

M/L in individual galaxies

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In this short report, I briefly review and illustrate different techniques used to derive mass (hence M/L) profiles of individual galaxies.

1 Introduction

The difficulty of determining the mass (of the stars, gas, dark matter) in individual galaxies conditions the uncertainty on the estimate of the corresponding mass-to-light ratio M/L . Various tracers have been used to probe the radial mass profiles of galaxies at scales from tens of kpc down to the inner parsec, starting with HI, ionised and molecular gas velocity curves (see Sofue & Rubin [1] and references therein), and including velocity dispersions and stellar proper motions as revealed in the Near-Infrared. High-resolution two-dimensional kinematic maps of the ionised ($H\alpha$) gas in nearby galaxies are now routinely obtained [2, 3], and used to better constrain their central mass distribution. A battery of new techniques has now been advocated as valid means for mass determination at large scales, getting help from globular clusters, planetary nebulae, satellite galaxies, or stellar streams, X ray distribution, and even lensing systems. In this short review, I illustrate a few of these techniques in turn.

2 Masses from X ray halos

The discovery of X ray halos around bright cluster galaxies led to its use as a tracer of the gravitational potential typically within 5–10 effective radii. Satellites such as ASCA and ROSAT allowed global mass measurements which confirmed the dominant role of the dark matter at these scales, and suggested a relation between the temperature of the hot gas and the central velocity dispersion of the stellar component (see [6, 7]). Such a relation led Loewenstein & White [7] to globally constrain the M/L of a sample of about 30 galaxies in clusters, implying a relatively low fraction of dark matter within $1 R_e$ of 20%, going up to 40–85% within $6 R_e$. These measurements are however conditioned by the assumption of hydrostatic equilibrium, and could be severely affected by (gravitational) perturbations in the environment of the galaxies. In order to minimise the effect of the surrounding intra-cluster medium, as well as the additional contamination from point-like sources, O’Sullivan & Ponman [4] studied the isolated elliptical galaxy NGC 4555 with the ACIS/Chandra instrument (Fig. 1), and found a large M/L_B of about 57 at 50 kpc implying a very significant fraction of dark matter.

Detailed mass profiles were subsequently derived by Fukuzawa *et al.* [8] for a sample of 53 early-type galaxies via data retrieved from the Chandra archive. They first found relatively

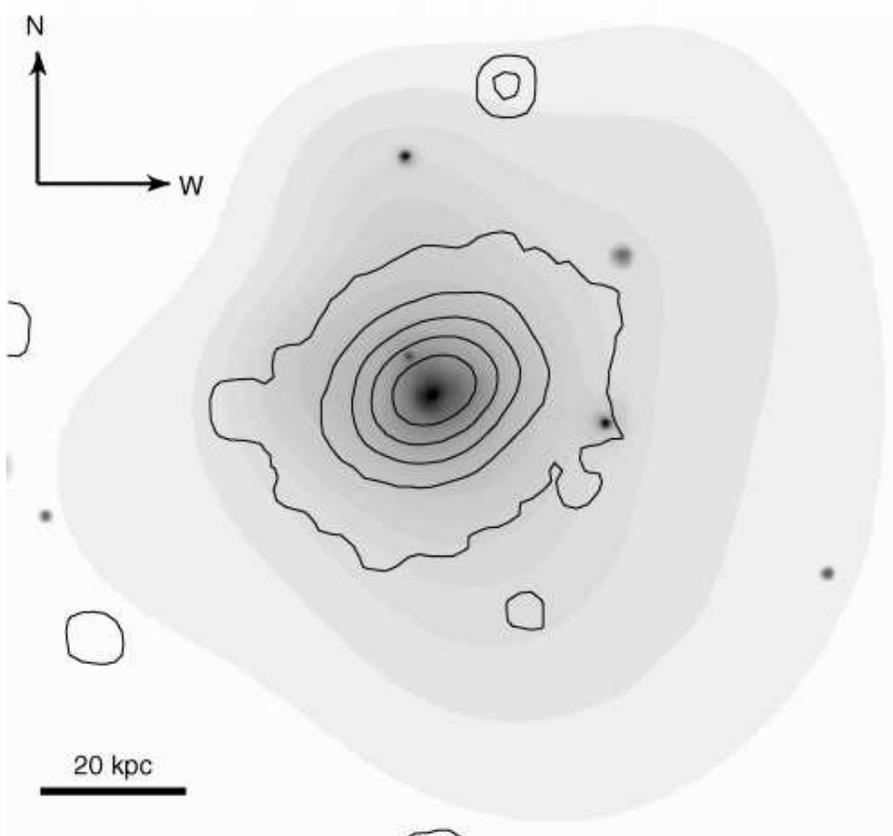


Figure 1: Smoothed X ray image of NGC 4555, with overlaid optical contours showing the extent of the stellar component of the galaxy. Extracted from O'Sullivan & Ponman [4].

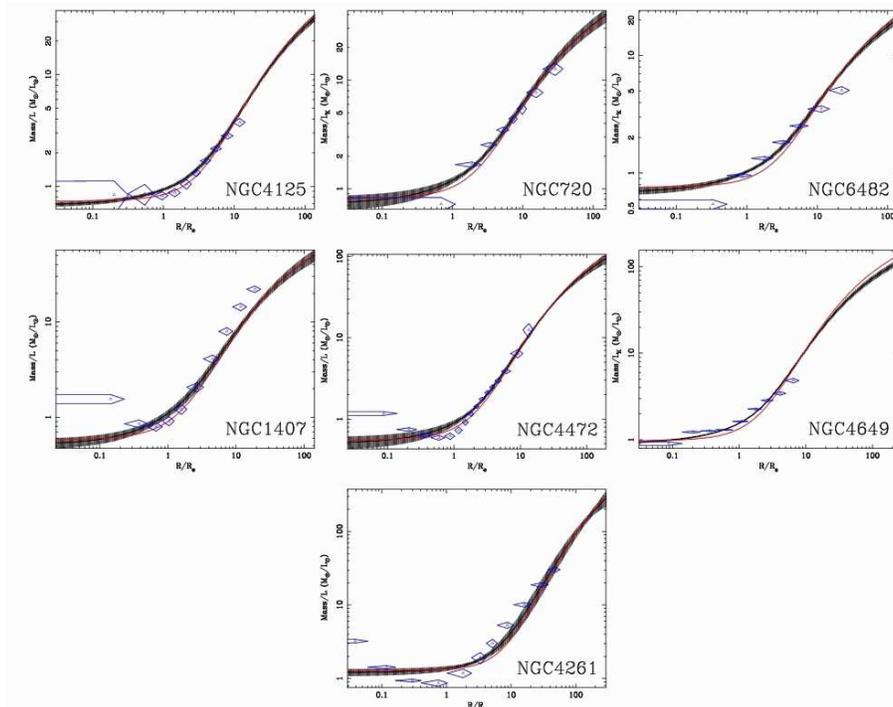


Figure 2: K band mass-to-light ratios for 7 galaxies, obtained by Humphrey *et al.* [5] via Chandra imaging . Extracted from Humphrey *et al.* [5] (see paper for details).

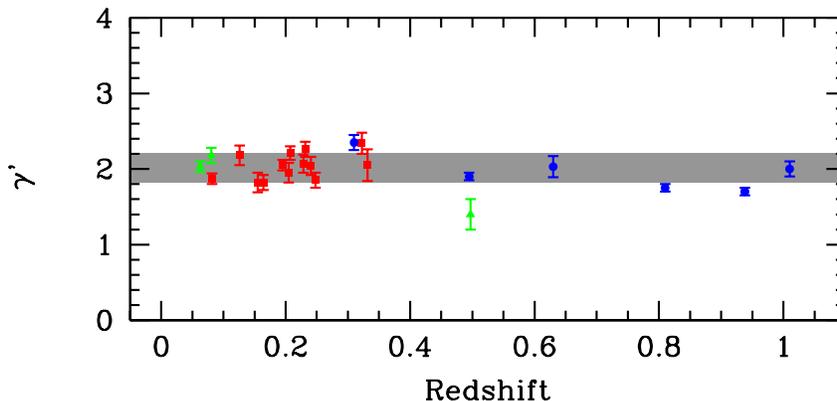


Figure 3: Logarithmic density slope γ of field galaxies plotted against redshift. The grey box indicates the rms spread of 0.19. Extracted from Koopmans *et al.* [10] (see paper for details).

good agreement with mass profiles within $1 R_e$ derived either from stellar population studies or dynamical modelling. Fukuzawa *et al.* [8] then emphasised the apparent dichotomy in the temperature profiles between X-ray luminous and dim galaxies, with the former exhibiting a temperature increasing with radius, while the latter show declining or flat profiles. The derived mass-to-light ratios seemed to be constant within the central $1 R_e$, but clearly rise up outwards (but see e.g., Pellegrini *et al.* [9]). Similar results were obtained by Humphrey *et al.* [5] for 7 nearby ellipticals, with the central M/L_K being consistent within $1 R_e$ with a Kroupa initial mass function (IMF; Fig. 2).

3 Lensing

As mentioned above, the main uncertainties in the determination of mass profiles from X ray studies result from the assumption of a spherical halo in hydrostatic equilibrium as well as from the difficulty to remove the background and point-like sources. Any technique has its own limitations, and it is therefore important to test various methods to gain confidence in the obtained results. Strong lensing is a gravitational effect and is therefore a natural path to probe mass in galaxies. This requires first accurate and high signal-to-noise imaging of the system, and usually assumes an a priori form for the underlying lens (e.g., isothermal sphere with $\rho \propto r^{-2}$). Such a technique has recently been mastered by Rusin & Kochanek [11] who used a sample of 22 lenses and the constraints provided by the fundamental plane to probe the mass profiles of early-type galaxies. As this study applies to the global sample of galaxies, it additionally assumes homology and a similar history. Optimising for the logarithmic density slope γ , Rusin & Kochanek [11] find that their sample of galaxies is better represented by nearly isothermal profiles, with an evolution of M/L_B with redshift given by $d \log (M/L_B)/dz = -0.5 \pm 0.19$, consistent with, e.g., the previous constraint obtained by van Dokkum *et al.* [12] of $-0.8 < d \log (M/L_B)/dz < -0.4$. A Salpeter IMF would then require a mean star formation redshift at $z > 1.5$.

A similar analysis but more detailed analysis was performed by Treu *et al.* [13] and Koopmans *et al.* [10] who made a joint stellar dynamical and strong lensing analysis of 15 early-type galaxies with redshift $0.06 < z < 0.33$ (Sloan Lens ACS Survey, SLACS). Velocity dispersions σ were obtained from the SDSS project, and ACS/HST data were used to derive the lensing parameters. After deriving the mass within the Einstein radius, the Jeans Equations were solved assuming isotropy and a density profile of the form $\rho \propto r^{-\gamma}$, to compare the expected dispersion with the measured SDSS values. They finally solved for the combined probability to estimate γ ,

and found slopes still consistent with isothermal spheres ($\gamma = 2$) within $R_e/2$, with no significant evolution with redshift (Fig. 3).

Weak lensing studies were also used by e.g., Hoekstra *et al.* [14], to constrain the Virial mass M_{vir} of galaxies. The measured signal probe then the average properties for a sample of relatively isolated galaxies, still allowing to examine the behaviour of mass in 7 bins of luminosity. Their results are consistent with a scaling of $M_{vir} \propto L^{1.5}$, and a lower stellar mass fraction in earlier-type galaxies.

4 Velocity profiles

One of the most standard technique for the determination of mass profiles relies on the abundant HI content of disk galaxies and its observed kinematics (see [1] and references therein). Some concerns were raised by the lack of spatial resolution in the central region which impairs the application of decomposition techniques to constrain the relative contribution of the stars, gas and dark matter. The use of H α mapping (via Fabry-Perot interferometers) seems to properly address this issue, although the complex dynamics expected in the central regions of spiral (and barred) galaxies enters then as an extra complication. A remarkable sample of 329 H α rotation curves of field spirals was obtained by Vogt *et al.* [15]. I should also mention the unique coverage of Virgo spirals conducted by Chemin *et al.* [3], which will permit a detailed study of the mass profiles as well as the impact of environment on the gas content, distribution and kinematics.

Two-dimensional maps are certainly a requirement if we wish to disentangle the global (circular?) motion from the effect of density waves. Via the combined use of high resolution ionised (H α) and molecular (CO) gas velocity fields, Simon *et al.* [16] constrained the mass variation with radius in the dwarf spiral NGC 2976. The addition of multi-colour optical and near-infrared images allowed the authors to suggest that the stellar mass fraction is relatively high in the central region, with the dark matter having then a profile shallower than $\rho \propto r^{-0.17}$, with the caveat that the obtained central M/L_K may be too low to be accounted by normal stellar populations. A similar study, but this time of a flocculent isolated spiral NGC 4414, had been conducted by Vallejo *et al.* [17], who combined high resolution CO data with extended HI rotation curve, to conclude that the mass-to-light ratio cannot be constant throughout the galaxy, but that dark matter has certainly a nearly negligible role in the central 7 kpc.

5 Bars, warps and rings

Density waves can in fact be a rather efficient tool to constrain the mass distribution in galaxies. By examining the gas response to the potential of a tumbling bar, Weiner *et al.* [18, 19] studied the pattern speed Ω_p and M/L of the bar in NGC 4123 (Fig. 4). The presence of strong shocks is clearly revealed in their Fabry-Perot H α maps and this significantly narrows down the range of allowed values for Ω_p and M/L . The study of the warp in NGC 5055 Battaglia *et al.* [20] was not as successful, as it does not seem to bring any strong constraint on the presence of dark matter in the outer part of that galaxy. This contrasts with the use of outer HI rings in early-type galaxies, as emphasised by Franx, van Gorkom & de Zeeuw [21] who showed that the gravitational potential is nearly circular in the plane of the observed ring, and that there is a significant increase of M/L with radius. A new case, namely the early-type disc galaxy NGC 2974, is now under study by Weijmans *et al.* using both HI data for the outer ring and integral-field spectroscopic SAURON data for the inner ionised gaseous component.

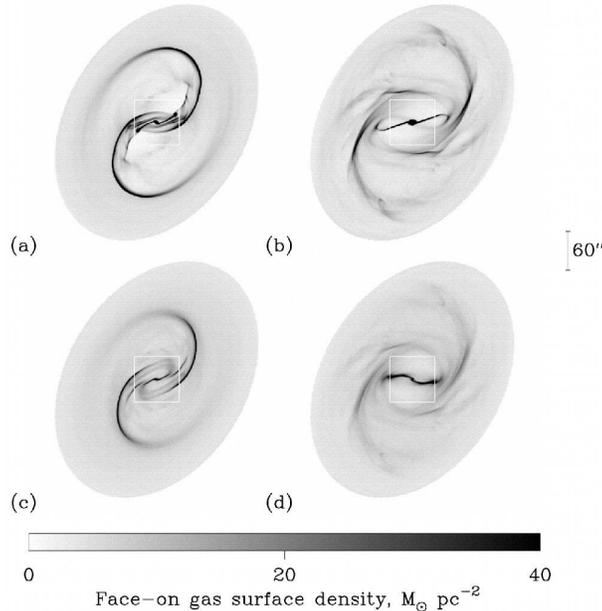


Figure 4: Gas response for different models of NGC 4123: these models are used to constrain the pattern speed of the bar as well as the mass-to-light ratio. Extracted from Weiner *et al.* (see [18] and [19] for details).

6 Stellar dynamics

Stellar kinematics has also been extensively used with the help of sophisticated dynamical models to constrain the mass-to-light ratios of nearby galaxies up to a few effective radii. The apparent simplicity implied by the extension and smoothness of the stellar component is unfortunately accompanied by the potential richness of the corresponding orbital structure. Strong assumptions on the geometry and dynamics of the systems are therefore, and once again, required to progress on this front. Even for simple spherical systems, there is a long known degeneracy between the anisotropy and the mass profile [22]. Sanchis *et al.* [23] have thus recently emphasised the importance of higher order velocity moments (and more specifically of the even moments) to break this degeneracy. Kronawitter *et al.* [24] included the velocity dispersion but also the fourth Gauss-Hermite term h_4 in their study of a small sample of early-type galaxies. Spherical models based on distribution function components showed that the M/L is increasing outwards in these galaxies with however rather standard values in the inner parts (consistent with observed stellar populations). They also convincingly showed that the derived increase in M/L is consistent with the one inferred from X ray halo studies.

The first significant attempt at deriving stellar M/L in flattened early-type galaxies was achieved by van der Marel [27], who solved the Jeans equations to model a sample of elliptical and lenticular galaxies. A clear trend of M/L increasing with luminosity was obtained, although with a relatively large scatter. The advent of more general modelling techniques, such as the Schwarzschild method [28, 29, 30] and its application to high quality stellar kinematics [31, 32, 33] led to impressive progresses in our understanding of the dynamical structure of nearby galaxies [34, 35, 26]. One nagging issue was the recurrent appearance of the degeneracy between black hole mass and M/L , clearly illustrated in the first ambitious study of this kind by Gebhardt *et al.* [34], which thus require both high spatial resolution and large-scale spectroscopic data. The even greater need for two-dimensional spectroscopy to obtain realistic models of galaxies was subsequently emphasised [36, 37]. An apparent degeneracy of the models with respect to the often unknown inclination parameter was also suggested by Krajnović *et al.* [37], the mass-to-light ratio not being significantly affected by this issue.

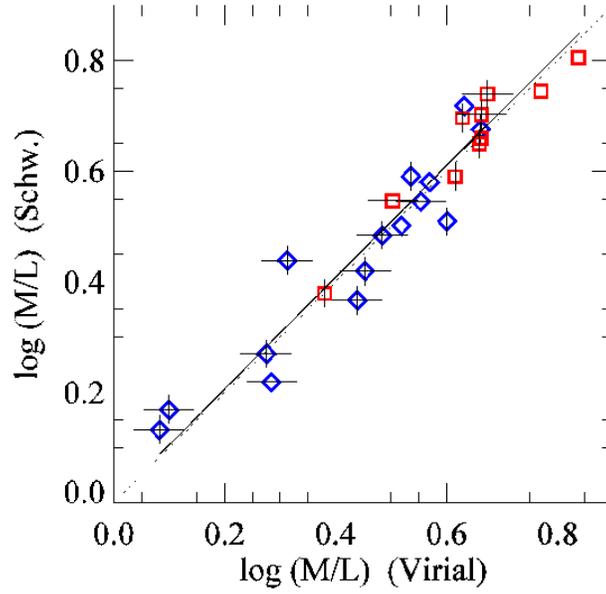


Figure 5: Dynamical M/L (as derived from Schwarzschild models) versus Virial M/L (derived from stellar kinematics) for a sample of 25 early-type galaxies obtained by Cappellari *et al.* [25]. Extracted from [25] (see paper for details).

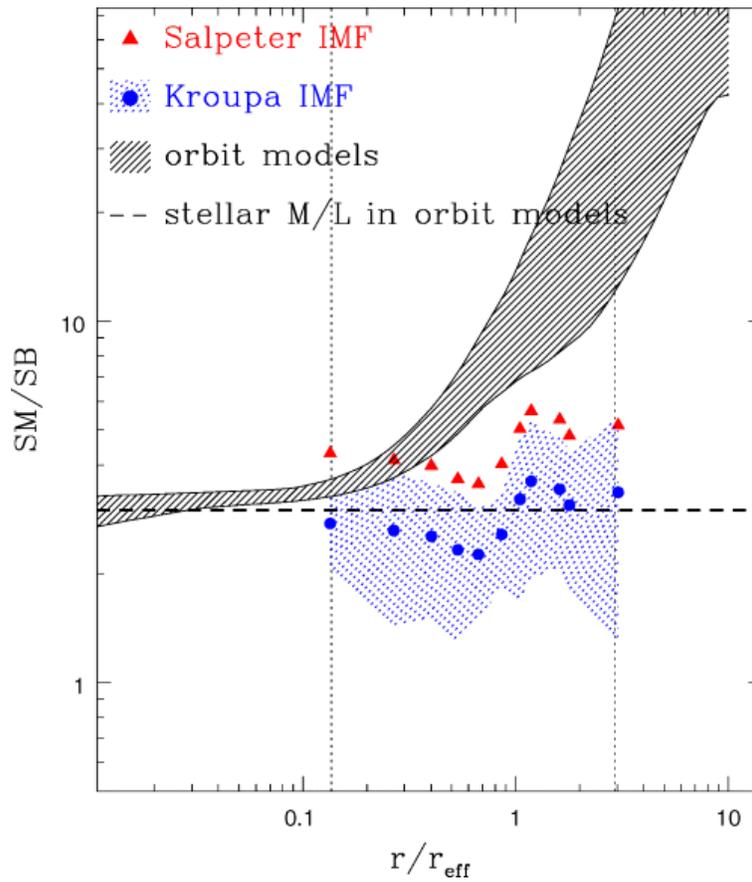


Figure 6: Surface mass versus brightness for the Coma galaxy NGC 4807 as predicted by the Schwarzschild model (grey area) and compared to the one expected from a Salpeter (red line) or Kroupa (blue line) IMF. Extracted from Thomas *et al.* [26] (see paper for details).

Following this path, Thomas *et al.* [26] obtained a rather strong constraint on the presence of dark matter at a few effective radii of the Coma galaxy NGC 4807 with an increase in M/L of more than an order of magnitude between 1 and 5 R_e (Fig. 6). The stars are, however, still dominant within 1 R_e as confirmed by Cappellari *et al.* [25] using state-of-the-art Schwarzschild models and integral-field data. This work also showed that the maximum contribution from non-homology of early-type galaxies to the tilt of the fundamental plane is about 6%, as the dynamical M/L (from dynamical models) and the M/L derived from the Virial theorem (as predicted using the stellar kinematic maps) agree amazingly well with each other (Fig. 5). This suggests that the tilt of the FP is dominated by a true variation of the M/L from galaxy to galaxy. A comparison of the dynamical M/L and the stellar M/L (obtained via stellar line indices) finally suggests that massive slowly rotating galaxies have a larger fraction of dark matter than fainter ones, with an upper limit of about 30% within 1 R_e [25].

7 The vanishing

Romanowsky *et al.* [38] recently probed the outer regions of NGC 3379 up to 3 R_e using the Planetary Nebulae Spectrograph finally concluding that dark matter was not required to reproduce the radial dispersion measurements. This result was severely questioned by Dekel *et al.* [39], who reminded us of the density/anisotropy degeneracy. They showed that a bias towards radial stellar orbits may be naturally expected at a few effective radii, which would produce a dispersion profile similar to the one observed in NGC 3379 even though the mass profile is dominated by dark matter. A recent, but still preliminary, measurement of the stellar velocity dispersion at $\sim 3R_e$ using the SAURON spectrograph by Weijmans *et al.* indicates that the bulk stellar population has in fact a rather constant dispersion profile, which would, if confirmed, favour the presence of a significant amount of dark matter, and reveal a significant discrepancy between different tracers.

8 Satellites, X-ray binaries and stellar populations

By studying the dynamics of small satellites around larger galaxies it is in fact possible to restrict the allowed parameter space for a set of mass models. This was achieved for the Andromeda galaxy by Geehan *et al.* [40] who analysed the stellar streams around M 31 and found a rather normal M/L for its disc and bulge. The original approach of Dehnen & King [41] included the study of the motions of 5 X-ray binaries (LMXB) detected in the Sculptor dwarf spheroidal. The rare occurrence of such binaries suggests that Sculptor must have retained all its LMXBs. Taking into account a visible mass of $10^7 M_\odot$, and a measured stellar velocity dispersion of only 11 km.s^{-1} , the mass distribution of Sculptor should be dominated by a dark halo of $10^9 M_\odot$ within 1.5 kpc, which would imply a total M/L of at least a few hundreds. This tentative result is one of the very few constraints we have on the mass distribution of dwarfs, but we should realise that it will be a challenge to confirm the assumptions on which it is based.

I should add the mention of two recent illustrative works where stellar mass-to-light ratios of nearby dwarfs were derived via spectral line indices [42, 43]. Central counter-rotating cores were revealed in both NGC 770 [42] and VCC 510 [43], their spectral signature and stellar synthesis models indicating metal poor nuclei, the possible remnants of a merger/accretion event.

I will finally end up with a brief word on Modified Newton Dynamics (MOND). Apart from the fruitful debate it triggered^a, MOND is at least useful for one purpose: as emphasised by McGaugh [44], it proposes that we should view the mass discrepancy in the outer parts of galaxies as an empirical relation. This empirical relation is a very useful "tracer", which can

^aA personal opinion, obviously

then be analysed in the light of stellar population models, dark matter, MOND or any preferred prescription.

9 Brief conclusions

Baryons seem to dominate the central parts of galaxies (within 1–2 R_e), probably even in dwarfs, and stellar mass-to-light ratios are consistent with the dynamical estimates in these regions. The mass discrepancy increases outwards, which suggests the presence of dark matter, including in early-type galaxies. The outer mass profiles are roughly consistent with NFW profiles, but these seem to fail to reproduce the central, shallow, density slopes.

Each technique mentioned above represents one path to the determination of mass profiles in individual galaxies. They all have their own specific (nagging) issues, and include many geometrical, physical, numerical assumptions which should be carefully examined in turn. As emphasised, point-like sources, background flux, counts and the assumption of hydrostatic equilibrium have to be considered when using X-ray spectroscopy and imaging. Strongly lensed systems are rare, and biased toward "relatively" high redshifts and large masses. HI, H α , and CO are clearly complementary, but we always need to examine large-scale perturbations, as well as the assumptions we make on the gas dynamics. Outer gas rings are efficient tools in this context but only probe the potential locally, and are, unfortunately, very rare. Density waves such as bars, spirals and warps are good tracers of the dynamics of the system (hence of its mass), but may not bring very strong constraints, and are usually restricted to the central regions. Stellar dynamics is complex and require state-of-the-art modelling with well tuned assumptions. Still, degeneracies exist which may sometime blur the robustness of the results. Tracers such as planetary nebulae, globular clusters or streams are obvious targets, but it is not clear if these are effectively good tracers and if basic assumptions such as stationarity can be applied. Finally M/L derived from stellar populations is probably the least robust parameter provided by spectral synthesis models, although we witness steady progress there. More generally, I think we can be relatively optimistic as we today follow the advent of new instruments, techniques, and numerical codes which clearly address the issues mentioned here. We then need to find out if such vastly different approaches deliver consistent answers when probing the same mass regimes.

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