The Stellar Populations (in the Outskirts) of M31

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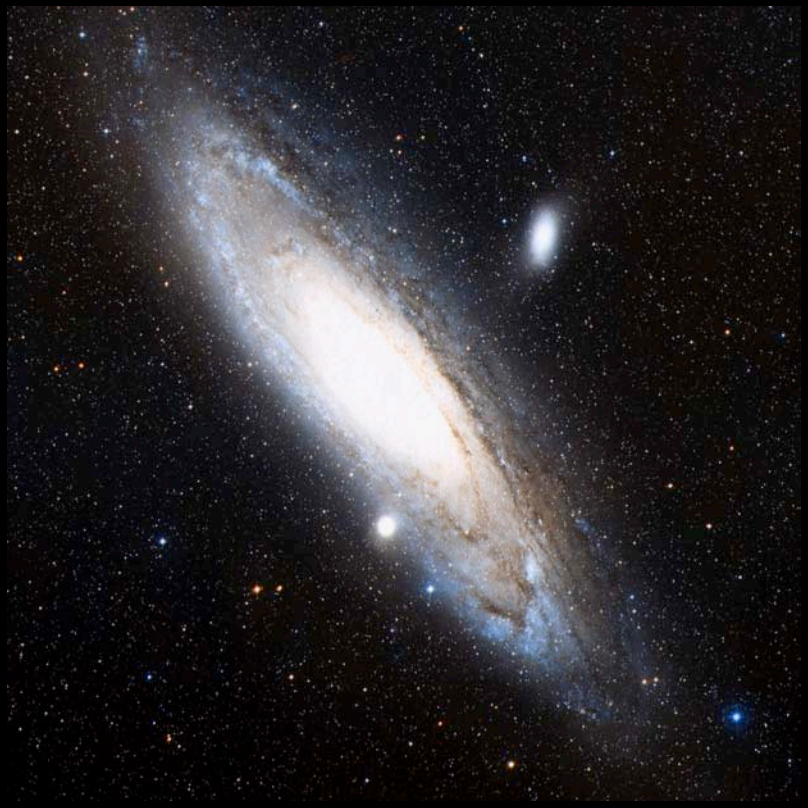
Outline

- M31: The Pre-2000 View
  - a quiescent, passively-evolving spiral
- M31: The Post-2000 View
  - existence of copious stellar substructure
  - existence of an extremely extended stellar halo
  - existence of (sometimes unusual) distant star clusters
- Putting it all together and looking beyond….

M31: Our Nearest Large Neighbour

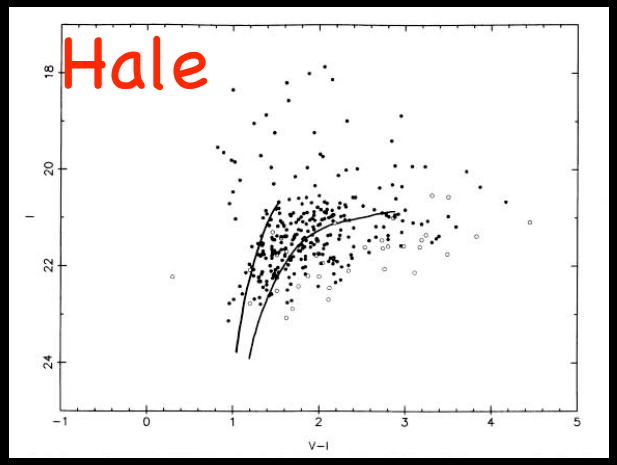
- M31 has long been thought of as the "sister" of our Milky Way
  - $M_{M31} \sim M_{MW}$
  - $Vrot_{M31} \geq Vrot_{MW}$
  - $L_{M31} \geq L_{MW}$
- at D=780 kpc, luminous stars are easily resolved from ground and space
- extragalatic perspective: uncomplicated view of "typical" spiral



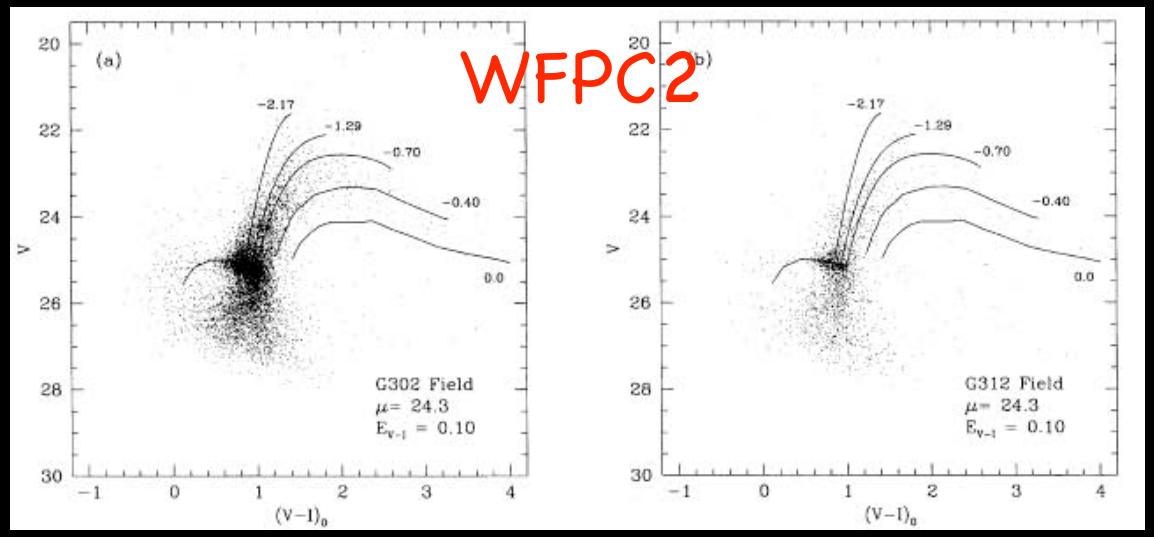
M31: The View Before 2000

Despite their "sisterhood", the outer regions of M31 and the Milky Way puzzingly different:

- stellar "halo" metallicities differ by ~1 dex
  - M31 [Fe/H]~-0.7 dex (GCs: [Fe/H]~-1.5 dex)
  - MW [Fe/H]~-1.6 dex (GCs: [Fe/H]~-1.5 dex)



Mould & Kristian 1986



Holland et al 1996; see also Rich et al 1996

M31: The View Before 2000

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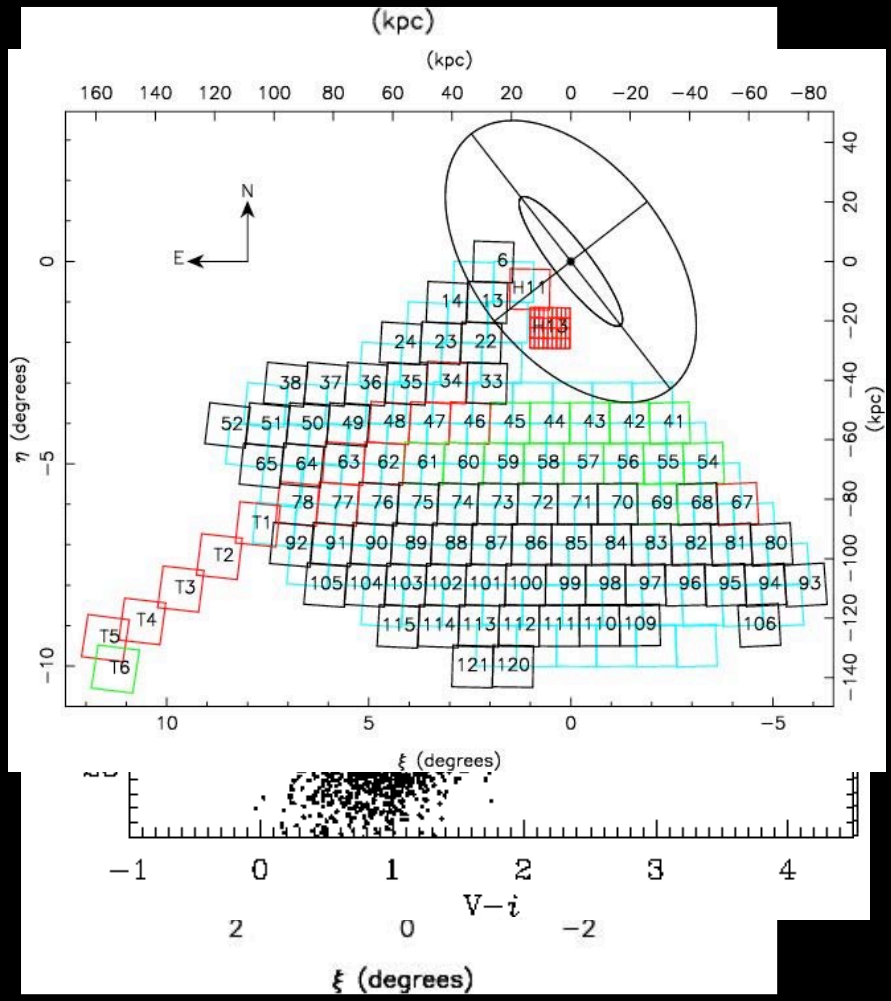
- stellar "halo" radial profiles differ:
  - M31 $R^{1/4}$ law
  - MW R^{-2} power-law
- MW halo dominated by a giant stream from the accreting Sagittarius dwarf, also interacting with the LMC
- M31 has a much richer globular cluster system (~500 members) than the Milky Way (~150 members)

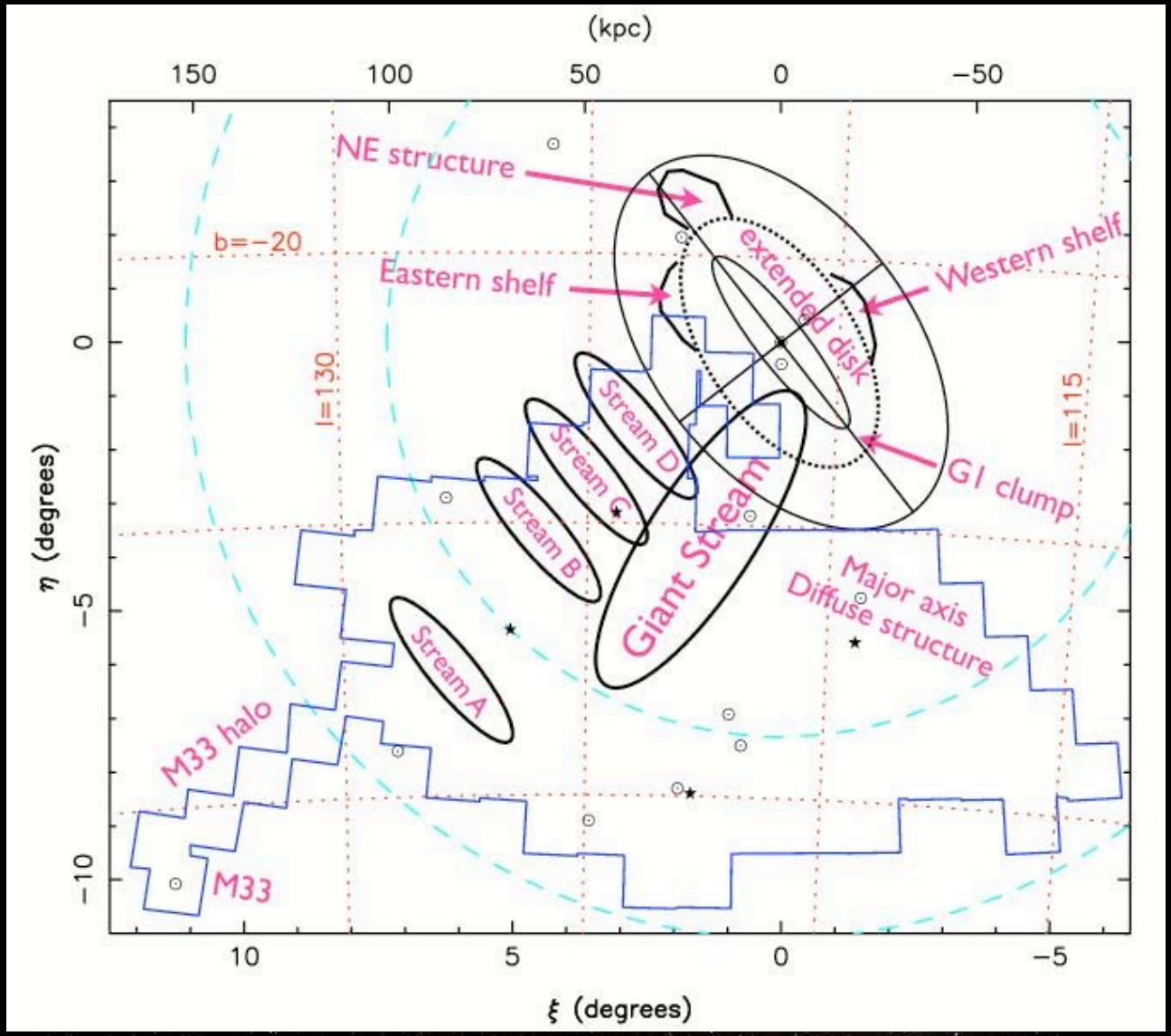
M31: The View After 2000

- wide-field imaging survey (V,i) conducted with the INT/WFC from 2000-2004
  - 164 pointings,~50 sq. deg
  - depth i~23.5 (top 3 mags of the RGB)
  - covers disk and inner "halo" to ~ 55 kpc
- wide-field imaging survey (g,i) conducted with MegaCam/CFHT from 2003-2006
  - 92 pointings, ~75 sq. deg
  - depth i~24.5
  - covers outer "halo" to ~150 kpc



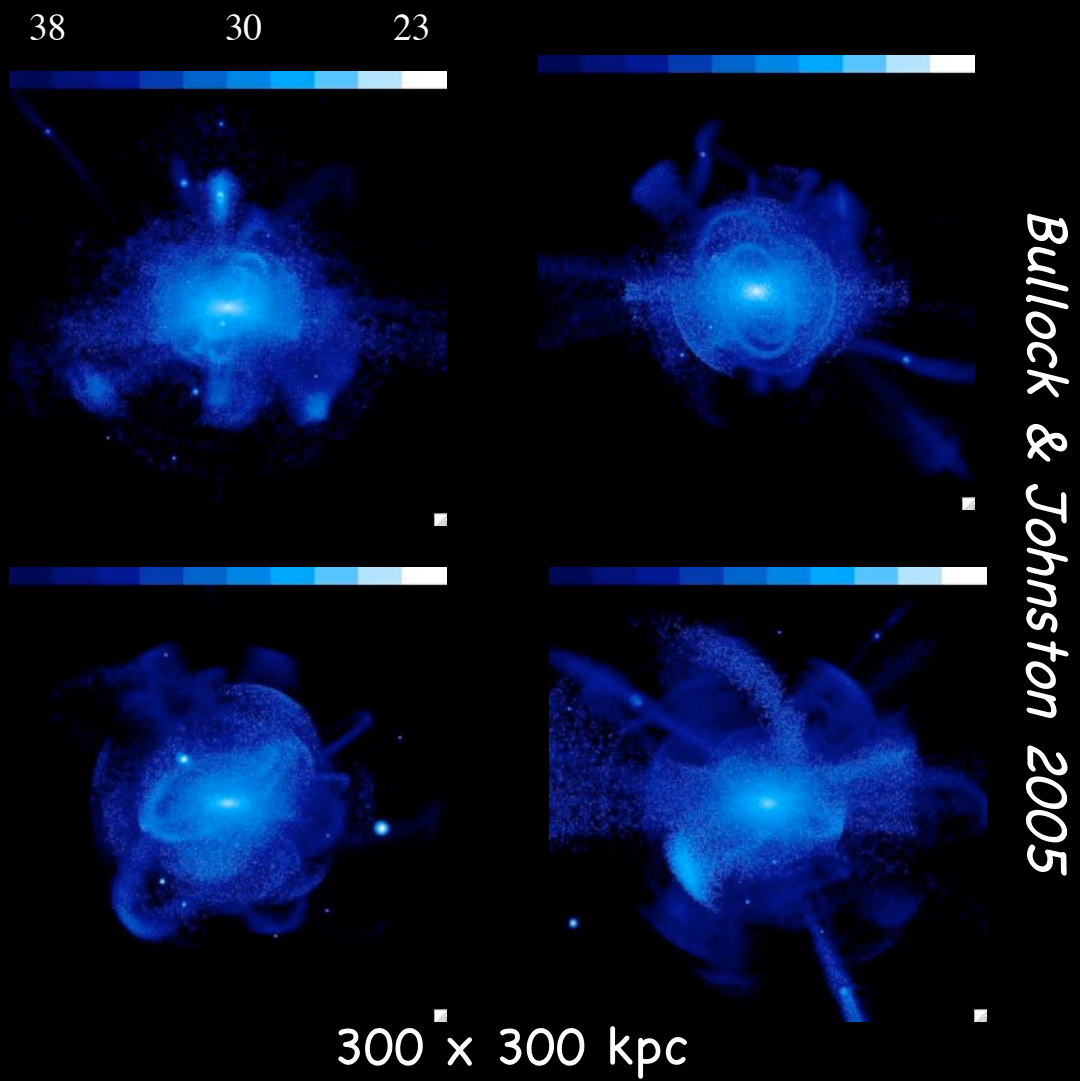
M31: The Wide-Field View in 2007

Ferguson et al 2002, Ibata et al 2007



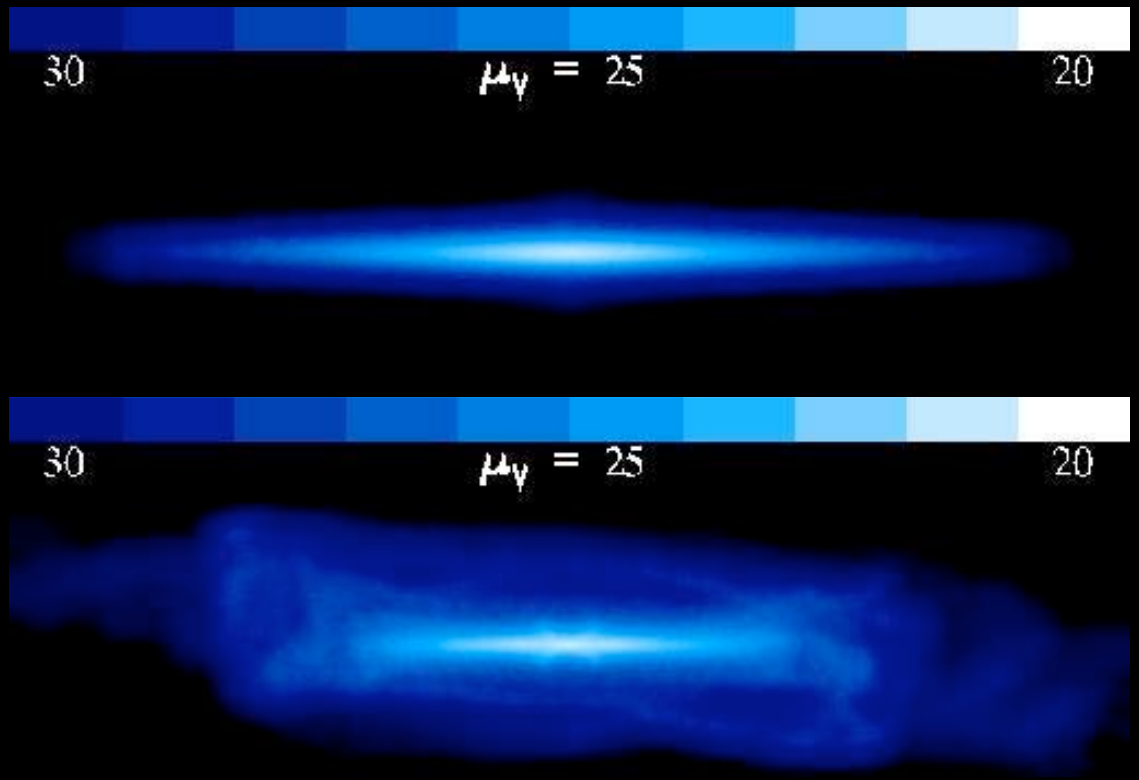
What is the Origin of the Substructure around M31?

In LCDM models, Milky Way-like galaxies should have accreted ~100-200 luminous satellites over past 12 Gyr leads to prediction of copious tidal debris from recent accretion events



Bullock & Johnston 2005

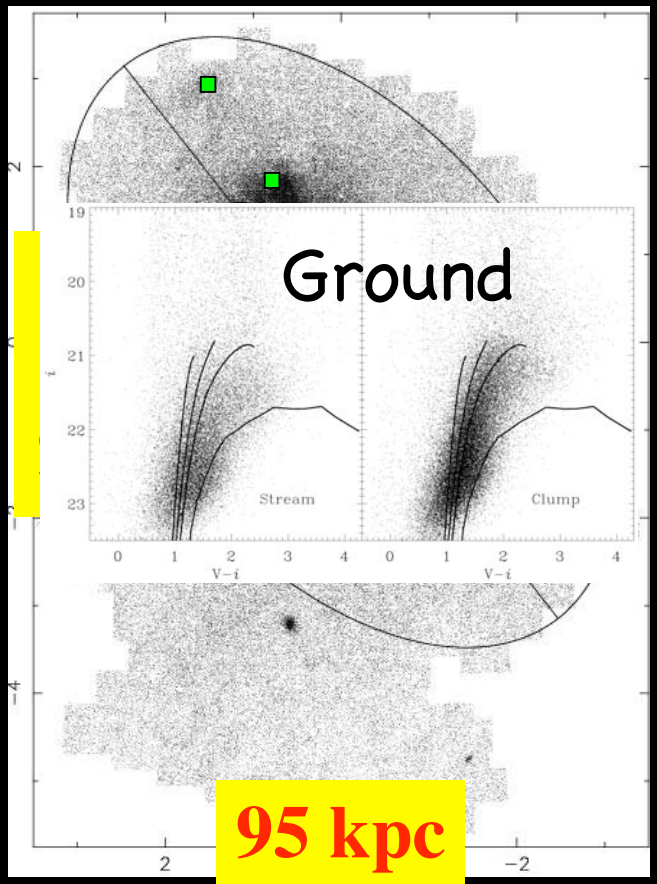
What is the Origin of the Substructure around M31?

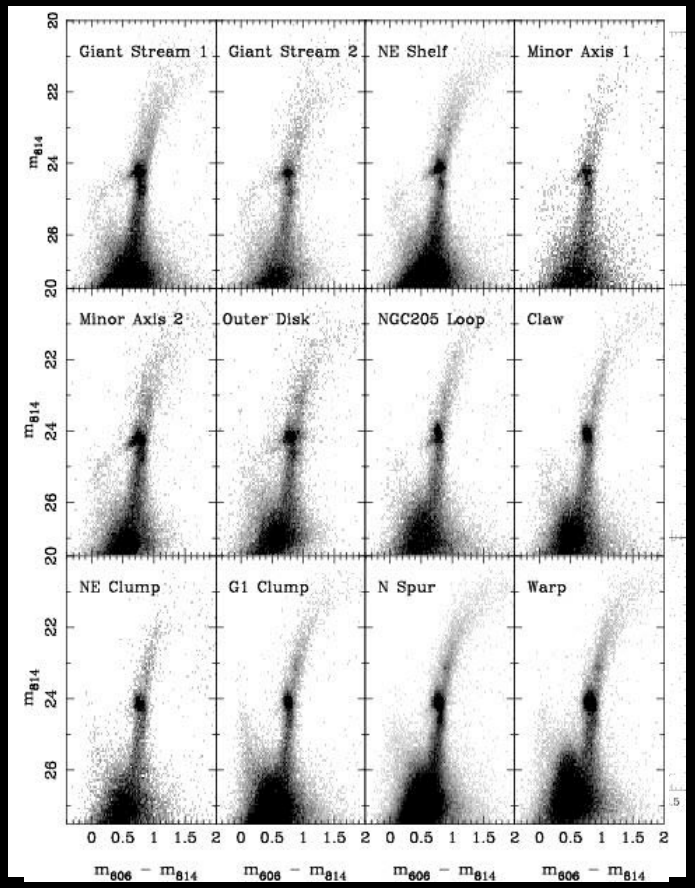


Disk heating can significantly perturb the outer reaches of the thin disks: viable origin of some/most of the low-latitude substucture...

Kazantzidis et al 2007, in prep; also Quinn et al 1991, Gauthier et al 2006

Probing M31 Substructure: The Messy Inner Halo

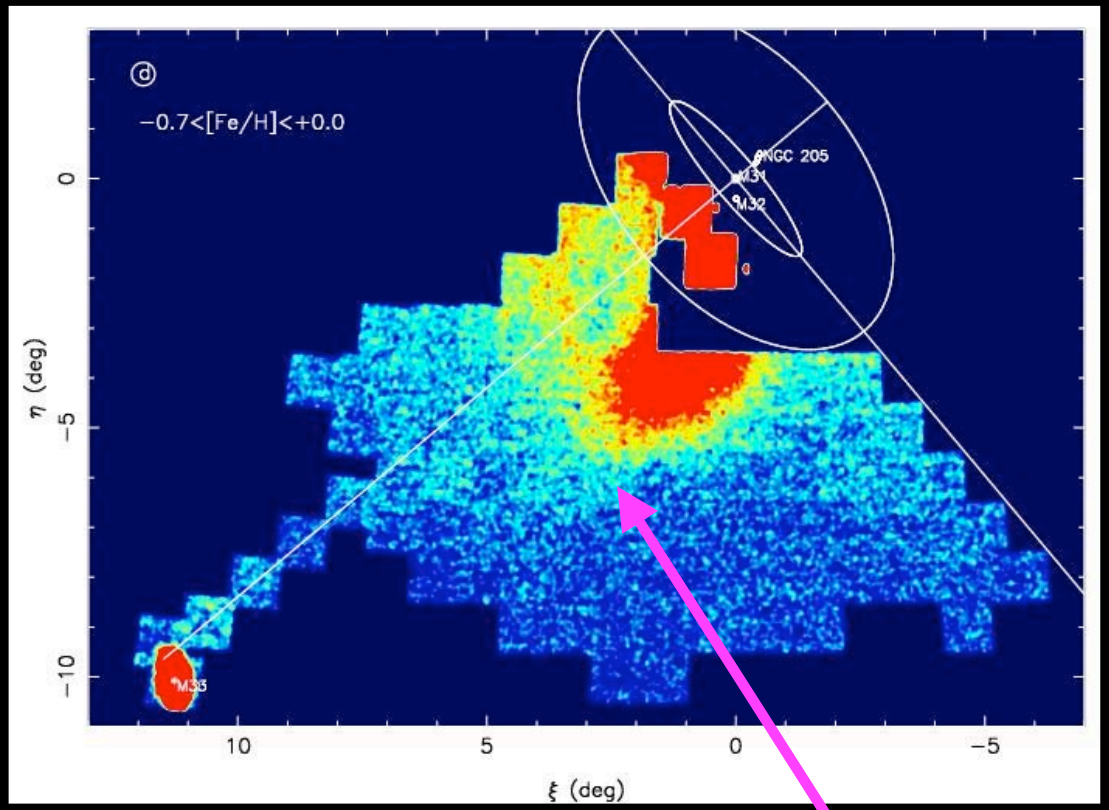


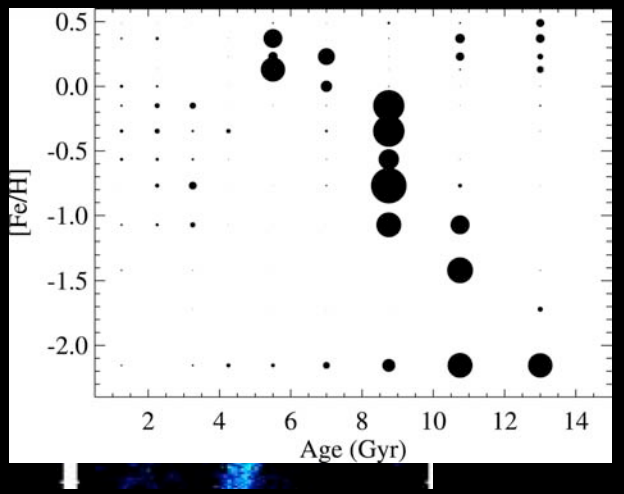


Deep HST/ACS observations reveal CMD variations between many substructures but the moderate metallicity is unlike typical dSph

Richardson et al 2007 in prep; also Ferguson et al 2005, Faria et al 2007

Probing M31 Substructure: The Giant Stream





Detailed CMD fitting yields <[Fe/H]>=-0.6 <age>=8.8 Gyr for stream progenitor: halo pollution!

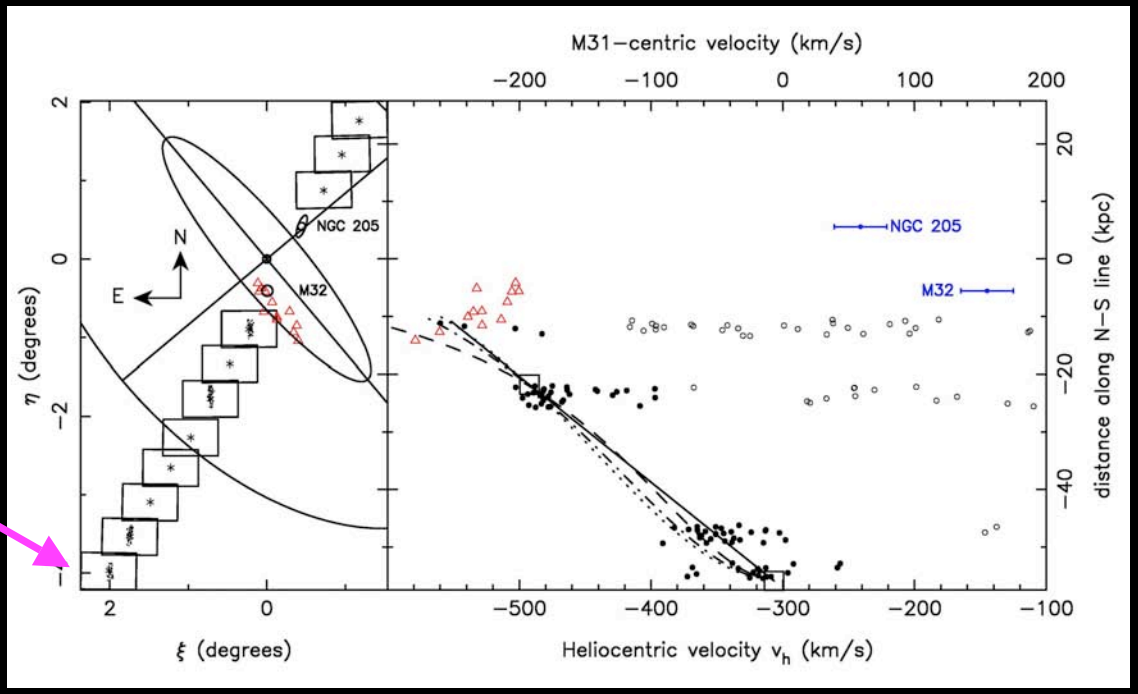
Brown et al 2006

100 kpc

Ibata et al 2007; also Ibata et al 2001, 2004, Ferguson et al 2002

Probing M31 Substructure: The Giant Stream

TRGB:100 kpc behind M31



Radial velocities of stream stars can be combined with distance estimates to derive constraints on the orbit of the progenitor: unlikely to be M32 or NGC205!

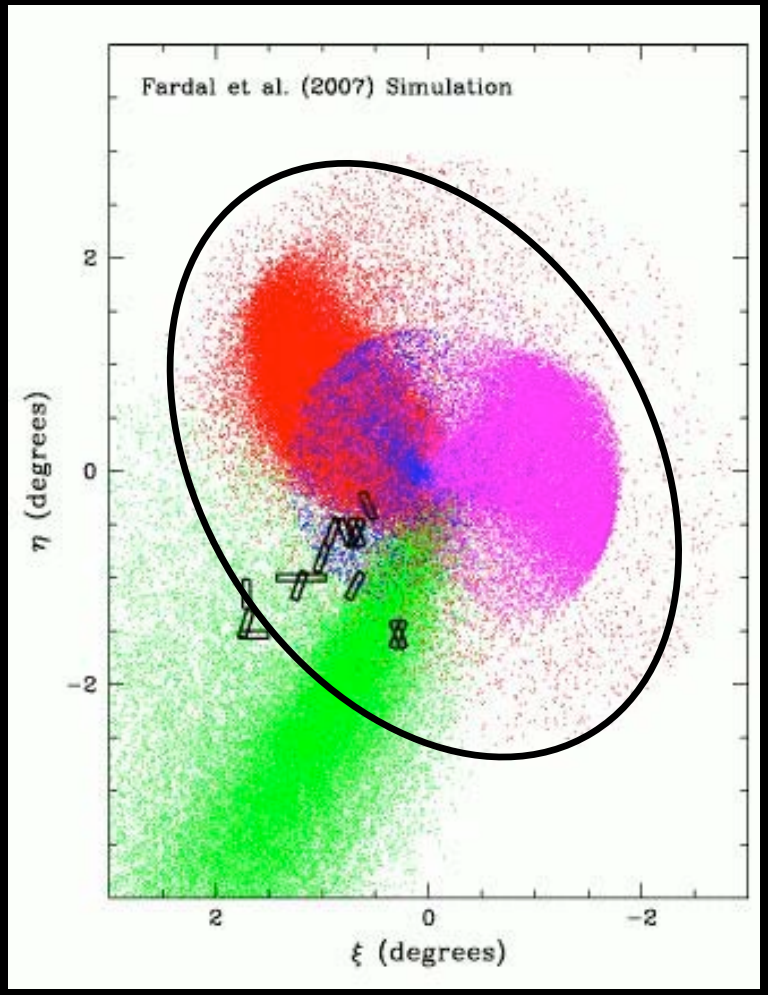
Ibata et al 2004, Guhathakurta et al 2006, Kalirai et al 2006, Fardal et al 2006, Font et al 2006

Probing M31 Substructure: The Giant Stream

Fardal et al 2007 conduct N-body simulation of stream progenitor in a realistic M31 potential

Green ⇒ 1st passage
Red ⇒ 2nd passage
Magenta ⇒ 3rd passage
Blue ⇒ 4th passage

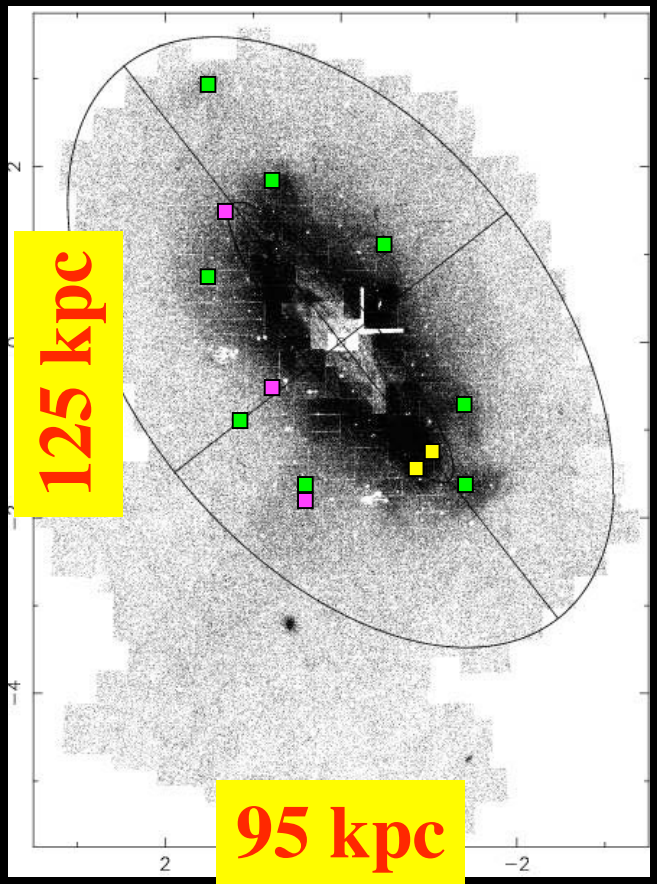
Progenitor remnant predicted to lie in the NE shelf region..

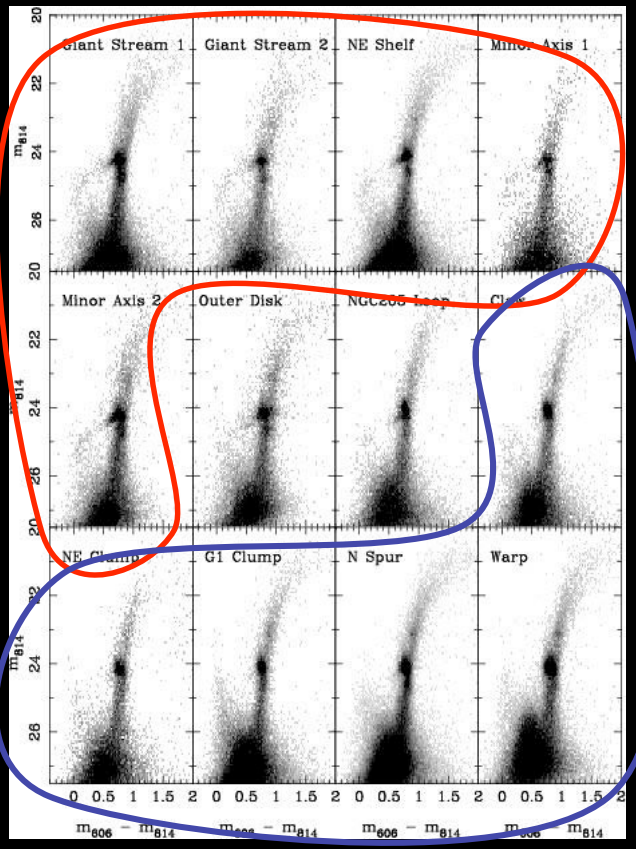


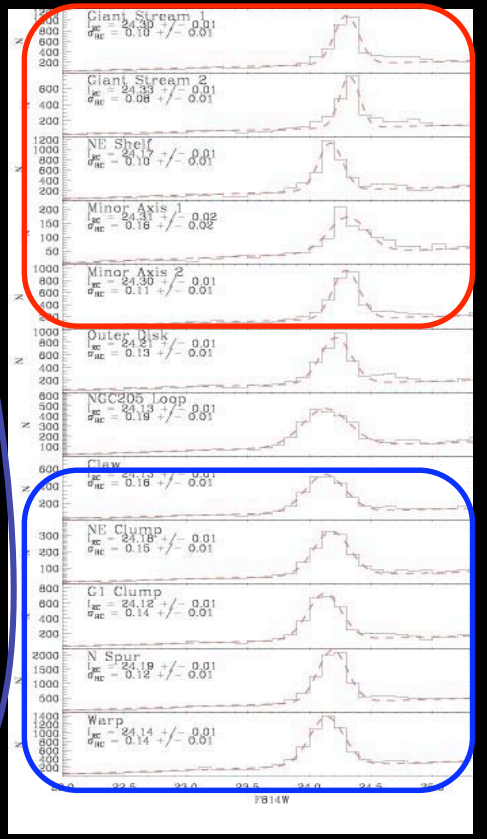
Fardal et al 2007, Gilbert et al 2007

Probing M31 Substructure: The Messy Inner Halo

"stream-like"



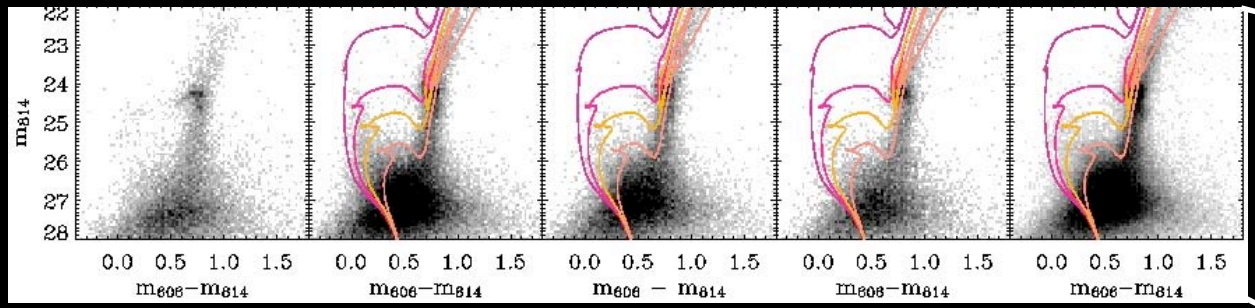




"disk-like"

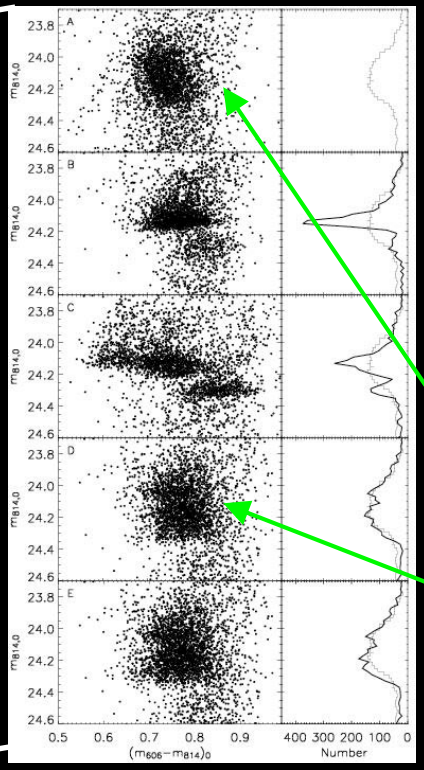
Richardson et al 2007 in prep

Low Latitude Substructure in M31



Young (<1 Gyr), moderately metal-rich ([M/H]~-0.4) stars present in all substructure near the major axis (even at 40 kpc!)

Detailed modelling of the red clump can constrain age and metallicity mix of the population: inferred SFH for G1 Clump in excellent agreement with expectations for outer disk

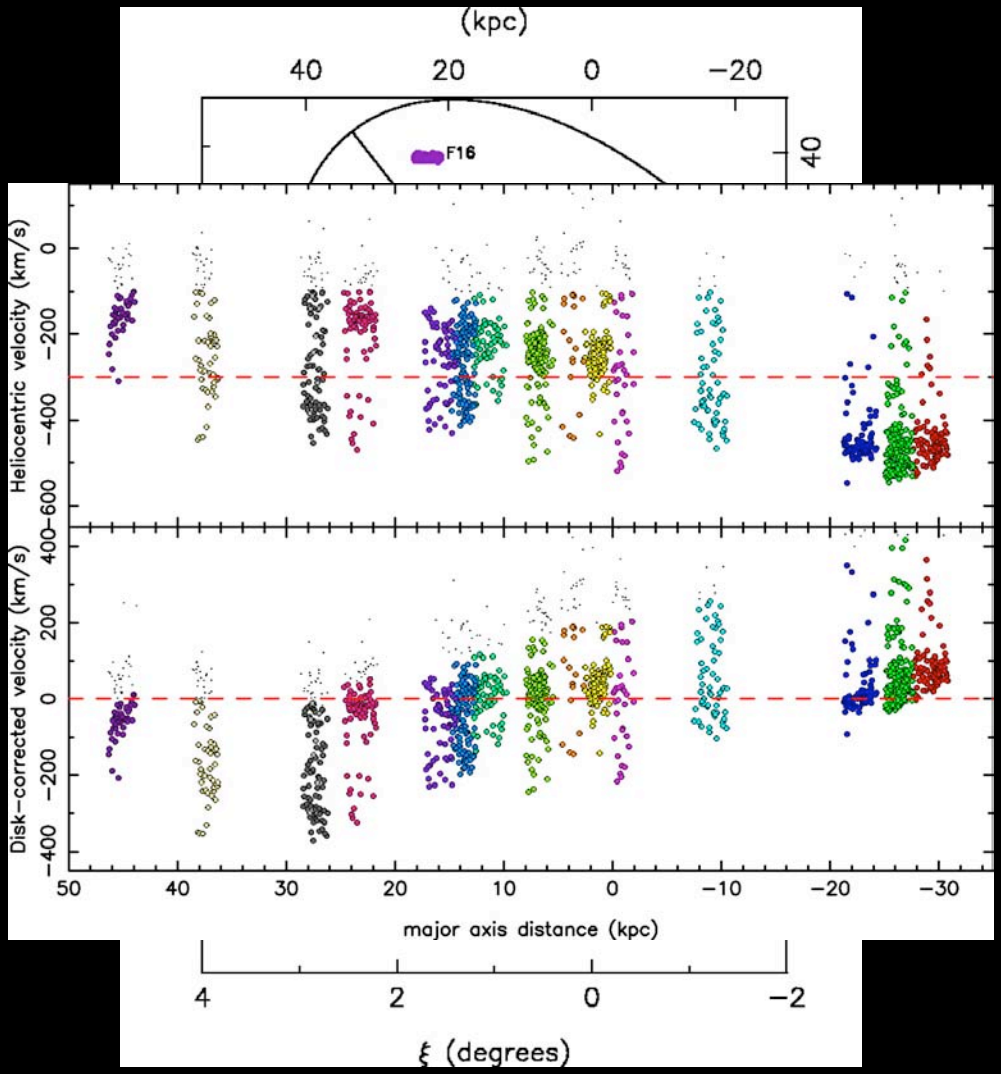


observed red clump

model with narrow Z, large age spread

Faria et al 2007, Richardson et al 2007 in prep

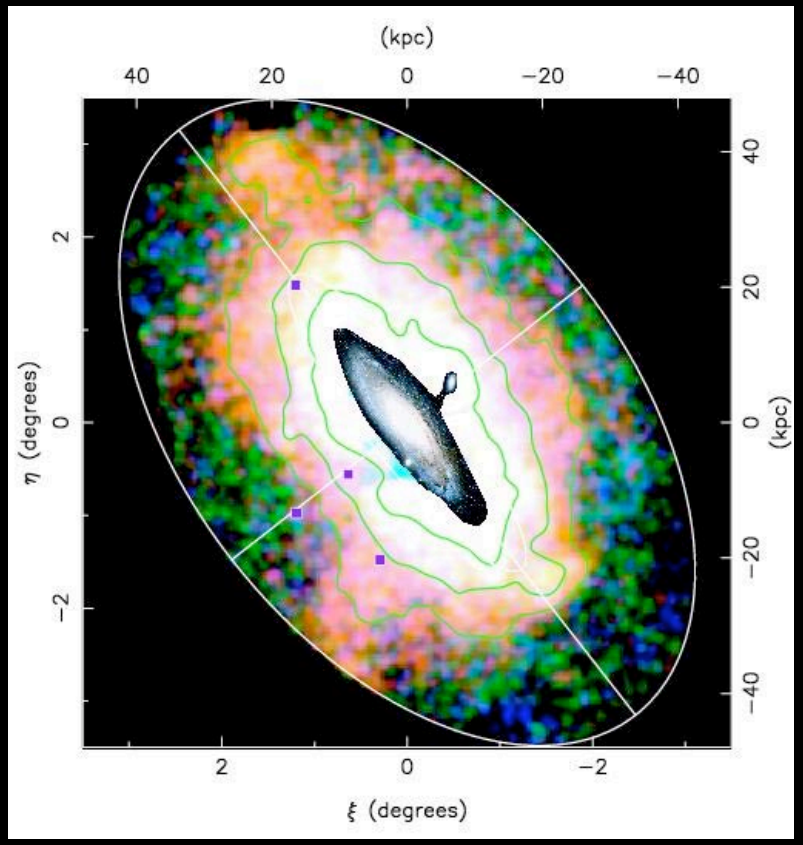
Low-Latitude Substructure in M31

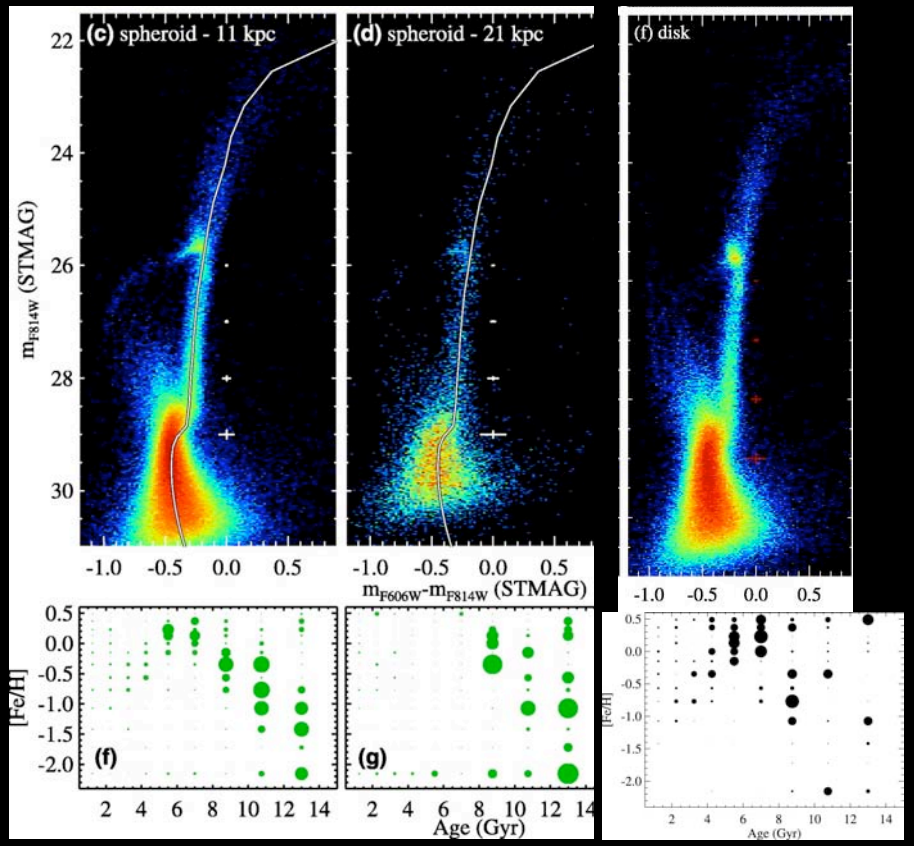


Reitzel et al 2004, Ibata et al 2005

- Keck/Deimos survey of ~3000 stars
- Strong signature of rotation in most major axis fields out to at least ~50 kpc and moderate velocity dispersion (~30-50 km/s)
- Along with HST stellar population constraints, this could suggest a splattered disk origin for much of the low-latitude debris

Probing M31 Substructure: The Messy Inner Halo

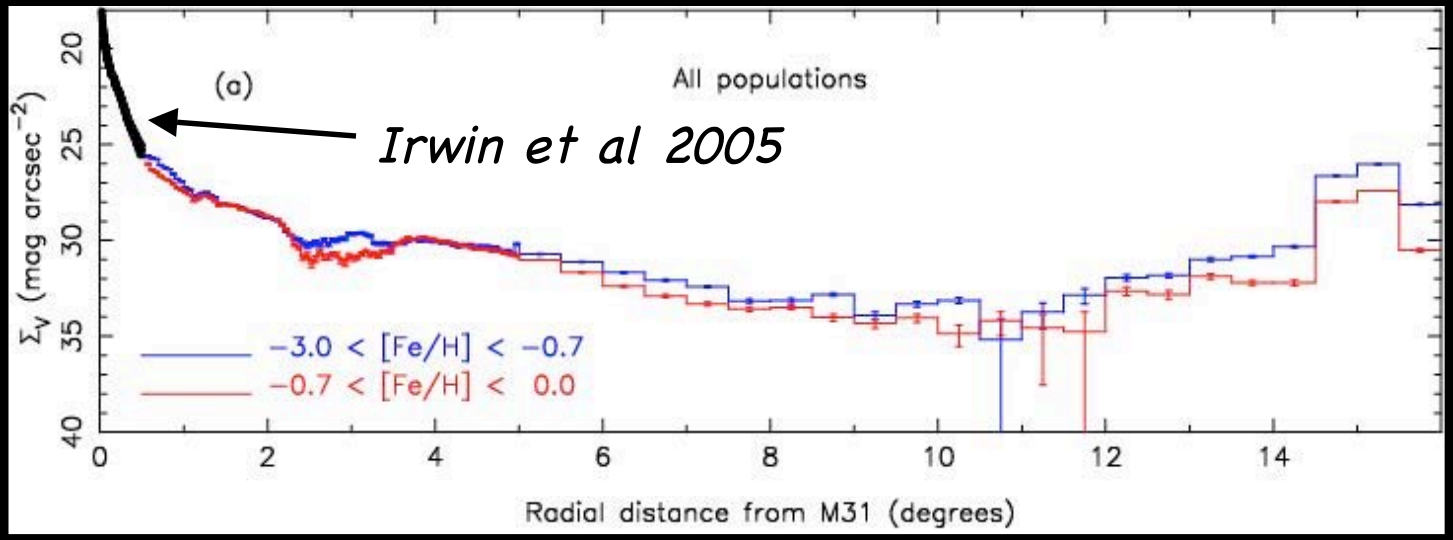




Brown's ultra-deep fields: contamination renders them very difficult to interpret (at present)!

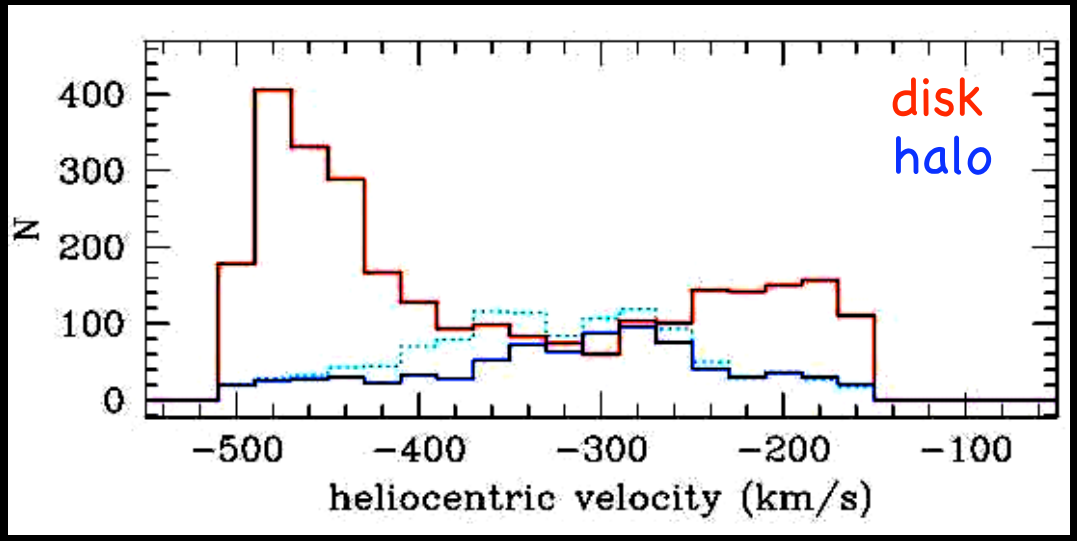
The Extended Stellar Halo of M31

Ibata et al 2007



- radial profile of the outer halo constructed from the MegaCam survey, after correcting for foreground
- "smooth" shallow decline out to 10 degrees from M31, where a possible stellar halo of M33 starts to dominate
- M31 halo can be fit by power-law of index ~-2 to ~150 kpc (exponential α~47 kpc); M33 exponential α~18 kpc

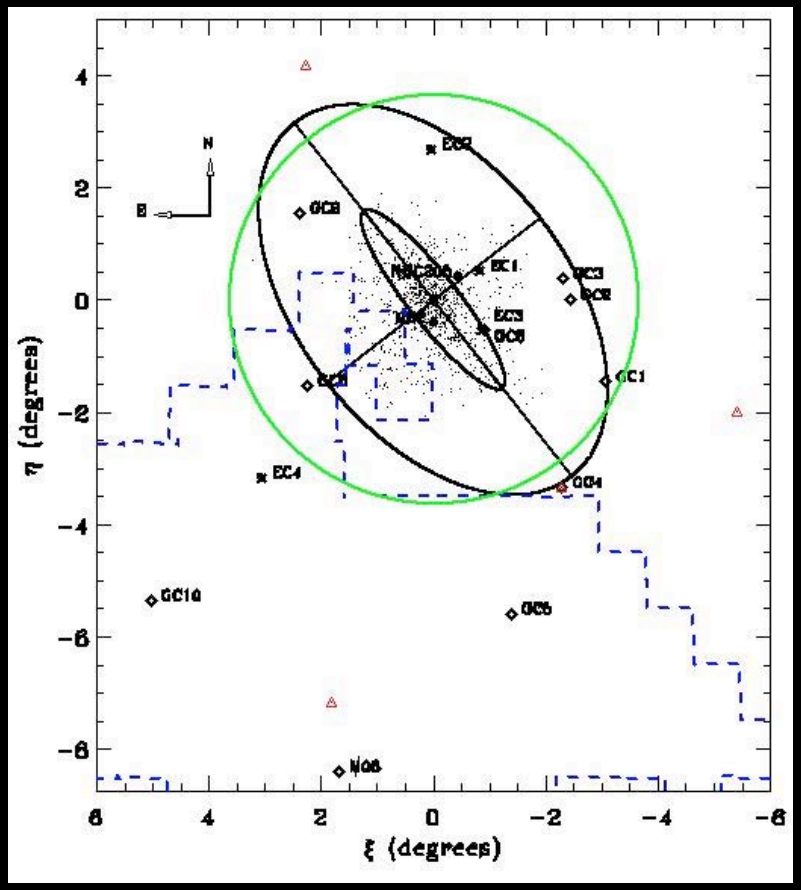
The Extended Stellar Halo of M31



Chapman et al 2006
Kalirai et al 2006

- Keck/DEIMOS spectra (~10,000) yield detection of hot kinematic component out to ~70 kpc
- σ~150 km/s at R=0 decreasing to 90 km/s
- [Fe/H] ~ -1.4 ± 0.2 dex; no strong metallicity gradient (c.f. -1.5 dex from RR Lyrae)

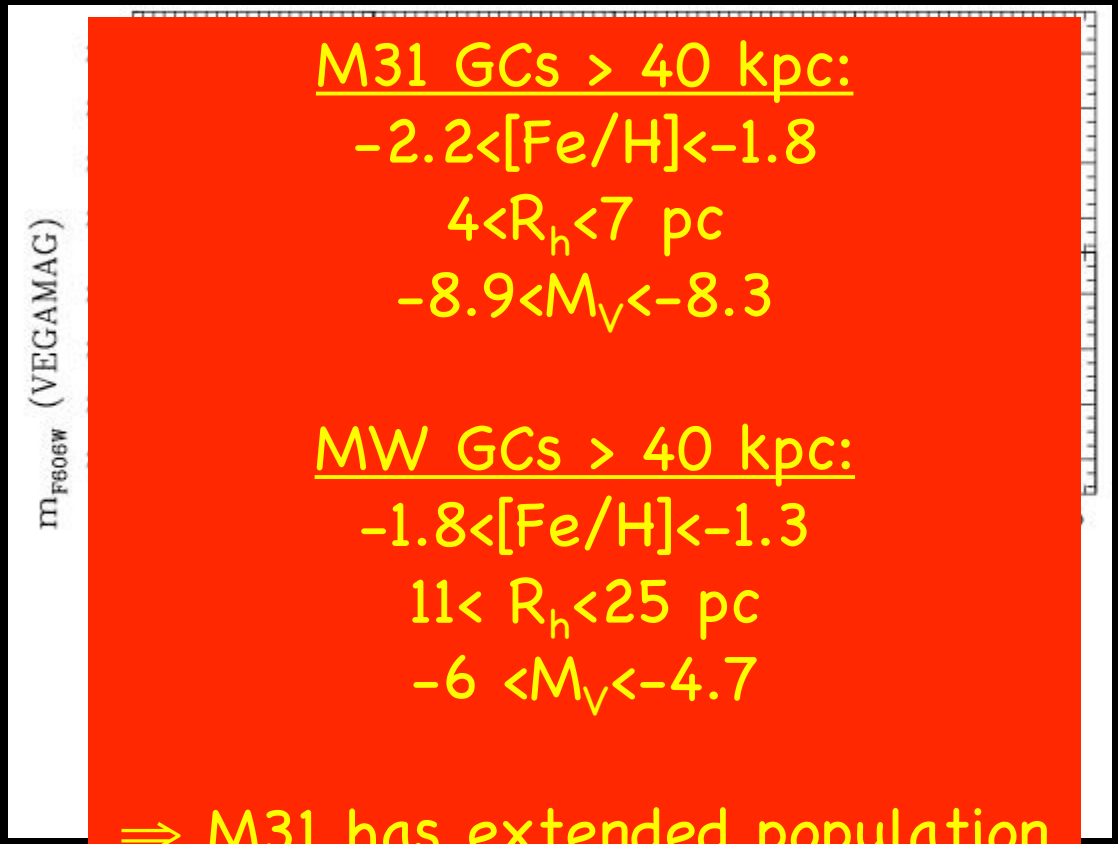
Outer Globular Clusters in M31



Huxor et al 2005, Huxor 2007, Martin et al 2006, Mackey et al 2006, 2007, Galleti et al 2007

- new sample of ~20+ outer GCs compiled from INT and CFHT/Megacam survey data
- our sample extends to R~116 kpc (11 GCs lie at R>30 kpc, 5 at R>50 kpc) (c.f. MW: 10 at R>30 kpc, 6 at R>50 kpc)
- both "classical" GCs and "extended" clusters identified

Classical GCs in the Outskirts of M31



M31 GCs > 40 kpc:

$-2.2<[Fe/H]<-1.8$

$4<R_h<7$ pc

$-8.9<M_V<-8.3$

MW GCs > 40 kpc:

$-1.8<[Fe/H]<-1.3$

$11< R_h<25$ pc

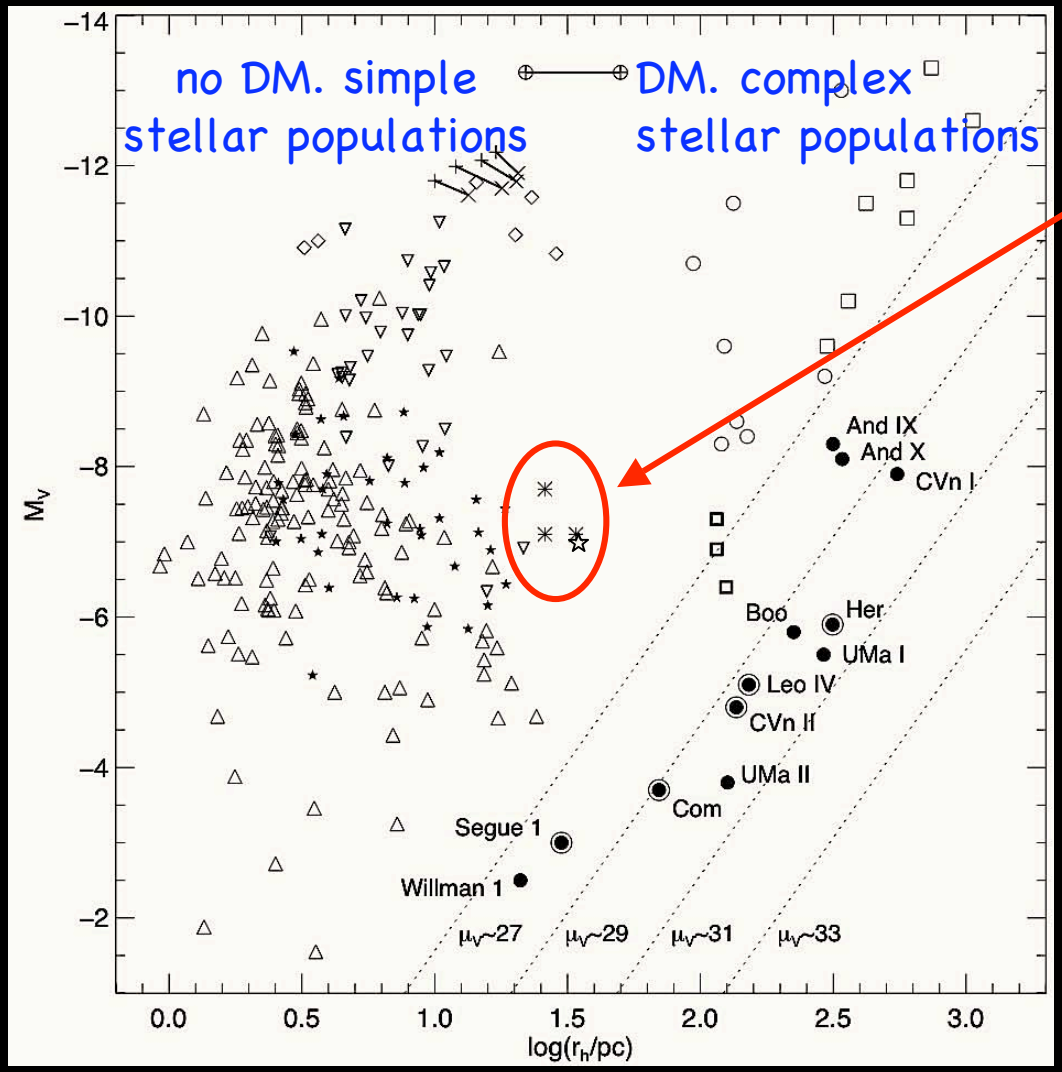
$-6 <M_V<-4.7$

⇒ M31 has extended population of luminous, compact, metal-poor globulars that is not seen in the Milky Way!

- M_v~-6 to -9, R_h~5 pc
- fitting Galactic GC fiducials implies [Fe/H]~-2.1 to -1.5 with exception of GC7 ([Fe/H]~-0.7], but beware of age!)
- range of HB morphologies present: evidence for a 2nd parameter problem?

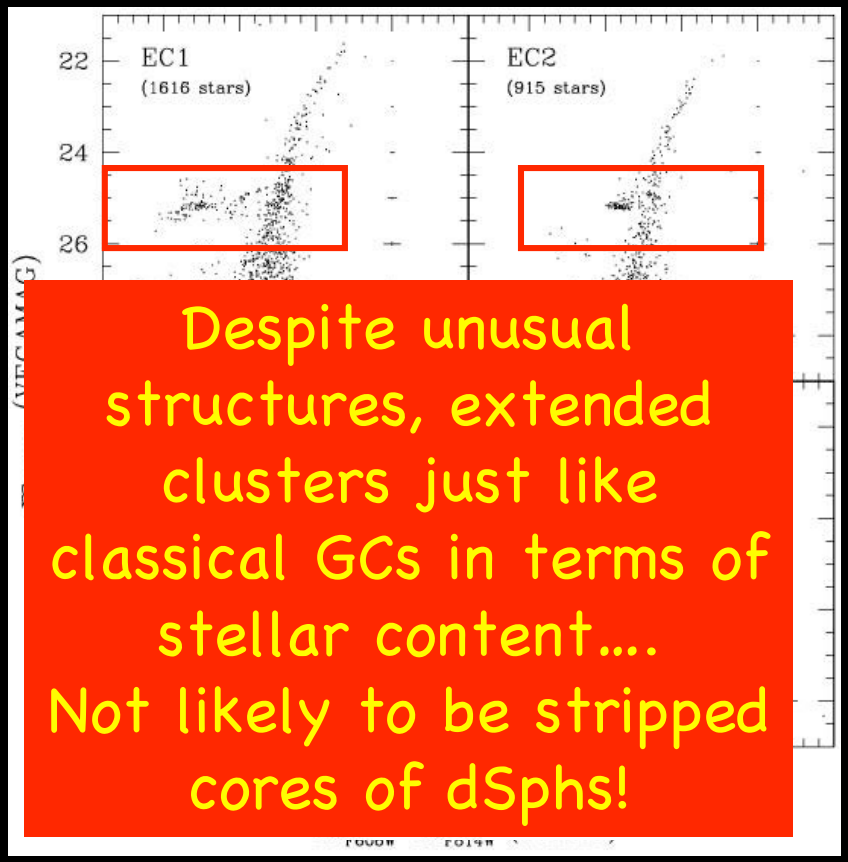
Extended Globular Clusters vs dSphs

Belokurov et al 2006



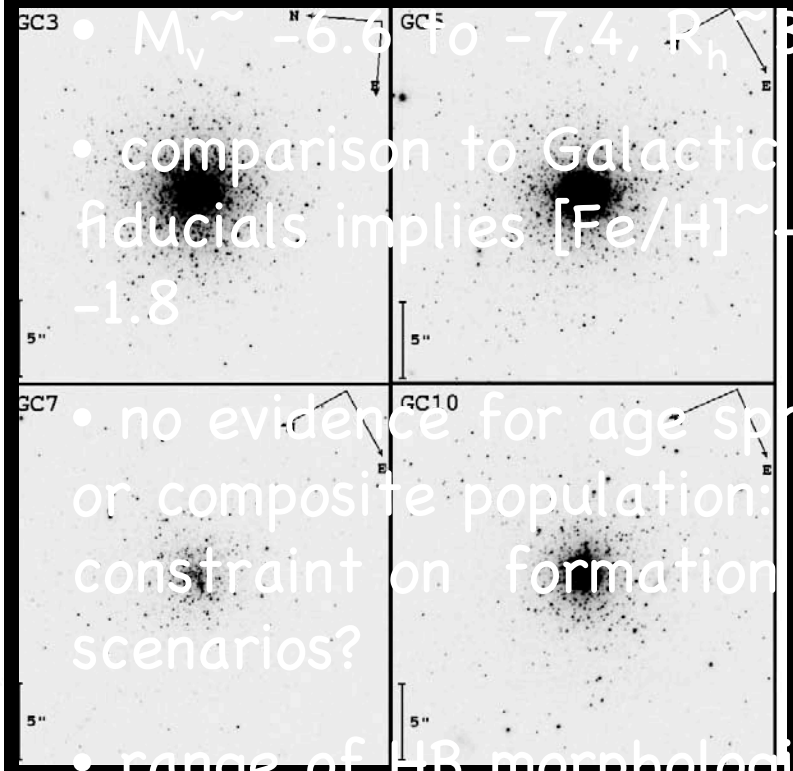
Extended GCs have M_V and R_h which place them near the gap between classical GCs and dSph: how do they compare in terms of stellar content?

Extended Globular Clusters in M31



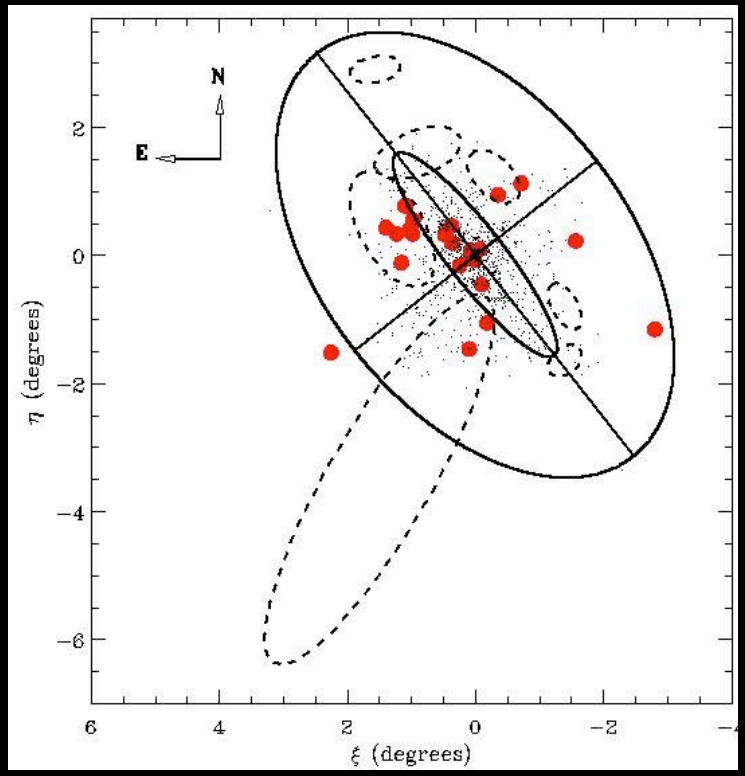
Despite unusual structures, extended clusters just like classical GCs in terms of stellar content....
Not likely to be stripped cores of dSphs!

Mackey et al 2006



- $M_V \sim -6.6$ to -7.4, $R_h \sim 30$ pc
- comparison to Galactic GC fiducials implies [Fe/H]~ -2.1 to -1.8
- no evidence for age spread or composite population: constraint on formation scenarios?
- range of HB morphologies present: strong 2nd parameter problem present

Young Globular Clusters around M31



Huxor et al 2007, in prep

Optical-IR colours of GC systems in M31 can be used to search for candidate young systems (<5 Gyr)

Search done on existing Revised Bologna Catalogue + our new GCs

~20 candidate young GCs identified; these trace a remarkable distribution on the sky with a high concentration in the NE Shelf!

Is this is progenitor remnant (c.f. Fardal et al 2007)?

Summary

- M31 is undergoing a significant accretion event at the present epoch, which is depositing a large number of metal-rich, intermediate stars into the inner halo (c.f. the Milky Way and Sagittarius). The progenitor has yet to be identified....

- Much of the remaining substructure in the inner halo is consistent with being splattered disk material..

- Underlying this recently deposited material is a less structured, extremely extended, metal-poor, hot "halo", which falls off as R^{-2} out to ~150 kpc (c.f. the Milky Way)

- The M31 GC population may contain further signatures of the host's assembly history