The accurate mass distribution of M87, the Giant Galaxy with imaged shadow of its supermassive black hole, as a portal to new Physics

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ABSTRACT

The very careful Event Horizon Telescope estimate of the mass of the supermassive black hole at the center of the Giant CD galaxy M87, allied with recent high quality photometric and spectroscopic measurements, yields a proper dark/luminous mass decomposition from the galaxy center to its virial radius. That provides us with decisive information on crucial cosmological and astrophysical issues. The dark and the standard matter distributions in a wide first time detected galaxy region under the supermassive black hole gravitational control. The well known supermassive black hole mass vs stellar dispersion velocity relationship at the highest galaxy masses implies an exotic growth of the former. This may be the first case in which one can argue that the supermassive black hole mass growth was also contributed by the Dark Matter component. A huge dark matter halo core in a galaxy with inefficient baryonic feedback is present and consequently constrains the nature of the dark halo particles. The unexplained entanglement between dark/luminous structural properties, already emerged in disk systems, also appears.

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1. INTRODUCTION

The distribution of Dark Matter (DM) in galaxies is extremely relevant for Cosmology and Particle Physics. Let us sketch the state of the art: the well-known ΛCDM scenario predicts, employing cosmological N-Body simulations, that the DM halo density, in any virialized object, follows the Navarro-Frenk-White (NFW) profile (Navarro et al. 1996a),

$ρ(r) ∝ r^{−1} (r + r_s)^{−2}$

with $r_s$ a length scale depending on the value of the halo mass. However, the individual and coadded kinematics of Spirals, Low Surface Brightness (LSB) galaxies and Dwarf Irregulars clearly show that the main baryonic component, a stellar disk of surface density$^1$ (Freeman 1970):

$Σ_*(r) = \frac{M_D}{2π R_D^2} e^{-r/R_D}$

is embedded in a dark halo with a cored density distribution (de Blok 2010; Salucci 2018; Karukes & Salucci 2016; Salucci 2019): $ρ(r) \propto (r_0 + r)^{−1}(r_0^2 + r^2)^{−1}$.\n
The above discrepancy between the empirical profile and the ΛCDM N-Body outcome simulation is particularly strong in $^1$ The size of the stellar disk is defined as $R_{opt} \equiv 3.2 R_D$
dwarfs and low luminosity disc systems Karukes & Salucci (2016). Remarkably, after a proper circular-velocity decomposition into its dark and luminous components, all disc systems, of stellar masses $5 \times 10^7 \, M_\odot \leq M_\ast \leq 3 \times 10^{11} \, M_\odot$, show a cored dark halo density profile (see also de Martino et al. 2020)). This is also shown by coadded studies of rotations curves (Salucci 2007; Salucci et al. 2007; Dehghan et al. 2020) (see also Di Paolo 2021). At high redshifts the situation is open although some evidences for dark matter cores are appearing Salucci et al. (2021). However, it is worth noticing that supernovae explosions in the stellar disks may originate a "baryonic feedback" capable of fabricating the observed DM cores from the original cusps Di Cintio et al. (2014). In these systems, however, another "anomaly" is still unexplained: the structural parameters of the mass distribution, i.e. $\rho_0$, $r_0$, and the disk mass and length scale $M_D$, $R_D$, are surprisingly very well correlated among themselves (Salucci 2019).

The above discussion introduces the primary goal of this work: to derive the mass distribution of the luminous and dark components of M87. This massive cD elliptical galaxy, located at the center of Virgo Cluster, is the biggest one in the Universe within a radius of 0.5 Gpc. In detail: its stellar spheroid mass is 20 times bigger than that of the disk of our Galaxy, while its dark halo mass is 100 times more massive. We will then investigate the galaxy structural properties in an extreme object.

Moreover, as any spheroidal galaxy, M87 has, at its center, a very supermassive black hole (SMBH), its mass estimates, obtained from different methods/measurements, have ranged from $(3.5 \pm 0.8) \times 10^9 M_\odot$ to $7.22^{+0.34}_{-0.40} \times 10^9 M_\odot$ (Walsh et al. 2013; Oldham & Auger 2016). This SMBH is the first and the only one so far to be imaged (as published in April 2019 (Akiyama et al. 2019a,b)). The image shows its shadow, surrounded by an asymmetric emission ring with a diameter of $3.36 \times 10^{-3}$ pc (0.01 ly). This result has a consequence for the present work: as a byproduct, the Event Horizon Telescope (EHT) has finely measured the SMBH mass: $(6.5 \pm 0.2 \, \text{stat} \pm 0.7 \, \text{sys}) \times 10^9 M_\odot$ (Akiyama et al. 2019b). Its value and small uncertainty play an essential role in the present work results. Finally, we assume for M87 the EHT distance of 16.5 Mpc (Akiyama et al. 2019a).

This work is organised as follows. In Section 2, we describe the method obtained to derive the M87 mass model accurately. In the next Section 3, we investigate the properties of the central SMBH and of the other mass components of this giant galaxy. In the conclusions, Sec. 4, we summarize our findings specifying how M87 serves as a cosmic laboratory for many unsolved mysteries of the Universe.

2. METHOD: DERIVING THE MASS DISTRIBUTION IN M87

The giant elliptical M87 is home to several different dynamical populations as Planetary Nebulae, Globular Clusters and Satellite Galaxies. They can be used as multiple, independent and well extended tracers of the galaxy gravitational field (see e.g. (Agnello et al. 2014; Salucci 2019; Schuberth et al. 2010; Napolitano et al. 2014)). This wealth of data, alongside high-resolution photometry and spectroscopy, allows careful mass modelling, also because, in this object, we can assume a spherical symmetry in all the mass components. The mass structure of M87 has been the subject of many studies (Strader et al. 2011; Murphy et al. 2011; Zhu et al. 2014). Recently, a substantial improvement on the determination of its gravitational potential has been obtained by Oldham & Auger (2016a) for a region extending from very near to the center out to the virial radius.

In relation with the galaxy DM halo density profile they adopted four models (Oldham & Auger 2016a): one cusped, the well-known NFW profile (Navarro et al. 1996b) and three cored: the LOG, the gNFW and the cgNFW ones. They found that the mass model with the DM cored profiles fared better in fitting the observational data than the cuspy ones (Navarro et al. 1996b). However, the above cored profiles raise doubts that they can describe the DM distribution in galaxies in a physically correct way. In fact, the LOG profile, introduced in the Universal Rotation Curve of Spirals (Persic et al. 1996), holds only out to their optical radii, outside which kinematical and weak lensing data strongly favour the Burkert profile (Salucci et al. 2000; Gentile et al. 2007; Salucci 2019), which declines with radius in the outermost halo regions (e.g. (Gentile et al. 2007)), while the LOG profile flattens there. The gNFW profile features an NFW profile with the addition of a core:

$$\rho(r) = \rho_0 \left(\frac{r}{r_s}\right)^{\alpha} \left(1 + \frac{r}{r_s}\right)^{-3-\alpha},$$

$\alpha$ is the inner slope, and $x = r/r_s$ with $r_s$ a length scale. However, this generalization of the NFW profile not only leads to multiple degeneracies (Klypin et al. 2001) but also increases, by one, the number of halo parameters, with no physical justification. In fact, in both simulations and observations, the resulting DM density profiles have just two free parameters (a halo density and a halo length scale) and seem to not require a third. Actually, in the above one finds a tight relationship connecting the two, reducing so the number of necessary parameters to just one (Salucci 2019). Finally, at large radii, this density profile does not necessarily converge to the NFW one. Similar arguments hold for the cgNFW profile also used in Oldham & Auger (2016a) that, besides, has two free parameters more than the NFW one.

Remarkably, in Spirals, LSBs, dwarf Irregulars, dwarf Spheroidals and also ellipticals, the Burkert DM halo profile (not considered in Oldham & Auger (2016a) alongside with
its luminous counterparts fits all the available kinematics, including individual and coadded RCs excellently (Salucci 2019). Therefore, in this work, we adopt the latter profile and so we can also compare its dark structure with that of galaxies of different Hubble types and halo mass.

The very recent study by Oldham & Auger (2016a) has derived the total mass distribution of M87 up to its virial radius at 1.3 Mpc. The stellar photometry, available out to 210 kpc, in Oldham & Auger (2016b), shows a 2D-light distribution which is very different from the Sersic profile, generally found in Ellipticals. We have an extended envelope, outside the inner stellar core, likely due to the fact that the M87 spheroid has been formed by a first burst of star formation, followed by a continuous infall of luminous matter lasting several Gyrs. The Nuker profile best models the surface luminosity profile of the stellar spheroid

\[ I(R) = I_0 \left( \frac{R}{R_b} \right)^{-\zeta} \left( 1 + \left[ \frac{R}{R_b} \right]^\alpha \right)^{\frac{\zeta-\eta}{\eta}}, \tag{2} \]

where, by following Oldham & Auger (2016b) we have: \( I_0 = 3.5 \times 10^9 \, L_\odot \, \text{kpc}^{-2} \), \( \zeta = 0.186 \), \( \eta = 1.88 \), \( r_b = 1.05 \) kpc and \( \alpha = 1.27 \). Moreover, in M87: \( M_B = -20.5 \), and the half light radius reaches the value of \( r_e = (73.5 \pm 7) \). It is important to remark that Eq.(2) provides us with an accurate stellar mass distribution also in the region \( 1 \, \text{kpc} < r < 5 \, \text{kpc} \), neighbouring the central SMBH. From Eq.(2) we derive the corresponding M87 "disk scale length" \( R_D \) in the following way: in spirals, \( R_D \) is the radius inside which the fraction of light is 0.2 times the total one, so we get: \( R_D^{M87} = 10 \pm 1 \) kpc. This galaxy has one of the largest half-light radii within the region wide 1Gpc of the Universe. However, the value of \( R_D^{M87} \) is in line with that of the most massive spirals. One can argue that the peculiarity in the M87 stellar distribution emerges only at \( r > 50 \) kpc, where the dark matter largely dominates the total mass distribution.

The mass profile of the luminous component is obtained from Eq. (2) by means of:

\[ M_\star(r) = -\left( \frac{M_{\text{sph}}}{L_B} \right) \int_0^r r^2 \left( \int_r^\infty \frac{dI(R)}{dR} \frac{dR}{\sqrt{R^2-r^2}} \right) \, dr. \tag{3} \]

This profile has just one free parameter: \( M_{\text{sph}} \), the spheroid mass.

The gravitating mass profile \( M(r) \) that we use in this work was obtained from the Jeans method applied to the kinematics of different tracers of the gravitational field which assure for M87 eleven independent data points (see Oldham & Auger (2016a)). They have derived the mass profile \( M(r) \) for the case of spherical symmetry and also found that possible kinematical anisotropies induce only a moderate effect in the mass profile. In fact, by varying the anisotropy content, the corresponding mass profiles \( \log M(r) \) result all very similar and lie, at any radius \( r \), within 0.2 dex from the isotropic solution (Oldham & Auger 2016a), see Fig. 1. It is worth noticing that these uncertainties in \( \log M(r) \) are much smaller than the range of the measured \( \log M(r) \) masses that is 2.5 dex, this opportunity is very rare for spheroidal galaxies. Therefore, in this work, we will adopt the isotropic profile \( \log M(r) \) of Oldham & Auger (2016a) to represent the gravitating mass profile of M87, and we consider the effect of kinematical anisotropies by assigning a 0.2 dex uncertainty to the log mass measurements.

For the DM, we adopt the Burkert profile; this choice is the only difference concerning the modelling in Oldham & Auger (2016a), but it is very substantial and, in addition, can also affect the resulting value of the mass of the luminous spheroid. Then:

\[ \rho_h(r) = \frac{\rho_0 \sigma_0^3}{(r + r_0)(r^2 + r_0^2)}, \tag{4} \]

where the core radius \( r_0 \) and the central density \( \rho_0 \) are the free parameters of the model. As result:

\[ M_h(r) = M_0 \left[ \log \left( 1 + \frac{r}{r_0} \right) \frac{\tan^{-1} \left( \frac{r}{r_0} \right)}{r_0} \right] + \frac{1}{2} \log \left( 1 + \left( \frac{r}{r_0} \right)^2 \right), \tag{5} \]

where \( M_0 = 6.4 \rho_0 \sigma_0^3 \). Let us notice that, in the global mass modeling of such giant galaxy of about \( 10^{14} M_\odot \), the EHT value for the central black hole mass \((6.5 \pm 0.2 \text{stat} \pm 0.7 \text{sys}) \times 10^8 M_\odot \) shows that the latter does not play any gravitational role (different is the situation in the innermost kpcs, see later). Therefore, the mass model, with its three
free parameters, reads as:

$$M_{\text{mod}}(r; M_{\text{ sph}}, r_0, \rho_0) = M_\star(r; M_{\text{ sph}}) + M_h(r; r_0, \rho_0).$$

(6)

Then, we proceed using the standard $\chi^2$ fitting the eleven independent data of the mass profile $M(r)$ with the mass model of Eq.(6) and obtaining so the three free parameters and the related triangular plots yielding their statistical uncertainties. It is evident in Fig.2 that the adopted DM profile allied with a much smaller contribution from the stellar spheroid, well reproduces the distribution of the gravitating mass of the galaxy. Therefore, the mass model can be written as: $M_{\text{mod}}(r; M_{\text{ sph}}, \rho_0, r_0)|_{\text{best fit}}$. The resulting values of the best-fit parameters are: $M_{\text{ sph}} = (1.3 \pm 0.1) \times 10^{12} M_\odot$ that leads to a mass-to-light ratio of $M_{\text{ sph}}/L_V = (8.6 \pm 1.2)M_\odot L_\odot^{-1}$, $r_0 = (91.2 \pm 9.0) \text{ kpc}$ and $\rho_0 = (4.7 \pm 0.9) \times 10^{-25} \text{ g/cm}^3$. The nominal value for the virial radius is $R_{200} = (1.3 \pm 0.2) \text{ Mpc}$; the halo mass within $R_{200}$ is $M_{200}^{\text{bestfit}} = (1.3 \pm 0.3) \times 10^{14} M_\odot$ and the luminous-dark mass ratio is about $10^{-2}$. Therefore, M87 is one of the biggest galaxies of the Universe at the upper end of the galaxy formation process. Noticeably, a particle situated at $R_{200}$, in rotation around the center of M87, would make a complete orbit in not less than 13 Gyr, the current age of the Universe, a fact that might be not a coincidence.

Let us define, for this spherical pressure dominated object, a circular velocity analog to that of the rotationally dominated disk systems for which:

$$V_{M87,\text{disk}}^2(r) = G M_{M87,\text{disk}}(r)/r \quad \text{where} \quad V_{M87,\text{disk}}(r) \text{ is the circular velocity that allows a point mass, at a distance } r \text{ from the center of any galaxy, to stay in rotational equilibrium. Then, for M87, considering also Eqs.(3),(5), we have:}$$

$$GM(r)/r = V_{M87}^2(r) = GM_{\text{mod}}/r = V_{\text{mod}}^2(r) = [V_{SMBH}^2(r) + V_e^2(r) + V_h^2(r)]_{\text{mod}}$$

(7)

since the model fits the data very well, e.g.: $M_{\text{mod}}(r) \simeq M(r)$, we can accurately determine the velocity profile (see Fig.(3)). Moreover, $V(R_{opt}) = \left(\frac{GM(M_{\text{opt}})}{R_{opt}}\right)^{1/2} = 360 \pm 5 \text{ km/s}$ and for a spherical and isotropic distribution we derive the dispersion velocity $\sigma(r_e)$ from: $G^{-1}V^2(r_e)r_e = G^{-1}3\sigma(r_e)^2 r_e$ that yields: $\sigma(r_e) = 358 \pm 5 \text{ km/s}$.

Not unexpectedly, the DM density in the outer parts of M87 ($r > 200 \text{ kpc} \ ) is also well represented by the collisionless NFW profile with a mass of $M_{M87} = 1.3 \times 10^{14} M_\odot$ and a concentration value of $c = 7$. This allows us to infer the M87 original DM profile by extrapolating $M_{NFW}^M(r)$ down to $r = 0$ so that, defining $X = r/R_{\text{vir}}$, we have:

$$V_{NFW}^2(X)^2 = G M_{200}/R_{\text{vir}} \frac{1}{X} \ln(1+cX) - \frac{cX}{1+cX} ,$$

(8)

with $M_{200} = 200 \frac{4}{3\pi} \rho_c R_{\text{vir}}^3$ and $\rho_c = 1.0 \times 10^{-29} \text{ g/cm}^3$. Then, $M_{NFW}(r) = G^{-1}V^2(XR_{\text{vir}})r$

The primordial distribution of the M87 DM halo leads us to realize that a significant fraction of the dark mass, once inside the radius $R_{\text{dom}}$, has gone missing: $\simeq \Delta M_{NFW}^M(R_{\text{dom}}) = M_{NFW}^M(M_{\text{dom}}) - M(R_{\text{dom}}) \sim 2 \times 10^9 M_\odot$.

A very relevant feature of the mass distribution of M87 is its huge DM core radius $r_0$: this is one of the first detections of DM cores as large as $\sim 100 \text{ kpc}$ (see also Di Paolo et al. (2019)). Such bare fact was also found by Oldham & Auger 2 $R_{\text{dom}}$ defines the region in which today the SMBH dominates the dynamics of M87, i.e. $R_{\text{dom}} = 1 \text{ kpc}$ (see Fig. 3).
Donato et al. (2009) discovered that, in all spirals, the central DM surface density \( \Sigma_0 \equiv \rho_0 r_0 \) is about constant:

\[ \Sigma_0 \sim 120^{\pm 200}_{-70} M_\odot/\text{pc}^2, \]

independently of the galaxy magnitude. Such relationship has been later confirmed across a range of 18 magnitudes (maximum circular velocity) and in galaxies of different Hubble types: dwarf spheroidal, dwarf irregualrs and LSBs (Salucci et al. 2012) (see also Salucci (2019)). We realise that M87 follows such a dark world - dark world quantities relationship within a factor 4. Furthermore, M87, with a stellar mass much higher than any other galaxy, is pivotal in indicating that in the above relationship also the stellar mass plays a role. A more accurate relationship involving two quantities of the DM component, \( \rho_0 \) and \( r_0 \) and one quantity of the luminous matter component \( M_{sph} \), emerges (\( \Sigma_0 \) in \( M_\odot/\text{pc}^2 \)):

\[
\log \Sigma_0 = 2.72 + \frac{1}{6} \log \left( \frac{M_{sph}}{10^{12} M_\odot} \right), 
\]

with the scatter less of 0.15 dex.

3. THE CENTRAL SUPER MASSIVE BLACK HOLE AS A MASS COMPONENT OF M87

The accurate mass model of M87 of previous Sec. 2 and the very precise EHT determination of the mass of its SMBH (Akiyama et al. 2019a,b) allow us to investigate the region in which the latter dominates the galaxy gravitational potential. First, we notice that, compared with other spheroidals, the fraction between the SMBH mass and the total stellar mass is quite high: \( 6 \times 10^{-3} \), especially considering that most of the \( 1.2 \times 10^{12} M_\odot \) of the M87 stellar spheroid has been accumulated at times much later than that of the formation of the SMBH. Using the full M87 mass model, we can derive the analogous circular velocity \( V(r) \) from \( r \sim 0.1 \text{ kpc} \) outwards, determining the various luminous, black hole and dark matter components. Let us stress that, in the region \( 0.1 \text{ kpc} < r < 10 \text{ kpc} \), we recover \( V(r) \) without having in this region dynamical measurements. The DM component here is negligible. The EHT independently measured the mass of the SMBH. Finally, this region’s stellar mass distribution is obtained through high-resolution photometry alongside dynamical measurements at 10-30 Kpc, where the stellar spheroids are the major massive component.

In Fig. 3 we plot such curve out to 4 kpc; we realize that inside 1 kpc, the SMBH component dominates that of the stellar halo and, therefore, the whole gravitational potential. Remarkably, such component gives an important contribution to the total velocity out to 4 kpc \( \sim 0.4 R_D \). This result is amazing: in late Spirals, of any mass, the radius of the dominance of the SMBH is lesser than \( 20 - 50 \text{ pc} \sim 0.05 R_D \) (Salucci et al. 2000). In Elliptical galaxies, we do not see a dynamically dominant SMBH component in that the SMBHs with masses of \( 10^8 - 9 M_\odot \) are buried inside stellar spheroids.
with a mass of $> 10^{11} M_\odot$ within $r_3$. To our knowledge, M87 is the unique object in which we can see the central black hole participating, with another mass component, in shaping the mass distribution of a galaxy. The two components, actually, looks fine-tuned and the circular velocity of M87 keeps constant from 0.4 kpc to 4 kpc in spite of the fact that they, in such region, have totally different velocity radial profiles: $V_{SMBH}(r) \propto r^{-1/2}$ which contrasts $V_*(r) \propto r^{1/2}$.

Another peculiar feature seems present in this region: a mysterious lack of DM. In fact, inside $0.1 R_D = 1$ kpc the extrapolated back dark mass $M_{NFW}^{M87}$ (1 kpc) is only $0.1\%$ of $M$ (1 kpc), computed from the M87* black hole mass and from accurate photometry and the mass to light ratio of the stellar spheroid. Inside $R_D$, where we have dynamical measurements of the total mass, the dark mass is $13\%$ of $M(R_D)$. Only at $r > 22$ kpc the dark matter contribution to the circular velocity overcomes that of the standard matter.

In spheroidals the well known $M_{BH} \propto \log \sigma_e$ relationship is a fundamental one e.g. Kormendy & Ho (2013):

$$\log \frac{M_{BH}}{10^{9} M_\odot} = -0.51 \pm 0.05 + (4.4 \pm 0.03) \log \frac{\sigma_e}{200 \text{ km/s}}.$$  

(10)

Since in M87 $M_{BH} = 6.5 \times 10^9 M_\odot$ and $\sigma_e \simeq (358 \pm 5) \text{ km/s}$, the EHT SMBH mass results $(0.2 \pm 0.04) \text{ dex}$ larger than the value predicted by Eq. (10), showing a $5 \sigma$ excess. Such excess, in mass (at $1\sigma$) is of the order of $(3 - 4.5) \times 10^9 M_\odot$. This is an important result, given the exquisite EHT black hole mass estimate and the fact that the Kormendy & Ho (2013) relationship is very tight. In fact, in the crucial process of the black hole mass growth, this result points to a role for the dark matter. This may be the first case in which one can argue that the DM component also contributed to the SMBH mass growth.

4. DISCUSSION AND CONCLUSIONS

For several issues of Cosmology and extra-galactic astrophysics the determination of the M87 dark and standard matter mass distributions of this work becomes a phenomenal test-bed and yields pivotal information. M87 is a giant cD galaxy of the total mass of $1.3 \times 10^{14} M_\odot$ which has, at its center, the usual SMBH, whose mass has been exquisitely measured in the process of imaging its shadow. In addition, we have an accurate mass distribution from 100 pc to 1 Mpc obtained by exploiting high quality photometric and spectroscopic measurements.

Remarkably, the M87* SMBH, almost uniquely in the local Universe, controls gravitationally a region $\simeq 1$ kpc wide, populated by more than $10^7$ stars of the stellar spheroid. In contrast, in our Galaxy, the central SMBH hole SgrA* dictates the motion of only a few thousand stars.

There is evidence that, inside $R_{dom} \simeq 1$ kpc, a relevant portion of the original DM halo mass has disappeared over the Hubble Time, in fact: $M_{DM}(R_{dom}, z_{form}) - M_{NFW}(R_{dom}, 0) \sim 2 \times 10^9 M_\odot$. On the other side, the EHT estimate of the M87* mass results bigger, by approximately the same amount, than the value expected from the well known $M_{SMBH} vs \log \sigma_e$, diagram, that people think born out of an Eddington accretion of standard matter onto a SMBH seed. The following argument also supports the presence of a dark infall on M87*. In the case of a Dark halo around a SMBH of $\sim 7 \times 10^9 M_\odot$ whose density at $r = R_{dom}$ is $\rho_{DM}(r)$ as found in the previous section, develops, for $r < R_{dom}$ a cusp so that: $\rho_{DM, \text{cusp}}(r) = \rho_{DM}(r_{dom}/R_{DM})^{-2.5}$. The mass inside this hypothetical cusp will be $2 \times 10^{11}$ totally incompatible with the DM mass dynamically estimated at 20 kpc.

These features may lead to the first observed case in which one can argue that the DM component also contributed to the SMBH mass growth. More generally, one can envisage that inside the innermost hundreds of parsec, the escape velocity from the giant black hole is much bigger than the dispersion velocity of the primordial Dark Matter halo particles. On this line, it is known that the capture of DM particles by the central black hole is a well studied physical process see e.g. Gammaldi et al. (2016). Furthermore, let us remind that the energy and angular momentum of the DM particles in the innermost kpc can be removed by the non-collisional status of the particles itself: e.g. in the scenario of self-interacting dark matter particles and in that of interacting dark matter-standard model particles e.g. Salucci et al. (2020).

The SMBH seems to have been, over the cosmological times, dynamically "live" in a surprising way: a "fine-tuning" between the mass of M87* SMBH and the mass distribution of its stellar spheroid appears. In fact, in the region inside 4 kpc the effective circular velocity keeps constant, despite that the stellar spheroid and the SMBH components have very different radial profiles and total masses. We can argue that the central SMBH has dynamically shaped the innermost portion of the stellar spheroid.

The $1 \times 10^{14} M_\odot$ massive M87 DM halo density is well reproduced by a Burkert profile with a $\sim 100$ kpc wide core radius. Outside the region in which the dark halo coexists with the stellar spheroid, $r > 200$ kpc, the DM density converges to the NFW profile characteristic of the collisionless DM regime, as it occurs in Spirals (Salucci 2019).

M87 is a benchmark for the idea that supernovae (SN) induced baryonic feedbacks, by flattening the original cuspy distribution, are the cause of the detected DM cores. The energy budget of this possible process can be easily computed. The (potential) energy $E_{cf}$ involved in the core forming
process, taking into account that, inside $r_0$, $\rho_{NFW}^{M87}(r) \gg \rho_{DM}^{M87}(r)$ is: $E_{cf} \sim 10^{62}$ erg. The stellar mass inside $r_0$ is about $\sim 8 \times 10^{11} M_\odot$ that implies, for a single burst of star formation with a Salpeter IMF, the explosions of $\sim 5 \times 10^9$ core collapse SNs, each of them providing an energy of $f_{cf}10^{51}$ erg to the core forming process, where $f_{cf} \sim 10^{-1} - 10^{-2}$. The cumulative feedback energy, therefore, does not reach $10^{60}$ erg $< < E_{cf}$. Notice that also in the biggest spirals the SN feedback is short of providing sufficient energy, but in M87 the failure is outstanding.

The stellar spheroid and the DM halo main structural length scales, $R_h^{M87}$ and $r_0$, already mysteriously related in disk systems of any mass and morphology (Salucci et al. 2019; Salucci et al. 2020), continue to be clone-like entangled also in this extremely different galaxy.

The M87 DM structural properties result decisive in one important test about the nature of the dark particles. A well preferred solution for the riddle of the observed cored DM distributions around galaxies involves the role of the Fuzzy Dark Matter (FDM) , a hypothetical particle (e.g. an Ultra Light Axion) with a mass of the order of $m_p = 10^{-22}$ eV that implies a de Broglie wavelength on the galaxy scales. FDM halos well reproduce the kinematics of Dwarf galaxies with halo masses $M_h \sim 10^{9-10} M_\odot$ e.g.: Schive et al. (2014); Hui et al. (2017); de Martino et al. (2020); Pozo et al. (2021) and references therein. At larger masses the situation is completely open. However, in combination with the recent result by Burkert (2020) according to which $\Sigma_0$, $r_0$ and the galaxy redshifts of halo formation $z_{form}$ are related by:

$$\frac{r_0^3}{\text{kpc}^3} = 0.25(1 + z_{form})\frac{75 M_\odot pc^{-2} 10^{-22} eV}{\Sigma_0} m_p$$ (11)

the present result draw light on an important feature. For our galaxy, of mass $M_{200}^{M87} = 1.3 \times 10^{14} M_\odot$, we have: $z_{form} < 5$, $\Sigma_0 \sim 500 M_\odot pc^{-2}$ and $r_0 \sim 90$ kpc, then Eq. (11) holds only for particle masses whose de Broglie wavelength are at the level of a Mpc scale and are so unable to account for the DM halo density cores. Considering the family of normal spirals, Burkert (2020) noticed the implausibility, in the current galaxy formation theory, of the $r_0 \propto (1 + z_{form})^{1/3}$ relationship in Eq. (11). Overall, in M87 we conclude that the inferred value of $r_0$ results totally inconsistent with the prediction of Eq. (11): the latter cannot be claimed to dictate the size of the constant density region in galaxies.

M87 provides evidence that the primordial DM halo distribution has been modified by the combined action of the central SMBH and the stellar spheroid during the entire life of the Universe. Therefore, it could be the place in which a new paradigm for the dark matter phenomenon arises: the latter’s nature will emerge by reverse engineering the entanglement among the dark-luminous structural properties that we detect in galaxies rather than coming from theoretical first principles.

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