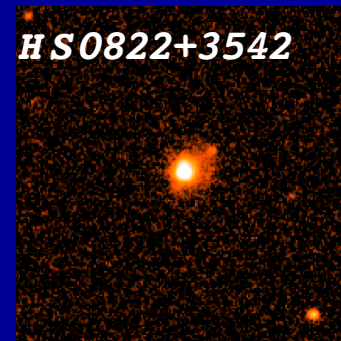
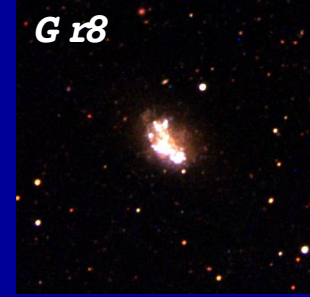
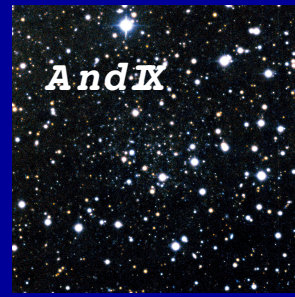
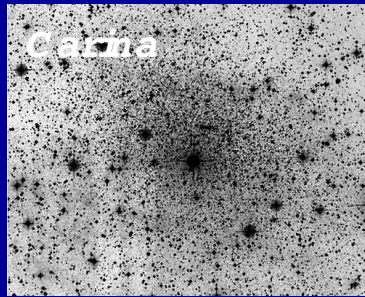
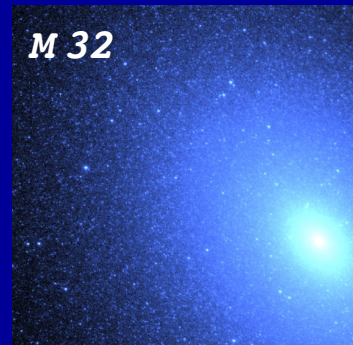


Dwarf galaxies: the most common galaxies



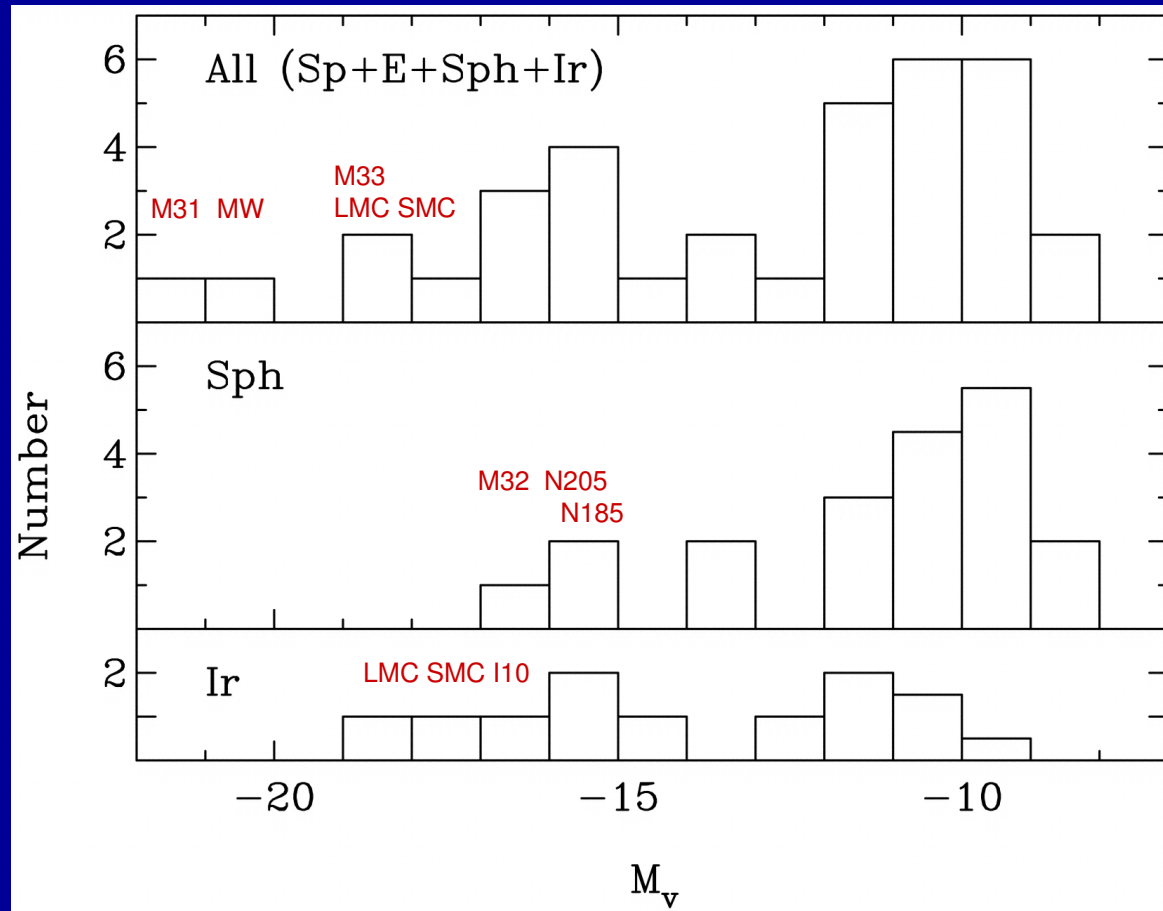
Dwarf galaxies

“Dwarf galaxies of the Local Group”: Mateo 1998 ARAA 36, 435

- **Large numbers**, especially in large clusters
- **Simplest** galactic systems known. But still have **complex star formation and chemical enrichment histories**.
- Low L dwarfs tend to be **metal poor**; the lowest L mostly primordial material.
- Among the **darkest** single galaxies known; important constraints on the distribution and nature of dark matter.
- Local Group: mix of dIrr and dSph/dE's among its low L galaxies; distributed very differently.
- Tides/interactions are important to the evolution of dwarfs and, possibly, their formation.

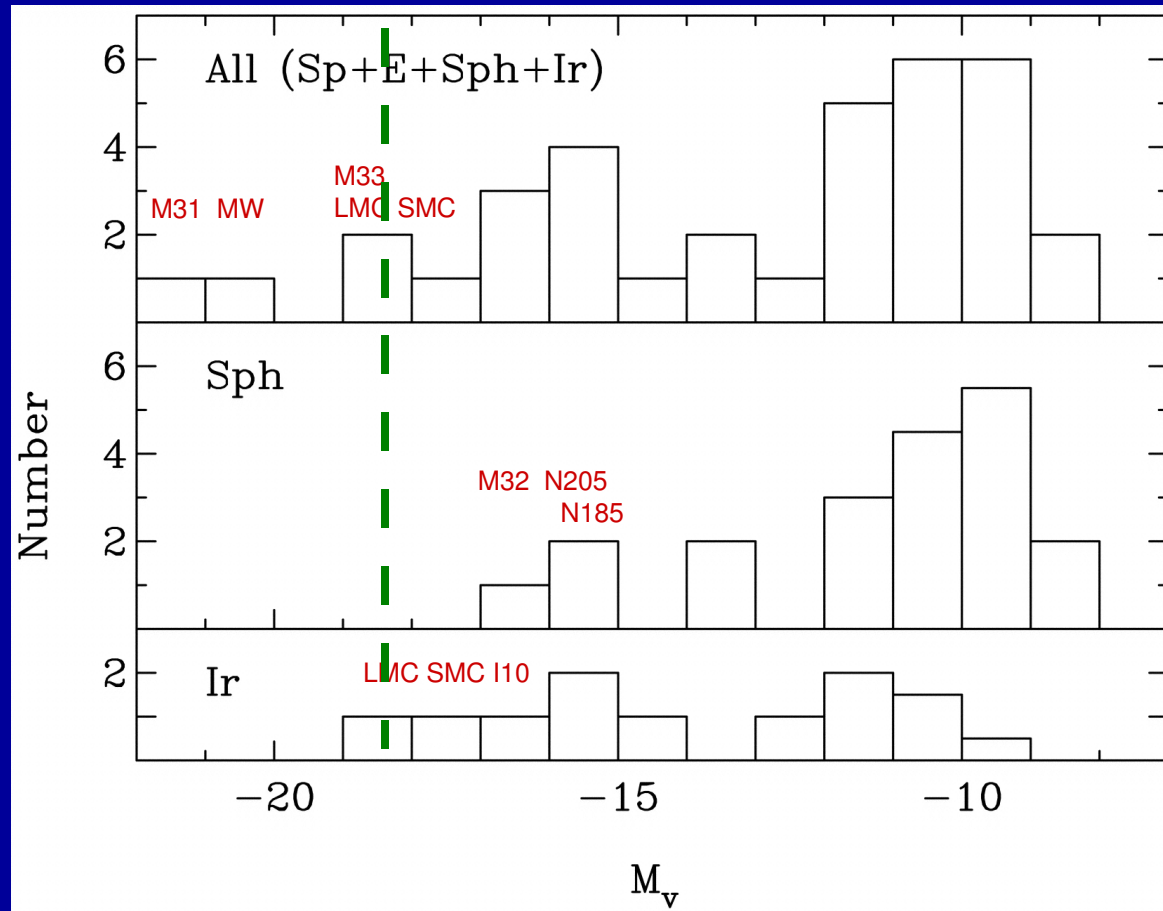
When is a galaxy a dwarf?

- Fainter
- Smaller (extent)
- Lower mass (rotation velocity/velocity dispersion)

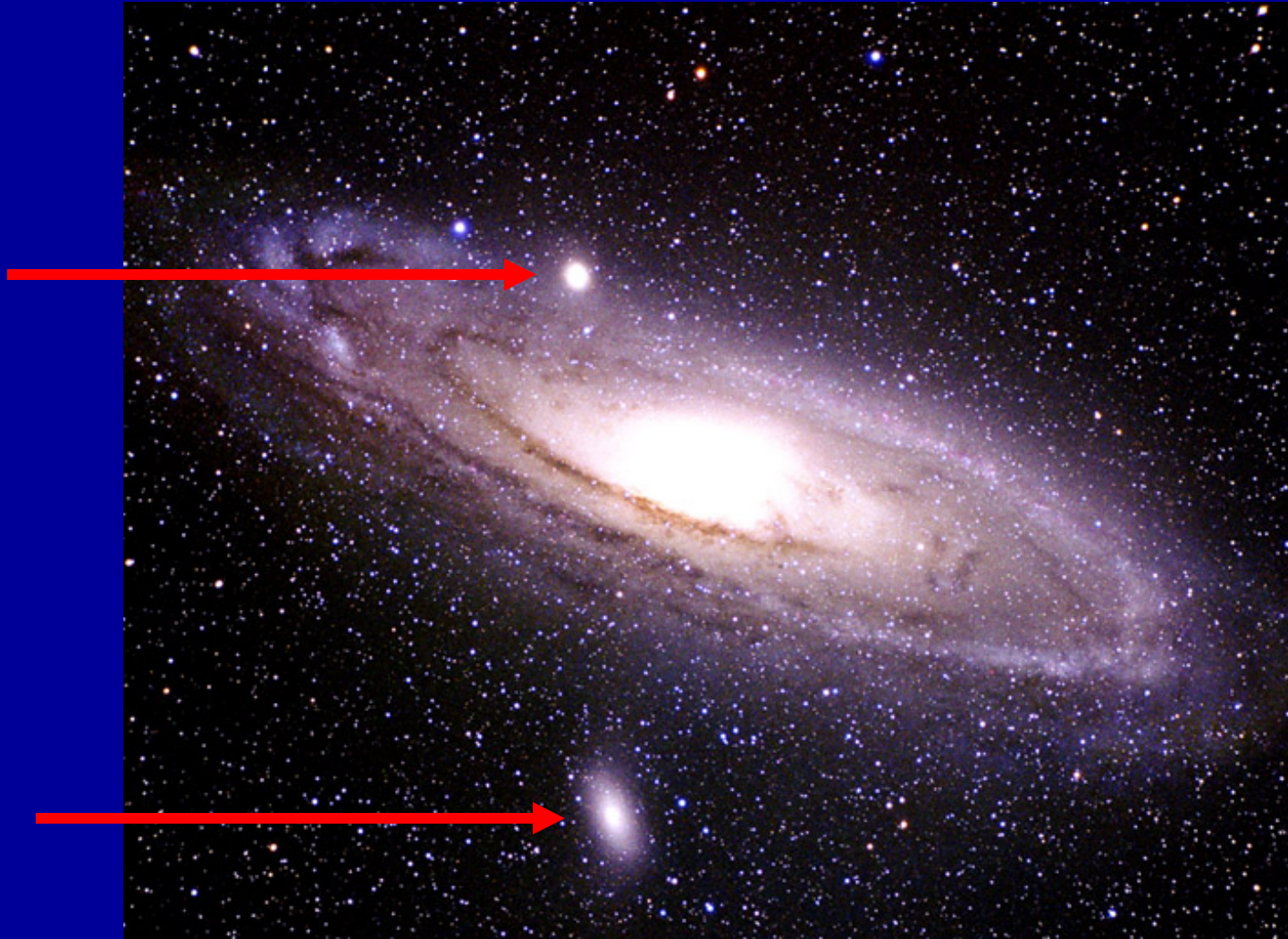


When is a galaxy a dwarf?

- Fainter
- Smaller (extent)
- Lower mass (rotation velocity/velocity dispersion)



M31, The Andromeda Galaxy



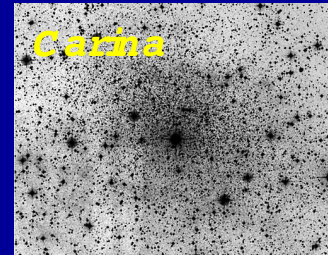
Dwarf galaxies



- dE, dSph, dIrr
- Low mass: detected only nearby
- Dark matter dominated
- Low abundances
- Stellar mass: 10^6 - $10^8 M_{\odot}$
- Blue Luminosity: 10^6 - $10^8 L_{\odot}$ ($M_B > -15$)
- Dynamical mass: 10^7 - $10^9 M_{\odot}$

Where they are gas-rich:

- HI mass: 10^6 - $10^8 M_{\odot}$
 - Sometimes, extensive HI
 - Evidence for dark matter



"Dwarf galaxies of the Local Group" Mateo 1998 ARAA

Elliptical galaxies display a variety of sizes and masses

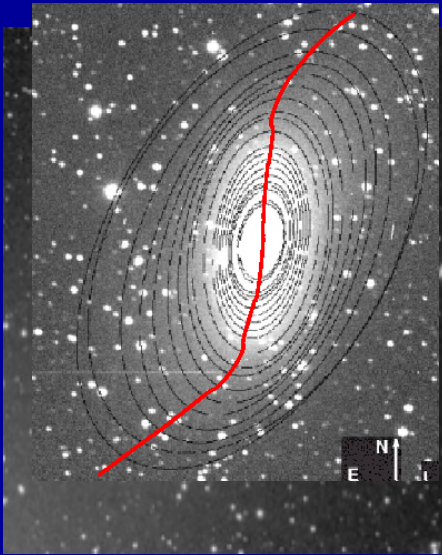
- *Giant elliptical galaxies* can be 20 times larger than the Milky Way
- *Dwarf elliptical galaxies* are extremely common and can contain as few as a million stars



Local Group dEs

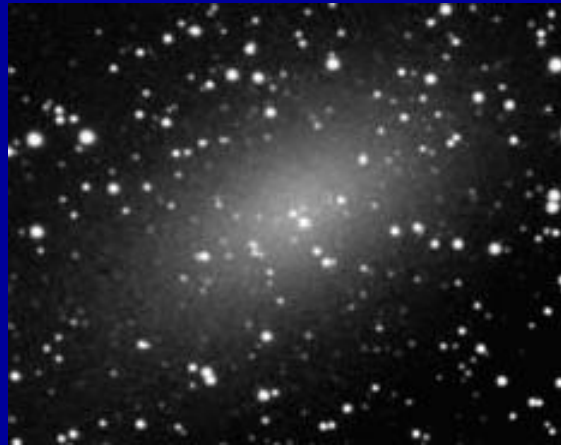
Keck/DEIMOS observations of Local Group dEs

NGC 205



(Choi, Guhathakurta & Johnston 2003)

NGC 147



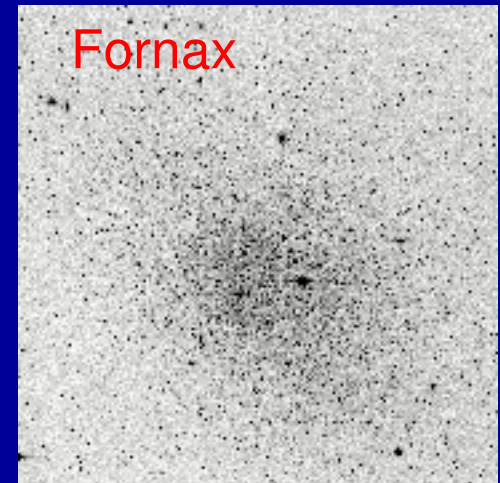
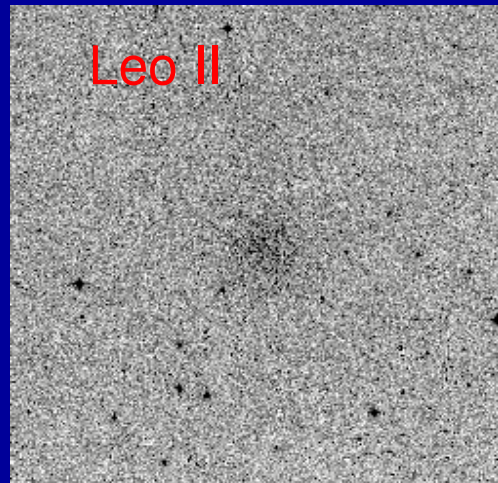
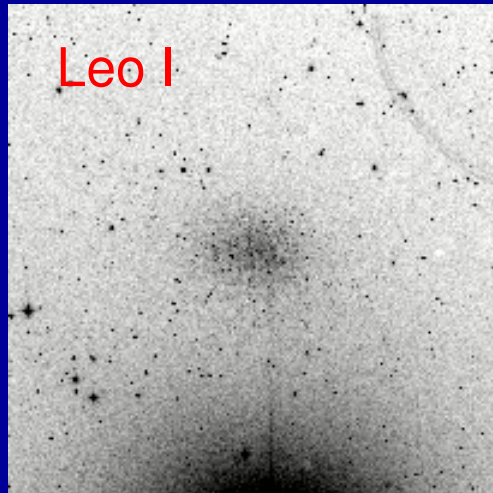
NGC 185



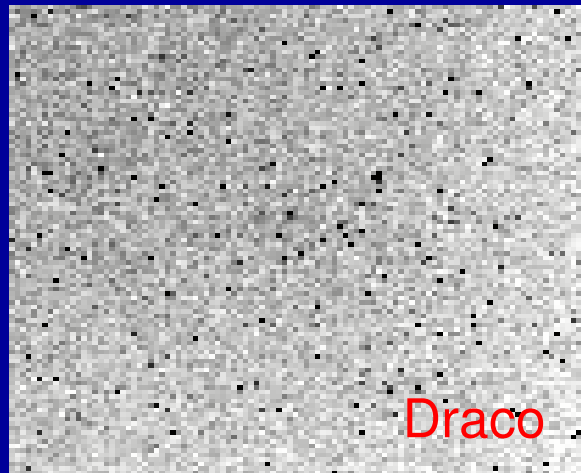
Surface photometry of NGC 205
consistent with early tidal disruption.

M. Geha
2006 Ringberg conference

Dwarf spheroidal: dSphs

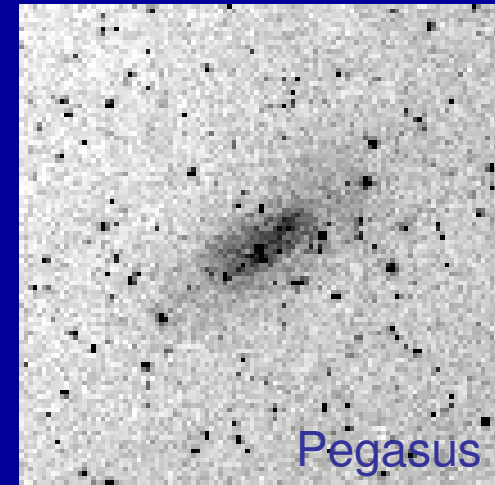


Half of dwarfs in the
Local Group are
dSphs

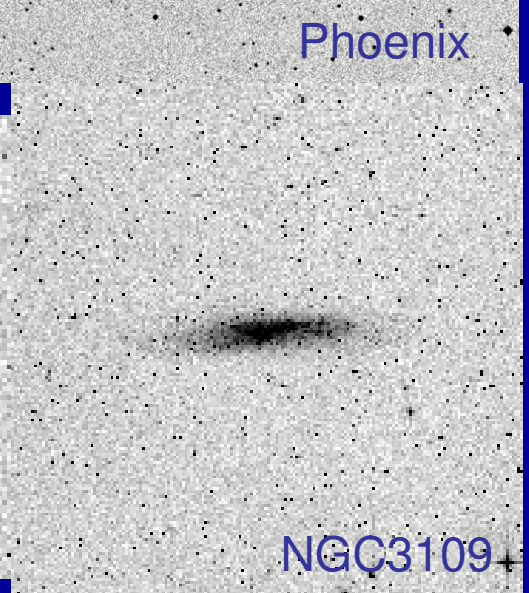
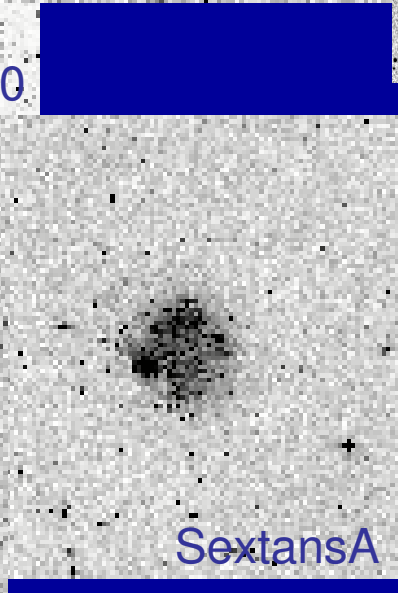
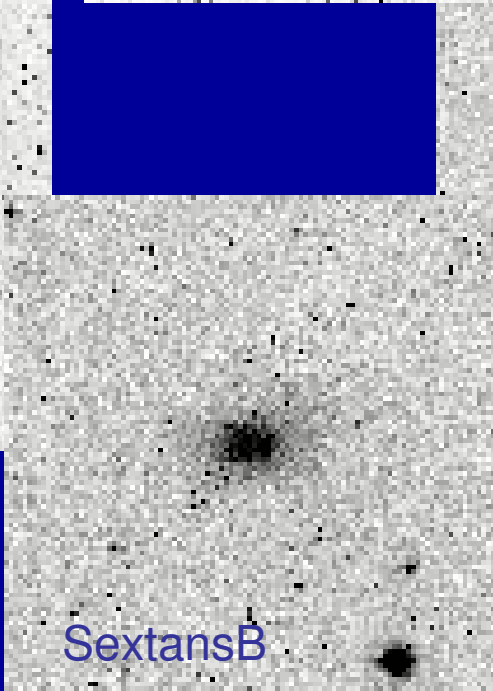
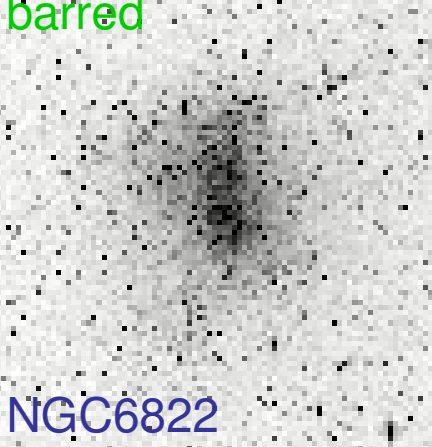
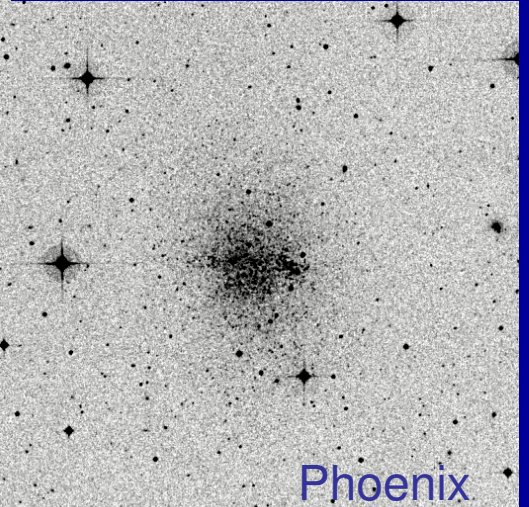
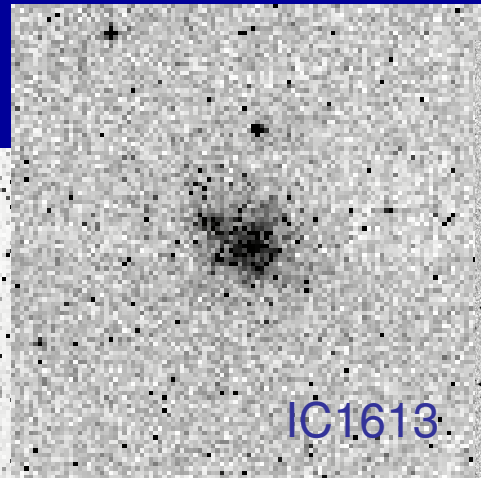
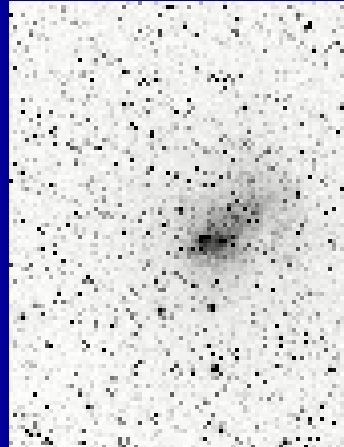


- dSphs are the most common type of galaxy
- Faintest ones emit less optical light than globular clusters
- Some retain their gas

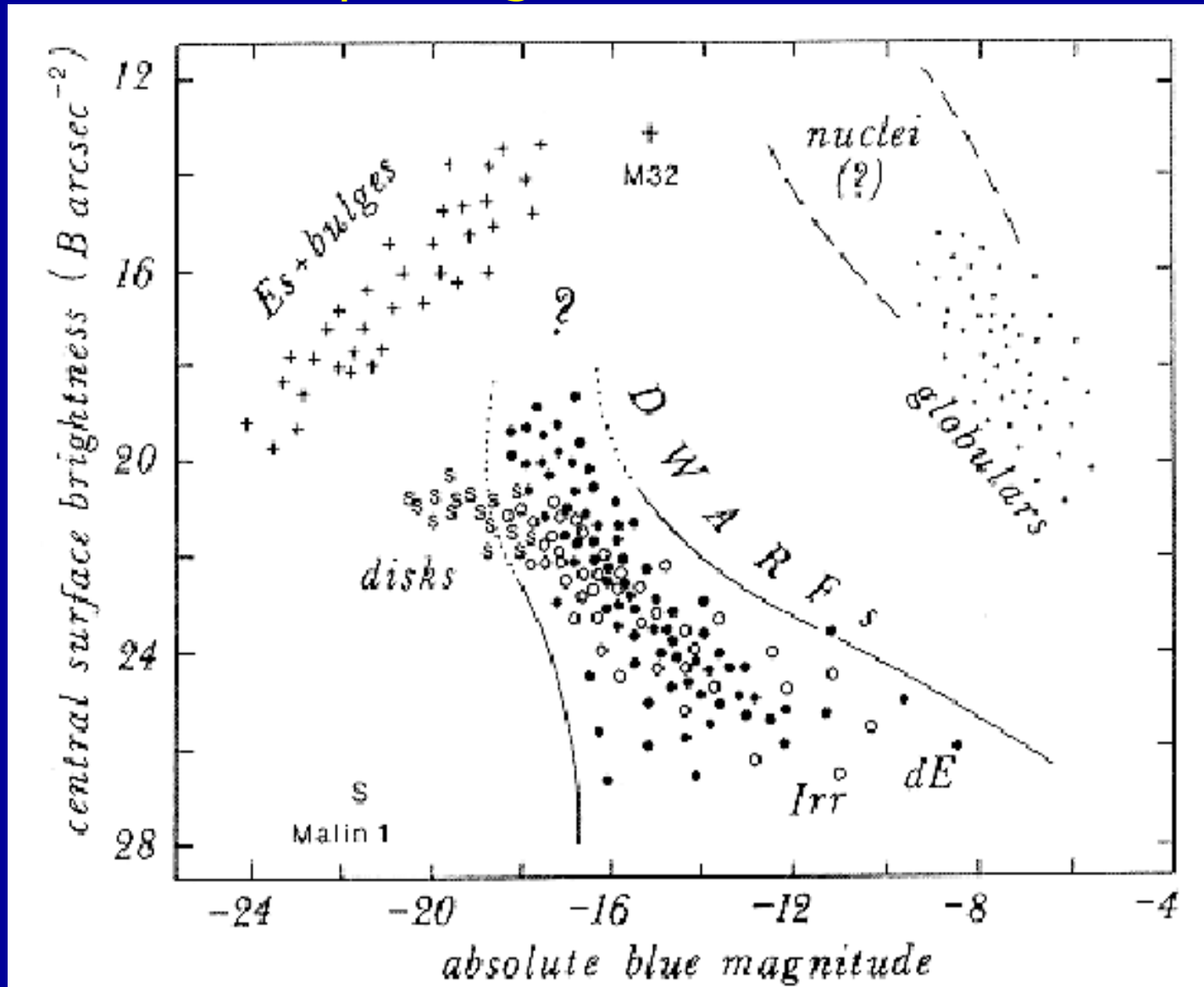
Dwarf irregulars: dIs



barred



Morphological Similarities



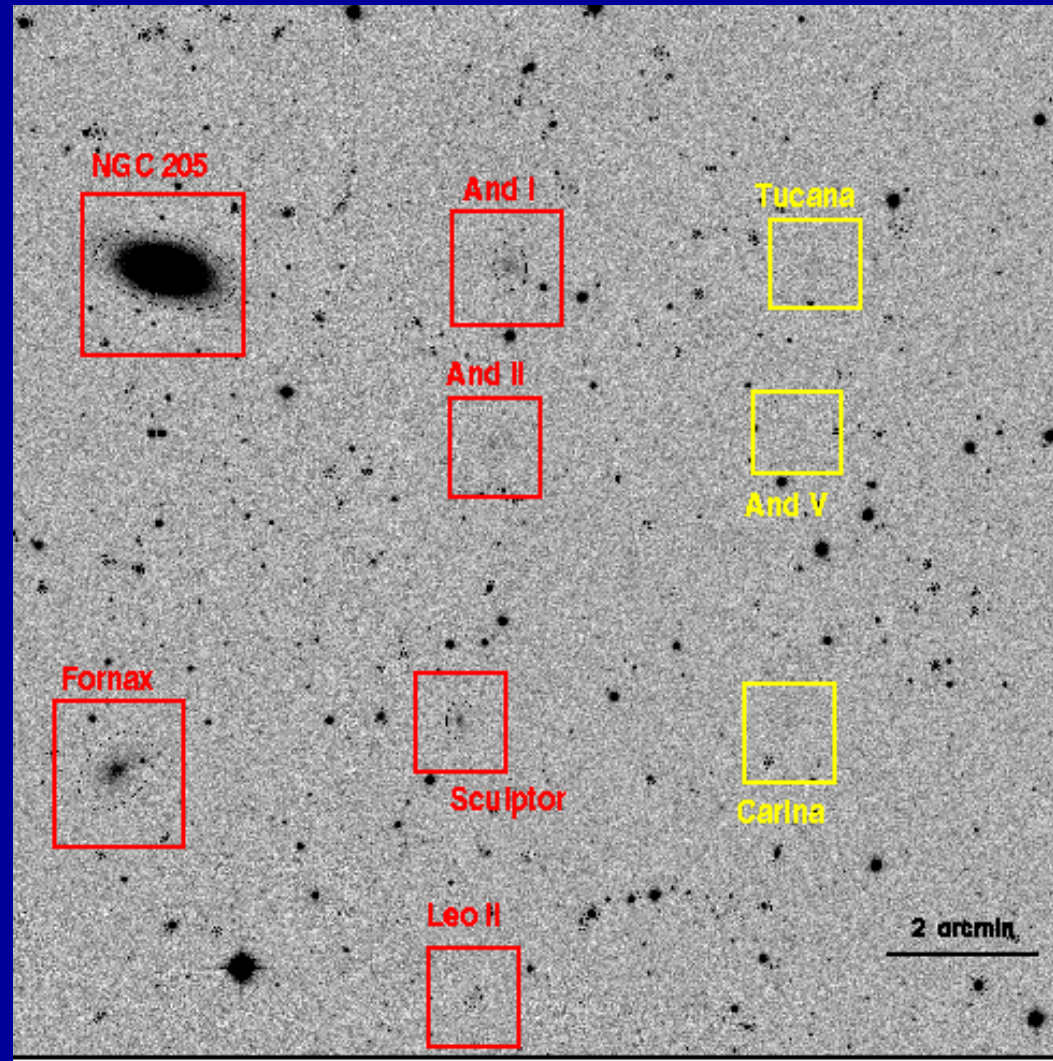
Dwarf galaxies are hard to find!

- dEs/dSphs found around giant galaxies
- dIs found at larger distances; some “isolated”

Here, we lump dEs and dSphs into the dE class.

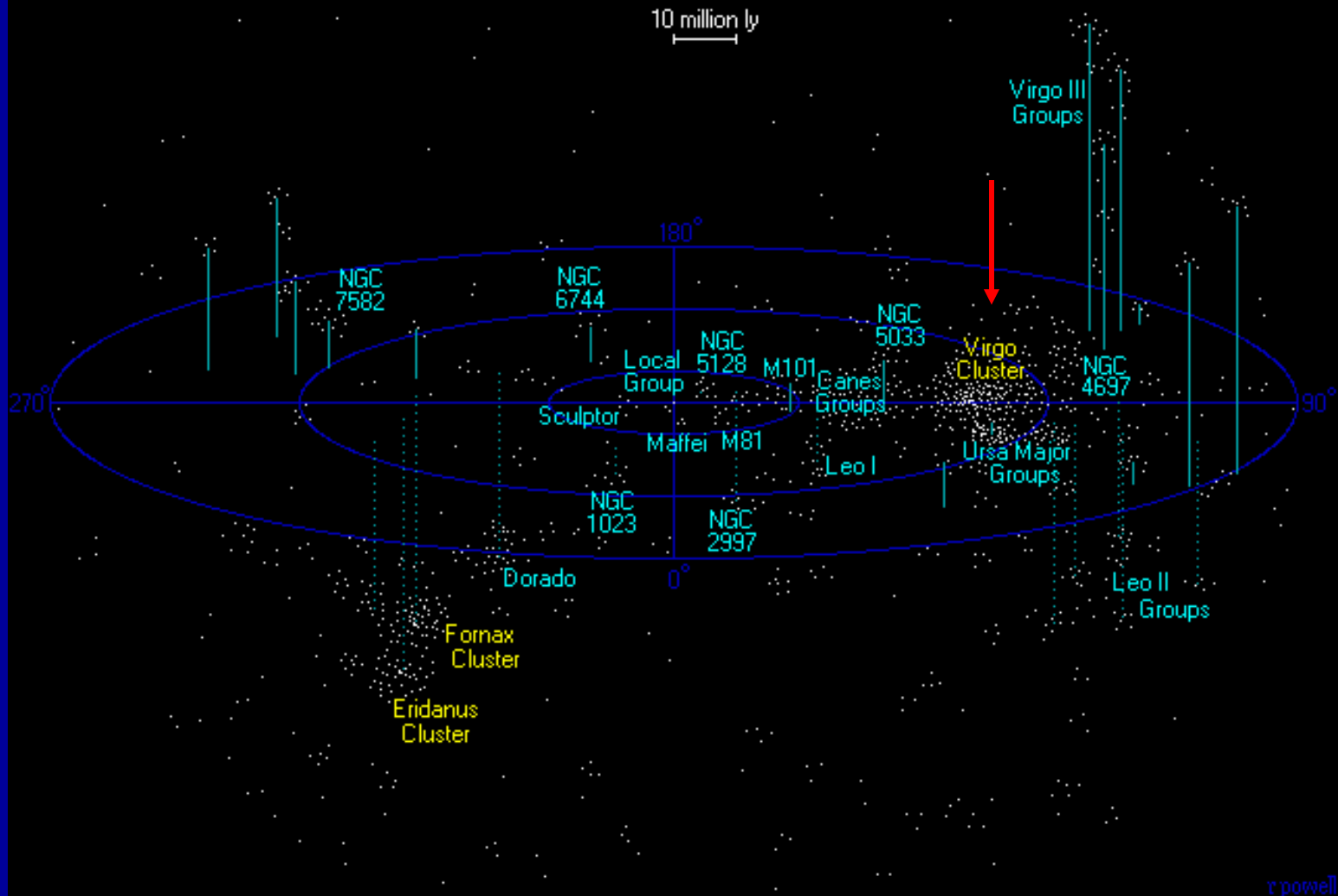
- dEs span a wide range in surface brightness
- Right: simulation of LG dEs if located at 10 Mpc

Katy Flint's homepage
<http://www.ciw.edu/flint>



The Local Supercluster

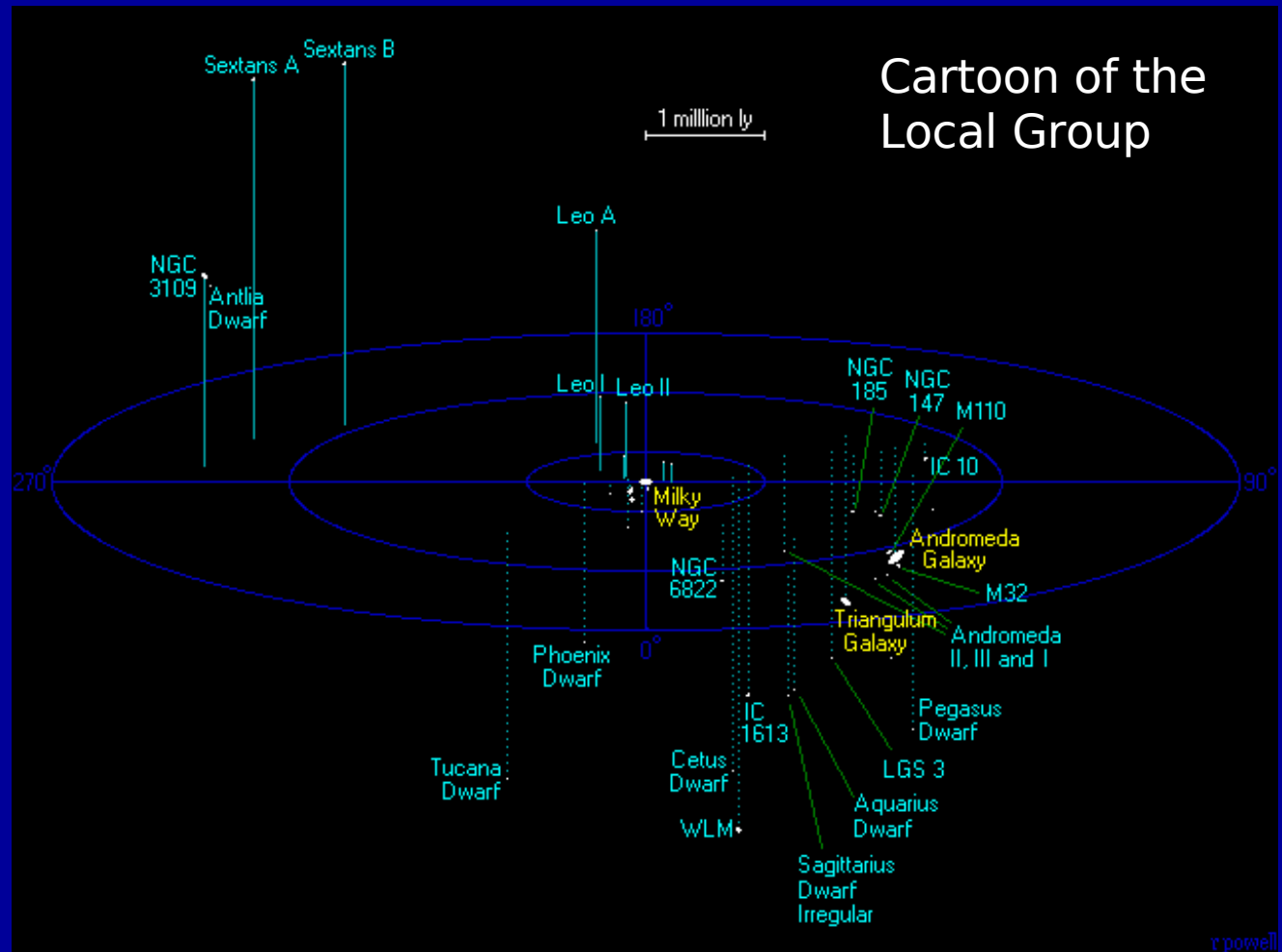
Cartoon of Local Supercluster



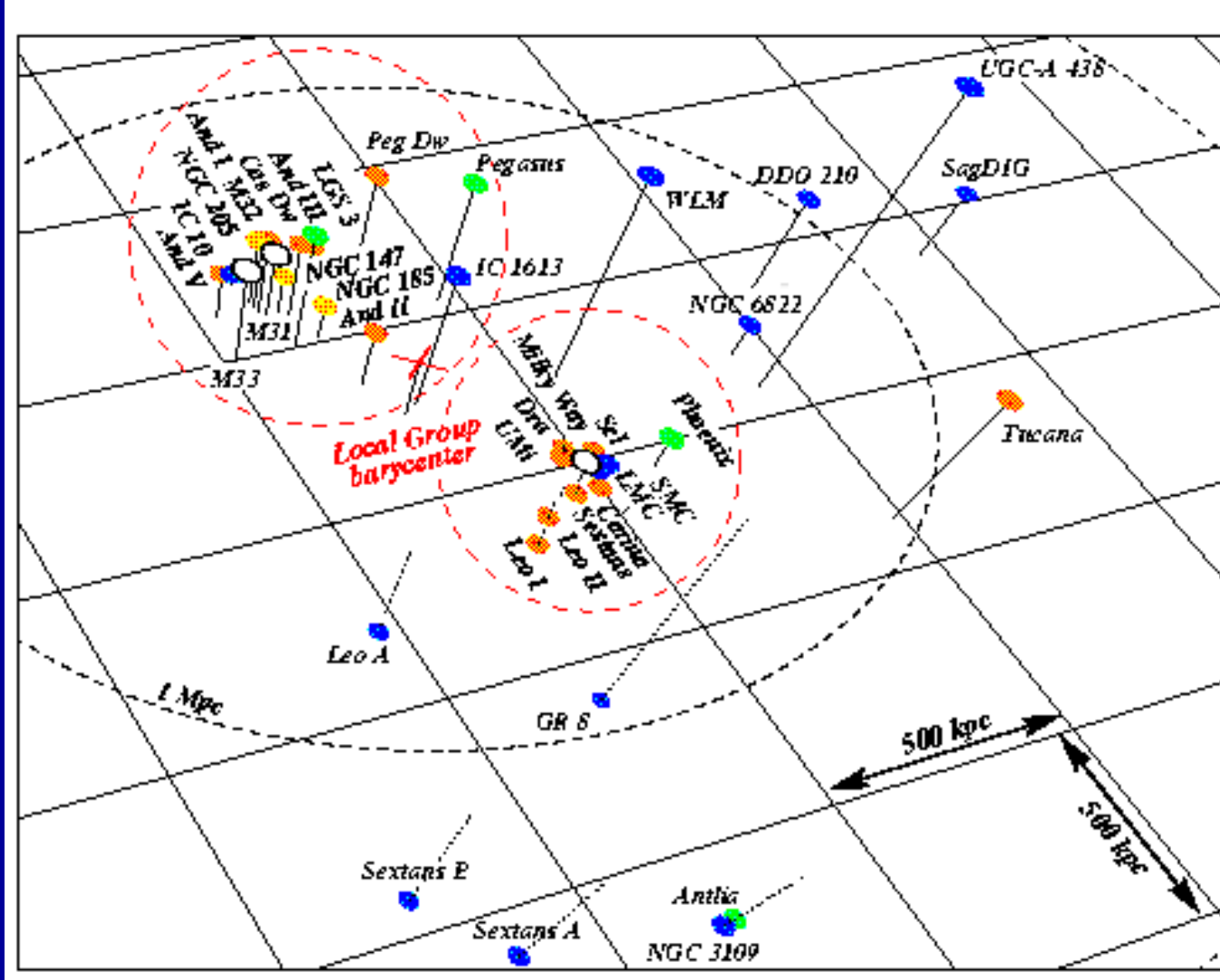
View from the Local Group

Hunting for low mass halos

Optically faint
and/or low HI
mass galaxies
can only be seen
nearby



Substructure in the Local Group



Galaxies mainly clustered around the two principal galaxies MW & M31

Fornax dSph



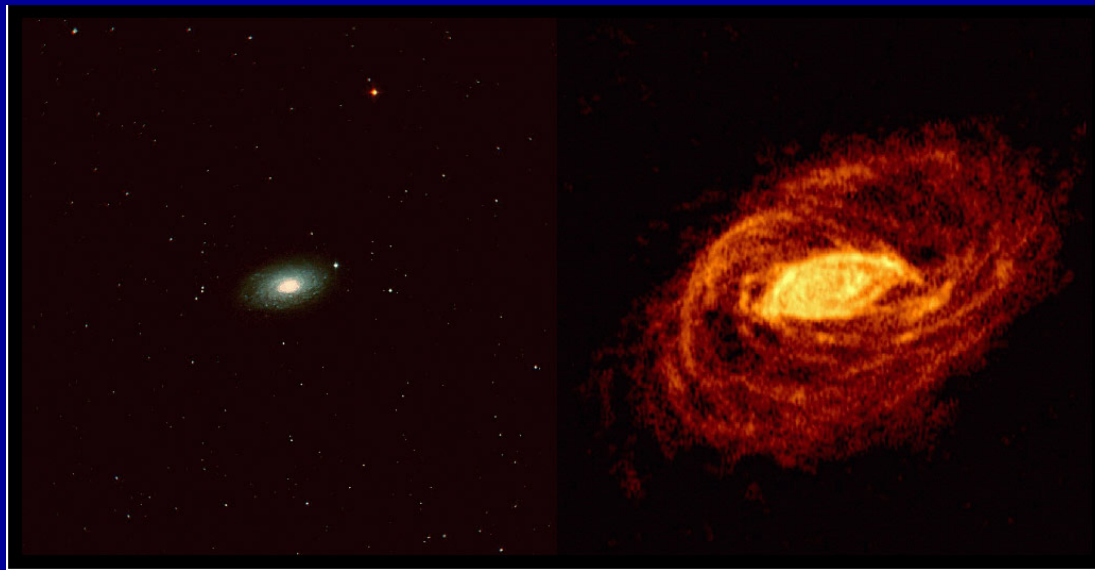
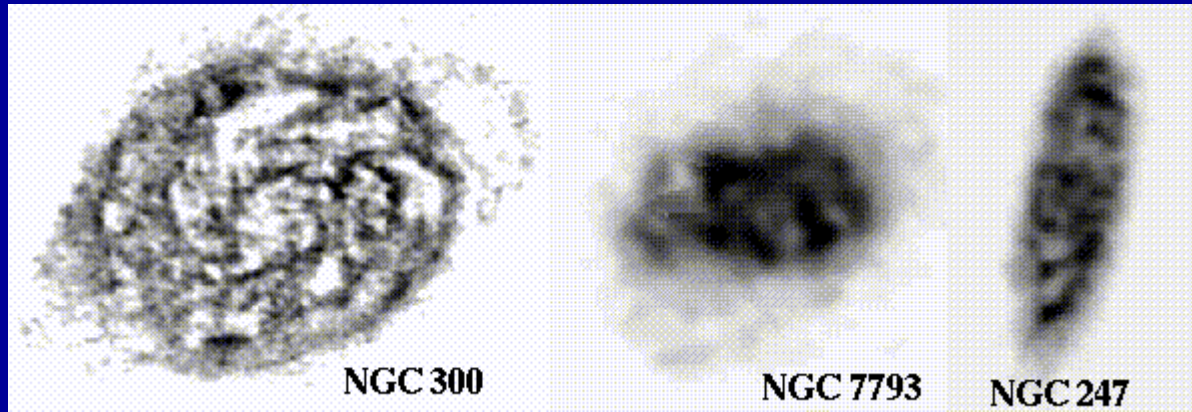
The Clouds of Magellan



The Magellanic Clouds



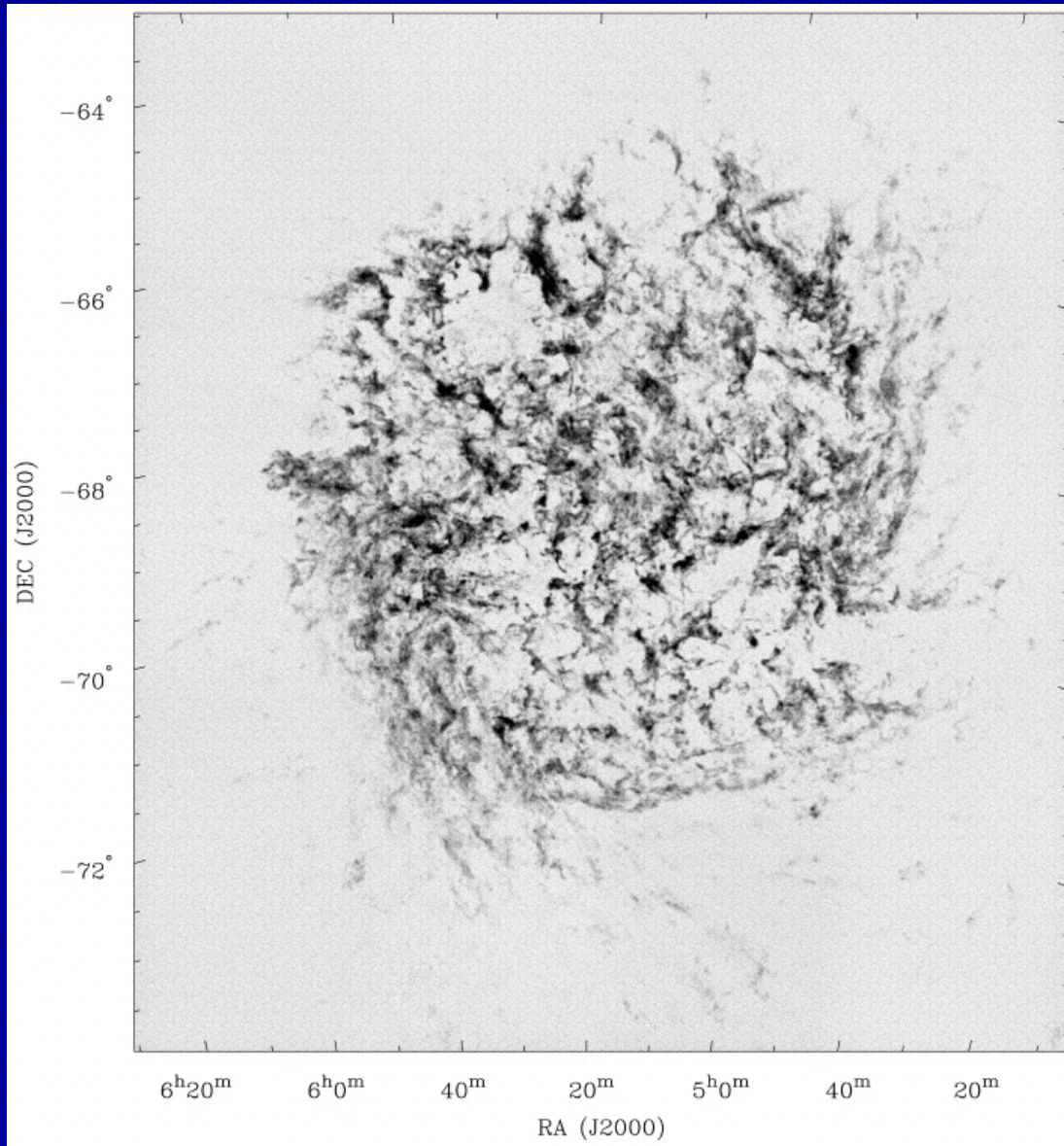
HI Gas in Galaxies



Optical and HI image of NGC5055
(Oosterloo et al.)

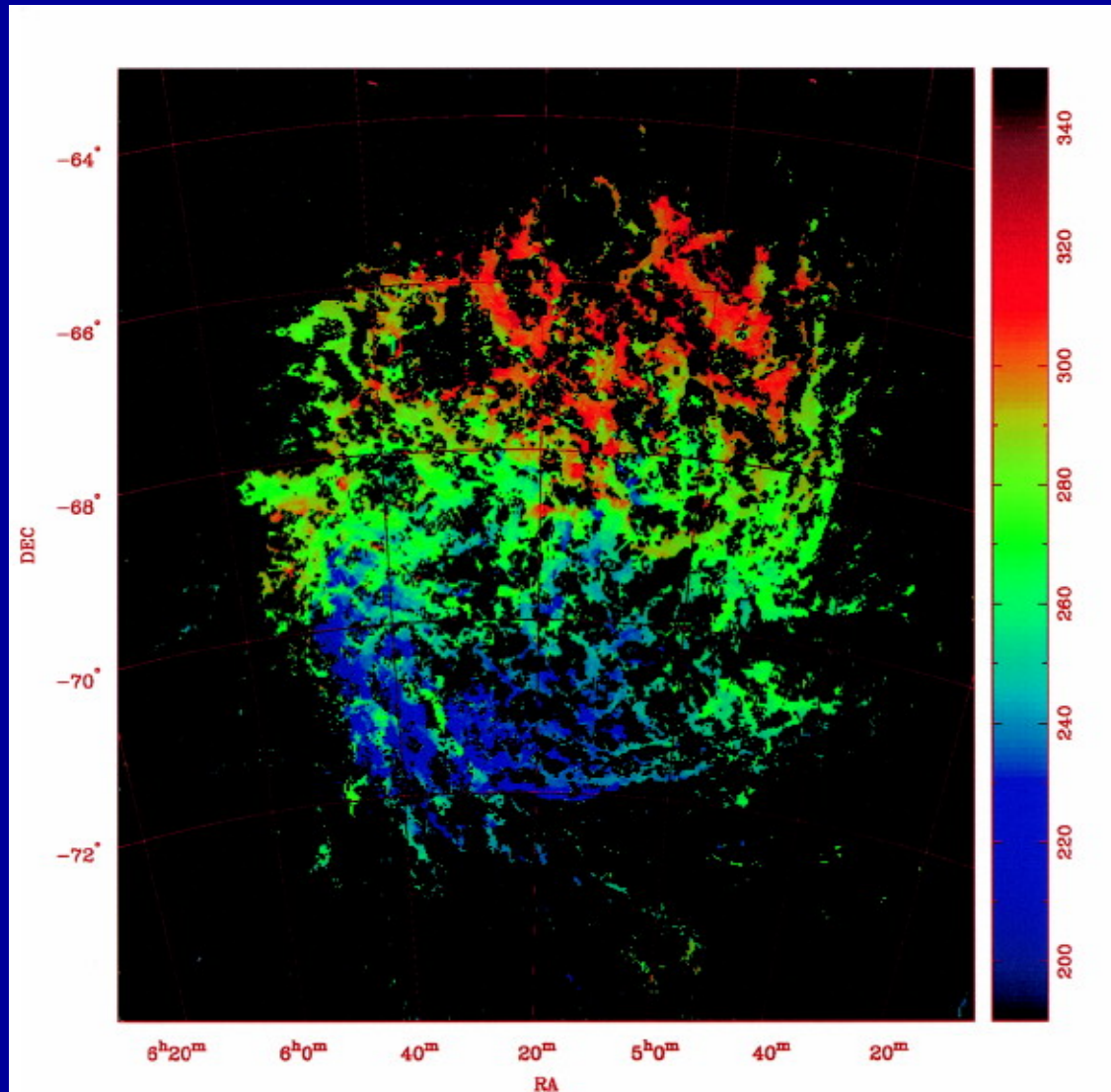
HI distribution in the LMC

Kim et al. 1998, ApJ 503:674



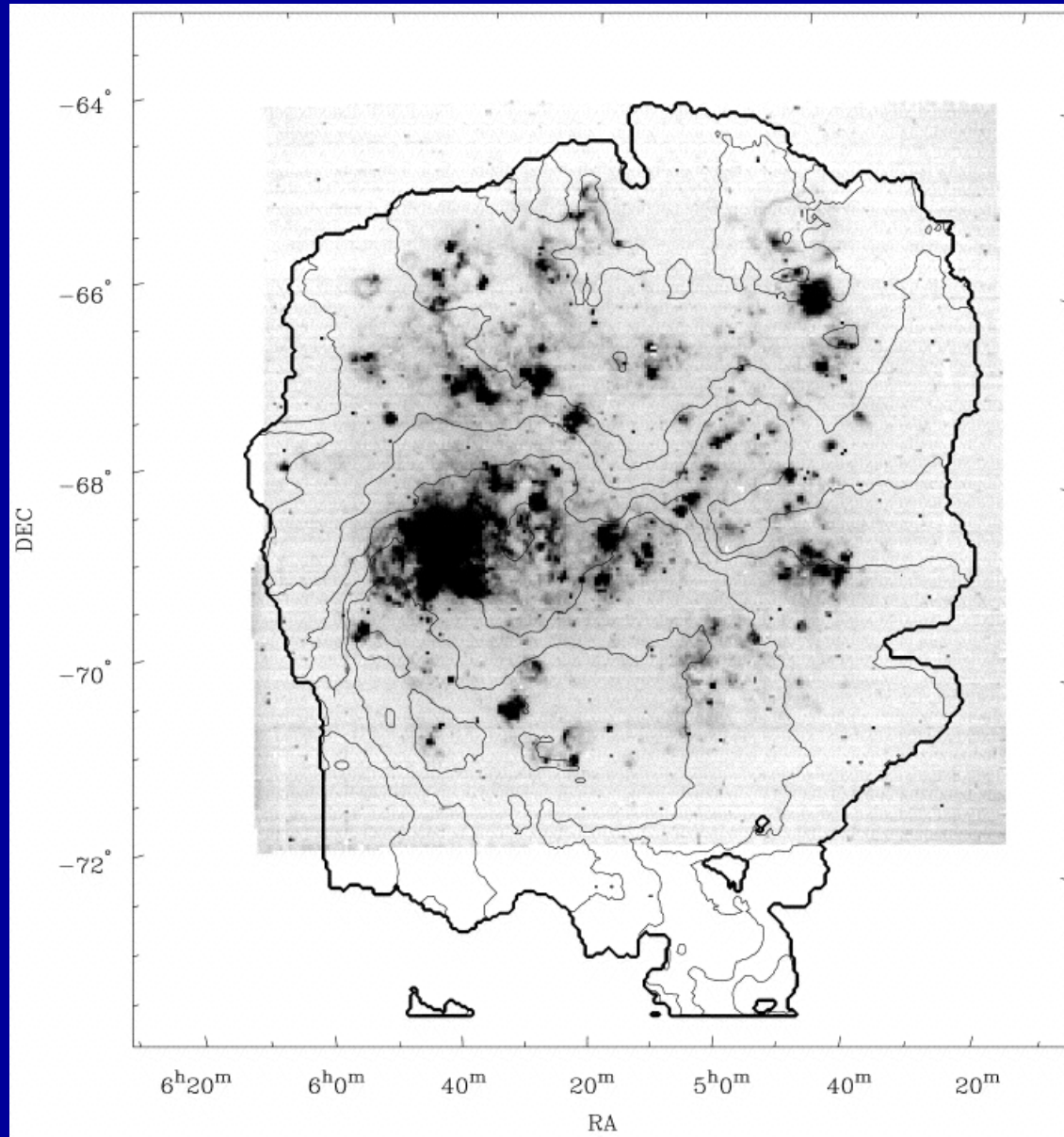
HI distribution in the LMC

Kim et al. 1998, ApJ 503:674



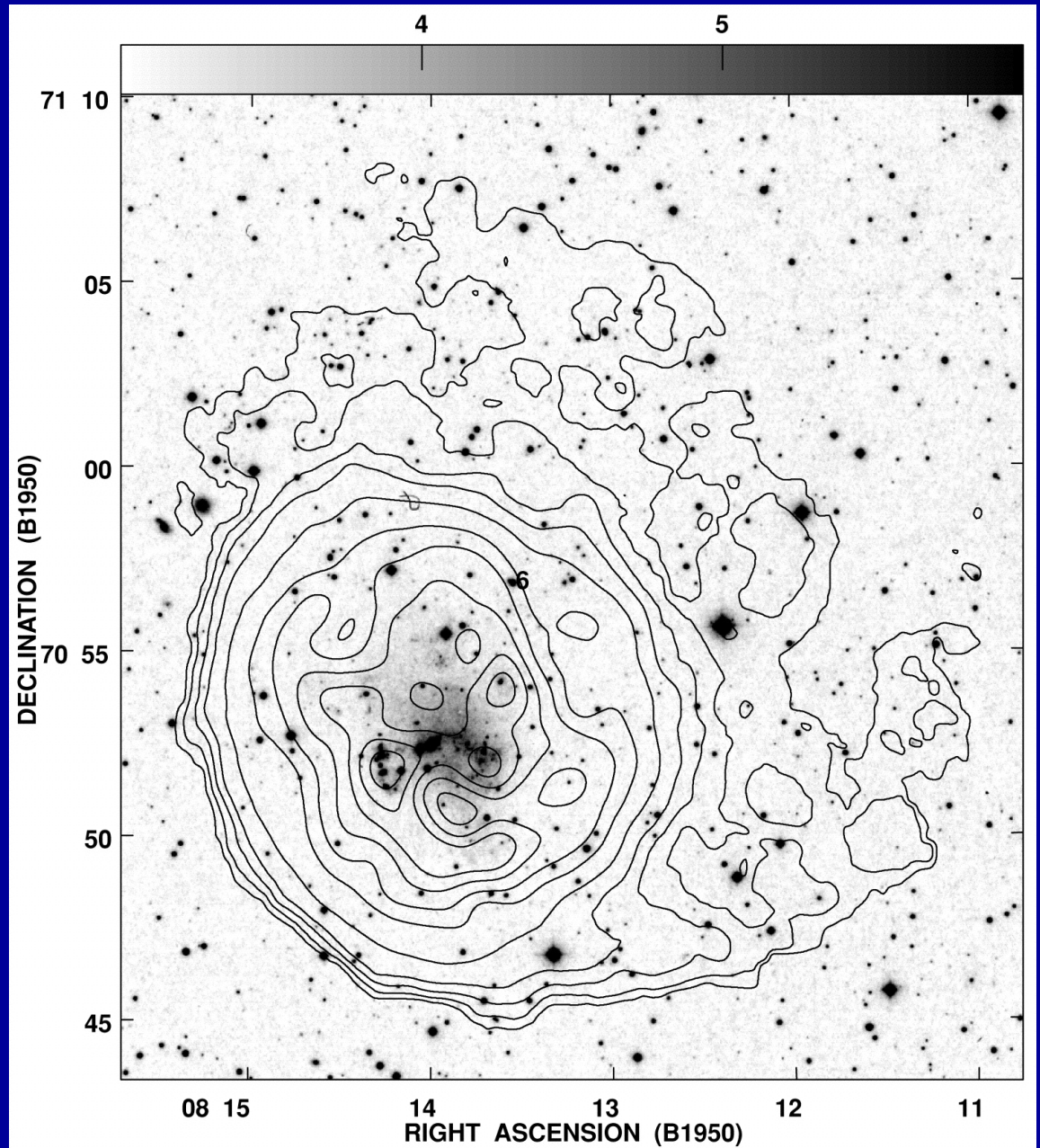
HI distribution in the LMC

Kim et al. 1998, ApJ 503:674



Blow out in Holmberg II

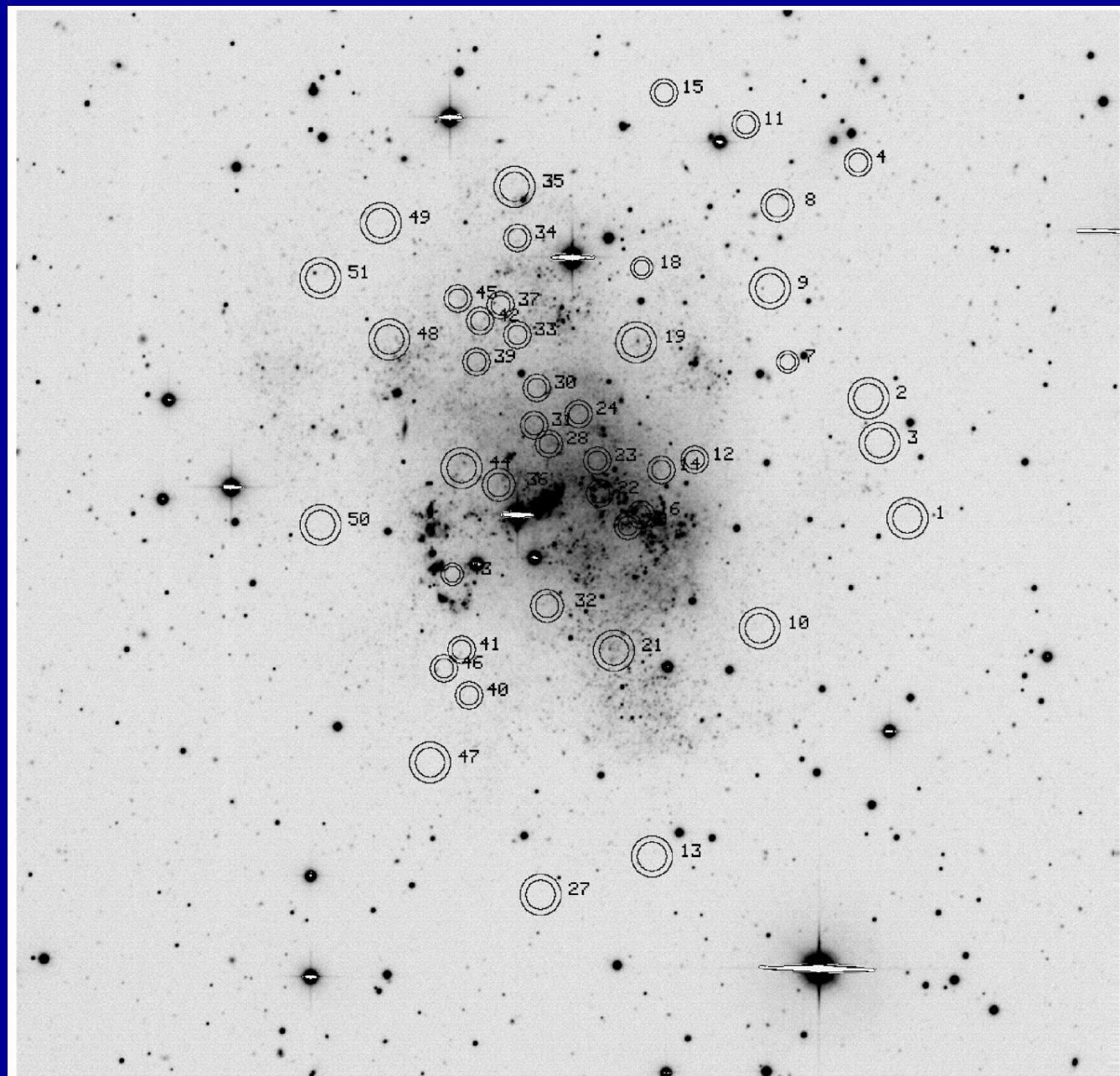
Bureau & Carignan
2002, AJ 123, 1316



Blow out in Holmberg II

Rhode et al. 1999

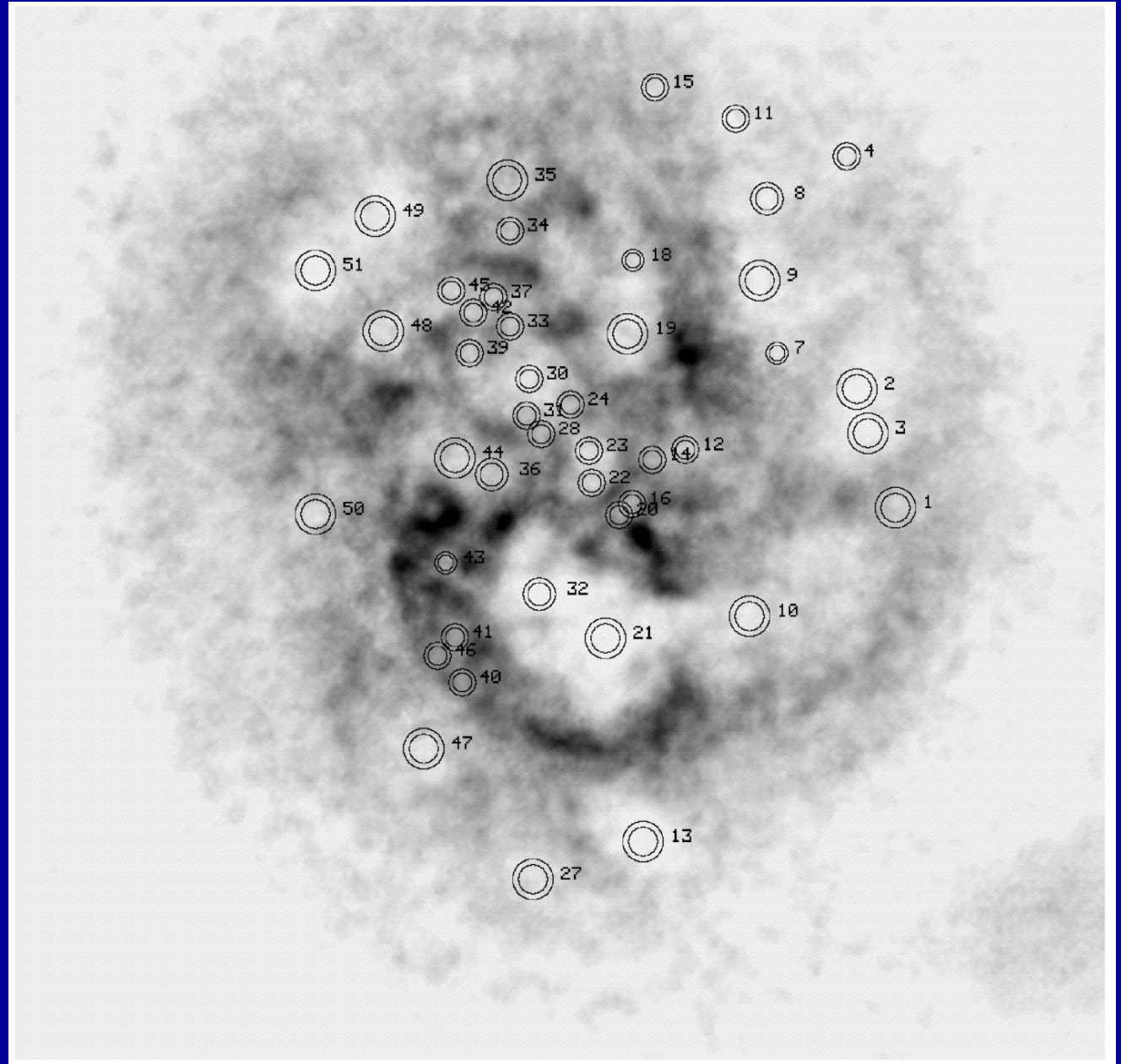
AJ 118, 323



Blow out in Holmberg II

Rhode et al. 1999

AJ 118, 323

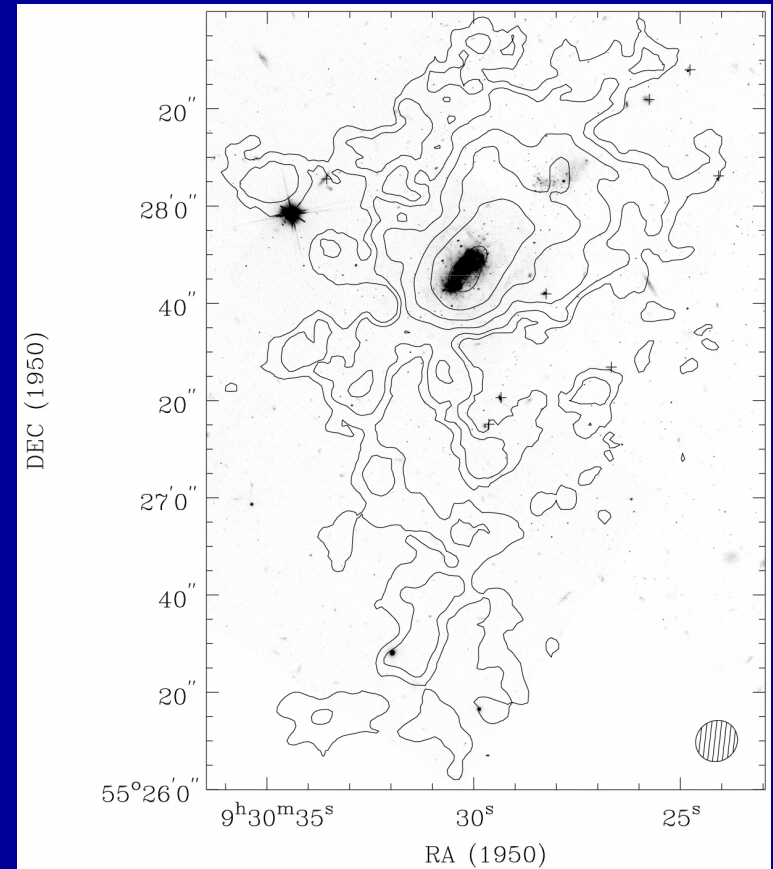


Starbursting and Blue Compact Dwarfs

- Small size
- Very blue
- Optical light dominated by line emission
- Young stellar population (and old stars?)
- Low metallicity



IZw 18: A Young Galaxy?



I Zw 18
van Zee et al. 1998

Star formation and dust in Dwarfs

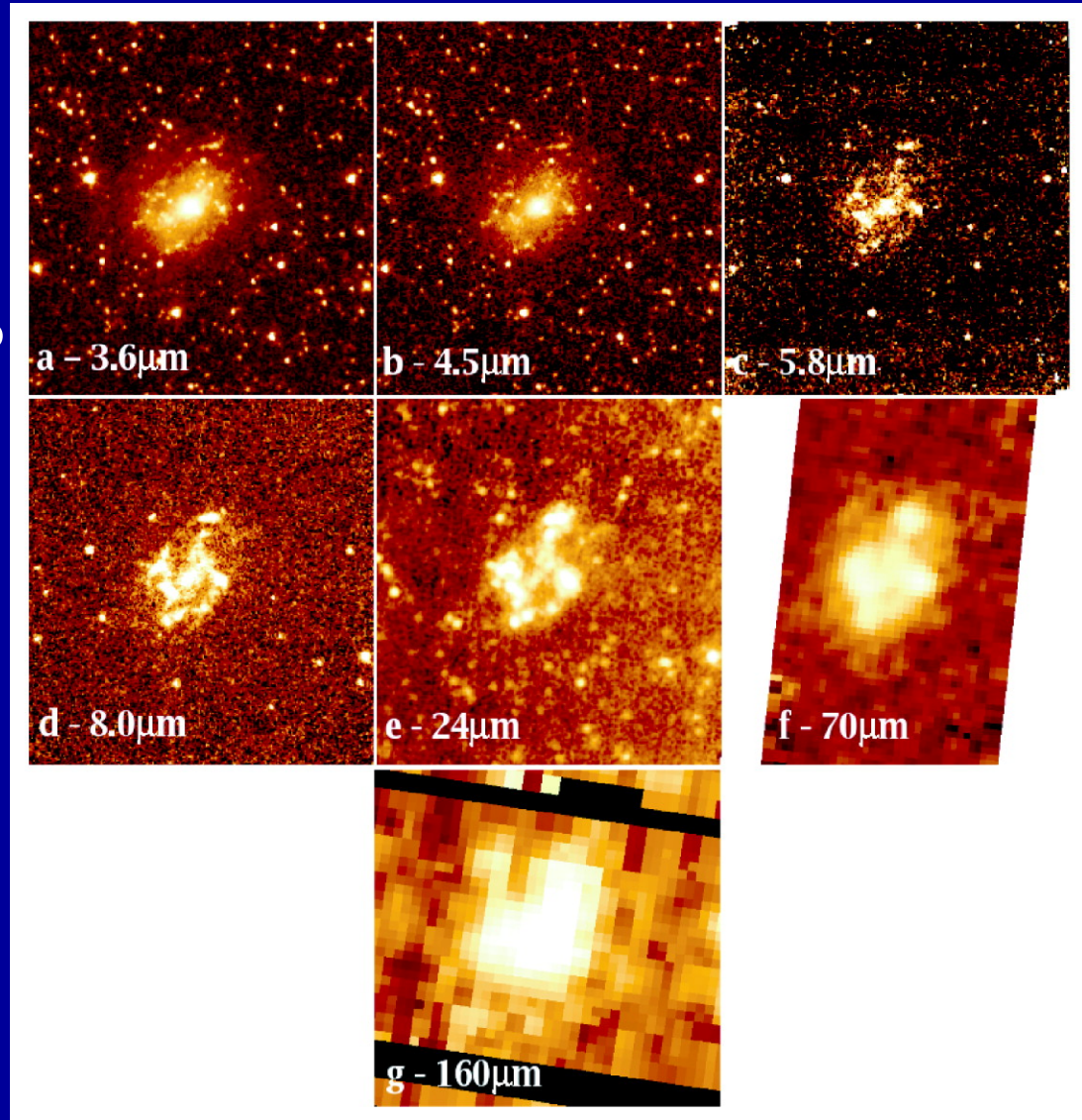
Hinz et al 2006

ApJ 651, 874

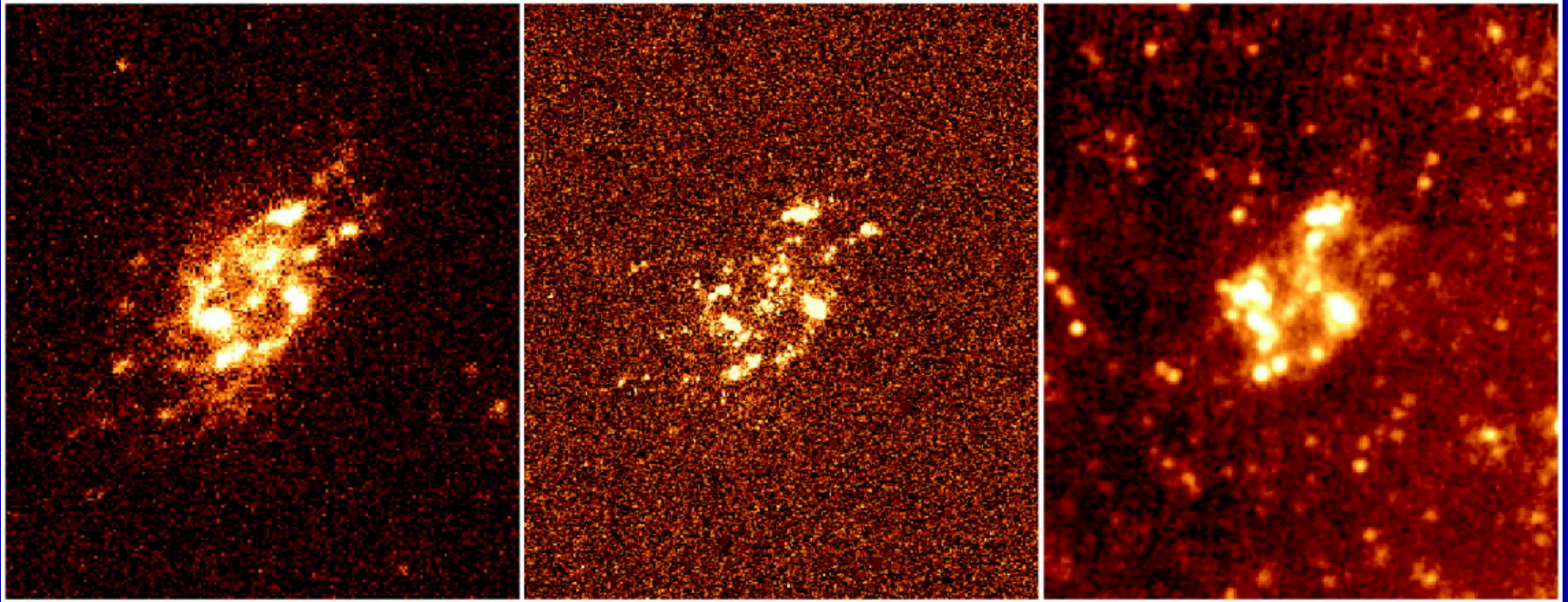
extended emission
in dwarf UGC 10445

Spitzer image in each
band.

Fields are 4.5' x 4.5'



Star formation and dust in Dwarfs



GALEX FUV image

H-alpha image

MIPS 24 micron

Hinz et al 2006

ApJ 651, 874

Fields are 4.5' x 4.5'

Transformations??

Different types of dwarfs:

dE - different scaling relations in
r, M, L, SB, etc (Kormendy 1985;
Kormendy and Freeman 2004).

dSph

dI

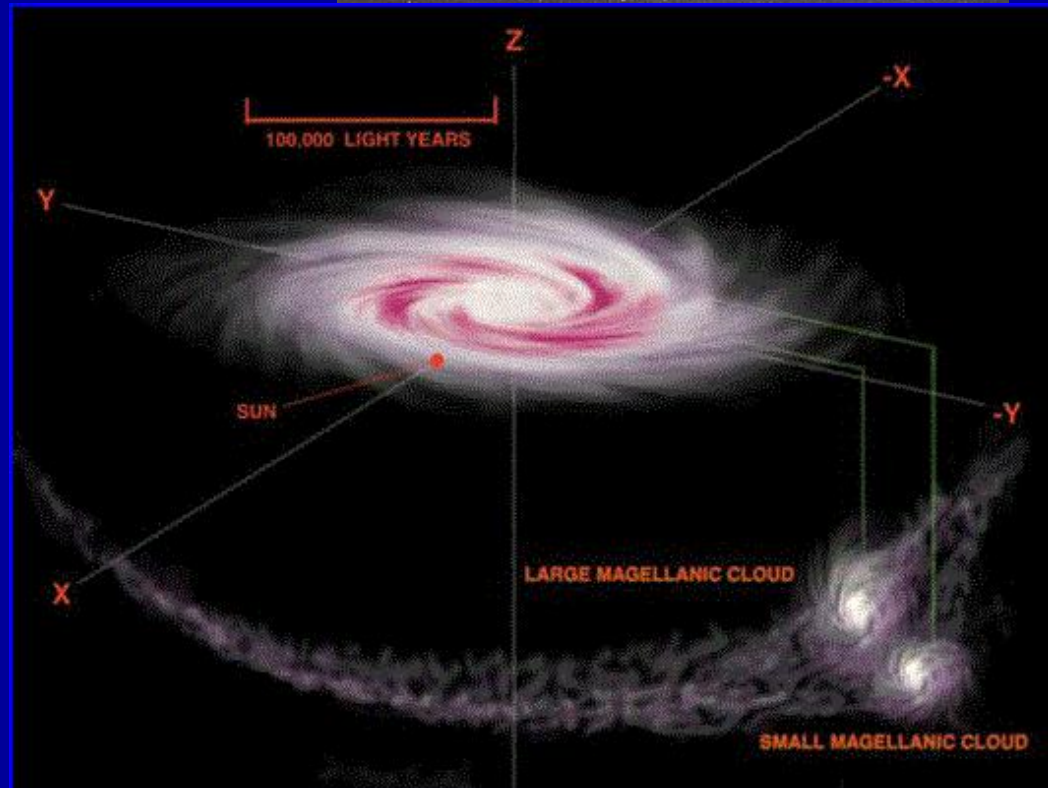
Hybrid/Transition cases (eg, LGS3, Phoenix)

What are the evolutionary relationships?

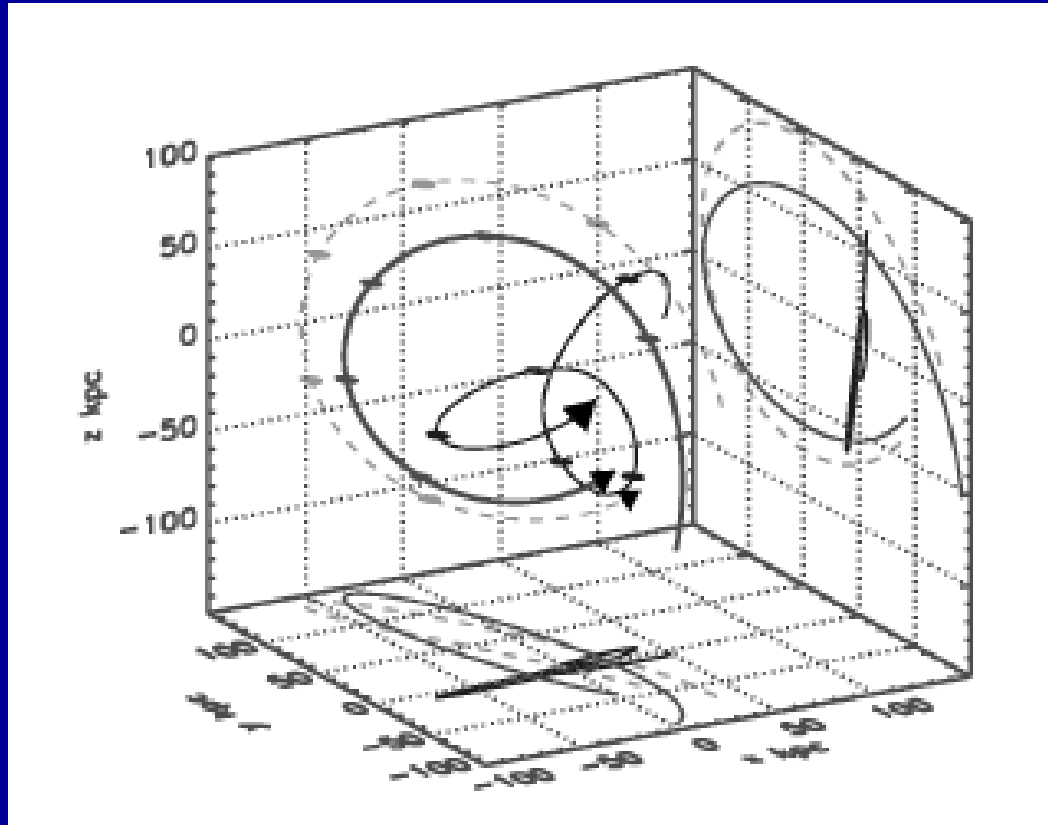
The Magellanic Clouds



- The Magellanic Clouds are contained within a common HI envelope.
- The Magellanic Stream traces their interaction with the MW.



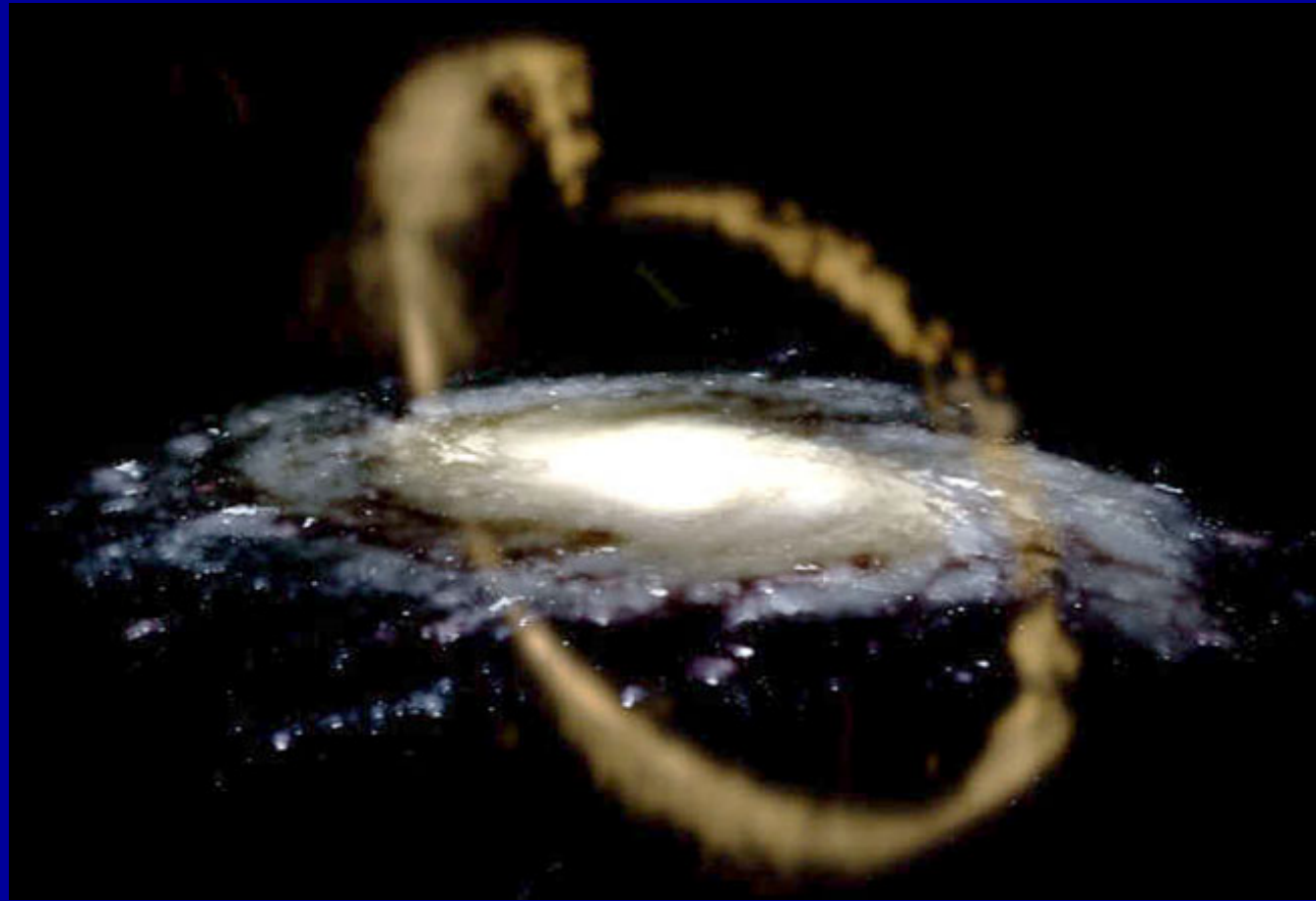
Dwarf-dwarf interactions?



LMC/Sgr Collision about 3 Gyr ago;
Zhao 1998, Majewski et al. 2006

The Sagittarius Dwarf

- Discovered in 1994 by Ibata et al.
- Small, relatively metal rich
- About 14 kpc away
- Being deformed by the Milky Way
- In 1998- 2MASS shows that stream circles whole sky

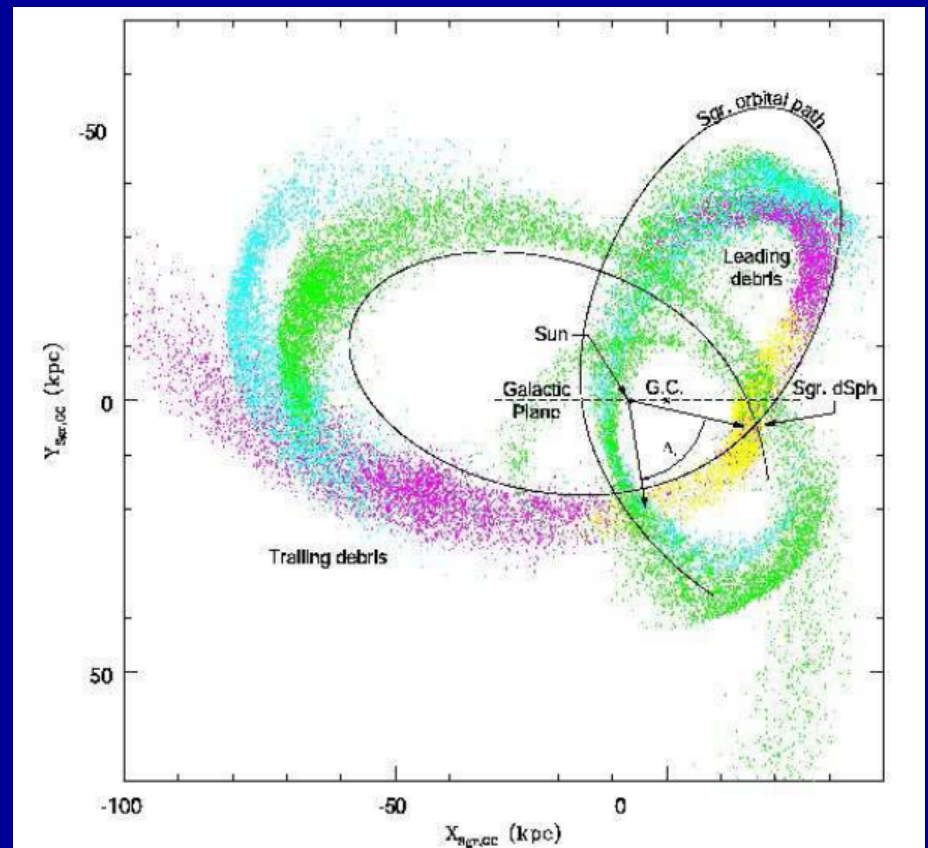


David Martinez-Delgado (MPIA) & Gabriel Perez (IAC), The Sagittarius Dwarf Tidal Stream Drawing. From: <http://antwrp.gsfc.nasa.gov/apod/ap050529.html>

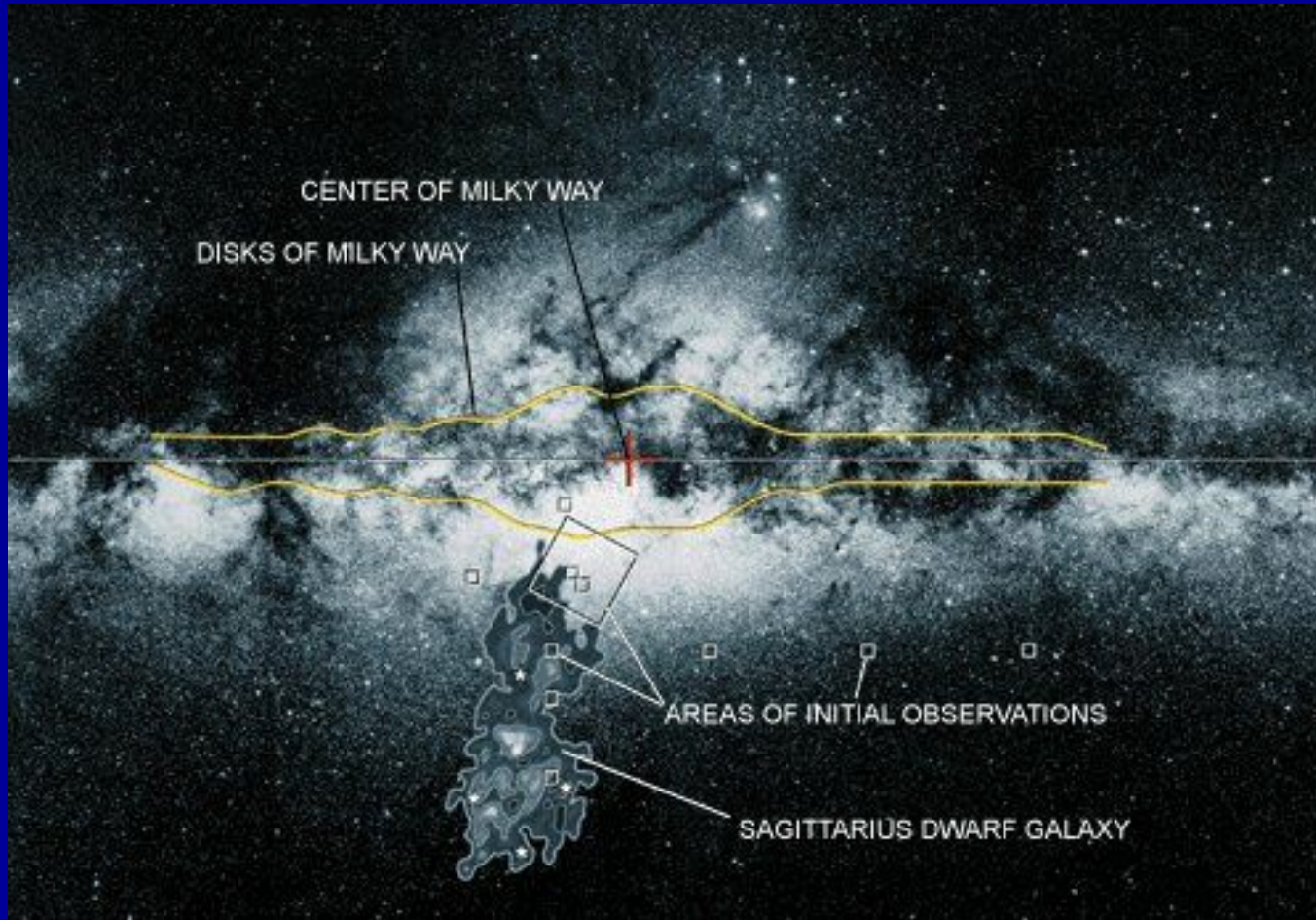
Sagittarius streams in 2MASS

- Used M-Giant Stars from the 2MASS database
- Computer modeling: N-body simulations
 - Mass and morphology of the Milky Way, mass and location of Sgr
- Used physical constraints to rule out certain models without a full trial
- Picked the best fitting oblate, prolate, and spherical models

Law, Johnston, Majewski, 1998

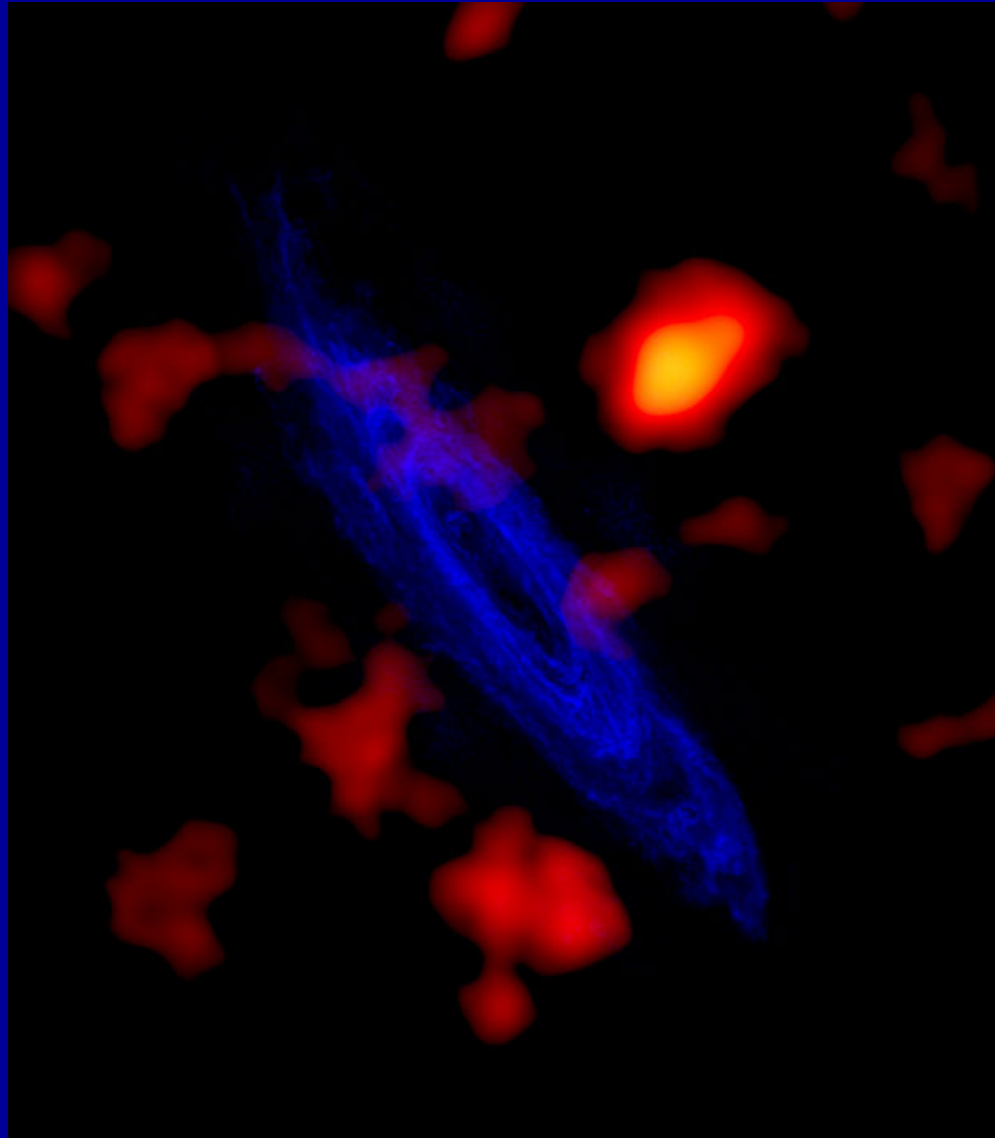


Tidal debris in the Milky Way?



Tidal debris is usually assumed to contribute to the spheroidal component of the galaxy—like the Sagittarius stream—but it may also contribute to the Galactic disk(s)

Streams around Andromeda



Tidal Remnants

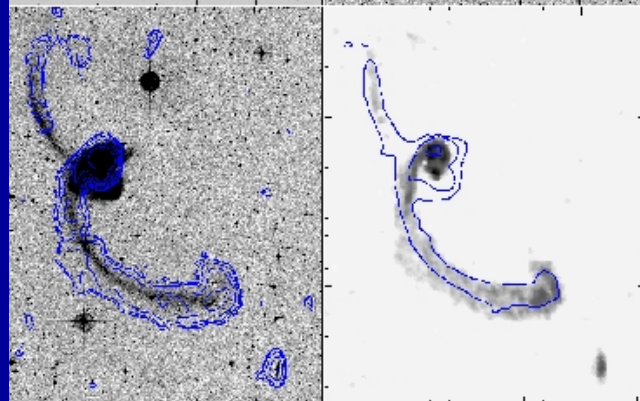
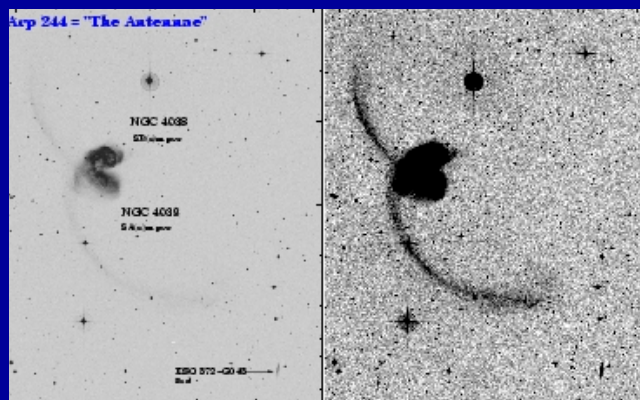
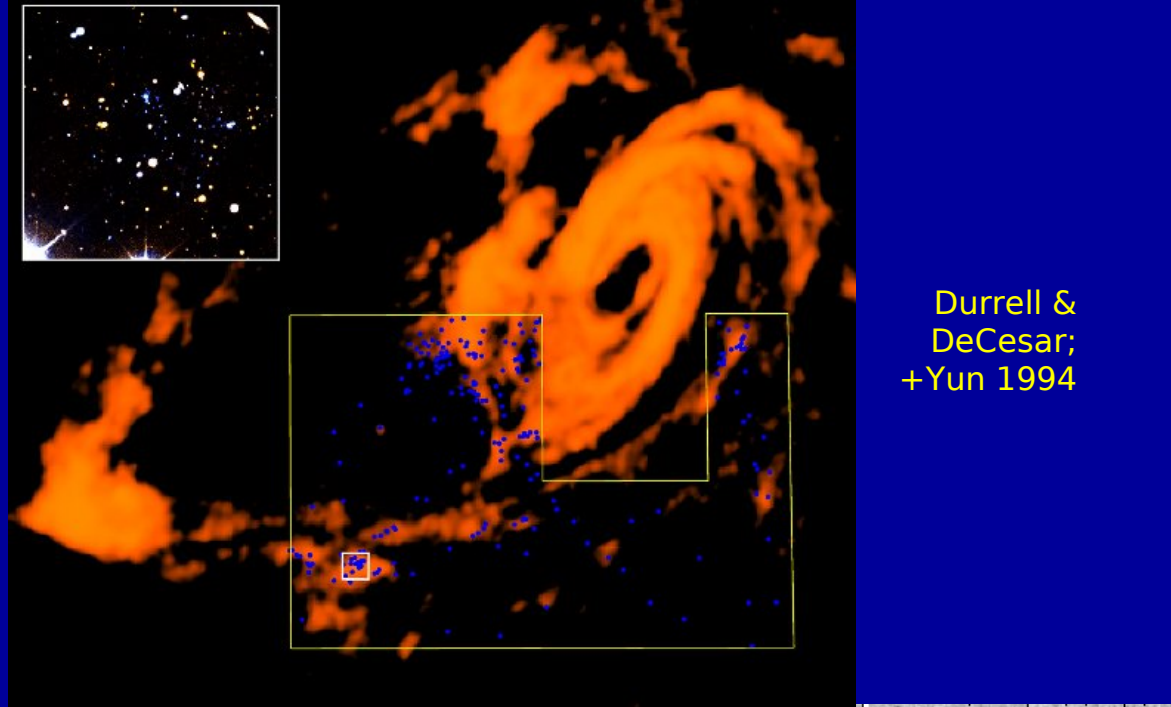


Figure 1. The Toomre Sequence merger NGC 4038/9.
H I: VLA C+D-array, 40" resolution, contours= $4 \times 10^{19} \text{ cm}^{-2} \times 2^{\text{n}}$.
Optical: DSS, FOV= $20' \times 24'$.
Notes: The H I concentration at the end of the southern tail is associated with a putative Tidal Dwarf Galaxy. For a close-up of the companion galaxy ESO 572-G045 see Fig. 77.
Reference: Hibbard, J.E., van der Hulst, J. M., Barnes, J. E., & Rich, R. M. 2001, AJ, in press.



H I traces event history even in absence of stellar debris.

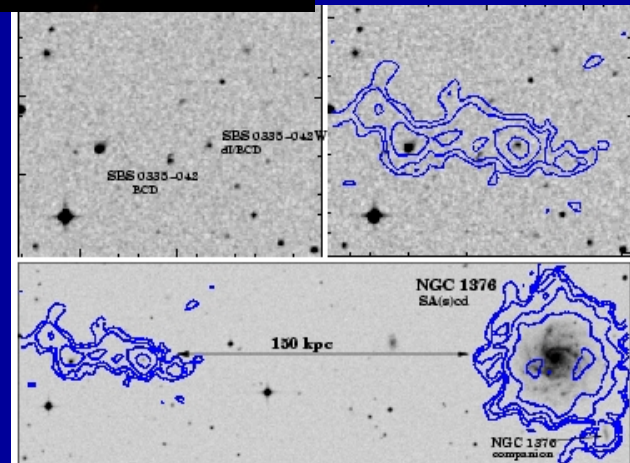
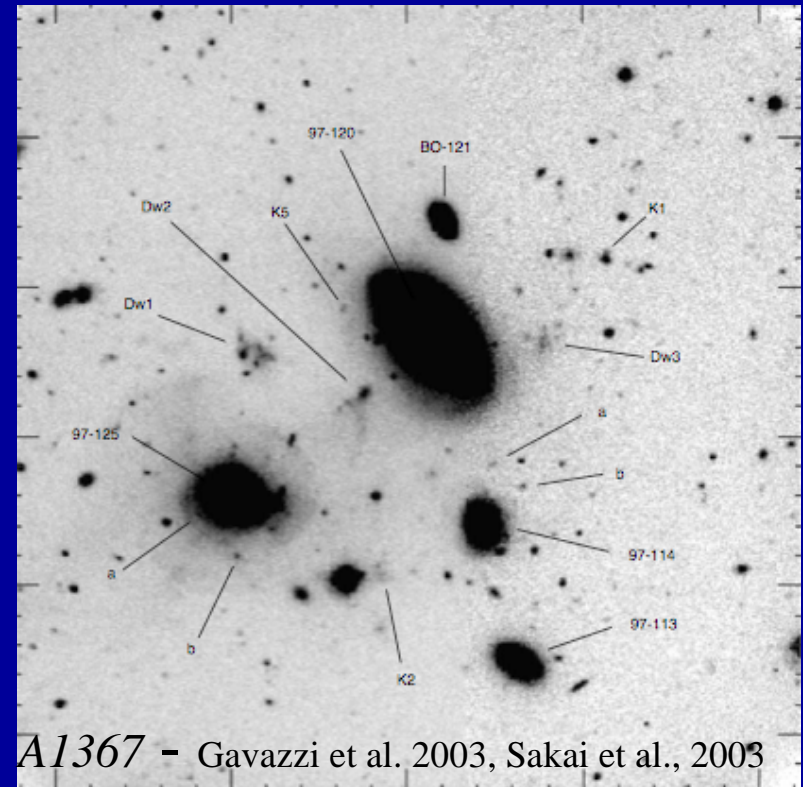
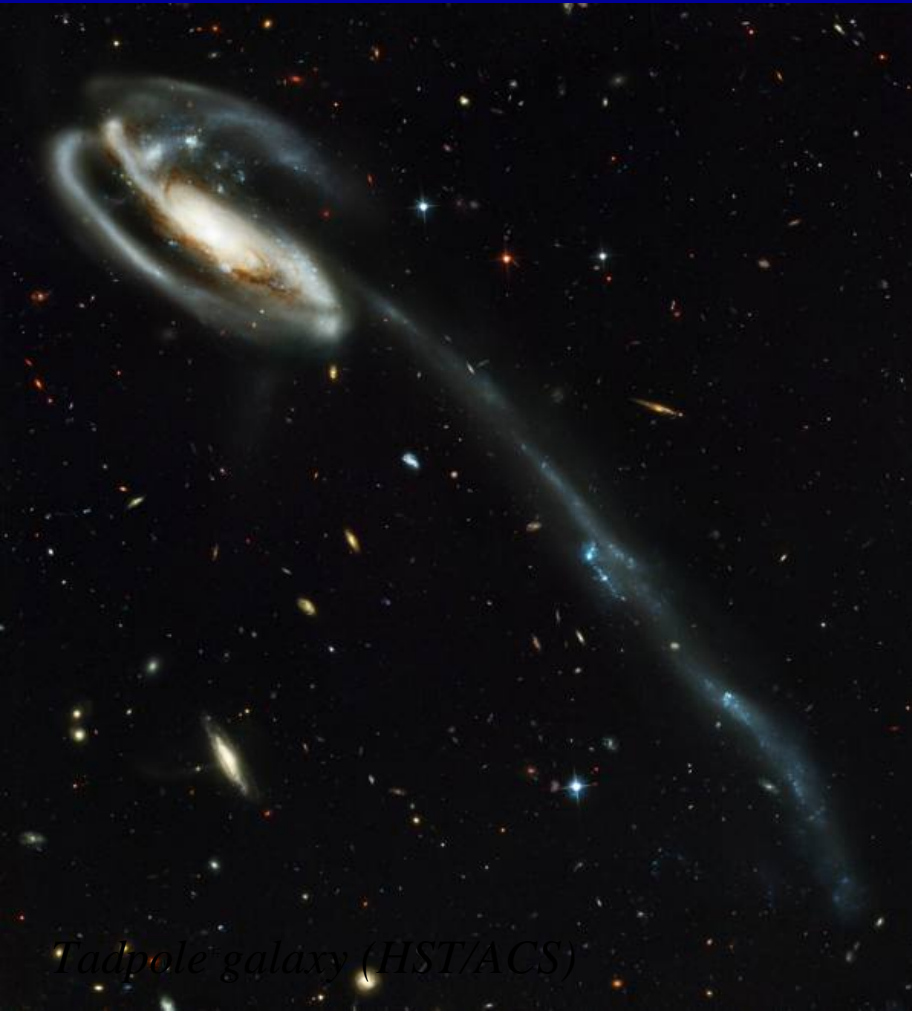


Figure 1. The Extremely Metal Poor Blue Compact Dwarf SBS 0335-052.
H I: VLA C+D-array, $20.5'' \times 15''$ resolution, contours= $1 \times 10^{20} \text{ cm}^{-2} \times 2^{\text{n}}$.
Optical: DSS, FOV= $4' \times 3'$ (top), $12' \times 4'$ (bottom).
Reference: Pustilnik, S.A., Brinks, E., Thuan, T.X., Lipovetsky, V.A., & Izotov, Y.I. 2001, AJ, 121, 1413.

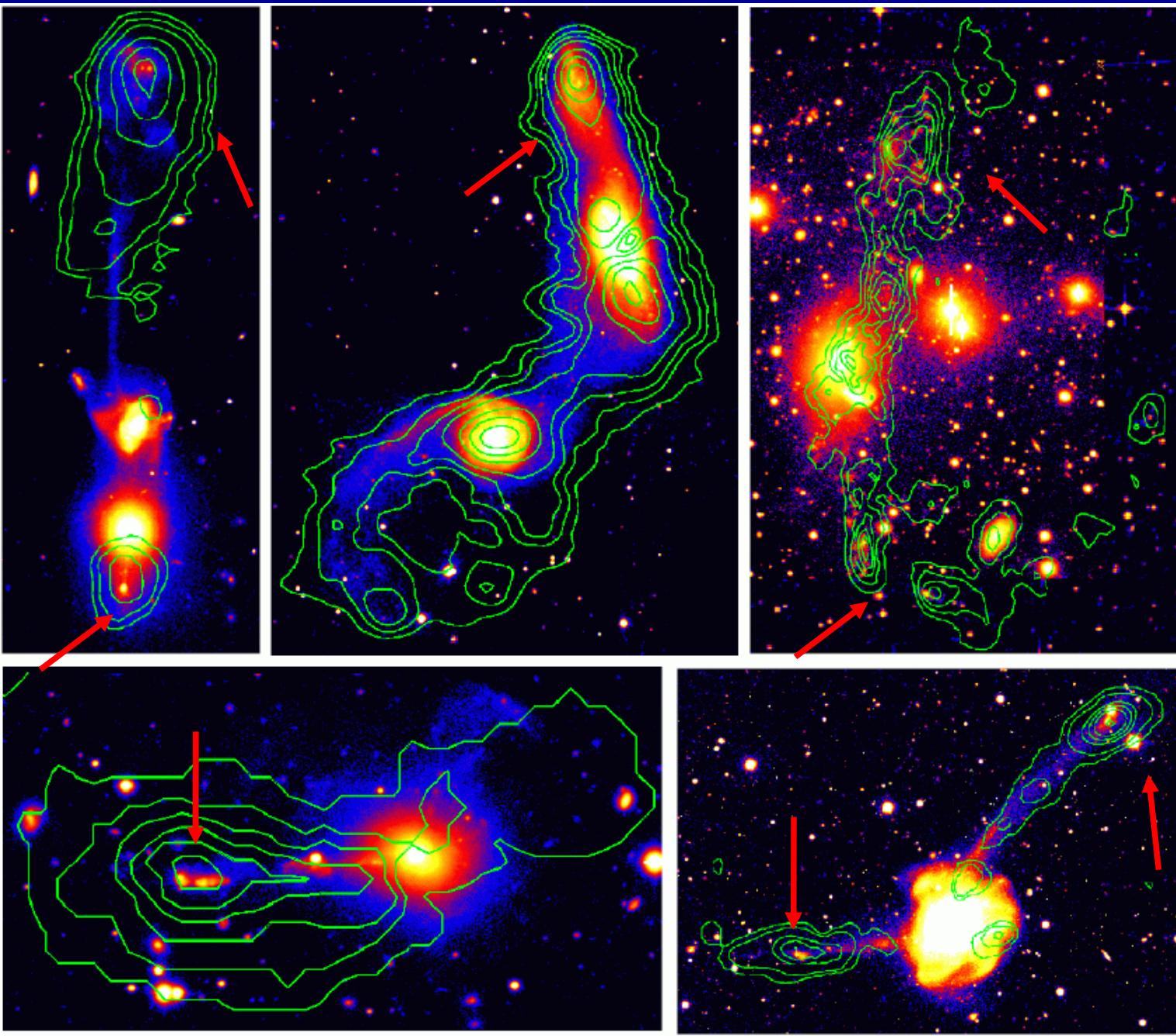
Other types of tidal objects

✓ Giant star-forming regions along tidal tails

✓ Detached « intergalactic » star forming regions



All called
« *Tidal Dwarf Galaxies candidates* »



A few examples of TDGs

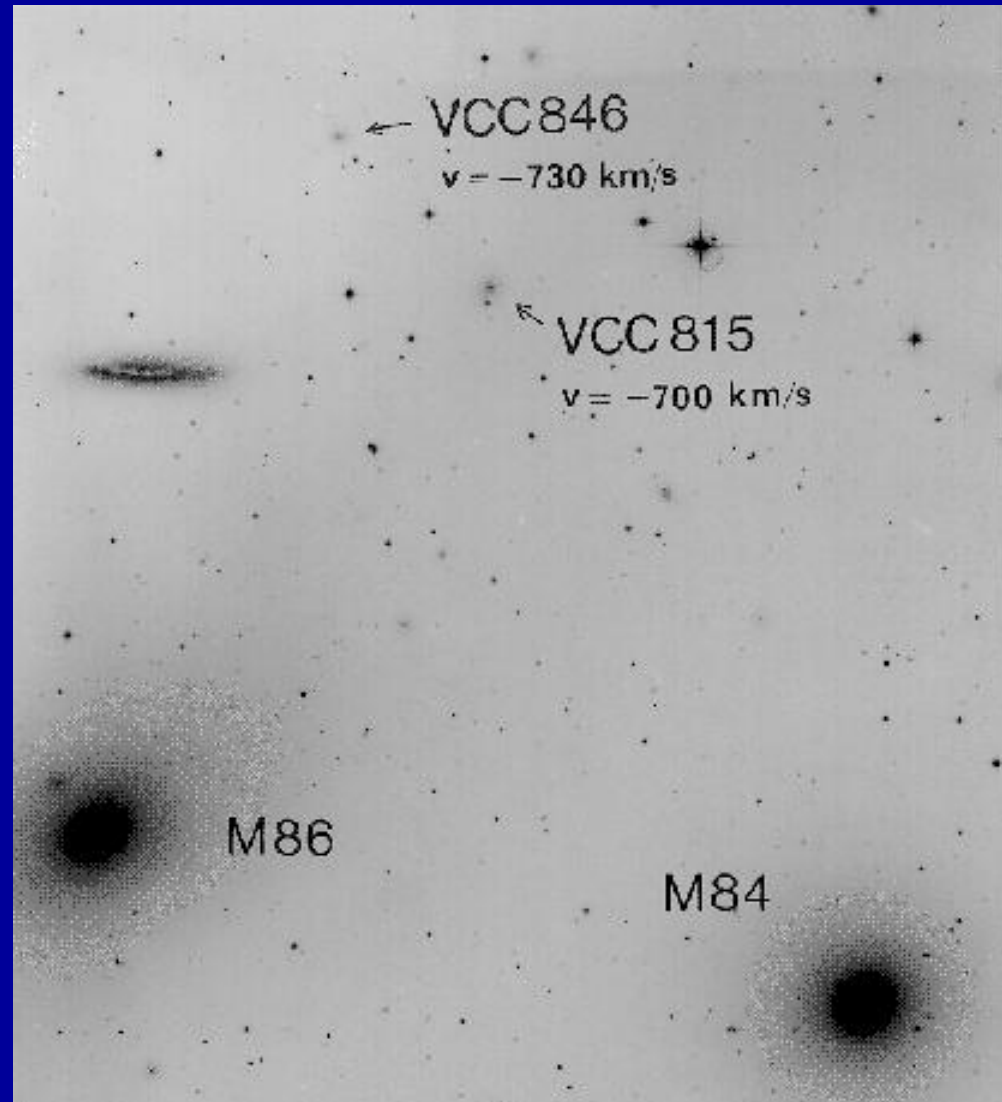
These are young, massive, gaseous, TDG candidates

Duc et al., 1996,1997, 1998,1999;
Hibbard et al., 1996;
Malphrus et al., 1997

Dwarf galaxies in Virgo

- BST in the VCC identified some 1000 dwarfs in Virgo
- 90% are dE's
- The remainder are dIs and BCDs

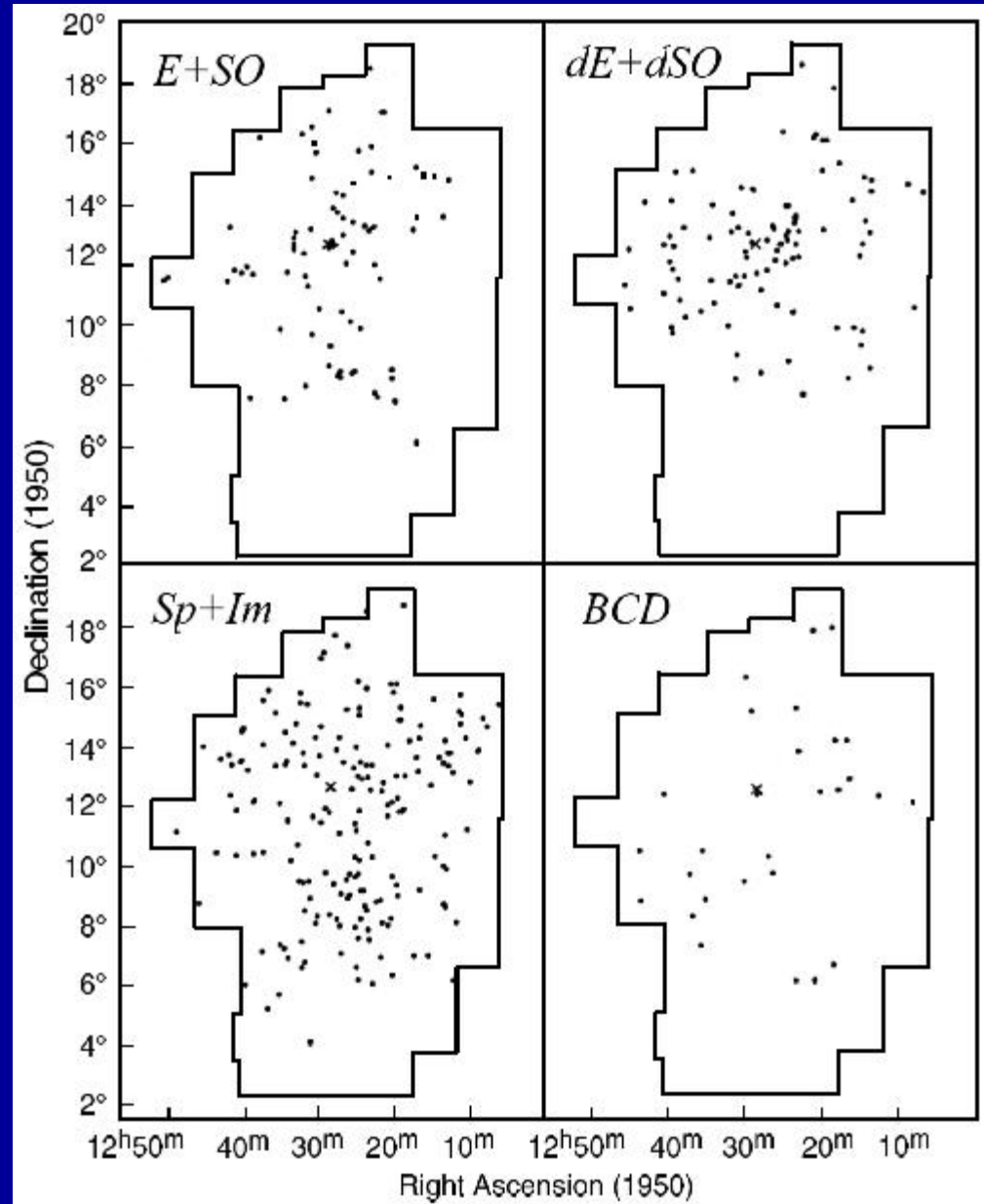
dEs are the dominant population in Virgo



dIs in Virgo

- dIs form a widely dispersed population
- dIs not preferentially stripped as might be expected due to shallower potential wells

Hoffman et al. 1987, 1989



dEs in Virgo

- dEs are widely distributed in Virgo.
 - Do not cluster around giants
 - Different dynamics from Es
- A significant fraction of dEs in Virgo are rotation dominated.

Binggeli et al. 2000, A&A, 359, 447

Conselice et al. 2001, ApJ 559, 791.

Oh & Lin 2000, ApJ 543, 620

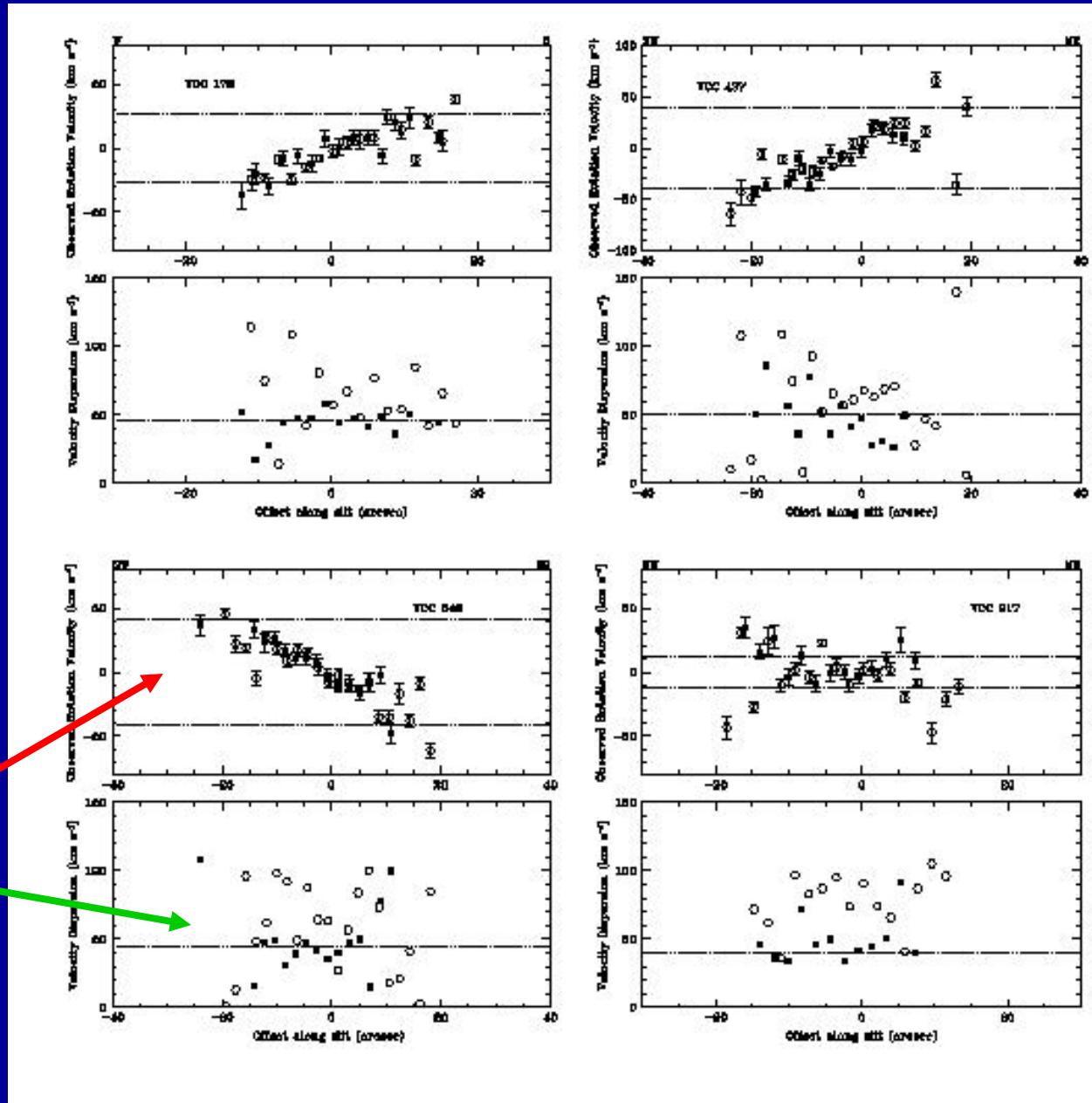
van Zee et al. 2004, AJ

Rotation of dEs in Virgo

Unlike dEs in the Local Group, some dEs in Virgo are rotation-dominated.

Long slit stellar absorption line spectroscopy from Palomar 5m

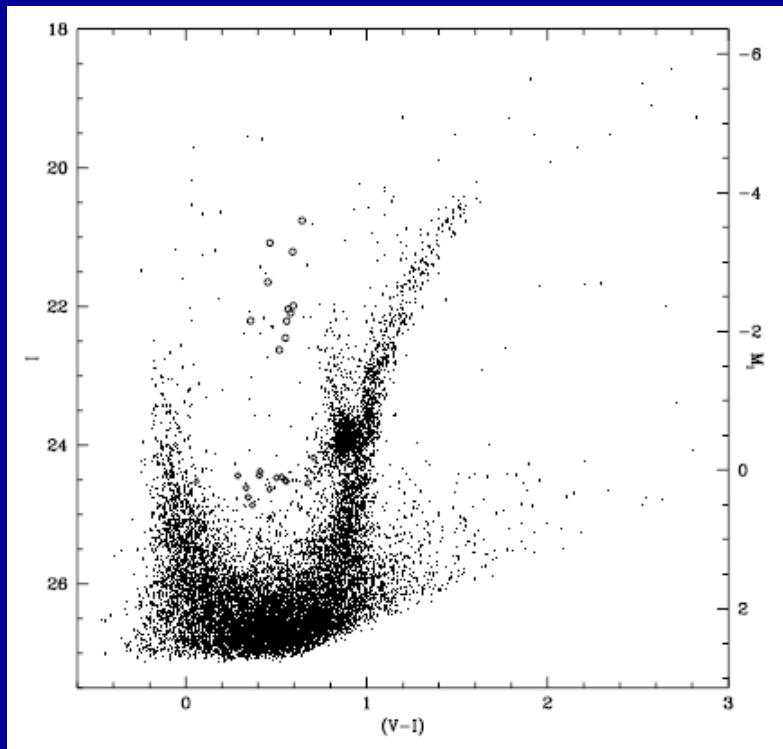
Rotation curve
Velocity dispersion



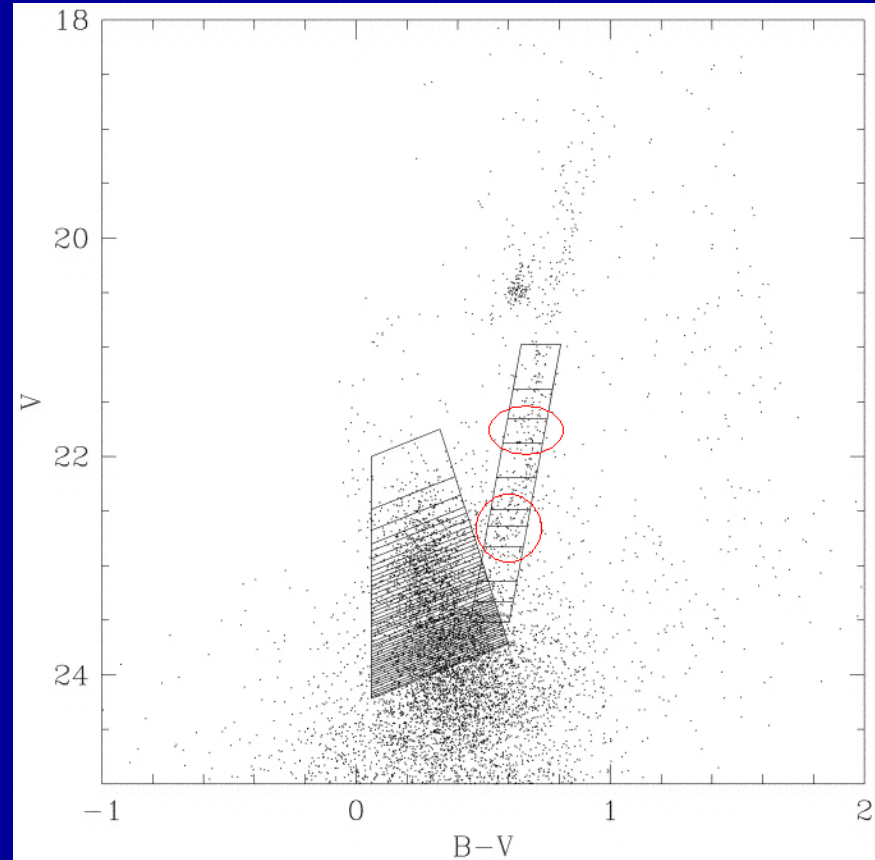
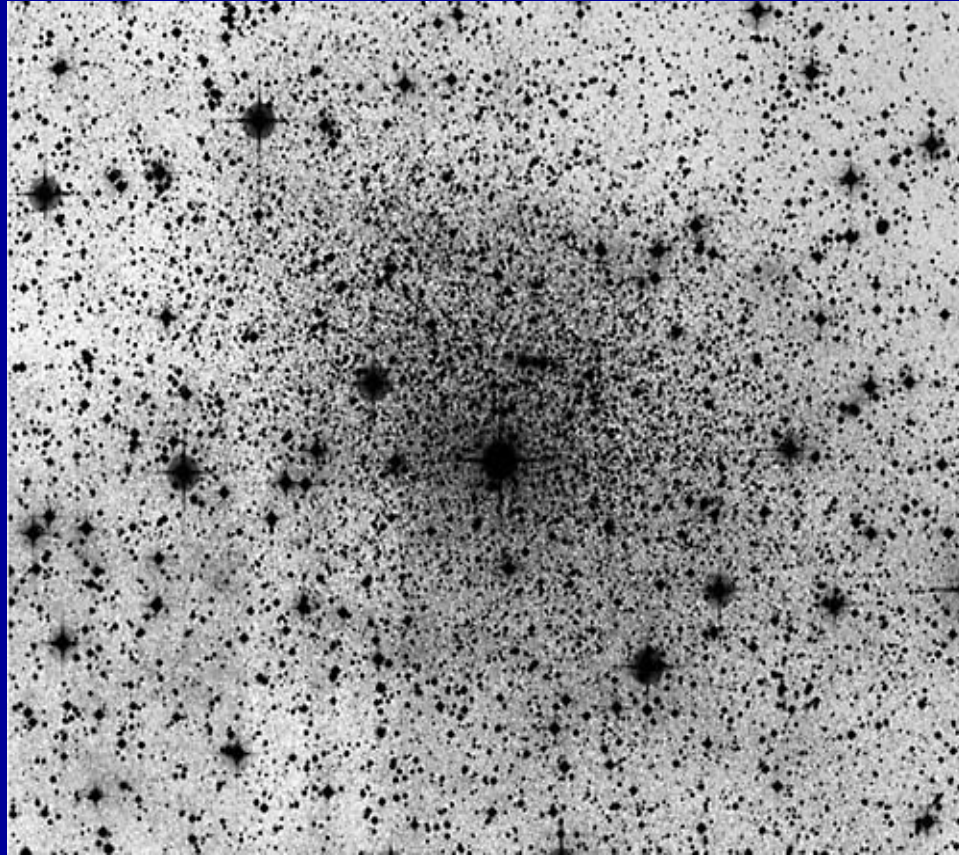
Observational Constraints

All dwarfs so studied have ancient stars (> 10 Gyr)

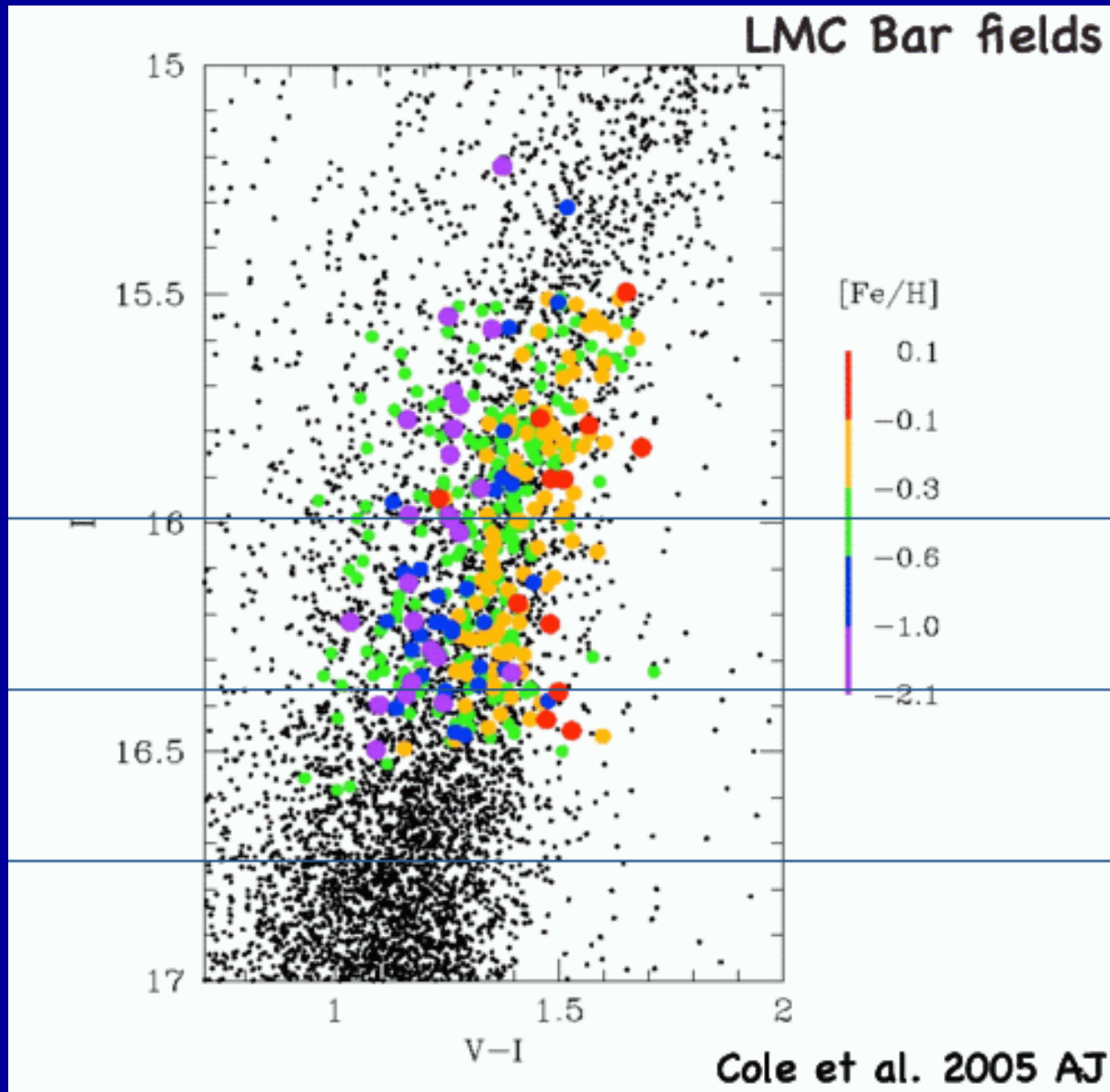
IC1613 – Dolphin et al.



The SFH of the Carina dSph galaxy



LMC CMD



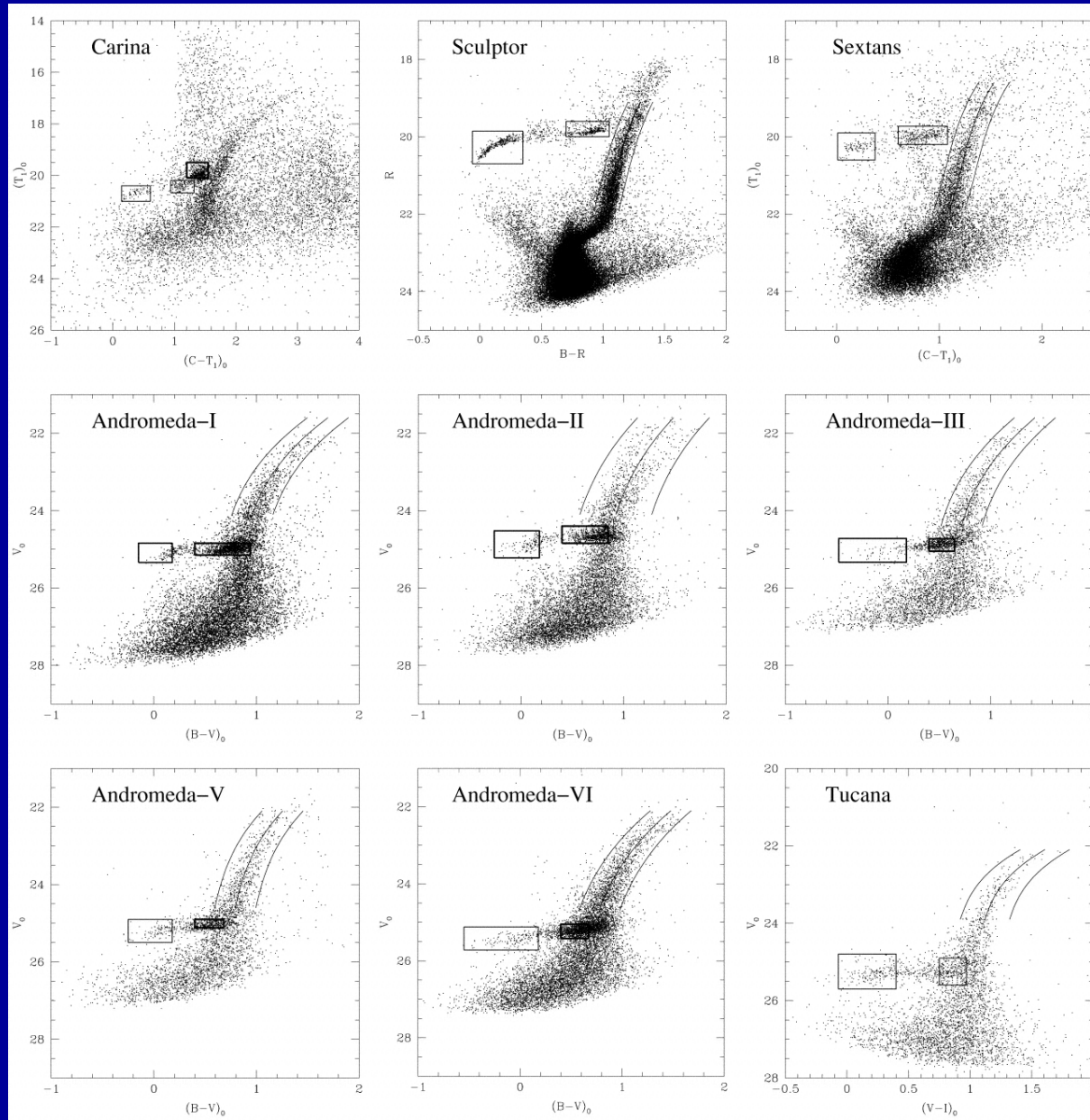
- Barred Irregular
- No obvious nucleus
- Many massive star clusters
- Rate of cluster formation peaked at > 13 Gyr ago; then no formation until ~ 4 Gyr ago.
- CMD's provide details of complex star formation histories of LG galaxies

Match to Synthetic CMD to Estimate Age and Metallicity

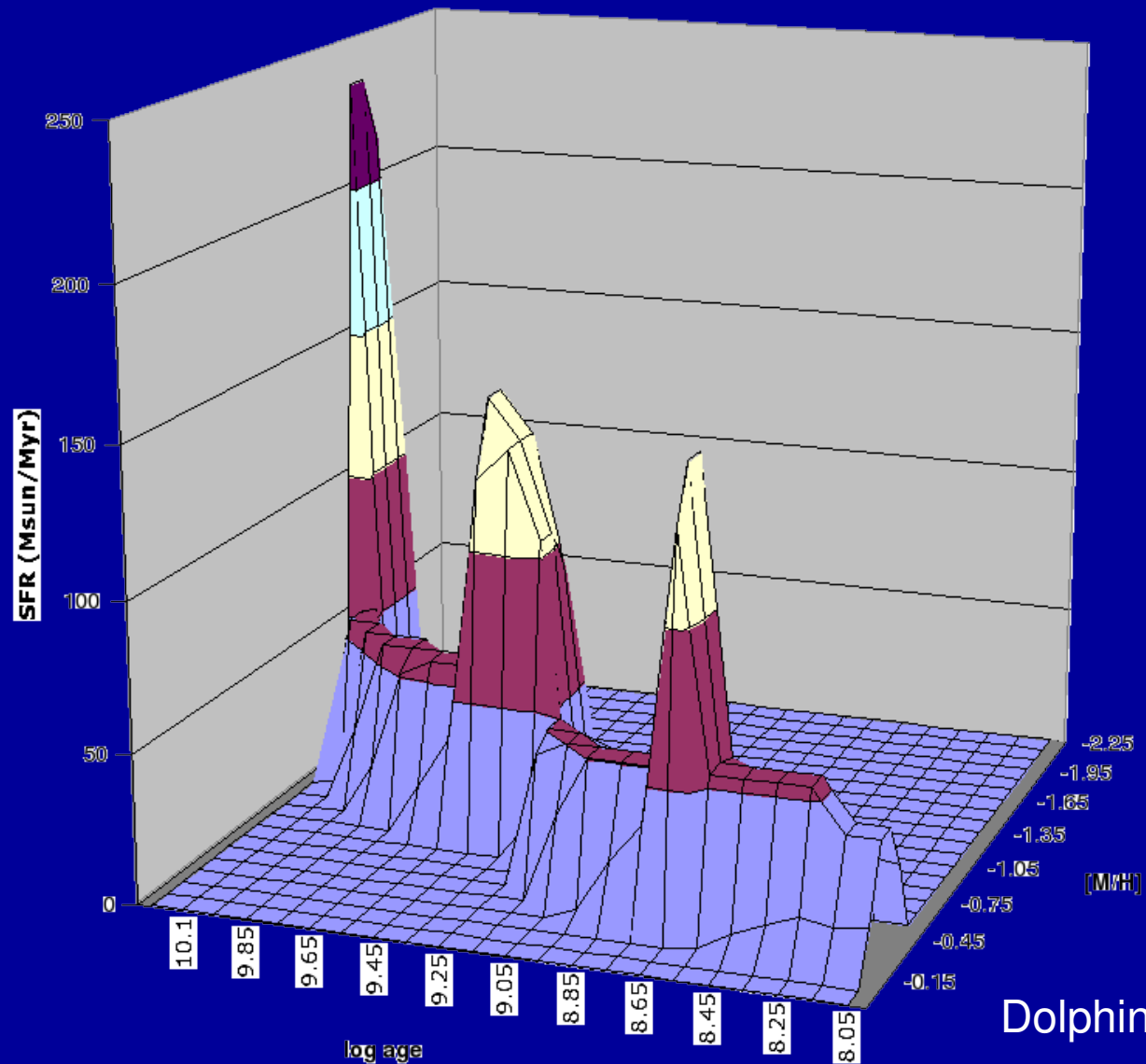
Need:

1. Star formation history
2. Stellar models and transformations
3. IMF
4. Binary star model
5. Distance
6. Extinction (constant and differential)
7. Incompleteness and photometric errors
8. Foreground/background contamination CMD

Color magnitude diagrams



Star Formation History



Dolphin 2006

Dwarf galaxies & metallicity

880

SKILLMAN, KENNICUTT, AND HODGE

Vol. 347

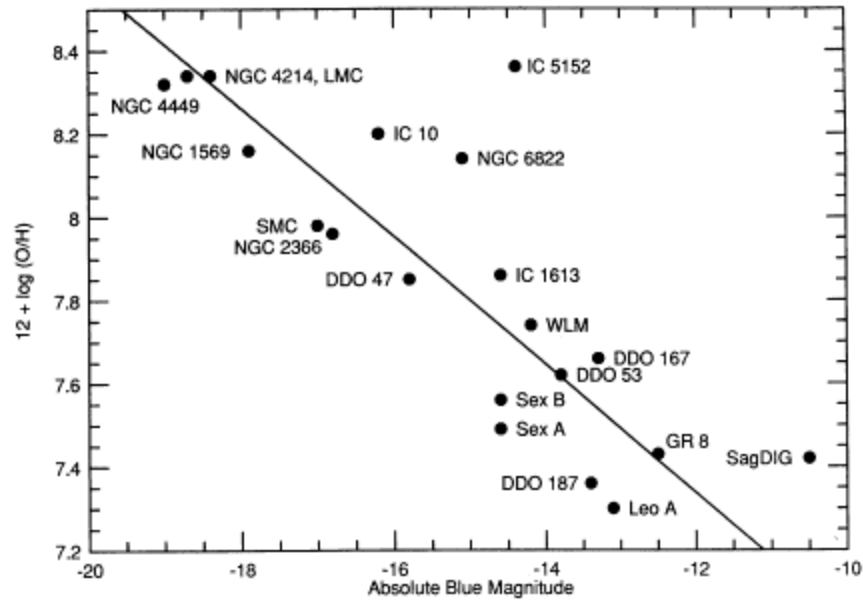


FIG. 1.—A plot of the log of the oxygen abundance vs. the absolute blue magnitude for nearby irregular galaxies. The individual galaxy points are labeled. The solid line shows the result of a mean least-squares fit to the data, excluding IC 5152.

Dwarf galaxies & metallicity

No. 2, 1989

O ABUNDANCES IN DWARF IRREGULAR GALAXIES

881

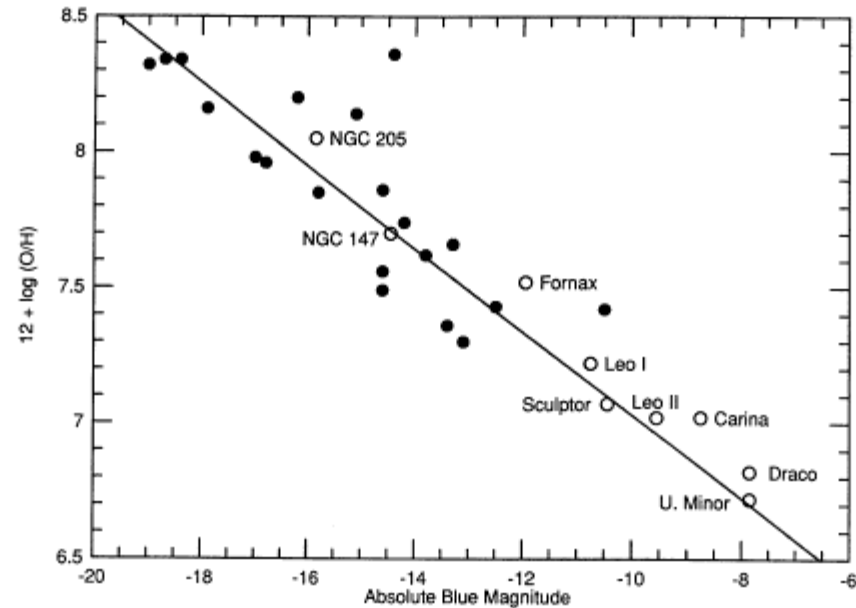


FIG. 2.—A plot of the log of the oxygen abundance vs. the absolute blue magnitude for nearby irregular and dwarf elliptical galaxies. The filled circles are the irregular galaxies from Fig. 1. The labeled open circles represent the dwarf elliptical galaxies. The abundances and absolute blue magnitudes for the dwarf elliptical galaxies are derived quantities as described in the text. The solid line is the relationship derived from the irregular galaxies alone, and is the same as show in Fig. 1.

Skillman, Kennicutt & Hodge

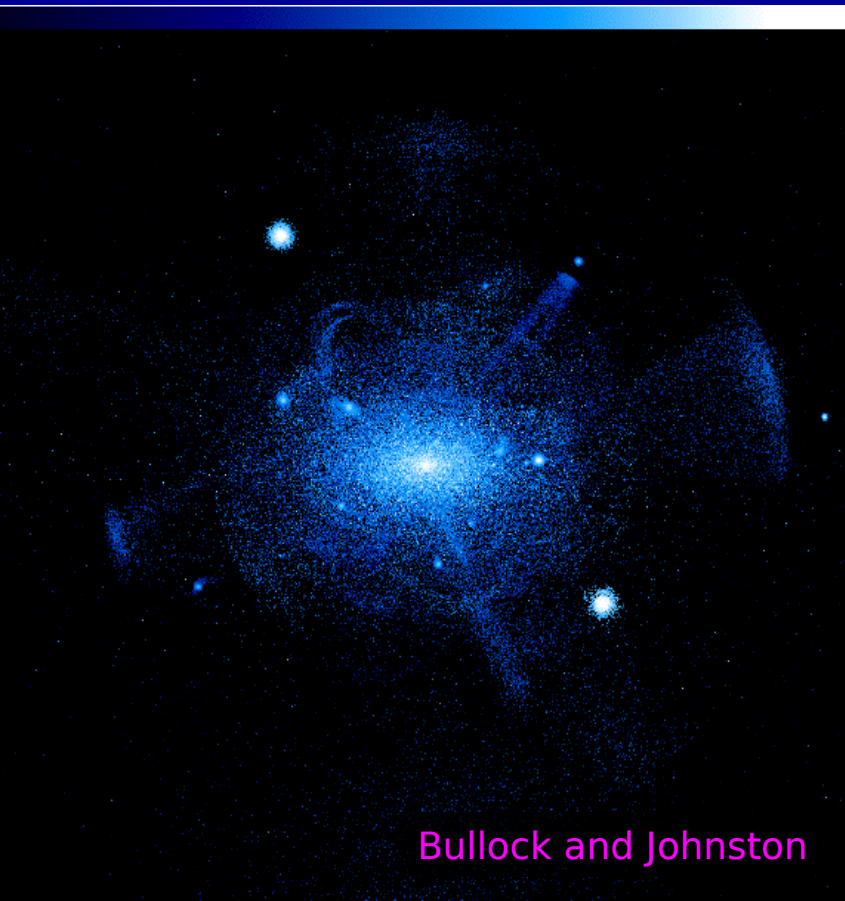
How and when do galaxies form?

- Numerical simulations predict the existence of lots of low mass halos, but so far, we have not found very many of them. Do they exist?

e.g. Kauffmann et al (1993)



Virgo collaboration (MPIfAp)

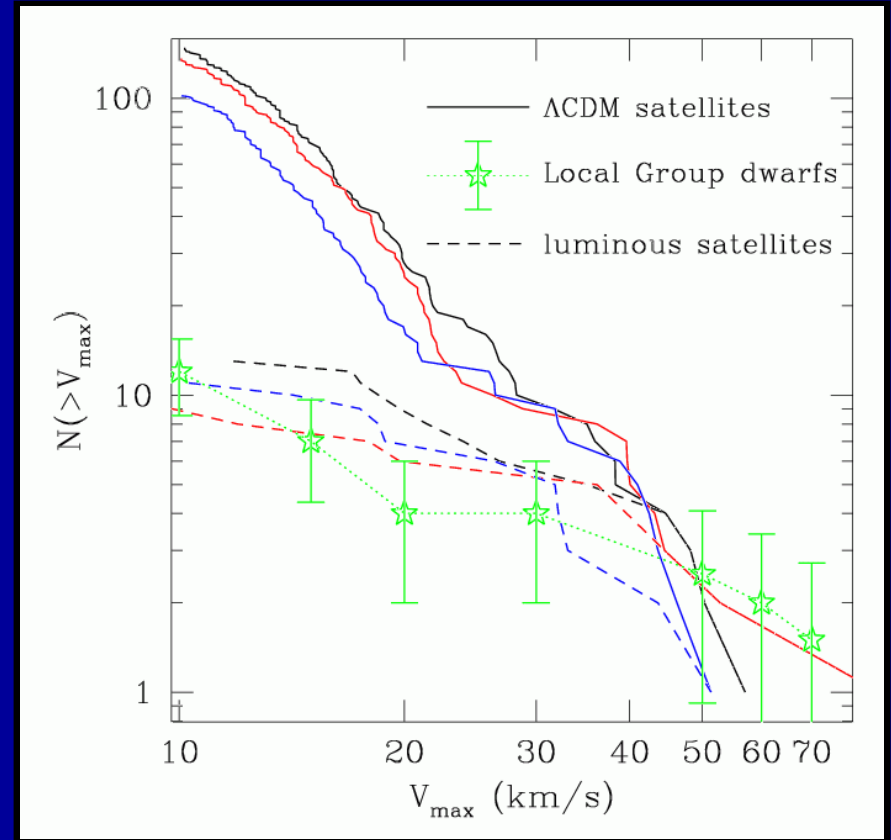
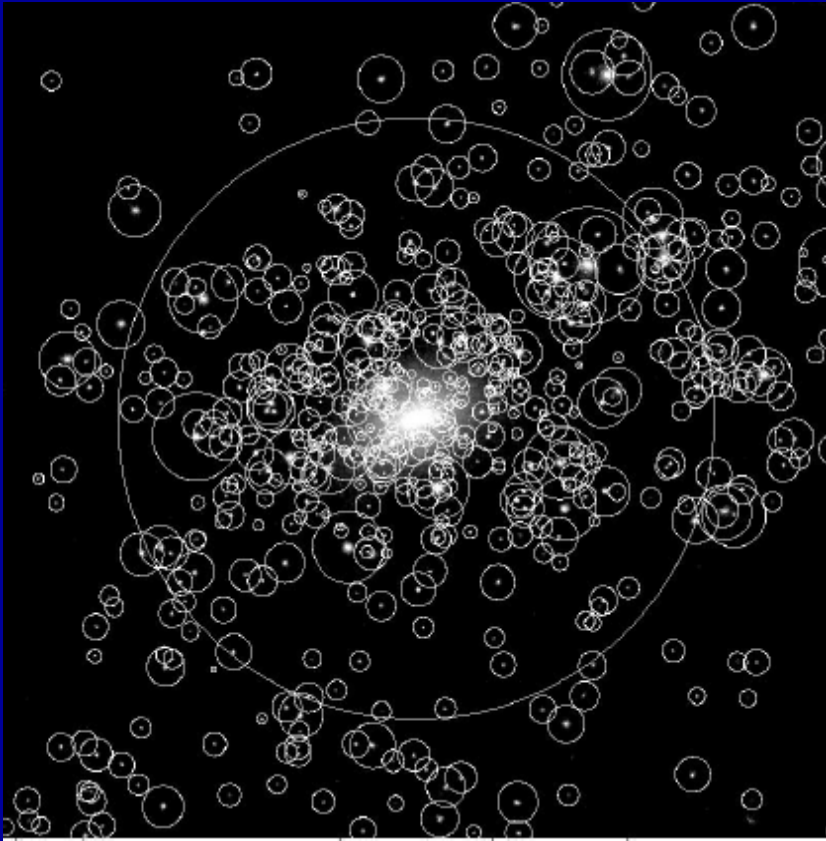


Bullock and Johnston

- Large galaxies (like the Milky Way and M31) form through merger and accretion of smaller systems

- Traces of discrete accretion events and interactions can be identified

The Missing Satellites Problem



Generally, the idea is to suppress the baryons, not try to suppress the smallest halos.

Kravtsov, Gnedin & Klypin (2004)

The “Missing Satellite Problem”

- Models/simulations predict large numbers of satellites
 - Kauffmann *et al.* (1993)
 - Klypin *et al.* (1999)
- The current census does not count them.
 - Faint end slope of the optical LF
 - Faint end slope of the HIMF
 - Willman *et al.* (2005) suggest that more than half of the MW satellites have not been identified because of extinction, surface brightness limits
- Nothing to detect?
 - Baryon loss during reionization (e.g., Efstathiou 1992; Barkana & Loeb 1999; Shaviv & Dekel 2003)
 - Can they (ever) form stars? (Verde *et al.* 2002)

