Near-Field Cosmology with Dwarf Elliptical Galaxies
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Kinematics and M/L ratios of dwarf spheroidals

N.W. Evans[1], M.I. Wilkinson[1], J.T. Kleyna[2], J.I. Read[1] and G. Gilmore[1]

[1]Institute of Astronomy, Madingley Rd, Cambridge, CB3 0HA, UK
[2]Institute for Astronomy, 2680 Woodlawn Drive, Honolulu, Hawaii 96822-1897, USA

Abstract. Recent results on the kinematics of the Draco and Ursa Minor dwarf spheroidals are reviewed.

1. Introduction

This subject has its genesis in a remarkable paper by Aaronson (1983), in which he measured the radial velocities of just 3 carbon stars in the Draco dwarf spheroidal (dSph) and used simple modelling to infer the presence of huge amounts of dark matter. The subject has blossomed in recent years because the radial velocities of hundreds, perhaps thousands, of giant stars in the nearby dSphs are now accessible with multi-object spectrographs on 4m and 8m class telescopes. The run of velocity dispersion with radius has now been mapped out for 5 of the Galactic dSphs – namely Fornax, Draco, Ursa Minor, Sculptor and Sextans (Mateo 1997; Kleyna *et al.* 2002, Wilkinson *et al.* 2004, Tolstoy *et al.* 2004, Kleyna *et al.* 2004). Estimates of mass-to-light ratios (M/L) confirm Aaronson's original finding that many of the dSphs are highly dark matter dominated. For example, Aaronson in 1983 found $M/L \sim 30$ in solar units for Draco, Mateo's review in 1998 quotes $M/L \sim 100$, while Kleyna *et al.* (2002) find $M/L \sim 440$. Understandably enough, the M/L ratio has increased, as more and more of the dSph dark halo is probed by discrete radial velocities.

There are 11 low luminosity Galactic dSph satellites (see e.g., Mateo 1998). This paper examines just two of them – Draco and Ursa Minor. They should look like twins, as they have a similar luminosity ($L \sim 10^5 L_\odot$), a similar size ($\sim 1°$), a similar central velocity dispersion ($\langle v^2 \rangle^{1/2} \sim 10$ kms^{-1}) and a similar heliocentric distance (~ 70 kpc). But, they actually look very different! Draco has a smooth, round appearance with regular isophotes and a simple stellar population. Ursa Minor has a highly distorted, irregular appearance with elongated isophotes. It has a secondary clump of stars offset from its centre and discernible in the photometry. The recent years have seen the velocity dispersion profiles of both Draco and Ursa Minor mapped out, and their M/L ratios reliably measured. Recently, Wilkinson *et al.* (2004) have reported the existence of kinematically cold populations at large radii in both the Draco and Ursa Minor dSphs. Both galaxies apparently exhibit a sharp decrease in the projected velocity dispersion at large radii. This result remains controversial and the basis of its validity will be examined here.

2. The Draco dSph

After Aaronson's pioneering paper, important work acquiring samples of radial velocities of giant stars was carried out by Armandroff, Olszewski & Pryor (1995) and

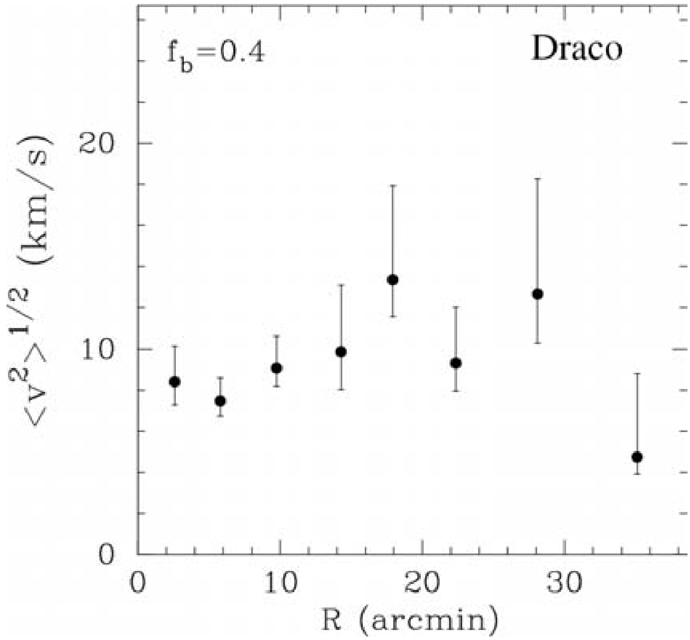

Figure 1. The variation of line-of-sight velocity dispersion with projected distance for the Draco dSph. The error bars denote 1σ uncertainties. A binary fraction $f_b = 0.4$ is assumed. [From Wilkinson *et al.* 2004]

Hargreaves *et al.* (1996). Recently, Wilkinson *et al.* (2004) used the multifibre instrument AF2/WYFFOS to observe the Draco dSph on the *William Herschel Telescope.* They drew Draco targets from the Sloan Digital Sky Survey, identifying candidates by drawing a polygon around the giant branch of a $V, V-I$ colour-magnitude diagram with a faint magnitude limit of $V < 20$. The data were reduced and cross-correlated with the two blue-most lines of the Calcium triplet, in the same manner as described by Kleyna *et al.* (2002). The final dataset contained 114 velocities within 30 kms^{-1} of Draco's mean velocity. The union of this dataset with the earlier ones of Kleyna *et al.* (2002) and Armandroff *et al.* (1995) has 207 unique objects with good velocities. A plot of the radial variation of the line of sight velocity dispersion $\langle v^2 \rangle^{1/2}$ derived from this data is shown in Figure 1. The dispersion is flattish out to about $30'$, but then drops at larger radii. The 30 kms^{-1} membership limits for Draco are fixed assuming that the dSphs' velocity distribution is Gaussian with a dispersion (including measurement error) of ≈ 10 kms^{-1}. Under these assumptions, less than one genuine Draco member is discarded by imposing a 30 kms^{-1} cut-off, with the possible exception of extreme binaries.

There are a number of ways to model the data. The simplest is to use the Jeans' equations to compute the underlying dark matter mass distribution, given the surface brightness and the velocity dispersion (Wilkinson *et al.* 2004). More rigorously, the phase space distribution function of a parameterised model can be convolved with the measurement errors and the binary velocity distribution to construct the likelihood of observing the data (Kleyna *et al.* 2002). Either way, the most likely mass interior to $\sim$600 pc is $\sim 8 \times 10^7 M_\odot$ (range $6.1 - 11 \times 10^7 M_\odot$), while the mass-to-light ratio is 440 (range $340 - 610$) in solar units for the V band. These results are insensitive to the fraction of binaries. The data can also be used to investigate the feasibility of Modified Newtonian Dynamics (MOND) by solving the Jeans equations with the MOND force terms. Even the 3σ lower limit of the MOND mass to light (M/L) ratio still requires some dark matter

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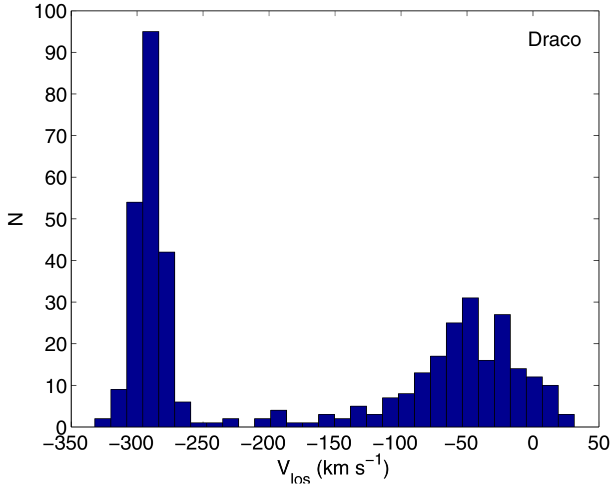

Figure 2. Histogram of the radial velocities of all the Draco candidates. Notice the sharp peak at Draco's mean velocity of -291 kms^{-1}, together with a ragged tail of Galactic foreground stars.

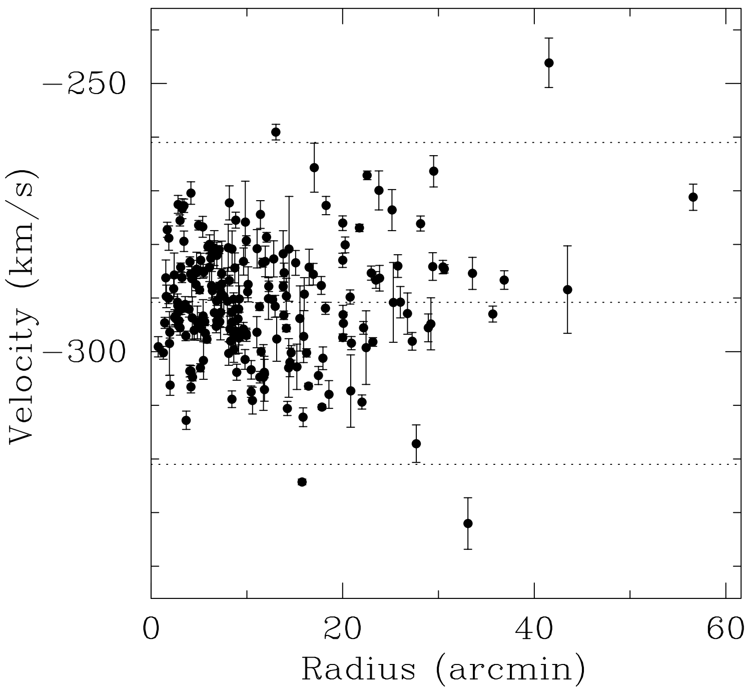

Figure 3. The radial velocities of all candidates, plotted against projected distance from the centre of the Draco dSph. Dashed lines show the 3σ velocity cut applied as a membership criterion, as well as the mean velocity of Draco.

to bring it into agreement with estimates based on Draco's stellar population (Kleyna *et al.* 2001). The conclusion is that MOND seems difficult to reconcile with the internal kinematics of dSphs.

One assumption that is open to criticism is the restriction of Draco membership to stars within 30 kms^{-1} of the mean. The radial velocities of the combined dataset, together with

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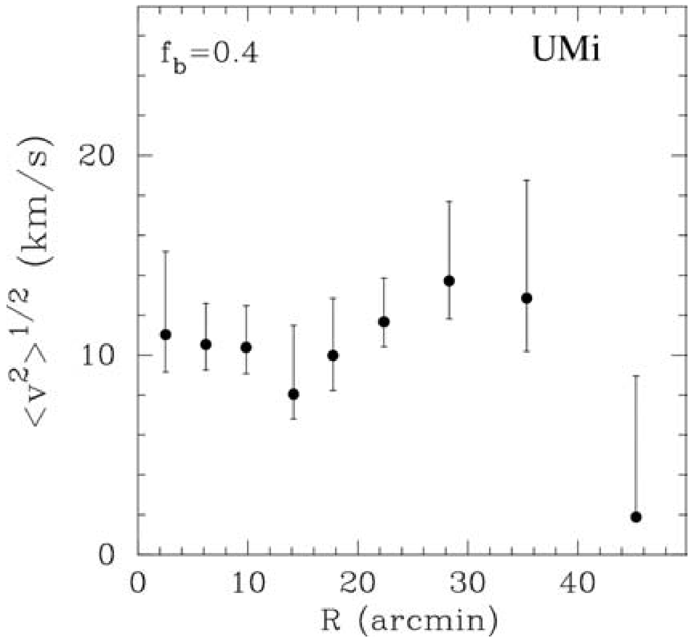

Figure 4. The variation of line-of-sight velocity dispersion with projected distance for the Ursa Minor dSph. The error bars denote 1σ uncertainties. A binary fraction $f_b = 0.4$ is assumed. [From Wilkinson *et al.* 2004]

those original Draco candidates removed by the velocity cut, are shown in Figure 2. Here, we see a sharp peak at the mean velocity of Draco (-291 kms^{-1}), together with the much broader distribution of contaminating Galactic stars, whose long and ragged tail reaches right up to the Draco peak. The velocity dispersion of Galactic halo stars is $\sim$120 kms^{-1}, and so Galactic contaminants are possible with radial velocities close to those of Draco's stars. Another way of visualizing the same data is shown in Figure 3, which plots radial velocities versus projected distance from Draco's centre. The membership criterion is $-261 < v < -321$ kms^{-1}. There are 4 stars just outside this region, which Wilkinson *et al.* (2004) exclude from Draco membership.

Recently, Lokas *et al.* (2005) have argued that the number of Galactic interlopers with Draco-like velocities is negligible. This result is obtained by running the Besancon Galaxy model (Robin *et al.* 2003) in the direction of Draco. However, the Besancon model is built from a number of smooth components and therefore neglects any possibility of halo substructure. The Besancon model was not designed to work in this regime and underpredicts the population of intervening stars. For example, it forces us to conclude that all the stars in Figure 2 with a radial velocity < -150 kms^{-1} belong to Draco. This includes stars that are some 15σ away from Draco's mean velocity!

3. The Ursa Minor dSph

Kleyna *et al.* (2003) and Wilkinson *et al.* (2004) used Kitt Peak 4m MOSAIC imaging to find candidate giant stars in the Ursa Minor dSph, for which they subsequently obtained AF2/WYFFOS spectroscopy. This yielded 143 stars within 30 kms^{-1} of the mean velocity of Ursa Minor ($\sim$$-245$ kms^{-1}. Forty-five of these objects are also present in the earlier dataset of Armandroff *et al.* (1995) and the union of these two datasets has 160 stars. A plot of the radial variation of the line of sight velocity dispersion $\langle v^2\rangle^{1/2}$

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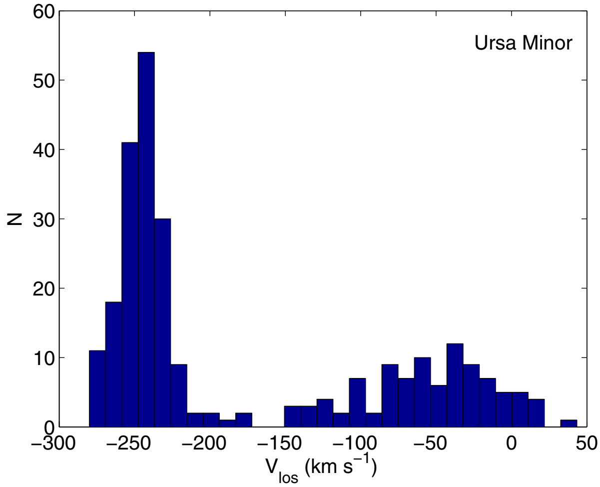

Figure 5. Histogram of the radial velocities of all the Ursa Minor candidates. There is a strong peak around Ursa Minor's mean velocity of −245 kms^{-1}, with a highly distended wing in the direction of Galactic contamination.

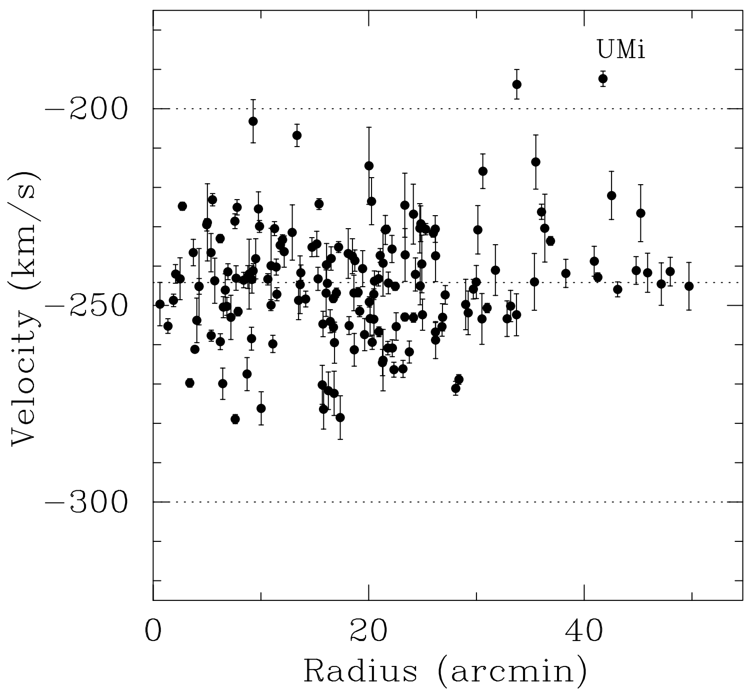

Figure 6. The radial velocities of all candidates, plotted against projected distance from the centre of the Ursa Minor dSph. Dashed lines show the velocity cuts applied as a membership criterion, as well as the mean velocity of Ursa Minor.

derived from this data is shown in Figure 4. The dispersion is flattish out to about 35′, but then falls very sharply at larger radii. The most likely mass interior to ∼600 pc is $\sim 2 \times 10^8 M_{\odot}$. Flattening and velocity anisotropy cause this number to be uncertain by at least a factor of 2. The mass-to-light ratio is ∼250 in solar units for the V band.

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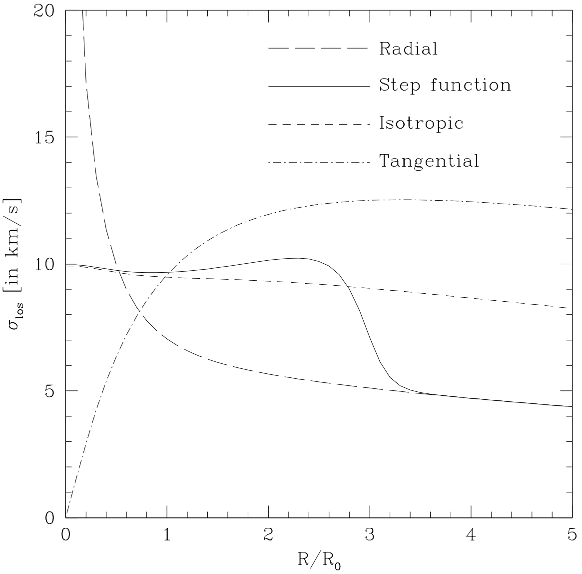

Figure 7. Line of sight velocity dispersion for a Plummer light profile in a dark matter halo assuming 4 different velocity anisotropy laws. Notice that even an extremely sharp change in the velocity ansiotropy does not permit the observable dispersion to fall to zero. [From Wilkinson *et al.* (2004)]

A remarkable discovery is the finding of a distinct, kinematically cold population centered on the secondary clump of stars visible in the surface brightness map. The stars in the clump comprise a kinematically distinct cold sub-population. This may be the residue of a disrupting star cluster, orbiting within the potential of a dark matter halo. However, such a clump can persist for a Hubble time only if the potential is near-harmonic. A cusped halo would destroy the clump within 1 Gyr (Kleyna *et al.* 2003, Wilkinson *et al.* 2005).

Let us return to the question of the velocity cuts which restrict Ursa membership in these studies. Figure 5 shows a histogram of the radial velocities of the combined dataset, together with those original Ursa Minor candidates removed by the velocity cut. There is a sharp peak at the mean velocity of Ursa Minor (-245 kms^{-1}). The wings are asymmetric and soiled with Galactic contaminants. Figure 6 plots radial velocities versus projected distance from Ursa Minor's centre. This shows an impressive bunching of radial velocities about the mean in the outer parts. Of the 12 most distant stars, 9 are within 5 kms^{-1} of the mean. It is this that causes the velocity dispersion to fall so dramatically. There are two stars on this plot presently excluded from Ursa membership and so lying above the dashed line. One of these stars would indeed contribute to the low outermost velocity dispersion datapoint in Figure 4. Should this star be included? If it were included, then the velocity distribution in the outer parts is very strange with a cold dominant population and a much sparser, very hot population.

The problem of separating Galactic contaminants from dSph members is the crucial one – and a difficult one – to solve. It may be that a larger sample of radial velocities of distant dSph stars will provide a clearer picture of the velocity distribution. However, it may be that high quality spectra of the problematic stars, from which metallicities can be extracted, will be needed to establish an unambiguous dSph or Galactic origin. A program to acquire these with HIRES on the *Keck Telescope* is already underway.

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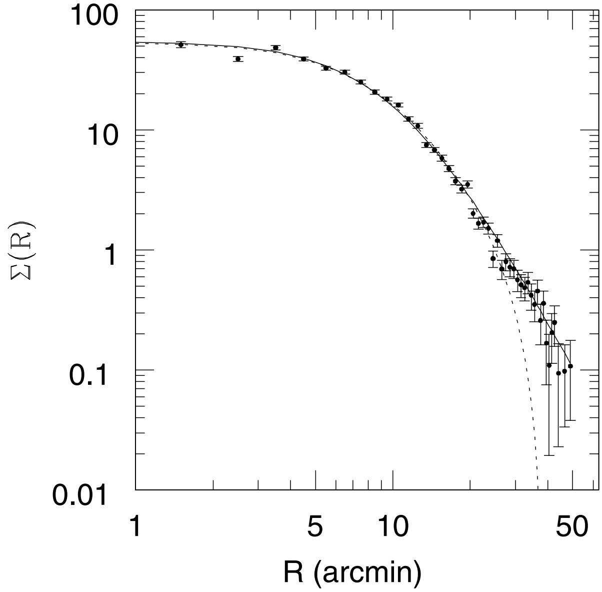

Figure 8. Azimuthally-averaged surface brightness profile of Draco based on imaging data taken with the INT, corrected for the effects of variable extinction. The solid and broken curves show the best-fitting Plummer and King profiles to the data within 25′, respectively. [From Wilkinson *et al.* (2004)]

4. Kinematically Cold Populations

Taking the decline in velocity dispersion at large radii in Figures 1 and 4 at face value, we can ask if there are any simple explanations. It is straightforward to show that no isotropic model can reproduce the fall. A sharp change in the velocity anisotropy from isotropy to radial anisotropy in the outer parts is perhaps possible. This is illustrated in Figure 7, in which the Jeans equations have been solved for a dSph light distribution in an isothermal dark halo assuming different velocity anisotropy laws. Even if a step function is used to change the anisotropy from the isotropic model to the extreme radial orbit model, then the velocity dispersion falls – but perhaps not as abruptly as the last Ursa Minor datapoint in Figure 4. However, the error on this last datapoint is substantial and so this explanation remains feasible.

A sharp edge to the light distribution is another possible cause of a falling velocity dispersion. If the stellar light ends abruptly at r_t, then the velocity dispersion behaves like $\langle v^2 \rangle^{1/2} \sim (r_{\rm t} - R)^{1/2}$ irrespective of whether the dark halo continues through $r_{\rm t}$. A natural explanation for the break in the light is tides produced by the Milky Way. Both dSphs are sufficiently massive that their current tidal radii lie well outside their mass distribution. However, for Draco, a sharp edge to the stellar distribution seems at first sight inconsistent with the photometry.

Figure 8 shows the azimuthally averaged surface brightness profile of Draco based on deep imaging with the *Isaac Newton Telescope*. This has been corrected for the effects of variable extinction using the reddening map of Schlegel *et al.* (1998). In contrast to earlier light profiles – such as those deduced by Odenkirchen *et al.*(2001) from Sloan Digital Sky Survey observations – this shows a break in the light profile of Draco at ∼25′. The light profile of Ursa Minor is already known to possess a similar feature (Palma *et al.* 2003) at about 34′. However, we can associate a tidally-limited model with both dSphs provided

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the excess of stars at $R \sim 25'$ is interpreted as an extra-tidal (and possibly unbound) population. For consistency with the kinematics, though, this population is being missed.

Another possibility is that Draco and Ursa Minor might contain multiple kinematic populations: a hot, inner "bulge-like" component and a cold, outer "disk-like" component. It is possible that the weak age gradients seen in Ursa Minor and the differences in the spatial distributions of Blue and Red Horizontal Branch stars in Draco may indicate more than one old population, which, if they have different kinematics, may offer a possible explanation.

5. Conclusions

There has been substantial progress over the last few years in mapping out the variation of velocity dispersion with radius in the dSphs. This has provided clear evidence for the existence of extended dark matter haloes in these systems. The future looks bright, with large-scale programs to survey the nearby dSphs on the VLT already underway (e.g., Koch *et al.*, 2005). This will enable both the metallicity and the kinematics of the dSphs to be simultaneously studied.

The behaviour of the velocity dispersion at large radii in the dSphs is controversial. Feynman's Law, as recounted in "Surely You're Joking, Mr Feynman", clearly applies:

'*You see, it all depended on one point at the every edge of the range of the data, and there's a principle that a point on the edge of the range of data – the last point – isn't very good, because if it was, they'd have another point further along. And the whole theory was based on the last point, which wasn't very good and therefore it's not proved.*

Although the methods used for assessing the membership of the Draco and Ursa Minor dSphs seem very reasonable, the final reckoning must await further datapoints!

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