What do GC orbits tell us about their formation and disruption?

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"Observed" orbits of GCs come from *formation* convolved with *disruption.*

What do we expect from GC formation?

Disk GCs: *in-situ formation, disk-like orbits*

Halo GCs:

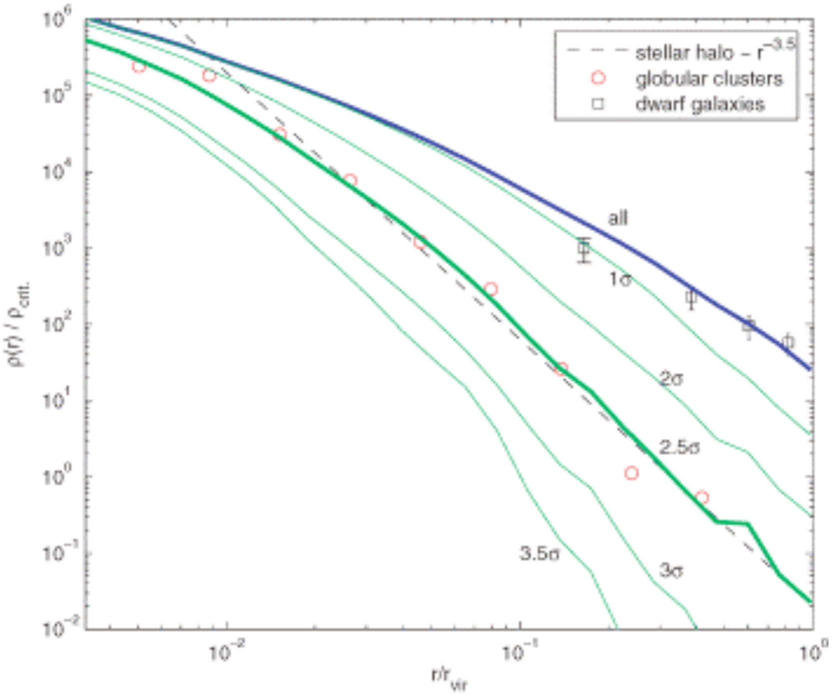
Let's cast GC formation as an aspect of *galaxy* halo formation. Almost every model for galaxy formation predicts radially-biased orbits in the halos (for stars, dark matter = DM, GCs, etc.; e.g. van Albada 1982). From here on, we will phrase this in terms of the ***spherically-averaged anisotropy parameter***:

$\beta \equiv 1 - \sigma_\theta^2/\sigma_r^2$ *($\beta > 0$ for radial orbits, $\beta = 0$ for isotropic, $\beta < 0$ for tangential)*

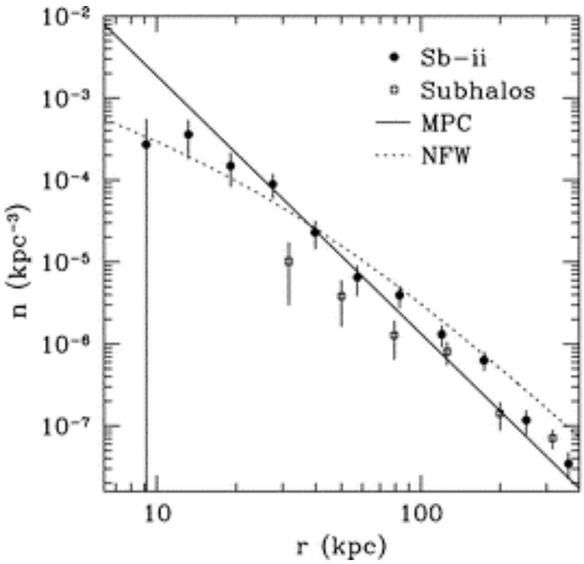
Cosmological infall:

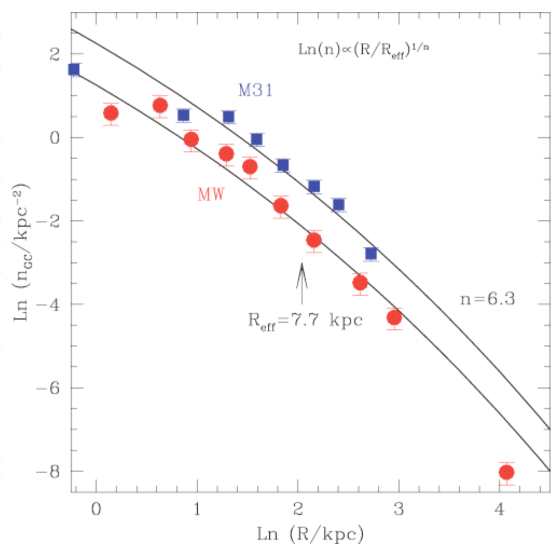
We generically expect radially-biased orbits in halos: infall of objects increases radial velocity component by conservation of energy; conservation of angular momentum increases tangential component too but this effect only becomes dominant inside ~15 kpc

A specific example from Diemand et al. (2005) and Moore et al. (2006) is the hypothesis that the metal-poor halo stars and GCs (MPGCs) as collisionless systems can be *associated* with some subset of DM particles that collapsed at the halo center at high redshift z_c—see *figure below*. The more centrally concentrated the stellar/GC system, the higher was z_c and β also turns out higher. In the MW halo, this exercise predicts $\beta \sim +0.5$.



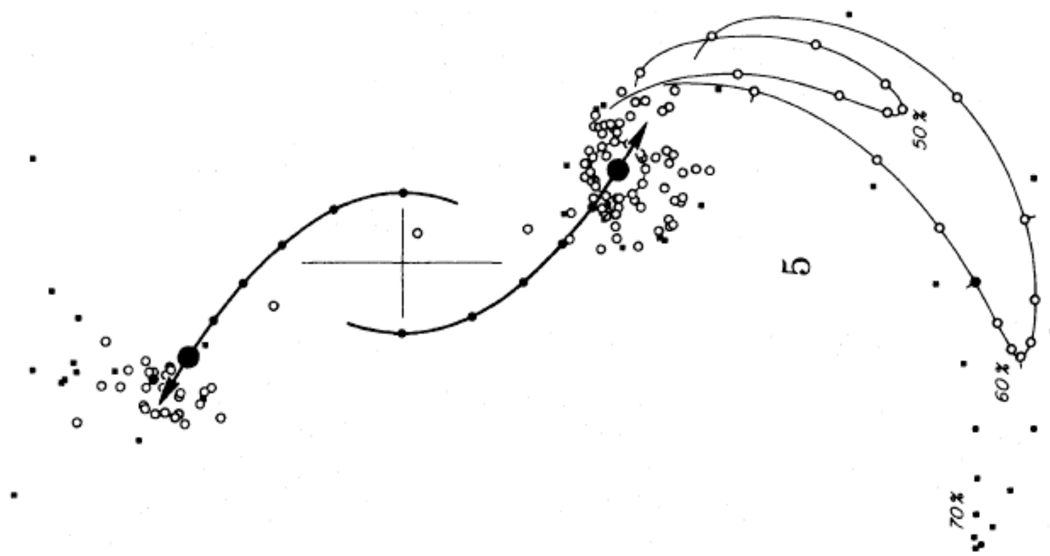
An exception to the general rule of radial anisotropy may involve accreting subhalos in hierarchical structure formation, where the **surviving** subhalos in particular may be roughly isotropic ($\beta \sim -0.2 - +0.1$; Sommer-Larsen et al. 1997; Mamon & Lokas 2005; Faltenbacher et al. 2005). Thus if the halo stars and GCs are associated with accreting satellite galaxies (by stripping or disruption), they may be isotropic. The simulations of GCs in Prieto & Gnedin (2008) appear to bear this out, with $\beta \sim 0$, but their GCS spatial density profile is far too extended ($R_{\rm eff} \sim 90$ kpc; *figure below left*). A similar idea in Abadi et al. (2006) does get the density profile right ($R_{\rm eff} \sim 8$ kpc; *figure below right*), and then the anisotropy is the usual $\beta \sim +0.5$. Clearly differences in the predictions between these models need to be resolved (different subgrid physics, dynamical friction treatments, etc.). Other scenarios for forming halo GCs could be explored for the spatio-kinematic predictions (Scannapieco et al. 2004). But if GCs turn out to have isotropic orbits, it may turn out to be **generically difficult to match both their density and anisotropy profiles simultaneously**.



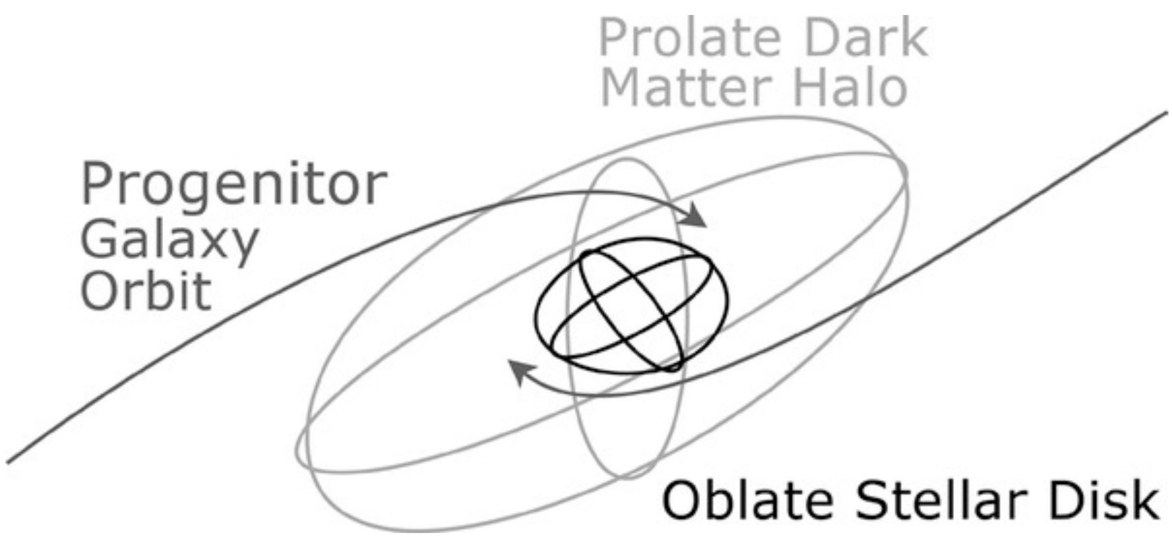


Elliptical galaxies:

The discussion so far was generic to different galaxy types, but let's consider more specifically the giant elliptical galaxies. These are generically thought to form in some kind of major merger of galaxies. The halos of these galaxies are then built up in the infall of tidal tails of material that were thrown outwards (Toomre & Toomre 1972; *see figure below*), and would therefore have radially-biased orbits (Dekel et al. 2005) for the halo stars, and both metal-rich and metal-poor GCs.



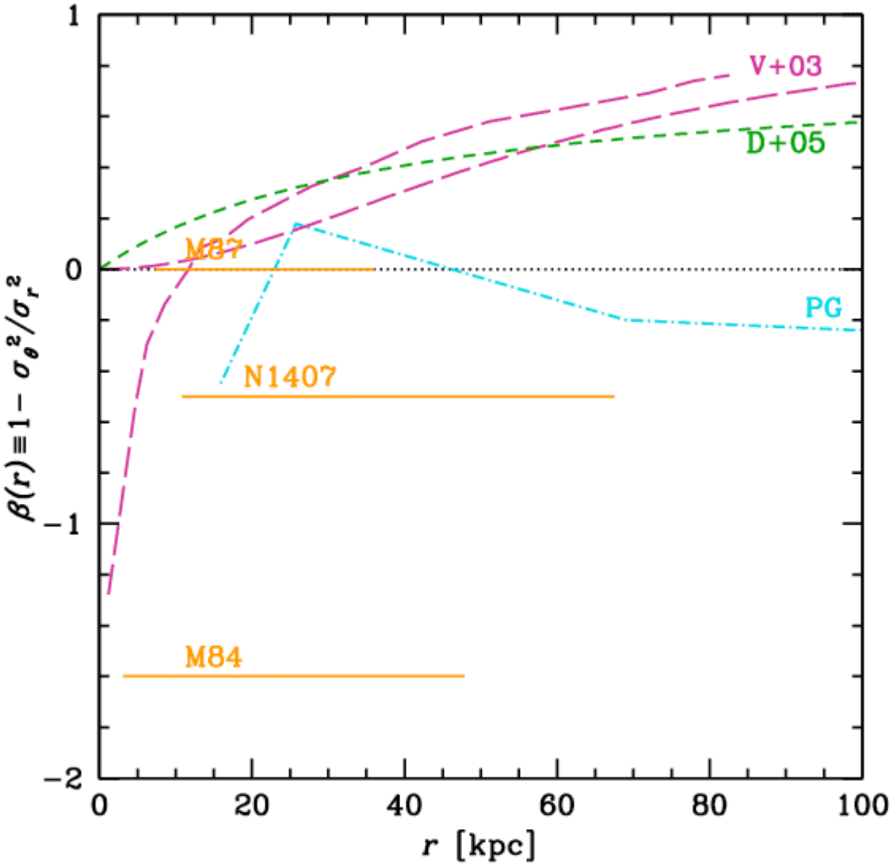
Now considering in more detail the subclass of **disky/fast-rotator ellipticals** (e.g. NGC 3379) which might be considered as basic binary major merger remnants, new work from L. Hoffman (KITP talk, 5 Mar 2009) suggests the metal-rich disk-associated GCs in the progenitor galaxies may end up on "x-tube" orbits in the remnant halos, while the MP GCs (halo origin) would presumably end up in a broader spread of orbits. See *schematic below* from Novak et al. (2006). Note that this is one example of why we use *spherically-averaged* β, since locally β could vary by a lot. Any younger GCs formed in the merger would probably have even more radial orbits than the old GCs (see Dekel et al. 2005), modulo disruption effects.



The predictions are less clear for boxy/slow rotator ellipticals which include massive **group-central galaxies** like M87. Simulations so far do indicate again $\beta \sim +0.5$ in their halos, but a caveat is that it has been notoriously difficult to produce a slow rotator that looks right in detail (Burkert et al. 2008; Novak 2008).

Although we still have little idea of just how the old GCs are formed, radial anisotropy seems a fairly safe bet as an *initial* prediction, especially in elliptical galaxies where the orbits will be dominated by merger dynamics *after* GC formation.

➔ Therefore consider the curve "D+05" (Diemand et al. 2005) as an "initial condition" for M87-like galaxies in the anisotropy *summary plot below*. ("PG" = Prieto & Gnedin 2008).



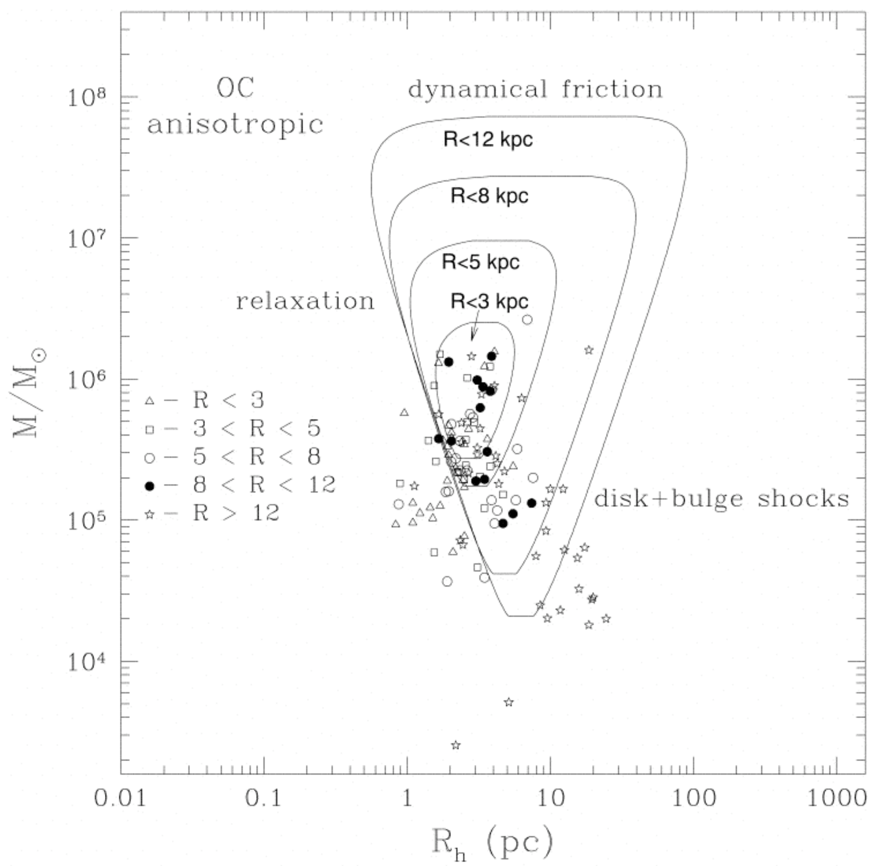
What do we expect from GC disruption/evolution?

<u>Processes:</u>

The main processes that disrupt/shrink GCs include:

- internal mass loss (two-body relaxation, binary heating, stellar mass loss, etc.)
- shocks (disk, bulge)
- dynamical friction

To summarize the effects of these processes on GCs of different masses and radii, below is a "**vital diagram**" for the MW (Gnedin & Ostriker 1997), with one choice for the initial GC orbits. See D. Chernoff talk (28 Jan 2009) for some more details. A similar diagram has been made for M87 (C. Waters, Ph.D. thesis).



Evaporation acts on compact clusters, and shocks on extended clusters, with more massive clusters being more resistant to both effects. The **only effect acting preferentially on high-mass clusters is dynamical friction**, which is normally considered to not be significant for GCs at > 5 kpc galactocentric distances since their current masses appear to be < 10^7 $M_\odot$. For reference, here is a dynamical friction timescale formula suited to GCs around M87:

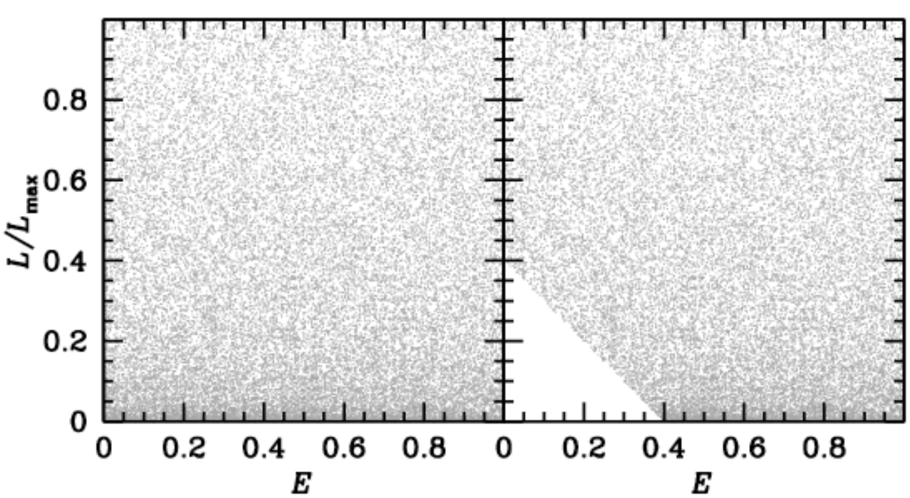
$$t_{\rm fric} \sim 10\ {\rm Gyr}\ (R/10\ {\rm kpc})^2\ ({\rm v_c}/500\ {\rm km/s})\ \ (M_{\rm GC}/10^8\ M_\odot)^{-1}$$

Also note that all of the disruption mechanisms above are strongest at the *pericenter* of an orbit $r_{\rm p}$, so for objects on the same mean orbital radius $\langle r \rangle$, the evolution will depend on eccentricity e, with generic expectations for the timescales to decrease as e increases, by a factor of ~2 (Lacey & Cole 1993; van den Bosch et al. 1999; Baumgardt & Makino 2003; Boylan-Kolchin et al. 2008; but see Taffoni et al. 2003; Jiang et al. 2008). **Therefore we *qualitatively* expect evolutionary effects to reduce the radial anisotropy of GCs** since the objects on radial orbits will be preferentially affected. Note however that these effects may depend on the details of how the initial tidal radius is defined (Shin et al. 2008).

Another possibility is that environmental effects *circularize* GC orbits. This question needs a careful treatment that takes into account realistic conditions for GCs in a galactic potential. Numerical simulations (van den Bosch et al. 1999; Colpi et al. 1999; Taffoni et al. 2003; Just & Penarrubia 2005) have generally found that this is not the case: the eccentricity loss at pericenter is nearly balanced by the eccentricity gain at apocenter, so *de/dt* ~ 0. On the other hand the numerical simulations of Tormen et al. (1998) and the analytical formalisms of Tsuchiya & Shimada (2000) and Zhao (2004) do predict circularization. It's not clear if this is a true discrepancy or if different initial conditions and timescales are being considered. Also the nature of orbits changes in a realistic triaxial potential, which could also impact the predictions for orbital decay and transformation (Capuzzo-Dolcetta & Vicardi 2005).

Now bringing all these evolutionary effects into the context of a galaxy's GC system, we can ask what the "final" distributions are for the GC masses, number densities, and orbit eccentricities. Near the galaxy center (~10 kpc in M87), evolutionary effects operate on all masses to deplete the overall number of GCs, resulting in "cored" GCS density profiles (Vesperini et al. 2003). One generically expects the mass-dependence of the evolution to change with galactocentric distance (cf. vital diagram *above*), which given power-law GCMF initial conditions should result in a final GCMF that changes drastically with distance. This is not observed in M87 or the Milky Way, with some possible explanations: (A) the models are too idealized, and the full cosmological context might mix up the GCMF somewhat; (B) high orbital eccentricity allows pericenters to be approximately the same for all GCs. Case (A) has not been worked out in detail yet. Case (B) requires far more extreme radial anisotropy than is predicted by theory (*above*) and than is permitted by observations of the "residual" objects (*below*)—see Fall & Zhang (2001); Vesperini et al. (2003).

The GCMF continues to be a puzzle that we set aside for the moment to isolate the orbit questions. Based on the combined predictions above of initial orbits for GCs and evolutionary processes, we could expect that in the galaxy halos (say outside ~ 10 kpc for M87), GCs of all masses are unaffected by orbit-dependent evolution, and their orbits reflect the cosmological mildly eccentric initial conditions. At smaller radii the orbital distribution will be shifted toward more tangential anisotropy—an effect that is stronger for lower-mass GCs. See the initial and final $\beta(r)$ profiles for M87 (*above figure*, "V+03") from Vesperini et al. (2003). Also see the schematic below for how the distribution of GC angular momenta with energy (at fixed mass) might evolve (*left/right: initial/final*). The schematic is the same for $|L|$ vs mass at fixed energy (or mean radius).



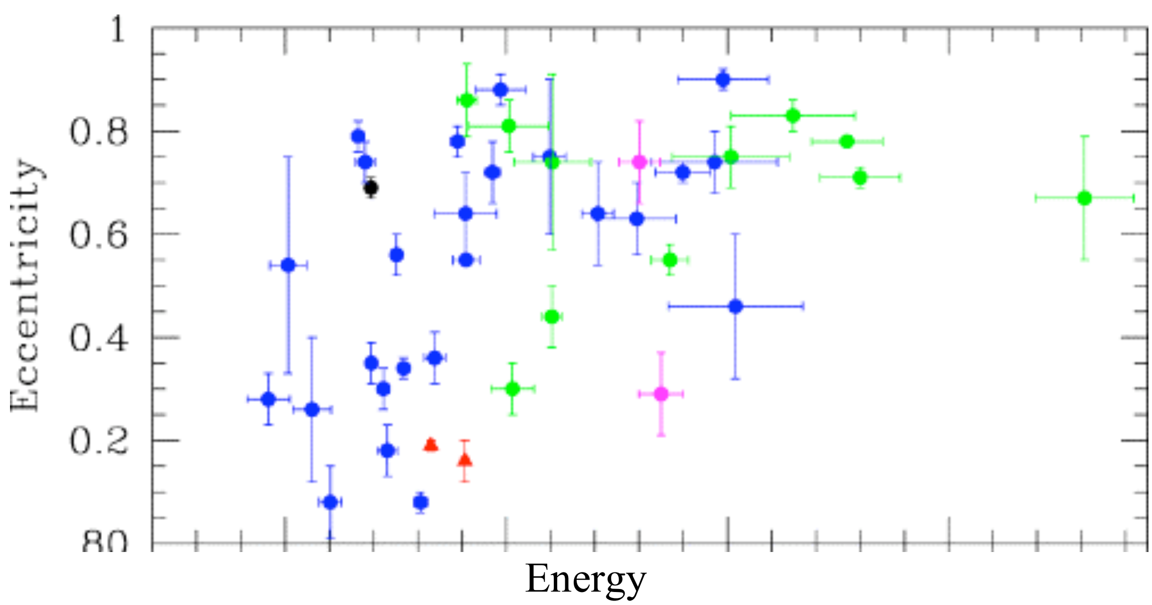
Note that this prediction is still shaky: in addition to some complications mentioned above, **it remains to see the problem treated in a full cosmological context**, with all the competing effects of mass loss, shocks and torques from the central galaxy and from other substructures, major galaxy mergers, back-reaction from stripped material (Fujii et al. 2006; Fellhauer & Lin 2007), etc.

What orbits do we observe?

<u>*The Milky Way*</u>

So what anisotropy is observed in the MW halo? Observations of all 3 velocity components of halo **stars** in the Solar neighborhood suggest $\beta \sim 0.25$ to 0.5 (Chiba & Beers 2000; Kinman et al. 2007). But the predictions aren't so clear in this region because of baryonic effects: one wants to go out to larger radii, to ~50+ kpc for the halo *in situ*. Here we currently have only one velocity component available, and uncertain knowledge of the DM and stellar density profiles, so the data can be fitted with almost any β (Thom et al. 2005; Battaglia et al. 2005; Diemand et al. 2005; Dehnen et al. 2006; Xue et al. 2008).

On the other hand, there are proper motions available at some level for at least ~40 **halo GCs**. As shown in the *figure below* from Mackey & Gilmore (2004), they have overall a median $e \sim 0.65$, which is increasing for high-energy (large radius) orbits ("old halo", "young halo", disk/bulge, Sgr GCs color-coded; see also Dinescu et al. 1999; Geisler et al. 2007). This might at first glance appear to confirm radial anisotropy, but van den Bosch et al. (1999) calculated that $\beta = 0$ corresponds to $\langle e \rangle \sim 0.55$ (cf. $\langle e \rangle \sim 0.33$ in Frenk & White 1980). **More work clearly needs to be done to estimate $\beta(r)$ for the MW GC system.** Also the **implications of the orbits need to be clarified**, e.g. it has been argued that both low- and high-eccentricity orbits are the signature of accreted GCs!



Another complication is that as shown in the plot above, the MW "halo" GCs comprise at least two subsystems, possibly due to in-situ formation vs accretion (e.g., Lee et al. 2007; Georgiev et al. 2009). Therefore more careful analyses need to consider the observed orbits of these subsystems separately in comparison to the counterpart subsystems in simulations.

Elliptical galaxies

We first consider the field stars. Recovering internal orbital properties from kinematical observations requires dynamical models that go beyond fits to simple rotation and velocity dispersion profiles, and include the *shape* of line-of-sight velocity distribution (LOSVD). This shape acts as a diagnostic of orbit anisotropy, and can be quantified in various ways including the Gauss-Hermite moment h_4, the kurtosis κ, and unparametrized LOSVDs. h_4 fitting is an excellent approach for integrated-light stellar kinematics, and might be useful as well for modeling discrete velocity data, but it is not clear how stable and readily interpretable it is in this context since the second moment must also be fitted to the discrete data set. κ is easier to compute quickly and has a more straightforward interpretation, although it is a formally unstable quantity:

$\kappa \sim \langle v^4 \rangle / \langle v^2 \rangle^2 - 3$

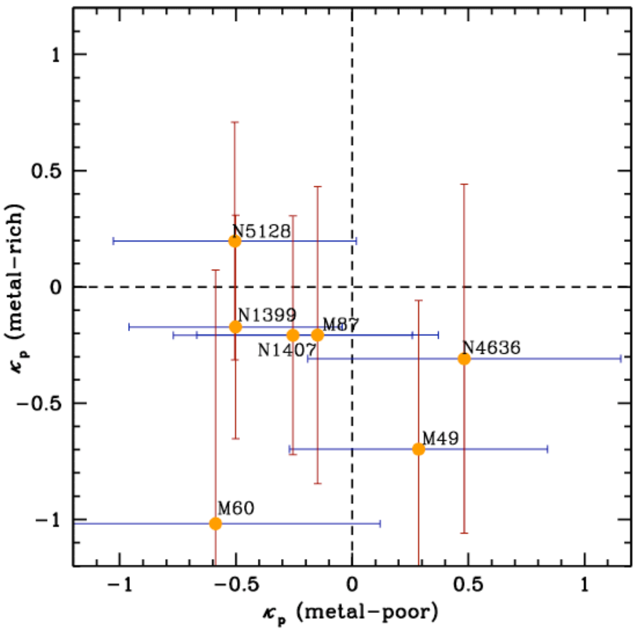
$\kappa > 0$ → radially-biased orbits

$\kappa \sim 0$ → isotropic orbits

$\kappa < 0$ → tangentially-biased orbits (*all in the case of an isothermal potential*)

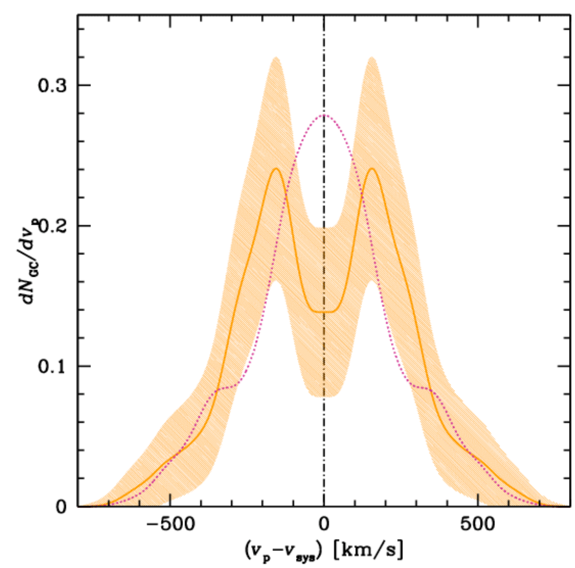
Modeling of stellar kinematics indicates mild radial anisotropy ($\beta \sim +0.2$) inside ~1–2 $R_{\rm eff}$ (Gerhard et al. 2001), which in more detail may not be as radial as expected from merger simulations (Thomas et al. 2009). In the outer regions (to ~7 $R_{\rm eff}$), planetary nebulae may be used as stellar proxies. Models so far suggest the expected $\beta \sim +0.5$ in fast rotators (Romanowsky et al. 2003; De Lorenzi et al. 2008, 2009; Napolitano et al. 2009), and near-isotropy in slow-rotators (*preliminary result*: Napolitano et al., in prep). As discussed above, the latter result appears to contradict expectations, but we already know that the models for forming these galaxies are missing something.

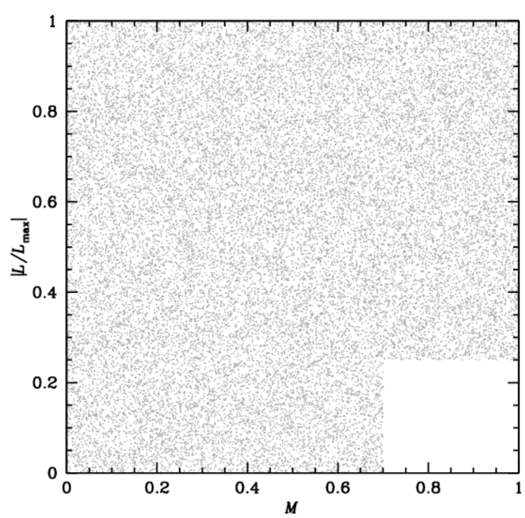
Now considering GCs, the only large enough kinematic samples so far are in the massive group-central slow rotators like M87. As summarized in Romanowsky et al. (2009), the results so far suggest near-isotropy as a general rule, with no clear systematic distinction between the metal-rich and metal-poor GCs (which is what one expects if the orbits are dominated by the galaxies' merger histories). The kurtosis plot *below* illustrates this from a directly observational perspective, and the anisotropy summary plot *above* shows some results after dynamical modeling (including detailed LOSVD-fitting Schwarzschild models in the case of M87; Romanowsky & Kochanek 2001). The isotropic or even tangential GC orbits may appear to contradict theoretical expectations, but as mentioned above, the PN orbits in these galaxies may be similar, so it may be **the galaxy formation theory that needs revising**.



Mass-dependence

An additional constraint is the mass-dependence of GC orbits, which has not been explored till now. Looking again at the kinematics data in the group-central ellipticals (at ~15 kpc typical galactocentric radius), there appears to be a widespread dependence of LOSVD shape on GC luminosity (see Romanowsky KITP talk, 15 Jan 2009). *Below left* is a diagram in one galaxy where the faint GCs have a Gaussian LOSVD, while the bright GCs have a double-peaked LOSVD characteristic of tangential orbits. *Below right* is a schematic of the implied orbital distributions, which is notably the **opposite** of what we might expect from theory (see *schematic above*). The dependence of this behavior on radius or metallicity is unclear.





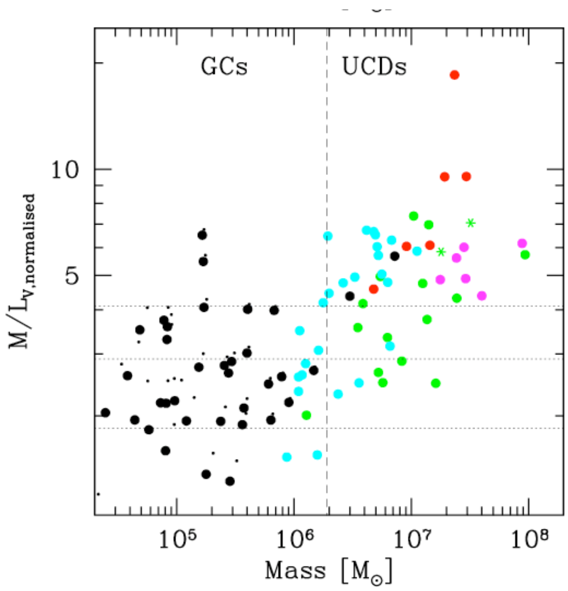
Solving the puzzle:

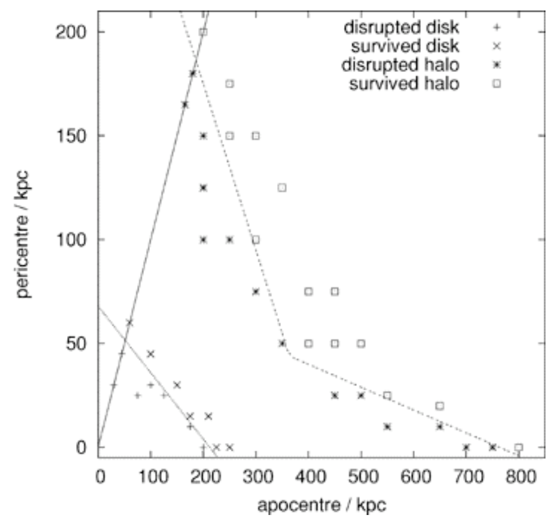
The tangential orbits for the bright GCs might be a product of **formation** or **evolution**. The only generic formation mechanism for tangential orbits is gas dissipation in disks, which should not be relevant for the old, merger-dominated halos of giant ellipticals.

For evolution, one might consider tangential orbits to be a **generic signature of "lucky survivors"** (where the objects on radial orbits have been disrupted). However, we still seem to need a **process that preferentially affects massive GCs**, while as discussed above, it is generally expected that orbital evolution occurs first for *less massive* GCs. The only process that acts preferentially on high-mass objects is dynamical friction, which is not thought to be important for GCs outside of galaxy centers. However, the **possibility remains that at least some GCs have or had DM halos**. According to the formula above, dynamical friction would be important if the GC masses were ~ 10^8 $M_\odot$.

Although traditionally GCs are considered to be free of DM, the absence of evidence (for DM) is not the same as evidence for absence—in particularly for past DM content. Simulations have found that GCs can form in DM minihalos at high redshift which are then stripped away when accreted to larger galaxies (Bromm & Clarke 2002; Mashchenko & Sills 2005; Saitoh et al. 2006). Observationally, this scenario is thought to explain special high-mass clusters like ω Cen and G1 (e.g., Freeman 1993; Hilker & Richtler 2000; Bekki & Chiba 2004), but there are also suggestions that more "normal" GCs could have lost ~90-99% of their mass (de Marchi & Pulone 2007; Vesperini et al. 2009). As a side note, it is plausible in this context that some present-day GCs could retain large amounts of DM which would be hard to detect (Mashchenko & Sills 2005; Baumgardt & Mieske 2008; Baumgardt KITP talk, 15 Jan 2009), and which are not necessarily ruled out by the occasional tidal tail (Moore et al. 1996) since the frequency of these features in a full cosmological context including substructures has not been studied.

If the most massive GCs did have primordial DM halos, it still remains to be worked out whether the additional mass could cause their orbits to become tangential (whether by circularization or by selective destruction). This possibility is suggestively related to the population of ultra-compact dwarf galaxies (UCDs) or dwarf-galaxy transition objects (DGTOs) which may be of very different origins than "true" GCs and may contain DM. The mass scale of the transition appears to be ~$1\text{–}2\times10^6$ $M_\odot$ (Rejkuba et al. 2007; Mieske et al. 2008; see *figure below left*), which is **uncannily similar to our inferred boundary between isotropic/tangential "GC" orbits**.





The interpretation then suggested is that these bright objects are the remnants of tidally stripped nucleated dwarf galaxies (again like ω Cen, see above). However, it is not clear that this explains the orbits. Given a primordial population of dwarfs, the unscathed ones should lie on preferentially tangential orbits, while the stripped ones (the DGTOs) **should be on preferentially radial orbits, not tangential as observed**. One would also expect to see the line-of-sight velocity dispersion of the DGTOs to be high near the galaxy center, not low as observed (Thomas et al. 2008). However, the simulations of Goerdt et al. (2008) suggest a more complex picture, where the "survival region" of orbits apparently depends on some convolution of pericentric distance and time spent at pericenter (see diagonal line between surviving and disrupted disks in *figure above right*). Thus it remains to be determined what LOSVDs are predicted for objects at a snapshot of time and distance.

Another speculative alternative is that the bright objects are bona fide GCs but that these originated in systematically higher-mass satellite subhalos than the rest of the GCs, and that the more massive subhalos had systematically more tangential orbits. Typical (low-sigma) subhalos are not expected to have initial or final orbital parameters with a strong dependence on mass (e.g., Gao et al. 2004), but one could revisit the Diemand/Moore picture and hypothesize that the bright GCs are connected to early high-sigma DM peaks. Unfortunately this scenario goes the wrong way, as the higher-sigma peaks would yield more radial orbits.

An additional consideration is that the tangential orbit bias for bright GCs does not necessarily mean that radial-orbit depletion occurred for bright GCs preferentially. A similar outcome might result if the depletion happens at all luminosities, which among the bright GCs leaves only tangential cases intact. *An analogy is that throughout the ocean, a range of sizes of schools of fish is found, except the largest schools are only found far from the fishing ports. This does not mean that only the largest schools are depleted by fisheries, but that the most extreme examples will always be ones that were unscathed.*

One can characterize this scenario by considering a two-dimensional distribution function of mass and line-of-sight velocity at a fixed radius (or energy) $f(M,\mathrm{v})$. One then constructs a continuity equation for f reflecting the inflows and outflows of objects from a region of (M,v) phase-space owing to mass shrinkage. If the system is completely scale-free (including a power-law form for the mass distribution dN/dm) then no further analysis is necessary: it is evident that no mass-dependence can develop for the LOSVD. If dN/dm has a scale-dependent high-mass cut-off (e.g., a Shechter function), then the observed LOSVD dependence might develop in principle—which remains to be worked out quantitatively.

More exotic speculations would be that dynamical friction is stronger than normally supposed because of an alternative form of dark matter or of gravity.

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