I*M*P*R*S on ASTROPHYSICS at LMU Munich

Astrophysics Introductory Course

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Powerpoint version with the help of Hanna Kotarba

Fall 2007

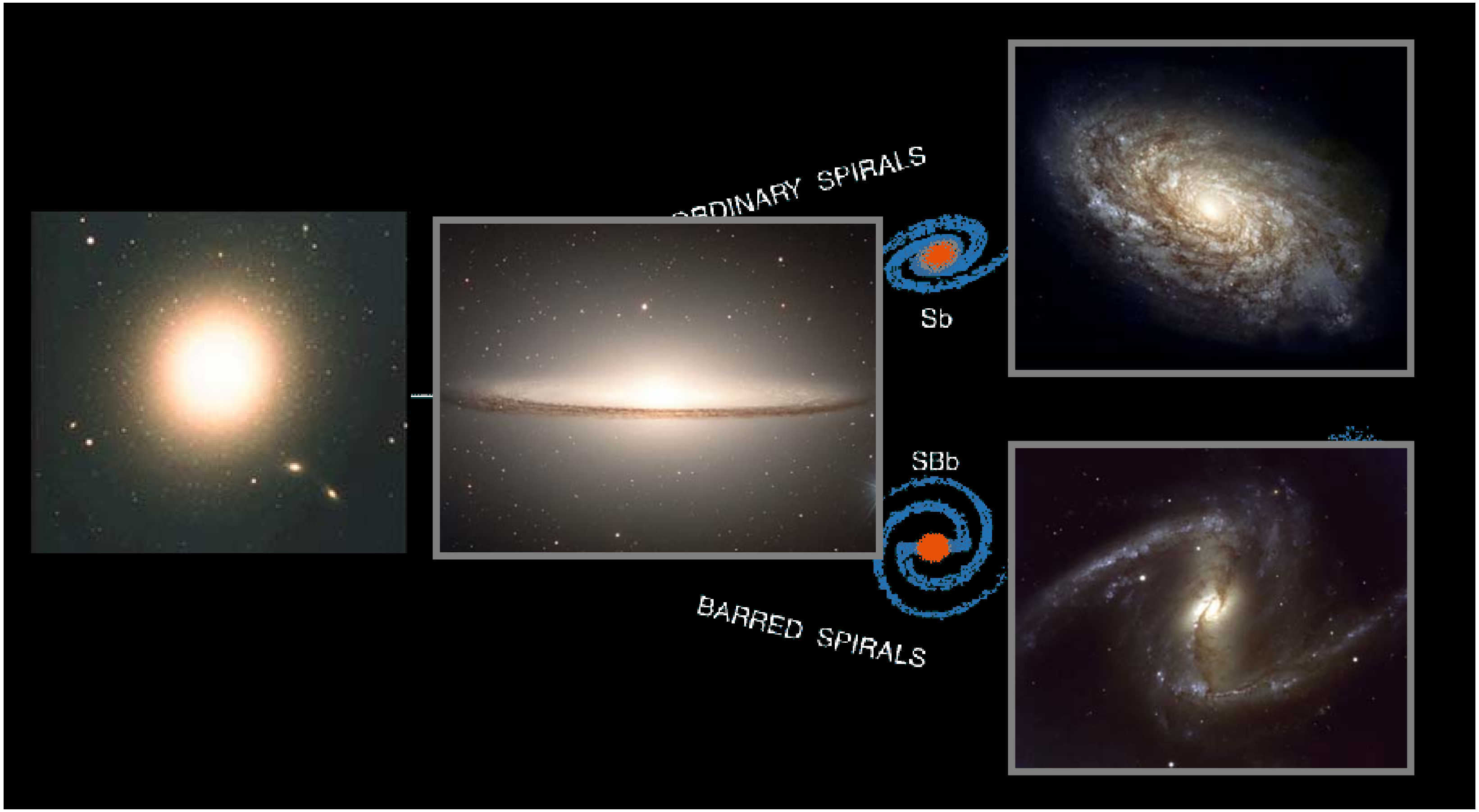
Chapter 11

Dwarf Galaxies

11.1 Overview

The Hubble Sequence of Giant Galaxies:

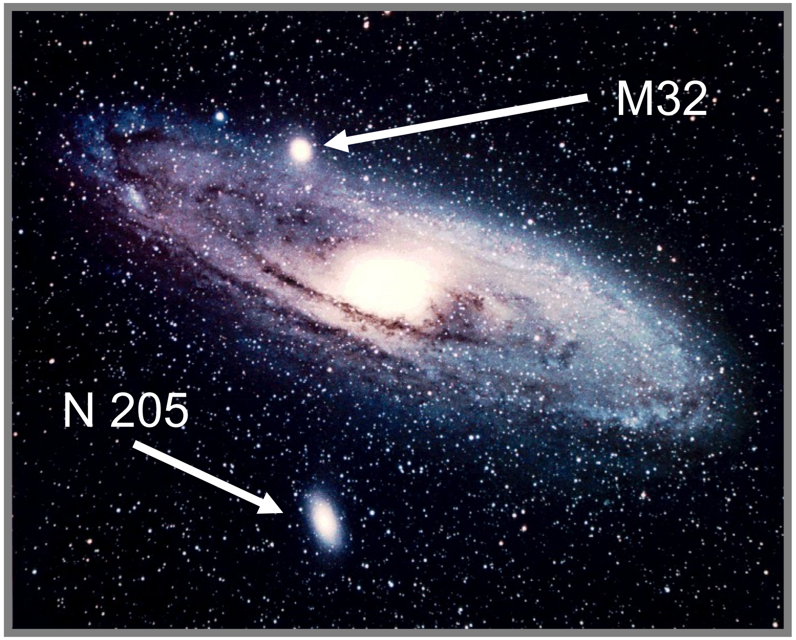
$$M \geq 10^{10}\ M_\odot$$



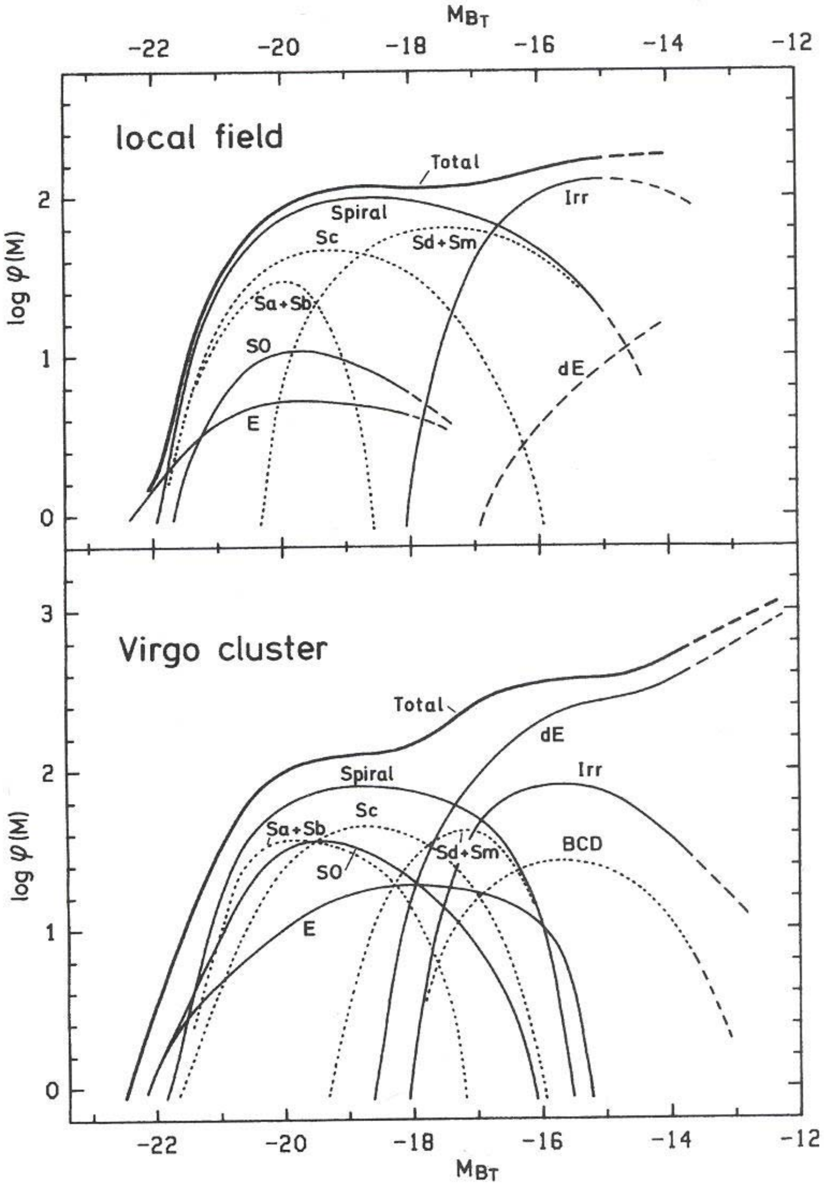
Dwarf Galaxies:

- ❖ Hubble could only detect luminous galaxies with $M_{vis} > 10^{10} M_{\odot}$
- ❖ **Most** of the galaxies in the Universe are **dwarf galaxies**
- ❖ Giant galaxies still dominate the **light** in the Universe.
- ❖ Dwarf galaxies are often observed as **satellites** of giant galaxies

→ **building blocks** of massive galaxies.

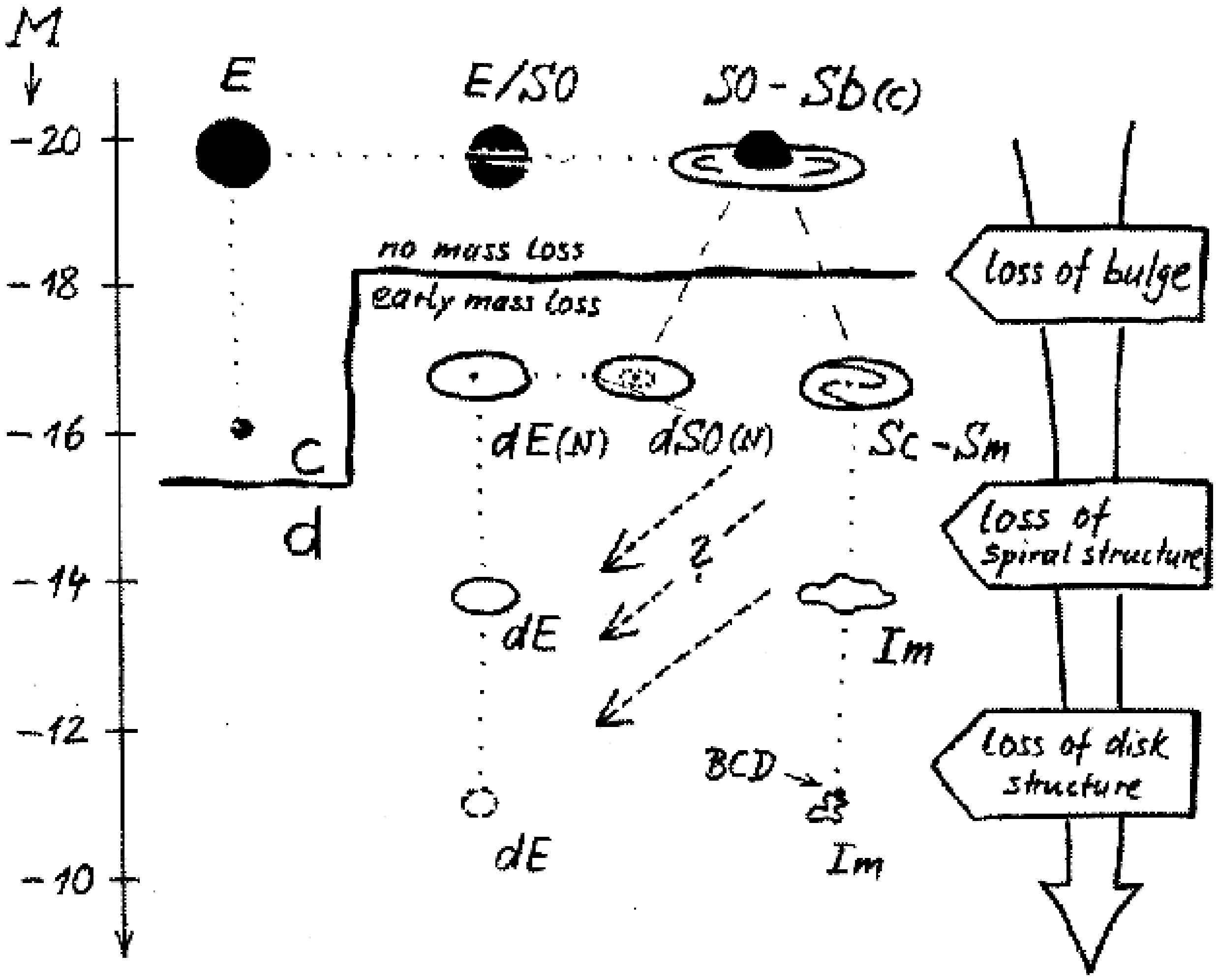


- ❖ Two dwarf galaxies orbit Andromeda: **M32**, **NGC 205**.



(Binggeli & Jerjen, 97)

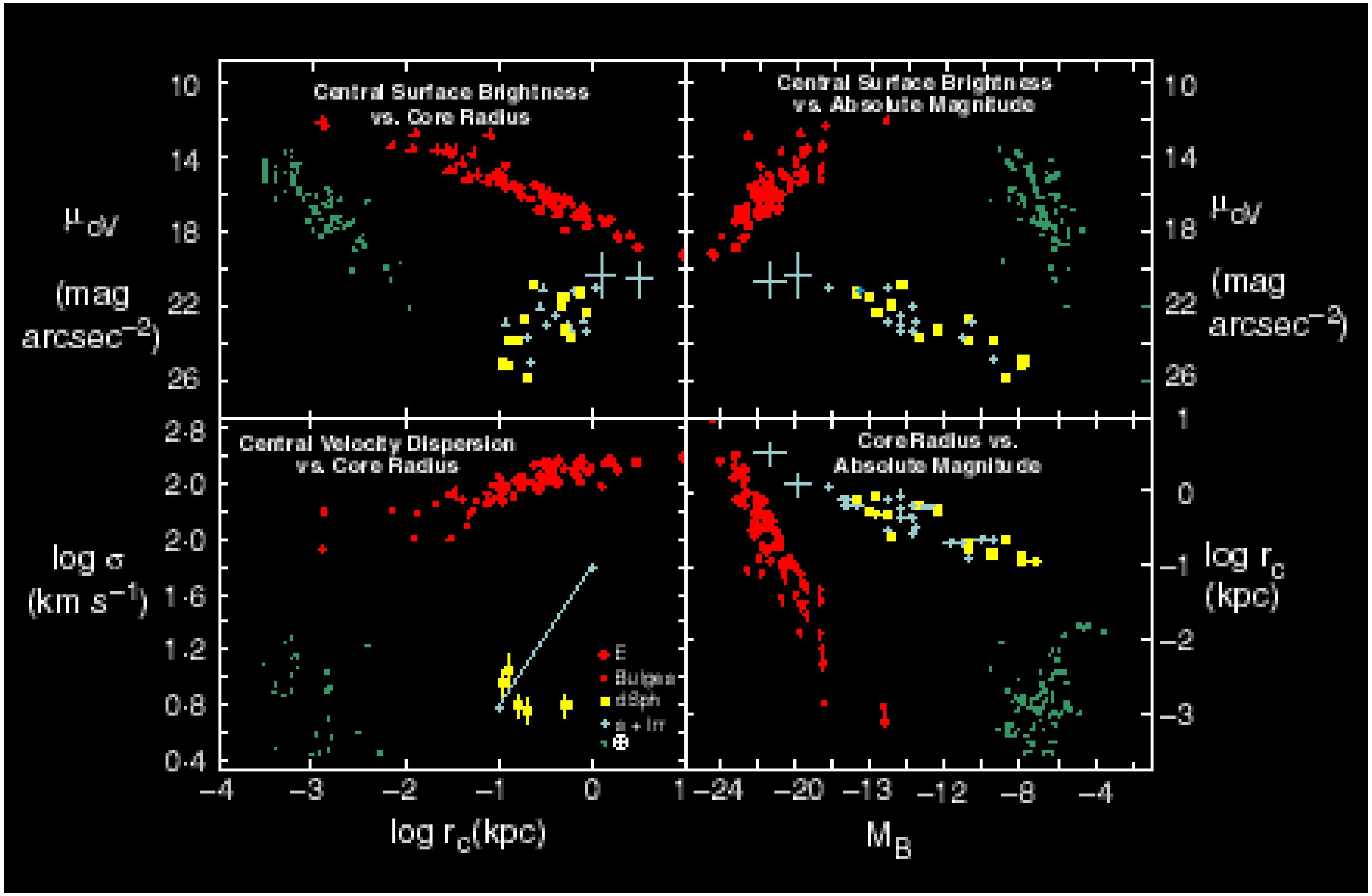
The Zoo of Dwarf Galaxies:



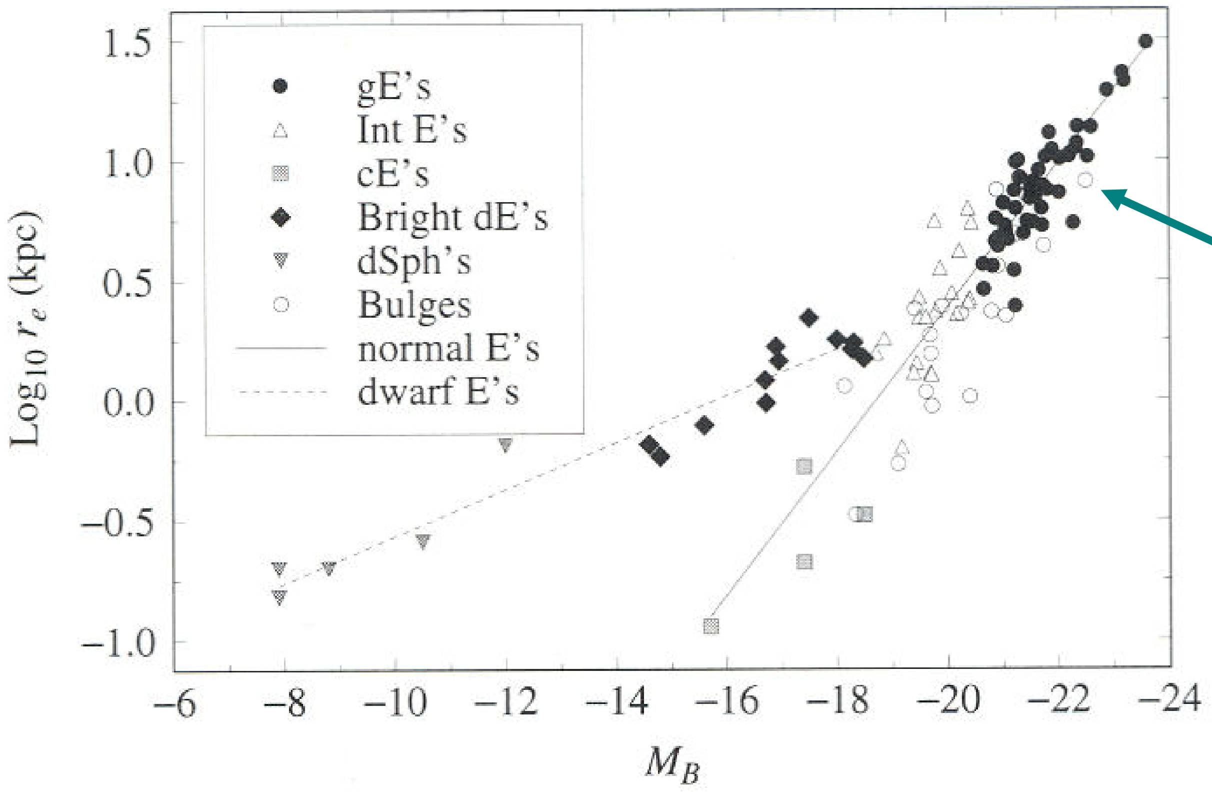
(Binggeli 93)

Core Properties of Stellar Systems in the Universe:

- ❖ All stellar systems in the Universe can be subdivided into **three distinct classes**.
- ❖ Core definition: surface density $\Sigma(r_c) = 0.5\,\Sigma(r = 0)$



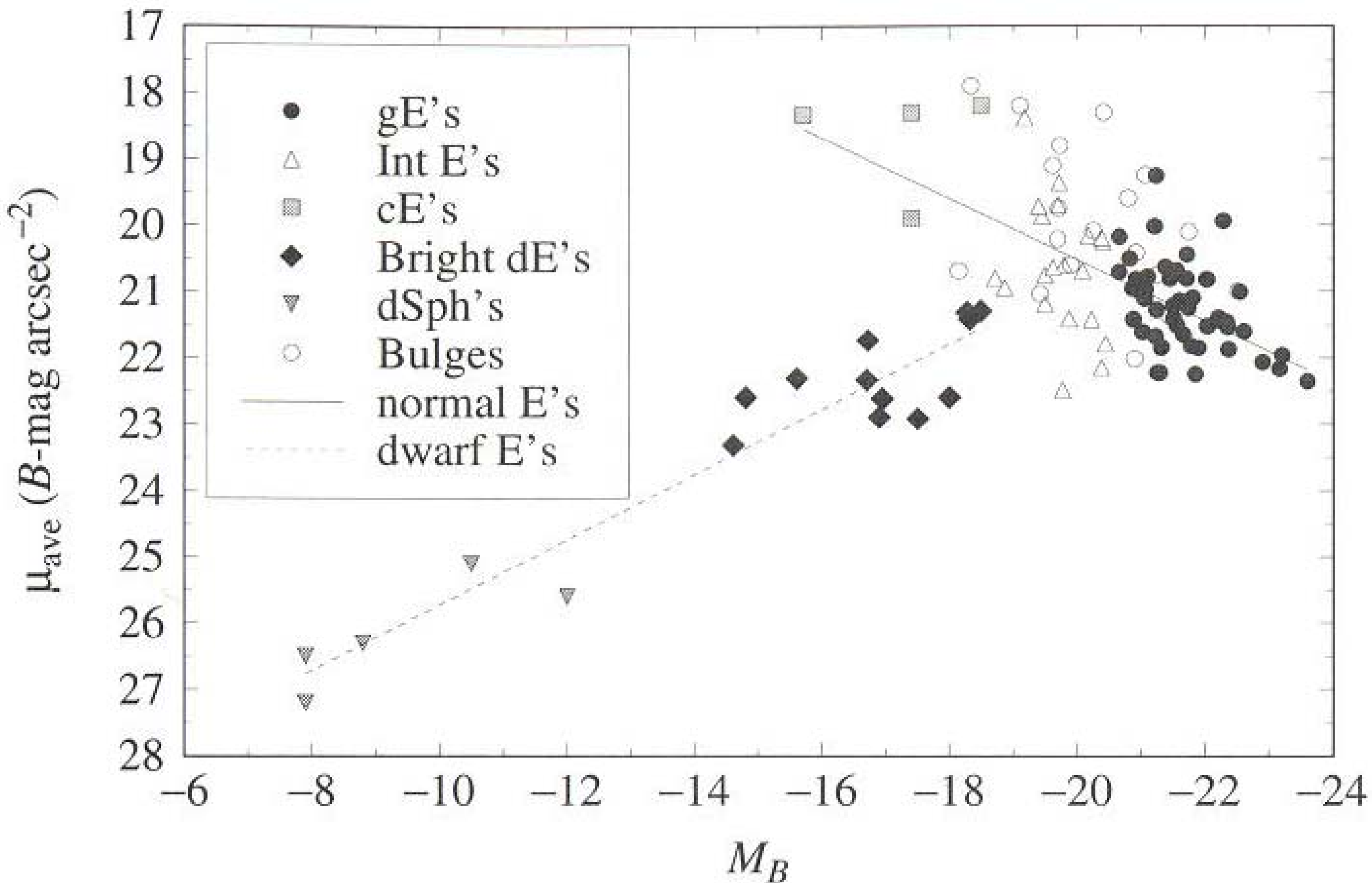
Normal ellipticals and dwarfs define **separate sequences** of effective radii as function of absolute magnitude.



bulges

(Carroll & Ostlie)

Normal ellipticals and dwarf systems define separate sequences of **average surface brightness** versus absolute magnitude.



(Carroll & Ostlie)

11.1. Dwarf ellipticals (dE) or dwarf spheroidals (dSph)

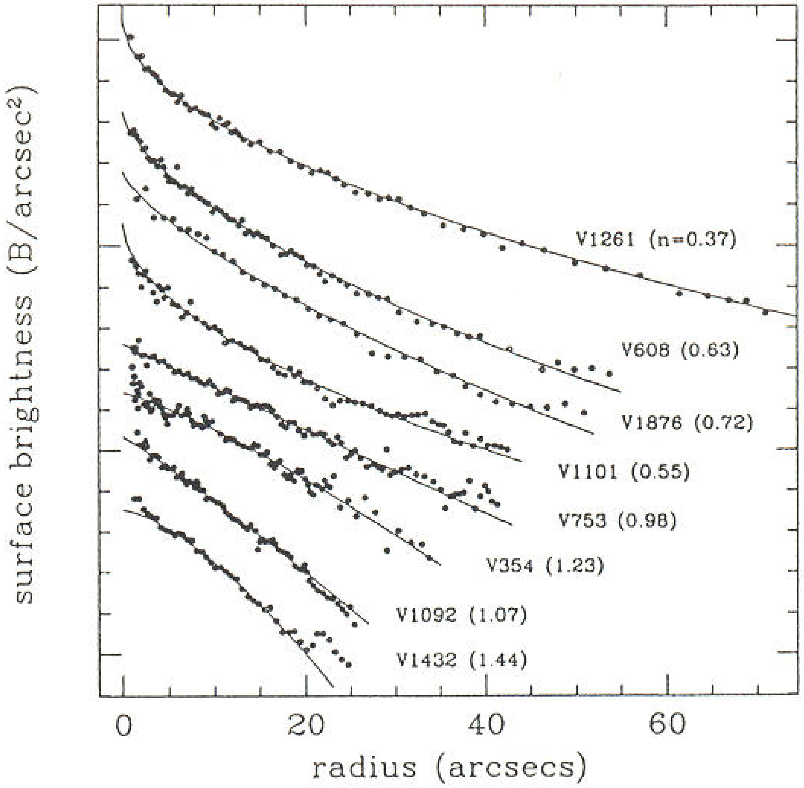
- Morphological **similar** to bright ellipticals
- Smooth **surface brightness distribution**
- Similar **ellipticity** distribution as bright ellipticals
- **No young stars**

But: exponential profiles

Sersic profiles:

$$\boxed{I(r) = I(0)\, e^{-b_n (r/r_e)^{1/n}}}$$

Sersic index



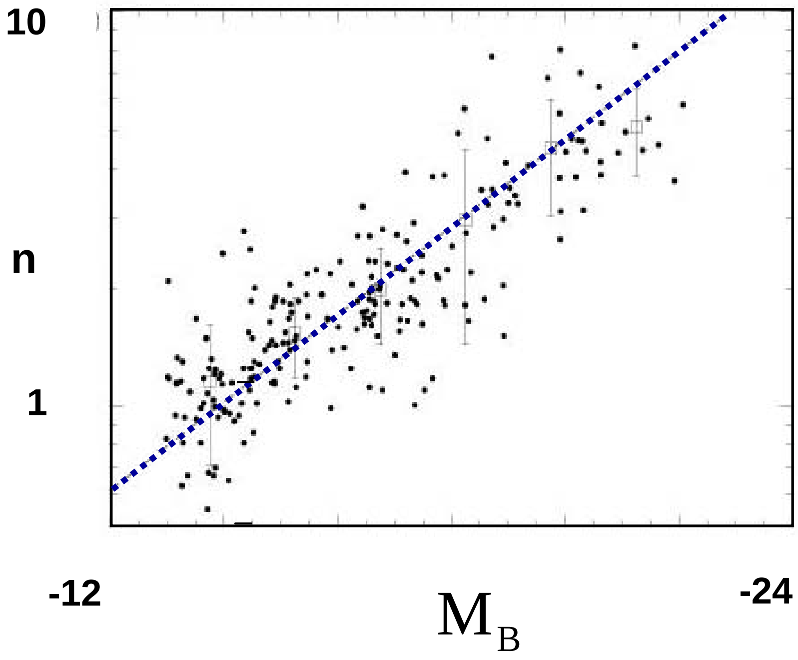
(Binggeli & Jerjen, 97)

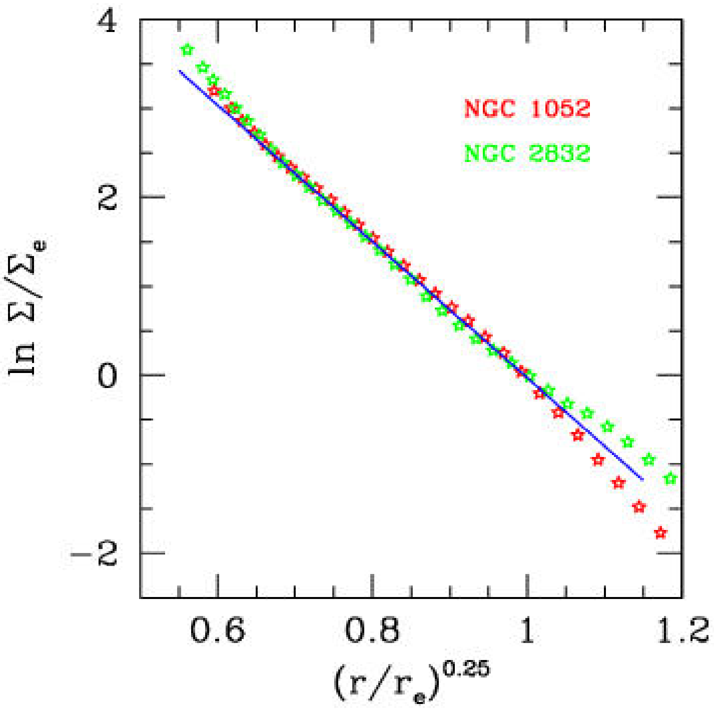
Giant ellipticals are described by the **de Vaucouleurs profile:**

$$I(r) = I(0)\, e^{-7.67 (r/r_e)^{1/4}}$$

More generalized profile:

$$I(r) = I(0)\, e^{-b_n (r/r_e)^{1/n}}$$

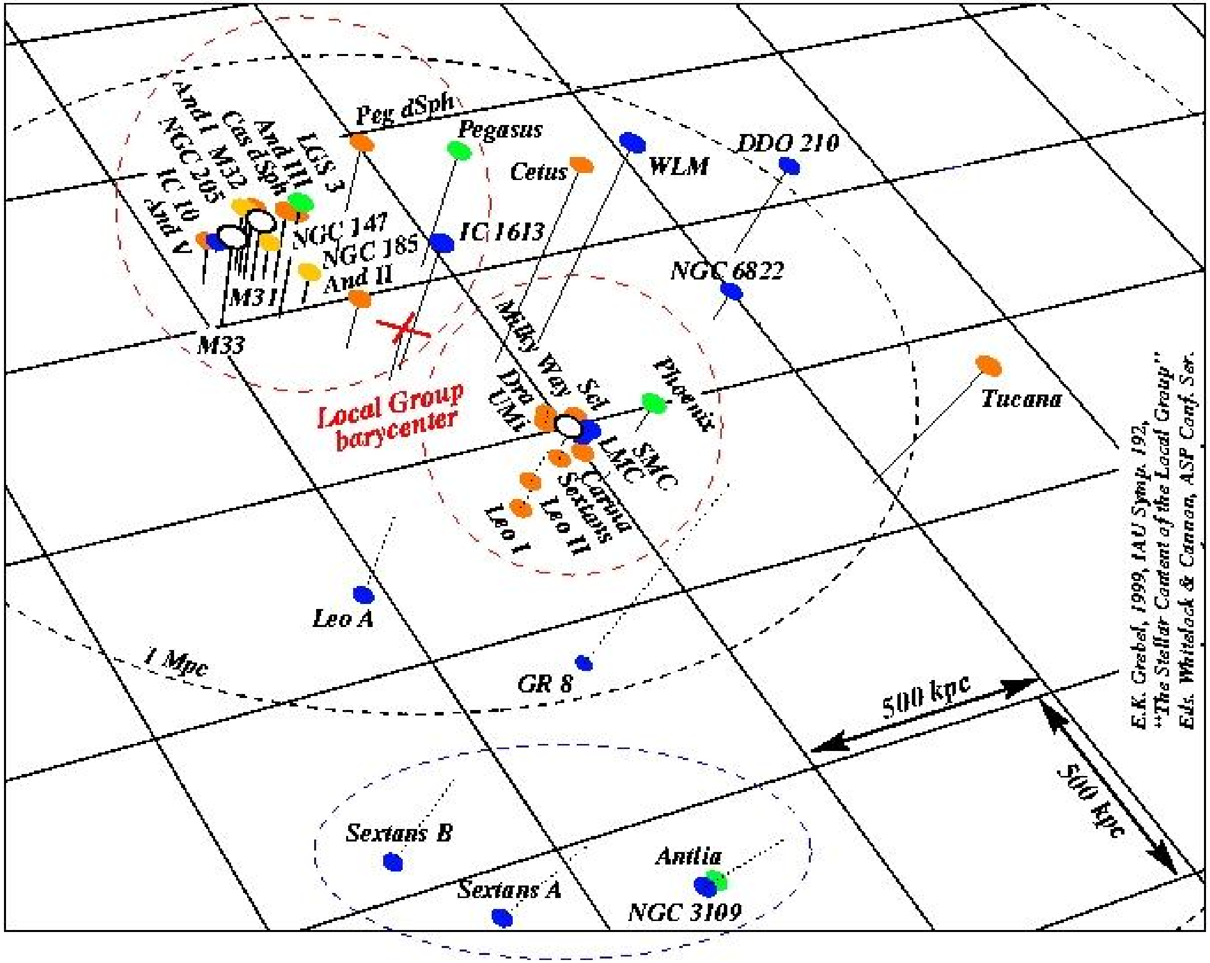




There exists a puzzling correlation of Sersic n with galaxy luminosity.

The dwarf spheroidals of the Local Group:

9 dSph galaxies named for the constellations in which they appear.

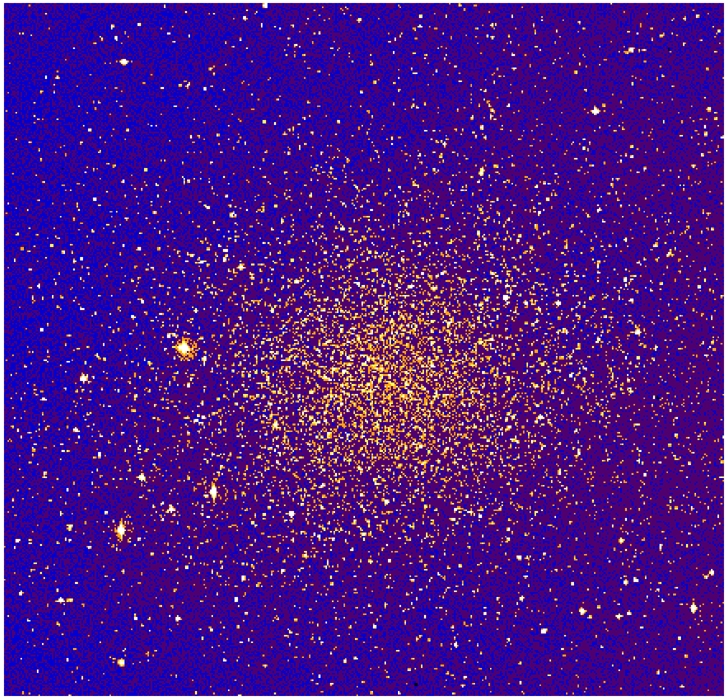


E.K. Grebel, 1999, IAU Symp. 192, "The Stellar Content of the Local Group" Eds. Whitelock & Cannon, ASP Conf. Ser.

Dwarf Galaxies and Globular Star Clusters:

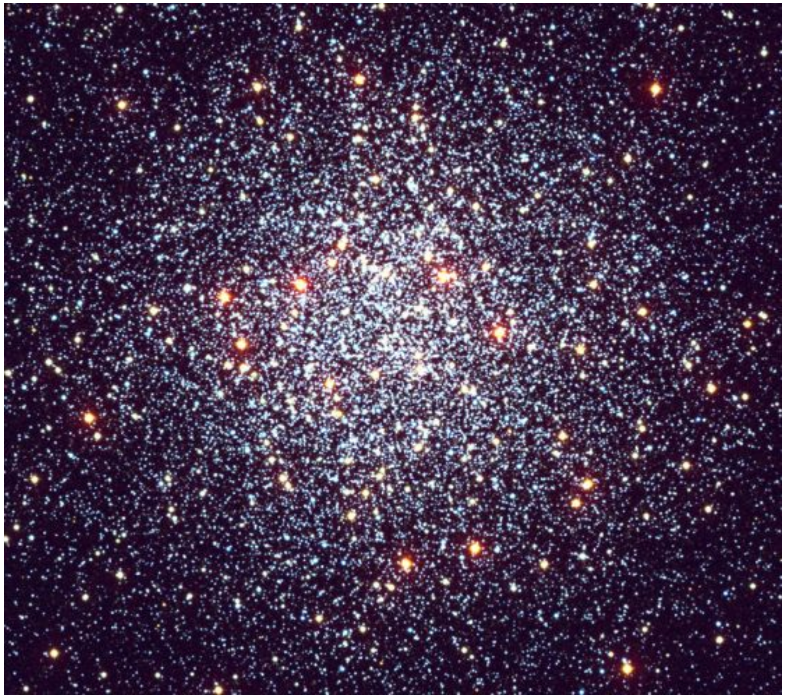
Similar masses but very different radii

The Sculptor Dwarf Galaxy



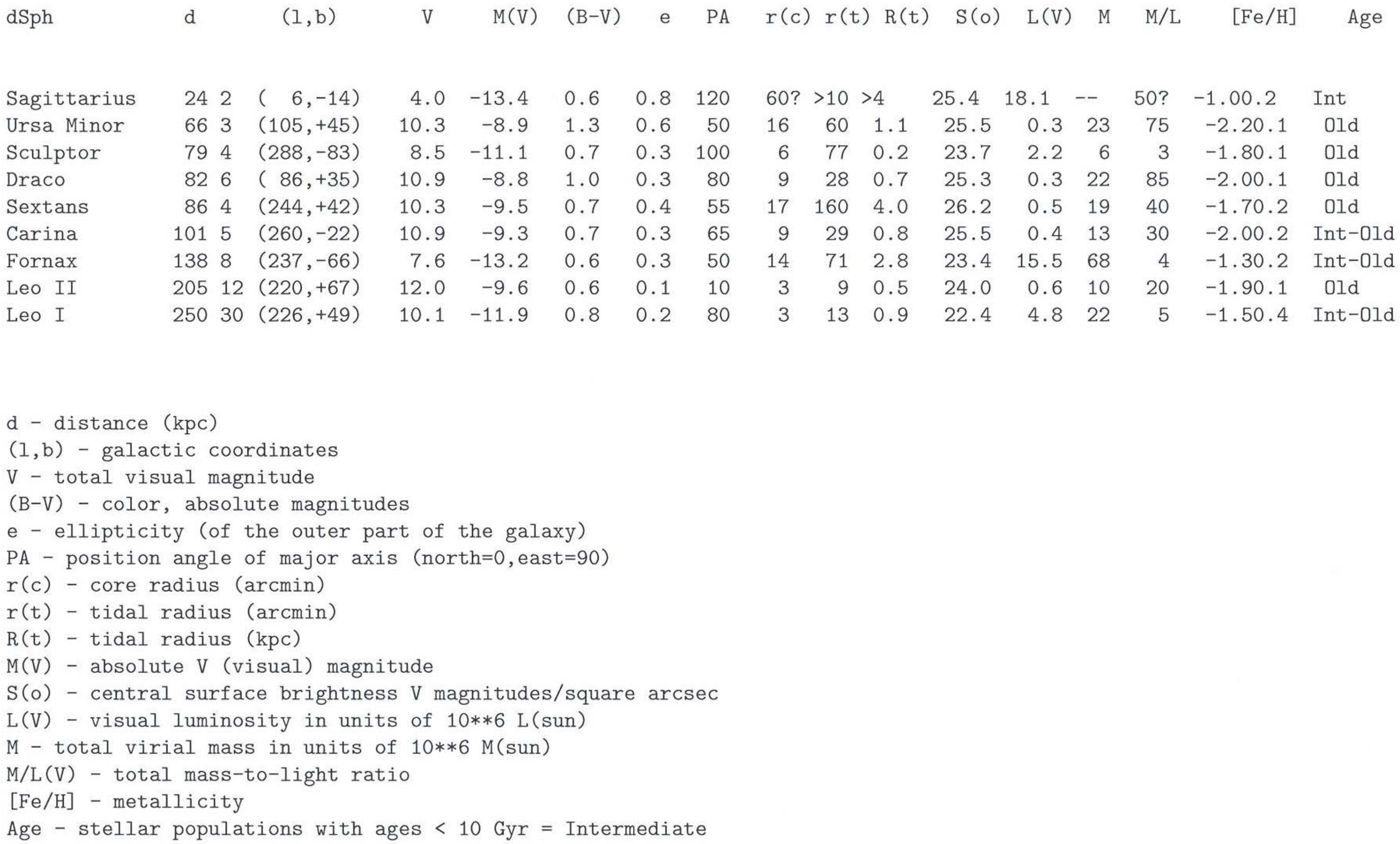
2 kpc

Globular Cluster M55



0.1 kpc

The dwarf spheroidals of the Local Group:



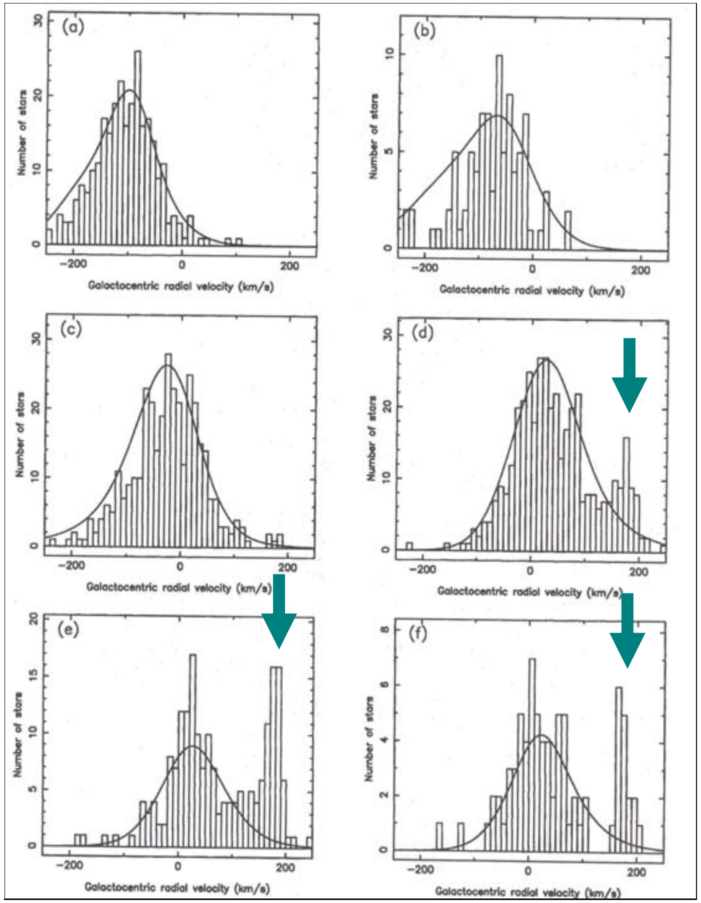
dSph	d	(l,b)	V	M(V)	(B-V)	e	PA	r(c)	r(t)	R(t)	S(o)	L(V)	M	M/L	[Fe/H]	Age
Sagittarius	24 2	(6,-14)	4.0	-13.4	0.6	0.8	120	60?	>10	>4	25.4	18.1	--	50?	-1.00.2	Int
Ursa Minor	66 3	(105,+45)	10.3	-8.9	1.3	0.6	50	16	60	1.1	25.5	0.3	23	75	-2.20.1	Old
Sculptor	79 4	(288,-83)	8.5	-11.1	0.7	0.3	100	6	77	0.2	23.7	2.2	6	3	-1.80.1	Old
Draco	82 6	(86,+35)	10.9	-8.8	1.0	0.3	80	9	28	0.7	25.3	0.3	22	85	-2.00.1	Old
Sextans	86 4	(244,+42)	10.3	-9.5	0.7	0.4	55	17	160	4.0	26.2	0.5	19	40	-1.70.2	Old
Carina	101 5	(260,-22)	10.9	-9.3	0.7	0.3	65	9	29	0.8	25.5	0.4	13	30	-2.00.2	Int-Old
Fornax	138 8	(237,-66)	7.6	-13.2	0.6	0.3	50	14	71	2.8	23.4	15.5	68	4	-1.30.2	Int-Old
Leo II	205 12	(220,+67)	12.0	-9.6	0.6	0.1	10	3	9	0.5	24.0	0.6	10	20	-1.90.1	Old
Leo I	250 30	(226,+49)	10.1	-11.9	0.8	0.2	80	3	13	0.9	22.4	4.8	22	5	-1.50.4	Int-Old

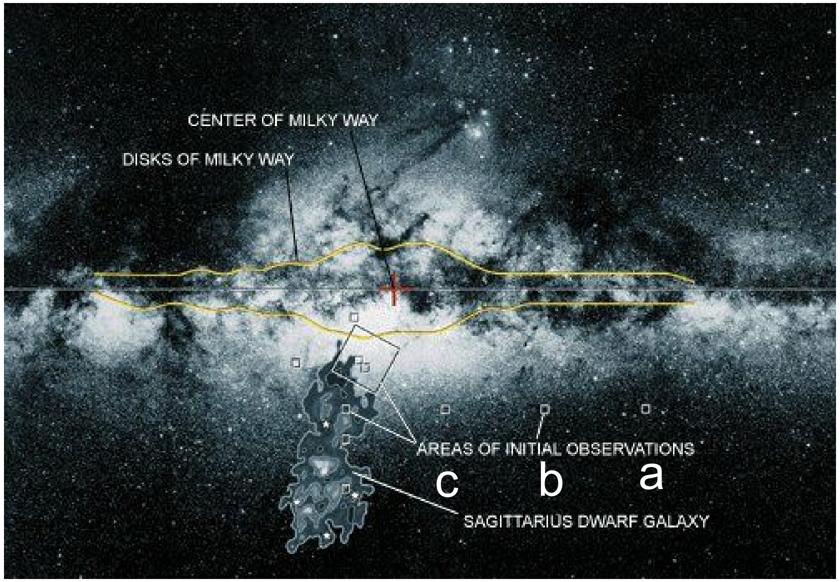
d - distance (kpc)
(l,b) - galactic coordinates
V - total visual magnitude
(B-V) - color, absolute magnitudes
e - ellipticity (of the outer part of the galaxy)
PA - position angle of major axis (north=0,east=90)
r(c) - core radius (arcmin)
r(t) - tidal radius (arcmin)
R(t) - tidal radius (kpc)
M(V) - absolute V (visual) magnitude
S(o) - central surface brightness V magnitudes/square arcsec
L(V) - visual luminosity in units of 10**6 L(sun)
M - total virial mass in units of 10**6 M(sun)
M/L(V) - total mass-to-light ratio
[Fe/H] - metallicity
Age - stellar populations with ages < 10 Gyr = Intermediate

The Sagittarius Dwarf Elliptical Galaxy:

- Galaxies like the **Milky Way** formed from smaller galaxies.
- Even after becoming a giant galaxy, the Milky Way still **devours** smaller **companions** that move **too close** to it.
- In **1994** a new object was discovered by **Ibata et al.** on the opposite side of the Galactic center

→ **SagDEG**

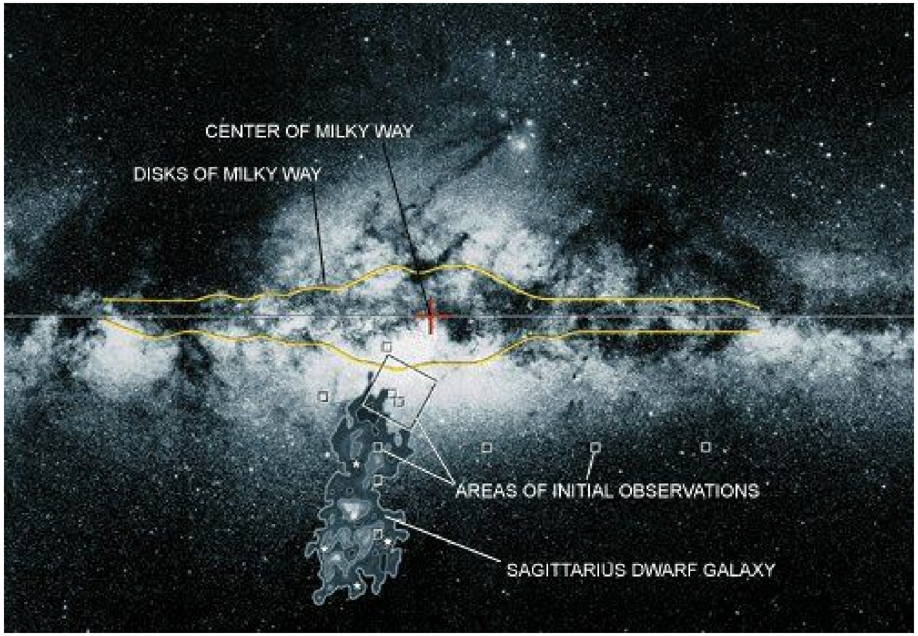


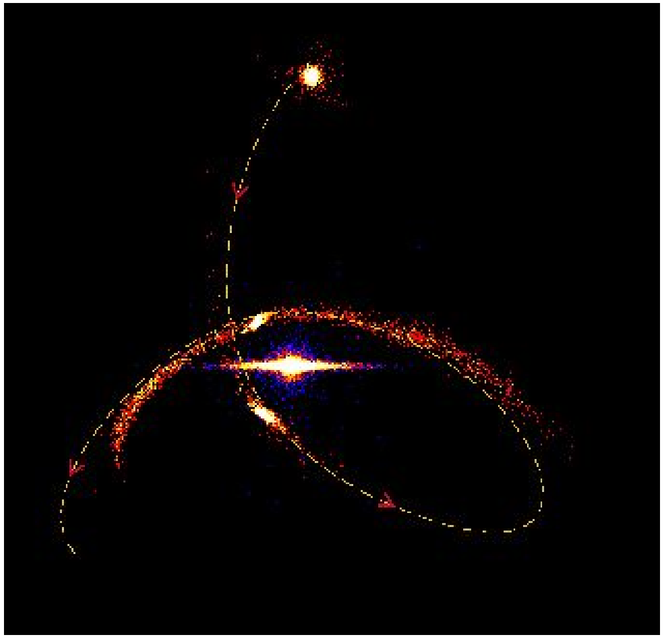


(Ibata)

- One of our **nearest neighbors** and comprised of mostly old stars (carbon stars).
- About **20 kpc** from the Sun on the opposite side of the Milky Way.
- The galaxy is **torn apart** by immense tidal forces of hundreds of millions of yrs
- In 1996, a **stream of stars** was found that completely encircles the Milky Way.
- Mass:

$$M \approx 10^7 - 10^8\ M_\odot$$



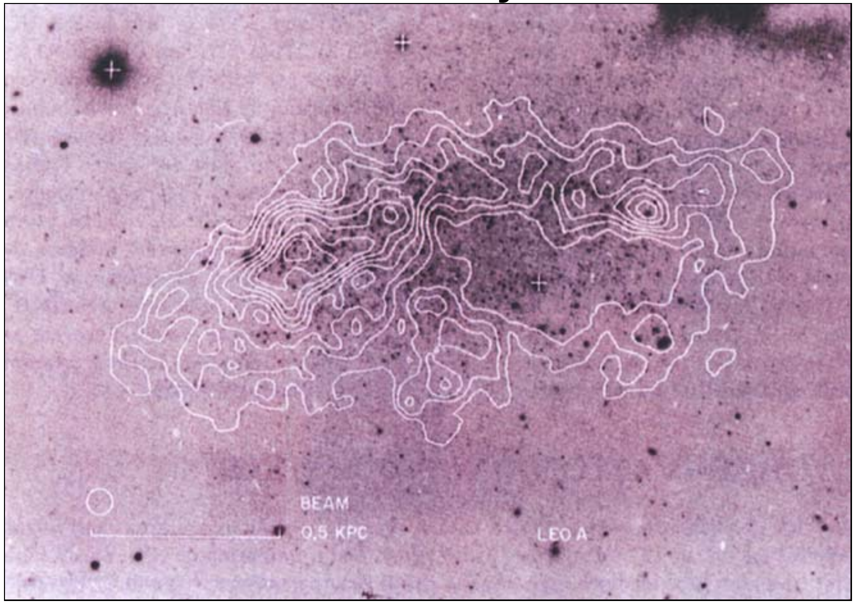


(Johnston et al.)

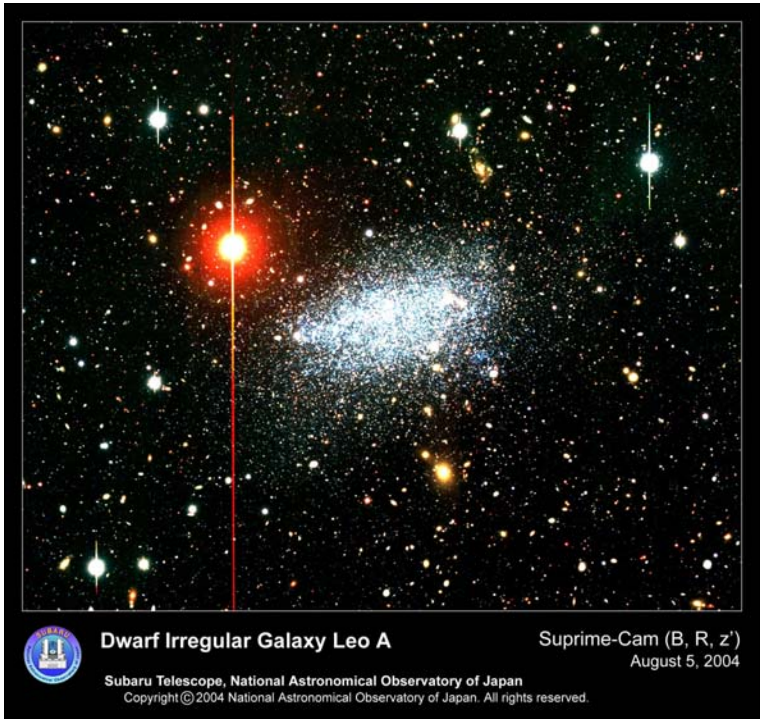
11.2. Dwarf irregulars:

- Brightness distribution in U,B,V shows **knots**, which correspond to **star formation** regions.
- The brightness distribution in the **IR** is smoother (**old stars**) and close to an **exponential profile**.

HI column density of Leo A



(Lo et al. 94, in Panchromatic View on Galaxies)



Dwarf Irregular Galaxy Leo A

Suprime-Cam (B, R, z')
August 5, 2004

Subaru Telescope, National Astronomical Observatory of Japan

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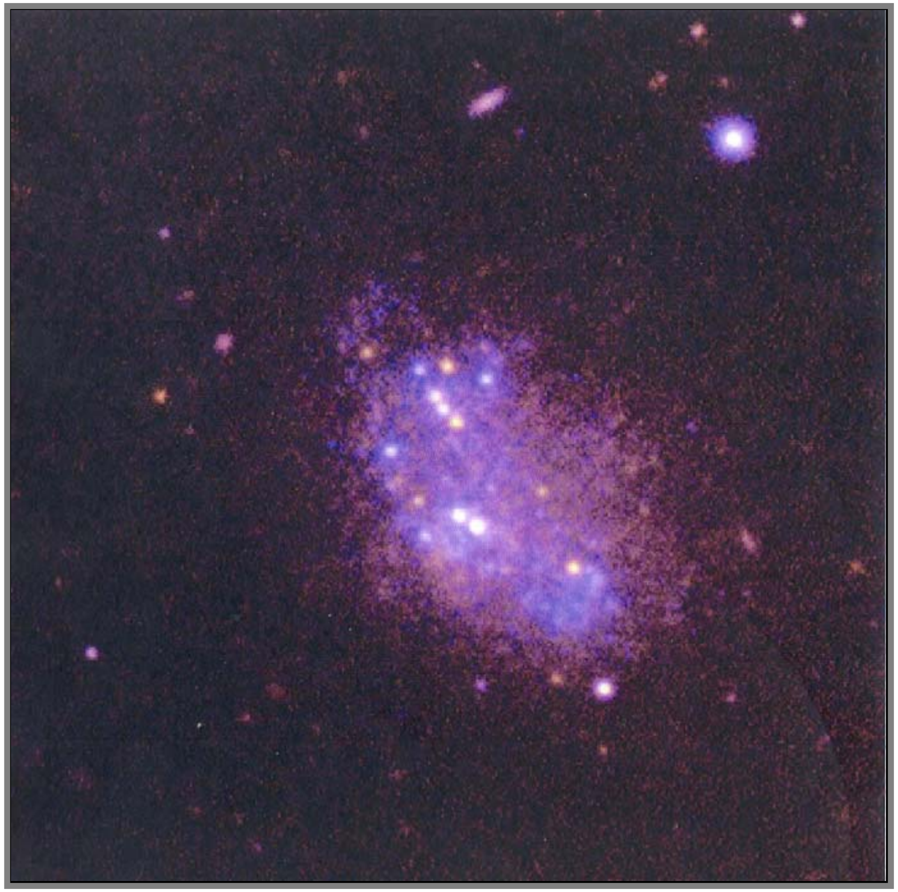


GR8: Wendelstein image by Claus Goessl

- Dwarf irregulars again show an **ellipticity distribution** similar to ellipticals and dwarf ellipticals, but not to spirals.

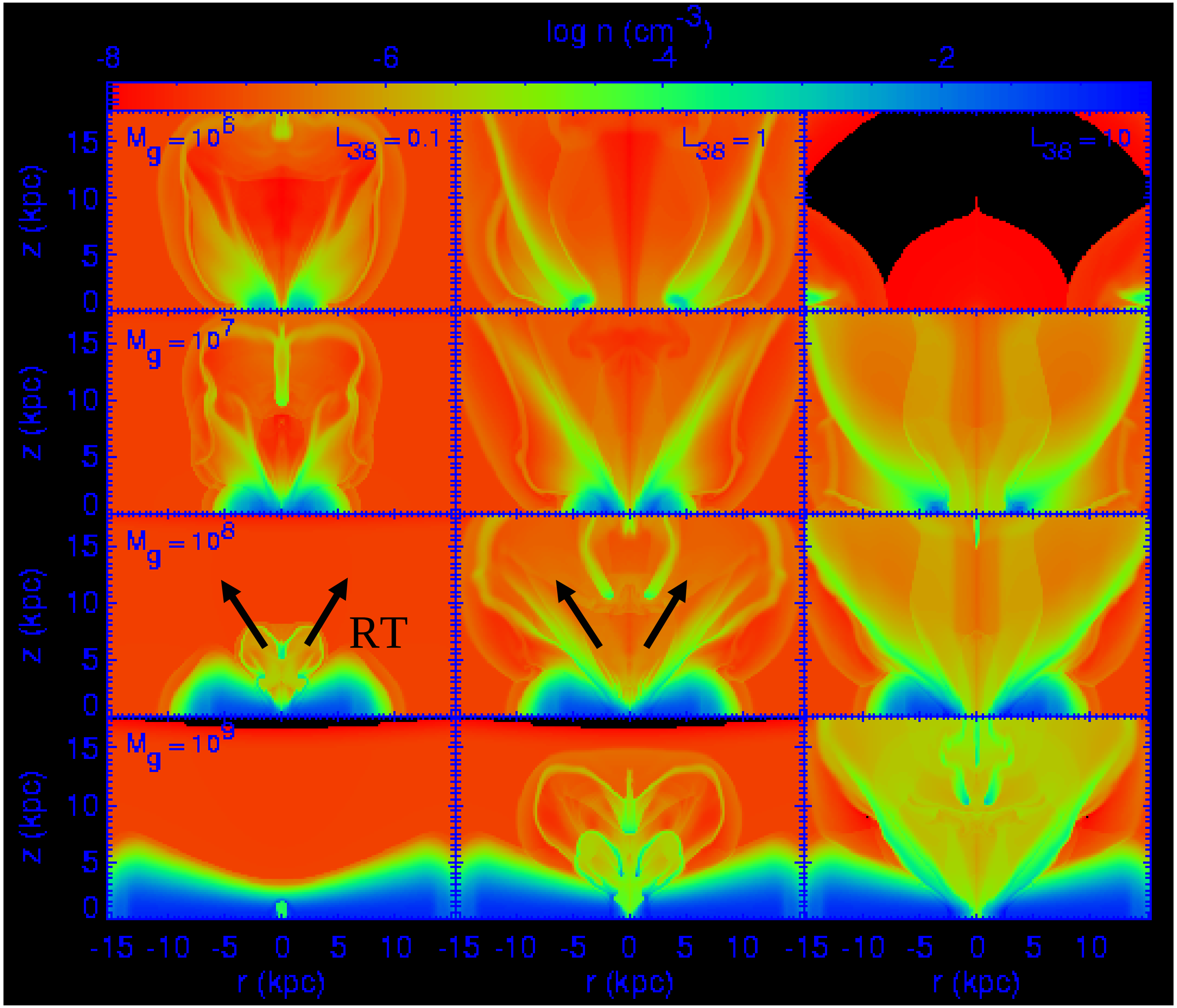
- The **HI gas distribution** is often much **more extended** than the distribution of stars.

- **HI** dominates the **baryonic mass** of the faintest objects.

- **Blue compact dwarfs:** extreme type of dIrr with star bursts concentrated in one very bright region**.** Some **BCD** may be genuinely **young objects** which form stars for the **first time** (e.g. I Zw 18)

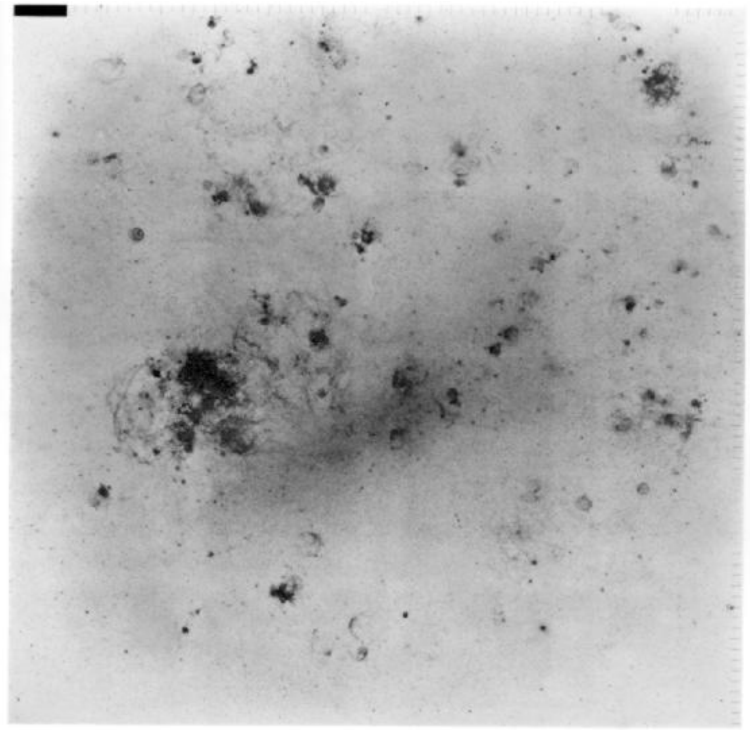
- **Star formation** in irregulars and BCDs leads to **bubbles** of HII gas that expands and can cause significant **gas loss**.

(Mac Low & Ferrara 99)



The Magellanic Clouds

The LMC in Hα



The LMC

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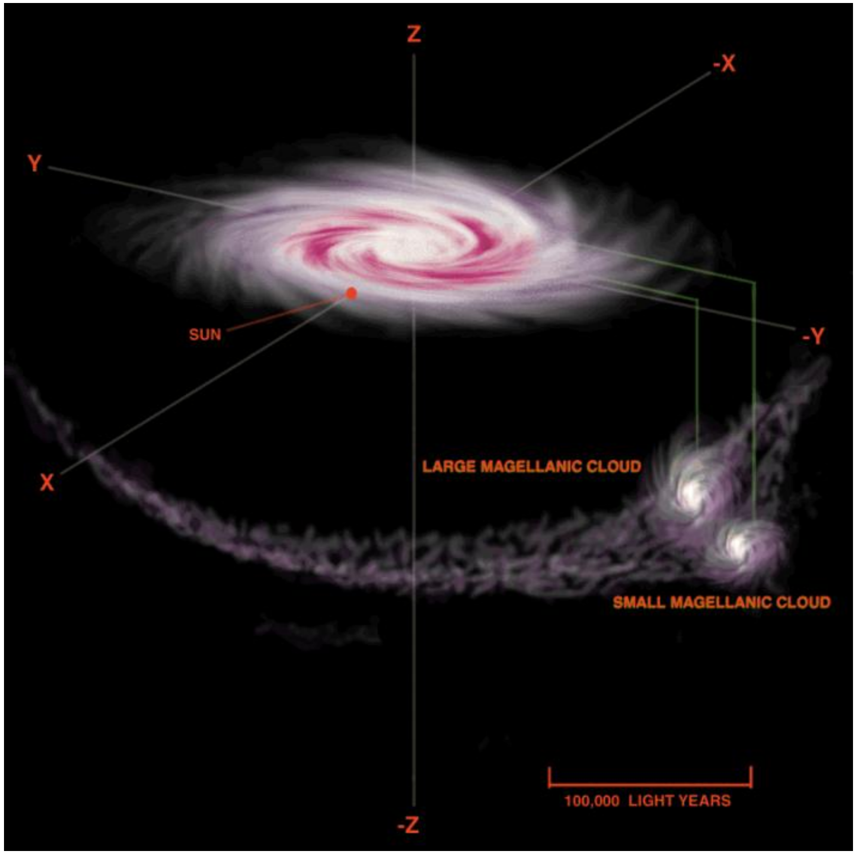
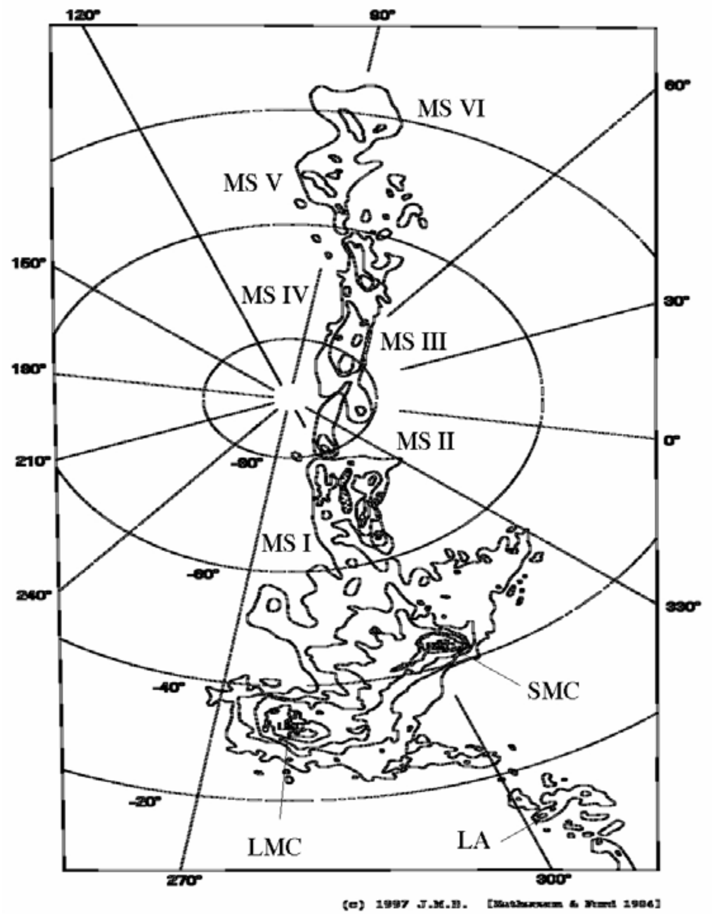
HI around the SMC and LMC





Mathewson, Ford 84, IAU Symp 108

11.3 Stellar populations and chemistry of dwarf galaxies

- **Dwarf ellipticals** are generally **old**, i.e. they started to form stars **> 10 Gyrs ago**. Some objects may also have had more **recent** episodes of star formation, until a **few Gyrs ago**.

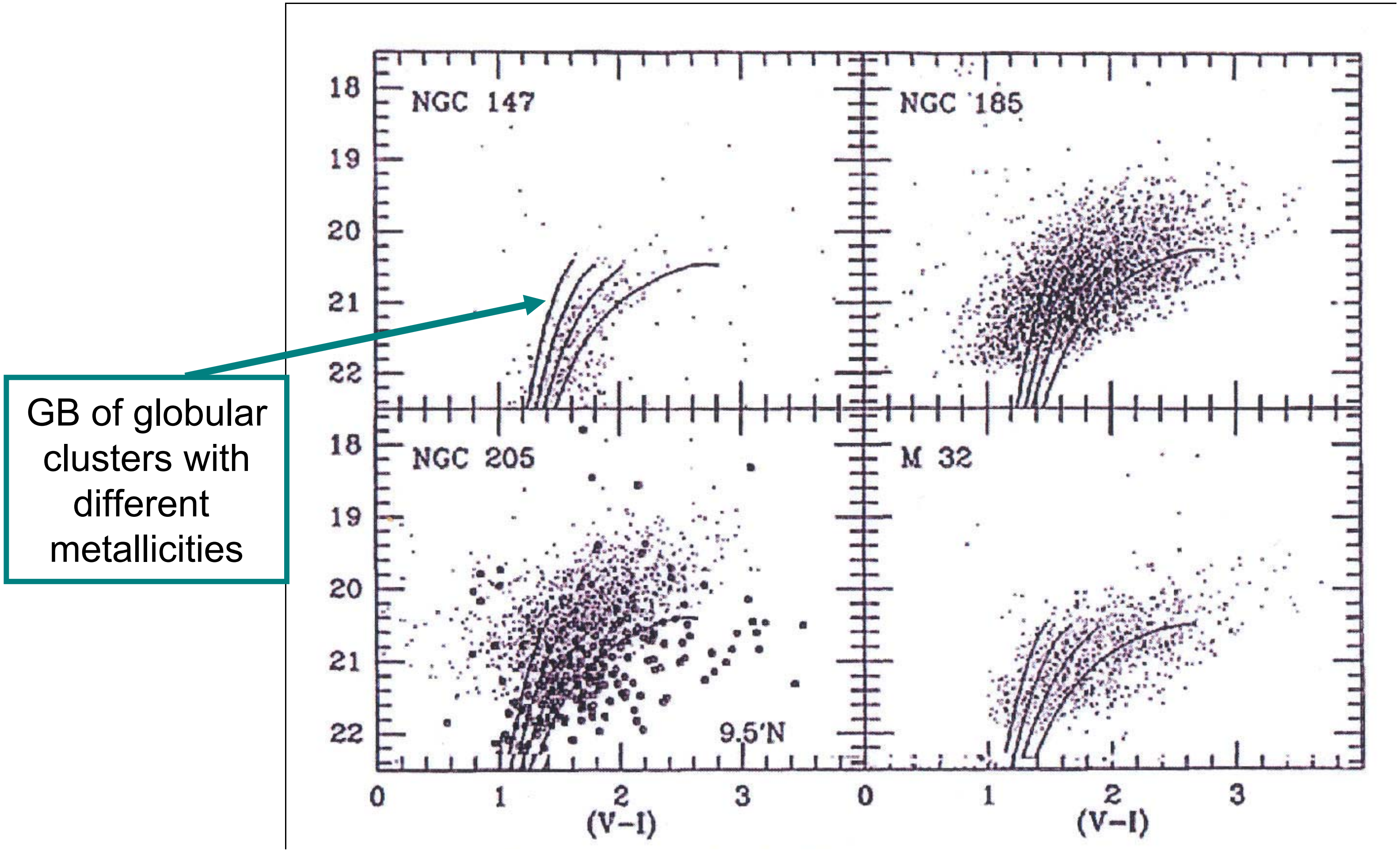
- These conclusions are mostly based on **dwarf companions** of the Milky Way which can be **resolved** in individual stars (see Hodge: 1989, ARAA 27, 139).

- Age determinations are more difficult for more **distant non-resolved dE**.

- **Irregulars** usually undergo **several bursts** of star formation, sometimes separated by long quiet periods. The oldest stars in the **LMC** are > 10 Gyrs ago. **3 Gyrs** ago a **burst** of star formation started again.

- **Fainter** objects have **fewer** bursts (BCDs)

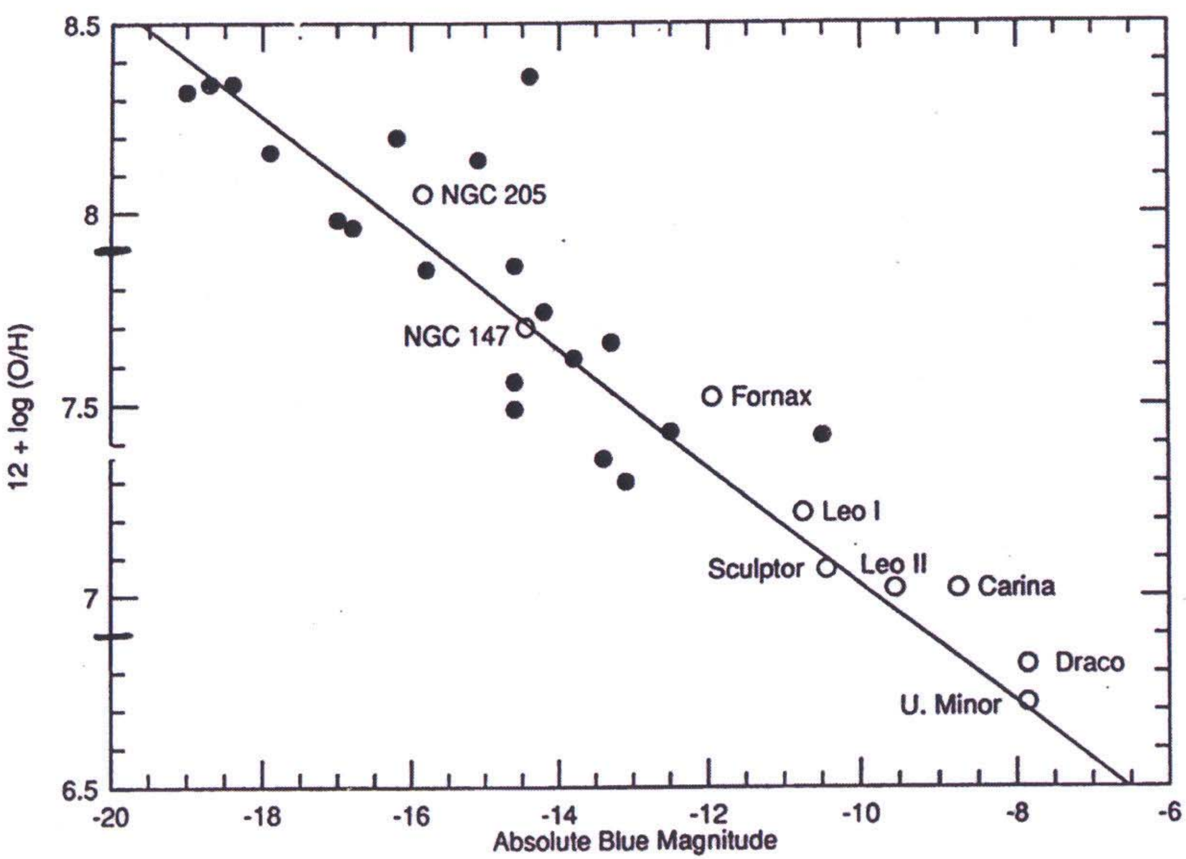
For dwarfs in the **Local Group** color luminosity diagrams can be derived and **metallicities** follow from the color of the giant branch.



GB of globular clusters with different metallicities

(Freedman 1992, IAU Symp. 149)

- The metallicity of **dwarf irregulars** can be derived from the **emission lines** of their interstellar medium.
- There exists a very strong **correlation** between **metallicity** and **luminosity**.
- Note that **dE** follow the same relation!



→ Both, dwarf ellipticals and dwarf irregulars follow a **single relation** between **metallicity** and **luminosity**:

$$Z \propto L_B^{0.4}$$

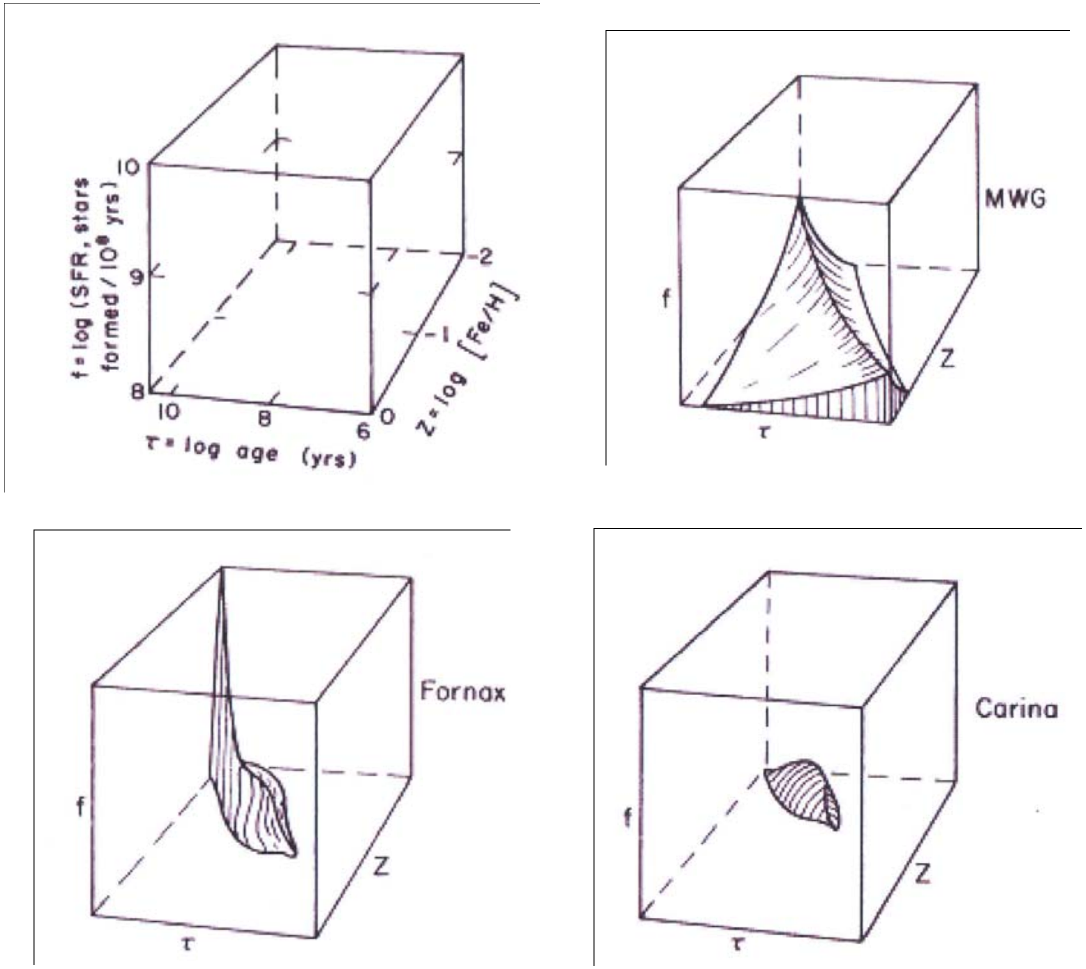
- ❖ Interestingly, the **gas-to-star ratio** does not seem to be very important.
- ❖ Apparently, the **metallicity** of the stars depends only on the **total number of stars** produced (luminosity) and **not** on the gas mass left at present time.

→

- ❖ The **enrichment history** must be different from the **closed box** model (Skillman & Bender 95, Rev. Mex.A.A. 3,25)

→ **galactic winds**

The Population Box:



(Hodge 1989, ARAA 27, 139)

11.4 Kinematics of Dwarf Galaxies

Dwarf elliptical galaxies:

- follow a similar relation between **luminosity** and **central velocity dispersion** as bright elliptical galaxies

$$L_B \propto \sigma_0^{2.5\ldots3}$$

- show **too little rotation** for their flattening and are therefore supported by **anisotropic velocity dispersion**. The **reason** for the anisotropy is **not** understood yet.
- of very **low** luminosities $10^6 - 10^7\ L_{B,\odot}$ can have **extremely high M/L**.

Dark matter in dwarf ellipticals:

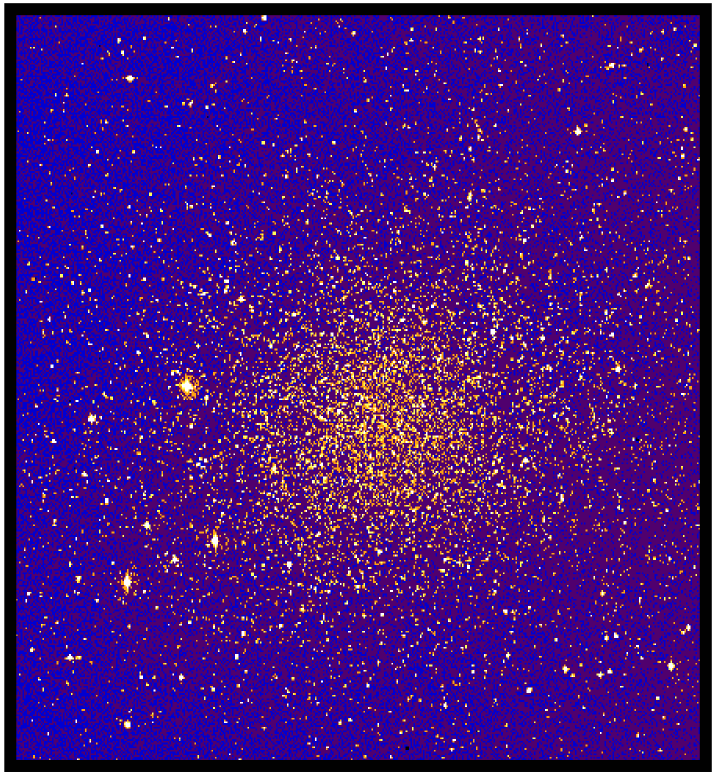
The gravitational **potential**:

grav. force $\vec{F}(\vec{x}) = -\vec{\nabla}\Phi(\vec{x})$

The potential of a **spherical** galaxy:

$$\Phi(r) = -\left[\frac{GM(<r)}{r} + 4\pi G\int_r^\infty \rho(r')r'dr'\right]$$

(Binney & Tremaine 1987; Galactic Dynamics)



Potential of a **uniform sphere** of density ρ

outer radius of sphere

$$\Phi(r) = -2\pi G\rho\left(a^2 - \frac{r^2}{3}\right)$$

The potential energy:

$$E_{pot} = 0.5\int \rho(r)\,\Phi(r)\,4\pi r^2 dr$$

- For a **homogeneous sphere**:

$$E_{pot} = -\frac{3}{5}\frac{GM^2}{a}$$

- We measure a **line-of-sight** velocity dispersion (z-direction): σ_0
- For $\sigma_x = \sigma_y = \sigma_z$ the total **kinetic energy** is estimated as:

$$E_{kin} = \frac{1}{2}M\left(\sigma_x^2 + \sigma_y^2 + \sigma_z^2\right) = \frac{3}{2}M\sigma_0^2$$

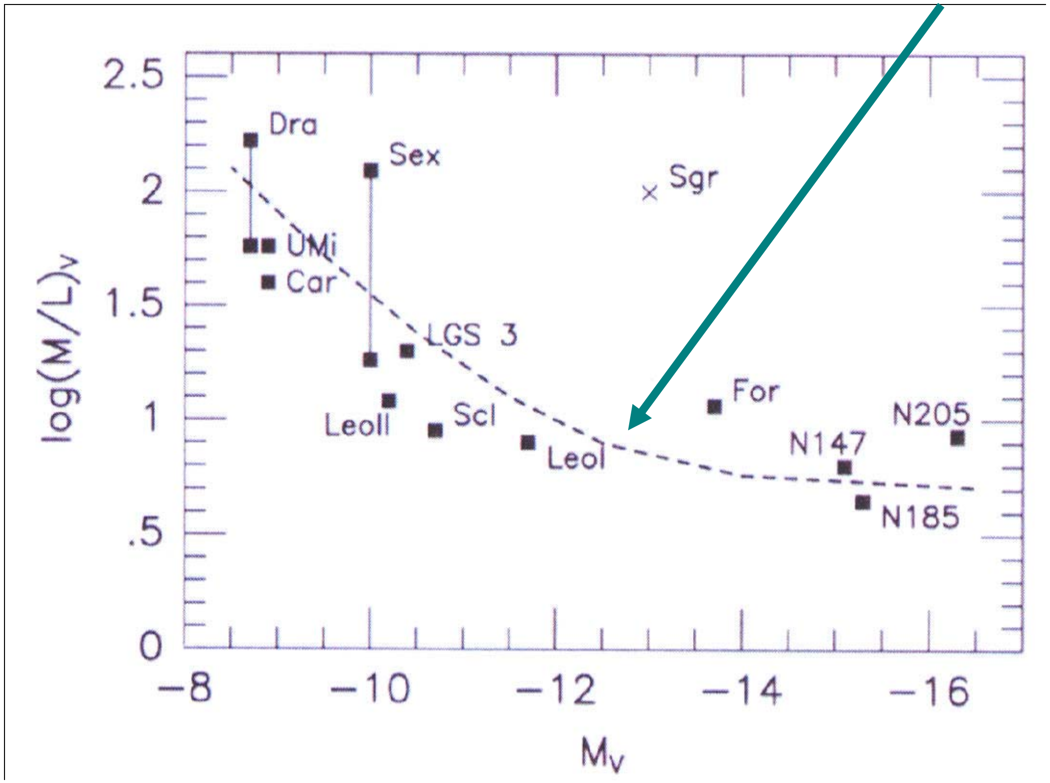
- **Virial theorem**:

effective radius

$$2\cdot E_{kin} = -E_{pot} \quad \Rightarrow \quad \boxed{M = \frac{5\sigma_0^2\, a}{G}}$$

The M/L for Local Group dwarf spheroidals:

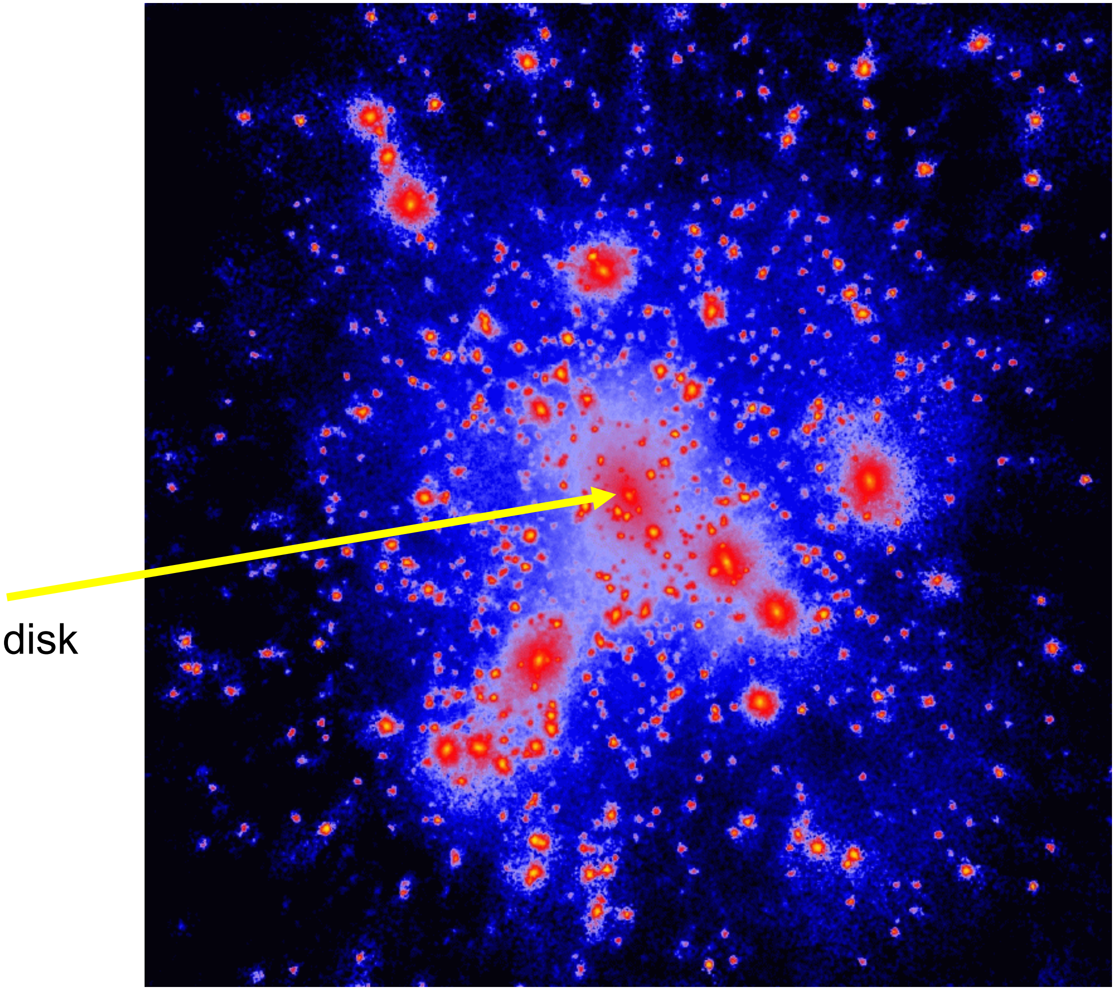
constant dark halo mass of $2.5\cdot10^{7}\,M_{\odot}$



(Mateo)

Below $M_V = -12$: $M/L \propto L^{-1}$

Structure of dark matter halos



(Moore, 2001)

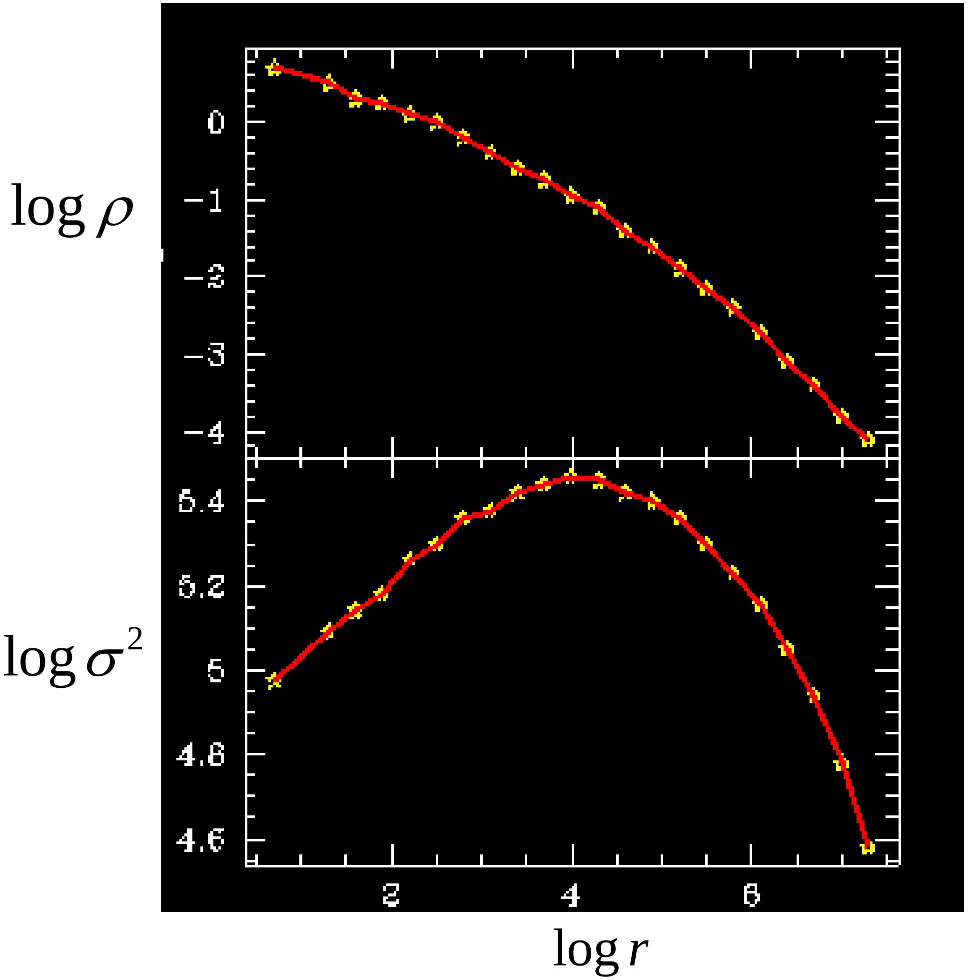
The density structure of dark matter halos:

CDM simulations (Navarro et al. 97, Moore et al. 98, Klypin et al. 2000) predict that dark halos have **universal density profiles:**

$$\boxed{\rho(r) \sim \frac{1}{r^{\gamma}(r_s + r)^{3-\gamma}}}$$

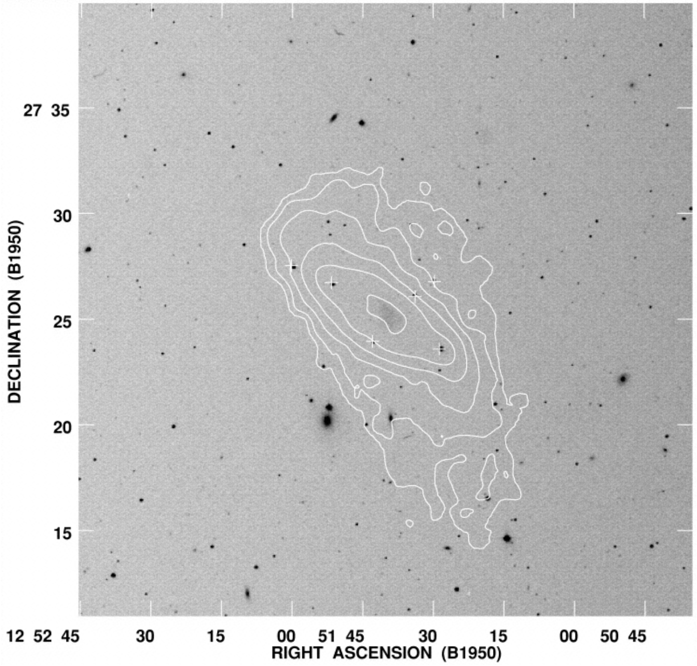
with $\gamma \approx 1-1.5$

Central density cusp results from a **temperature inversion**.



Dark matter in DDO 154

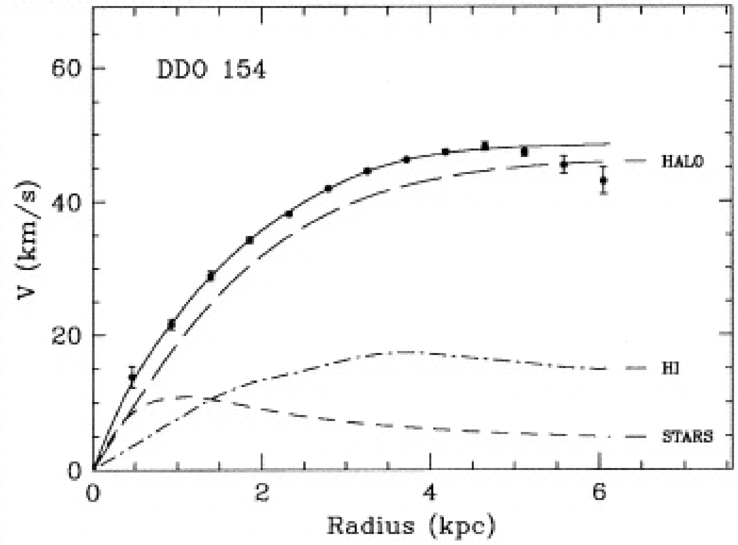
HI surface contour

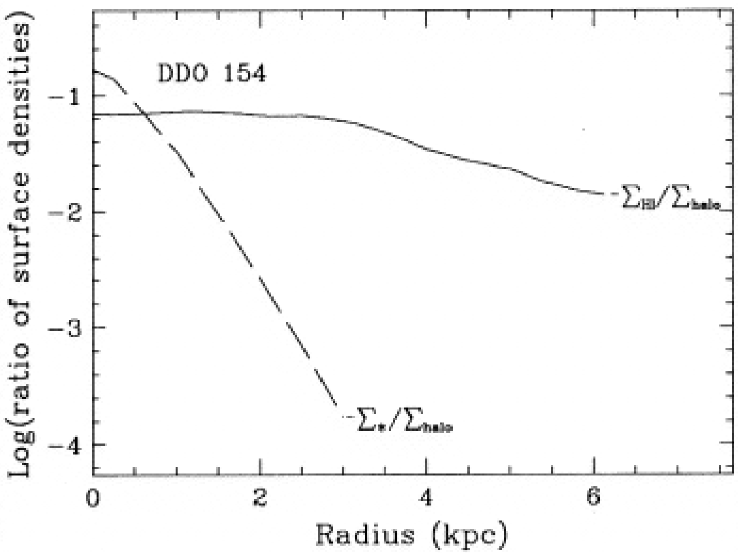


$$M_* \approx 5 \cdot 10^7 M_\odot$$

$$M_{HI} \approx 3 \cdot 10^8 M_\odot$$

$$M_{DM} \approx 4 \cdot 10^9 M_\odot$$



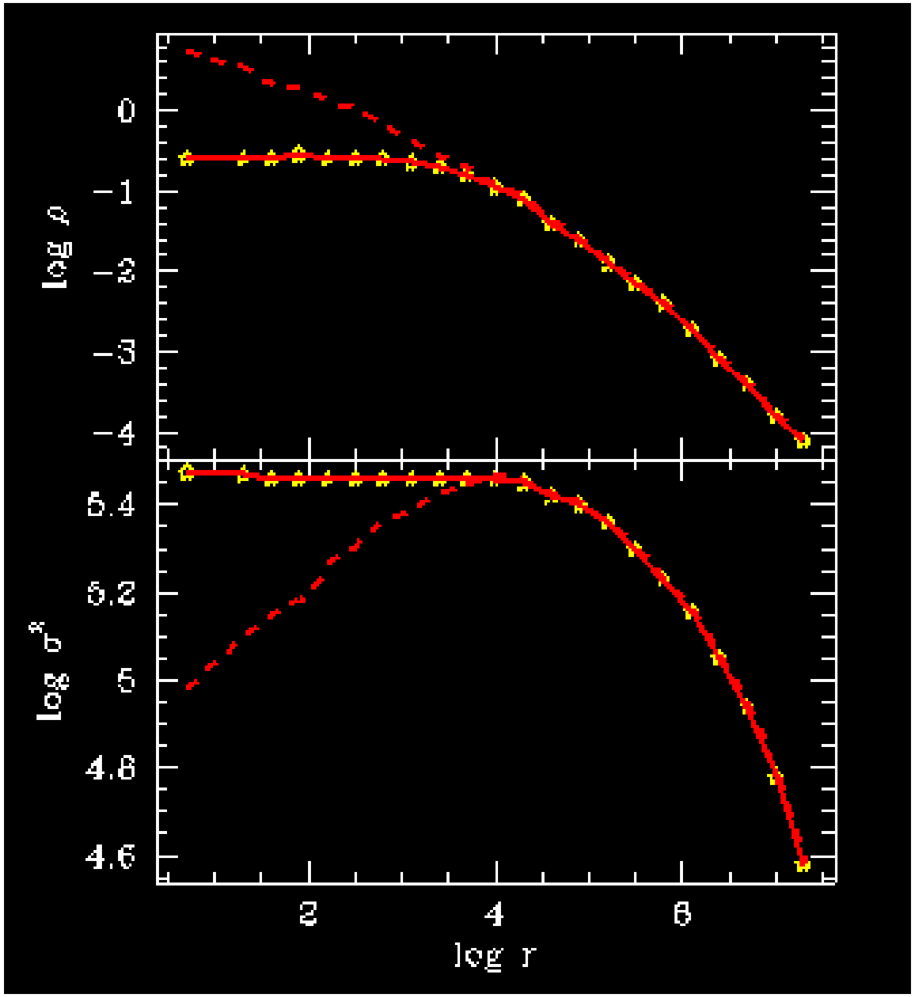


Predicted

$$\rho(r) \sim \frac{1}{r^{1.5}(r_s + r)^{1.5}}$$

Observed

$$\rho(r) \sim \frac{1}{(r_s + r)(r_s^2 + r^2)}$$



In contrast to models of **hierarchical clustering**, dark matter cores are **isothermal** with a **flat** density distribution.