Measuring Mass of Super Massive Black Holes by Examining Spiral Galaxy Pitch Angle

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Theory:

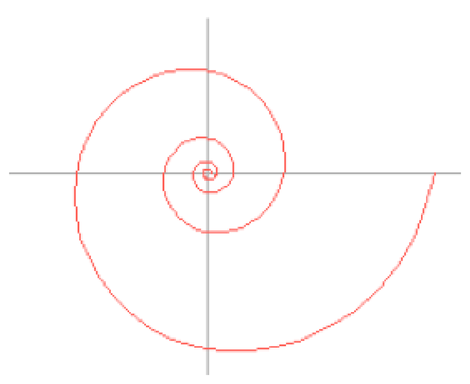
It is theorized and widely accepted that at the center of nearly all spiral galaxies lies a Super Massive Black Hole (SMBH). The gravitational potential provided by the SMBH plays a crucial role in the structure and geometry of its host spiral galaxy—especially with how tightly wound the spiral arms are. The larger the gravitational potential (i.e. the more massive SMBH), the greater the tendency for the spiral arms to be more attracted to the center, resulting in a tighter spiral galaxy. Thus a correlation exists between how tightly wound a spiral galaxy is and the mass of the SMBH at the center of the galaxy. Simply by using a telescope to obtain images of spiral galaxies, the mass of a host SMBH can readily be measured by calculating the spiral pitch angle of the galaxy. This provides a very simplistic and relatively quick method to determine SMBH mass.

Introduction:

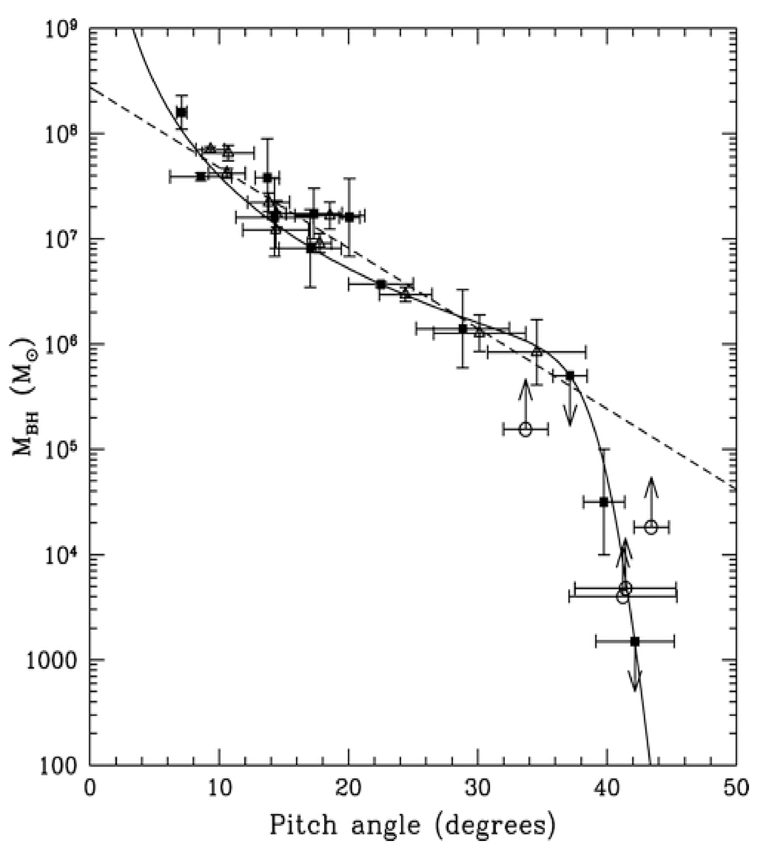
The degree to which spiral galaxy arms deviate from being a perfect circle is called the pitch angle, *P* of the spiral galaxy. Thus a circle has a pitch angle of 0 degrees, while a spoke has a pitch angle of 90 degrees.

The core geometry of all spiral galaxies has the shape of a logarithmic spiral (displayed below) which is parameterized by an exponential function of the pitch angle *P* of the spiral galaxy:

$$r = e^{\theta \cdot \tan(P)}$$



In 2008, the Arkansas Galaxy Evolution Survey (AGES) discovered a relationship between spiral arm pitch angle, *P* and SMBH mass [1]:



This graph relates the mass of a SMBH (in solar masses) to the pitch angle of the host spiral galaxy. From the plot, one can see that the SMBH mass increases as the pitch angle decreases. Therefore, the tighter the spiral galaxy, the greater the SMBH mass.

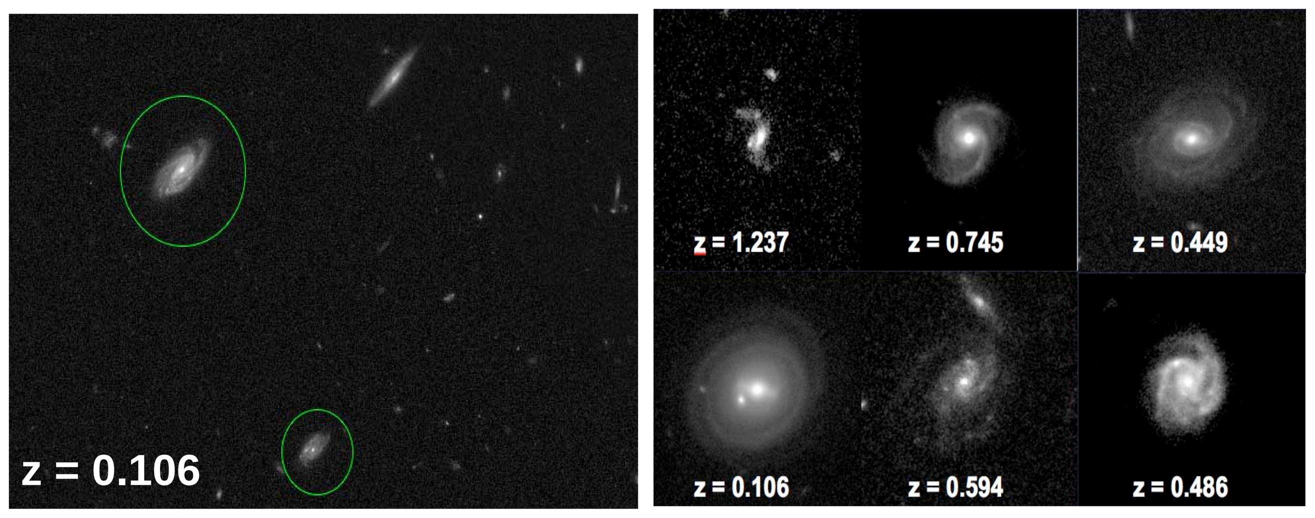
By using this data and following the Nuker Law[2], a formula was derived to relate the mass of a SMBH to the spiral arm pitch angle of the host galaxy.

$$M_{BH} = 2^{(\beta-\gamma)/\alpha} M_{BH_b} \left(\frac{P_b}{P}\right)^{\gamma} \left[1 + \left(\frac{P}{P_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$

The variables α, β, γ are just constants to make this function have a Nuker profile. Furthermore, M_{BH_b} and P_b are just reference values, making the value of the pitch angle *P* the only variable in this equation. Thus by only knowing the pitch angle of a spiral galaxy, the mass the SMBH at the center of the galaxy can be determined. Thus if the pitch angle of a spiral galaxy is known, then the mass of the central SMBH can be determined.

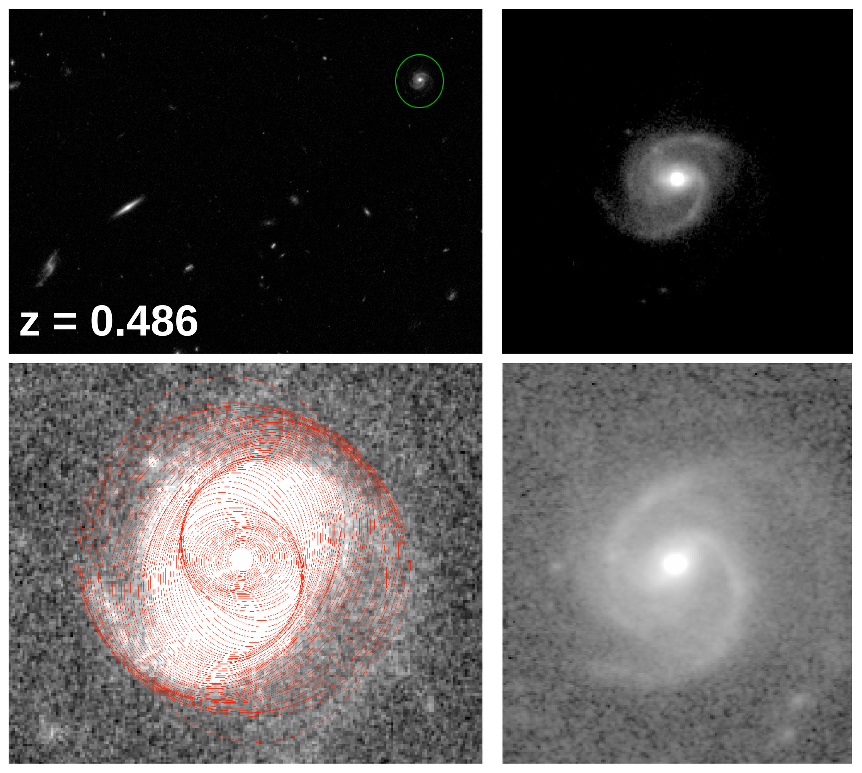
Experiment:

Using the Hubble Space Telescope (HST), many spiral galaxies and clusters of spiral galaxies with red shifts ranging from z = 0.1 to z = 1.3 were collected for observation from various Hubble fields. Samples include:



However, upon collection from the HST, most galaxies are not face-on with the telescope. For images to be properly analyzed, the galaxy must be straight-on, and further analyses require the image of the galaxy to be a perfect circle. Therefore, the Image Reduction and Analysis Facility (IRAF) is used to de-project the image such that the galaxy is face-on and is circular.

To correct the image, IRAF is first used to take the original image and generate a contour plot of isophotes, or regions of constant luminosity, of the galaxy. This plot is used to determine the ellipticity, which is utilized to project the image to a circle.



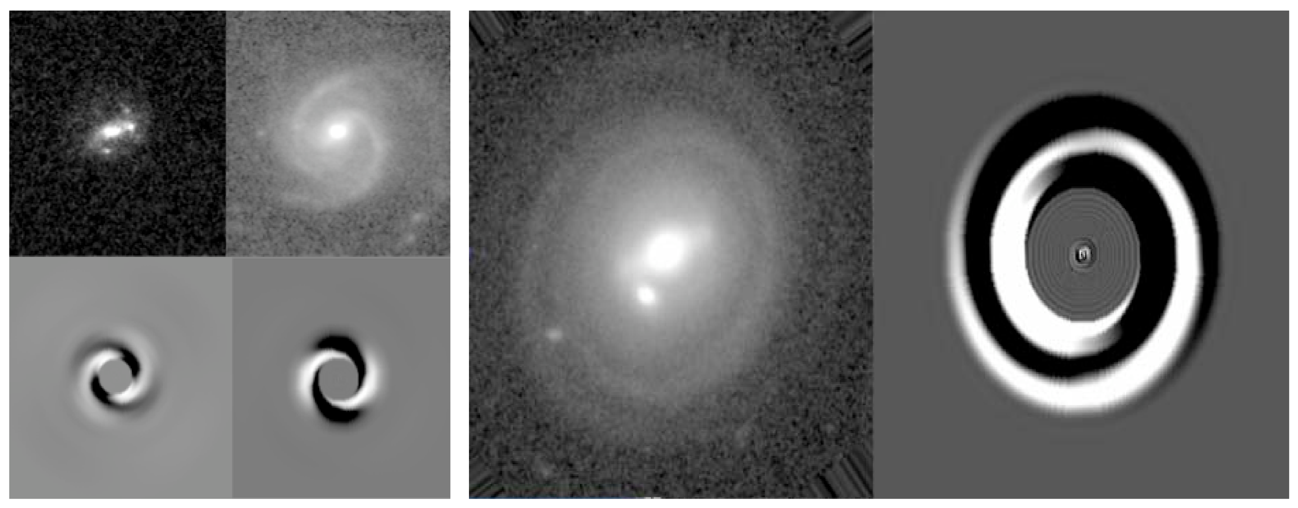
Top Left: Original image of galaxy cluster taken with the Hubble Space Telescope. The galaxy being studied is circled.

Top Right: Local image of spiral galaxy being studied, it is classified as AGES 3.

Bottom Left: Contour plot of isophotes of AGES 3. These isophotes, or regions of constant luminosity, are used to conform the galaxy to a perfect circle

Bottom Right: Resulted de-projected image of AGES 3. Note that the galaxy is a perfect circle and is front-on with the telescope

Now that the image is circular and face-on, a Fast Fourier Transform (FFT) of the image of the galaxy is performed. This results in the image of the galaxy showing only the present periodicity in the galaxy. Hence, all that remains in the image is the spiral structure of the galaxy. Any non-periodic features such as interstellar media, radiation jets, or accretion disks are not present in the FFT, allowing for easy detection of the spiral arm geometry.

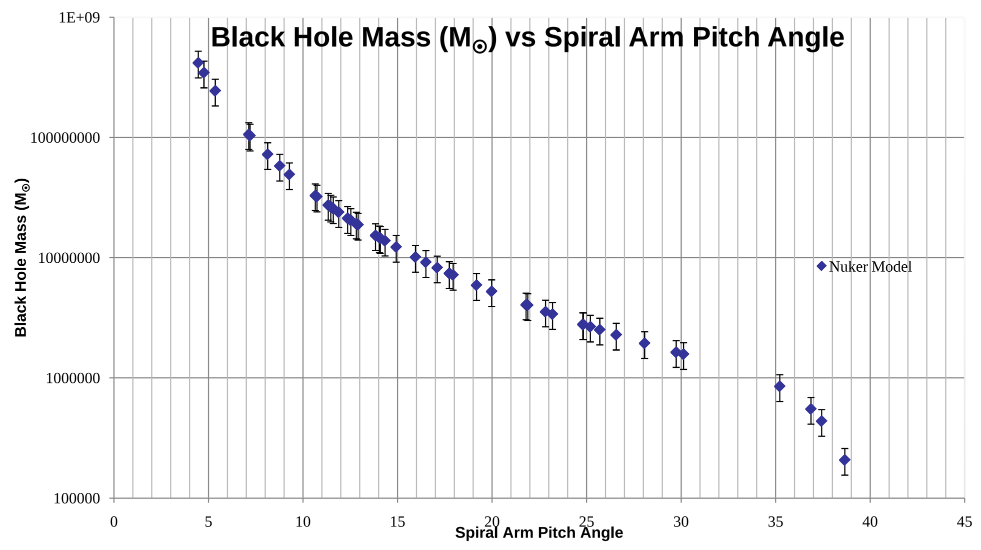


De-projected images of some original galaxies along with their resultant FFT images. Note that only the spiral structure remains visible, showing the true geometry of each galaxy. This allows for easy and quick measurement of the spiral arm pitch angle of the galaxy. The middle galaxy and middle FFT is the spiral galaxy AGES 3.

With the FFT result, IRAF is used to easily measure the pitch angle of the galaxy. Therefore, since pitch angle is known, the mass of the central SMBH is easily determined from the Nuker model equation. This process is repeated for every spiral galaxy investigated in this study.

Results:

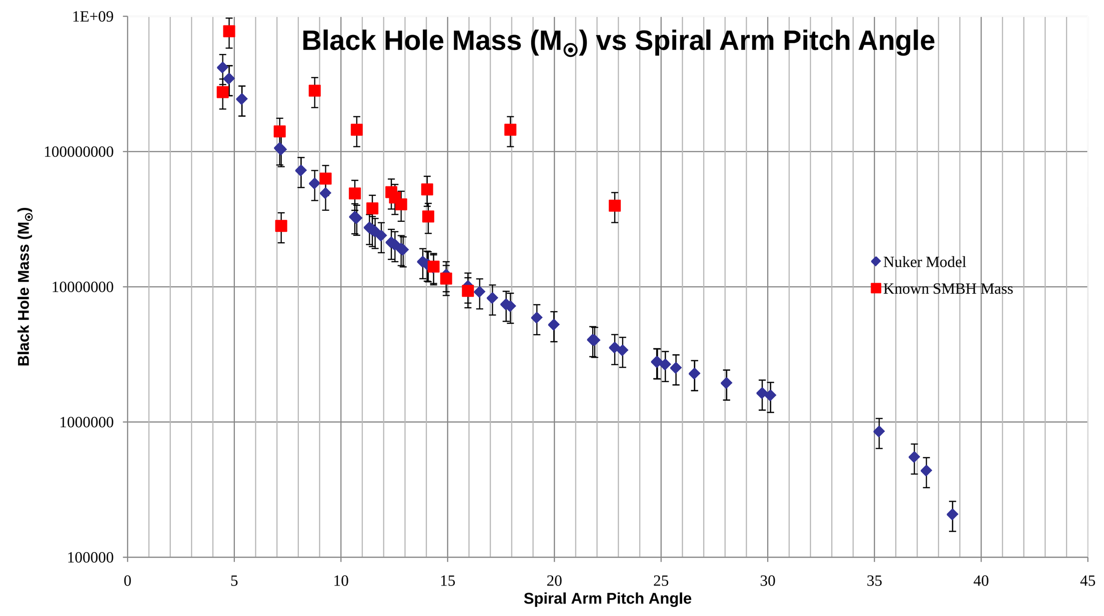
A total of 61 spiral galaxies were examined, and pitch angles were determined for each in order to measure the mass of their central SMBH by using the Nuker Model. The results are displayed on the following plot:



Left: Logarithmic plot showing the solar masses of each SMBH as a function of spiral arm pitch angle.

Notice that a majority of the SMBH are found between one million and ten million solar masses.

To further justify this method of determining SMBH mass, pitch angles of spiral galaxies with known SMBH masses[3] were measured and compared to the Nuker Model.



Logarithmic plot displaying SMBH mass as a function of its host galaxy spiral arm pitch angle. The blue series shows the Nuker model and the red series is data taken by comparing known SMBH mass with spiral arm pitch angle of the host spiral galaxy.

The closer the known SMBH mass is to the Nuker Model, the more precise the measurement is. A majority of the known SMBH masses falls along the Nuker Model, corroborating the pitch angle method of measuring SMBH mass.

Conclusions:

This study shows a very simple and efficient method to measuring the masses of SMBH at the center of spiral galaxies. The plot above showing known SMBH mass and pitch angle is a clear indicator that this method is also a precise way to measure SMBH mass. Previous methods for measuring SMBH required long term measurements of spectral lines, velocity distributions, reverberation mappings, and luminosities of the host galaxies. On the contrary, the pitch angle method requires only an image of a galaxy in order to measure the mass of a SMBH.

Knowing the mass of a SMBH is critical in the study of dark matter, the mass function of the universe, and galactic dynamics. Further studies are looking at how pitch angle is perturbed by having a galaxy located in a galaxy cluster. This study displays the easiest possible way to measure black hole mass.

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References & Acknowledgements:

[1] Seigar M., et al. 2008. The Astrophysical Journal., 678, L95.[2] Lauer, T., et al. 1995. The Astrophysical Journal., 110, 2647. [3] Misty Bentz; University of California, Irvine; Department of Physics and Astronomy

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