Hunting for Intermediate-Mass Black Holes Using X-ray and Optical Images of Galaxies

Eli Brunner-Huber, Marc Seigar

University of Minnesota Duluth

Introduction

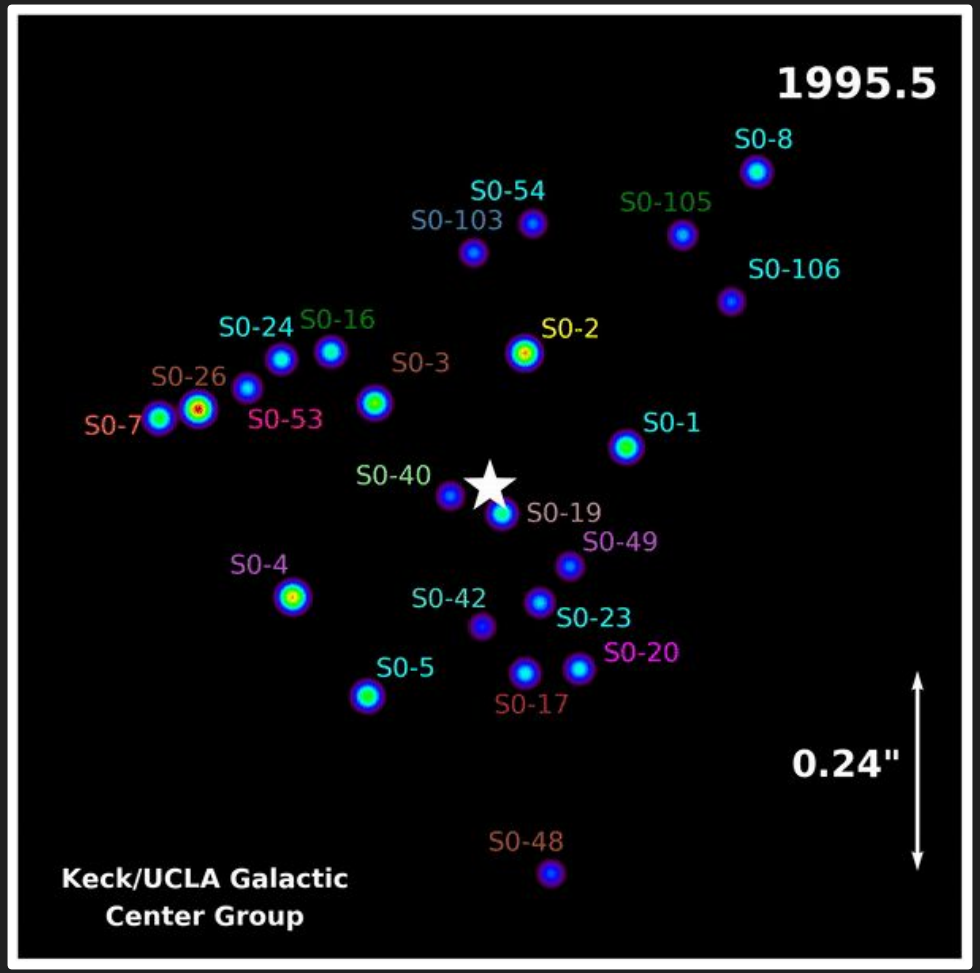
- Centers of spiral galaxies contain supermassive black holes (SMBHs)
  - $>10^5$ solar masses
- There also exist stellar-mass black holes
  - $<10^2$ solar masses
- What about the range in between these two classifications?
  - Intermediate-mass black holes (IMBHs)
  - Could provide insight into the processes which form SMBHs, which are relatively unknown at this point

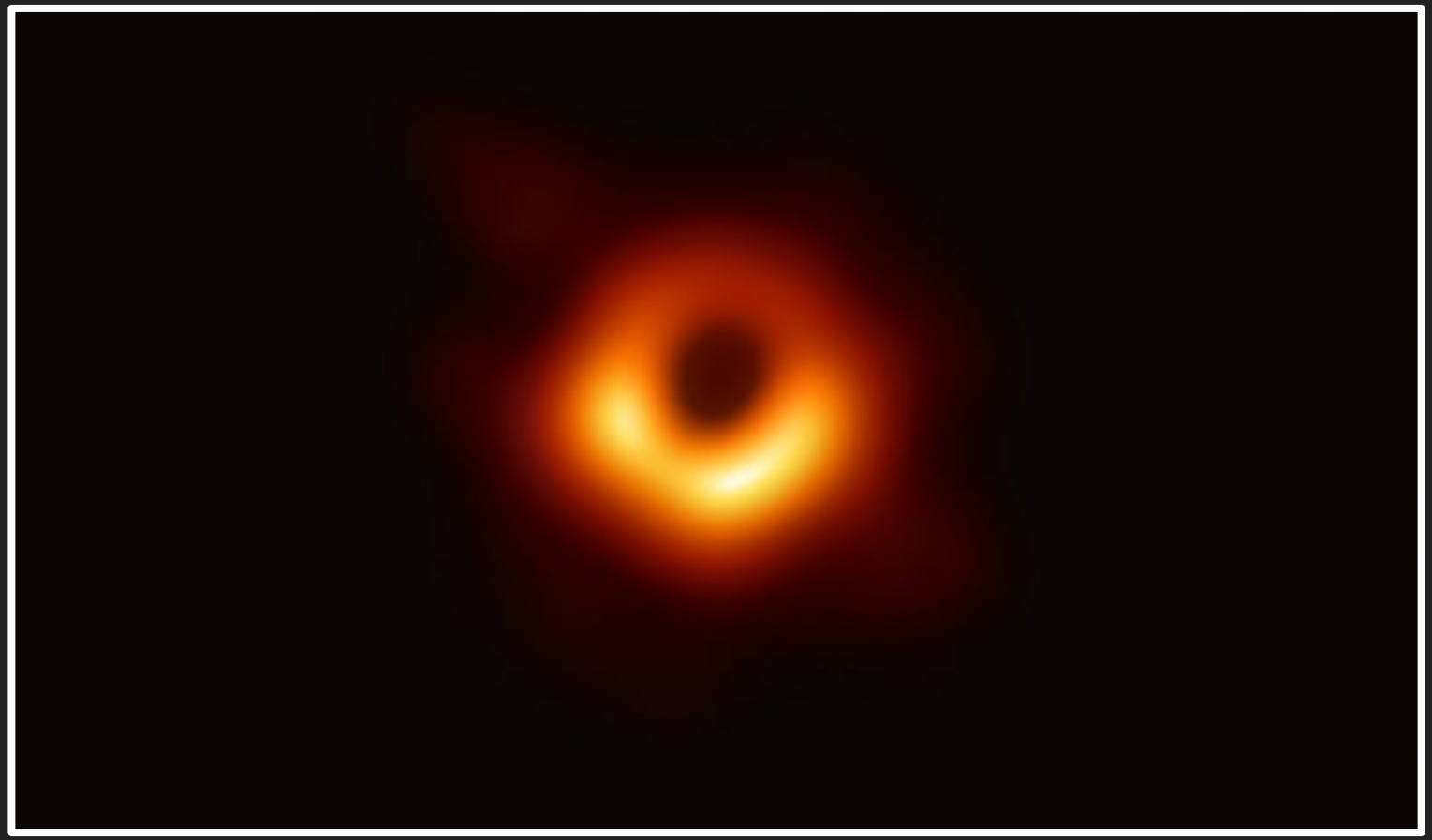
$$10^2 \text{ M(sun)} < \text{IMBHs} < 10^5 \text{ M(sun)}$$

Range of Interest

How do we find these black holes?

- Velocity Dispersion Method
  - Measures velocities of stars orbiting black hole to find its gravitational influence on them and therefore its mass
- X-ray analysis
  - Analyses radiation from the accretion disk surrounding the black hole emitted as material falls inward towards the event horizon


1995.5
S0-8
S0-54
S0-105
S0-103
S0-106
S0-24
S0-16
S0-2
S0-3
S0-26
S0-7
S0-53
S0-1
S0-40
S0-19
S0-49
S0-4
S0-42
S0-23
S0-20
S0-5
S0-17
0.24"
S0-48
Keck/UCLA Galactic
Center Group



Credit: Event Horizon Telescope Collaboration et al.

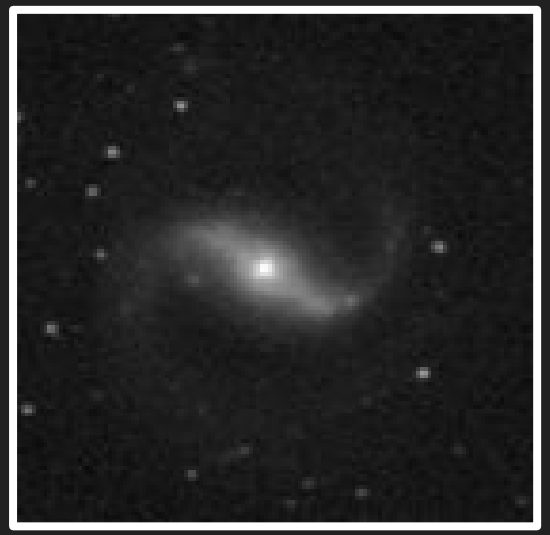
An easier way to find IMBHs?

- Both of these methods require very precise telescope data, a lot of time, and most likely money
  - What if we could find an easier way to detect and measure the masses of black holes at the centers of spiral galaxies?

Spiral arm pitch angle and its relationship to black hole mass

- All spiral galaxies have a pitch angle, which measures the relative “tightness” of the spiral arms to the galactic center

NGC 2835 (PA: 36.9 ± 2.3)

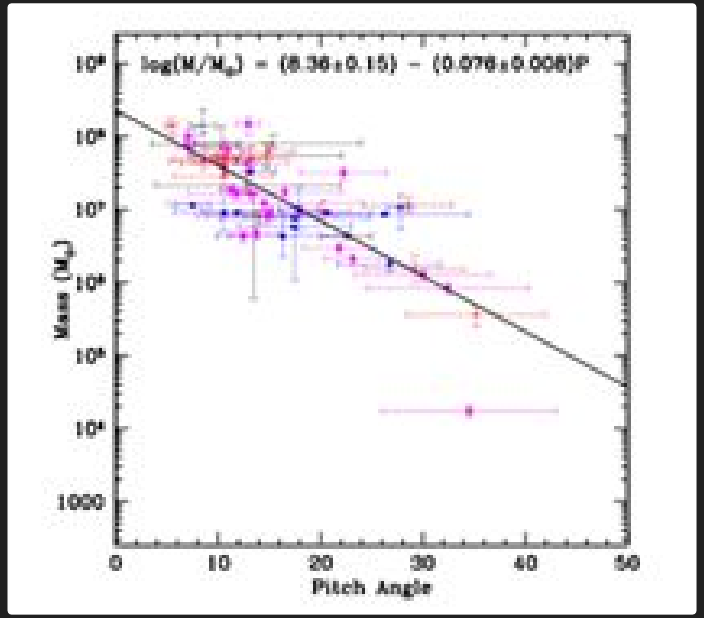


NGC 5135 (PA: 58.0 ± 6.4)

We can use spiral arm pitch angle to find a black hole's mass!

- In previous work, it has been found that there is a direct relationship between a galaxy's spiral arm pitch angle and the central black hole's mass (Berrier et al. 2013; Seigar et al. 2008)

$$\log(M/M(\text{sun})) = (8.36 \pm 0.15) - (.076 \pm .008)P$$



Data

- Optical images for this project were collected from NASA's Extragalactic Database, which has images and various measurements of many extragalactic objects, including spiral galaxies
    - Also taken were measurements of major vs. minor axes of galaxies, telescopes that imaged the galaxies, and the wavelengths at which they were images
- Candidate galaxies were found through the Carnegie Irvine Galaxy Survey, a database giving identifiers and Hubble types of many galaxies

Deprojection

- To effectively analyze galaxies, they were first deprojected into a simulated face-on orientation using the Image Reduction and Analysis Facility (IRAF)
  - Reverses the effects of perspective on the image of the galaxy

NGC 1090 before deprojection

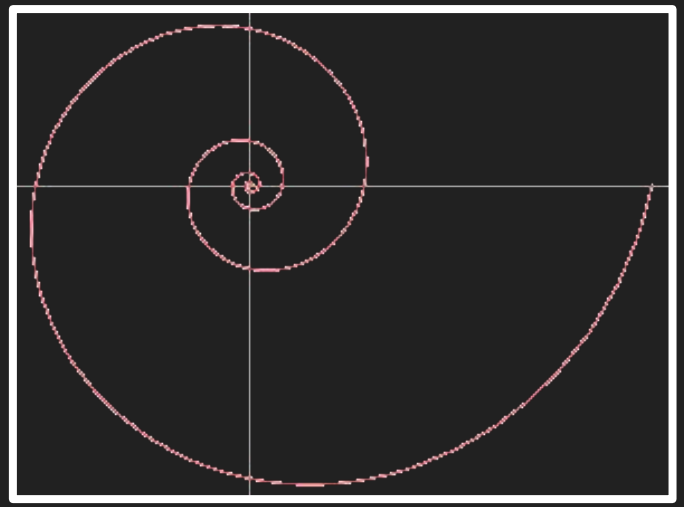
NGC 1090 after deprojection

Calculation of spiral arm pitch angle

- Once deprojected in IRAF, galaxies were subjected to a program called the Parallelized 2-Dimensional Fast Fourier Transform (P2DFFT)
  - Analyzes galaxy as a superposition of logarithmic spirals and calculates average pitch angle

Logarithmic spiral of mode 1 (correlating to a single-armed galaxy) described by the equation:

$$r = r_0 e^{\Theta \tan(\varphi)}$$



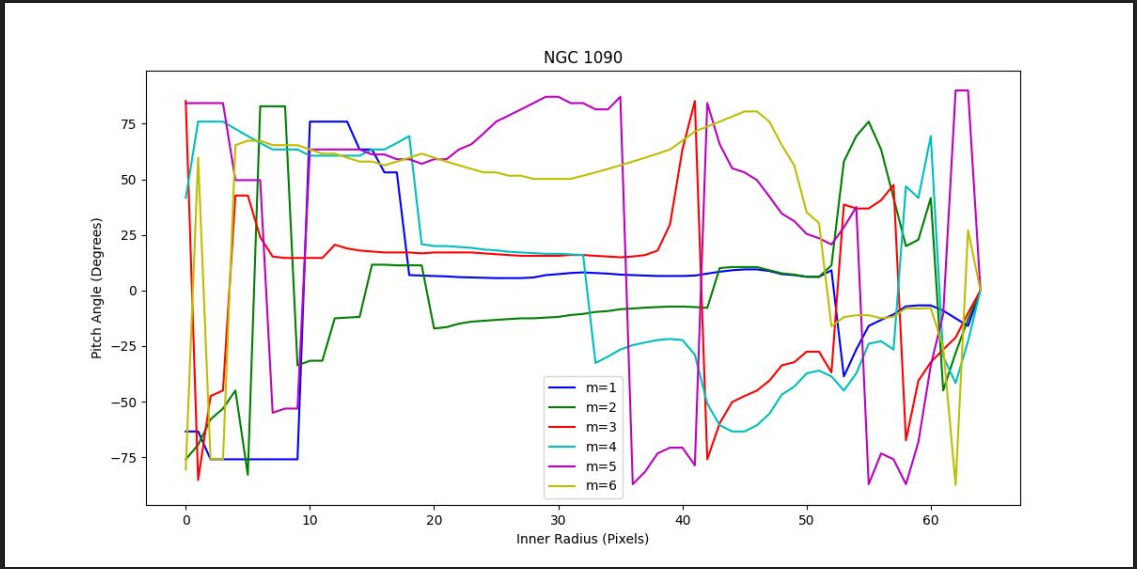
Results

- Using the relationship in Berrier et al. 2013 (listed before), BH mass estimations were made for each galaxy in the sample (13 galaxies)
  - Identified 7 galaxies as candidates for hosting IMBHs!
  - Further proof of concept

Galaxy	Pitch Angle (deg)	BH Mass ($M_{BH}/M_{\odot}$)
NGC 578	15.9 ± 1.6	$1.32^{+.44}_{-.33} \times 10^7$
NGC 1042	58.0 ± 6.4	$6.85^{+14.8}_{-4.68} \times 10^3$
NGC 1090	6.7 ± 0.4	$6.88^{+.51}_{-.48} \times 10^7$
NGC 1599	53.1 ± 5.7	$1.65^{+2.95}_{-1.06} \times 10^4$
NGC 1672	63.4 ± 7.1	$2.60^{+6.70}_{-1.87} \times 10^3$
NGC 1784	8.8 ± 0.6	$4.72^{+.537}_{-.482} \times 10^7$
NGC 2763	63.4 ± 7.1	$2.60^{+6.70}_{-1.87} \times 10^3$
NGC 2835	36.9 ± 2.3	$3.03^{+1.55}_{-1.03} \times 10^5$
NGC 3261	38.7 ± 3.5	$2.19^{+1.92}_{-1.02} \times 10^5$
NGC 3513	20.9 ± 1.3	$5.37^{+1.41}_{-1.12} \times 10^6$
NGC 4939	53.1 ± 5.7	$1.65^{+2.95}_{-1.06} \times 10^4$
NGC 5054	59.7 ± 4.6	$5.05^{+6.49}_{-2.84} \times 10^3$
NGC 5135	58.0 ± 6.4	$6.85^{+14.8}_{-4.68} \times 10^3$

Visual confirmation of pitch angle

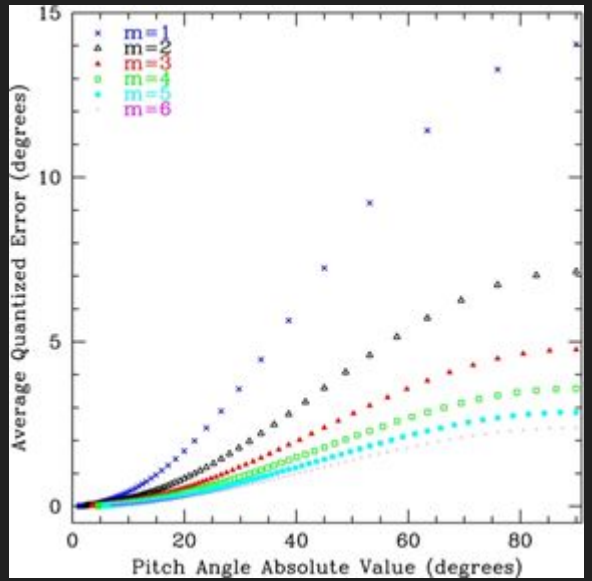
- As a sanity check of the reported pitch angles, plots of the measured pitch angle vs. the inner radius at which it was calculated were generated for each galaxy



Pitch angle vs. radius plot for NGC 1090, which reported a 6.7 ± 0.4 degree pitch angle

Error Determination

- Largest source of error in the calculation of the spiral arm pitch angle (and thus the BH mass) is the method by which P2DFFT reports pitch angles. Rather than as a continuum, P2DFFT reports pitch angles in quantized steps.



Third-ordered best-fit polynomials used to calculate the quantized pitch angle error due to the non-continuum structure of P2DFFT, from Davis et al. 2012. For the purpose of this paper, only the polynomials for modes 1, 2, and 3 are used, which are as follows:
m = 1, $y = -4 \times 10^{-5}x^3 + 0.0058x^2 - 0.0137x + 0.0234$;
m=2, $y = -2 \times 10^{-5}x^3 + 0.0029x^2 - 0.0084x + 0.0222$;
m = 3, $y = -4 \times 10^{-5}x^3 + 0.002x^2 - 0.0064x + 0.0214$.
(Davis et al. 2012.)

Conclusion and Future Work

- By combining the powers of IRAF, P2DFFT, and optical images of spiral galaxies, approximate masses for the galaxies' central BHs have been calculated and 7 identified as candidates for hosting IMBHs
  - For galaxies with lower pitch angles, it has been shown that BH mass estimations agree with currently accepted mass ranges of SMBHs

- Future work, beginning this summer, will use other BH mass estimation methods (x-ray analysis) to reinforce the measurements made in this project and confirm the candidates as hosts of IMBHs
  - Additional proof of concept for the pitch angle estimation method

Acknowledgements

- Dr. Marc Seigar
- Dr. Burcin Mutlu-Pakdil
- UMD’s UROP Program
- Planetarium Staff