

Testing the robustness of black hole mass measurements with ALMA and MUSE

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Abstract. We present our ongoing work of using two independent tracers to estimate the super-massive black hole mass in the nearby early-type galaxy NGC 6958; namely integrated stellar and molecular gas kinematics. We used data from the Atacama Large Millimeter/submillimeter Array (ALMA), and the adaptive-optics assisted Multi-Unit Spectroscopic Explorer (MUSE) and constructed state-of-the-art dynamical models. The different methods provide black hole masses of $(2.89 \pm 2.05) \times 10^8 M_{\odot}$ from stellar kinematics and $(1.35 \pm 0.09) \times 10^8 M_{\odot}$ from molecular gas kinematics which are consistent within their 3σ uncertainties. Compared to recent $M_{\text{BH}} - \sigma_e$ scaling relations, we derive a slightly over-massive black hole. Our results also confirm previous findings that gas-based methods tend to provide lower black hole masses than stellar-based methods. More black hole mass measurements and an extensive analysis of the method-dependent systematics are needed in the future to understand this noticeable discrepancy.

Keywords. galaxies: kinematics and dynamics, galaxies: nuclei, galaxies: individual (NGC6958)

1. Introduction

Vast improvements in astronomical instrumentation have led to more than hundred robust massive black hole mass (M_{BH}) measurements in local galaxies (e.g., [van den Bosch 2016](#); [Saglia et al. 2016](#)). Combining these mass estimates with different host galaxy bulge properties, such as bulge mass, stellar velocity dispersion, and light concentration, revealed remarkably tight correlations which suggest a co-evolution between the massive black hole and their host galaxy ([Kormendy & Ho 2013](#)). However, determining M_{BH} is a challenging procedure, and it is not possible to use one single method across the full sample of galaxies. The methods differ in their model assumptions and in the dynamical tracer (e.g., stars or gas) which is used to probe the gravitational potential in the vicinity of the massive black hole. Problematically, measurements from different dynamical tracers often give discrepant results, raising the question whether the variety of methods forces an additional bias on the scaling relations. Connecting mass results from different methods is necessary to evaluate the robustness and universality of the measurement results and thus crucial for improving the understanding of the interplay between the central black holes and their host galaxies. In this work, we make use of state-of-the-art instruments and modeling methods to add a new mass comparison to the catalog and investigate possible measurement systematics.

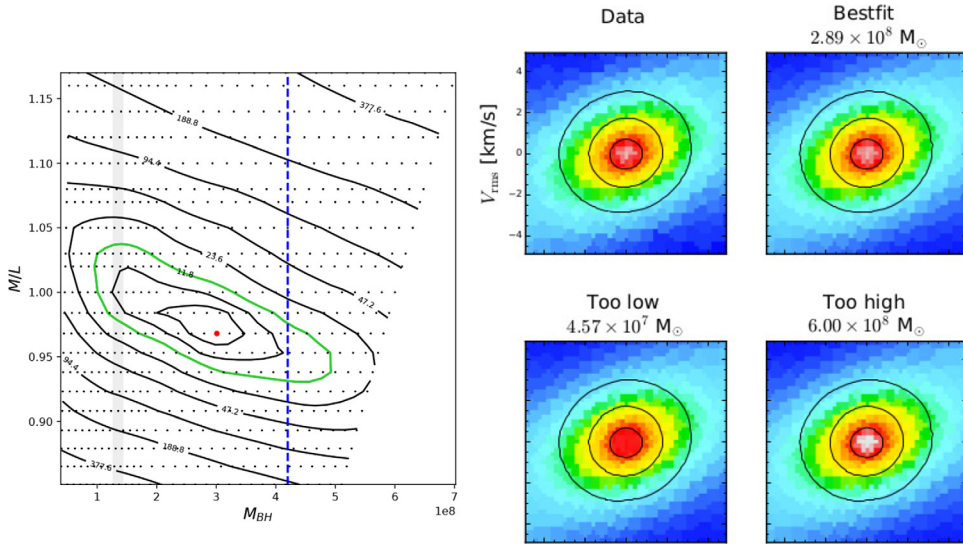


Figure 1. Results of the dynamical Schwarzschild models to estimate M_{BH} of NGC 6958. The *left panel* shows the grid of our models (indicated as black dots) over various M/L and M_{BH} values. The best-fitting model is shown as large red dot. The overplotted contours indicate the significance, the green contour denoting the 3σ level. We also added the 3σ threshold of the KinMS models from the molecular gas observations (gray shaded region). The dashed blue line indicates the formally minimal M_{BH} that we expect to be robustly detectable (based on the resolution of our data). The *right panel* shows a V_{rms} comparison ([110, 250] km s^{-1}) between our data, the model with the best-fitting black hole as well as models of clearly too low and too high M_{BH} .

2. NGC 6958 - an ideal candidate

Different M_{BH} measurement methods for a single galaxy can only be applied for a handful of galaxies. Nearby early-type galaxies with signatures of regular molecular gas are ideally suited for such a cross-comparison of different methods. In this work, we have targeted the isolated (Madore *et al.* 2004) massive early-type galaxy NGC 6958 from the WISDOM survey (Onishi *et al.* 2017). The galaxy shows clear signs of a regularly rotating nuclear molecular gas disk and regular stellar rotation within $10''$ from the center. As such, NGC 6958 is a good case to test and compare different dynamical tracers.

3. Methods

The M_{BH} of NGC 6958 was estimated using two independent state-of-the-art methods based on different dynamical tracers. An overview of the methods is given in the following.

Integrated stellar kinematics. We observed NGC 6958 as science verification project with the GALACSI adaptive-optics assisted MUSE instrument (science program 60.A-9193(A); PI= D. Krajnović). The angular resolution of our observations was determined to be $0.7''$. From the reduced MUSE data cube, we obtained the stellar kinematics by fitting MILES (Sánchez-Blázquez *et al.* 2006; Falcón-Barroso *et al.* 2011) stellar templates to the observed spectra between 4800 \AA and 6500 \AA with pPXF (Cappellari & Emsellem 2004). The galaxy features very regular rotation and a significant velocity dispersion within $10''$ and is therefore suitable for this test. We ran Schwarzschild (1979) orbit superposition models in a grid of constant H-band mass-to-light ratio (M/L) [$0.85 M_{\odot}/L_{\odot}$, $1.17 M_{\odot}/L_{\odot}$] and M_{BH} [$4.5e7 M_{\odot}$, $5.8e8 M_{\odot}$] at an inclination of 37° . In Figure 1, the grid and a comparison between the data and different models are presented. From the χ^2

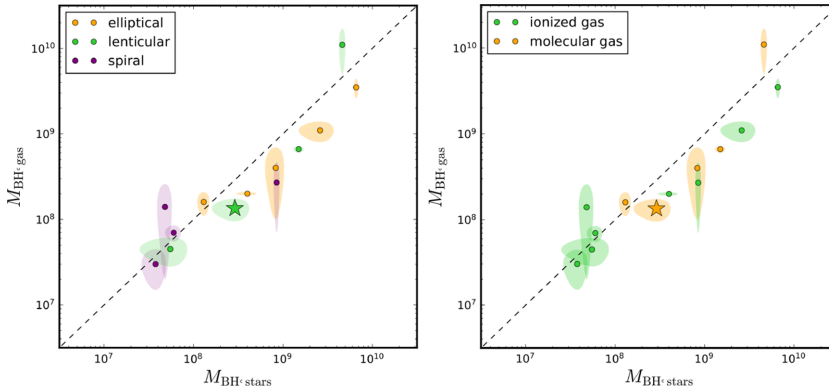


Figure 2. Cross comparisons between different M_{BH} measurement methods. Shown are all objects which have both a stellar and a gas-based estimate. Colour coded are either different galaxy types (*left panel*) or different tracers (*right panel*). NGC 6948 is denoted as star. Despite the low number statistics, gas kinematics provide significantly lower M_{BH} than stellar kinematics. Adapted and extended from [Kormendy & Ho \(2013\)](#).

distribution, we derived the best-fitting parameters to be $M_{\text{BH}} = (2.89 \pm 2.05) \times 10^8 M_{\odot}$ and $M/L = 0.98 \pm 0.06 M_{\odot}/L_{\odot}$ within 3σ significance ($\Delta\chi^2 = 11.8$). For details about the method, we refer to [Krajnović et al. \(2018\)](#) and [Thater et al. \(2019\)](#).

Molecular gas kinematics. We also used $^{12}\text{CO}(2-1)$ emission to trace the central gravitational potential of NGC 6958. Observations were obtained with ALMA in cycle 3 (program 2015.1.00466.S, PI: Onishi) and have a beam size of $0.7'' \times 0.49''$, which is comparable to the angular resolution of the MUSE observations. We constructed a dynamical model of the molecular gas emission using the publicly available KINematic Molecular Simulation (KinMS; [Davis et al. 2013](#)), taking the beam-smearing and spatial and velocity binning into account. Therefore, we ran a Markov chain Monte Carlo method to determine the best-fitting parameters for the black hole mass, H-band M/L, gas distribution, inclination, and additional auxiliary parameters. We ran the fitting routine for 3×10^6 iterations and obtained a preliminary best-fitting black hole mass of $(1.35 \pm 0.09) \times 10^8 M_{\odot}$, mass-to-light ratio in the H-band of $0.83 \pm 0.03 M_{\odot}/L_{\odot}$, inclination of $41.0 \pm 0.2^{\circ}$ (after marginalizing over the remaining best-fitting parameters). We caution that the errors are currently very small and we will re-examine their calculation.

4. Discussion and implications

The two discussed methods provide black hole masses which are different, but consistent within their 3σ uncertainties. The derived H-band M/L is slightly higher for the stellar kinematics measurement.

$M_{\text{BH}} - \sigma_e$ relation. Using the stellar kinematic information covering the effective radius of the bulge, we also obtained the bulge effective velocity dispersion for NGC 6958 to be $\sigma_e = 161 \pm 5 \text{ km s}^{-1}$. The predicted value based on the $M_{\text{BH}} - \sigma_e$ scaling relation is $\sim 1 \times 10^8 M_{\odot}$ ([van den Bosch 2016](#); [Saglia et al. 2016](#)). Both of our applied mass measurement methods provide slightly over-massive black hole compared with these scaling relations, whereas the predicted value is more consistent with the molecular gas kinematics measurement.

Comparison. In the literature, there exists only a handful of galaxies whose black hole masses were determined through multiple methods. While these are consistent in some cases, in more than half of the measurements there is a systematic difference between

the stellar-dynamical and gas-dynamical mass estimates (e.g., Verdoes Kleijn *et al.* 2002; Gebhardt *et al.* 2011; Walsh *et al.* 2013; Barth *et al.* 2016), with the latter typically being significantly smaller (see Figure 2). Our new measurements follow this trend, the stellar-based M_{BH} being about twice as massive as the molecular gas-based M_{BH} . While the number statistics for the comparisons is still small, Figure 2 suggests that the discrepancy tends to occur for elliptical galaxies, for black hole masses above $\sim 10^8 M_{\odot}$ and independent of the usage of ionized or gaseous kinematics as a tracer.

Systematics of the methods. A possible explanation is that the discrepancy between the methods is caused by inaccurate modeling assumptions in the gas dynamics method. This could be of particular concern for massive elliptical galaxies as their gas motion often suggest the presence of substantial random motions (Noel-Storr *et al.* 2003, 2007) presumably agitated by nongravitational forces associated with radio jets (Verdoes Kleijn *et al.* 2006). Jeter *et al.* (2019) analyze the effect of including non-Keplerian motions when modeling ionized gas kinematics and conclude that the derived masses could increase by a factor 2. Therefore, improving the models of ionized gas kinematics could resolve the discrepancy between the ionized gas dynamics and stellar kinematics (see their Figure 4). Further analysis of the systematics of the different methods is crucial to understand this mass discrepancy.

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