



Modeling the “Dark-matter Dominated” Dwarf Galaxy Segue 1 with a Supermassive Black Hole

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Abstract

The dwarf spheroidal galaxy, Segue 1, is thought to have one of the largest ratios of dark matter to stellar mass. Using orbit-based dynamical models, we model Segue 1, including a dark halo and a central black hole. The best-fit model requires a black hole mass of $4.5 \pm 1.5 \times 10^5 M_\odot$. The value of the black hole mass is similar either with or without a dark halo. The mass-to-light ratio of the stars is poorly constrained by the dynamical modeling, reflecting that Segue 1 is dominated by mass other than stars. Dynamical models that exclude a black hole provide a worse fit and require a dark halo with very-small-scale radii of below 100 pc. Additionally, the zero black hole models require a stellar orbital distribution that is highly radially biased. The model with a black hole provides an orbital structure that is close to isotropic, more similar to other well-studied systems. We argue that the two-parameter models of stars and black hole provide a better description of Segue 1 than the three-parameter models of stars and two dark halo components. Additional support for a central black hole comes from a significant increase in the central rotation. Using individual velocities, we measure a rotation amplitude of $9.0 \pm 2.4 \text{ km s}^{-1}$. Segue 1 is likely being tidally stripped at large radii, and we might be witnessing the remnant nucleus of a more massive system. Alternatively, given the high black hole mass relative to the stellar mass, Segue 1 is analogous to the Little Red Dots seen in the early Universe.

Unified Astronomy Thesaurus concepts: [Black holes \(162\)](#)

1. Introduction

Dark matter and black holes play critical—and often overlapping—roles in galactic dynamics. Though neither directly radiates electromagnetically, they both can determine the motions of bodies that emit light in the vicinity of their strong gravitational potentials. This work illustrates a dynamical modeling approach for disentangling these two influences in a subtle case, the dwarf galaxy Segue 1.

A substantial part of the mass-energy budget of the observable Universe is a gravitationally attractive component dark matter that does not interact with other fundamental particles in the Standard Model yet is thought to play a dominant role in the formation of galactic structure (W. H. Press & P. Schechter 1974; J. F. Navarro et al. 1996). Dark matter, roughly 6 times as abundant as its baryonic matter counterpart, is theorized to undergo self-interactions within the dark sector (D. N. Spergel & P. J. Steinhardt 2000) and may even convert from the dark to visible sector and back via high-energy processes such as photon-paraphoton kinetic mixing in astrophysical contexts (R. Anantua & O. K. Baker 2010). The detailed nature of dark matter, whether sub-electron-volt axion particles (R. D. Peccei 2008) or asteroid-mass primordial black holes (B. Curd et al. 2024) or yet larger massive compact halo objects (C. Alcock et al. 2000), is an active

research area. Though cosmological simulations of large-scale structure formation are agnostic to the subgrid nature of dark matter, dynamical modeling of relatively small systems, such as the dwarf spheroidal galaxies, may reveal stark observational signatures of dark halos and the nature of the dark matter particle (J. S. Bullock & M. Boylan-Kolchin 2017). For a more comprehensive understanding of dark matter and its role in galactic dynamics, see, e.g., T. A. Porter et al. (2011), G. Bertone & D. Hooper (2018), E. G. M. Ferreira (2021), and B. Carr & F. Kuhnel (2022).

Another part of the mass-energy budget in the observable Universe is black holes, with both strong support from theory and observations. For a nonrotating mass distribution, a black hole of mass M_{BH} is formed when the mass is contained within its Schwarzschild horizon $r_s = \frac{2GM_{\text{BH}}}{c^2} \equiv 2M$ (for rotating black holes, the outer horizon lies between 1 and $2M$). Given that the black hole radius scales linearly with its mass, the average density contained within the horizon scales as $1/M_{\text{BH}}^2$ is an easy requirement for the vast majority of galaxies to satisfy in order to contain central supermassive black holes (SMBHs). Our trillion solar mass Milky Way is an average-sized galaxy that hosts a 4 million $M_\odot$ SMBH, Sagittarius A*, at the Galactic center (A. M. Ghez et al. 2008; S. Gillessen et al. 2009; GRAVITY Collaboration et al. 2022). Though compact, the central black hole has an outsized impact on galactic dynamics, with the mass tightly related to galaxy properties, e.g., stellar velocity dispersion via the M – σ relation $M_{\text{BH}} \propto \sigma^4$ (L. Ferrarese & D. Merritt 2000; K. Gebhardt et al. 2000a) and serving as a central engine governing active galactic nucleus feedback. For dwarf galaxies, or globular clusters containing thousands to millions of stars, black holes

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Table 1
Observed Properties of Segue 1 from Key Studies

Parameter	Value	Sources
D (kpc)	23 ± 2	V. Belokurov et al. (2007)
R.A. (hh:mm:ss)	$10:07:03.2 \pm 1.7$	N. F. Martin et al. (2008)
Decl. (deg:arcmin:arcsec)	$+16:04:25 \pm 15$	N. F. Martin et al. (2008)
PA (deg)	85 ± 8	N. F. Martin et al. (2008)
$E(B - V)$ (mag)	0.034	N. F. Martin et al. (2008)
ϵ	$0.48^{+0.10}_{-0.13}$	N. F. Martin et al. (2008)
r_h (arcmin)	$4.4^{+1.2}_{-0.6}$	N. F. Martin et al. (2008)
M_V (mag)	$-1.5^{+0.6}_{-0.8}$	N. F. Martin et al. (2008)
$L_V(L_\odot)$	340	J. D. Simon et al. (2011)
$\mu_{V,0}$ (mag arcsec $^{-2}$)	$27.6^{+1.0}_{-0.7}$	N. F. Martin et al. (2008)
M ($M_\odot$)	$5.8^{+8.2}_{-3.1} \times 10^5$	J. D. Simon et al. (2011)
M/L_V ($M_\odot/L_\odot$)	3400	J. D. Simon et al. (2011)
N_*	65 ± 9	N. F. Martin et al. (2008)
v_{hel} (km s $^{-1}$)	206.4 ± 1.3	M. Geha et al. (2009)
v_{GSR} (km s $^{-1}$)	114 ± 2	M. Geha et al. (2009)
σ (km s $^{-1}$)	$3.7^{+1.4}_{-1.1}$	J. D. Simon et al. (2011)
[Fe/H] (dex)	-3.3 ± 0.2	M. Geha et al. (2009)

from stellar remnants may partake in multibody dynamical interactions either accreting or ejecting most of the black holes. There is a handful of cases with black holes in these low-mass systems (K. Gebhardt et al. 2002; N. Lützgendorf et al. 2013; M. J. Bustamante-Rosell et al. 2021), although some of the results remain controversial.

The dwarf spheroidal galaxy Segue 1 was one of the Milky Way satellite galaxies discovered by the Sloan Digital Sky Survey in the optical+IR (V. Belokurov et al. 2007) as part of the Sloan Extension for Galactic Understanding and Exploration (H. J. Newberg & Sloan Digital Sky Survey Collaboration 2003). J. D. Simon et al. (2011) provide stellar radial velocities and show that Segue 1 is dominated by mass other than stars. They infer a dynamical mass-to-light ratio that is over 1000, which remains the largest ratio measured. Being the most dark-component-dominated galaxy, Segue 1 becomes an essential object to understand the properties of dark matter halos, since the dark matter halo should suffer limited effects from baryonic processes.

Our approach in this Letter is to model Segue 1 with dynamical models that have limited assumptions. It is important to consider mass components that we know exist in the Universe based on observations, like stars and black holes, in addition to components that are strongly understood to exist, like dark matter.

We use a distance to Segue 1 of 23 kpc, where 1' equals 6.66 pc. For more Segue 1 parameters, see Table 1.

2. Observational Properties of Segue 1

Typically for dynamical models of diffuse sources, one would measure a surface brightness profile representing the distribution of the tracer light. In the case of Segue 1, the object is so sparse on the sky that we must rely on number counts. M. Niederste-Ostholt et al. (2009) provide stellar number counts. To separate the Segue 1 stars from the galactic stars, they rely on colors, and the low metallicity of Segue 1 helps to discriminate. M. Niederste-Ostholt et al. (2009) provide number counts ranging from 1' to 9'.

A consideration for Segue 1 is that it is being tidally stripped by the Galaxy. The stars in the tidal streams are not dynamically

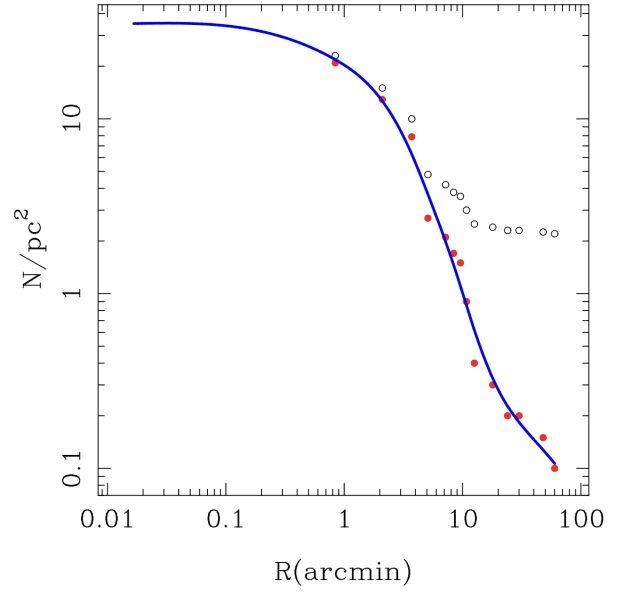


Figure 1. The projected number count profile for Segue 1. The open circles are the data from M. Niederste-Ostholt et al. (2009). The solid red circles represent the data after subtraction of the tidal effects. The blue line is the smoothing spline that we use for the deprojection.

bound to Segue 1 and should be removed from the dynamical analysis and hence, the number density profile. We assume a uniform density for the tidal stream. The number density at the farthest radial extent determines this uniform value, where we use two stars per squared parsec subtracted at all positions. A similar analysis is discussed in M. J. Bustamante-Rosell et al. (2021), where they focus on Leo 1. They find tidal subtraction has little effect on the central kinematics since the amount of light subtracted in the central regions is around 10%. The situation is similar for Segue 1. While the tidal model used for subtraction will have little consequence for the central mass profile, it is critical for a robust model of the dark matter halo.

In addition to the larger radii correction to the number counts from the tidal effects, we have to extrapolate the number density into the central regions. This extrapolation is required for the dynamical models in order to understand the tracer population distribution in the center. The amount of mass in stars within the extrapolated region is small enough that it will have an insignificant effect on the mass profile.

Figure 1 shows the estimated projected number density profile using the data from M. Niederste-Ostholt et al. (2009). The open symbols are the observed values, the red solid points are the values after the subtraction of the tidal feature, and the line is our smoothed estimate where we show the extrapolation into the central region. We follow the same method of smoothing and deprojection of the number density profile as outlined in K. Gebhardt et al. (1996), where they provide a nonparametric estimate of the 3D density profile given the projected profile.

2.1. Stellar Kinematics

Stellar kinematics come from J. D. Simon et al. (2011). In that paper, they carefully select members of Segue 1 using their spectra taken with high resolving power, which they also use for the radial velocity measurements. There are 71 members extending out to 13', although for the modeling,

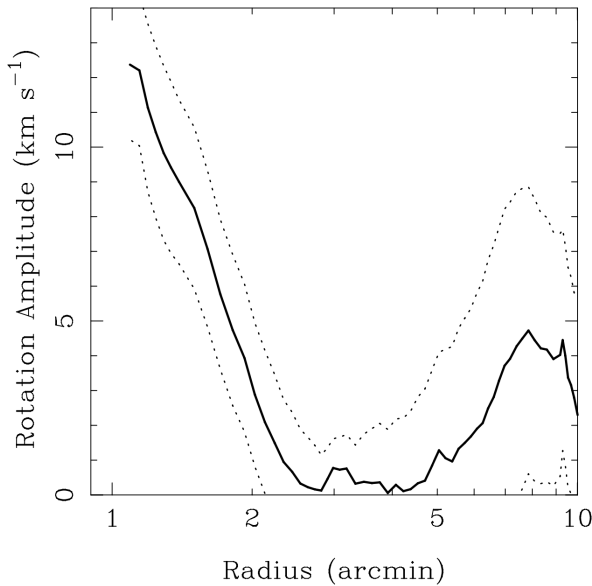


Figure 2. Amplitude of the rotation as a function of radius. We use radial bins of 21 stars for most of Segue 1, going to a minimum of 15 stars at the center and outer bins. In each radial bin, we fit a sinusoid as a function of position angle and plot the amplitude of the fit. The thick solid line represents that amplitude, and the dotted lines represent the 68% confidence bands. There is a large rise in the rotation in the central region, significant at over 99%. Beyond 2', there is no significant rotation.

we require an assumed mass density out to 60'. J. D. Simon et al. (2011) bin the velocities into five radial bins and measure the velocity dispersion. The most robust approach, which we adopt here, is to use the full line-of-sight velocity distribution, with the same spatial bins as the dynamical models. We generate velocity profiles from the individual velocities using an adaptive kernel estimate (B. Silverman 1986) as explained in detail in K. Gebhardt et al. (1996). For the 71 velocities, we use six spatial bins. This binning assures that we have enough sources for a robust determination of the uncertainties and have enough spatial information to properly resolve the dynamical signal. We have also run models using the dispersions as provided by J. D. Simon et al. (2011); we find similar results although with larger uncertainties on the black hole mass due to the larger central bin.

2.2. Central Rotation

Segue 1 demonstrates a large and significant increase in rotation in the central region. Figure 2 shows the rotation amplitude as a function of radial bins. We use a similar analysis as in K. Gebhardt et al. (1995), where we fit a sinusoid to the individual velocities in an annulus. For the majority of radial bins, we use 21 individual stars for the fit, and we go down to 15 stars at the central outer edges. The amplitude of the sinusoid fit is the rotation velocity. We use a least-squared minimization for the fit and a Monte Carlo for the 68% uncertainties. The thick black line in Figure 2 is the velocity amplitude, and the dotted lines represent the 68% uncertainties. The velocity amplitude rises to over 10 km s⁻¹ at 1', coming from 15 individual velocities. The smallest annulus where we have 21 stars is at 1.4'. That annulus provides a rotation amplitude of 9.0 ± 2.4 km s⁻¹, with a significance of rotation above 99%. Going down to smaller radial bins with

the number of stars less than 15 shows a continual increase in rotation up to 14 km s⁻¹.

J. D. Simon et al. (2011) measure a velocity dispersion of Segue 1 of 4 km s⁻¹. A rotational amplitude of 9–14 km s⁻¹ in the central region is a dramatic increase. The two main options for generating such a large rotation increase is either (1) a large rise in the central density or (2) that Segue 1 is being tidally destroyed in a systematic way into the center.

3. Dynamical Modeling

We use orbit-based models as originally described by M. Schwarzschild (1979). These models provide the most general solution assuming axisymmetry and dynamical equilibrium. There are multiple examples and tests for these models, and they have been heavily used (K. Gebhardt et al. 2000b; C. Siopis et al. 2009; R. C. E. van den Bosch et al. 2012). The models presented here are the same as those used in K. Gebhardt et al. (2000b).

For these models, we assume a gravitational potential, sample the stellar orbital phase space, and then fit orbital weights that provide the best match to the kinematic data. We change the gravitational potential, repeat the process, and find the goodness of fit for each potential. We generally run about 20k orbits for each model. The goodness of fit is the χ^2 of the model and data. The most important aspect of these models is to make sure phase space is sampled both in range and density of parameters. Other state-of-the-art models are Jeans analysis with various assumptions like Jeans anisotropic modeling (M. Cappellari 2008) and action integral as applied to the Galaxy (J. Binney & E. Vasiliev 2023). We focus on the orbit-based models as they are the most general.

3.1. Modeling Results

As inputs to the dynamical models, we require the density distribution of the tracer population, the kinematics for the tracer population, and the profile for a particular gravitational potential. Instead of a nonparametric gravitational potential, we use four parameters: the stellar-mass-to-light ratio, black hole mass, dark matter circular velocity, and dark matter scale radius. The dark matter profiles are a cored logarithmic, which is often used in galaxy models. M. J. Bustamante-Rosell et al. (2021) find that the cored-logarithmic provides a better fit than a Navarro–Frenk–White (J. F. Navarro et al. 1997) for the dwarf spheroidal galaxy, Leo 1, which is a similar object to Segue 1.

$\Phi_{\text{tot}}(r) = \Phi_{\text{stars}}(r) + \Phi_{\text{DM}}(r) + \Phi_{\text{BH}}(r)$ (M. J. Bustamante-Rosell et al. 2021) defines the gravitational potential of stars, dark matter, and black hole, respectively. We then sample orbits over the available phase space. By forcing the fit to the density profile of the tracer population, we impose consistency between the input stellar profile and the output tracer profile. The fit to the kinematic data provides the one-number goodness of fit, in terms of χ^2 , for each attempted model. Sampling the four parameters, we run about 20,000 models.

Figure 3 shows the χ^2 versus each of the four parameters. The top left plots the stellar-mass-to-light ratio, top right is the black hole mass in solar units, bottom left is dark matter halo circular velocity in kilometers per second, and bottom right is dark halo scale radius in kiloparsecs. Each panel plots all attempted models, which is why the points cover much of the

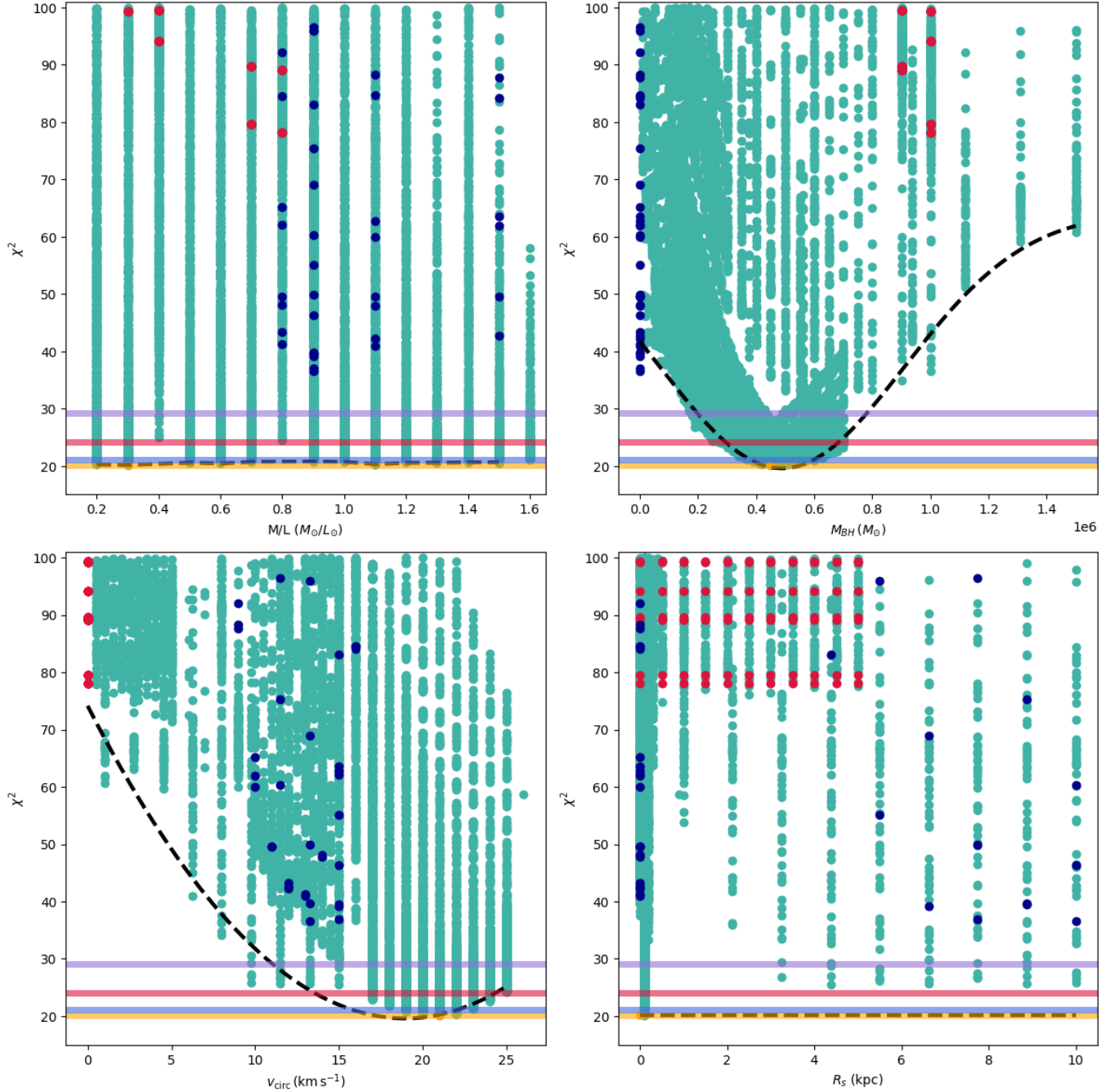


Figure 3. χ^2 vs. each of the four parameters. The top left is stellar-mass-to-light ratio, the top right is black hole mass in solar masses, the bottom left is dark matter circular velocity, and bottom right is dark matter scale radius. In each panel, we plot all models, and a contour along the bottom in χ^2 determines the best-fit value and the uncertainty. The red points highlight those models that have no dark halo, and the blue points highlight those models that have no black hole. The green points are the other models that vary all four parameters. The shaded horizontal regions indicate σ values ranging from 0 to 3. The dashed line represents a best fit.

region. In order to provide the best-fit value and uncertainty, one would use a trace along the bottom of the χ^2 contour.

In this figure, we highlight models where there is no dark halo as red points and those with no black hole as blue points. This distinction is important for interpretation of the results and orbital structure.

3.2. Models with No Black Hole

A three-parameter fit of the stellar M/L , dark matter circular velocity, and dark matter scale radius provides an adequate fit

only when allowing for a dark halo scale radius that is small. In that case, the dark matter profile begins to mimic a centrally concentrated object. The density of the dark matter in these models reaches $2.4 M_{\odot} \text{pc}^{-3}$. Allowing for high central dark matter (DM) densities causes the outer radial kinematics to have a poor fit. K. Hayashi et al. (2023) also find a high central density for Segue 1, measuring a radial density profile that is steeper than all other dwarf galaxies. If we use a dark matter profile that is more typical than what has been used for these systems, we find a model that has a significantly worse fit. In order to provide an even higher central DM density, we would

Table 2
Analysis Results

Parameter	Best Fit	Parameter Domain
$M_{\text{BH}} (M_{\odot})$	4.5×10^5	$0 - 1.5 \times 10^6$
$M/L (M_{\odot}/L_{\odot})$	0.3	0.2–20
$R_s(\text{kpc})$	1	0–10
$V_{\text{circ}} (\text{km s}^{-1})$	21	0–26

Note. The “parameter domain” column indicates the range of initial parameters explored; subsequent runs focused on the area that produced the best fit.

have to employ a new parameterized model for the dark matter. Our point in this work is to show that instead of generating a new DM profile, a simple alternative is to include a central mass concentration, such as a black hole.

Using the cored-logarithmic profile, there is little to constrain the actual overall DM mass. Basically, the scale radius and the circular velocity are degenerate, and we have no constraint on the upper mass limit. We find a similar result using an NFW model. For NFW, the χ^2 is slightly worse with an increase of four, but the need for a high central density remains. As we discuss, we can provide a robust measure of the central mass density and little constraint on the outer mass density.

3.3. Models with a Black Hole

Models varying the black hole, dark halo, and stellar-mass-to-light are shown as the green points in Figure 3. In the top-left panel, one notices that the stellar-mass-to-light ratio is unconstrained and goes down to zero. The implications are that the stars contribute little to nothing of the gravitational potential. A high density sampling of the black hole mass around a value of zero for the stellar mass can be seen as the extensions for dark matter circular velocity of 15 km s^{-1} and scale radius of 0.5 kpc. This high density sampling does not change the best-fit black hole mass. We do not explore these models further since we know that stars have mass, and we should at least include a contribution of the stars to the gravitational potential.

In order to estimate the best-fit values and the uncertainties, we trace the bottom of the χ^2 plots in these four panels. The red points on the plots show models with no dark halo. While they provide a worse fit, they require an even larger black hole mass. This increase can be understood as the need to have additional mass to compensate for the lack of dark halo. The black hole mass we infer is $4.5 \pm 1.5 \times 10^5 M_{\odot}$. The uncertainty is 1σ , which is 68% confidence when marginalized over the other three parameters. The uncertainties on the dark matter parameters are poorly constrained. The main takeaway from the dark matter profile is that (1) the steep central density profile is hard for the cored-logarithmic or NFW to reproduce and (2) the parameters would be best fit with data at large radii where the tidal effects are the strongest. Table 2 summarizes the results for the models with a black hole and a dark matter halo.

3.4. Stellar Orbital Structure

The orbit-based models allow for the most general distribution of dispersion anisotropies. That is, we do not force any parameterization on the internal dispersions. Not

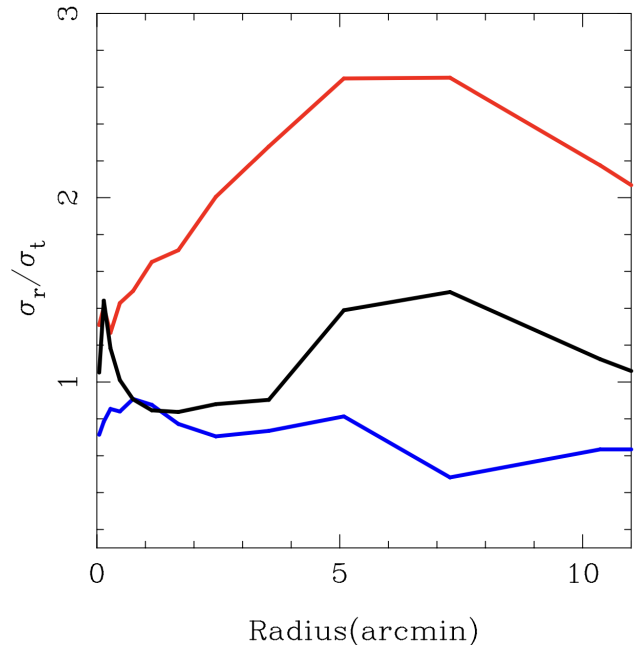


Figure 4. Ratio of internal dispersions σ_r/σ_t for three different models. The blue and black lines represent models that include a black hole with a mass of approximately $4.5 \pm 1.5 \times 10^5 M_{\odot}$. These models show close-to-isotropic dispersions in the central regions of Segue 1. In contrast, the red line represents a model with a dark halo but no black hole, exhibiting significant radial anisotropy. Such high radial anisotropy values are uncommon in other stellar systems.

only does this allow for the best fit to the observations but also allows us to explore whether the orbital structure is consistent with other systems.

Figure 4 shows the ratio of the radial to tangential dispersions for three representative models. For each model, we average over all angles and plot as a function of radius. For most stellar systems, the trend is typically to have close-to-isotropic orbits with an increase in the tangential dispersion closer to the black hole (K. Gebhardt et al. 2011; J. Thomas et al. 2014). The increase in tangential anisotropy is thought to be due to adiabatic destruction of stars in radial orbits that get close to the black hole, as seen in similar levels in M. Milosavljević & D. Merritt (2001).

The three models in Figure 4 are no black hole in red, no dark halo in blue, and best overall (black hole and dark halo) in black. The no-dark-halo and the best overall models are very similar and show close-to-isotropic orbits with an increase in the tangential component in the central regions. The no-black-hole model requires significant radial anisotropy. This high level of radial anisotropy has not been seen in other systems (K. Gebhardt et al. 2003) and is likely improbable.

3.5. Dark Matter Profile

There are two profiles used to describe the distribution of dark matter: cuspy-NFW and cored profiles. The NFW profile has a logarithmic distribution of dark matter, concentrating a significant amount in the center of the galaxy, resulting in a density that decreases exponentially from the center (J. F. Navarro et al. 1996). In contrast, the cored dark matter profile distributes dark matter more evenly throughout the

inner core rather than concentrating it densely at the center (F. Governato et al. 2010).

Segue 1, being one of the closest dwarf galaxies to us, has been extensively studied and modeled using the NFW profile. The models require an extremely high mass-to-light (M/L) ratio, which contributes to the theory that Segue 1 is “dark matter dominated.” Alternatively, our modeling suggests that incorporating a central SMBH with a mass of $(4.5 \pm 1.5) \times 10^5 M_\odot$ improves the fit for both profiles. The cored dark matter halo yielded a χ^2 value of 20, compared to a χ^2 value of 24 for the original NFW profile. Regardless, neither profile can fully capture the complex inner mass structure of the dwarf galaxy (K. Hayashi et al. 2023), but if the galaxy contains an SMBH, the emergence of cored profiles may be explained by its formation and growth.

Recently, a “black hole star” pathway was proposed by R. P. Naidu et al. (2025), suggesting that an early black hole seed, surrounded by dense gas, can accrete matter at super-Eddington rates, ultimately achieving SMBH masses on the order of $10^6 M_\odot$. If such a mechanism operated in the early progenitor of Segue 1, it could naturally account for the presence of an SMBH in this dwarf galaxy. This finding aligns with the mass range reported by A. Askar et al. (2023), which indicates that nearby dwarf galaxies may host SMBHs with masses around $10^5 M_\odot$.

The feedback from growing black holes, along with episodes of intense star formation—including radiation pressure, stellar winds, and supernovae—can expel gas and temporarily alter the central gravitational potential. Such feedback has been shown to redistribute dark matter in simulations, producing cored profiles in dwarf galaxies (F. Governato et al. 2010). Additionally, because cored systems are less tightly bound, they are more susceptible to tidal disruption and are more readily stripped compared to those with an NFW density profile (J. Peñarrubia et al. 2010; R. Errani et al. 2022). Moreover, as these dwarfs orbit the Milky Way, environmental processes such as tidal forces and ram pressure can quench star formation (C. M. Simpson et al. 2018), which offers a natural explanation for the broad metallicity range of $-3.7 \lesssim [\text{Fe}/\text{H}] \lesssim -1.5$ observed in Segue 1 (A. Frebel et al. 2014).

3.6. Concerns

The small amount of kinematic data is a concern, implying a possibility of overinterpretation of the results. While this overfitting needs to be considered, the more robust approach is to use orbit-based models in order to understand the allowed parameter space. In this case, the dynamical model with two parameters for the gravitational potential provides a good fit compared those with three parameters. The preferred model has a central black hole and a dark halo.

Another concern is that the central kinematic measurement is biased high due to stellar binaries inflating the projected velocity dispersion. This concern is studied in J. D. Simon et al. (2011), where they estimate an upper limit of $1\text{--}2 \text{ km s}^{-1}$ that might need to be removed in quadrature from the measured dispersion. They infer a measurable binary fraction around 10%, consistent with studies in globular clusters (K. Gebhardt et al. 1994). A higher binary fraction could be possible for wide binaries, but these would have a smaller effect on the measured velocity dispersion. Binaries are unlikely to be the cause for the increase in velocity dispersion

in the central region, although additional studies are warranted. Even more importantly, the significant increase in the rotational velocity toward the center would not be explained by a large binary population. Thus, a large central mass concentration is required even if there is a large population of binaries.

Segue 1 is being tidally stripped by the Milky Way. We model the tidal effects in the observed number counts, similar to what was done in M. J. Bustamante-Rosell et al. (2021). The central region, where the tidal effects are minimal, drive the fits to the black hole models, so the tidal model will be insignificant for the black hole mass estimate. M. J. Bustamante-Rosell et al. (2021) showed a similar lack of effect on the black hole mass estimate for Leo 1. The estimate of the dark matter halo will be directly affected by the tidal model. Thus, the measure of the black hole mass is robust, and further work for a robust estimate of the dark halo profile requires more detailed models of the tidal effects.

4. Implications

K. Hayashi et al. (2023) model Segue 1 using an NFW halo and find a steep central density slope, with the highest density yet reported. The central density that we infer is similar to that of K. Hayashi et al. (2023), except our central density is due to a black hole as opposed to highly concentrated dark matter. The alternative explanation of a black hole is a more natural explanation than the steep dark matter profile.

If Segue 1 is an accreted galaxy, as suspected, it should not be a surprise that there is a black hole in the center. Except for one galaxy, M33 (K. Gebhardt et al. 2001), we have yet to discover a galaxy that has neither a black hole nor a significantly low upper limit.

The “dark-matter”-dominated galaxy Segue 1 has most of its mass in material that is dark. In this case, that material is primarily in the black hole as opposed to a standard dark halo.

There are two main considerations that may influence our interpretation. First, the extraordinary nature of a system with order 10^5 solar masses of a black hole but only around $3 \cdot 10^4$ solar masses in stars may push models beyond their current regime of applicability. However, this large ratio may simply reflect the extraordinary intrinsic nature of the source. The second consideration stems from tidal effects. If the radial anisotropy of Segue 1 is because it is being disrupted from equilibrium due to tidal effects, then any dynamical modeling is suspect, and Segue 1 may indeed be comprised primarily of dark matter and stars originating from a larger population that has been tidally stripped. Tidal effects, though, are mitigated in our analysis (see Figure 1), which only focuses on the compact central region where tidal effects are minimal.

Our result may reveal a consequence of the outlier properties of Segue 1, which, in addition to its extremely high mass-to-light ratio, also has a very wide metallicity distribution (with most stars $\Delta[\text{Fe}/\text{H}] > 0.8$ dex; D. Webster et al. 2016). This lends support to a brief, clustered star formation scenario early in the history of Segue 1 in which it never amassed a large stellar population to be stripped to begin with. Similar structures, with very massive black holes and low stellar mass, are seen in the early Universe (J. Matthee et al. 2025; A. J. Taylor et al. 2025), typically called Little Red Dots. We may be witnessing a larger phenomenon of local dark remnants (with no dark matter halo). R. P. Naidu et al. (2025) find that there may be a large population of $10^5 M_\odot$

SMBHs in the early Universe. Segue 1 could be a relic of this phenomenon. It will be illuminating to carry out a similar investigation with other dwarf spheroidals.

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