

A Possible “Too-Many-Satellites” Problem in the Isolated Dwarf Galaxy DDO 161

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ABSTRACT

The abundance of satellite galaxies provides a direct test of Λ CDM on small scales. While satellites of Milky Way-mass galaxies are well studied, those of dwarf galaxies remain largely unexplored. We present a systematic search for satellites around the isolated dwarf galaxy DDO 161 ($M_\star \approx 10^{8.4} M_\odot$) at a distance of 6 Mpc. We identify eight satellite candidates within the projected virial radius and confirm four satellites through surface brightness fluctuation distance measurements from deep Magellan imaging data. With four confirmed satellites above $M_\star^{\text{sat}} > 10^{5.4} M_\odot$, DDO 161 is the most satellite-rich dwarf galaxy known to date. We compare this system with predictions from the TNG50 cosmological simulation, combined with currently established galaxy–halo connection models calibrated on Milky Way satellites, and find that DDO 161 has a satellite abundance far exceeding all current expectations. The rich satellite system of DDO 161 offers new insight into how low-mass galaxies occupy dark matter halos in low-density environments and may provide new constraints on the nature of dark matter.

Keywords: Dwarf galaxies (416); Galaxy groups (597); Distance measure (395); Luminosity function (942)

1. INTRODUCTION

The abundance of satellite galaxies provides a powerful test of the Λ CDM paradigm on small scales. In this model, the hierarchical growth of structure predicts that dark matter halos of all masses should host dark matter subhalos, whose luminous counterparts are satellite galaxies (Bullock & Boylan-Kolchin 2017). Early comparisons between observations and theoretical predictions revealed a stark discrepancy: the Milky Way (MW) and M31 appeared to host far fewer satellites than the predicted number of dark matter subhalos, a tension known as the “missing satellites problem” (Klypin et al. 1999; Moore et al. 1999). Over the past two decades, this apparent conflict has been largely resolved by a combination of deeper, wide-field imaging surveys that revealed large populations of ultra-faint satellites (e.g., Simon 2019; Cerny et al. 2023; Savino et al. 2025; Tan et al. 2025) and theoretical advances showing that not every dark matter subhalo is able to form a galaxy. For

instance, the ultraviolet background generated during cosmic reionization, which can strongly suppress gas accretion and cooling in low-mass subhalos, could prevent low-mass dark matter halos from forming a galaxy (e.g., Bullock et al. 2000; Kravtsov et al. 2004; Sawala et al. 2016). The number of satellites around MW-mass hosts is now broadly consistent with Λ CDM predictions once these effects are taken into account (Kim et al. 2018; Nadler et al. 2020; Santos-Santos et al. 2022). However, a few recent studies found an excess of satellites around MW-like galaxies (e.g., Homma et al. 2024; Müller et al. 2024; Kanehisa et al. 2024), hinting at a possible “too-many-satellites” problem.

With the satellite systems of MW-like galaxies increasingly well characterized in the Local Volume and beyond (e.g., Carlsten et al. 2022; Mao et al. 2024), attention has recently turned to test an analogous prediction from the Λ CDM model: dwarf galaxies themselves, despite their lower masses, should also host their own satellites (e.g., Dooley et al. 2017a,b; Sales et al. 2017). While satellites of individual dwarf galaxies have been identified through targeted deep imaging studies (e.g., Sand et al. 2015; Carlin et al. 2016, 2024; Davis et al.

2021; Medoff et al. 2025; Doliva-Dolinsky et al. 2025), systematic searches have only recently begun, most notably with the ELVES-DWARF (Li et al. 2025) and ID-MAGE (Hunter et al. 2025) surveys. These surveys are assembling the first statistically meaningful samples of satellites of dwarf galaxies in the Local Volume. The number of confirmed satellites identified in these studies so far is broadly consistent with expectations from the Λ CDM framework and our current understanding of galaxy formation (Li et al. 2025), although the sample size remains small.

In this Letter, we present the satellite population of DDO 161, an isolated dwarf galaxy with a stellar mass of $M_\star \approx 10^{8.4} M_\odot$ at $D = 6$ Mpc and one of the hosts studied in the ELVES-DWARF survey (Li et al. 2025; Li et al., in prep). Deep imaging and surface brightness fluctuation (SBF) distance measurements reveal a surprisingly rich satellite system with four satellites. The satellite stellar mass function significantly exceeds predictions from both cosmological simulations and semi-analytical models. This discovery indicates a possible “too-many-satellites” problem for dwarf hosts, and could offer new insights into galaxy formation in the low-mass and low-density regime.

This paper is structured as follows. We describe the properties of DDO 161 and the satellite search in Section 2, then present distance measurements for the satellite candidates in Section 3. In Section 4, we show the satellite stellar mass function and satellite abundance for DDO 161, and compare with predictions from both cosmological simulation TNG50. In Section 5, we check various factors that might alleviate the discrepancy between observation and theoretical predictions, and discuss the implications in Section 5. In this work, we adopt a flat Λ CDM cosmology with the present-day matter density $\Omega_m = 0.3$ and a Hubble constant of $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. The photometric results are presented in the AB system (Oke & Gunn 1983). The stellar masses calculated in this work are based on a Kroupa (2001) initial mass function. We apply a Milky Way dust extinction correction using the dust map in Schlegel et al. (1998) recalibrated by Schlafly & Finkbeiner (2011).

2. SATELLITE CANDIDATES AROUND DDO161

2.1. Properties of DDO 161

DDO 161 is an isolated dwarf galaxy at a distance of $D_{\text{TRGB}} = 6.03 \pm 0.20$ Mpc, determined from the tip of the red giant branch (TRGB) method (Karachentsev et al. 2017). Its heliocentric recession velocity is $v_h = 744 \text{ km s}^{-1}$ (Meyer et al. 2004). Prior to our investigation, DDO 161 was known to have one companion,

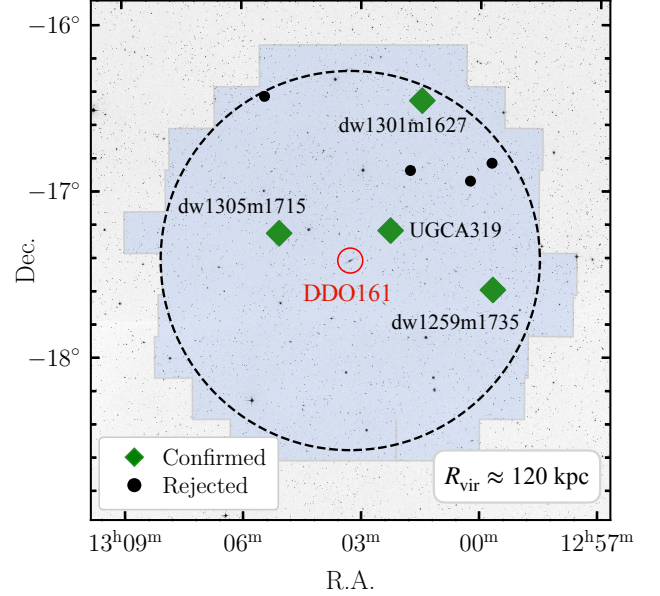


Figure 1. Satellite candidates of DDO 161. The footprint of the Legacy Surveys data used for satellite search is shown in blue. The black dashed circle corresponds to the projected virial radius of $R_{\text{vir}} \approx 120$ kpc. The confirmed satellites are shown as green diamonds, and rejected candidates are shown as black dots.

UGCA 319, which lies 32 kpc away in projection and at a distance of $D_{\text{TRGB}} = 5.75 \pm 0.18$ Mpc (Karachentsev et al. 2017) with a similar heliocentric velocity of $v_h = 750 \text{ km s}^{-1}$ (Kourkchi et al. 2020), confirming their physical association.

We estimate the stellar mass of DDO 161 as follows. It has apparent magnitudes of $B = 13.50$ mag (Makarov et al. 2014; Karachentsev et al. 2013) and $V = 13.07$ mag (Cook et al. 2014), both in the Vega system. After correcting for Galactic and internal extinction following Karachentsev et al. (2013), its absolute magnitude is $M_B = -16.04$ mag. Using the color-mass-to-light ratio ($M_\star/L$) relation from Bell et al. (2003)⁴, we estimate its stellar mass to be $M_\star \approx 10^{8.3 \pm 0.2} M_\odot$ based on the B -band photometry. Karachentsev et al. (2017) reported a K_s -band luminosity of $\log L_{K_s} = 8.75$, corresponding to $M_\star \approx 10^{8.5} M_\odot$ assuming $(M_\star/L)_{K_s} \approx 0.6$ (Bell et al. 2003). However, since this K_s luminosity was not directly measured but inferred from B -band photometry, it should be used with caution. Other independent measurements yield $M_\star = 10^{8.11 \pm 0.38} M_\odot$ from Leroy et al. (2019) and $M_\star = 10^{7.91} M_\odot$ from WISE photometry (de Blok et al. 2024).

⁴ $\log(M_\star/L)_B = 1.737 \cdot (B - V) - 1.092$

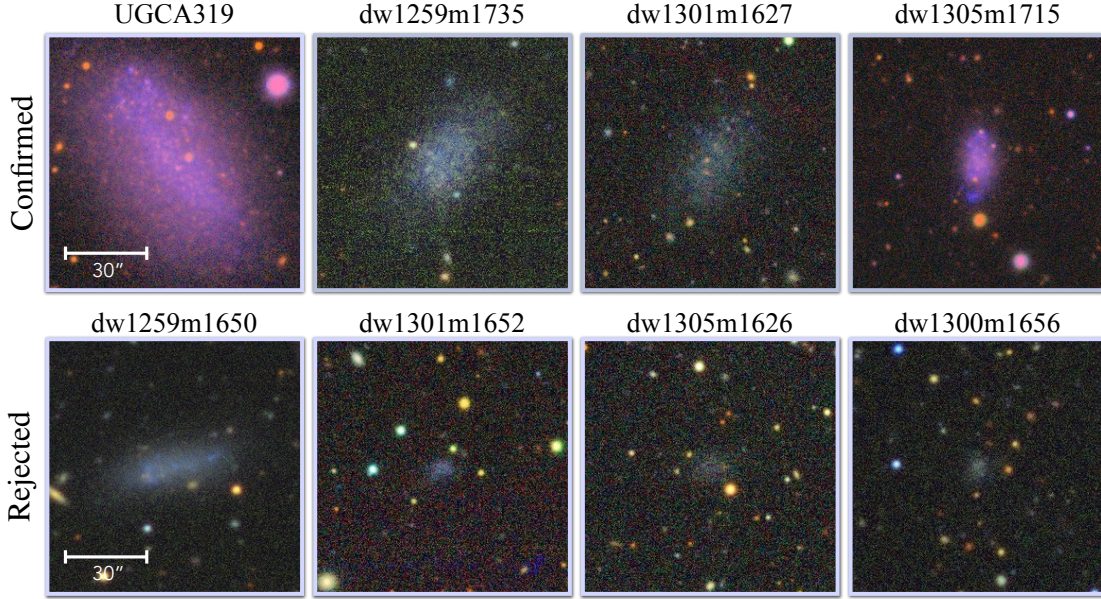


Figure 2. Cutout color-composite images of the satellite candidates of DDO 161 from the Legacy Surveys DR10. Cutouts are $1.5'$ on a side. The top row shows the four confirmed satellites, and the bottom row shows the four rejected candidates. UGCA 319 and dw1305m1715 only has g and i -band data, lacking r -band coverage.

Taking these results together, we adopt a fiducial stellar mass of $M_{\star} = 10^{8.4} M_{\odot}$, and consider a range of $10^{8.1} < M_{\star} < 10^{8.7} M_{\odot}$ when comparing with theoretical predictions in §4. This interval encompasses the published estimates of stellar mass from the literature, and places DDO 161 at a mass comparable to that of the Small Magellanic Cloud ($M_{\star} \approx 10^{8.5} M_{\odot}$; Skibba et al. 2012). Using the stellar-to-halo mass relation of Rodríguez-Puebla et al. (2017), we estimate a corresponding halo mass of $\log M_{\text{vir}}/M_{\odot} = 11.0 \pm 0.1$. The resulting virial radius, following the definition in Bryan & Norman (1998), is $R_{\text{vir}} \simeq 120 \pm 10$ kpc.

To understand the environment of DDO 161, we check the tidal indices from Karachentsev et al. (2013), which quantify the local tidal field contributed by neighboring *massive* galaxies. DDO 161 has a tidal index of $\Theta_1 = -0.9$, $\Theta_5 = -0.5$, and $\Theta_j = -1.1$, all indicating that it resides in a weak external tidal field and is dynamically isolated from any massive neighbors. As pointed out by Karachentsev et al. (2017), DDO 161 is dynamically well separated from the nearest neighbor KK 176 ($\log M_{\star}/M_{\odot} \approx 7.44$). Its nearest massive galaxies are NGC 5068 ($\log M_{\star}/M_{\odot} \approx 9.73$, 1 Mpc away from DDO 161) and NGC 5236 ($\log M_{\star}/M_{\odot} \approx 10.86$, 1.8 Mpc away), confirming that DDO 161 is indeed very isolated.

2.2. Satellite Search

We perform a systematic search for satellite candidates around DDO 161 using the Legacy Surveys Data

Release 10 data⁵ (Dey et al. 2019). We search for satellite candidates around DDO 161 within a projected radius of ~ 120 kpc. Our satellite detection closely follows Carlsten et al. (2022) and Li et al. (2025). First, we mask out bright stars by cross-matching with GAIA (Gaia Collaboration et al. 2021). Then, we identify and replace bright sources and their associated diffuse light with sky noise by applying surface brightness thresholding. We smooth this cleaned image with a Gaussian kernel of 2.5–3.5 times the PSF size to emphasize low surface brightness objects. Then we run Source Extractor (Bertin & Arnouts 1996) in both g and i bands with a low detection threshold of $2\text{--}2.5\sigma$ to detect objects, and we only keep objects detected in both bands. All candidates were visually inspected to reject spurious detections, including scattered light from bright stars, galaxy outskirts, tidal features, and Galactic cirrus.

For each remaining object, we fit a Sérsic model to obtain the photometric and structural properties using IMFIT (Erwin 2015). Physical properties, such as stellar mass and physical size, are estimated assuming all objects lie at the host distance of 6 Mpc and adopting the $g-i$ color- $M_{\star}/L$ relation from Into & Portinari (2013), which has been widely used in recent dwarf galaxy studies. We find consistent stellar masses when applying the newer calibration of de los Reyes et al. (2025). However, for consistency with our previous works (e.g., Carlsten

⁵ <https://www.legacysurvey.org/dr10/description/>

Table 1. Photometric Properties of DDO 161 and its Satellite Candidates

Name	R.A.	Dec.	R_{proj}	m_g	$g - i$	M_V	$\log M_*$	r_{eff}	Comp.
	(deg)	(deg)	(kpc)	(mag)	(mag)	(mag)	($M_\odot$)	(kpc)	
DDO 161	195.8184	−17.4218	0	...	...	...	8.40 ± 0.30	...	...
UGCA 319	195.5643	−17.2416	32	14.22 ± 0.08	0.35 ± 0.04	-14.82 ± 0.08	7.50 ± 0.07	0.81 ± 0.04	1.00
dw1305m1715	196.2662	−17.2573	48	16.72 ± 0.09	0.25 ± 0.04	-12.29 ± 0.09	6.36 ± 0.08	0.24 ± 0.01	1.00
dw1259m1735	194.9186	−17.5966	92	17.49 ± 0.09	0.52 ± 0.04	-11.62 ± 0.09	6.41 ± 0.08	0.45 ± 0.03	1.00
dw1301m1627	195.3665	−16.4598	110	17.89 ± 0.10	0.63 ± 0.04	-11.26 ± 0.10	6.39 ± 0.08	0.50 ± 0.03	1.00
dw1259m1650	194.9275	−16.8348	109	17.32 ± 0.09	0.46 ± 0.04	-11.77 ± 0.09	6.40 ± 0.08	0.45 ± 0.03	1.00
dw1301m1652	195.4400	−16.8801	69	19.77 ± 0.13	0.33 ± 0.06	-9.27 ± 0.13	5.24 ± 0.11	0.15 ± 0.02	0.90
dw1305m1626	196.3557	−16.4339	117	20.02 ± 0.14	0.84 ± 0.06	-9.13 ± 0.14	5.81 ± 0.12	0.21 ± 0.02	1.00
dw1300m1656	195.0628	−16.9428	91	20.83 ± 0.17	0.73 ± 0.09	-8.34 ± 0.18	5.34 ± 0.16	0.12 ± 0.02	0.96

NOTE—Properties of DDO 161 and its satellite candidates, including name, R.A., Dec., projected distance from the host R_{proj} , g -band apparent magnitude, $g - i$ color, V -band absolute magnitude (M_V), estimated stellar mass ($\log M_*$), and half-light radius (r_{eff}), and completeness. For the satellite candidates, the stellar mass and half-light radius are estimated assuming the candidates are at the distance of the host, and are only meaningful for the confirmed ones. The estimated stellar mass of DDO 161 is described in §2.1.

et al. 2022; Li et al. 2025) and because r -band photometry is unavailable for two satellites, we adopt Into & Portinari (2013) in this work. Photometric uncertainties are estimated following Carlsten et al. (2021) by injecting and recovering mock galaxies in the Legacy Surveys data. To further exclude background galaxies, we remove an additional 25 objects that are $> 2\sigma$ outliers from the average mass–size relation of dwarf galaxies from Carlsten et al. (2021). This method efficiently removes background galaxies as demonstrated in Li et al. (2025).

In total, we identified eight satellite candidates within $R_{\text{vir}} = 120$ kpc from DDO 161 in projection. Their basic properties are listed in Table 1, and their spatial distribution on the sky is shown in Figure 1. The blue footprint indicates the coverage of the Legacy Surveys data used for the search. The cutout images of all candidates are shown in Figure 2.

We quantify our search completeness by injecting mock galaxies into the Legacy Surveys data, as detailed in Appendix A. Our search is $> 50\%$ complete at $M_g < -8$ mag and approaches unity at $M_g < -8.5$ mag for satellites lying within 1σ from the average mass–size relation. We therefore adopt $M_g = -8.5$ mag as our effective detection limit, corresponding to a stellar mass of $M_* \approx 10^{5.4} M_\odot$ assuming an average color of $g - i = 0.5$ mag. This limit is comparable to that in the ELVES-DWARF survey (Li et al. 2025) and is deeper than the average limit of the ELVES survey, due to our use of a larger smoothing scale and a lower detection threshold.

Table 2. SBF Distances of Satellite Candidates

Name	D_{SBF}	(S/N) $_{\text{SBF}}$	v_h	Status
	(Mpc)		(km s $^{-1}$)	
UGCA 319	...	...	750	Confirmed
dw1305m1715	$6.21^{+0.46, 0.97}_{-0.39, 0.73}$	20.2	...	Confirmed
dw1259m1735	$5.96^{+0.37, 0.79}_{-0.33, 0.64}$	15.4	...	Confirmed
dw1301m1627	$6.31^{+0.52, 1.13}_{-0.47, 0.91}$	8.9	...	Confirmed
dw1259m1650	$12.61^{+1.11, 2.44}_{-0.93, 1.73}$	8.2	...	Rejected
dw1301m1652	$13.96^{+4.78, \infty}_{-2.36, 3.62}$	2.1	...	Rejected
dw1305m1626	> 8.57	0.7	...	Rejected
dw1300m1656	> 12.12	−0.6	...	Rejected

NOTE—SBF distances of satellite candidates, including name, median distance, and 1σ and 2σ uncertainties, the signal-to-noise ratio of SBF measurement, confirmation status, and heliocentric velocity if available. UGCA 319 has a TRGB distance of 5.75 ± 0.18 Mpc from Karachentsev et al. (2017). For dw1305m1626 and dw1300m1656, the distances correspond to the 2σ distance lower limit.

3. DISTANCE MEASUREMENT

Reliable distance measurements are essential to confirm that the satellite candidates identified in Section 2 are physically associated with DDO 161 rather than being foreground or background galaxies. Apart from UGCA 319, which has a published TRGB distance, none of the other candidates have existing distance or velocity measurements. Spectroscopic follow-up of such low-surface-brightness dwarfs is challenging, and TRGB distances require space-based imaging. As an alterna-

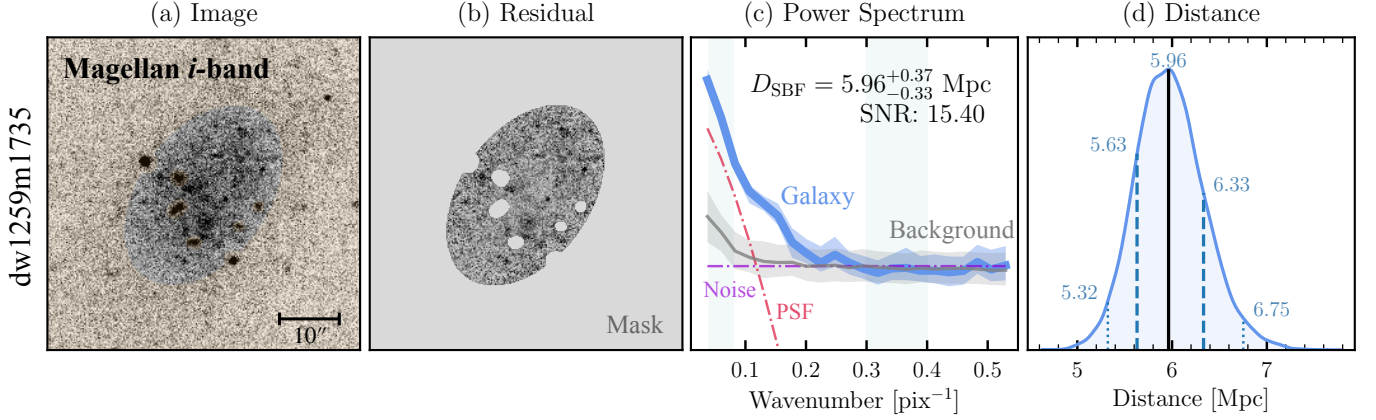


Figure 3. Example SBF distance measurement, for a confirmed satellite dw1259m1735. (a) Magellan *i*-band image. (b) Residual image after subtracting a smooth galaxy model and masking bright sources, on which the SBF signal is measured. (c) Azimuthally averaged power spectrum (blue) fitted with the PSF (red) and white noise (purple) components. The gray shaded region marks the contribution from the unmasked background sources. (d) SBF distance distribution showing the median, 1σ (16–84th percentile), and 2σ (2.5–97.5th percentile) intervals. The SBF distance agrees with the host distance of 6 Mpc, confirming dw1259m1735 as a satellite of DDO 161.

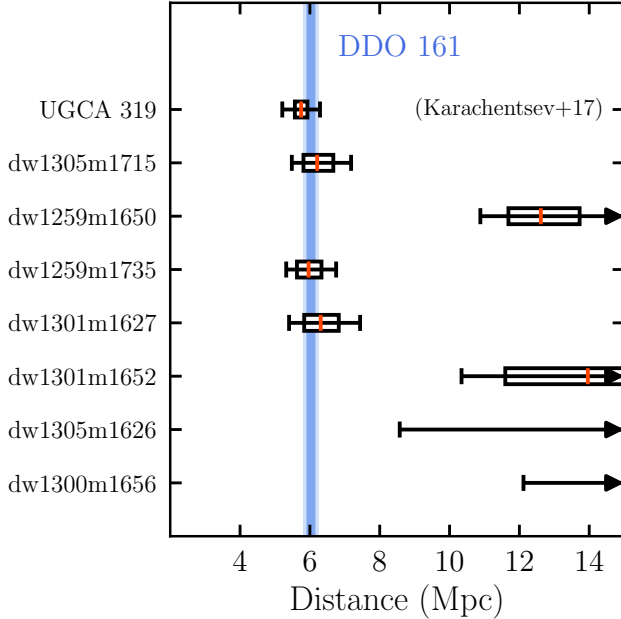


Figure 4. Distances of satellite candidates associated with DDO 161. The blue vertical line and shaded region indicate the TRGB distance of DDO 161 ($D = 6.03 \pm 0.25$ Mpc). For each satellite, the red tick marks the median distance, while the box and whiskers show the 1σ (16–84% percentile) and 2σ (2.5–97.5% percentile) ranges of the measured distances, respectively. Arrows correspond to distance lower limits. For UGCA 319, the TRGB distance from Karachentsev et al. (2017) is adopted, whereas all other distances are from SBF measurements in this work.

tive, we employ the surface brightness fluctuation (SBF) technique (Tonry & Schneider 1988; Greco et al. 2021; Cantiello & Blakeslee 2023), which enables distance measurements from deep ground-based imaging alone.

While less precise than TRGB, the typical SBF distance uncertainty ($\sim 10\%$) is sufficient to distinguish true satellites at the host distance from background galaxies. The method has been extensively validated and successfully applied to diffuse dwarf galaxies in the ELVES and ELVES-DWARF surveys (Carlsten et al. 2022; Li et al. 2025).

To obtain the imaging data with sufficient resolution and depth required for SBF measurement, we carried out a follow-up campaign with the 6.5 m Magellan Telescope, targeting all eight satellite candidates. Each candidate was observed with the Inamori Magellan Areal Camera and Spectrograph (IMACS; Dressler et al. 2011) in the *i* band, with a total integration time of 30–40 min per target under excellent seeing conditions ($0''.5$ – $0''.6$). Data reduction followed the procedure described in Li et al. (2024), including bias subtraction, flat-fielding, astrometric and photometric calibration, and stacking. Photometric calibration was based on the DECam Local Volume Exploration Survey (DELVE; Drlica-Wagner et al. 2021, 2022) DR2 catalog. An example Magellan image is shown in panel (a) of Figure 3. These data reach sufficient depth and resolution to measure SBF signals for galaxies at ~ 6 Mpc.

We measure SBF distances following the procedure described in Carlsten et al. (2019) and Li et al. (2025). The SBF technique exploits the fact that the pixel-to-pixel flux variance of a galaxy image depends on distance: as distance increases, the galaxy appears progressively smoother. These fluctuations arise from Poisson variations in the number of bright stars per resolution element (see Cantiello & Blakeslee 2023 for a review).

An example SBF measurement in this work is illustrated in Figure 3. For each target, we first construct a

smooth model of the galaxy by fitting a Sérsic model to the image (panel a), then build the residual image by subtracting the smooth model and dividing by the square root of the smooth model (panel b). We also mask out compact sources such as globular clusters and unresolved background galaxies by excluding sources brighter than $M_i < -5.0$ mag. We then compute the azimuthally averaged power spectrum of the residual image, which is modeled as the sum of a PSF power spectrum and a constant white-noise floor (panel c). The amplitude of the PSF component represents the measured SBF signal. To correct for contamination from unmasked background sources, we repeat the same analysis on blank fields near each target and subtract their contribution. The measured SBF signal is converted to a distance (panel d) using the i -band SBF calibration in [Carlsten et al. \(2019\)](#). Distance uncertainties are estimated via Monte Carlo sampling over the galaxy color uncertainty, power spectrum fitting range, masking threshold, and background field choice.

The resulting SBF distances are listed in Table 2 and summarized in Figure 4. We use the TRGB distance for UGCA 319 and SBF distances for all other satellite candidates. We classify a satellite candidate as confirmed if its SBF distance agrees with the host distance within 2σ and the SBF signal-to-noise ratio exceeds $S/N > 5$. Candidates whose 2σ distance range does not overlap with the host distance are rejected. Based on these criteria, four satellites are confirmed and four are rejected, as demonstrated in Figure 4. The confirmed systems are visibly semi-resolved even in the Legacy Surveys imaging.

For the confirmed satellites, we calculate their absolute magnitudes, stellar masses, and physical sizes assuming the host distance of 6.03 Mpc (see Table 1). Variations in distance across the host’s virial volume ($D \pm R_{\text{vir}}$) change the inferred stellar masses by less than 0.03 dex, which is well below the photometric uncertainties. The quoted stellar mass uncertainties include contributions from both photometric errors and the distance variation within the virial volume, but do not account for systematic uncertainties in the adopted color– M_*/L relation. The most massive satellite, UGCA 319, has a measured stellar mass of $\log M_*/M_\odot = 7.50 \pm 0.07$, which agrees quite well with $\log M_*/M_\odot = 7.6$ from [Leroy et al. \(2019\)](#) and the K_s -luminosity-based stellar mass of $\log M_*/M_\odot = 7.6$ from [Karachentsev et al. \(2017\)](#) when assuming $\log M_*/L_{K_s} = -0.4$.

4. RESULTS

We quantify the satellite population of DDO 161 in Figure 5. The left panel shows the cumulative satellite

stellar mass function. To account for the measurement uncertainties in stellar mass, we generate 1000 Monte Carlo realizations of the stellar mass function by resampling each satellite’s measured M_* within its uncertainty, shown as the red shaded region. DDO 161 hosts one relatively massive companion, UGCA 319, with $M_* \approx 10^{7.5} M_\odot$, roughly 1/10 of the host’s stellar mass. It has three additional satellites, all with $M_* \approx 10^{6.4} M_\odot$, yielding a total of four confirmed satellites above our completeness limit of $M_*^{\text{sat}} > 10^{5.4} M_\odot$.

In the right panel of Figure 5, we compare DDO 161’s satellite abundance with other dwarf hosts from the literature. Gray diamonds show systems within $D < 3.5$ Mpc that have been surveyed to at least a comparable depth, including the LMC, M33 ([Pace 2024](#)), NGC 3109 ([Doliva-Dolinsky et al. 2025](#)), NGC 300 ([Sand et al. 2024](#)), NGC 55 ([Medoff et al. 2025](#)), NGC 2403 ([Carlin et al. 2024](#)), and NGC 4214 ([Carlin et al. 2021](#)). Among these, only NGC 3109 and NGC 55 are considered isolated. The yellow diamonds denote the isolated dwarf hosts from the first results of ELVES-DWARF survey ([Li et al. 2025](#)), while turquoise squares show low-mass hosts from the ELVES survey ([Carlsten et al. 2022](#)), only including confirmed satellites. DDO 161 stands out as a clear outlier, hosting more satellites than other dwarf hosts with comparable stellar mass, representing one of the richest satellite systems around a dwarf galaxy. Such a satellite abundance exceeds the model predictions from [Sales et al. \(2013\)](#) and [Dooley et al. \(2017a\)](#).

To better interpret DDO 161’s rich satellite population, we compare our observations with predictions from the TNG50 simulation ([Pillepich et al. 2018, 2019](#); [Nelson et al. 2019](#)), the highest-resolution simulation in the IllustrisTNG suite of cosmological hydrodynamical simulations. TNG50 follows the evolution of cosmic structure in a 50 Mpc box with a dark matter particle mass of $m_{\text{DM}} = 4.5 \times 10^5 M_\odot$ and a baryonic mass resolution of $m_{\text{bar}} = 8.5 \times 10^4 M_\odot$, making it capable of resolving satellite systems in dwarf-mass halos. Halos and subhalos are identified using the standard FoF and SUBFIND algorithms ([Davis et al. 1985](#); [Springel et al. 2001](#)). For each halo, we define the central galaxy as the most massive subhalo and its satellites as subhalos within the 3-D virial radius that are not centrals of smaller FoF groups.

With the mass resolution of TNG50, the central galaxies with stellar masses similar to DDO 161 are well resolved in both dark matter and stellar components. Therefore, we compute the stellar masses of central galaxies as the sum of all stellar particles within twice the stellar half-mass radius, following standard practice in TNG50 (e.g., [Shi et al. 2020](#); [Engler et al. 2021](#)).

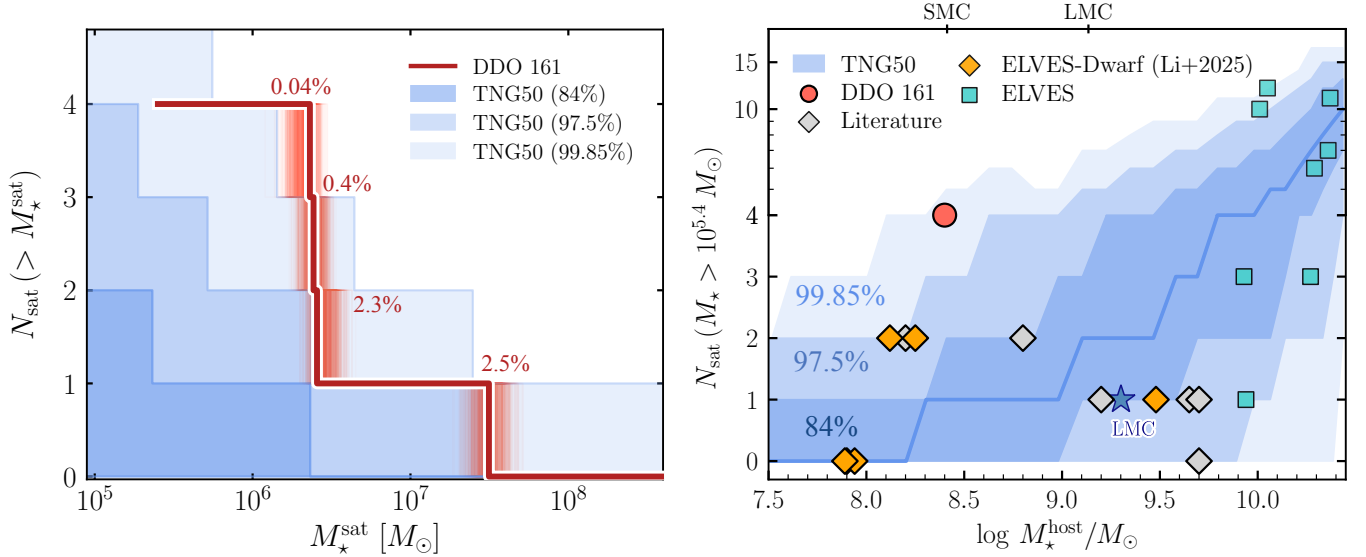


Figure 5. *Left:* Cumulative satellite stellar mass function for DDO 161 (red). To account for the measurement uncertainties in stellar mass, we generate 1000 Monte Carlo realizations of the stellar mass function by resampling $M_{\star}^{\text{sat}}$ within its uncertainty. Blue shaded regions show the 84%, 97.5%, and 99.85% percentiles of the TNG50 predictions, assuming the stellar-to-halo mass relation of Nadler et al. (2020). Percentages marked along the red curve indicate the fraction of systems in TNG50 with an equal or greater number of satellites than observed. DDO 161 lies in the extreme tail of the distribution, hosting significantly more satellites than predicted. *Right:* Number of satellites per host above $M_{\star}^{\text{sat}} > 10^{5.4} M_{\odot}$ as a function of host stellar mass. DDO 161 (red circle) is compared with hosts from individual literature studies (gray diamonds), the ELVES-DWARF survey (yellow diamonds; Li et al. 2025), and the ELVES survey (turquoise squares; Carlsten et al. 2022). Blue contours denote the 84%, 97.5%, and 99.85% percentiles of the TNG50 predictions. DDO 161 stands out clearly as an outlier, hosting a satellite population far richer than expected for its stellar mass.

In contrast, satellites with $M_{\star} \lesssim 10^7 M_{\odot}$ are only marginally resolved (Benavides et al. 2025), although their dark matter subhalos remain well resolved. Therefore, we populate subhalos using the empirical stellar-to-halo mass relation (SHMR).

To select systems analogous to DDO 161 in both stellar mass and environment, we first identify central galaxies with stellar masses in the range $10^{8.1} < M_{\star}^{\text{host}} < 10^{8.7} M_{\odot}$, corresponding to DDO 161’s estimated stellar mass range (§2.1). We further require that no more massive halo resides within 1 Mpc to ensure an isolated environment. This results in a sample of 857 analogs to DDO 161. The host halo masses have a median of $10^{10.85} M_{\odot}$, with a 2.5–97.5% percentile range of $10^{10.5} - 10^{11.2} M_{\odot}$, and the distribution is mildly skewed toward higher masses. For each host, we obtain the peak halo mass (M_{peak}) of each satellite from its mass assembly history and assign stellar masses using the empirical SHMR of Nadler et al. (2020), which is a popular galaxy-halo connection model calibrated on satellites of the Milky Way. To incorporate the intrinsic scatter in this relation, we generate 100 Monte Carlo realizations of the stellar masses for each satellite. In Section 5, we also explore using alternative SHMRs and using the semi-analytical models, and get consistent results.

The predicted cumulative satellite stellar mass function from TNG50 is shown in the left panel of Figure 5. The blue shaded regions mark the 84%, 97.5%, and 99.85% percentiles of the TNG50 prediction. The numbers marked along the red curve indicate the fraction of systems in TNG50 with more satellites than observed. Only 2.5% of TNG50 hosts contain a massive satellite like UGCA 319, and 2.3% have two satellites similar to DDO 161. When the third satellite is included, the fraction drops to 0.4%. The probability for a DDO 161-like galaxy to host four satellites above $M_{\star}^{\text{sat}} > 10^{6.2} M_{\odot}$ is merely 0.04%. Because the satellite count distribution is non-Gaussian (Boylan-Kolchin et al. 2010; Mao et al. 2015), we quantify the tension using percentiles rather than standard deviations. Nevertheless, the observed system lies at the 0.04% tail of the TNG50 distribution, which would correspond to a deviation of $> 3\sigma$ in the context of a Gaussian distribution.

The right panel of Figure 5 shows the predicted number of satellites per host above $M_{\star}^{\text{sat}} > 10^{5.4} M_{\odot}$ as a function of host stellar mass. The TNG50 predictions, shown as blue shaded regions, agree well with observations of other dwarf hosts from the literature, the ELVES-DWARF survey, and the ELVES survey. DDO 161 still stands out as a pronounced outlier. The discrepancy is slightly smaller than that inferred from

the satellite mass function because the satellite count is a less informative statistic than the full stellar mass function. We also note that NGC 4631, a MW-like host ($M_\star \approx 10^{10.05} M_\odot$) in the ELVES survey with 12 confirmed satellites, is also an outlier.

To summarize, DDO 161 is the most satellite-rich dwarf galaxy found to date, and it is in clear tension with predictions based on the currently established galaxy-halo connection model calibrated on MW satellites.

5. DISCUSSION

In this Letter, we present the discovery of an extremely rich satellite population of an isolated dwarf galaxy DDO 161. It has a stellar mass of $M_\star^{\text{host}} \approx 10^{8.4} M_\odot$, similar to that of the Small Magellanic Cloud. DDO 161 hosts four satellites above $M_\star > 10^{5.4} M_\odot$ confirmed with direct distance measurements. This high satellite abundance represents an extreme outlier (at a 0.04% level) compared with theoretical expectations derived from cosmological simulations and the empirical SHMR calibrated on Milky Way satellites (Nadler et al. 2020).

We estimate the likelihood of finding a system as extreme as DDO 161 within the Local Volume ($D < 10$ Mpc; total volume about 4000 Mpc³). In the TNG50 simulation, there are 857 analogs to DDO 161 (in terms of both stellar mass and environment) within a (50 Mpc)³ box, implying that only ~ 30 such analogs should exist in the entire Local Volume (< 10 Mpc). Among 30 systems, the chance of encountering an outlier at the 0.04% level (Figure 5) is effectively zero. In the real universe, the Karachentsev et al. (2013) catalog lists ~ 200 dwarf galaxies with $10^8 < M_\star < 10^9 M_\odot$ at $D < 10$ Mpc, including both satellites and isolated systems. Among these galaxies, we would expect only ~ 0.08 galaxies that are 0.04%-percentile outliers. Given that DDO 161 is one of only ~ 30 isolated dwarf hosts targeted by the ELVES-DWARF survey, the discovery of such a satellite-rich system is an exceedingly rare event, unlikely to be explained by statistical chance alone.

Observationally, reducing the tension between DDO 161 and theoretical predictions would require lowering the inferred stellar masses of its satellites by roughly 1 dex to bring the system into the 97.5% (2σ) percentile of the TNG50 distribution. As shown in Figure 5, the measurement uncertainties alone (red shaded region) are not sufficient to alleviate the tension. The intrinsic scatter and systematic bias in the color- $M_\star/L$ relation are smaller than 0.2 dex (de los Reyes et al. 2025). Moreover, stellar mass is often underestimated for a star-forming dwarf galaxy, as bright young stars can outshine the older population. Thus, uncertainties

in the stellar mass estimates are likely insufficient to explain the discrepancy.

We therefore consider possible explanations on the theoretical side. To test whether the discrepancy arises from the limitations of the TNG50 simulation such as resolution and artificial subhalo disruption (van den Bosch & Ogiya 2018; Benson & Du 2022), we compare its predictions with those from the semi-analytical model SATGEN⁶ (Jiang et al. 2021; Green et al. 2021). SATGEN constructs halo merger trees and follows the evolution of subhalos under the influence of tidal stripping and heating from the host halo, dynamical friction, and baryonic effects. For this comparison, we take the host halo masses of the DDO 161 analogs identified in TNG50 and generate corresponding satellite populations using SATGEN. Both TNG50 and SATGEN therefore share the same host halo masses, isolating differences arising only from the treatment of subhalos. For SATGEN, the stellar mass of each satellite is then assigned using the same SHMR from Nadler et al. (2020), based on subhalo peak mass. As shown by the purple dashed line in Figure 6, the 97.5% (2σ) percentile line from SATGEN agrees closely with that from TNG50, confirming that the tension with DDO 161 is not driven by artifacts or resolution issues in TNG50.

We then explore whether alternative SHMRs could help alleviate the tension, as different SHMRs essentially represent different galaxy formation efficiencies. In Figure 6, we compare the 97.5% percentile of satellite stellar mass functions using several established SHMRs in the literature: Manwadkar & Kravtsov (2022, M22), based on the semi-analytical model GRUMPY (Kravtsov & Manwadkar 2022); Danieli et al. (2023, D23), calibrated on satellites of MW-like hosts from the ELVES survey; and Kado-Fong et al. (2025, KF25), derived from the field dwarfs in the SAGA background sample (Kado-Fong et al. 2024). As shown in Figure 6, DDO 161 remains an outlier across all models. The Manwadkar & Kravtsov (2022) relation yields the smallest discrepancy because it has a shallower slope and higher normalization than other SHMRs, but still with only $\sim 0.4\%$ of analog hosts exhibiting similarly rich satellite systems. None of the currently established SHMRs can reconcile the observed satellite abundance of DDO 161 with theoretical predictions.

A physical explanation for such an unusually satellite-rich system remains elusive. Most alternative dark matter models, including warm and self-interacting dark matter, predict *fewer* low-mass subhalos than the cold

⁶ <https://github.com/JiangFangzhou/SatGen>

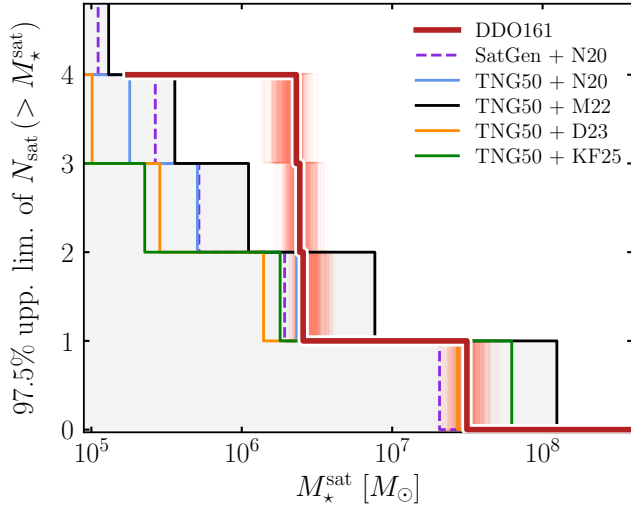


Figure 6. The predicted 97.5% percentiles of cumulative satellite stellar mass functions for DDO 161 analogs. The blue line shows results from the TNG50 simulation using the Nadler et al. (2020) SHMR, while the purple dashed line shows predictions from the semi-analytical model SATGEN using the same SHMR. The close agreement between SATGEN and TNG50 indicates that the discrepancy with DDO 161 is not driven by numerical effects in the simulation. Additional curves show TNG50 predictions using alternative SHMRs from the literature (M22, Manwadkar & Kravtsov 2022; D23, Danieli et al. 2023; KF25, Kado-Fong et al. 2025). None of the currently established SHMRs can reproduce the high satellite abundance observed around DDO 161.

dark matter paradigm (e.g., Bullock & Boylan-Kolchin 2017; Gutcke et al. 2025), and thus cannot explain the observed excess of satellites. Dynamically speaking, one possibility is that DDO 161 accreted UGCA 319 together with a bound group of companions, analogous to the Magellanic Clouds (Sales et al. 2017). However, such group-infall events are already captured in cosmological simulations like TNG50 and therefore do not fully resolve the discrepancy. Another possibility is that DDO 161 resides within or near a filamentary structure, where recent infall or enhanced subhalo accretion could

transiently elevate its satellite abundance. The TNG50 volume may not sample such environments adequately. Checking whether neighboring galaxies also show similarly enhanced satellite populations would help test this scenario.

A more plausible explanation is that the SHMR for satellites in dwarf groups differs from that calibrated for Milky Way-like systems, reflecting an environmental dependence (Read et al. 2017; Garrison-Kimmel et al. 2017; Engler et al. 2021; Christensen et al. 2024). However, other studies have found little or no environmental variation in the SHMR (e.g., Watson & Conroy 2013; Shi et al. 2020; Danieli et al. 2023). Simulations by Christensen et al. (2024) suggest a steeper SHMR in the field, whereas observations by Kado-Fong et al. (2025) find only weak environmental dependence in observation. For a given intrinsic scatter, a steeper SHMR would worsen the tension by producing even fewer satellites above a given stellar mass limit. On the other hand, a shallower relation, such as that proposed by Read et al. (2017) for field dwarfs in SDSS, could alleviate the discrepancy for DDO 161 but would overpredict satellites around other dwarf hosts. The real SHMR may also deviate from a single power law, following a piecewise or curved form that current models do not capture (Santos-Santos et al. 2022). In any case, DDO 161 provides powerful empirical constraints on the SHMR in the low-mass regime, particularly within dwarf groups where it remains poorly understood.

The discovery of such a satellite-rich dwarf galaxy underscores the importance of building a statistical sample of satellites around dwarf hosts. DDO 161 is part of the ongoing ELVES-DWARF survey, which will provide a uniform census of ~ 40 isolated dwarf hosts within 10 Mpc (Li et al., in prep). If confirmed in additional systems, such “too-many-satellites” cases would offer powerful tests of Λ CDM on small scales and new insight into galaxy formation in the low-mass and low-density regime.

APPENDIX

A. SATELLITE DETECTION COMPLETENESS

We quantify the completeness of our satellite search following the procedure described in Li et al. (2025). Mock dwarf galaxies are injected into the same Legacy Surveys images used for the satellite detection. Each mock galaxy is modeled with a Sérsic light profile with Sérsic index $n = 1$, and its properties are uniformly drawn in the following ranges: the absolute g -band magnitude in $-12.5 < M_g < -8$ mag, central surface

brightness in $23.5 < \mu_0(g) < 28$ mag arcsec $^{-2}$, color in $0.2 < g - i < 1.3$, and ellipticity in $0 < \varepsilon < 0.5$. Mock galaxies are injected into both g and i -band images with a density of 12 per $0.25^\circ \times 0.25^\circ$ brick. Then the images went through the same detection pipeline. The detection completeness is thus defined as the ratio of recovered to injected galaxies. As shown in Figure 7, we achieve a $> 50\%$ completeness to $M_g \approx -8$ mag, and

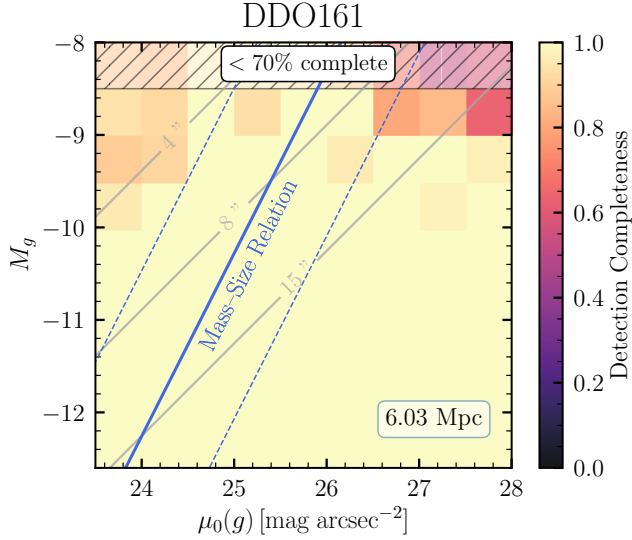


Figure 7. Detection completeness as a function of central surface brightness $\mu_0(g)$ and absolute magnitude M_g . The average mass–size relation of dwarf satellites from [Carlsten et al. \(2021\)](#) is shown as the blue line. Our search is highly complete for satellites with $M_g < -8.5$ mag.

nearly unity for satellites brighter than $M_g \lesssim -8.5$ mag lying within 1σ of the mass–size relation.

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Software: NumPy (Harris et al. 2020), Astropy (Astropy Collaboration et al. 2013), SciPy (Jones et al. 2001), Matplotlib (Hunter 2007), SExtractor (Bertin & Arnouts 1996), SWarp (Bertin et al. 2002), PSFEx (Bertin 2011), sep (Barbary 2016), imfit (Erwin 2015), sfdmap, SatGen (Jiang et al. 2021)

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