Implications for dwarf spheroidal mass content from interloper removal

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21 July 2009

ABSTRACT
We use Diaferio (1999)'s caustic method to identify the member stars of five dwarf spheroidal (dSph) galaxies of the Milky Way, the smallest dark matter (DM) dominated systems in the Universe. We show that, after successful rejection of interlopers, the line-of-sight velocity dispersions are substantially smaller than previous calculations. With this, we use Jeans modelling to show that the DM content interior to 300 pc appears to increase with satellite luminosity. Moreover, if we assume that MOND provides the true law of gravity, a correct identification of interlopers implies that these dSphs have reasonable values for their mass-to-light ratios, alleviating one of the claimed problems of MOND.

1 INTRODUCTION
Impressive observations by Walker et al. (2007) and Mateo et al. (2008) have accurately catalogued thousands of stars in the vicinity of the eight classical dwarf spheroidal galaxies (dSphs) of the Milky Way. By binning these line-of-sight (los) velocities as a function of projected radius and by computing the root mean squared (RMS) velocity within each bin, it is possible, through Jeans analysis, to reconstruct the mass profile with considerably less uncertainty than with only central los velocity dispersions.

By fitting mass models to these and to the ultra-faint dSphs that were discovered with the aid of the SDSS survey, Strigari et al. (2008) have proposed that the mass within 300 pc of every dSph galaxy, over four orders of magnitude in luminosity, lies in a small range near $10^7 M_\odot$.

This result is at odds with the naive expectation that more luminous galaxies reside in more massive halos; one therefore needs to conclude that the Strigari et al. (2008) result is of some fundamental significance to the dark matter particle which creates the halos at high redshift, in which the dSph galaxies form, or to feedback processes which control star formation.

Several other analyses have been made that rely on the los velocity dispersions, for instance the calculation of the dSph mass-to-light ratios $M/L$ (the only truly free parameter) in Modified Newtonian dynamics (MOND) by Angus (2008) and the mass modelling performed by Walker et al. (2009).

An issue may exist with these studies because they depend crucially on the dSph (and all the stars within the projected tidal radius) being in virial equilibrium, except for some very obvious field stars which can and have been rejected. In general, there is no concrete way to know if a star is bound to the dSph or not. This is especially true of the cold dark matter (CDM) paradigm, since in principle we can have any density profile of dark matter halo which can simply be increased to accommodate a fast star. Nevertheless, a re-analysis of the SDSS discovered dSphs Segue I (Niederste-Ostholt et al. 2009) and Hercules (M. Wilkinson, private communication), that has been performed with alternative techniques to the one presented here, has demonstrated that neither of these two ultra-faint dSphs are as massive as previously thought, and unbound stars are frighteningly common.

The point is that if the bound stars have RMS velocities of $\sim 10 \, \text{km} \, \text{s}^{-1}$ and just a few unbound stars have velocities of (for instance) $\sim 20 \, \text{km} \, \text{s}^{-1}$, the unbound stars dominate the combined RMS velocity. Since in Newtonian dynamics galaxy mass is proportional to the second power of the velocity dispersion (and to the fourth power in modified dynamics) it is absolutely critical to make sure the stars used in the Jeans analysis are bound.

This is contrary to the mass modelling of spiral galaxies and clusters of galaxies. For instance, the masses of spiral galaxies are usually measured from the velocities of the neutral hydrogen gas which is forced to be on circular orbits and tidal features would leave very obvious signatures. For one thing, escaped gas along the los would have a totally different density to the gas inside the galaxy. Secondly, warps are relatively easy to identify in gas, but not from discontinuous stars.
The same is true for clusters of galaxies where the mass is inferred from the measured temperature and density of the X-ray emitting plasma. Furthermore, cluster masses can be measured with gravitational lensing (e.g., Clowe et al. 2006) or the caustic method (Diaferio & Geller 1997; Diaferio 1999), which both ignore the state of equilibrium.

Another important consideration is that the central regions of clusters are tidally influenced only slightly by their surroundings, both because of their mass dominance and the time scales involved. Similarly, most spirals exist blissfully in the field: consider even the "high density" of the local group spirals. At the opposite end of the spectrum, dSphs are in close proximity to their hosts (∼100kpc) and the tidal field is rapidly changing as their orbits are shorter (∼100Myr). Furthermore, the dSphs are extremely low surface brightness and extended, as opposed to the globular clusters, their counterparts in mass and position.

As mentioned above, there is a method called the caustic technique which utilises the three known phase-space coordinates to delineate caustics in the los velocity-projected radius diagram which enclose the bound stars. Although the caustic technique was originally designed to study the mass profiles of galaxy clusters beyond the virial radius (Diaferio 2009), it can also function as an interloper identifier. This actually works independently of the gravity theory because the caustics are basically escape velocity curves and are generated in response to the proximity of stars to each other in the los velocity-projected radius diagram. Of course, in Newtonian gravity, this can be related to the enclosed mass, but it can also be used to confirm if stars are bound.

This is of particular significance for the ultra-faint dSphs because lack of stars, greater susceptibility to tides and more severe impact of interlopers aggravate the problem, but in contrast to the ultra-faint dSphs, the classical dSphs have a highly statistically significant number of stars, which the caustic technique requires to operate effectively.

After we have the confirmed stars as members, we can recompute the los velocity dispersion as a function of projected radius and perform our Jeans analysis in both MOND (to check whether the M/Ls are consistent with the stellar populations) and in Newtonian dynamics to investigate the claim that the mass within a radius of 300 pc is similar for every dSph.

Here we make use of the recently published data collected by Walker et al. (2009b) for Sculptor, Fornax, Carina and Sextans, as well as Leo I from Mateo et al. (2008).

2 CAUSTIC METHOD

The caustic technique (Diaferio 1999) was originally used to identify galaxy members and compute mass profiles in clusters of galaxies, from the central region to beyond the virial radius. This technique has proven to be very effective in estimating the mass profiles of galaxy clusters from N-body simulations, independently of the dynamical state of the cluster. Considering that the technique can identify members in potentially any system, we have modified it to be used for interloper removal in dSphs. The principle is the same, i.e., from the velocity diagram (los velocity vs. projected radius to the centre), the technique locates the curve which represents the escape velocity of the system. Therefore, the stars within these caustics are members of the system and they can be used to calculate the velocity dispersion profile.

In the velocity diagram of an astrophysical system, the components populate a region whose amplitude decreases with increasing r. This amplitude A has been identified by Diaferio & Geller (1997) with the escape velocity along the line of sight, i.e., $A^2(r) = \langle v^2_{\text{esc,los}} \rangle$. To locate the caustics, it is necessary to determine a set of candidate member stars of the dSph. These stars will provide a centre, a size and a value for the los velocity dispersion, once they have been arranged in a binary tree (Figure 1), according with their pairwise energy

$$E_{ij} = -G \frac{m_i m_j}{R_{ij}} + \frac{1}{2} \frac{m_i m_j}{m_i + m_j} (\Delta v)^2 .$$

In this expression $R_{ij}$ is the projected separation on the sky between the stars $i$ and $j$, $m_{i,j}$ are their masses, $(\Delta v)$ is their los velocity difference and $G$ is the gravitational constant.

In the following, we assign the same mass to every star. Therefore the tree automatically arranges the stars in potentially distinct groups with a single parameter only, the star mass. To get effectively distinct groups and to specifically define the set of candidates, we need to cut the tree at some level. This level sets the node from which the candidate members are hanging. The level is defined by the "σ plateau" extreme closer to the root, as described below.

2.1 σ plateau

We can identify the main branch of the binary tree as the branch that emerges from the root and follows the nodes from which the largest number of leaves hang (highlighted in Figure 1). Following the main branch of the tree, from the root to the leaves, the los velocity dispersion $\sigma_{\text{los}}$ of the stars hanging from a given node $x$ initially decreases rapidly. It then reaches a long plateau and again rapidly drops towards the end of the walk (Figure 2). The plateau indicates the presence of a nearly isothermal system and the nodes $x_1$ and $x_2$ (where $\sigma_{\text{los}}$ abruptly changes its slope) are good candidates for the system/substructure identification. The σ plateau only appears when the stellar mass $m$ in eq. 1 lies within a proper range $[m_1, m_2]$, which depends on the dSph considered. In fact, each star is a tracer of the velocity and density fields, namely of the gravitational potential well of the system; therefore, the parameter $m$ entering eq. 1 represents a fraction of the total mass of the system and is not necessarily close to the real mass of a star. The appearance of the σ plateau guarantees that any
value of \( m \) within the range \([m_1, m_2]\) is appropriate. By varying \( m \) within this range, we can estimate the systematic errors on the velocity dispersion derived from the caustic technique. Specifically, we apply the caustic technique for three values of \( m \): \( m = m_1 \), \( m = m_2 \), and a random value in between.

2.2 Final members

The candidate members are the stars hanging from the node \( x_1 \). These stars determine the centre of the system: the systemic velocity is the median of the velocities, while the celestial coordinates of the centre are the coordinates of the two-dimensional density peak. To find the peak we compute the 2D density distribution on the sky \( f_q(\alpha, \delta) \) with the adaptive kernel method described in Diaferio (1999). It goes without saying that the caustic technique centres and the centres used by Walker et al. (2007) and Mateo et al. (2008) are indistinguishable.

In the plane \((r, v)\) (Figure 3), where \( r \) is the projected distance and \( v \) the los velocity of each star from the dSph centre, the caustics are the curves satisfying the equation \( f_q(r, v) = \kappa \). Here \( f_q(r, v) \) is the star distribution in the plane, and \( \kappa \) is the root of the equation

\[
\langle v_{\text{los}}^2 \rangle_{\kappa, R} = 4\langle v^2 \rangle.
\]

The function \( \langle v_{\text{los}}^2 \rangle_{\kappa, R} = \int_0^R A^2_\kappa(r)\varphi(r)dr/\int_0^R \varphi(r)dr \) is the mean caustic amplitude within \( R \), \( \varphi(r) = \int f_\kappa(r, v)dv \), \( \langle v^2 \rangle^{1/2} \) is the velocity dispersion of the candidate members and \( R \) is their mean projected separation from the centre. The stars within the upper and lower caustics are the dSph members, used to compute \( \sigma_{\text{los}}(r) \).
3 RESULTS

For the five dSphs, we separate the stars into radial bins of 100 pc (150 pc for Fornax). We then evaluate the standard deviation of the velocities of the star members in each bin around the systemic velocity, which gives us the los velocity dispersion (losVD) as a function of the projected radius. Figure 3 shows the velocity diagram of the five dSphs and Figure 5 shows the cleaned losVDs for the star members identified with the medium of the three sets of caustics we locate. The losVD as calculated by Walker et al. (2007) are also overplotted for reference.

Clearly, our losVDs are significantly smoother (in particular for Carina and Fornax) and lower (most noticeably Sextans and Sculptor) than the originals. The key point here is that the caustic technique has not significantly altered the magnitude of the losVD for the most distant and luminous dSphs (Leo I and Fornax). For these larger dSphs, it has merely pruned some outlying stars. Alternatively, for Sextans and Sculptor, the VDs have changed considerably and one can immediately see the non-symmetrical distribution of stars in the velocity diagram (Figure 4) before the caustic technique is applied.

The nominal error bars of 0.5 km s$^{-1}$ on each losVD bin are given as a guide only and as a reference for $\chi^2$ statistics. In truth, the combined error from basic observational error on velocity, distance and using different star masses in the caustic technique (leading to different losVDs) is larger. Moreover, other errors orthogonally come from the dSph luminosity and light profile making a fully inclusive error analysis virtually impossible. What is certain is that if the caustic technique has successfully removed the majority of interlopers, the models reproducing the losVD across the projected radius should not systematically err by more than 0.5 km s$^{-1}$.

To each of the five dSphs, we made a Jeans analysis to infer their DM halo properties or to infer their $M/L$ ratios in light of MOND. All the dSph parameters such as luminosity, distance and light profile are taken from Angus (2009).

3.1 Dark halo properties

To demonstrate how quantitatively different the DM halos required to fit the cleaned losVDs are, we used the cored dark halo density profile $\rho(r) = \rho_{DM,0}[1 + (r/r_{DM})^2]^{-\gamma_{DM}}$ (cusped halos achieve just as good fits as shown in Angus & Diaferio 2009) applied in Angus (2009) (where we refer interested readers to find a detailed description of the models) along with centrally isotropic, but radially decreasing, velocity anisotropies ($\beta(r) = \beta_o - \frac{3br^2}{r^2 + b^2}$). The parameters of all the models are given in Table 1. From this we plot the enclosed mass within 300 pc for each of our 5 dSphs and compare with the analysis of Strigari et al. (2008). One can see in Figure 6 that instead of a constant enclosed mass, independent of dSph luminosity, we find a clear trend for our sample of five. How significant this is will only be known once a similar analysis has been completed on the ultra-faint dSphs and the remaining 3 classical dSphs. Sadly, some of the impact of this result is clouded because the original fits to the losVDs by Walker et al. (2007) were made by marginalising the central data points within 300 pc, and this is why some of our data points still exceed the enclosed mass of Strigari et al. (2008), even though our losVDs are lower. To counteract this, we overplot the enclosed mass from fits made by Angus (2009; where extra emphasis was placed on fitting the inner data points as well as the outer ones) and the trend for the enclosed mass to decrease after interloper removal is obvious.

Clearly this might not be the end of the story, the other dSphs may remarkably align with $10^7 M_\odot$. Furthermore, they may have different velocity anisotropies than presented here, although these are the simplest models that can achieve good...
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Figure 4. Velocity diagrams for our 5 dSphs with the 3 sets of caustics overplotted (see §3.3). The dark pink diamonds indicate stars that are members of all three caustics, the black circles are stars that are members of no caustics and the blue stars are members of at least one, but not all the caustics.

fits to the data. Interestingly, Wolf et al. (2009) used a technique which enables the measurement of the enclosed mass at a single radius (coincidentally the half-light radius) which is independent of velocity anisotropy. The half-light radius of Carina is close to 300 pc and their value is identical to ours.

3.2 MOND

In Milgrom’s MOdified Newtonian Dynamics (MOND) the only free parameter when Jeans modelling the dSphs is the mass-to-light ratio $M/L$ of the stars. Naturally, this $M/L$ must conform to population synthesis models with a reasonable initial mass function, which in the V-band is roughly 1-3 in solar units. Preliminary analysis of the dSphs by Angus (2008; whose method we precisely follow here) demonstrated that the more luminous dSphs had sensible $M/L$s (around unity), but that
Figure 5. Line-of-sight velocity dispersion profiles for the Walker et al. (2007) uncleaned samples (gray circles) and our cleaned samples (red squares). In the left-hand panels we overplot the best fit MOND models (parameters listed in Table 2) and in the right-hand panels we plot the best fit cored dark matter halo models (parameters in Table 1). The two lines either side of the best fit are the best fit assuming the data points were increased (green) or decreased (blue) by 0.5 km s$^{-1}$. 
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Figure 6. The enclosed dark mass within 300 pc as a function of dSph luminosity. The purple dots are from Strigari et al. (2008) and the red squares are our cleaned samples presented in Figure 5. The empty circles correspond to the fits of Angus (2009) to the uncleaned Walker et al. (2007) data, using the same cored dark halos as we implement here.

\[
\begin{align*}
dSph & \quad M_{300} \times 10^6 M_\odot & \quad \rho_{DM,0} \times 10^{-3} M_\odot pc^{-3} & \quad r_{DM} [kpc] & \quad \chi_\mathrm{DM} & \quad r_\beta [kpc] & \quad \chi_2/n \\
Carina & 10.0 \pm 1.0 & 6.7 \pm 1.0 & 0.15 & -2.1 & 0.5 & 0.7 \\
Fornax & 25 \pm 4 & 7.0 \pm 0.7 & 0.21 & -1.6 & 0.75 & 0.05 \\
Sculptor & 17.0 \pm 2.5 & 8.2 \pm 0.8 & 0.18 & -2.2 & 0.03 & 0.04 \\
Sextans & 9.6 \pm 1.6 & 6.0 \pm 1.0 & 0.15 & -2.0 & 0.8 & 0.2 \\
Leo I & 16.0 \pm 1.5 & 5.4 \pm 0.7 & 0.17 & -1.6 & 0.75 & 1.1 \\
Carina-1 & 10.0 & 6.9 & 0.15 & -2.1 & 0.5 & 0.7 \\
Carina-3 & 8.9 & 9.8 & 0.14 & -2.3 & 0.4 & 1.1 \\
Sextans-1 & 9.6 & 6.0 & 0.15 & -2.0 & 0.8 & 0.2 \\
Sextans-3 & 10.0 & 6.4 & 0.15 & -2.0 & 0.8 & 0.4 \\
\end{align*}
\]

Table 1. List of the parameters used in fitting the dark halos to the cleaned los velocity dispersions. All velocity anisotropies are parametrised as \( \beta(r) = -\frac{\bar{v}_r}{\bar{v}_\beta} \), except Sculptor which requires \( \beta(r) = -\frac{\bar{v}_r}{\bar{v}_\beta^3} \). In addition, we give the enclosed masses at 300 pc and \( \chi^2/n \) statistics for our fits. The first five rows refer to the caustics used in the main analysis, but the bottom four rows show the fits for two additional sets of caustics for both the Carina and Sextans dSphs, as discussed in §3.3.

the low luminosity dSphs, i.e. Carina, Sextans and Draco, had \( M/L_\odot \)s that were too high. We have re-analysed the dSphs after removing the interloper stars and have found that it leaves all 5 dSphs with comfortable \( M/L_\odot \)s (Figure 7). The velocity anisotropies used are parametrically given in Table 1. In particular, Sextans has dropped from a \( M/L_\odot \) of 9.2 to 2.5, and Carina from 5.6 to 2.0. Significantly, Leo I has not changed from 1.4 and Fornax has changed from 1.4 to 1.0. Therefore, it appears that unbound stars are a problem with a significance that increases the more nearby or low luminosity the dSphs are.

An important point to grasp here is that the mere presence of the non-equilibrium stars is unusual in terms of the DM paradigm because tidal forces are too feeble at their current locations. There are numerical studies of tidal harassment of dSphs by e.g. Klimentowski et al. (2008) and Lokas et al. (2008), but all rely on the dSphs plunging to pericentres that are a factor of five nearer the Milky Way (\( \approx 20 \) kpc) than expected from the observed proper motions (Piatek et al. 2006, 2007, 2008, Table 2). Furthermore, given the observed disk of satellites (Kroupa et al. 2005) and that the Magellanic Clouds are not bound to the Milky Way (Kallivayalil et al. 2006b,a) these orbits are improbable, so other mechanisms should be investigated.

However, in MOND the dSphs are more loosely bound and the internal dynamics vary with distance from the Milky Way (due to the so-called external field effect, e.g. Milgrom 1983, 1995, Angus 2008), thus giving a possible mechanism for plunging orbits. This idea is currently being studied with high-resolution N-body simulations in MOND (Angus et al. in prep).

Furthermore, in the DM paradigm, it is not obvious that stars can be easily stripped out of the dSph (although detailed studies are being made, e.g. Wetzel & White 2009), because the DM halo protects the dSph from tidal disruption, especially at the current distances of the dSphs. On the other hand, in MOND the extra gravity which binds the stars of the dSph together depends not only on the internal gravity of the dSph, but also on the external gravity exerted by the Milky Way. When this external gravity reaches a similar magnitude to the internal gravity of the dSph, the internal gravity decreases towards the simple Newtonian gravity of the stars. For this reason, dSphs are more susceptible to tidal disruption in MOND.
Figure 7. Inferred $M/L$s in MOND using the old data (green asterisks, [Angus 2008]) and our cleaned samples (blue squares). $M/L$s consistent with population synthesis models exist between the red dashed lines.

Figure 8. A comparison between the los velocity dispersions found using different star masses in the caustic technique as discussed in §3.3. The red data points corresponding to the best caustics are supplemented by blue and green points in each radius bin that signify the two other, extremal sets of caustics. A best fit model is fitted to each series of data points of the same colour. The top two figures are for the Carina dSph and the bottom two figures represent Sextans. The MOND fits are given in the left panels and the DM fits on the right.

3.3 Star masses

The star mass mentioned in §2 is the only free parameter included in the caustic technique. To estimate the response of the caustics to changes in the star mass, we produced three sets of caustics for each dSph by setting three different values of the star mass (as shown in Figure 8). The highest and lowest values contain the range in which we find a recognisable $\sigma$ plateau.
This mass range is $1.3 - 1.4 \times 10^7 M_\odot$ for Fornax; $2 \times 10^6 - 2 \times 10^7 M_\odot$ for Leo I; $1.8 \times 10^5 - 1.4 \times 10^6 M_\odot$ for Carina; $3.5 \times 10^5 - 7 \times 10^5 M_\odot$ for Sculptor and $8 \times 10^4 - 4.5 \times 10^5 M_\odot$ for Sextans.

The differences in the three sets of caustics for each dSph are not significant (Figure 4), and the number of stars lying within the widest caustics and outside the narrowest one do not cause a large variation in the losVD profiles. This emphasises that the method is robust. Nevertheless, to identify the spread in the context of the mass models, we fit models to the losVD from each caustic set for Carina and Sextans. The three models used for Carina and Sextans are barely distinguishable (see details in Table 2) and yield MOND $M/L$s and DM enclosed masses that differ from the main caustics at roughly the same level as the errors we find by adding 0.5 km s$^{-1}$ to the observed losVDs in the case of Sextans, but far lower for Carina.

### 4 CONCLUSION

Here we have applied the caustic technique to remove star interlopers in the 5 classical dSphs observed by Walker et al. (2007, 2009a) and Mateo et al. (2008). We have applied the technique to each dSph, taking into account the systematics introduced by the free parameter in the binary tree construction, namely the star mass. We have found that there are no major discrepancies between the caustics calculated from each star mass (as shown by Figure 4 and the two tables) in the mass range where a $\sigma$ plateau appears. Consequently, the velocity dispersion profiles are not strongly dependent on this parameter of the caustic technique.

Using this technique we have shown that unbound/non-equilibrium stars are all too common in the low luminosity dSphs of Carina and Sextans. Removing these interlopers gives very different enclosed masses within 300 pc for fitted dark halo models. We have found that the mass increases by a factor of three while the luminosity increases by a factor of ten. Thus, the common mass scale proposed by Strigari et al. (2008) becomes uncertain. Intriguingly, we also investigated the implications for MOND, which are altogether more positive. Original analysis by Angus (2008) showed the $M/L$s of the high luminosity dSphs were perfectly reasonable, but the low luminosity dSphs had abnormally high $M/L$s, in particular Sextans and Draco, casting serious doubt on MOND’s validity. After removing the interloper stars identified by the caustic technique, Sextans has a realistic $M/L$ of 2.5 in solar units. We still await the final data release for Draco and Ursa Minor by Walker et al. (2007), but eye inspection of their Figure 1 shows them to be likely highly contaminated by unbound stars.

### ACKNOWLEDGMENTS

GWA’s research is supported by Università di Torino and Regione Piemonte. The authors also acknowledge partial support from the INFN grant PD51.

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#### Table 2

| dSph     | $R_{MW}$ [kpc] | $L_v$ [$10^5 L_\odot$] | $M/L$ | $\rho_{\ast, o}$ [$10^{-2} M_\odot pc^{-3}$] | $r_\beta$ [kpc] | $\beta_0$ | $\chi^2/n$ |
|----------|----------------|-------------------------|-------|---------------------------------------------|----------------|-----------|-------------|
| Carina   | 101±5          | 4.4                     | 2.0   | 2.0±0.5                                     | 4.7±1.0        | 0.5       | -0.16       | 0.6         |
| Fornax   | 138±8          | 158                     | 1.0   | 1.0±0.15                                    | 3.2±0.5        | 1.7       | -0.084      | 0.1         |
| Sculptor | 87±4           | 28                      | 0.9   | 0.9±0.2                                     | 12±2           | 188       | -0.235      | 0.38        |
| Sextans  | 95±4           | 2.5                     | 2.5   | 2.5±0.4                                     | 0.42±0.08      | 1.4       | -0.23       | 0.1         |
| Leo I    | 257±8          | 48                      | 1.4   | 1.4±0.3                                     | 5.5±1.1        | 1.1       | 0.08        | 0.7         |
| Carina-1 | 2.1            | 4.9                     | 0.5   | 0.5                                         | -0.16          | 0.8       |             |             |
| Carina-3 | 1.9            | 4.2                     | 0.5   | 0.5                                         | -0.16          | 1.1       |             |             |
| Sextans-1| 2.5            | 0.42                    | 1.4   | 1.4                                         | -0.23          | 0.1       |             |             |
| Sextans-3| 3.1            | 0.53                    | 1.3   | 1.3                                         | -0.23          | 0.6       |             |             |
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