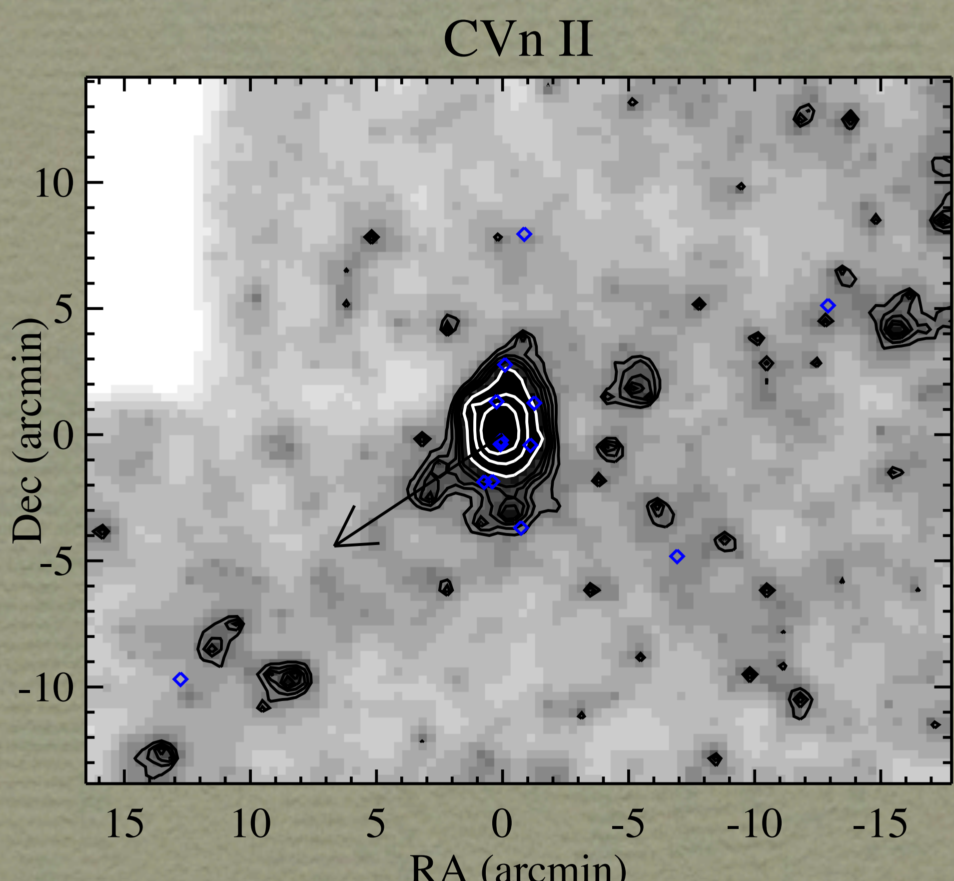
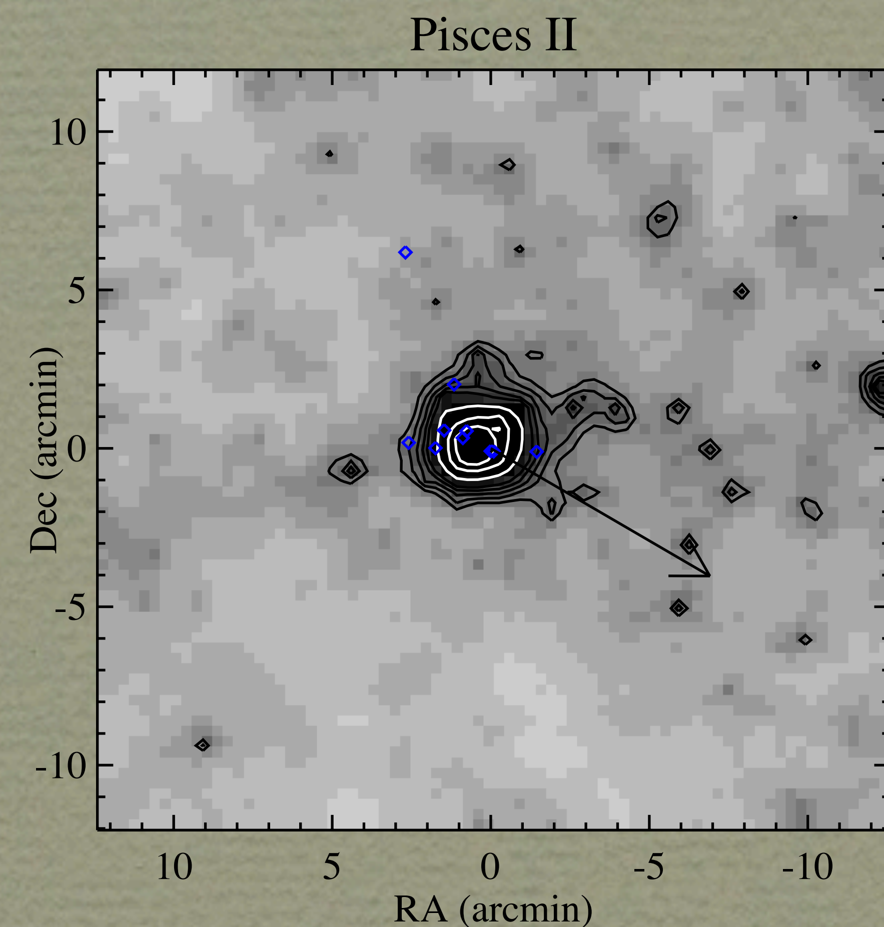
THE STRUCTURE AND STAR FORMATION HISTORY OF THE NEW MW SATELLITES





David Sand (UCSB/LCOGT)
w/ Caldwell, Olszewski, Seth, Strader, Willman, Zaritsky

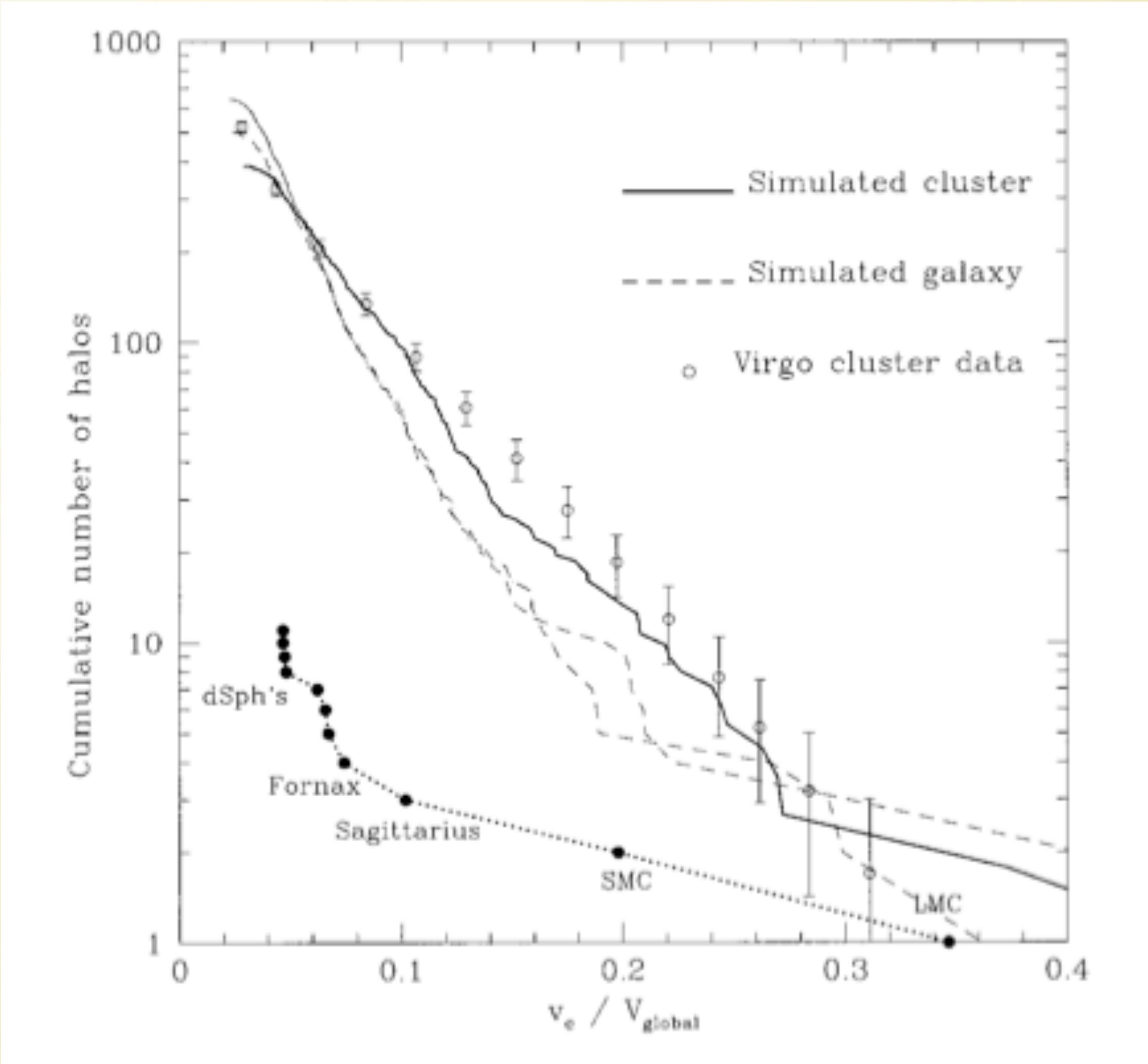
SF in Dwarf Galaxies -- Lowell 2012

Outline

- Brief Motivation -- What is the structure and SFH of the new MW satellites? What fraction are being tidally stripped? Ultimate goal is to connect observations with CDM simulations.
- Detailed SFH and structure analysis of 5 of the new MW satellites: Hercules, Leo IV, Leo V, Canes Venatici II, and Pisces II
- Compile structural data on the new satellites (and the classical dSphs).

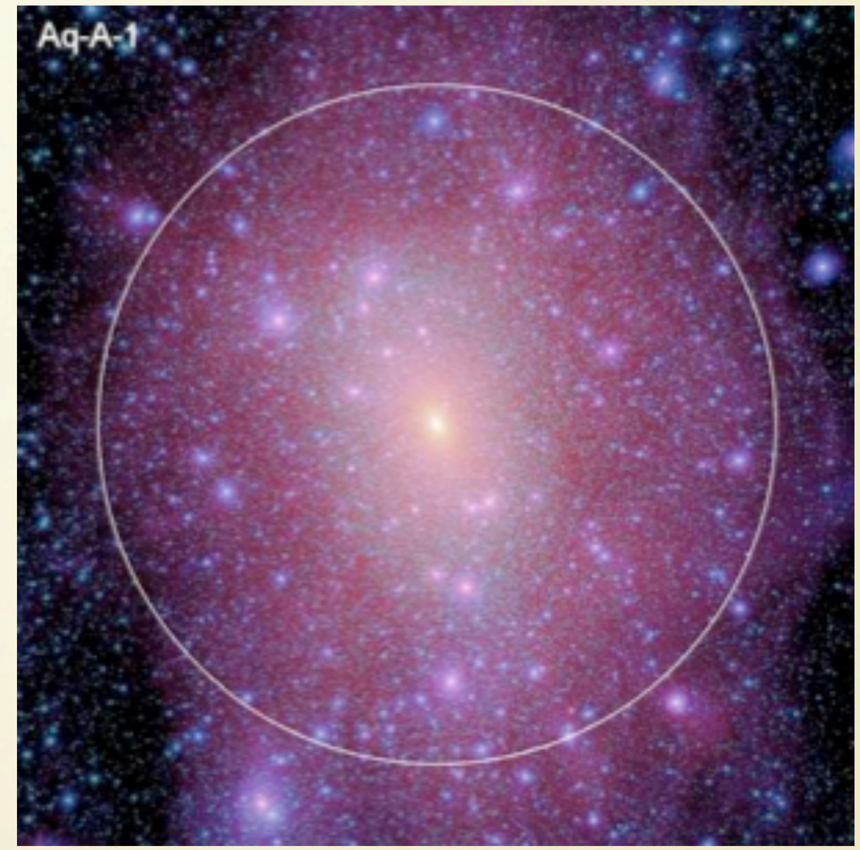
Context: The 'missing satellites problem' Mismatch in the Number of Subhalos

- Within the virial radius, the MW should contain ~500 halos larger than Draco
- The galaxy cluster satellite function could reproduce numerical predictions, but not for a halo the size of the MW!



Moore et al. 1999; Clear lack of MW satellites, pre-SDSS (see also Klypin et al. 1999)

The place of the new dwarfs -- Do they fit with CDM?



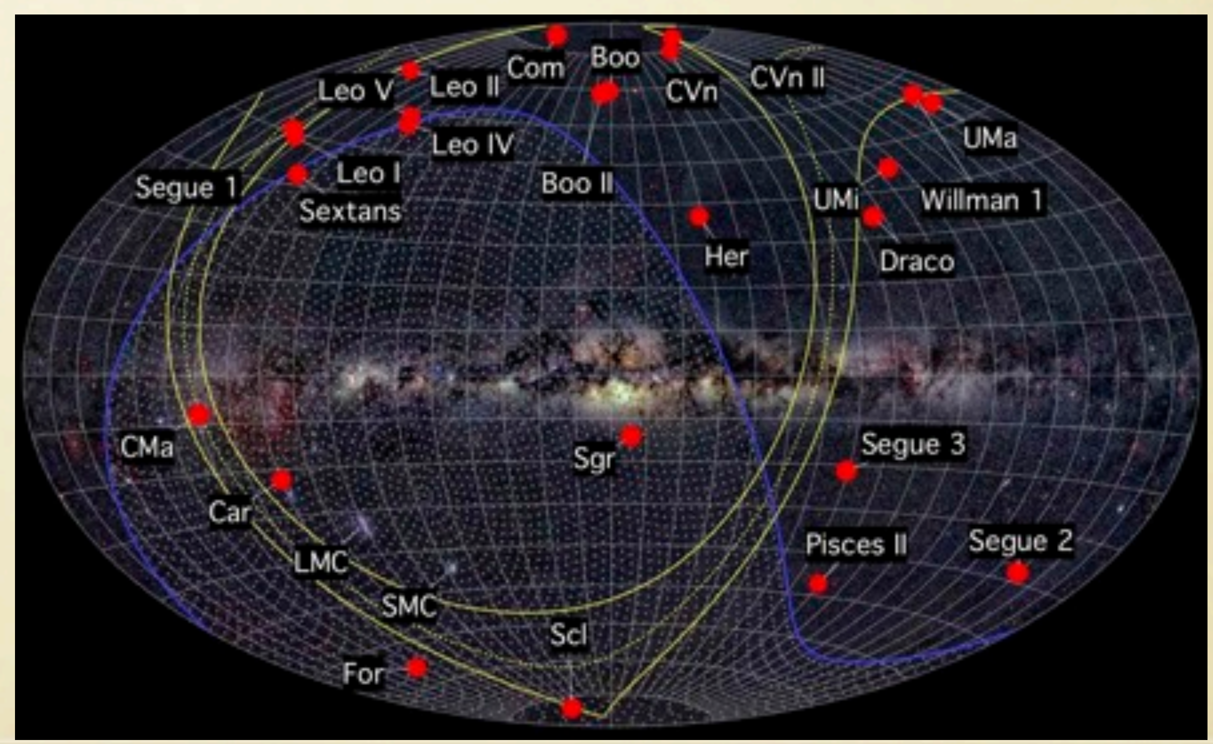
Connecting observations with simulations is not trivial! We must have a deep observational understanding of the new satellites in order to put them in context.

Key questions include:
Are they all dark matter dominated?

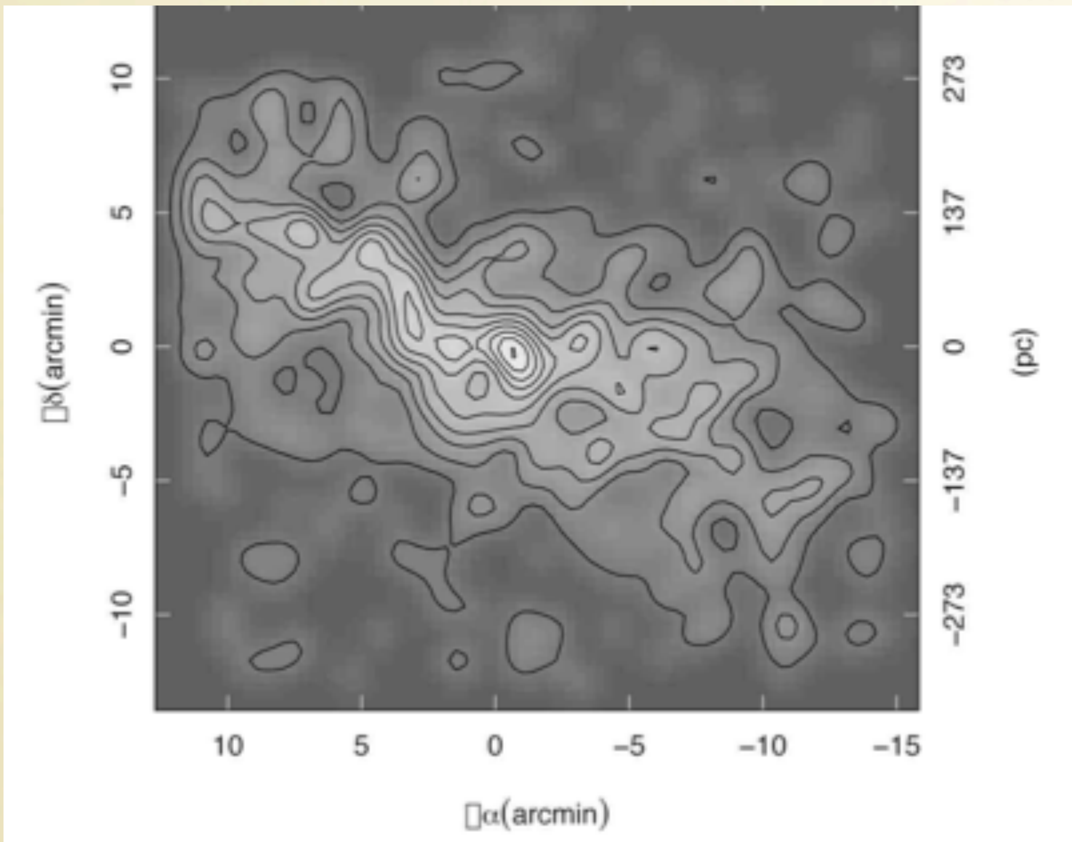
Are they the remnants of larger progenitors?

What is their star formation history?

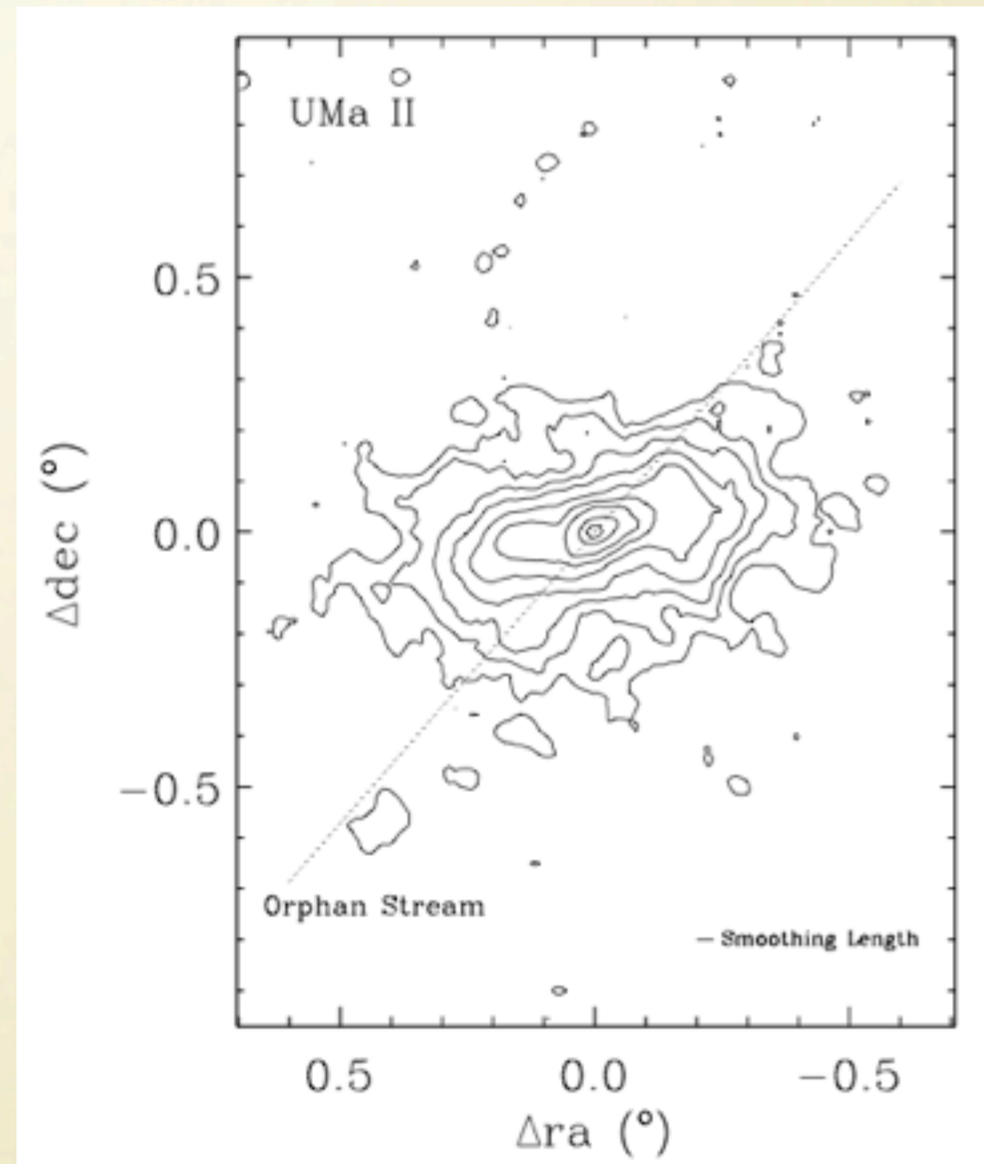
What is their orbital history?



Are the new dwarfs the disrupted cores of larger progenitors?



Ursa Major I has an ellipticity of e~0.5-0.8 (Martin et al. 2008; Okamoto et al. 2008)



Ursa Major II shows signs of ongoing interaction, spans 1.2 deg on the sky, with e~0.5 (Munoz et al. 2010)

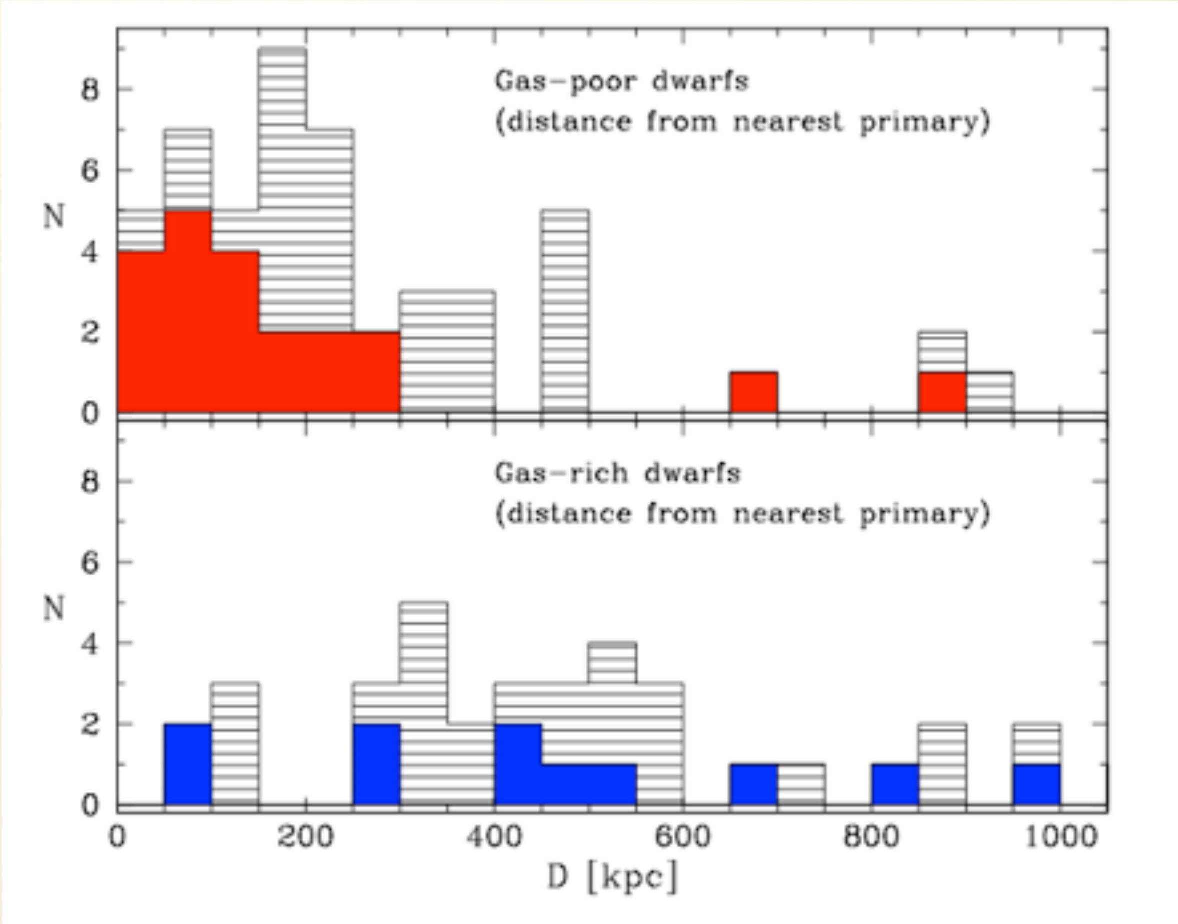
Nature vs. Nurture? What drives the SFH of the satellite galaxies?

Of the 9 ‘classical’ MW dSphs, the 4 most distant (d>90 kpc) experienced extended SF, with a fraction occurring <10 Gyrs ago (Dolphin 2005). The four closest dSphs all had truncated SF, with all stars forming >10 Gyrs ago.

This supports a model where SF in the nearby dwarfs was halted by environmental effects, such as tidal/ram pressure stripping or local ionizing radiation.

BUT, the four nearest classical dSphs are also the least luminous. Is truncated SF just a function of their presumably smaller potential wells?

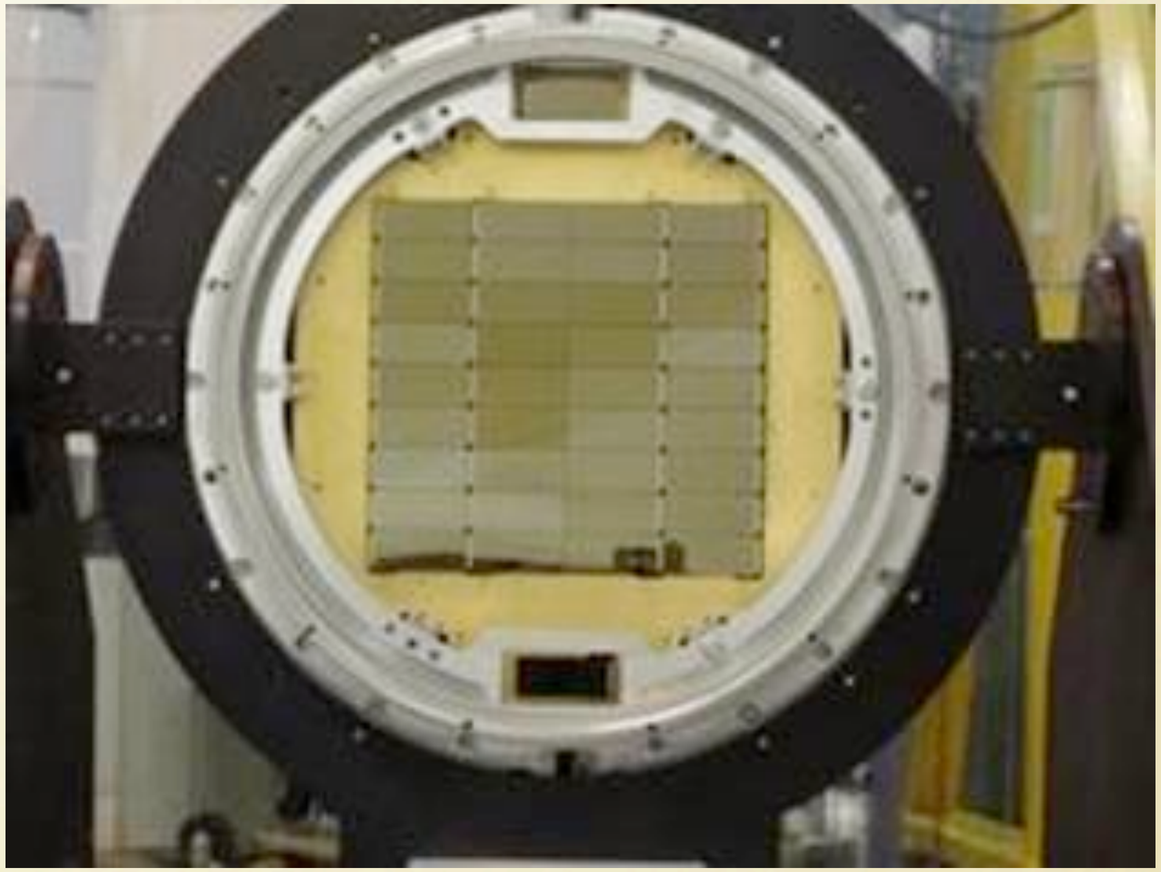
A systematic study of the SFHs of the new MW satellites can test this model.



Grebel 2004

A deeper look at the new dwarfs

- Measure their star formation history and metallicity via CMD-fitting techniques; i.e. StarFISH (Harris & Zaritsky 2001)
- Measure their structural parameters
- Search for signs of extended structure; i.e. tidal streams.
- Look for larger trends. For example, SFH as a function of MW distance.



Megacam on the MMT (and now Magellan) ~24x24 arcmin

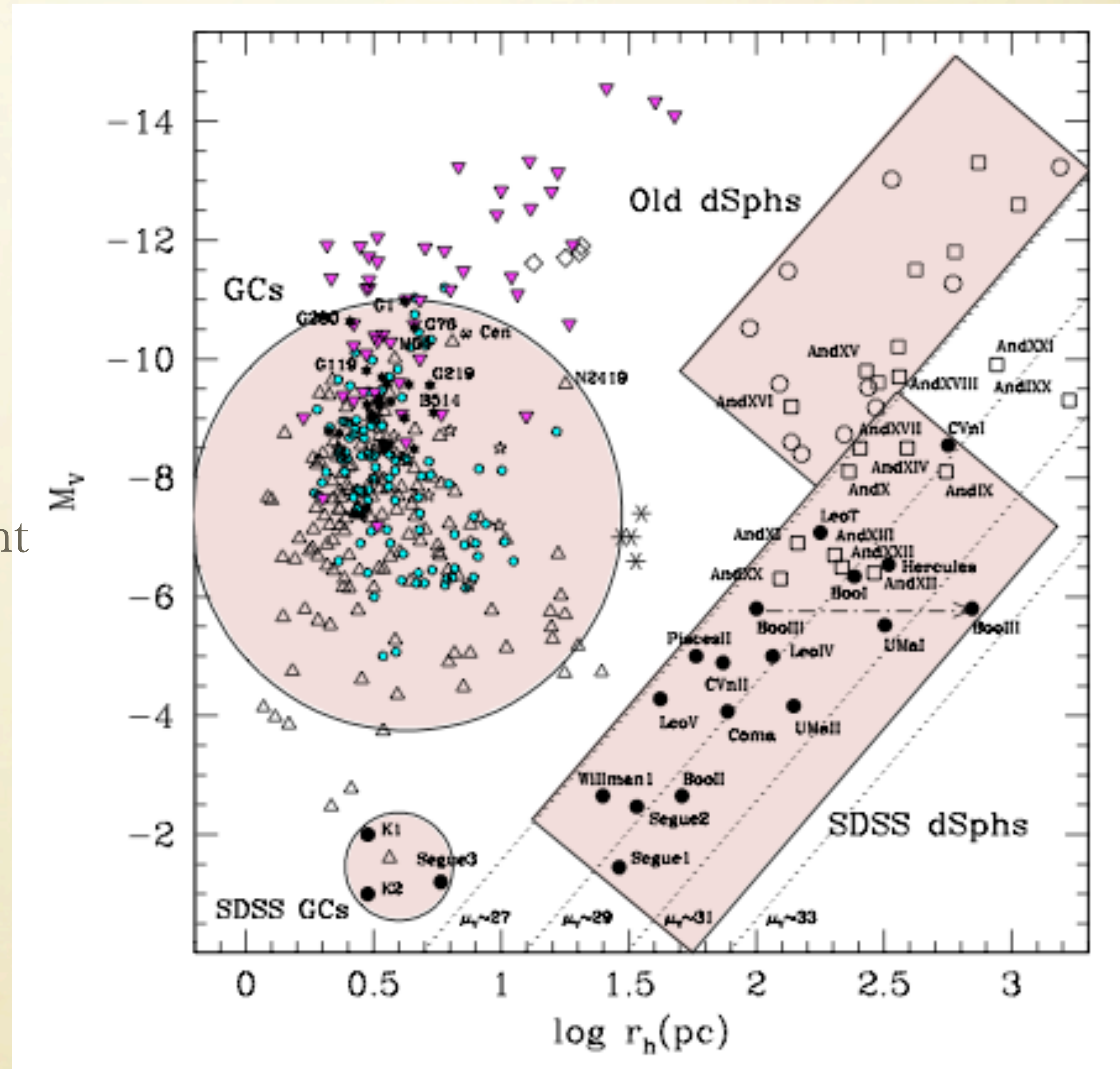
The place of the new dwarfs

Focus on 5 dwarfs
(Sand et al. 2009, 2010, 2011)

Hercules (at 130 kpc) is unusually extended, with e~0.6 (Coleman et al. 2007), making it a good candidate to search for tidal streams

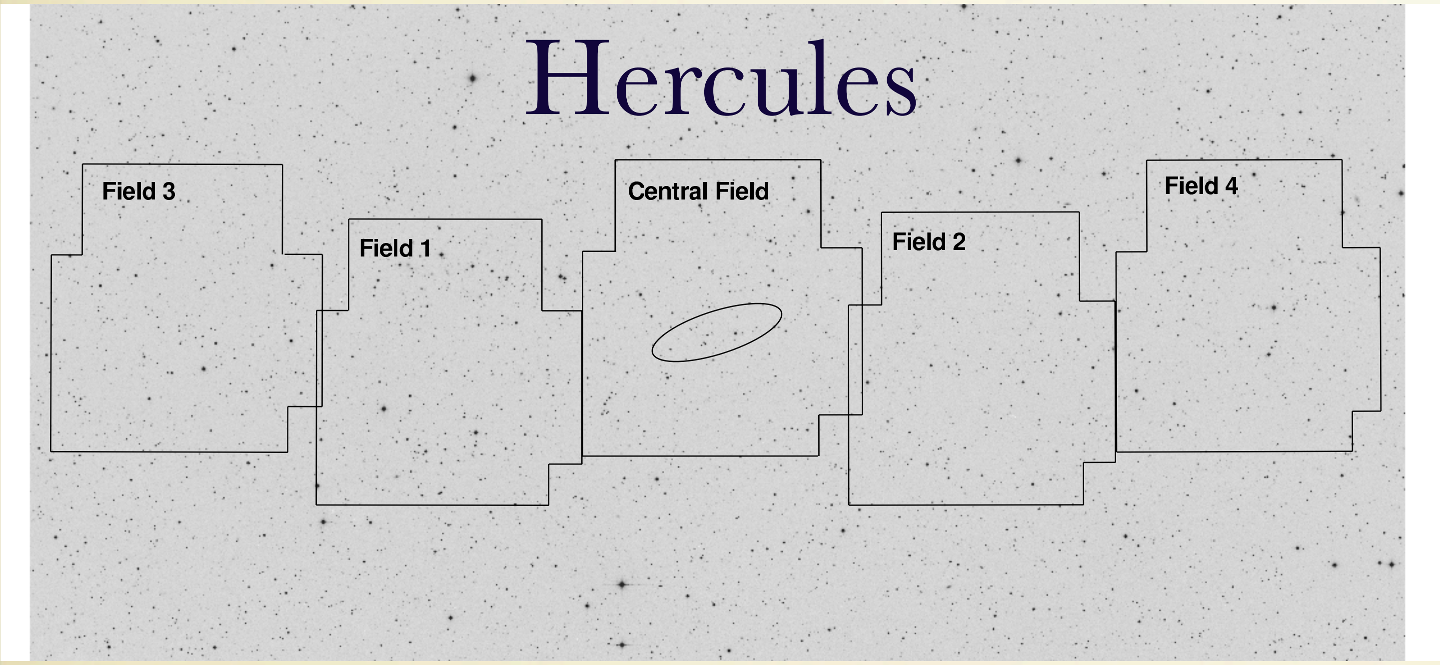
Leo IV may be a 'thick' red giant branch, indicating multiple epochs of star formation or a spread in metallicity. Leo V was found to be only ~2 deg away. Are they associated?

Leo V, Pisces II & CVn II all at >150 kpc and have half light radii of ~70 pc

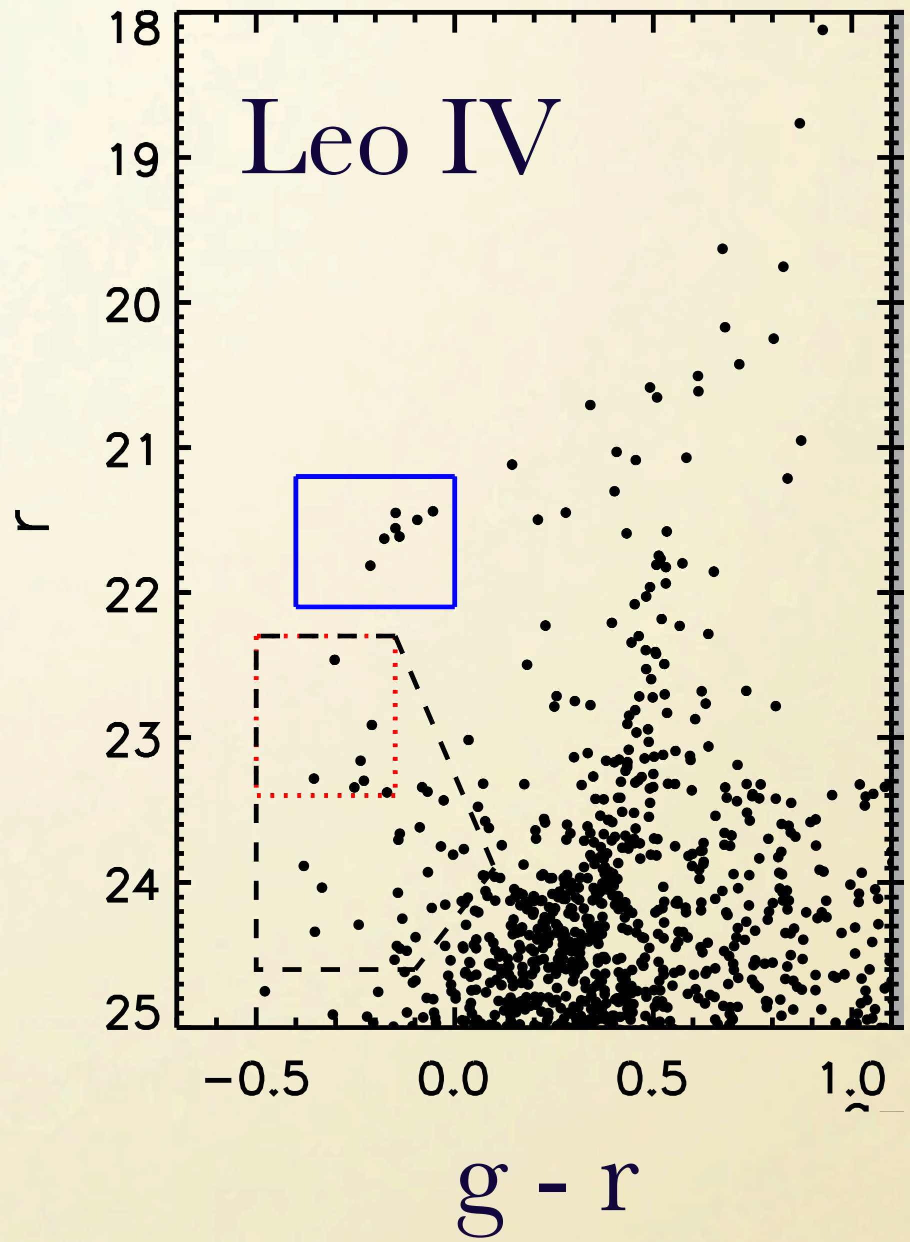


Taken from Clementini 2010

The observations



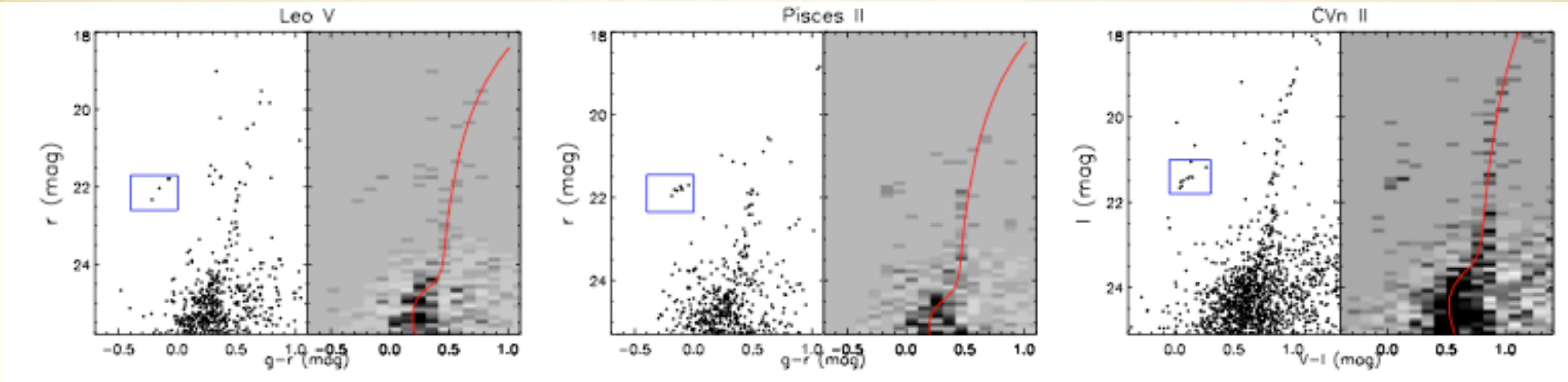
Hercules -- 5 LBT pointings, 30 min per filter in B,V,r



The new data goes ~3 mag deeper than the original SDSS discovery data

Leo IV -- Central pointing only; 25 min per filter in g,r

More Observations



Sand et al. 2011

- Color magnitude diagrams within 2r_h.
- These observations are still hard even with Magellan/Subaru
- Data goes down to main sequence turnoff
- Very sparsely populated but still have a clear blue horizontal branch

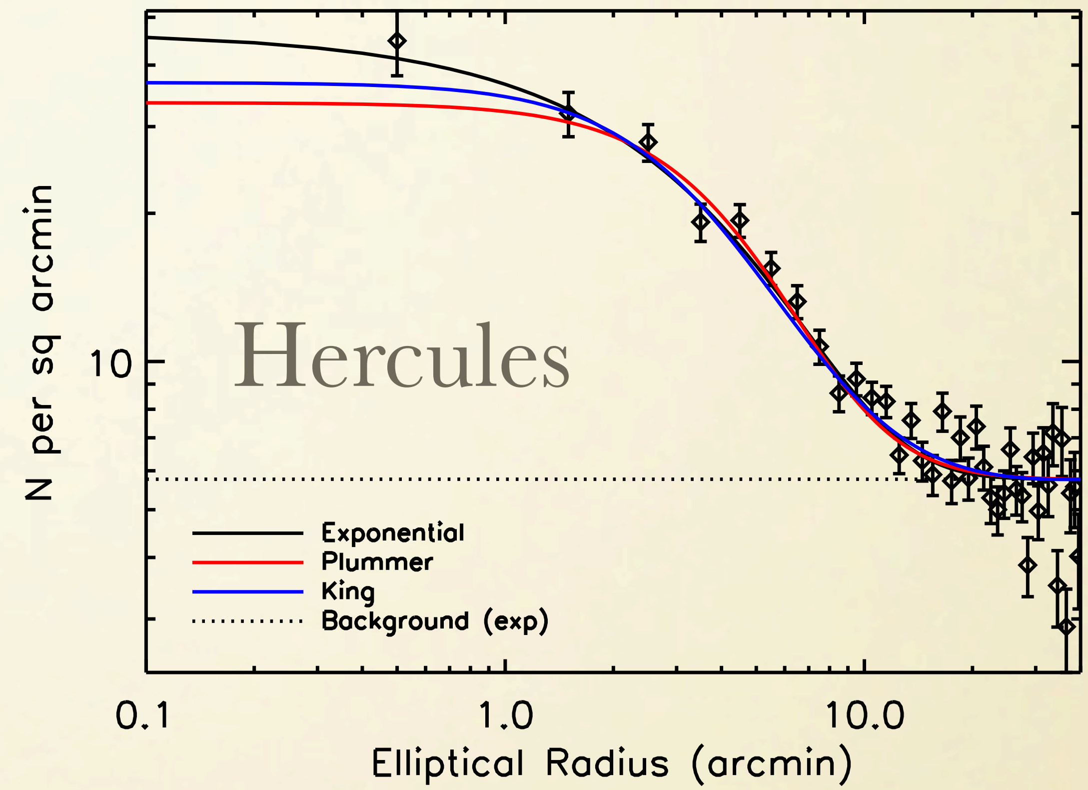
PARAMETERIZED STRUCTURAL FITS

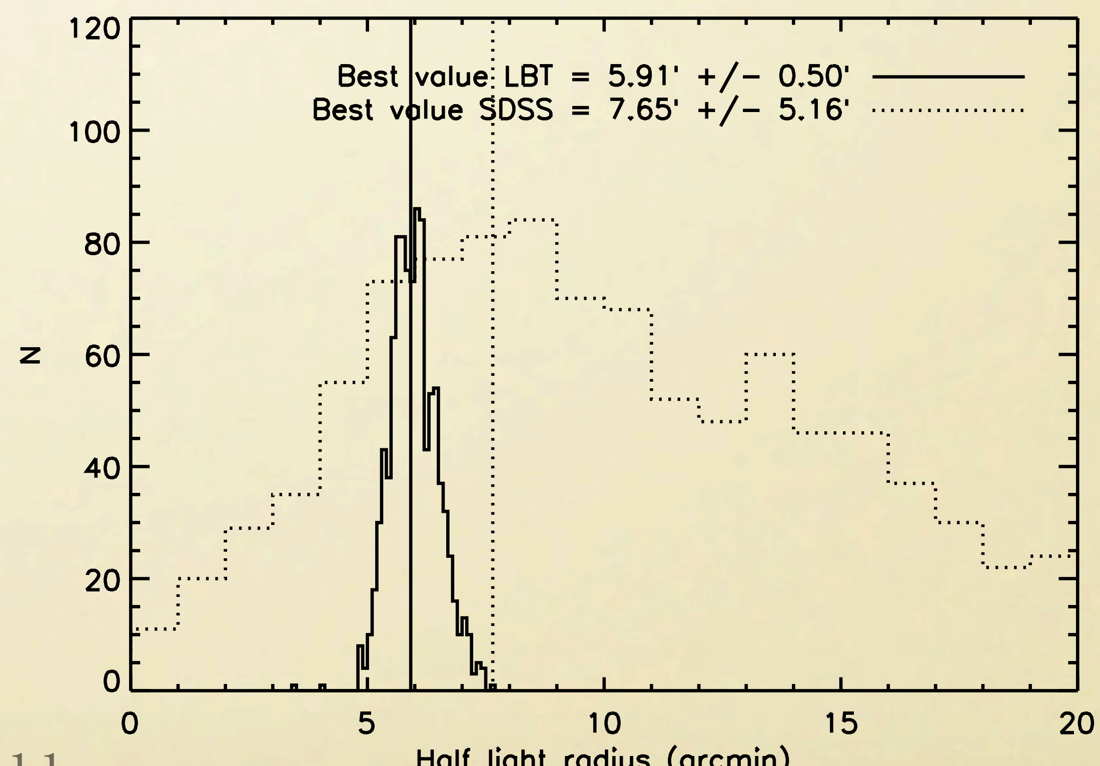
--We adopt a Max-Likelihood technique to measure the parameterized structure of the new dwarfs, with a background term (Martin et al. 2008).
--Uncertainties are estimated via 1000 bootstrap resamples.
-- Hercules ellipticity is e~0.65!

$$\Sigma_{\rm King}(r) = \Sigma_{0,K}\left(\left(1+\frac{r^2}{r_c^2}\right)^{-\frac{1}{2}} - \left(1+\frac{r_t^2}{r_c^2}\right)^{-\frac{1}{2}}\right)^2$$

$$\Sigma_{\rm Plummer}(r) = \Sigma_{0,P}\left(1+\frac{r^2}{r_P^2}\right)^{-2}$$

$$\Sigma_{\rm exp}(r) = \Sigma_{0,E}\exp\left(-\frac{r}{\alpha}\right),$$



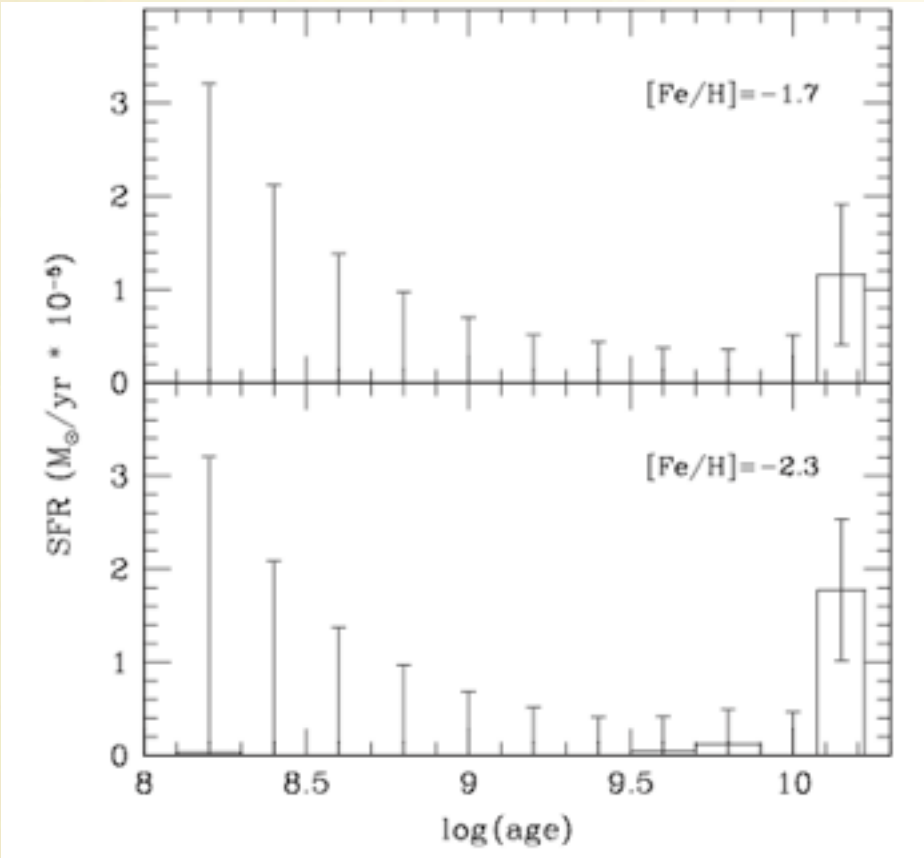


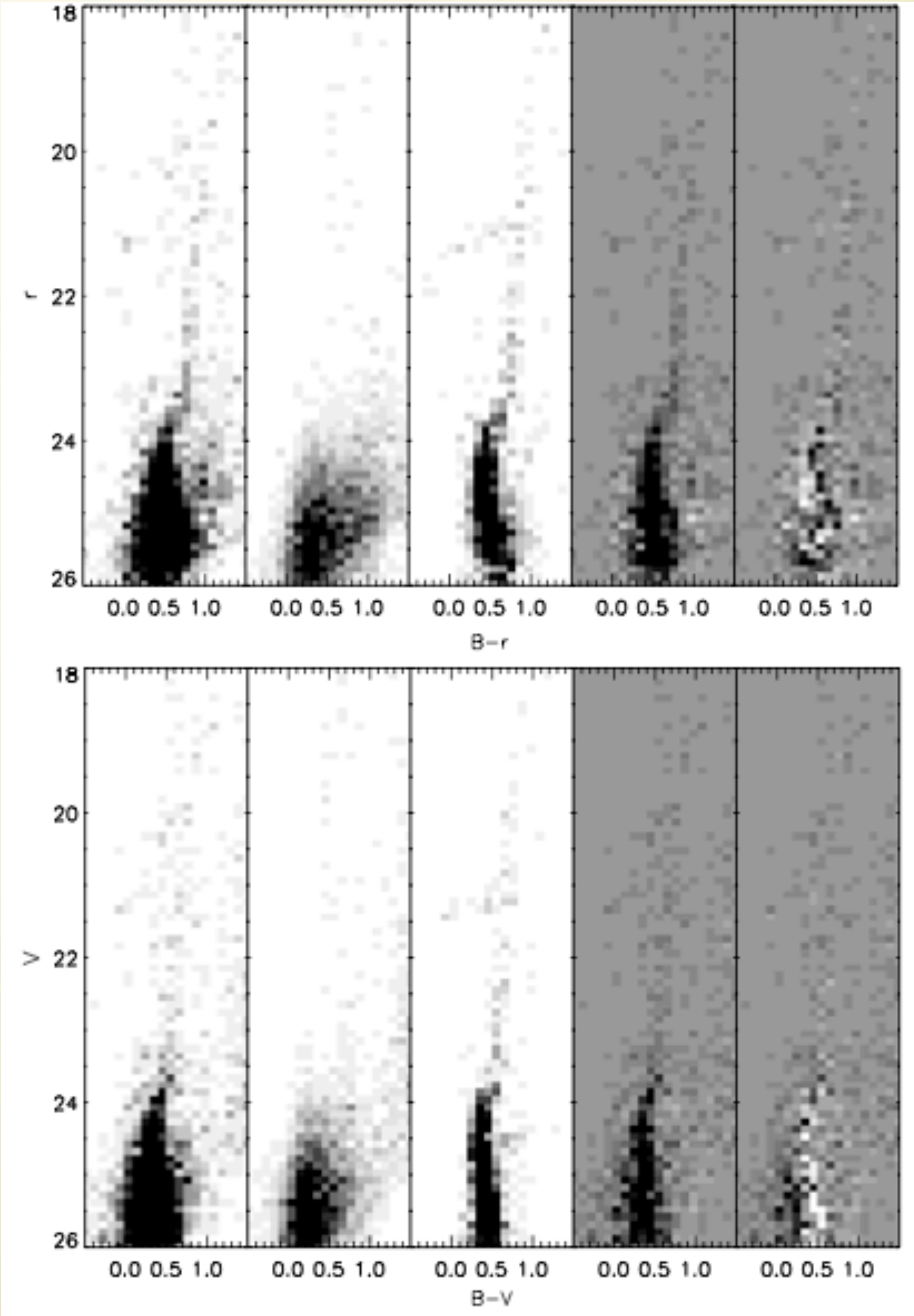
See also Munoz et al. 2011

Star-formation history via CMD-fitting

- StarFISH (Harris et al. 2001) takes a library of theoretical isochrones and includes the effects of extinction, photometric errors, completeness and binarity to produce realistic model CMDs.
- A minimization routine is used to find the linear combination of model CMDs that best matches the observed photometry.

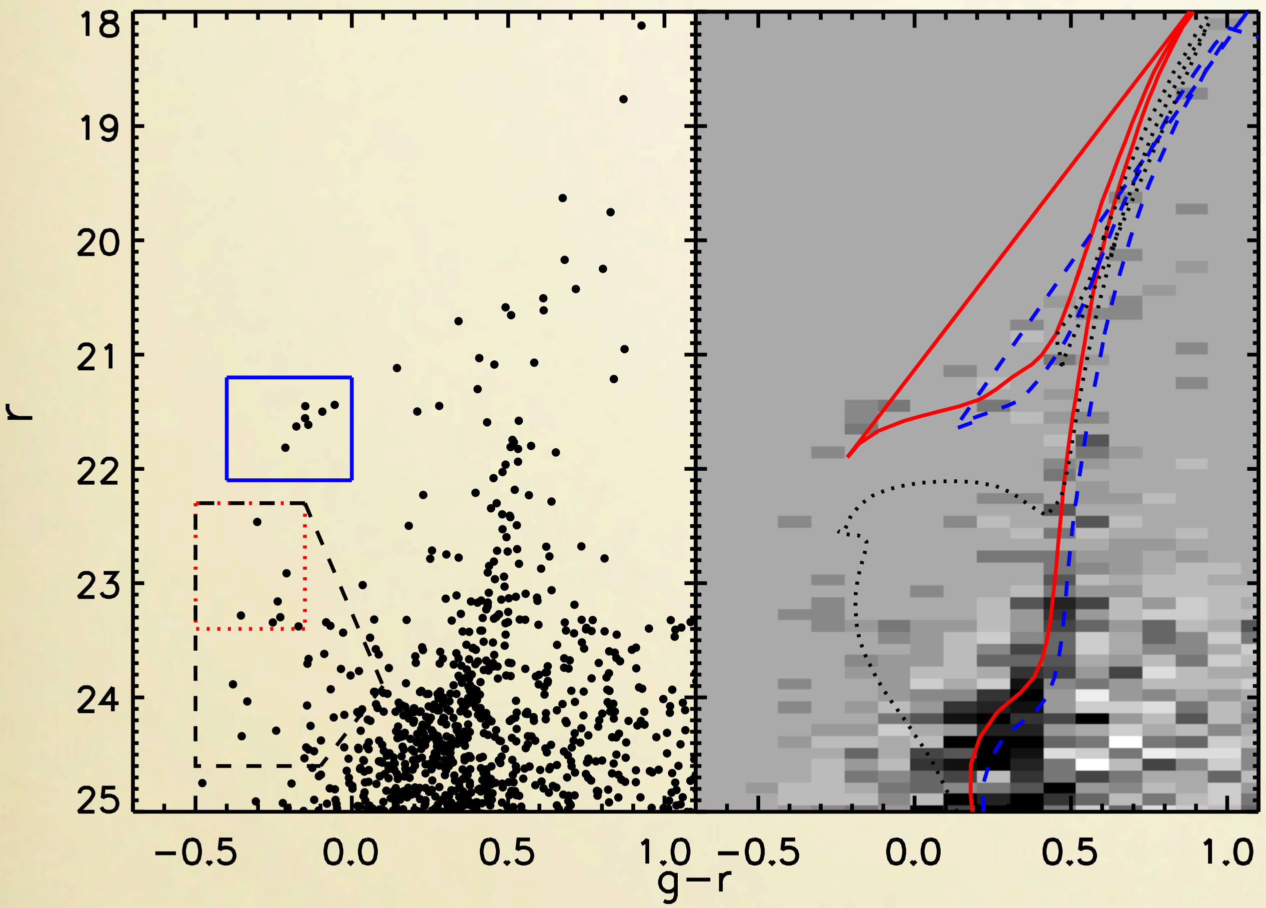
Star Formation of Hercules

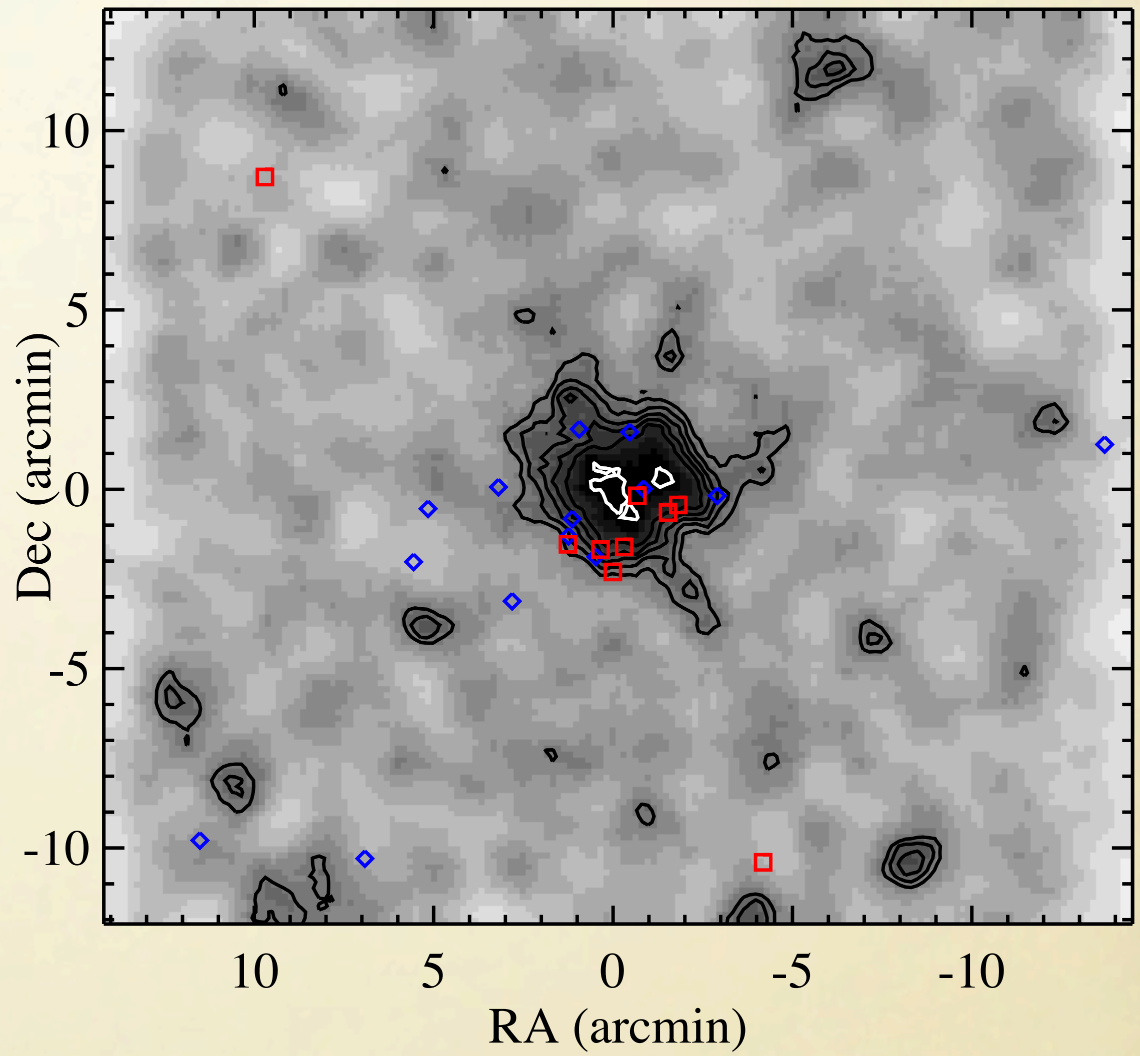




- Hercules is predominantly old and metal poor (consistent with e.g. Kirby et al. 2008), although we cannot rule out low levels of recent star formation

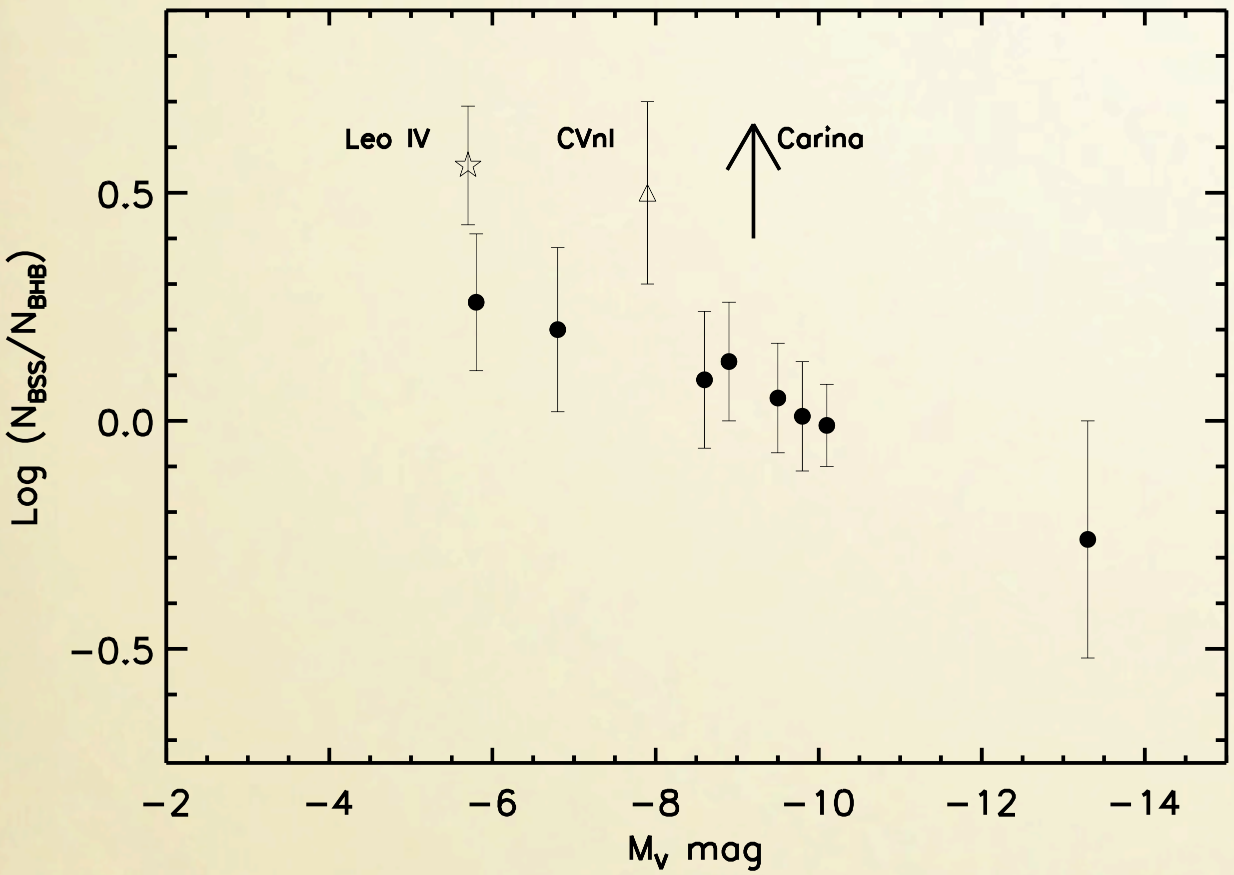
Are there young stars in Leo IV??



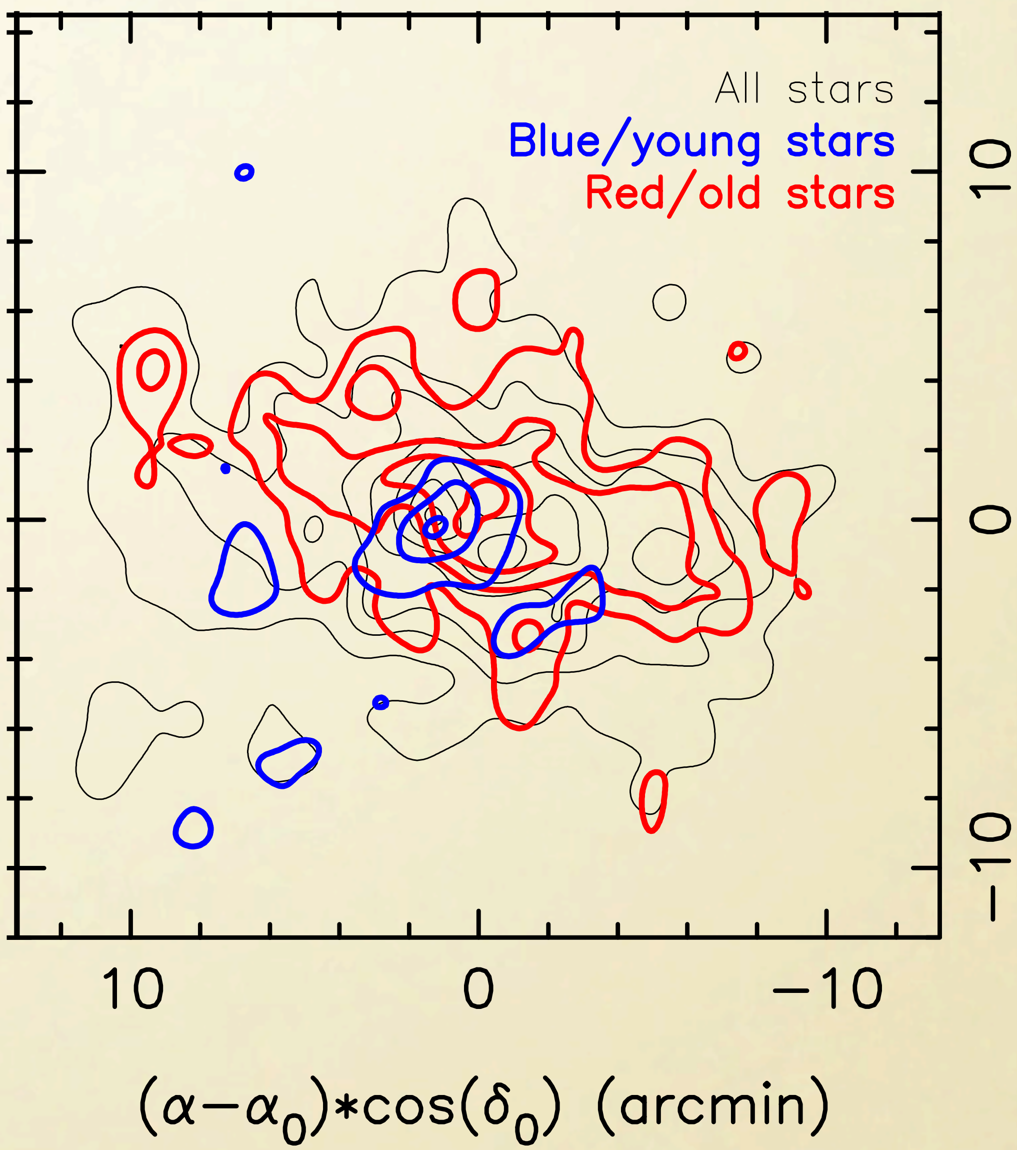


Stars that would lie on the ~2 Gyr main sequence seem to be segregated within the body of Leo IV

Are there young star forming regions in the other new dwarfs?



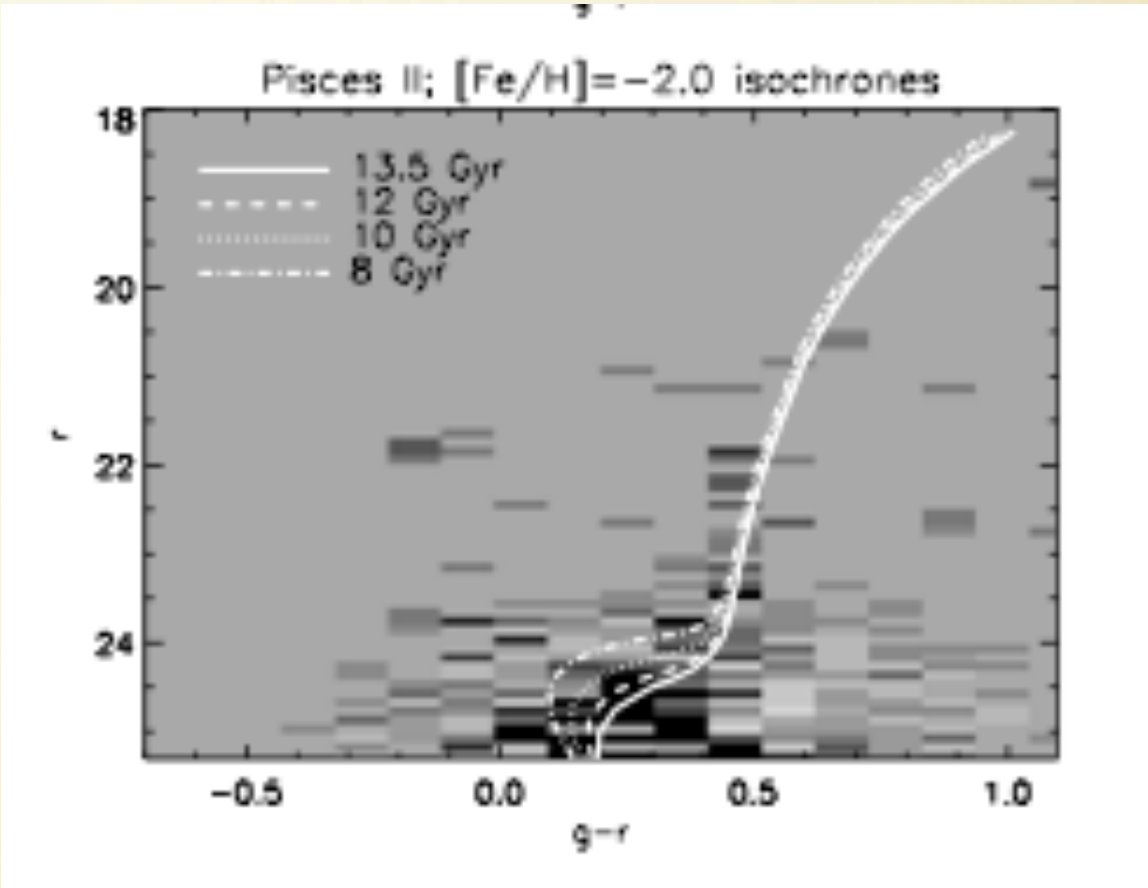
So far, only Leo IV and Canes Venatici I have an excess of 'blue plume' stars, which appear to be segregated with respect to the dwarf as a whole



Canes Venatici I; Martin et al. 2008

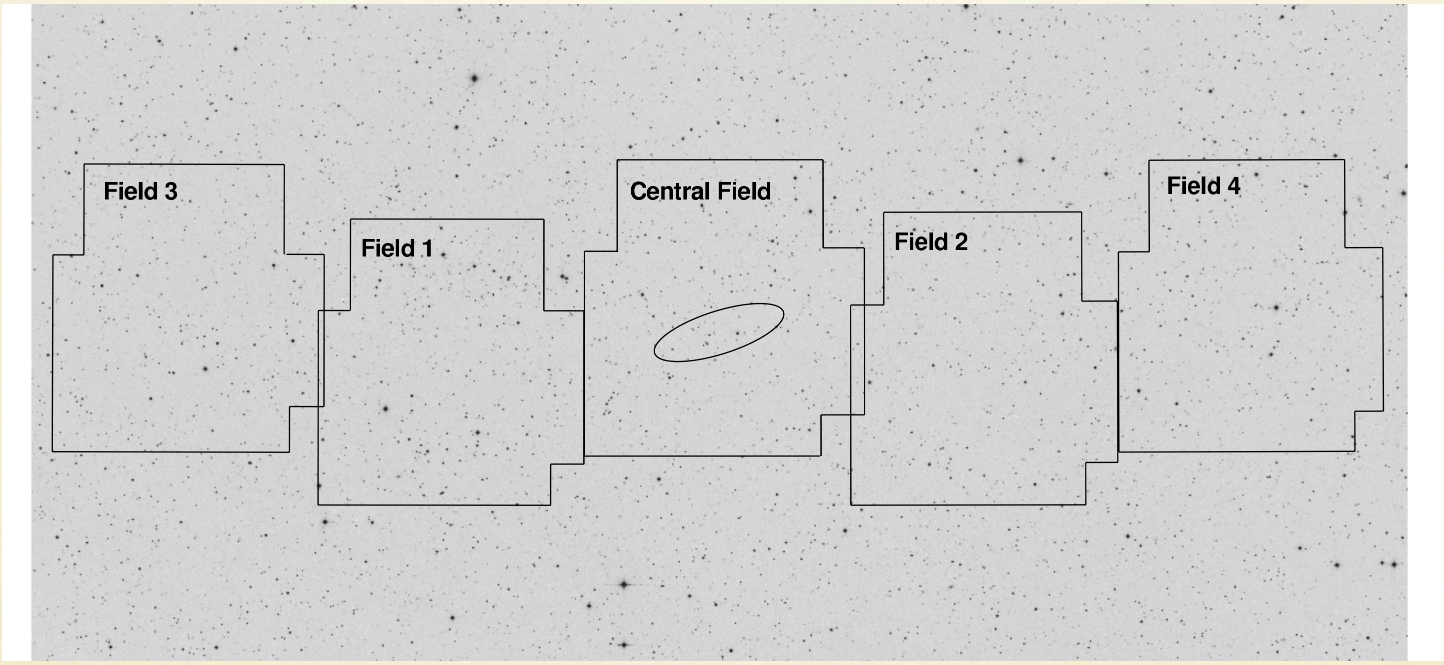
Star Formation History Summary

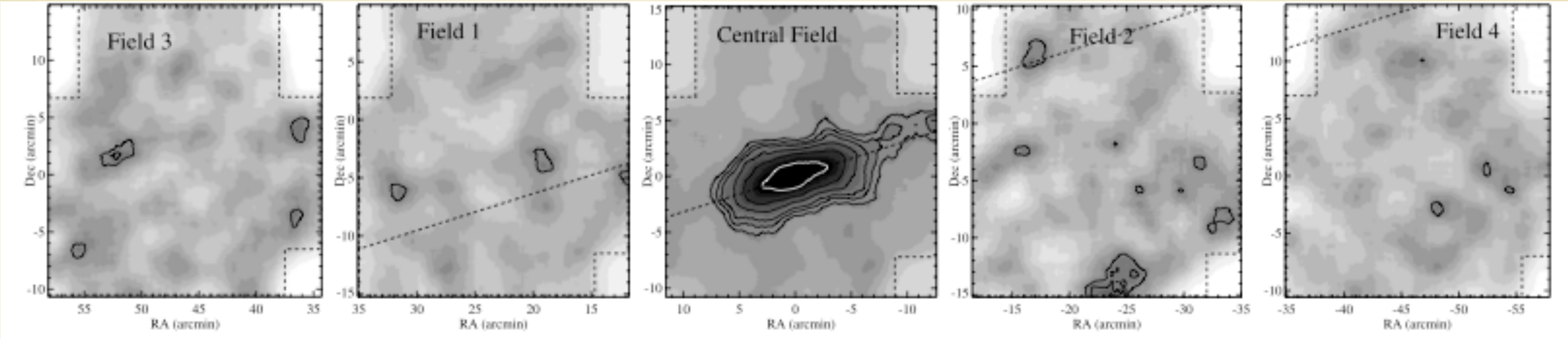
- All the new MW sats are dominated by old (>10 Gyr) and metal poor ([Fe/H]<-2) stellar pops.
- Leo IV & CVn I *may* have had a sprinkling of more recent SF.
- The other satellites were too faint to definitively say that they have/have not had more recent SF.
- It will always be *very* hard to distinguish 12 & 13 Gyr stellar ages (for instance). How do you find reionization fossils?



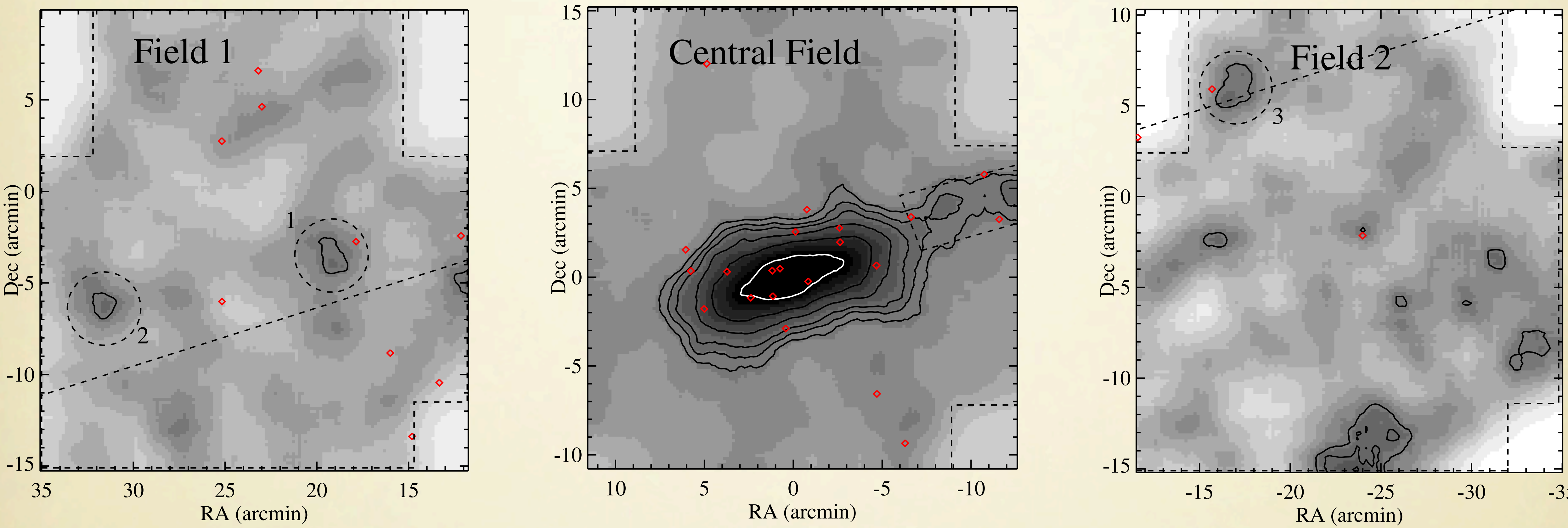
Pisces II, CVn II and Leo V are all consistent with [Fe/H]~-2, >12 Gyr old stellar pops. No sign of young stars. (Sand et al. 2011)

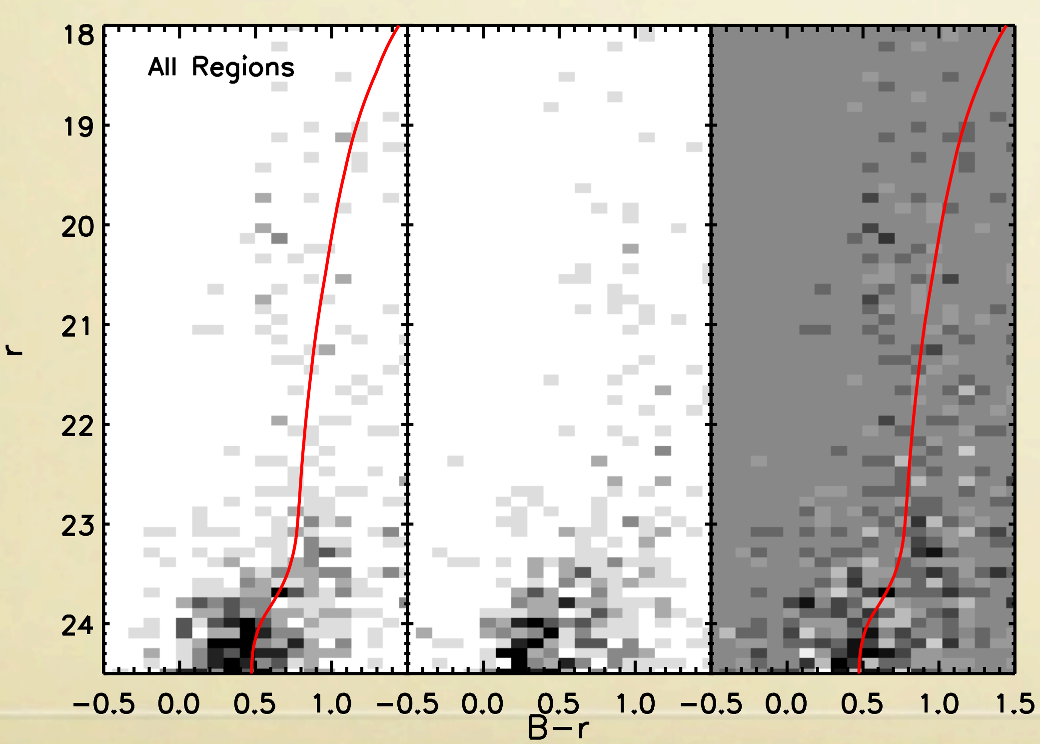
Search for extended structure -- smoothed maps of Hercules

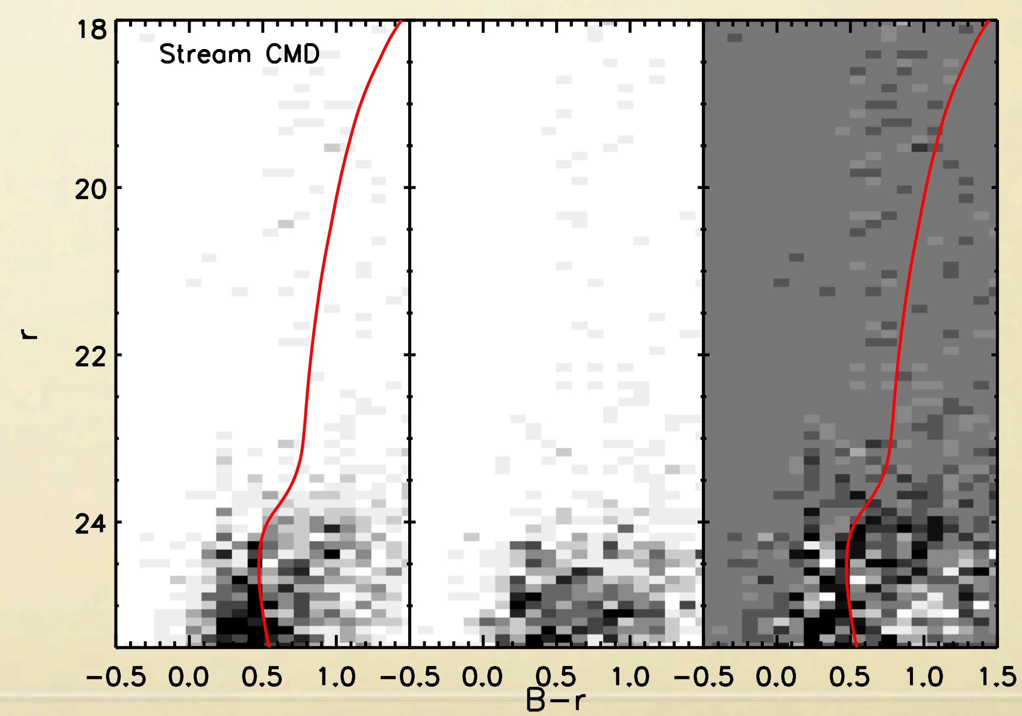




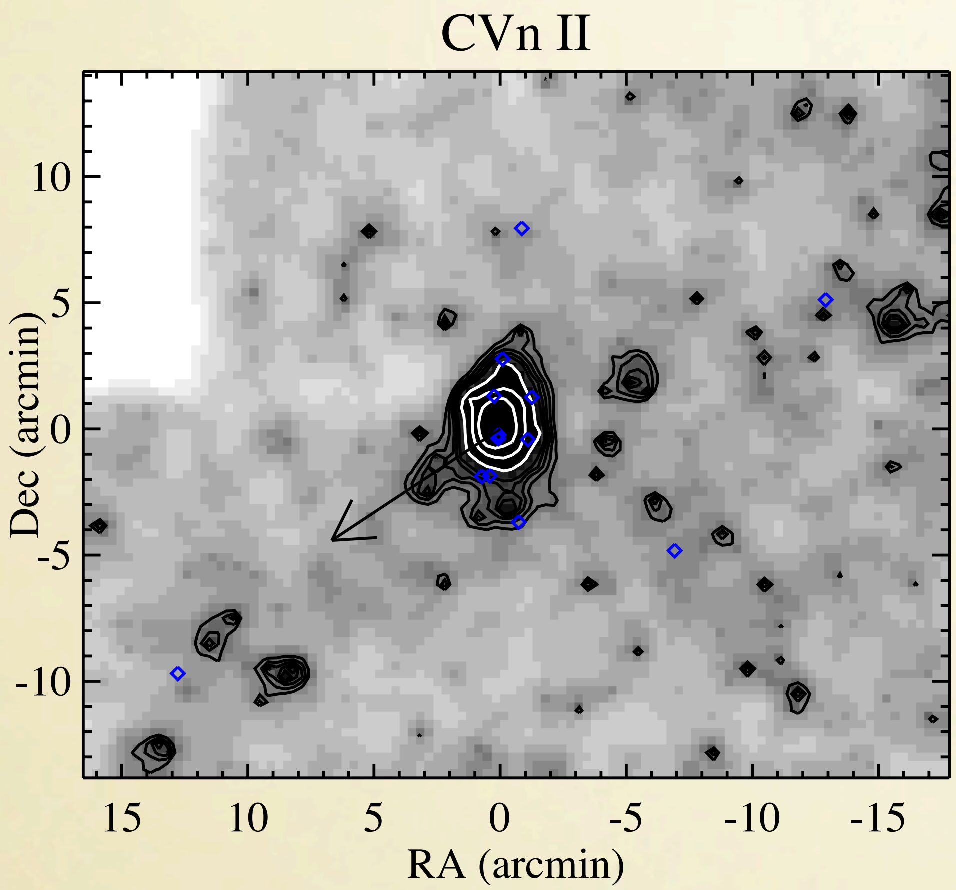
Signs of external structure in Hercules?

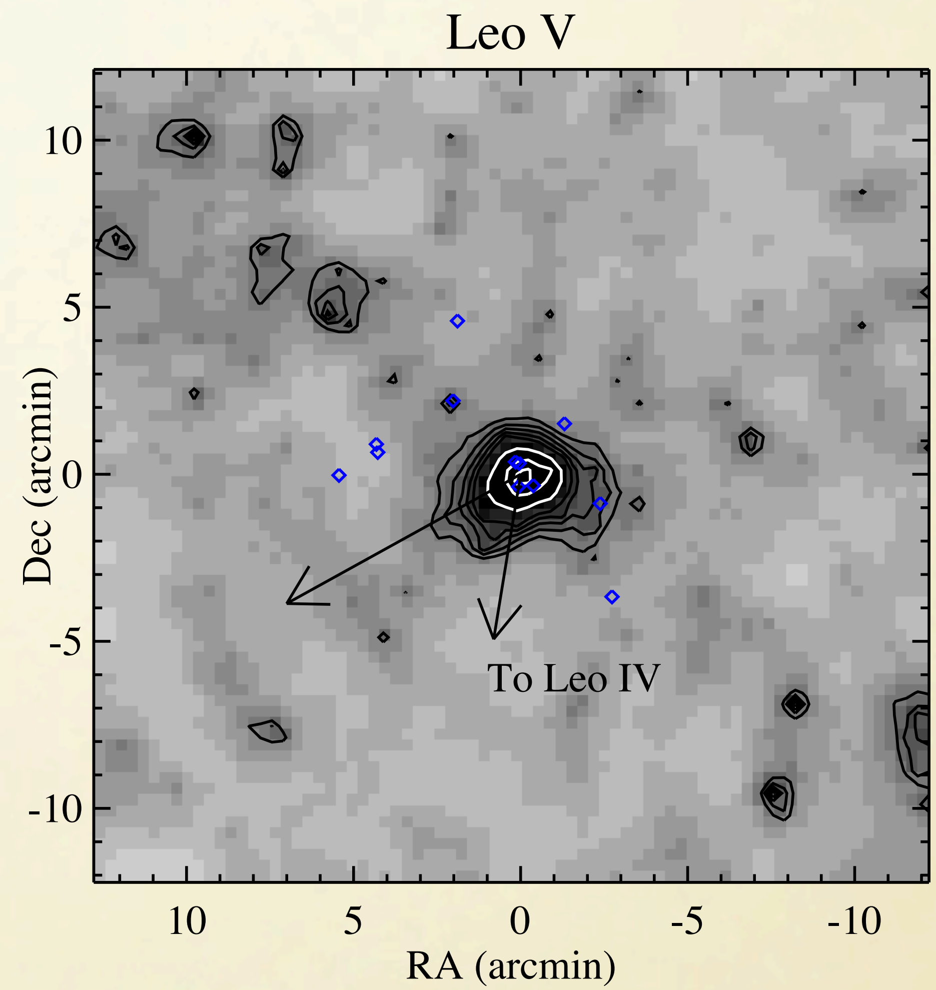






Some Signs of Tidal Disturbance

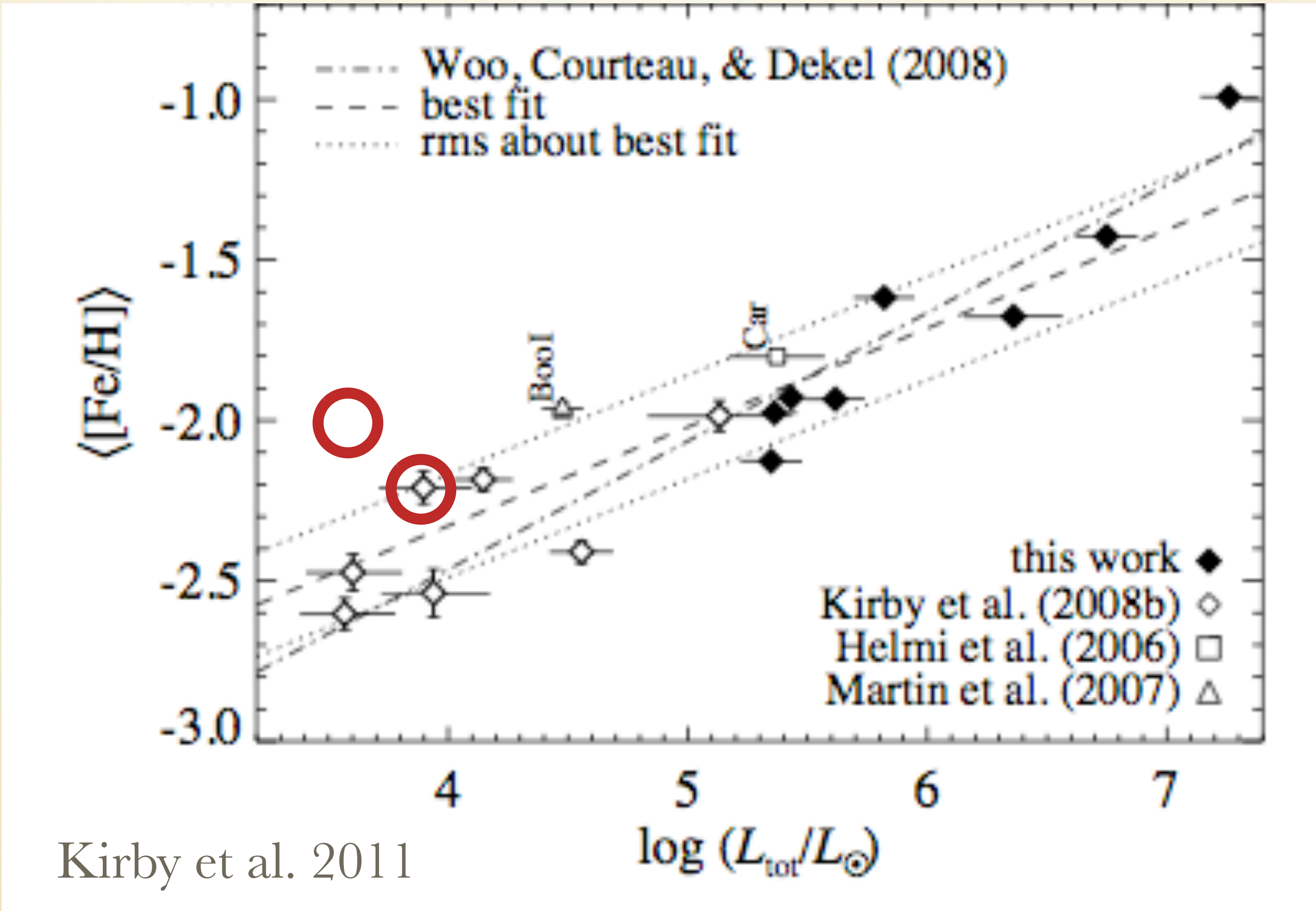




Sand et al. 2011

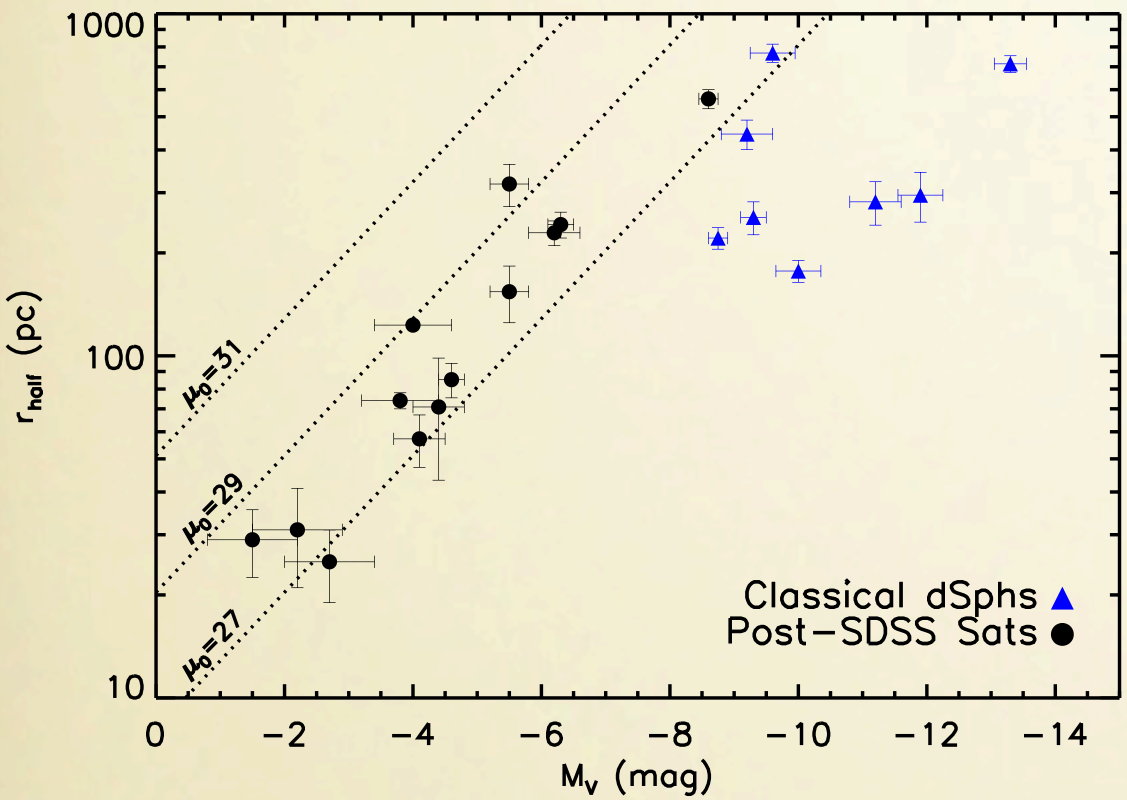
- Both Leo V and CVn II show possible stream-like features.
- Leo V's BHB distribution is more extended than the other ridgeline stars.

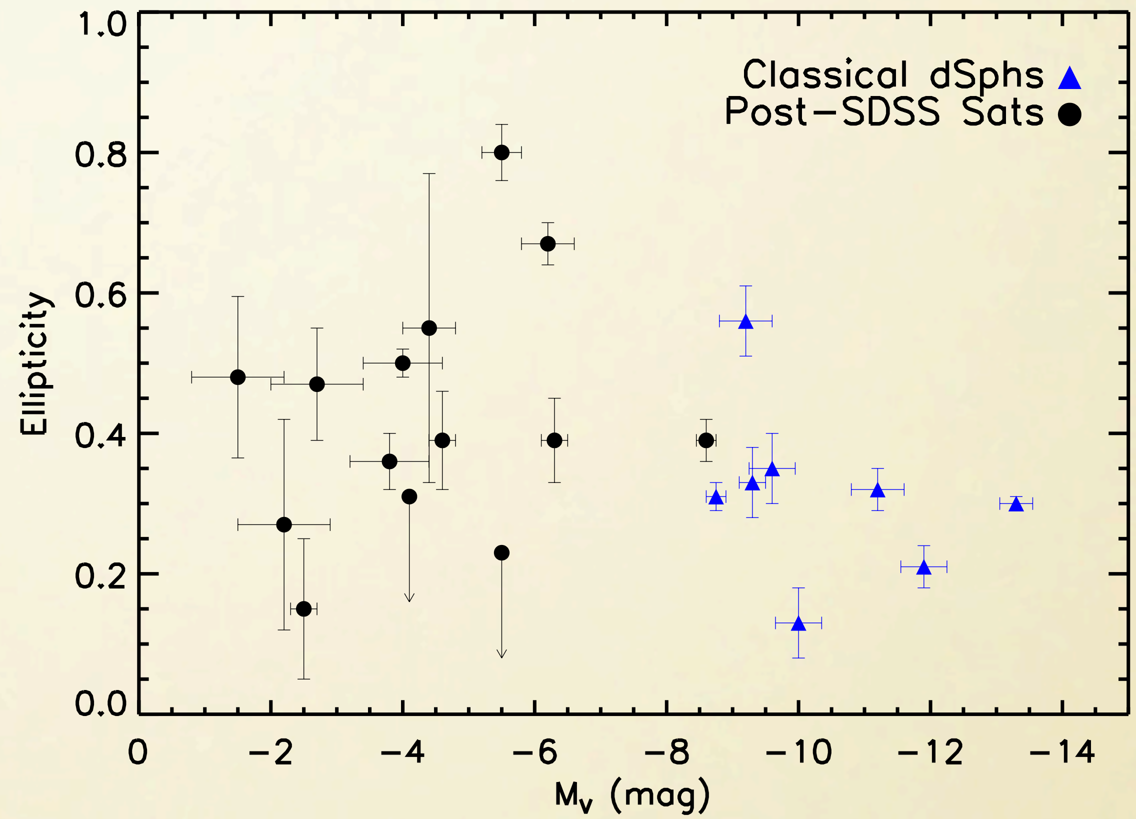
Outliers in [Fe/H] vs L space



Structural Properties of the new Satellites

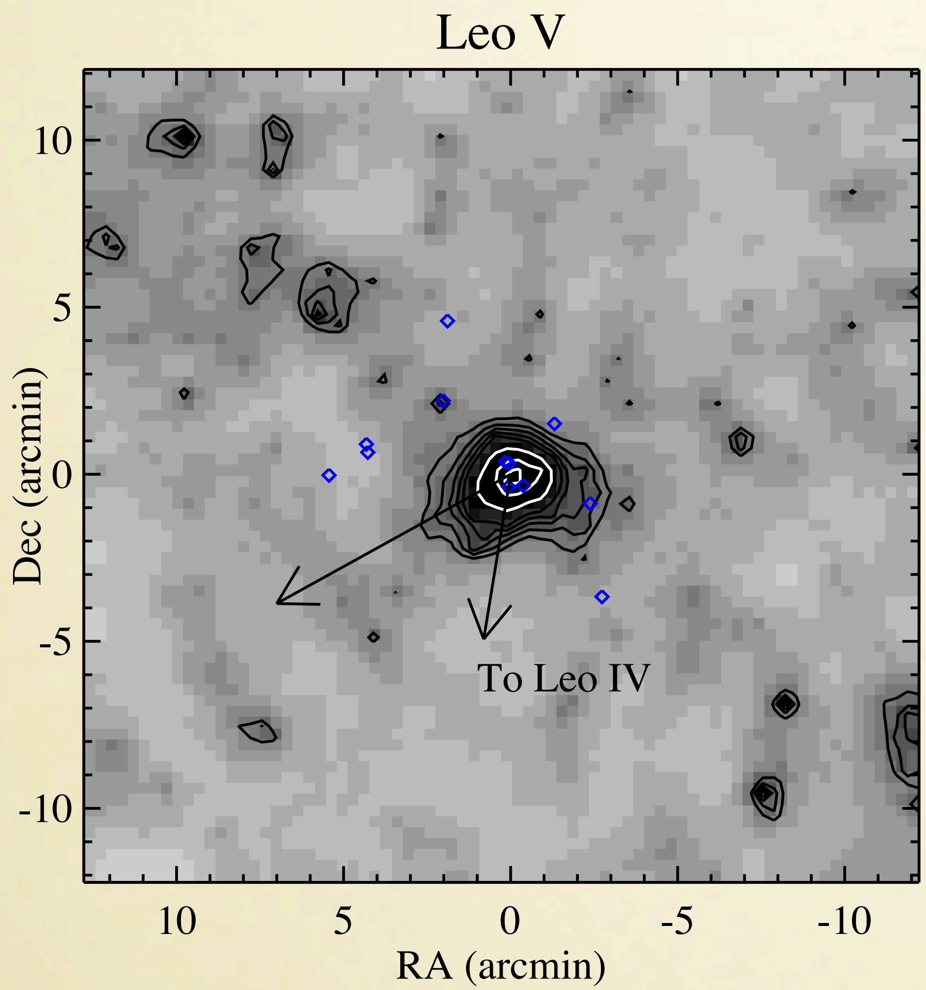
Sand et al. 2011

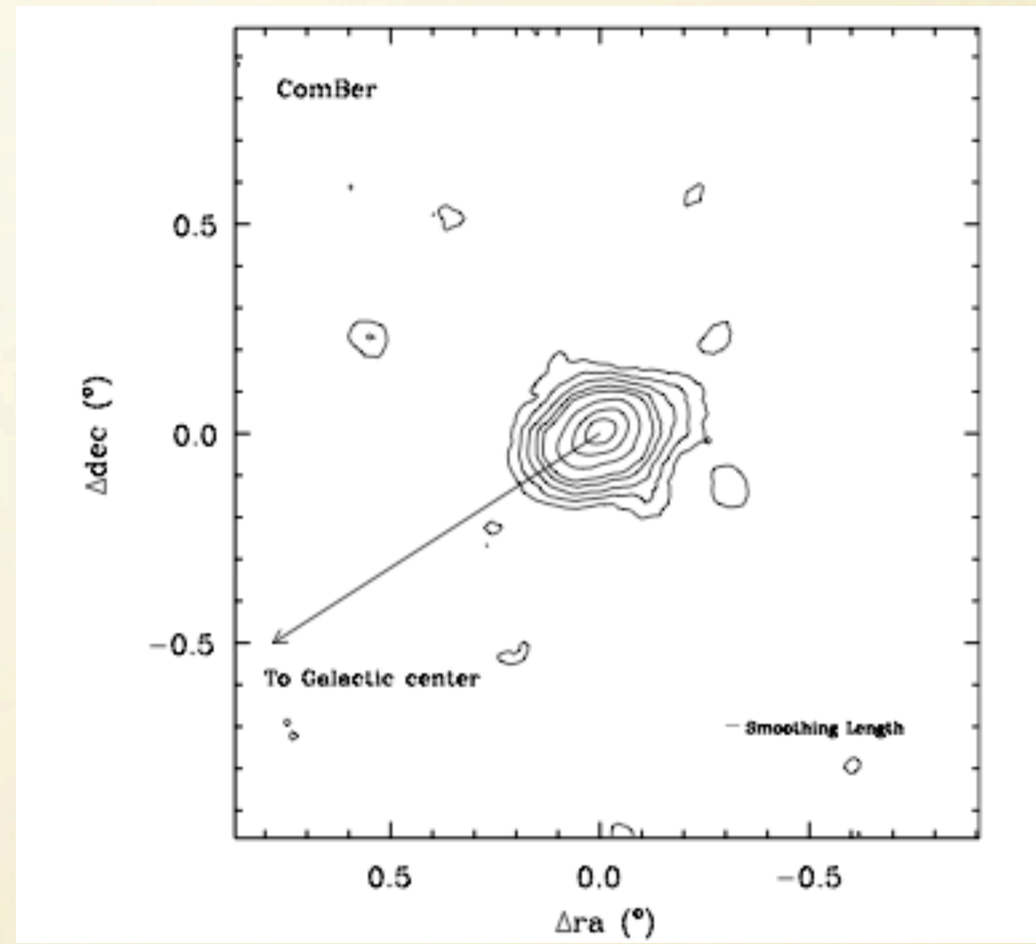




- There may be low surface brightness, 'faint and large' satellites to be discovered.
- Contrary to early estimates based on SDSS data alone, the classical dSphs and new satellites do not have a different ellipticity distribution.

SATELLITE ORIENTATION





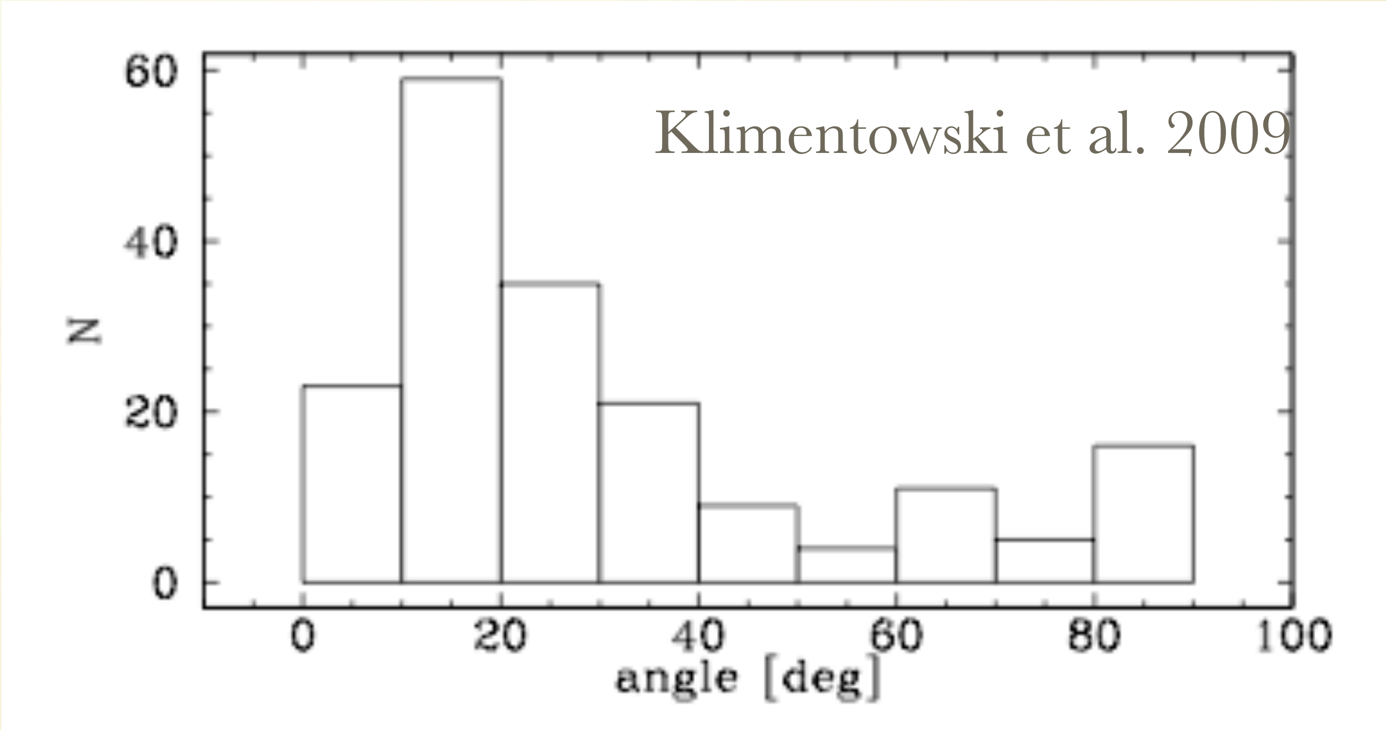
Coma Berenices; Munoz et al. 2010

Intriguing that some new satellites seem to point towards the GC (in projection).

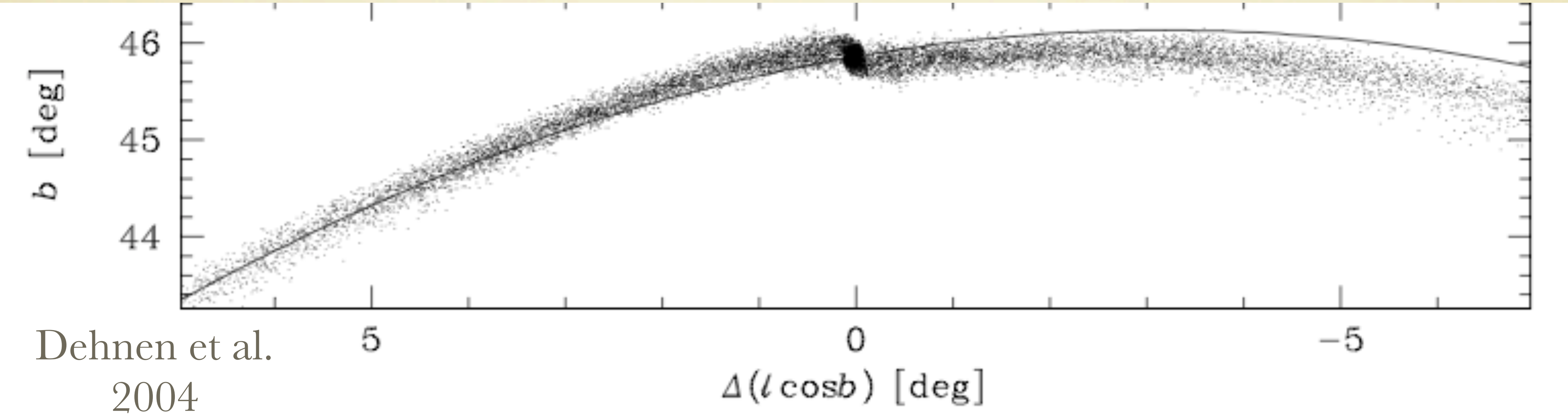
Orientation of tidally stripped tails

'Inner' tail points roughly in direction of gravity vector. Outer tails roughly follow the GC/dwarf orbit.

Can some subset of the new dwarfs be sculpted by tides and leave an observable imprint?



Orientation distribution from a simulation of dwarf on r_p/r_a=0.2; baryons + DM

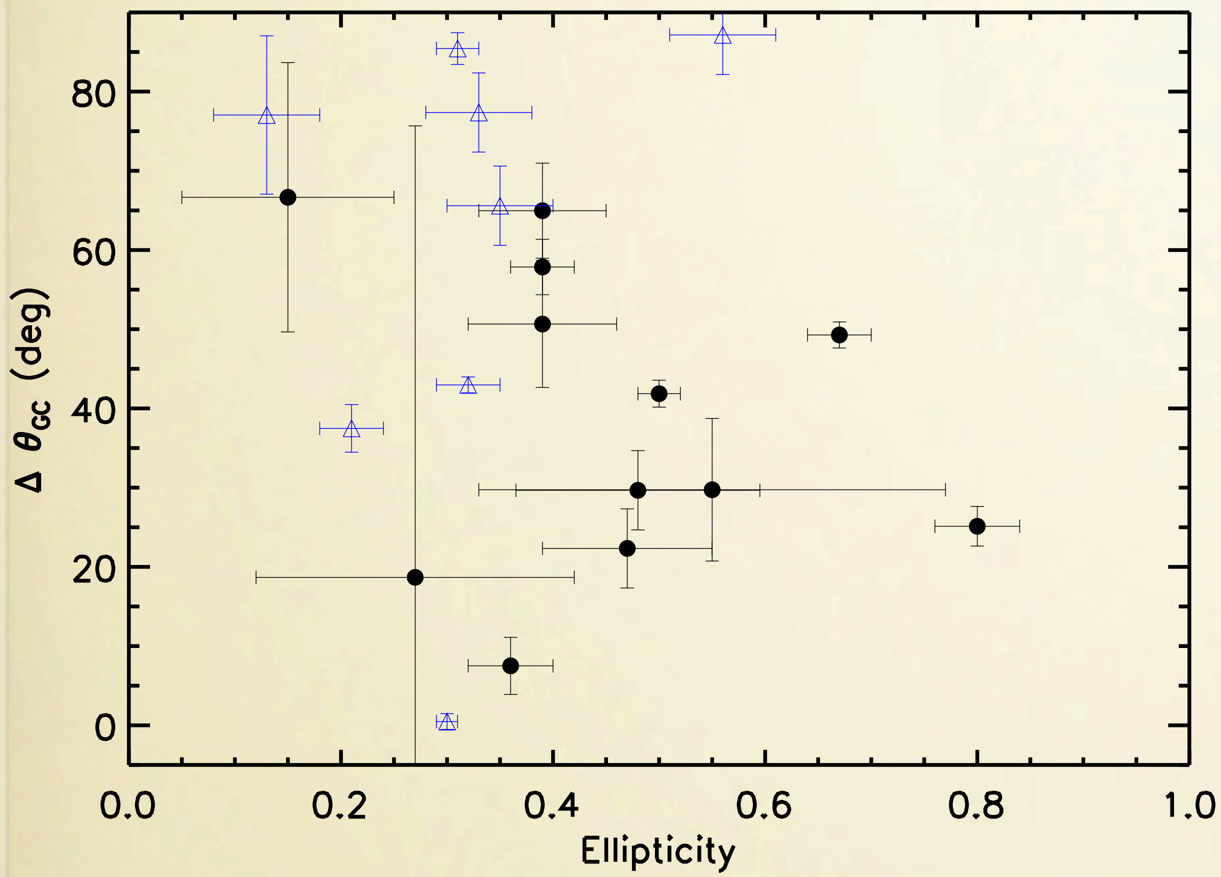


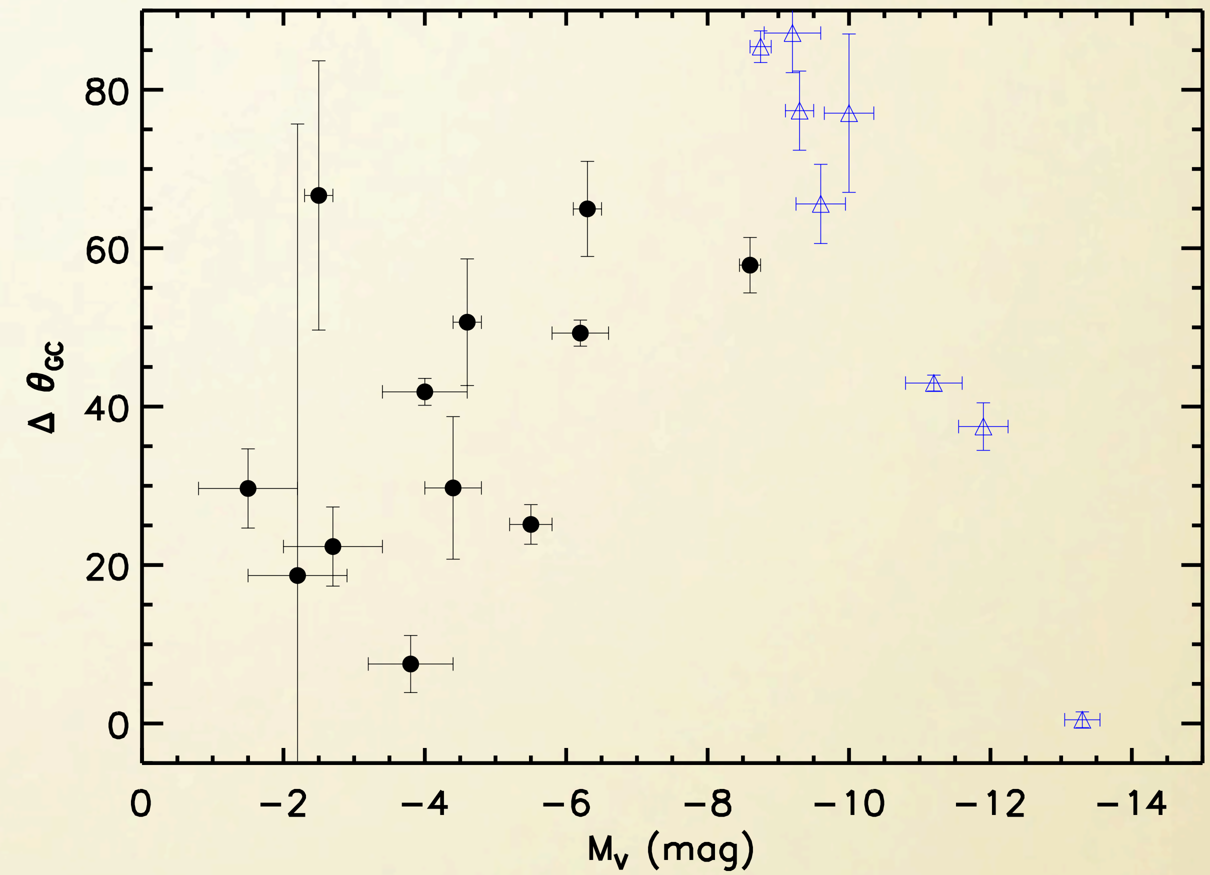
Dehnen et al. 2004

Orientation of all the MW satellites

Black: post-SDSS satellites; Blue: Classical dSphs

Sand et al. 2011





The faintest (and nearest) satellites are the most aligned with the MW center.

For the highest ellipticity ultrafaint satellites, $20° \leq \Delta\theta_{GC} \leq 40°$ -- in rough agreement with tidal stirring scenario

Many caveats....projection effects, comparing with inner tidal tails in simulations, etc.

Summary

- We have undertaken a large observational campaign to gather deep imaging of the new MW satellites to characterize their SFH and structure.
- There have been several surprises: 1) some systems have had very small, recent star formation episodes. 2) Many systems show evidence for tidal stripping of varying degrees.
- Based on the most recent data, the ultra-faints and the classical dSphs have similar ellipticity distributions (with some clear outliers)
- There is some evidence that the faintest and most elliptical new satellites have been sculpted by tidal forces.
- Stay tuned for an analysis of the rest of the new satellites soon.