



A Self-Consistent Data-Driven Approach to Modeling Massive Galaxies, Black Hole Growth and Merger Rates

Karthik Mahesh Varadarajan

Francesco Shankar, Daniel Roberts, Hao Fu, M. Bernardi, C. Marsden, A. Lapi, N. Menci, V. Allevato, A. V. Alonso Tetilla, F. Fontanot, L. Boco, A. Smith, and many more...

04/02/2025 – Ten Years to LISA: New Challenges and Opportunities in Multimessenger/Multiband Science

Outline

 $\begin{array}{l} & \text{BH-Galaxy Scaling Relations} \rightarrow \text{Validation} \\ & (\text{Residuals}) \rightarrow \text{P}(\text{L}|\text{M}_{gal}, z) + \text{DM/Galaxy} \\ & \text{Evolution} \rightarrow \text{BH Evolution and Scaling} \\ & \text{Relations} \rightarrow \text{BH Merger Rates} \rightarrow \text{GWB} \end{array}$

Which is the most fundamental?



Kormendy & Ho 13

Two SMBH mass functions?



M-σ and NANOGrav Observations



G. Sato-Polito, M. Zaldarriaga, and E. Quataert, 2025

Red shaded region uses $M_{\rm BH}\text{-}\sigma$ relation

Dashed-line region uses M_{BH} -M* relation

Blue shaded region is from NANOGrav

Merger rates using a full semi-empirical model

Take-home message *I*: There is tension between NANOGrav and M-σ inferred GWB predictions

How do residuals work?



George Grekousis 2020

- Calculate residuals of y(x)-y_{fit}(x)
- Calculate residuals of z(x)-z_{fit}(x)
- Calculate correlation coefficient between the two residuals, if strong then NO underlying correlation with x!

σ more fundamental than Mgal



FS, ..., KMV et al. MNRAS, resubmitted

Data from Sahu et al. 2020

Take-home message *II*: Stellar velocity dispersion is more fundamental → possible signature of AGN feedback? Possible tension with PTA?

From $P(L_x|M^*,z)$ relation to SMBH scaling relations



Almost constant evolution of M_{BH} - M_{gal} relation



FS+20, as in direct observations from, e.g., Suh+20, Carraro+20, Tanaka+24...

From $P(L_x|M^*,z)$ relation to SMBH scaling relations



Take-home message III: Accretion models point to relatively constant SMBH scaling relations with time

Effect of mergers is modest



Summary

 $\begin{array}{l} & \text{BH-Galaxy Scaling Relations} \rightarrow \text{Validation} \\ & (\text{Residuals}) \rightarrow \text{P}(\text{L}|\text{M}_{gal}, z) + \text{DM/Galaxy} \\ & \text{Evolution} \rightarrow \text{BH Evolution and Scaling} \\ & \text{Relations} \rightarrow \text{BH Merger Rates} \rightarrow \text{GWB} \end{array}$

Next-steps:

 \rightarrow Compute implied GWB

→ Initial calculations show we are not able to predict consistency with PTA if radiative efficiencies > 10%