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The extreme relic galaxy NGC 1277 is dark matter deficient.

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Abstract

Relic galaxies are extremely compact early-type objects that have failed to accrete an extended envelope of stars. We observed the relic galaxy NGC 1277 with the integral field George and Cynthia Mitchel spectrograph (GCMS). The observations also include the regular early-type galaxy NGC 1278, which is used for comparison. We obtained resolved kinematics of both targets and performed a Jeans modelling to determine their dark matter content and distribution. We find that, whereas NGC 1278 has a dark matter fraction compatible with the expectations from models, NGC 1277 displays a negligible dark matter fraction within the radius of 6 kpc (five effective radii) from which we recovered stellar kinematics. We propose that the fact that NGC 1277 is dark matter deficient might explain its relic status. This is because for a galaxy lacking an extended dark matter halo, dynamical friction is greatly reduced, resulting in a small efficiency at accreting satellites.

1 Introduction

The current paradigm for the formation of early-type galaxies (ETGs) is that they are the result of two distinct successive phases of formation (see [16]). First, a dense core is quickly formed. Afterwards, an extended envelope is slowly accreted as smaller objects are cannibalised. In doing so, the size of the ETG increases by a factor of roughly four (e.g., [2]).

A minute fraction of ETGs skip the second evolutionary phase and are left as the passively-evolved remains of the compact ETGs at a redshift $z \sim 2$. These objects, called relic galaxies, are extremely interesting because they allow us to directly study the properties of the early ETGs without suffering from envelope contamination. NGC 1277, discovered by [18], is the cleanest relic galaxy known to date. It is located in the dense environment of the Perseus Cluster, at an estimated distance of 65 Mpc [1].

Here, we study the kinematics of NGC 1277 obtained from deep integral field data. To do so, we used the Jeans Anisotropic Modelling (`JAM`) code [4, 6]. The dataset covers the nearby regular ETG NGC 1278 that we used to obtain a direct comparison between the properties of a relic galaxy and those of an ETG that has undergone the full two-phase evolution.

2 The data

The data were obtained with the George and Cynthia Mitchel spectrograph (GCMS) at the 2.7 m Harlan J. Smith telescope. The fibres of the instrument are $4\farcs16$ in diameter and cover a field of view of $100'' \times 100''$. Through a dithering scheme we obtained a large filling factor and an equivalent exposure time of 2.5 hours per position. We performed our analysis using the spectral range 4400 Å − 6650 Å. The data have a radial coverage of 6 kpc for NGC 1277 (about five effective radii) and 12 kpc for NGC 1278 (about three effective radii).

In order to mitigate the effects of the low angular resolution of the GCMS, we complemented our dataset with kinematics of the innermost $1''.6 \times 1''.6$ of NGC 1277 obtained by [20] using NIFS, an adaptive-optics-assisted (AO-assisted) integral field spectrograph.

3 Galaxy resolved kinematics and MGE modelling

To obtain resolved stellar kinematics, we fitted the spectra from the GCMS fibres using `pPXF` [8, 7]. For each fibre, we computed the velocity corrected for the mean recession velocity of the galaxy, V, and the velocity dispersion, σ. We calculated $V_{\rm rms} \equiv \sqrt{V^2+\sigma^2}$, as it is a necessary input for the dynamical modelling (Sect. 4). We selected for further processing the fibres with a good signal-to-noise ratio (S/N > 7 per spectra pixel) and where the error in $V_{\rm rms}$ is smaller than $65\,{\rm km\,s^{-1}}$.

The main goal of the Jeans modelling is to characterise the dark matter halo of the target galaxies. To disentangle the dark matter dynamical effects from those of the baryonic component, baryonic mass distribution models were required. We created them using the code by [3] in order to compute a multi-Gaussian expansion (`MGE`) of baryonic mass maps derived from *HST* colour maps. We assumed mass-to-light ratios based on colours following the recipes from [17, 10] and a Salpeter initial mass function (IMF).

4 Jeans modelling

`JAM` was used to produce Jeans models of the target galaxies. For dark matter haloes we assumed a Navarro-Frenk-White profile with a characteristic radius $r_{\rm s} = 100\,{\rm kpc}$. The Jeans models were fitted to the $V_{\rm rms}$ maps using the Adaptive Metropolis algorithm code `adamet` [5]. The fitted parameters were:

- The deprojected axial ratio of the flattest `MGE`, $q_{\star\,\rm min}$. This is equivalent to fitting the inclination of the galaxy.
- The shape of the velocity ellipsoid, which was parametrised by either β_z or β_r, depending on the alignment of the ellipsoid (cylindrical or spherical, respectively).
- The mismatch parameter α, which is a multiplying factor of the mass map that accounts for differences between the actual IMF of the object and the assumed Salpeter IMF.
- The central black hole mass, $M_{\rm BH}$.
- The dark matter fraction within 6 kpc, $f_{\rm DM}(6\,{\rm kpc})$,

For NGC 1277 we fitted $M_{\rm BH}$ using the AO-assisted NIFS kinematics. The resulting mass was fixed in the fit of the more extended GCMS data. Because NGC 1277 is disc-dominated, we assumed it to have a cylindrically-aligned velocity ellipsoid. Since NGC 1278 is a slow rotator, we assumed that its ellipsoid is spherically-aligned. The inferred posterior probability distribution functions of the model parameters are shown in Figs. 1 and 2.

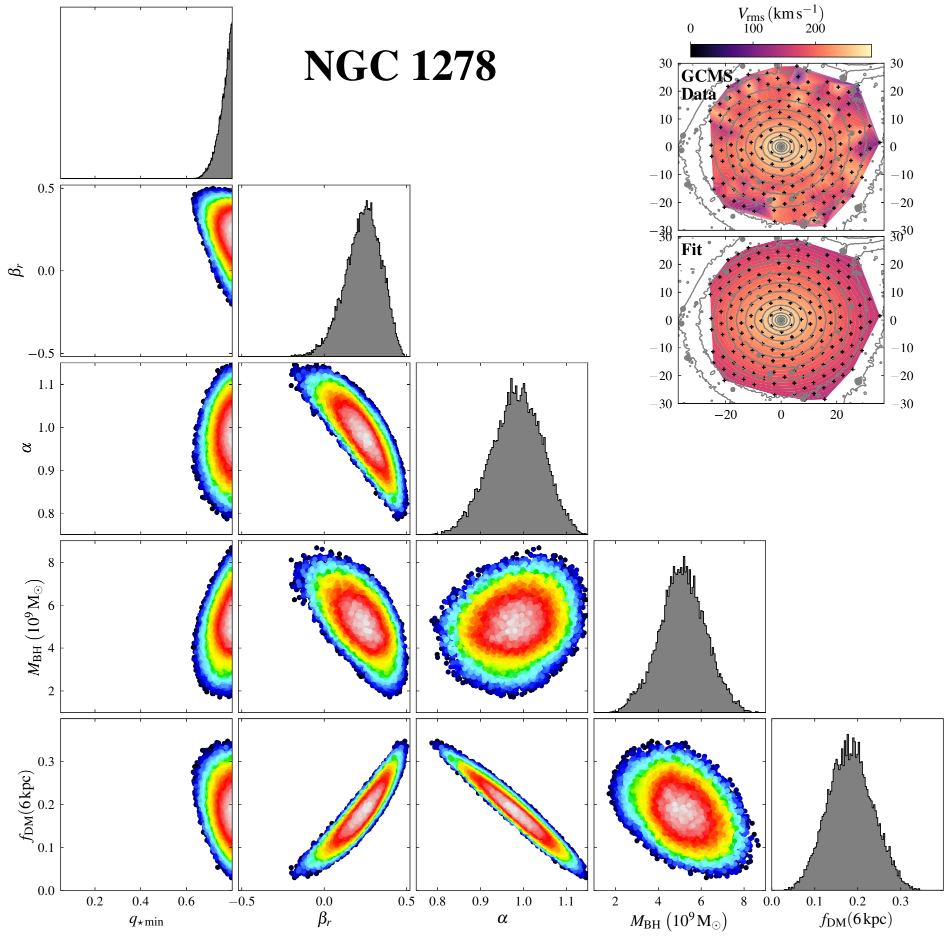

Figure 1: Result of the Jeans modelling to the GCMS-based $V_{\rm rms}$ map of NGC 1278. The panels show the probability distribution of the fitted parameters marginalised over either two parameters (contour plots), or one parameter (histograms). In the contour plots, white shades indicate the maximum likelihood and blue shades correspond to a three-sigma confidence level. The upper-right panels show the observed and the fitted $V_{\rm rms}$ maps. The grey contours correspond to surface brightness contours separated by 0.5 mag arcsec^{-2} intervals, and the black + signs indicate the position of the centre of the GCMS fibres.

5 Discussion

As a sanity test, we checked that the fitted central black hole mass for NGC 1277 is compatible with that obtained by previous authors [11, 20, 14]. We thus confirm that the central black hole in NGC 1277 is over-massive according to several scaling relations, but not quite as much as postulated by [19], who found $M_{\rm BH} > 10^{10}\,{\rm M}_\odot$.

The large mismatch parameter value of $\alpha \approx 1.2$ indicates that NGC 1277 has a bottom-heavy IMF, confirming the results by [15, 12]. On the other hand, NGC 1278 has a smaller

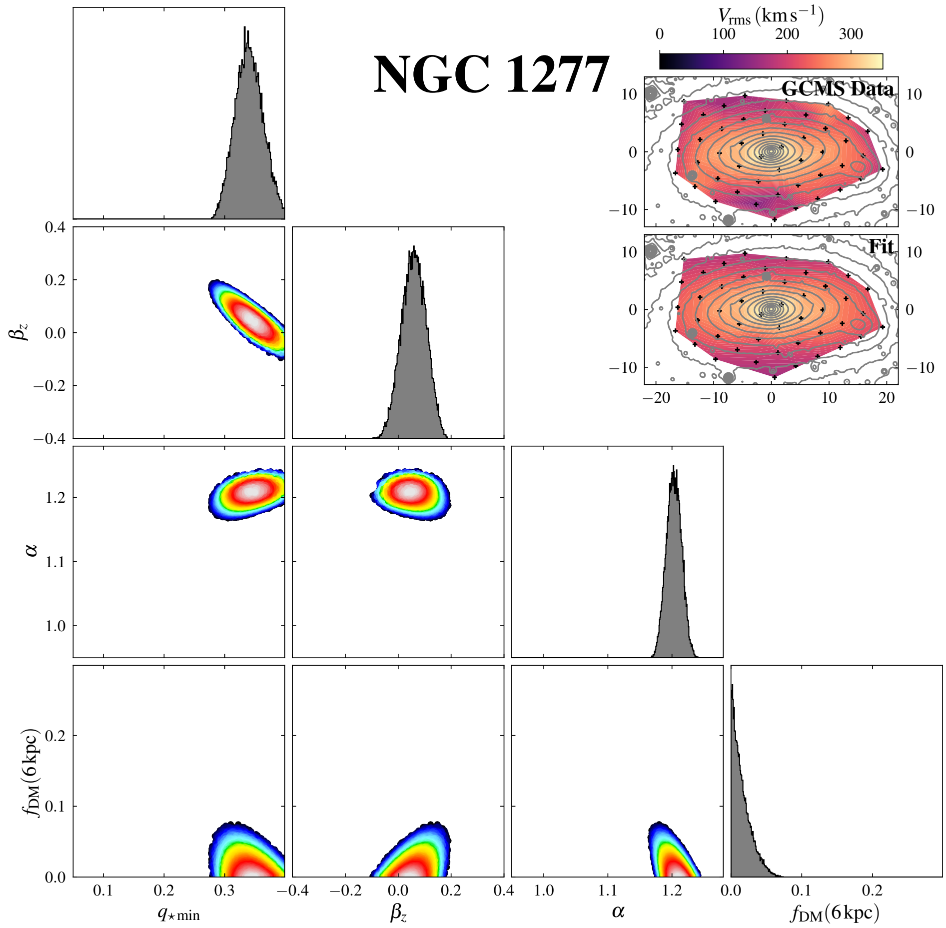

Figure 2: Same as Fig. 1, but this time for NGC 1277. Here the black hole mass was fixed to $M_{\rm BH} = 4.58 \times 10^9\,{\rm M}_{\odot}$, as obtained from the AO-assisted kinematics measured by [20].

α, indicating an IMF in line with that of regular ETGs.

The most striking result of the fits is that NGC 1277 has a negligible fraction of dark matter within 6 kpc. Combining the stellar-mass-to-halo relation from [13] with the dark matter halo shape parametrisation from [9], we found that this result is in a strong tension with the expected fraction $f_{\rm DM}(6\,{\rm kpc}) \approx 0.1$. On the other hand, the measured dark matter halo in NGC 1278 is fully compatible with the expectations.

How is it possible that one of the densest known galaxies has formed within an under-dense dark matter halo? The parsimony aesthetical criterion suggests that the two peculiarities of the galaxy (the relic status and the lack of detectable dark matter) are related. We propose that there is a causation between the lack of dark matter and the failure to accrete a stellar envelope. Indeed, the smaller the density of the dark matter halo, the lesser the effect of dynamical friction. Hence, small galaxies approaching NGC 1277 are not dragged inwards as efficiently as in a galaxy with a regular dark matter halo, resulting in little envelope growth.

To test the plausibility of the above scenario we need to find a viable formation mechanism to explain a compact giant galaxy with little dark matter. In a study by [21] one such galaxy is found within the $1.2 \times 10^6\,\mathrm{Mpc}^3$ volume of the Illustris simulation. It is very suggestive that this number is close to the observed density of relics (three in $5 \times 10^6\,\mathrm{Mpc}^3$; [12]).

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