Exploring the Supermassive Black Hole - Galaxy Connection

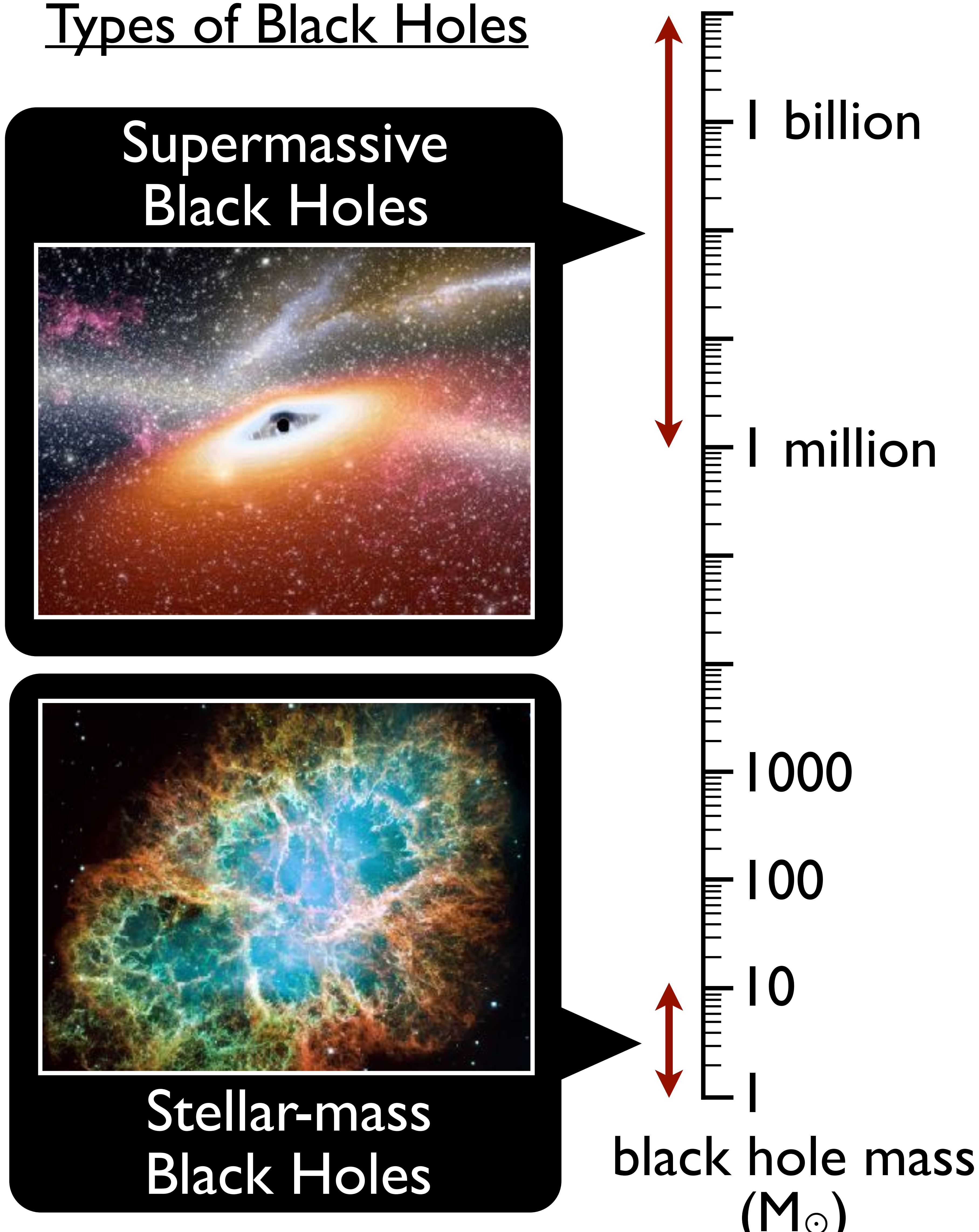
Jonelle Walsh (Texas A&M)

TMT Science Forum

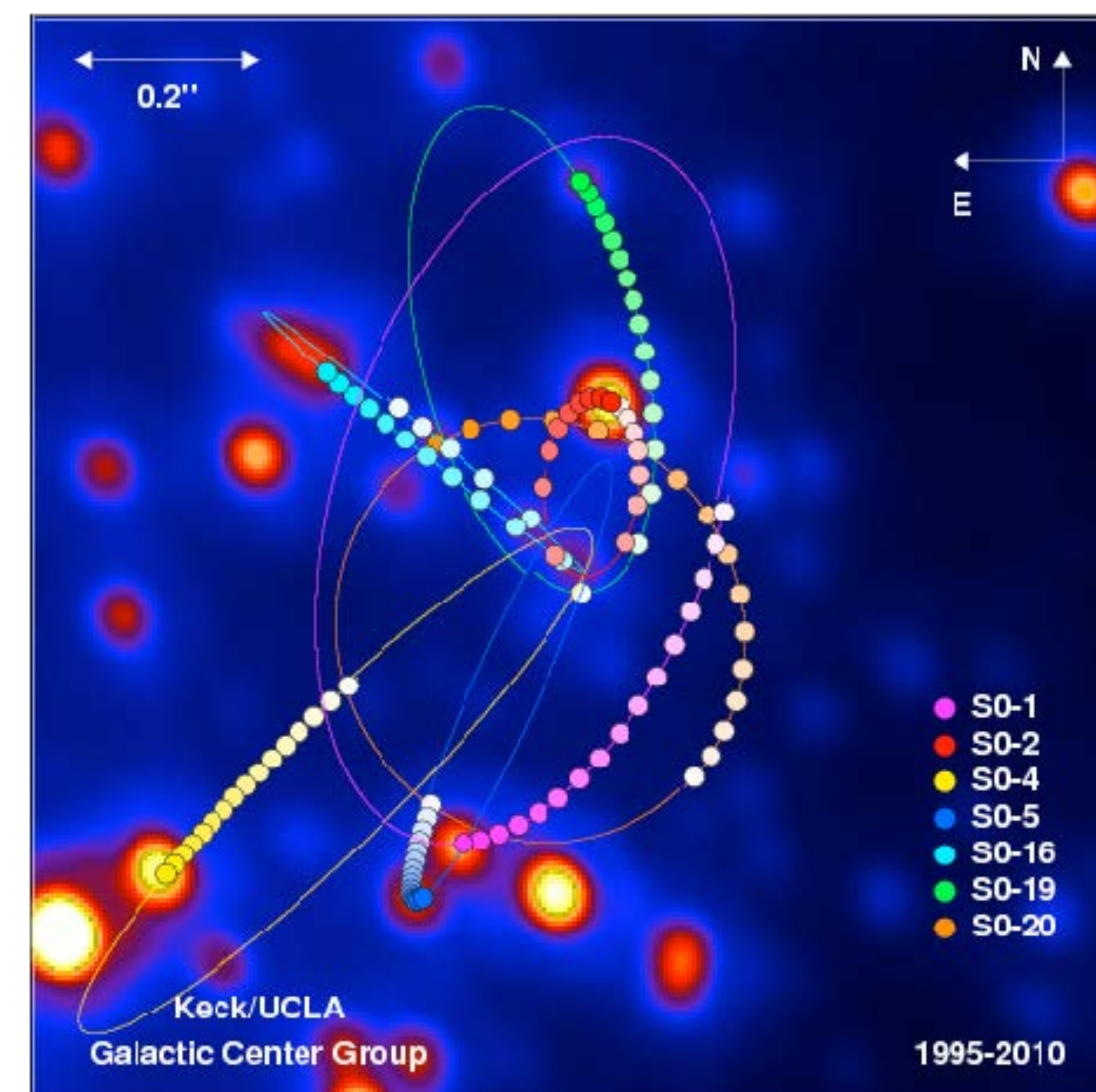
Dec 10, 2018

Introduction: Black Holes are Everywhere

<u>Types of Black Holes</u>



- 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}).

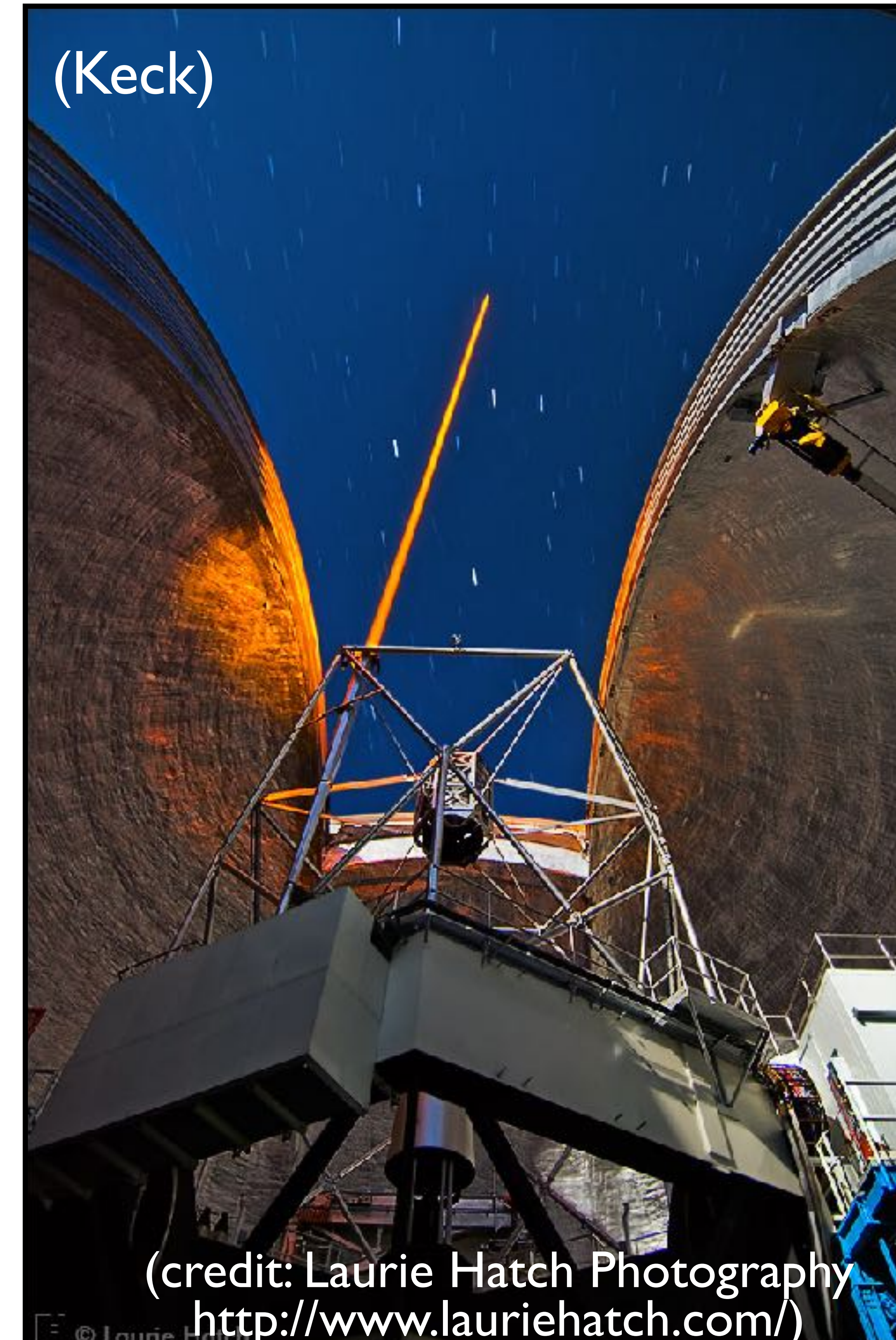
- Typical values for r_{sphere} are small, so we are limited to studying nearby (~100 Mpc) objects.

- HST has played a fundamental role in detecting BHs over the past two decades.

Dynamical Searches for Black Holes

- 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).



Black Hole Mass Measurement Methods

STELLAR DYNAMICS

- Widely applicable, BUT…
- Models are complex.
- Models can be biased due to a number of systematic effects.
  - M_{BH} - M/L - DM degeneracies
  - intrinsic shape/ orientation effects

(e.g., Gebhardt & Thomas 2009, van den Bosch & de Zeeuw 2010, Rusli et al. 2013, McConnell et al. 2013)

IONIZED GAS DISKS

- Conceptually simple, BUT…
- Assumption of circular rotation must be verified.
- Often the observed velocity dispersion is larger than that predicted from models.
  - what is the physical origin and what does that mean for M_{BH}?

(e.g., Barth et al. 2001, Verdoes Kleijn et al. 2006, Walsh et al. 2010)

MASER DISKS

- Produce some of the most precise M_{BH}'s, BUT…
- Disks are rare — they require special physical conditions and nearly edge-on inclinations.
- There can be significant gravitational contributions from disks themselves that lead to departures from Keplerian rotation.

(e.g., Miyoshi et al. 1995, Lodato & Bertin 2003, Pesce et al. 2015)

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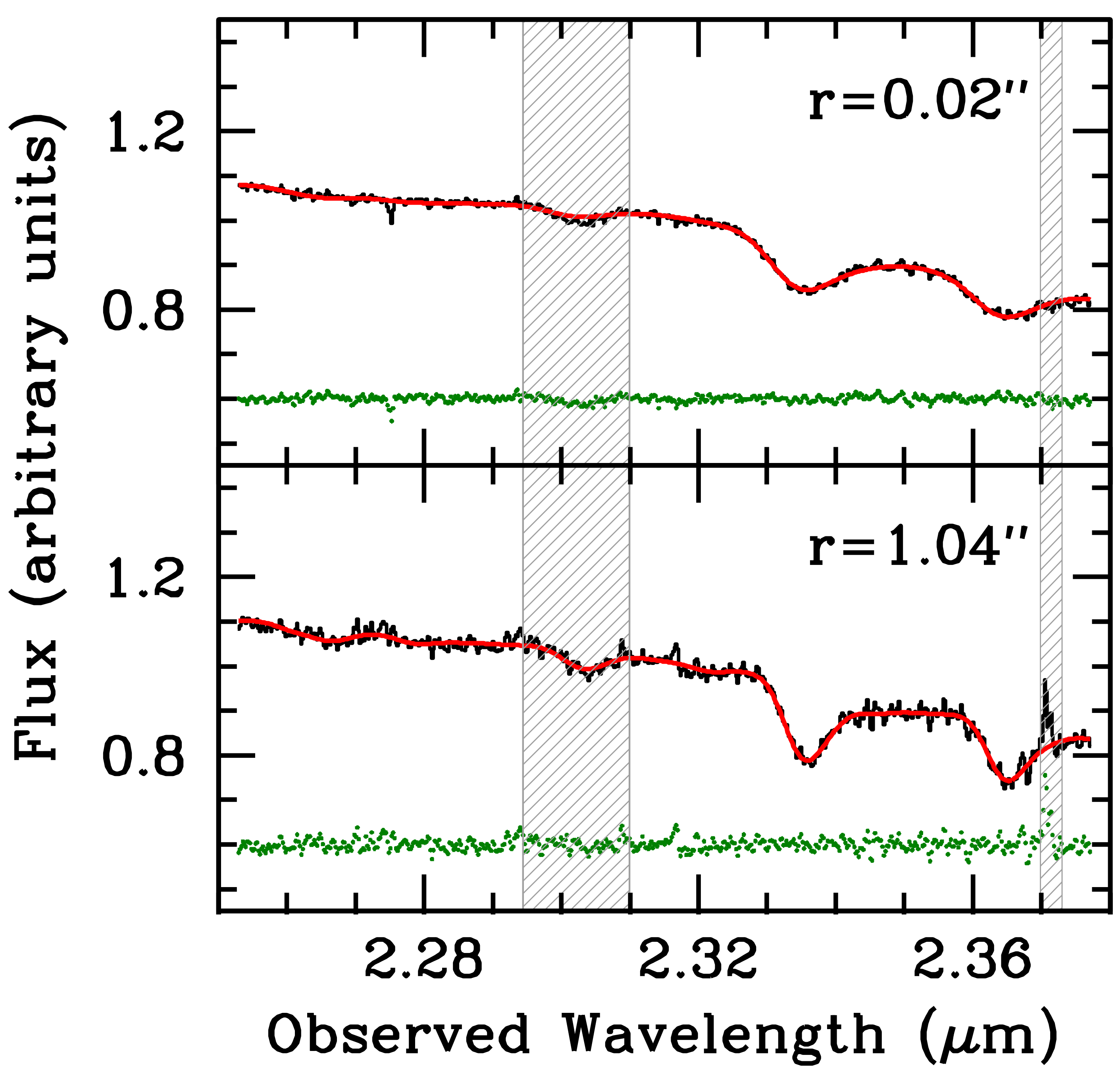
A Stellar-Dynamical Black Hole Mass Measurement Example

- Stellar-dynamical measurements require high-angular resolution spectroscopy, high-angular resolution imaging, and large-scale spectroscopy.

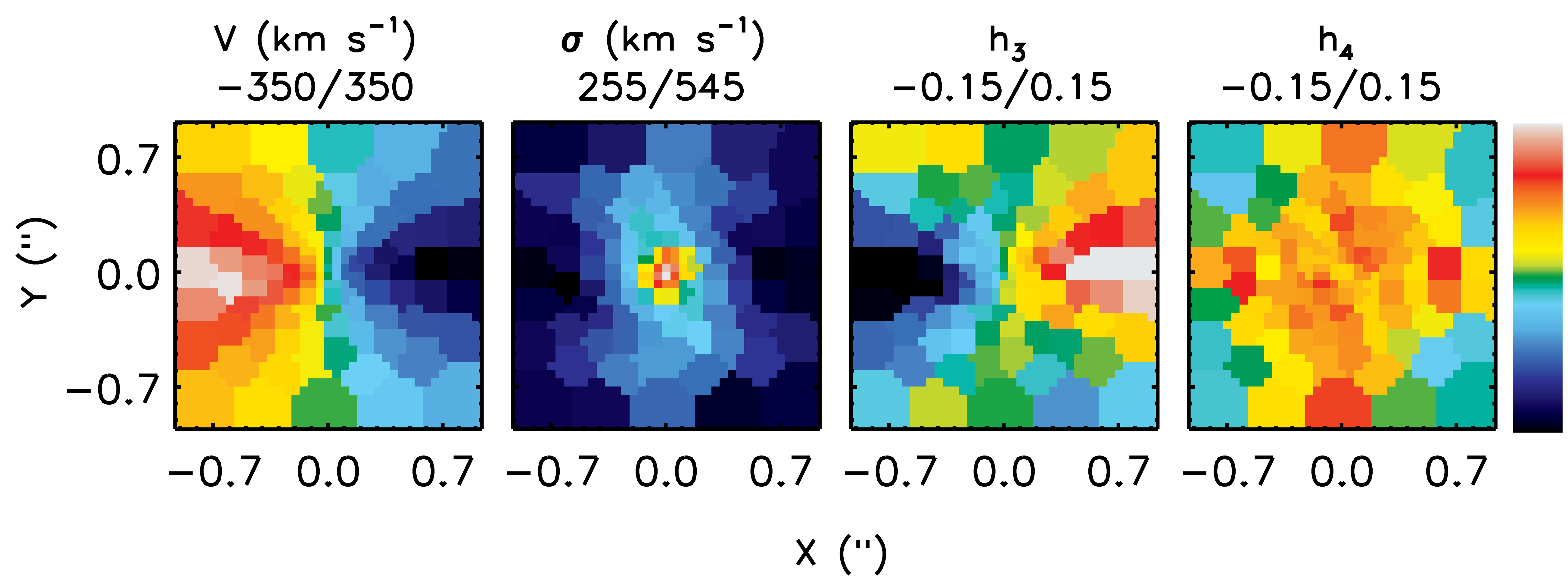
NGC 1277



(Walsh et al. 2016)

- Obtained Gemini/NIFS observations assisted by LGS AO. The IFU data probes the central ~1" (340 pc) region with a PSF ~0.15".

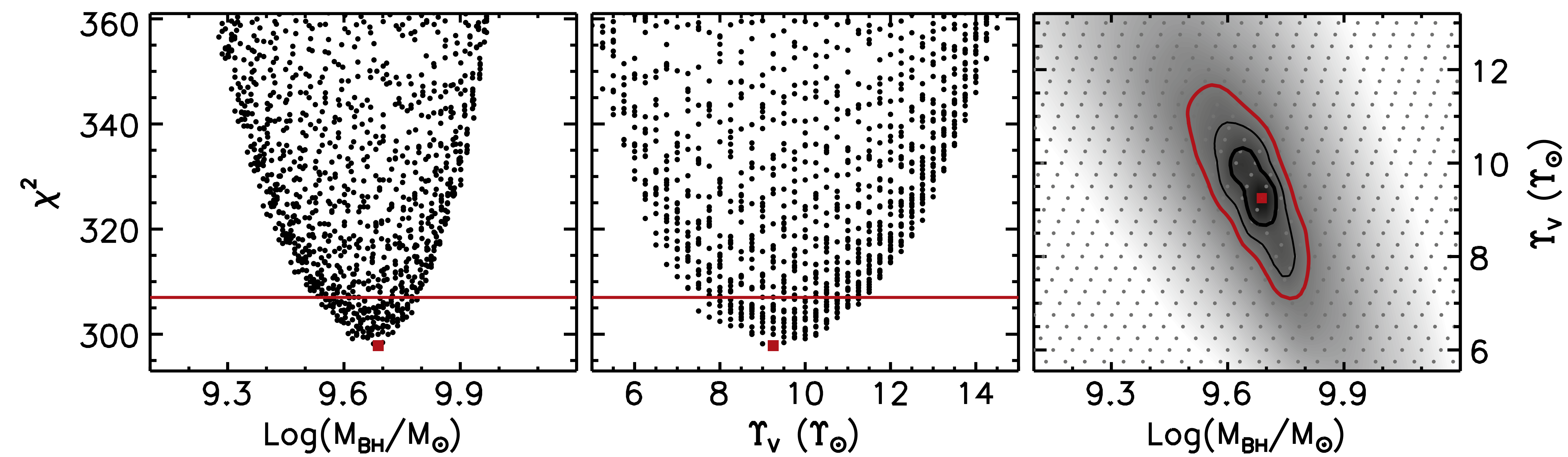
- Measured the line-of-sight velocity distribution (LOSVD) of stars as a function of spatial location. LOSVD parameterized with V, σ, h_3, and h_4.



A Stellar-Dynamical Black Hole Mass Measurement Example

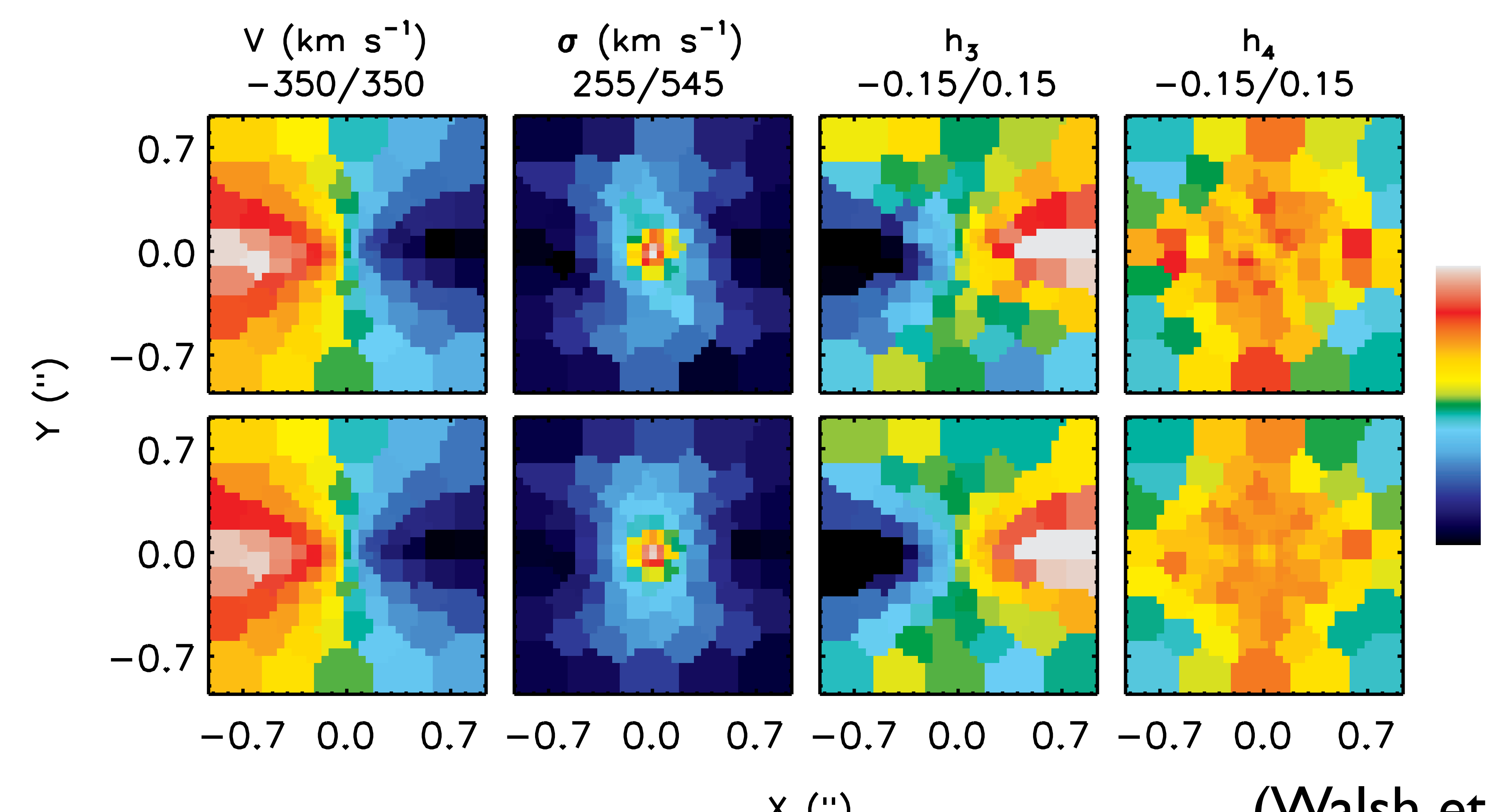
- Construct orbit-based models using supercomputers.
- Potential consists of contributions from the BH, stars, and dark matter.
- Integrate orbits in the potential. Assign weights to each orbit such that the superposition matches the observed kinematics and surface brightness.
- Repeat for different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

(e.g., Gebhardt et al. 2003, Valluri et al. 2004, Thomas et al. 2004, Cappellari et al. 2006, van den Bosch et al. 2008)



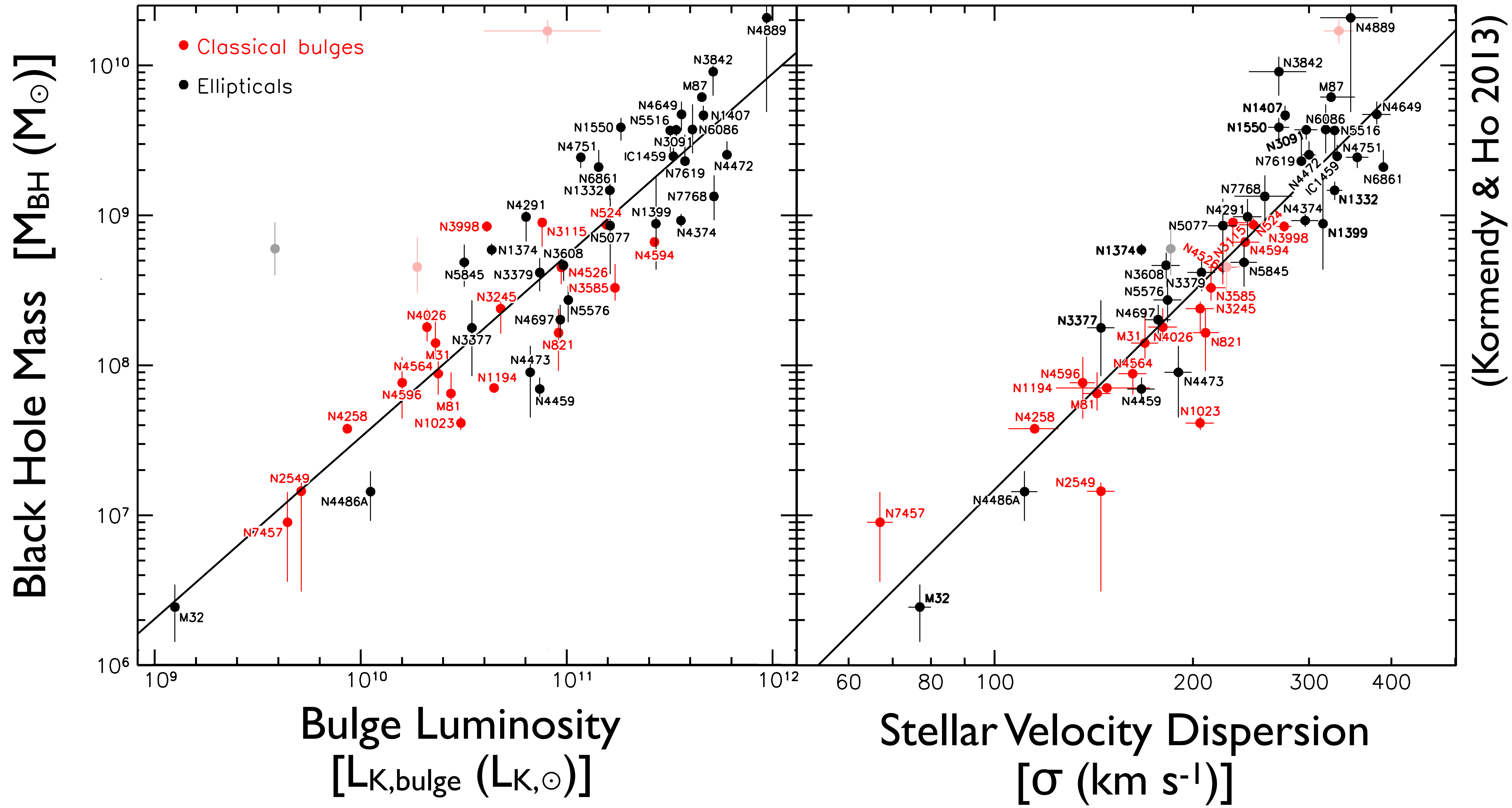
NGC 1277

$M_{BH} = (4.9 \pm 1.6) \times 10^9 \, M_\odot$



(Walsh et al. 2016)

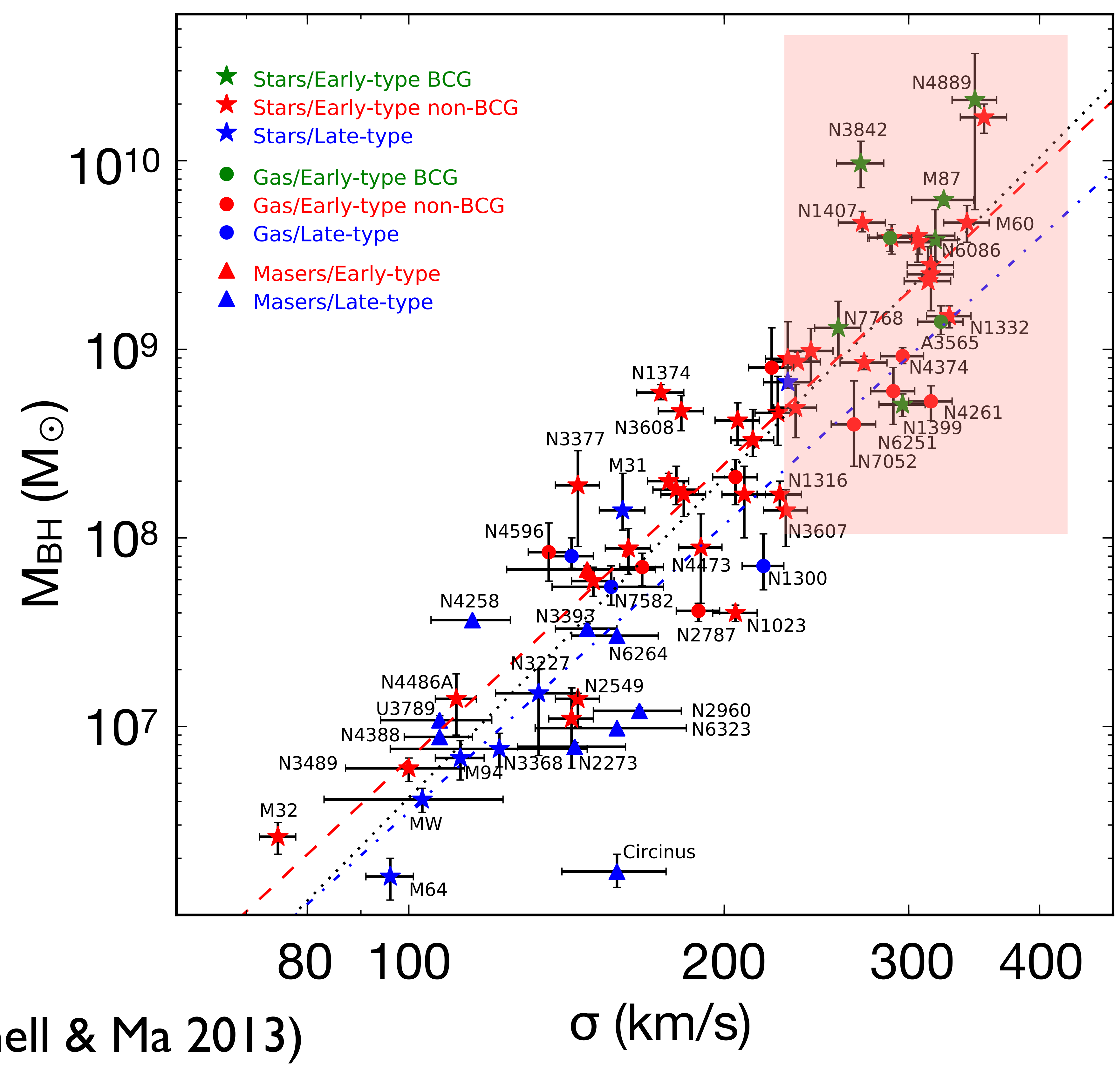
The Black Hole - Galaxy Relations



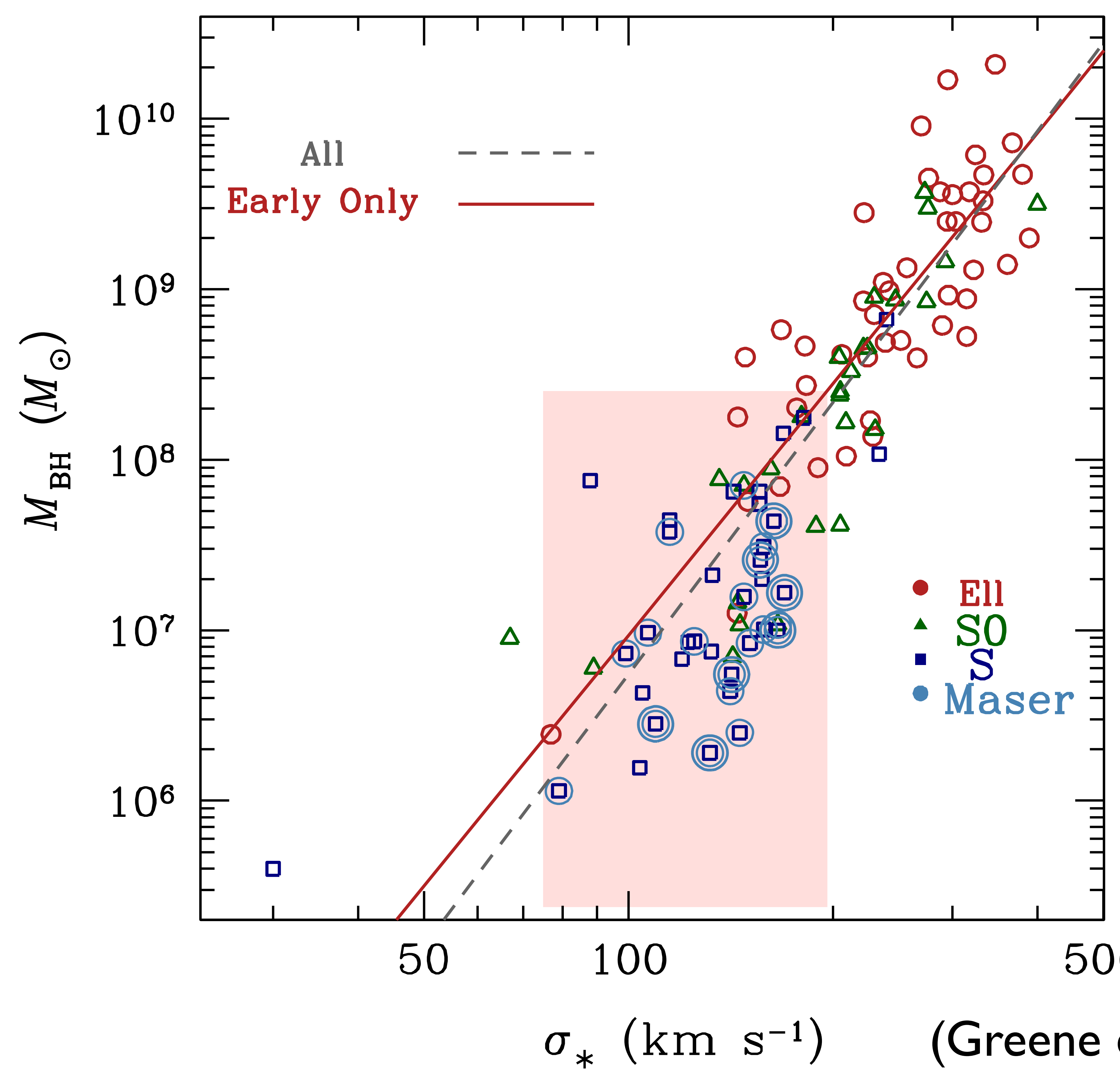
✦ The relations indicate that BHs, which occupy scales of $\lesssim 10^{-4}$ pc in galaxy nuclei, correlate by the large-scale (~1 kpc) bulge properties of their host galaxy, implying that BHs and galaxies somehow grow and evolve together.

The Black Hole - Galaxy Relations

- ✦ The local BH mass census is highly incomplete, particularly for low- and high-mass BHs.
- ✦ Recent work detecting high-mass BHs in BCGs and cored galaxies suggest that these objects lie above M_{BH} - σ (e.g., McConnell et al. 2011, 2012, Thomas et al. 2016). There are hints that spiral galaxies with low-mass BHs exhibit large scatter below the M_{BH} - σ and M_{BH} - L_{bul} relations (e.g., Greene et al. 2010, Läsker et al. 2014, 2016).



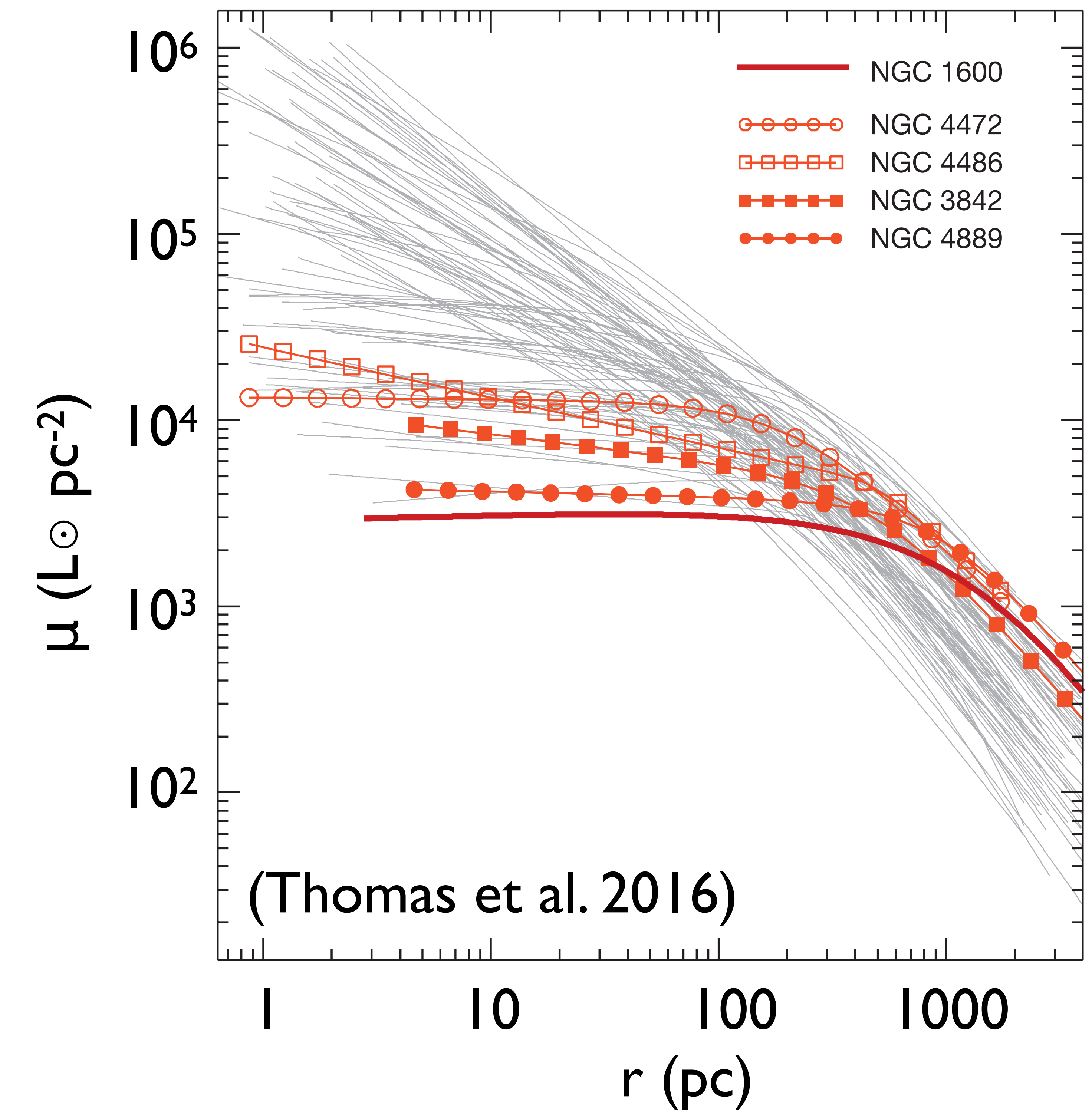
(McConnell & Ma 2013)



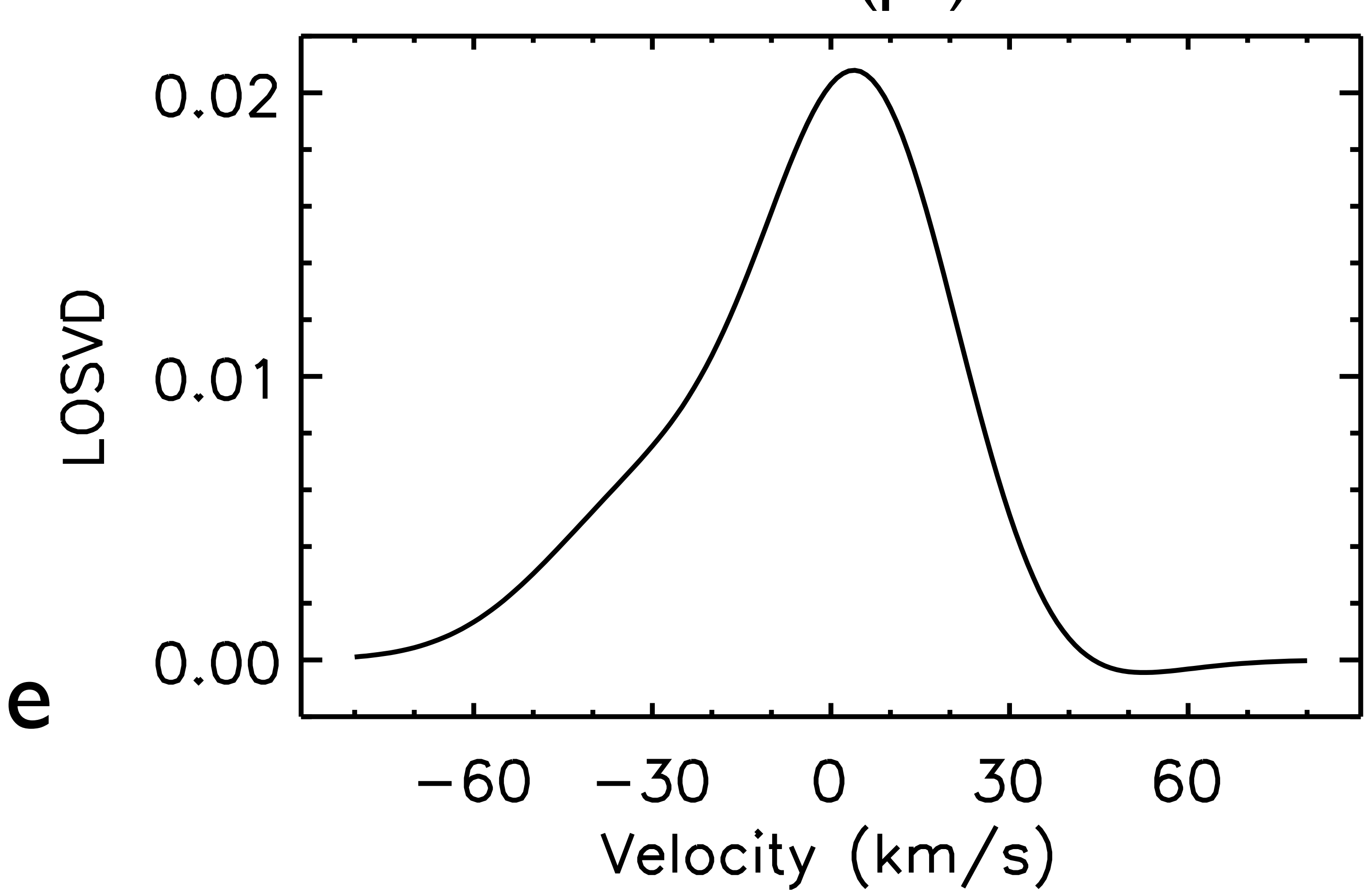
(Greene et al. 2016)

Current Limitations

- Detecting high-mass BHs is challenging because:
  - They are rare, and require searches over large distances.
  - The physical extent of r_{sphere} is large, but the angular size is small for distant objects.
  - They tend to be found in galaxies with central surface brightness cores.



- Detecting low-mass BHs is challenging because:
  - The physical extent of r_{sphere} is small. We are limited to studying only the closest objects.
  - High S/N and moderately high spectral resolution is needed to measure the LOSVD.

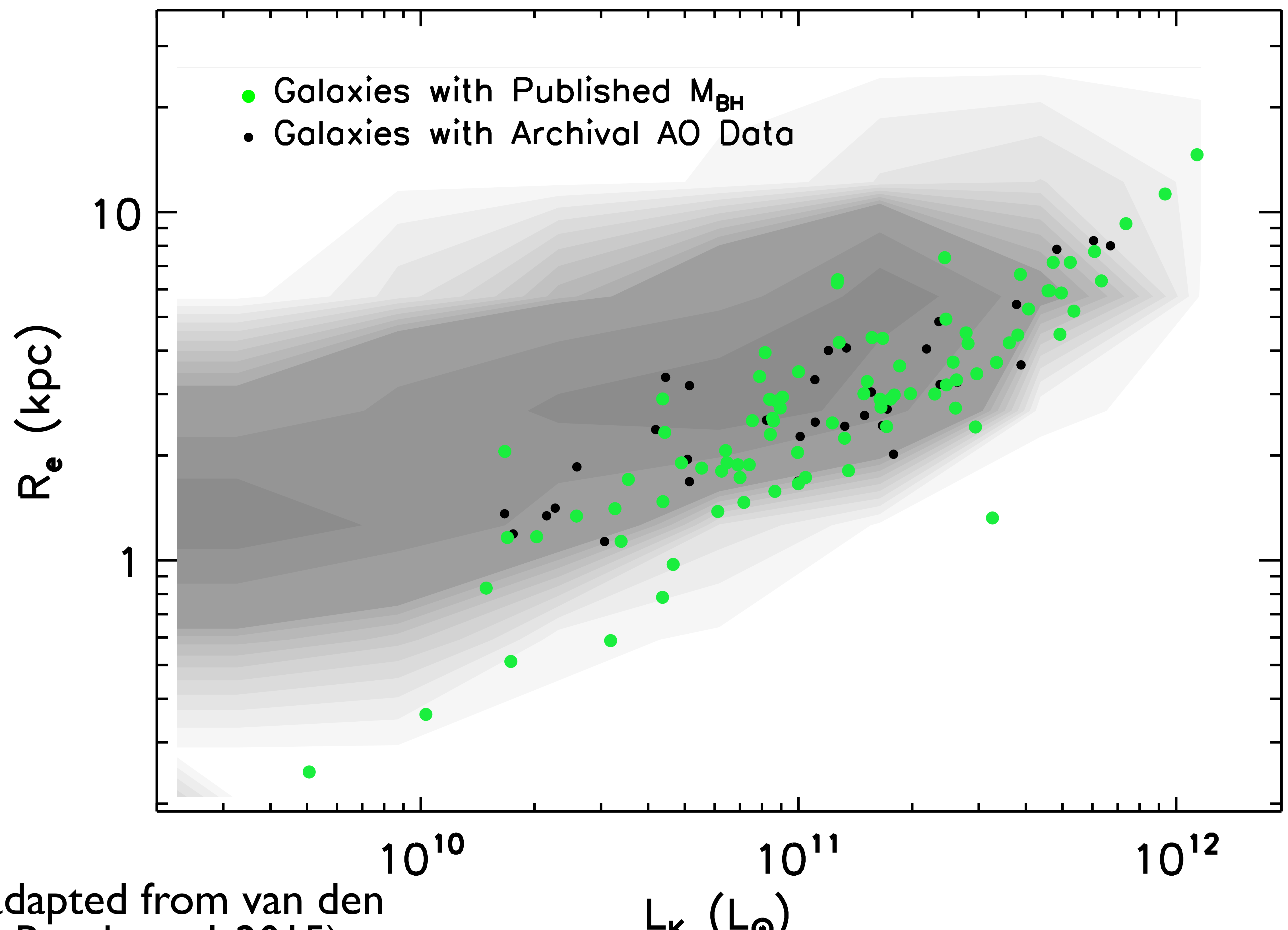


▶ TMT's exquisite angular resolution and sensitivity will enable the robust measurement of both high and low-mass BHs.

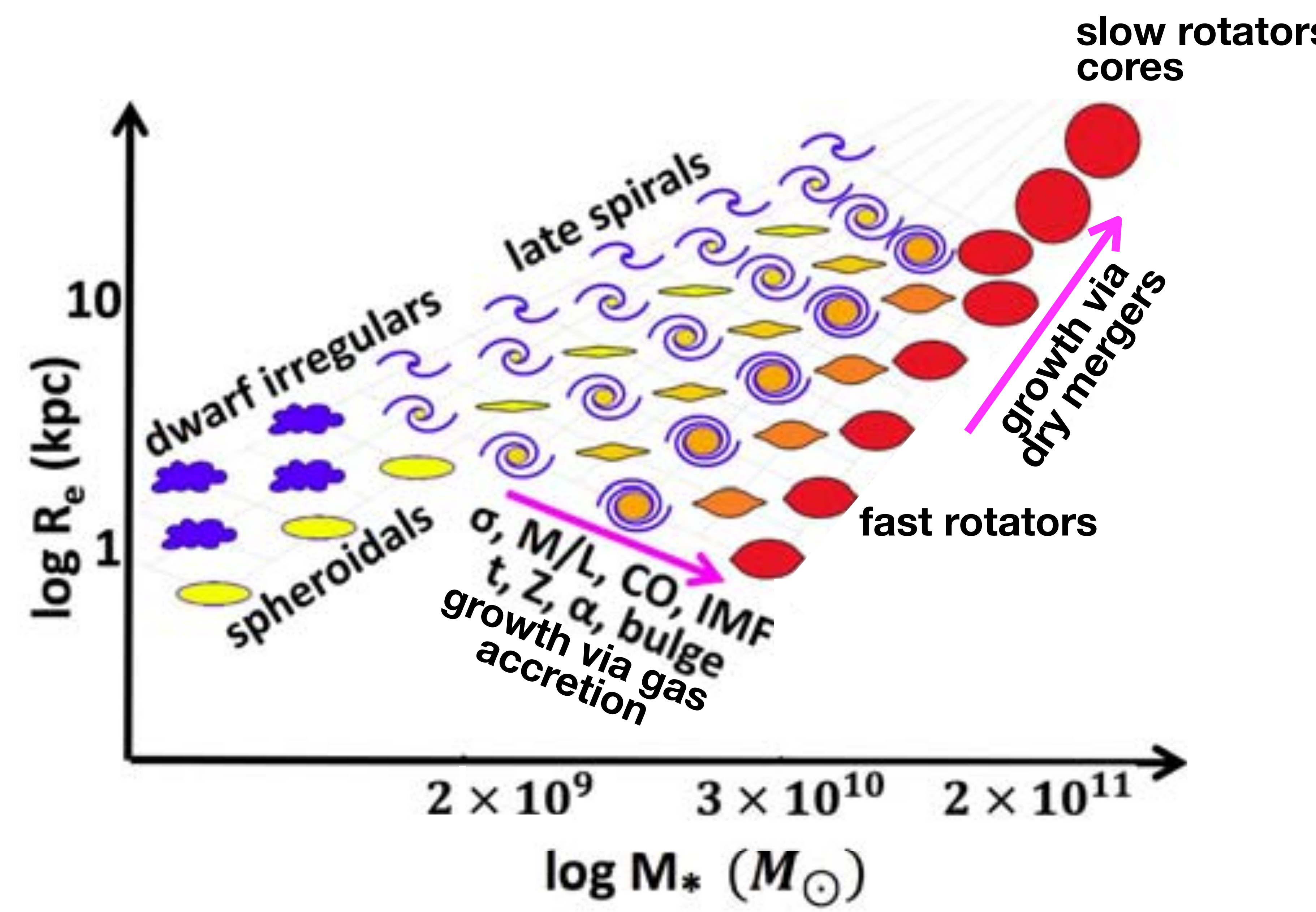
The Current Sample is Not Representative

- Dynamical M_{BH} measurements have been made in a biased set of galaxies that are not representative of the local galaxy population (e.g., van den Bosch et al. 2015, Shankar et al. 2016).

- 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 van den Bosch et al. 2015)



(adapted from Cappellari 2016)

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.

USA

Jonelle Walsh (PI)
Karl Gebhardt
Aaron Barth
Benjamin Boizelle
Jenny Greene
Kayhan Gültekin
Inger Jørgensen
Tod Lauer
Nora Lützgendorf
Chung-Pei Ma
Renuka Pechetti
Anil Seth
Monica Valluri

Germany

Markus Kissler-Patig
Davor Krajnović
Sabine Thater
Glenn van de Ven
Jakob Walcher
Akin Yilidirm

Australia

Holger Baumgardt
Richard McDermid

Canada

John Blakeslee
Laura Ferrarese

Brazil

Roderik Overzier
Thaisa Storchi-Bergmann
Daniel Grün

Argentina

Carlos Donzelli

Netherlands

Mariya Lyubenova

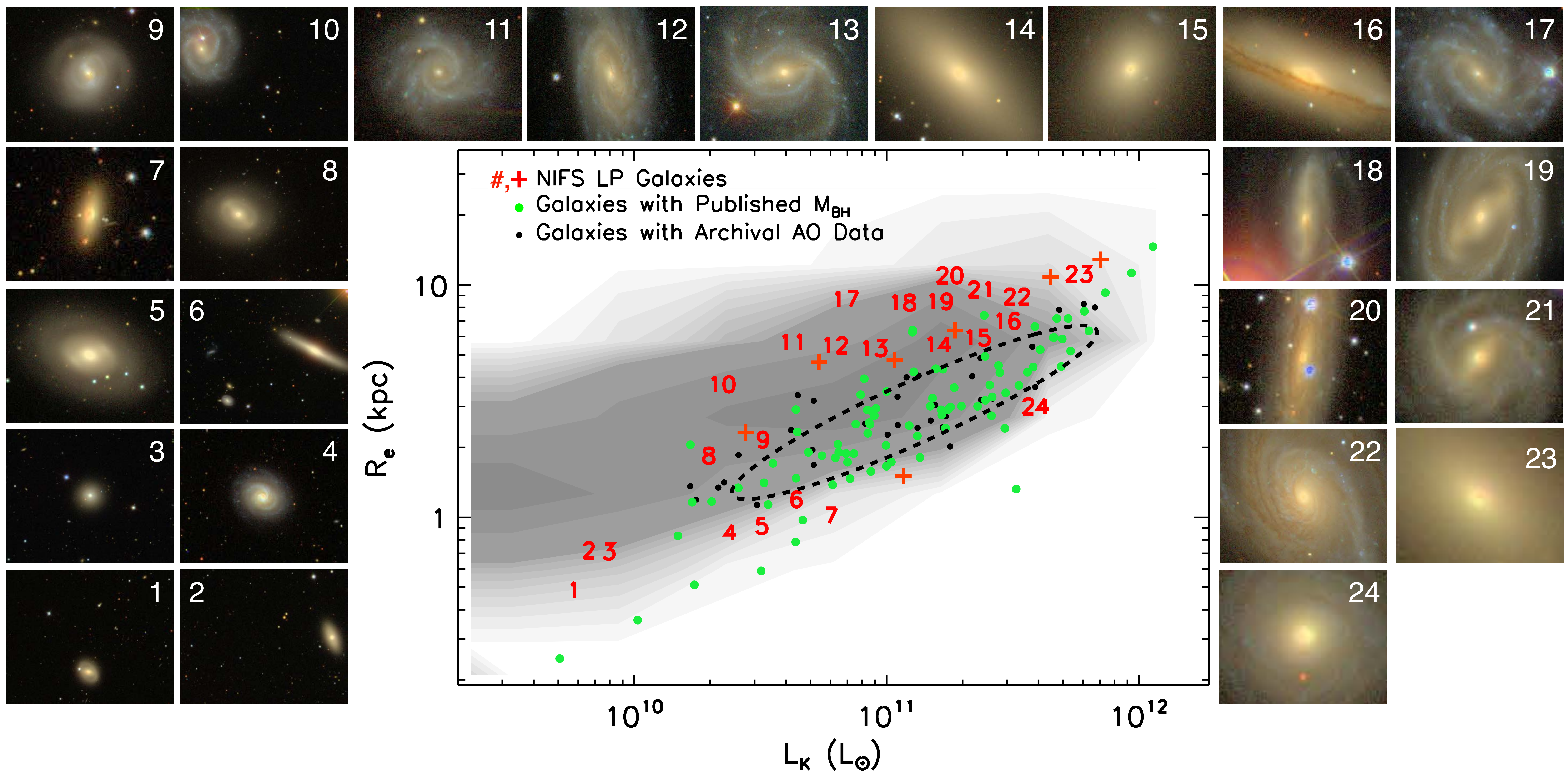
Chile

Bryan Miller

Finland

Ronald Läsker

A Gemini Large Program to Measure Black Holes



- ✦ We will produce the largest uniform survey of black hole masses carried out so far, and will begin to address a bias in the galaxies for which M_{BH}'s have been measured.
- Remaining upsampled region requires observational facilities with better angular resolution and sensitivity.

Fundamental Questions

- Given the uncertainties in the scaling relations, the exact role BHs play in galaxy evolution and the primary physical mechanisms that drive the empirical correlations are far from understood.

- Other basic questions remain unanswered:

    - Do BHs and galaxies grow in lockstep with one another over time, or do the growth of BHs precede that of host galaxies, or vice-versa?

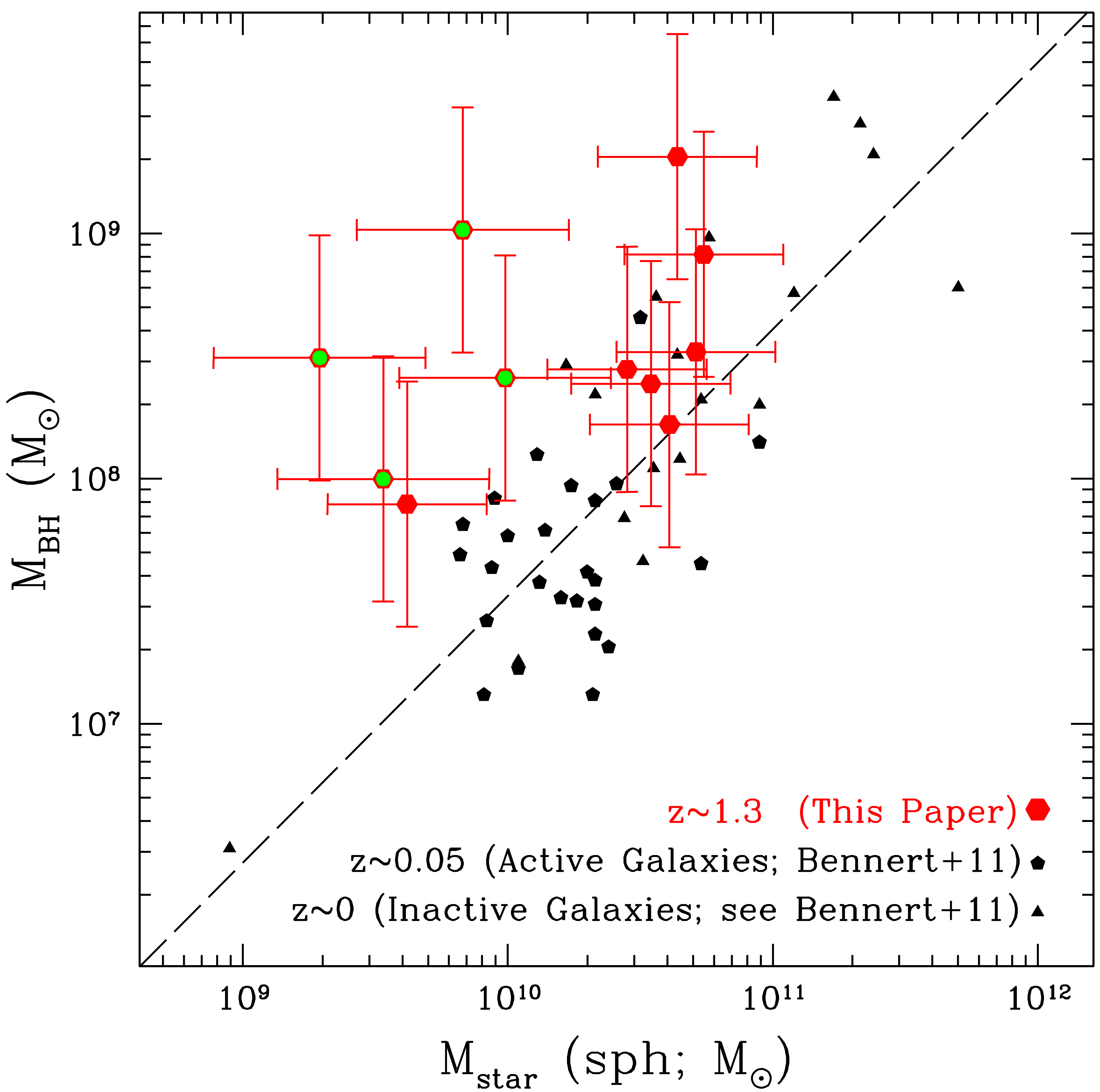
    - Are there BHs in low-mass galaxies and in globular clusters?

    - How do supermassive BHs form, what are the initial seed masses, and how can they acquire enough mass so quickly after the Big Bang?

- TMT will allow us to explore these open questions, and gain insight into the interplay between BHs and galaxies.

Redshift Evolution of the Black Hole - Galaxy Relations

(Bennert et al. 2011)

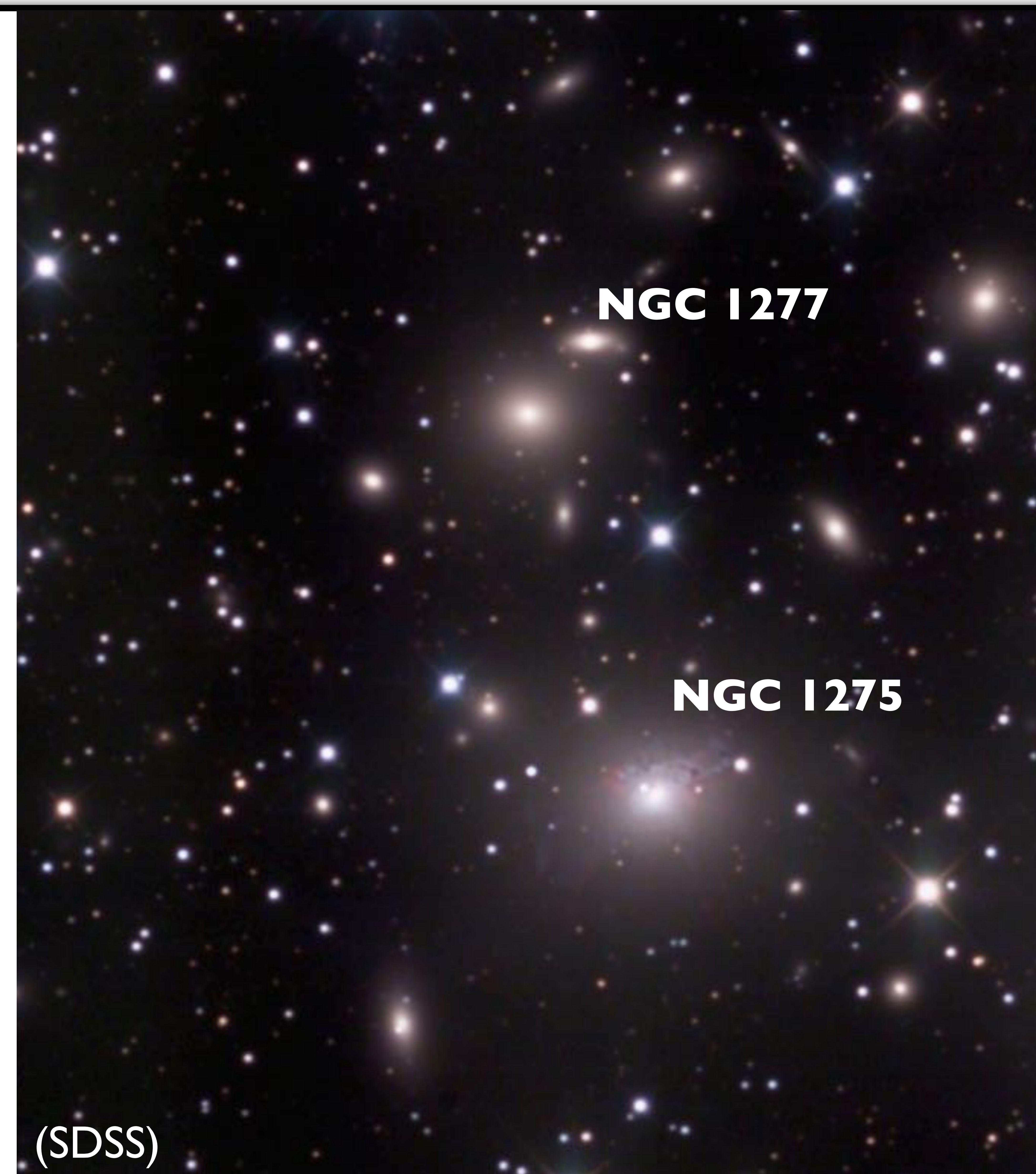


- Currently, we cannot search for redshift evolution in the BH relations using dynamical mass measurements. We need to estimate M_{BH} using properties of broad emission lines in AGN.
- Some studies report a positive evolution, such that BH growth precedes bulge growth (e.g., Woo et al. 2006, 2008, Merloni et al. 2010, Matuoka et al. 2014), but others find no change in the relations (e.g., Salviander & Shields 2013, Shen et al. 2015).
- Selection biases can lead to false identification of evolution in the relations (e.g., Later 2007, Shen & Kelly 2010, Schulze & Wisotzki 2014).

Dynamical Black Hole Mass Measurements in Local, Compact Galaxies

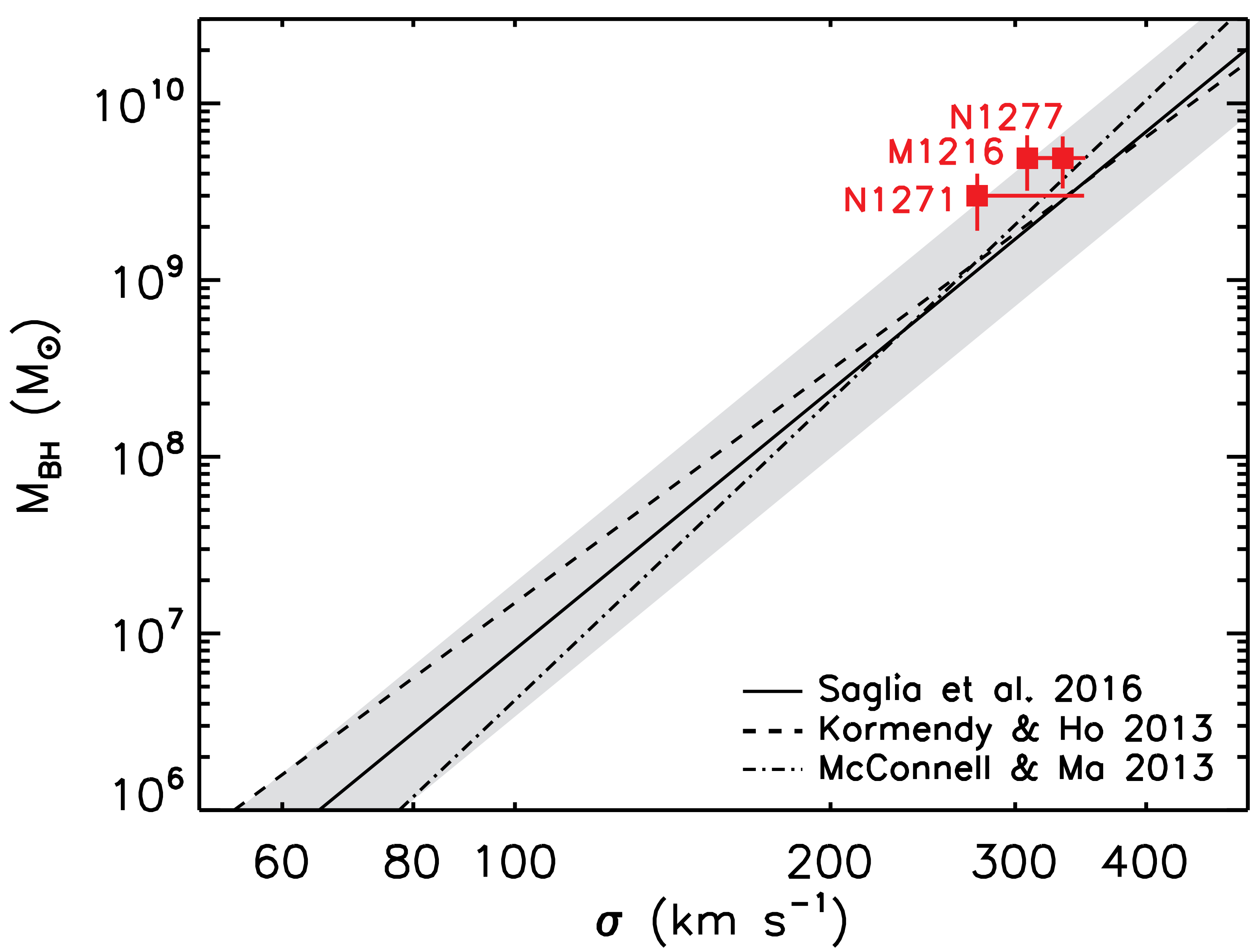
- NGC 1277 is part of a sample of nearby, early-type galaxies that have small sizes and luminosities for their large stellar velocity dispersions:
  - $r_e \sim 1\text{-}3$ kpc
  - $L_K \sim 5\times10^{10}\ L_\odot - 2.5\times10^{11}\ L_\odot$
  - $\sigma_c > 250$ km s^{-1}

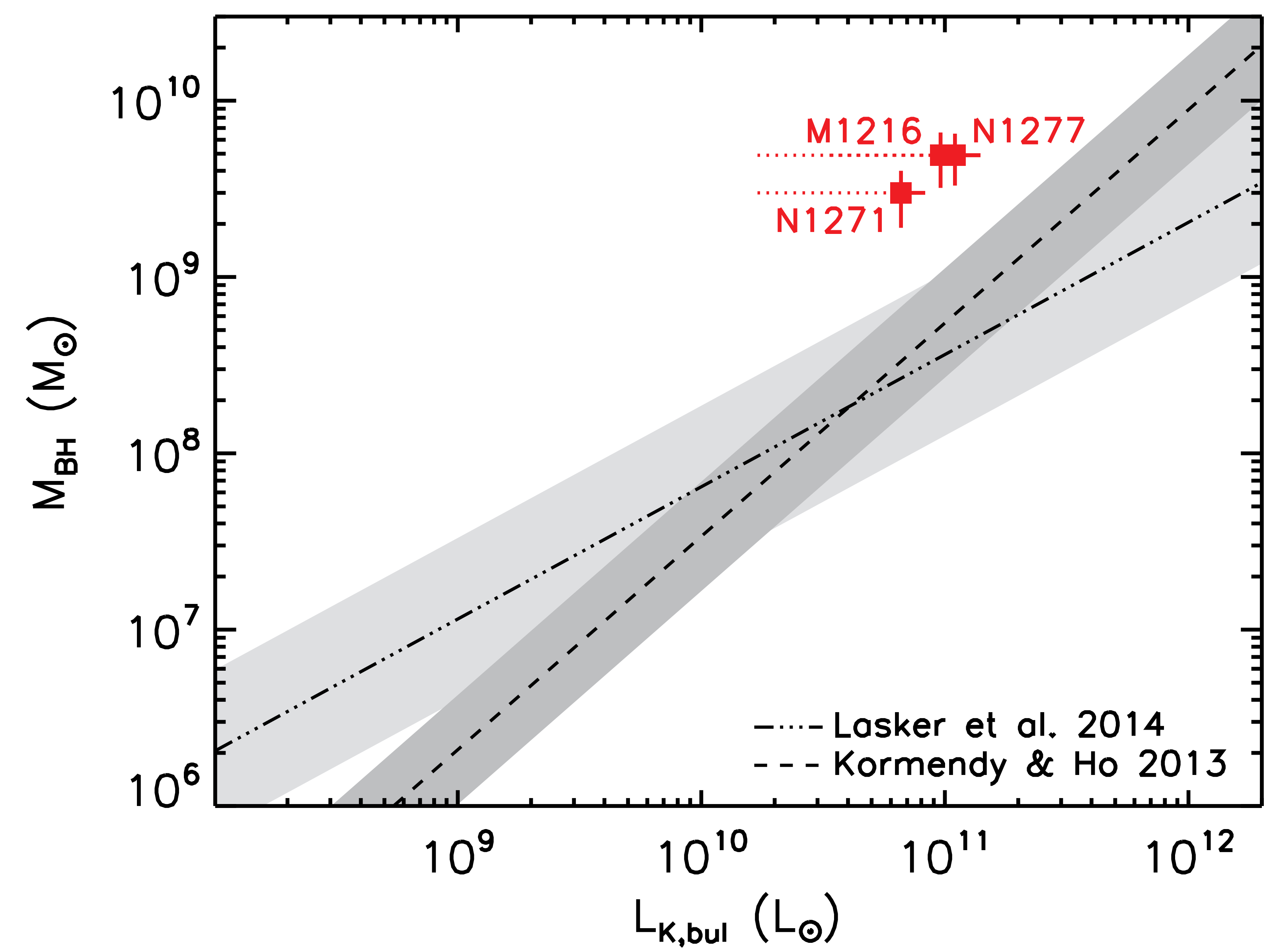
- Objects are interesting because they:
  - host some of the most massive BHs known
  - are different from the massive elliptical galaxies expected to host the heaviest BHs (e.g., Dalla Bontá et al. 2009, Gebhardt et al. 2013)
  - appear similar to z~2 galaxies ("red nuggets") (e.g., Szomoru et al. 2012)



Dynamical Black Hole Mass Measurements in Local, Compact Galaxies

- NGC 1271, NGC 1277, and Mrk 1216 host some of the most massive BHs dynamically detected to date, with M_{BH} ~(3-5)x10^9 $M_\odot$ (Walsh et al. 2015, 2016, 2017). They are surprising positive outliers from M_{BH} - L_{bul}.

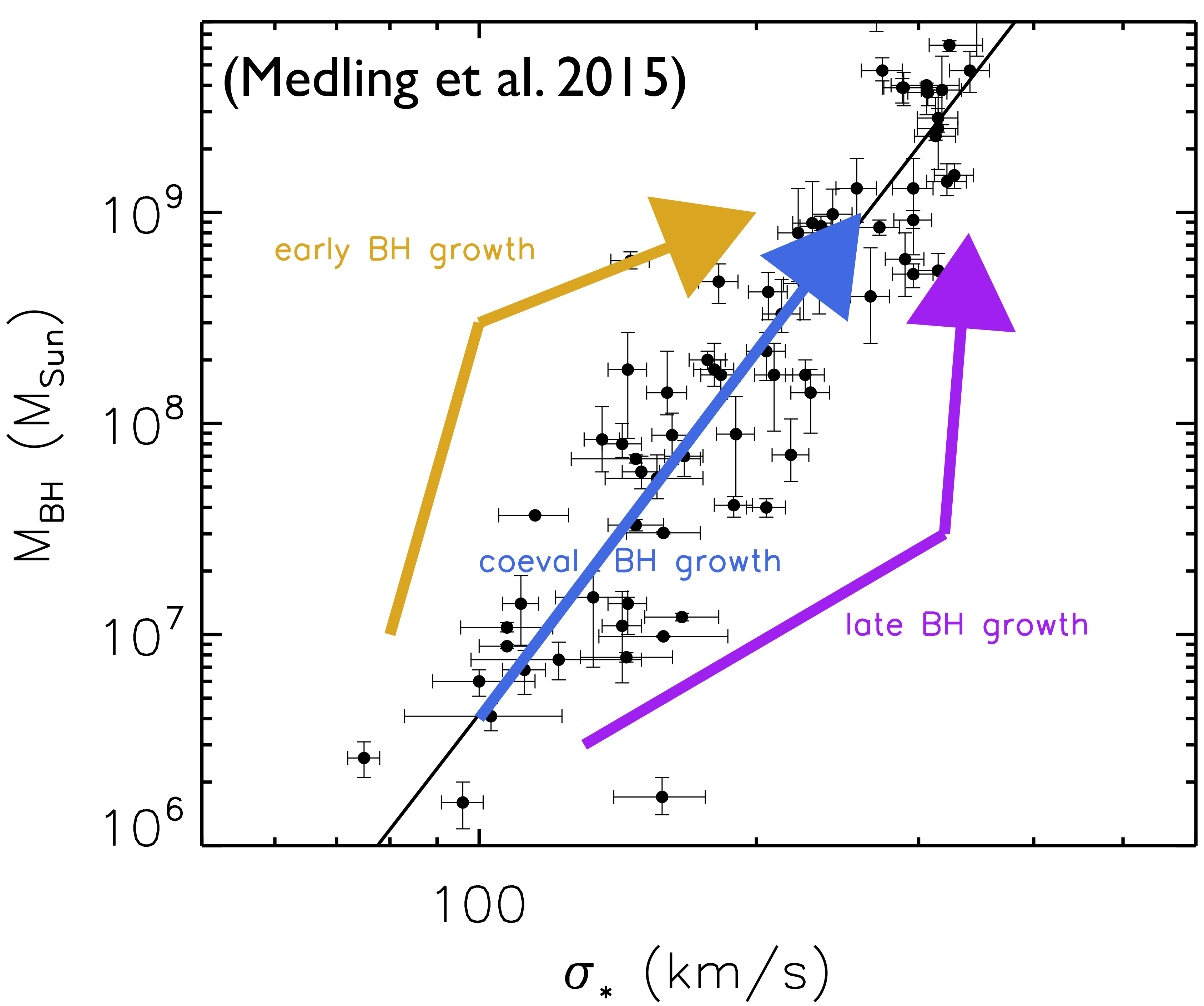


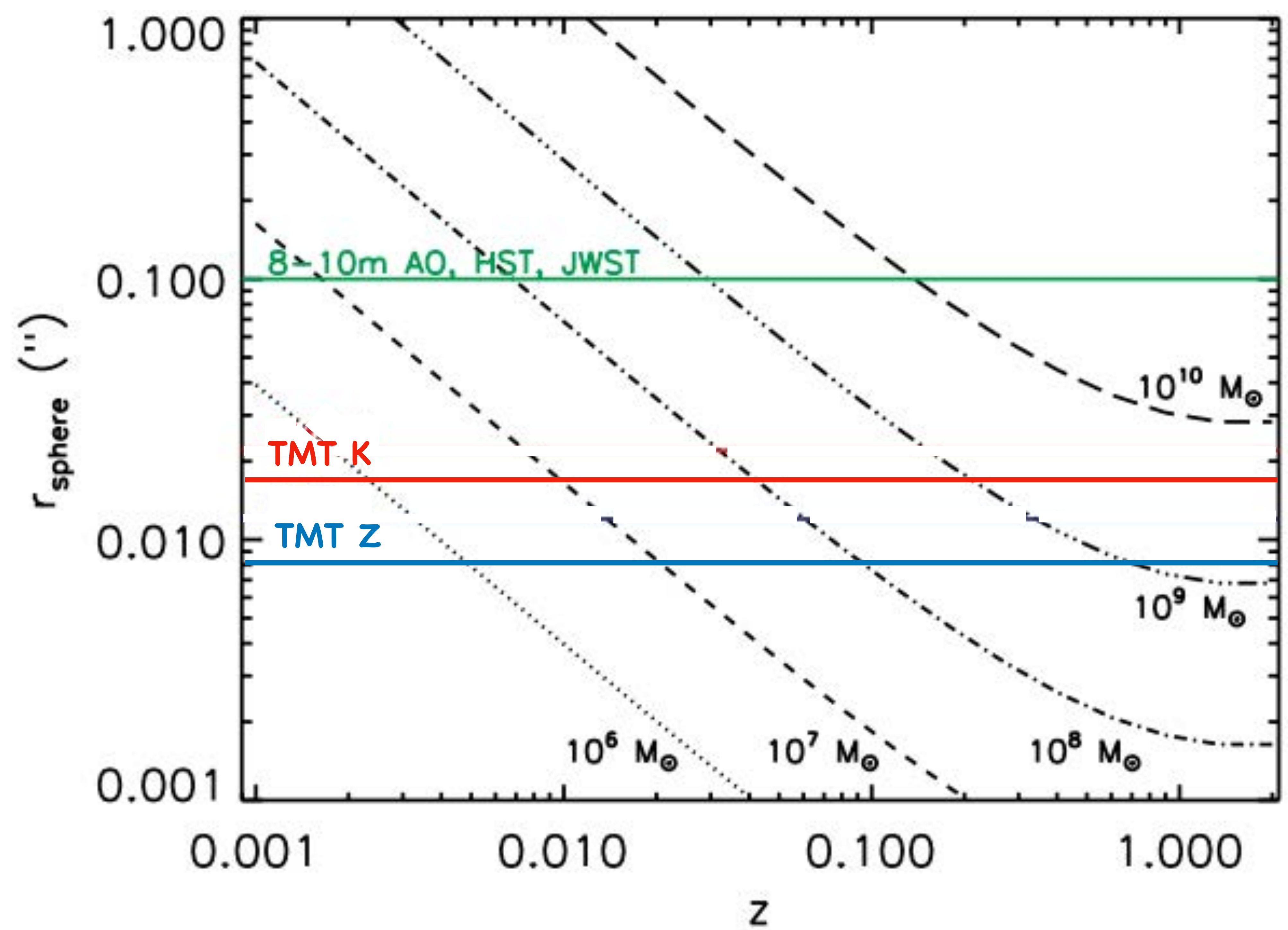


- Given the similarities to the z~2 galaxies (e.g., Ferré-Mateu et al. 2015, 2017, Yildirim et al 2017, Beasley et al. 2018), perhaps the local compact galaxies are relics, and reflect the relationship between BHs and galaxies at earlier times. Perhaps BH growth precedes that of its host galaxy.

Direct Searches for Redshift Evolution with TMT

- ✦ TMT will facilitate the first direct search for evolution in the BH relations. We can dynamically measure M_{BH} in various redshift bins and compare to the local relations.
- ✦ This is best accomplished with high-mass BHs because angular resolution is no longer a concern.

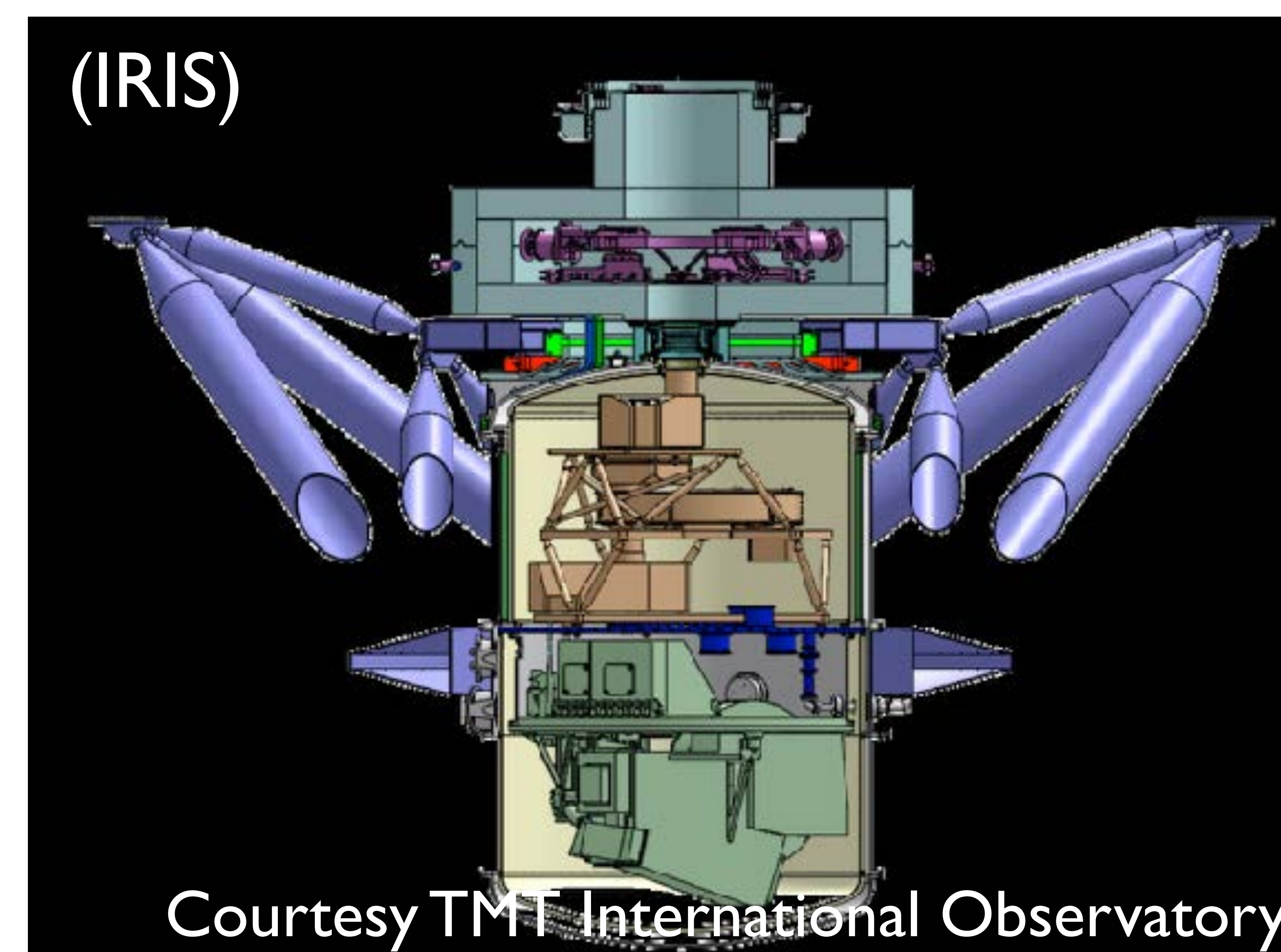




(KSP team: Gültekin, Gebhardt, Walsh, Greene, U, Malkan, Barth, Juneau)

Direct Searches for Redshift Evolution with TMT

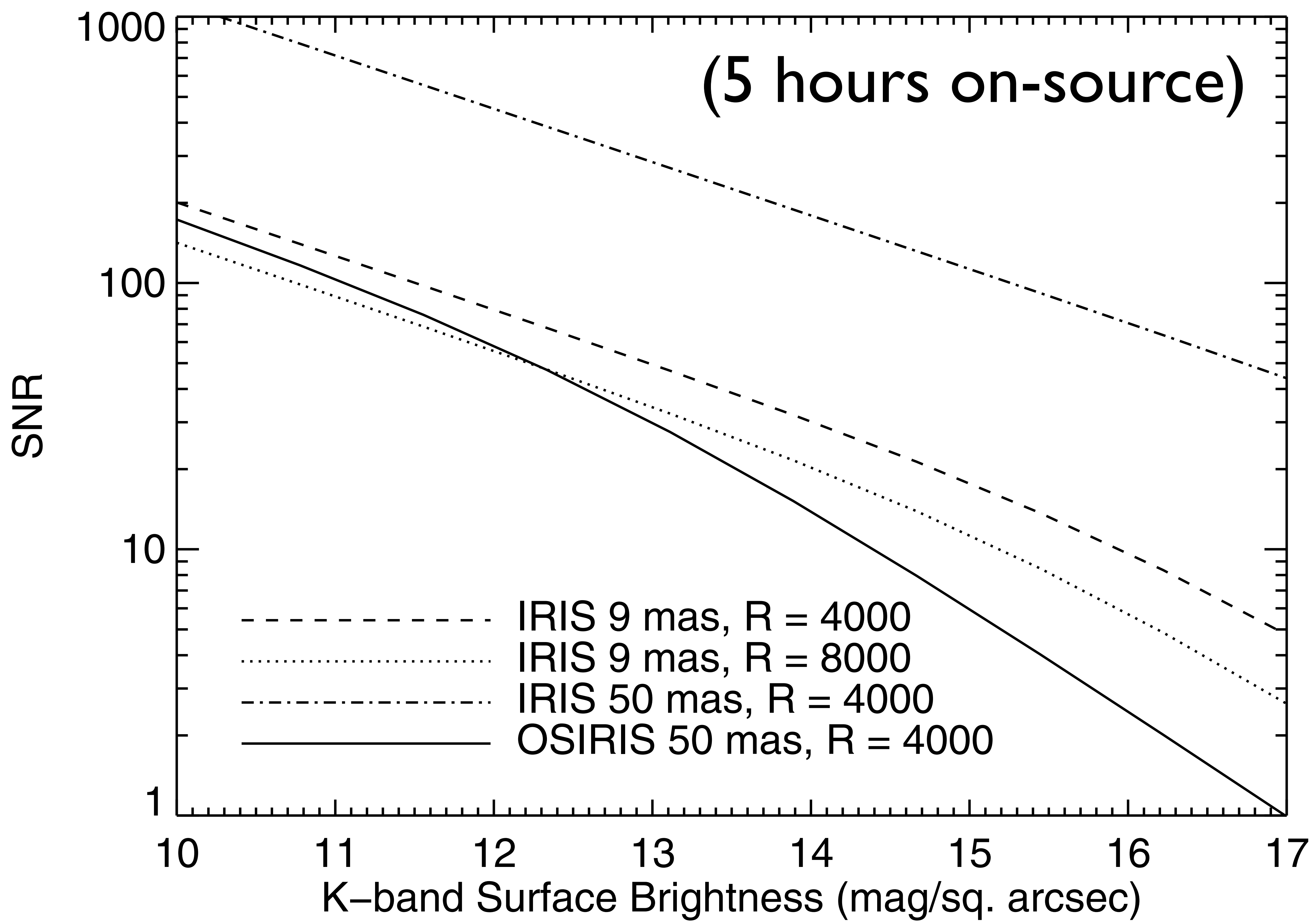
- ✦ We will use the IRIS imager to determine the luminous mass distribution, and the integral-field spectrograph to map out the stellar kinematics in the central regions of galaxies.
- ✦ For $z \lesssim 1.5$, we will measure kinematics from the 2.22 μm CO bandheads, 1.6 μm CO bandheads, and 0.85 μm Ca II triplet. Beyond $z > 1.5$, we will use emission lines (Hα), provided that the gas is in regular rotation.
- ✦ R~4000 is sufficient spectral resolution for the high-mass BHs. We will make use of the 9 mas pixel scale.



(KSP team: Gültekin, Gebhardt, Walsh, Greene, U, Malkan, Barth, Juneau)

Direct Searches for Redshift Evolution with TMT

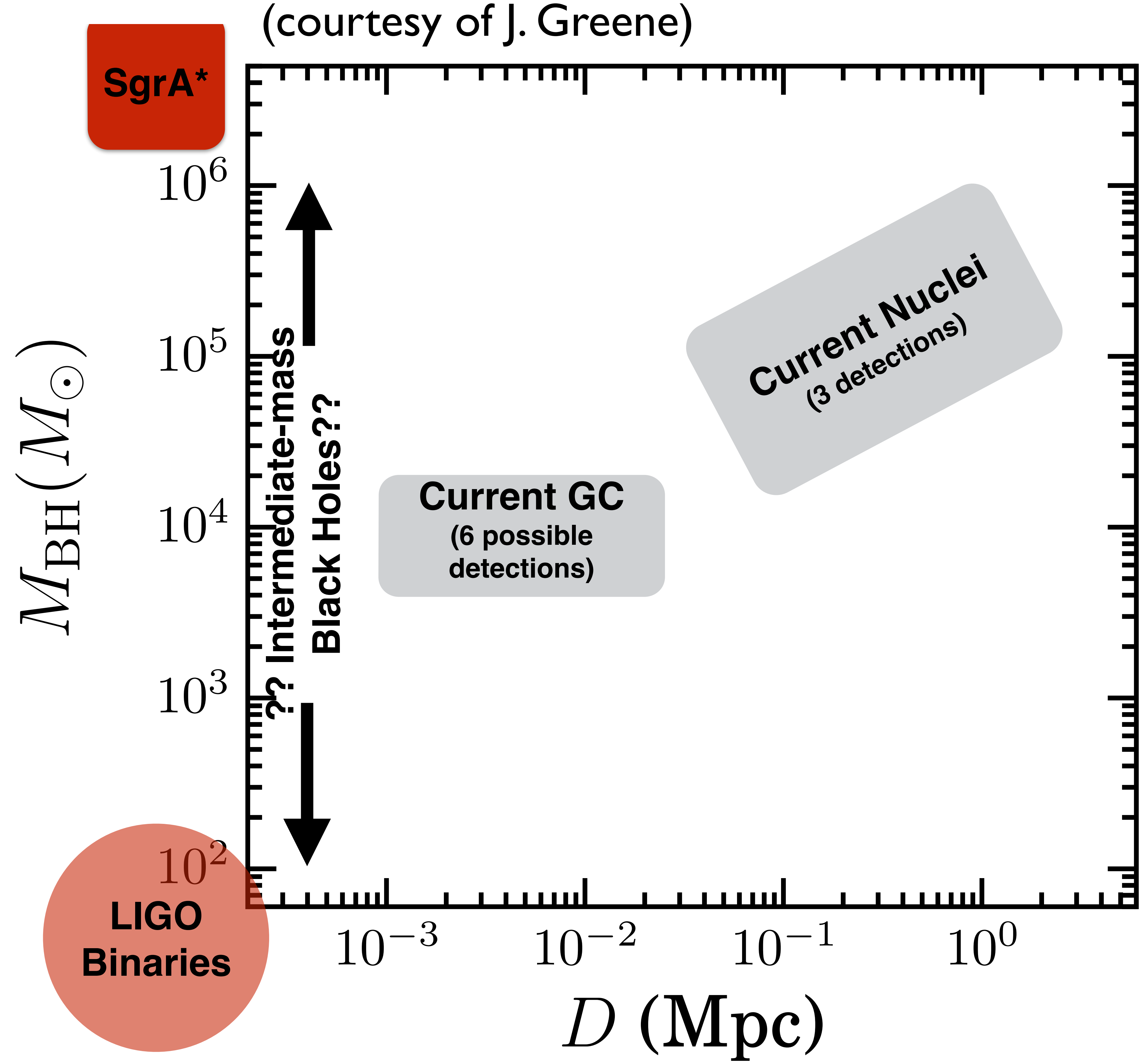
(Do et al. 2014)

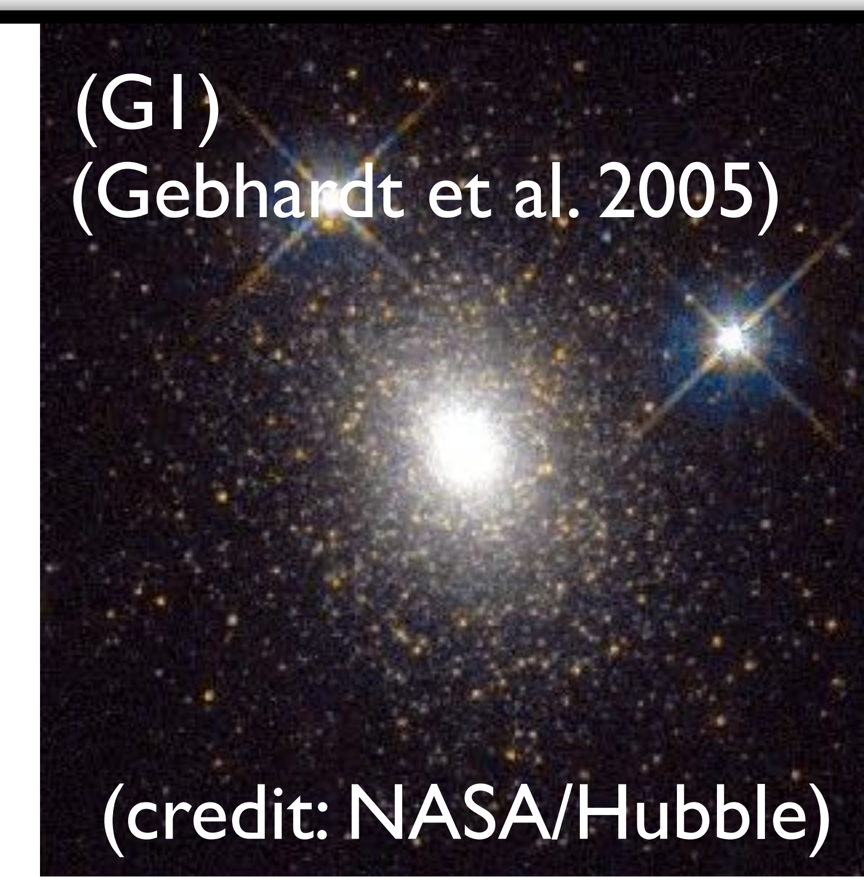


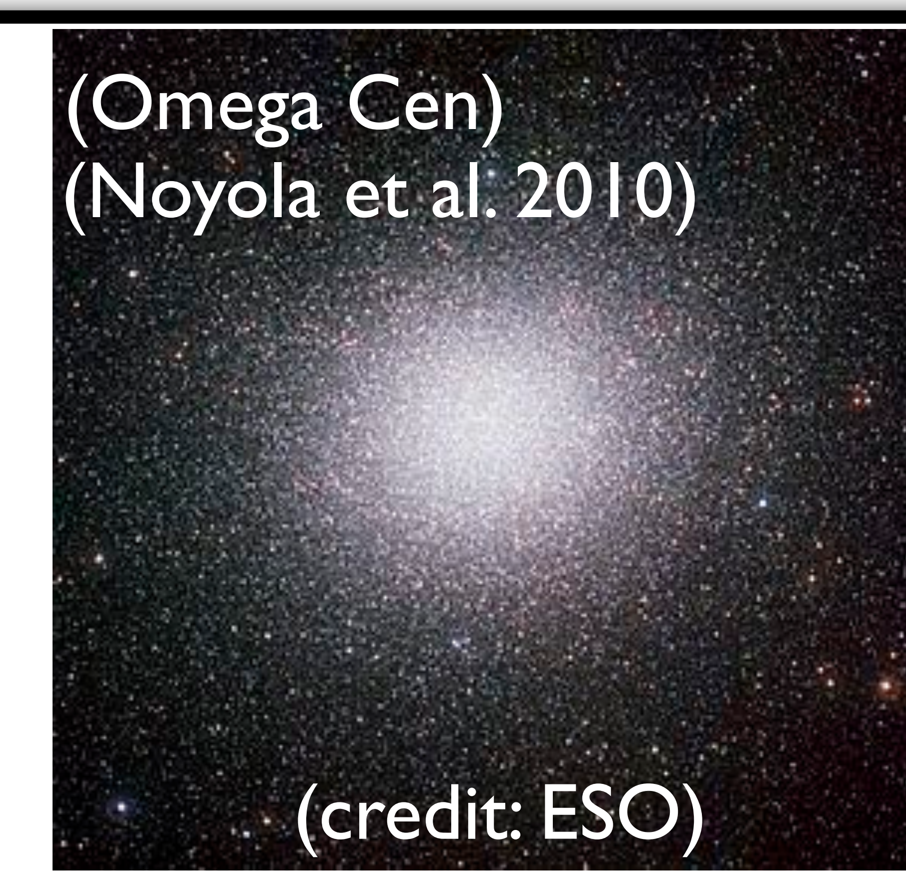
- We estimate exposure times using the central surface brightness of M87 [V=16.2 mag/arcsec^2 (Kormendy et al. 2009); assumed K=13.2 mag/arcsec^2], accounting for surface brightness dimming and luminosity evolution (Gebhardt et al. 2003).
- Aim for S/N = 40 in an unbinned lenslet. Included time for offset sky exposures (1 sky for every 1.5 hours on-source).
    - 10 BHs with $M_{BH} > 10^{10}\ M_{\odot}$ locally (40 hours)
    - 10 BHs in each of four redshift bins (z~0.1, 0.5, 1.0, 1.5); 40 BHs total (510 hours)

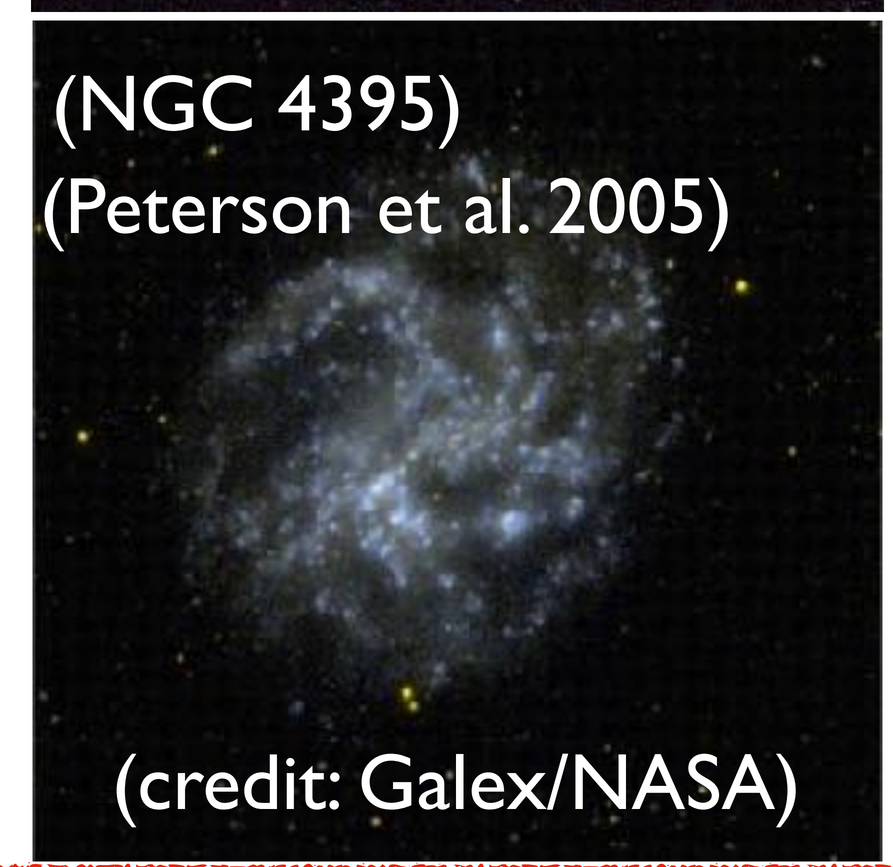
(KSP team: Gültekin, Gebhardt, Walsh, Greene, U, Malkan, Barth, Juneau)

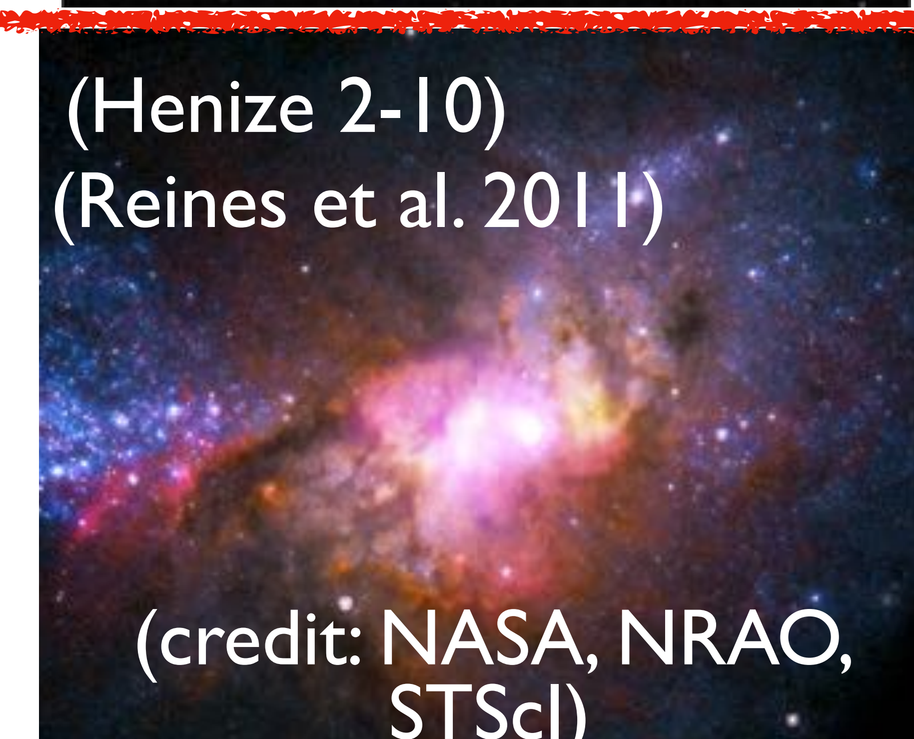
Intermediate-Mass BHs and BH Seeds





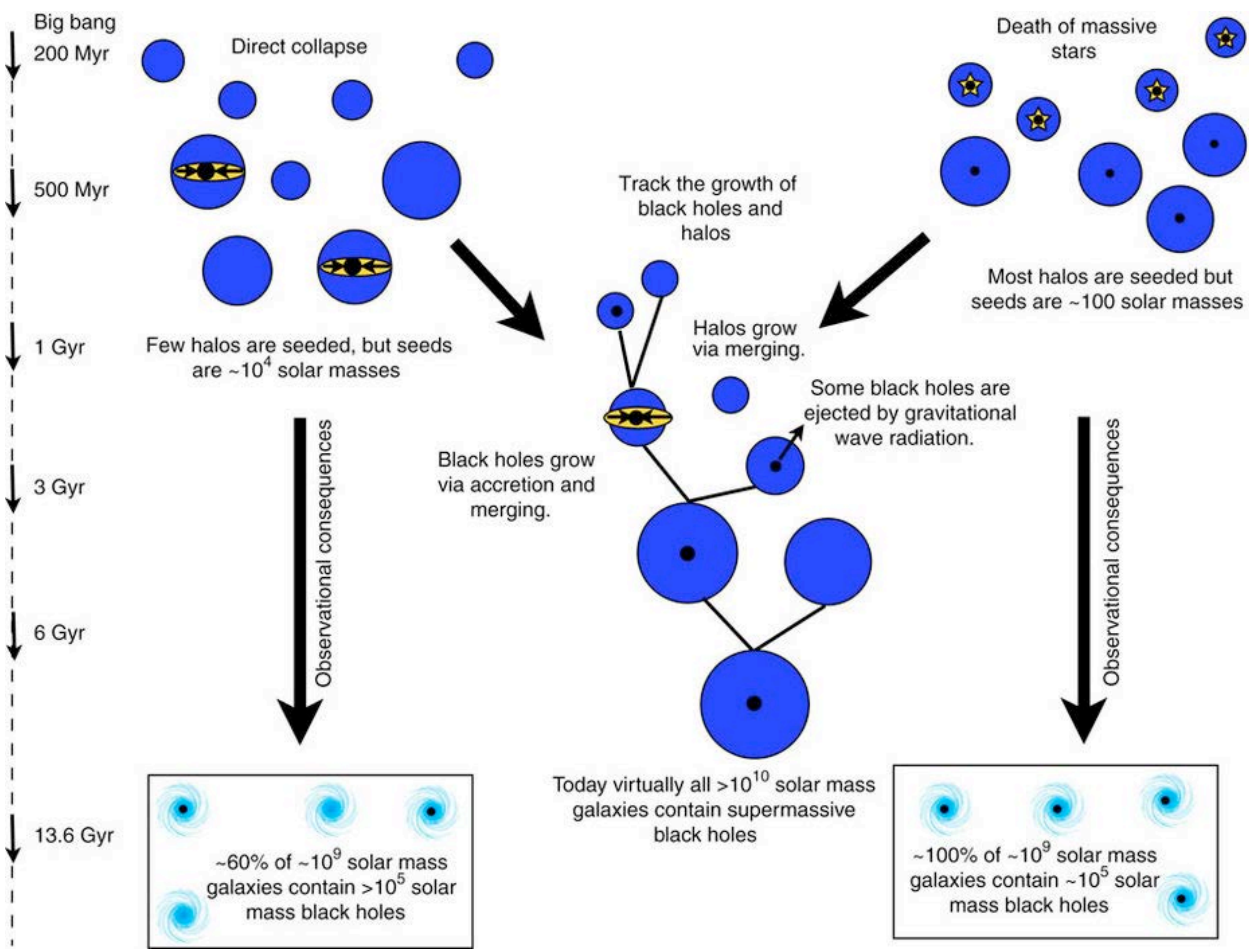






- There are some dynamical hints for IMBHs in globular clusters and low-mass galaxies, but the results are controversial due to insufficient spatial resolution and sensitivity.

Intermediate-Mass BHs and BH Seeds



(Greene 2012)

- TMT will be sensitive to 10^3 M$_\odot$ BHs at the distance of Andromeda, and 10^4 M$_\odot$ BHs at 3-5 Mpc.
- The systems that might host IMBHs have dispersions ~15-30 km/s. We need both high spectral and high spatial resolution.
- R~8000 is needed, but R~10,000 preferred.
- See Tuan Do's talk, Wednesday 9:20 am in the "Local Universe, Nearby Galaxies and Black Holes" breakout session!

(KSP team: Bellini, Do, Libralato, Greene, Gultekin, Gebhardt, Walsh, Barth, Baldassare)

Summary

- The local BH mass function is incomplete, and we do not know exactly what roles BHs play in galaxy evolution.
- We need more M_{BH} measurements at the ends of the BH mass scale and in a wider variety of galaxies.
- TMT's angular resolution and sensitivity will open up new regimes:
    - We can dynamically measure the most massive BHs in the Universe, exploring the extreme end of BH evolution.
    - We can dynamically measure the smallest BHs in the Universe, exploring the mass function of initial BH seeds.
    - We can directly trace redshift evolution in the BH scaling relations over a meaningful baseline, exploring when/how BHs and galaxies grow.