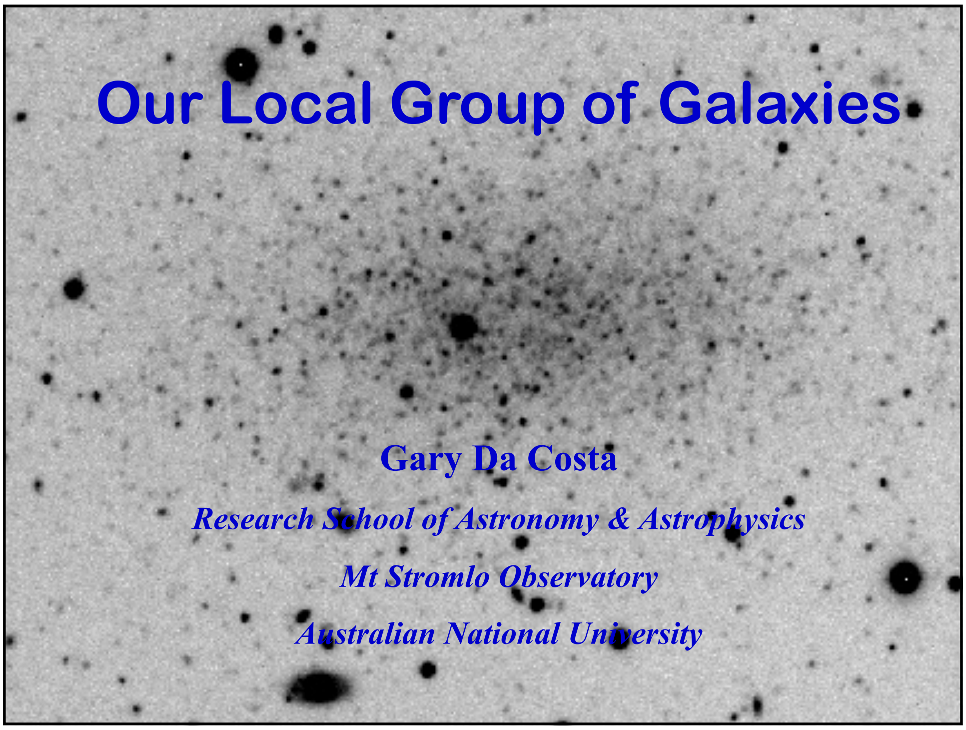


The Local Group is our local Universe:

It is a physical (i.e. gravitationally bound) association of at least ~60 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 galaxy 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 x 10^{10} L_{sun})

  M31 and the Milky Way dominate the mass of the LG

2

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 it is 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 $M_V > -17$ ($L_V < 5 \times 10^8 L_{sun}$).

3

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 <u>not</u> 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 ~ -16 while the faintest have M_V ~ -10 or fainter.

4

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 30 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 $M_V \sim -5$ (new discoveries even fainter).

5

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.

6

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.

7

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) significantly exceeds 100 in solar units , 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) allows the exploration of properties like mean metallicity of the member stars as a function of L.
This provides a connection to formation processes.

8

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 (>30 objects) of low luminosity, low surface brightness systems have been discovered in the last decade or so.

• This is largely because of the availability of digital imaging surveys like the Sloan Digital Sky Survey (SDSS) and the availability of wide-field digital imaging cameras like DECam on the CTIO 4m telescope in Chile.

• *Digital imaging data allows the application of sophisticated search techniques that can find systems that are barely recognizable otherwise.*

9

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 photographic plate (see Irwin et al 1990 MNRAS 244 16P).

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

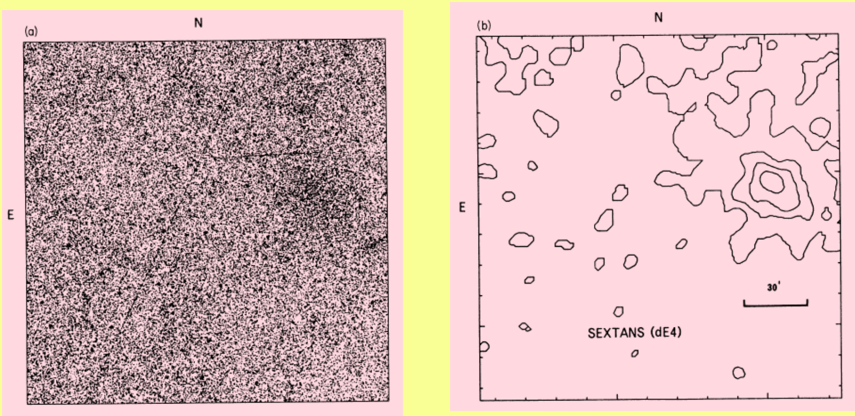
• Sagittarius was discovered in 1995 in a spectroscopic survey of the radial velocities of red giant stars towards the Galactic Centre (see Ibata et al 1995 MNRAS 277 781).

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

10

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*

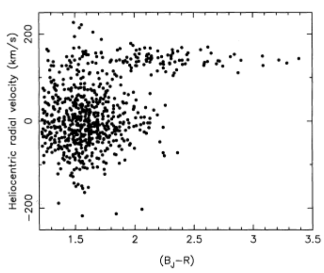
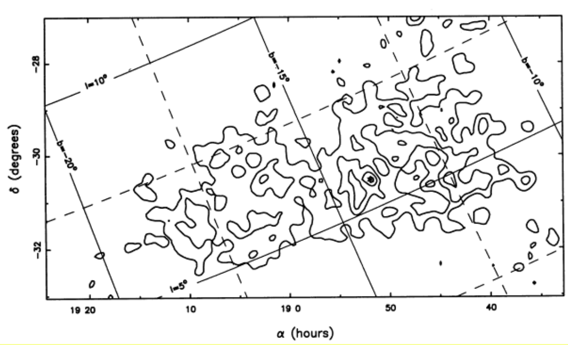


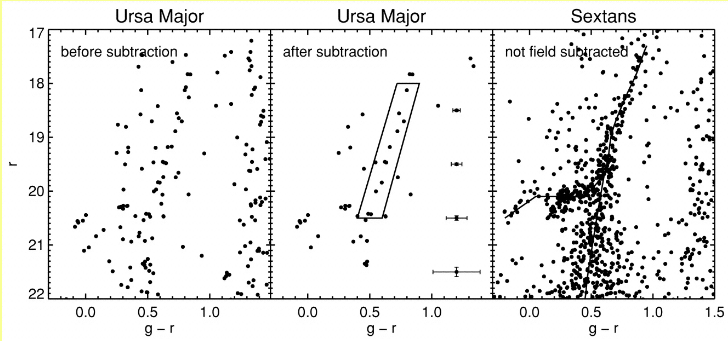
Figure 4. The heliocentric radial velocity–colour distribution of the sample of stars observed at $\ell = 5°$, $b = -12°, -15°, -20°$. The moving group of stars is centred at a velocity of 140 km s^{-1}. (Colours have not been corrected for reddening.)



The Sgr dSph has proved to be a very interesting object – it 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)

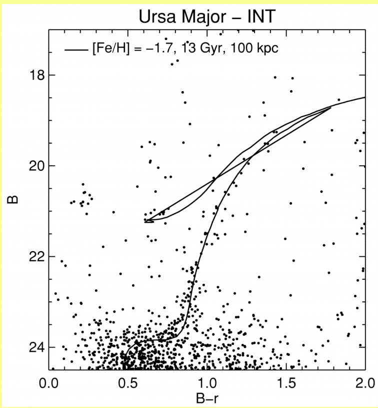


Found by deliberate digital search for spatial concentrations of stars with red giant branch colours in the SDSS database, followed-up with deeper imaging. Ursa Major lies at ~100kpc from the Galactic Centre.

13

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)



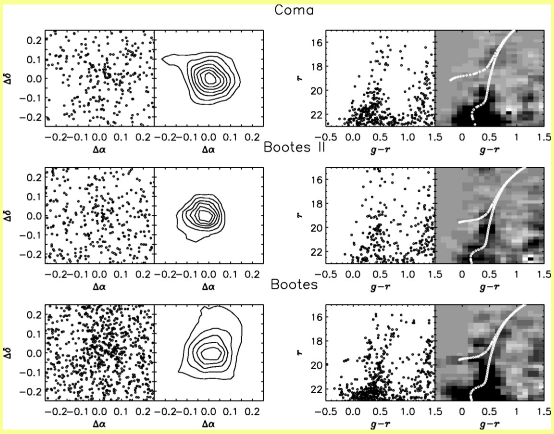
The existence of a large number of faint stars corresponding to the main sequence turnoff confirms Ursa Major as a real object.

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.

14

How complete is the list of Milky Way dSph companions?

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



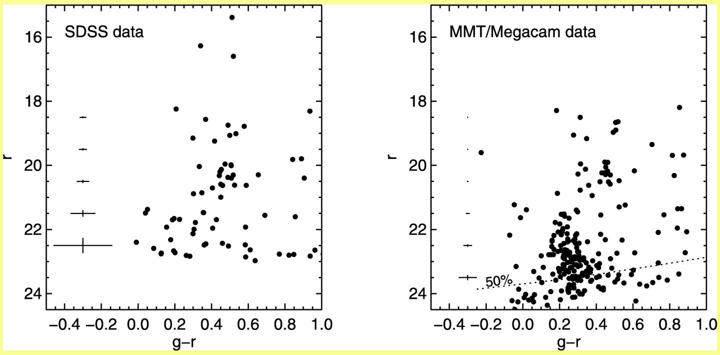
Seeking a spatial density enhancement of stellar images selected to lie in an appropriate magnitude and colour range. Confirm with deeper imaging from a larger telescope.

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

15

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.

16

How complete is the list of Milky Way dSph companions?

- The SDSS added ~dozen new Milky Way satellite galaxies – these systems have become the prototypes for the "Ultra-Faint Dwarf" galaxy classification. See, for example, Koposov et al 2008, ApJ, 686, 279 and Walsh, Willman & Jerjen, 2009, AJ, 137, 450.
- The ultra-faint 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).
- On going searches of the southern hemisphere sky are continuing to find additional Ultra-Faint systems. There are two major programs:

The Dark Energy Survey (see https://www.darkenergysurvey.org/) and the Stromlo Milky Way Satellites Survey (see http://www.mso.anu.edu.au/~jerjen/SMS_Survey.html) that is led here by Assoc Prof Helmut Jerjen.

17

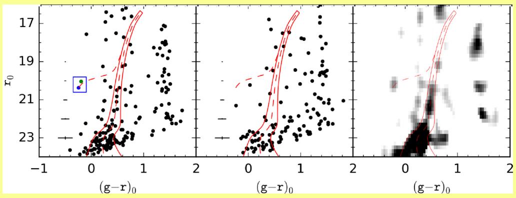
How complete is the list of Milky Way dSph companions?

- Both surveys use the DECam imager on the 4m telescope at Cerro Tololo Observatory in Chile. This camera consists of 62 2kx4k CCDs arranged in a ~circular pattern covering a field-of-view of ~3 square degrees. It allows faint imaging of large areas of sky in relatively modest amounts of telescope time.
- The Dark Energy Survey is primarily concerned with understanding the nature of the 'dark energy' that drives the current accelerating expansion of the Universe.
- But analysis of the DES images is also generating a substantial number of new ultra-faint dwarf galaxy satellites of the Milky Way (see Li et al 2017, ApJ, 838, 8 and references therein).
- Many of these new systems lie relatively close the Large Magellanic Cloud suggesting they may be associated with that system (see Drlica-Wagner et al 2016, ApJ, 833, L5 and references therein).

18

How complete is the list of Milky Way dSph companions?

- The Stromlo Milky Way Satellites Survey also uses DECam but concentrates on areas of the southern sky that are outside the DES region.
- So far the survey has found 3 very low luminosity star clusters (Kim 1,2 and 3) and 2 new ultra-faint Milky Way companions (Horologium II and Pegasus III). See Kim et al 2016a, ApJ, 820, 119 and Kim et al 2016b, ApJ, 833, 16 and references therein.



Discovery of Ho II. Left: dwarf central regions; middle: field region; right: difference (grey scale depiction). From Kim et al 2016, ApJ, 808, L39. Mv of the system is -2.6 +/- 0.3.

19

How complete is the list of Milky Way dSph companions?

- *How do we know the new objects are ultra-faint dwarf galaxies and not star clusters?*
- There are 4 distinguishing characteristics:

* at fixed luminosity, dwarf galaxies have larger scale radii than star clusters

* dwarf galaxies are dark matter dominated, star clusters do not have any dark matter

* dwarf galaxies possess internal ranges in abundance of elements like iron, low luminosity star clusters do not.

* dwarf galaxies follow a correlation between mean abundance and luminosity, star clusters do not.

Except for the first, the other characteristics require observations of individual member stars, which is challenging for the more distant systems.

20

How complete is the list of Milky Way dSph companions?

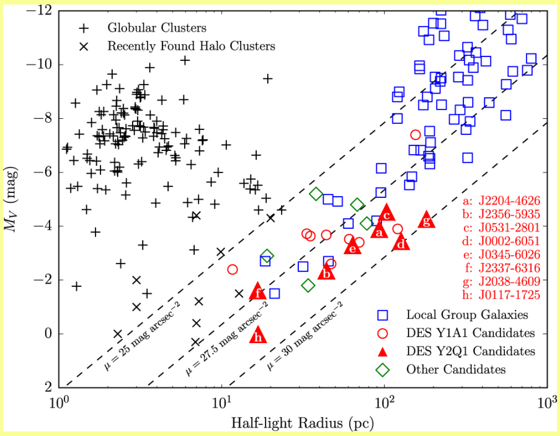
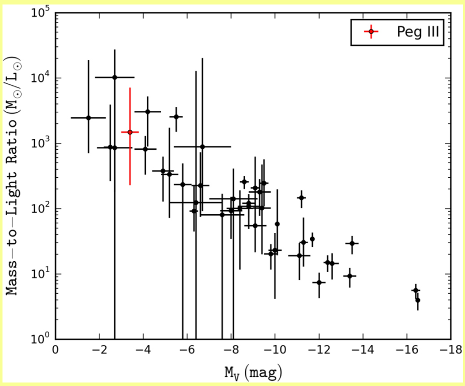


Figure from Drlica-Wagner et al 2015, ApJ, 813, 109. Brighter than Mv ~ -5 the cluster/galaxy separation is clear, but at low luminosities the discrimination is less clear-cut. Dwarf galaxies follow a ~constant surface brightness line – most likely an observational selection effect.

21

How complete is the list of Milky Way dSph companions?

- Results from Kim et al 2016, ApJ, 833, 16



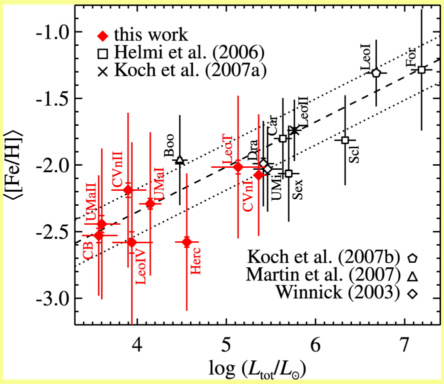
Dwarf galaxies show a trend of increasing mass-to-light ratio with decreasing luminosity, implying an increasing contribution from dark matter to the total mass.

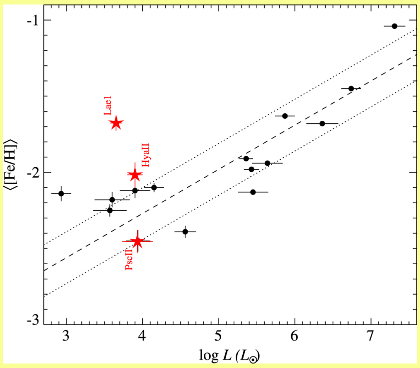
(Measuring M/L requires the measurement of the velocity dispersion from individual stellar velocities, a radius scale and the total luminosity, plus assuming the system is in equilibrium.)

Globular clusters show no such trend – the M/L values are ~1 – 3 in solar units independent of luminosity and there is no evidence for any dark matter.

22

How complete is the list of Milky Way dSph companions?





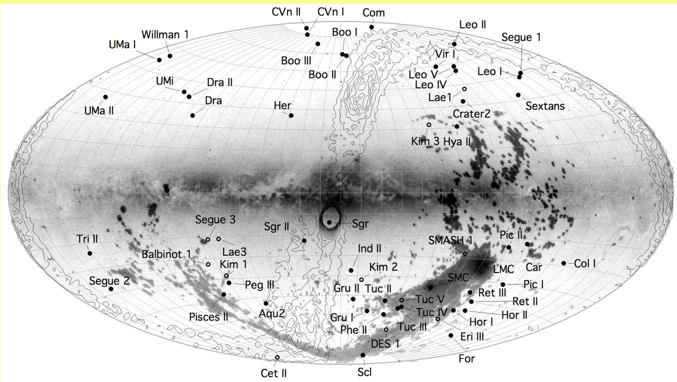
Mean metallicity <[Fe/H]> versus Luminosity diagrams from Kirby et al (2008, ApJ, 685, L43) and Kirby et al (2015, ApJ, 810, 56) for dwarf galaxies. Globular clusters show no such relation. Laevens 1 is classified as a star cluster given its location in the right panel.

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

23

How complete is the list of Milky Way dSph companions?

- **Here is the current view of the Milky Way's satellites (courtesy Helmut Jerjen)**



Additional discoveries will likely come from the *LSST* program (8.4 telescope, on Cerro Pachon in Chile, see www.lsst.org) which will survey the southern sky to unprecedentedly faint levels.

24

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, AJ, 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 many additional systems through the Pan-Andromeda imaging survey – PAndAS. See Martin et al 2016, ApJ 833, 167. *The latest additions AndXXXI, AndXXXII and AndXXXIII* come from the Pan-STARRS survey – see Martin et al 2014, ApJ, 793, L14 and Rhode et al 2017, ApJ, 836, 137.

25

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 probably no gas-rich dwarfs missed as they would have been detected in all-sky HI surveys.

26

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".

27

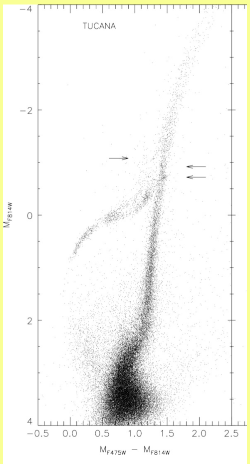
So why do we care about finding additional satellites and Local Group members?

• 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…???

28



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)