Galactic Dynamics in the Era of Large Surveys
Proceedings IAU Symposium No. 353, 2019
M. Valluri & J. A. Sellwood, eds.

doi:10.1017/S1743921319008767

Galactic dynamics and DM profile of NGC1380 with ALMA and VLT/MUSE

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Abstract. In order to understand the interaction between dark matter and baryonic matter in the galaxy evolution history, it is fundamental to constrain dark matter (DM) distribution in galaxies. However, it is difficult to constrain DM profile in the central region of early type galaxy because of the lack of extended neutral hydrogen gas and the degeneracy between dynamical stellar M/L and DM profile. To resolve this difficulty, we conducted combined analysis of ALMA cold molecular gas kinematics and MUSE stellar kinematics of early type fast rotator galaxy NGC1380. In addition, we used HST image to trace the stellar luminosity distribution. With the help of high resolution of ALMA image and large field of view of MUSE, we derived the central BH mass, stellar bulge, disk and DM profile.

Keywords. DM, galaxies: kinematics and dynamics, halo, structure

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1. Introduction

The cosmological model including dark energy and cold dark matter as the dominant form of energy (Λ CDM) has succeeded well to reproduce the large-scale structure of the universe. For the halo density profile, Navarro *et al.* (1996) proposed a double power law density profile with $\rho \propto r^{-1}$ in the inner region and $\rho \propto r^{-3}$ in the outer region. The generalized form of NFW profile can be written following Zhao (1996)

$$\rho(r) = \frac{\rho_0}{(r/r_s)^{\gamma}(1 + r/r_s)^{3-\gamma}} \tag{1.1}$$

where $\gamma = 1$ correspond to the original NFW profile.

NFW profile are introduced to match their DM-only simulations. Deviations from this profile have been observed in some galaxies. For example, late type galaxies have often been found to have shallower inner density slopes (lower gamma value in eq (1); Oh *et al.* 2011). These discrepancy suggest that different flavor of DM particles including self-interacting DM are required (e.g. Rocha *et al.* 2013), or DM-only N-body simulations are inadequate to capture the DM evolution on the galactic scale due to the absence of dissipative process associated with baryonic physics. To create observed shallower DM profile, several processes, including star formation feedback processes which is effective for low mass galaxies (Pontzen & Governato 2012) and dynamical friction during gas poor merger (El-Zant *et al.* 2004) which may have happened in the past of high mass galaxies are suggested.

To distinguish these effect and understand which process is the most important, it is crucial to measure the DM profile for galaxies with a wide range of mass and morphologies in different environments, which have experienced different formation histories. So far, many good measurements of DM profile for late type galaxies have been done with HI gas kinematics, which is excellent kinematic tracer because of its radial extent which is often larger (sometimes 3 to 4 times larger) than that of the stellar disk. (Bosma 1978)

For early-type galaxies in the cluster, however, measuring DM profile is much more difficult. Because HI gas disks are scarce around early-type galaxies especially in cluster environment, we need to have other kinematical tracers of the gravitational potential in order to obtain DM profile in these galaxies.

Very recently, excellent capabilities of the Multi Unit Spectroscopic Explorer (MUSE) on Very Large Telescope (VLT) enabled one to obtain good quality spectra even for the outer part of stellar halo that extends to 3 ≈ 4 times the effective radius (Fornax3D; Sarzi *et al.* 2018).

In contrast to HI gas, cold molecular gas (CO) are also detected in the central region of several early type galaxies independent of the environment (22 % of early type galaxies in volume limited survey ATLAS 3D; Young *et al.* 2011). With the great sensitivity and resolution of ALMA, cold molecular gas with low velocity dispersion (∼10km/s) have been resolved to subarcsecond scale (Boizelle *et al.* 2017).

We measured central BH mass, stellar bulge, disk and DM for early type galaxy NGC1380 by combining VLT/MUSE stellar kinematics and ALMA CO(2-1) gas kinematics. Stellar kinematics have large field of view out to 10kpc where gravitational potential of DM starts to dominate. However stellar kinematics do not have enough resolution to accurately map out the central BH and the bulge distribution. We used high resolution CO(2-1) kinematics to complement the stellar kinematics and accurately measure the central BH and stellar mass. Following sections will describe the observational data and the method how we incorporate CO(2-1) modeling and stellar kinematics modeling into final mass model.

2. Observational data

NGC1380 is a fast-rotator early-type galaxy (Pota *et al.* 2013) in Fornax cluster. We adopted a luminosity distance of 17.1 Mpc (Boizelle *et al.* 2017), thus 1 arcsec ≈ 82 pc, measured from surface brightness fluctuations by Mei *et al.* (2000) with a Cepheid zero-point correction (Mei *et al.* 2005).

Hubble space telescope (HST) I band imaging data of NGC1380 (ACS/WFC/f814w) was downloaded from Hubble legacy archive (HLA). We chose this filter to have good compromise among better angular resolution, lesser dust absorption and lager field of view. Its angular resolution of 0.15" (FWHM of point spread function) is comparable to ALMA resolution ∼ 0.18" (FWHM of beam size for minor axis). HST field of view ≈ 105" covers most of the region of our MUSE observation (≈ 120").

CO(2-1) line in NGC1380 was observed with Band 6 receiver on ALMA as a part of the program 2013.1.00229.S. The data were downloaded from the ALMA archive and reduced with pipeline script provided with the data. The resulting beam size was 0.24" × 0.18" ≈ 21 pc × 16 pc where BH sphere of influence of the estimated BH mass of 3.9×10^8 (from the empirical relation between the stellar velocity dispersion) is 33pc ≈ 0.37". The resulting image of similar procedure was published by Boizelle *et al.* (2017).

NGC1380 was observed with MUSE instrument mounted on UT4 telescope of the ESO VLT in Chile. This observation was conducted as a part of Fornax3D project (Sarzi *et al.* 2018) The observations on NGC1380 were conducted on Dec 2016; Jan 2017; Nov 2017 for central pointing, middle pointing, and halo pointing respectively. The data are fully reduced by the Fornax3D team with a pipeline. Then from the resulting image, stellar kinematics are extracted by utilizing a standard technique developed for other Integral field unit data and the extracted stellar kinematic data are thankfully given to us. The reduction process and data are already published in (Sarzi *et al.* 2018)

https://doi.org/10.1017/S1743921319008767 Published online by Cambridge University Press

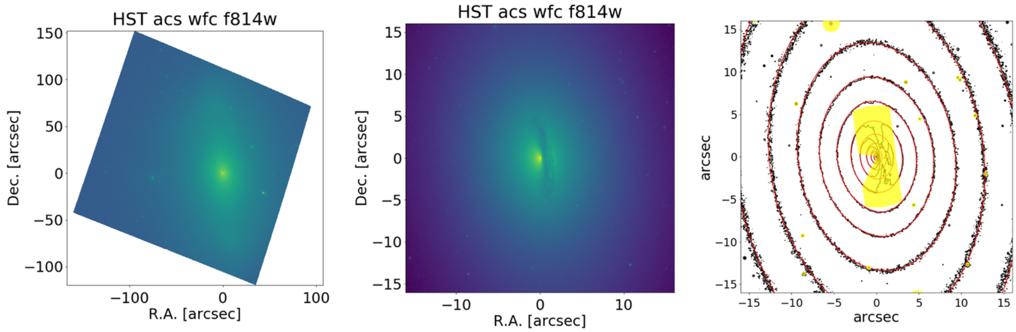

Figure 1. HST image taken with ACS/F814W filter Left: Full Field of View is shown (250" × 250"). Center: the zoom-in view of the central region of NGC1380 is shown (32" × 32"). Right: MGE model (red) overlaid to the F814W observation (black) in contours. The region with significant dust absorption (shown in yellow) is masked out during the MGE fit.

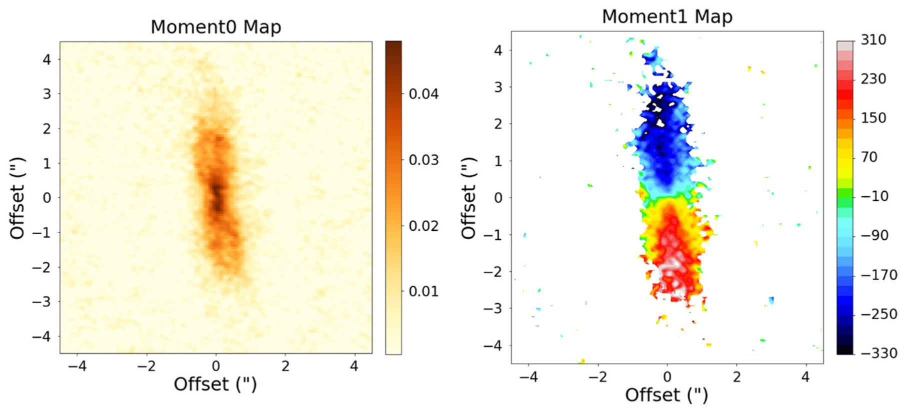

Figure 2. (Left) CO(2-1) gas intensity map, (Right) intensity weighted velocity map.

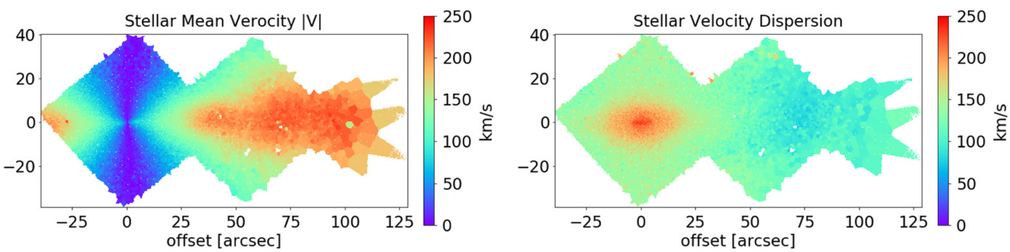

Figure 3. Extracted line of sight stellar kinematics with pPXF from Voronoi-binned MUSE data. The images are reproduced from Sarzi *et al.* (2018) Figure 7.

3. Method

Our strategy is to constrain BH mass and stellar mass well in the central region (radius of 6" ≈ 500pc) with the cold gas kinematics. Then we constrain DM profile with the stellar kinematics which is available in a wide field of view (radius of 120" ≈ 10kpc) with the help of information of the central cold gas modeling.

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To obtain intrinsic density distribution of star in NGC1380 for dynamical modeling we parametrized surface brightness distribution obtained with HST imaging by multiple gaussian expansion method (MGE; Cappellari 2002)(See Figure 1). Dynamical modeling with simple disk rotation model is conducted with ALMA high angular resolution data. For stellar distribution we assumed de-projected MGE and free but a spatially uniform mass to light ratio (M/L). The free parameters are stellar M/L, BH mass, inclination, velocity dispersion of the gas and other nuisance parameter. We followed Davis *et al.* (2013) and Onishi *et al.* (2015) and used KinMS code (Davis *et al.* 2013) to take the observational effect into account. Simple gas rotational disk model reproduce observed data cube well. The best fit model parameters and their posterior distributions are found by MCMC sampling with emcee code (Foreman-Mackey *et al.* 2013) marginalizing nuisance parameters.

With Jeans Anisotropic Models (JAM; Cappellari 2008) of stellar kinematics, we found that the substantial DM halo needs to exist to maintain flat velocity profile at large radius. We assumed the mass distribution of central BH, deprojected MGE times free M/L for stellar component and generalized DM profile (see eq. 1.1 free ρ_0 and γ) which we also model with MGE as well as stellar component. However, mass model obtained with ALMA cold gas modeling cannot reproduce the central high velocity dispersion peak in the stellar kinematics data ($\leqslant 10" \approx 900$ pc), which may indicate several possibilities including the inadequacy of the constant anisotropy over the galaxies and hidden non-axisymmetric bar structure. Therefore we masked central region of the stellar kinematics data and we obtained DM profile by using posterior distribution of BH mass and stellar M/L ratio from ALMA modeling as a prior knowledge with a bayesian inference. We obtained final BH mass, M/L ratio and DM profile. Full results will be presented in Tsukui *et al.* in preparation.

Acknowledgements

We thank Fornax 3D team for providing stellar kinematics data of NGC1380.

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