# SUMMARY OF PREVIOUS AND CURRENT RESEARCH: THE STRUCTURE AND DYNAMICS OF ELLIPTICAL GALAXIES

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## 1. Introduction

Although our understanding of elliptical galaxies has improved dramatically in recent years, there are still many important unresolved questions. Not only is their formation history uncertain, but some of their fundamental present-day properties are unknown — in particular, the shapes and radial profiles of their dark matter halos, and the phase-space distribution of their stellar orbits. I have been engaged in a series of theoretical studies using an array of modeling tools in an effort to shed light on these questions. (I am also working on a dynamical model of the Galactic center, which I will not discuss in this summary.)

## 2. Deprojection Uncertainties in Axisymmetric Galaxies

The simplest of a galaxy's intrinsic properties, its three-dimensional luminosity distribution $\nu(\mathbf{r})$, is well determined observationally only under the assumption of spherical symmetry. For an axisymmetric galaxy, there is a "cone of ignorance" in Fourier space that is not sampled in projection, so that the deprojection from the surface brightness $I(\mathbf{R})$ to $\nu$ is in general not unique (Rybicki 1987; Gerhard & Binney 1996; Kochanek & Rybicki 1996). This deprojection degeneracy increases with inclination, from the edge-on case where the solution is unique, to the pole-on case where the galaxy's vertical structure is completely undetermined. We set out to determine if a realistic galaxy could harbor significant "konus densities" (density distributions that are invisible in projection), and if so, to examine the effects on the galaxy's dynamics (Romanowsky & Kochanek 1997).

Our deprojection algorithm is fully non-parametric, and by construction guarantees the solution $\nu$ to be positive, and monotonic in the radial direction. We used both simulated and real photometry data for elliptical galaxies. We found that the deprojection uncertainty is very large, even at moderate inclinations, with a variety of smooth, well-behaved solutions for $\nu$ possible for a given galaxy image $I$; the implied konus densities typically resembled disks (see Figure 1). Assuming a constant mass-to-light ratio and a two-integral distribution function, we solved for the potential $\Phi(\mathbf{r})$ and used the Jeans equations to find the stellar velocities (radial and tangential) as a function of radius. The solutions with and without a konus disk produced very different stellar dynamics, but in projection these differences were attenuated, and were generally undetectable with typical velocity measurement uncertainties. The net conclusion is that significant dynamical subsystems can exist in early-type galaxies and leave no detectable trace on the photometry and the projected velocities.

## 3. X-ray Isophote Twists

A promising avenue for observationally determining the distribution of dark matter in early-type galaxies is by the analysis of X-ray emission from hot gas in the halo potential. Since various galaxy formation models make different predictions as to the final shapes of the dark halos, it would be useful to determine the intrinsic shapes of halos in real galaxies; in particular, how triaxial are they? A radial gradient of the triaxiality of a galaxy's potential (such as might arise from a difference in shape between the stellar and

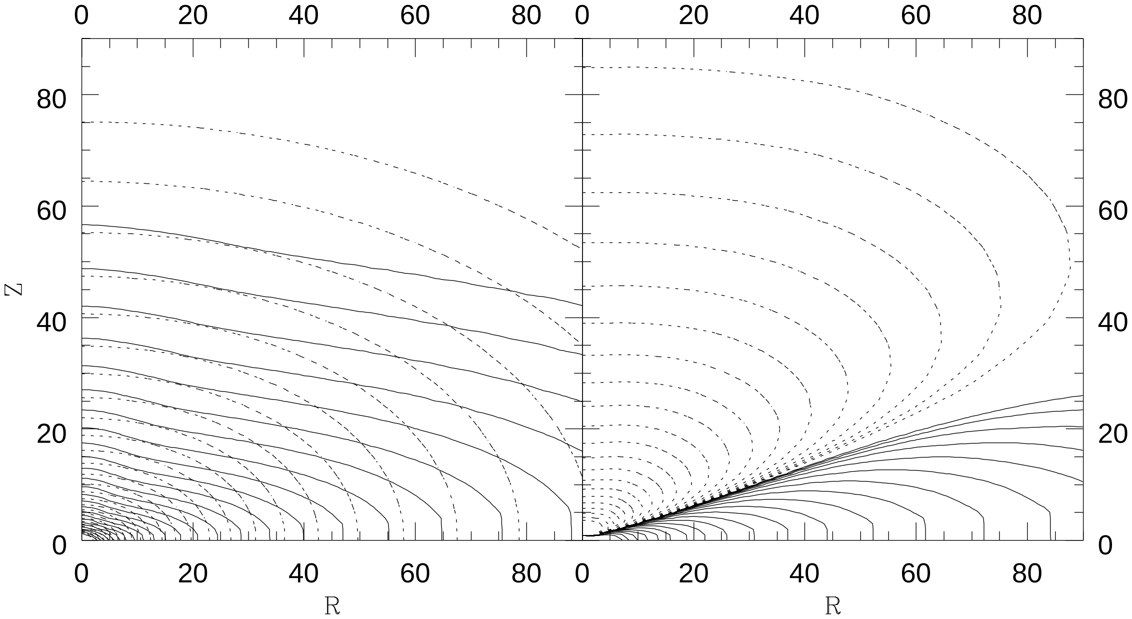


**Figure 1.**—Deprojected luminosity density $\nu$ of model galaxy image, in the meridional plane. When projected edge-on, the input $\nu$ corresponds to an E4 modified Hubble profile, with a core radius of 1.7; here the galaxy is 30° from pole-on. The contour levels are logarithmically spaced. *Left*: Input $\nu$ (*dotted contours*) and final $\nu$ solution (*solid contours*). *Right*: Contour plot of the konus density, or the difference between the final and input $\nu$. The solid contours denote positive density, and the dotted contours denote negative density.

dark matter components) can produce a radial twist in the X-ray isophotes (Binney 1978; Buote & Canizares 1996), analogous to the isophote twists seen in projected stellar light (Mihalas & Binney 1981). We have studied the characteristics of such twists in physically-motivated elliptical galaxy models (Romanowsky & Kochanek 1998).

We numerically calculated the X-ray emission from simple model galaxies with a variety of stellar and halo shapes, and found that the axes of the X-ray isophotes follow those of the projected mass to a very good approximation; most of the isophote twist occurs inside the stellar effective radius $R_{\rm eff}$. We used the shape parameters suggested by observations of stellar kinematics (Franx *et al.* 1991) and by simulations of halo formation (Dubinski & Carlberg 1991; Dubinski 1994) to predict the distribution of X-ray twists expected for a large sample of galaxies. We found that the prolateness of the halos in dissipationless simulations implies a mean total twist of 16°, while a 5° mean twist is implied by the more oblate halos in simulations that include dissipation (see Figure 2). Current X-ray telescopes do not have sufficient resolution to see such twists in galaxy cores, but one could look for misalignments between the stellar and the outer X-ray isophotes (at $\sim 3R_{\rm eff}$), and thereby constrain the galaxy formation models. We also examined the case of the elliptical galaxy NGC 720, which shows a sharp X-ray isophote twist of $\sim$ 30° at 1–2 $R_{\rm eff}$ (Buote & Canizares 1994, 1996). This twist could not be reproduced by our models, suggesting that the halo and the stars are intrinsically misaligned.

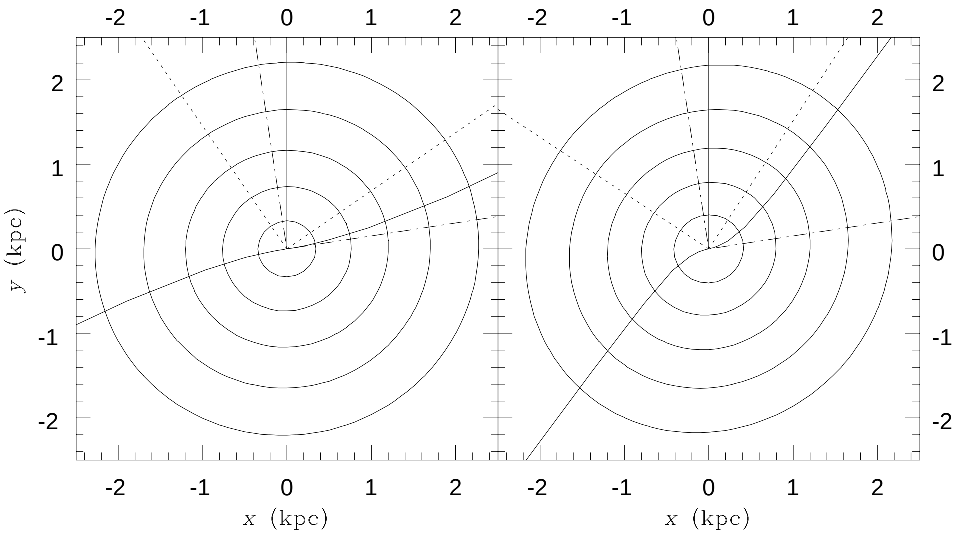


**Figure 2.**—X-ray isophotes of two model galaxies. The contours are logarithmically spaed, with central levels omitted for clarity. The major and minor axes of the projected mass are marked for the halo (*dotted*) and the light (*dot-dashed*). The kinematic minor axis is marked by a vertical solid line. The (twisting) X-ray major axis is shown by a solid line. The stellar effective radius is 5.4 kpc, and the spherical-polar projection angles are $(\theta, \phi) = (41\overset{\circ}{.}5, 22\overset{\circ}{.}5)$. *Left*: Model with halo from the dissipational scenario. *Right*: Dissipationless model.

## 4. Stellar Dynamics of Lens Galaxies

In principle, measurements of the the time delay between the images in a gravitational lens system can be used to directly determine the Hubble constant $H_0$, with none of the intermediate steps characterizing "distance ladder" approaches (Refsdal 1964). The prototypical lens system Q0957+561 has a well-measured time delay (*e.g.*, Kundić *et al.* 1997), but suffers from a "mass sheet degeneracy", where the mass in the system can be traded between the lens galaxy and the surrounding cluster — an operation that does not affect the lensing observables, but directly alters the derived value for $H_0$ (Falco *et al.* 1985). A measurement of the central stellar velocity dispersion $\hat{\sigma}_{\rm p}$ of the galaxy (Falco *et al.* 1997) could be used to independently find the galaxy mass, and thus break the degeneracy. However, numerous theoretical studies have shown that the systematic uncertainty in converting from a central $\hat{\sigma}_{\rm p}$ to a mass is enormous even for a spherical system, owing to the unknown stellar velocity distribution anisotropy (Tonry 1983; Richstone & Tremaine 1984). Previous models of this system have arrived at small systematic uncertainties in this conversion by making dubious assumptions about the anisotropy (Grogin & Narayan 1996). PG 1115+080 is the second system with a time delay (Schechter *et al.* 1997). The lens galaxy's total mass is well constrained, but not its radial profile, which again introduces a large systematic uncertainty in $H_0$ (Impey *et al.* 1998). A measurement of the galaxy's central $\hat{\sigma}_{\rm p}$ (Tonry 1998) may put useful constraints on the lens models.

We have explored the stellar dynamics of these two lens galaxies in order to set rigorous limits on $H_0$ (Romanowsky & Kochanek 1999). We used a very general spherical orbit modeling method that fits a comprehensive library of stellar orbits in a given potential to a set of stellar surface brightness and velocity data (Schwarzschild 1979; Richstone & Tremaine 1984;

Rix *et al.* 1997). The resulting orbit solutions are non-parametric, and physical by construction. As expected, the range of permitted solutions for Q0957+561 is large, resulting in a 73% uncertainty in the galaxy mass (and in $H_0$). To further constrain the mass, we placed observationally-motivated restrictions on the line-of-sight velocity distribution (LOSVD); the more extreme solutions can be ruled out by their peculiar LOSVDs. To quantify these restrictions, we assembled a sample of 28 nearby elliptical galaxies with higher-order velocity moment measurements (Bender *et al.* 1994), and created "mean profiles" of the velocity dispersion $\hat{\sigma}_{\rm p}(R)$ and the fourth-order Gauss-Hermite moment $h_4(R)$. The mean profiles are remarkably universal: the rms velocity profile is flat to $1.5R_{\rm eff}$, and the LOSVD is everywhere consistent with Gaussianity ($h_4 = 0$). Application of these profiles as constraints on the orbit model reduced the range permitted for the mass (a 16% uncertainty), which in combination with the Grogin & Narayan (1996) lens model yielded 2-$\sigma$ limits on $H_0$ of $61^{+13}_{-15}$ km s$^{-1}$. Similarly, we applied the mean profile constraints to orbit models of the PG 1115+080 lens galaxy, but found that none of the lens models (and their associated $H_0$ values) could be ruled out.

## 5. Mass Distribution and Globular Cluster Dynamics in M87

The radial distribution of dark matter in elliptical galaxies has been generally difficult to determine due to the dearth of unambiguous tracers of the potential at large radii. Observational capabilities have recently been developed to obtain large sets of velocity data for globular clusters (GCs) and planetary nebulae around nearby galaxies. Since these data can be taken at much larger radii than traditional stellar kinematic measurements, with proper modeling they are powerful tools for probing the halo potential. The nearby giant elliptical M87 (= NGC 4486) is the first galaxy to have available a large enough number of GC data to begin putting robust constraints on the halo's radial profile ($\sim$ 220 velocities; *c.f.* Merritt & Tremblay 1993).

We are constructing galaxy models to fit the surface brightness and velocity data for both the GCs (*e.g.*, Harris 1986; Lauer & Kormendy 1986; McLaughlin 1995; Mould *et al.* 1990; Cohen & Ryzhov 1997) and the stars (Caon *et al.* 1990; Lauer *et al.* 1992; van der Marel 1994; Sembach & Tonry 1996). We hope that the combination of these data over a broad radial range ($R \sim 0''$–$500''$, where $R_{\rm eff} \sim 100''$) will provide strong constraints on the dark matter distribution. We will attempt to rigorously rule out a constant mass-to-light ratio model, and we will examine the suitability of the halo profiles from hierarchical clustering simulations (*e.g.*, Navarro, Frenk, & White 1996) for describing the dark matter distribution in M87. We employ the spherical orbit modeling method described above, extending it to include the discrete velocities of the GCs. This method makes full use of the high-velocity tail of the GC LOSVD in order to probe the depth of the potential.

We will also examine the orbit structure of the globular cluster system (GCS), in search of clues to its formation history. It has long been known that the GCS of M87 has a much larger core radius than the stellar distribution, and that the galaxy has an unusually high number of GCs for its luminosity. Furthermore, there is a clear bimodal distribution of the GCs, with differing colors, metallicities, and radial distributions (*e.g.*, Lee & Geisler 1993), similar to what is seen in other galaxies (Forbes *et al.* 1997). To explain these features, there have been a variety of different scenarios proposed for GC formation, accretion, destruction, etc. (see Harris 1998 for a review). By examining separately the dynamics of the two GC subsystems, we hope to provide some insight on their formation histories, and by inference on the formation history of the galaxy itself.

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