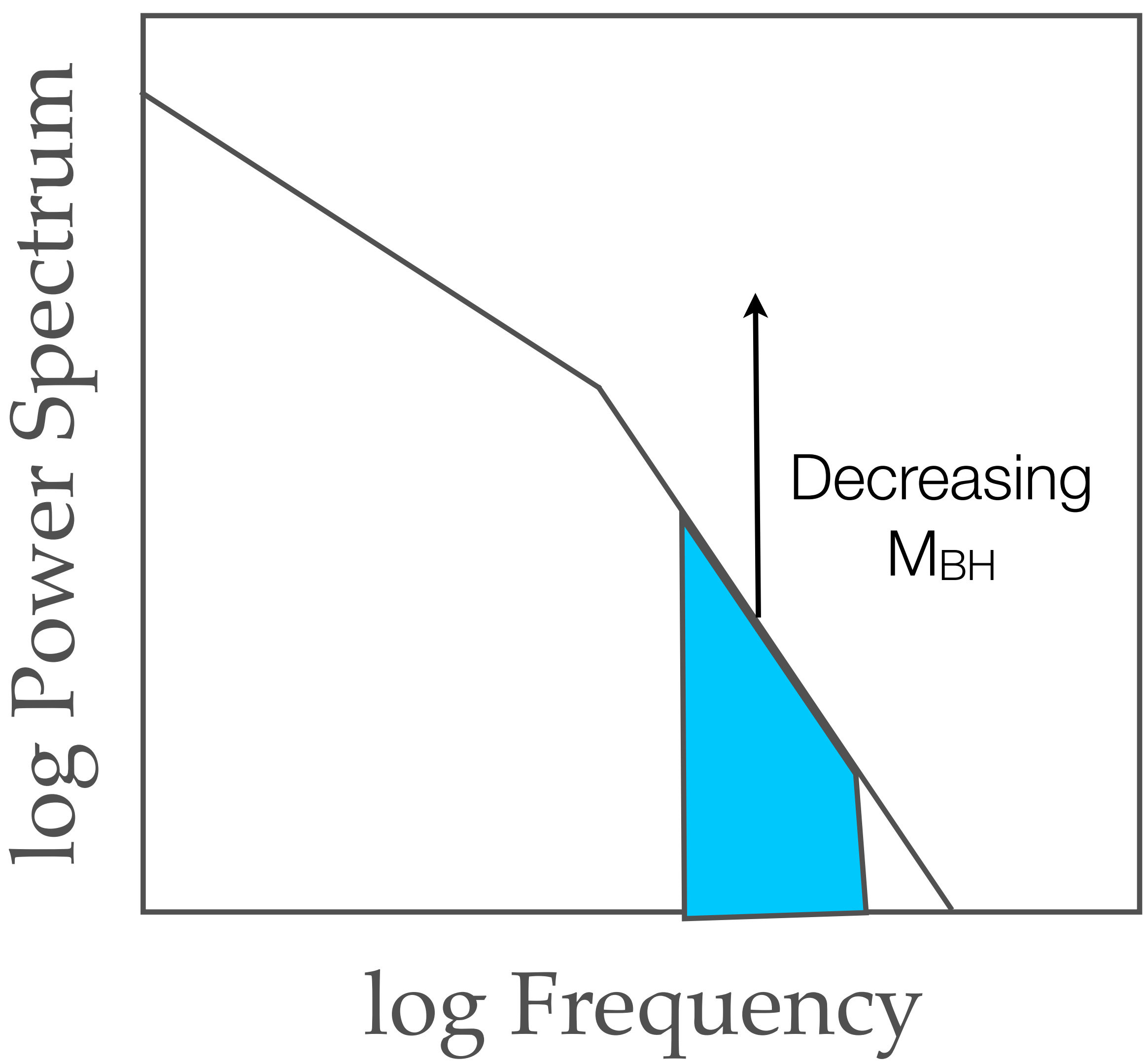
log Frequency



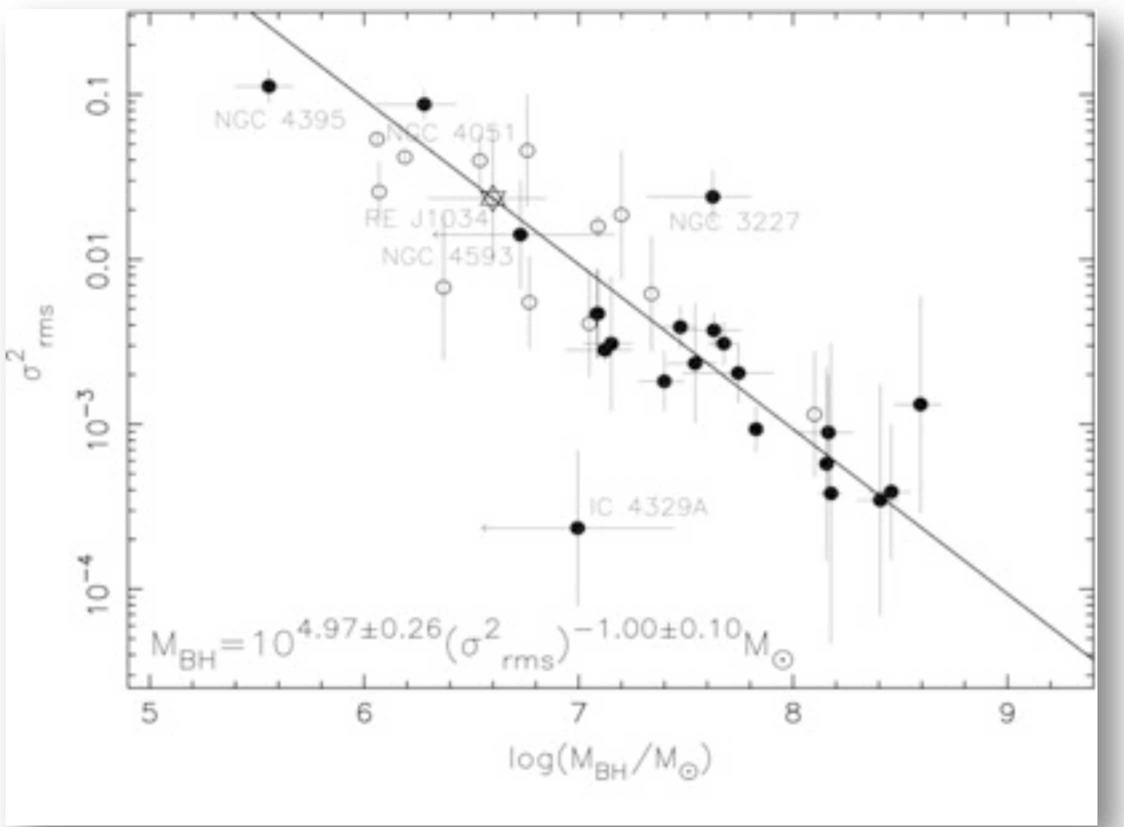
McHardy (2013)

See also, e.g., Yu & Lu (2001), Nikolajuk+(2004), Papadakis (2004), O'Neill+(2005), Miniutti+(2009), Caballero-Garcia+(2012)

X-ray variability features scale with black hole mass



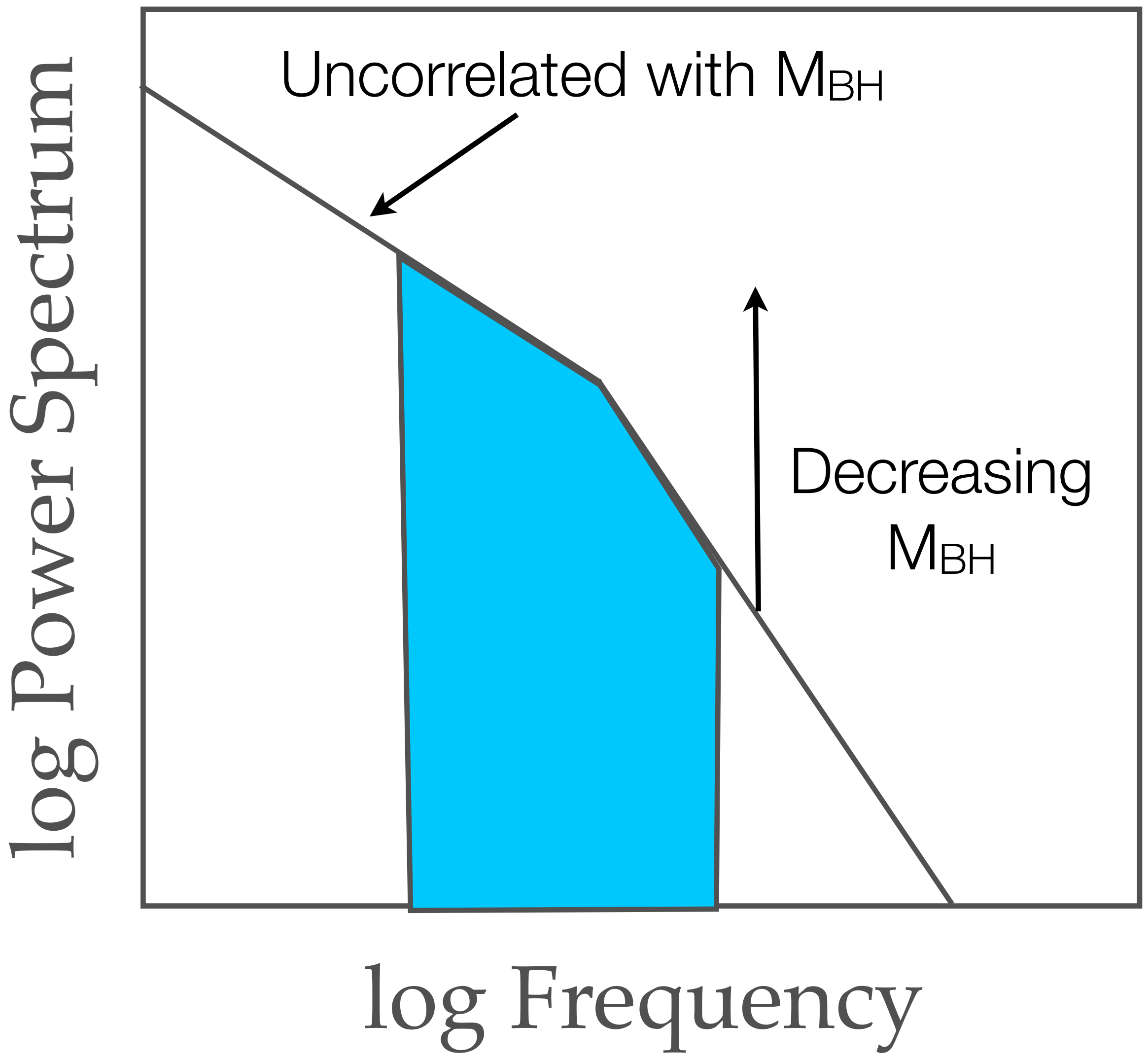
Excess X-ray Variance



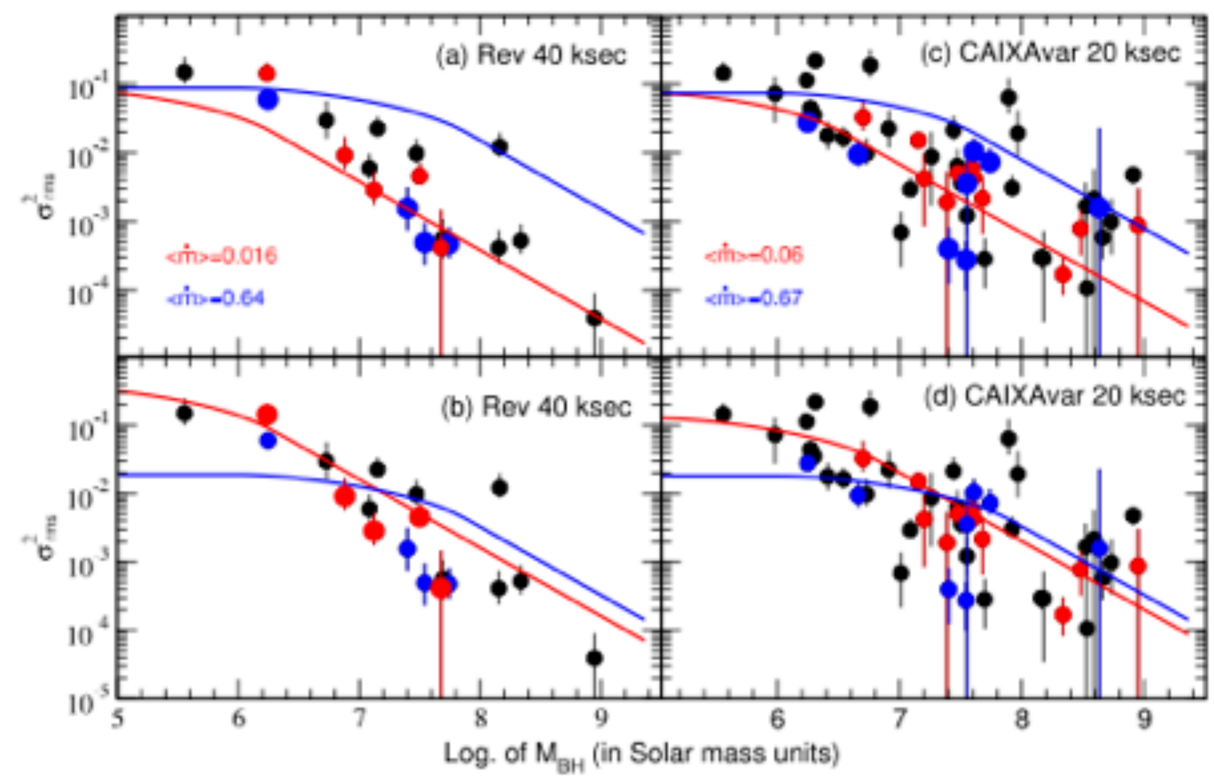
Zhou+(2010)

See also, e.g., Yu & Lu (2001), Nikolajuk+(2004), Papadakis (2004), O'Neill+(2005), Miniutti+(2009), Caballero-Garcia+(2012)

X-ray variability features scale with black hole mass

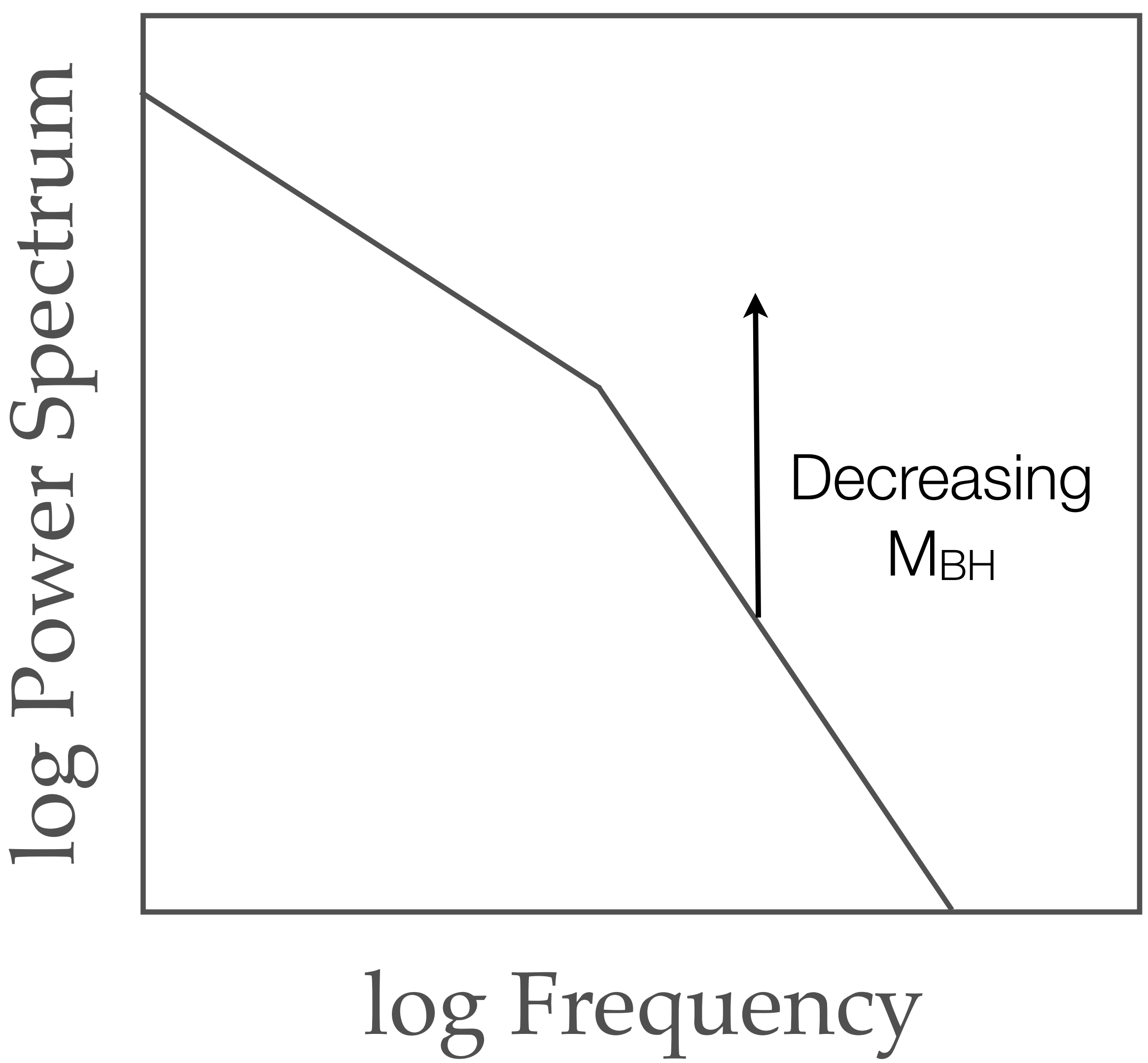


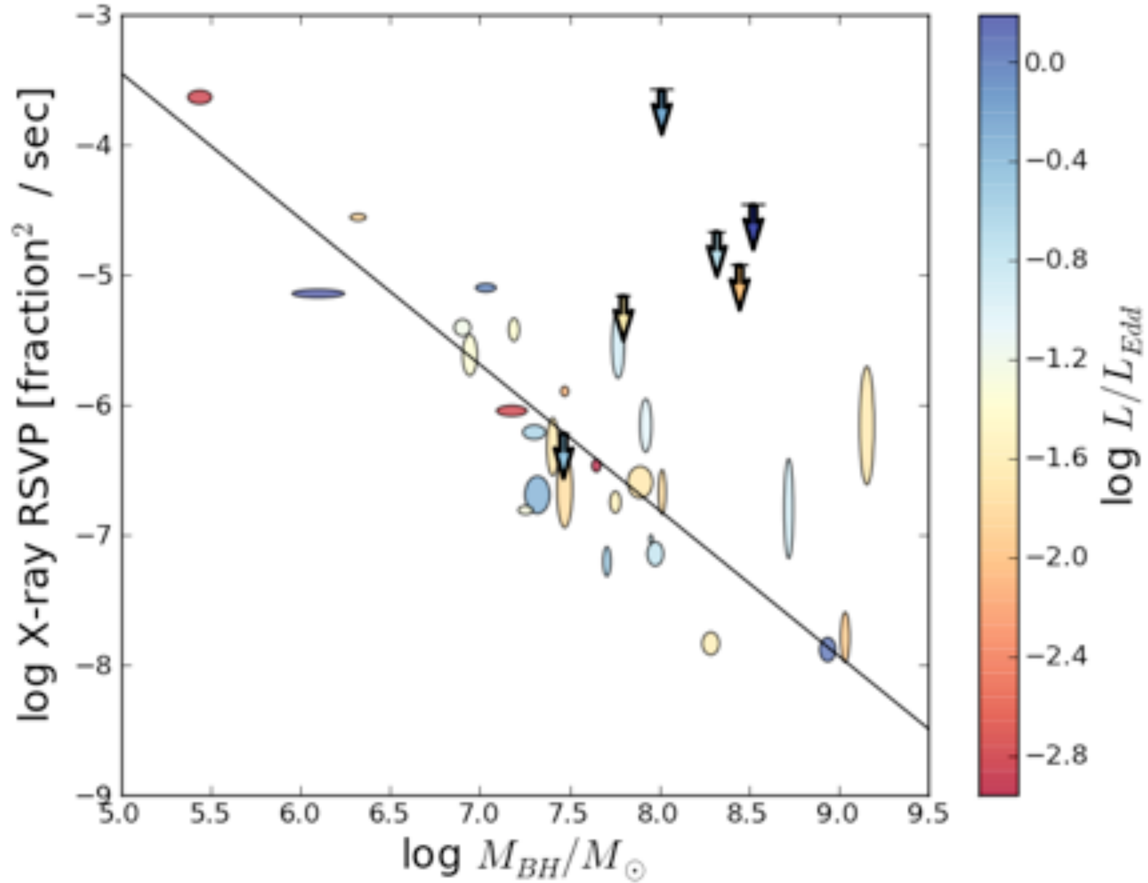
Excess X-ray Variance



See also, e.g., Yu & Lu (2001), Nikolajuk+(2004), Papadakis (2004), O'Neill+(2005), Miniutti+(2009), Caballero-Garcia+(2012)

X-ray variability features scale with black hole mass

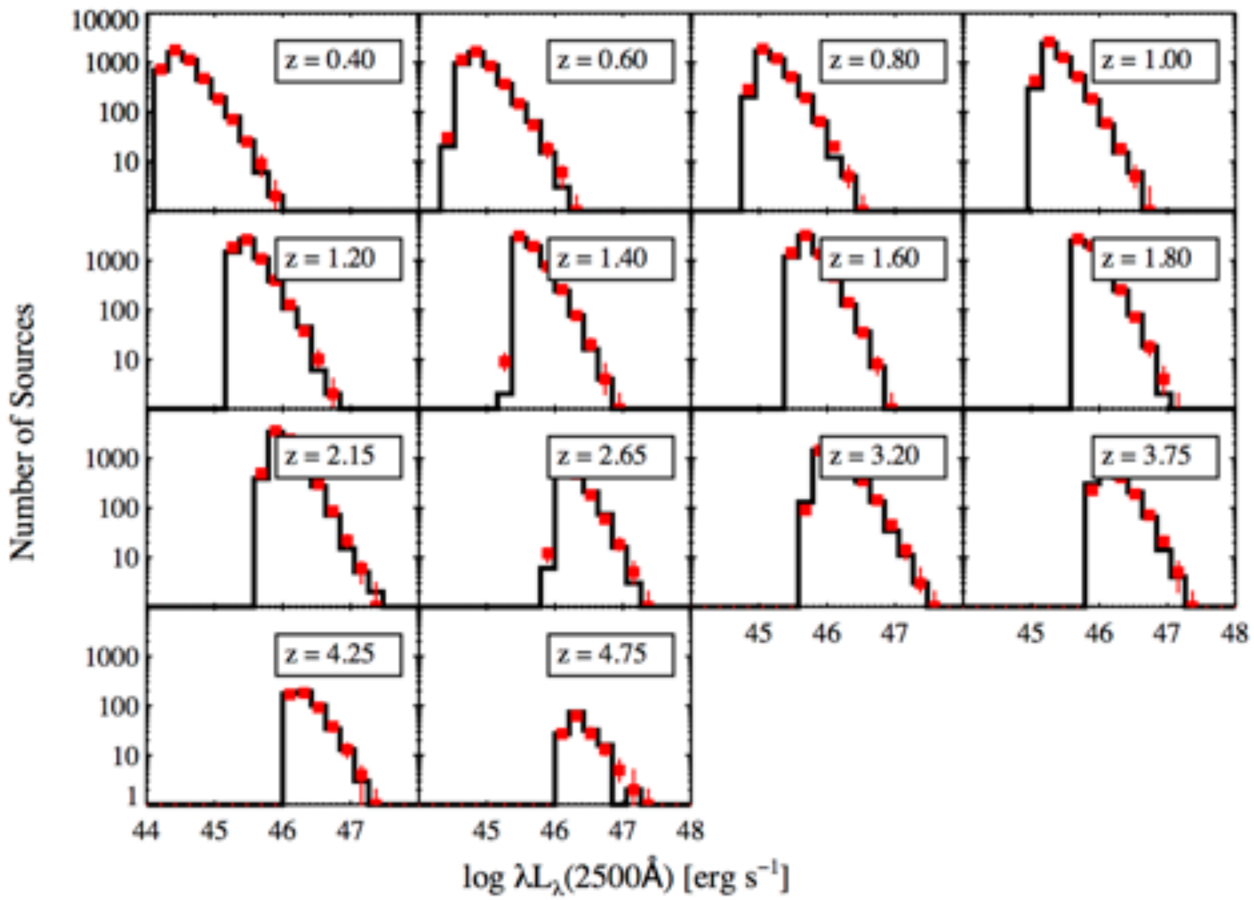


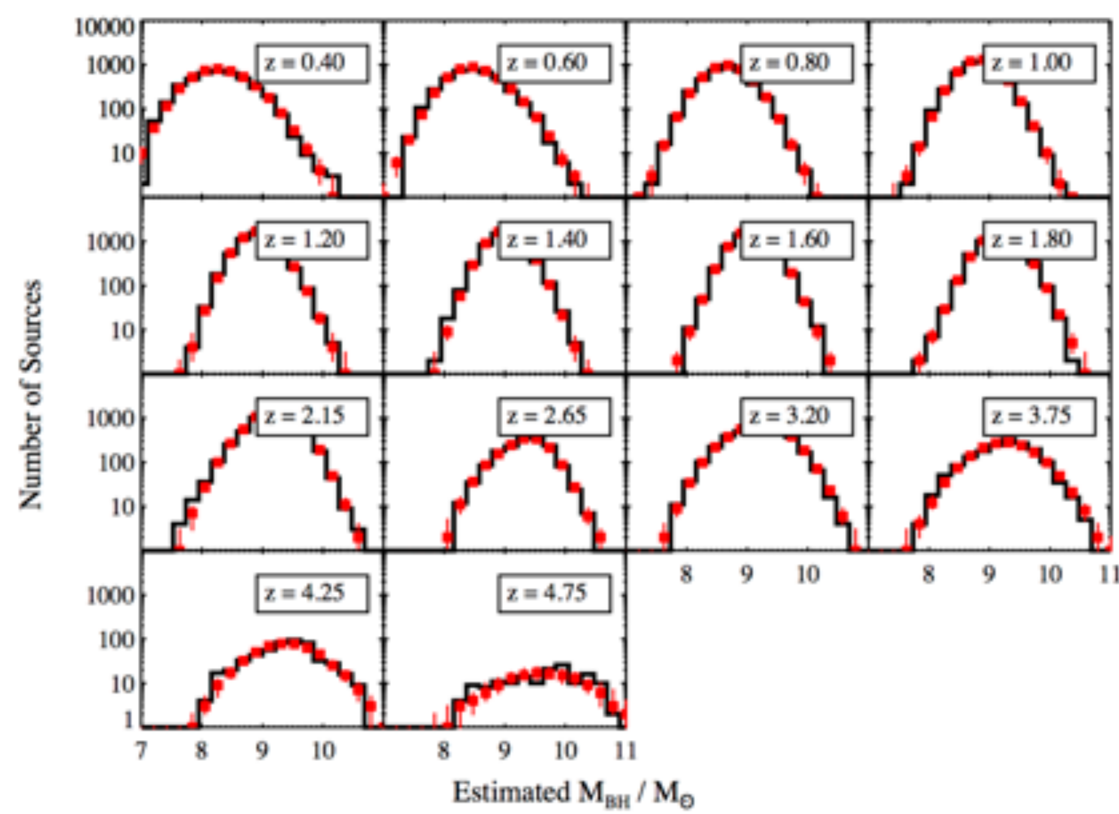


Kelly+(2013)

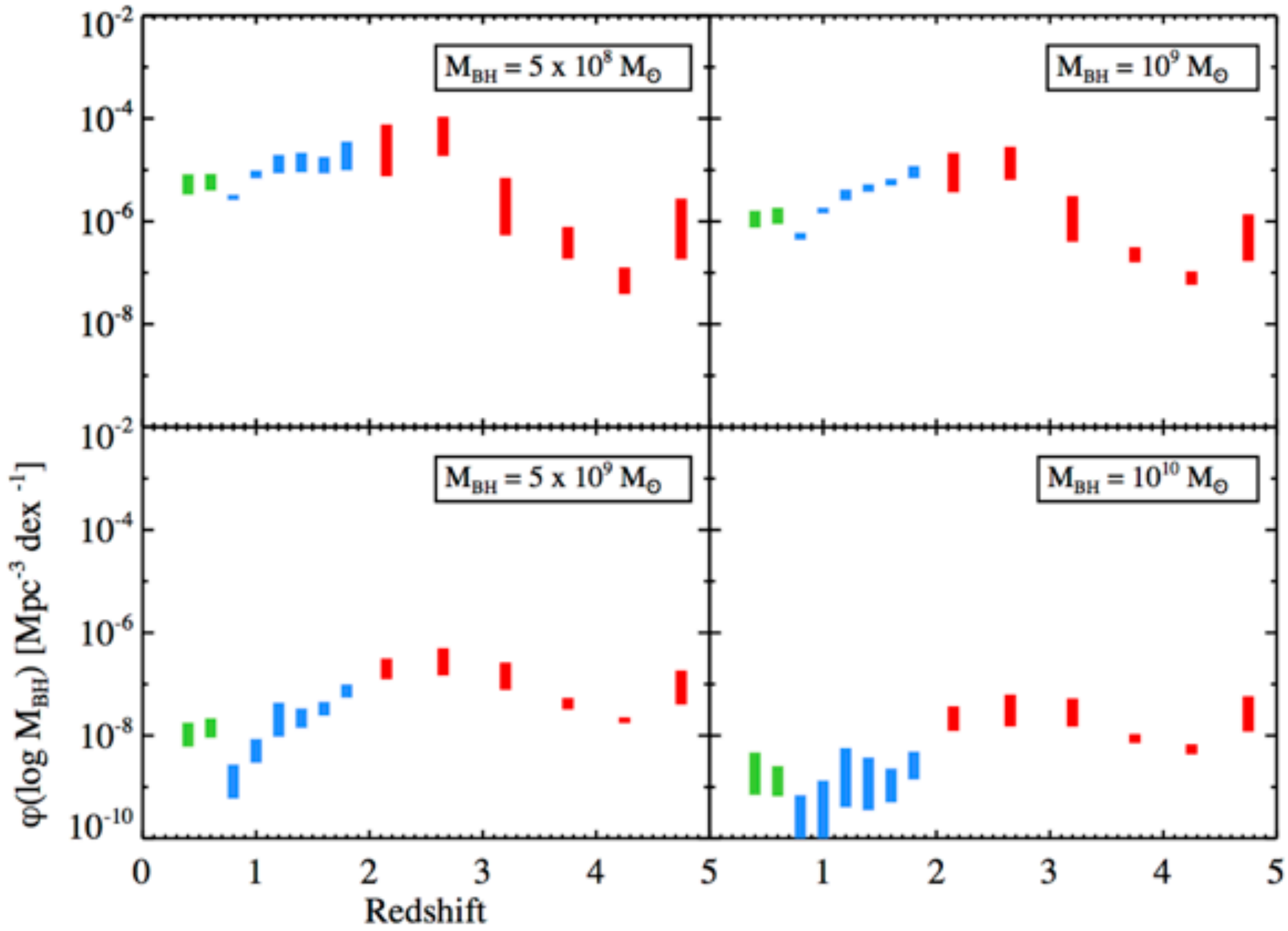
See also, e.g., Yu & Lu (2001), Nikolajuk+(2004), Papadakis (2004), O'Neill+(2005), Miniutti+(2009), Caballero-Garcia+(2012)

Checking the Fit



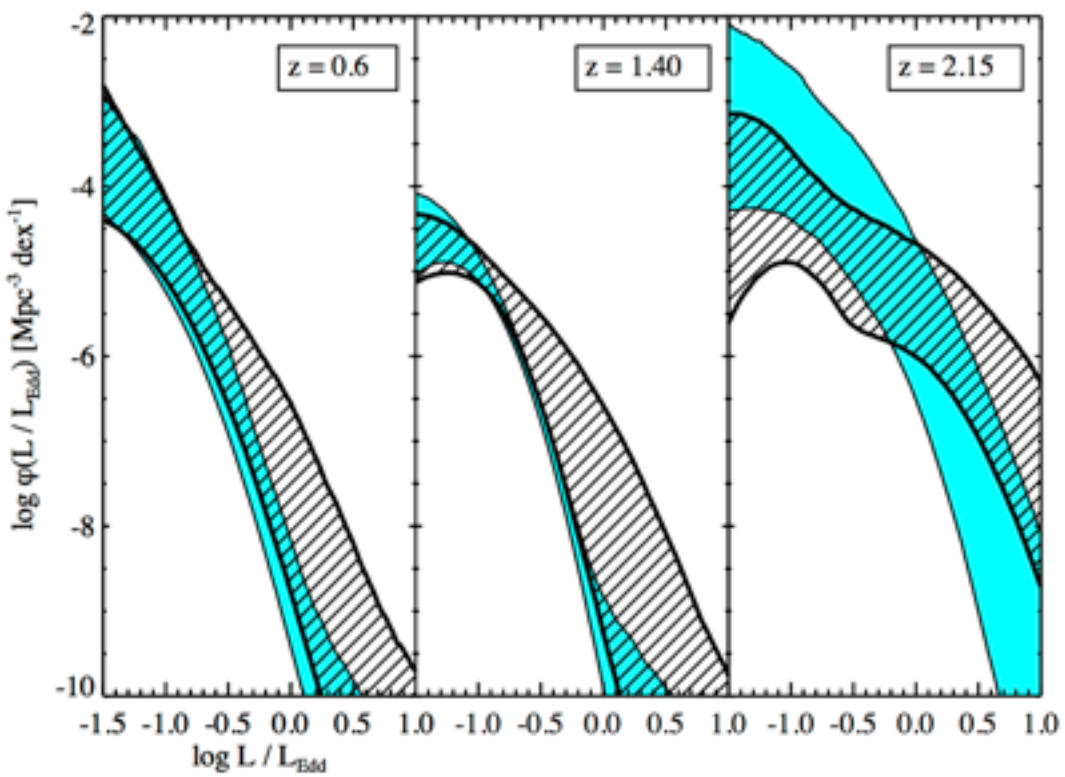


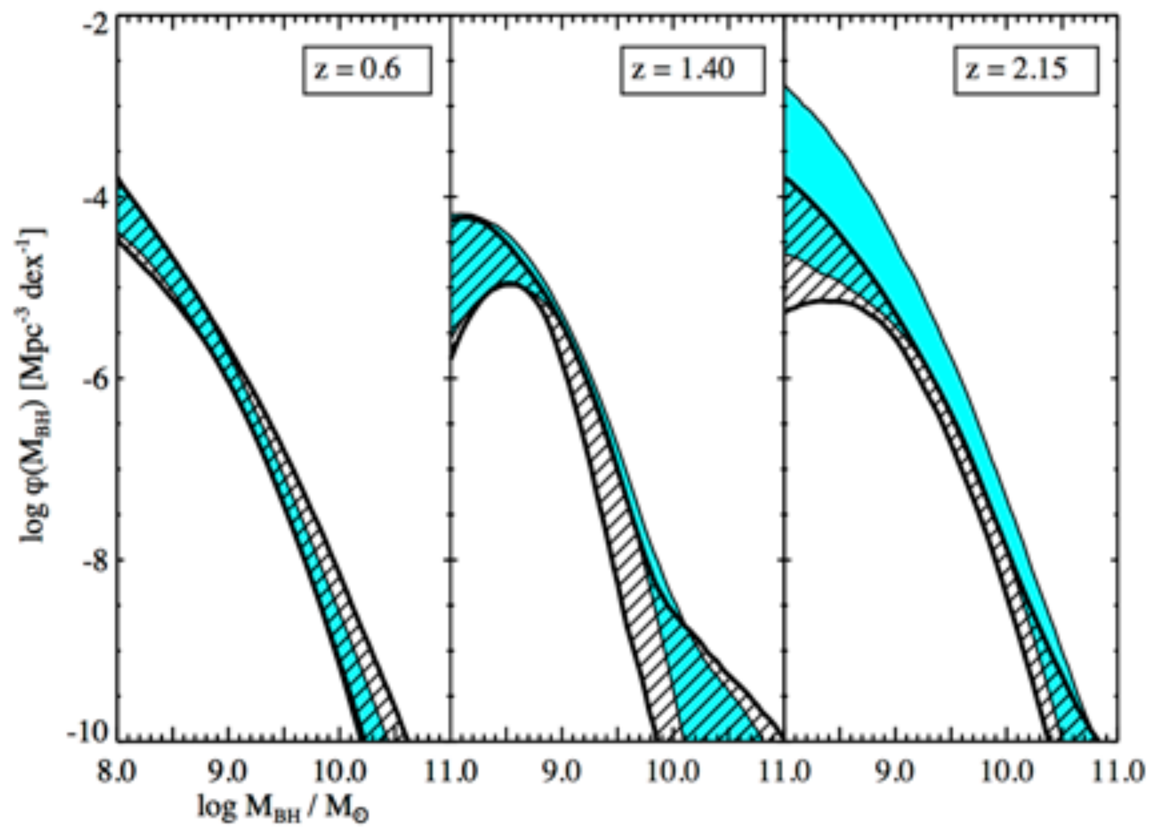
Downsizing



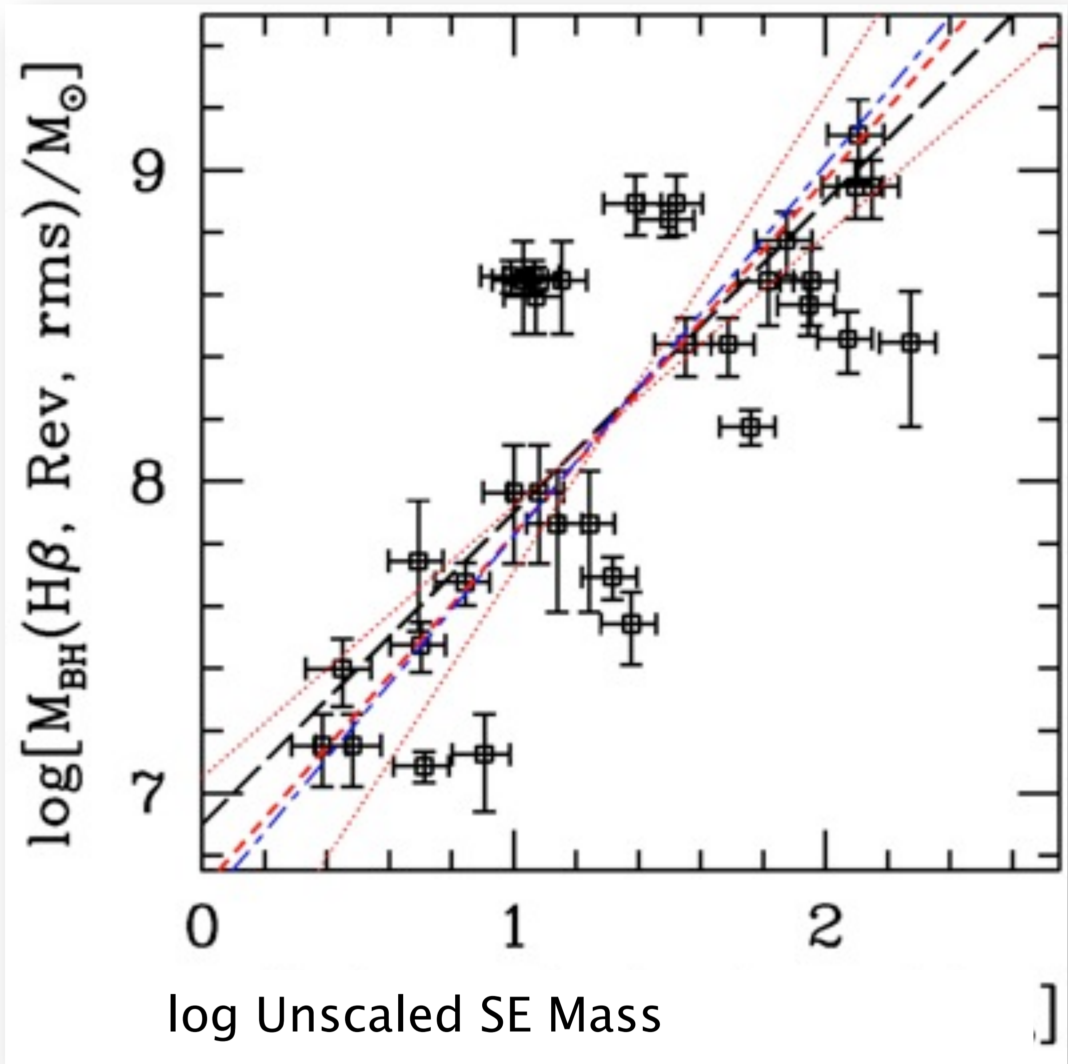
$M_{BH} = 5 \times 10^8 M_\odot$
$M_{BH} = 10^9 M_\odot$
$M_{BH} = 5 \times 10^9 M_\odot$
$M_{BH} = 10^{10} M_\odot$
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
$\varphi(\log M_{BH})$ [Mpc^{-3} dex^{-1}]
0 1 2 3 4 5 1 2 3 4 5
Redshift

Alternative models: Luminosity-dependent bias



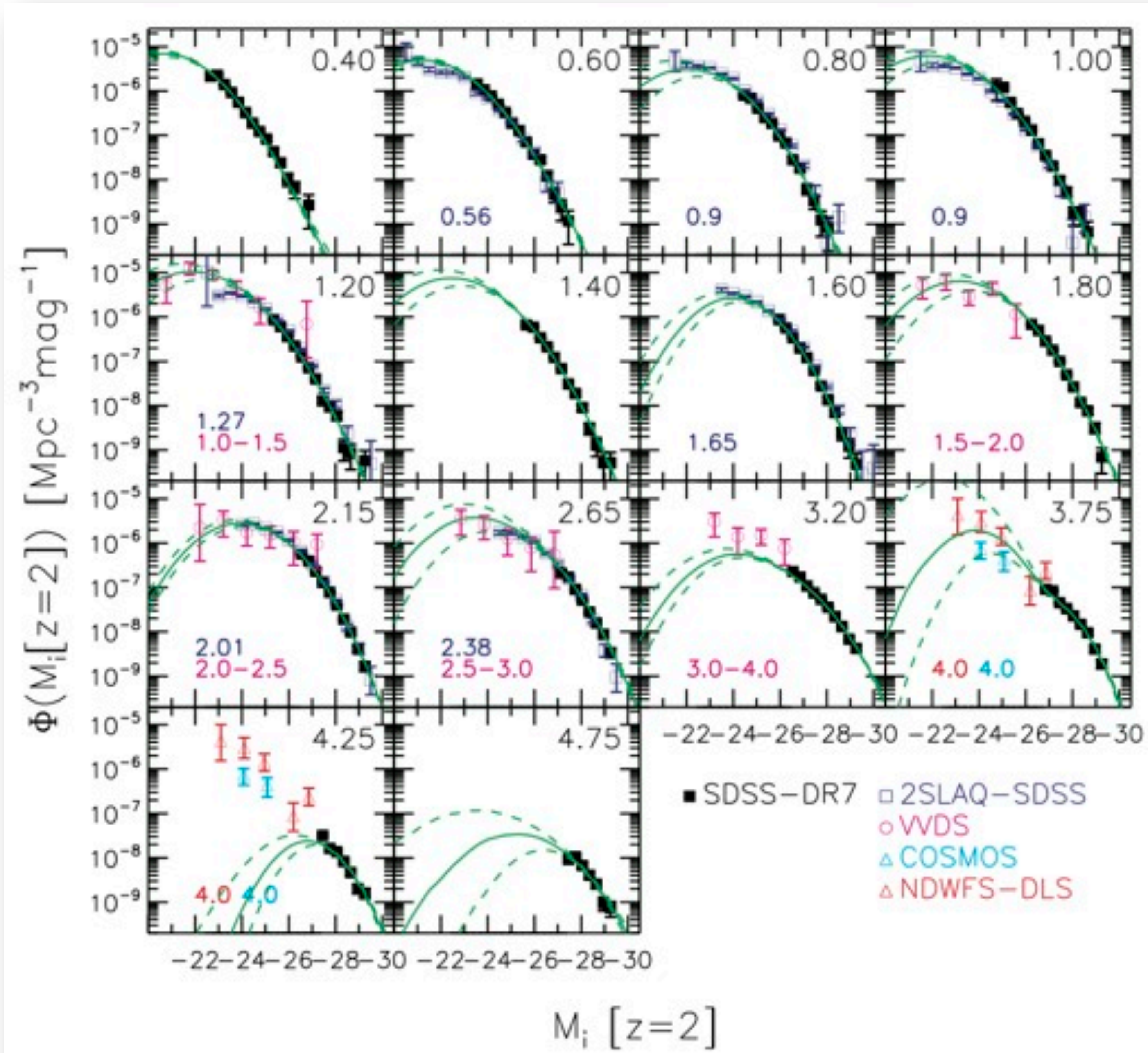


Broad-line mass estimates



Vestergaard & Peterson (2006)

Implied luminosity function



Shen & Kelly (2012)