SWINBURNE

CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING

OzGrav

Morphology-dependent Black Hole Mass Scaling Relations

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Background image credit:
James Josephides, Alister Graham

Super-Massive Black Holes

$$10^5 M_\odot - 10^{10} M_\odot$$

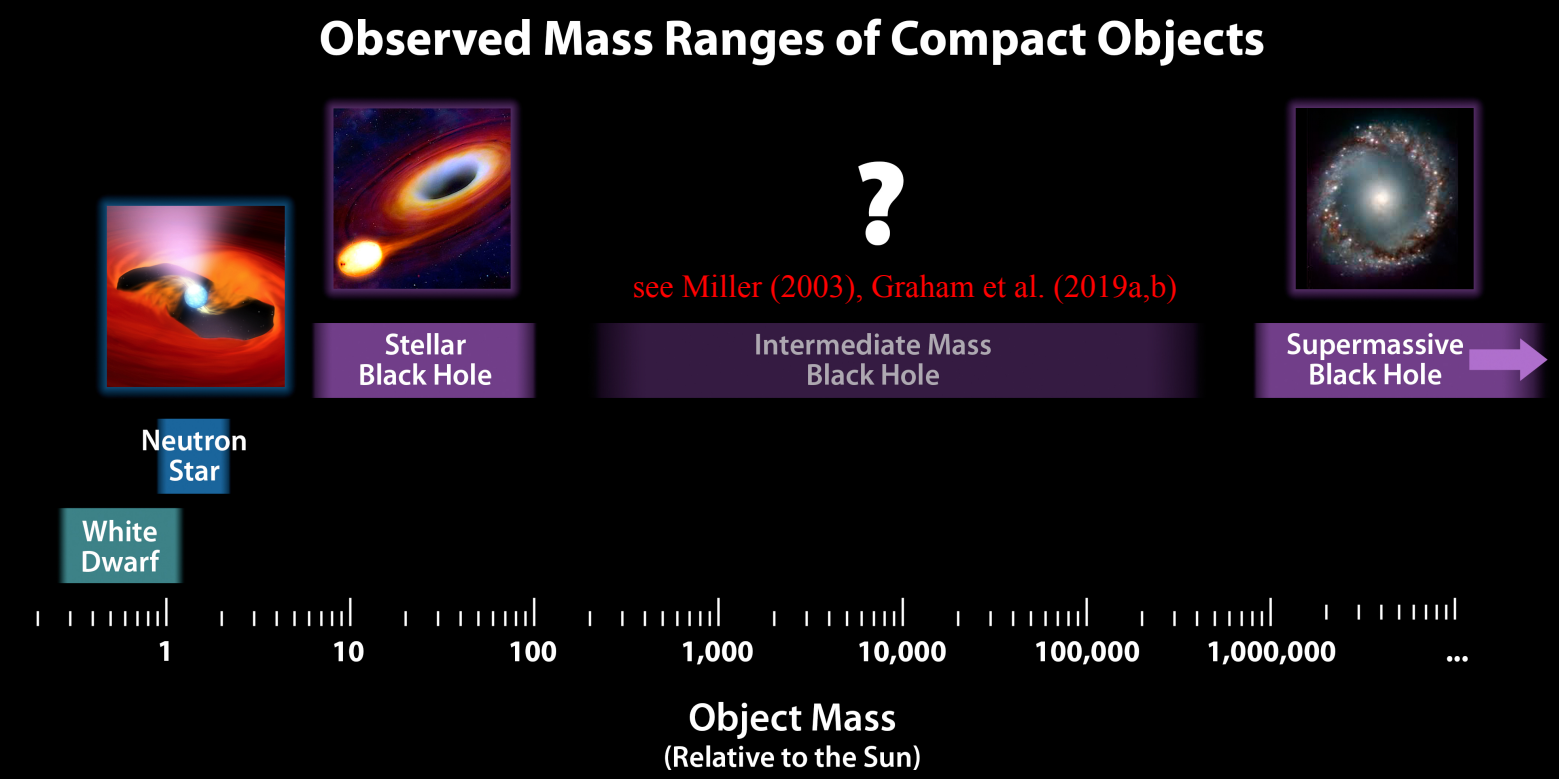


Image credit: NASA/JPL-Caltech

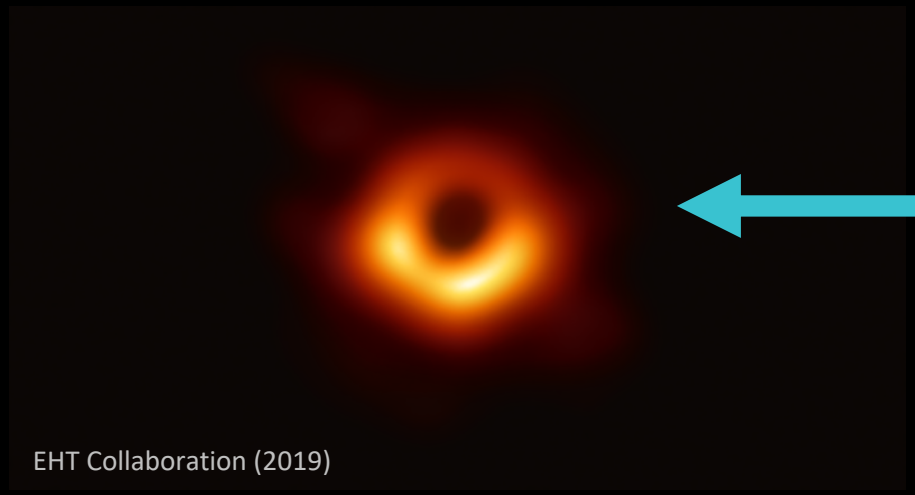
~ 140 SMBH

From (direct) primary measurement methods:

- Proper Motion
- Stellar Dynamics
- Gas Dynamics
- Megamaser Kinematics
- Direct Imaging

The catalog of the SMBH masses with their original sources is available in Savorgnan et al. (2016), Sahu et al. (2019a,b) for ETGs and Davis et al. (2019) for LTGs

Black Hole Mass Scaling Relations


EHT Collaboration (2019)

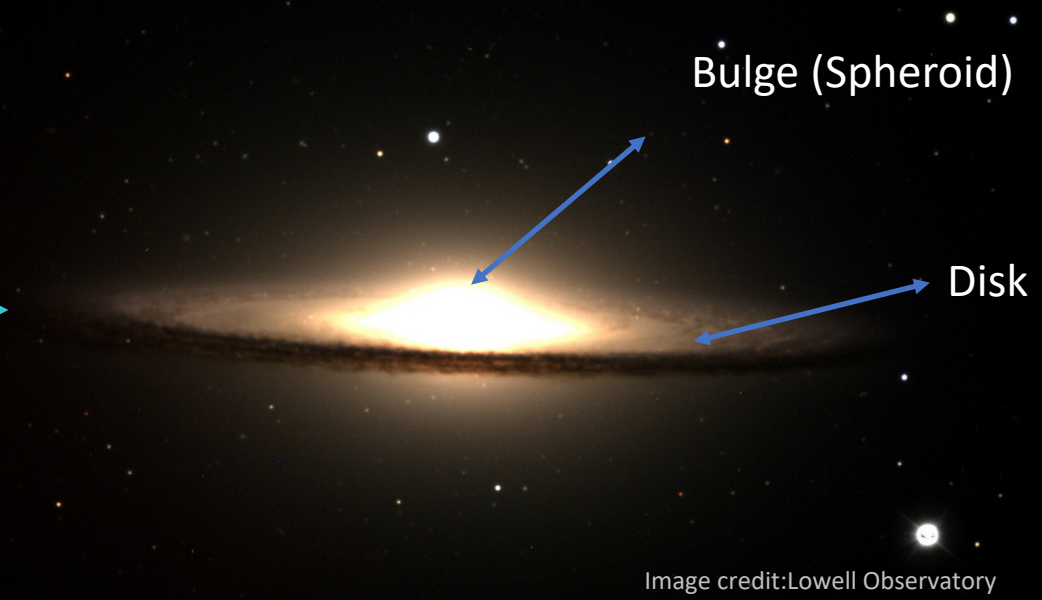


Image credit:Lowell Observatory

Black hole mass

M_{BH}

vs

Galaxy Properties

Bulge mass, Total galaxy mass [Sahu et al. 2019a, Davis et al.(2018, 2019)]

Stellar velocity dispersion [Sahu et al. 2019b]

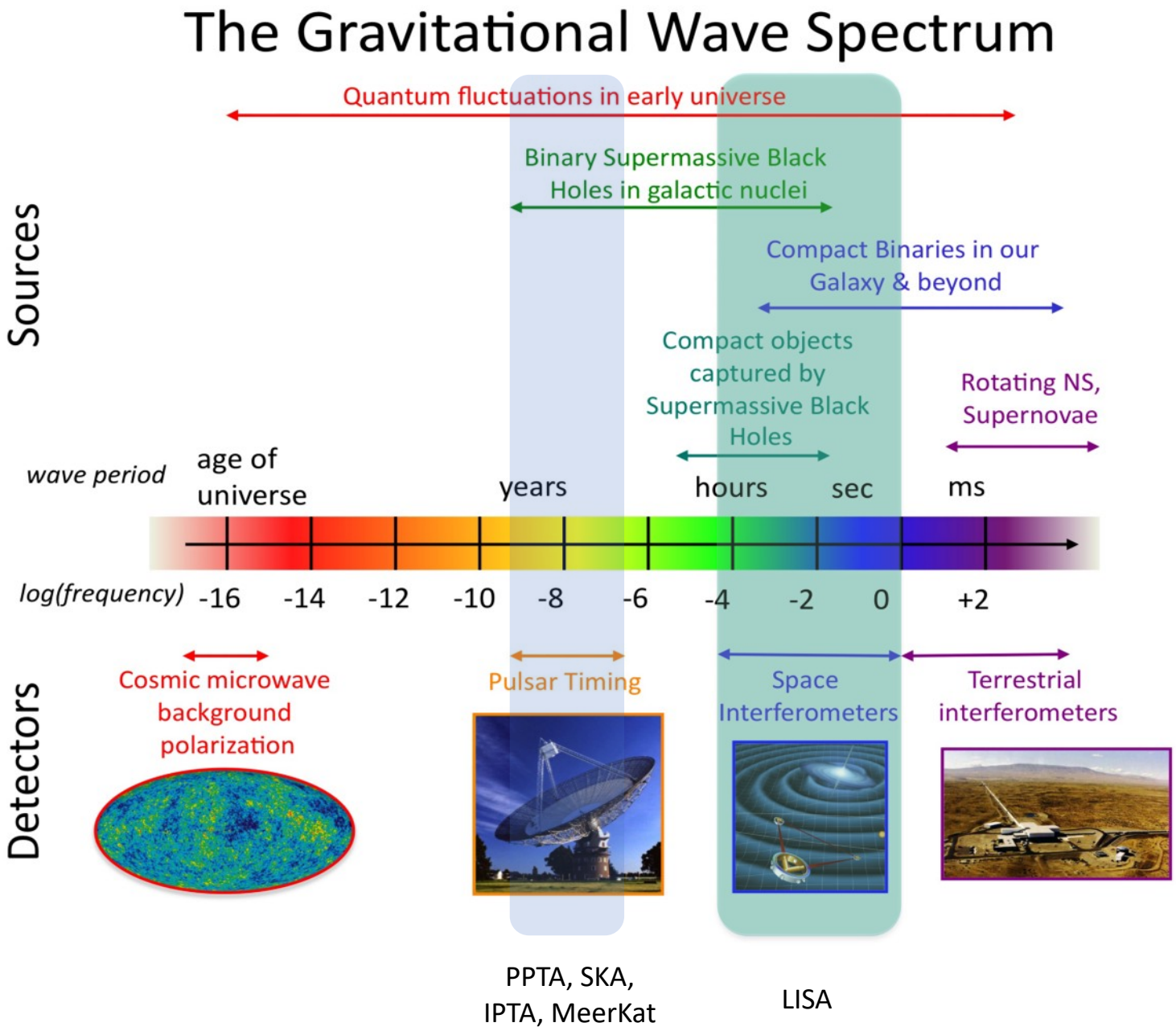
Sérsic index, Half-light radius [Sahu et al. 2020a, in prep.]

Internal (3D) mass density [Sahu et al. 2020b, in prep.]

Importance of BH Scaling Relations

- To estimate the central black hole mass in galaxies where it is difficult to resolve BH SOI.
- To calculate virial f-factors used to convert virial mass to BH mass during reverberation mapping. [Onken et al. 2004; Bennert et al. 2011; Bentz & Katz 2015; Yu et al. 2019]
- Aids simulations, analytical, and theoretical studies trying to study the co-evolution of galaxy properties with central BH and the feedback. [Marconi et al. 2008, Volonteri & Ciotti 2013, Heckman & Best 2014]
- To calculate the black hole mass function: a crucial tool for cosmologists. [e.g. Fukugita & Peebles (2004)]
- Predictions for the detection of long-wavelength GW signals using PTA and LISA. [Shannon et al. 2015, Sesana et al. 2016)
- Many more!

Image Credit:NASA Goddard Space Flight Center



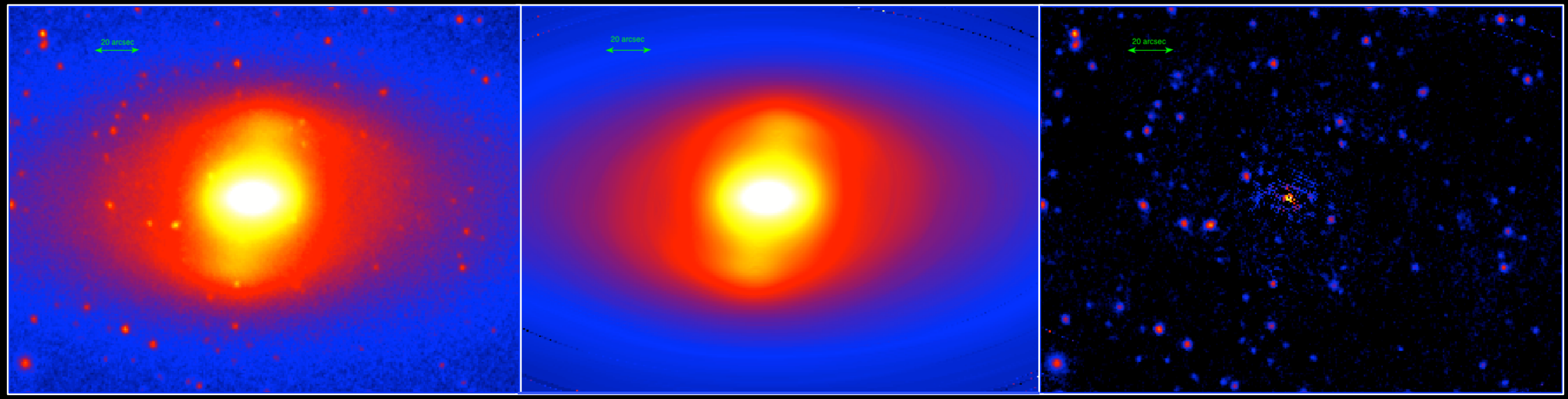
Black Hole Scaling Relations with the Bulge Stellar Mass and Total Galaxy Stellar Mass.

Sahu et al. (2019a) & Davis et al. (2018, 2019)

Isophotal Modeling using **Isofit & Cmodel** [Ciambur 2015]

- Higher Fourier Harmonic Coefficients : To quantify perturbations in each isophote
- Eccentric Anomaly (ψ): For uniform sampling of elliptical isophote

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

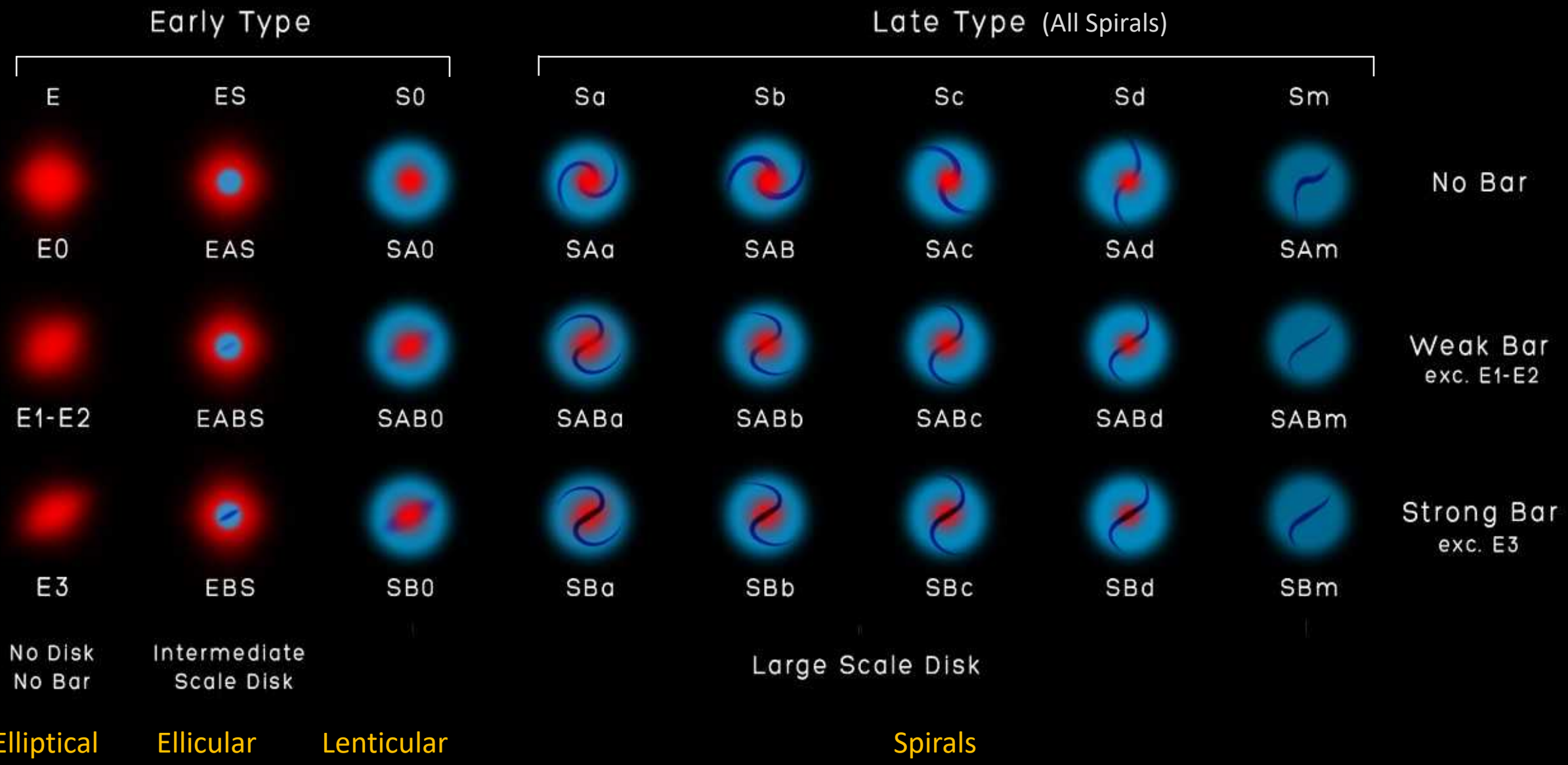


Galaxy Model Residual

Multi-component decomposition of galaxy light using **Profiler** [Ciambur 2016]

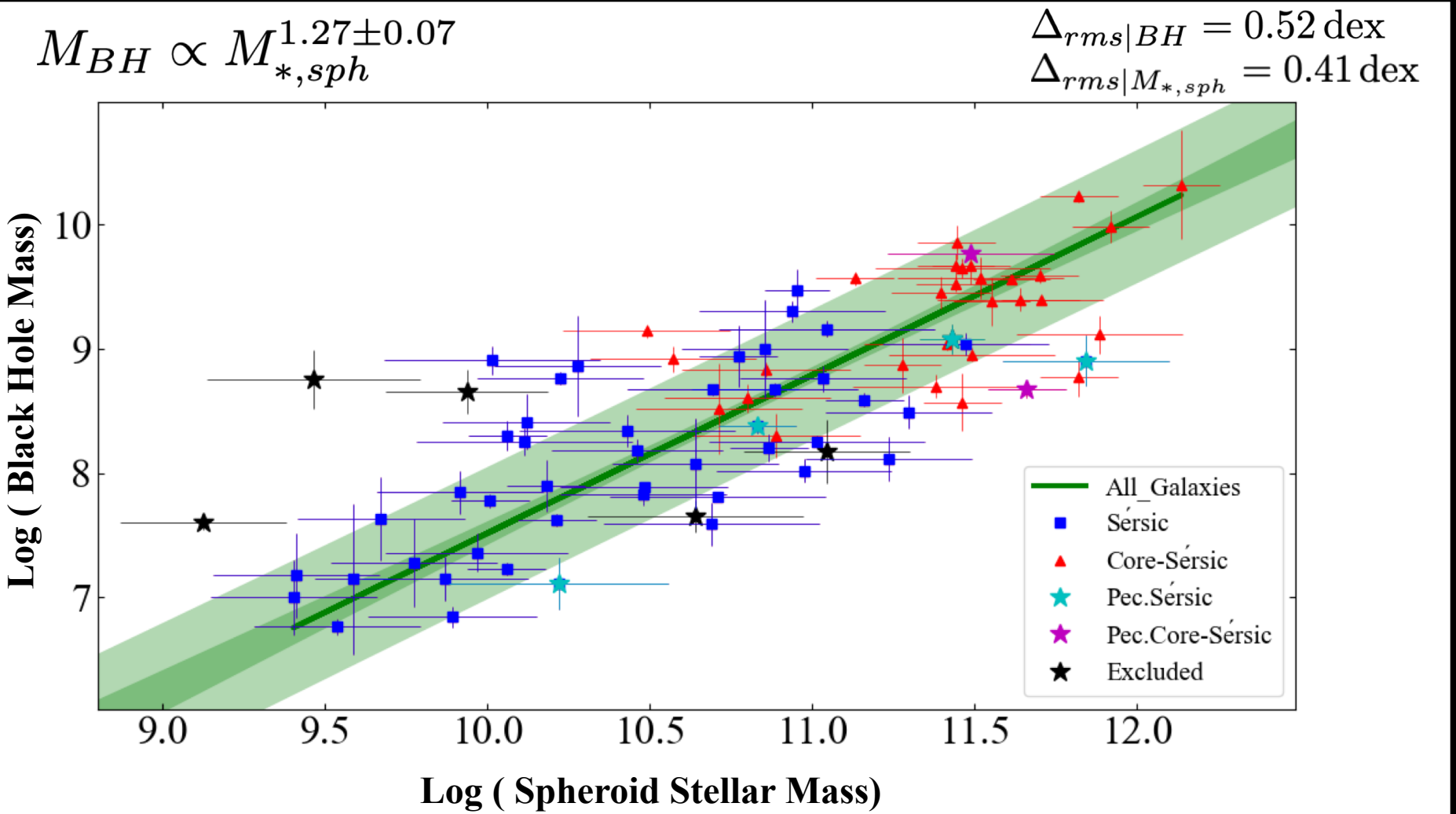
Graham (2019a)

The Grid of Galaxy Morphology



Sahu et al. (2019a)

Non-Linear M_{BH}–M_{bulge} Relations for ETGs

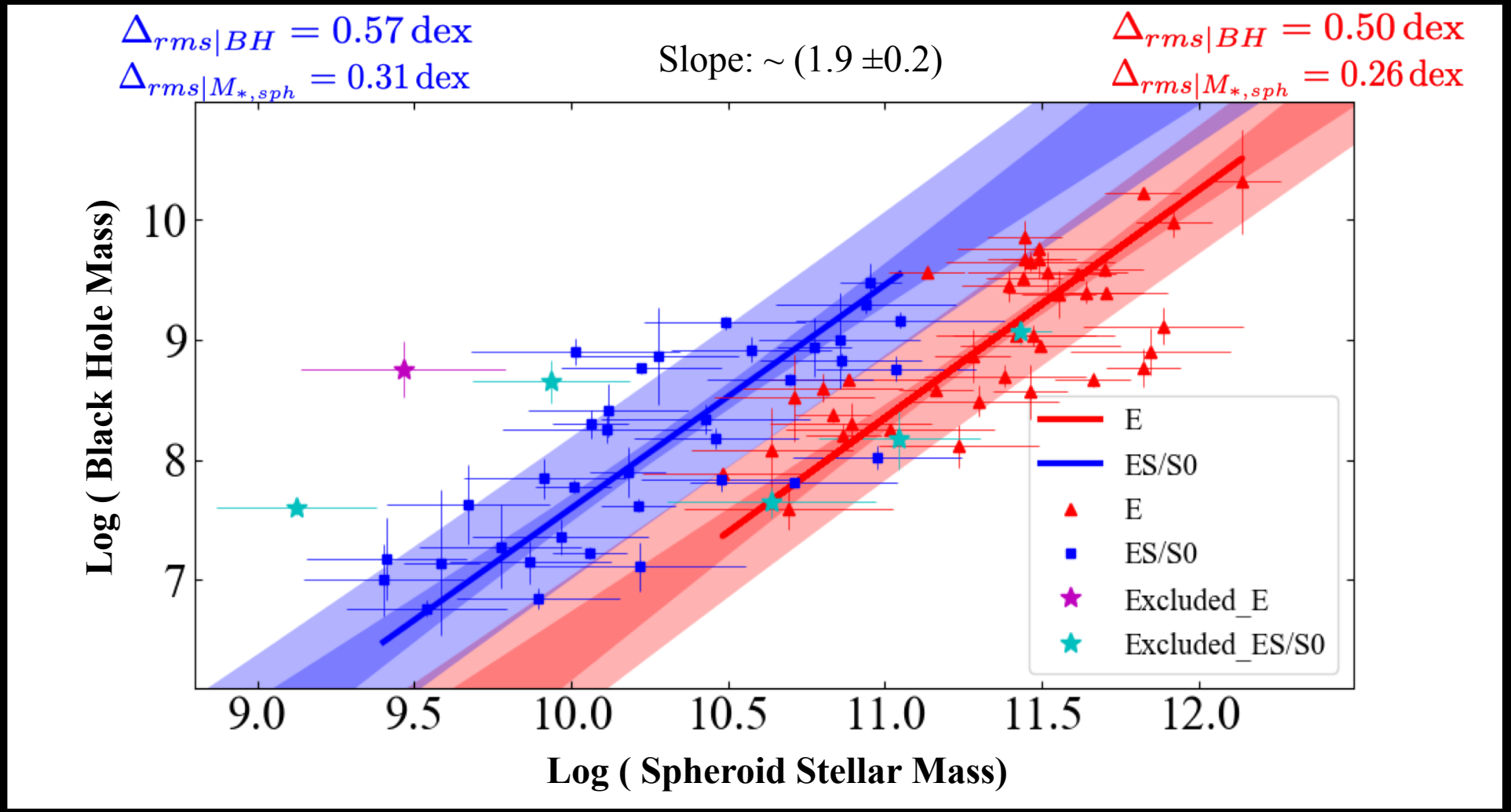


Green line: best-fit symmetric regression line
Dark shaded region: $\pm1\sigma$ uncertainty on slope and intercept
Light shaded region: $\pm1\sigma$ scatter in the data

Fractional growth in M_{BH} is greater than fractional growth in $M_{*,sph}$

Sahu et al. (2019a)

ETGs with (ES, S0) and without (E) a disk



ETGs without disk (E):

- Spheroid dominated
- $M_{*,sph} \sim M_{*,gal}$

ETGs with a disk (ES/S0):

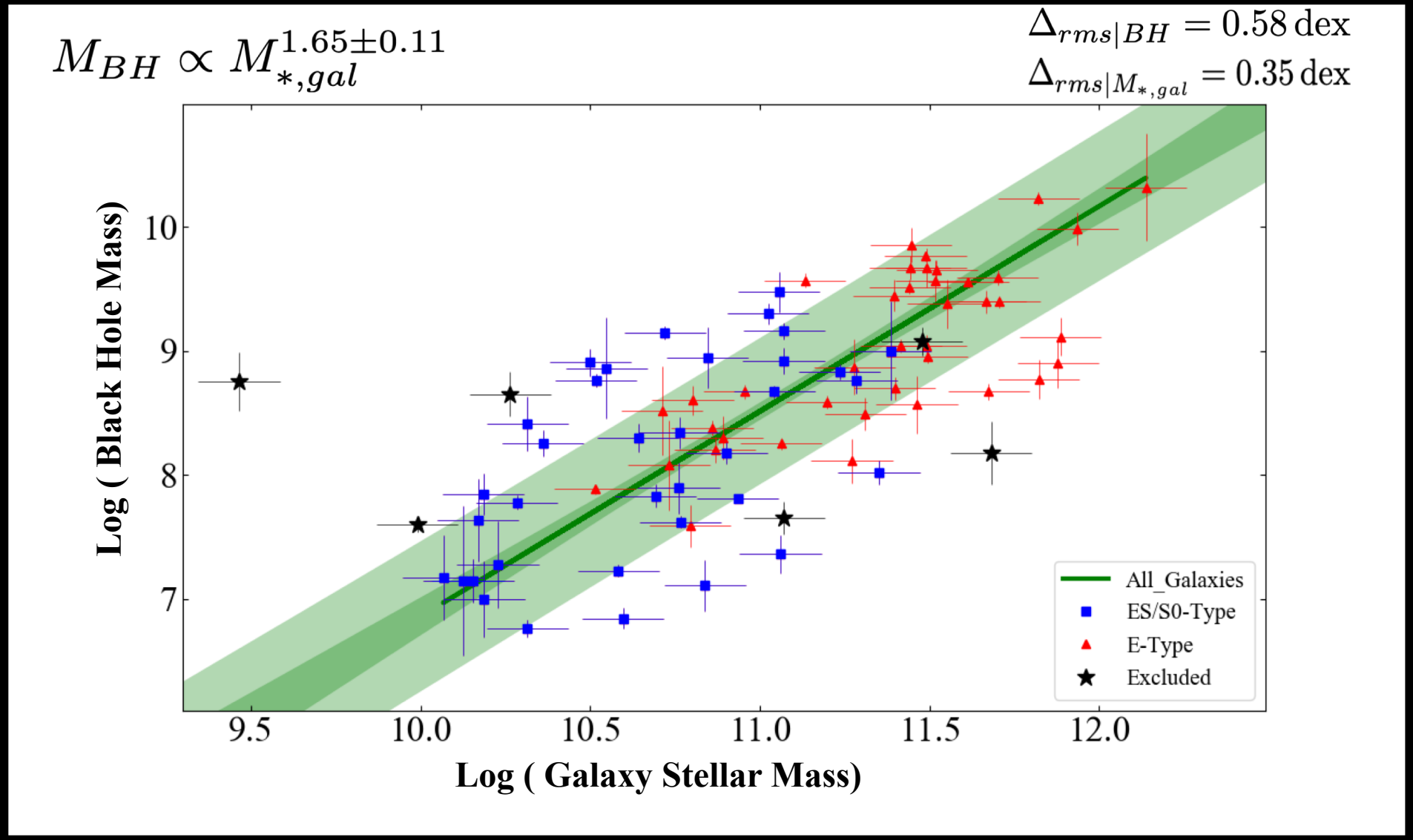
- Bulge and disk both are dominant.
- $(M_{*,sph} + M_{*,disk}) \sim M_{*,gal}$

This was subsequently observed in a recent simulation by Marshall et al.(2020)

Reason behind offset? → Smaller bulge mass and size of ES/S0 galaxies

Sahu et al. (2019a)

M_{BH} also correlates with total galaxy stellar mass ($M_{*,gal}$) for ETGs



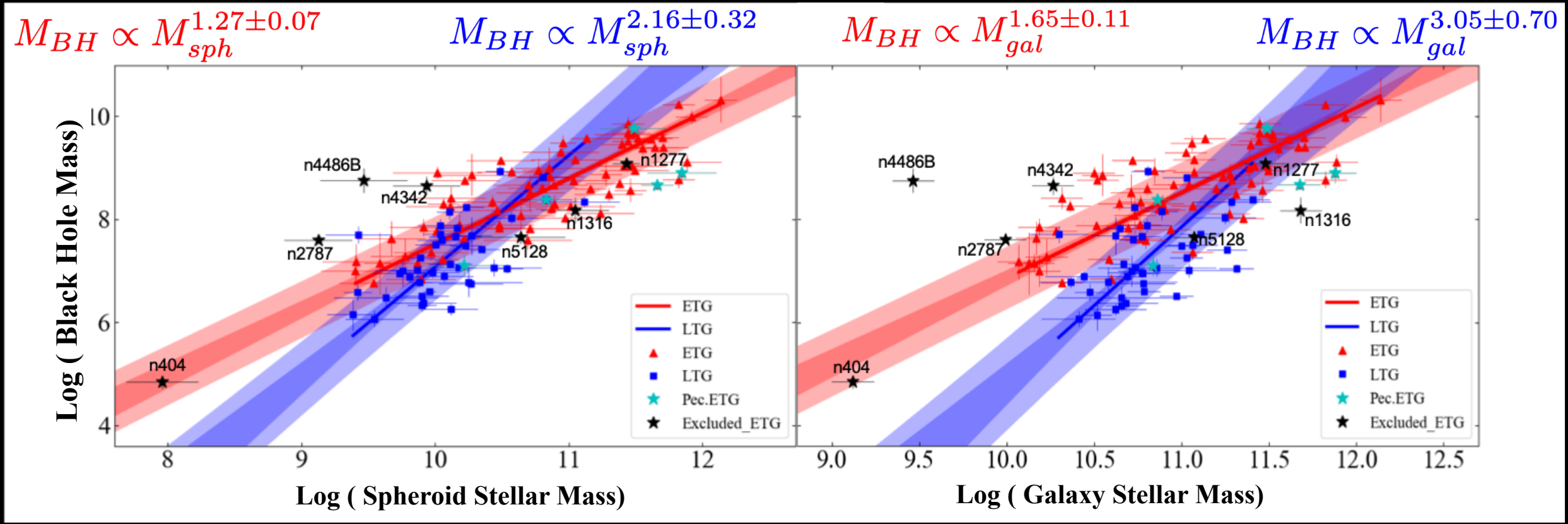
LTGs: Benjamin Davis et al. (2018, 2019)

Offset disappears!

Sahu et al. (2019a) + Davis et al. (2019)

ETGs and LTGs

LTGs follow the scaling correlations with slopes ~ twice that of ETGs



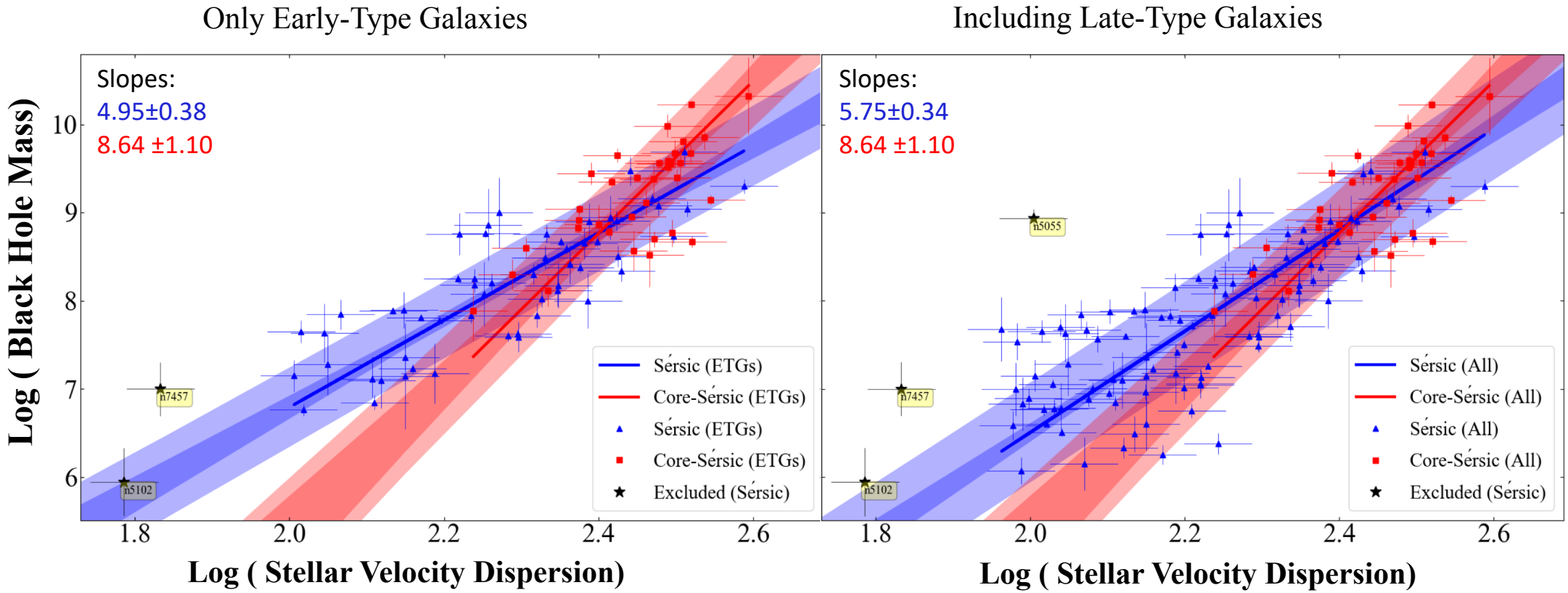
- Simulations reporting steeper (at the low-mass end) and bent relations [Cirasuolo et al. 2005; Fontanot et al. 2006; Dubois et al. 2012; Khandai et al. 2012; Bonoli et al. 2014; Neistein & Netzer 2014; Angles-Alcazar et al. 2017]
- M_{BH}(accretion rate) → M_* (SFR) → Galaxy Morphology (ETG vs LTG) [Calvi et al. 2018]
- Steeper Relation? As gas becomes available fractional mass gain in M_{BH} > fraction stellar mass gain of the host spheroid [Diamond-Stanic & Rieke 2012; Seymour et al. 2012; LaMassa et al. 2013; Yang et al. 2018]

Black Hole Scaling Relations with the central Stellar Velocity Dispersion

Sahu et al. (2019b)

Sahu et al. (2019b)

Broken M_{BH} — Central Stellar Velocity Dispersion (σ) Relation



The bent relation is linked with the evolutionary paths of Sérsic and Core-Sérsic Galaxies

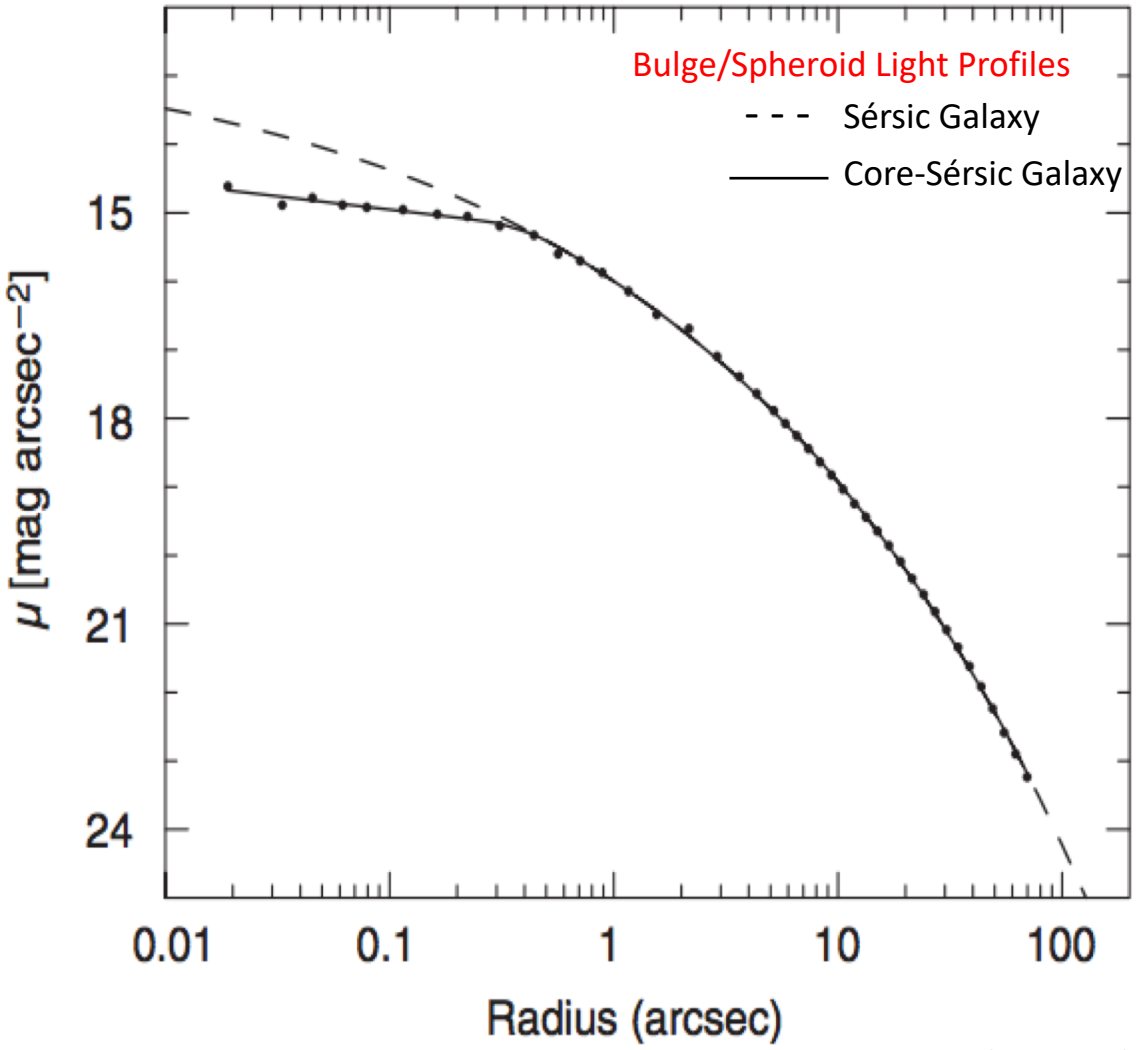
[Ciotti & van Albada 2001, Oser et al. 2012, Shankar et al. 2013, Hilz et al. 2013, Volonteri & Ciotti 2013, Bogdan et al. 2019]

Core- Sérsic:	Dry Mergers	Mild increase in **σ** with respect to mass
Sérsic:	Gas abundant accretion or wet mergers	Significant increase in **σ** with respect to mass

Core- Sérsic and Sérsic Galaxies

Sérsic's (1963, 1968): $R^{1/n}$ model

Core-Sérsic (Graham et al. 2003): Power law + $R^{1/n}$ model



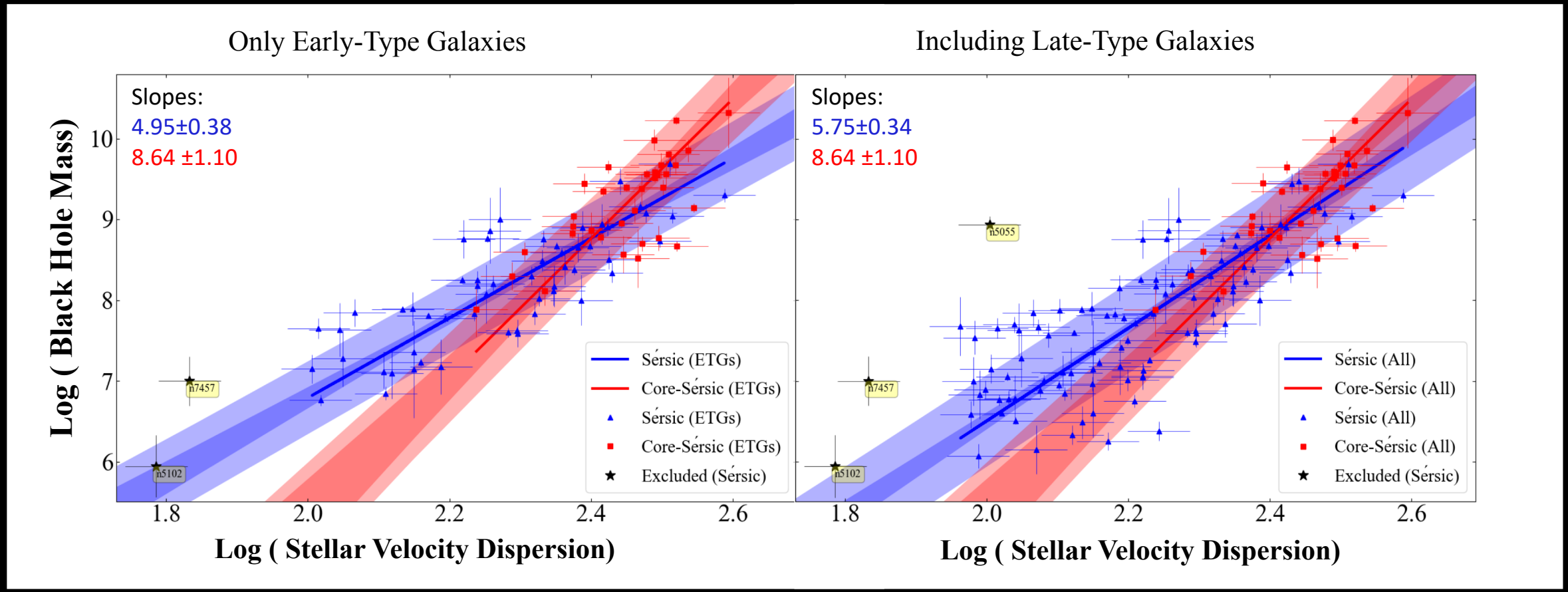
Graham et al. (2003)

Core- Sérsic : Dry (gas poor) major mergers

Sérsic: Gas abundant (wet) mergers or gas abundant accretion

Sahu et al. (2019b)

Broken M_{BH} — Central Stellar Velocity Dispersion (σ) Relation



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Black Hole Mass Scaling Relations Are Dependent on Galaxy Morphology!

- ETGs and LTGs follow two different M_{BH} -M_{sph} and M_{BH} -M_{gal} relations. M_{BH} correlates with M_{gal} as strongly as with M_{sph}.
- ETGs with (ES/S0) and without (E) a disk are found offset in the M_{BH}-M_{sph} diagram.
- Both, M_{BH} -M_{sph} and M_{BH} –M_{gal} relations are non-linear, i.e., the ratios M_{BH}/M_{sph} and M_{BH}/M_{gal} are not constant.
- Sérsic and Core-Sérsic galaxies define two different relations in the M_{BH} -σ and also the L-σ diagrams.

More results!! checkout 👉 Sahu et al. (2019a,b) and Davis et al. (2018, 2019)

Stay tuned for M_{BH} –n, M_{BH} –Re, and M_{BH} –spatial density (ρ) relations [Sahu et al. (2020 a, b) in preparation]

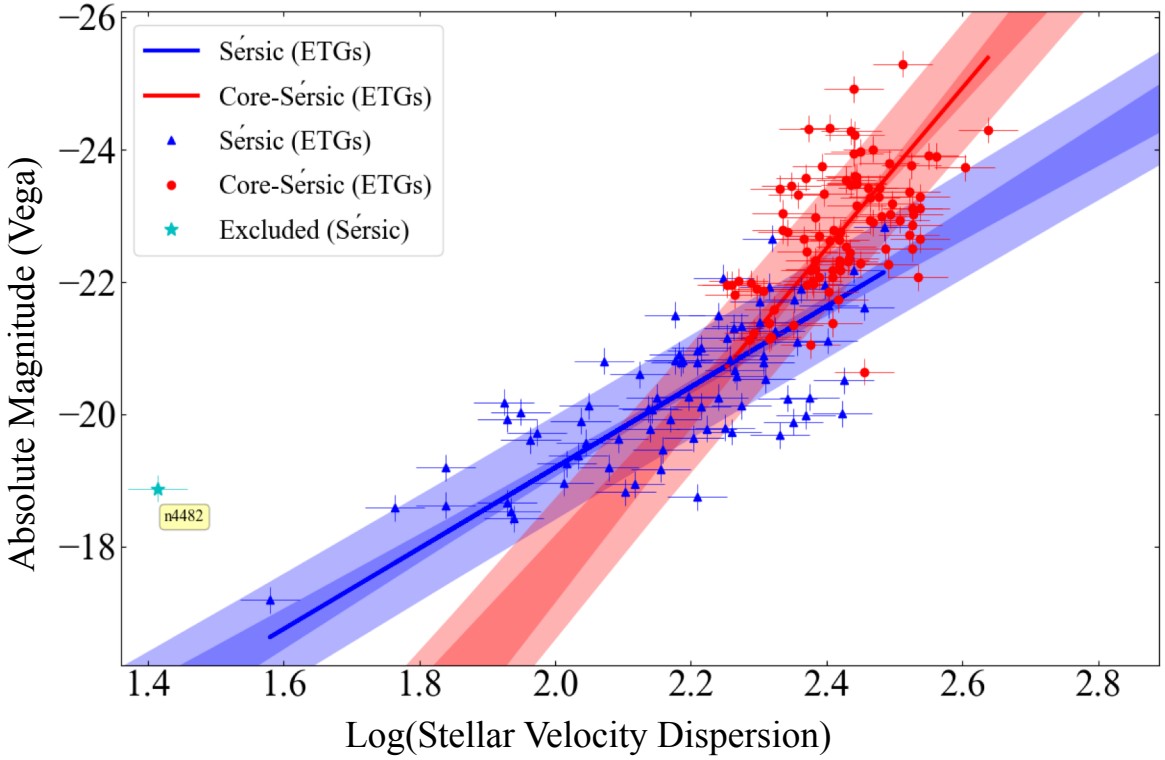
Back up slides

Sahu et al. (2019b)

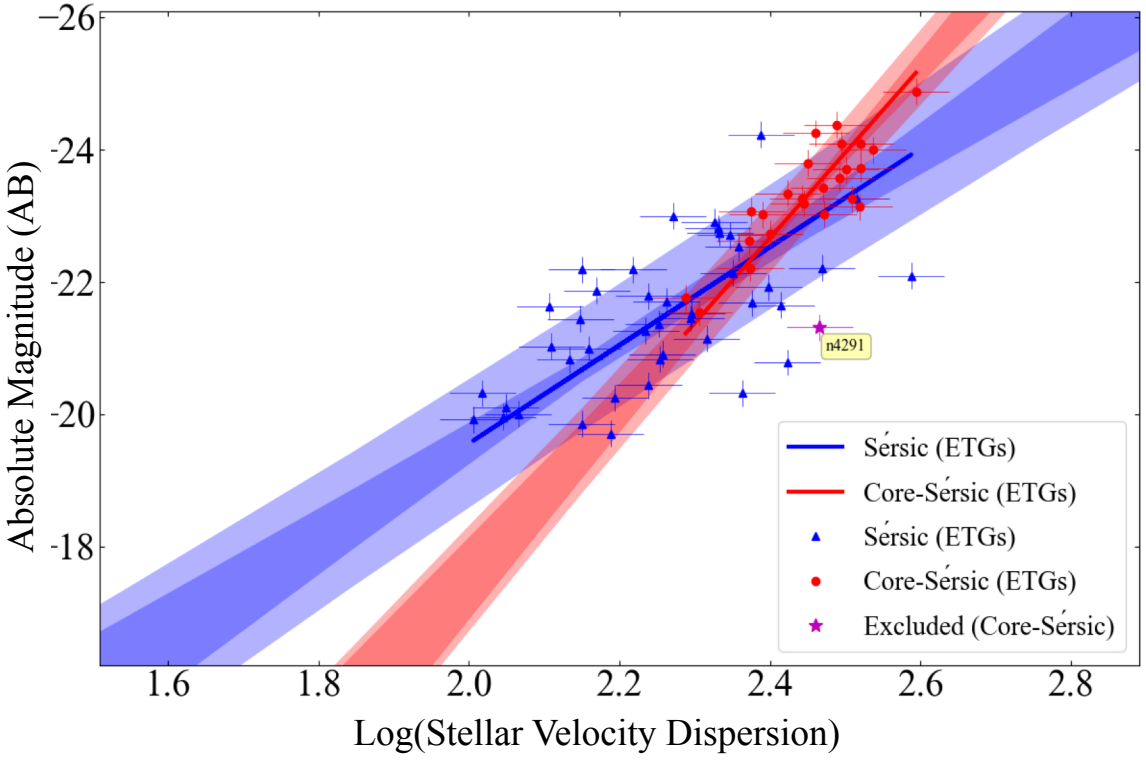
Broken L—σ Relation

A break in Faber-Jackson Relation

V-band



3.6 μm



V-band data taken from Lauer et al. (2007)

Sérsic: $L \propto \sigma^{2.44\pm0.18}$

Core- Sérsic: $L \propto \sigma^{4.86\pm0.54}$

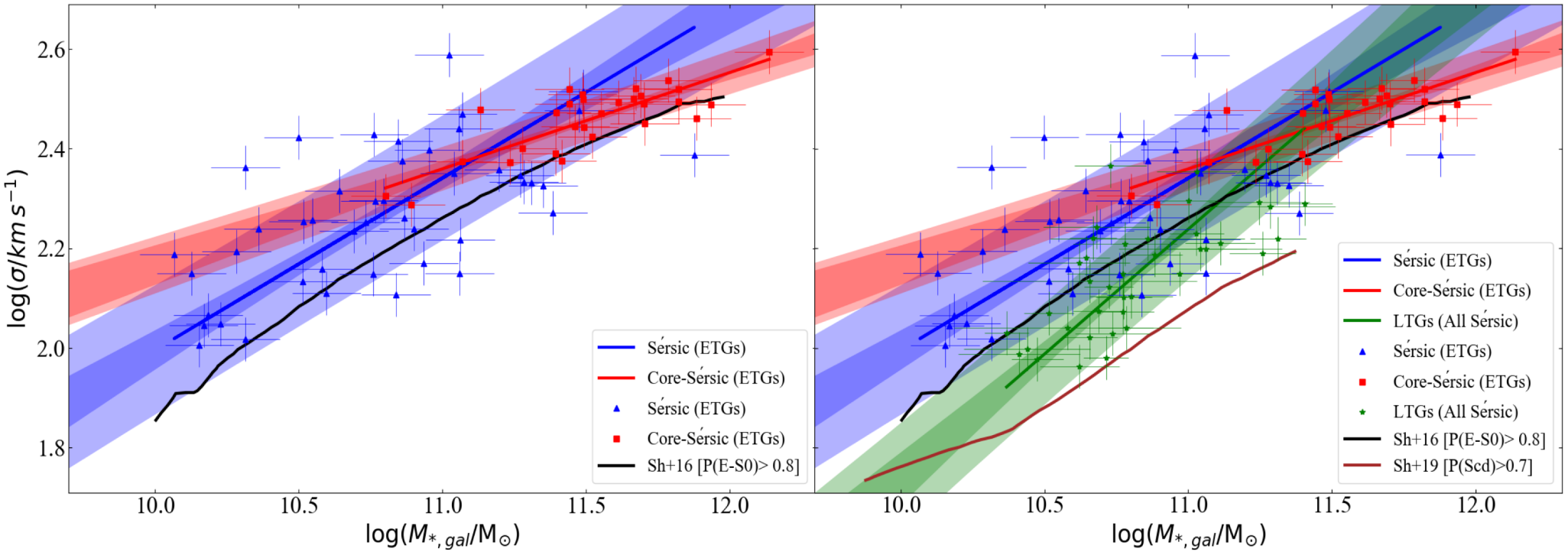
Sérsic: $L \propto \sigma^{2.97\pm0.43}$

Core- Sérsic: $L \propto \sigma^{5.16\pm0.53}$

Other studies suggesting double or bent relation (in R and B-bands as well) : Schechter (1980), Binney (1982), Farouki et al. (1983), Davies et al. (1983), Held et al. (1992), de Rijcke et al. (2005), Matković & Guzmán (2005), Lauer et al.(2007), Cappellari et al. (2013), Kormendy & Bender (2013), Graham & Soria (2019), etc.

Sahu et al. (2019b)

Comparison with Shankar et al. (2016, 2019)



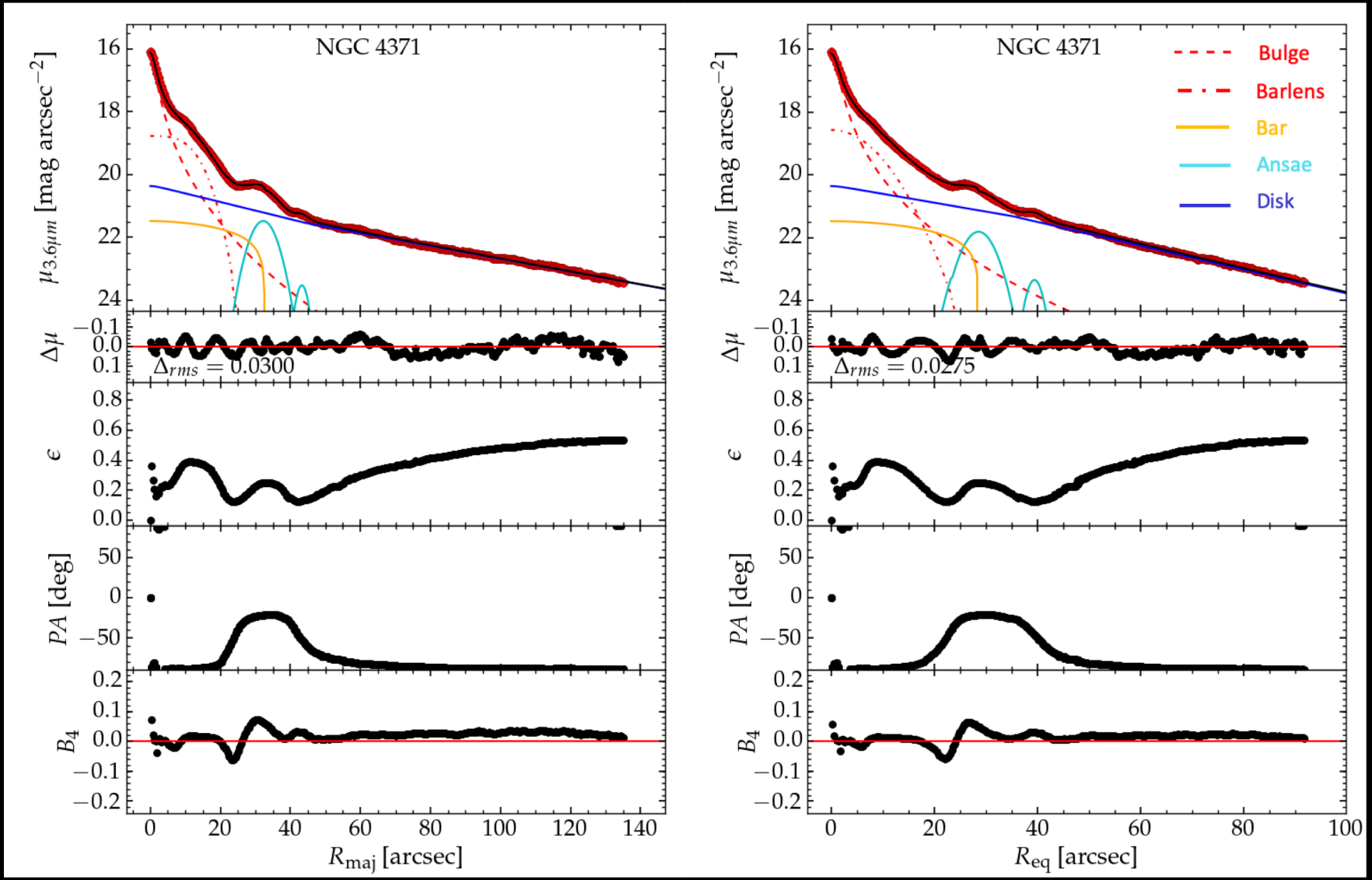
Black Curve for ETGS: Obtained using SDSS data for local galaxies with P(E-S0) > 0.8

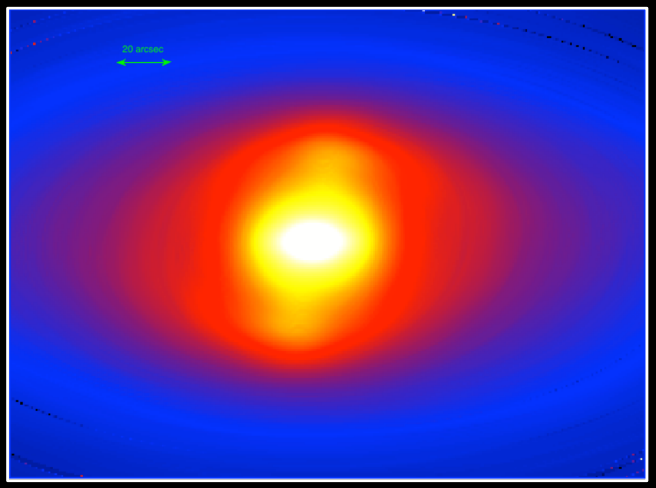
Brown Curve for Late Spirals: Obtained using SDSS data for local galaxies with P(Scd) > 0.7

Disassembling Galaxy Light

Major Axis Profile

Equivalent Axis Profile





NGC 4371

Profiler [Ciambur (2016)]

$$R_{eq} = \sqrt{(R_{maj} \times R_{min})}$$

Stellar mass-to-light ratio from Meidt et al. (2014)

Sahu et al. (2019a)