How do massive black holes grow along with their host galaxy?

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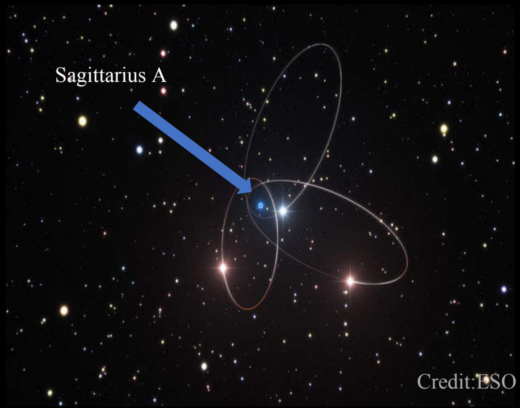
Direct image/silhouette of the black hole in the galaxy M87
(Event Horizon Telescope Collaboration, 2019)

Stellar-mass black holes (<~100 times the mass of our Sun) and supermassive black holes (SMBHs: 10^5 to 10^{10} solar masses) are known to exist. However, only a small handful of intermediate-mass black holes (IMBHs) have been detected, including the recent addition of GW190521's remnant black hole announced by the LIGO-VIRGO collaboration. In general, it is expected that a typical galaxy will have up to 10^6 stellar-mass black holes, perhaps 10-10^3 IMBHs, but just one SMBH feeding on the gas and stars at the centre of the galaxy. Friction between inspiraling gas and dust can release an enormous amount of electromagnetic energy, and powerful bipolar outflows are thought to regulate the properties of the host galaxy which feeds the black hole. Our observational study is discovering new, and better quantifying existing, correlations between the black hole mass and the host galaxy properties in an effort to understand the SMBH/galaxy coevolution.



We have used the largest sample to date of ~140 galaxies with directly measured (not inferred) black hole masses, including Sagittarius A* at the centre of our own Galaxy, the Milky Way.

Observed Mass Ranges of Compact Objects

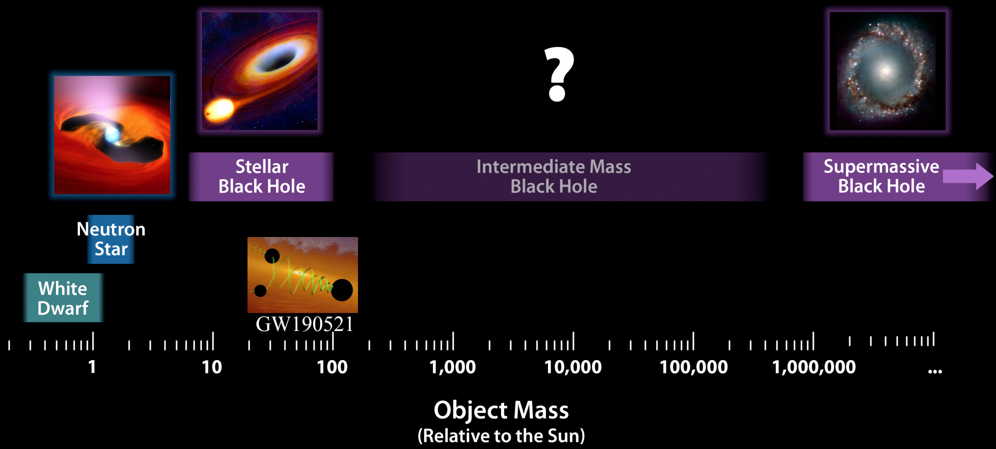
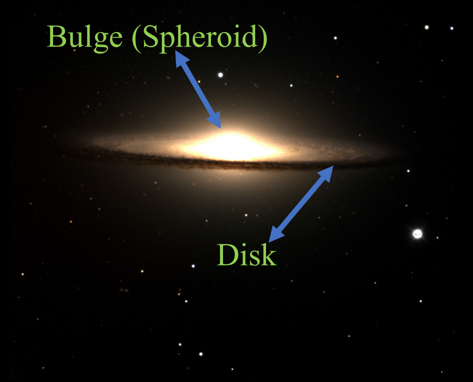


Image credit: NASA/JPL-Caltech

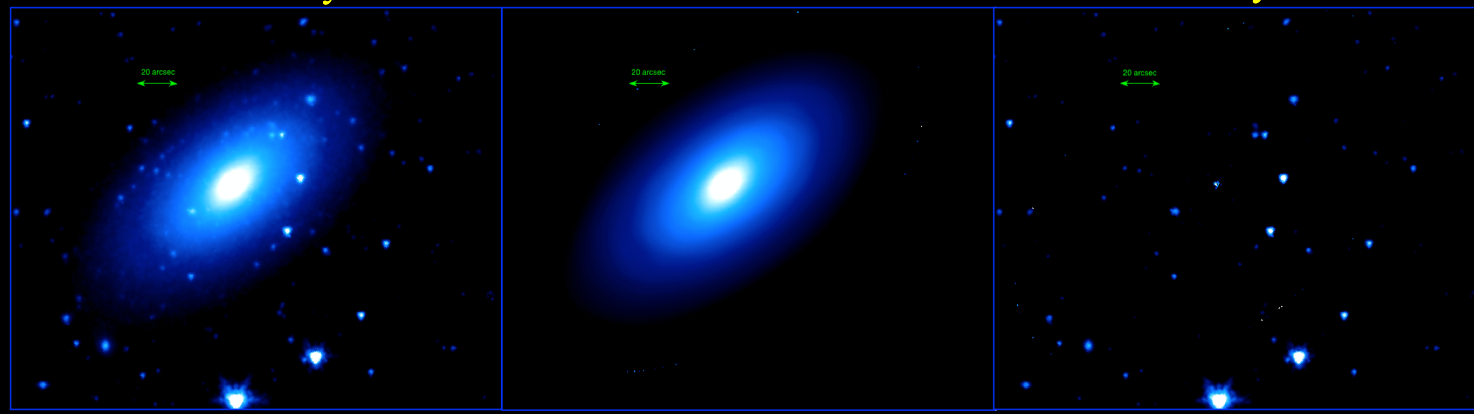


A galaxy may have an ellipsoidal bulge (also called spheroid), a rotating stellar disk, and other components like a bar, ring etc. Since the bulge of a galaxy immediately surrounds the SMBH, a relation has been expected between black hole mass and the bulge mass. However, measuring the mass of the bulge of a galaxy is challenging, especially when it is a multi-component galaxy.

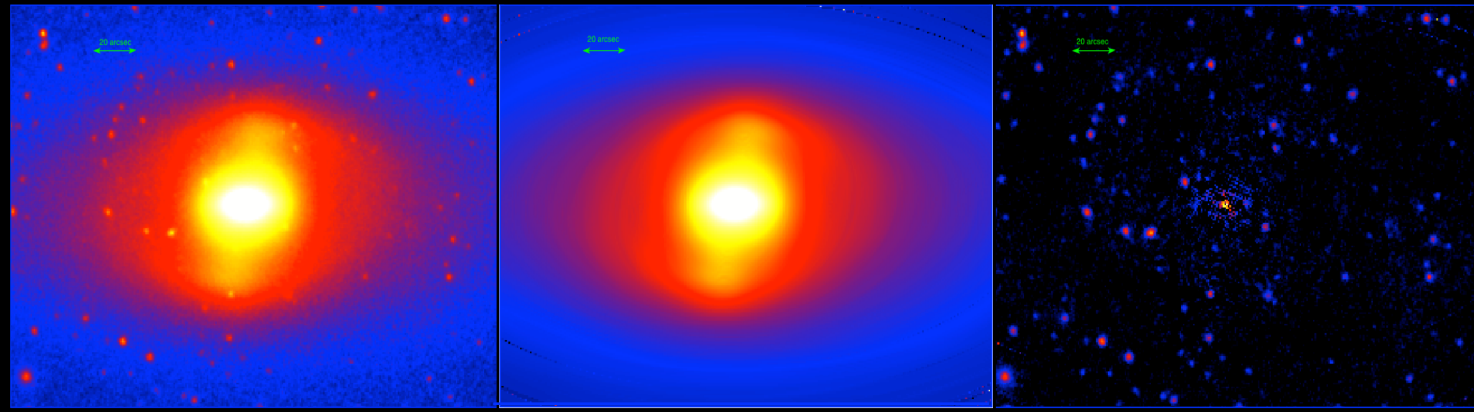
We generate a 2D isophotal model of our galaxies (see examples: NGC 7457 and NGC 4371), which capture all the structural and photometric properties of the galaxy.

We perform a multi-component decomposition where we disassemble the total galaxy light into its components and use an appropriate stellar mass-to-light ratio to convert the bulge luminosity into bulge stellar mass.

Galaxy | Model | Galaxy - Model



NGC 7457: A two-component ETG with a Bulge, and a Disk



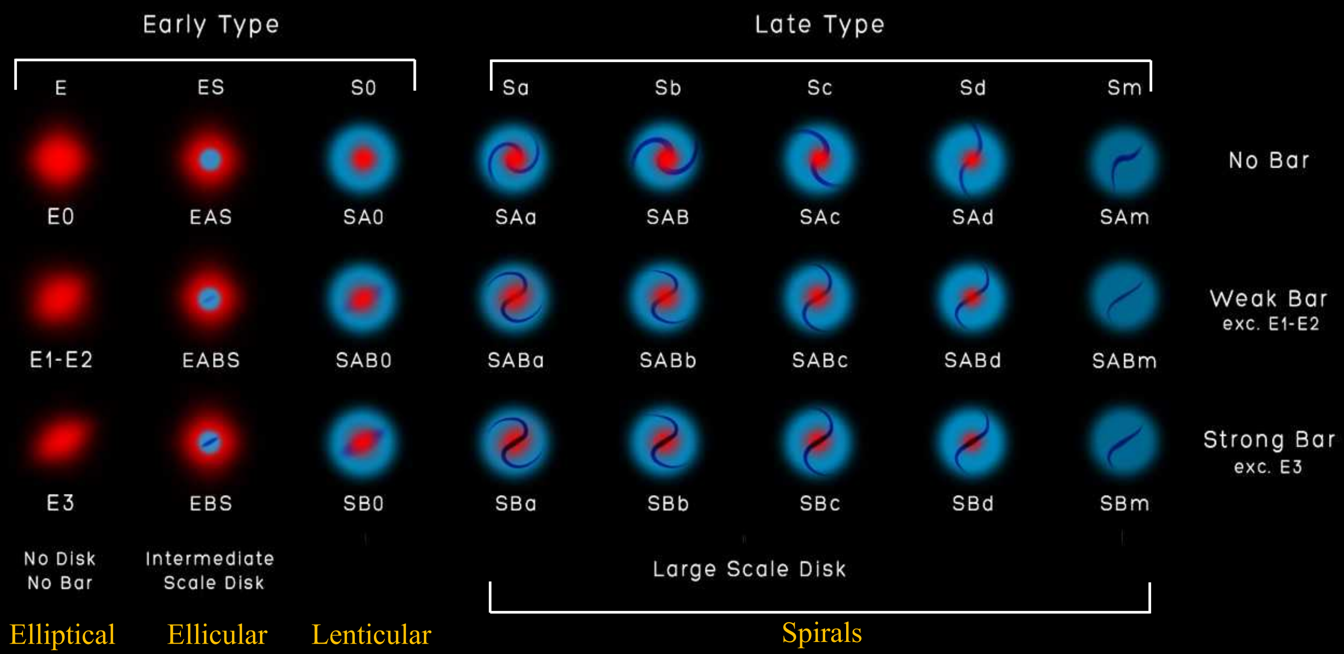
NGC 4371: A multi-component ETG with a Bulge, Bar-lens, Bar, Ansae, Disk

A detailed description of galaxy modelling and the multi-component decomposition using a new in-house software can be found in Sahu et al. (2019a)

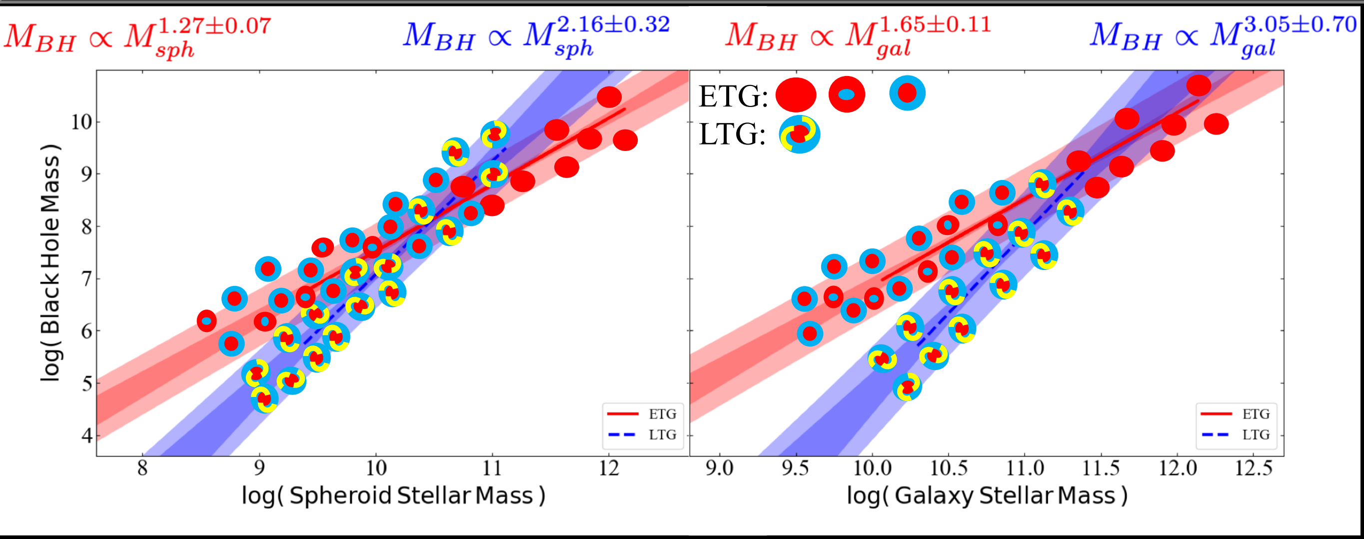
Various galaxy types i.e. morphology

Our detailed modelling and multicomponent decomposition lead us to identify the morphology of galaxies in our sample, which enabled us to investigate the dependence of black hole scaling relations on galaxy morphology.

In our galaxy sample, we have early-type galaxies (ETGs) as well as late-type galaxies (LTGs). In general, ETGs comprise of elliptical (E), ellicular (ES), and lenticular (S0) galaxies. Whereas, LTGs comprises of all kinds of spiral galaxies as represented in the right diagram taken from Graham (2019).



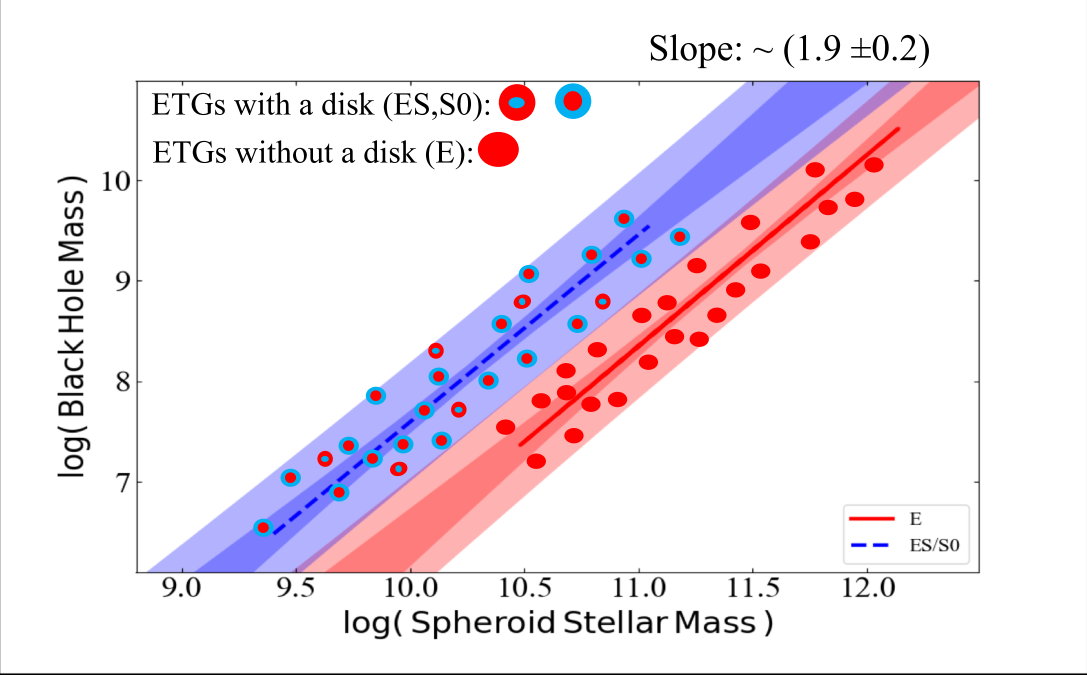
Observed relations



We found that:

- There is a tight correlation between black hole mass and host galaxy's bulge mass (left panel). However, ETGs and LTGs define two different relations, called the red sequence and blue sequence, respectively, plus we have discovered a dramatic twist to the red sequence (shown on the next page).
- Black hole mass also correlates with total galaxy mass (right panel). Here as well, ETGs and LTGs follow two different relations.
- The galaxy mass can be directly used to estimate the central black hole mass.

Symbols used here are only for illustration. The exact data-points can be seen in Sahu et al. (2019a)



See Sahu et al. (2019a) for more details.

Upon further dividing ETGs into ETGs which have a rotating disk (ES and S0) and ETGs which do not (E), we found that

- The two subpopulations follow different relations between black hole mass and bulge mass, offset from each other by more than an order of magnitude in black mass.
- This offset is because of smaller spheroid mass and size in ETGs with a disk.
- To accurately estimate the black hole mass of an ETG using its bulge mass, one must know whether or not the galaxy has a stellar disk.

Conclusions

- The correlations between black hole mass and both the bulge and total galaxy stellar mass are dependent on galaxy morphology, which is expected given the difference in the formation physics depending on morphology. Different relations suggests different ways SMBH's mass co-evolves with the host stellar mass. All these relations are non-(log) linear, suggesting the growth rate of the black hole mass is greater than the growth rate of the host stellar mass.
- These black scaling relations now enable us to more accurately estimate the black hole mass in other distant galaxies, calibrate morphology aware virial factors used in the reverberation mapping method, and improve the predictions for the detection of long wavelength gravitational waves by pulsar timing arrays and the upcoming space interferometer LISA. Additionally, the blue and red sequence provide improved constraints for simulations trying to reproduce the joint evolution of black holes and galaxies.
- To know more about the latest correlations between black hole mass and other galaxy properties, e.g. the central stellar velocity dispersion, central light concentration, size, and internal density see Sahu et al. (2019b), Sahu et al. (2020a, accepted in APJ), and Sahu et al.(2020b, in preparation).

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