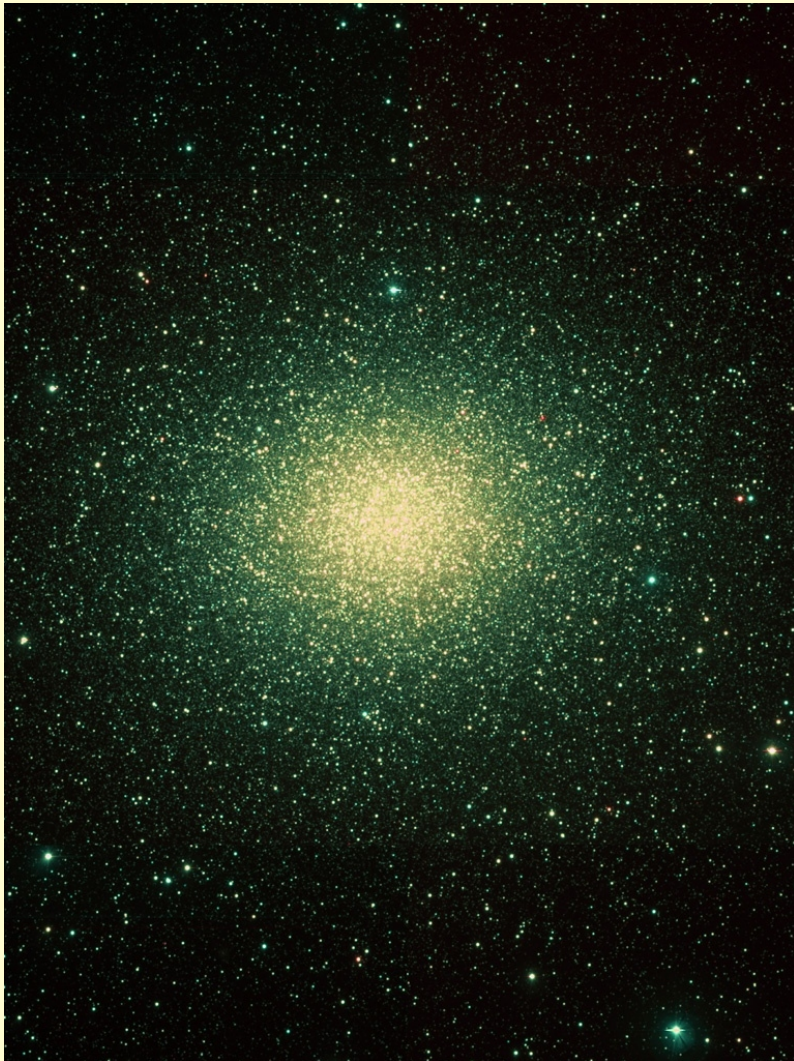# Dynamics of the outer parts of ω Centauri

Gary Da Costa

Mt Stromlo Observatory, Research School of Astronomy & Astrophysics, Australian National University

ω Centauri has been known to be an unusual stellar system for almost 4 decades.

Unlike most (but not all!) globular clusters its member stars possess a large range in heavy element abundance and show distinctive element-to-iron abundance ratios.

There is also evidence for a range in Helium abundance and for an age spread of order ~2 Gyr.
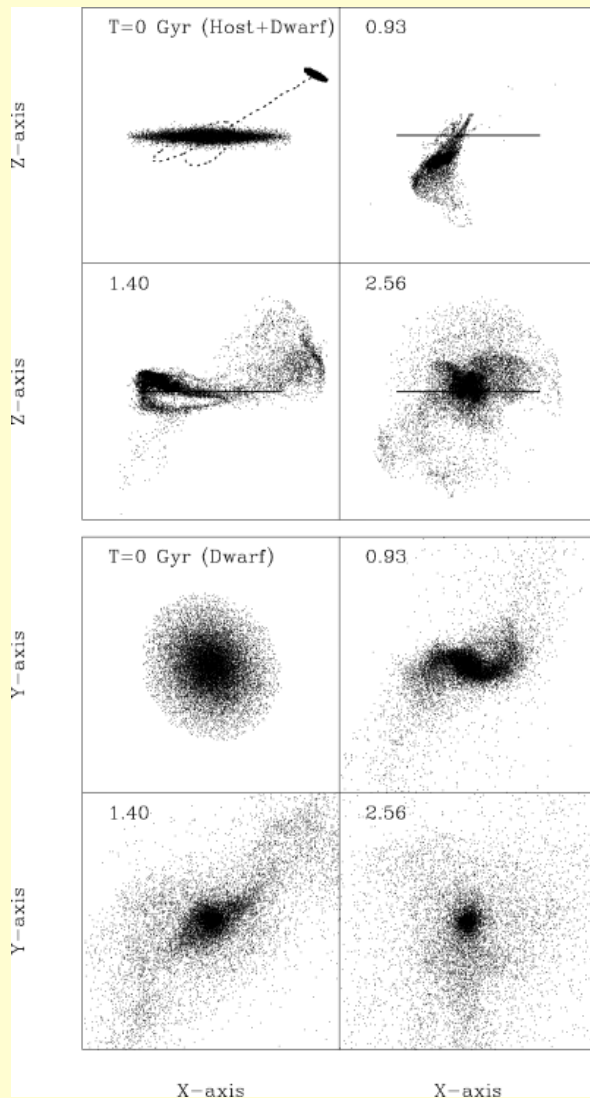
Figure from Bekki & Freeman (2003)

These characteristics have led to the suggestion that ω Centauri has not evolved in isolation but is instead the nuclear remnant of a now disrupted nucleated dwarf galaxy that has been accreted by the Milky Way.

Despite the tightly bound (apo- and peri-Galactic distances of 6.2 and 1.2 kpc) and retrograde current orbit of ω Cen, Bekki and Freeman have shown that this disruption/accretion process is dynamically plausible.

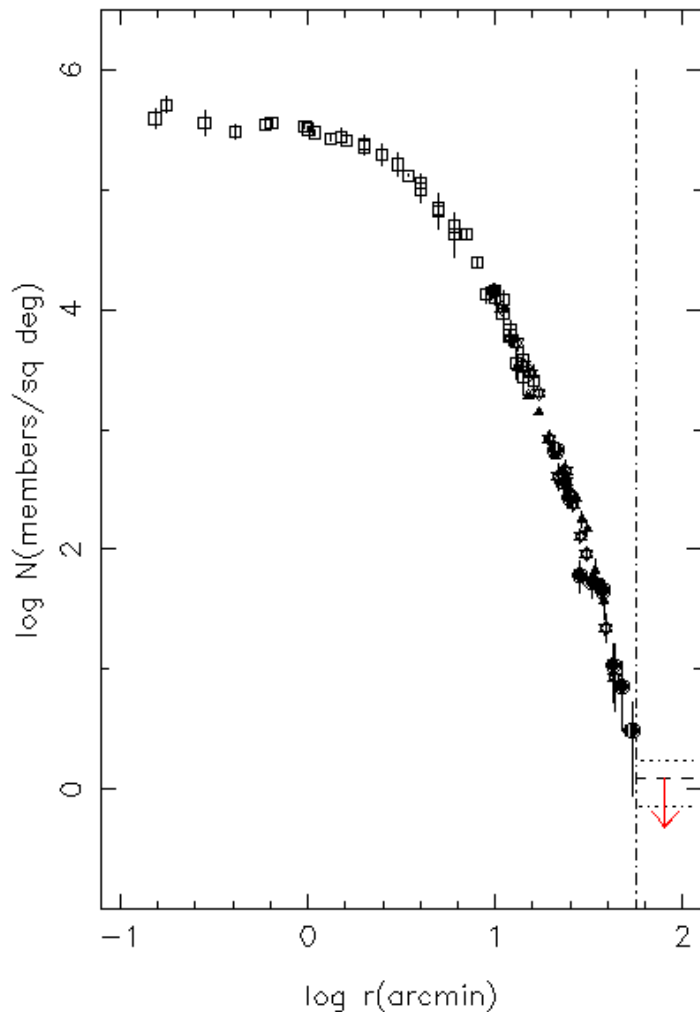*Research School of Astronomy & Astrophysics*

Figure from Da Costa & Coleman (2008)

The spectroscopic survey of Da Costa & Coleman (2008) showed that there is little evidence for any significant extra-tidal population surrounding ω Cen at the present day - gave an upper limit of 0.7% for the fraction of the cluster mass contained between 1 and 2 tidal radii.
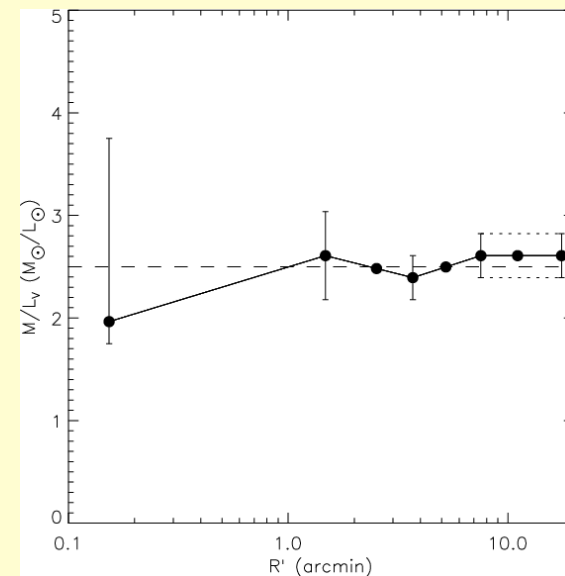
Requires the stripping process to be largely complete at early epochs.

Stars from the disrupted dwarf galaxy are now widely distributed around the Galaxy.

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While the nucleosynthetic history of ω Cen is complicated and not fully understood, the dynamics of the present day stellar system, at least for the part of the cluster containing most of the stellar mass, are relatively well established.

There have been a number of models of the system (e.g. Meylan 1987, Meylan et al 1995, Merritt et al 1997, Giersz & Heggie 2003, van der Marel & Anderson 2010) which, within their assumptions, reproduce well the observational data. The most detailed model is that of van de Ven et al (2006).

This axisymmetric model, which includes rotation and radially varying anisotropy, suggests no change in M/L with radius, at least within the inner parts.

Necessary to keep in mind that models of van de Ven et al (2006), for example, fit, and are constrained by, the available observational data. *In the case of the velocity dispersion profile, the data have been limited, until recently, to a radius of about 20' from the cluster centre, less than half the 'tidal' radius of ~57'.*

And the outer parts may well contain some interesting astrophysics…

• For example, if ω Cen is a nuclear remnant, then it is possible that it has retained some of the dark matter content of the original dwarf. The best place to constrain the dark matter content is in the outer parts where the stellar densities are low.

• Further, it appears that the line-of-sight velocity dispersion profile beyond ~20' may be relatively flat, rather than declining as expected.

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Currently, there are two studies of the velocity dispersion beyond ~20' - Sollima et al (2009), based on a VLT/FLAMES radial velocity survey, and Scarpa & Falomo (2010) which combines the Sollima et al (2009) data with the earlier data of Scarpa et al (2003).

• Sollima et al (2009) conclude that a simple dynamical model in which mass follows light, within classical Newtonian theory of gravitation, can reproduce the available data.

• Scarpa & Falomo (2010) conclude "the cluster velocity dispersion at large radii is found to clearly deviate from the Newtonian prediction" and "best explained by a breakdown of Newtonian dynamics below a critical acceleration".

The combined sample contains ~100 stars between 22' and 30' but only a dozen or so beyond 30' (~0.5 x 'tidal' radius).

To add further information into this debate, I've used the AAOmega multi-fibre spectrograph at the AAT to identify additional outer members of ω Cen, particularly beyond 30' from the cluster centre.

Note on why this isn't easy...

• ω Cen is at low Galactic latitude so field contamination is high to begin with.

• Cluster star density drops by factor of *5x* between 20' and 30' and by a further factor of *10x* between 30' and 40', while the area that needs to be surveyed goes up by r^2, as does the number of contaminating non-members (uniformly distributed).

• Extensive survey only feasible with instrument like AAOmega which allows up to 400 candidates per observation over 1 deg radius field.

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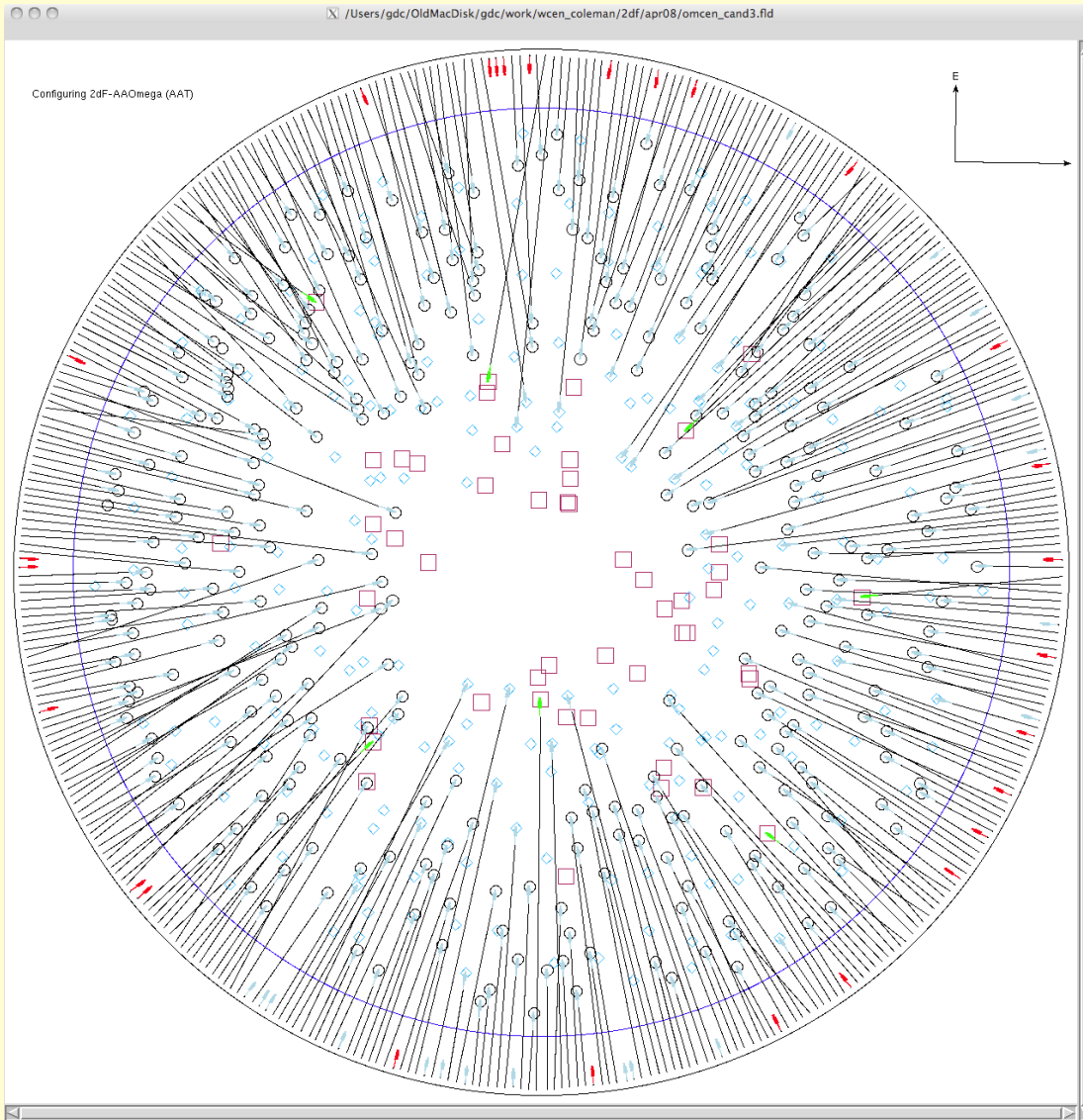
The one degree radius of AAOmega field-of-view is conveniently matched to the size of the area to be surveyed - so observe multiple configurations centered on the cluster.

Red arm of the bench mounted double beam spectrograph configured with 1700D grating centred at Ca triplet. Spectra have scale of 8.5 kms^{-1}/pix at 8600Å.

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Two samples observed:

- 20 < r' < 30 - known cluster members from Da Costa & Coleman (2008). 101 stars.

- 30 < r' < 60 - known members plus unobserved candidates from Da Costa & Coleman (2008) (15.4 < V < 16.75) plus fainter candidates from same photometry set (16.75 < V < 17.2).

Velocities determined via cross-correlation with spectrum of a radial velocity standard template. Typical precision of <1.5 kms^{-1} from repeat observations. Despite less than ideal weather, about 2000 candidates observed over 3 nights.

For candidate ω Cen members, heliocentric velocities corrected for perspective rotation before analysis.

Results:

AAOmega Sample (224 Stars V > 100 kms−1)
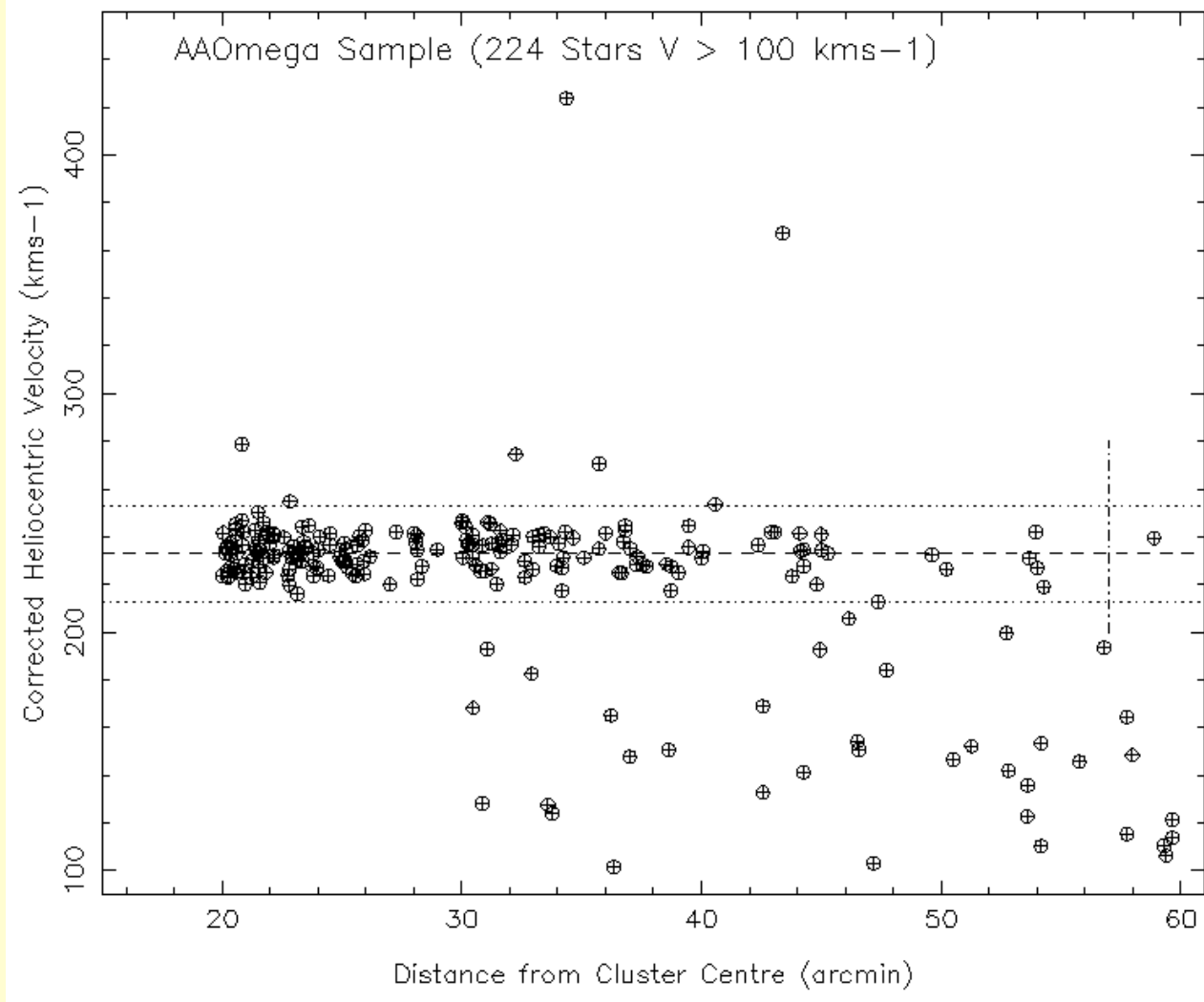
Results - using all stars in the 213-253 kms^{-1} window
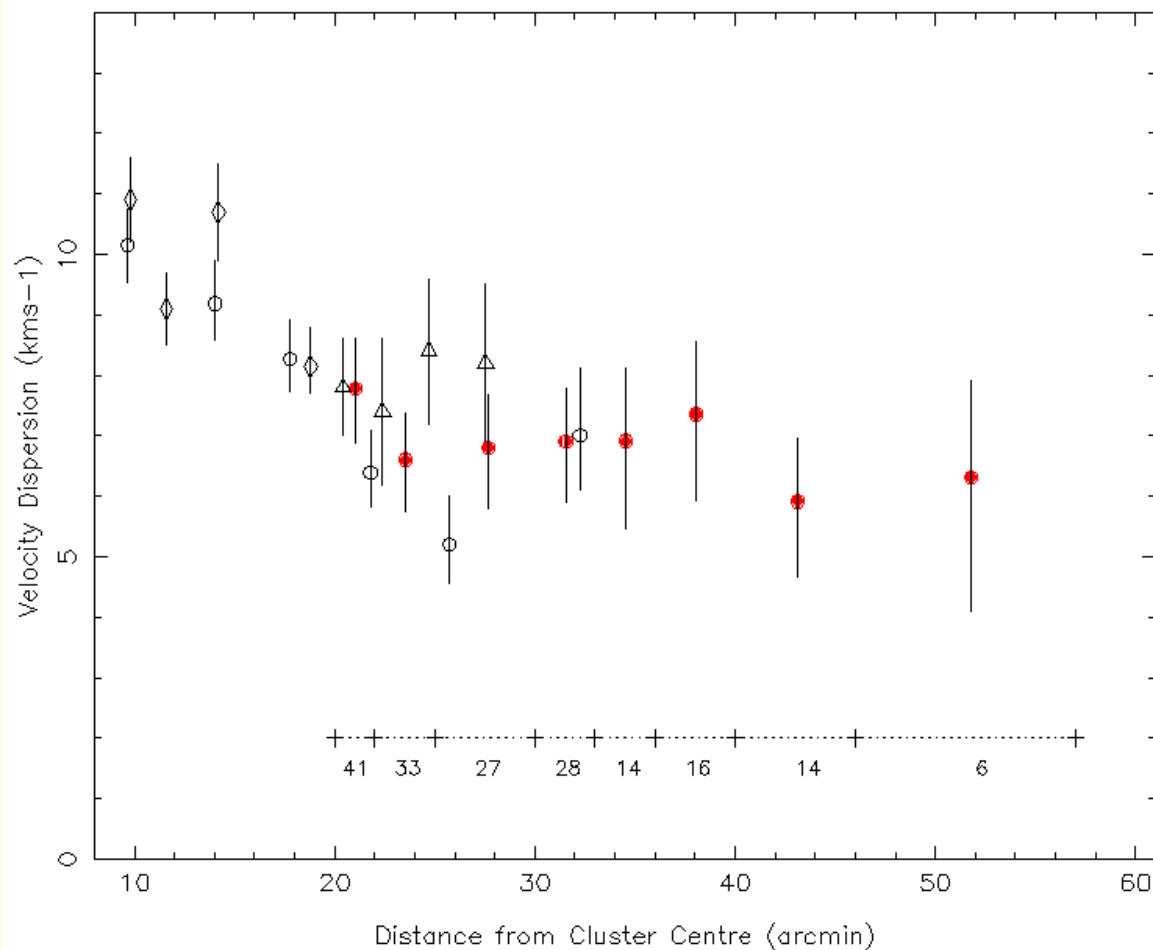
Red points are new determinations from the AAOmega observations. σ(los) calculated using maximum likelihood technique. Numbers of stars and width of each annulus shown.

Agreement with other data is excellent in region of overlap.

Open circles: Sollima et al. (2009); *Triangles*: Scarpa et al. (2003); *Diamonds*: σ(los) from van de Ven (2006).

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Results - using all stars in the 213-253 kms^{-1} window
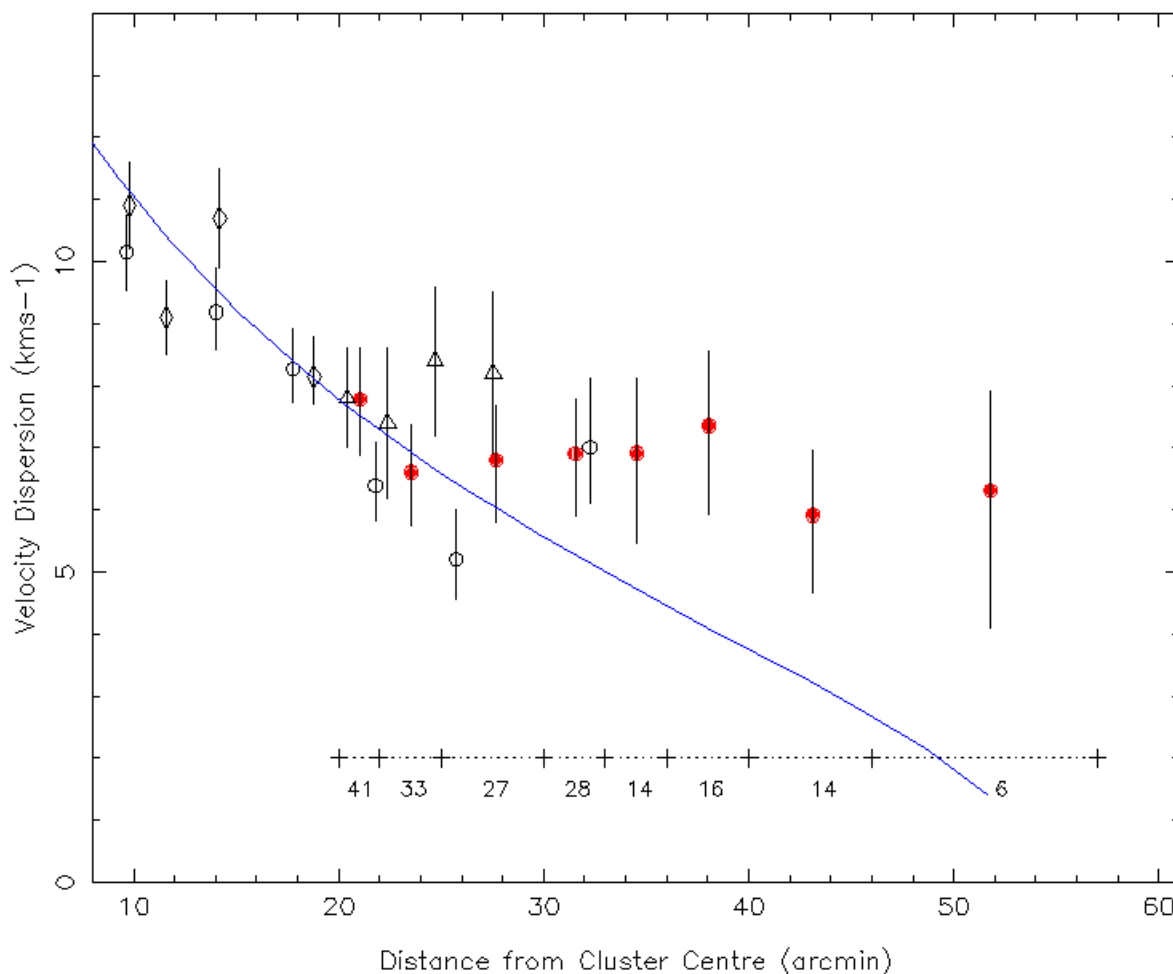
As an illustration of "expected" profile, the blue curve shows σ(los) for a simple King (1966) model scaled with a central σ(los) of 15 kms^{-1} and scale (core) radius of 2.6'. Like more sophisticated models, the fit is acceptable out to r ~ 25' but not beyond.

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But is it reasonable to assume that *all* the stars in the 213-253 kms^{-1} window are cluster members? Probably not!

Remember that the cluster surface density profile is dropping rapidly with radius while the field star surface density is constant.


Estimated the contamination as follows: at position of ω Cen a galactic rest frame velocity of zero corresponds to 167 kms^{-1}. Assume then that the 10 stars between 160 and 200 kms^{-1} and 30'-60' are *halo objects* with a dispersion of 100 kms^{-1}. This then allows us to predict the number of interloping halo objects in the 213-253 kms^{-1} interval.
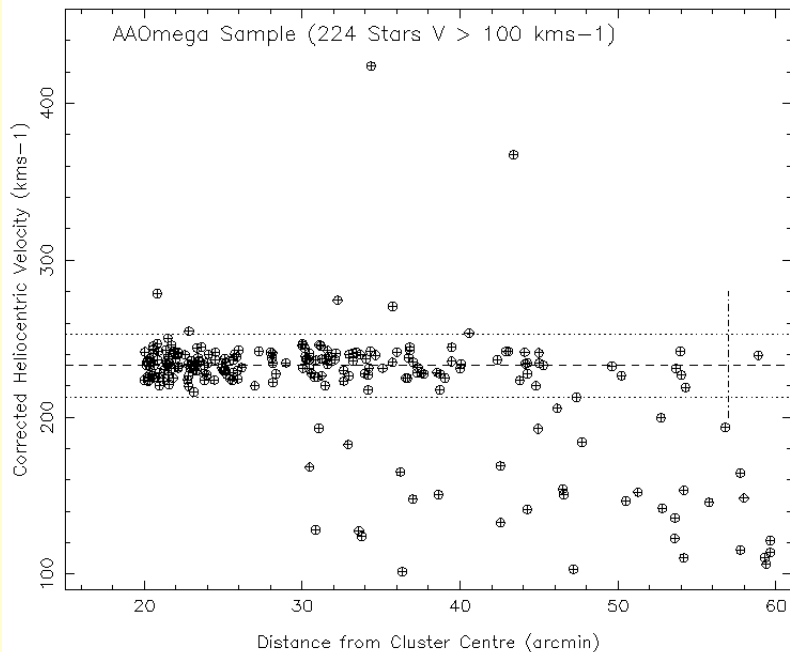
For each annulus we then have for 213-253 kms^{-1}:

| Annulus	N_{obs}	Predicted halo	N_{halo}
30'-33'28	0.6 ± 0.2	1, not 2	
33'-36'14	0.6 ± 0.2	1, not 2	
36'-40'16	0.9 ± 0.3	1, perhaps 2	
40'-46'14	1.6 ± 0.5	2 or 3, not 4	
46'-57' 6	3.5 ± 1.1	maybe all 6!	

• So the first conclusion is that *can't place any weight on the observed σ(los) for the outermost annulus, as the contamination is dominant*. But for the others the contamination is negligible or minor…
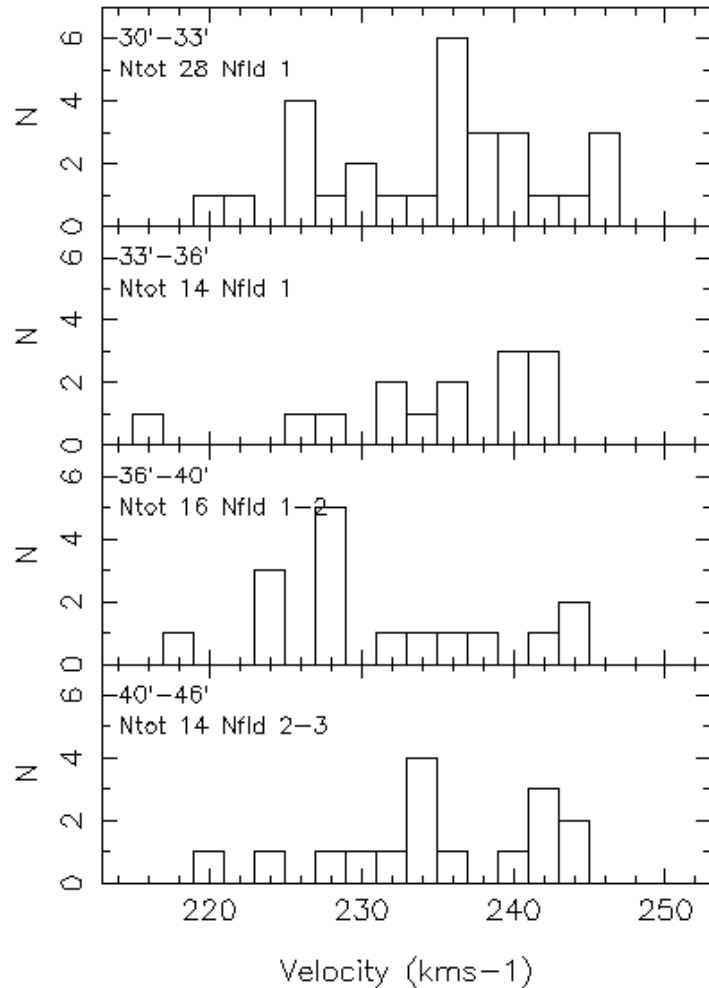
While we now have an estimate of the contamination, it doesn't tell us which star or stars to reject. So, as an exercise, looked at outcome of removing the expected number in such a way as to reduce the dispersion as much as possible. So if…

30'-33': drop lowest velocity star

33'-36': drop lowest velocity star

36'-40': drop lowest and highest

40'-46': drop lowest and two highest

Outcome:
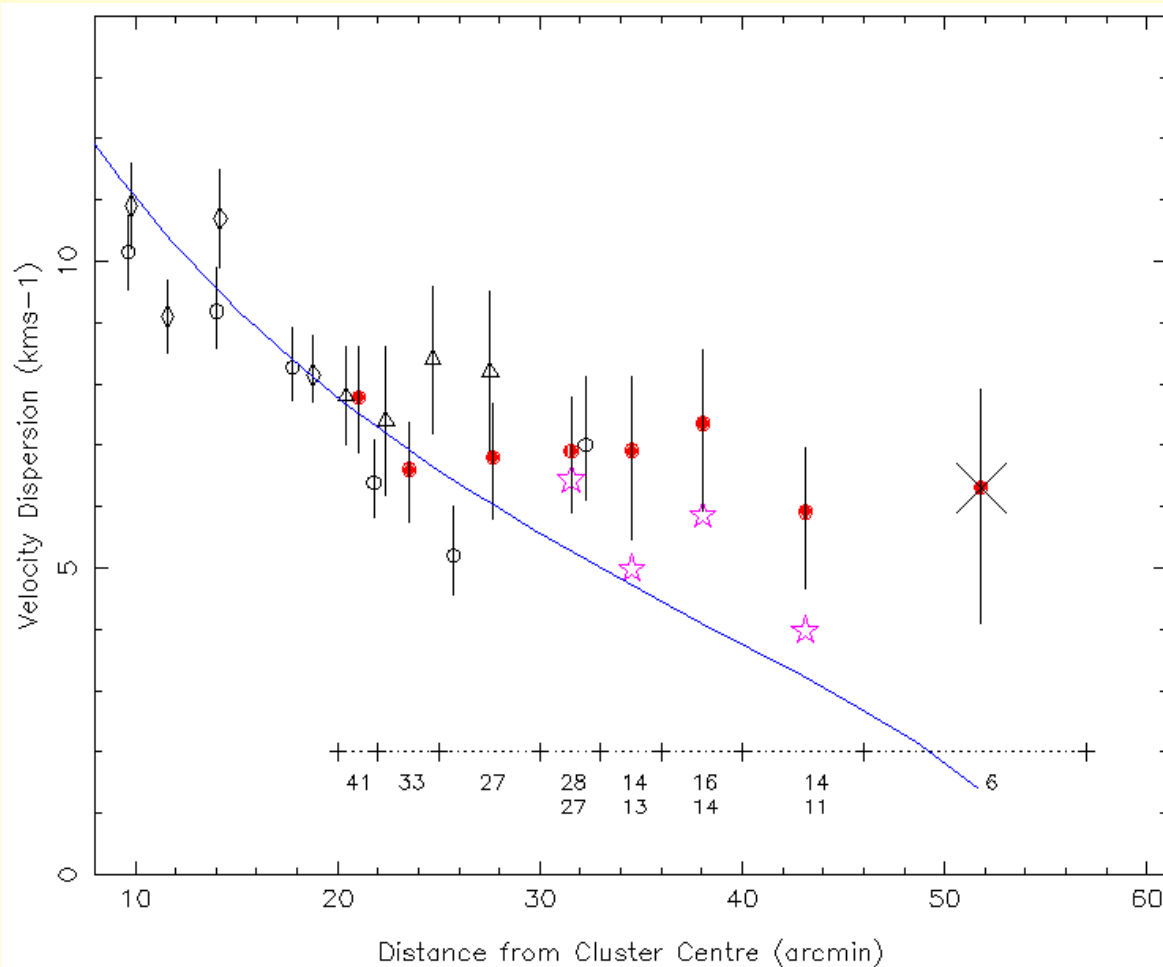
Star symbols represent σ(los) values if we choose the contamination to reduce the dispersion as much as possible.

Could argue that now see σ(los) decreasing as expected, *but reality probably lies between the red dots and the purple stars…*

Conclusions:

• *Actual velocity dispersion profile for ω Cen is probably flatter beyond ~25' than the predictions of models that reproduce the dynamics of the inner regions, where most of the mass lies.*

But what does that mean? The answer lies in remembering that **ω Cen is not an isolated system**.

• It is moving in a varying Galactic potential on its orbit (apo- and peri-Galactic distances of 6.2 and 1.2 kpc), crossing the disk twice every 120 Myr. Each time it crosses the Galactic plane the 'disk-shocking' impulse adds energy to the outer parts of the cluster.
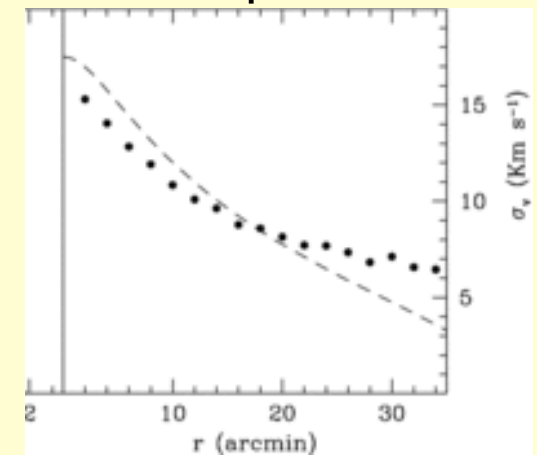
Indeed using the parameters of the van de Ven et al (2006) model can show that the average change in a star's velocity |Δv| as a result of a Galactic plane crossing is of the same order as the dispersion (~6 kms^{-1}) at a radius of ~30 - 35'.

Conclusions:

In other words, as previously suggested by van de Ven et al. (2006) and Sollima et al. (2009), *the dynamics of the outer parts of ω Cen*, where there is but a small fraction of the total mass, *are dominated by external influences*.

What's needed, if you want to enquire as to whether there is any evidence for dark matter in the outer parts of the system for example, is a full model of the presumably quasi-equilibrium process (system has made many 10's of orbits) in which the cluster orbits in the varying potential of the Galaxy and suffers 'disk-shocking' as it crosses the Galactic plane.

Some steps along these lines were made by Sollima et al (2009) who showed in a N-body model simulation that the velocity dispersion profile is indeed raised above that of isolated model.

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