Galaxies and Their Central Black Holes

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Science and Evolution of Gemini Observatory
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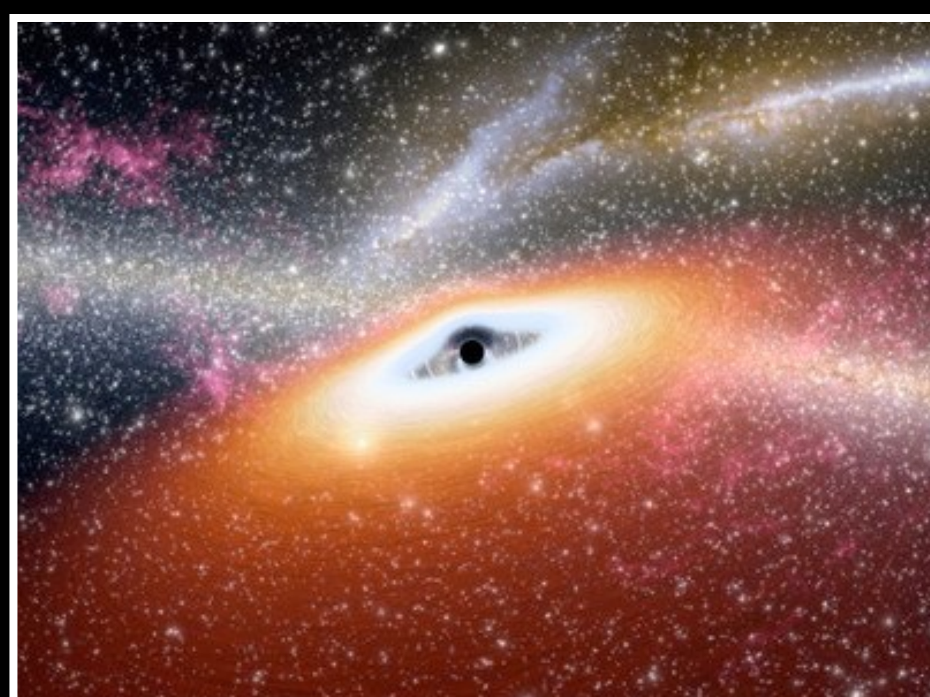
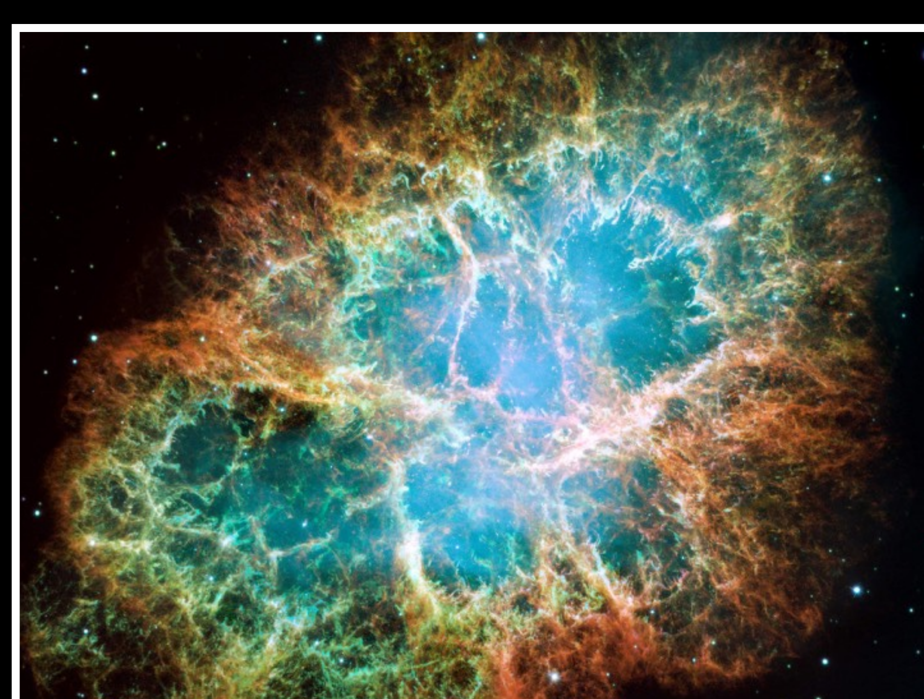
Introduction: Black Holes are Everywhere!

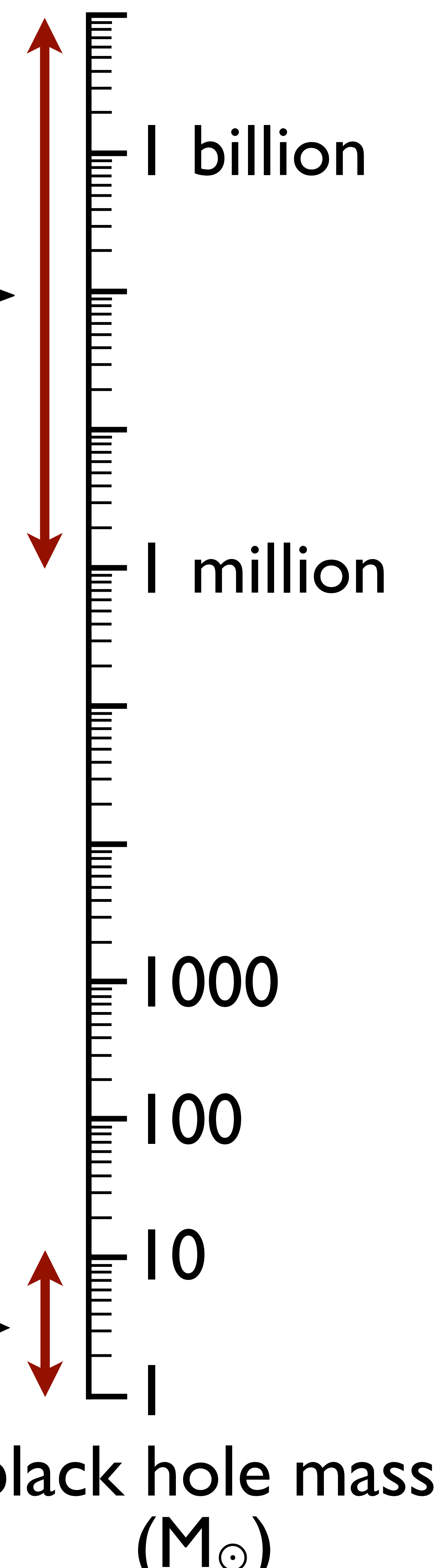
Types of Black Holes

Supermassive Black Holes

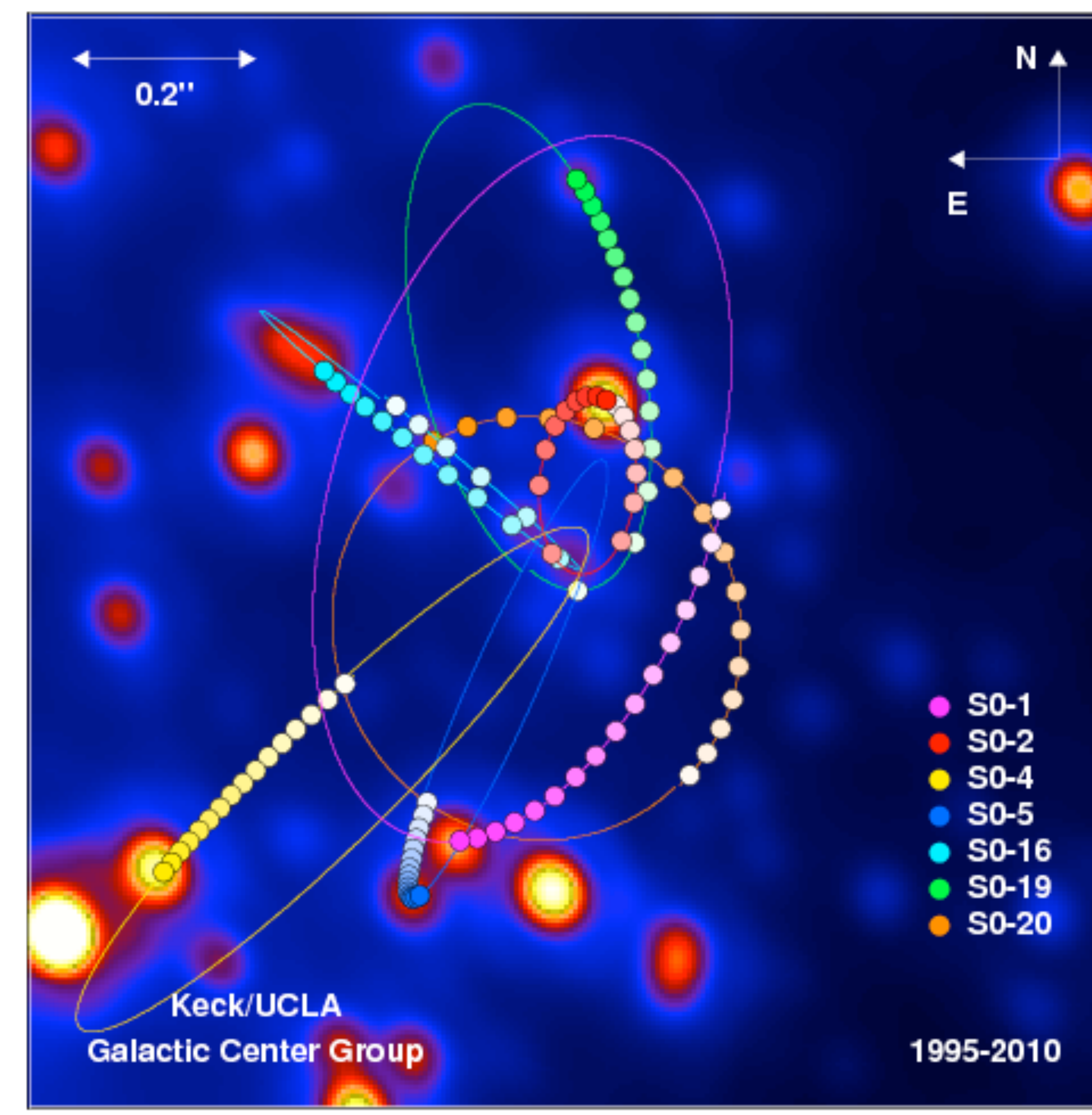




Stellar-mass Black Holes



- Supermassive BHs reside in essentially every massive galaxy.
- The strongest evidence we have for a BH comes from the Milky Way (e.g., Genzel et al. 2010, Boehle et al. 2016).



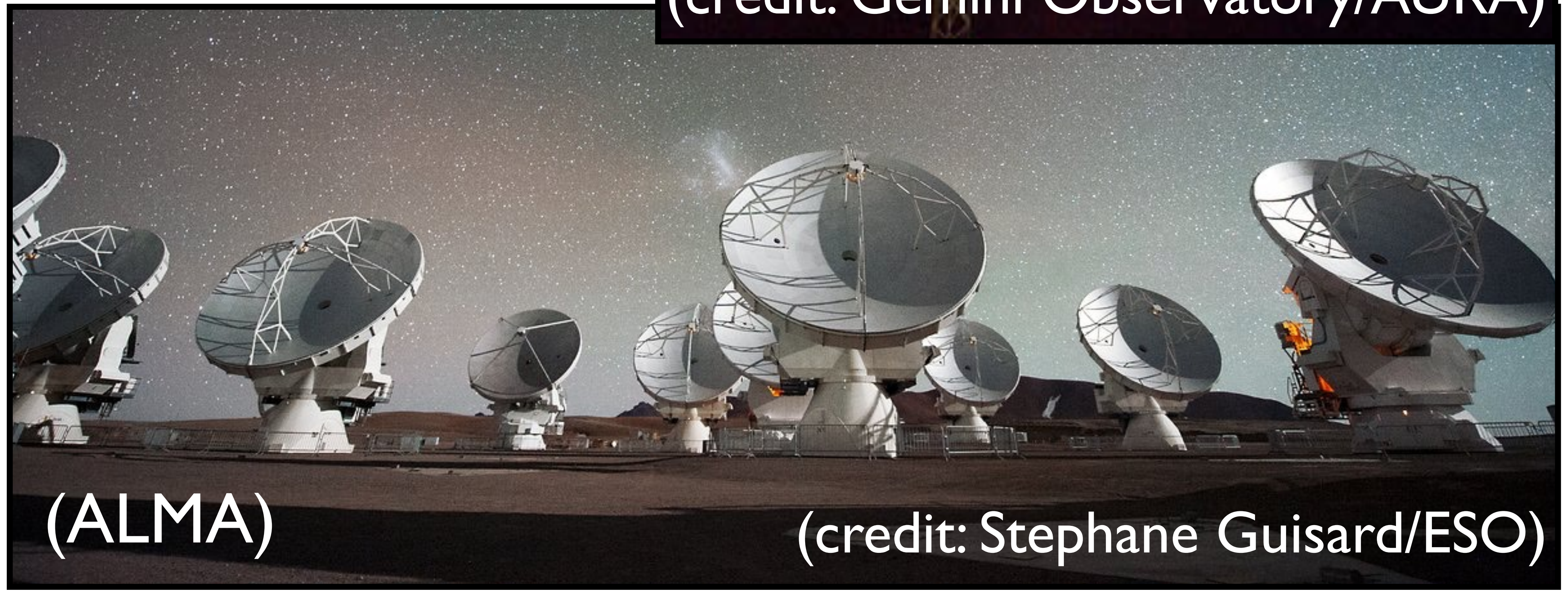
(This image was created by Prof. Andrea Ghez and her research team at UCLA and are from data sets obtained with the W. M. Keck Telescopes.)

- Beyond the Milky Way, BHs have been dynamically detected in ~100 galaxies (e.g., Saglia et al. 2016).

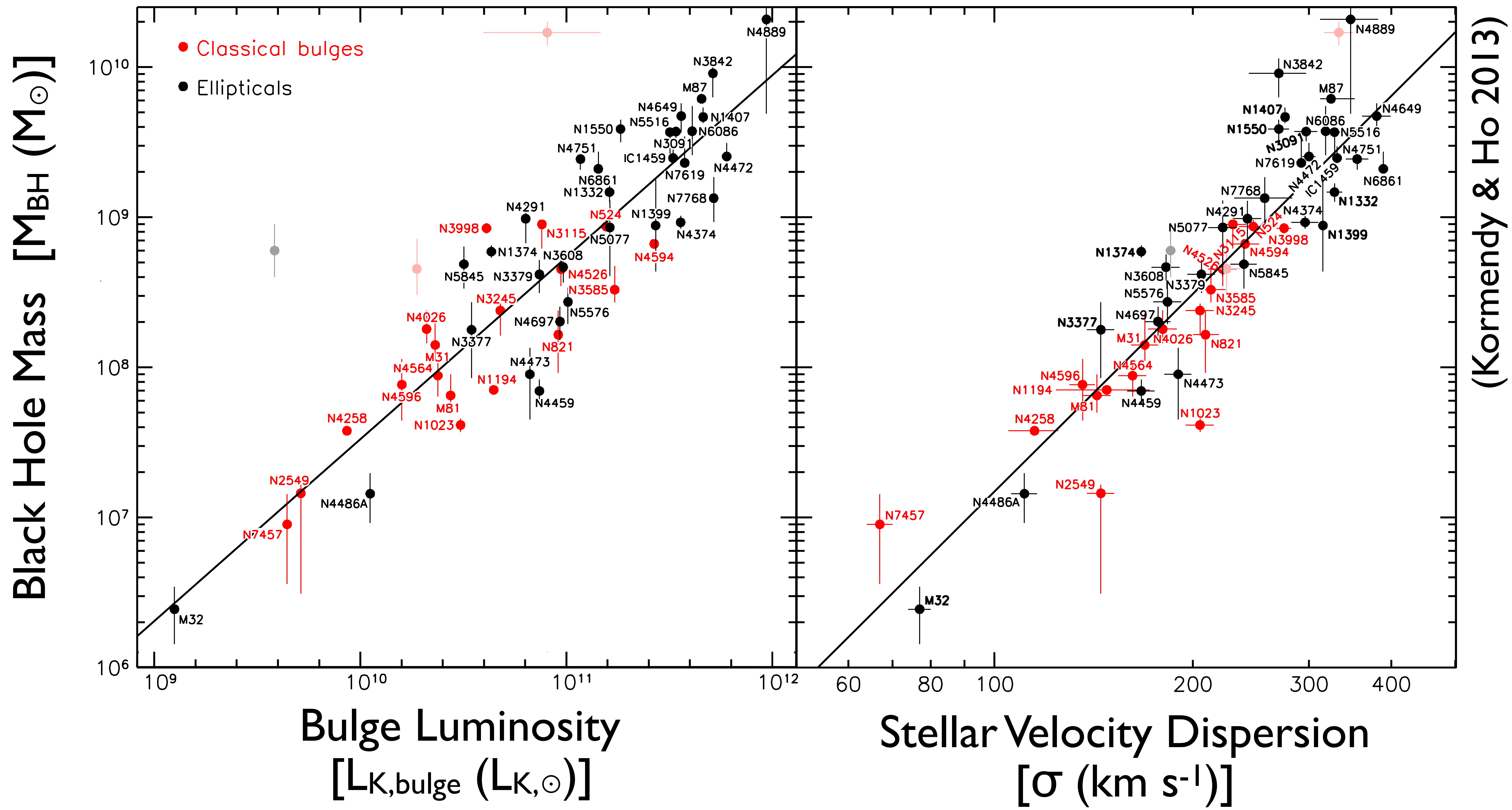
Dynamical Searches for Black Holes

- Precise M_{BH} measurements require high angular resolution observations.
- Observations need to probe region over which the BH potential dominates — the BH sphere of influence (r_{sphere}).
- Typical values for r_{sphere} are small, so we are limited to studying nearby (~100 Mpc) objects.

- HST has played a fundamental role in detecting BHs over the past two decades.
- Significant progress has recently been made using large ground-based telescopes + AO (e.g., Mazzalay et al. 2016, Erwin et al. 2018, Krajnović et al. 2018).
- ALMA also provides superb sensitivity and angular resolution high enough to directly detect molecular gas within r_{sphere} (e.g., Barth et al. 2016, Onishi et al. 2017, Davis et al. 2017).



The Current Black Hole Relations



- ✦ The correlations suggest that BHs and galaxies grow in tandem, but we still do not have a good understanding of the exact role that BHs play in galaxy evolution. We need more robust M_{BH} measurements that:
  - ✦ better sample the extremes of the BH mass scale
  - ✦ probe a wider range of galaxy types with diverse evolutionary histories

HET Massive Galaxy Survey

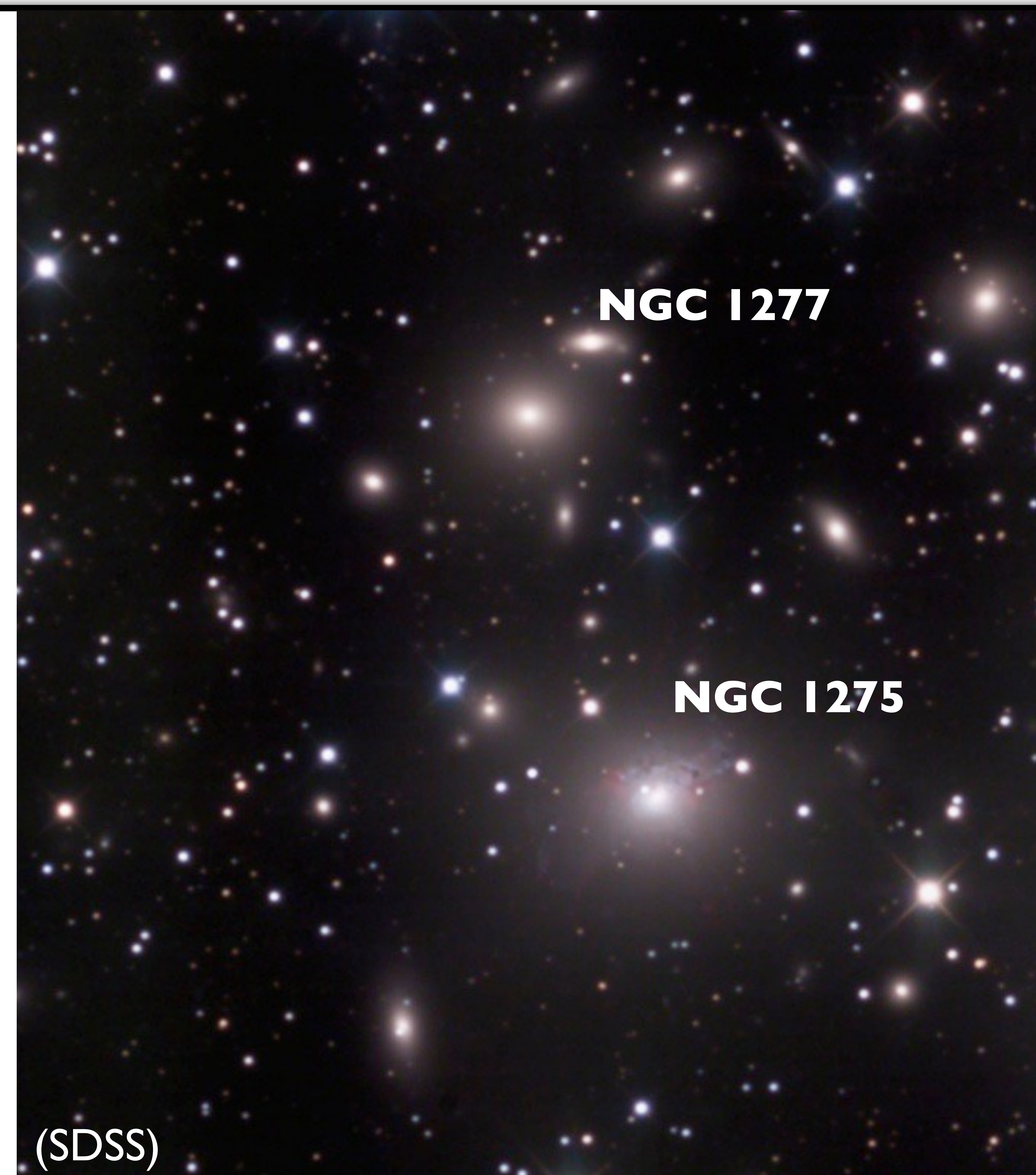
- Observed 1022 galaxies over the course of 9 trimesters.
- Obtained optical spectra with HET/LRS.
- Measured stellar velocity dispersions of nearby, massive galaxies.
- The survey allows us to make best use of high-angular resolution facilities.

(van den Bosch et al. 2015)

Compact, High-dispersion Galaxies

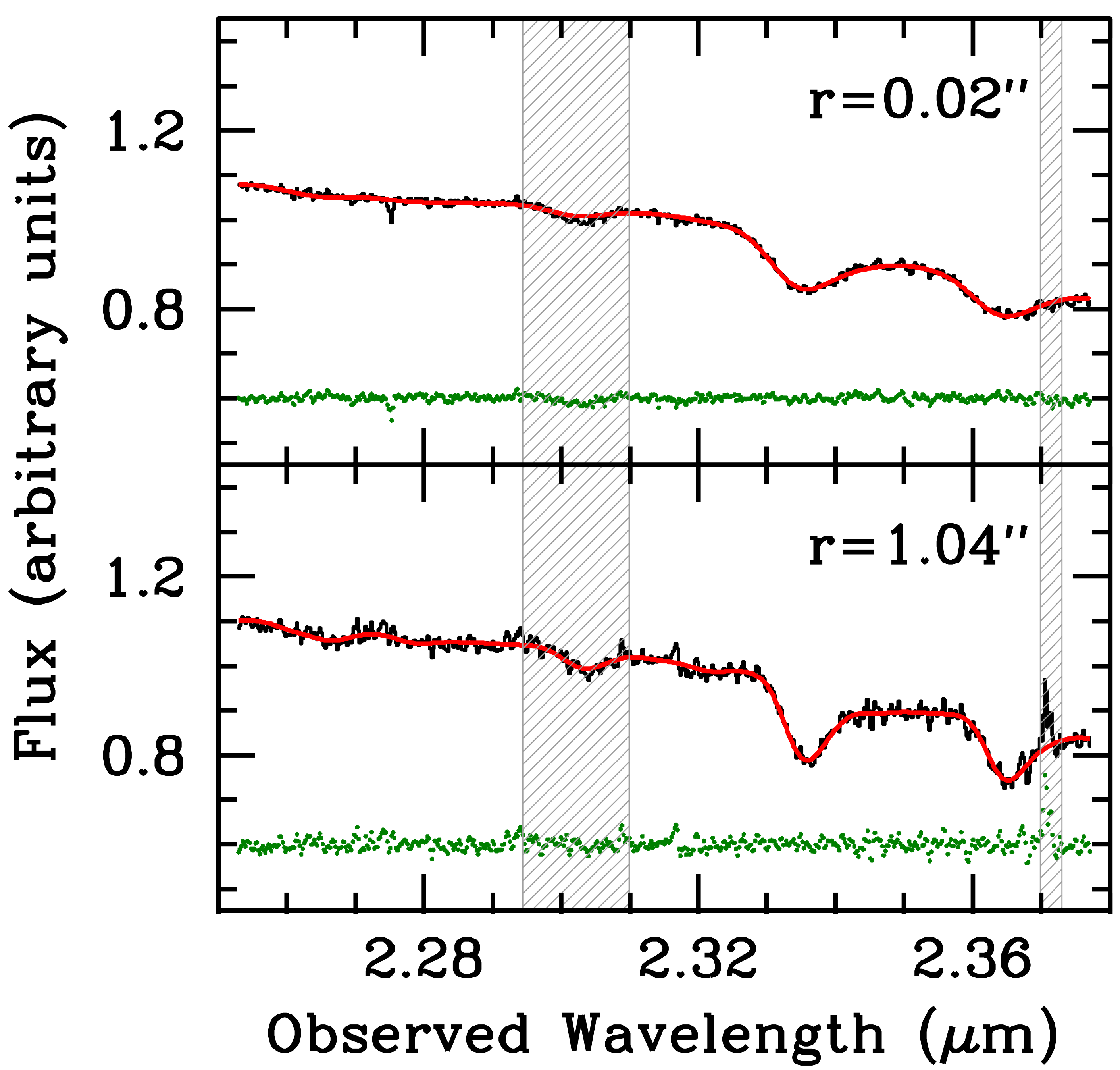
- The HET survey uncovered early-type galaxies that have small sizes and luminosities for their large stellar velocity dispersions:
  - $r_e \sim 1\text{-}3$ kpc
  - $L_K \sim 5\times10^{10}\ L_\odot - 2.5\times10^{11}\ L_\odot$
  - $\sigma_c > 250$ km s^{-1}

- Objects are interesting because they:
  - could host some of the most massive BHs known
  - are different from the massive elliptical galaxies expected to host the largest BHs (e.g., McConnell et al. 2011, 2012, Thomas et al. 2016)
  - appear similar to z~2 galaxies ("red nuggets") (e.g., Ferré-Mateu et al. 2015, 2017, Yildirim et al 2017, Beasley et al. 2018)



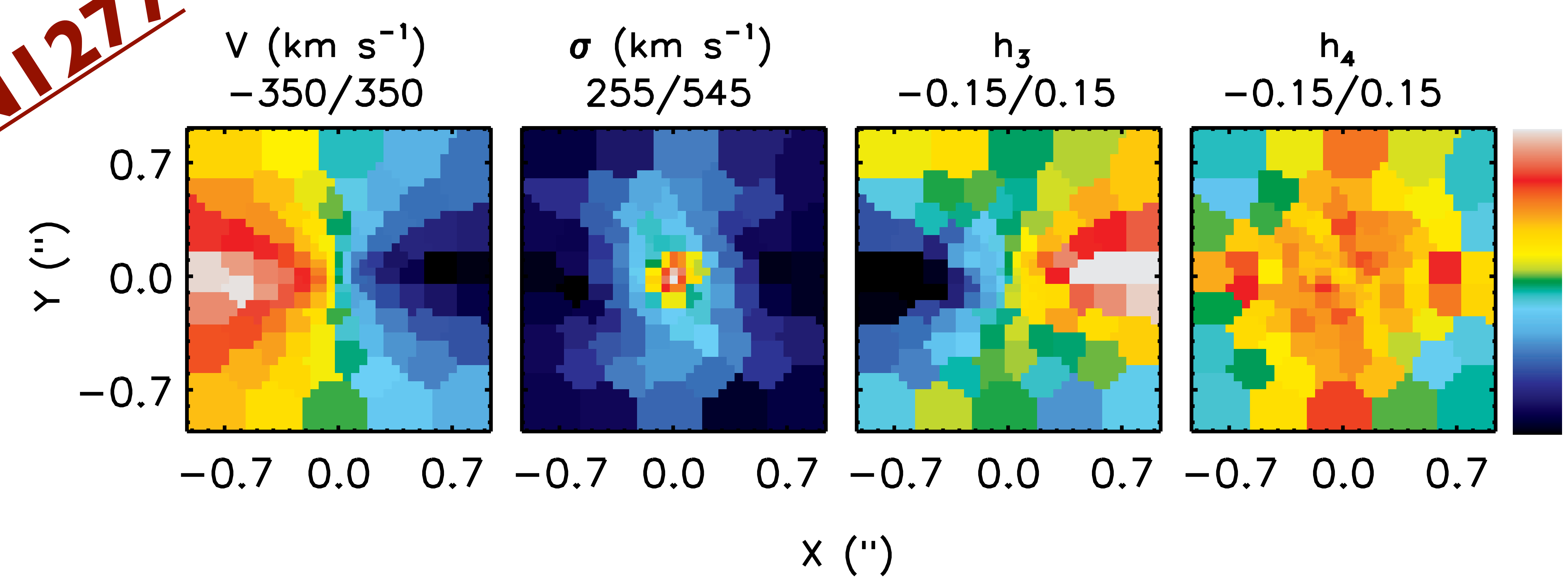
Compact, High-dispersion Galaxies: Observations

- Acquired HST near-infrared images and large-scale IFU data from PPAK at Calar Alto Observatory (Yildirim et al. 2017).
- Obtained IFU data assisted by LGS AO from Gemini/NIFS (Walsh et al. 2015, 2016, 2017) and Keck/OSIRIS for 6 galaxies.
  - probes the central ~1" (~330-530 pc) region with a PSF ~0.15"
  - with the AO system, r_{sphere} is resolved if galaxies follow M-σ

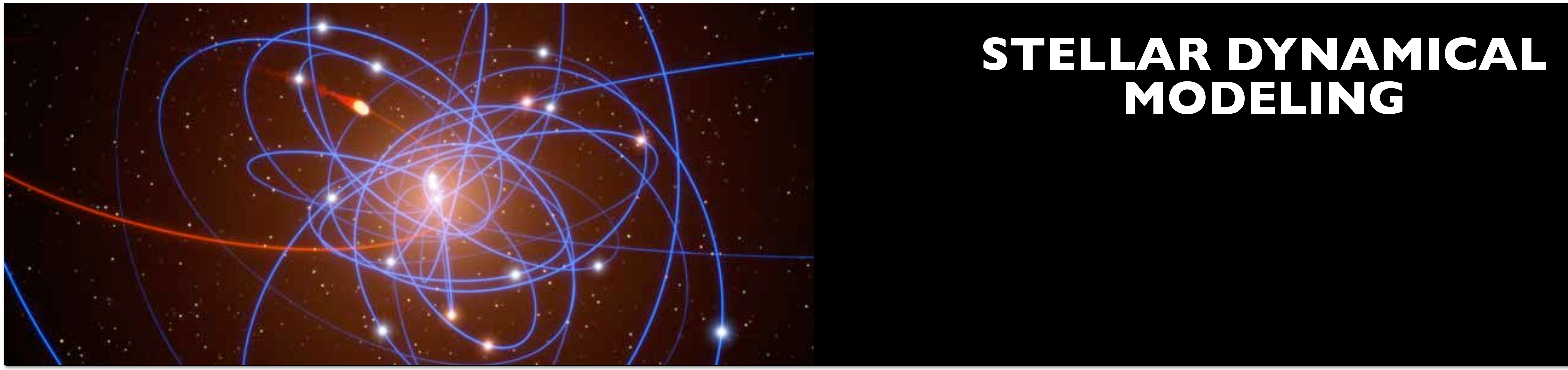


- From IFU data, we measured the velocity distribution of stars (V, σ, h_3, h_4) as a function of spatial location.

N1277



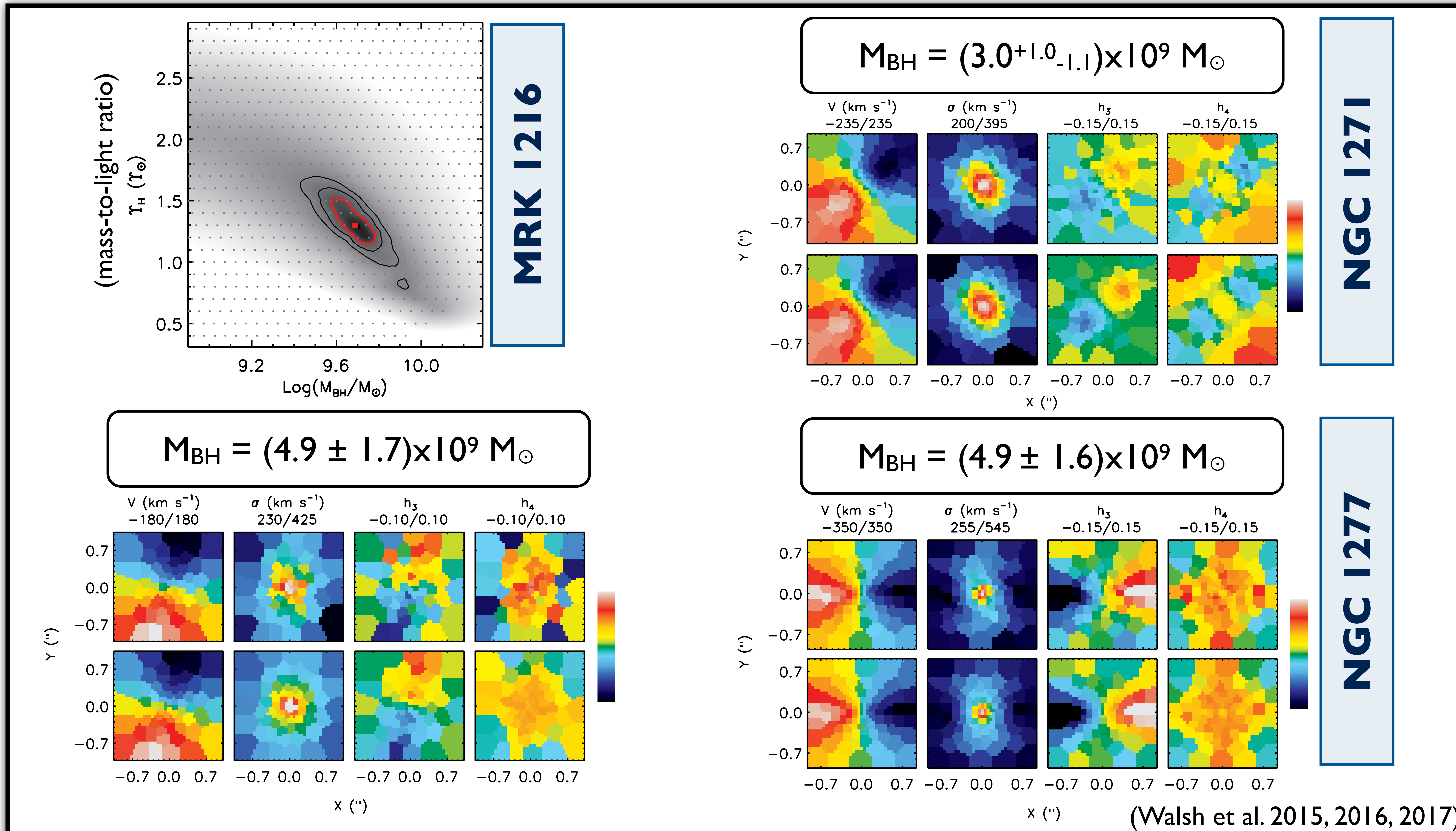
Compact, High-dispersion Galaxies: Modeling Procedure



- ✦ Construct orbit-based models using supercomputers.
- ✦ Potential consists of contributions from the BH, stars, and dark matter.
- ✦ Integrate orbits in the potential. Assign weights to each orbit such that the superposition matches the observed kinematics and surface brightness.
- ✦ Repeat for different combination of parameters until lowest χ^2 is found.

(van den Bosch et al. 2008)

Compact, High-dispersion Galaxies: Modeling Results

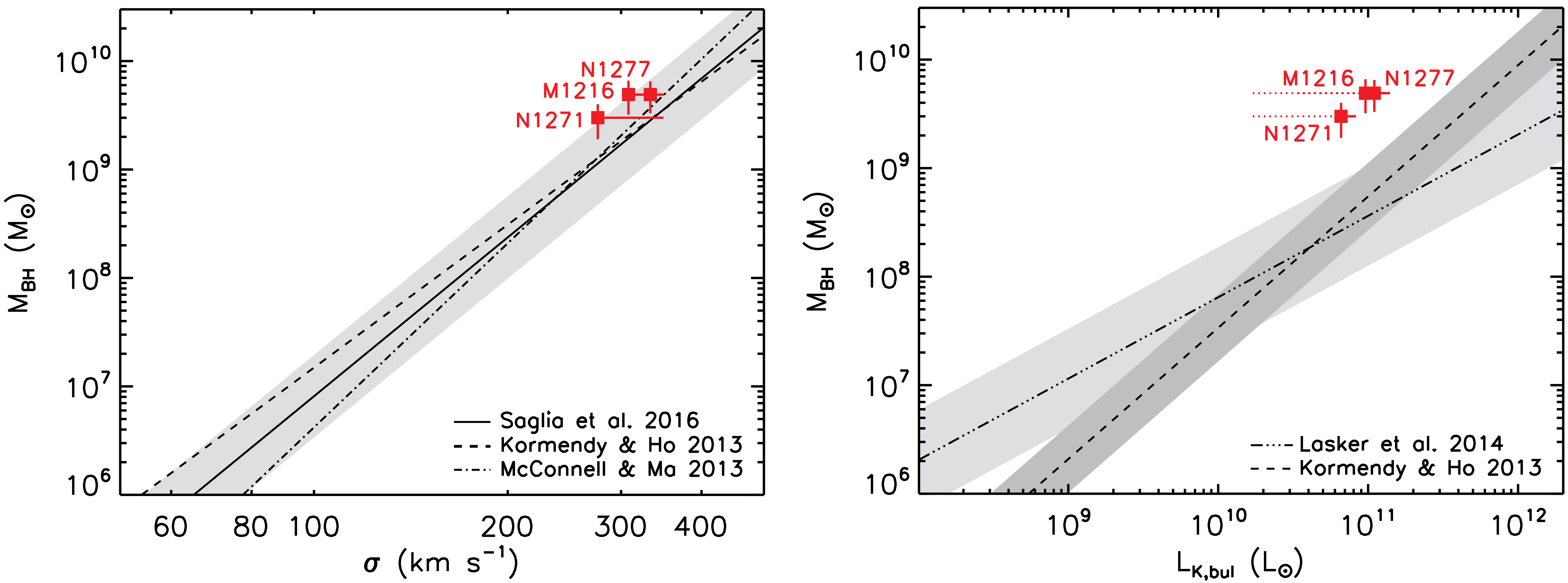


(Walsh et al. 2015, 2016, 2017)

Compact Galaxies and the Black Hole Scaling Relations

- NGC 1271, NGC 1277, and Mrk 1216 host some of the most massive BHs dynamically detected to date, with M_{BH} ~$(3\text{-}5)\times10^9\ M_\odot$.

- All are surprising positive outliers from M_{BH} - L_{bul}. Even when conservatively using the galaxy's total luminosity (instead of the bulge luminosity), the galaxies are 2σ outliers.



(Walsh et al. 2017)

Over-massive Black Holes in Compact Galaxies

How did such large BHs end up in a relatively modest galaxies?

- Maybe the compact galaxies fall in the tails of a distribution between BH and galaxy properties that have yet to be fully established.

Over-massive Black Holes in Compact Galaxies

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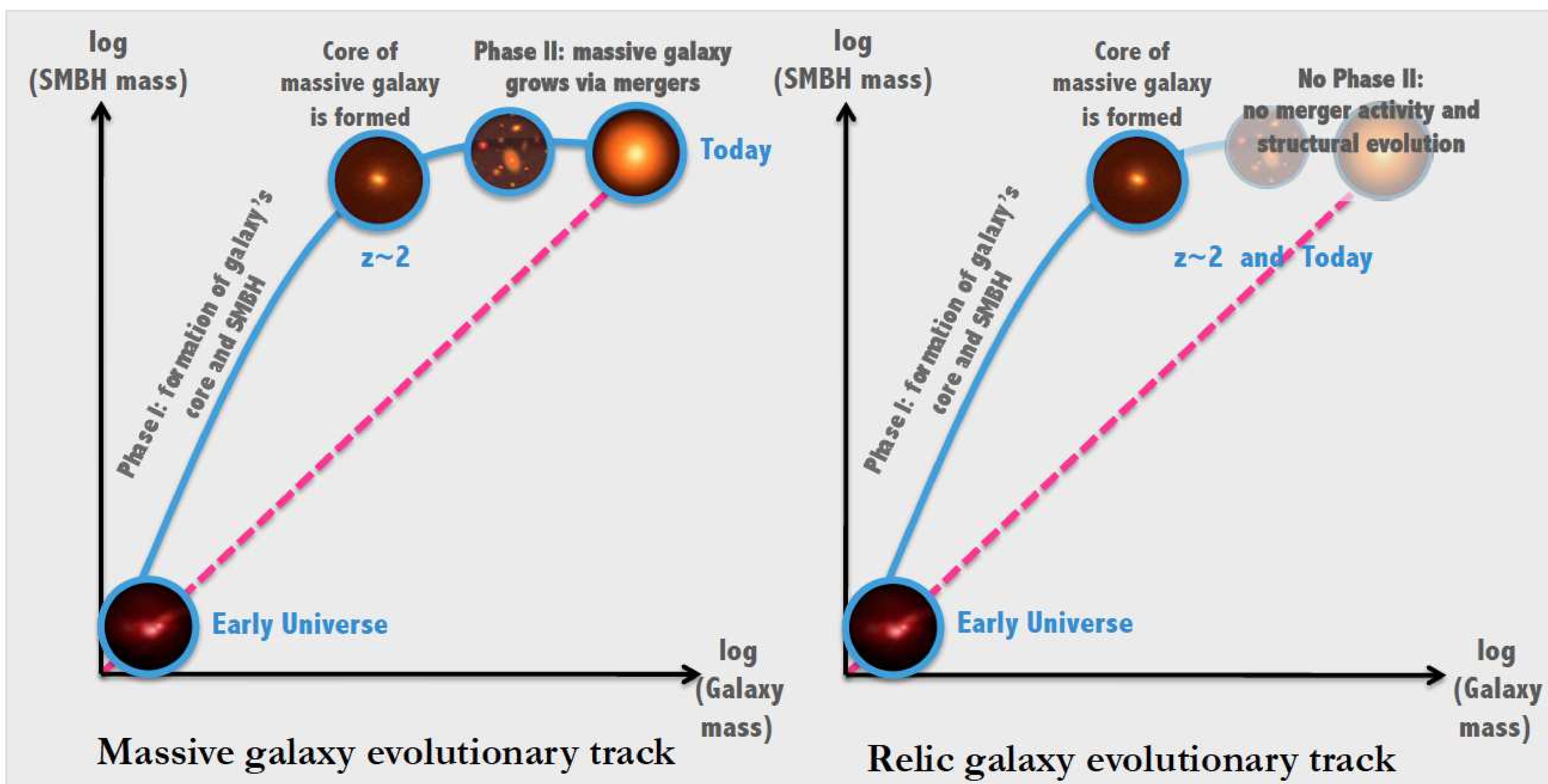
- Maybe the compact galaxies fall in the tails of a distribution between BH and galaxy properties that have yet to be fully established.

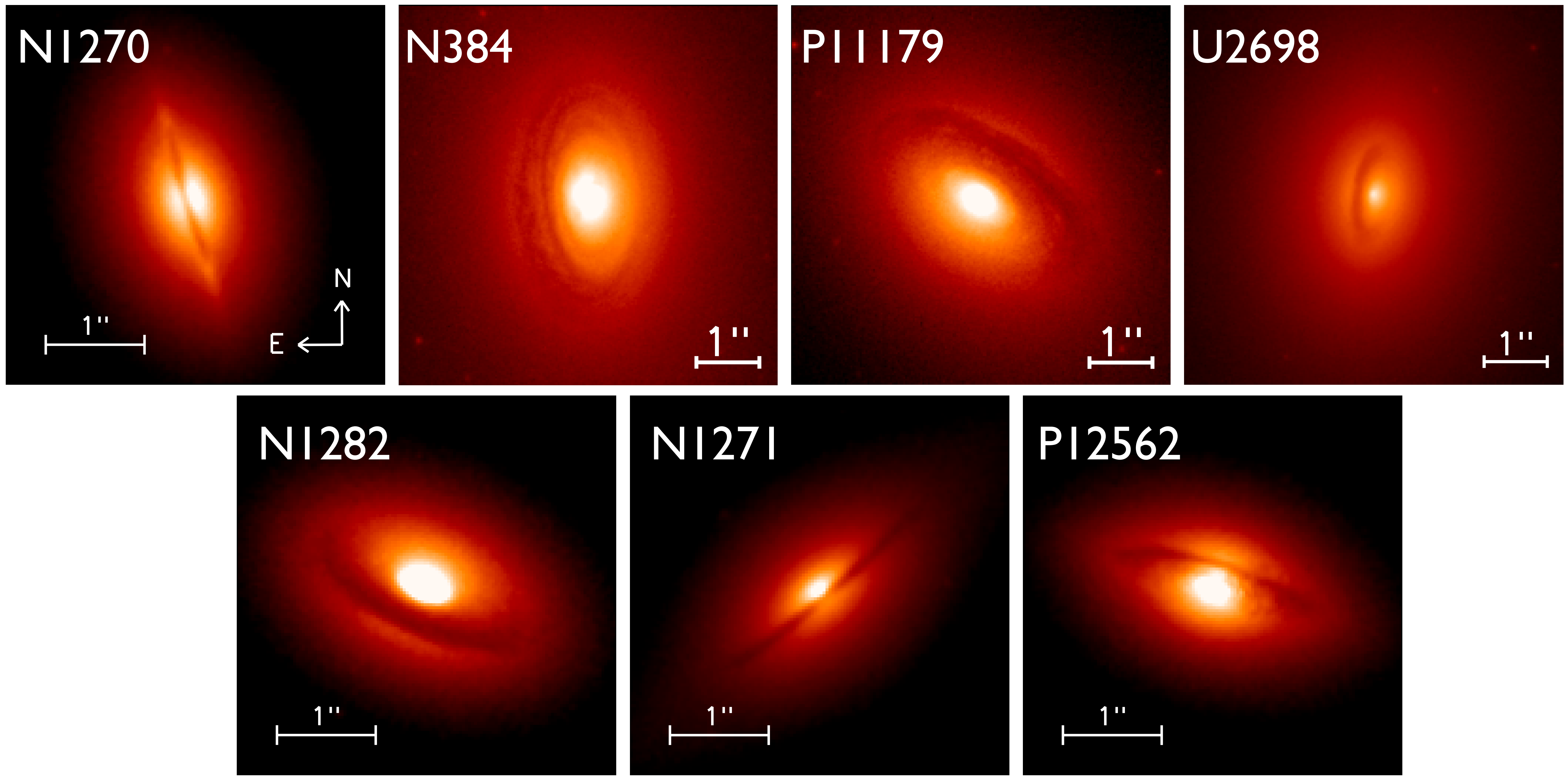
- Given the similarities to the z~2 galaxies, perhaps the local compact galaxies are relics, and reflect the relationship between BHs and galaxies at earlier times.
  - perhaps BH growth precedes that of its host galaxy!



(Ferre-Mateu et al. 2015)

ALMA Observations of the Compact Galaxies

- There are 8 compact, high-dispersion galaxies from the HET survey that have nuclear dust disks. This suggests the presence of cleanly rotating molecular gas.

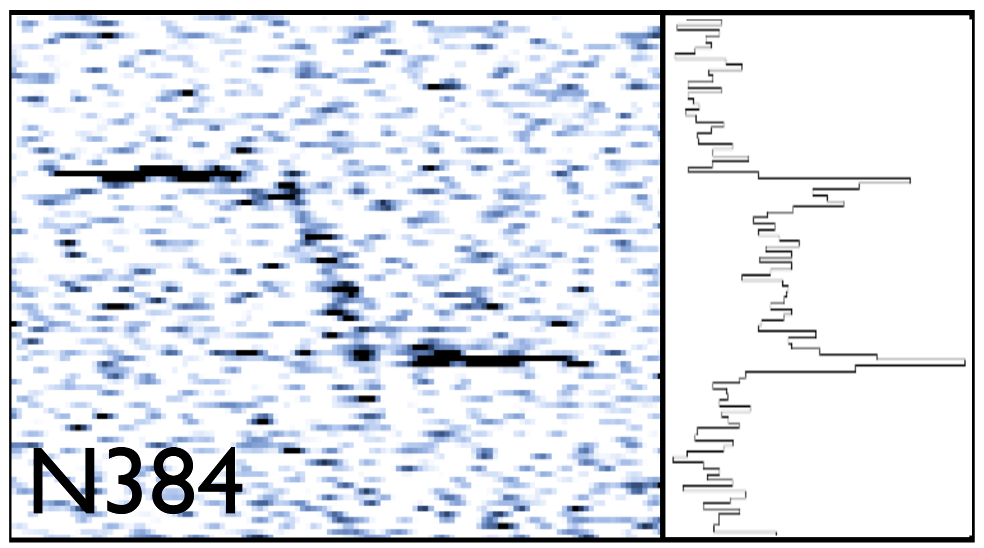


- Obtained Cycle 4 ALMA data to test for the presence of CO emission within r_{sphere}, measure the emission-line kinematics, and calculate gas-dynamical M_{BH}'s for 3 compact galaxies from the HET survey.

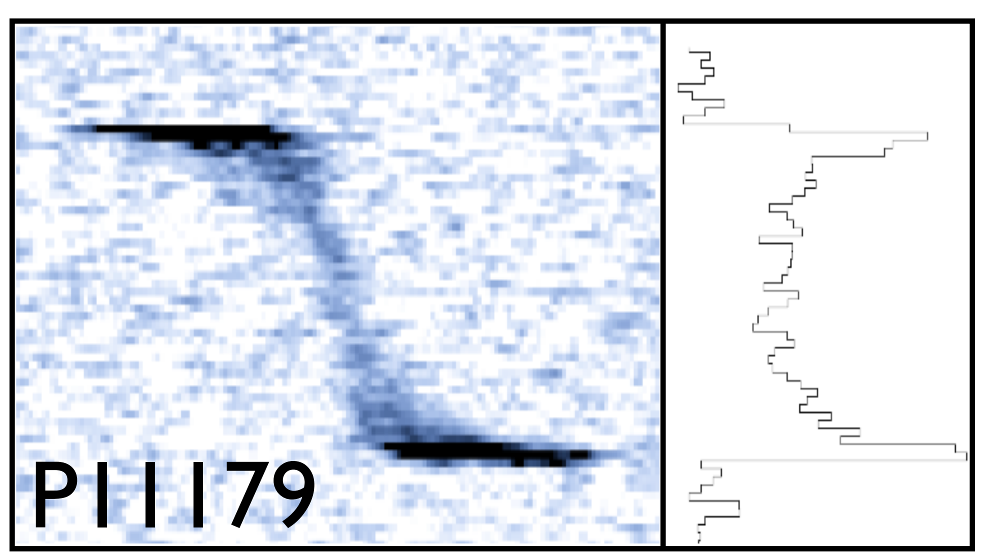
ALMA Observations of the Compact Galaxies

- Initial kinematic measurements of the CO gas for all 3 compact galaxies observed with ALMA show regular rotation [courtesy of Benjamin Boizelle (UC Irvine)].

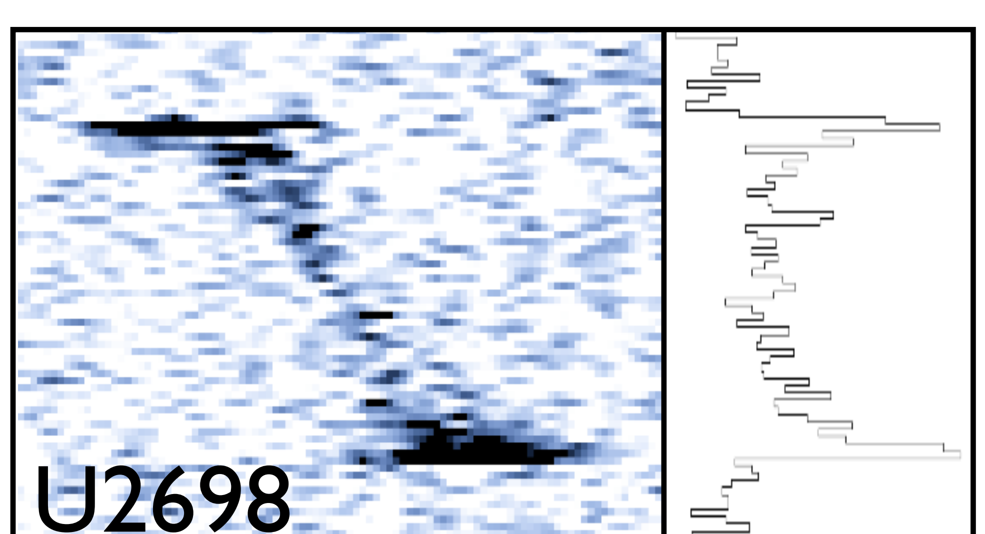
0.20" resolution, on-source time of 30 min.

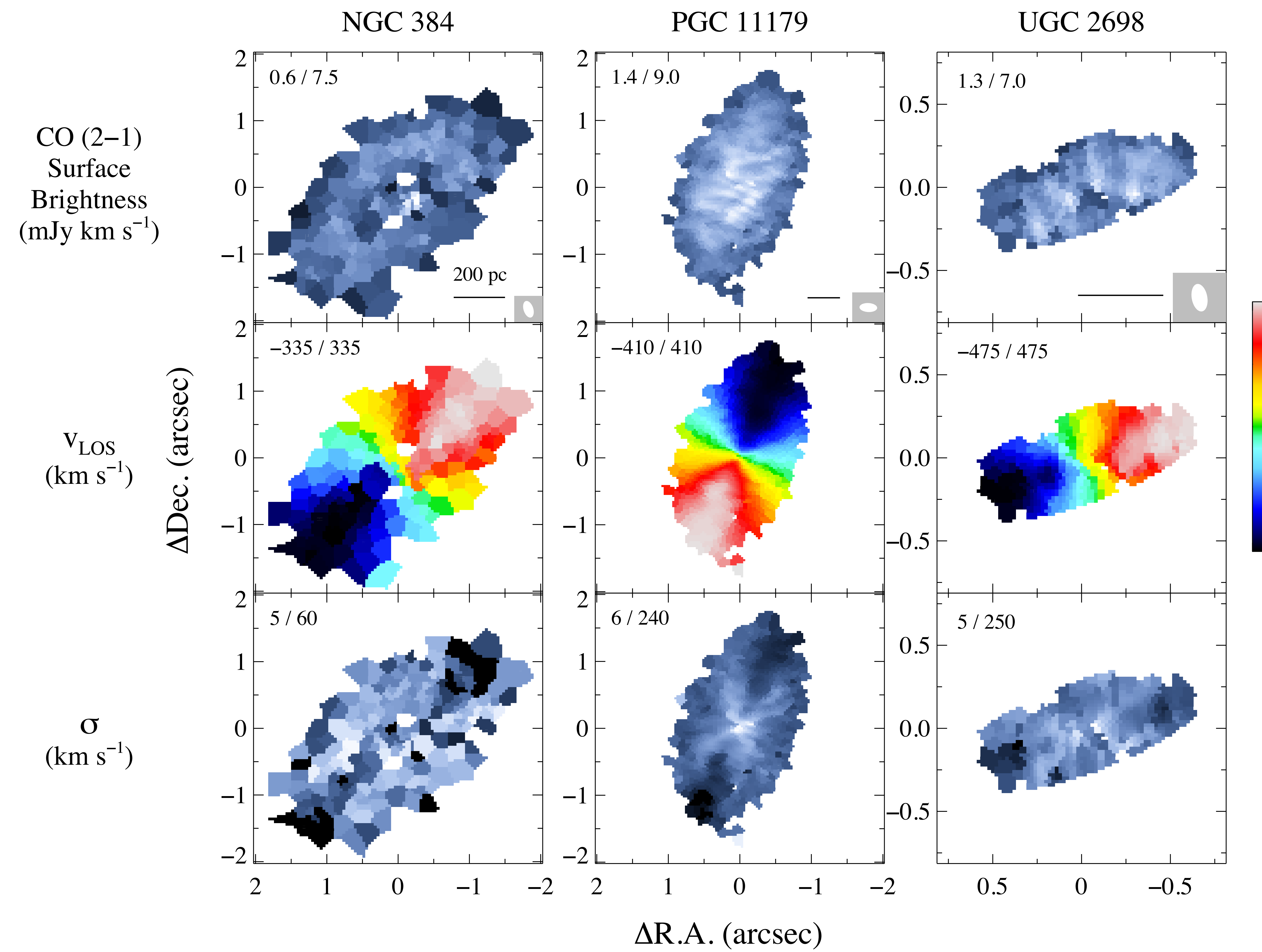


0.22" resolution, on-source time of 25 min.



0.14" resolution, on-source time of 33 min.





A Gemini Large Program to Measure Black Holes

- Awarded 253 hours with Gemini North to measure M_{BH} using stellar-dynamical modeling methods in 31 galaxies using AO-assisted NIFS.

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<u>Chile</u>

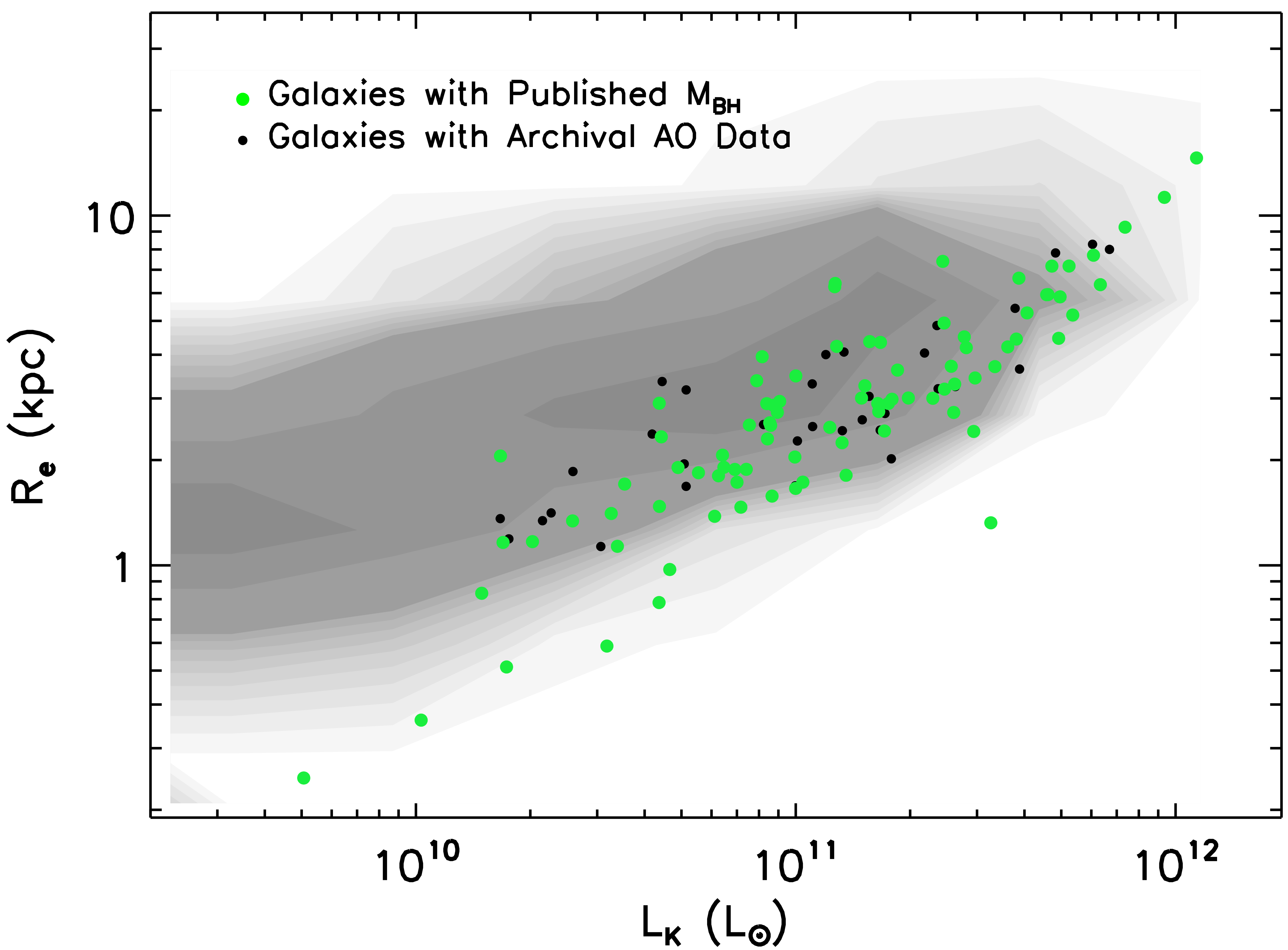
Bryan Miller

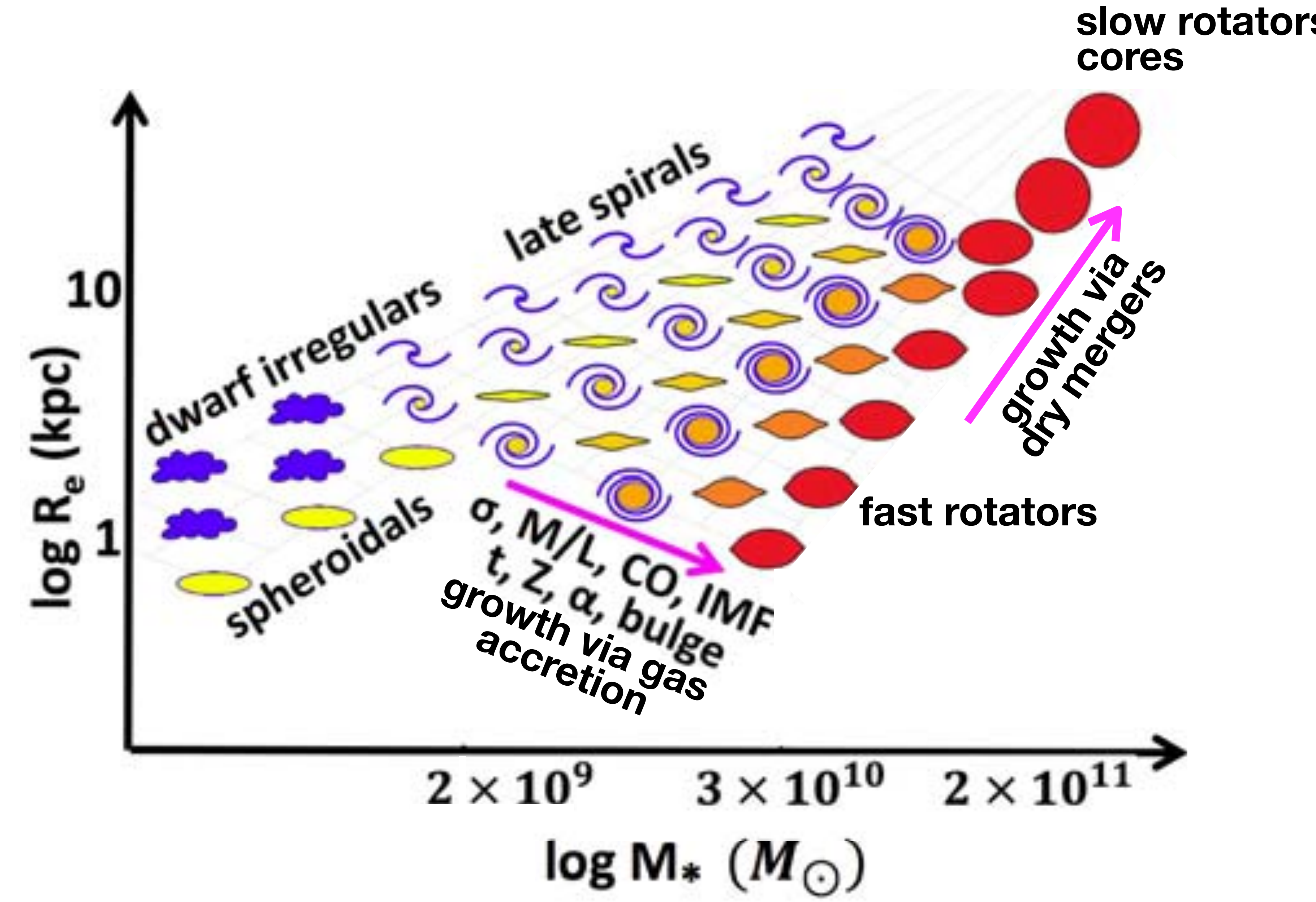
<u>Finland</u>

Ronald Läsker

A Gemini Large Program to Measure Black Holes

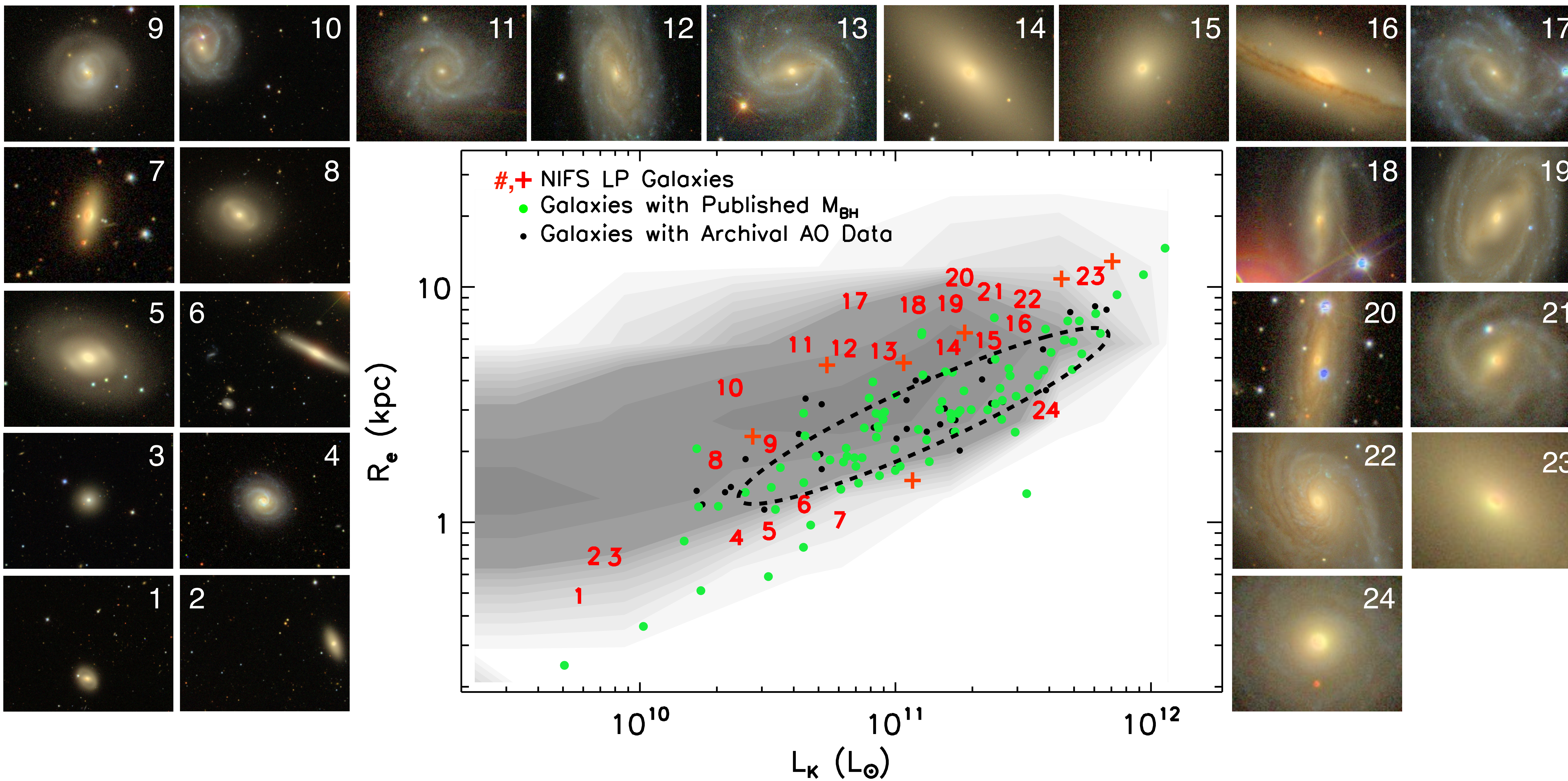
- M_{BH} measurements have been preferentially made in galaxies with small sizes at a given luminosity relative to the nearby galaxy population.
- Proper sampling of the luminosity-size space is crucial for covering a wide variety of galaxies that have experienced diverse growth pathways (e.g., Cappellari 2016, Krajnovic et al. 2018).





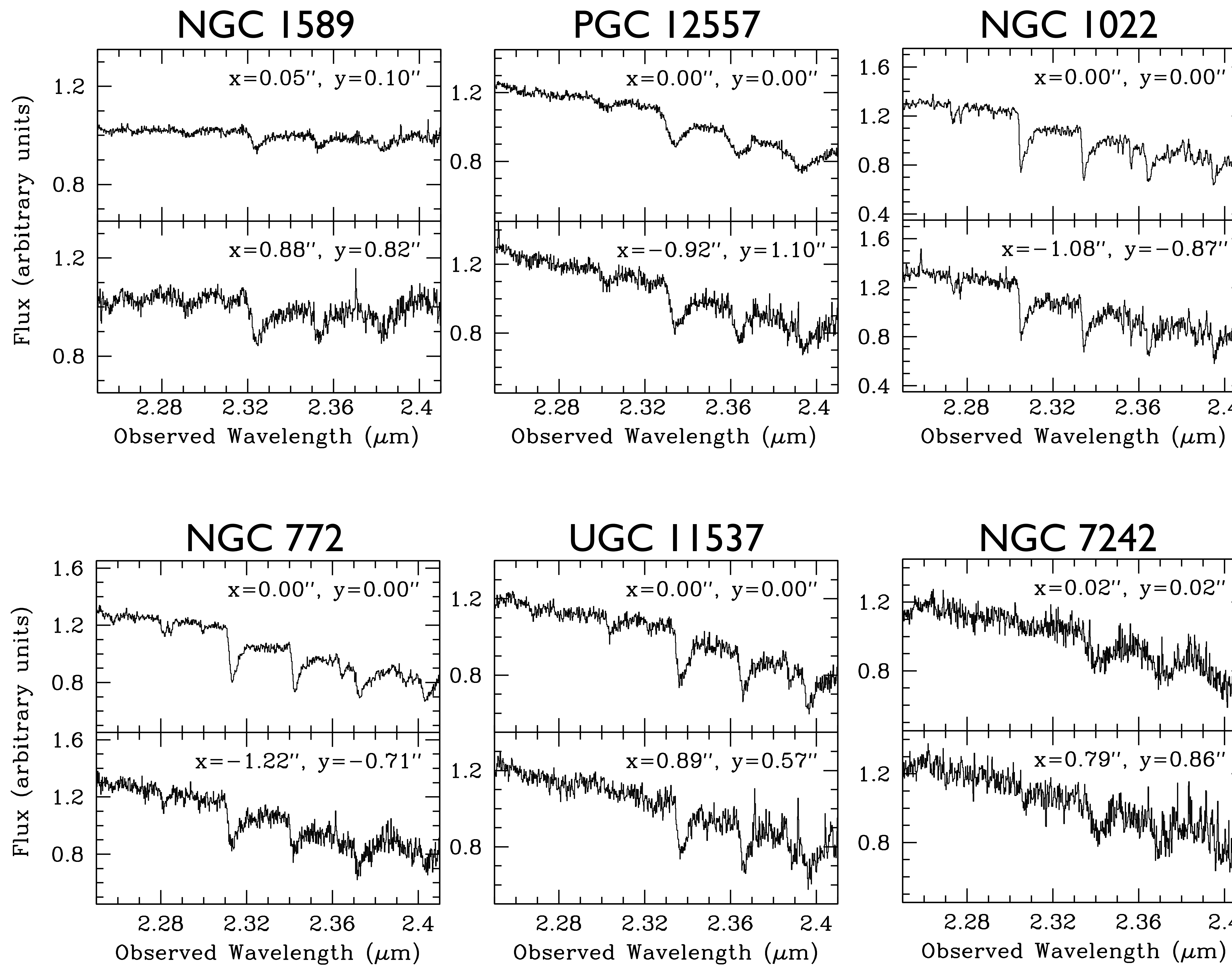
(adapted from Cappellari 2016)

A Gemini Large Program to Measure Black Holes



A Gemini Large Program to Measure Black Holes

- We obtained AO Gemini/NIFS observations of 6 galaxies using 36 hrs.

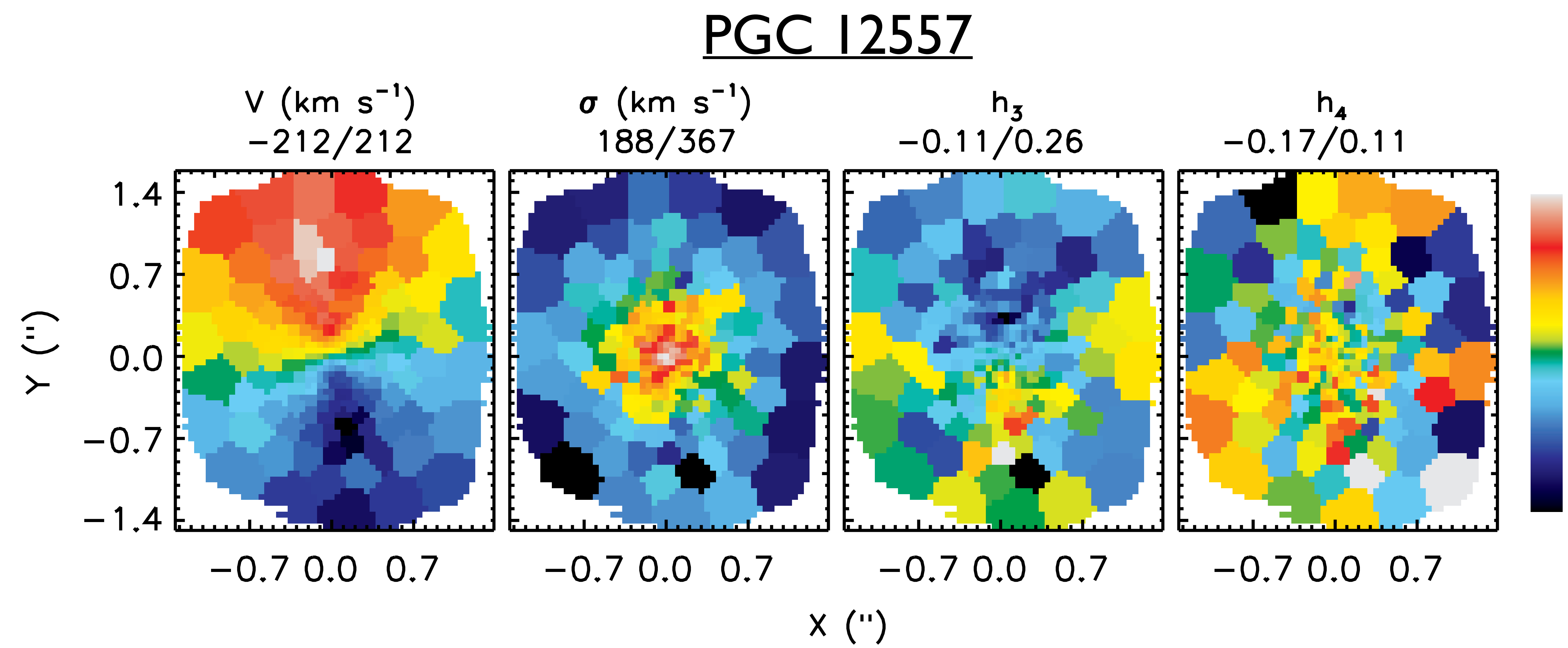


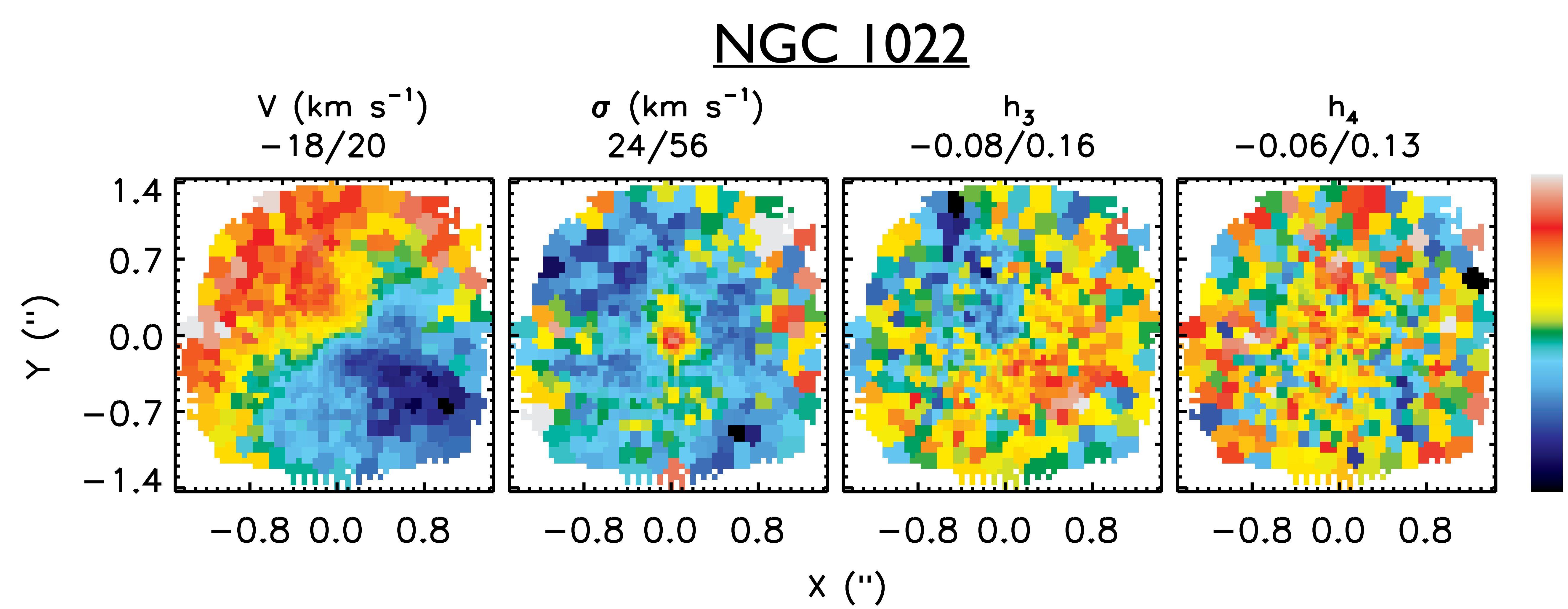
A Gemini Large Program to Measure Black Holes

- We obtained AO Gemini/NIFS observations of 6 galaxies using 36 hrs.

- We have approved HST cycle 25 and mid-cycle 24 observations for all 31 galaxies. Thus far, 16 galaxies have been observed with WFC3 in the F475W, F814W, and F160W filters.

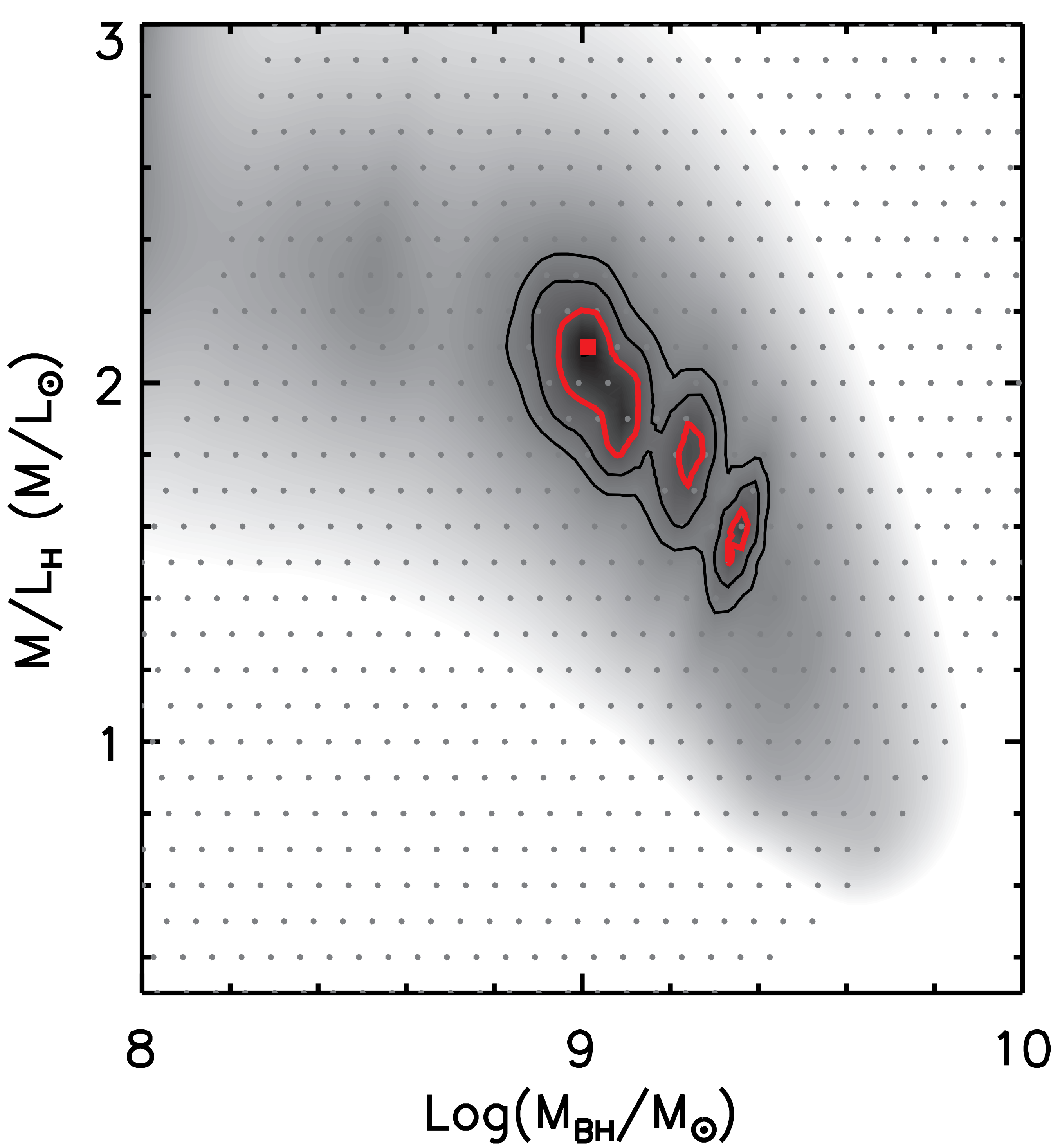
- We have observed most of the 31 galaxies with HET/LRS2 and have completed VIRUS-P/VIRUS-W observations of 16 galaxies from the 2.7m telescope at McDonald Observatory.



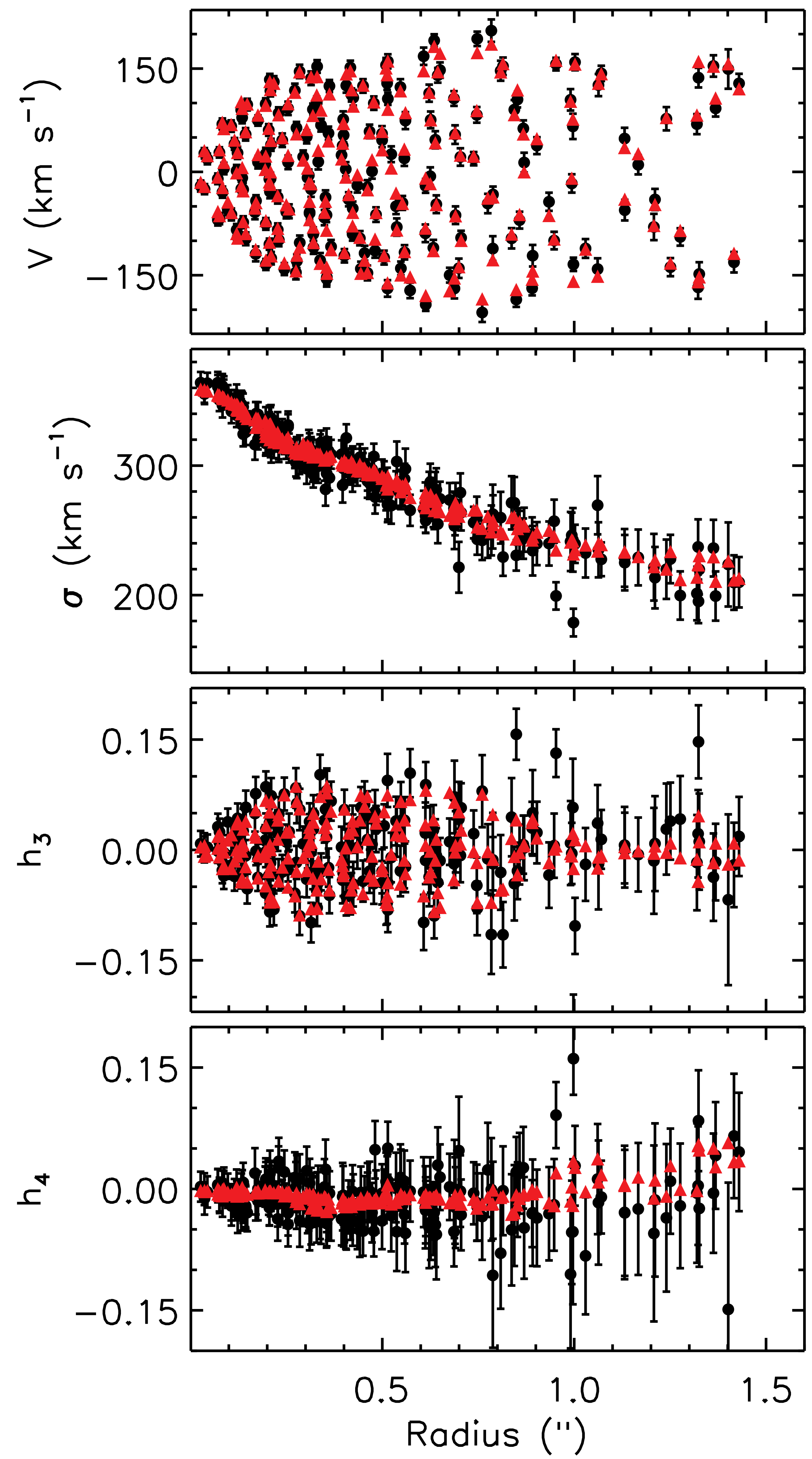


A Gemini Large Program to Measure Black Holes

PGC 12557



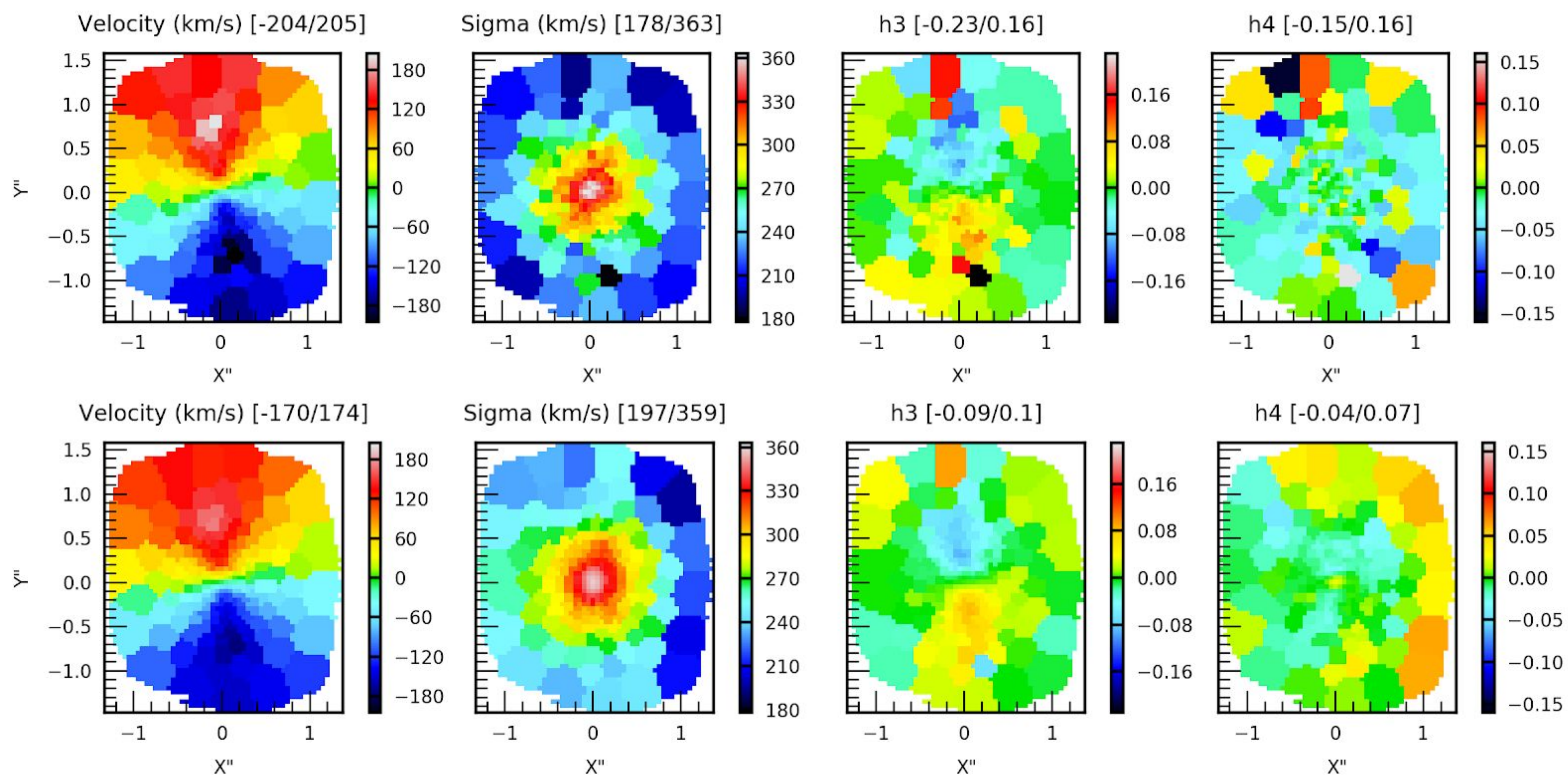
$M_{BH} = (1.0^{+1.2}_{-0.1}) \times 10^9\ M_\odot$



- Using the NIFS stellar kinematics and HST F160W image, we constructed orbit-based models (van den Bosch et al. 2008), assuming an oblate axisymmetric shape and *i*=75°.
- The AO PSF was described by the sum of two circular Gaussians, with dispersions of 0.07'' and 0.27'' and weights of 0.51 and 0.49, respectively.
- Sampled 31 values of M_{BH} between 10^8-10^{10} $M_\odot$, 28 M/L_H values between 0.3-3.0 $M/L_\odot$, and 3 NFW halos with c=10 and dark matter fractions of 10, 100, 1000.

A Gemini Large Program to Measure Black Holes

- We tested running an independent axisymmetric stellar-dynamical modeling code (Valluri et al. 2004) and found consistent results for PGC 12257, with $M_{BH} = 2.0 \times 10^9\ M_\odot$ and $M/L_H = 1.5\ M/L_\odot$.



[courtesy of Chinmaya Verma (IIT Kharagpur) and Monica Valluri (Michigan)]

- This study will address a bias in the galaxies for which M_{BH}'s have been measured, could re-invent the BH scaling relations, and will provide a deeper understanding of the interplay between BHs and galaxies.

Summary

- We need more M_{BH} measurements, particularly at the extremes of the BH mass scale and in a wider range of galaxy types with varied evolutionary pasts.

- From stellar-dynamical modeling of AO observations, we find $M_{BH} \sim (3\text{-}5) \times 10^9\ M_\odot$ for 3 HET compact, high-dispersion galaxies. The objects are outliers from M_{BH}-L_{bul} and, given the similarities to the z~2 galaxies, could hint that BH growth precedes host galaxy growth.

- ALMA provides an exciting opportunity to measure M_{BH} through gas-dynamical methods. We will derive M_{BH} for 3 compact, high-dispersion galaxies, ultimately looking to compare to stellar-dynamical determinations.

- Detailed investigations of large, carefully selected samples using a homogenous approach is the ideal way to make major progress in the field prior to the next generation of extremely large telescopes.