

Euclid: The r_b - M_* relation as a function of redshift. I. The $5 \times 10^9 M_\odot$ black hole in NGC 1272[★]

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ABSTRACT

Core ellipticals, massive early-type galaxies with almost constant inner surface brightness profiles, are the results of dry mergers. During these events a binary black hole is formed, destroying the original cuspy central regions of the merging objects and scattering stars that are not on tangential orbits. The size of the emerging core correlates with the mass of the finally merged black hole. Therefore, the determination of the size of the core of massive early type galaxies provides key insights not only on the mass of the black hole, but also on the origin and evolution of these objects. In this work we report the first *Euclid*-based dynamical mass determination of a supermassive black hole. We perform it by studying the centre of NGC 1272, the second most luminous elliptical galaxy in the Perseus cluster, combining the *Euclid* VIS photometry coming from the Early Release Observations of the Perseus cluster with VIRUS spectroscopic observations at the Hobby-Eberly Telescope. The core of NGC 1272 is detected on the *Euclid* VIS image. Its size is $1''.29 \pm 0''.07$ or 0.45 kpc, determined by fitting PSF-convolved core-Sérsic and Nuker-law functions. We deproject the surface brightness profile of the galaxy, finding that the galaxy is axisymmetric and nearly spherical. The two-dimensional stellar kinematics of the galaxy is measured from the VIRUS spectra by deriving optimally regularized non-parametric line-of-sight velocity distributions. Dynamical models of the galaxy are constructed using our axisymmetric and triaxial Schwarzschild codes. We measure a black hole mass of $(5 \pm 3) \times 10^9 M_\odot$, in line with the expectation from the $M_{\text{BH}}-r_b$ correlation, but eight times larger than predicted by the $M_{\text{BH}}-\sigma$ correlation (at 1.8σ significance). The core size, rather than the velocity dispersion, allows one to select galaxies harboring the most massive black holes. The spatial resolution, wide area coverage, and depth of the *Euclid* (Wide and Deep) surveys allow us to find cores of passive galaxies larger than 2 kpc up to redshift 1.

Key words. Galaxies: kinematics and dynamics; elliptical and lenticular, cD; individual: NGC 1272; nuclei; photometry

1. Introduction

Massive early-type galaxies (ETGs) are commonly found at the centre of galaxy clusters and are the result of mostly dissipationless mergers. During these events nuclear supermassive

black hole (SMBH) binaries are formed. Gravitational slingshots eject stars on radial orbits from the center of the remnant galaxy, destroying the power-law surface brightness distributions found in lower luminosity ellipticals (Faber et al. 1997). Gravitational wave recoil (Khonji et al. 2024) can enhance the scouring mechanism. Through this core-scouring mechanism the surface brightness profile $I(r)$ of most massive ETGs becomes al-

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most constant within a break (or core) radius r_b , and for $r \leq r_b$ one finds $I(r) \propto r^{-\gamma}$, with $\gamma < 0.3$ (Faber et al. 1997). The break radius r_b is tightly correlated with the mass of the central black hole (Rusli et al. 2013a; Thomas et al. 2016), and anti-correlated with the central surface brightness (Mehrgan et al. 2019). A broader correlation between r_b and luminosity or stellar mass of the galaxies is also established (Laine et al. 2003; Rusli et al. 2013a). Moreover, within r_b the distribution of orbits becomes tangentially anisotropic (Thomas et al. 2014), as only stars avoiding the center can survive the scouring (Milosavljević & Merritt 2001; Thomas et al. 2014; Rantala et al. 2018, 2019). Although alternative explanations for the formation of cores have been proposed, such as the “tidal deposition” discussed by Nasim et al. (2021) and the feedback by active galactic nuclei, see Teyssier et al. (2011), Martizzi et al. (2012), and Choi et al. (2018), they fail to explain this tangential anisotropy signature.

Black Holes (BHs) with dynamically measured masses larger than $10^{10} M_\odot$, i.e., hypermassive BHs or HMBHs, are still rare. They cannot be found using the $M_{\text{BH}}-\sigma$ relation (Saglia et al. 2016): a dissipationless merger of equal mass galaxies doubles the mass of the resulting BH, but keeps constant or even reduces the velocity dispersion of the system (Naab et al. 2009). A large fraction of brightest cluster galaxies (BCGs) in the local Universe have relatively low velocity dispersions: Kluge & Bender (2023) measure on average a velocity dispersion of 250 km s^{-1} for their large sample of BCGs, with only 10% of objects having $\sigma > 300 \text{ km s}^{-1}$. The $M_{\text{BH}}-\sigma$ relation translates $\sigma = 250 \text{ km s}^{-1}$ into BH masses around only about $6 \times 10^8 M_\odot$. Nevertheless, HMBHs are found in BCGs, the largest ($4 \times 10^{10} M_\odot$) in Holm 15A (Mehrgan et al. 2019). The most promising way to search for them is to select massive ETGs, in particular BCGs, with core radii of the order or larger than 0.6 kpc (Holm 15A has a core radius of 4 kpc). The Euclid Wide and Deep Surveys will allow us to find these objects in large numbers and out to redshifts around 1, thanks to their excellent spatial resolution, large area coverage, and depth. Here we report the detection of the $1''.29$ (or 0.45 kpc) core of NGC 1272, measured on the *Euclid* ERO VIS (Euclid Collaboration: Cropper et al. 2024) image of the Perseus cluster (Cuillandre et al. 2024a,b), and the dynamical determination of the mass of its BH.

The galaxy is the second brightest elliptical galaxy of Perseus. With a total magnitude in the V band corrected for Galactic absorption V_T^0 of 11.27 (de Vaucouleurs et al. 1991), we compute a luminosity of $L = 1.3 \times 10^{11} L_\odot$ using 72 Mpc as the distance of the cluster (Kluge et al. 2024), with which $1''$ translates to 0.35 kpc . The stellar mass of the galaxy is $9 \times 10^{11} M_\odot$, using our dynamically determined mass-to-light ratio of $7 M_\odot/L_\odot$ (see Sect. 3) and the effective radius quoted in de Vaucouleurs et al. (1991) is $57''$ or 20 kpc . With these properties NGC 1272 belongs to the class of cD galaxies, the most massive ellipticals. We expect such objects to be triaxial with a low V/σ parameter (the ratio between the mean stellar velocity V and the velocity dispersion σ of the galaxy), to be detected as radio sources and to have extended X-ray emission (Bender et al. 1989). Consistent with this, Veale et al. (2017) present stellar kinematics of NGC 1272 obtained with the VIRUS-P spectrograph and classify the galaxy kinematically as a slow-rotator. Park et al. (2017) detect a faint radio source at its center and McBride & McCourt (2014) study the properties of the double jets emerging from the center of the galaxy (which are bent with a curvature radius of 2 kpc). Arakawa et al. (2019) detect and study the X-ray minicorona of the galaxy, measuring a temperature of 0.63 keV and a size of 1.2 kpc .

The structure of the paper is the following. In Sect. 2 we describe the photometric and spectroscopic observations of NGC 1272. The dynamical modeling is presented in Sect. 3. We draw our conclusions in Sect. 4, where we discuss the prospect of exploiting the *Euclid* survey (Euclid Collaboration: Mellier et al. 2024) to find large cores up to redshift 1 to probe the formation redshift of the most massive black holes in galaxies.

2. Observations

NGC 1272 was observed during the early days of the *Euclid* survey, as part of the pointings covering the Perseus galaxy cluster (Cuillandre et al. 2024b), one of the objects selected for the Early Release Observations (ERO) program. The VIS (Euclid Collaboration: Cropper et al. 2024) and NISP (Euclid Collaboration: Jahnke et al. 2024) ERO images of the cluster were reduced as described in Cuillandre et al. (2024a). Based on this dataset, studies of the Perseus intracluster light and intracluster globular clusters are described in Kluge et al. (2024) and of its dwarf galaxy population in Marleau et al. (2024).

In Sect. 2.1 we make quantitative use of the VIS image of NGC 1272, with pixel size and resolution of $0''.1$ and $0''.17$, respectively. We used the near-infrared images (with $0''.3$ pixels) to assess the absence of dust in the central regions of the galaxy. The complementary spectroscopic information is described in Sect. 2.2.

2.1. Photometry

Figure 1 shows a cutout of the *Euclid* VIS image of NGC 1272. The isophote shape analysis was performed following Bender & Moellenhoff (1987). Figure 3 shows the resulting surface brightness profile calibrated to the V-band for compatibility with the results of Rusli et al. (2013a). We perform the calibration by integrating the profile in circular apertures, that we shift to reproduce the aperture photometry listed in Hyperleda¹. Finally, we adopt the correction for Galactic absorption and cosmological surface brightness dimming adopted in de Vaucouleurs et al. (1991) by matching our aperture magnitude within $57''$, the half-luminosity radius, to $V_T^0 + 2.5 \log_{10} 2$, half the total luminosity of the galaxy. We measure the photometry out to $147''$ from the center, down to $24.9 \text{ mag arcsec}^{-2}$, five times the distance reached by our stellar kinematics. The galaxy is round, with ellipticities smaller than 0.15 and isophotes showing only small deviations from perfect ellipses. For radii larger than about $45''$, the center of the isophotes starts drifting towards the direction of NGC 1275 and the position angle twists by 70° . In the inner $1''.2$ the surface brightness increase towards the center slows down, pointing to the presence of a core.

The size of the cores of ETGs has been determined in the past using the Nuker law (Faber et al. 1997) and the core-Sérsic law (Graham et al. 2003). Pros and cons of the two approaches have been discussed at length in the literature and depend on how well the outer parts of a galaxy can be described by either law. In the following we rely on both approaches as a way to estimate systematic effects affecting our measurements.

We start deriving the size of the core of NGC 1272 by fitting a 5000×5000 pixels ($250'' \times 250''$) image extracted from the VIS mosaic with the PSF-convolved core-Sérsic function provided by the *Imfit* code² of Erwin (2015), using the image of a star extracted in the vicinity of the galaxy as the PSF. Fitting larger

¹ <http://atlas.obs-hp.fr/hyperleda/>

² <https://www.mpe.mpg.de/~erwin/code/imfit/index.html>

cutouts requires prohibitively large computing time without improving the determination of the core size. As implemented in [Erwin \(2015\)](#), the core-Sérsic function is:

$$I_{\text{CS}}(r) = I' \left[1 + \left(\frac{r_b}{r} \right)^{\alpha_{\text{CS}}} \right]^{\gamma_{\text{CS}}/\alpha_{\text{CS}}} \exp \left[-b_n \left(\frac{r^{\alpha_{\text{CS}}} + r_b^{\alpha_{\text{CS}}}}{r_e^{\alpha_{\text{CS}}}} \right)^{1/n\alpha_{\text{CS}}} \right], \quad (1)$$

where

$$I' = I_{\text{CS},b} 2^{-\gamma_{\text{CS}}/\alpha_{\text{CS}}} \exp \left[b_n \left(2^{1/\alpha_{\text{CS}}} \frac{r_b}{r_e} \right)^{1/n} \right] \quad (2)$$

and $b_n \sim 2n - 1/3 + 4/405n$. Similarly, the Sérsic function is:

$$I_{\text{S}}(r) = I_e \exp \left[-b_n \left(\frac{r}{r_e} \right)^{1/n} \right]. \quad (3)$$

Here r_e is the half-luminosity radius, I_e the intensity at r_e , n the Sérsic index, r_b the break radius and $I_{\text{CS},b}$ the intensity at r_b , $-\gamma_{\text{CS}}$ is the slope of the power-law inner profile, and α_{CS} specifies the sharpness of the transition to the outer, Sérsic profile. In Table 1 and 3 we provide the values of $\mu_V(r_e)$ and $\mu_V(r_b)$ that calibrate the surface brightness profiles $\mu_{\text{S}} = -2.5 \log_{10} I_{\text{S}}/I_e + \mu_V(r_e)$ and $\mu_{\text{CS}} = -2.5 \log_{10} I_{\text{CS}}/I_{\text{CS},b} + \mu_V(r_b)$ to the V -band.

The core-Sérsic model reproduces the surface brightness of the galaxy accurately, with residuals less than 0.1 mag, even if it has a constant ellipticity and position angle. The resulting parameters of the fit are given in Table 1; in particular, the size of the core is perfectly resolved by the spatial resolution of the VIS image. According to [Thomas et al. \(2016\)](#), we expect this to match the size of the sphere of influence of the central black hole of the galaxy. The best fitting value of n (21.1) is unrealistically large, as is the one of r_e , two orders of magnitudes larger than the size of the fitted image; this stems from the almost power-law behavior of the outer profile, typical of BCGs ([Kluge & Bender 2023](#)). Both parameters are to be considered as a convenient parametrization of the galaxy profile out to the limit of the image and increasing with the image size. More importantly, the values of r_b and γ_{CS} do not depend much on this choice. The statistical errors listed in Table 1 (and further below in Tables 2 and 3) are minute, because the number of independent points in the image is huge. We have rounded them up to the first or second digit. Fitting the surface brightness of Fig. 3 with a 1-dimensional Sérsic profile without PSF-convolution delivers similar results within the systematic errors estimated below.

We explore further the systematic errors affecting the estimation of the core radius by fitting the same image with the `Imfit` implementation of the (PSF-convolved) Nuker-law:

$$I_{\text{N}}(r) = I_{\text{N},b} 2^{(\beta_{\text{N}} - \gamma_{\text{N}})/\alpha_{\text{N}}} \left(\frac{r_b}{r} \right)^{\gamma_{\text{N}}} \left[1 + \left(\frac{r}{r_b} \right)^{\alpha_{\text{N}}} \right]^{(\gamma_{\text{N}} - \beta_{\text{N}})/\alpha_{\text{N}}}. \quad (4)$$

Here $-\gamma_{\text{N}}$ is the asymptotic logarithmic slope inside r_b , $-\beta_{\text{N}}$ is the asymptotic outer slope, and the α_{N} parameter describes the sharpness of the break; $I_{\text{N},b}$ is the intensity at r_b and the surface brightness profile $\mu_{\text{N}}(r) = -2.5 \log_{10} I_{\text{N}}/I_{\text{N},b} + \mu_V(r_b)$ is calibrated to the V band through the value of $\mu_V(r_b)$ given in Table 2. The Nuker fit delivers a core-size determination similar to what found using the core-Sérsic function, see Table 2, and, as noted above, describes reasonably well the outer power-law behavior of the galaxy profile.

Inspection of the NIR images (see Fig. 2) confirms that the central region of NGC 1272 is not strongly affected by dust: core

sizes between $1''.25$ and $1''.29$ are obtained when fitting these images. The slope of the surface brightness profile inside r_b is between 0.1 (from the Nuker fit) to 0.2 (from the core-Sérsic fit), in the range expected for core ellipticals ([Faber et al. 1997](#)).

A more realistic estimate of the effective radius of the galaxy that catches better the varying ellipticity and PA profiles (see Fig. 3) is obtained by fitting a two-component model, an inner core-Sérsic plus an outer Sérsic profile. The results are listed in Table 1 and 3. The core radius is somewhat larger and the inner slope γ_{CS} of the profile somewhat shallower than above. We show in Fig. 4 the fractional residuals between image and model that in absolute sense are always smaller than 0.1. The surface brightness is reproduced with a root mean square (RMS) of 0.028 mag (see Fig. 3).

[de Rijcke et al. \(2009\)](#) collected F555W and F814W ACS images of NGC 1272 with the Hubble Space Telescope (HST), with pixel size and resolution a factor 2 better than our *Euclid* VIS images. We perform core-Sérsic fits to $179'' \times 184''$ images with `Imfit`, fixing the value of n to the result obtained from the VIS image. The results are given in Table 1, where we calibrate $\mu_b = -2.5 \log I_b$ to the V -band as above. We measured $r_b = 1''.27$ and $1''.25$ in the two bands, demonstrating that possible color gradients do not affect strongly the determination of r_b .

The statistical errors reported in Table 1, 2, and 3 are minute due to the large number of pixels fitted. More significant are the systematic errors that come from the different fitting functions used to measure r_b . Averaging the five estimates of r_b presented above one gets $1''.29$, or 0.45 kpc, with root mean square (RMS) of $0''.07$, which we adopt as our measurement error.

We deproject the surface brightness profile using the axisymmetric deprojection code of [Magorrian \(1999\)](#), assuming that the galaxy is edge-on, as is usually done in this case ([Lipka & Thomas 2021](#)). Other options are explored below, when triaxial deprojections are considered. The blue line in Fig. 3 shows that this deprojection reproduces the ellipticity profiles, but cannot reproduce the PA profile (assumed to be constant in axisymmetric deprojections). The intrinsic flattening profile $q(r)$, where $q = c/a$ and a and c are the major and minor semi-axes of the galaxy, derived in this way is around 0.9 (see Fig. 5).

We also explore the range of possible triaxial deprojections following [de Nicola et al. \(2020\)](#). The reconstructed p and q profiles (where $p = b/a$ and b is the intermediate semi-axis of the galaxy) are shown in Fig. 5 and demonstrate that the galaxy is almost spherical and close to axisymmetric, with $p \approx 1$ and $q \approx 0.9$. For some viewing angles the strong PA radial variation (see Fig. 5) forces a twist of the principal axis with radius, which explains why the p and q profiles can become larger than one at same distance ([de Nicola et al. 2020](#)).

The deprojection with the lowest RMS in surface brightness is obtained at angles $(\theta, \phi, \psi) = (64^\circ, 124^\circ, 23^\circ)$, roughly 26° above the equatorial plane and about 34° away from the intermediate axis. However, it is clear that reconstructing the true orientation of the galaxy is almost impossible, given its almost spherical geometry. The green line in Fig. 3 shows that this deprojection does reproduce the PA profile (additionally to the ellipticity profile). We further explore alternative deprojections with comparably good surface brightness RMS: a (mildly) prolate and an (almost) spherical deprojection (similar to the axisymmetric one, but matching the PA twist). Both are obtained assuming that the line of sight is along the major axis of the galaxy and starting the deprojection routine with constant profiles $q(r) = 0.7$ and $q(r) = 0.95$ in the prolate and spherical cases, respectively.

Table 1. Parameters of the core-Sérsic best fits.

| Image | PA [deg] | $1 - B/A$ | n | r_e [$''$] | $\mu_V(r_b)$ [mag arcsec $^{-2}$] | r_b [$''$] | α_{CS} | γ_{CS} |
|------------------|-----------------|-----------------|------------------|-------------------|---------------------------------------|-------------------|-----------------|-----------------|
| VIS | -34.1 ± 0.1 | 0.10 ± 0.01 | 21.14 ± 0.02 | $22807^a \pm 126$ | 17.83 ± 0.01 | 1.24 ± 0.01 | 3.99 ± 0.01 | 0.21 ± 0.01 |
| VIS ^b | -35.4 ± 0.1 | 0.15 ± 0.01 | 12.1 ± 0.1 | 34.9 ± 1.0 | 17.93 ± 0.01 | 1.41 ± 0.01 | 2.47 ± 0.01 | 0.15 ± 0.01 |
| F555W | -35.1 ± 0.1 | 0.11 ± 0.01 | 21.14 | $18392^a \pm 4$ | 17.85 ± 0.01 | 1.27 ± 0.01 | 3.41 ± 0.01 | 0.17 ± 0.01 |
| F814W | -34.8 ± 0.1 | 0.11 ± 0.01 | 21.14 | $16246^a \pm 1$ | 17.83 ± 0.01 | 1.25 ± 0.01 | 3.64 ± 0.01 | 0.19 ± 0.01 |

Notes. We list the fitted image (column 1), the position angle (column 2), the ellipticity (column 3), the values of n , r_e , $\mu_V(r_b)$, r_b , α_{CS} , and γ_{CS} (columns 4, 5, 6, 7, and 8, respectively), see Eq. 1.

^(a) The value is unrealistically large, see text. ^(b) With second Sérsic component, see Table 3.

Table 2. Parameters of the Nuker best fit.

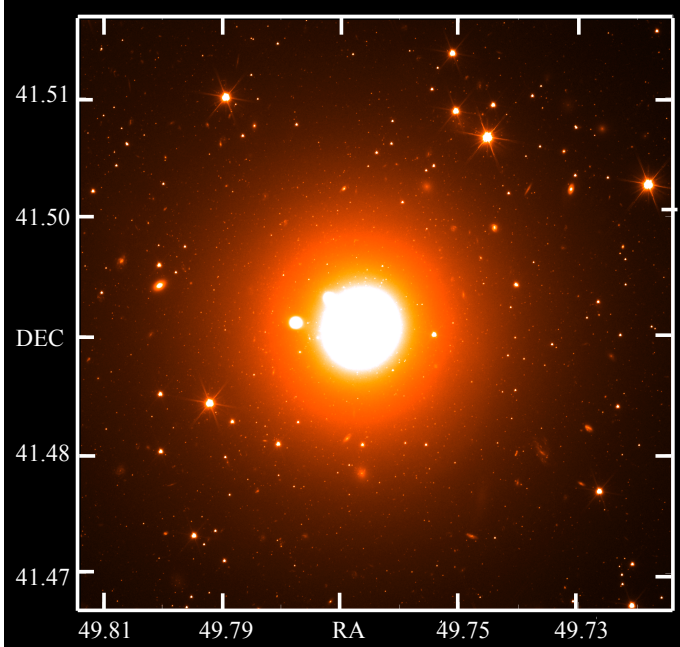
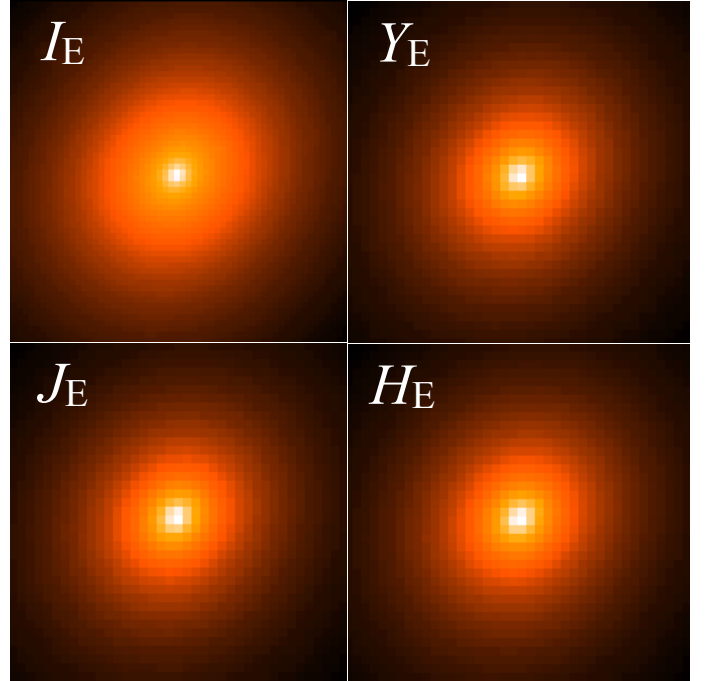
| Image | PA [deg] | $1 - B/A$ | $\mu_V(r_b)$ [mag arcsec $^{-2}$] | r_b [$''$] | α_N | β_N | γ_N |
|-------|-----------------|-----------|---------------------------------------|-------------------|-----------------|-----------------|-----------------|
| VIS | -33.9 ± 0.1 | 0.1 | 17.86 | 1.29 ± 0.01 | 2.35 ± 0.01 | 1.42 ± 0.01 | 0.12 ± 0.01 |

Notes. We list the fitted image (column 1), the position angle (column 2), the ellipticity (column 3), the values of $\mu_V(r_b)$, r_b , α_N , β_N , and γ_N (columns 4, 5, 6, 7, and 8, respectively), see Eq. 4.

Table 3. Parameters of the second Sérsic component.

| Image | PA [deg] | $1 - B/A$ | n | r_e [$''$] | $\mu_V(r_e)$ [mag arcsec $^{-2}$] |
|-------|----------------|----------------|-----------------|-------------------|---------------------------------------|
| VIS | 50.3 ± 0.1 | 0.14 ± 0.1 | 2.62 ± 0.01 | 140.8 ± 0.1 | 25.04 ± 0.01 |

Notes. We list the fitted image (column 1), the position angle (column 2), the ellipticity (column 3), the values of n , r_e , $\mu_V(r_e)$ (columns 4, 5, and 6, respectively), see Eq. 3.

**Fig. 1.** A cutout of the *Euclid* VIS image of NGC 1272.**Fig. 2.** The I_E , Y_E , J_E , and H_E cutouts of the inner $6'' \times 6''$ of NGC 1272.

2.2. Spectroscopic observations and kinematics

We observed NGC 1272 spectroscopically with the Visible Integral-field Replicable Unit Spectrograph (VIRUS) at the

Hobby-Eberly Telescope (HET) on 3 March 2022. The pointing of the telescope was optimized to observe NGC 1275; as

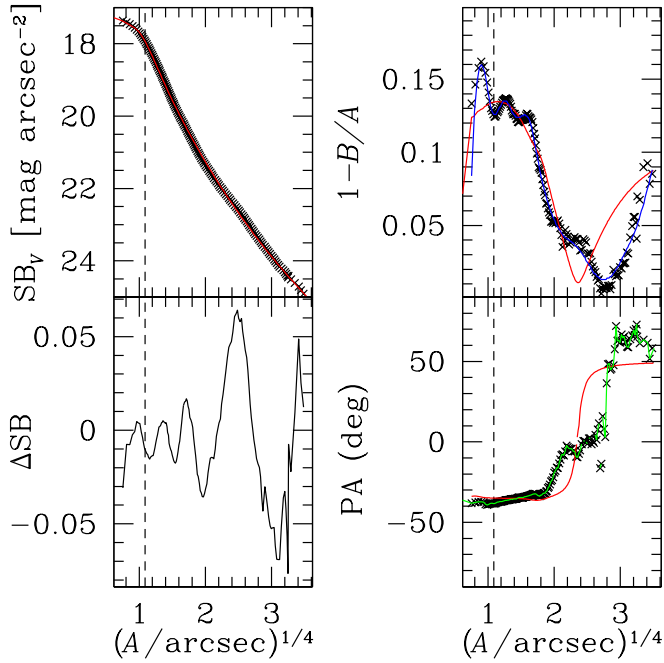


Fig. 3. *Top Left:* surface brightness profile of NGC 1272, measured from the *Euclid* VIS image, calibrated to the *V*-band and corrected for Galactic absorption and cosmological dimming, as a function of the 1/4 power of the semi-major distance A on the sky in arcsec. *Bottom Left:* the difference ΔSB between the surface brightness profile of NGC 1272 and the surface brightness of the core-Sérsic+Sérsic model. *Right:* ellipticity $1 - B/A$, where B is the semi-minor axis length on the sky (top) and PA (bottom) as a function of the 1/4 power of A . The solid red lines show the core-Sérsic+Sérsic model. The dashed lines show its core radius. The blue line shows the ellipticity profile of the axisymmetric deprojection. The green line shows the PA profile of the triaxial deprojection.

as a result the integral field unit (IFU) covering NGC 1272 was slightly off-center and did not uniformly cover the galaxy. The seeing reported during the observations was $\text{FWHM} = 2''.36$. The diameter of the single fiber is $1''.5$. Given the size of the core measured above (a diameter of $2''.6$), the spatial resolution of this data set is (just) enough to resolve the sphere of influence of the central black hole of the galaxy. Rusli et al. (2013b) find that in such a case an unbiased recovery of the BH mass is possible if the dark matter halo of the galaxy is taken into account in the dynamical modeling, as we are doing here, see below. The data cover a wavelength interval ranging from 3470 \AA to 5540 \AA with a spectral resolution of 5.6 \AA .

We used the Voronoi tessellation method of Cappellari & Copin (2003) to spatially bin the spectral data for a target average signal-to-noise (S/N) of 40. With this target S/N, spectra were only binned together starting approximately $3''$ from the center of the galaxy, thus maximizing the spatial resolution of our data within the core region. In this way we ended up with a total of 110 spatial bins. We measured the stellar kinematics using WINGFIT (Thomas, in prep.), which delivers optimally smoothed non-parametric line-of-sight velocity distributions (LOSVDs) using the model optimization approach of Thomas & Lipka (2022). The stellar kinematic fits were performed using the MILES library (Sánchez-Blázquez et al. 2006) of stellar templates. Following the strategy laid out in Mehrgan et al. (2023), we performed a careful pre-selection of templates in order to minimize distortions of the LOSVDs due to template

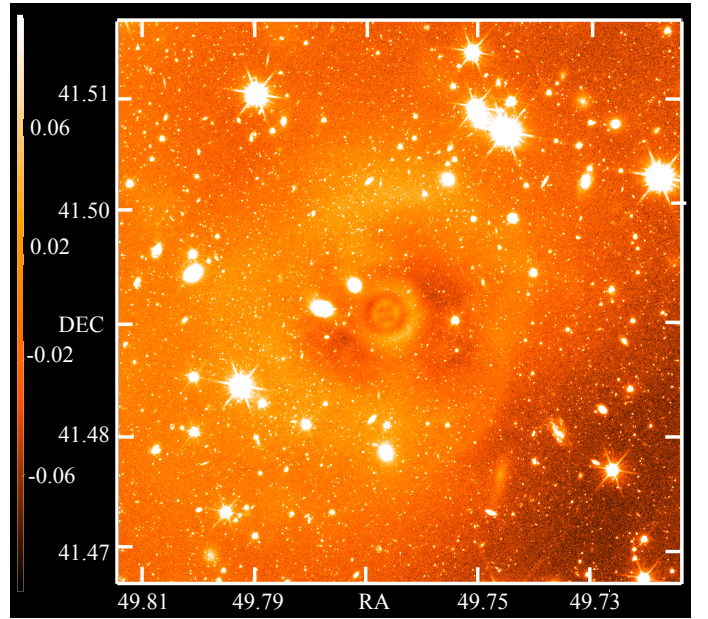


Fig. 4. Percentage residuals after subtraction of the core-Sérsic + Sérsic model.

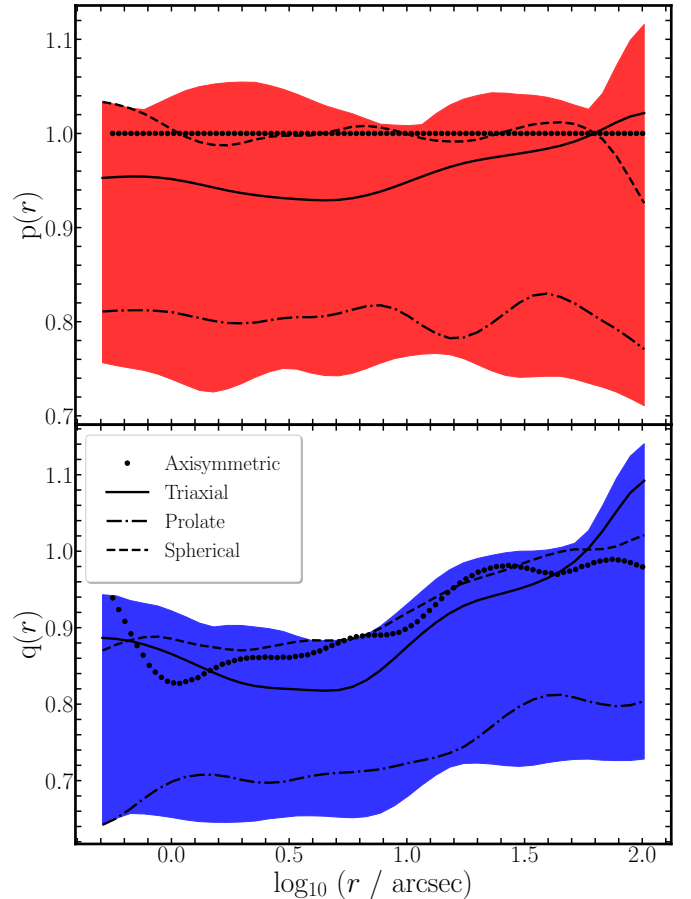


Fig. 5. Profiles of $p(r)$ and $q(r)$ (where $p = b/a$, $q = c/a$ and a , b and c are the major, intermediate and minor semi-axis of the galaxy) derived from the axisymmetric (dotted), triaxial (full line), the spherical (dashed line), and prolate (dashed-dotted line) deprojections of the galaxy, as a function of the distance r from the center. The red and blue shaded areas show the whole range of allowed deprojections with $\text{RMS} \leq 1.2 \times \text{RMS}_{\min}$ (de Nicola et al. 2020, 2022b,a).

mismatch. To this end we fitted the average spectrum of the central 2'' of the galaxy using all the templates of the MILES library with a Gauss-Hermite LOSVD that was fixed to be symmetric around a line-of-sight velocity of zero. We then used the 18 templates that in the best fit received a non-zero weight as the template set with which we subsequently fitted all bins of the galaxy with non-parametric LOSVDs (without the symmetry constraint on the LOSVD). Also following Mehrgan et al. (2023), we used no additive polynomials in the fit and only a minimal third-order multiplicative polynomial. Fits were performed in the wavelength interval between 4700 and 5400 Å. The resulting 2-dimensional kinematic maps are shown in Fig. 6; the corresponding radial profiles can be seen in Fig. 7. We measured the stellar kinematics out to a maximum distance of 38'', or 0.66 times the effective radius quoted by de Vaucouleurs et al. (1991). The galaxy has small mean rotation (at most $v = 20 \text{ km s}^{-1}$), a relatively low velocity dispersion σ around 250 km s^{-1} , increasing to 270 km s^{-1} towards the center (admittedly with only one point within 1 arcsec from the center), almost zero third-order Hermite parameter h_3 and zero fourth-order Hermite parameter h_4 , decreasing to about -0.05 towards the center. The data presented by Veale et al. (2017) match these findings, though their h_4 is always about 0. We averaged $(v^2 + \sigma^2)^{0.5}$, with equal or luminosity weights, to get an estimate of σ_e , the velocity dispersion within the half-luminosity radius (even if our stellar kinematics reaches out only two-thirds of r_e , see above). We find $\sigma_e = 247 \pm 3 \text{ km s}^{-1}$, which we adopt in Sect. 4.

For the subsequent dynamical analysis we sampled and fit the non-parametric LOSVDs between $\pm 1400 \text{ km s}^{-1}$, with $N_{\text{vel}} = 25$ velocity bins, not the Hermite parameters. An example LOSVD measured near the center of the galaxy is shown in Fig. 8, where the red line connects the values produced by the best-fitting base model. Finally, to ensure that we are able to estimate the uncertainties of our dynamical models we split our data into four quadrants (indicated by q1, q2, q3, and q4 in Fig. 6) along the minor and major axes of the galaxy for the axisymmetric dynamical models, and into two halves (quadrants q1/q4, northern, and q2/q3, southern) split by the major axis for the triaxial analysis. By modeling quadrants/halves independently, we can estimate the uncertainties of our best-fit modeling parameters from the scatter between them. However, the orientation and positioning of the IFU give us a much better coverage of the q3 and q4 quadrants, or the east side of the galaxy. Therefore, we expect the most reliable dynamical constraints to come from these regions.

3. Dynamical modeling

Given the results presented in Fig. 5 (NGC 1272 is almost spherical and axisymmetric, but triaxiality and a prolate shape cannot be excluded), we construct both axisymmetric and triaxial Schwarzschild models of the galaxy.

The axisymmetric modeling is similar to that of Mehrgan et al. (2024), with the following modifications. We fit the four quadrants both independently and together, determining the mass of the central black hole M_{BH} and the stellar mass-to-light ratio Υ_* (i.e., no radial variations of Υ_* are considered, because of the rather coarse and sparse sampling of our stellar kinematics). We use a spherical Zhao (1996) halo with $\alpha = 1$ and $\beta = 3$, defined by ρ_{10} , the dark matter (DM) density at 10 kpc, r_s , the scale radius of the halo allowed to vary up to the largest distance probed by our kinematics (Lipka et al. 2024), and $\gamma_{\text{DM}} \geq 0$, the inner slope of the DM halo:

$$\rho_{\text{DM}}(r) = \frac{k}{(r/r_s)^{\gamma_{\text{DM}}} (1 + r/r_s)^{3-\gamma_{\text{DM}}}}, \quad (5)$$

and $k = \rho_{10} (10 \text{ kpc}/r_s)^{\gamma_{\text{DM}}} (1 + 10 \text{ kpc}/r_s)^{3-\gamma_{\text{DM}}}$.

The triaxial modeling follows de Nicola et al. (2024) and uses the Schwarzschild code SMART (Neureiter et al. 2021) to determine M_{BH} and Υ_* , considering a DM halo that is triaxial, described by its shape parameters p_{DM} , q_{DM} plus ρ_{10} and γ_{DM} , fixing r_s to a large value (158 kpc). We model the northern (quadrants q1 and q4 in Fig. 6) and southern (quadrants q2 and q3 in Fig. 6) halves of the galaxy separately to assess the systematic uncertainties.

In both the axisymmetric and triaxial cases we maximize the quantity $\hat{S} = S - \hat{\alpha} \chi^2$ to determine the orbital weights. Here χ^2 is calculated from the model fit to the observed non-parametric LOSVDs, and S is the Boltzmann entropy (Thomas et al. 2004). The deprojected light distributions are used as a constraint and the parameter $\hat{\alpha}$ is the smoothing of the models, determined following the prescriptions of Lipka & Thomas (2021) and Thomas & Lipka (2022), which involve the determination of the effective degrees of freedom m_{eff} . The parameters M_{BH} , Υ_* , ρ_{10} , and r_s (in both the axisymmetric and triaxial cases), plus p_{DM} and q_{DM} in the triaxial case, are determined by minimizing the generalized Akaike information criterion $\text{AIC}_p = \chi^2 + 2m_{\text{eff}}$ over a grid of $\hat{\alpha}$ values.

The resulting axisymmetric best-fits to the kinematics are shown in Fig. 7; the derived parameters for the different fit types are listed in Table 4. Our base result is the axisymmetric model of the entire stellar kinematic data set. It fits the kinematics very well (see red line in Fig. 7), delivering a reduced χ^2 of $\chi^2/(N_{\text{data}} - m_{\text{eff}}) = 0.91$. Figure 9 shows M_{BH} , $\Upsilon_{*,V}$, ρ_{10} , and γ_{DM} as a function of the quality of the fit measured by the AIC_p value. Every parameter is well constrained, with small statistical errors (so small that we do not quote them in Table 4). In particular, we detect a black hole of $5 \times 10^9 M_{\odot}$, a mass-to-light ratio $\Upsilon_{*,V}$ of $7.1 M_{\odot}/L_{\odot}$, in between the values derived from our stellar population analysis for the Kroupa or the Salpeter initial mass function (IMF, see below), a DM density at 10 kpc (approximately 30'') similar to the values reported for other massive elliptical galaxies (Mehrgan et al. 2024) and a cored DM density profile. We compute the radius r_{SOI} of the sphere of influence of the black hole as the distance from the center where the total mass (stellar plus DM without black hole) equals M_{BH} (Thomas et al. 2016). Our r_{SOI} matches the value of r_b and is larger than half the FWHM of the seeing of the spectroscopic observations. This, together with the modeling of the dark matter halo of the galaxy, allows an unbiased estimate of the BH mass (Rusli et al. 2013b).

We gauge our (systematic) errors by looking first at the axisymmetric modeling of the two quadrants covering a decent part of the galaxy, q3 and q4. Here the BH mass can be as low as $1.8 \times 10^9 M_{\odot}$ and $\Upsilon_{*,V}$ as large as $8.9 M_{\odot}/L_{\odot}$, with slightly larger DM densities. Further insights into our systematic errors are gained from the triaxial SMART modeling. All models fit the kinematic data well, with $\chi^2/(N_{\text{data}} - m_{\text{eff}})$ between 0.6 and 1.0. The best-fitting triaxial model delivers $M_{\text{BH}} = (5.9 \pm 1.7) \times 10^9 M_{\odot}$, averaging over the two halves of the galaxy; the smallest and largest values for the BH mass are obtained fitting the southern half of the galaxy (where the kinematic coverage is relatively sparse) in the prolate and spherical cases, respectively. The dynamical stellar mass-to-light ratio $\Upsilon_{*,V}$ ranges from 4 to $7.7 M_{\odot}/L_{\odot}$. The density of the DM halo ($\log_{10} \rho_{10}/[M_{\odot} \text{ kpc}^{-3}] =$

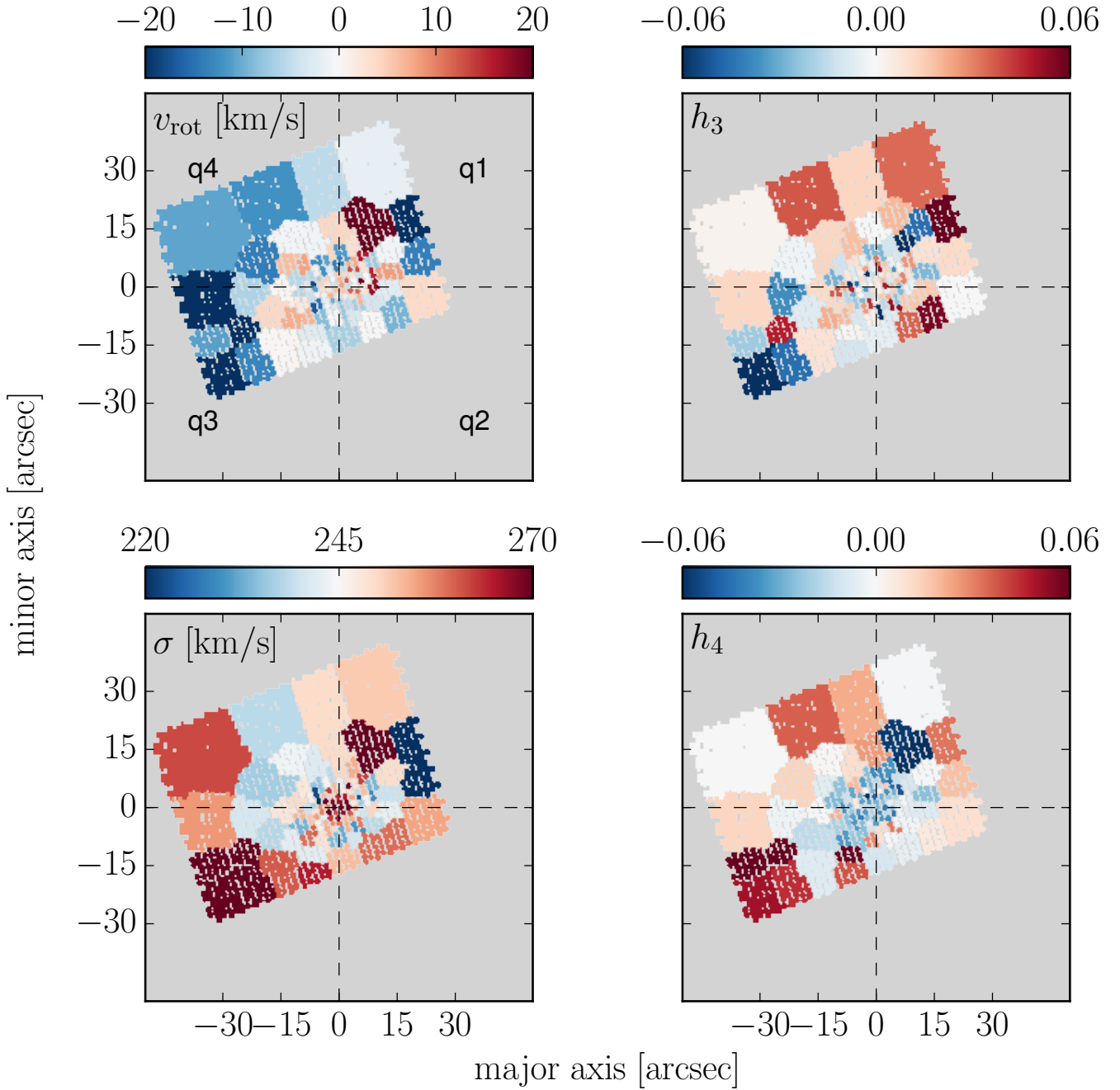


Fig. 6. Two-dimensional stellar kinematics of NGC 1272. The horizontal and vertical dashed lines show the major and minor axes of the galaxy, respectively. North is up and east is to the left.

7.3 ± 0.3 , averaging over all triaxial models and halves) agrees with the axisymmetric result. The slope γ_{DM} of the DM density profile is smaller than 1, but possibly steeper than the cored halo determined axisymmetrically. In Table 4 we quote as errors of our base result the RMS of the nine listed best-fitting models. Finally, the best fitting shape of the DM halo is spherical ($p_{\text{DM}} = q_{\text{DM}} = 1$), with only the prolate case delivering $p_{\text{DM}} = 0.9$.

Figure 10 summarizes the spherically averaged stellar and total mass profiles derived by the dynamical models we considered. The total mass distribution is robustly determined in the region probed by the measured kinematics, with only small deviations between the different models. Inside the sphere of influence (roughly the size of the core) the differences between

the profiles reflect the observed scatter in the black hole mass. The stellar mass profiles scale according to the derived $\Upsilon_{*,V}$ values. The dark halo mass equals the stellar mass at approximately the outermost radius probed by our stellar kinematics. Using the best-fit value $\Upsilon_{*,V} = 7.1 M_\odot/L_\odot$, we estimate the total stellar mass of the galaxy from the total luminosity $L = 1.3 \times 10^{11} L_\odot$ quoted in the Introduction to be $9 \times 10^{11} M_\odot$, which we use in Sect. 4.

The anisotropy β profile (where $\beta = 1 - \sigma_{\text{T}}^2/\sigma_{\text{R}}^2$, and σ_{T} and σ_{R} are the spherical tangential and radial velocity dispersions, respectively) is not particularly well constrained, but displays the typical feature of core ellipticals (Thomas et al. 2014). Figure 11 shows that the β profile of the base model becomes tangentially anisotropic within the core radius (the result of core

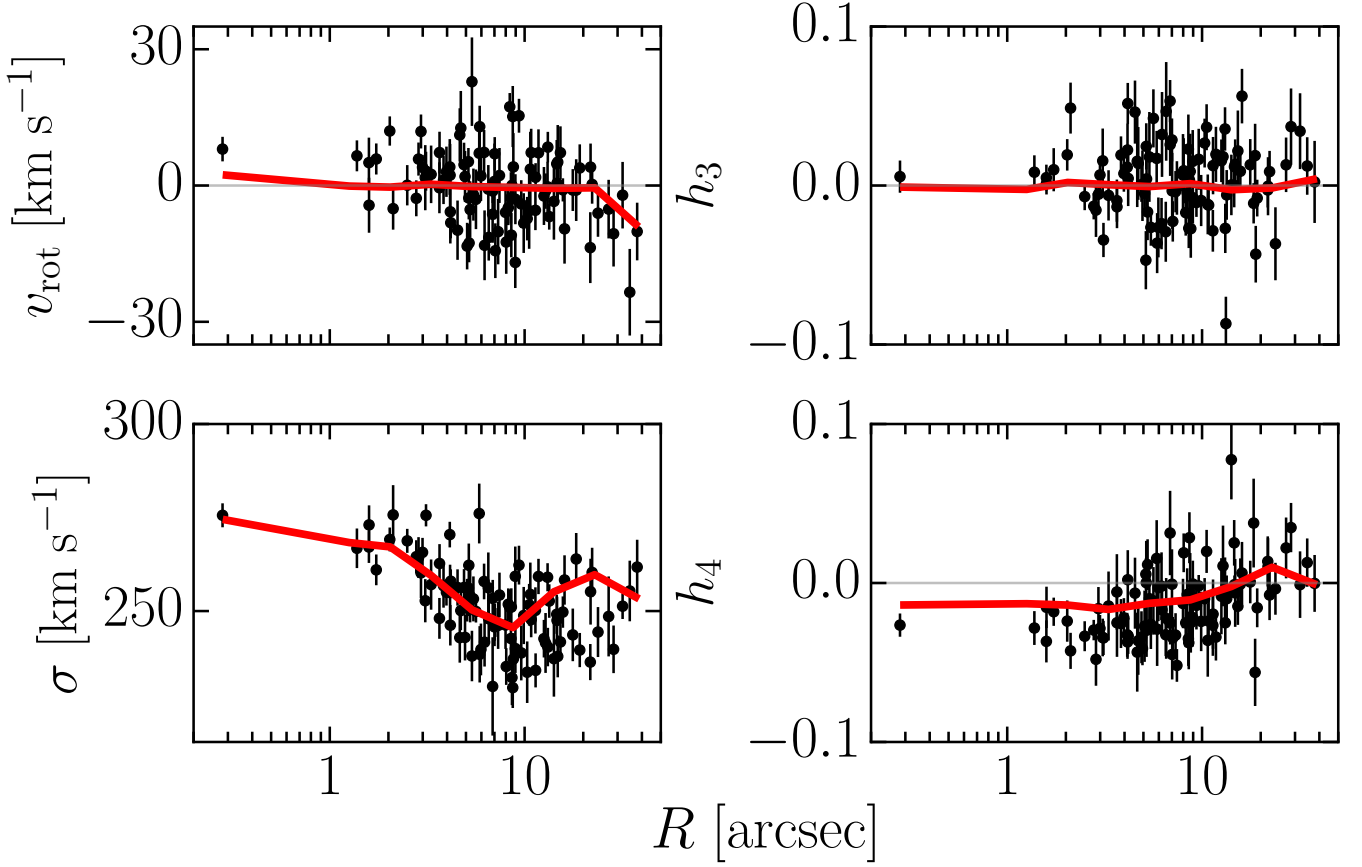


Fig. 7. Radial stellar kinematics of NGC 1272. The red lines show the axisymmetric fit to the stellar kinematics of the galaxy (black data points with error bars) as a function of the distance R from the center of the galaxy on the sky.

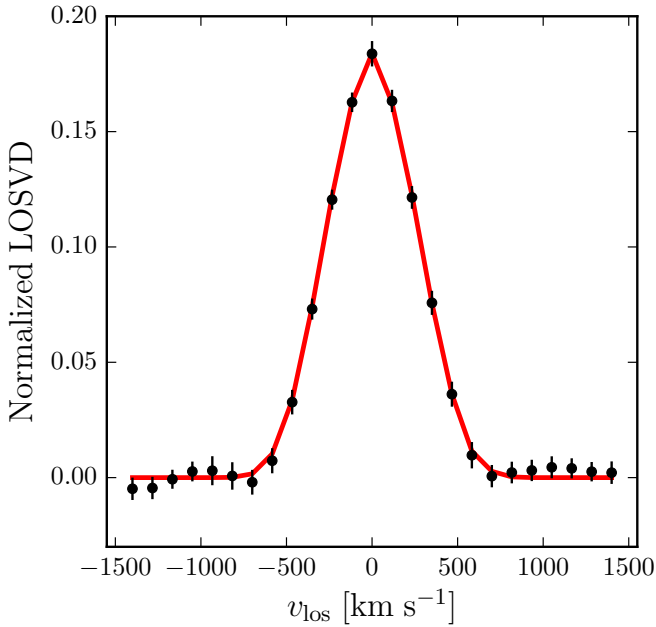


Fig. 8. Line-of-sight velocity distribution measured at 4 arcsec from the center of NGC 1272 (filled circles with error bars). The red line connects the values provided by the base model.

spherical model. The triaxial model is overall mildly tangentially anisotropic, while the prolate model is radially anisotropic outside the core.

Measuring Lick indices and fitting them with the simple stellar population models of [Thomas et al. \(2003\)](#) and [Maraston \(2005\)](#), we find that the best-fit has a simple stellar population as old as the Universe, a slightly above Solar metallicity and is more than a factor of two overabundant in α -elements. The derived V-band mass-to-light ratio is $6 M_{\odot}/L_{\odot}$ with a Kroupa-IMF and $8 M_{\odot}/L_{\odot}$ with a Salpeter IMF. This matches the dynamically determined $\Upsilon_{*,V}$, without unambiguously preferring one of the two options.

Finally, we estimate the mass that has been expelled from the core during its formation. We consider the core-Sérsic solution obtained with the second Sérsic component (see second line of Table 1) and consider the Sérsic function with $n = 12.1$, $r_e = 34''.9$ and $\mu_V(r_e) = 23.57$ that reproduces the core-Sérsic solution outside the core region. We integrate the luminosity difference, or the luminosity deficit L_{def} , between the two functions out to $8''$, finding $L_{\text{def}} = 2.7 \times 10^9 L_{\odot}$. Using the dynamically determined $\Upsilon_{*,V} = 7 M_{\odot}/L_{\odot}$, this translates into a mass deficit of $M_{\text{def}} = 1.9 \times 10^{10} M_{\odot}$, or $3.8 M_{\text{BH}}$, in the range found by [Rusli et al. \(2013a\)](#). According to the simulations of [Gualandris & Merritt \(2008\)](#), mass deficits up to $5 \times M_{\text{BH}}$ can result from single dry mergers.

scouring) and more isotropic in the outer part, similarly to the

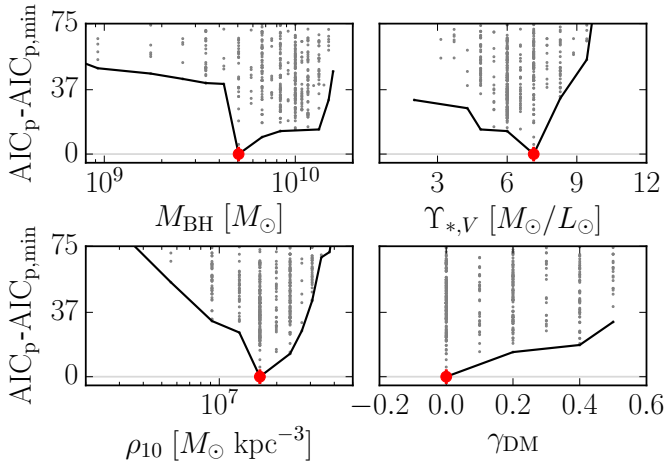


Fig. 9. The results of the axisymmetric modeling of NGC 1272 of the complete stellar kinematic dataset. As a function of the quality of the fits measured by the AIC_p we show: from left to right, from top to bottom: the black hole mass M_{BH} ; the dynamical V -band mass-to-light ratio $\Upsilon_{*,V}$; the DM density at 10 kpc ρ_{10} ; the inner slope of the DM density profile γ_{DM} . The gray points show the individual models, the red dots show the best-fitting model, the black lines the lower envelope of the gray points distributions.

4. Conclusions

We have presented a measurement of the size (0.45 kpc) of the core of NGC 1272, based on the VIS image of the Perseus cluster taken as part of the *Euclid* ERO campaign. The dynamical modelling of the stellar kinematics collected with the VIRUS spectrograph at the HET allowed us to measure the mass $(5 \pm 3) \times 10^9 M_\odot$ of the BH at the center of the galaxy. While in line with expectations from the $M_{BH}-r_b$ correlation of Thomas et al. (2016), the central surface brightness versus M_{BH} correlation of Mehrgan et al. (2019), and the $M_{BH}-M_*$ relation of Saglia et al. (2016), the BH mass of NGC 1272 is a factor of 8 larger than predicted by the $M_{BH}-\sigma$ relation of Saglia et al. (2016), or 1.8 times the 1 sigma error combined with the intrinsic scatter in the relation (see Fig. 12). This corroborates the conclusion that the velocity dispersion is not the best indicator of the black hole mass for core galaxies with stellar masses of the order of or larger than $10^{12} M_\odot$: five out of the six galaxies with such a stellar mass in Fig. 12 have BH masses larger than predicted by the $M_{BH}-\sigma$ relation. Therefore, the most efficient and rapid method to search for galaxies harboring the most massive black holes is to look for passive objects with large cores and low central surface brightness. In the local Universe, a galaxy with a core size of 1 kpc contains a black hole with a mass of $10^{10} M_\odot$.

The *Euclid* VIS images in the I_E band deliver a PSF with FWHM $\approx 0''.17$ with pixel size of $0''.1$, with a depth of 24.5 mag in the Wide Survey (at 10σ for extended sources) and 2 mag deeper in the Deep Survey. Near-infrared Y_E , J_E , and H_E images provide photometry with $0''.3$ pixels. Combined with ground-based images, the surveys will deliver not only photometric redshifts for each detected source, but also physical parameters, such as stellar masses and sizes. At the end of the mission, the Wide Survey will cover about 14,000 deg² of extragalactic sky, along with 50 deg² at the Deep Survey. This unprecedented dataset will allow us to search for galaxies with cores larger than 2 kpc out to redshift 1 (where they will subtend an angle of $0''.5$ on the sky) as a function of stellar mass. We will establish up to which redshift the correlation between r_b and total stellar mass

Table 4. The parameters of the axisymmetric and triaxial dynamical modelling.

| Model | M_{BH} [$10^9 M_\odot$] | $\Upsilon_{*,V}$ [M_\odot/L_\odot] | $\log_{10} \rho_{10}$ [$M_\odot \text{kpc}^{-3}$] | γ_{DM} | r_{SOI} [$''$] |
|-------------|--------------------------------|---|--|---------------|-----------------------|
| Axisymm. | 5.1 ± 3.2 | 7.1 ± 1.5 | 7.2 ± 0.2 | $0^{+0.3}$ | 1.24 ± 0.4 |
| Axisymm. Q3 | 1.8 | 8.9 | 7.3 | 0 | 0.8 |
| Axisymm. Q4 | 5.9 | 7.7 | 7.4 | 0 | 1.24 |
| Triaxial N | 4.3 | 7.7 | 7.6 | 0.6 | 0.8 |
| Triaxial S | 7.6 | 6.4 | 7.3 | 0.6 | 1.2 |
| Prolate N | 7.6 | 6.4 | 7.1 | 0.0 | 1.5 |
| Prolate S | 1.0 | 5.1 | 7.0 | 0.2 | 0.7 |
| Spherical N | 7.6 | 6.4 | 7.4 | 0.0 | 1.5 |
| Spherical S | 10.9 | 3.9 | 7.8 | 0.8 | 1.7 |

Notes. We list the model type (column 1), the black hole mass (column 2), the dynamically determined mass-to-light ratio (column 3), the logarithm of the dark matter density at 10 kpc (column 4), the inner slope of the dark matter density profile (column 5, bound to be larger or equal to 0), and the radius of the BH sphere of influence (column 6).

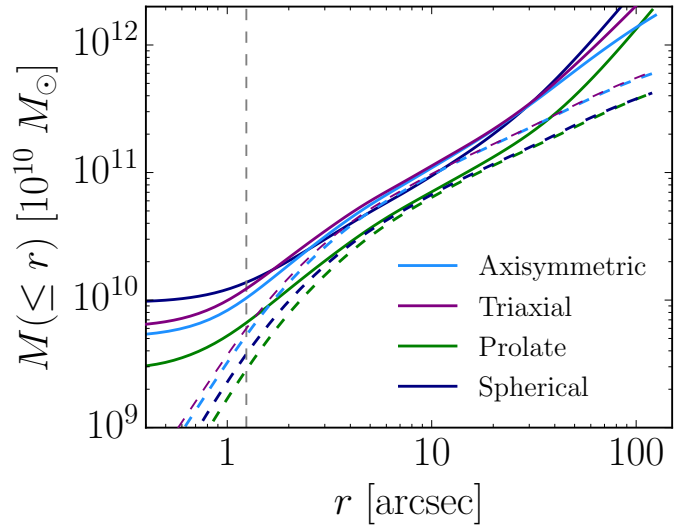


Fig. 10. Spherically-averaged mass profiles of NGC 1272. The solid and dashed lines show the total and stellar profiles, respectively. The triaxial, prolate, and spherical models are averaged over the two sides. The vertical dashed line shows the position of the core radius.

exists (see Fig. 13) and study its possible evolution with a large statistical sample, indirectly probing the possible coevolution of black holes and galaxy properties at the highest BH mass end. For example, the blue cross in Fig. 13 shows the position of the BCG of the EDISCS cluster CL1216 at redshift 0.8 (Saglia et al. 2010). We measured the size of its core in the available HST images, deriving 1.5 kpc (or $0''.5$) from a core-Sérsic fit, and 2.21 kpc (or $0''.7$) from a Nuker fit. Such a core will be measurable in the VIS mosaics of the Wide survey. With a stellar mass of $\log_{10} M_*/M_\odot = 11.82$ the BCG appears to have a larger core than local core ellipticals of similar mass. Using the local r_b-M_{BH} relation, we estimate that an HMBH with mass larger than $10^{10} M_\odot$ could be already in place at such a high redshift in this galaxy. Spectroscopic follow-up (possible at the Extremely Large Telescope) of selected galaxies with similarly large and bright cores will deliver the dynamical mass confirmation.

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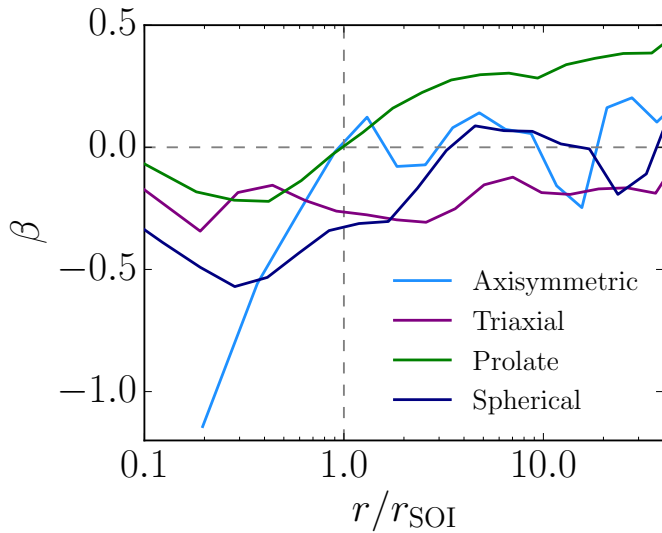


Fig. 11. Anisotropy profiles β (where $\beta = 1 - \sigma_T^2/\sigma_R^2$, and σ_T and σ_R are the spherical tangential and radial velocity dispersions, respectively) of the different models. The triaxial, prolate and spherical models are averaged over the two sides. The distances to the center are in units of the core radius.

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References

- Arakawa, N., Fabian, A. C., & Walker, S. A. 2019, *MNRAS*, 488, 894
 Bender, R. & Moellenhoff, C. 1987, *A&A*, 177, 71
 Bender, R., Surma, P., Doeberlein, S., Moellenhoff, C., & Madejsky, R. 1989, *A&A*, 217, 35
 Cappellari, M. & Copin, Y. 2003, *MNRAS*, 342, 345
 Choi, E., Somerville, R. S., Ostriker, J. P., Naab, T., & Hirschmann, M. 2018, *ApJ*, 866, 91
 Cuillandre, J. C., Bertin, E., Bolzonella, M., et al. 2024a, *A&A*, submitted, arXiv:2405.13496
 Cuillandre, J. C., Bolzonella, M., Boselli, A., et al. 2024b, *A&A*, submitted, arXiv:2405.13501
 de Nicola, S., Neureiter, B., Thomas, J., Saglia, R. P., & Bender, R. 2022a, *MNRAS*, 517, 3445

- de Nicola, S., Saglia, R. P., Thomas, J., Dehnen, W., & Bender, R. 2020, *MNRAS*, 496, 3076
 de Nicola, S., Saglia, R. P., Thomas, J., et al. 2022b, *ApJ*, 933, 215
 de Nicola, S., Thomas, J., Saglia, R. P., et al. 2024, *MNRAS*, 530, 1035
 de Rijcke, S., Penny, S. J., Conselice, C. J., Valcke, S., & Held, E. V. 2009, *MNRAS*, 393, 798
 de Vaucouleurs, G., de Vaucouleurs, A., Corwin, Herold G., J., et al. 1991, *Third Reference Catalogue of Bright Galaxies* (Springer)
 Erwin, P. 2015, *ApJ*, 799, 226
 Euclid Collaboration: Cropper, M., Al-Bahlawan, A., Amiaux, J., et al. 2024, *A&A*, submitted, arXiv:2405.13492
 Euclid Collaboration: Jahnke, K., Gillard, W., Schirmer, M., et al. 2024, *A&A*, submitted, arXiv:2405.13493
 Euclid Collaboration: Mellier, Y., Abdurro'uf, Acevedo Barroso, J. A., et al. 2024, *A&A*, submitted, arXiv:2405.13491
 Faber, S. M., Tremaine, S., Ajhar, E. A., et al. 1997, *AJ*, 114, 1771
 Graham, A. W., Erwin, P., Trujillo, I., & Asensio Ramos, A. 2003, *AJ*, 125, 2951
 Gualandris, A. & Merritt, D. 2008, *ApJ*, 678, 780
 Khonji, N., Gualandris, A., Read, J. I., & Dehnen, W. 2024, *ApJ*, 974, 204
 Kluge, M. & Bender, R. 2023, *ApJS*, 267, 41
 Kluge, M., Hatch, N. A., Montes, M., et al. 2024, *A&A*, submitted, arXiv:2405.13503
 Laine, S., van der Marel, R. P., Lauer, T. R., et al. 2003, *AJ*, 125, 478
 Lipka, M. & Thomas, J. 2021, *MNRAS*, 504, 4599
 Lipka, M., Thomas, J., Saglia, R., et al. 2024, arXiv e-prints, arXiv:2409.11458
 Magorrian, J. 1999, *MNRAS*, 302, 530
 Maraston, C. 2005, *MNRAS*, 362, 799
 Marleau, F. R., Cuillandre, J. C., Cantiello, M., et al. 2024, *A&A*, submitted, arXiv:2405.13502
 Martizzi, D., Teyssier, R., & Moore, B. 2012, *MNRAS*, 420, 2859
 McBride, J. & McCourt, M. 2014, *MNRAS*, 442, 838
 Mehrgan, K., Thomas, J., Saglia, R., et al. 2019, *ApJ*, 887, 195
 Mehrgan, K., Thomas, J., Saglia, R., Parikh, T., & Bender, R. 2023, *ApJ*, 948, 79
 Mehrgan, K., Thomas, J., Saglia, R., et al. 2024, *ApJ*, 961, 127
 Milosavljević, M. & Merritt, D. 2001, *ApJ*, 563, 34
 Naab, T., Johansson, P. H., & Ostriker, J. P. 2009, *ApJ*, 699, L178
 Nasim, I. T., Gualandris, A., Read, J. I., et al. 2021, *MNRAS*, 502, 4794
 Neureiter, B., Thomas, J., Rantala, A., et al. 2023, *ApJ*, 950, 15
 Neureiter, B., Thomas, J., Saglia, R., et al. 2021, *MNRAS*, 500, 1437
 Park, S., Yang, J., Oonk, J. B. R., & Paragi, Z. 2017, *MNRAS*, 465, 3943
 Rantala, A., Johansson, P. H., Naab, T., Thomas, J., & Frigo, M. 2018, *ApJ*, 864, 113
 Rantala, A., Johansson, P. H., Naab, T., Thomas, J., & Frigo, M. 2019, *ApJ*, 872, L17
 Rusli, S. P., Erwin, P., Saglia, R. P., et al. 2013a, *AJ*, 146, 160
 Rusli, S. P., Thomas, J., Saglia, R. P., et al. 2013b, *AJ*, 146, 45
 Saglia, R. P., Opitsch, M., Erwin, P., et al. 2016, *ApJ*, 818, 47
 Saglia, R. P., Sánchez-Blázquez, P., Bender, R., et al. 2010, *A&A*, 524, A6
 Sánchez-Blázquez, P., Peletier, R. F., Jiménez-Vicente, J., et al. 2006, *MNRAS*, 371, 703
 Teyssier, R., Moore, B., Martizzi, D., Dubois, Y., & Mayer, L. 2011, *MNRAS*, 414, 195
 Thomas, D., Maraston, C., & Bender, R. 2003, *MNRAS*, 339, 897
 Thomas, J. & Lipka, M. 2022, *MNRAS*, 514, 6203
 Thomas, J., Ma, C.-P., McConnell, N. J., et al. 2016, *Nature*, 532, 340
 Thomas, J., Saglia, R. P., Bender, R., Erwin, P., & Fabricius, M. 2014, *ApJ*, 782, 39
 Thomas, J., Saglia, R. P., Bender, R., et al. 2004, *MNRAS*, 353, 391
 Veale, M., Ma, C.-P., Thomas, J., et al. 2017, *MNRAS*, 464, 356
 Zhao, H. 1996, *MNRAS*, 278, 488

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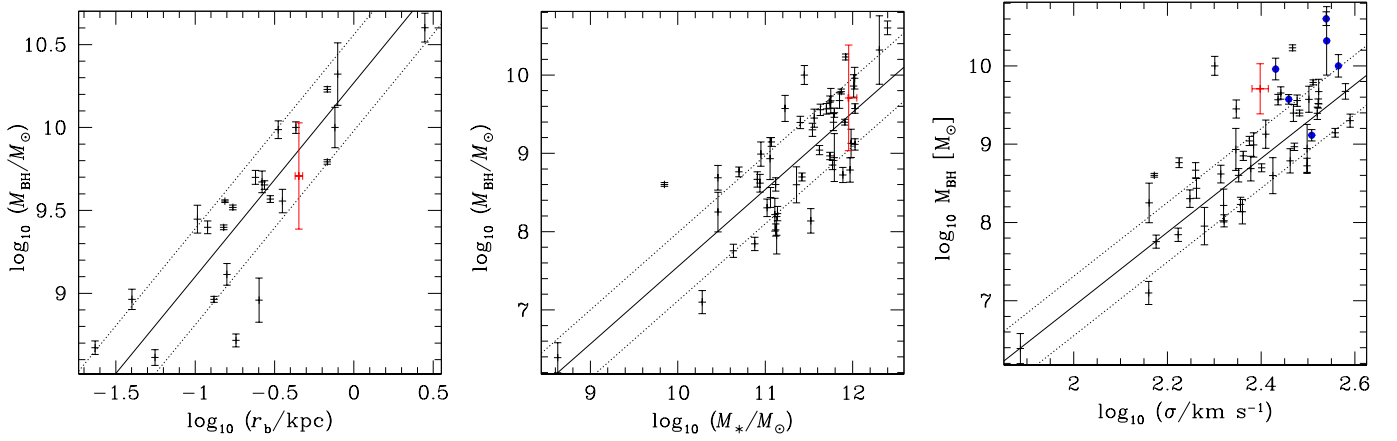


Fig. 12. Position of NGC 1272 (in red) on the $M_{\text{BH}}-r_b$ (left), on the $M_{\text{BH}}-M_*$ (middle) and on the $M_{\text{BH}}-\sigma$ (right) relation. The black data points are from Rusli et al. (2013a), Saglia et al. (2016), Thomas et al. (2016), Mehrgan et al. (2019), Neureiter et al. (2023), and de Nicola et al. (2024). The blue datapoints are core ellipticals with stellar mass larger than $10^{12} M_\odot$. While the galaxy follows the $M_{\text{BH}}-r_b$ given by Thomas et al. (2016) and the $M_{\text{BH}}-M_*$ relation of Saglia et al. (2016) for the sample of CorePowerE, it deviates by a factor of 8.4 from the $M_{\text{BH}}-\sigma$ relation of Saglia et al. (2016), or by a factor of 1.8 of the 1σ error combined with the intrinsic scatter (shown by the dotted lines).

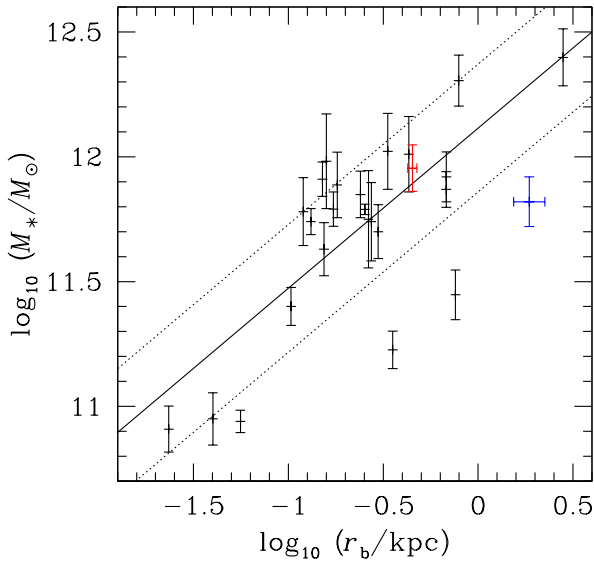


Fig. 13. Correlation between the core radius r_b and stellar mass M_* . The black datapoints are from Rusli et al. (2013a), Saglia et al. (2016), Thomas et al. (2016), Mehrgan et al. (2019), Neureiter et al. (2023), and de Nicola et al. (2024). NGC 1272 is shown in red. The blue cross shows the position of the BCG on the EDISCS cluster CL1216 (Saglia et al. 2010). The black solid line shows $\log_{10}(M_*/M_\odot) = 0.64 \log_{10}(r_b/\text{kpc}) + 12.1$; the dotted lines show the $\pm 1\sigma$ scatter (0.26 dex) in the relation.

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