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# JD1 – Dark Matter in Early-type Galaxies: Overview

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**Abstract.** We summarize the motivations and main conclusions of the joint discussion "Dark Matter in Early-type Galaxies".

**Keywords.** Galaxies: elliptical and lenticular, cD – Galaxies: formation – Galaxies: evolution

## 1. Motivations

It is now commonly accepted that galaxies form inside deep gravitational potential wells dominated by dark matter halos. The existence of cold dark matter (CDM) is a fundamental cornerstone of our standard cosmological model.

However, our understanding of dark matter halos is far from satisfactory, particularly as far as early-type galaxies are concerned. In fact, the very existence of dark matter halos around early-type galaxies is still in question. Although they have been detected around early-type galaxies for over a decade (e.g. Saglia, Bertin & Stiavelli 1992; Franx, van Gorkom & de Zeeuw 1994), there have been claims that they are not always required (Romanowsky *et al.* 2003).

Improving our understanding of early-type galaxies and their dark matter halos is essential to test galaxies formation models. First, in the standard hierarchical model of galaxy formation, early-type galaxies are believed to result from major mergers of smaller galaxies (and halos). Therefore they provide the ultimate test of the merging hypothesis. Second, as their central regions are baryon dominated while their outer regions are believed to be dark matter dominated, they represent an ideal testing ground for the poorly understood interactions between baryons and dark matter. Third, additional information about the interplay between dark matter and baryons is provided by the still unexplained tight and non-trivial correlations between observables, known as scaling relations or scaling laws (e.g., the Fundamental Plane; Djorgovski & Davis 1987; Dressler *et al.* 1987). Fourth, being the most massive galaxies in the universe, their dark matter halos are in principle detectable out to high-redshift, thus enabling direct evolutionary studies. Finally, as the most massive galaxies in the universe they are also expected to host the most massive satellites and therefore are an ideal testing ground for the abundant satellite population predicted by CDM simulations and undetected in the local group (e.g., Kravtsov 2009).

Two sets of obstacles need to be overcome to improve our understanding of dark matter in early-type galaxies. From an observational point of view these systems typically lack the optical emission lines and diffuse gas that is so effective in tracing the dark matter halos of spiral galaxies. Therefore, alternative mass tracers must be found and exploited. From a modeling point of view, the triaxiality of early-type galaxies introduces fundamental degeneracies in interpreting projected observables in terms of intrinsic threedimensional properties (e.g. the so-called “mass-anisotropy degeneracy”).

Substantial progress has been achieved on all these issues in the past few years using a combination of new technologies (e.g. integral field spectrographs on large telescopes and sensitive and high resolution X-ray satellites), new techniques (e.g. strong and weak gravitational lensing) as well as new theoretical insights (e.g. improved understanding of the role of active galactic nuclei). The goal of this meeting is to review and discuss recent progress and identify key questions for the future. In particular the following topics were identified by the organizing committee (chaired by the two authors of this summary and composed of Luca Ciotti, Wyn Evans, Ortwin Gerhard, Dan Maoz, Priyamvada Natarajan, Takaya Ohashi, and Silvia Pellegrini):

(*a*) Stellar and dark matter density profiles.
(*b*) Stellar and dark matter substructure.
(*c*) Empirical scaling relations.
(*d*) Formation mechanisms.
(*e*) Cosmic evolution.
(*f*) Observational and modeling techniques.
(*g*) Ongoing and future surveys.

## 2. Meeting Conclusions

Highlights of the individual contributions to the meeting are given in this volume. In this section we present a short summary of the panel discussion that concluded the meeting. The questions presented to the panel were:

(*a*) *Is there unambiguous evidence for dark matter in early-type galaxies?* The general consensus of the meeting was that observational evidence for dark matter around early-type galaxies has improved dramatically, especially with measurements currently extending to many effective radii using dynamical tracers, X-ray observations that probe the regions where stellar mass and traditionally the dark-matter halo starts, and also weak lensing which probes much further out. However, the picture is more complicated than imagined a decade ago and it now seems that the fraction of dark matter inside a fixed radius (e.g. the effective radius) might be a strong function of the mass of the galaxy, increasing both for masses larger *and* smaller than those corresponding to a luminosity of a few $L_*$.

(*b*) *Are modified gravity theories competitive with dark matter?* Here the jury is still out, although our understanding and observational tests have dramatically improved over the last few years (e.g. Bradač *et al.* 2006; Clowe *et al.* 2006). The development of relativistic theories of MOND has lead to new tests through gravitational lensing and stellar dynamics. Also N-body simulations that can be tested against observations are now performed in alternative gravities.

(*c*) *What methods/techniques or combination thereof are most effective at answering specific questions related to the topics of this meeting?* The consensus is that there is not a single “magic” technique or method that can answer all the questions about dark matter unambiguously, but that different methods have to be combined and compared.

(*d*) *Are there recognizable trends in dark matter properties with respect to early-type galaxies properties such as stellar mass or velocity dispersion?* Dramatic progress has been made over the last decade, showing that not all galaxies have identical distributions of dark matter, as predicted by pure dark-matter simulations. The DM content seems to be a strong function of the mass of the galaxy. Recent simulations seem to suggest that this trend is due to feedback from active galactic nuclei for the high-mass galaxies and possibly due to supernovae feedback for the lower-mass galaxies.

(*e*) *Is there dark matter substructure around early-type galaxies?* This is still very much an open question. Whereas tremendous progress has been made in the study of satellites around the Milky Way and the Local Group galaxies, far less, if anything at all is known about substructure around early-type galaxies. Here gravitational lensing appears to be a very promising method, which allows one through a number of observables (flux-ratios, astrometry, time-delays) to probe small scale fluctuations in the potential/mass-distribution of the lens galaxies. Both flux-ratio anomaly and gravitational-imaging methods have now claimed the discovery of substructure around galaxies, but considerable more research in this area is still essential.

(*f*) *What do the mass profiles of early-type galaxies look like? Are universal profiles a good fit to the data?* The answer to this question might again be a function of galaxy stellar mass. Whereas for the more massive ($> L_*$) elliptical galaxies typically isothermal-like total density profiles are found, lower-mass elliptical might still be consistent with the absence of a massive dark matter halo in their inner regions and a density profile that is steeper than isothermal. Likewise the dark matter density profiles may be close to NFW or steeper for massive early-type galaxies, and possibly flatter at dwarf galaxies and cluster scales, although much more work is needed to establish robust trends.

(*g*) *Why are there such tight scaling relations if star formation depends on micro-physics while galaxy dynamics seems dominated by gravitational (DM) macro physics?* Whereas progress has been made on explaining these tight relations and the importance of dark matter for example in the tilt of the Fundamental Plane, many other relations exist as well, including the black-hole to spheroid mass relation, the mass-metallicity relation. Although it seems clear that these relations must be tightly coupled to the formation history of early-type galaxies, theory is still not fully capable of explaining them from first principles. The existence of such tight relations implies that the micro-physics of star formation and black-hole physics somehow know about the large scale physics of galaxy formation and assembly (where gravity dominates). This suggest a strong feedback mechanism between the active nucleus and the interstellar medium. However, precisely how the AGN couples to the ISM and regulates star formation is not clear yet.

(*h*) *What open questions are "most interesting" for future studies?* As often progress may come from the most unexpected directions. However, what seem critical in the future to further our understanding, is to couple physics on small scales, be it dark-matter physics or the physics of star formation and AGN to events that occur on large macroscopic scales (i.e. galaxy assembly, etc). This requires covering an enormous dynamics range in scales and masses.

(*i*) *What tools (techniques/telescopes/instruments/surveys) will we need to answer these questions?* Major new facilities are coming online (e.g. ALMA) or will come online in the coming decade (e.g. TMT/ELT, LSST, SKA, JWST, etc) that all will have a tremendous impact on all the questions posed above. The coming decade promises to be transformational in the study of galaxies as testing ground of astrophysics and cosmology. Early-type galaxies in particular, because of their relative "simplicity" compared to other galaxies (e.g. spirals, irregulars), are expected to play a major role in improving our understanding of (i) structure formation in the early Universe (ETGs form at the highest-density peaks of the universe), (ii) super-massive black-hole formation and physics, (iii) dark-matter halos and mass-substructure, and (iv) the physics of dark-matter itself.

## 3. Conclusions

We are now in a golden age of studying the structure, formation and evolution of galaxies. In particular massive ETGs provide a test bed of the physics of galaxy formation, dark matter, dynamics, gravity, etc. Whereas enormous progress has been made over the last decade in these fields, we expect that the coming decades will be perhaps even more exiting. With new facilities coming online we will move from studying single ETGs to large ensembles spanning a wide range in masses, redshifts, and other properties. Dramatic improvements in theory and numerical simulations to include ever more sophisticated physics will be needed to interpret and understand the ever growing body of observational evidence. The challenge will be finding ways to implement and control all the relevant fundamental physics, tying together the small and large scales.

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