The Pitch Angle Distribution Function and Its Role in Understanding Galactic Disks

Daniel Kennefick

University of Arkansas

Abstract

We present our determination of the nuclear supermassive black hole mass (SMBH) function for spiral galaxies in the local universe, established from a volume-limited sample consisting of a statistically complete collection of the brightest spiral galaxies in the southern ($\delta < 0°$) hemisphere. Our SMBH mass function agrees well at the high-mass end with previous values given in the literature. At the low-mass end, inconsistencies exist in previous works that still need to be resolved, but our work is more in line with expectations based on modeling of black hole evolution. This low-mass end of the spectrum is critical to our understanding of the mass function and evolution of black holes since the epoch of maximum quasar activity. A limiting luminosity (redshift-independent) distance, D_L = 25.4 Mpc (z = 0.00572) and a limiting absolute B-band magnitude, M_B = -19.12 define the sample. These limits define a sample of 140 spiral galaxies, with 128 measurable pitch angles to establish the pitch angle distribution for this sample. This pitch angle distribution function may be useful in the study of the morphology of late-type galaxies. We then use an established relationship between the logarithmic spiral arm pitch angle and the mass of the central SMBH in a host galaxy in order to estimate the mass of the 128 respective SMBHs in this volume-limited sample. This result effectively gives us the distribution of mass for SMBHs residing in spiral galaxies over a lookback time, $t_L \leq 82.1\, h^{-1}_{67.77}$ Myr and contained within a comoving volume, $V_C = 3.37 \times 10^4\ h^{-3}_{67.77}\,\mathrm{Mpc}^3$. We estimate that the density of SMBHs residing in spiral galaxies in the local universe is $\rho = 5.54^{+6.55}_{-2.73} \times 10^4\, h^3_{67.77}\ M_\odot\ \mathrm{Mpc}^3$. Thus, our derived cosmological SMBH mass density for spiral galaxies is $\Omega_{BH} = 4.35^{+5.14}_{-2.15} \times 10^{-7}\ h_{67.77}$. Assuming that black holes grow via baryonic accretion, we predict that $0.0020^{+0.0023}_{-0.0010}\, h^3_{67.77}$% of the universal baryonic inventory (Ω_{BH}/ω_b) is confined within nuclear SMBHs at the center of spiral galaxies.

The Black Hole *M*ass – *P*itch Angle Relation

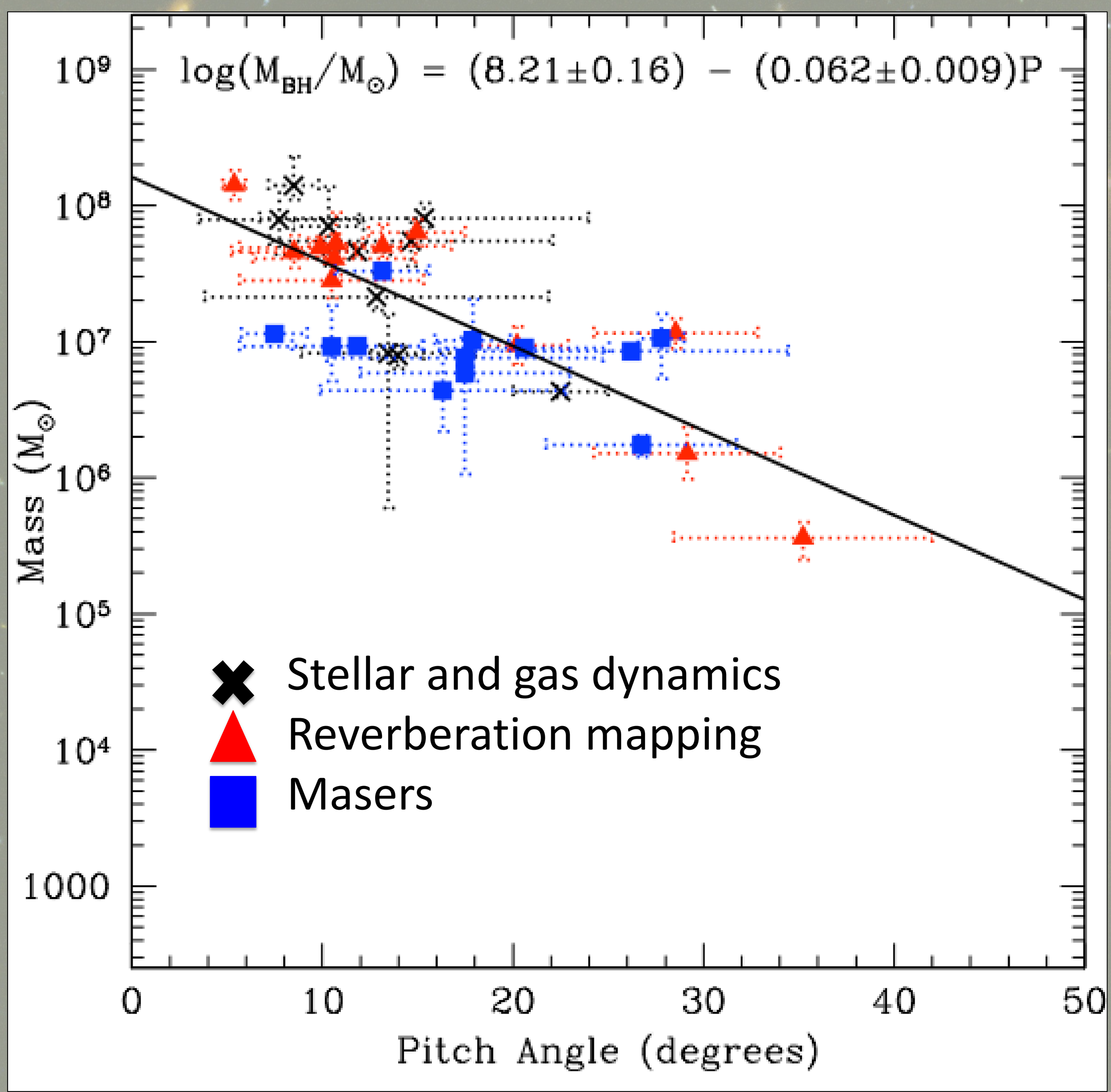

Fig. 1. — The black hole mass (M) plotted against pitch angle (P) for all available direct black hole mass measurements (stellar and gas dynamics, reverberation mapping, and masers; indicated by black X's, red triangles, and blue squares, respectively) of SMBH masses for spiral galaxies compared to those galaxies' pitch angles. This provides a linear fit with:

$$\log(M/M_\odot) = (8.21 \pm 0.16) - (0.062 \pm 0.009)|P| \qquad (1)$$

(where M is measured in solar masses and P in degrees). The fit has a reduced χ^2 of 4.68 with a scatter of 0.38 dex (Berrier et al. 2013) compared to the scatter for the M-σ relation for the case of spiral galaxies of 0.56 dex (Gültekin et al. 2009). This tool is potentially superior when compared to other methods for this class of galaxy, and has the advantage of being relatively easily measured from imaging data alone. The theoretical basis of this relation is dictated by the density wave theory of spiral structure, which demands that spiral structure should depend on the central mass.

Method

Because of inherent difficulties in estimating black hole masses in late-type galaxies, efforts to develop a black hole mass function (BHMF) have so far focused on early-type galaxies. We believe the M-P relation is an important tool for use in redressing the balance, especially considering that late-types are probably a majority of galaxies which contain black holes. Therefore, we have used the 2DFFT method of Davis et al. (2012) to measure the pitch angles for a complete sample of spiral galaxies (see Figure 2) and subsequently transformed their pitch angles into the representative nuclear SMBH mass as predicted by the M-P relation (see Figure 1, Equation (1)). This has produced a pitch angle distribution for spiral galaxies in our Local Universe (see Figure 3) and furthermore a black hole mass distribution (see Figure 4) for SMBHs residing in late-type galaxies in our Local Universe. Finally, we were able to define a BHMF for local spiral galaxies (see Figure 5).

The Volume-Limited Sample

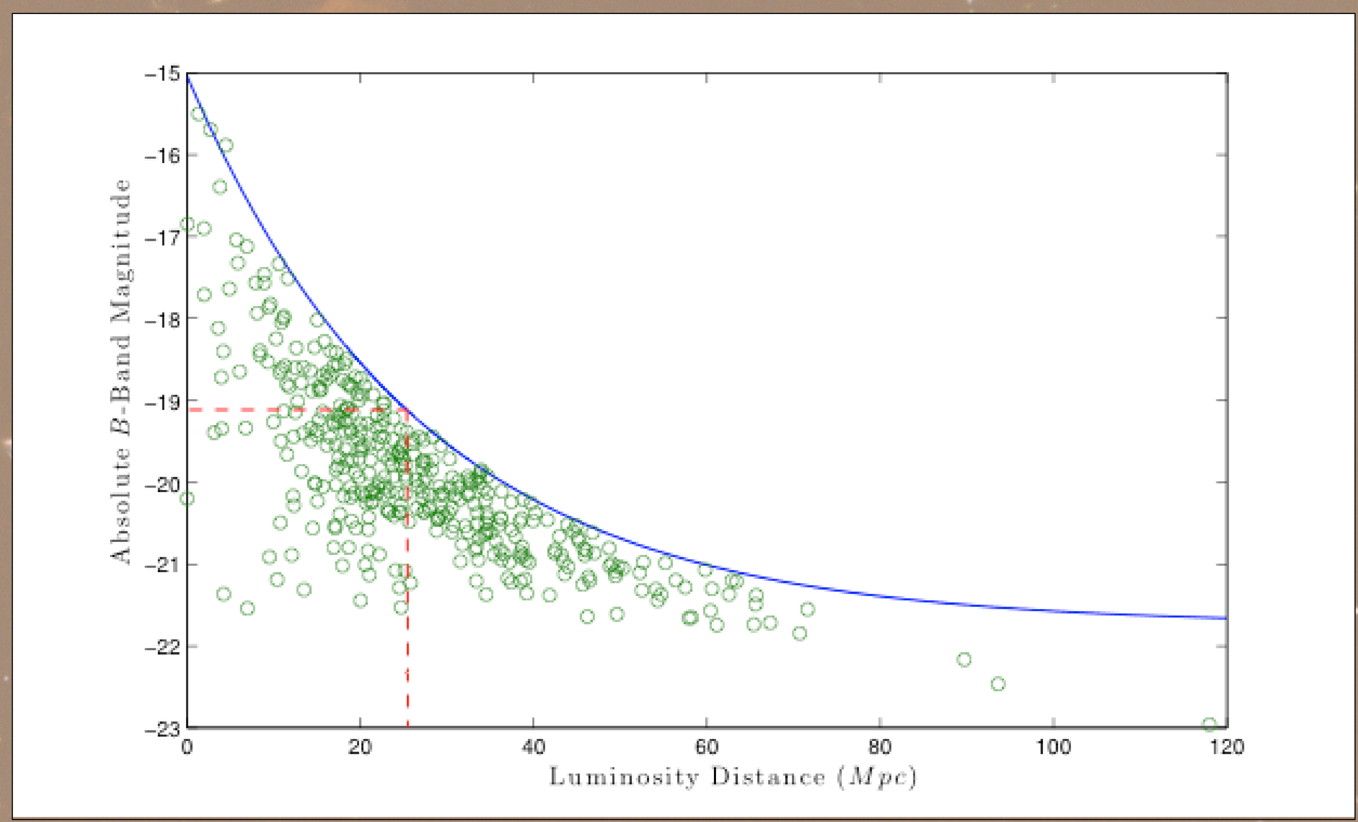

Fig. 2. — Luminosity distance vs. absolute B-band magnitude for all of the spiral galaxies (385) found using the magnitude-limiting selection criteria ($B_T \leq 12.9$ and $\delta < 0°$). The upper limit absolute magnitude can be modeled as an exponential and is plotted here as the solid blue line. The dashed red rectangle is constructed to maximize the number of galaxies in the volume-limited sample. The limiting luminosity distance and absolute B-band magnitude are set to be 25.4 Mpc and -19.12, respectively.

The Pitch Angle Distribution

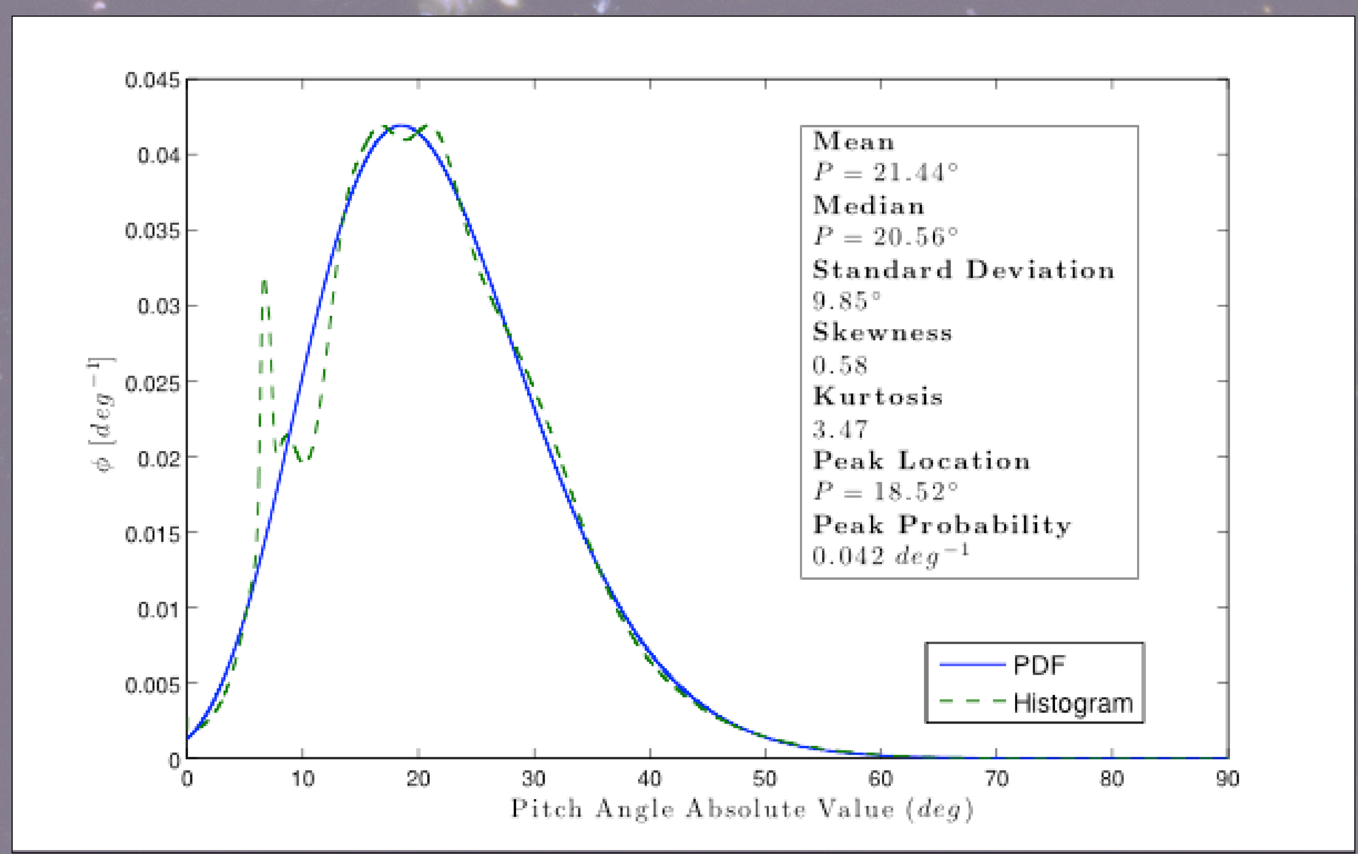

Fig. 3. — Pitch angle distribution (dashed green line) and a probability density function (PDF; solid blue line) fit to the data. The pitch angle distribution is a "binless" histogram that we modeled by allowing each data point to be a Gaussian, where the pitch angle absolute value is the mean and the error bar is the standard deviation. The pitch angle distribution is then the normalized sum of all the Gaussians. The resulting PDF is defined by μ = 21.44°, median = 20.56°, σ = 9.85°, skewness = 0.58, kurtosis = 3.47, and a most probable pitch angle absolute value of 18.52° with a probability density value of ϕ = 0.042 deg^{-1}.

The Black Hole Mass Distribution

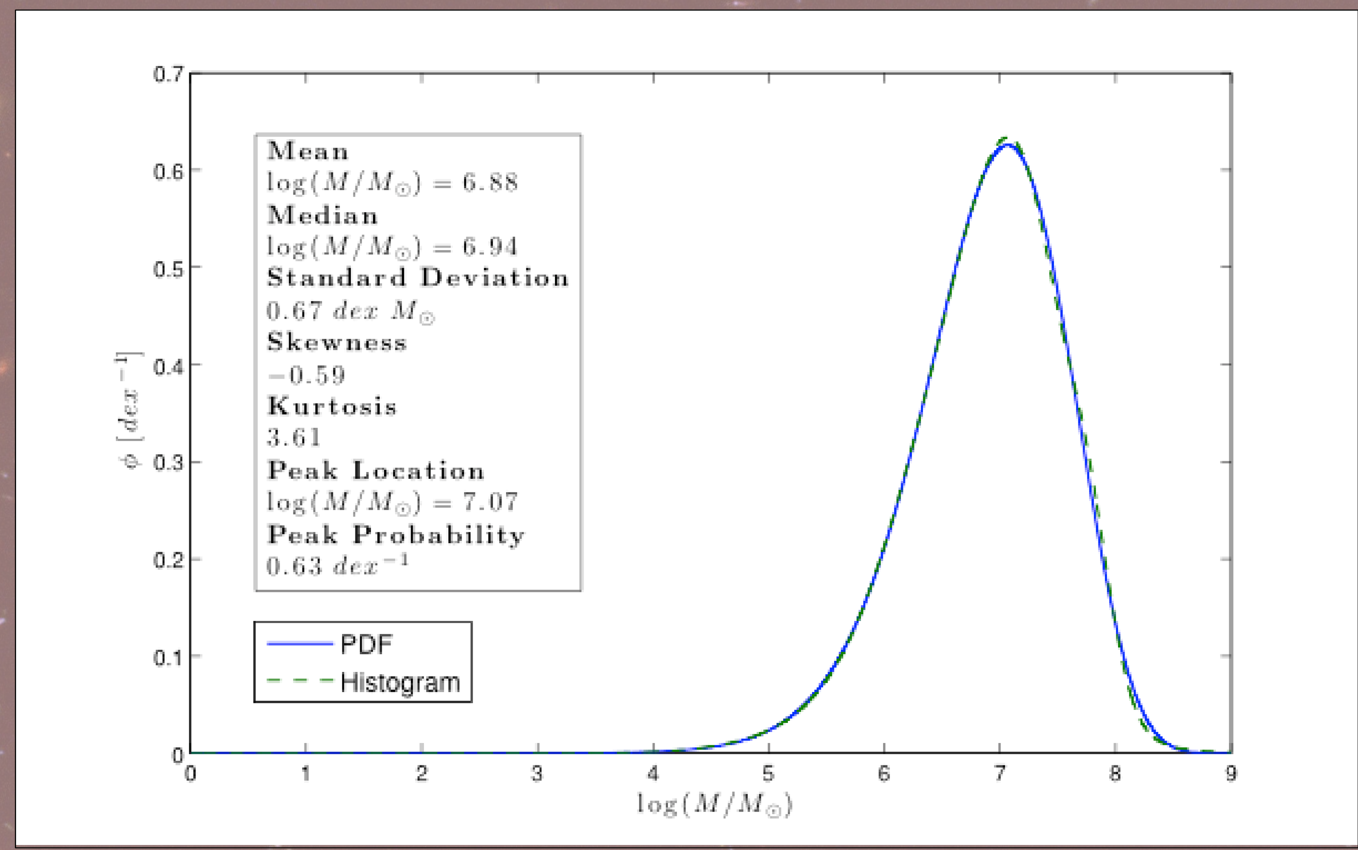

Fig. 4. — Black hole mass distribution (dashed green line) and a PDF (solid blue line) fit to the data. The black hole mass distribution is a "binless" histogram that we modeled by allowing each data point to be a Gaussian, where the black hole mass (converted from pitch angle measurements via Equation (1)) is the mean and the error bar is the standard deviation. The black hole mass distribution is then the normalized sum of all the Gaussians. The resulting PDF is defined by μ = 6.88 dex $M_\odot$, median = 6.94 dex $M_\odot$, σ = 0.67 dex $M_\odot$, skewness = -0.59, kurtosis = 3.61, and a most probable SMBH mass of $\log(M/M_\odot)$ = 7.07 with a probability density value of ϕ = 0.63 dex^{-1}.

The Black Hole Mass Function

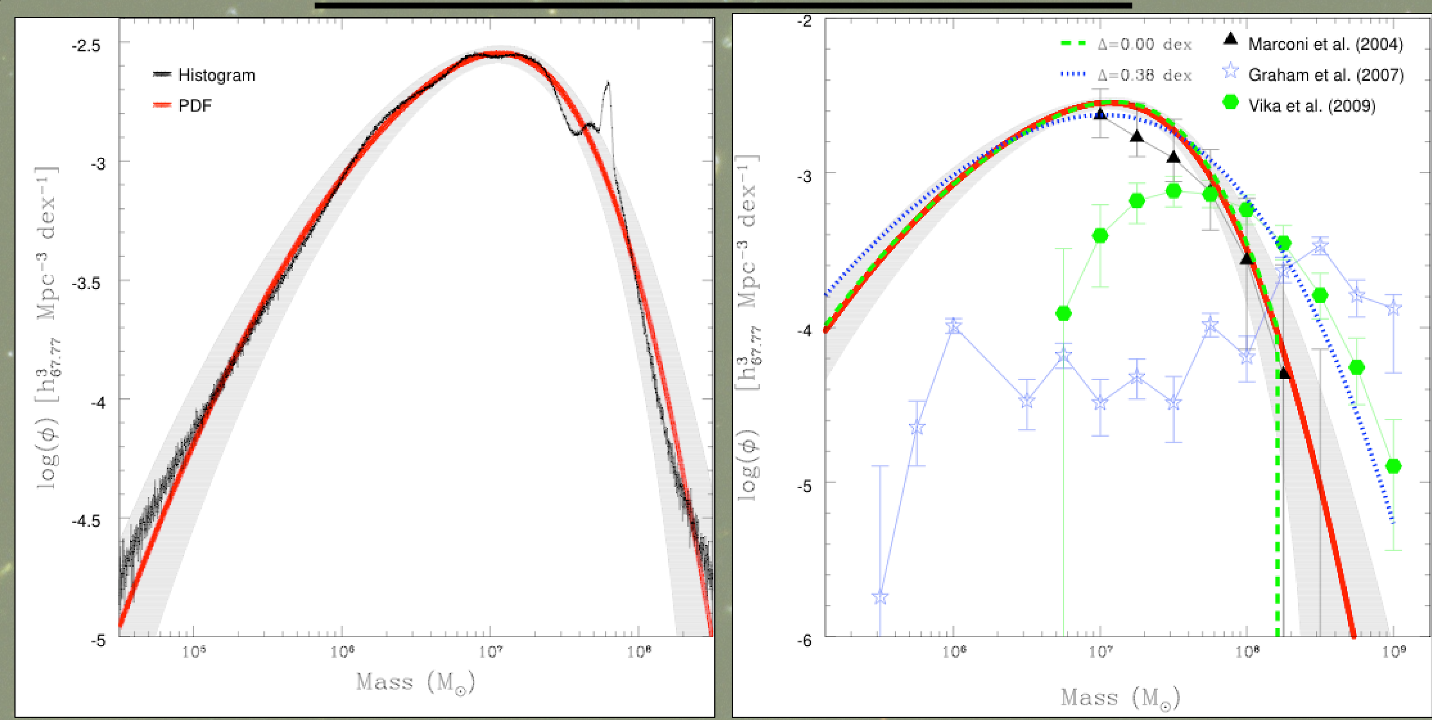

Fig. 5. — Left: Markov Chain Monte Carlo sampling of the late-type BHMF (rough **black** line) with the best fit model PDF (solid red lines) surrounded by a ±1σ error region (gray shading). Right: BHMF comparison with zero (dashed green line) and 0.38 dex intrinsic dispersion (dotted blue line); with those of Marconi et al. (2004), depicted by **black** triangles; Graham et al. (2007), depicted by blue stars; and Vika et al. (2009), depicted by green hexagons.

Publication

Davis, B. L., Berrier, J. C., Johns, L., Shields, D. W., Hartley, M. T., Kennefick, D., Kennefick, J., Seigar, M. S., and Lacy, C. H. S. 2014, ApJ, 789, 124

References

Berrier, J. C., Davis, B. L. Kennefick, D., Kennefick, J., Seigar, M. S., Barrows, R. S., Hartley, M. T., Shields, D. W., Bentz, M. C., & Lacy, Ch. H. S. 2013, *ApJ*, **769, 132**

Davis, B. L., Berrier, J. C., Shields, D. W., Kennefick, J., Kennefick, D., Seigar, M. S., Lacy, C. H. S., & Puerari, I. 2012, *ApJS*, **199, 33**

Gültekin, K., Richstone, D. O., Gebhardt, K. Lauer, T. R., Tremaine, S., Aller, M. C., Bender, R., Dressler, A., Faber, S. M., Filippenko, A. V., Green, R., Ho, L. C., Kormendy, J., Magorrian, J., Pinkney, J., & Siopis, C. 2009, *ApJ*, **698, 198**

Graham, A. W., Driver, S. P., Allen, P. D., & Liske, J. 2007, *MNRAS*, ***378*, *198***

Marconi, A., Risaliti, G., & Gilli, R. et al. 2004, *MNRAS*, ***351*, *169***

Vika, M., Driver, S. P., Graham, A. W., & Liske, J. 2009, *MNRAS*, ***400*, 1451**

We gratefully acknowledge funding from NASA, grant #NNX08AW03A.