Dynamical Searches for Black Holes with ELTs

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TMT
THIRTY METER TELESCOPE

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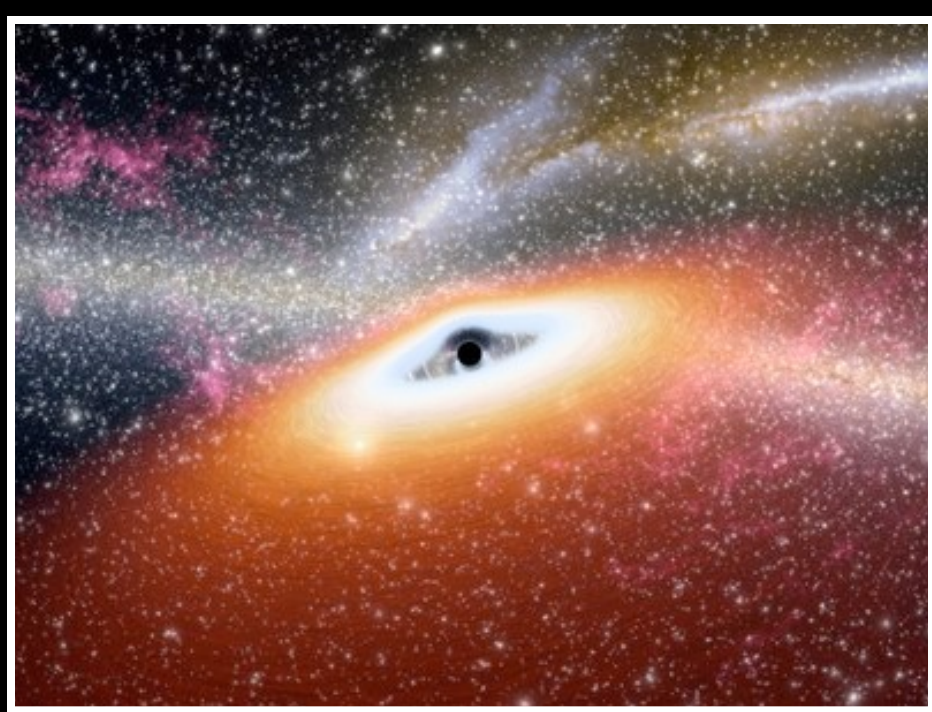
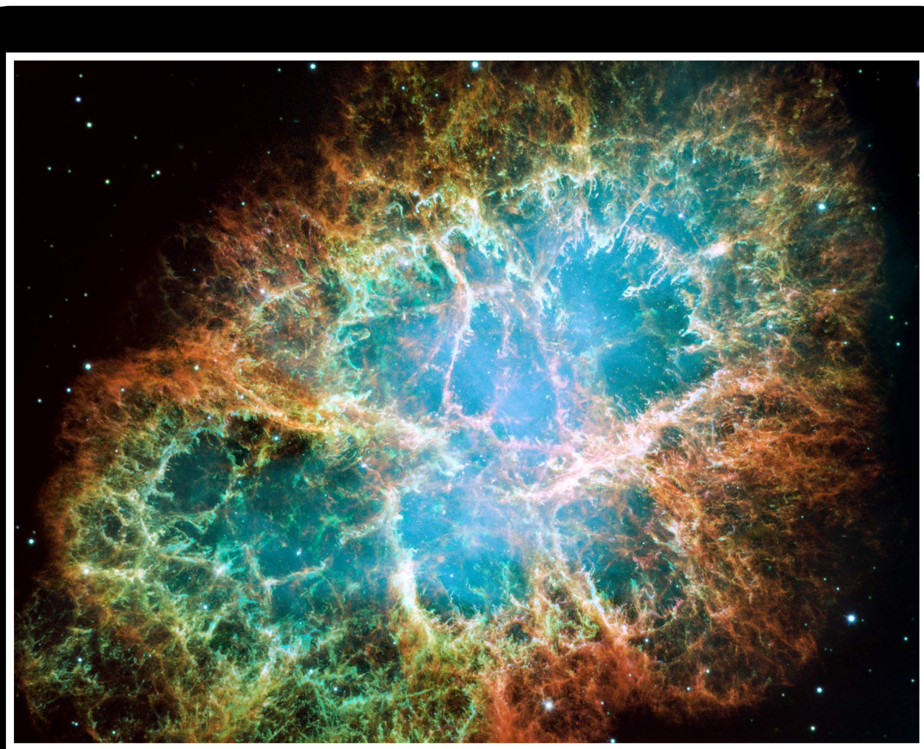
Black Holes Are Everywhere!

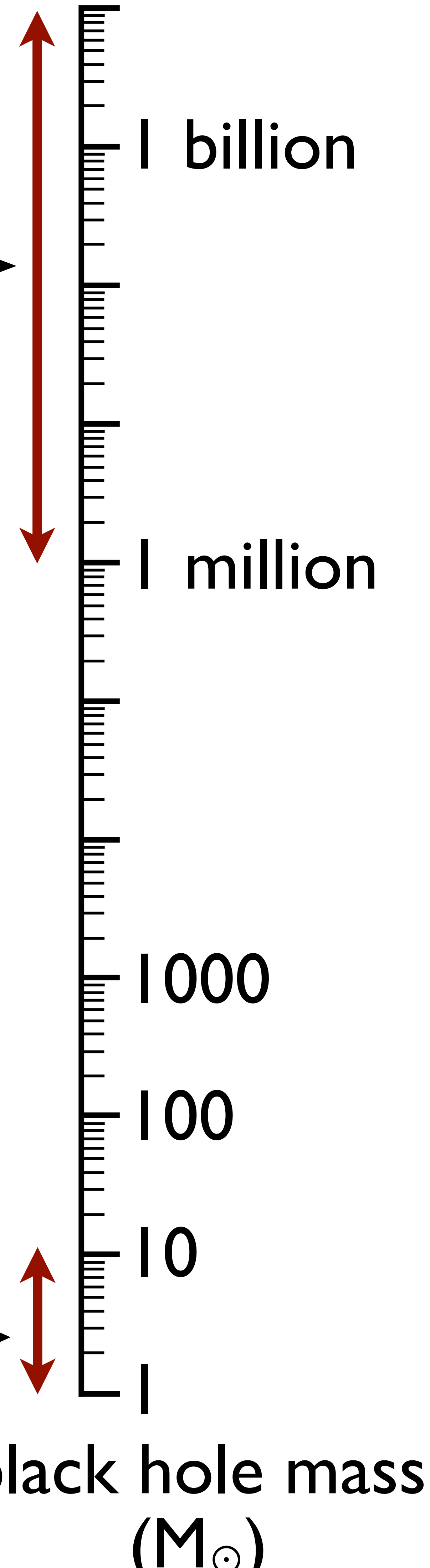
<u>Types of Black Holes</u>

Supermassive Black Holes

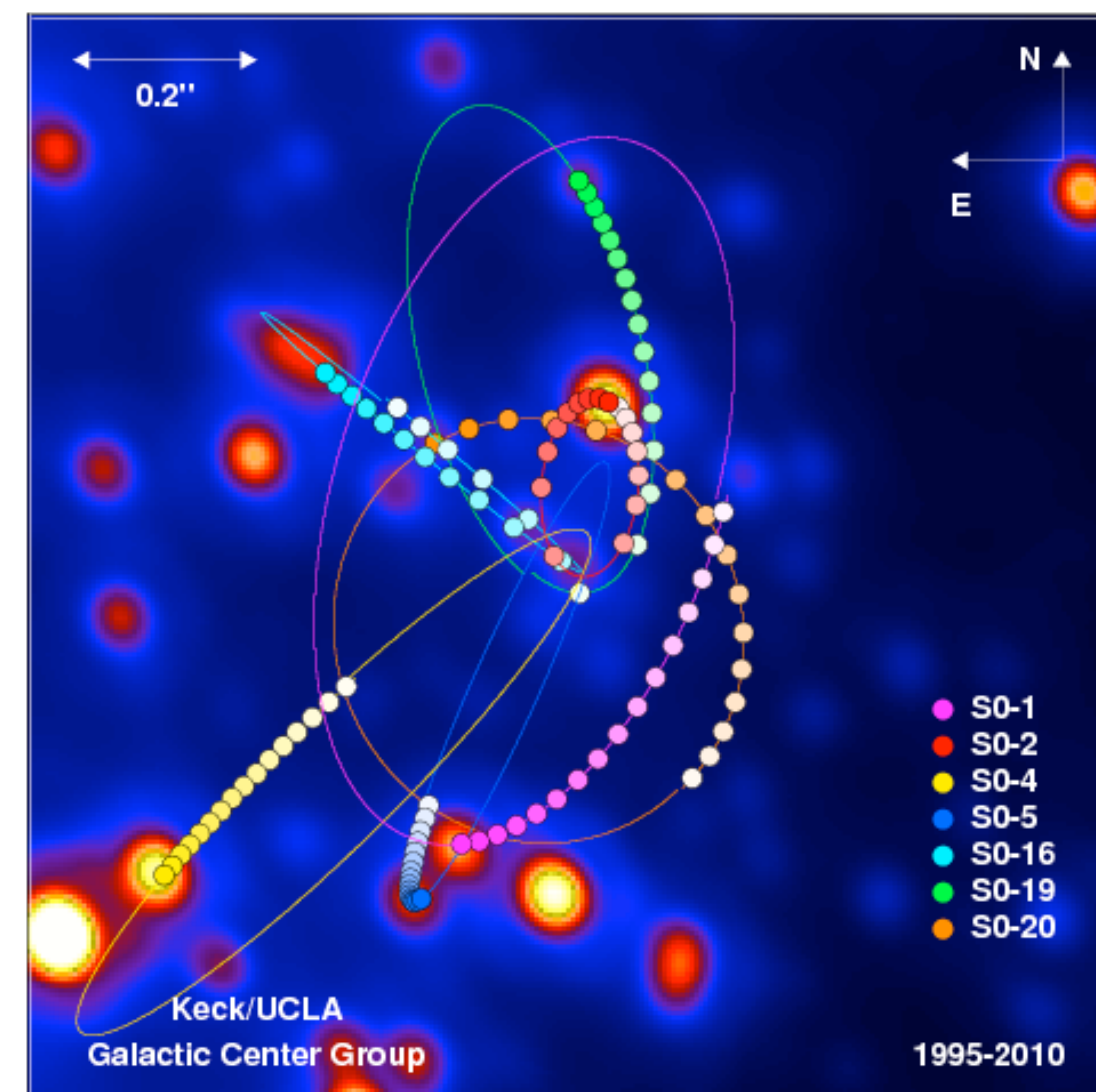


Stellar-mass Black Holes





- Supermassive black holes (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).



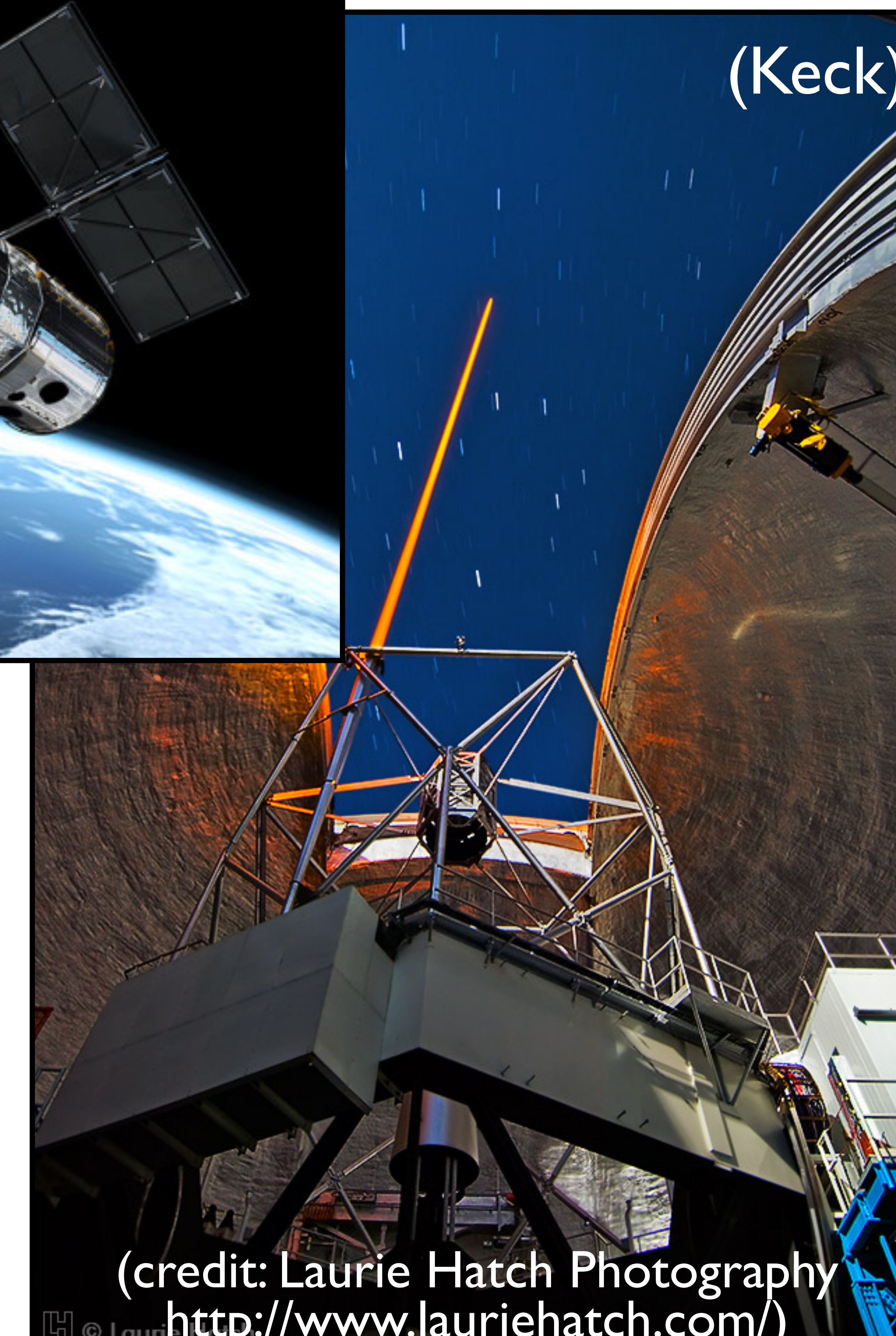
(This image was created by Prof. Andrea Ghez and her research team at UCLA and are from data sets obtained with the W. M. Keck Telescopes.)

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

Dynamically Detecting Black Holes

- The most widely used method for detecting a BH and measuring its mass (M_{BH}) is to fit dynamical models to the observed stellar kinematics.

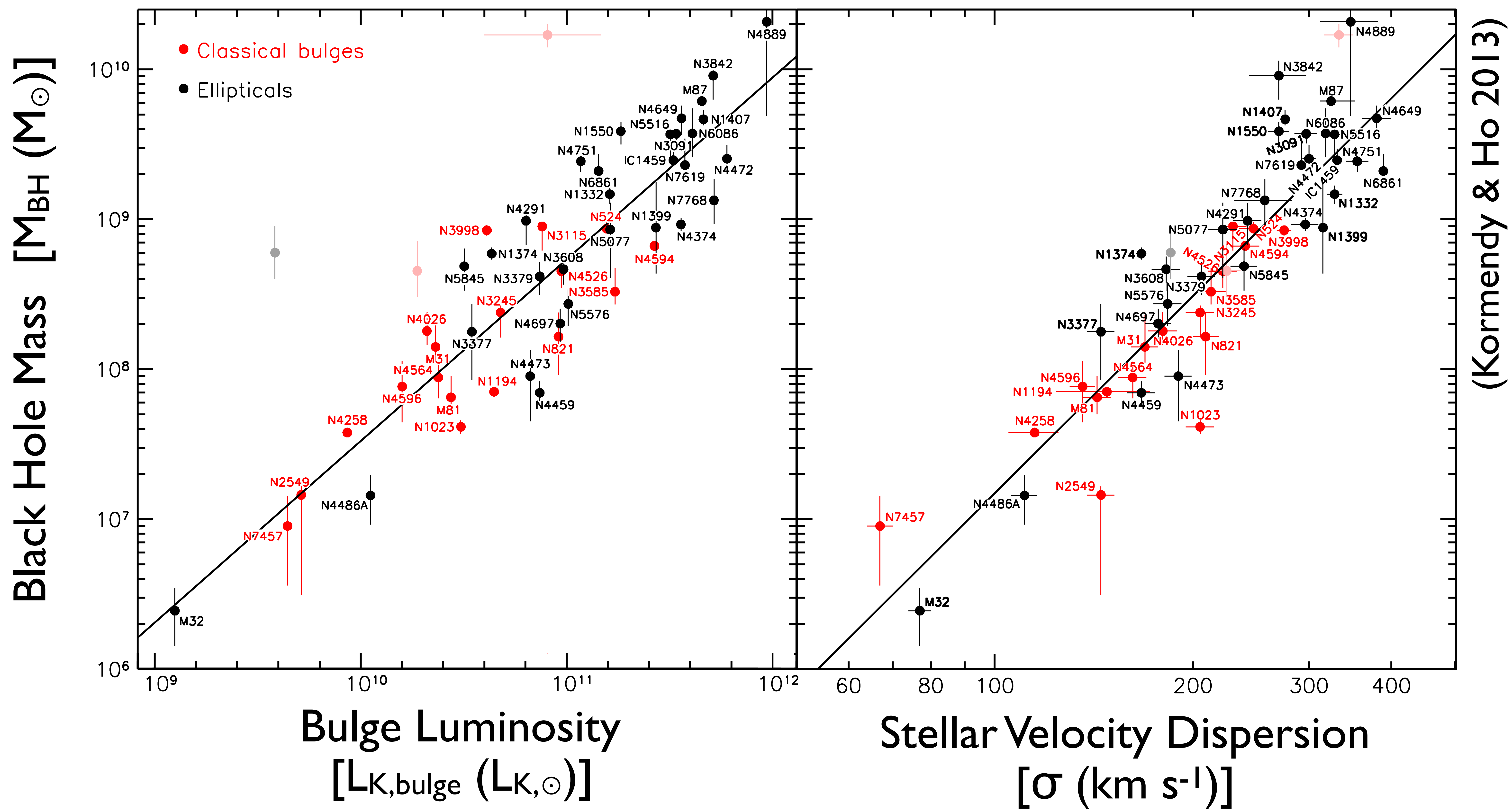
- Observations need to probe the region over which the BH potential dominates — the BH sphere of influence (r_{sphere}).



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

- The *Hubble Space Telescope* (*HST*) has played a fundamental role in detecting BHs over the past two decades. More recently, significant progress has been made using large ground-based telescopes + adaptive optics (AO) (e.g., Mazzalay et al. 2016, Erwin et al. 2018, Krajnović et al. 2018).

The Black Hole - Host Galaxy Relations

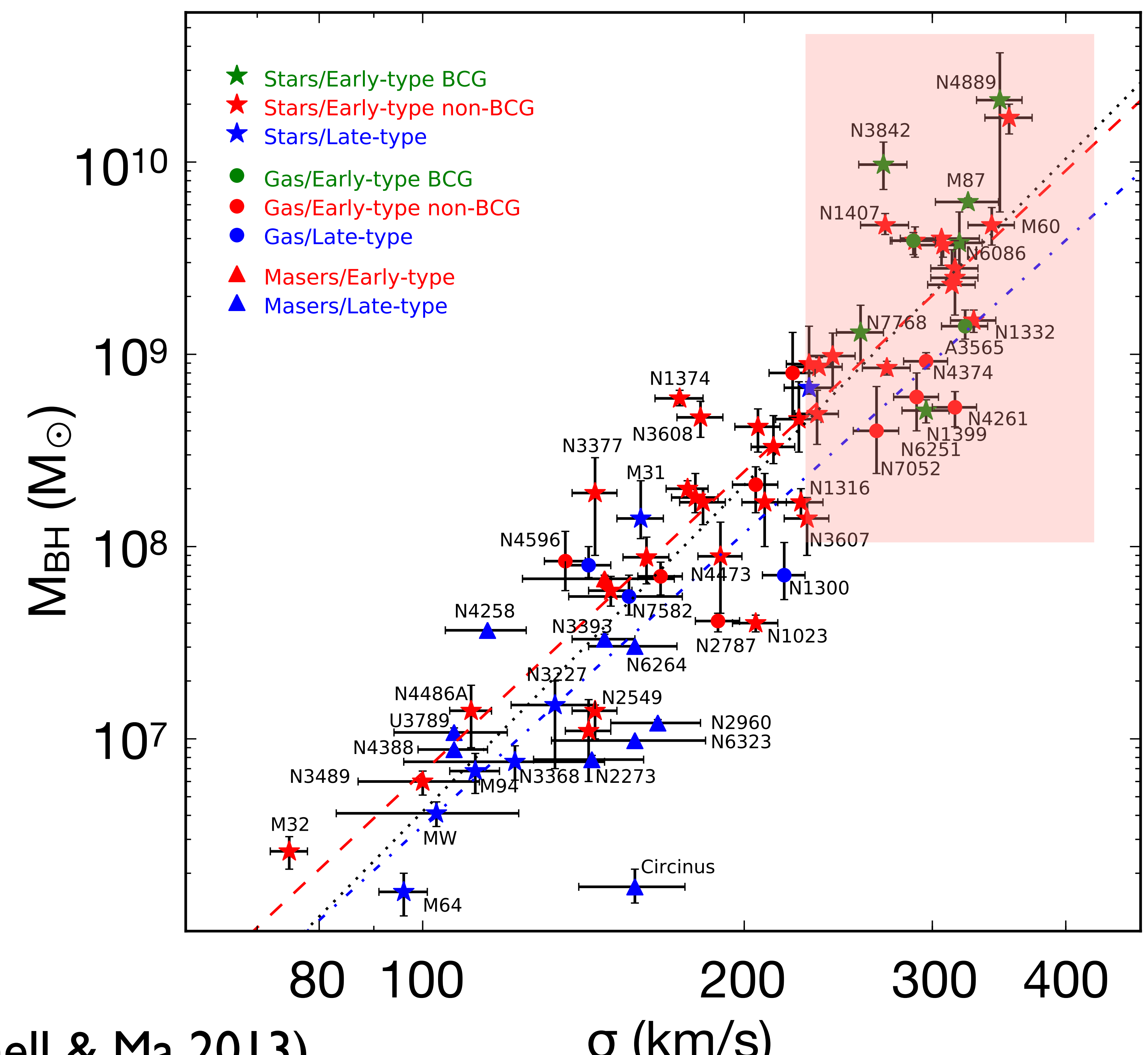


✦ The relations indicate that BHs, which occupy scales of $\lesssim 10^{-4}$ pc in galaxy nuclei, correlate by the large-scale (~1 kpc) bulge properties of their host galaxy, implying that BHs and galaxies somehow grow and evolve together.

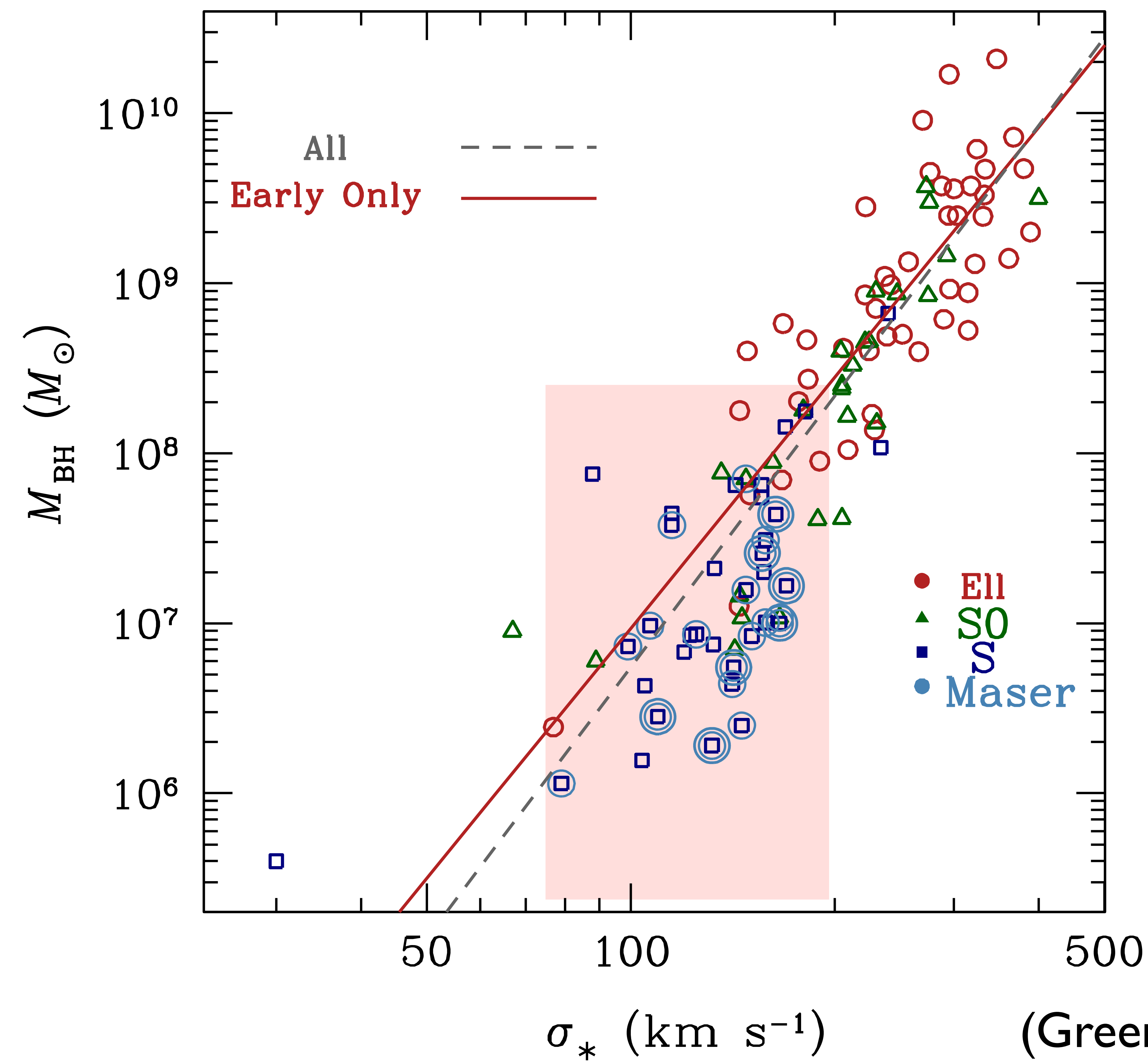
The Black Hole - Host Galaxy Relations

✦ The local BH mass census is highly incomplete, particularly for low- and high-mass BHs.

✦ Recent work detecting high-mass BHs in BCGs suggest that these objects lie above M_{BH}-σ (e.g., McConnell et al. 2011, 2012, Mehrgan et al. 2019). 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).



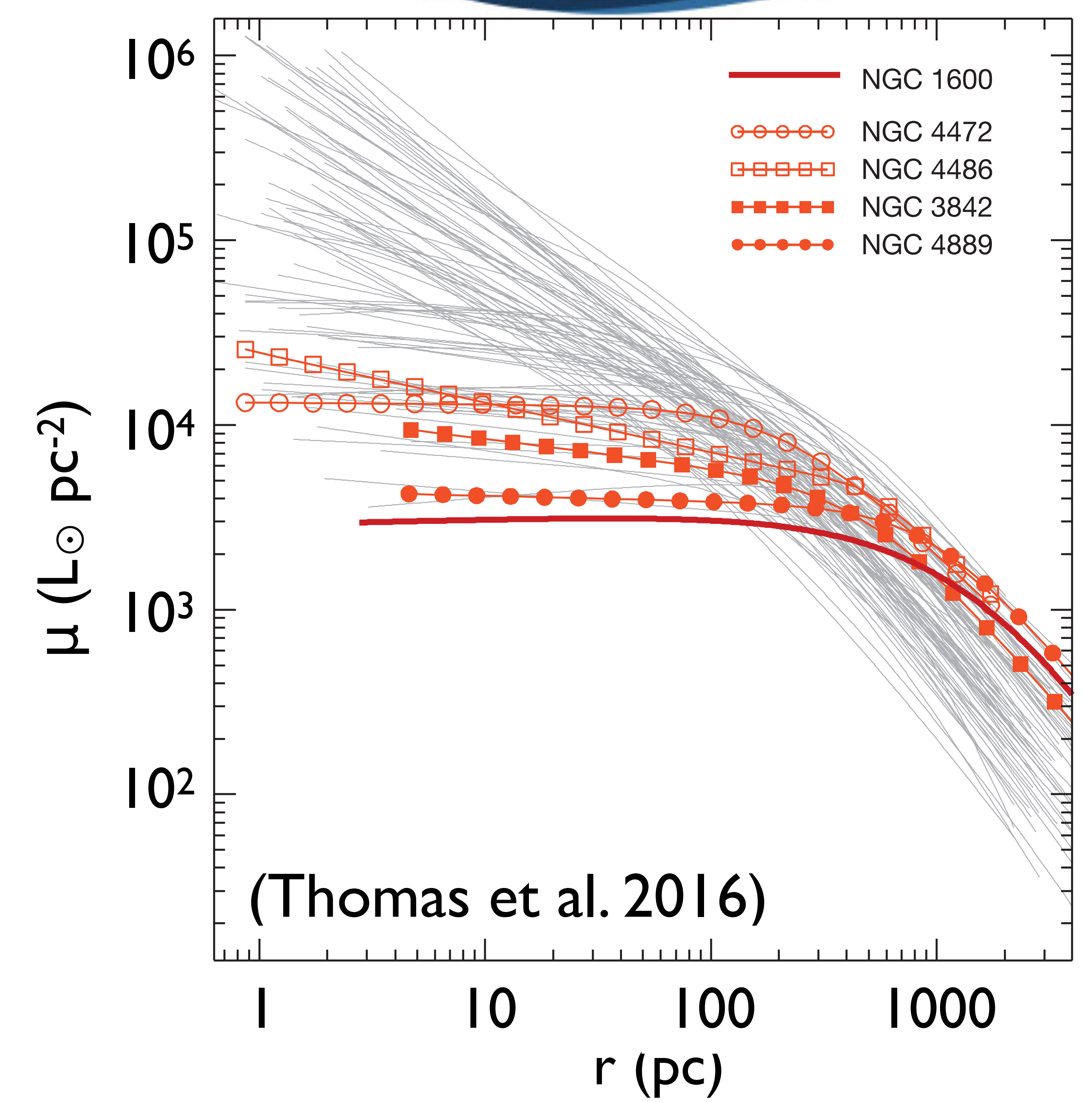
(McConnell & Ma 2013)



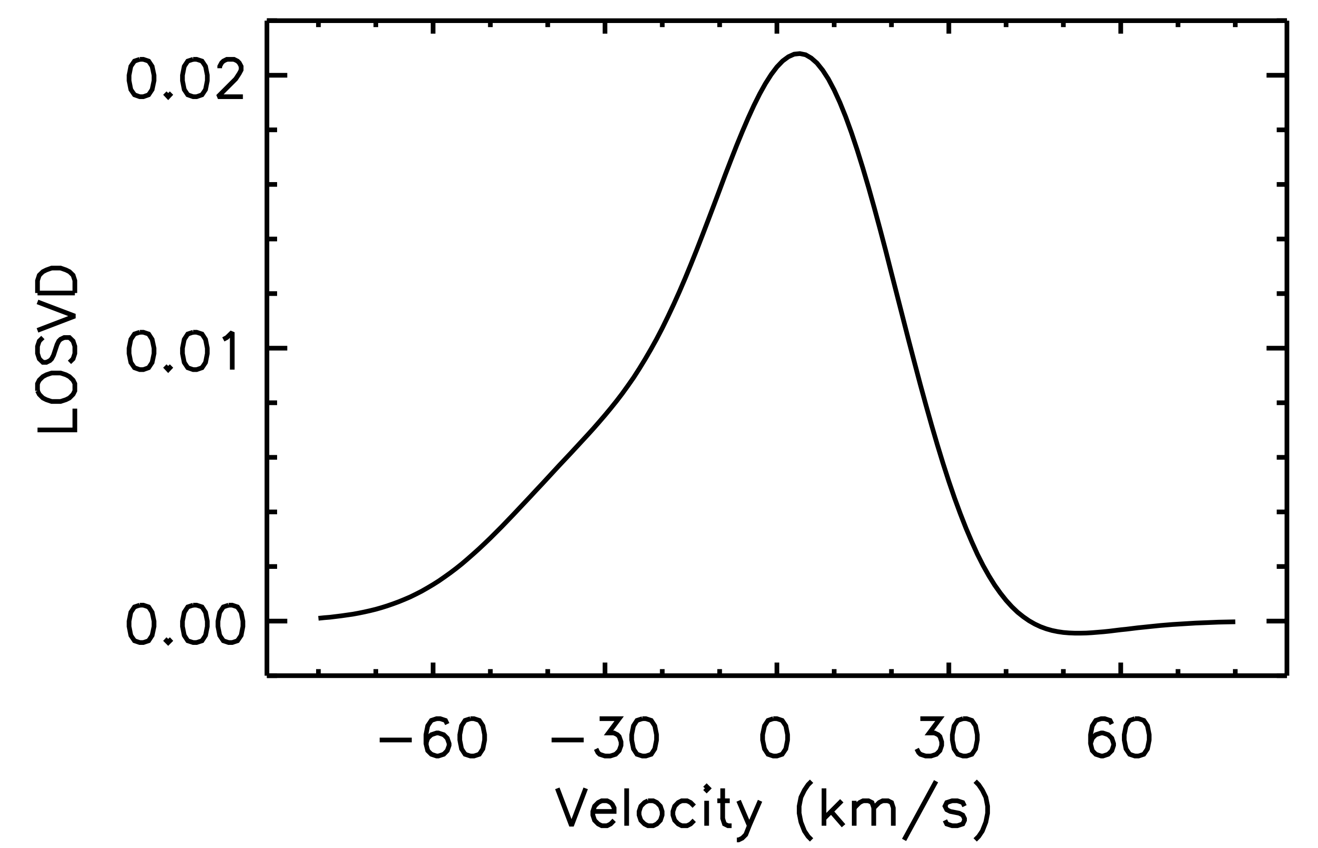
(Greene et al. 2016)

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 line-of-sight velocity distribution (LOSVD).

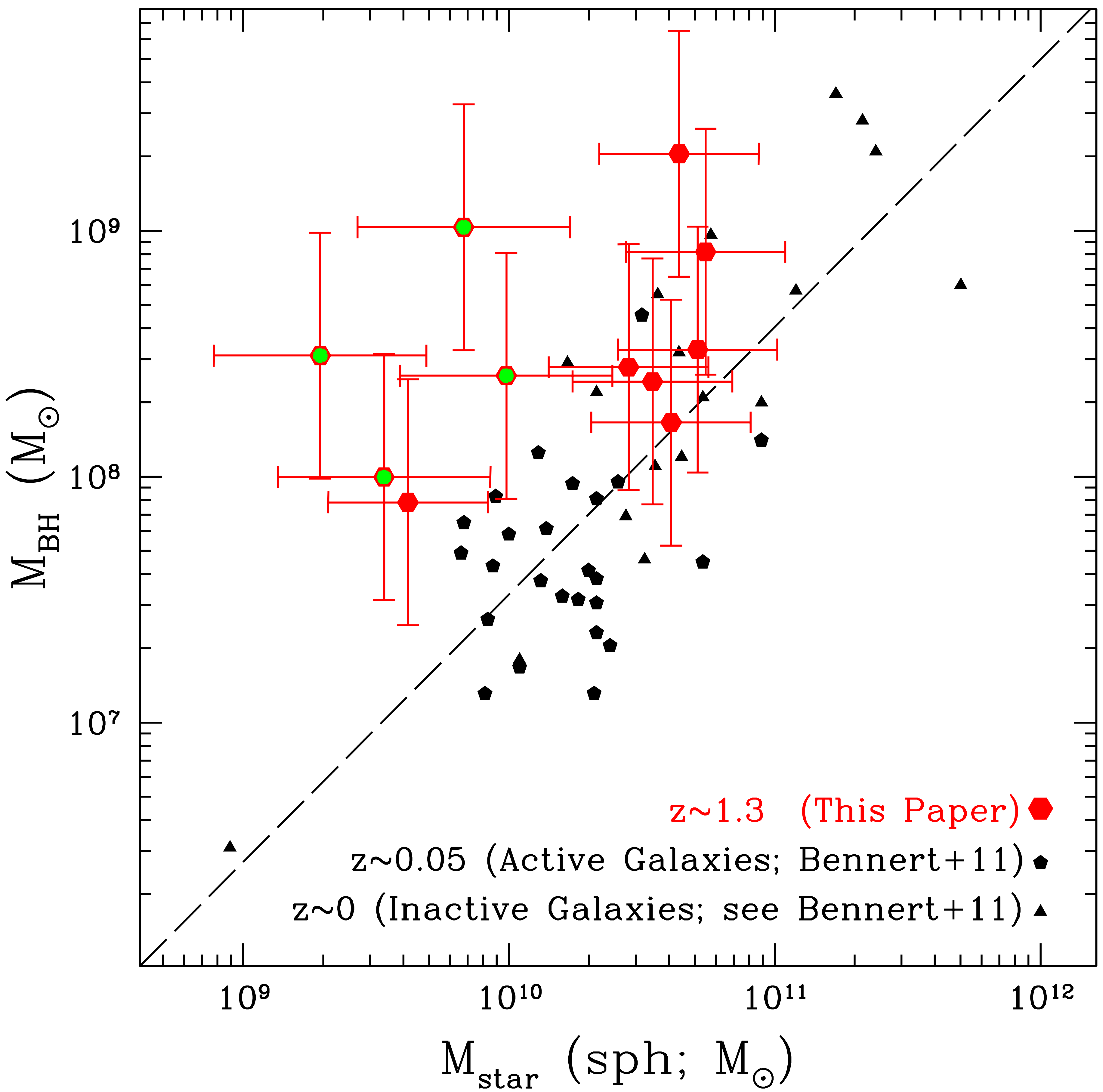


Fundamental Questions

- 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 fundamental 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?

Redshift Evolution of the Black Hole Scaling Relations

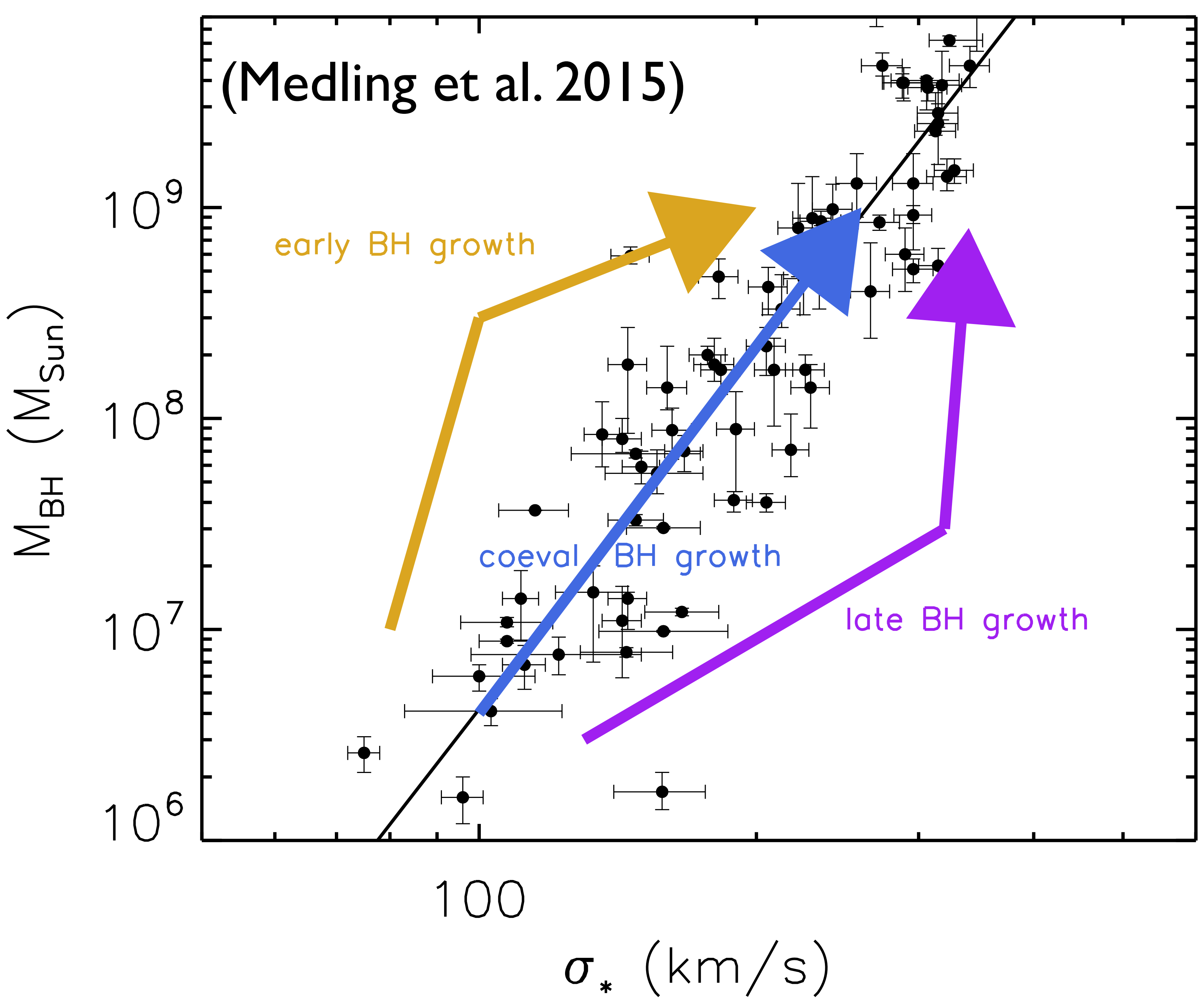
(Bennert et al. 2011)

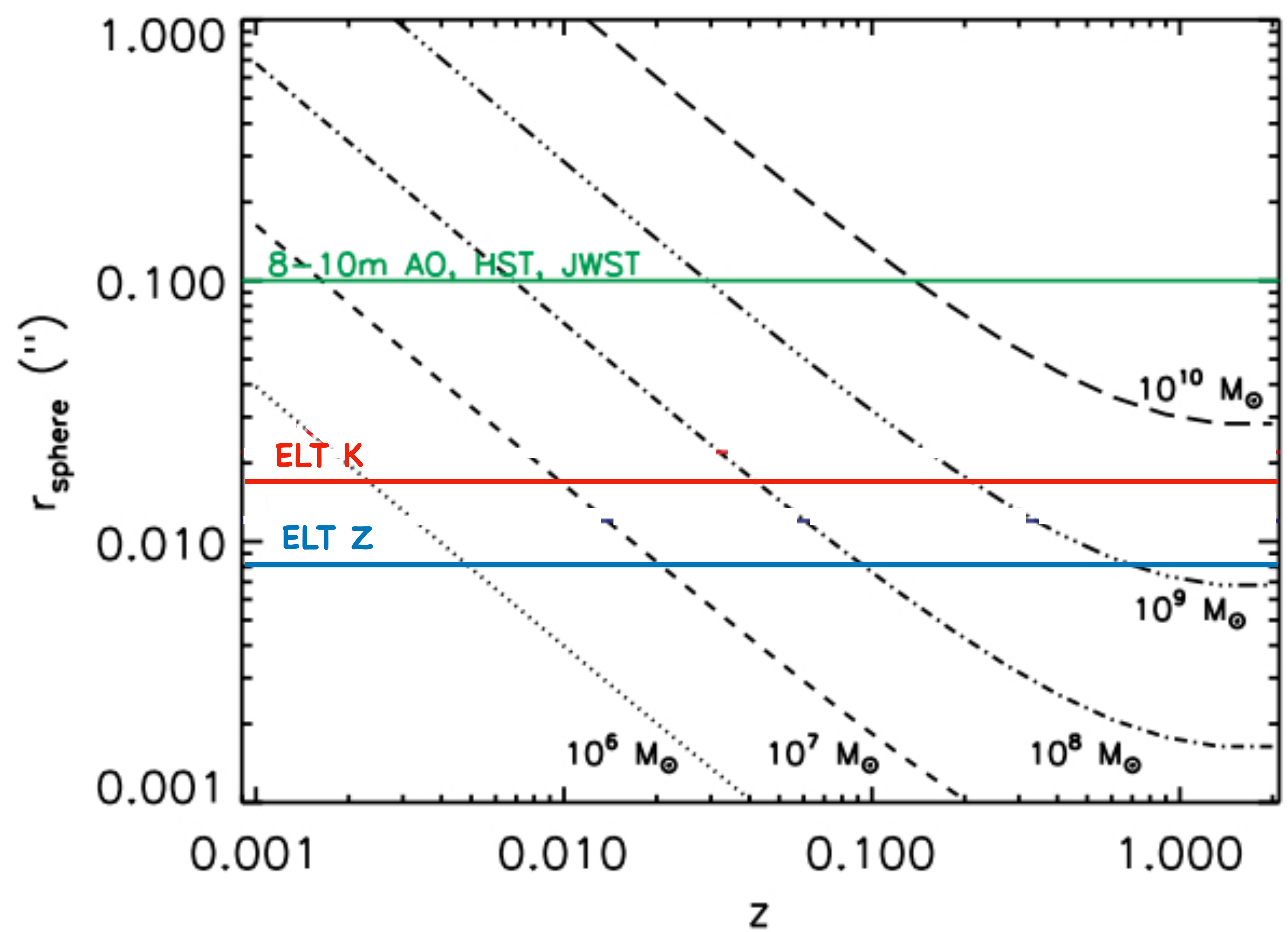


- Currently, we cannot search for redshift evolution in the BH relations using dynamical mass measurements. We need to estimate M_{BH} using properties of broad emission lines in active galaxies.
- Some studies report a positive evolution, such that BH growth precedes bulge growth (e.g., Woo et al. 2006, 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).

Direct Searches for Redshift Evolution with ELTs

- ✦ The U.S. ELTs with AO 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.





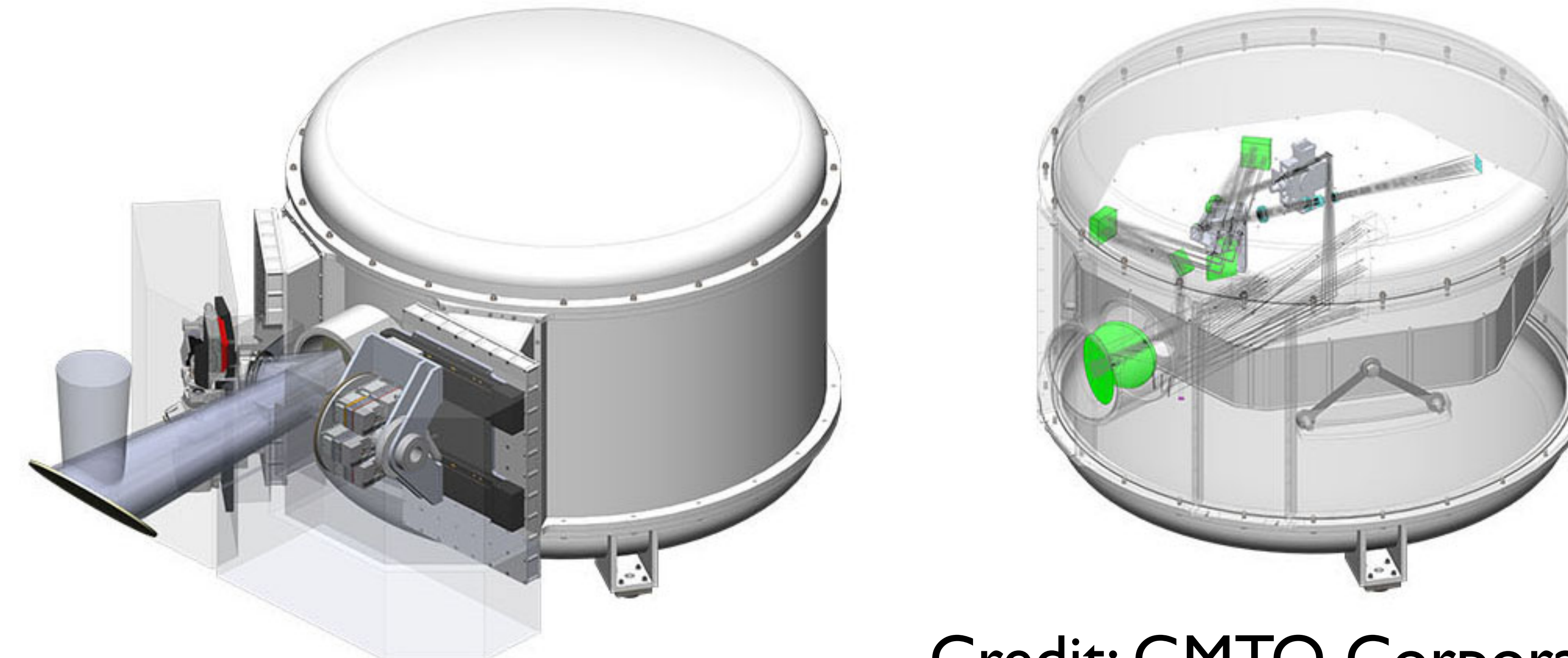
Direct Searches for Redshift Evolution with ELTs

- We will GMTIFS and IRIS with AO. We will determine the luminous mass distribution with the imager and map the stellar kinematics in the central regions of galaxies with the integral-field spectrograph.

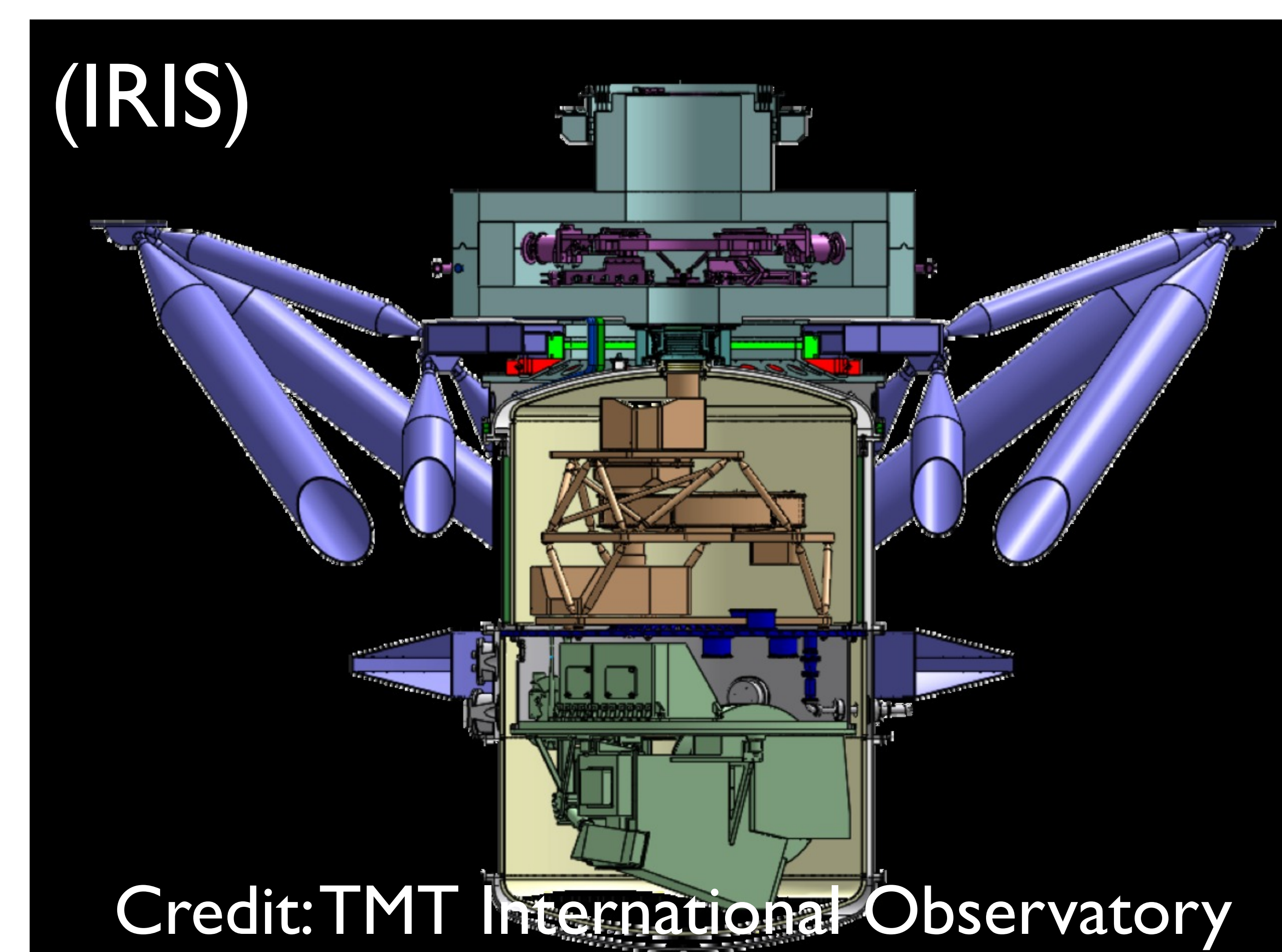
- For $z \lesssim 1.5$, we will measure kinematics from the 2.22 μm CO bandheads, 1.6 μm CO bandheads, and 0.85 μm Ca II triplet. Beyond $z > 1.5$, we will use emission lines (Hα), provided that the gas is in regular rotation.

- R~4000-5000 is sufficient spectral resolution for the high-mass BHs. We will make use of the 9 mas (IRIS) and 12 mas (GMTIFS) pixel scale.

(GMTIFS)



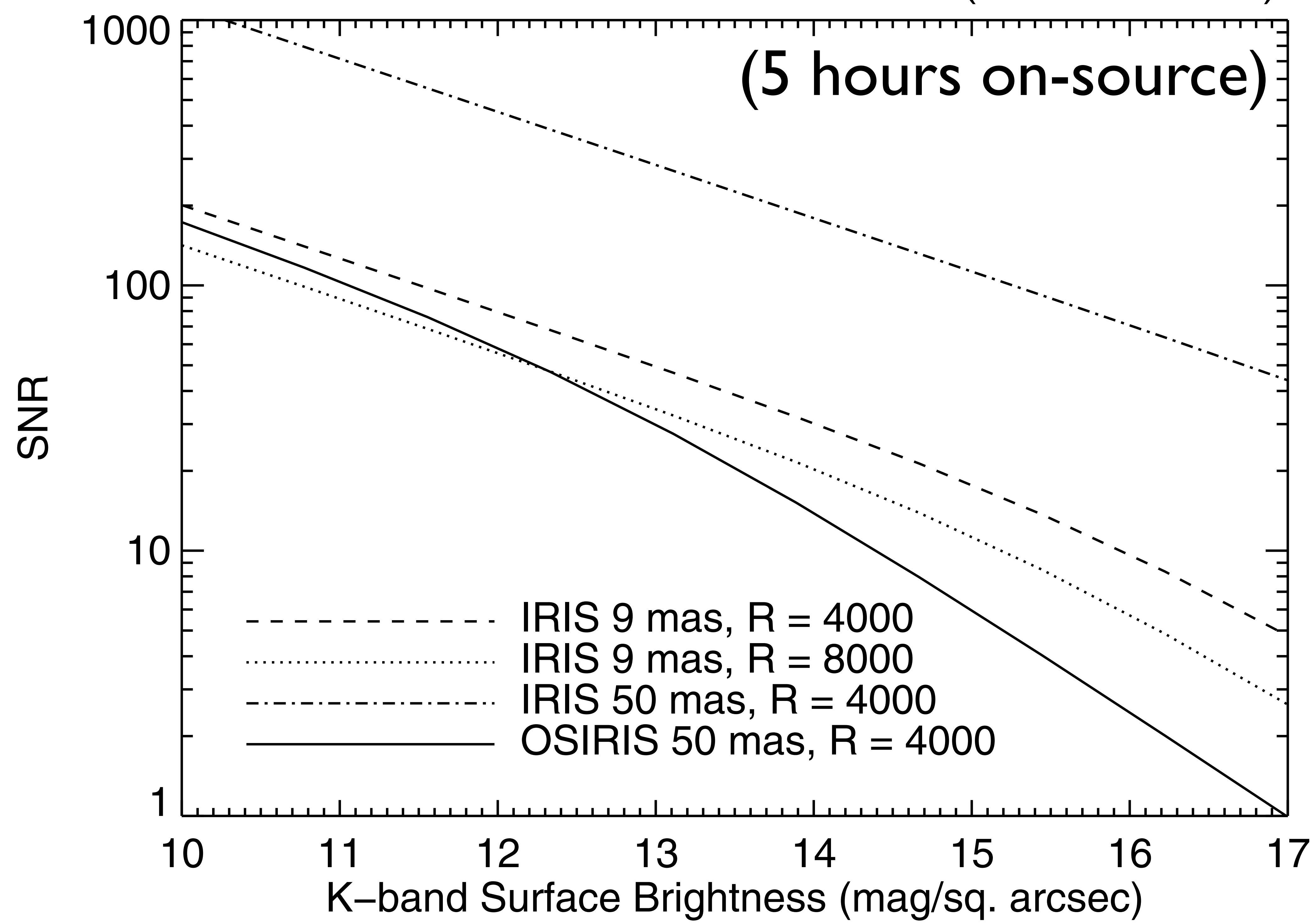
Credit: GMTO Corporation



(Gültekin, Barth, Gebhardt, Greene, Ho, Juneau, Ma, Seth, U, Valluri, Walsh, 2019 BAAS, 51, 287)

Direct Searches for Redshift Evolution with ELTs

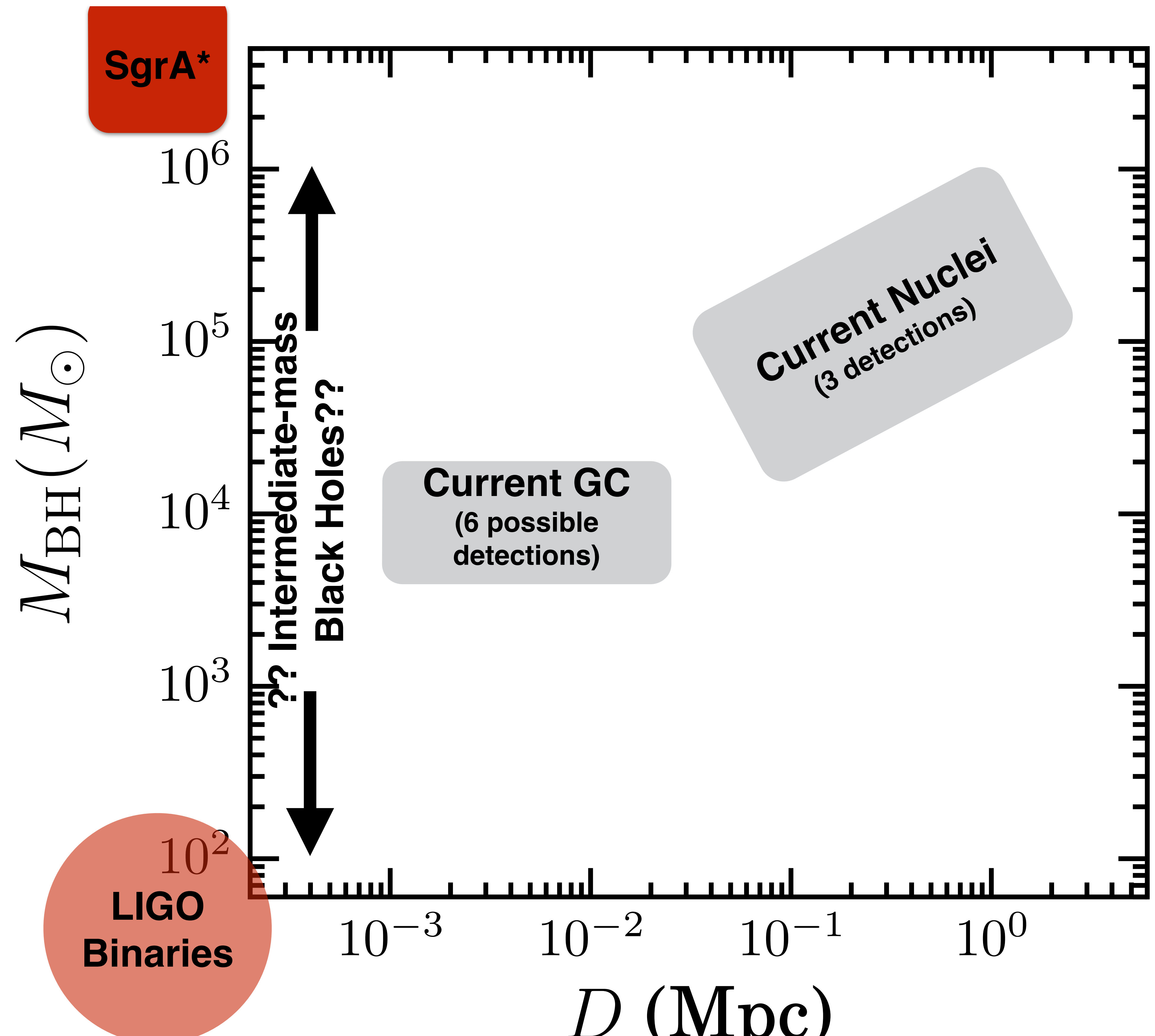
(Do et al. 2014)

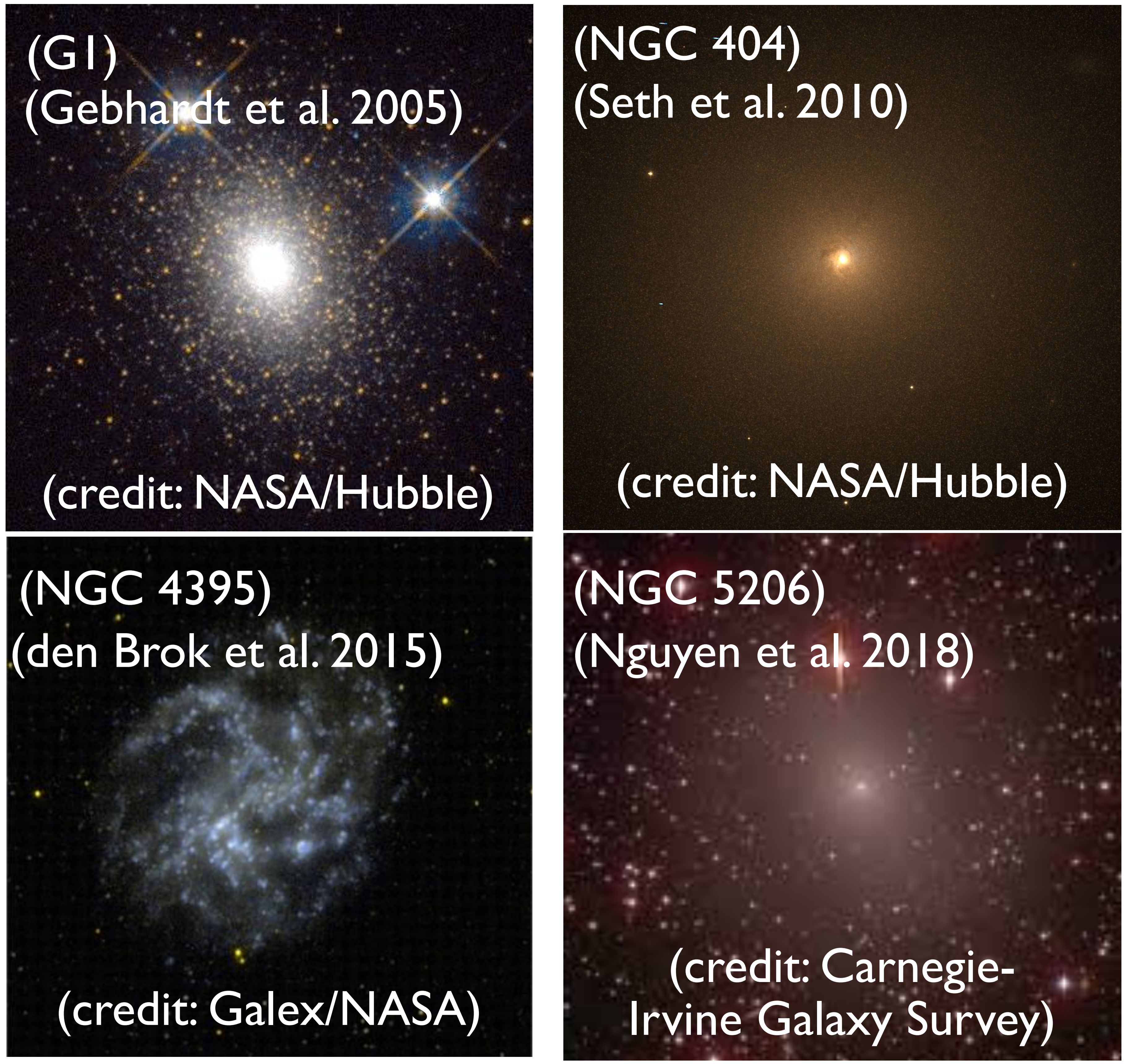


- We estimated exposure times using the central surface brightness of M87 [V=16.2 mag/arcsec^2 (Kormendy et al. 2009); assumed K=13.2 mag/arcsec^2], accounting for surface brightness dimming and luminosity evolution (Gebhardt et al. 2003).
- We aimed for S/N~40 in an unbinned lenslet and included time 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)

(Gültekin, Barth, Gebhardt, Greene, Ho, Juneau, Ma, Seth, U, Valluri, Walsh, 2019 BAAS, 51, 287)

Intermediate-mass Black Holes and Black Hole Seeds





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

(Greene, Barth, Bellini, Bellovary, Holley-Bockelmann, Do, Gallo, Gebhardt, Gültekin, Haiman, Hosek, Kim, Libralato, Lu, Nyland, Malkan, Reines, Seth Treu, Walsh, Wrobel, 2019 BAAS, 51, 83)

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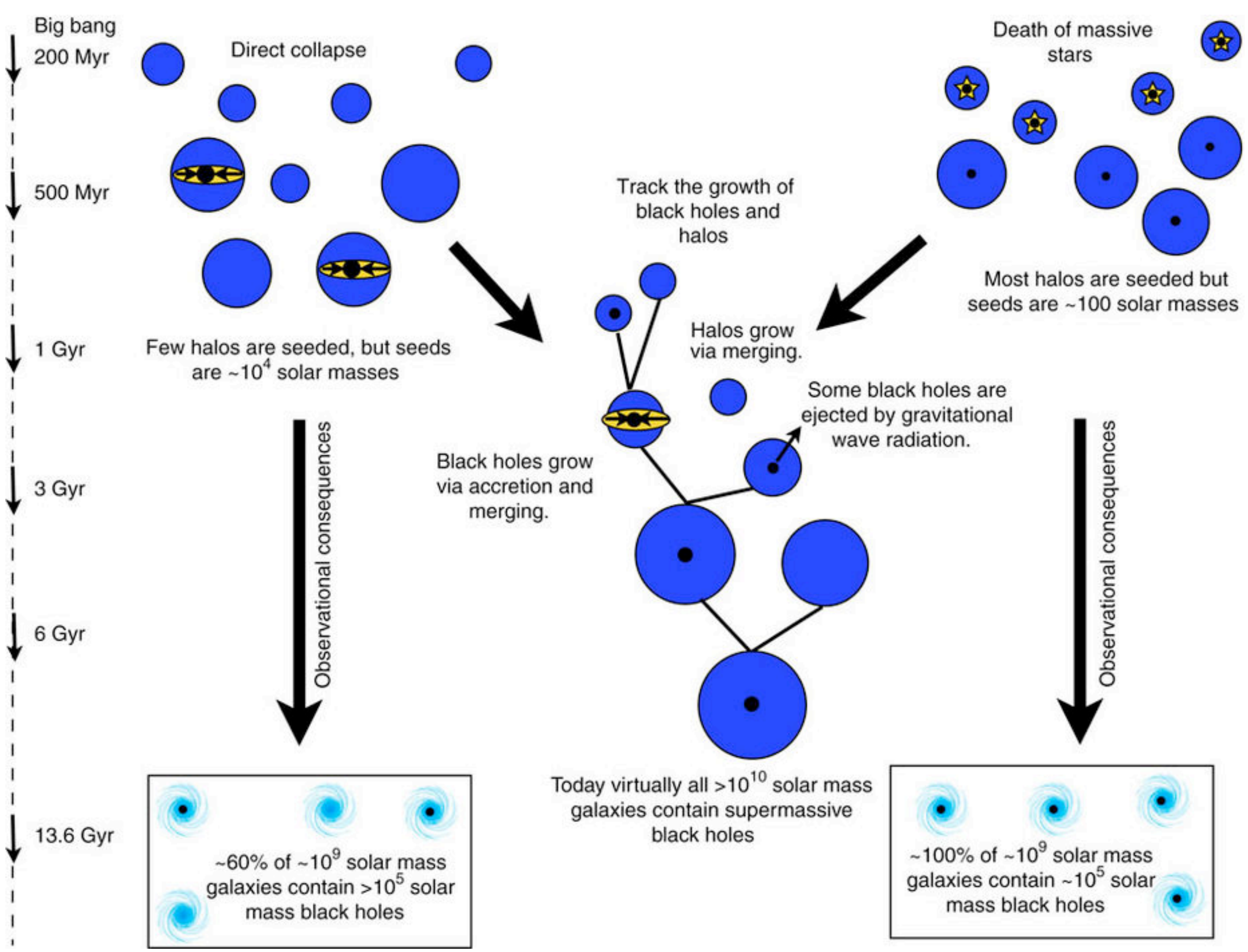
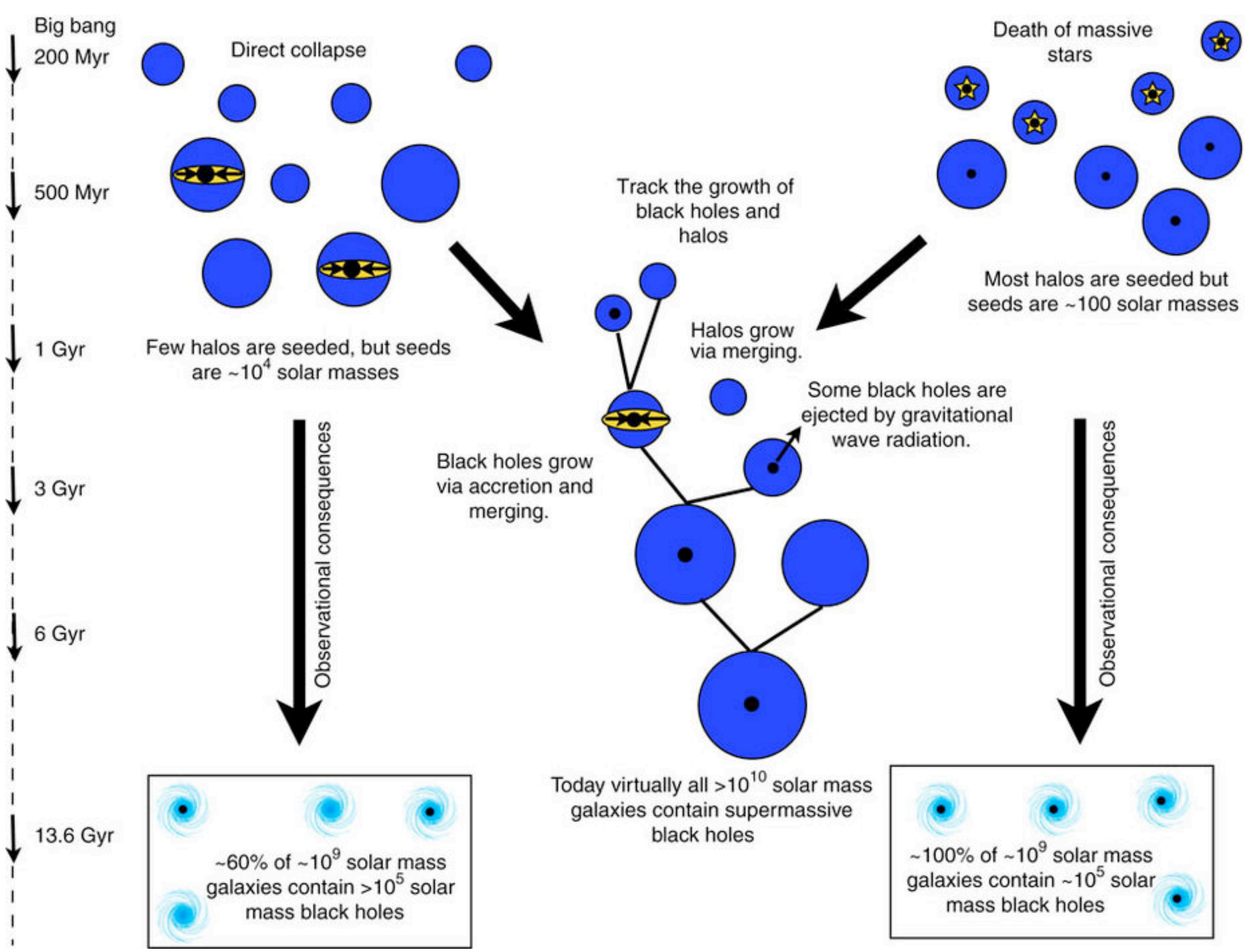


(Greene 2012)

(Greene, Barth, Bellini, Bellovary, Holley-Bockelmann, Do, Gallo, Gebhardt, Gültekin, Haiman, Hosek, Kim, Libralato, Lu, Nyland, Malkan, Reines, Seth Treu, Walsh, Wrobel, 2019 BAAS, 51, 83)

Intermediate-mass Black Holes and Black Hole Seeds



(Greene 2012)

- GMTIFS and IRIS will be sensitive to 10^3 $M_\odot$ BHs at the distance of Andromeda, and 10^4-10^5 $M_\odot$ BHs at distances of 3-5 Mpc.
- The systems that might host IMBHs have dispersions ~15-30 km/s. We need R~8000, but R~10,000 is preferred.
- Using the GMTIFS exposure time calculator with the 6 mas pixel scale and R=10,000, we estimated that we can reach S/N~30-50 in 3-7 hours per source.
- Including sky exposures and overheads, we need ~200 hours to observe 5 of the most luminous globular clusters in Andromeda and the nuclei of 25 late-type spirals within 5 Mpc.

(Greene, Barth, Bellini, Bellovary, Holley-Bockelmann, Do, Gallo, Gebhardt, Gültekin, Haiman, Hosek, Kim, Libralato, Lu, Nyland, Malkan, Reines, Seth Treu, Walsh, Wrobel, 2019 BAAS, 51, 83)

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.

- GMT and TMT's angular resolution and sensitivity will open up new regimes:

    - We can directly trace redshift evolution in the BH scaling relations using the highest mass BHs.

    - We can dynamically search for nearby IMBHs and explore the mass function of BH seeds.