A Cuspy Dark Matter Halo

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Abstract

The cusp–core problem is one of the main challenges of the cold dark matter paradigm on small scales; the density of a dark matter halo is predicted to rise rapidly toward the center as $r^{-\alpha}$ with $\alpha$ between −1 and −1.5, while such a cuspy profile has not been clearly observed. We have carried out the spatially resolved mapping of gas dynamics toward a nearby ultradiffuse galaxy (UDG), AGC 242019. The derived rotation curve of dark matter is well fitted by the cuspy profile as described by the Navarro–Frenk–White model, while the cored profiles including both the pseudo-isothermal and Burkert models are excluded. The halo has $\alpha = -(0.90 \pm 0.08)$ at the innermost radius of 0.67 kpc, $M_{\text{halo}} = (3.5 \pm 1.2) \times 10^{10} M_{\odot}$, and a small concentration of 2.0 ± 0.36. The UDG AGC 242019 challenges alternatives of cold dark matter by constraining the particle mass of fuzzy dark matter to be $<0.11 \times 10^{-22}$ or $>3.3 \times 10^{-22}$ eV, the cross section of self-interacting dark matter to be $<1.63 \text{ cm}^2 \text{ g}^{-1}$, and the particle mass of warm dark matter to be $><0.23 \text{ keV}$, all of which are in tension with other constraints. The modified Newtonian dynamics is also inconsistent with a shallow radial acceleration relationship of AGC 242019. For the feedback scenario that transforms a cusp to a core, AGC 242019 disagrees with the stellar-to-halo mass ratio dependent model but agrees with the star formation threshold dependent model. As a UDG, AGC 242019 is in a dwarf-sized halo with weak stellar feedback, late formation time, normal baryonic spin, and low star formation efficiency (SFR/gas).

Unified Astronomy Thesaurus concepts: Galaxy dynamics (591); Interstellar atomic gas (833); Galaxy dark matter halos (1880); Dark matter density (354); Dwarf galaxies (416)

1. Introduction

The cosmological model of cold dark matter and dark energy, i.e., ΛCDM, has achieved tremendous success in understanding the cosmic structure across time on large scales, but this model is challenged by observations on small scales such as the cusp–core problem, the missing dwarf problem, the too-big-to-fail problem, etc. (for a review, see Weinberg et al. 2015).

In cosmological simulations of cold and collisionless dark matter, a dark matter halo has a density profile that rises toward the center with a power index of −1 to −1.5 (Moore 1994; Burkert 1995; Navarro et al. 1997; Moore et al. 1998; Ghigna et al. 2000; Jing & Suto 2002; Wang et al. 2020), referred to as a cuspy profile. However, over the past decades, much shallower or even flat core-like profiles toward centers have been found in most, if not all, observed data of nearby galaxies through mapping dynamics of gas and stars. Early studies with H I interferometric data reveal shallow dark matter central profiles in individual galaxies (Carrigan & Beaulieu 1989; Jobin & Carrigan 1990; Lake et al. 1990). Studies with higher spatial resolution for a larger sample of dwarfs and low surface brightness galaxies further confirmed the central flatness of the rotation curve and derived a median dark matter density slope of about −0.2 toward the centers (de Blok et al. 2001; Oh et al. 2011, 2015). Optical observations of ionized gas such as H α can achieve higher spatial resolution than the H I data and confirmed the median density slope of about −0.2 with long-slit spectra for a large sample of dwarf galaxies (Spekkens et al. 2005). Although the rotation curves from the long-slit spectroscopic data are sensitive to the assumed dynamical center, the position angle of the kinematic major axis, etc., further studies with optical integral field units have suggested the insignificance of the above effects and validated dark matter profiles with central shallower slopes (Kuzio de Naray et al. 2008; Adams et al. 2014).

Among the few galaxies whose halos can be described by cuspy profiles, the one with the highest signal-to-noise ratio is DDO 101, which has a central dark matter slope of $-1.02 \pm 0.12$ (8.5σ; Oh et al. 2015). However, this object can be fitted equally well with a cored profile; the difference in the reduced $\chi^2$ is only 0.02 for a degree of freedom (dof) of six (see Oh et al. 2015). This is because of the limitation on the spatial resolution and extent of the observed rotation curve, as well as different models for cuspy and cored profiles (see Section 3.2). For example, the density slope of a Navarro–Frenk–White (NFW) model for a cuspy profile varies from −1 at the center to −3 at infinity, while the pseudo-isothermal (ISO) model for a cored profile has a slope from zero at the center to −2 at infinity, so that both models may perform well on fitting the data with a limited spatial extent. In order to identify a definitive cuspy dark matter halo, it is thus required to demonstrate not only the validity of cuspy models but also the invalidity of cored models. For DDO 101, the large uncertainty in its distance further challenges the reliability of its cuspy profile (Read et al. 2016b). Studies of local dwarf spheroidal galaxies also suggest cuspy profiles in a few objects, among which the highest-probability one is Draco with a central density slope of $-1.0$ at 5.0σ and 6.8σ by Jardel et al. (2013) and Hayashi et al. (2020), respectively. However, it has not been demonstrated whether a cored model can fit the data or not for this object, as done for DDO 101. And furthermore, systematic uncertainties are complicated for these studies in which the velocity dispersion among individual stars as a function of the galactic radius is used to measure the dark
matter distribution. The orbital anisotropy, the method to model stellar orbits, the dark matter shape, and the limited number of member stars are all found to affect the conclusions (Evans et al. 2009). Specifically, a recent study of simulated galaxies by Chang & Necib (2020) emphasized the importance of a large number of stars in order to unambiguously measure the dark matter distribution. If the number of stars is less than 10,000, an intrinsic cored profile cannot be reliably differentiated from a cuspy profile. For Draco, there are only ~468 member stars (Walker et al. 2015). Fortunately, these systematic uncertainties are significantly eliminated for H I interferometric data, as seen in simulated galaxies (Kuzio de Naray et al. 2009; Kuzio de Naray & Kaufmann 2011). This is mainly because gas is collisional and the dynamics can be relatively easily described by tilted-ring models (Begeman 1989; Di Teodoro & Fraternali 2015). In summary, the above few claimed cuspy profiles of dark halos are not definitive.

There are two solutions to the small-scale controversies of \( \Lambda \)CDM. One is to modify the nature of dark matter so that it is no longer cold but instead self-interacting, fuzzy or warm. These modifications can retain the properties of the universe on large scales as predicted by \( \Lambda \)CDM but resolve its small-scale challenges. Fuzzy cold dark matter, also known as ultra-light scalar particles, has a mass around \( 10^{-22} \) eV (e.g., Hu et al. 2000; Schive et al. 2014). The uncertainty principle of its wave nature acts on kiloparsec scales, smoothing the density fluctuations and preventing the growth of small halos and formation of central cusps. The self-interacting dark matter transports “heat” (higher velocity dispersion) from the outer region to the “cooler” inner region of a halo. It leads to a constant density core with isothermal velocity dispersion (e.g., Spergel & Steinhardt 2000; Rocha et al. 2013; Tulin & Yu 2018). If dark matter is warm, it decouples from the primordial plasma at relativistic velocity, thus free streaming out of small density peaks. As a result, the structure formation at small scales is suppressed (e.g., Avila-Reese et al. 2001; Lovell et al. 2014). The warm dark matter scenario is found to have a “catch-22” problem; i.e., if the “cusp–core” problem is resolved, the requirement for the particle mass cannot form small galaxies in the first place, and vice versa (e.g., Macciò et al. 2012).

Another solution is to keep the cold dark matter paradigm but invoke efficient gravitational interaction between dark and baryonic matter through stellar feedback (Navarro et al. 1996; Governato et al. 2010). Overall, as gas falls into the inner region of the halo, star formation takes place, and the subsequent feedback through supernovae expels an appreciable amount of gas and stars to large radii. This baryonic matter pulls dark matter particles to migrate outward through pure gravitational interaction, lowering the central density of dark matter. The overall efficiency of this interaction and its effects is still under investigation (Di Cintio et al. 2014; Read et al. 2016a, 2019; Tollet et al. 2016; Benéz-Llambay et al. 2019; Bose et al. 2019). In addition to the stellar feedback, other mechanisms have also been proposed, such as dynamical friction between gas clouds and dark matter particles (Nipoti & Binney 2015).

A definitive cuspy profile from observations will prove the validity of the cold dark matter paradigm on subgalactic scales while challenging other types of dark matter. As shown in Figure 1, the object AGC 242019 is an ultradiffuse galaxy (UDG) identified by the Arecibo Legacy Fast ALFA (ALFALFA) survey of H I galaxies (Leisman et al. 2017). This galaxy has a stellar mass of \((1.37 \pm 0.05) \times 10^9 M_\odot\), an H I mass of \((8.51 \pm 0.36) \times 10^8 M_\odot\), and a star formation rate (SFR) of \((8.2 \pm 0.4) \times 10^{-3} M_\odot \text{yr}^{-1}\), as listed in Table 1. Its receding velocity is \(2237 \pm 25 \text{ km s}^{-1}\) after correcting for the Virgo, Great Attractor, and Shapley superclusters (Mould et al. 2000). In the cosmological frame of \( h = 0.73, \Omega_0 = 0.27, \) and \( \Omega_k = 0.73, \) the corresponding distance is 30.8 Mpc and the uncertainty is estimated to be 5%, given that it is an isolated field galaxy (see Section 4.2).

2. Observations and Data Reduction

2.1. Radio Interferometric Observation of H I Gas with the VLA

Our L-band observations were performed with the Karl G. Jansky Very Large Array (VLA) through two projects corresponding to the D configuration (19B-072; PI: Y. Shi) and the C and B configurations (20A-004; PI: Y. Shi). The D-configuration observations were performed on 2019 September 21 and 23, each with 1.5 hr observing time and \( \sim 66 \) minutes on-source time. A total of 27 antennas were employed in both executions, with the first under overcast weather conditions and the second under clear weather conditions. The projected baselines of the D-configuration array are in the range of 34–1050 m. The flux and bandpass calibrator was 3C 295, and the gain calibrator was J1419+0628. We configured the spectrometers with a mixed setup. The spectral line window that covers the H I 21 cm line has a bandwidth of 128 MHz and a channel width of 32.3 kHz \((\sim 6.9 \text{ km s}^{-1})\), while the remaining windows cover a frequency range between 963.0 and 2017.0 MHz to optimize the sensitivity for the radio continuum.

The C-configuration observations were performed on 2020 February 4, 9, and 13, each with 2 hr observing time and \( \sim 90 \) minutes on-source time. Two observations were conducted with 25 antennas, while the rest were observed with 26 antennas, mostly under overcast or clear weather conditions. The projected baselines of the C configuration are in the range of 40–3200 m. In the C-configuration observations, the 21 cm emission line was observed with a spectral line window that has a channel width of 5.682 kHz \((\sim 1.2 \text{ km s}^{-1})\) and a bandwidth of 32 MHz. The remaining windows cover a frequency range between 963.0 and 2017.0 MHz for optimizing the radio continuum bandwidth. The flux and bandpass calibrator was 3C 286, and the gain calibrator was J1419+0628.

The B-configuration observation was performed with five executions during 2020 July and August, each with 2 hr observing time and \( \sim 90 \) minutes on-source time. In most executions, 27 antennas were employed under cloudy conditions. The projected baselines of the B configuration are in the range of 230–11,000 m. The hardware setup and calibrators were the same as those used for the C-configuration observations.

We reduced all data manually with the Common Astronomy Software Applications (CASA) package (McMullin et al. 2007) V5.6.1. Both D-configuration observations were severely affected by radio frequency interference (RFI). Therefore, we calibrated and flagged the data manually. Approximately 20% of the data have to be flagged across different frequency ranges. The data obtained on 2019 September 21, including the calibrators, have about three times higher noise than that estimated from the VLA sensitivity estimator, for unknown
The dynamical center and systematic velocity are obtained by setting them as free parameters when running Barolo.

The final spectrally matched line-only data from the D, C, and B configurations were combined together with the concat task.

In the end, we inverted the visibility data to the image plane and cleaned the data cube with Briggs’ robust parameter of 2.0 using the tclean task. The final D + C + B data cube has velocity coverage of 500 km s\(^{-1}\) and a channel width of 32 kHz, corresponding to a velocity resolution of \(\sim 7\) km s\(^{-1}\). The rms noise level reaches 0.26 mJy beam\(^{-1}\) channel\(^{-1}\) with a restoring synthesis beam size of 9″85 × 9″33 and a position angle of 17°56.

The HI intensity map is shown in Figure 2(a). The integrated spectrum of the B + C + D configuration has a flux of 3.8 ± 0.16 Jy km s\(^{-1}\), which is comparable to the flux of 3.4 Jy km s\(^{-1}\) obtained with Arecibo (Leisman et al. 2017), as shown in Figure 2(b). The total HI gas mass is \((8.51 ± 0.36) \times 10^8 M_\odot\). A slightly higher flux as seen by the VLA in the red wing may be caused by a small offset of the Arecibo beam from the galaxy center, given the large size of the galaxy of 2′ in diameter. The radial profile of the gas mass surface density is shown in Figure 2(c). The channel map is shown in Figure 3.

We also tested tilted-ring modeling with the combined data using the B + C configurations and found essentially no difference, except for a higher noise level. However, the better velocity resolution leads to better estimates of the pressure support, which has a very minor contribution to the decomposition of the rotation curve.

2.2. Broadband Images

The coadded images at 3.6 and 4.5 μm were obtained from the Wide-field Infrared Survey Explorer (WISE) archive (Wright et al. 2010) with spatial resolutions of 6″0 and 6″8, respectively. The target is well detected at 3.6 μm, as presented in Figure 4(a), but shows almost no detection at 4.5 μm. To derive the radial profile of the stellar mass surface density as presented in Figure 4(b), a few nearby bright stars in the field were subtracted using the stellar point-spread functions.\(^4\) The stellar mass based on the 3.6 μm image is estimated to be \((1.37 ± 0.05) \times 10^8 M_\odot\).

\(^4\) http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/sec4_4c.html
Each frame was processed of the VLA compared to Arecibo ($\Upsilon$ ratio). Figure 2.

The optical extent of the galaxy, with one pointing toward a nearby bright star for astrometric calibration. Each exposure was 30 minutes, and the total on-source integration time varied from 2.0 to 3.5 hr at each pixel. For every 1–2 hr, an off-target blank sky and a standard star were observed. The seeing was between 1\arcsec and 2\arcsec. Each frame was first reduced following the standard procedure by pyWiFeS (Childress et al. 2014) and then was subtracted by the median value of the sky frame at each wavelength. Individual frames were aligned with each other to produce the final mosaic images with the positions of the H2 clumps, as the continuum emission was too faint. The absolute astrometry was obtained through alignment with the brightest star in the mosaic field of view. Since H2 clumps are not perfect point sources, we estimated the final astrometric uncertainty to be about 1\arcsec. To correct the barycentric velocity offset and any possible intrinsic instrumental shift, the wavelength solution of each night was further cross-calibrated based on H2 lines of the same clumps observed during different nights. The integrated H2 flux map is presented in Figure 4(c) with the integrated spectrum shown in Figure 4(d).

3. Data Analysis

3.1. The Derivation of the Rotation Curve of the Dark Matter

We derived the rotation curve of the dark matter by first obtaining the total rotation curve from the HI and H2 data with a correction for the pressure support and then quadratically subtracting the gas and stellar gravity contributions as detailed below.

3.1.1. The Observed Rotation Curve from Tilted-ring Fitting to the HI Data Cube

We fitted the tilted-ring model to the HI 3D data cube with 3DBarolo (Di Teodoro & Fraternali 2015) to obtain the rotation curve as listed in Table 2. The radial width of each ring is set to 9\arcsec, which is roughly the beam size, so that each ring is independent. We adopted uniform weighting (WFUNC = 0) and least-squares minimization (FTYPE = 1). All other optional parameters are set as default. The full list of the setup is included in Table A1.

The angular resolution and signal-to-noise ratio were good enough to set the rotation velocity, velocity dispersion, position angle, and inclinations as free parameters for each ring. Before running this setup, we first ran a model by also setting the dynamic center and the systematic velocity as free parameters and then fixed them to the mean values of all rings as listed in Table 1. The scale height was fixed to 100 pc, independent of the radius. If the height is varied by a factor of 5 (see below), the conclusion remains unchanged. We do not notice that 3DBarolo is not able to remove effects fully due to the disk height for a thick disk (Iorio et al. 2017). When running 3DBarolo, we adopted the “two-stage” fitting method, which allows a second fitting stage after regularizing the first-stage parameter sets. As shown in Figure 5, the radial profiles of the inclination and position angles from the first-stage fitting are regularized by fitting a Bezier function, based on which the second-stage fitting is performed. The errors of the derived rotation velocity and velocity dispersion in 3DBarolo (Di Teodoro & Fraternali 2015) are estimated through a Monte Carlo procedure.

Figure 2. The HI data of AGC 242019. (a) HI intensity. (b) Integrated spectra of the VLA compared to Arecibo's spectrum (Haynes et al., 2018). (c) Radial profile of the gas mass surface density corrected for inclination and helium.

for a Kroupa stellar initial mass function and a mass-to-light ratio $\Upsilon_{3.6 \mu m} = 0.6 (M_\odot / L_{3.6 \mu m})$ (see below), with a half-light radius of 3.7 kpc.

The optical $g$ and $r$ images were obtained from the Dark Energy Camera Legacy Surveys (Dey et al. 2019). The far-ultraviolet image was retrieved from the Galaxy Evolution Explorer (GALEX) data archive. The integrated flux was converted to an SFR of $(8.2 \pm 0.4) \times 10^{-3} M_\odot$ yr$^{-1}$ for a Kroupa stellar initial mass function (Leroy et al. 2008).

2.3. Integral Field Unit Observation of H2 by Australian National University 2.3 m

Integral field unit observations of H2 were carried out with the Wide-Field Spectrograph (WiFeS) on board the Australian National University 2.3 m telescope on the nights of 2020 March 21–22, May 26, and July 20–22. An R7000 grism (5290–7060 Å) at a resolution of 7000 was adopted to cover the H2 emission line. WiFeS has a field of view of $25^\prime \times 38^\prime$. As shown in Figure 4(a), exposures were taken at several positions to cover the whole optical extent of the galaxy, with one pointing toward a nearby bright star for astrometric calibration. Each exposure was 30 minutes, and the total on-source integration time varied from 2.0 to 3.5 hr at each pixel. For every 1–2 hr, an off-target blank sky and a standard star were observed. The seeing was between 1\arcsec and 2\arcsec. Each frame was first reduced following the standard procedure by pyWiFeS (Childress et al. 2014) and then was subtracted by the median value of the sky frame at each wavelength. Individual frames were aligned with each other to produce the final mosaic image using the positions of the H2 clumps, as the continuum emission was too faint. The absolute astrometry was obtained through alignment with the brightest star in the mosaic field of view. Since H2 clumps are not perfect point sources, we estimated the final astrometric uncertainty to be about 1\arcsec. To correct the barycentric velocity offset and any possible intrinsic instrumental shift, the wavelength solution of each night was further cross-calibrated based on H2 lines of the same clumps observed during different nights. The integrated H2 flux map is presented in Figure 4(c) with the integrated spectrum shown in Figure 4(d).

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Carlo method. We also ran 3DBarolo with only the receding and approaching sides, respectively. The velocities from three runs are within the 1σ errors, while the velocity dispersions are also within the errors except for the innermost radius, which is shown in Figure B1 of Appendix B. As shown in Figure 5, the derived rotation velocity and velocity dispersion vary well within the 1σ error bars before and after regularization.

As shown in Figure 6, within the outer boundary of the last ring, the residual of the H I intensity is dominated by the observed flux noise, and the residuals of the velocity and velocity dispersions show small amplitudes with medians of 1.9 and 1.8 km s$^{-1}$, respectively. Figure 7 further shows the position–velocity diagram along the major and minor axes. Overall, the observation matches the best-fit model well.

As gas is collisional, pressure support is a driver of gas motion in addition to gravity (Bureau & Carignan 2002; Oh et al. 2015; Iorio et al. 2017; Pineda et al. 2017). A gas disk in equilibrium satisfies

\[ V_{\text{circ}}^2 = V_{\text{rot}}^2 + V_P^2, \]

where the circular velocity $V_{\text{circ}} = \sqrt{\frac{R}{\partial R}}$ solely reflects the effect of the gravitational potential, $V_{\text{rot}}$ is the observed rotation velocity, and $V_P$ is the velocity driven by the pressure. Here $V_P$ is related to the gas density ($\rho$) and velocity dispersion ($\sigma_v$) following

\[ V_P^2 = -R\sigma_v^2 \frac{\partial \ln(\rho \sigma_v^2)}{\partial R}. \]

Assuming that the scale height is independent of the radius and that the disk is thin, the above equation becomes

\[ V_P^2 = -R\sigma_v^2 \frac{\partial \ln(\sigma_v^2 \Sigma_{\text{obs}} \cos i)}{\partial R}, \]

where $\Sigma_{\text{obs}}$ is the observed gas mass surface density, and $i$ is the inclination angle. Following Equation 3, the pressure support correction is implemented in 3DBarolo (Iorio et al. 2017). For AGC 242019, the correction is small, with $|V_{\text{circ}} - V_{\text{rot}}|$ being smaller than $\sim$1.0 km s$^{-1}$ across the radius. In this case, only the error of $V_{\text{rot}}$ is propagated to $V_{\text{circ}}$ while ignoring the error of $V_A$. The radial profile of $V_{\text{circ}}$ is referred to as the observed rotation curve.

Note that our HI data have a spectral resolution of 7 km s$^{-1}$, which is comparable to or even lower than the derived velocity dispersion shown in Figure 5. To check the effect of the limited spectral resolution, we also performed tilted-ring fitting on the HI data cube from the B and C configurations that has a

Figure 3. Channel map of the H I data. The contour levels are 1, 3, 4.5, and 6 mJy km s$^{-1}$. The white and red contours indicate the observations and best-fit models, respectively.
The spectral resolution of 2.4 km s\(^{-1}\). The difference in the velocity dispersion between the two data is within the 1\(\sigma\) error, and the difference in the derived rotation curve is within the 1\(\sigma\) error too.

### 3.1.2. The Observed Rotation Curve from the H\(\alpha\) Map

The H\(\alpha\) emission is clumpy and sporadic across the disk. As a result, tilted-ring modeling cannot be performed for the H\(\alpha\).
data in the same way as for the H I data. Instead, we adopted the same ring parameters from the H I data, including the center position, inclination angle, and position angle, to convert the line-of-sight velocities into the rotation curve. As shown in Figure 4(c), we used a circular aperture with a radius of 2 kpc to extract the spectrum of the Hα region and measured the line-of-sight velocity, whose error was estimated through a Monte Carlo method, by randomly inserting a Gaussian error at each data point and iterating 1000 times.

The velocity was then converted into the rotation curve with the following steps. (1) We first correct for the absolute wavelength of the optical integral field unit data by comparing the Hα velocity to the H I velocity at the same position. (2) The line-of-sight velocity is then converted into the rotation velocity by $V_{rot} = V_{los}/\sin(i)/\cos(\theta)$, where $i$ is the inclination angle and $\theta$ is the azimuthal angle from the major axis in the plane of the unprojected disk. Here the inclination and position angles are also interpolated based on the result from the H I fitting. (3) The dynamical center from the H I ring is adopted. (4) Individual velocities are then rebinned at a width of 1.0 kpc to have enough points to obtain the mean value as shown in Figure 8. Except for the outermost bin, where only one data point is available, the error of the mean is obtained through the Monte Carlo method, which fits a mean value after it randomly inserts a Gaussian error at each data point and iterates 1000 times. To obtain the pressure support correction for the Hα, we assumed that the radial shapes of the Hα gas mass surface density and velocity dispersions are similar to those of H I (Adams et al. 2014). The velocity dispersions of the Hα clumps after correcting for the thermal broadening (10 km s$^{-1}$) are about the same as those of H I at similar locations. As a result, we adopted the $V_P$ from the H I data to correct for the Hα rotation velocity.

Since our Hα emission is sporadic and the errors of the rotation curve are only based on those detected regions, we used the Hα rotation curve as a sanity check of the H I curve.

3.1.3. The Contribution to the Rotation Curve from the Gravity of Gas

The radial profile of the gas mass surface density derived from the tilted-ring modeling is shown in Figure 2(c). We used this profile to estimate the gas rotation curve using the ROTMOD task (Begeman 1989) in the GIPSY package. The gas mass has been corrected for helium by multiplying it by a factor of 1.36. The vertical distribution of the gas disk is assumed to be “SECH-SQUARED” with a scale height of 0.1 kpc. By varying the gas mass surface density with its error, we used the Monte Carlo method to estimate the uncertainty of the rotation curve. We then varied the scale height from 0.02 to 0.5 kpc to quantify the effect of the scale-height uncertainty on the rotation curve. The two types of errors were summed quadratically to get the final error.

3.1.4. The Contribution to the Rotation Curve from the Gravity of Stars

To estimate the stellar mass distribution, we first derived the radial profile of the 3.6 μm surface brightness at a bin width of 3″, half of the resolution FWHM. The ellipse parameters derived by the above H I dynamical modeling were used, for which the inclination and position angles were interpolated. We then converted this brightness into the stellar mass profile using $T_{3.6\, \mu m} = 0.6 M_{\odot}/L_{\odot, 3.6\, \mu m}$ with a Kroupa stellar initial mass function (see below), as shown in Figure 4(b). To extend the profile to 10 kpc, an exponential disk was fitted to the part outside a radius of 4 kpc.

To measure the stellar contribution to the rotation curve, we use the ROTMOD task (Begeman 1989) in GIPSY, where the vertical distribution was assumed to be “SECH-SQUARED” with a scale height of 0.2 kpc. The errors of the stellar mass surface density are dominated by the subtraction of the sky background, and its effects on the rotation curve are simulated with the Monte Carlo method. We also varied the scale height from 0.01 to 0.5 kpc to obtain the uncertainty due to the scale height. The above two errors were quadratically added to represent the final error of the stellar rotation curve.

3.2. The Models of the Dark Matter Halo

The models of the cuspy dark matter halo are motivated by numerical simulations of dark matter, including an NFW model (Navarro et al. 1997) and an Einasto model (Einasto 1965). The models of the cored dark matter halo are observationally motivated, including the ISO model (Begeman et al. 1991) and Burkert model (Burkert 1995).

(1) An NFW halo model (Navarro et al. 1997) has a density profile of

$$\rho_{NFW}(R) = \frac{\rho_c \delta_{\text{char}}}{(R/R_s)(1 + R/R_s)^2},$$  \hspace{1cm} (4)

where $\rho_c = 3H^2/(8\pi G)$ is the present critical density, $\delta_{\text{char}}$ is dimensionless density contrast, and $R_s$ is the scale radius. Here $R_s$ is related to $R_{200}$ through the concentration $c = R_{200}/R_s$, where $R_{200}$ is the radius within which the halo average density is 200 times the present critical density. Here $\delta_{\text{char}} = \frac{200\delta_c}{3}$ with $\delta_c = \frac{1}{\ln(1 + c) - c/(1 + c)}$. The halo mass with $R_{200}$ is $M_{200} = \frac{100H^2 R_{200}^3}{G}$. The inner density profile of the NFW model shows a cusp with $\rho \propto R^{-1}$. The corresponding rotation velocity of the NFW model is

$$V_{NFW}(R) = V_{200} \sqrt{\frac{\ln(1 + cx) - cx/(1 + c)}{x(\ln(1 + c) - c/(1 + c))}},$$  \hspace{1cm} (5)

where $V_{200}$ is the circular velocity at $R_{200}$ with $V_{200} = R_{200} \Omega_c$, and $x = R/R_{200}$.

(2) An ISO halo model (Begeman et al. 1991) is observationally motivated to describe the presence of a central
where $\rho_0$ is the central density and $R_C$ is the core radius of the halo. The rotation velocity is

$$V_{\text{ISO}}(R) = \frac{\rho_0 R_C^2}{1 + (R/R_C)^2}.$$  

(6)

where $\rho_0$ is the central density and $R_C$ is the core radius of the halo. The rotation velocity is

$$V_{\text{ISO}}(R) = \sqrt{\frac{2\ln(1 + x) + \ln(1 + x^2) - 2 \arctan(x)}{x[3 \ln(2) - 2 \arctan(1)]}},$$

(9)

where $x = R/R_c$ and $V_C$ is the circular velocity at the core radius.

3.3. Priors and Setups of the Rotation Curve Modeling

We fitted the above three dark matter models to the rotation curve of dark matter through Bayesian inference with the Python code PyMC3 (Salvatier et al. 2016). We adopted the No-U-Turn Sampler (NUTS) with 5000 samples, 2000 tunes, four chains, and target_accept = 0.99.

As listed in Table 3, the prior of each parameter of a dark matter model is described with a bounded normal distribution, whose lower-limit bound is set to zero. The mean of the distribution is set with some prior knowledge as detailed below, and the standard deviation is set to twice the mean.
The prior $R_{200}$ of the NFW model is set to have a mean of 75 kpc, corresponding to a halo mass of $5 \times 10^{10} M_\odot$, as expected by the stellar mass versus halo mass relationship given our stellar mass of $(1.37 \pm 0.05) \times 10^8 M_\odot$ (Santos-Santos et al. 2016). At this halo mass, the halo concentration is about 10 in simulations (Macciò et al. 2007), giving a mean prior $R_S$ of 7.5 kpc.

Since the core radius of a cored dark matter halo is on a kiloparsec scale (Oh et al. 2015), the mean prior $R_C$ of the ISO model is set to 2 kpc. The mean prior $V_{\text{norm}}$ of the ISO model is thus set to 25 km s$^{-1}$, so that the galaxy is on the baryonic Tully–Fisher relationship (Mancera Piña et al. 2020) given its stellar mass of $(1.37 \pm 0.05) \times 10^8 M_\odot$ and an H I mass of $(8.51 \pm 0.36) \times 10^8 M_\odot$. Similarly, the mean prior $R_C$ of the Burkert model is set to 2 kpc, and the mean prior $V_C$ of the model is set to 35 km s$^{-1}$.

The fitting is convergent. By exploring the full posterior distribution, the best-fit parameter is given as the mean of the distribution, and the error is given by the standard deviation, as well as the 3% and 97% highest posterior density (HPD). The percentage of small Pareto shape diagnostic values ($k < 0.7$) is also listed. A larger diagnostic value indicates that the model is incorrectly specified.

### 4. Results

#### 4.1. The Rotation Curve of Dark Matter

Figure 9(a) shows the observed rotation curve of AGC 242019. The H I measurements cover a radial extent of 9 kpc, while the H\alpha data cover the central 5 kpc in radius. Two data sets are overall consistent with each other in the overlap region. The rotation curve rises all the way up to the last measurable radius.

Figure 9(b) shows the rotation curve of dark matter after quadratically subtracting the gas and stellar gravity contributions. The sampling of the H I curve is at the beam size, while the H\alpha curve has a radial bin of 1.0 kpc. As shown in the figure, the H\alpha curve is overall well consistent with the H I curve over the spatial extent covered by both data sets. As mentioned before, since the H\alpha emission is sporadic and the errors of the H\alpha rotation curve are only based on the detected regions, its rotation curve is only used for the sanity check of the H I curve. We fitted the H I curve with two spherical halo models, namely, the NFW model (Equation (5), Navarro et al. 1997) and the ISO model (Equation (7), Begeman et al. 1991), through the Python code PyMC3 (Salvatier et al. 2016) to
represent the cuspy and cored profiles, respectively. The ISO model is too steep at the inner radii, whereas the NFW model matches the observed data in the overall fitting, which is also illustrated by the fitting residuals as shown in Figure 10. To quantitatively discriminate between the two models, we performed a leave-one-out (LOO) predictive check (Vehtari et al. 2015). We found that the estimated effective number of parameters ($p_{\text{loo}} = 1.6$) of the NFW model is smaller than the real number of free parameters, i.e., two, while that of the ISO model has $p_{\text{loo}} = 6.3$, significantly larger than two (see Table 4). This quantitatively indicates that the NFW model is valid, while the ISO model is ruled out. The corresponding difference in the reduced $\chi^2$ is 1.9 for dof = 5, equivalent to a Gaussian significance of 3.0$\sigma$. As listed in Table 4, some Pareto diagnostic value $k$ of the ISO model is larger than 0.7, further indicating that the model is incorrectly specified. We also ran the fitting by including the H$\alpha$ and obtained a similar difference in $p_{\text{loo}}$ values and $\Delta(\chi^2/\text{dof}) = 2.8$ for dof = 9 between the two models, equivalent to a Gaussian significance of 5.0$\sigma$.

The Burkert model is another observationally motivated formula to describe a cored dark matter halo (Equation (9), Burkert 1995). Its density profile is flat toward the center, which is like the ISO model, but it has a power-law index of $-3.0$ toward infinity, which is like the NFW model. As shown in Figure 9(b) and listed in Table 5, the Burkert model gives a bad fitting too, with $p_{\text{loo}} = 4.4$, much larger than (1.6) that of the NFW model.

The best-fit NFW model has a halo scale radius of $\sim 33$ kpc. Such a large cusp is well spatially resolved given that its size relative to the H I beam is 24. This suggests that the presence of the cusp is not an artifact caused by a limited spatial resolution (de Blok et al. 2001; Oh et al. 2015). The dark matter halo has a mass of $(3.5 \pm 1.2) \times 10^{10} M_\odot$ within $R_{200}$, the radius at which the average halo density is 200 times the average cosmic density. Due to the fact that the rotation curve does not reach the flat part, the constraints on the $R_{200}$ (or $M_{\text{halo}}$) and $R_5$ do not reach a small error. But a small halo concentration of only $2.0 \pm 0.36$ is conclusive. This is much smaller than the median concentration of 15 at the same halo mass in the local universe.


### Table 4

| Rotation Curves | NFW Model | ISO Model |
|-----------------|-----------|-----------|
|                 | \( R_{200} \) | \( R_e \) | \( p_{iso} \) | \( k' \) (<0.7) | \( \chi^2/\text{dof} \) | \( V_{nom} \) | \( R_C \) | \( p_{iso} \) | \( k' \) (<0.7) | \( \chi^2/\text{dof} \) |
| \( \text{H I} \) (fiducial) | 65.0 ± 7.4 | 33.3 ± 9.1 | 1.6 | 100% | 1.60 | 16.7 ± 1.9 | 2.5 ± 0.5 | 6.3 | 86% | 3.51 |
| \( \text{H I} + \text{H}\alpha \) (fiducial) | 64.6 ± 7.1 | 33.1 ± 8.7 | 1.2 | 100% | 1.90 | 17.1 ± 1.7 | 2.2 ± 0.4 | 5.8 | 100% | 4.74 |
| \( \text{H I} \) \((\text{T}_{1.6 \, \mu m} + 3\sigma)\) | 59.5 ± 7.2 | 31.5 ± 9.3 | 1.4 | 100% | 1.32 | 16.3 ± 2.3 | 2.3 ± 0.5 | 7.3 | 86% | 3.55 |
| \( \text{H I} \) \((\text{T}_{1.6 \, \mu m} - 3\sigma)\) | 67.2 ± 7.7 | 33.6 ± 9.1 | 1.8 | 100% | 1.82 | 16.9 ± 1.8 | 2.5 ± 0.4 | 6.5 | 86% | 3.50 |
| \( \text{H I} \) (distance + 3\sigma) | 62.1 ± 6.7 | 33.9 ± 9.2 | 1.7 | 100% | 1.66 | 15.2 ± 1.8 | 2.6 ± 0.5 | 7.1 | 86% | 3.46 |
| \( \text{H I} \) (distance − 3\sigma) | 73.8 ± 8.5 | 33.9 ± 8.9 | 1.9 | 100% | 1.97 | 19.5 ± 2.0 | 2.3 ± 0.4 | 6.2 | 86% | 3.55 |
| \( \text{H I} \) (5 \times height) | 60.7 ± 7.4 | 30.6 ± 9.0 | 1.0 | 100% | 1.14 | 17.5 ± 2.6 | 2.2 ± 0.5 | 6.7 | 86% | 3.29 |
| \( \text{H I} \) (height/5) | 61.6 ± 7.4 | 31.4 ± 9.1 | 1.1 | 100% | 1.34 | 17.6 ± 3.0 | 2.2 ± 0.6 | 9.9 | 86% | 3.93 |

### Notes.

- The percentage of the Pareto diagnostic values that are “good” and “ok” (\( k < 0.7 \)).
- The reduced \( \chi^2 \) is given for the best-fit result with PyMC3.

### Table 5

| \( V_C \) (km s\(^{-1}\)) | \( R_C \) (kpc) | \( p_{iso} \) | \( k' \) (<0.7) | \( \chi^2/\text{dof} \) |
|-----------------|--------------|-------------|-------------|-------------|
| 25.7 ± 1.9      | 4.4 ± 0.7    | 4.4         | 86%         | 3.34        |

### Notes.

- The percentage of the Pareto diagnostic values that are “good” and “ok” (\( k < 0.7 \)).
- The reduced \( \chi^2 \) is given for the best-fit result with PyMC3.

(see Macciò et al. 2007). The implication of this small concentration on the formation of the galaxy is discussed in Section 5.3.

To constrain the innermost density slope \( \alpha_{\text{innermost}} \) of the dark matter halo, we derived the density profile of dark matter from the rotation curve (de Blok et al. 2001) as shown in Figure 11. Following de Blok et al. (2001) and Oh et al. (2015), we measured \( \alpha_{\text{innermost}} \) by carrying out the least-squares fitting to the density profile within the break radius and defined the error of \( \alpha_{\text{innermost}} \) as the difference between the result including the first data point outside the break radius and the result including only data points within the break radius. Here the break radius is the radius where the density profile shows a maximum change in the slope. If adopting the core radius of the best-fit ISO model as the break radius, \( \alpha_{\text{innermost}} = −(0.96 ± 0.12) \). If adopting the scale radius of the best-fit NFW model as the radius, \( \alpha_{\text{innermost}} = −(0.90 ± 0.08) \). Here the error is given by the least-squares fitting, since the scale radius of the NFW model is larger than the last ring. Two measurements indicate a statistical significance of about 10\( \sigma \) that the dark matter halo of AGC 242019 is cuspy down to a radius of 0.67 kpc.

#### 4.2. The Systematic Uncertainties of the Dark Matter Rotation Curve

The identification of a cuspy profile in AGC 242019 is robust against systematic uncertainties from several aspects.

1. Position and inclination angles. Since these two angles have been set as free parameters during the fitting, their uncertainties have already been included in the derived rotation curve. For comparison, we further estimated the photometric position and inclination angles based on the \( r \)-band image. The galaxy in the \( r \)-band is somewhat asymmetric with clumpy features, but outside the radius of 8\( \text{kpc} \), the position and inclination angles converge to \((2 ± 2)^\circ \) and \((67 ± 3)^\circ \), respectively. These results are consistent with the values derived from the dynamic fitting of the \( \text{H I} \) data, as shown in Figure 5 and listed in Table 2.

2. Mass-to-light ratio in 3.6 \( \mu \text{m} \). The rotation velocity due to stellar gravity is proportional to the square root of the stellar mass-to-light ratio. The overall stellar contribution to the observed rotation curve is small, so our result is not sensitive to the mass-to-light ratio \( \chi_{3.6 \, \mu m} \), as detailed here. The mass-to-light ratio in a broad band is obtained by fitting a synthetic spectrum to the observed spectrum or a broadband spectral energy distribution. The uncertainties of the stellar population synthesis model, the star formation history, the dust extinction, the metallicity, and the initial mass function all result in the variation of the derived mass-to-light ratio.

With the measured stellar mass and SFR of AGC 242019, we assumed a low metallicity with \([\text{Fe/\text{H}}]=-1\) and suppressed asymptotic giant branch (AGB) stars, as seen in some low surface brightness dwarfs (Schombert et al. 2019), to derive the \( \chi_{3.6 \, \mu m} \) of our target to be 0.6 (Schombert et al. 2019). The preceding assumption about AGB stars causes the mass-to-light ratio to be \( \sim 30\% \) larger than that in normal galaxies. The \( \chi_{3.6 \, \mu m} \) is also color-dependent (Bell et al. 2003; Zibetti et al. 2009; Jarrett et al. 2013; Meidt et al. 2014; Shi et al. 2018; Schombert et al. 2019; Telford et al. 2020). As the object is not detected in 4.5 \( \mu \text{m} \), we used the radial variation in \( g − r \) color with a median of 0.3 and standard deviation of 0.03. Converting to \( B − V=0.98 \times (g − r) + 0.22 \) (Jester et al. 2005), the variation in \( \chi_{3.6 \, \mu m} \) is expected to have a standard radial deviation as small as 0.02 dex (Schombert et al. 2019); thus, its effects on the rotation curve of dark matter are negligible.

The systematic uncertainties due to the differences in star formation histories, initial mass functions, and stellar population models among different studies are much larger, even at a fixed color (Bell et al. 2003; Zibetti et al. 2009; Jarrett et al. 2013; Meidt et al. 2014; Schombert et al. 2019; Telford et al. 2020). As a result, we adopted 0.1 dex as the 1\( \sigma \) error to encompass the results in different studies. We then varied
Sky Survey, the error in the distance is dominated by the uncertainty of the Hubble constant and the peculiar velocity. The heliocentric velocity is 2237 km s⁻¹ after correcting for the Virgo, Great Attractor, and Shapley superclusters (Mould et al. 2000). We estimated the residual error to be 100 km s⁻¹, which corresponds to an infalling velocity toward an imaginary dark matter halo with 10¹⁴ M☉ at a separation of 50 kpc. By adopting a local Hubble constant of 73 km s⁻¹ with 2.5% uncertainty (Riess et al. 2016), the distance has a 1σ uncertainty of 5%. We varied this distance by ±3σ to investigate its effect on the dark matter rotation curve. As listed in Table 4 and shown in Figure 12, the cusp-like NFW model is again advocated against the core-like ISO model for both distances.

(4) The scale height of the gas disk. For a thick disk, emissions from adjacent rings are projected to be in the same pixels, which causes beam smearing and affects the measurements of the inclination and position angles. By increasing and decreasing the scale height by a factor of 5 to 500 and 20 pc, respectively, the NFW model is still much better than the ISO model, as shown in Figure 12 and Table 4.

(5) The noncircular motion. As shown in Figure 6, the median amplitude of the residual velocity obtained by 3DBarolo fitting is small, i.e., ≈2 km s⁻¹. During the fitting, the line-of-sight velocities are assumed to be entirely circular motions, while noncircular motions cause the real circular velocity to be underestimated. To quantify the amplitude of noncircular motions, we carried out harmonic decomposition with the GIPSY task RESWRI (Begeman 1989). As detailed in previous studies (Schoenmakers et al. 1997; Trachternach et al. 2008), the line-of-sight velocity of each ring can be decomposed into

\[ v_{\text{los}}(r) = v_{\text{sys}}(r) + \sum_{m=-1}^{N} \left( c_m(r) \cos m \psi + s_m(r) \sin m \psi \right), \]

where \( r \) is the radial distance of each ring from the dynamical center, \( v_{\text{sys}}(r) \) is the system velocity, \( \psi \) is the azimuthal angle in the plane of the disk, and \( v_{\text{los}}(r) = v_{\text{sys}}(r) + c_1(r) \cos \psi \) corresponds to a pure circular motion scenario. In this study, we expanded the velocity up to \( m = 3 \), as has been adopted in other studies (Schoenmakers et al. 1997; Trachternach et al. 2008).

To run RESWRI, we used the 2D velocity field produced by 3DBarolo as the input, fixed the dynamical center and system velocity to those determined by 3DBarolo, and set the rotation velocity, inclination angle, and position angle of each ring as free parameters. With the derived \( c_m \) and \( s_m \), the amplitude of each noncircular harmonic component with \( m > 1 \) is defined as

\[ A_m(r) = \sqrt{c_m^2(r) + s_m^2(r)}, \]

and for \( m = 1 \), where \( c_1 \) is the circular motion,

\[ A_1(r) = \sqrt{s_1^2(r)}. \]

The total amplitude of noncircular motion is given by

\[ A_{\text{tot}}(r) = \sqrt{s_1^2(r) + c_1^2(r) + s_2^2(r) + c_2^2(r) + s_3^2(r) + s_3^2(r)}. \]

The measured harmonic component can be used to quantify the elongation of the potential \( \epsilon_{\text{pot}} \) at each radius as follows:

\[ \epsilon_{\text{pot}} \sin 2 \phi_2 = \frac{(s_3 - s_1)}{c_1(1 - q^4)}, \]

where \( \phi_2 \) is an unknown angle between the minor axis of the elongated ring and the observer in the plane of the ring, and \( q = \cos i \), with \( i \) being the inclination angle of the disk.
Figure 13. Results of harmonic expansion of noncircular motions. (a) Individual $c$ component up to the harmonic order of 3. (b) Individual $s$ component up to the harmonic order of 3. (c) Amplitude of each harmonic order. (d) Total harmonic amplitude. (e) Ratio of the total harmonic amplitude to the circular velocity. (f) Elongation of the potential as described by $\epsilon_{\text{pot}} \sin 2\phi_2$.

Figure 13 shows the result of the harmonic decomposition. As shown in Figure 13(a), the radial $c_m$ fluctuates around 0 km s$^{-1}$ with amplitudes $\lesssim 2$ km s$^{-1}$. The radial $s_m$ shows similar behaviors with amplitudes $\lesssim 2$ km s$^{-1}$. As a result, the $A_m$ of each harmonic component is in general $\lesssim 2$ km s$^{-1}$. Figure 13(d) shows that the total amplitude $A_{\text{tot}}$ is only about 2 km s$^{-1}$. As shown in Figure 13(c), all of the amplitudes are small fractions of the circular velocities at the corresponding radii that are $<15\%$.

Compared to other galaxies with similar absolute magnitudes (Trachternach et al. 2008), AGC 242019 is indeed a galaxy without stronger noncircular motions. Compared to simulated galaxies where noncircular motions result in noticeable underestimations of circular velocities (Oman et al. 2019), the noncircular amplitude of $\sim 2$ km s$^{-1}$ in AGC 242019 is much less than the simulated values of 20–30 km s$^{-1}$. Therefore, we expect that the noncircular motion of AGC 242019 should not affect the derived rotation curve of dark matter. Finally, the derived $\epsilon_{\text{pot}} \sin 2\phi_2$, as shown in Figure 13(f), suggests a spherical gravitational potential.

(6) The triaxiality of a dark matter halo. In this study, a spherical dark matter halo is assumed, while a halo has been found to be moderately triaxial in numerical simulations (Jing & Suto 2002; Bailin & Steinmetz 2005). However, a typical triaxial mass distribution results in only a small deviation in the density from the spherical assumption. Within the scale radius of the halo, the difference is only $10\%$–$20\%$, which is much smaller than the required variation of a factor of 3 to decrease the inner slope by 0.5 (Knebe & Wiel"{e}r 2006). Numerical modeling of the rotation curve further suggests that the halo triaxiality cannot significantly change the shape of the curve to make an intrinsic cusp be a core (or vice versa) in the observed data (Kuzio de Naray et al. 2009; Kuzio de Naray & Kaufmann 2011).

(7) Beam smearing. The tool 3D Barolo takes the beam smearing into account in the tilted-ring fitting (Di Teodoro & Fraternali 2015). It first builds a gas disk in three spatial dimensions and three velocity dimensions, and then it convolves this artificial disk to the observed spatial resolution for comparison with the observed 3D data cube to derive the best-fitting parameters. It has been shown that 3D Barolo is able to recover the rotation curve even at a low spatial resolution, i.e., two resolution elements over the semimajor axis (Di Teodoro & Fraternali 2015). The semimajor axis of AGC 242019 is resolved into $\sim 7$ beams in the H I map. In addition, the H$\alpha$ map has a rebinned spatial resolution (4$''$ in diameter) that is twice as high as that of the H I map. Although our H$\alpha$ clumps are mainly distributed along the major axis with a narrower spatial extent, the overall shape of the H$\alpha$-derived rotation curve is consistent with the H I curve, demonstrating that the beam-smearing effect on the H I rotation curve has been largely removed by 3D Barolo (Di Teodoro & Fraternali 2015).

(8) The contributions from molecular and ionized gas. The very low surface density of AGC 242019 results in a low midplane pressure with $P_{\text{ext}}/k \lesssim 10^3$ cm$^{-3}$ K, which gives a molecular-to-atomic gas ratio of $\lesssim 5\%$ (see their Figure 3 and Equation (12) in studies of nearby galaxies; Blitz & Rosolowsky 2006; Leroy et al. 2008). We also checked that the atomic gas alone is sufficient to place the galaxy in the extended Schmidt law (Shi et al. 2011, 2018), consistent with a negligible fraction of molecular gas.

The ionized gas mass can be estimated from the H$\alpha$ luminosity by $M_{\text{HII}} = m_p \frac{L_{\text{HII}}}{4\pi L_{\text{H}}}$ (Osterbrock & Ferland 2006), where $m_p$ is the proton mass, $L_{\text{HII}}$ is the H$\alpha$ luminosity in erg s$^{-1}$, and $N_e$ is the electron volume density in cm$^{-3}$. By assuming a low $N_e$ of 100 cm$^{-3}$, we found that, even at the peak spaxel as shown in Figure 4(c), an ionized gas mass surface density of 0.025 $M_\odot$ pc$^{-2}$ is too small to affect the derived rotation curve of dark matter.
5. Discussions

Through measurements of the dynamics of atomic and ionized gas, we demonstrate that the dark matter halo of AGC 242019 can be well fitted by the cuspy profile as described by the NFW model while excluding cored models, including ISO and Burkert. Here we discuss its constraints on the alternatives of standard cold dark matter and implications for the role of feedback and formation of UDGs.

5.1. Implications for the Alternatives of Standard Cold Dark Matter

5.1.1. Fuzzy Cold Dark Matter

Through numerical simulations, a halo of fuzzy cold dark matter is found to be composed of a soliton core superposed on an extended halo (Hu et al. 2000; Schive et al. 2014). The latter can be represented by the NFW model, while the former can be approximately described by

\[ \rho_c(r) \approx \frac{1.9(m_\psi/10^{-23} \text{eV})^{-2}(R_c/\text{kpc})^{-4}}{(1 + 9.1 \times 10^{-2}(r/R_c)^2)^{\frac{4}{3}}} \frac{M_\odot}{\text{pc}^{-3}}, \]

where \( m_\psi \) is the particle mass and \( R_c \) is the core radius. The soliton core is linked to the total halo through the core–halo relationship (Schive et al. 2014), which gives

\[ R_c = 1.6(m_\psi/10^{-22} \text{eV})^{-1}(M_\odot/10^9 M_\odot)^{-1/3} \text{kpc}. \]

As shown in Figure 9(b), an NFW model fits the density profile of AGC 24019 very well, which shows negligible residual density for the soliton core to account for. As a result, the possible contribution to the dark matter density from the soliton core should not exceed the observed error at all radii, which can be used to constrain the \( m_\psi \). For each radius, we estimated the density of the soliton core as a function of the particle mass \( m_\psi \) with the best-fit \( M_\odot = (3.5 \pm 1.2) \times 10^{10} M_\odot \) through the above two equations. It is found that the measurements at the innermost two radii give the strongest constraints on \( m_\psi \). The 3\( \sigma \) observed errors at two radii constrain the \( m_\psi \) range to be \( 0.06 \times 10^{-22} \) or \( 2.7 \times 10^{-22} \text{eV} \). Compared to the constraint from the Ly\( \alpha \) forest, which \( m_\psi < 1.0 \times 10^{-22} \) or \( 2.3 \times 10^{-22} \text{eV} \), the dynamics of AGC 242019 gives a factor of about 20 times smaller constraint on the upper bound of the lower range. As shown in Figure 14(a), if adopting the 3% HPD halo mass of \( 1.5 \times 10^{10} M_\odot \), \( m_\psi < 0.11 \times 10^{-22} \) or \( 3.3 \times 10^{-22} \text{eV} \), whose upper bound of the lower range is still 10 times lower than the constraint by the Ly\( \alpha \) forest. If somehow our error is underestimated by a factor of 2, the upper bound of the lower range only increases by a factor of \( \sim 1.6 \), and the lower bound of the upper range decreases by a factor of \( \sim 1.2 \). Therefore, the constraint by AGC 242019, along with the one from the Ly\( \alpha \) forest, is inconsistent with the typical \( m_\psi \) of \( \sim 10^{-22} \text{eV} \) that is required to explain the dynamics of other galaxies with cored dark matter halos (Hu et al. 2000; Schive et al. 2014). It is thus found that there is no \( m_\psi \) value that can reconcile all of the observational facts.

5.1.2. Self-interacting Dark Matter

Self-interacting dark matter transmits kinetic energy from the outer part inward to form a constant density core. For the interaction to be efficient, the scattering rate per particle should be important, that is, at least once over the galaxy age (Spergel & Steinhardt 2000; Rocha et al. 2013; Tulin & Yu 2018),

\[ \Gamma(r) \tau_{\text{age}} \approx \rho(r)(\sigma/m)v_{\text{rms}}(r)\tau_{\text{age}} \sim 1, \]

where \( \Gamma(r) \) is the scattering rate per particle, \( \rho(r) \) is the dark matter density at a radius of \( r \), \( \sigma/m \) is the section per particle mass, and \( v_{\text{rms}} \) is the relative velocity of dark matter particles. The above equation can be rewritten as

\[ \frac{\sigma/m}{\Gamma \text{ cm}^2 \text{ g}^{-1}} \approx \left( \frac{9.2 \text{ Gyr}}{\tau_{\text{age}}} \right) \left( \frac{0.01 M_\odot \text{ pc}^{-3}}{\rho(r)} \right) \left( \frac{50 \text{ km s}^{-1}}{v_{\text{rms}}} \right). \]

For AGC 242019, the NFW model fits the rotation curve well down to the innermost radius. This sets the upper limit to the radius of a possible density core and the lower limit to the above \( \rho(r) \) if dark matter is self-interacting in AGC 242019. If the halo forms around \( z = 2 \), we get \( \tau_{\text{age}} = 10 \text{ Gyr} \). The \( v_{\text{rms}} \) is set to be the virial velocity at the virial radius, which is \( 47 \text{ km s}^{-1} \). We have \( \sigma/m < 1.63 \text{ cm}^2 \text{ g}^{-1} \) for AGC 242019.

As shown in Figure 14(b), existing studies prefer somewhat larger \( \sigma/m \) on galaxy scales (Zavala et al. 2013; Elbert et al. 2015; Kaplinghat et al. 2016) and smaller values on cluster scales (Randall et al. 2008; Harvey et al. 2015; Kahlhoefer et al. 2015; Kaplinghat et al. 2016). Such a velocity dependence of the cross section seems to reconcile the results over different scales (Kaplinghat et al. 2016). However, the cuspy dark matter halo of AGC 242019 may challenge this simple picture, whose upper limit on \( \sigma/m \) is somewhat in tension with the lower bound of the \( \sigma/m \) range as required by cored halos of other dwarf galaxies.

5.1.3. Warm Dark Matter

In warm dark matter, the density core has a size that can be approximately by Hogan & Dalcanton (2000) and Macciò et al. (2012),

\[ r_{\text{core}}^2 = \frac{\sqrt{3}}{4\pi Q_{\text{max}}} \frac{1}{v_{\text{rms}}^2 0.5}, \]

where \( v_{\text{rms}} \) is the velocity dispersion (i.e., the mass) of the halo. Here \( Q_{\text{max}} \) is the maximum phase density as given by

\[ Q_{\text{max}} = 1.64 \times 10^{-3} \left( \frac{\rho_1}{\rho_\alpha} \right) \left( \frac{m}{\text{keV}} \right)^{4} \frac{M_\odot}{\text{pc}^{-3}} (\text{km s}^{-1})^{0.5}. \]

where \( m \) is the mass of warm dark matter, and \( \rho_1/\rho_\alpha \) is the local density relative to the critical density:

\[ \frac{m}{\text{keV}} = 0.37 \left( \frac{1}{\rho_1/\rho_\alpha} \right)^{0.25} \left( \frac{\text{kepc}}{r_{\text{core}}^{0.5}} \right) \left( \frac{\text{km s}^{-1}}{v_{\text{rms}}^{0.5}} \right)^{0.25}. \]

As shown in Figure 14(c), the innermost radius of the cuspy halo of AGC 242019 leads to \( m > 0.23 \text{ keV} \). The figure also includes the constraints from the LITTLE THINGS galaxies (Oh et al. 2015) that are derived from the core radius and the velocity at the outermost measurable radius listed in their Table 2. It seems that there is no consistent mass range that can explain all observational facts. Warm dark matter is known to have a “catch-22” problem: the requirement for the particle mass to solve the cusp–core problem will result in no formation of small galaxies in the first place. Our discovery of a cuspy dark matter halo in AGC 242019 will further challenge the warm dark matter scenario such that, even on kiloparsec scales,
5.1.4. The Modified Newtonian Dynamics

Unlike massive disk galaxies whose baryonic disk surface density rises exponentially toward their galactic centers, AGC 242019 shows a much flatter profile with a density deficit in the central region. Such a distinct spatial offset between the baryonic matter and the dynamical mass leads to increasing baryonic matter relative to dark matter at larger radii, in contrast to galaxies in general. This can be quantified by the logarithmic relationship between the observed and baryonic radial acceleration, as shown in Figure 14(d). From inner (smaller symbols) to outer (larger symbols) radii, the data are closer to the no dark matter line, demonstrating the increasing baryonic matter relative to the dark matter at larger radii.

The modified Newtonian dynamics (MOND) paradigm (Milgrom 1983) has been proposed as an alternative to dark matter theory for interpreting dynamical features. However, MOND cannot explain the dynamics of AGC 242019 as specified by the radial acceleration relationship shown in Figure 14(d). The relationship has a slope of 0.15 ± 0.11, as given by the linear fitting of the data with errors on both axes (Kelly 2007). However, the MOND only allows a slope ranging from 1.0 in the classical regime to 0.5 at the low acceleration limit by adjusting its fundamental constant $a_0$. The slope of AGC 242019 is thus 3.2σ below the threshold in the MOND, although it lies on the extrapolation of the relationship defined by late-type galaxies (Lelli et al. 2017).

5.2. Implications for the Role of Feedback in Producing Cored Dark Matter Halos

It is found that the effect of baryonic feedback on the density profile of dark matter depends on the stellar-to-halo mass ratio ($M_*/M_{\text{halo}}$, e.g., Di Cintio et al. 2014; Tollet et al. 2016), as shown in Figure 15. In the low-$M_*/M_{\text{halo}}$ regime ($<0.01\%$), the feedback is not strong enough to expel baryons, and no dark matter core forms. In the high $M_*/M_{\text{halo}}$ regime ($>3\%$), the significant contribution to the potential from baryonic matter cancels out the feedback effect and even produces a...
Besides the star formation threshold, the duration of star formation may also be important, as recognized in some simulations (Read et al. 2016a). As long as star formation proceeds long enough, e.g., $\sim 10$ Gyr for a halo mass of $10^9 M_\odot$, and a longer timescale for a larger halo, a halo core always forms. The UDG AGC 242019 has a halo mass of $(3.5 \pm 1.2) \times 10^{10} M_\odot$, and its low concentration implies a late formation time (see next section), which may explain its cuspy profile given the above scenario.

5.3. Implications for Formation of UDGs

The UDGs are low stellar mass dwarfs but with sizes typical of spiral galaxies (Abraham & van Dokkum 2014; Leisman et al. 2017). They are found in all environments, including galaxy clusters, galaxy groups, and the field. Many mechanisms have been proposed to understand their origin: they may be normal dwarf galaxies but experience star formation feedback that redistributes gas and stars to larger radii (Governato et al. 2010; Di Cintio et al. 2014; Jiang et al. 2019), they may live in a high-spin dark matter halo with extended gas distributions and low efficiencies in converting gas into stars (Amorisco & Loeb 2016), and some environmental effects, such as ram pressure stripping or tidal puffing, may be important in their formation (Yozi & Bekki 2015; Jiang et al. 2019).

The dark matter halo of AGC 242019 has a mass of $(3.5 \pm 1.2) \times 10^{10} M_\odot$, which is typical of a halo hosting a dwarf. This suggests that AGC 242019 is not a failed massive galaxy, unlike other UDGs found in clusters (Beasley et al. 2016; van Dokkum et al. 2016). Although UDGs may have diverse origins, our measurements are more reliable. In the studies of Beasley et al. (2016) and van Dokkum et al. (2016), the halo mass was inferred from one to two velocity data points by assuming a halo concentration.

The cuspy halo of AGC 242019 also suggests that the feedback has not been strong enough over its history to expel a large amount of baryonic matter to large distances. Otherwise, a cored halo should have already formed, like in other dwarf galaxies, as suggested by feedback models (Navarro et al. 1996; Governato et al. 2010). Thus, AGC 242019 has experienced weak feedback over its history. This seems to be consistent with the deviation of UDGs from the Tully–Fisher relationship; gas and stars are not expelled out of the disk, so that a UDG contains more baryons at a given maximum circular velocity that roughly represents the halo mass (Mancera Piña et al. 2020). The UDG AGC 242019 has a maximum circular velocity of $47$ km s$^{-1}$ and a baryonic mass of $(9.88 \pm 0.36) \times 10^8 M_\odot$, placing it slightly above the Tully–Fisher relationship too. With the accurate measurement of the halo mass, AGC 242019 is found to be off both the $M_\ast$ versus $M_{\text{halo}}$ and $M_{\text{baryon}}$ versus $M_{\text{halo}}$ relationships (Santos-Santos et al. 2016). The low SFR of AGC 242019 also suggests weak ongoing stellar feedback as implied by the relationship between the SFR and the ionized gas velocity dispersion (e.g., Yu et al. 2019). Our regular velocity field with small noncircular motion, as shown in Section 4.2, is consistent with weak ongoing feedback too.

The halo of AGC 242019 has a small concentration of $2.0 \pm 0.36$, which is much smaller than the median concentration of 15 at the same halo mass in the local universe, as expected from simulations (Macciò et al. 2007). This difference is most likely because AGC 242019 is an isolated halo that originated from a tiny initial density peak in early times and
collapsed recently. It is found that the halo concentration decreases with a later formation time (Zhao et al. 2003; Lu et al. 2006). A “young” halo thus suggests late formation of AGC 242019, as compared to dwarf irregulars (Butler et al. 2017). However, as discussed before, AGC 242019 has a higher baryon/halo mass ratio as compared to galaxies in general. We derived the halo masses of dwarf irregulars following Butler et al. (2017) and compared them with AGC 242019. As shown in Figure 16(b), AGC 242019 still has a similar specific angular momentum at a given halo mass as compared to the average of dwarf irregulars. The result may be against the model that a UDG forms in a high-spin dark matter halo (Amorisco & Loeb 2016).

As shown in Section 5.2, AGC 242019 has a low star formation efficiency, consistent with the model of Amorisco & Loeb (2016). If placing it on the extended star formation law (Shi et al. 2011, 2018), we found that AGC 242019 follows the law as shown in Figure 16(c). This suggests that its low star formation efficiency is regulated by its low stellar mass surface density.

In summary, AGC 242019 forms in a dwarf-sized halo with late formation time. It has weak feedback, low star formation efficiency, and a normal specific angular momentum of baryons at a given halo mass.

### 6. Conclusions

We have carried out the spatially resolved mapping of gas dynamics toward a nearby UDG, AGC 242019. It is found that AGC 242019 has a cuspy dark matter halo at a high confidence, which demonstrates the validity of the cold dark matter paradigm on subgalactic scales. Our main conclusions are as follows.

1. The UDG AGC 242019 has an overall regular velocity field. After subtracting the baryonic contribution, the rotation curve of dark matter is well fitted by the cuspy profile as described by the NFW model, while the cored profiles, including both the ISO and Burkert models, are excluded. The result is robust against various systematic uncertainties.

2. The central density slope of the dark matter halo is found to be \(-0.90 \pm 0.08\) at the innermost radius of 0.67 kpc.

3. The UDGS AGC 242019 poses challenges to alternatives of standard cold dark matter by constraining the particle mass of fuzzy dark matter to be \(<0.11 \times 10^{-22}\) or \(>3.3 \times 10^{-22}\) eV, the cross section of self-interacting dark matter to be \(<1.63 \text{ cm}^2 \text{ g}^{-1}\), and the particle mass of warm dark matter to be \(>0.23\) keV, all of which are in tension with other constraints.

4. The UDGS AGC 242019 lies on the extrapolation of the radial acceleration relationship as defined by spirals and dwarf galaxies. However, the slope of the relationship defined by AGC 242019 is \(0.15 \pm 0.11, 3.2\sigma\) below the threshold (0.5) of the MOND.

5. In the cold dark matter paradigm, the cuspy halo of AGC 242019 supports the feedback scenario that transforms cuspy halos to cored halos, as frequently seen in other galaxies. However, the detailed physical process is unclear. The cuspy halo of AGC 242019 is inconsistent with the stellar-to-halo mass ratio dependent model and consistent with the star formation threshold dependent model. But even for the latter, the observed star formation efficiency (SFR/gas) is much lower than what is adopted in simulations. It may be consistent with the scenario that the duration of star formation is the key driver.

6. As a UDG, AGC 242019 has a halo mass of \((3.5 \pm 1.2) \times 10^{10} M_\odot\), implying its formation in a dwarf-sized halo. The
Appendix A
The Full Setup to Run 3DBarolo

In Table A1, the full list of parameters to run 3DBarolo is given.

Table A1
The Full Parameter List for 3DBarolo

| Parameters | Values |
|------------|--------|
| Checking for bad channels in the cube [checkChannels] | False |
| Using Robust statistics? [flagRobustStats] | True |
| Writing the mask to a fitsfile [MAKEMASK] | False |
| Searching for sources in cube? [SEARCH] | False |
| Smoothing the data cube? [SMOOTH] | False |
| Hanning smoothing the data cube? [HANNING] | False |
| Writing a 3D model? [GALMOD] | False |
| Fitting a 3D model to the data cube? [3DFIT] | True |
| Number of radii [NRADII] | 7 |
| Separation between radii (arcsec) [RADSEP] | 9 |
| X center of the galaxy (pixel) [XPOS] | 415.19 |
| Y center of the galaxy (pixel) [YPOS] | 405.49 |
| Systemic velocity of the galaxy (km s$^{-1}$) [VSYS] | 1840.46 |
| Initial global rotation velocity (km s$^{-1}$) [VROT] | 30 |
| Initial global radial velocity (km s$^{-1}$) [VRAD] | $-1$ |
| Initial global velocity dispersion (km s$^{-1}$) [VDISP] | 5 |
| Initial global inclination (deg) [INC] | 69.90 |
| Initial global position angle (deg) [PA] | 2.0025 |
| Scale height of the disk (arcsec) [Z0] | 0.7 |
| Global column density of gas (atoms cm$^{-2}$) [DENS] | $-1$ |
| Parameters to be minimized [FREE] | VROT, VDISP, PA, INC |
| Type of mask [MASK] | SEARCH |
| Side of the galaxy to be used [SIDE] | B |
| Type of normalization [NORM] | LOCAL |
| Layer type along $z$ direction [LTYPE] | Gaussian |
| Residuals to minimize [FTYPE] | $\chi^2$ |
| Weighting function [WFUNC] | Uniform |
| Weight for blank pixels [BWEIGHT] | 1 |
| Minimization tolerance [TOL] | 0.001 |
| What side of the galaxy to be used [SIDE] | B |
| Two stages minimization? [TWOSTAGE] | True |
| Degree of polynomial fitting angles? [POLYN] | Bezier |
| Estimating errors? [FLAGERRORS] | True |
| Redshift of the galaxy? [REDSHIFT] | 0 |
| Computing asymmetric drift correction? [ADRIFT] | True |
| Overlaying mask to output plots? [PLOTMASK] | False |
| rms noise to add to the model [NOISERMS] | False |
| Using cumulative rings during the fit? [CUMULATIVE] | False |
| Full parameter space for a pair of parameters [SPACEPAR] | False |
| Generating a 3D data cube with a wind model? [GALWIND] | False |
| Fitting velocity field with a ring model? [2DFIT] | False |
| Deriving radial intensity profile? [ELLPROF] | False |

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Figure B1. Comparison in the derived rotation velocities and velocity dispersions by using both sides, only the receding side, and only the approaching side of the H I data.

Appendix B

Different Runs of 3DBarolo

In Figure B1, we compare the derived rotation velocities (before the pressure support correction) and velocity dispersions by running 3DBarolo with both sides of the gas disk, only the receding side, and only the approaching side.

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