Kinematics of the outer halo of M87 as mapped by planetary nebulae*, **

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ABSTRACT

Aims. We present a kinematic study of a sample of 298 planetary nebulae (PNs) in the outer halo of the central Virgo galaxy M 87 (NGC 4486). The line-of-sight velocities of these PNs are used to identify subcomponents, to measure the angular momentum content of the main M 87 halo, and to constrain the orbital distribution of the stars at these large radii.

Methods. We use Gaussian mixture modelling to statistically separate distinct velocity components and identify the M 87 smooth halo component, its relaxed substructures, and the intra-cluster (IC) PNs. We compute probability weighted velocity and velocity dispersion maps for the smooth halo, and its specific angular momentum profile (\(\lambda_R\)) and velocity dispersion profile.

Results. The classification of the PNs into smooth halo and ICPNs is supported by their different PN luminosity functions. Based on a Kolmogorov–Smirnov (K–S) test, we conclude that the ICPN line-of-sight velocity distribution (LOSVD) is consistent with the LOSVD of the galaxies in Virgo subcluster A. The surface density profile of the ICPNs at 100 kpc radii has a shallow logarithmic slope, \(\sigma_{\text{ICPN}} \sim 0.8\), dominating the light at the largest radii. Previous B – V colour and resolved star metallicity data indicate masses for the ICPN progenitor galaxies of a few \(\times 10^9 M_\odot\). The angular momentum-related \(\lambda_R\) profile for the smooth halo remains below 0.1, in the slow rotator regime, out to 135 kpc average ellipse radius (170 kpc major axis distance). Combining the PN velocity dispersion measurements for the M 87 halo with literature data in the central 15 kpc, we obtain a complete velocity dispersion profile out to \(R_{\text{avg}} \sim 135\) kpc. The \(\sigma_{\text{ICPN}}\) profile decreases from the central 400 kpc \(s^{-1}\) to about 270 kpc \(s^{-1}\) at 2–10 kpc, then rises again to \(\sim 300 \pm 50\) kpc \(s^{-1}\) at 50–70 kpc, to finally decrease sharply to \(\sigma_{\text{ICPN}} \sim 100\) kpc \(s^{-1}\) at \(R_{\text{avg}} \sim 135\) kpc. The steeply decreasing outer \(\sigma_{\text{ICPN}}\) profile and the surface density profile of the smooth halo can be reconciled with the circular velocity curve inferred from assuming hydrostatic equilibrium for the hot X-ray gas. Because this rises to \(v_{\text{X}} \sim 700\) kpc \(s^{-1}\) at 200 kpc, the orbit distribution of the smooth M 87 halo is required to change strongly from approximately isotropic within \(R_{\text{avg}} \sim 60\) kpc to very radially anisotropic at the largest distances probed.

Conclusions. The extended LOSVD of the PNs in the M 87 halo allows the identification of several subcomponents: the ICPNs, the “crown” accretion event, and the smooth M 87 halo. In galaxies like M 87, the presence of these subcomponents needs to be taken into account to avoid systematic biases in estimating the total enclosed mass. The dynamical structure inferred from the velocity dispersion profile indicates that the smooth halo of M 87 steepens beyond \(R_{\text{avg}} = 60\) kpc and becomes strongly radially anisotropic, and that the velocity dispersion profile is consistent with the X-ray circular velocity curve at these radii without non-thermal pressure effects.

Key words. galaxies: clusters: individual: Virgo cluster – galaxies: halos – galaxies: individual: M 87 – stars: abundances – planetary nebulae: general

1. Introduction

Several studies are currently concentrating on the dramatic size growth of passive galaxies with redshift (van Dokkum et al. 2010; Cimatti et al. 2012) with the goal of establishing the structural analogues in local massive galaxies. Within the cosmological framework, a variety of different models have been put forward to explain the mass size growth (see e.g. Huang et al. 2013), among which the two-phase formation scenario appears to be in the best agreement with observational constraints. In this scenario, the innermost region of massive galaxies formed the majority of their stars at \(z \lesssim 3\) on short timescales (Thomas et al. 2005), while the stars in the outermost regions were accreted at later epochs as a consequence of mostly dry mergers or accretion events (Oser et al. 2010, 2012; Cook et al. 2016). Then the outermost regions of local massive galaxies should contain the fossil records of the accretions events in form of spatial and kinematic substructures because the growth is expected to occur at comparatively low redshifts and the dynamical timescales are long (Bullock & Johnston 2005).

In the local universe, massive galaxies are found in the densest regions of galaxy clusters, hence a fraction of the stars in their extreme outer regions might in fact be part of the intra-cluster light (ICL), i.e. a stellar component that is not gravitationally bound to a single galaxy, but orbits in the cluster potential. A galaxy’s halo and the ICL both result from hierarchical accretion; however, they differ in their kinematics and their different levels of dynamical relaxation (Dolag et al. 2010; Longobardi et al. 2015a;
Bohringer 1995; Mei et al. 2007). It is classified as a cD-galaxy, in dynamical equilibrium. Photometric surveys suggest that the Virgo cluster core is not yet a complex network of extended tidal features revealed by deep present in-falling towards the cluster core, and the presence of types (Binggeli et al. 1987). The evidence that many galaxies are...nicely described by a single Sersic fit with $n \sim 1$ (Kormendy et al. 2009; Janowiecki et al. 2010) and an extended halo that reaches out to $R \sim 150$–200 kpc. Its total stellar mass is estimated to be $M \sim 10^{12} M_\odot$. The dynamical structure of M87 is dominated by random motions, without significant rotation (van der Marel 1994; Sembach & Tonry 1996; Gebhardt et al. 2011). A low-amplitude kinematically distinct core (Emsellem et al. 2014), a slow rotational component (Murphy et al. 2011; Emsellem et al. 2014), and a rising stellar velocity dispersion profile with radius (Murphy et al. 2011) were measured in recent studies. Several independent tracers were used to probe the mass distribution of M87: X-ray measurements (Nulsen & Bohringer 1995; Churazov et al. 2010), integrated stellar kinematics (Murphy et al. 2011, 2014), GC kinematics (Côté et al. 2001; Strader et al. 2011; Romanowsky et al. 2012; Zhu et al. 2014), and PN kinematics (Arnaboldi et al. 2004; Doherty et al. 2009). All of these studies show consistently that M87 is one of the most massive galaxies in the local Universe, but there are considerable variations among studies using different tracers.

Of particular interest is whether the hot ($T \sim 1$ keV) low-density $(n < 0.1$ cm$^{-3}$) X-ray envelope (Forman et al. 1985) around M87 is quiescent enough to assume hydrostatic equilibrium. In this case, we can use the temperature and density profiles derived from the X-ray spectra to obtain the cumulative mass profile and gravitational potential, and then estimate the orbital anisotropy of the stars from their dispersion profile. Non-thermal contributions to the pressure measured from X-ray data can be studied by comparing the potential inferred from the X-rays with mass estimates from stellar kinematics (e.g. Churazov et al. 2008, 2010).

The goal of this paper is to identify the PNs in the smooth M87 halo, using accurate velocities and following the approach of Longobardi et al. (2015a). We work with the sample of 253 PNs M87 halo PNs$^1$ and the 45 intra-cluster (IC) PNs, for which LOSVs are available with an estimated median velocity accuracy of 4.2 km s$^{-1}$. We determine the rotation $\nu$ and velocity dispersion $\sigma$ for the M87 halo in the region from ~20 kpc to ~200 kpc. From these measured profiles we aim to answer the question whether the halo stellar population, its mean square velocity, and its degree of relaxation change smoothly with radius, such that it eventually reaches ICL properties, or whether the halo and ICL are distinct populations and dynamical components. Furthermore, we investigate whether the halo dispersion profile is consistent with the mass profile inferred from X-rays and what this tells us about the orbital anisotropy and its variations in the outer halo region.

The paper is structured as follows. In Sect. 2 we revisit the PN LOSV distribution (LOSDV) and re-identify M87 halo PNs and ICPNs. In Sect. 3 we estimate the smoothed velocity field for the M87 halo PNs, and determine the amplitude of rotation and the $\lambda(R)$ angular momentum parameter as a function of radius. In Sect. 4 we determine our fiducial composite velocity dispersion profile for M87 and derive the circular velocity curve from a simple Jeans model. This circular velocity curve is then compared with that measured from X-ray observations in Churazov et al. (2010). Finally, we discuss our results in Sect. 5 and give our conclusions in Sect. 6. In the Appendix, we provide the detailed PN LOSVDs for the outer halo of M87 in different radial bins and the complete M87 PN catalogue using the data from the PN photometric and spectroscopic surveys carried out.

$^1$ Compared to Longobardi et al. (2015a) (254), one repeated object has been discarded.
with Suprime-Cam mounted on the Subaru Telescope and the FLAMES spectrograph installed on the VLT.

In this work the systemic velocity of M 87 is $V_{sys} = 1307.0 \pm 7 \text{ km s}^{-1}$ (Allison et al. 2014), and we adopt a distance modulus of 30.8 for M 87 (Longobardi et al. 2015a), implying a physical scale of 73 pc arcsec$^{-1}$.

### 2. Kinematics of M 87 and the Virgo intra-cluster stars

We begin our investigation on the kinematics of halo and IC PNs by adopting a similar approach to that of Longobardi et al. (2015a) who applied a robust sigma estimator (McNeil et al. 2010) to separate the asymmetric broad wings of the LOSVD of the ICL, from the nearly symmetric main distribution of velocities centred at the systemic velocity of M 87, the galaxy halo.

The halo-ICL dichotomy is illustrated in Fig. 1 where we show the projected phase-space distribution for halo (red asterisks) and IC (blue asterisks) PNs, $V_{LOS}$ versus major axis distance, on the basis of the classification by Longobardi et al. (2015a). Because the two components overlap in velocity, Longobardi et al. (2015a) argued that a fraction of the PNs whose LOSV values are in the range of the M 87 main halo may also be IC PNs; this is investigated further in Sect. 2.3.

To illustrate the effect of the ICL on the velocity dispersion profile, we compute the LOSVD running average and running dispersion for the total PN sample (M 87 halo plus IC PNs, green lines) and for the halo PNs only (black lines), independently on both sides of the M 87 major axis. While the mean velocity curves are very similar, the running dispersion curves are widely different. The running dispersion of the M 87 plus IC PNs (green line) quickly rises to a value which is similar to the velocity dispersion of the Virgo subcluster A/Virgo core $\sim 700 \text{ km s}^{-1}$ (Binggeli et al. 1987; Conselice et al. 2001) with no further radial variation on both sides of the M 87 major axis. The running dispersion of only the M 87 halo PNs behaves differently: it is almost constant at $270 \rightarrow 290 \text{ km s}^{-1}$ out to 30–40 kpc and then shows a rise at about 70 kpc, followed by a steep decline.

We emphasise that the strong radial variations in the running dispersion for the M 87 halo PN LOSV are measured independently on both sides of the galaxy. Furthermore, the drop to small values of the running dispersion at the largest major axis distances is significant because (1) it is observed over several subsequences of the halo running dispersion, (2) the running dispersion curve reaches small values on both sides of the M 87 photometric major axis, and (3) the measurements of the M 87 halo PN velocities come from two independent data sets. In the north of M 87, i.e. for $R > 0$ in Fig. 1, the outermost PN velocities were measured by Doherty et al. (2009), while in the south of M 87, i.e. $R < 0$ in Fig. 1, the measured velocities are from Longobardi et al. (2015a). The typical velocity errors are $4.2 \text{ km s}^{-1}$ for the PNs from Longobardi et al. (2015a), and $\sim 3.0 \text{ km s}^{-1}$ for PNs from Doherty et al. (2009).

Binning the PN velocities in Fig. 1 in six elliptical bins with major axis distances in the range 20 kpc $< R < 170$ kpc, we compute the velocity dispersion profile for the M 87 halo plus IC PNs. We also compute the halo-only velocity dispersions in these bins, using the robust estimator from McNeil et al. (2010) as described in Longobardi et al. (2015a). These values are given in Table 1, and the halo dispersions are plotted in Fig. 1 (full black circles).

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2 These quantities represent the mean velocity and velocity dispersion of subsequences of $n$ adjacent PN velocities along the major axis. Here $n = 30$. 
Table 1. Velocity dispersion estimates from the PN sample in the outer region of M 87.

<table>
<thead>
<tr>
<th>$R$ (kpc)</th>
<th>$\sigma_{\text{halo+ICL}}$ (km s$^{-1}$)</th>
<th>$\sigma_{\text{robust halo}}$ (km s$^{-1}$)</th>
<th>$\sigma_{\text{halo-no crown}}$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>243.6 ± 69.5</td>
<td>256.7 ± 33.1</td>
<td>269.1 ± 34.7</td>
</tr>
<tr>
<td>45</td>
<td>358.5 ± 70.0</td>
<td>301.7 ± 23.3</td>
<td>284.0 ± 22.7</td>
</tr>
<tr>
<td>70</td>
<td>506.4 ± 57.5</td>
<td>248.3 ± 26.5</td>
<td>290.6 ± 32.1</td>
</tr>
<tr>
<td>90</td>
<td>691.8 ± 61.0</td>
<td>361.7 ± 26.5</td>
<td>362.6 ± 30.4</td>
</tr>
<tr>
<td>120</td>
<td>794.6 ± 67.8</td>
<td>328.1 ± 37.1</td>
<td>254.6 ± 36.7</td>
</tr>
<tr>
<td>170</td>
<td>–</td>
<td>154.6 ± 36.4</td>
<td>126.9 ± 36.6</td>
</tr>
</tbody>
</table>

Notes. Column 1: major axis distance. Columns 2, 3, and 4: velocity dispersions and their uncertainties for the M 87 halo and IC PNs, the M 87 halo PNs from the robust estimate of Longobardi et al. (2015a), and the M 87 halo PNs with the crown PNs statistically subtracted (see text for details).

For the M 87 halo plus IC PN LOSV sample, the velocity dispersion increases from $\sigma_{\text{halo+ICL}} = 243.6 \pm 69.5$ km s$^{-1}$ at $R = 20$ kpc to $\sigma_{\text{halo+ICL}} = 794.6 \pm 67.8$ km s$^{-1}$, at $R = 120$ kpc. For the M 87 halo PNs only, the velocity dispersion is almost constant at a value of $\sigma_{\text{robust halo}} = 268.9 \pm 48.4$ km s$^{-1}$ between 20 and 70 kpc. It then increases to $\sigma_{\text{robust halo}} = 361.7 \pm 26.5$ km s$^{-1}$, at $R = 90$ kpc, and then declines steeply at larger radii, reaching $\sigma_{\text{robust halo}} = 154.6 \pm 36.4$ km s$^{-1}$ at $R = 170$ kpc.

In Fig. 1, we also plot the M 87 velocity dispersion measurements from the integrated stellar light using the IFU VIRUS-P (Murphy et al. 2011, 2014). These measurements indicate a steep increase in the two outermost bins at $R > 30$ kpc. The comparison with the PN velocity dispersion suggests that the reason for the rise in the velocity dispersion in the IFU kinematics is the contribution of the ICL at large distances where we expect the M 87 stellar halo surface brightness to decrease rapidly and the ICL to become significant.

Having realised the contribution of the Virgo IC stars to the kinematics of the outer regions of M 87, we now focus on the galaxy halo. In the following sections we investigate whether the strong radial dependence observed in the $\sigma_{\text{robust halo}}$ is an intrinsic property of the M 87 halo or whether it signals the presence of additional velocity components.

2.1. A shell in a sea of stars: the kinematic footprint of the crown of M 87

Direct evidence of a low-mass satellite accretion onto the M 87 halo comes from the cold features observed in the projected phase-space of discrete PNs and GCs (Longobardi et al. 2015b; Romanowsky et al. 2012) and from the orbital properties of GCs (e.g. Agnello et al. 2014) and ultra-compact dwarfs (UCDs; Zhang et al. 2015). Once these cold substructures are identified in phase space, we can recover the kinematics of the main halo component.

In their recent study, Longobardi et al. (2015b) used Gaussian mixture models (GMMs) to statistically separate the PNs of their newly discovered “crown” substructure from the LOSVD of the 253 M 87 halo PNs as classified by Longobardi et al. (2015a). This resulted in a total of 53 PNs that had a small average probability ($\gamma_c \sim 0.3$) of being part of the M 87 main halo. We now use this information and compute the velocity dispersion of the remaining M 87 halo. As seen in Fig. 1 (red and black full dots, respectively), the sigma profile without the crown does not change substantially. The contribution by the accreted satellite reduces the LOS velocity dispersion in those radial bins where the number of crown stars is largest. It is clear that the strong radial variation in the velocity dispersion profile remains an intrinsic property of the M 87 main halo.

2.2. Outliers in the M 87 halo

In Fig. 1, we see two pairs of PNs in the southern region of M 87 (at negative distances), where the two PNs in each pair have very similar positions and velocities (red circles). Both PN pairs are clearly outside the velocity distribution of their neighbours. We now determine how likely such velocity configurations are by using conditional probability theory, which states that the probability of event $V_i$ and event $V_j$ is

$$P(V_i, V_j) = P(V_j | V_i),$$

i.e. the probability of event $V_i$ times the probability of event $V_j$ given that event $V_i$ occurred. In our case we can assume that the first PN of each pair is at a random position and velocity just like most other PNs, so the relevant probability is $P(V_j | V_i)$.

$P(V_j | V_i)$ has two parts, a photometric part $P_{\text{phot}}$ that is the probability of finding a second PN within the measured relative distance $d\mathbf{D}$ to the first, and a kinematic part $P_{\text{kin}}$ that is the probability of finding it within the measured $dV = ||V - V_i||$ from the first PN. The photometric part can be estimated from the PN number density profile from Sect. 2.3.3 below and a Gaussian halo velocity distribution centred on $V_{\text{sys}} = 1307$ km s$^{-1}$ and with dispersion $\sigma \sim 300$ km s$^{-1}$, the probability $P(V_j | V_i) = P_{\text{phot}} \times P_{\text{kin}}$ of observing both pairs of PNs is $< 0.3\%$.

These low values support the classification of these PNs as kinematic outliers, even if their velocities overlap with the range of velocities for the M 87 main halo. It is interesting to note that these PN pairs close to M 87 overlap spatially with a photometric stream in the southern part of M 87, recently identified by Milhos et al. (2017). These authors interpreted this photometric feature as debris from a tidally dissolved dwarf galaxy (marked as small arrow in the central panel of their Fig. 5). Thus, from here on the four PNs are flagged as outliers and assigned to the ICL.

2.3. Residual contributions from the ICL to the M 87 halo LOSVD

We now analyse in more detail the LOSVD of the remaining M 87 halo and investigate whether it contains residual contributions from the ICL. In what follows we examine the generalised histogram where each PN is represented by a Gaussian distribution$^3$, weighted by its membership probability, $\gamma_c$, of belonging to the M 87 halo.

In Fig. 2 we show the generalised histogram for four M 87 halo PN (sub)samples. These are (i) the M 87 halo PNs from Longobardi et al. (2015a), (ii) the PNs along the major axis only and the PNs along the major axis, and (iii) north of and (iv) south of the orbital plane.

$^3$ The kernel size is 80 km s$^{-1}$, corresponding approximately to $\sigma_{\text{M87}}$, where $\sigma_{\text{M87}} = 298.4$ km s$^{-1}$ is the velocity dispersion associated with the M 87 halo from the robust procedure in Longobardi et al. (2015a). This kernel size represents a compromise between faithful structure representation and noise smoothing.
of the M 87 centre (see the insets in each panel with the selected PNs depicted in red). All LOSVDs for the four subsamples show a multi-peaked distribution, with a secondary peak at 1000 km s$^{-1}$. The probability that such a secondary peak is caused by low number statistics is $\sim$18\% (see text for details).

In order to verify whether this second peak is statistically significant we performed a Monte Carlo analysis. We simulated 100 LOSVDs that were drawn from a single Gaussian distribution with sample size matching the number of the M 87 halo PN sample. For each of the 100 simulated LOSVD, we randomly extracted three subsamples to simulate the LOSVD along the minor axis, and the major axis north and south. Only 18\% of the simulated sets of LOSVDs show a double-peak structure in all four subsamples. Hence, we are confident that the 82\% level (1.5 $\times$ $\sigma$) that the feature corresponding to the second peak is real.

In Fig. 2 the distributions along the minor axis and major axis north show an additional third peak at $v_\Pi \approx 1800$ km s$^{-1}$. However, we note that this feature is more likely to occur as the result of low number statistics, with a probability higher than 50\%, i.e. less than $1.0 \times \sigma$.

### 2.3.1. Gaussian mixture model for the M 87 halo LOSVD:
identification of the $v_\Pi \approx 900$ km s$^{-1}$ peak

Following Longobardi et al. (2015b), we assume that the remaining M 87 halo LOSVD can be described by a mixture of $K$ Gaussian distributions, and use a GMM to identify the individual kinematic structures (see Pedregosa et al. 2011; Longobardi et al. 2015b for more details). The GMM implements the expectation-maximisation (EM) algorithm for fitting mixture-of-Gaussian models. However, our estimated Gaussian mixture distribution starts from a weighted sample as we already removed the crown contribution statistically. We modified the GMM routine accordingly.

In this case we have a set of weighted data, $x_i$, the PN velocities in our case, where each measurement has a corresponding weight, $\gamma_i$. We want to estimate the parameters of a Gaussian mixture distribution using this set of weighted data. The Gaussian density function (PDF) can be written as

$$p(x) = \sum_{k=1}^{K} p_k(x | \mu_k, \sigma_k) P_k,$$

where $p_k(x | \mu_k, \sigma_k)P_k$ is the individual mixture component centred on $\mu_k$ with a dispersion $\sigma_k$, and $P_k$ is the mixture weight. The EM procedure is as follows:

1. **E-step**: Computing the posterior probabilities of the $i$th measurement to belong to the $k$th Gaussian components at step $m$, weighted by $\gamma_i$,

$$\Gamma_{ik}^{m} = \frac{p_k(x_i | \mu_k, \sigma_k)P_k}{p(x_i)} \times \gamma_i,$$

where $p(x_i) = \sum_{k} P_k$. In the following, we call this the E-step in the EM process has been modified such that the posterior probability of the $i$th measurement to belong to the 4th Gaussian component at step $m$, $\Gamma_{4k}^{m}$, always carries the starting weight $\gamma_i$ of that measurement. At the end of the algorithm, each PN velocity is allocated a posterior probability that quantifies its association with each Gaussian component, denoted $\Gamma_{ik}$. Subsequently, we use $\Gamma_i = \Gamma_{i4}$ to denote the probability of belonging to the smooth halo component.

We run the GMM on the M 87 halo PN subsamples along the minor axis, and the major axis north and south (Fig. 2 top right and bottom panels). Moreover, as we have higher number statistics, the major axis samples are further divided into two elliptical bins covering radial ranges $R \leq 55$ kpc and $R > 55$ kpc. The GMM identifies the double-peak structure in all these subsamples, for which we show the histograms of the data along with the best-fit GMM in Fig. 3.

The M 87 halo PN LOSVD is then decomposed into two Gaussian mixtures. The main component contributes about 80\% of the total PN sample and is centred at the systemic velocity of M 87, $v_{sys} = 1307$ km s$^{-1}$ (see Table 3). Within the uncertainties, there is no significant variation in its central velocity along the northern side of the galaxy; however, south of M 87 and for $R > 5$ kpc, it peaks at 1378.2 $\pm$ 39.5 km s$^{-1}$, suggesting the presence of ordered motion along the LOS at these distances (see Sect. 3 for a more detailed analysis). The velocity dispersion values averaged over the southern and northern major axis increase from $\sigma_{halo} = 242.1 \pm 22.3$ km s$^{-1}$ at $R \leq 55$ kpc to $\sigma_{halo} = 299.7 \pm 26.2$ km s$^{-1}$ for $R \leq 55$ kpc. Along the minor axis, the velocity dispersion of the main component is larger, with $\sigma_{halo} = 367.6 \pm 44.0$ km s$^{-1}$, but still within 1.5$\sigma$ of the values measured in the outermost bin along the major axis.

The second Gaussian component is centred at $v_\Pi = 888.7 \pm 23.1$ km s$^{-1}$, with a nearly constant velocity dispersion, $\sigma_\Pi = 97.9 \pm 15.6$ km s$^{-1}$. In the following, we call this the
\( v_{II} = 900 \text{ km s}^{-1} \) component. Its mean velocity is constant along the major axis within the uncertainties. However, along the minor axis it has a higher value: \( v_{II, \text{minor axis}} = 1050.7 \pm 30.7 \text{ km s}^{-1} \). The contribution of the secondary component to the total LOSVD does not vary across the galaxy and contributes a total of 24 PNs, representing \( \sim 10\% \) of the PN sample associated with the M 87 halo in Longobardi et al. (2015a). For completeness, all the Gaussian fitting parameters are listed in Table 2.

2.3.2. The ICPN LOSVD: comparison with the velocity distribution of the galaxies in the Virgo cluster core

We now ask the question about the origin of the second Gaussian component in the M 87 halo LOSVD. Dynamical studies of the bright central regions of non-rotating elliptical galaxies show that their LOSVDS are nearly Gaussian, with deviations of the order of 2\% (Gerhard 1993; Bender et al. 1994). The secondary component in the M 87 halo LOSVD contributes 10\% of the total; it clearly represents a larger deviation from a single-Gaussian velocity distribution. We note that its average velocity, \( v_{II} = 888.7 \pm 23.1 \text{ km s}^{-1} \), is close to the mean value determined for the velocity distribution of galaxies in the Virgo subcluster A (Binggeli et al. 1987). This suggests that this kinematic component could be a part of the Virgo ICL.

We can sharpen the argument further by comparing the LOSVD of all identified ICPNs, including the \( v_{II} = 900 \text{ km s}^{-1} \) component, to the LOSVD of the galaxies in the Virgo subcluster A around M 87. Because the ICPNs are not yet dynamically relaxed, we expect that their LOSVD may still resemble that of the galaxies from which they likely originate. For the comparison we compute the LOSVD of all galaxies in the Virgo subcluster A (Binggeli et al. 1985, 1987) within \( \sim 2 \) deg of M 87. Figure 4 shows that these galaxies have a distinctly non-Gaussian LOSVD, with multiple narrow peaks and broad asymmetric wings, broadly similar to the ICPN (see also the discussion in Doherty et al. (2009)).

![Fig. 3. Histograms of the LOSVD along the M 87 major (top four panels) and minor axis (bottom centre panel). The larger number of tracers associated with the M 87 halo allows us to divide the halo PN sample into northern (top left panels) and southern (top right panels) subsamples; moreover, the PN subsamples along the major axis are further divided in two elliptical bins, as given in the panels. The best-fit GM model (thick black line) identifies in all subsamples two Gaussian components (green lines). Dashed histograms represent the PN LOSVD prior to the statistical subtraction of the crown substructure.](image-url)

**Table 2.** Gaussian fitting parameters from the GMM decomposition of the M 87 halo PN LOSVD for the subsamples along the minor axis, major axis north, and major axis south.

<table>
<thead>
<tr>
<th>( R ) (kpc)</th>
<th>( V_{\text{halo}} ) (km s(^{-1}))</th>
<th>( \sigma_{\text{halo}} ) (km s(^{-1}))</th>
<th>( W_{\text{halo}} ) (%)</th>
<th>( V_{II} ) (km s(^{-1}))</th>
<th>( \sigma_{II} ) (km s(^{-1}))</th>
<th>( W_{II} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major axis north</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R \leq 55 )</td>
<td>1304.9 ± 44.2</td>
<td>89</td>
<td>9080.8 ± 37.2</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>242.1 ± 31.2</td>
<td></td>
<td>1293.2 ± 26.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R &gt; 55 )</td>
<td>1305.0 ± 33.9</td>
<td>87</td>
<td>875.9 ± 45.2</td>
<td>13</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>299.7 ± 23.9</td>
<td></td>
<td>110.8 ± 31.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major axis south</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R \leq 55 )</td>
<td>1293.7 ± 45.0</td>
<td>88</td>
<td>866.5 ± 31.7</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>242.2 ± 31.2</td>
<td></td>
<td>77.7 ± 22.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( R &gt; 55 )</td>
<td>1378.2 ± 39.5</td>
<td>90</td>
<td>884.5 ± 63.8</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>276.7 ± 27.9</td>
<td></td>
<td>90.3 ± 45.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minor axis</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>1295.8 ± 21.8</td>
<td>90</td>
<td>1050.7 ± 30.7</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>367.6 ± 44.0</td>
<td></td>
<td>81.4 ± 43.9</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Notes.** Column 1: major axis distance. Columns 2, 3, 4, and 5: velocity, velocity dispersion, and weight of each mixture component identified by the GMM.

To carry out a quantitative assessment, we use a Kolmogorov–Smirnov (K–S) test between the LOSVDS of the Virgo subcluster A galaxies and the ICPNs. The latter includes the 45 PN velocities in the broad asymmetric wings identified by Longobardi et al. (2015a), the 24 PN velocities from the \( v_{II} = 900 \text{ km s}^{-1} \) component identified by the GMM analysis in Sect. 2.3.1, and the two pairs of high-velocity PNs identified as kinematic outliers in Sect. 2.2. We carry out the K–S test in the velocity range \( v_{LOS} \leq 1100 \text{ km s}^{-1} \) because for \( 1100 \text{ km s}^{-1} < v_{LOS} < 2000 \text{ km s}^{-1} \) the GMM did not have enough information to identify ICPNs that overlap there with most of the M 87 halo PNs. The result of the K–S test gives a
97% probability that the ICPN LOSVD is drawn from the same underlying distribution as that of the LOSVD of the Virgo galaxies around M 87. The comparison of the two LOSVDs is shown in Fig. 4.

The asymmetry and skewness of the LOSVD of the galaxies in the Virgo core and ICL could arise from the merging of subclusters along the LOS as described by Schindler & Boehringer (1993). In their simulations of two merging clusters of unequal mass, the LOSVD is found to be highly asymmetric with a long tail on one side, and a cut-off on the other side just (107 yr) before the subclusters merge. Around M 87, the long tail is towards small and negative LOSVs, and the cut-off is at positive velocities, consistent with the merging of the two subclusters centred around M 87 and M 86 (Doherty et al. 2009).

2.3.3. PNLF and spatial density profiles of the ICL and the M 87 halo

In this section we describe the effect of the reclassification of the νH ≃ 900 km s−1 component as ICL on the PN luminosity function (PNLF) and on the number density distributions of the M 87 halo PNs and ICPNs.

Longobardi et al. (2015a) showed that their kinematically separated halo PN and IC PN populations had different PNLFs. The IC PNLF differs from the M 87 halo PNLF by having a small value of the c2 parameter in the generalised PNLF formula (Longobardi et al. 2013) and by the presence of a morphological signature denoted as a “dip” located about 1−1.5 magnitudes below the bright cut-off of the PNLF. PN population studies relate the presence of this dip to recent star formation (Jacoby & De Marco 2002; Ciardullo et al. 2004; Hernández-Martínez & Peña 2009; Reid & Parker 2010; Ciardullo 2010). The recent work of Gesicki et al. (2018) showed that this dip appears in the PNLF for predominantly opaque nebulae in intermediate stages of expansion.

In M 87 we find that once the νH ≃ 900 km s−1 component is removed, the halo PNLF no longer shows any sign of a dip (see Fig. 5). In this figure, the empirical PNLF is shown together with the fit of the generalised analytic formula for the PNLF, with the brightest cut-off at magnitude 26.3 and c2 = 0.72. When the 24 PNs from the νH ≃ 900 km s−1 component and the four kinematic outliers (see Sect. 2.2) are merged with the previously identified ICPN sample from Longobardi et al. (2015a), the IC PNLF dip has higher statistical significance than the earlier analysis (lower panel of Fig. 5). We conclude that the morphology of the PNLFs thus provides independent support to the classification of the νH ≃ 900 km s−1 component as part of the ICL.

We conclude this section by comparing the revised number density profiles of the M 87 halo and IC PNs with the surface brightness profiles of M 87 (see Fig. 6). The IC PN profile now has a slightly steeper gradient than previously quantified by Longobardi et al. (2013, 2015a), but it remains shallower than that of the M 87 halo PNs. It is fitted by a power law IC = R−α with αIC = 0.79 ± 0.15, so it is not consistent with a flat distribution.

2.4. Summary: LOSVD for the M 87 smooth halo

On the basis of the robust sigma and the GMM analysis in this section, we identified the PN outliers and PNs associated with either the revised ICL component or the crown substructure. Each PN velocity measurement then comes with a probability of belonging to the M 87 smooth halo. Thus, we can determine the first (velocity) and second (velocity dispersion) moments of the LOSVD in different regions of the sky and build the corresponding 2D maps. These are the goals of the next section.

3. Two-dimensional kinematics of the M 87 smooth halo: ordered vs. random motions

3.1. Two-dimensional average velocity map

In this section we investigate the average properties of the PN kinematics of the M 87 smooth halo. We build a probability weighted 2D average velocity field using an adaptive Gaussian kernel that matches the spatial resolution to the local density of measurements (Coccato et al. 2009), and weights each PN velocity by the membership probability Γi that the PN belongs to the M 87 smooth halo component (see Sect. 2).
At the position of each source \((x_P, y_P)\) the mean velocity and velocity dispersion are

\[
<V(x_P, y_P)> = \frac{\sum_i V_{iLOS}\cdot w_{P_i}}{\sum_i w_{P_i}},
\]

and

\[
<\sigma(x_P, y_P)> = \left[ \frac{\sum_i V_{iLOS}^2\cdot w_{P_i}}{\sum_i w_{P_i}} - <V(x_P, y_P)'^2 - \Delta V^2 \right]^{1/2}.
\]

where \(V_{iLOS}\) is the \(i\)th PN LOSV and \(\Delta V\) is the instrumental error, given by the median uncertainty on the velocity measurements, i.e. \(\Delta V = 4.2\) km s\(^{-1}\); \(w_{P_i}\) is the \(i\)th PN weight given by

\[
w_{P_i} = \exp \left\{ -\frac{D_i^2}{2k(x_P, y_P)^2} \times \Gamma_i \right\},
\]

where \(D_i\) is the distance of the \(i\)th PN to \((x_P, y_P)\), and \(k\) is the amplitude of the kernel. Following Coccato et al. (2009), \(k\) is defined to be dependent on the local density of the tracers, \(\rho(x, y)\), via

\[
k(x, y) = A \sqrt{\frac{M}{\pi \rho(x, y)}} + B,
\]

with \(M = 20\) representing the number of nearest neighbours considered in the smoothing technique. \(A\) and \(B\) are chosen by processing simulated sets of PNs for a given density, velocity gradient, and velocity dispersion as inferred from the data. The simulations returned the following values for \(A = 0.25\) and \(B = 20.4\) kpc. Thus, each PN is assigned a weight which depends on the distance, on the amplitude of the kernel (in turn depending on the local tracer’s number density\(^4\)), and on its probability of belonging to the M 87 smooth halo component. As described in Coccato et al. (2009, 2013), we can also

\(^4\) See Coccato et al. (2009) for a full description of the smoothing technique.
associate errors on the derived smoothed velocity field by generating 100 different data sets of mock radial velocities with the same positions on the sky as for the real sample of PNs. As the same smoothing procedure is applied to the synthetic data, the statistics of these simulated velocity fields give us the error associated with the smoothed velocity values at the PN positions in our field.

In Fig. 7, we plot the positions of the M 87 halo PNs on the sky, colour-coded on the basis of their LOSV values. The sizes of their symbols are proportional to their probability, \( \Gamma \), of belonging to the M 87 smooth halo (large symbols; instead, tiny symbols are used for ICPNs). The resulting mean velocity field is given in the central panel. The galaxy’s inner regions are dominated by random motion, with the mean velocity centred on the systemic velocity of M 87, 1307 km s\(^{-1}\). At large radii the system becomes more complex. There are ordered motions along the photometric major axis, with approaching velocities to the north-west, and receding velocities to the south-east side of M 87. Large velocity values are also measured in the north-east regions, without any symmetric counterpart to the south-west.

From Fig. 7 (central panel), it is clear that the amplitude of the ordered motions along the major axis is small, of the order of \( \sim 30 \) km s\(^{-1}\). This value is within the level of uncertainties, as shown by the error map in the bottom panel of Fig. 7. However, because of its symmetric properties, we consider it real, and it is furtheranalysed in the next section.

The smooth velocity values \( \sim 30 \) km s\(^{-1}\) obtained to the north-east of M 87 are also consistent with zero, given the uncertainties. As they appear only on one side of the galaxy, this suggests that here we are measuring a local velocity perturbation driven by the presence of a few high-velocity PNs at \( \sim 1800 \) km s\(^{-1}\) (about 2\( \sigma \) from the systemic velocity of M 87).

### 3.2. Does the M 87 outer halo rotate?

The amplitude and axis of rotation are evaluated by approximating the mean velocity field with that of an axisymmetric rotator. In that case the mean velocities are modelled by a cosine function of the form

\[
<\nu_{\text{sys}}>(PA, R) = \nu_{\text{sys}}(R) + \nu_{\text{cos}}(R) \cos[PA - PA_{\text{kin}}(R)],
\]

where \( R \) is the major axis distance of each PN from the galaxy’s centre, PA its position angle on the sky (Cohen & Ryzhov 1997). The fitted values \( \nu_{\text{sys}} \), \( \nu_{\text{cos}} \), and \( PA_{\text{kin}} \) represent the M 87 systemic velocity, the amplitude of the ordered motion, and the kinematic PA, with errors derived from fit uncertainties. To identify possible kinematic decoupling, we divide our PN sample kinematic PA, with errors derived from fit uncertainties. To identify possible kinematic decoupling, we divide our PN sample

\[
R \leq 43.8 \\
43.8 < R \leq 73.0 \\
R \geq 73.0
\]

<table>
<thead>
<tr>
<th>( R ) (kpc)</th>
<th>( \nu_{\text{sys}} ) (km s(^{-1}))</th>
<th>( \nu_{\text{cos}} ) (km s(^{-1}))</th>
<th>( PA_{\text{kin}} ) (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R \leq 43.8 )</td>
<td>1304.62 ± 3.81</td>
<td>4.70 ± 5.77</td>
<td>104.71 ± 70.92</td>
</tr>
<tr>
<td>( 43.8 &lt; R \leq 73.0 )</td>
<td>1306.59 ± 3.87</td>
<td>16.59 ± 6.27</td>
<td>115.21 ± 18.51</td>
</tr>
<tr>
<td>( R \geq 73.0 )</td>
<td>1305.14 ± 4.06</td>
<td>26.76 ± 7.05</td>
<td>161.43 ± 10.64</td>
</tr>
</tbody>
</table>

**Notes.** The systemic velocity is constant as a function of the distance and in good agreement with the value from the literature. At large distance the cosine term \( \nu_{\text{cos}} \) increases. The kinematic position angle in the outermost bin, \( PA_{\text{kin}} \), is at 160°.

### 3.3. Cumulative specific angular momentum \( \lambda_R \) of the M 87 halo

On the basis of the complete 2D velocity information, Emsellem et al. (2007) introduced the \( \lambda_R \) parameter as a proxy for the projected specific angular momentum of the stars, defined as

\[
\lambda_R = \frac{\sum_i F_i | <V_i> - \nu_{\text{sys}} |}{\sum_i F_i \sqrt{(<V_i> - \nu_{\text{sys}})^2 + <\sigma_i>^2}}
\]

where \( F_i \) is the flux associated with the \( i \)th point, and \( <V_i> \) and \( <\sigma_i> \) are defined in Eqs. (2) and (3). The \( \lambda_R \) parameter measures the significance of rotation as a function of the distance from the galaxy’s centre. Galaxies are then classified as fast rotators, \( \lambda_R \geq 0.1 \) (nearly axisymmetric systems with aligned photometric and kinematic axes, with a rising \( \lambda_R \) profile), and slow rotators, \( \lambda_R < 0.1 \) (nearly round massive galaxies with a significant misalignment between photometric and kinematic axes, moderate degree of triaxiality, and a flat or decreasing \( \lambda_R \) profile).

We use the probability weighted averaged 2D velocity and velocity dispersion fields to compute the PN \( \lambda_R \) profile in the surveyed area of the M 87 halo. In line with Coccato et al. (2009), the weighting factor \( F_i \) is replaced by \( 1/c_R \) when summing over the PNs. Here the spatial completeness factor \( c_R \) is taken from Longobardi et al. (2015a). As discussed by Coccato et al. (2009), this procedure incorporates the weighting by the local stellar surface density by computing a number-weighted sum. In Fig. 7, we show the resulting \( \lambda_R \) profile for major axis distances in the range 10 kpc \( \leq R \leq 140 \) kpc for the M 87 halo. The profile is almost flat in the inner \( \sim 70 \) kpc, and then slowly increases to values of \( \sim 0.11 \), thus touching the fast-rotators regime (dot-dashed line in Fig. 7, right panel).

To assess the cause for this increase in \( \lambda_R \), we compare the observed \( \lambda_R \) parameter from the 2D field with that computed using the cosine fit from Eq. (6), with \( \nu_{\text{sys}} \), \( \nu_{\text{cos}} \), and \( PA_{\text{kin}} \) given in Fig. 8 (left panel). As shown in Fig. 8 (right panel, black continuous line), the transition from the inner to the outer regions is still signalled by an increase in the \( \lambda_R \) profile with major axis distance. However it flattens at a value of \( \lambda_R \sim 0.05 \) and never reaches the 0.1 threshold. This difference is driven by the fact that the cosine fit does not represent the apparent streaming velocity in the north of M 87 which we argued above comes from a few high-velocity PNs with velocities \( \sim 1800 \) km s\(^{-1}\).

\[ \lambda_R \text{ profile from fluctuations in the mean velocity field is different from that described in Wu et al. (2014) which results from fluctuations in the velocity distribution around the local mean velocity.} \]

\[ ^{10} \text{This increase in the } \lambda_R \text{ profile from fluctuations in the mean velocity field is different from that described in Wu et al. (2014) which results from fluctuations in the velocity distribution around the local mean velocity.} \]
Previous studies found that slow rotator galaxies typically increased their rotation from the central regions in their halos, with some entering the regime $\lambda_R > 0.10$ (Coccato et al. 2009; Arnold et al. 2014; Pulsoni et al. 2018). In the case of M 87 the $\lambda_R$ parameter also rises in the halo, but only to values $\lambda_R \approx 0.05$, remaining safely in the slow rotator regime.

4. Velocity dispersion profile of the stellar tracers in M 87

PNs are single stars whose velocities are a discrete realisation of the LOSVD of the stellar population in a given region of a galaxy. PNs are ubiquitous probes of the kinematics of the parent stars at radii where the surface brightness is too faint to measure absorption line features with the required S/N. Hence they are very well suited to complement the stellar-kinematic measurements in the inner regions. In this section, we combine measurements of the second moment of the LOSVD, $\sigma$, from absorption line kinematics in the inner high surface brightness regions with those from the PN LOSVDs at large radii, obtaining the velocity dispersion profile out to $\sim 170$ kpc along the major axis. We also discuss velocity dispersion measurements for the GC and UCD systems in M 87 in comparison with the composite $\sigma$ profile of the stars.

4.1. Sigma profile within a 20 kpc radius in M 87

M 87 has been the target of many spectroscopic studies with the goal of determining the integrated mass profile from the inner regions to the outermost radii. Velocity dispersion measurements from absorption line spectroscopy (long slits and IFS) available in the literature are reproduced in Fig. 9. In this figure, the velocity dispersion profile of the stars in M 87 is plotted as function of the isophotal average ellipse radius, $R_{avg} = (ab)^{1/2}$, where $a$ and $b$ are the isophote major and minor axes.

At $R_{avg} \leq 5$ kpc, the absorption line measurements from van der Marel (1994); Sembach & Tonry (1996) and Emsellem et al. (2014) show a characteristic profile for hot stellar systems. It has a central peak at $\sigma \sim 400$ km s$^{-1}$, then declines to a value of $\sigma \sim 270$ km s$^{-1}$ at $\sim 2$ kpc and remains flat out to $\sim 10$ kpc. At these radii the $\sigma$ measurements from the literature agree within their uncertainties; however, we note that the values from Sembach & Tonry (1996) were corrected for a 7–10% systematic velocity offset attributed by the authors to the large slit width adopted for their observations (for more details see discussion in Sembach & Tonry 1996; Romanowsky & Kochanek 2001; Doherty et al. 2009).

In addition to the MUSE IFS data (Emsellem et al. 2014), VIRUS-P IFS data from Murphy et al. (2011) are also available in this region. At $R > 1$ kpc, the IFS VIRUS-P measurements have a systematic positive offset of $\sim 30$ km s$^{-1}$ with respect to the MUSE and slit data. This offset is present when the $\sigma$ measurements are obtained from the combined analysis of four wavelength regions (G-band, H-beta, Mg b, iron; filled cyan triangles in Fig. 9). When $\sigma$ values are measured only in the Mg b region of the spectrum (Murphy et al. 2011, open cyan triangles in Fig. 9), then the VIRUS-P and MUSE data sets agree. Then the IFS VIRUS-P measurements (Murphy et al. 2011, open cyan triangles) extend the $\sigma(R)$ profiles to larger radii. In the radial range $5$ kpc $< R_{avg} < 20$ kpc, they signal an increase in the velocity dispersion values to $\sim 280$ km s$^{-1}$.

At radial distances $10$ kpc $< R_{avg} < 20$ kpc, GCs and UCD galaxies have also been identified and their LOSVDs measured. Red and blue GC sample velocity dispersions from...
Fig. 9. Velocity dispersion profile for the halo of M 87 as function of the average ellipse radius, \( R_{\text{avg}} = (ab)^{1/2} \) of the isophote (for \( R > 400'' \) we have assumed a constant ellipticity of \( e = 0.4 \)). In the inner 80'' = 5 kpc, we show the absorption line data from van der Marel (1994; squares), Sembach & Tonry (1996; green diamonds), and from Emsellem et al. (2014; orange diamonds). Cyan triangles present IFS VIRUS-P data from Murphy et al. (2011, 2014), for the case when the velocity dispersion is computed making use of the entire spectral region (filled triangles) or when it is calculated only from the Mg b region (large open triangles). The yellow shaded area indicates our fiducial velocity dispersion profile of the stars from absorption line spectroscopy (long slit/IFS) in the radial range out to \( \sim 200'' = 15 \) kpc. The magenta full dots show the new PN velocity dispersion values for our whole sample, i.e. without separation between M 87 halo PNs and ICPNs. The fiducial range of \( \sigma \) estimates we obtain for the M 87 smooth halo PNs alone is indicated by the dark grey area, with boundaries given by the robust estimates of sigma (black line) and by the simple RMS of the halo PN data (dashed black line). The light grey area includes the respective 1\( \sigma \) uncertainties for these values added as well. Thus, the PN kinematics trace a \( \sigma \) profile for the M 87 halo with a strong radial dependence, increasing from 20 to 90 kpc and then decreasing strongly, reaching a minimum value of \( \sim 100 \) km s\(^{-1} \) at \( R_{\text{avg}} \approx 130 \) kpc (\( R_{\text{maj}} \approx 170 \) kpc). For comparison, red and blue stars show GC velocity dispersion data from Agnello et al. (2014), while black asterisks, and blue and red crosses indicate sample velocity dispersions for UCDs, and blue and red GCs, respectively, as presented in Zhang et al. (2015).

Agnello et al. (2014) and Zhang et al. (2015) are shown as red and blue crosses and plus symbols, respectively. While the \( \sigma \) values of the red GCs are in better agreement with those from the stars (within the uncertainties), blue GC \( \sigma \) values deviate sharply. The velocity dispersion values for the population of Virgo UCDs (black asterisks; Zhang et al. 2015, see Sect. 5 for more discussion) are similar to those of the blue GCs except for the outermost point, which is closer to the red GC dispersion.

4.2. Velocity dispersion profile of the smooth M 87 halo from 20 kpc out to 170 kpc

In Sect. 2 we investigated the influence of the ICL on the PN LOSVDs at radii \( R > 20 \) kpc. In the IFS VIRUS-P data, the presence of the ICL is disclosed by the sudden increase in \( \sigma \) from \( \sim 300 \) km s\(^{-1} \) to nearly \( 600 \) km s\(^{-1} \) (Murphy et al. 2014\(^7\)). The comparison of these values with the running dispersion of the M 87 PN LOSV sample in Fig. 1 shows very good agreement. We note that, because the ICL is unrelaxed (Longobardi et al. 2015a), these high \( \sigma \) values include a significant contribution from unmixed orbital motions and do not trace the enclosed mass only. Therefore, for a proper mass analysis of the M 87 halo, the ICL contribution must be subtracted.

In the course of the extensive analysis carried out in Sect. 2, we computed the probability that each PN is associated with the smooth M 87 halo; we can thus use this probability to compute the histograms of the PN LOSV for the smooth M 87 halo only, in different outer radial bins. These histograms are shown in Appendix A. They have limited statistics and may thus deviate from Gaussian LOSVDs. To characterise the associated uncertainties, we computed the velocity dispersion values using the robust sigma algorithm\(^8\) and the direct RMS values from the PN LOSVDs in these bins. The estimated radii and velocity dispersions using either method are listed in Table 4 for all bins. For small samples the robust sigma may underestimate the true velocity dispersion due to overclipping, and the direct RMS sigma may overestimate it due to its sensitivity to velocities in the wings of the distribution, and so we take these

\(^7\) In that paper, dispersion values are computed using the information coming from the entire spectral region between 4100 Å–5400 Å.

\(^8\) For a short description of this technique see Appendix A. More details can be found in Longobardi et al. (2015a).
two determinations as the boundaries of our fiducial range of velocity dispersion values from the PN LOSVDs for the smooth M87 halo. This range is shown by the dark shaded area in Fig. 9, with the lower boundary from the robust sigma depicted by the black continuum line and the RMS estimates by the dashed line, respectively. The range of velocity dispersions obtained by also adding the 1σ uncertainties of the two determinations is shown as a light grey shaded area.

Our fiducial range of velocity dispersion values for the smooth M87 halo indicates a strong variation in the σ(R) profile with radius. The σ(R) profile from PN LOSVDs extend the slowly rising trend captured by the IFS measurements (Murphy et al. 2014) out to $R_{\text{avg}} \simeq 17$ kpc, with σ rising to about 280 km s$^{-1}$ there. The fiducial velocity dispersion range from PNs indicate a further rise in the dispersion to $\sigma \simeq 300$ km s$^{-1}$ at $50 < R_{\text{avg}} < 70$ kpc, followed by a steep decline to $\sigma \simeq 100$ km s$^{-1}$, at $R_{\text{avg}} \sim 135$ kpc (corresponding major axis radii are 1.3 times larger). We note that the rise and steep drop of the PN velocity dispersion profile is seen on both the NE and SW sides of M87 (see Fig. 1).

In the next section we investigate whether this strong radial variation in the velocity dispersion profile is consistent with a change in the physical properties of the stellar orbits in these outer regions in dynamical equilibrium. We approach this problem with an approximate analysis based on the spherical Jeans equations, connecting the circular velocity curve inferred from X-ray observations with the surface brightness profile for the smooth M87 halo.

### 4.3. Gravitational potential, density, and orbital anisotropy in the outermost halo of M87

Studies using stellar kinematics, lensing, and X-ray observations (see e.g. Gerhard et al. 2001; Treu et al. 2006; Gavazzi et al. 2007; Churazov et al. 2010) have indicated that the gravitational potentials of elliptical galaxies are approximately isothermal. With this assumption, i.e. that the circular velocity $v_c$ is constant, Churazov et al. (2010) showed that the spherical Jeans equation leads to simple relations between $v_c$, the LOS velocity dispersion profile $\sigma(R)$, and the surface brightness profile $I(R)$. For the case of a system with either isotropic or radial orbital distribution, the relations between $v_c$ and the local properties of $\sigma(R)$ and $I(R)$ are

\[
\sigma_{\text{iso}}^2(R) = v_c^2 \frac{I}{1 + \alpha + \eta}, \quad \sigma_{\text{rad}}^2(R) = v_c^2 \frac{I}{(\alpha + \eta)^2 + \delta - 1}, \quad \delta = \beta - 1 \tag{8}
\]

where $\alpha$ and $\eta$ are the negative of the logarithmic radial gradients of $I(R)$ and $\sigma(R)$, and $\delta$ is the second logarithmic derivative of $I(R)\sigma^2(R)$; see Eqs. (22, 23) in Churazov et al. (2010) for further detail. Churazov et al. (2010) used the above equations to infer the circular velocity $v_{\text{c, opt}}$ from the optical data $I(R)$ and velocity dispersion profile $\sigma(R)$ at different radii, and for comparison with the circular velocity curve $v_{c,X}$ derived from X-ray emissivity and temperature maps for M87 from Chandra and XMM-Newton. Their analysis led to a best-fit relation between these two estimates of $v_{\text{c, opt}} \sim 1.10 - 1.15 v_{c,X}$, implying an average contribution by non-thermal pressure of 20–30% for six X-ray bright galaxies, with a particularly large value for M87.

Given our new assessment of the M87 outer halo kinematics, we carried out an independent comparison of the total enclosed mass profiles from a dynamical estimate using optical data, and from the most recent X-ray information obtained by combining that data of Churazov et al. (2010) with those of Simionescu et al. (2017) at larger radii. Our approach is the following. We adopt the circular velocity curve from the X-ray maps out to 2500 arcsec, and predict the LOS $\sigma(R)$ profile from the surface brightness distribution of the smooth and relaxed stellar halo of M87 using Eq. (8). We derive the expected velocity dispersion curves in the isotropic and completely radially anisotropy cases with the goal of comparing with our fiducial $\sigma(R)$ profile that combines absorption line kinematics with the PN LOS velocity dispersion for the smooth M87 halo component.

Results are shown in Fig. 10. In panel A, we show the surface brightness profile of the M87 smooth halo, indicated by the red crosses and red shaded area, the latter indicating the 1σ uncertainty. This surface brightness profile is computed from the extended photometry of M87 in Kormendy et al. (2009) (black crosses, with continuous black line showing the Sersic fit with $n \sim 11$) by subtracting off the ICL contribution (blue line and light blue shaded area, the latter indicating its 1σ uncertainty). The contribution from the ICL was determined in Sect. 2.3.2 and Fig. 6 from the kinematical tagging of the ICPNs. As the inferred ICL surface brightness is of the same order as the surface brightness of the M87 smooth halo at these large distances, it must be taken into account, i.e. subtracted, so as to have a consistent set of tracer profiles in the Jeans analysis. We note that this analysis cannot be performed for the combined halo plus ICL, because the LOSVD of the ICL shows that it is not in equilibrium in the gravitational potential. Because of the extended tails of its LOSVD, it would lead us to incorrectly infer masses that are too high at the largest radii.

The adopted $v_c = v_{c,X}$ is plotted in Panel B. It is a combination of three parts: (i) a flat profile out to 200″ (~15 kpc) fitted to the data from Churazov et al. (2010); (ii) an increasing profile obtained after differentiating a smooth non-linear fit to the M87 X-ray potential data in the range from 200″ (~15 kpc) to 1200″ (88 kpc), as presented in Churazov et al. (2010, their Fig. 1); and (iii) from 1200″ onward, the circular velocity corresponding to the NFW profile fitted by Simionescu et al. (2017) to their Suzuki data within 400 kpc. The obtained $v_c = v_{c,X}$ profile summarises the observational evidence that the circular velocity rises more steeply than an isothermal profile at large radii. We can nonetheless use the local Eq. (8) with this circular velocity profile to estimate velocity dispersions, because $v_{c,X}$ varies only slowly with radius as is confirmed by panel B considering the logarithmic radius scale.

Panel C then shows the expected velocity dispersions $\sigma_{\text{iso}}$ and $\sigma_{\text{rad}}$ according to Eq. (8), overplotted on the observed M87 sigma profile as presented in Fig. 9. The comparison between

### Table 4. Velocity dispersion estimates for the smooth M87 halo as a function of the major axis distance.

<table>
<thead>
<tr>
<th>$R_{\text{robust}}$ (kpc)</th>
<th>$\sigma_{\text{robust}}$ (km s$^{-1}$)</th>
<th>$\sigma_{\text{RMS}}$ (km s$^{-1}$)</th>
<th>$\sigma_{\text{RMS}}$ (km s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25.2</td>
<td>218.4 ± 26.7</td>
<td>25.9</td>
<td>256.5 ± 29.3</td>
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<tr>
<td>51.5</td>
<td>245.6 ± 28.0</td>
<td>51.7</td>
<td>287.7 ± 29.3</td>
</tr>
<tr>
<td>74.3</td>
<td>248.0 ± 30.0</td>
<td>74.3</td>
<td>371.9 ± 47.3</td>
</tr>
<tr>
<td>95.8</td>
<td>252.0 ± 43.6</td>
<td>96.2</td>
<td>345.1 ± 53.0</td>
</tr>
<tr>
<td>118.6</td>
<td>161.9 ± 24.5</td>
<td>118.4</td>
<td>270.4 ± 34.8</td>
</tr>
<tr>
<td>170.0</td>
<td>99.6 ± 31.5</td>
<td>167.2</td>
<td>150.4 ± 31.9</td>
</tr>
</tbody>
</table>

Notes. Columns 1 and 3: major axis distance. Columns 2 and 4: velocity dispersion and their uncertainties for the M87 smooth halo given by the robust estimate and by the simple RMS of the data (see text for details).
Fig. 10. Velocity dispersion profile out to 2000 arcsec compared with predictions from Jeans equations. Panel A: surface brightness profile of the M 87 smooth halo (red crosses and shaded area) obtained from the extended photometry (Kormendy et al. 2009), after subtracting the ICL contribution (blue line and shaded area). The black continuous line shows the Sersic fit with \( n = 11 \) to the M 87 halo+ICL extended photometry. The adopted circular velocity profile is shown in panel B. This is a combination of a flat profile (red line) out to 200″ and an increasing profile for larger distances (dashed red line, see text for more information). Panel C: velocity dispersion profile \( \sigma(R) \) from this work (data points, fiducial range from PNs, and legend as in Fig. 9). Large dots represent the expected \( \sigma \) values computed from Eq. (8) at the average radii of the radial bins, for isotropic (orange) and completely radial (red) orbital anisotropy. The comparison with the fiducial range of \( \sigma \) values for halo PNs (shaded area) suggests that the distribution of orbits changes from near-isotropic at \( \sim 200″ \) to strongly radial at \( \sim 2000″ \).

5. Discussion

5.1. The Virgo ICL: an unrelaxed component in the cluster core

In Sect. 2, we carried out a careful analysis of the PN LOSVs in the velocity range 500–2000 km s\(^{-1}\) around M 87. We identified a velocity component at \( v_{\perp} \approx 900 \) km s\(^{-1}\) and two pairs of outliers as ICPNs. The complete LOSVD for the ICPN population was then obtained by combining the newly identified 28 ICPNs with those in the extended velocity wings from Longobardi et al. (2015a). The resulting ICPN LOSVD around M 87 has a peak at \( v_{\perp} \approx 900 \) km s\(^{-1}\) with extended wings, skewed towards negative velocities (Fig. 4). The identification of the additional 28 ICPNs was supported independently by the increased statistical significance of the dip in the ICL PNLF, and led to improved constraints on the spatial distribution of the ICL thanks to better spatial coverage and statistics. The ICL radial surface density distribution is now consistent with a power law

\[
\rho_{\text{ICL}} \propto R^{-\alpha},
\]

with \( \alpha_{\text{ICL}} = 0.79 \pm 0.15 \), which is shallower than the Sersic profile for the smooth M 87 halo. The different PNLFs and spatial distributions confirm and strengthen the assessment by Longobardi et al. (2015a) that the M 87 halo and ICL are distinct components. We note that the transition from M 87 to ICL is relatively sudden both in surface brightness and in kinematics (LOSVD). Such sharp transitions are not expected in relaxed clusters. For example, around M 49 in the Virgo subcluster B, the BCG plus IGL system displays a continuous radial transition in both kinematics and stellar population properties (Hartke et al. 2018).

The dynamical properties of the ICL around M 87 can be used as a benchmark for advanced hydrodynamical simulations of galaxy clusters. The separation of central galaxy (M 87) and
ICL on the basis of different LOSVDs has similar aspects as the classification as function of binding energy of stellar particles in simulated cluster centres (Dolag et al. 2010; Cui et al. 2014). Stars with high binding energies come from mergers of fairly massive progenitors, i.e. relaxation and merging processes that led to rapid changes in the gravitational potential. As a result these particles have lost memory of their progenitors, while particles with low binding energies still reflect the dynamics of their lower mass satellite progenitors. In particle tagging methods (Cooper et al. 2015) BCGs and ICL have thus been associated with relaxed/unrelaxed accreted components.

The Illustris TNG simulations (Pillepich et al. 2018) made detailed predictions on ICL fractions and spatial distributions that can be compared with the results from the current investigation. In what follows we assume a total halo mass of \(3 \times 10^{13} \, M_\odot\) for the Virgo cluster (Karachentsev & Nasonova 2010). For this halo mass, the Illustris TNG simulations predict a best-fitting power-law slope of \(\alpha_{\text{TNG,ICL}} \sim -2.2\) to the 2D stellar mass surface density of the central M 87 halo and ICL. In the outermost region, in the inner 150 kpc we measure \(-\alpha \sim (-2.0 \pm 2.5)\), in approximate agreement. The ICL alone has a shallower radial profile there, \(\alpha_{\text{ICL}} \approx -0.8\).

For the Virgo cluster halo mass, the simulations predict approximate ICL stellar mass fractions out to the virial radius of \(-0.35\) for an aperture >30 kpc, and of \(-0.2\) for an aperture >100 kpc (Pillepich et al. 2018, their Fig. 10). From Longobardi et al. (2015a), in the radial range 7 kpc < \(R\) < 150 kpc the V-band luminosities of the M 87 halo and ICL are \(L_{\text{halo}} = 4.42 \times 10^{10} \, L_\odot\) and \(L_{\text{ICL}} = 0.53 \times 10^{10} \, L_\odot\), respectively. For the M/L ratios, \(\gamma^*_\odot\), we adopt values assigned by the colour-mass-to-light ratio (McGaugh & Schombert 2014), using the \(B-V\) colours measured for the outer halo and ICL, respectively. For the M 87 outer halo, we adopt \(\gamma^*_\odot = 2.3\) for a colour of \(B-V = 0.76\), as in Longobardi et al. (2015b); for the ICL, \(\gamma^*_\text{ICL} = 1.0\) for a colour \(B-V \approx 0.6\) measured at 130 kpc from the centre of M 87 (Mihos et al. 2017). These luminosities and M/L ratios result in a stellar mass fraction of 0.05 for the ICL for \(R < 150\) kpc around M 87. This appears lower than the predicted values, but the comparison depends on how quickly the slope of the ICL density steepens outside our observed range.

The Illustris TNG simulations also make predictions on the minimum progenitor stellar mass, such that satellites of this mass and higher contribute 90% of the total ex situ stellar mass around nearby massive ellipticals (Longobardi et al. 2015b). However, because of the likely accretion origin of also the smooth outer halo, and the long associated phase mixing timescales at \(R \sim 100\) kpc, we expect that this component too would show lower mass or amplitude substructures if it were possible to look at its phase-space with a much larger number of stellar tracers. Nonetheless the working concept of the smooth halo is useful because the approximately Gaussian LOSVDs enable us to determine well-defined velocity dispersions and tracer densities for carrying out a Jeans analysis of the mass and anisotropy at large radii.

M 87 is an X-ray bright elliptical galaxy and the gravitational potential can be traced directly by modelling the hot gas atmosphere, under the assumption of hydrostatic equilibrium (e.g. Nulsen & Bohringer 1995). However, the comparison between the circular speed profiles computed from dynamical modelling of the stars’ LOS velocities and from the X-ray data in several nearby massive ellipticals including M 87 has indicated that the depth of the potential well derived from the X-ray emitting hot gas is systematically lower than the corresponding optical value (from stars) such that \(v_{\text{circ}} = \eta \times v_{\text{X}}\) with \(\eta = 1.10 \pm 0.14\) (Churazov et al. 2010). This implies that the mass estimates from X-ray data underestimate the enclosed total mass by 21%–30%, and has been considered as evidence for a significant non-thermal pressure support (Churazov et al. 2008; Gebhardt & Thomas 2009; Shen & Gebhardt 2010; Das et al. 2010).

Nonetheless we were able in Sect. 4.3 to obtain a consistent interpretation of the tracer density and velocity dispersion profile of the smooth halo in the gravitational potential obtained from the X-ray data of Churazov et al. (2010) and Simionescu et al. (2017). Using the local, spherically symmetric Jeans analysis method of Churazov et al. (2010) we found that the radial variation in the LOS dispersion profile \(\sigma(R_{\text{avg}})\), rising from 270 to 300 km s\(^{-1}\) in the radial range 10 kpc \(\leq R_{\text{avg}} \leq 70\) kpc followed by a decline to 100 km s\(^{-1}\) at \(R_{\text{avg}} = 135\) kpc, can be reproduced by an isotropic stellar orbital distribution in the radial range up to \(\sim 60\) kpc, which becomes strongly radially anisotropic outside 70–135 kpc. The strong decline at the largest radii is similar to what is measured in our own Milky Way halo (see Fig. 15 in Bland-Hawthorn & Gerhard 2016). The strong radial dependence of \(\sigma(R_{\text{avg}})\) for the smooth M 87 halo can be generated from a flat and then rising \(v_{\text{X}}\), a steeper \(I(R)\) for the smooth M 87 halo, as shown in panels A and B of Fig. 10, and a varying orbital anisotropy profile with radial dependence indicated in panel C of Fig. 10). This simplified picture provides a consistent

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9 These luminosities account for the fraction of ICPNs in the range of velocities covered by the M 87 halo.
description of the velocity dispersion profile for the smooth M 87 halo, and sets the basis for a more sophisticated dynamical model to follow.

We also computed the predicted $\sigma_{ICL}^2$ profile from the X-ray circular velocity profile $v_{c, X}$ and the full Sersic profile ($n = 11$ including the ICL; from K09) for an isotropic orbital distribution. Even with an increasing circular speed and a flat surface brightness profile the predicted $\sigma(R_{vir})$ at 135 kpc is $\sim 540 \text{ km s}^{-1}$, i.e. it does not rise fast enough to reproduce the upward $\sigma$ profile obtained when the ICL PNs are included (magenta full dots in Fig. 9). This is due to the non-Gaussian ICL LOSVD, and supports previous assessments that the ICL around M 87 is not (or not yet) in dynamical equilibrium.

We note that the modelling of the smooth halo indicates very strong radial anisotropy at the outermost radii probed by the PN data. This suggests that if the hydrostatic interpretation of the X-ray data significantly underestimated the M 87 circular velocity curve at $\sim 100$ kpc radius, it would be difficult to find a dynamical equilibrium model matching the low dispersion there. Thus, non-thermal pressure contributions may in fact be small at those radii, and the hydrostatic pressure of the X-ray emitting gas therefore traces the enclosed mass. We also note that the new modelling obviates the need for a truncation of the density inferred by Doberty et al. (2009) because the new velocity dispersion profile and surface density profile of the smooth halo appear consistent with the mass distribution from X-rays. This is ultimately due to the better statistics in the new ICPN data which allowed us to subtract the (non-equilibrium) ICL component from both the surface brightness and LOS velocity dispersion data.

5.3. M 87 kinematics as traced by GCs and ultra-compact dwarfs

In addition to PNs, GCs and UCDs are used as bright tracers to measure LOSVs and thus overcome the limits represented by the very low surface brightnesses characteristic of the outer regions of the M 87 halo. It is of interest then to compare the results from the different tracers in order to assess any similarities or discrepancies, and to understand the origin of the latter.

Strader et al. (2011) presented a detailed kinematic analysis of a sample of $\sim 400$ GC LOSVs that covers the M 87 halo out to 40′ ($\sim 175$ kpc). They found that all the GC populations are characterised by rotation that becomes stronger at large radii. However GC subsamples with different average colours have rotation that differs both in amplitude and direction.

By comparing Strader et al. (2011) results to the PN kinematics of the M 87 smooth halo presented in this study, we found differences that are most significant with respect to the kinematics of the metal-poor GC subsample. The fiducial velocity dispersion profile of the smooth M 87 halo as traced by the stars and PNs is in broad agreement with the red GC population, within the uncertainties (see also Fig. 9). Unlike the red GCs subsample though, the PN velocity field for the M 87 smooth halo did not show any signatures of rotation along the photometric minor axis (see discussion in Sect. 3). For distances larger than 10′, the bluer GC population and the M 87 smooth halo PNs are rotating about the galaxy’s photometric minor axis, with the former having a larger amplitude of rotation.

The different kinematics shown by the different GC populations may be related to a Virgo ICGC population in addition to a M 87 GC halo population. Durrell et al. (2014) provided evidence for a Virgo ICGC populations on the basis of an excess of number counts in the Virgo core within the extended area surveyed by the Next Generation Virgo Cluster Survey. Both Durrell et al. (2014) and Ko et al. (2017) found an ICGC population mostly associated with blue GCs. This is consistent with results from simulations (e.g. Ramos et al. 2015), who showed that galaxies moving into Virgo-like clusters are stripped mainly of their blue GC component (see also Longobardi et al. 2018, for the first definitive kinematic detection of the ICGC population in the Virgo cluster). We can then speculate that the more metal-poor GCs contain a large fraction of IC population with its distinct kinematics. It is interesting to note that the LOSVD associated with the “green” GCs, as identified by Strader et al. (2011), shows a secondary peak in their distribution (see Fig. 23 in their work) similar to what has been identified as the $v_\text{HI} \sim 900 \text{ km s}^{-1}$ component in the PN M 87 halo sample, and later associated with the Virgo ICL in Sect. 2). If there is a fraction of red ICGCs, we expect it to be lower.

A more recent study presented by Zhang et al. (2015) analysed the properties of a sample of UCD galaxies within 2 square degrees centred on M 87, and compared it to the properties of the red and blue GC population. Their results show that the surface number density profile of the UCDs is shallower than that of the blue GC sample in the inner 15′ and becomes as steep as the red GC component at larger radii. Moreover, they showed that the entire UCD system presents a larger amplitude rotation than the GCs, with a rotational axis that is more aligned with the red GC population in the same radial range. These results show that the UCD system around M 87 is kinematically distinct from the GC population, and also from the M 87 halo PNs. The presence of distinct populations of tracers with multi-spins and different kinematics can be understood in terms of an extended mass assembly of the M 87 halo. Tidal interactions and different specific frequencies of the tracers, depending on the progenitor satellites galaxies, can explain the occurrence of the kinematical diversity in the halo of bright ellipticals like M 87 (Coccato et al. 2013).

6. Conclusions

In this work we analysed the kinematics of 298 PNs in the outer regions of M 87, covering the galaxy halo and intra-cluster stars out to average radius $R_{vir} \sim 135$ kpc (corresponding to $\sim 170$ kpc along the major axis). Our main results are the following:

(i) Including a newly identified $v_\text{HI} = 900 \text{ km s}^{-1}$ component, the intra-cluster stars have a strongly non-Gaussian LOSVD with a peak at that velocity, and strong, asymmetric wings. The shape of the LOSVD is consistent with the LOSVD of the galaxies in the Virgo subcluster A, and indicates that the ICL stars around M 87 as well as the subcluster A galaxies are not (yet) in dynamical equilibrium, signalling the ongoing build-up of the Virgo cluster.

(ii) The so-called dip in the intra-cluster PN luminosity function has strengthened with respect to earlier analyses, while no dip is seen in the PNLF of the M 87 halo. This independently supports the kinematic classification of the PNs into halo and ICL. The surface density profile of the kinematically tagged ICPNs decreases as a power law with radius, with negative logarithmic slope $-\alpha_{ICL} \sim -0.79 \pm 0.15$ in this region.

(iii) Based on the previously published $B - V$ colour (Mihos et al. 2017) and on resolved HST photometry (Williams et al. 2007), the metallicity of the ICL population is estimated as [Fe/H] $\approx -1.0$. This suggests masses of a few $10^9 M_\odot$ for the ICL progenitor galaxies, which is an order of magnitude
less massive than the predictions from the Illustris TNG simulation (Pillepich et al. 2018).

(iv) The PNs in the smooth M 87 halo, i.e. the part of the halo which is approximately phase-mixed at the resolution of our PN survey, thus have a somewhat steeper surface density profile than the total surface brightness profile from Kormendy et al. (2009) for halo and ICL together. The rotation of these stars in the outer halo is small, \( \leq 25 \text{ km s}^{-1} \), safely in the slow rotator regime. The velocity dispersion profile of the smooth halo PNs rises slowly from the \( \sigma \approx 270 \text{ km s}^{-1} \) at \( r = 2-10 \text{ kpc} \) seen in integrated spectra to \( \sigma = 300 \pm 50 \text{ km s}^{-1} \) at average ellipse radii \( R_{\text{avg}} \approx 50-70 \text{ kpc} \), but then declines steeply down to \( \sigma = 100 \text{ km s}^{-1} \) at \( R_{\text{avg}} \approx 135 \text{ kpc} \).

(v) Simple dynamical models indicate that the surface density and velocity dispersion profiles of the smooth halo PN tracers at these large radii are consistent with being in approximate dynamical equilibrium in the gravitational potential inferred from hydrostatic analysis of the X-ray emitting gas. The X-ray circular velocity curve rises steeply outside \( 30 \text{ kpc} \), reaching \( v_{\text{c}} \sim 700 \text{ km s}^{-1} \) at \( 200 \text{ kpc} \). This requires a change in the anisotropy of the halo stellar orbits from an approximately isotropic distribution in the radial range up to \( 60 \text{ kpc} \) to strongly radially anisotropic configuration at the largest radius probed, \( R_{\text{avg}} \approx 135 \text{ kpc} \), as would be expected if the outer halo was accreted from infalling satellites.

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References


Appendix A: LOSVD of the M87 outer regions

This appendix provides additional information on the fiducial $\sigma$ profile and its dependencies on the uncertainties associated with (i) the identification of the ICL stars in the range of velocities associated with the M87 halo, (ii) limited number statistics, and (iii) deviations of the LOSVD in radial bins from a Gaussian distribution. In Fig. A1, we show the PN LOSVDs in six radial bins; they are those adopted in Fig. 9 and the $\Delta R$ is indicated on the top of each panel. In each panel, we illustrate the modification of the LOSVDs, depending on the application of the different constraints.

In each panel, we plot the histogram of the PN LOSVD associated with the M87 halo by Longobardi et al. (2015a) with the black continuous line; the histogram delimited by the red continuous line is computed for the PN LOSVs without the $v_H \approx 900\text{ km s}^{-1}$ component, and represents the smooth M87 halo. The PN LOSVDs clearly deviate from a straight Gaussian distribution and are affected by limited number statistics in the outermost bins. Hence we proceed to estimate the second moment of the PN LOSVDs for the smooth M87 halo as a fiducial range, whose limits are given by the values obtained from the standard deviation from the measured LOSVs (upper limit) and from a robust sigma estimate from the LOSVD (lower limit).

In each panel, we show two Gaussian profiles, one with mean and dispersion values obtained from a robust procedure (blue continuous line), and the other with mean and dispersion computed as simple mean and standard deviation of the LOSVs in the bin (green continuous line). The value obtained from the robust estimate is computed according to McNeil et al. (2010) and Longobardi et al. (2015a). The red shaded histogram presents the PN LOSVDs selected by applying the robust estimator in each bin.

The range of values for the second moment of the PN LOSVDs associated with the smooth M87 halo in the different radial bins is shown in Fig. 9 as a grey shaded area function of the distance, and represents our fiducial velocity dispersion profile.

Appendix B: PN catalogue

Here we present the M87 PN catalogue obtained from the PN photometric and spectroscopic surveys carried out with Suprime-Cam mounted on the Subaru Telescope and the FLAMES spectrograph installed on the VLT, respectively, and presented in Longobardi et al. (2013, 2015a). In this catalogue we provide the PN coordinates (J2000 system), the [OIII]$\lambda 5007\text{ Å}$ magnitudes, and heliocentric $V_{LOS}$ measured from a Gaussian fit to the [OIII]$\lambda 5007\text{ Å}$ emission. In high S/N spectra, we also detect the redshifted [OIII] $\lambda 4959/5007\text{ Å}$ doublet. Typical S/N for the spectroscopically confirmed PN [OIII]$\lambda 5007\text{ Å}$ cover a range of $2.5 \leq S/N \leq 15.0$ per resolution element. From the repeated observations of the same candidates in different FLAMES plate configurations we estimated the median deviation of velocity measurements to be $4.2\text{ km s}^{-1}$, and that the hole distribution covers a range of $0.6 < \Delta V < 16.2\text{ km s}^{-1}$. In the case of repeated observations the given heliocentric velocity has been estimated from the spectrum with the highest S/N. Longobardi et al. (2015a) discussed a statistical approach to determine the fraction of misclassified PNs based on the analysis of stacked PN spectra. They determined that 2% of the entire sample (seven PNs) could represent misclassified spectra (for more details see Longobardi et al. 2015a).

The table is divided into three parts: (i) PNs that have a higher probability of belonging to the smooth halo component and PNs that have a high probability of belonging to the crown structure (indicated by *: Longobardi et al. 2015b), (ii) PNs that have a higher probability of belonging to the additional ICL component as determined in this work (see Sect. 2) and (iii) PNS that have been assigned to the ICL component by Longobardi et al. (2015a). This table is only available in electronic form at the CDS.
**Fig. A1.** Planetary nebula LOSVDs in six radial bins from the M87 centre; the radial range is displayed above each panel. In each panel, the histogram limited by the black continuous line shows the LOSVD of the M87 halo PNs as classified in Longobardi et al. (2015a). The histogram limited by the continuous red line shows the PN LOSVDs of the smooth M87 halo once the \( v_\text{II} \approx 900 \text{ km s}^{-1} \) component is accounted for. For smooth M87 halo PN LOSVDs we further plot two Gaussians, one with mean and dispersion computed as simple mean and standard deviation of the LOSV data (green continuous line), and another whose mean and dispersion value computed from the robust estimator (McNeil et al. 2010; Longobardi et al. 2015a, blue continuous line), and (2). The red shaded histogram shows the PN LOSVDs once the robust estimator is applied. We note that in the fourth and fifth radial bin the velocity dispersion estimates deviate the most because of the deviation of LOSVDs from a Gaussian and the limited statistics.