# BLACK HOLE MASS SCALING RELATIONS

Benjamin L. Davis[1,2], Alister W. Graham[2], Nandini Sahu[1,2], and Ewan Cameron[3]

[1]Australian Research Council Centre of Excellence for Gravitational Wave Discovery
[2]Centre for Astrophysics and Supercomputing, Swinburne University of Technology
[3]Oxford Big Data Institute, University of Oxford

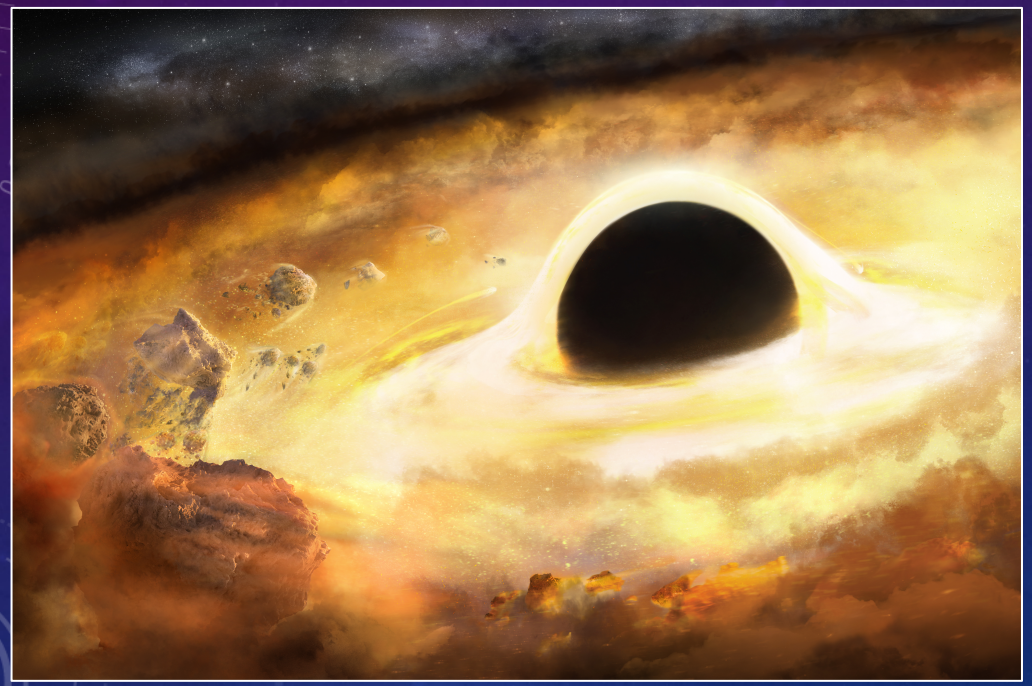

Image Credit: James Josephides

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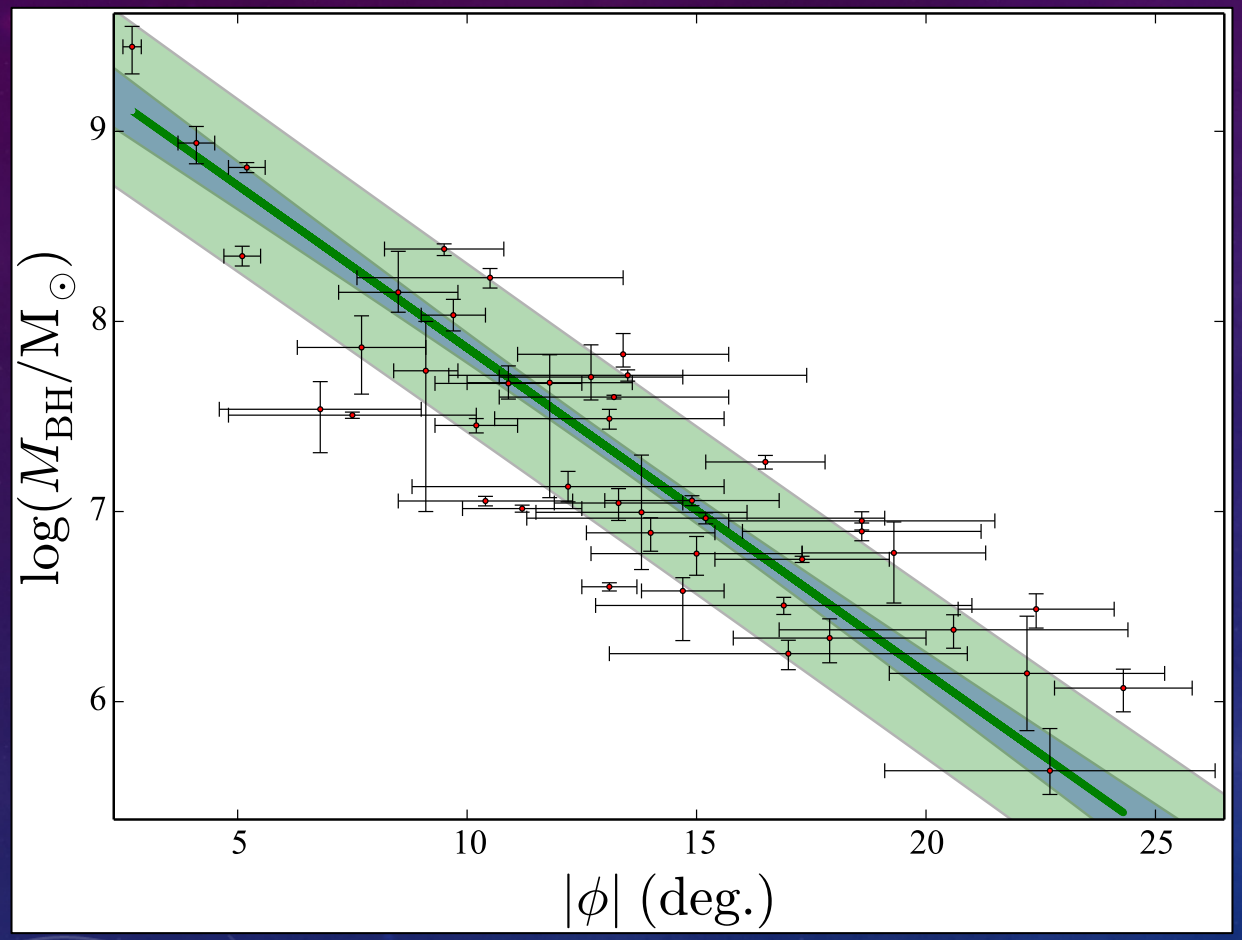
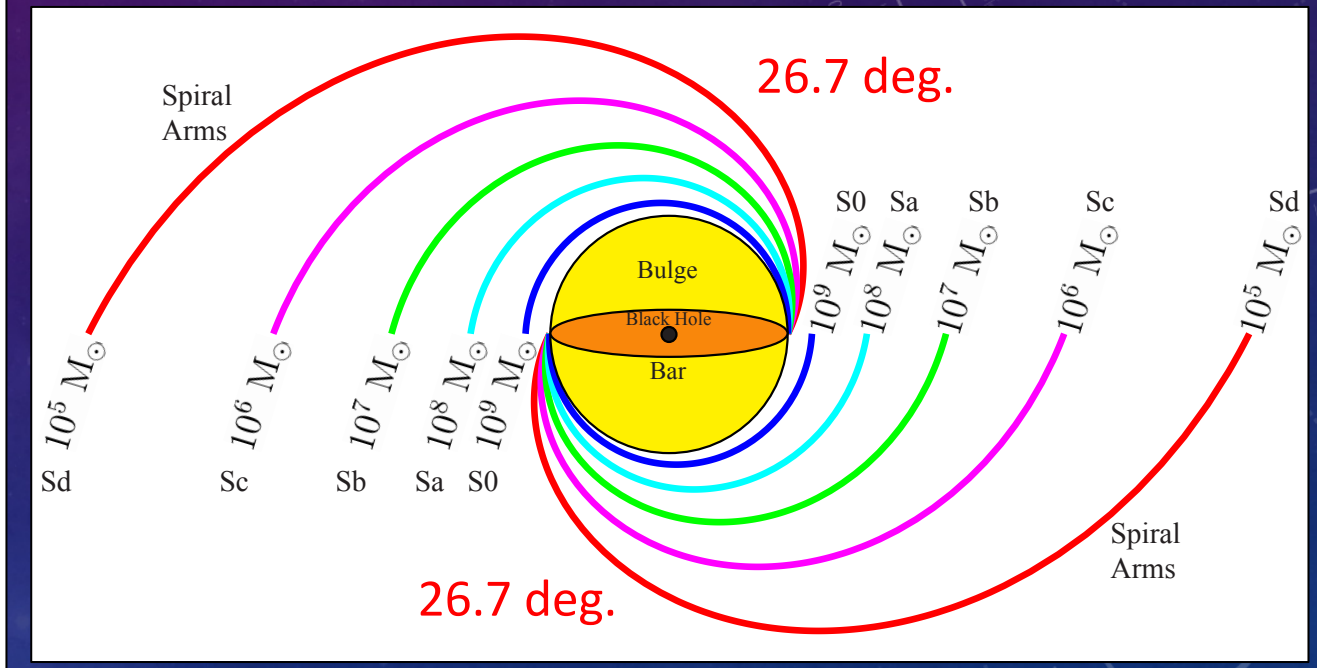
# Data & Methodology

- The largest to date sample of supermassive black holes (SMBHs) with directly measured masses
  - Independently measured masses via direct measurement techniques:
    - Proper motion of stars orbit a SMBH (i.e., Sgr A*)
    - Stellar dynamics - kinematics of the stellar disk within the sphere of influence of a SMBH
    - Gas dynamics – kinematics of the gaseous disk within the sphere of influence of a SMBH
    - Direct imaging of the shadow (event horizon) of a SMBH (i.e., M87*)
- 132 SMBHs residing in 84 early-type and 48 late-type galaxies (as distant as ~260 Mpc)
- We have produced measurements of the bulge, disk, and galaxy stellar masses for all of the sample.
- For the spiral galaxies, we have measured their spiral-arm pitch angles and estimated their dark matter halo masses via their maximum disk rotational velocities.

# The $M_{BH}$-$\phi$ Relation



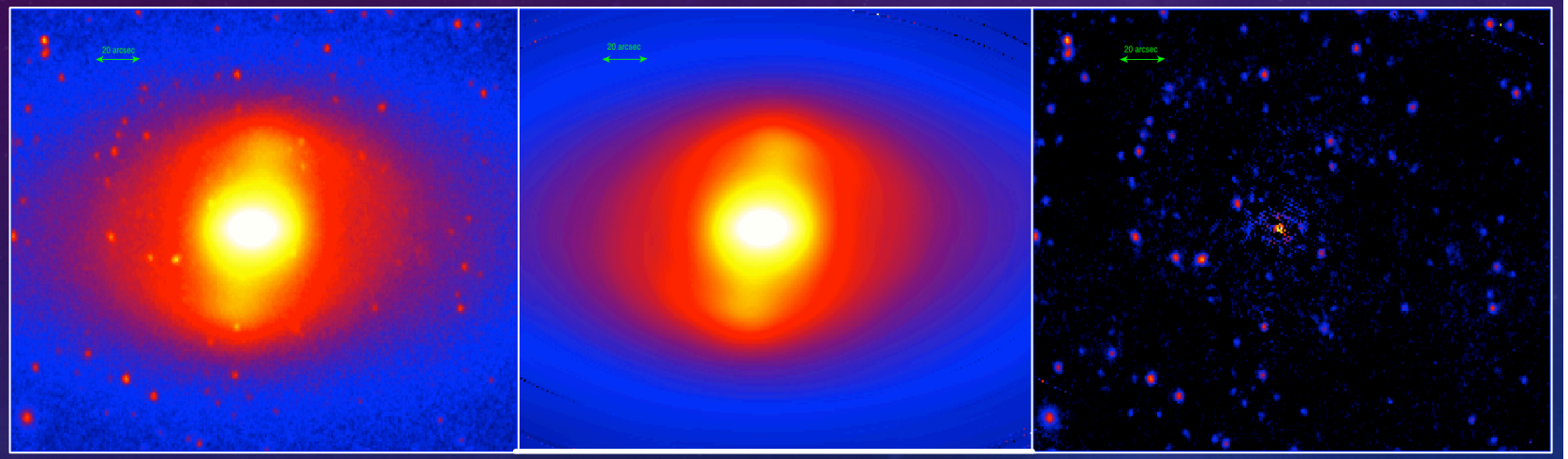

Seigar et al. (2008); Berrier et al. (2013); Davis, Graham, & Seigar (2017)

# Surface Brightness Profile via *Profiler* (Ciambur 2016)

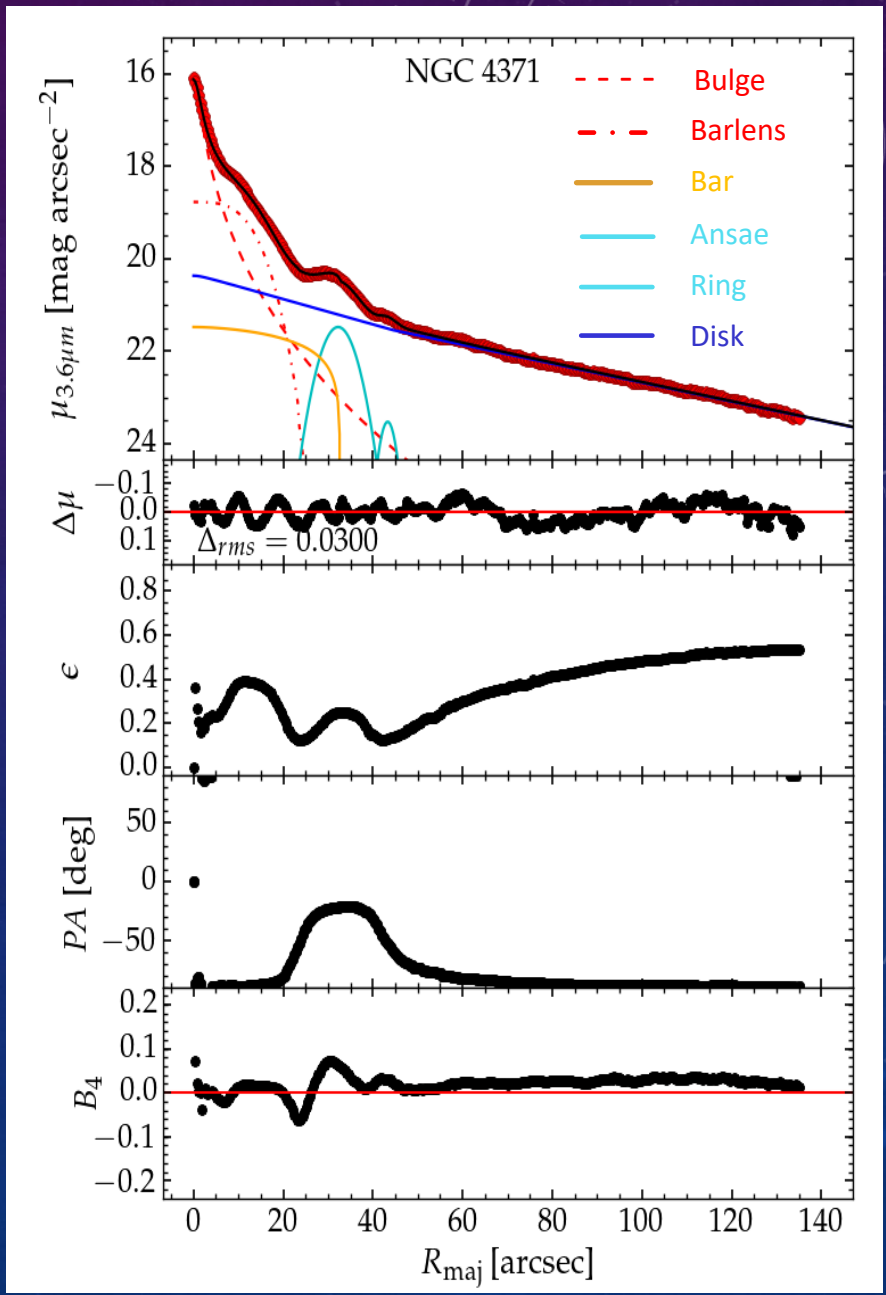
## Modeling a Lenticular Galaxy from Our Sample

NGC 4371 – SB(r)0

$M_{BH} \sim 7 \times 10^6 M_\odot$

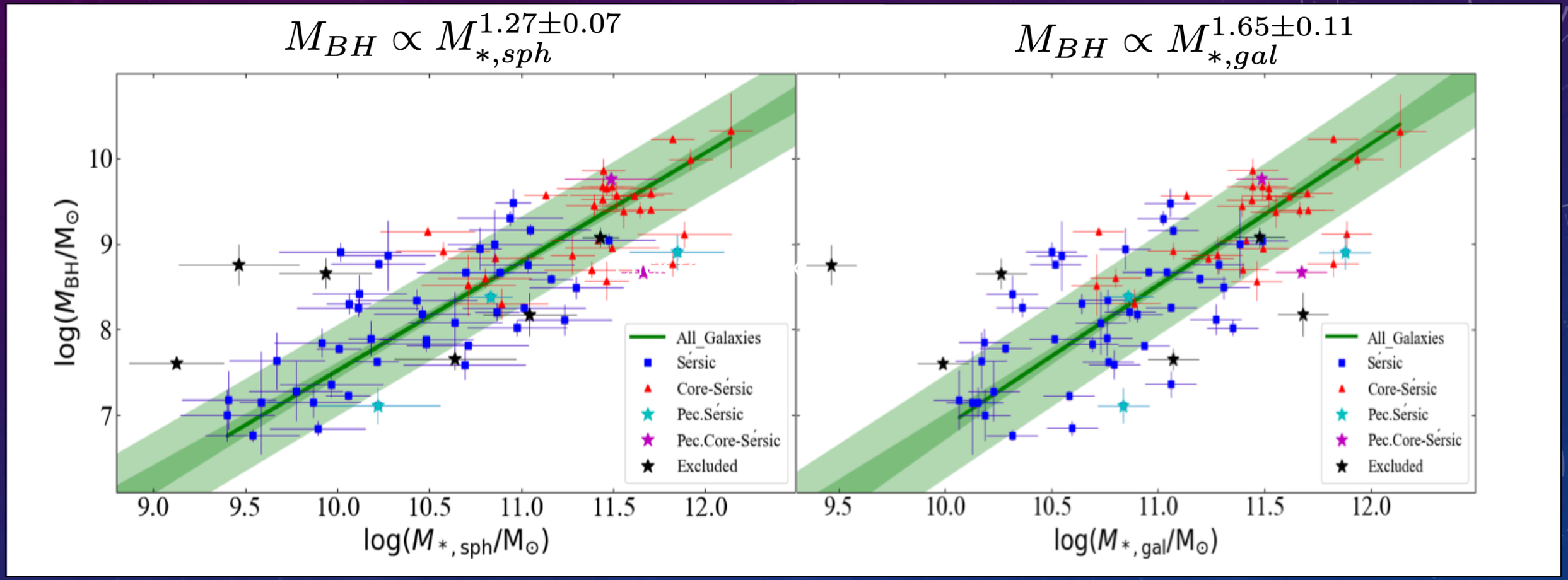


Galaxy Model Residual




Sahu, Graham, & Davis (2019)

# Scaling Relations for Early-type Galaxies

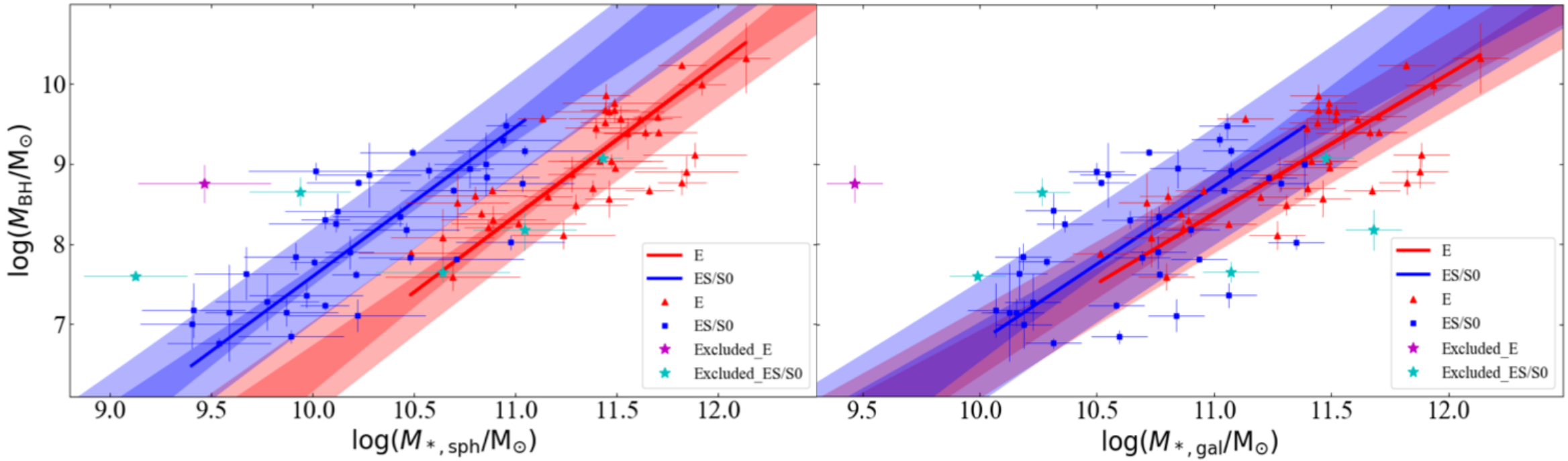



Sahu, Graham, & Davis (2019)

# Slow (E) and Fast (ES/S0) Rotators

Offset by 1.12 dex (more than ~13 times) in $M_{BH}$ direction

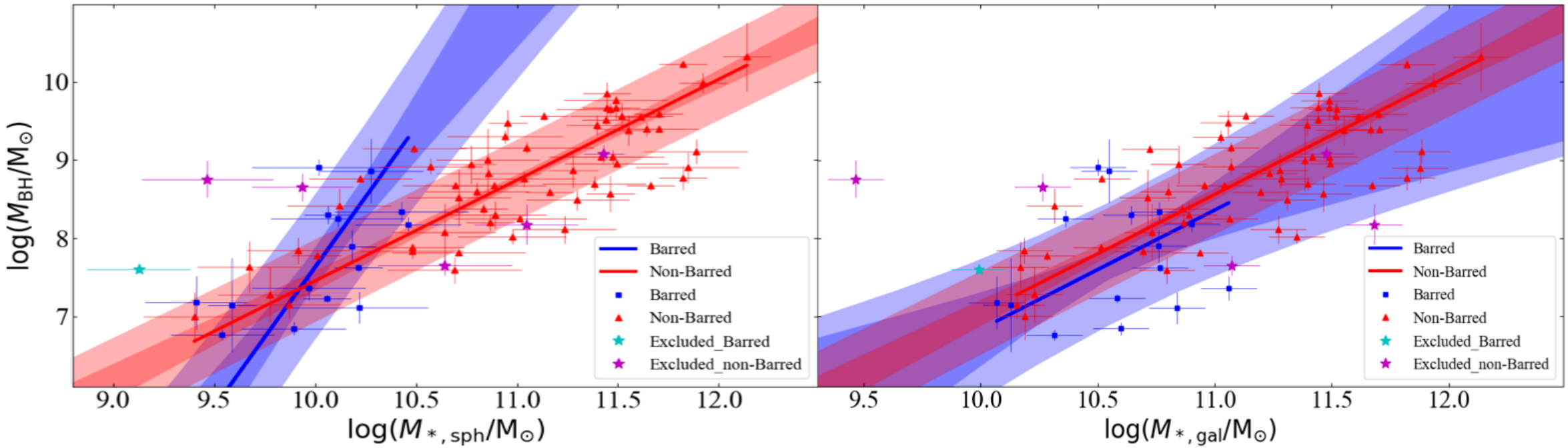
Both populations tend to follow a single relation




Sahu, Graham, & Davis (2019)

# Barred and Non-Barred Galaxies

Our conclusions are limited due to a small sample size of only 15 barred galaxies

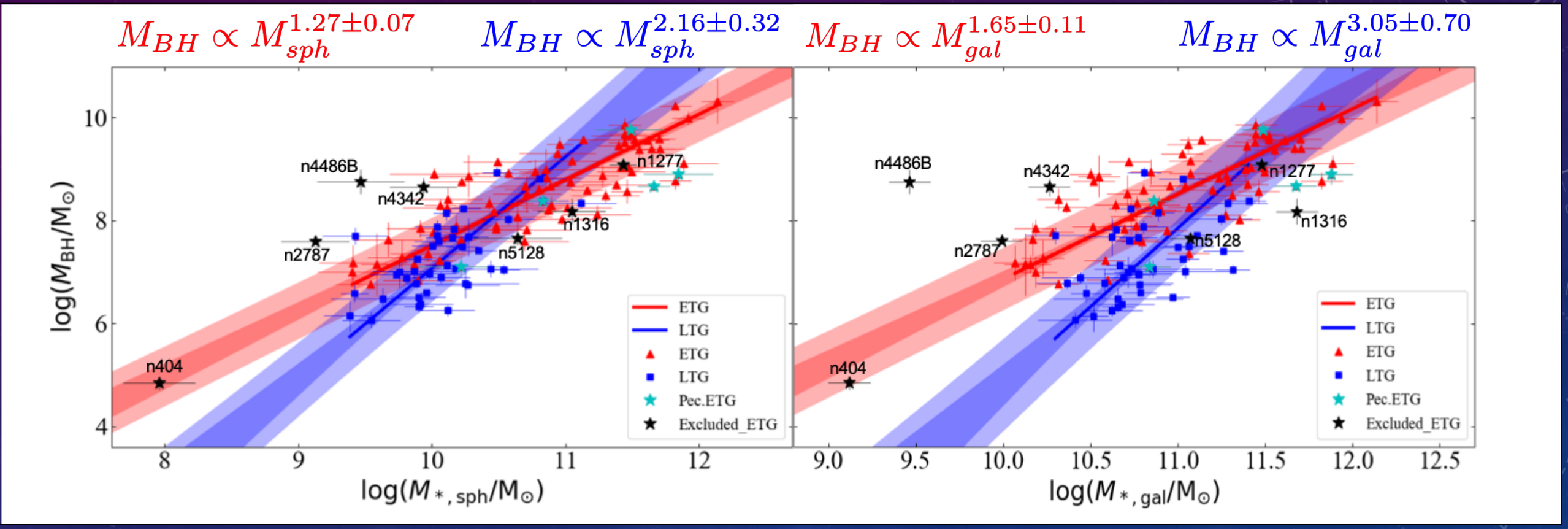



We find that barred and non-barred galaxies follow the same $M_{BH}$ --- $M_{gal}$ relation.

Sahu, Graham, & Davis (2019)

# Early-type and Late-type Galaxies

Late-type galaxies follow scaling correlations with slopes twice that of early-type galaxies

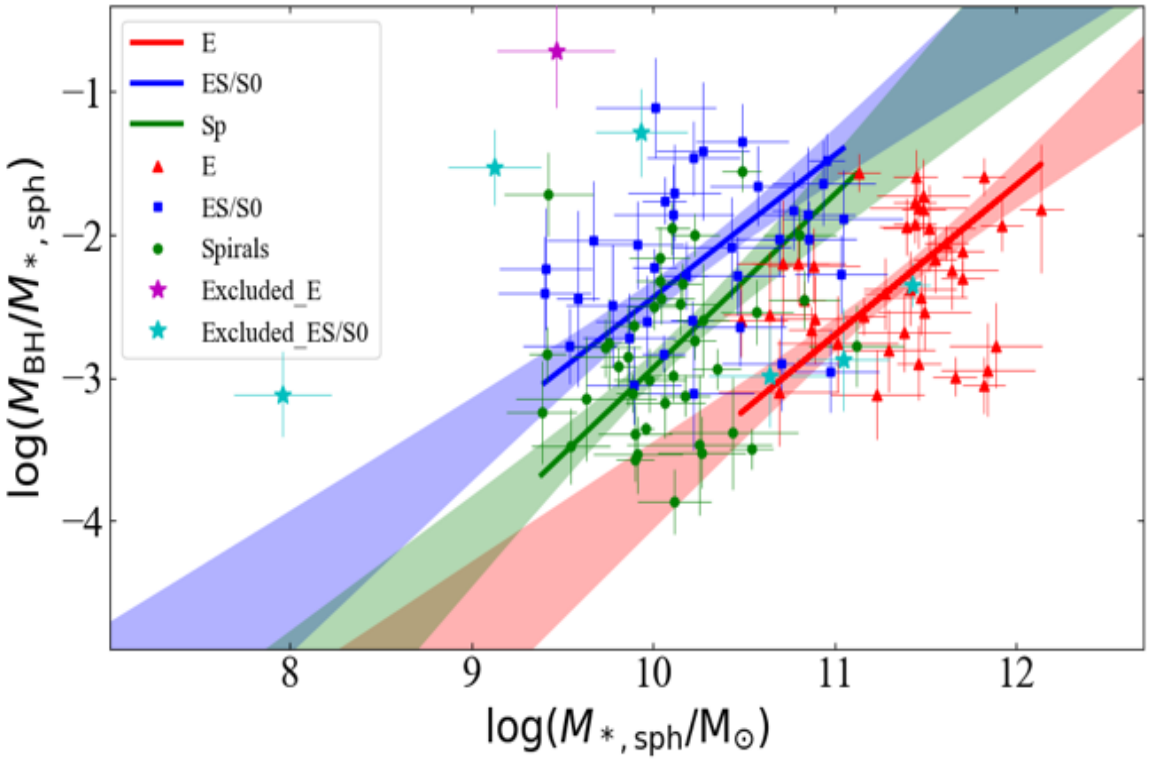



Davis, Graham, & Cameron (2018, 2019)
Sahu, Graham, & Davis (2019)

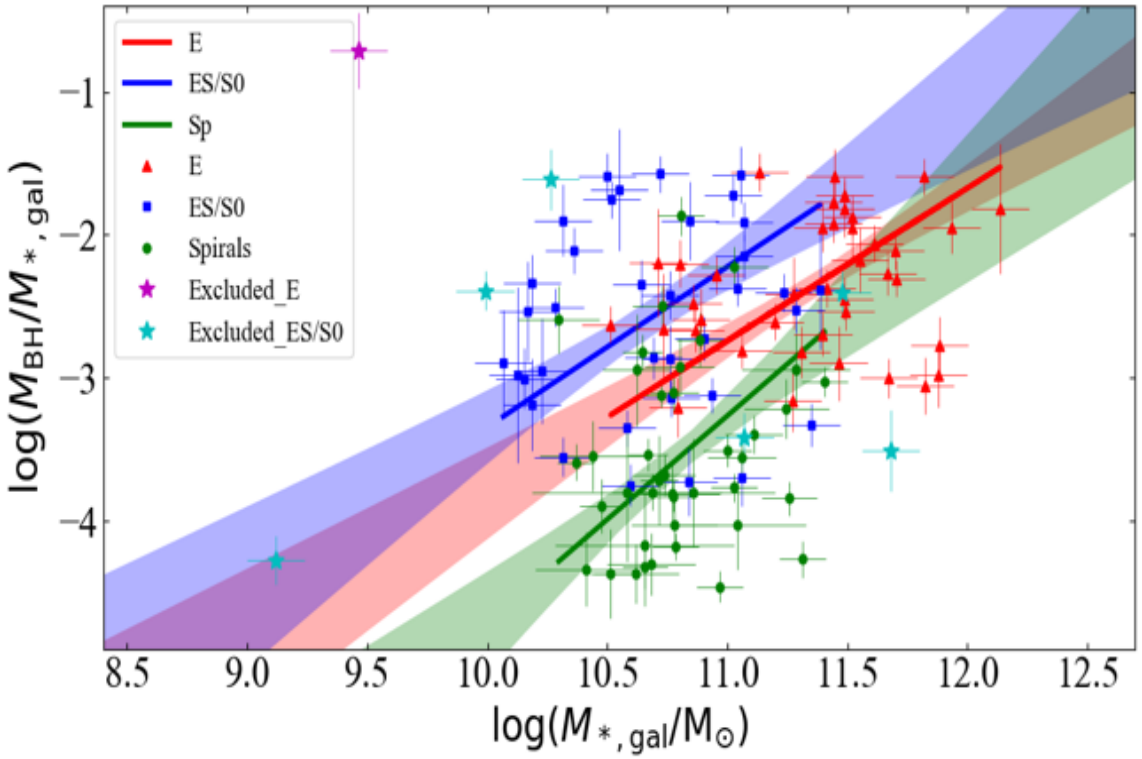
# E, ES/S0, and Sp Type Galaxies

$M_{BH}/M_{*,sph}$ and $M_{BH}/M_{*,gal}$ ratios are not constant

Slopes: 1.00, 1.05, 1.22




Slopes: 1.12, 1.07, 1.45

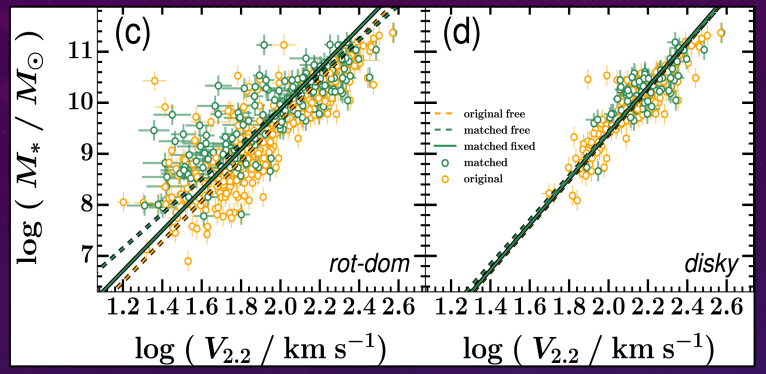



Sahu, Graham, & Davis (2019)

# A Consistent Set of Scaling Relations

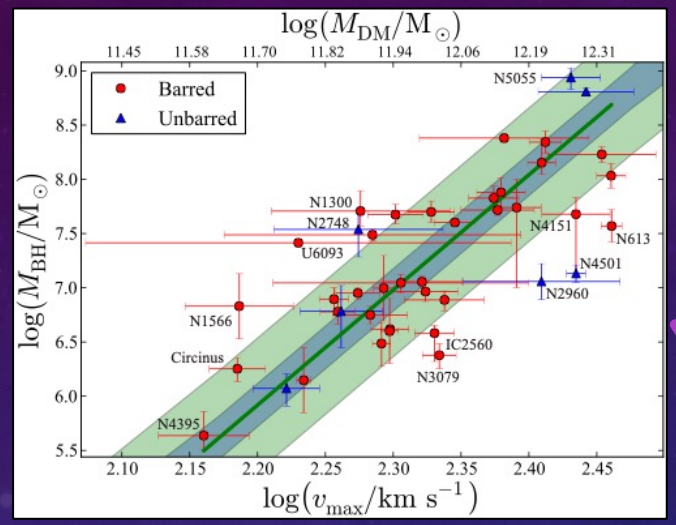
Tully-Fisher Relation

$M_{*,gal}$—$V_{max}$



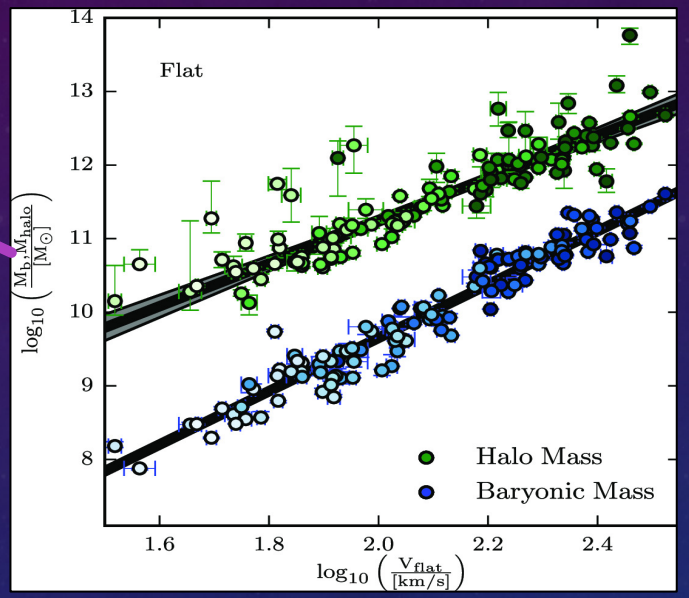

Tiley et al. (2019)

$M_{BH}$—$V_{max}$

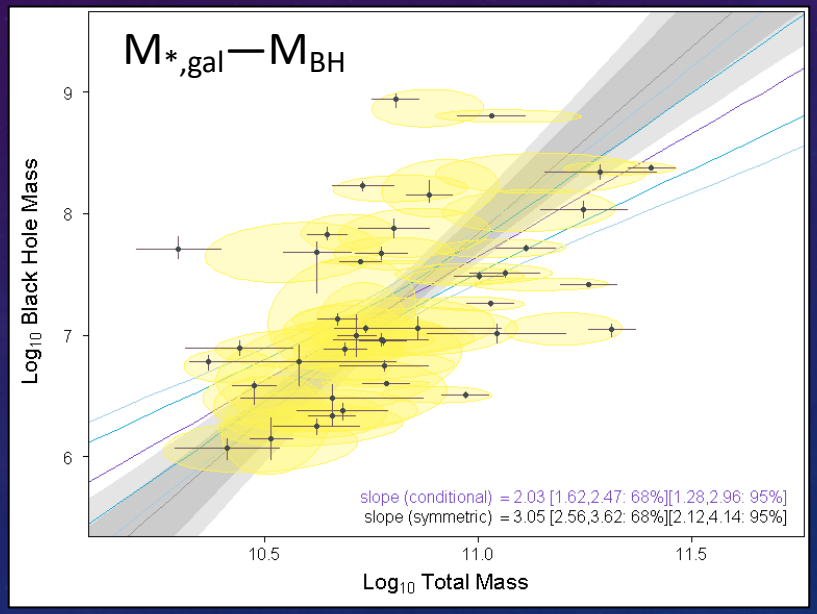



Davis, Graham, & Combes (2019)

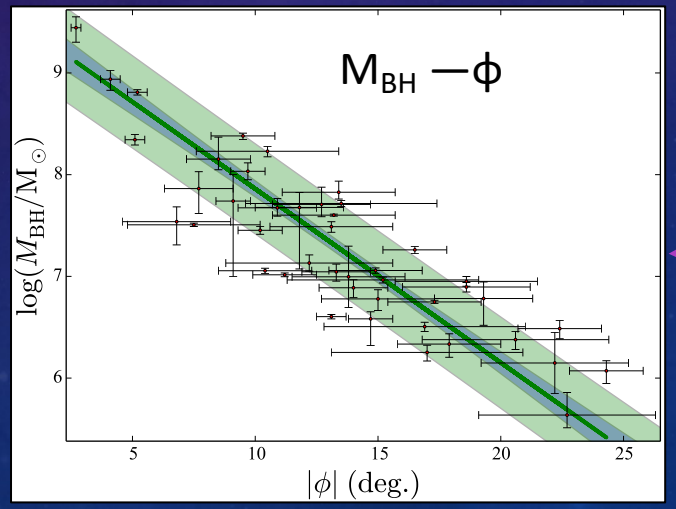
$M_{DM}$—$V_{max}$



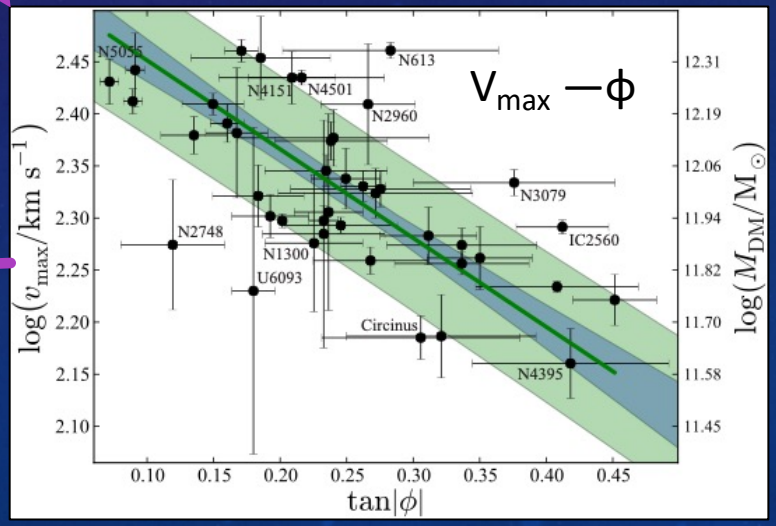

Katz et al. (2019)




Davis, Graham, & Cameron et al. (2018)




Davis, Graham, & Seigar (2017)




Davis, Graham, & Combes (2019)

# Implications

- Estimation of black hole mass in distant galaxies and quasars.
- Prediction of gravitational waves from merging SMBH, actively being searched for by pulsar timing arrays and future space-based interferometers (e.g., PPTA, EPTA, NANOGrav, MeerKat, and LISA).
- Understanding the growth rate of black hole mass relative to the SFR in the host galaxy and AGN feedback models, and constraining AGN virial factor measurements.
- Aids formation and coevolution theories of black holes and the galaxies which harbor them.
- Provides important benchmarks for *N*-body simulations to compare their black hole growth rates.