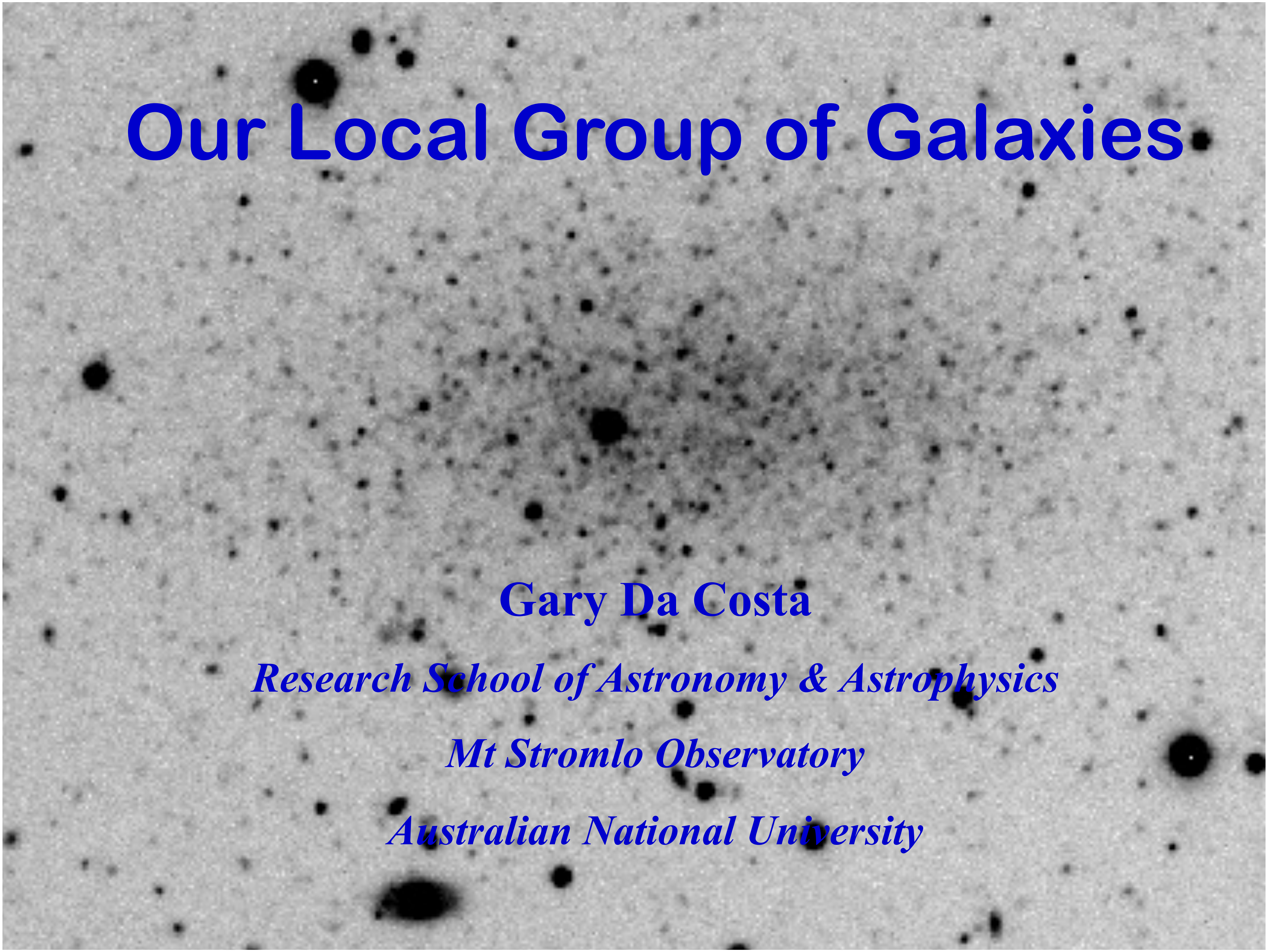
Our Local Group of Galaxies
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The Local Group is our local Universe:

It is a physical (i.e. gravitationally bound) association of at least ~50 galaxies (continues to increase as new satellites of the Milky Way and M31 are discovered) with a radius of ~1.3 Mpc.

Nearly all galaxy types are found in the Local Group – only a high luminosity elliptical is lacking.

Components:

- ***2 large spiral (disk) galaxies***

  the Milky Way, and Andromeda (M31)

  M31 is somewhat larger and more luminous than the Milky Way: M_V (M31) ~ -21.1 while M_V (MWG) ~ -20.6

  (M_V = -20.6 corresponds to 1.4×10^{10} L_{sun})

  M31 and the Milky Way dominate the mass of the LG

Local Group Components (cont'd):

- *1 smaller and less luminous spiral (disk) galaxy*

  M33 M_V (M33) ~ -18.9

- *The proto-type of the "Magellanic Irregular" class*

  The Large Magellanic Cloud (LMC) M_V (LMC) ~ -18.1

This galaxy lacks the spiral-arm structure evident in the MWG, M31 and M33, although still primarily a disk galaxy.

All these galaxies contain significant amounts of gas and are currently forming stars.

- **The remaining galaxies in the Local Group are classified as *Dwarfs*. All have $M_V > -17$ ($L_V < 5 \times 10^8 L_{sun}$).**

Local Group Components (cont'd):

Dwarf galaxies fall into two basic categories:

Dwarf Irregulars (dIrrs)

- **These galaxies contain relatively large amounts of gas, and are currently forming stars or have done so at recent epochs. Gas content characterized by the ratio of the mass in gas to the blue luminosity of the dwarf: M_{HI}/L_B. For dIrrs, $M_{HI}/L_B > 1$ (solar units).**

- **They also have a "clumpy appearance" in that they lack overall symmetry. They are also not generally found near the large galaxies of the Local Group (although the SMC is an obvious exception).**

- **Examples: SMC, NGC 6822, IC 1613….**

- **The brightest systems have $M_V \sim -16$ while the faintest have $M_V \sim -10$.**

Local Group Components (cont'd):

Dwarf Ellipticals (dEs) and Dwarf Spheroidals (dSphs)

- **These galaxies contain no (or very little gas) so that $M_{HI}/L_B < 10^{-2}$ (solar units). They are not forming stars now, nor have they done so recently in any significant way.**
- **They have a "smooth appearance" and are generally elliptical in shape, with the surface brightness largest in the centre decreasing uniformly outwards. With a couple of exceptions, they are found near the large galaxies of the Local Group.**
- **For example, the Milky Way has at least 20 dE/dSph companions while M31 most likely has a similar number (still being discovered).**
- **The brightest systems have $M_V \sim -16$ while the faintest have $M_V \sim -6$ (new discoveries even fainter).**

Local Group Components (cont'd):

So intrinsically faint small galaxies dominate the Local Group by number, but the large galaxies dominate the total mass and the total luminosity.

Proximity of Local Group galaxies means that they can be studied in much greater detail than more distant systems.

In particular, can study individual stars in all Local Group galaxies, allowing direct inferences on properties such as star formation histories, chemical abundances and so on.

Why should we care about dwarf galaxies?

- Because these are supposedly 'simple' systems, so we should be able to readily understand their evolutionary histories (but in fact they are quite complex).

- Because they are probably the 'building blocks' of larger galaxies – in the hierarchical model of structure formation, large galaxies are formed from mergers/accretions of lower mass objects at early times. The current Local Group Dwarfs are the survivors of this process.

Why should we care about dwarf galaxies?

- **Because they have high DARK MATTER content – in some dwarfs the mass/light ratio (with mass measured via the velocity dispersion of the stars or via the circular velocity of the gas) exceeds 100, while the mass-to-light ratio of the stars is typically of order unity. These are DARK MATTER dominated systems.**

- **Because the large range in luminosity (mass) lets us explore properties like mean metallicity as a function of L. This connects to formation processes.**

How complete is the Local Group census?

- Despite the proximity of the Local Group, our census of the total number of galaxies in the LG is likely to be significantly incomplete!

- Significant numbers (>20 objects) of low luminosity and low surface brightness galaxies have been discovered in the last decade or so.

- This is largely because of the availability of the Digital Sky Survey (DSS) and more recently availability of surveys like the Sloan Digital Sky Survey (SDSS).

- *The SkyMapper Southern Sky Survey will most likely find an additional ~20-30 faint satellites of the Milky Way.*

How complete is the list of Milky Way dSph companions?

- Scl and Fornax were discovered by Shapley in the 1930s, while Draco, Ursa Minor, Leo I and Leo II were added in the 1950s from the Palomar Sky Survey. Carina was added in the late 1970s from the Southern Sky Survey. These were all found by eye searches of photographic plates.

- Sextans was discovered in 1990 via a machine scan of a Southern Sky Survey plate (see Irwin et al 1990 MNRAS 244 16P).

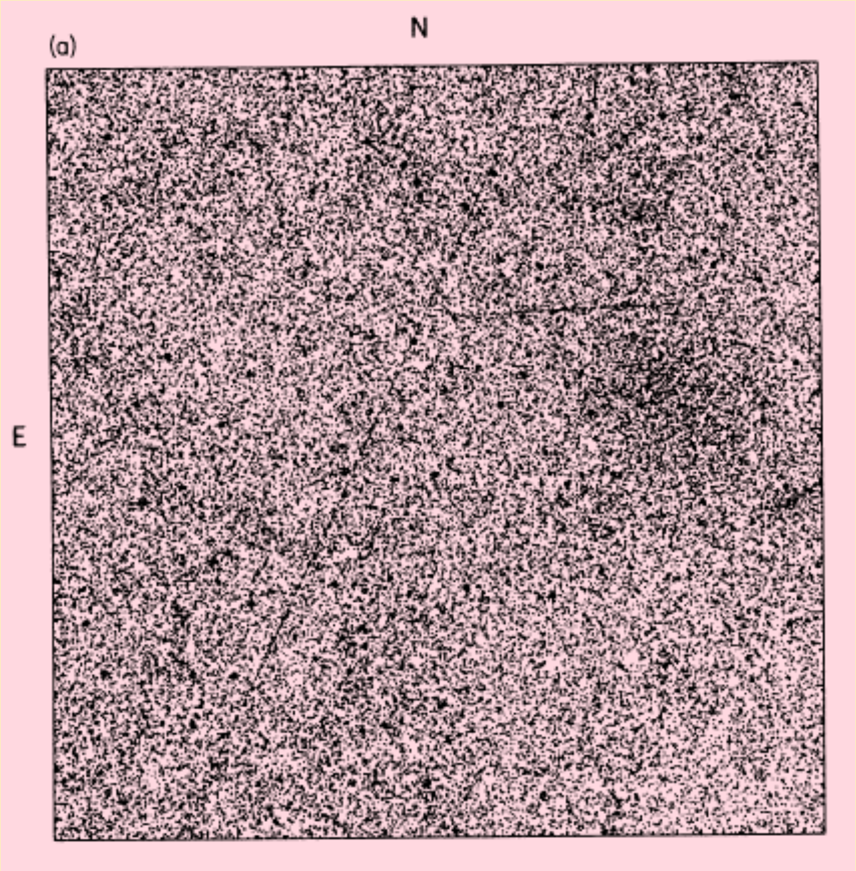
This was a case of "one person's noise is another person's signal"!

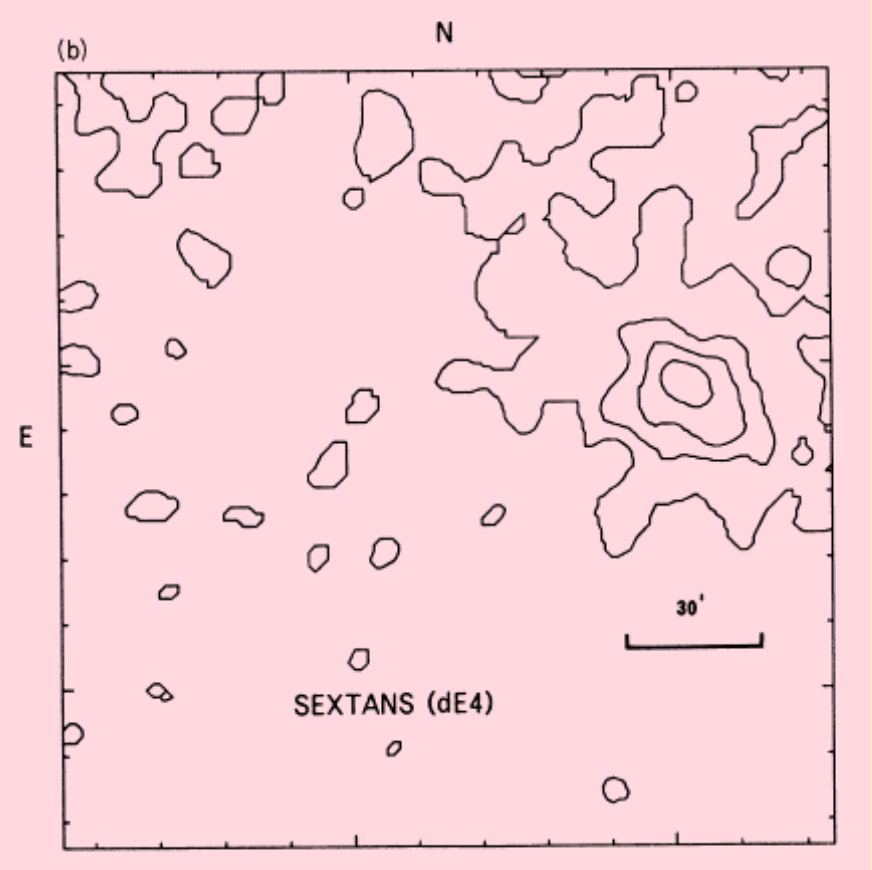
- Sagittarius was discovered in 1995 in a spectroscopic survey of the radial velocities of red giant stars towards the Galactic Centre (see Ibata et al 1995 MNRAS 277 781).

This was a case of a PhD student finding something more interesting is his data than he originally anticipated!

How complete is the list of Milky Way dSph companions?

- Sextans





Left panel shows x,y plot of locations of stars 'discarded' from a scan of a photographic plate carried out as part of the generation of the APM galaxy catalogue. The right panel is a contour plot. Field is ~3 x 3 deg.

How complete is the list of Milky Way dSph companions?

- **Sagittarius**

786 *R. A. Ibata, G. Gilmore and M. J. Irwin*

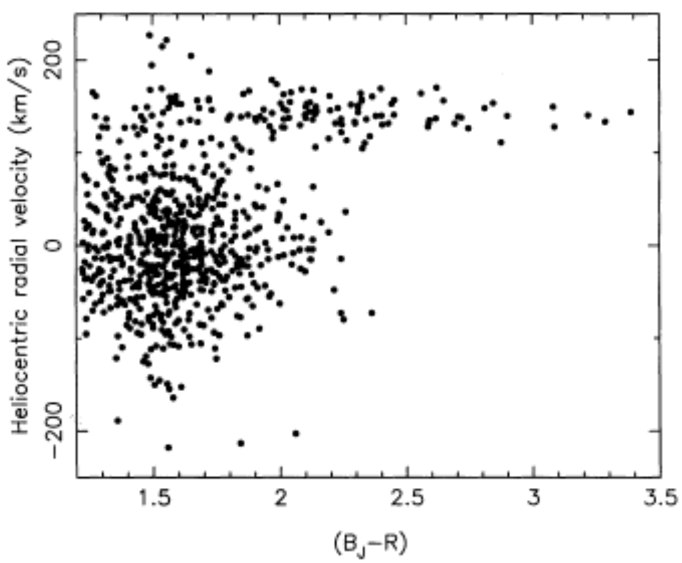
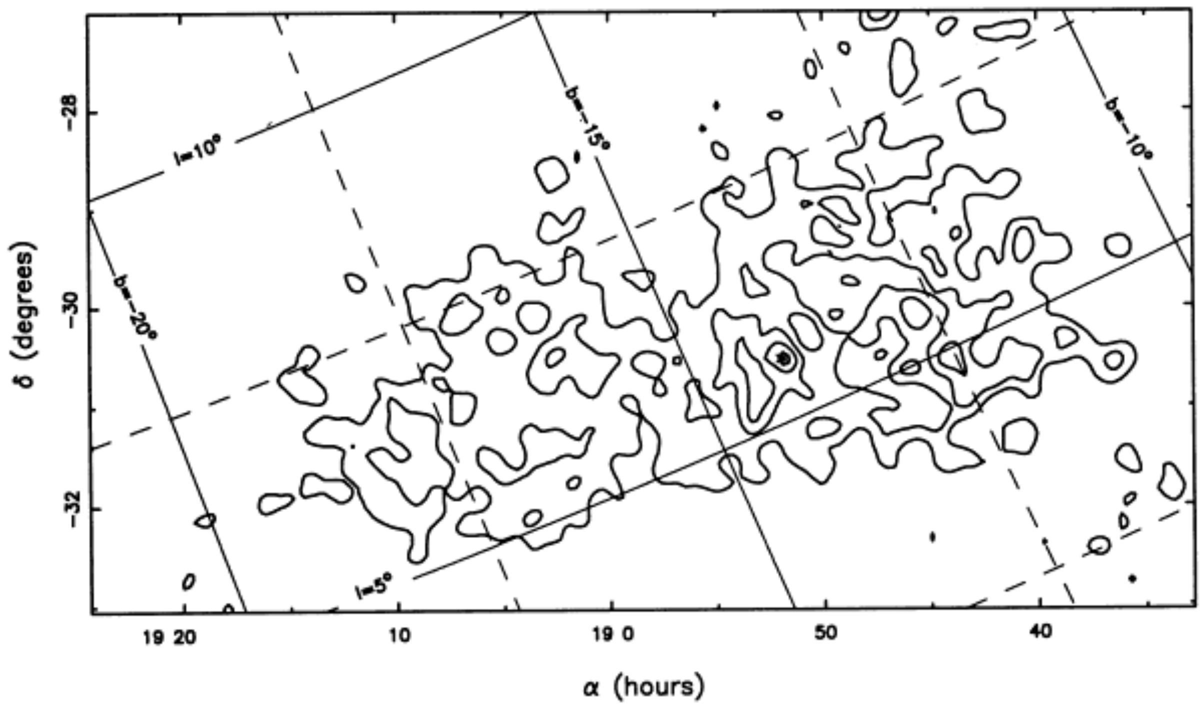


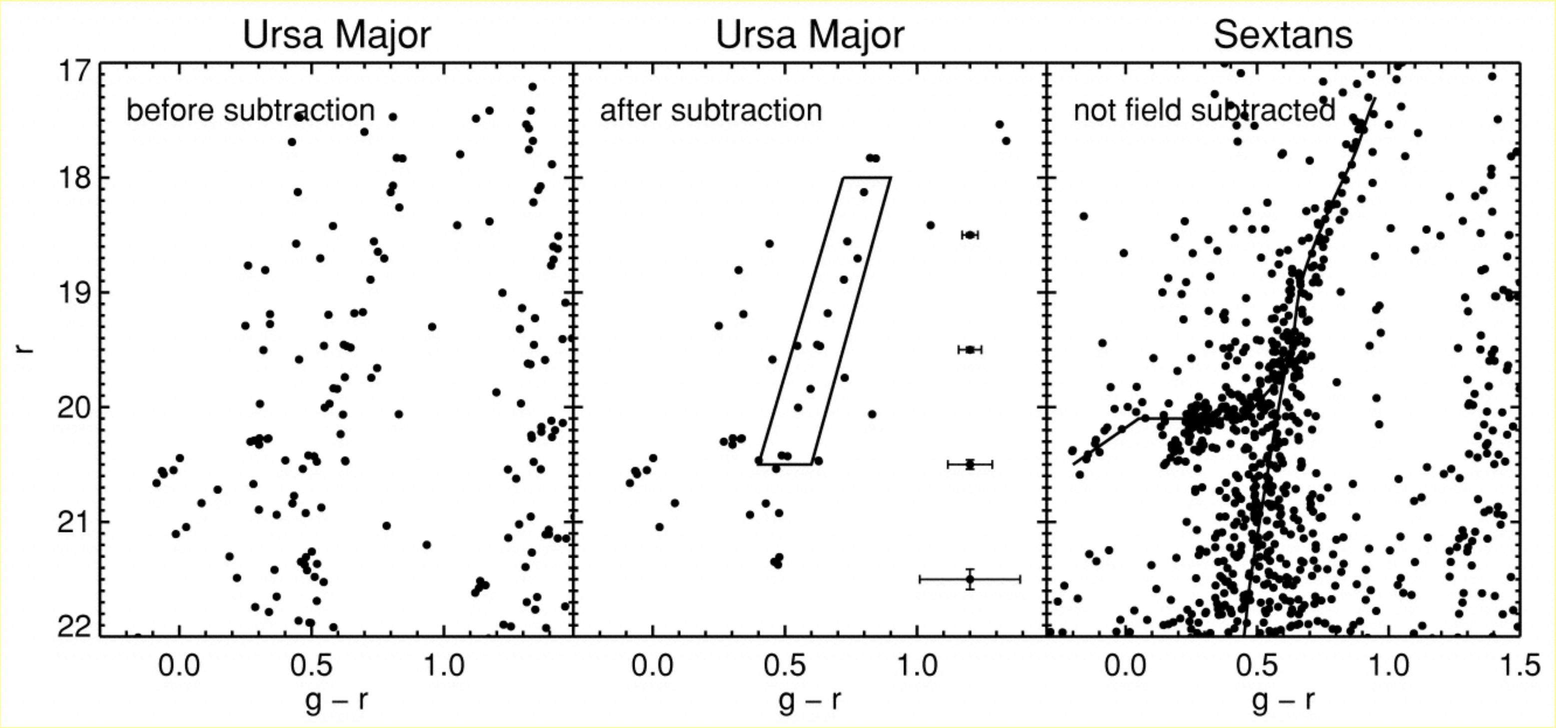
Figure 4. The heliocentric radial velocity–colour distribution of the sample of stars observed at $\ell = 5°$, $b = -12°, -15°, -20°$. The moving group of stars is centred at a velocity of 140 km s^{-1}. (Colours have not been corrected for reddening.)



The Sgr dSph has proved to be a very interesting object - has 4, perhaps 6+, globular clusters of its own, and is currently being disrupted by the tidal field of the Galaxy. Sgr stars are spread over a large part of the sky, tracing out the orbit. See Law & Majewski 2010 ApJ 714 229 and refs therein.

How complete is the list of Milky Way dSph companions?

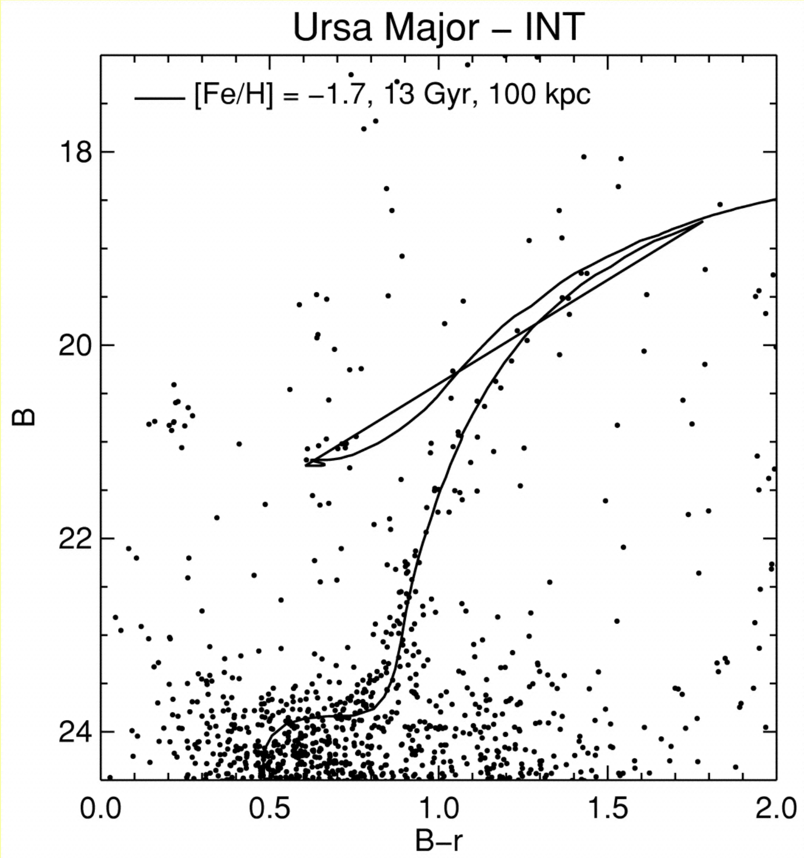
- **Ursa Major - one of the new additions from the SDSS survey** **(see Willman et al 2005 ApJ 626 L85)**



Found by deliberate search for spatial concentrations of stars with red giant branch colours in the SDSS database, followed-up with deeper imaging. Ursa Major lies at ~100kpc from the Galactic Centre.

How complete is the list of Milky Way dSph companions?

- **Ursa Major - one of the new additions** (see Willman et al 2005 ApJ 626 L85)

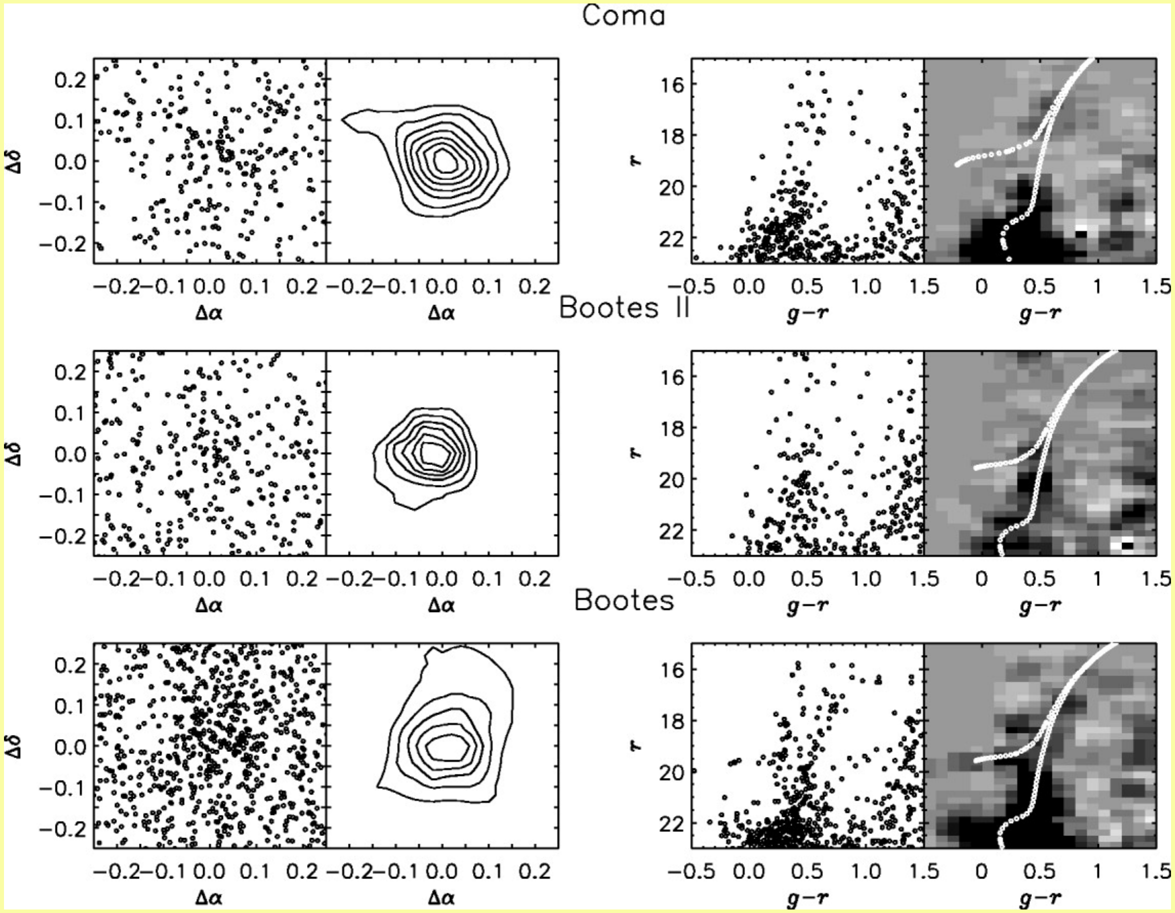


The existence of a large number of faint stars corresponding to the main sequence turnoff confirms Ursa Major as a real object.

With M_V ~ -6.8, Ursa Major is currently one of the faintest galaxies known, but it's one the brightest of the newly discovered MW companions.

How complete is the list of Milky Way dSph companions?

• **Bootes II - another new dwarf satellite** (see Walsh, Jerjen & Willman 2007, ApJ, 662, L83)

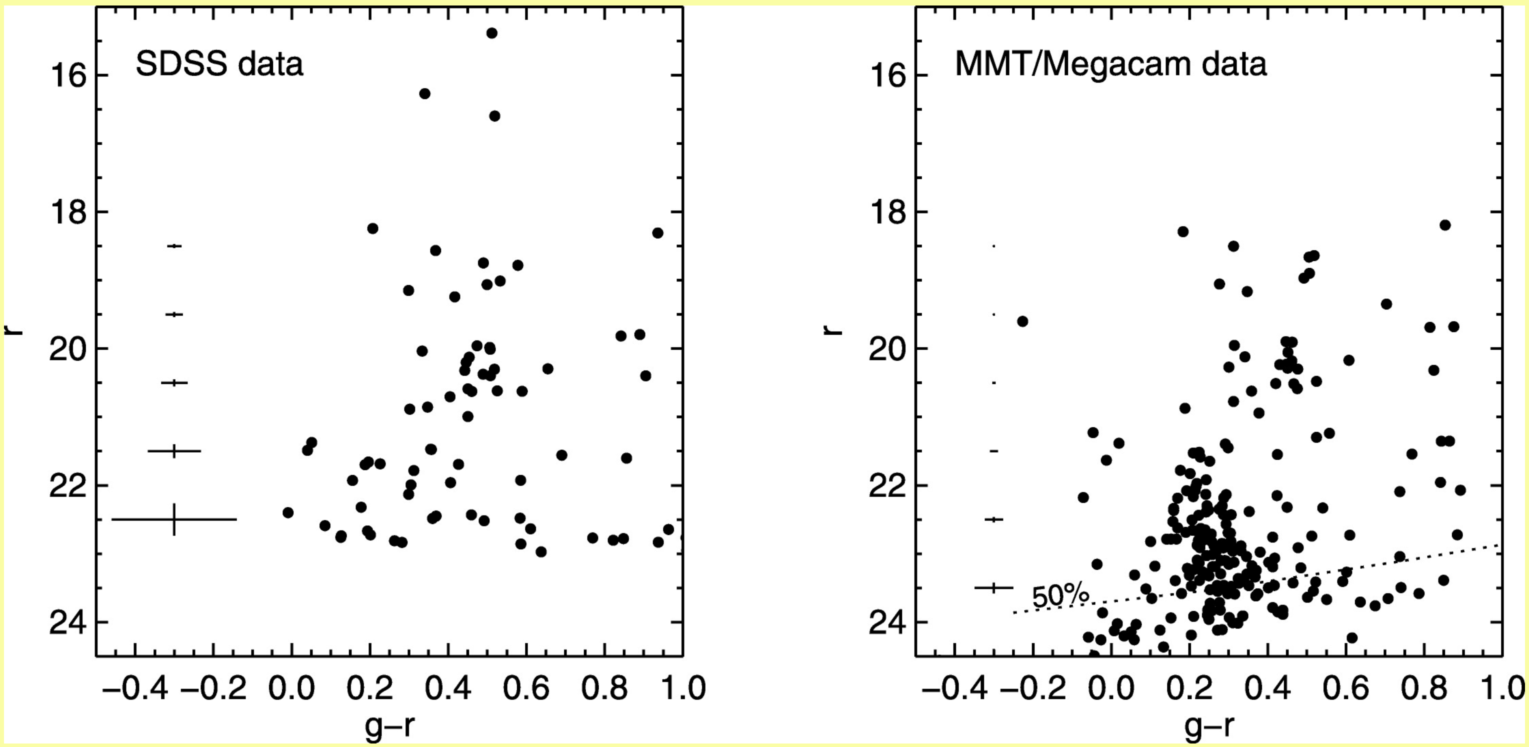


Seeking a spatial density enhancement of stellar images selected to lie in an appropriate magnitude and colour range. Confirm with deeper imaging from a larger telescope.

With M_V ~ -2.3±0.7, Bootes II is one of the faintest of the newly discovered MW companions.

How complete is the list of Milky Way dSph companions?

- **Bootes II - confirmation imaging (Walsh et al 2008, ApJ, 688, 245)**



As for Ursa Major, the existence of a significant number of faint stars corresponding to the main sequence turnoff confirms Bootes II as a real object. Distance is ~40 kpc.

How complete is the list of Milky Way dSph companions?

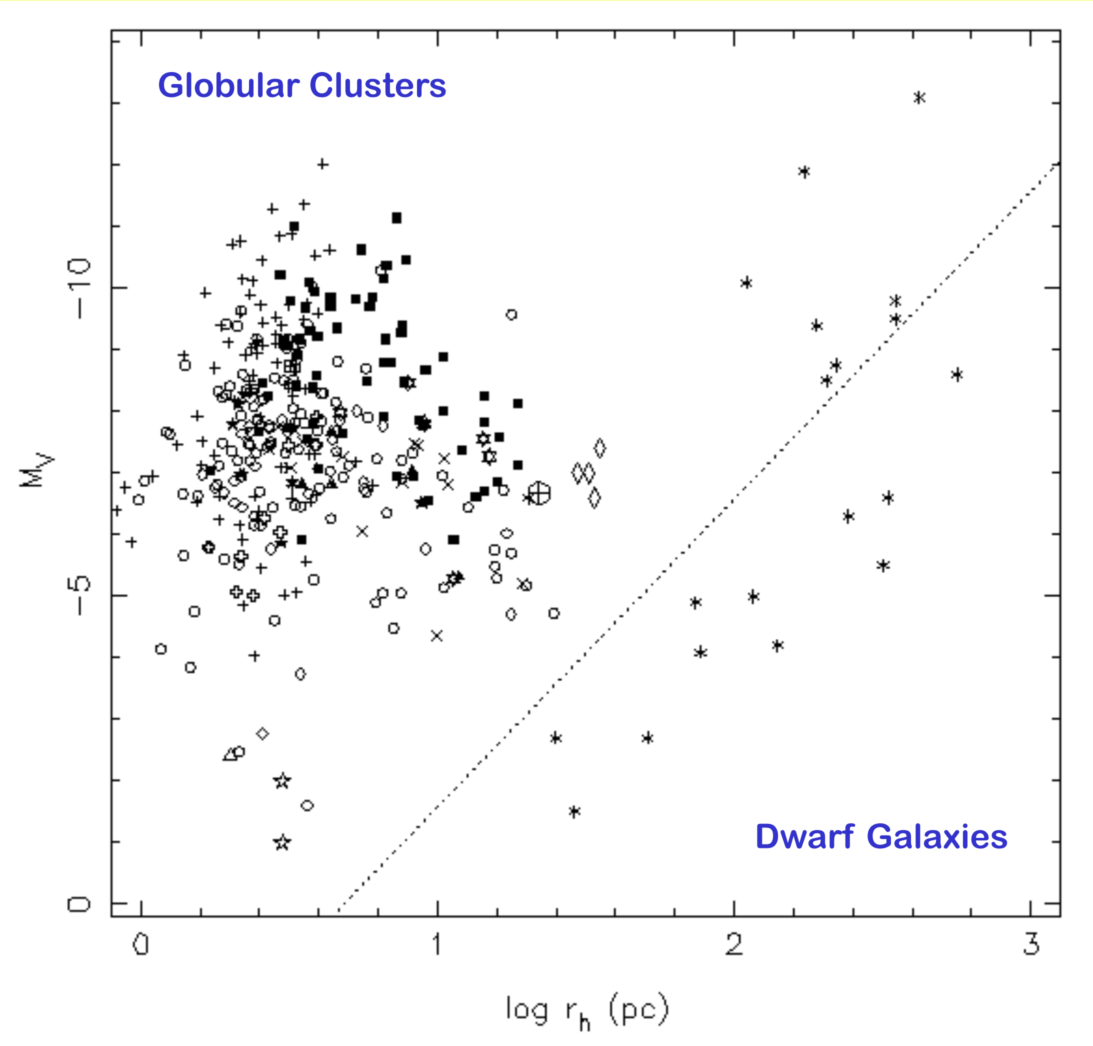
- The current score is that ~dozen definite new Milky Way satellite galaxies have been discovered from the SDSS alone in the past few years: see, for example, Koposov et al 2008, ApJ, 686, 279 and Walsh, Willman & Jerjen, 2009, AJ, 137, 450.

- These systems range in absolute magnitude from $M_V \approx -3$ or fainter (comparable to the luminosity of a single bright red giant!) to $M_V \approx -8$ (only just fainter than the faintest of the previously known systems).

- The properties of these new systems can tell us a lot about galaxy formation, especially at the smallest scales. This is currently a very active field of research.

How complete is the list of Milky Way dSph companions?

• **How do we know the new objects are dwarf galaxies and not star clusters? Basically because at fixed luminosity dwarf galaxies are about x10 larger than star clusters.**

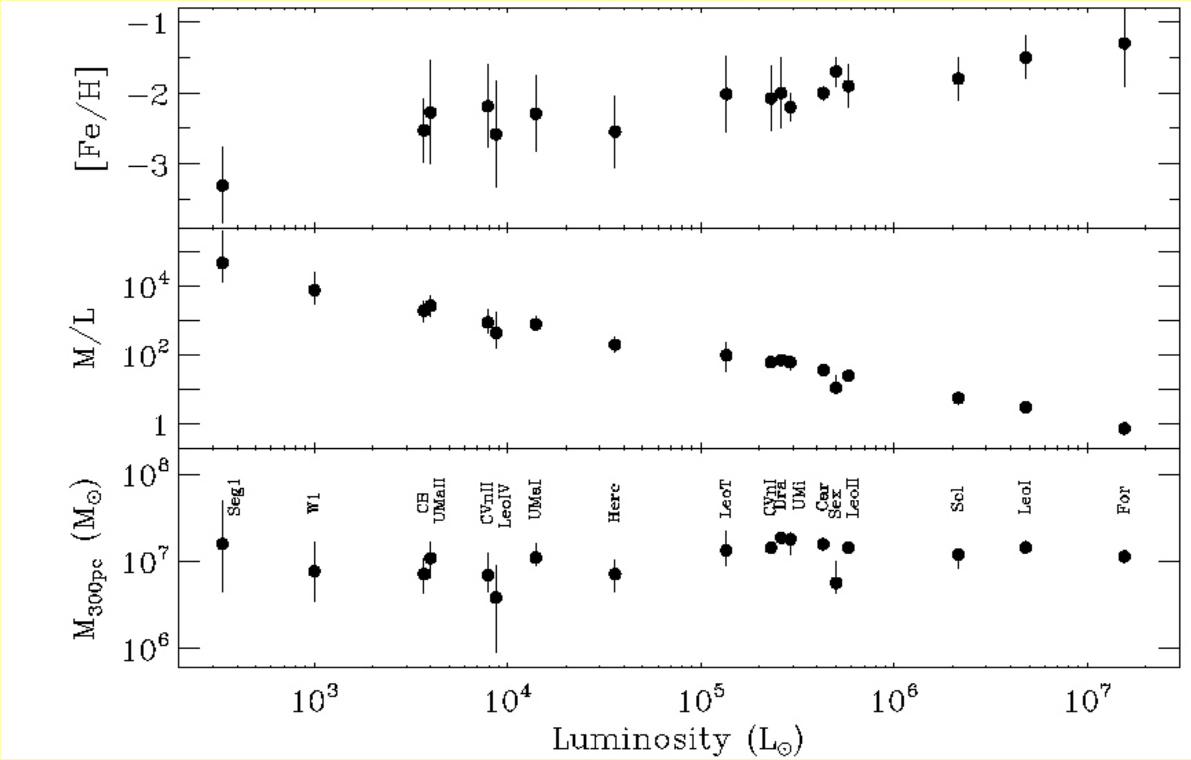


Dashed line corresponds to a constant effective surface brightness of 27 V mag/arsec^2.

Newly discovered dwarfs seem to follow a constant surface brightness line - are there yet larger faint systems?

How complete is the list of Milky Way dSph companions?

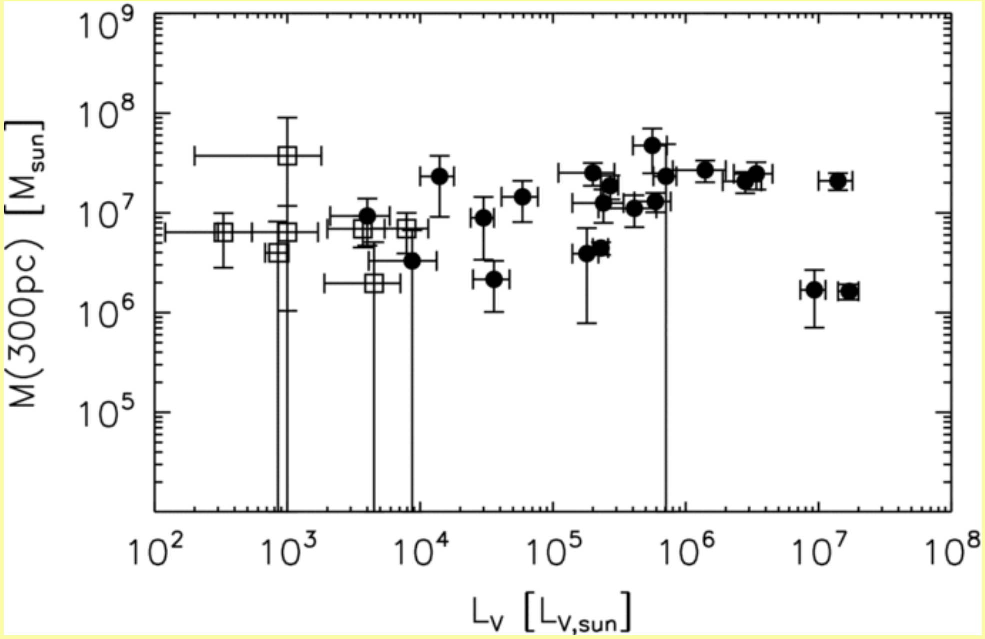
- **Results from Geha et al. 2009 (ApJ, 692, 1464):**



Over more than 4 orders of magnitude in luminosity, mean abundance smoothly decreases while mass-to-light ratio rises, such that the mass inside ~300pc is essentially constant!

How complete is the list of Milky Way dSph companions?

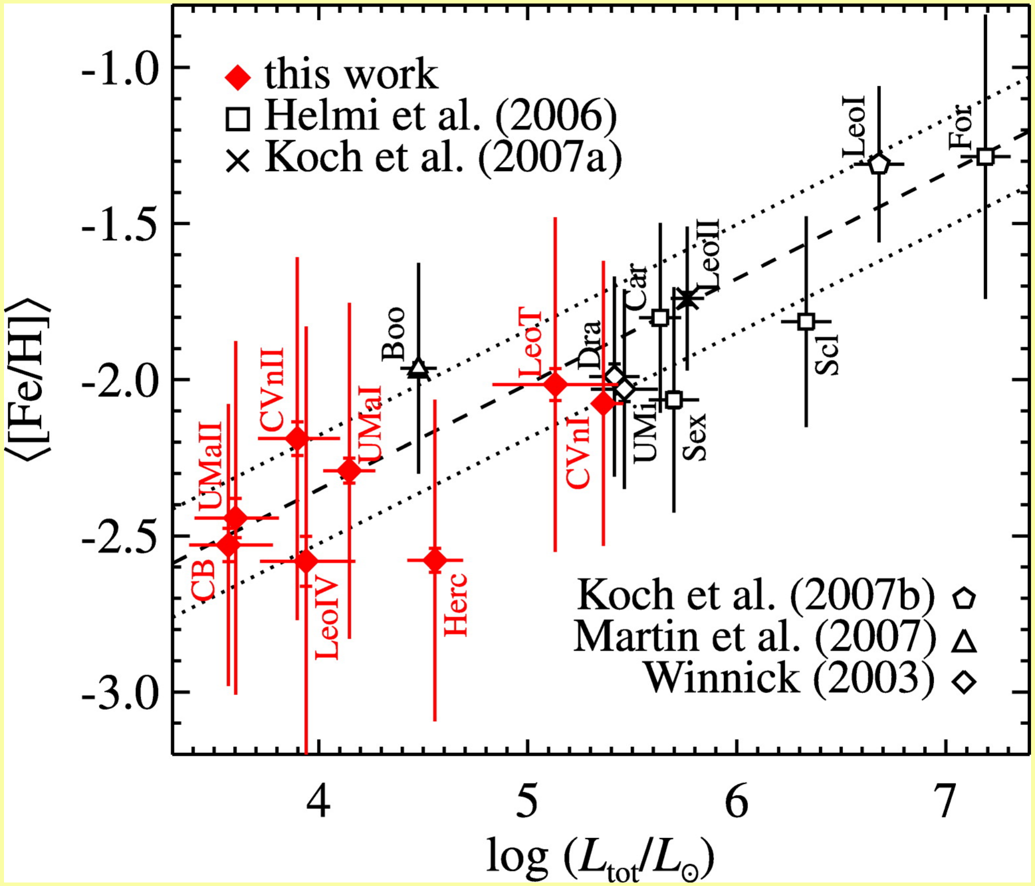
- **Other teams find similar results:**



Walker et al (2009, ApJ, 704, 1274) also find that the total mass inside 300pc is essentially constant - although they note that for the lowest luminosity systems, the M(300pc) values are extrapolations and there is no direct evidence that the dark matter halo extends to such a radius, so the actual dark matter halo mass is likely lower than 10^7 M_{sun}.

How complete is the list of Milky Way dSph companions?

- **Other teams find similar results:**



Luminosity - mean abundance relation from Kirby et al. (2008, ApJ, 685, L43). Note also that a characteristic which distinguishes low luminosity dwarf galaxies from globular clusters is that the dwarf galaxies all show internal abundance ranges in elements like Fe, Ca whereas globular clusters don't.

How complete is the list of Milky Way dSph companions?

- These results raise all sorts of questions:

- is the ~constant (dark matter) mass a characteristic of galaxy formation, or does it say something about dark matter physics? (standard ΛCDM theory has no preferred mass scale) - see Strigari et al. 2008, Nature, 454, 1096

- how do you get the well defined luminosity-mean metallicity relation, especially when the stars are effectively ‘test particles’ in a dark matter dominated potential?

Understanding the processes that set these relations is the key to understanding galaxy formation at the smallest scales.

Again studying the new objects we will find with *SkyMapper* is going to be a crucial contribution to this field. (Good PhD topic!)

How complete is the list of Milky Way dSph companions?

• Given the discovery of a dozen or so new dwarfs in the SDSS, and given that the SDSS covers only about ~1/4 of the sky, it would seem reasonably likely that there are more low-luminosity Milky Way dSph companions waiting to be discovered. What's required is an SDSS-like survey of the Southern Sky…

• *Such a survey is the major science task for the new RSAA wide-field 1.3m telescope at Siding Spring Observatory.*

The SkyMapper telescope will most likely start taking survey data in [insert your best guess! Within the next few months?] assuming no further problems arise in the current commissioning and science verification phase (see www.mso.anu.edu.au/skymapper).

On longer timescales there are also the *Pan-Starrs* project (4x1.8 telescopes in Hawaii, see pan-starss.ifa.hawaii.edu/public/science/stars.html) and the planned *LSST* (8.4 telescope, on Cerro Pachon adjacent to Gemini-S in Chile, see www.lsst.org).

How complete is the list of Milky Way dSph companions?

• Grey area shows region of the sky covered in Data Release 6 of the SDSS. Previously known MW satellites are marked in blue, new discoveries in red. Solid black line and middle grey stripe are at declination zero - inside is the region to be surveyed with SkyMapper. Likely to find ~20-30 new faint dwarf MW companions.

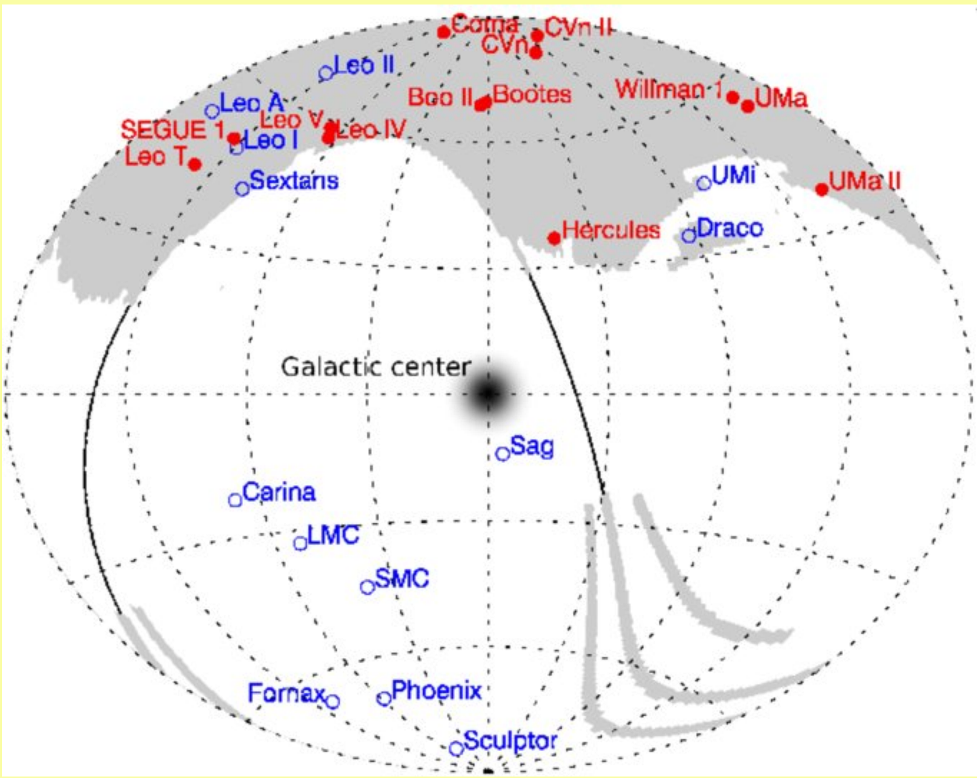


Figure from Walsh, Willman and Jerjen (2009, AJ, 137, 450). Aitoff projection in galactic coordinates.

How complete is the list of M31 dE/dSph companions?

- The relatively bright M31 dE companions M32, NGC 147, NGC 185 and NGC 205 have been known for centuries. In the early 1970s van den Bergh discovered three fainter dE satellites - And I, II and III. These were all found by eye searches of photographic plates.

- In the late 90s three more dE satellites were discovered - two by deliberate search using digitally processed photographic Sky Survey data and a third by eye scans of Sky Survey films (see Armandroff et al 1998 AJ 116 2287, Armandroff et al 1999 118 1220). Known as And V, And VI (Peg) and And VII (Cas).

- Since then there have been further additions - e.g. And IX discovered through analysis of SDSS images (Zucker et al 2004, ApJ 612, L121) and additional systems through deeper imaging surveys (latest additions are And XXIII - And XXVII, see Richardson et al 2011, ApJ, 732, 76; AndXXVIII, Slater et al 2011, ApJ, 742, L14; And XXIX, Bell et al 2011, ApJ, 742, L15).

How complete is the list of Local Group members that are not associated with the Galaxy or M31?

- This list has varied somewhat over the past decade or so as better data (e.g. deep color-magnitude diagrams) have provided better distance estimates, leading to improved LG membership (or not) classifications.

- There are only been two 'new' isolated LG galaxies added in recent years. These are the isolated dEs Tucana and Cetus. Tucana was discovered by accident while Cetus was the only LG object found in a visual scan of the entire southern sky survey (on photographic films).

- Finding such objects is very difficult as you need deep photometry (to get beyond the Galaxy) over effectively the entire sky - a task for LSST probably.

- Note - we know there are no gas-rich dwarfs missed as they would have been detected in HI surveys.

So why do we care about finding additional satellites and Local Group members?

• **Because one the major problems for ΛCDM theories of structure formation, which apparently do a good job of reproducing the overall observed galaxy distribution on large scales, is that for the Local Group they predict many more low mass dark matter halo satellites than the number of known dwarf galaxies, *by 1-2 orders of magnitude*. This is known as the "missing satellites problem" (see Klypin et al 1999 ApJ 522 82 and Moore et al 1999 ApJ 524 L19).**

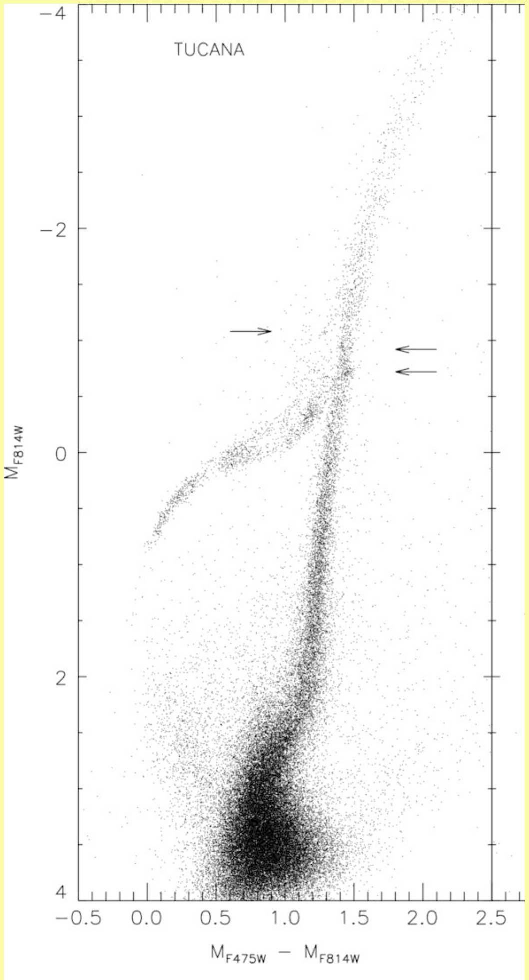
• **The solution probably lies in the complex physics of star formation in the early universe but "the better the local data the better the constraints".**

So why do we care about finding additional satellites and Local Group members?

- And from my point-of-view the more objects, the more the chance (?) of figuring out what drives the surprisingly complex star formation histories of these supposedly simple systems.

- For example, there is the well known *morphology-density* relation in which the majority (but not all !) of the isolated dwarf galaxies in the Local Group are (star-forming, gas-rich) *dIrrs*, not dEs - isolated dEs are rare.

This hints at the role of the ‘parent’ galaxy in governing the evolution of the satellite dwarfs (e.g. gas removal mechanisms such as ram-pressure stripping in a hot halo preventing gas retention to the present-day), yet how does Tucana fit in…???



Tucana is an isolated Local Group dEs far from any large galaxy, yet it shows very little evidence for any on-going star formation and it currently contains no gas.

Based on its current location it should be a gas-rich dIrr?.

Was it once close to M31 or the Milky Way ??

HST photometry of Tucana from Monelli et al (2010 ApJ, 722, 1864).

Bottom line: **still a lot of interesting Astronomy and Astrophysics to do in our own backyard!**

(slides available from www.mso.anu.edu.au/~gdc/talks/talks.html)