GALAXIES

Lecture 1-2

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Textbooks

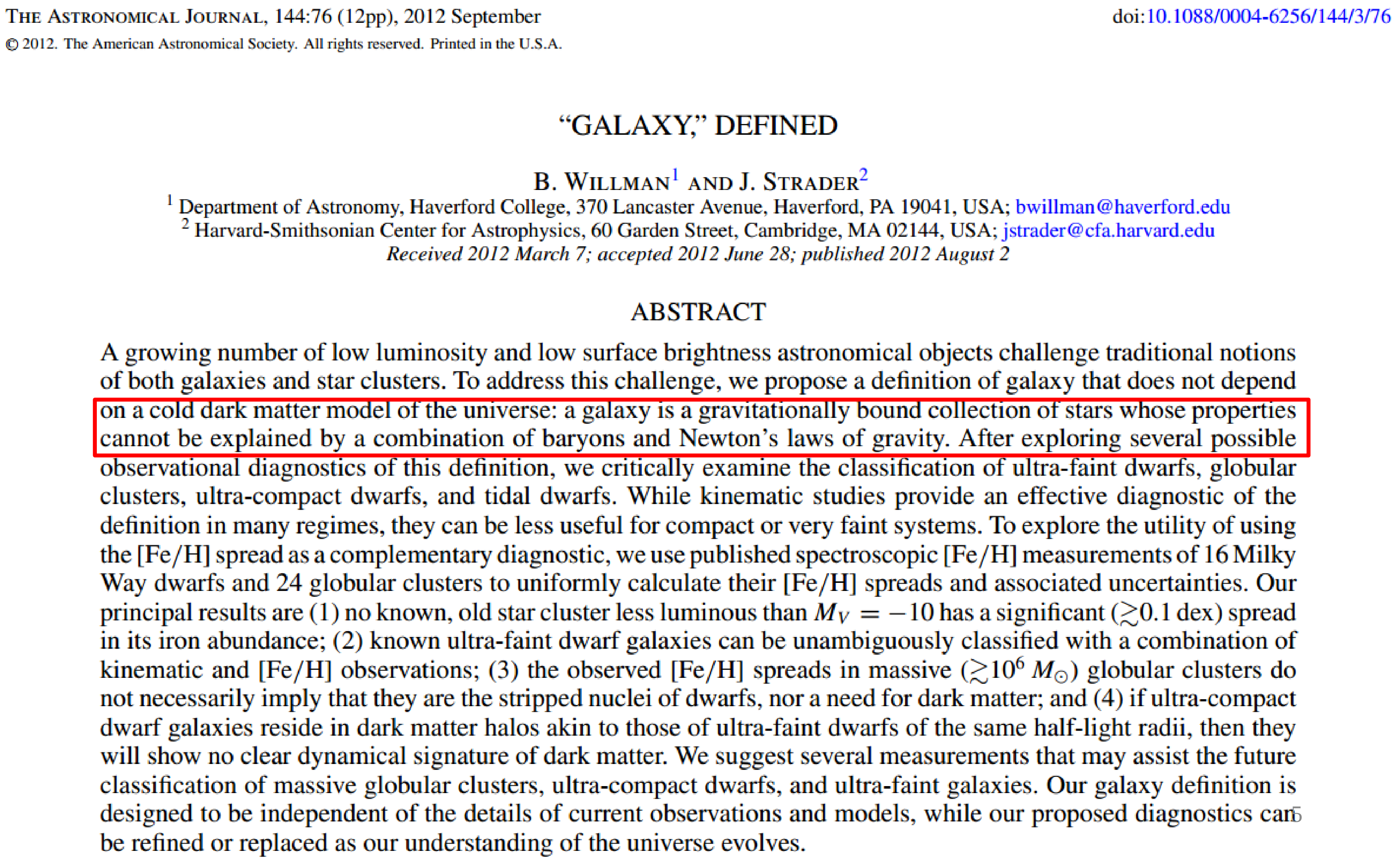
- J. Binney, S. Tremaine, „Galactic dynamics”, 2008
- L. Sparke, J. Gallagher, „Galaxies in the universe”, 2007
- P. Schneider, „Extragalactic astronomy and cosmology”, 2006
- H. Mo, F. van den Bosch, S. White, „Galaxy formation and evolution”, 2010
- M.S. Longair, „Galaxy formation”, 1998

Plan

1. Structure of galaxies: haloes and disks, circular velocities, NFW profile, exponential disk, Sersic profile
2. The Milky Way and galaxies of the Local Group
3. Orbits of stars in different potentials
4. Distribution functions, Jeans modeling, orbit-superposition models
5. Bars in galaxies: formation, evolution, orbital structure, dependence on environment
6. Spiral structure: geometry of spiral arms, formation scenarios
7. Interactions: tidal evolution and mergers, properties of merger remnants
8. Galaxy formation in cosmological context, cold and hot dark matter scenarios, top hat model, problems of theory on small scales

What is a galaxy?

What is a galaxy?



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"GALAXY," DEFINED

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ABSTRACT

A growing number of low luminosity and low surface brightness astronomical objects challenge traditional notions of both galaxies and star clusters. To address this challenge, we propose a definition of galaxy that does not depend on a cold dark matter model of the universe: a galaxy is a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity. After exploring several possible observational diagnostics of this definition, we critically examine the classification of ultra-faint dwarfs, globular clusters, ultra-compact dwarfs, and tidal dwarfs. While kinematic studies provide an effective diagnostic of the definition in many regimes, they can be less useful for compact or very faint systems. To explore the utility of using the [Fe/H] spread as a complementary diagnostic, we use published spectroscopic [Fe/H] measurements of 16 Milky Way dwarfs and 24 globular clusters to uniformly calculate their [Fe/H] spreads and associated uncertainties. Our principal results are (1) no known, old star cluster less luminous than $M_V = -10$ has a significant ($\gtrsim$0.1 dex) spread in its iron abundance; (2) known ultra-faint dwarf galaxies can be unambiguously classified with a combination of kinematic and [Fe/H] observations; (3) the observed [Fe/H] spreads in massive ($\gtrsim 10^6\ M_\odot$) globular clusters do not necessarily imply that they are the stripped nuclei of dwarfs, nor a need for dark matter; and (4) if ultra-compact dwarf galaxies reside in dark matter halos akin to those of ultra-faint dwarfs of the same half-light radii, then they will show no clear dynamical signature of dark matter. We suggest several measurements that may assist the future classification of massive globular clusters, ultra-compact dwarfs, and ultra-faint galaxies. Our galaxy definition is designed to be independent of the details of current observations and models, while our proposed diagnostics can be refined or replaced as our understanding of the universe evolves.

Galactic dynamics

- What is a galaxy?

A system of 10^5-10^{12} stars with possibly other components, gravitationally bound, isolated or in cluster, basic unit in cosmological context

- What is dynamics?

Theory of how systems and their components evolve under gravity, differs from kinematics in that we are more interested in underlying forces than just motions

Approaches

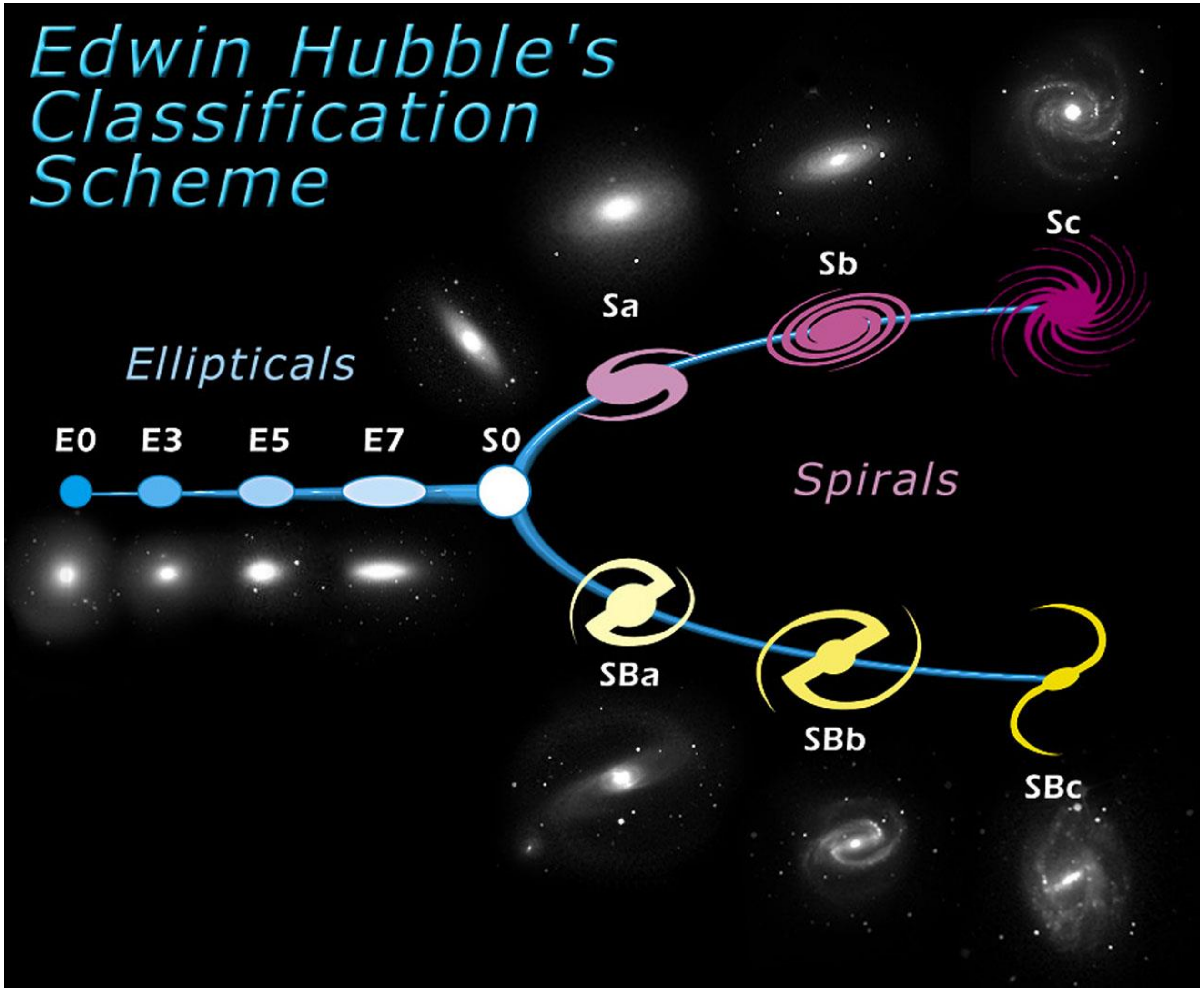
In studying galactic dynamics we borrow from:

- Newtonian gravity theory (no need for relativistic corrections unless in centers of galaxies or close binaries)
- Celestial mechanics – because underlying mechanisms are the same
- Statistical mechanics – because we are dealing with large numbers of stars
- Plasma physics – to model the gas content

Approximations

- The galaxies can be treated as collisionless systems
- Stars can be described as moving in a smooth gravitational potential generated by all the components
- Stationary models can be constructed (with density constant at each point)
- We can assume that galaxies are isolated

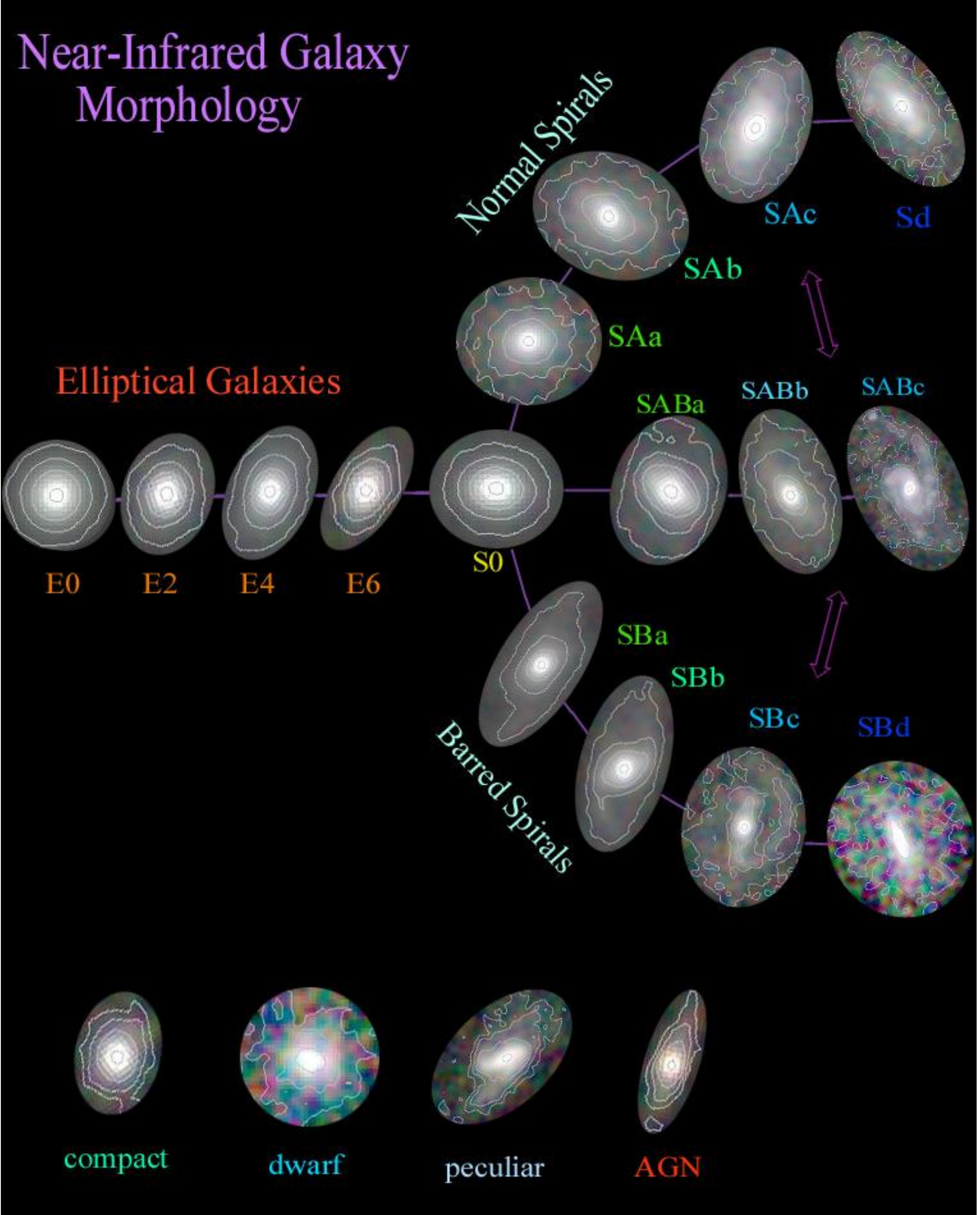
Morphological classification



„c,d” classification represents the most open arms

„a” classification the most tightly wound

Elliptical of type En has ellipticity $\varepsilon = 1 - b/a = n/10$



More recent version

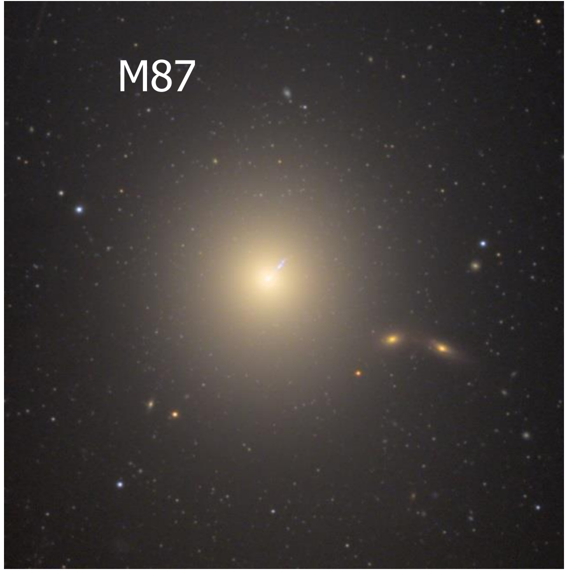
De Vaucouleurs version of the tuning-fork diagram

SA - normal spiral

SAB – normal-barred spiral (weak bar)

SB – barred spiral

Examples



Galaxy of type E0 central in the Virgo cluster,

distance 15.9 Mpc, discovered in 1781

Galaxy of type SBb in the Fornax cluster,

distance 18 Mpc, discovered in 1826

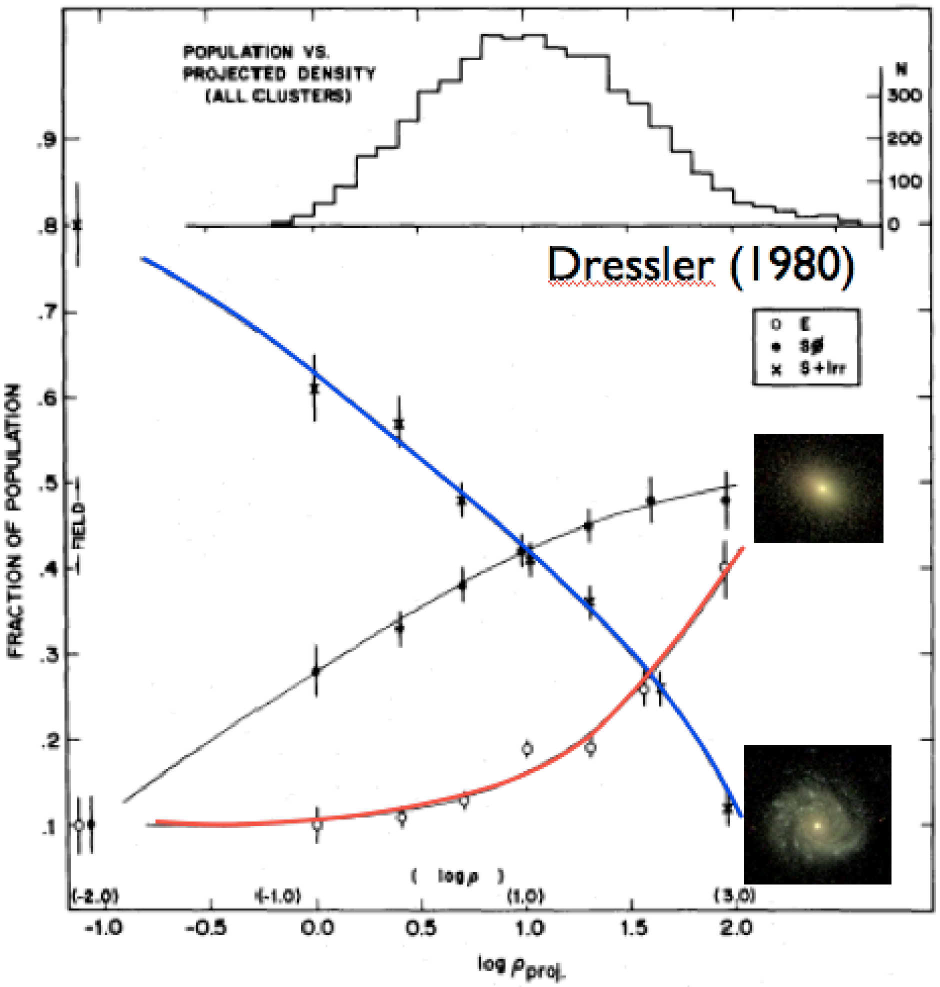
Galaxy of type SABcd

distance 6.4 Mpc,

discovered in 1781

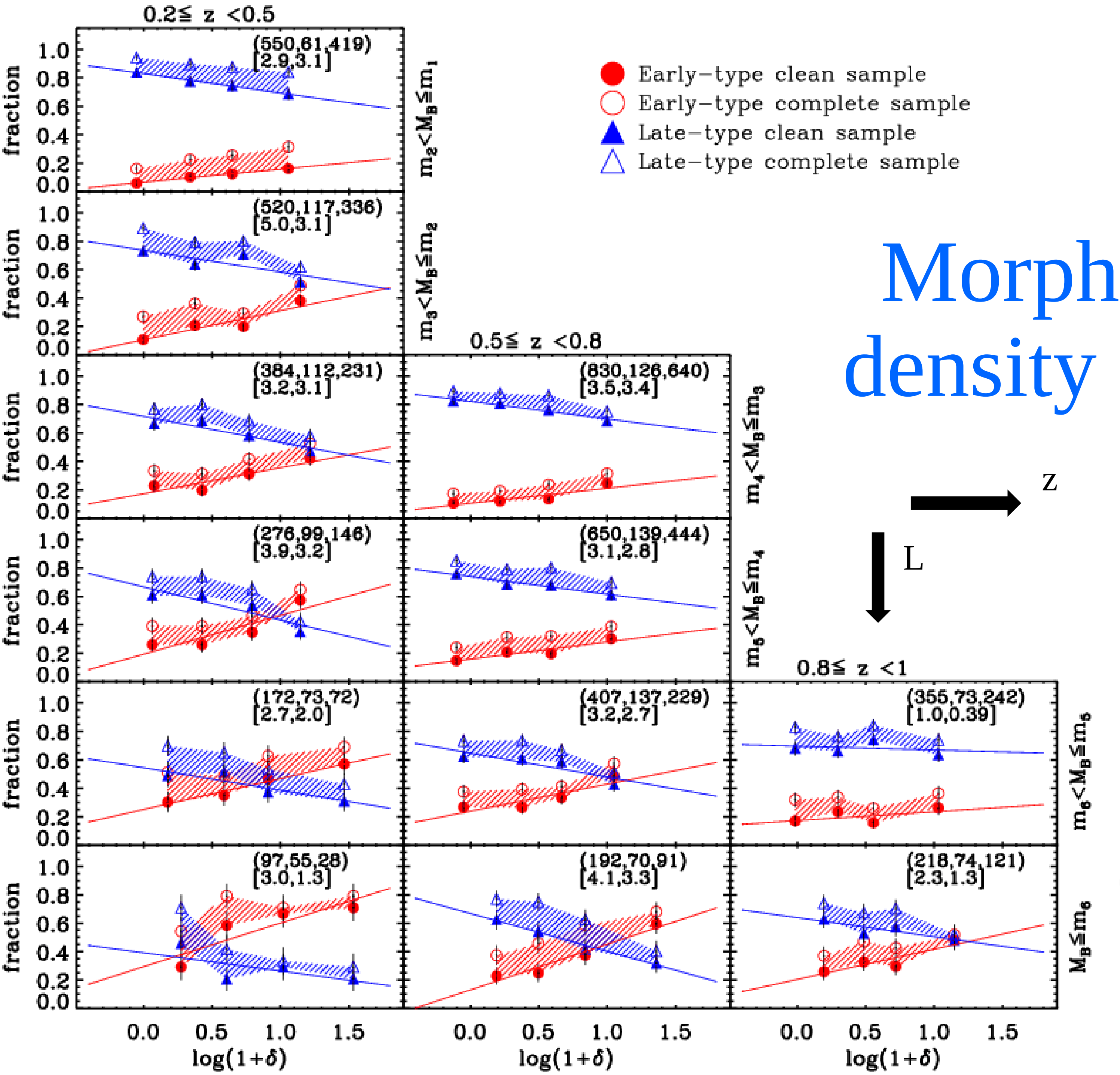
Elliptical galaxies

- Smooth, featureless stellar systems
- No cool gas or dust
- Some hot gas
- Old stellar populations
- No new stars formed
- Hot systems, supported by random motions of stars
- Dominate in groups and clusters



Dressler (1980)

Morphology-density relation



Tasca et al. 2009

zCosmos survey

Luminosity function

- Luminosities of elliptical galaxies vary in the large range between 10^4 $L_\odot$ and 10^{12} $L_\odot$
- Luminosity function describes relative numbers of galaxies of different luminosities
- Φ(L)dL is the number of galaxies in the luminosity range (L,L+dL)
- Schechter luminosity function:

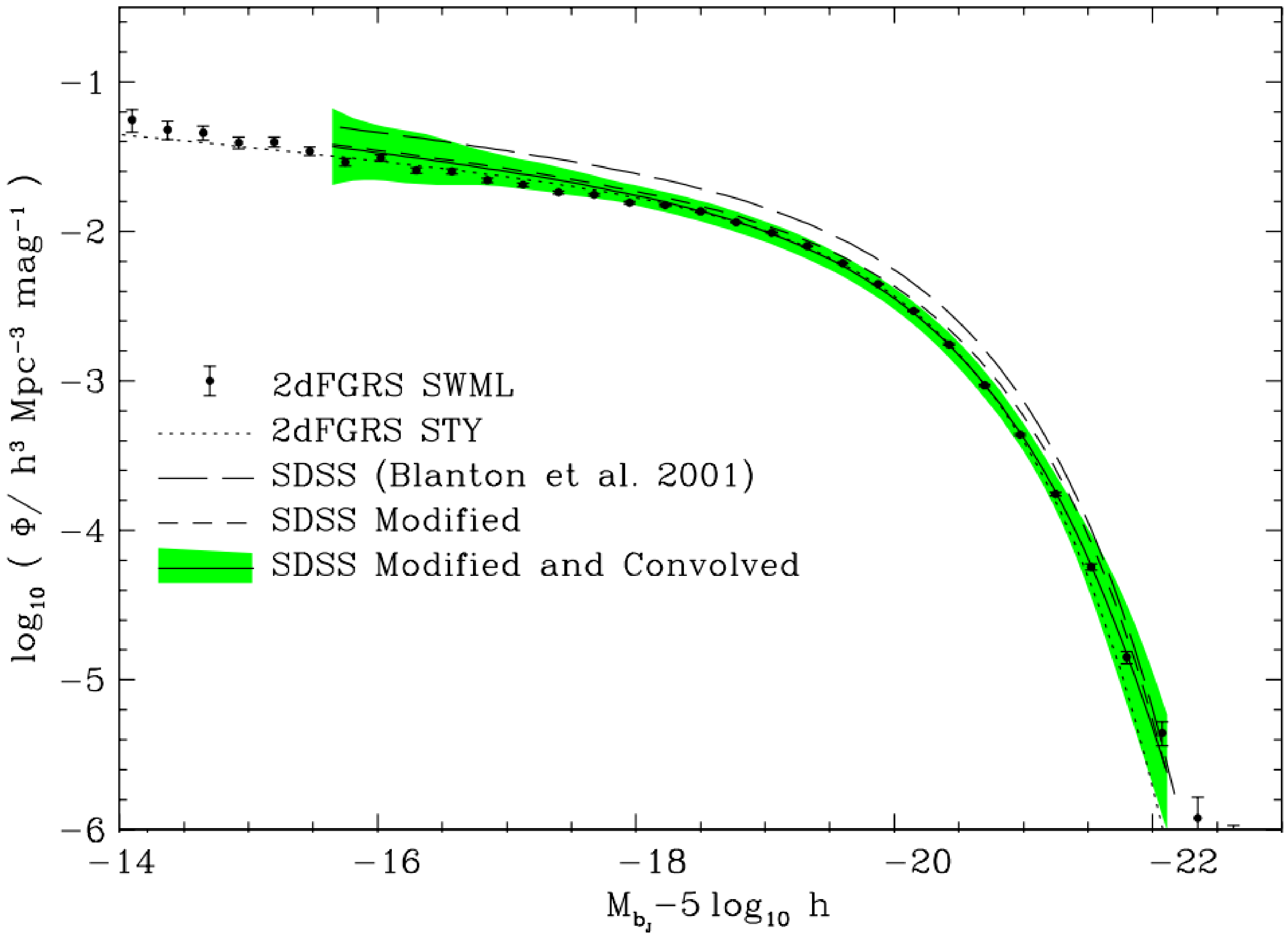
$$\phi(L)dL = \phi_*\left(L/L_*\right)^\alpha \exp(-L/L_*)dL/L_*$$

$$\phi_* \sim 5\times10^{-3}\,Mpc^{-3}$$

$$\alpha = -1.1$$

$$L_* \sim 3\times10^{10}\,L_{sun}$$

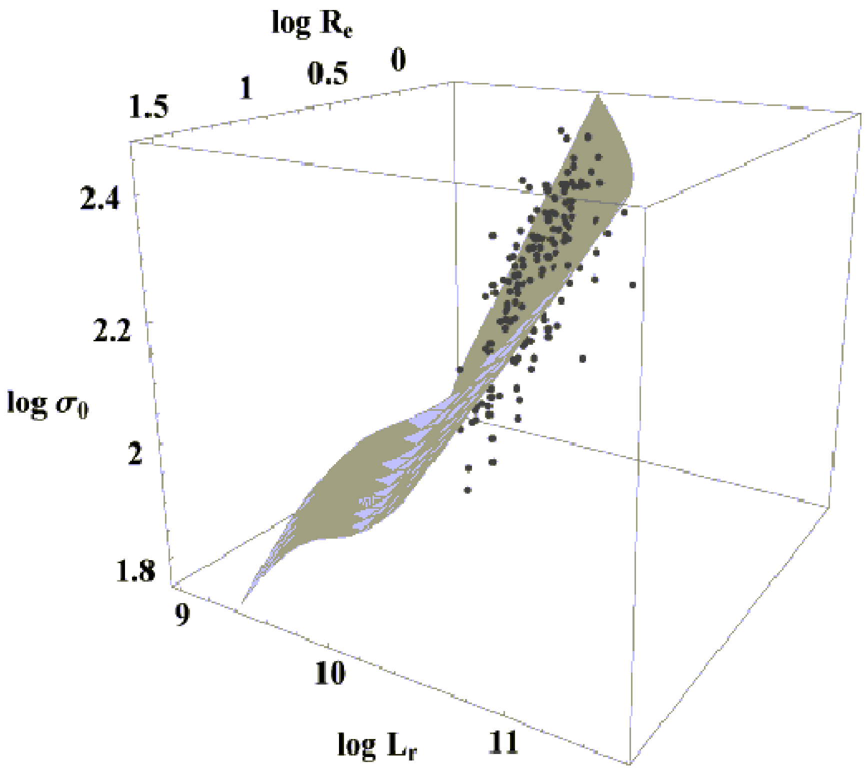
Examples of LF



Norberg et al. 2002

Fundamental plane

- The luminosity, size and velocity dispersion of elliptical galaxies are correlated
- When plotted in 3D space they form a 2D surface, the fundamental plane



$$\log R_e = 1.24\log\sigma - 0.82\log\langle I_e\rangle + const$$

Projections of the FP

- Faber-Jackson law

(more luminous galaxies have larger velocity dispersions)

$$L \sim \sigma^4$$

- Kormendy law

(larger galaxies have lower surface brightness)

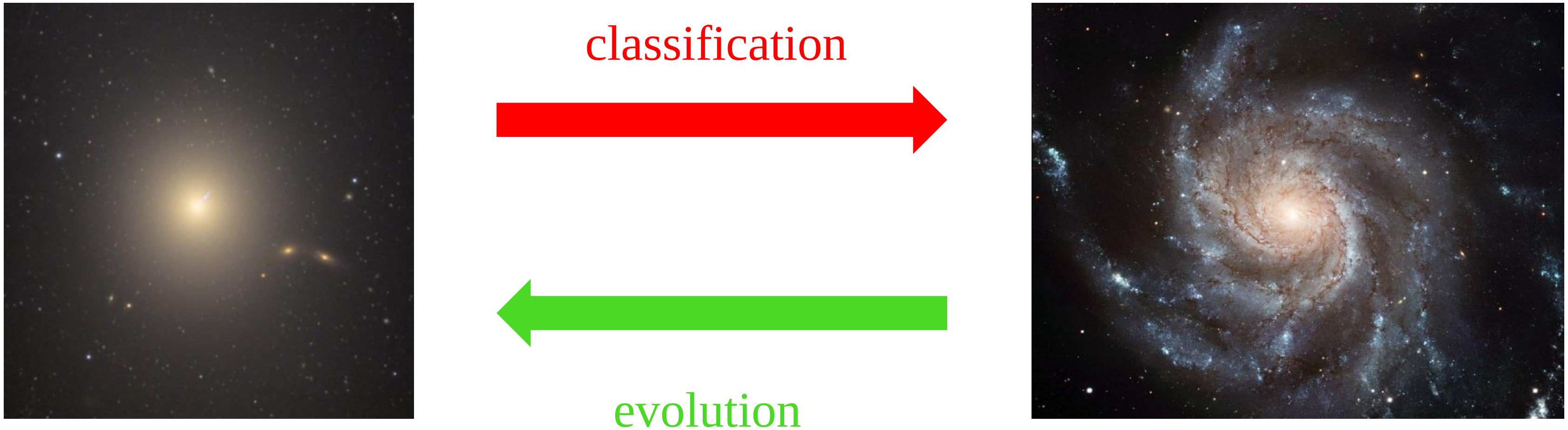
$$R_e \sim \langle I \rangle_e^{-0.83}$$

- Third law

(more luminous galaxies have lower surface brightness)

$$\langle I \rangle_e \sim L^{-3/2}$$

Early vs late type



classification →

← evolution

early type

late type

Historically, ellipticals were termed early-type galaxies, while spirals were termed late-type galaxies, although this is opposite to the evolutionary sequence which has since been established

Spiral galaxies

- Contain a prominent disk composed of stars, gas and dust
- The disk contains spiral arms, a kind of filaments forming stars
- Spiral arms vary is shape, length etc.
- The interstellar gas usually extends to much larger radii than the stars, probably because gas density is too low to form stars
- In low density regions spirals dominate (60%), but are rare in dense regions like cores of galaxy clusters

More to it

Transition a → d means:

- More open spiral arms
- Decrease in the size and luminosity of the bulge
- Increase in gas content
- Spiral arms become more clumpy

Spiral arms

Elmegreen (1990) classified galaxies
according to the type of spiral arms
into 3 types:

- flocculent spiral galaxies (with many short arms, such as NGC2841),
- multi-armed spirals (e.g. M33)
- grand design galaxies (with two main spiral arms, e.g. M51).

All of these types may or may not exhibit bars. Around 60%, of galaxies show some grand design structure, either in the inner or the entire part of the disc

Lenticular galaxies

- Transition objects between elliptical and spiral galaxies
- They have a rapidly rotating disk but no spiral structure
- They have little or no gas and do not show any recent star formation
- They are rare in the field but comprise about half of galaxies in clusters
- Lenticulars may be spirals accreted by clusters and depleted of gas by interactions with the hot gas in the cluster

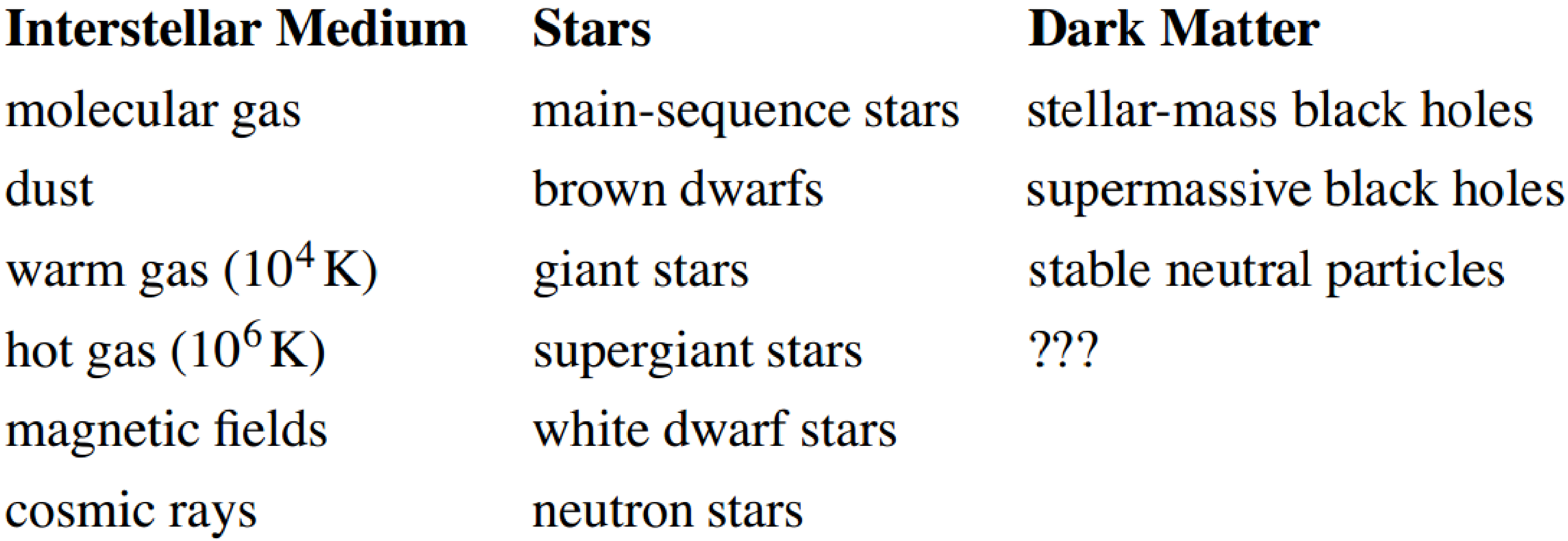
Irregular galaxies

- Beyond Sd we have less luminous galaxies with less defined spiral structure
- Usually these are dwarf galaxies with chaotic distribution of stars
- Good examples are Large and Small Magellanic Clouds
- They are extremely gas-rich, the interstellar gas fraction may exceed 30% of stellar mass
- Interacting galaxies also are classified as irregular because of their distortions

Lessons from morphology

- The Hubble classifications are usually associated with the long-term evolution of galaxies, whereas the classification by Elmegreen is instead associated with their current properties and environment
- Trends in star formation rate, bulge-to-disc ratio, and age of disc stars now indicate an evolutionary sequence from Sd to Sa
- Sa type galaxies are thought to have already used up much of their gas and exhibit lower star formation rates compared to Sc and Sd types

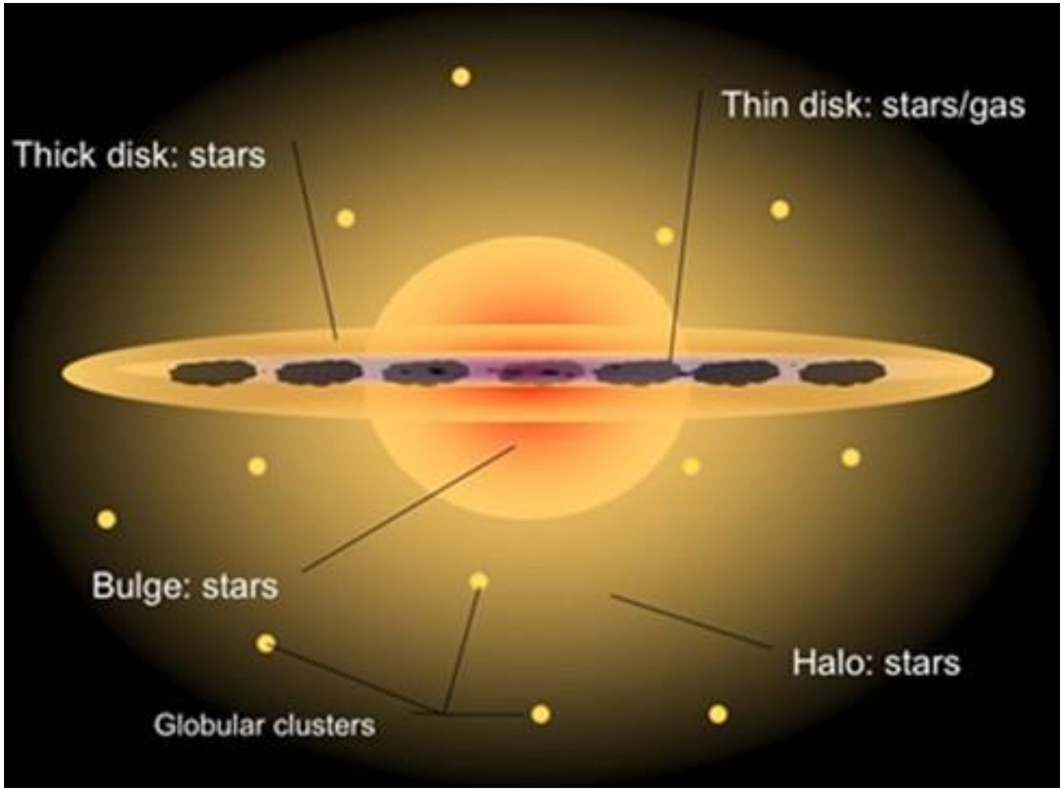
Content of galaxies



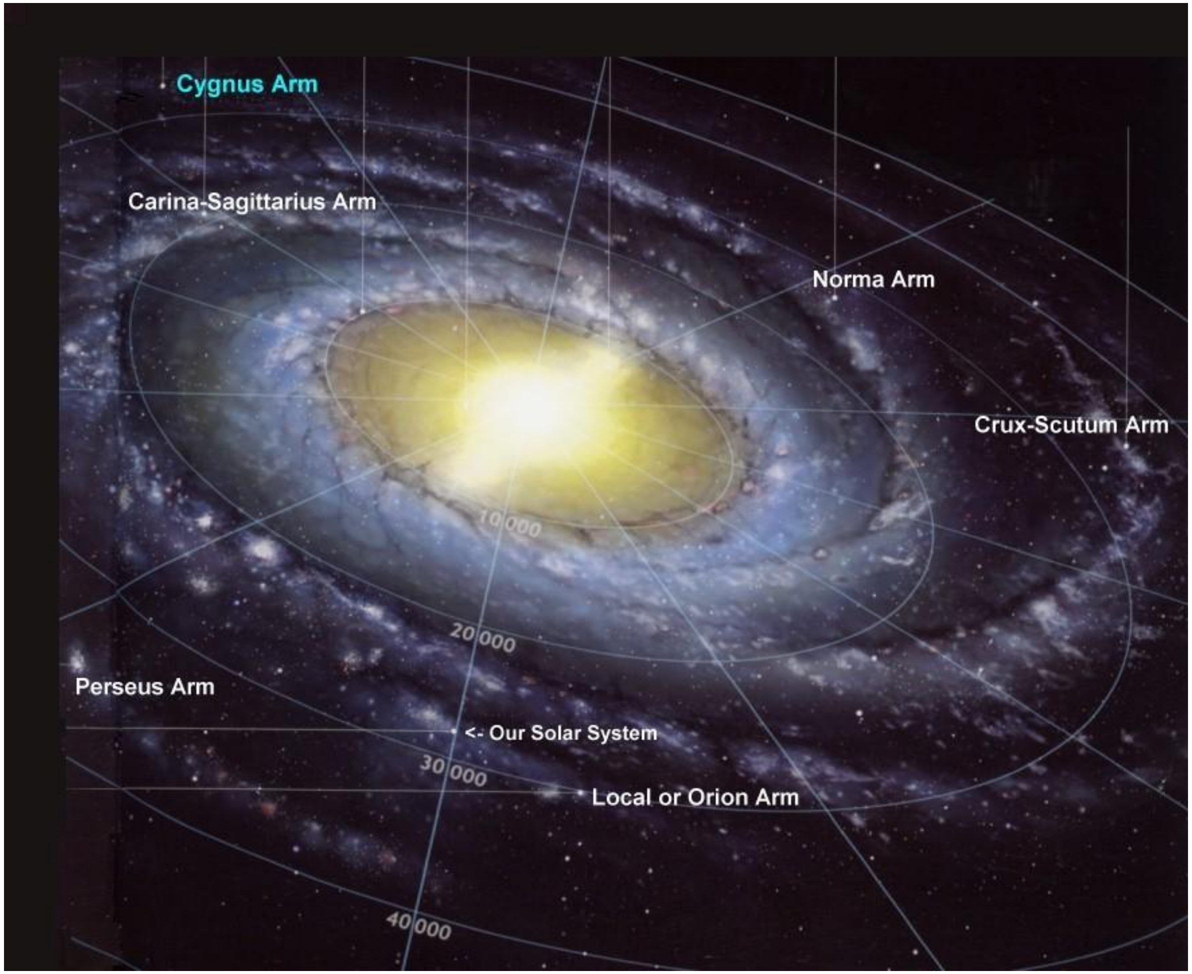
Interstellar Medium	**Stars**	**Dark Matter**
molecular gas	main-sequence stars	stellar-mass black holes
dust	brown dwarfs	supermassive black holes
warm gas (10^4 K)	giant stars	stable neutral particles
hot gas (10^6 K)	supergiant stars	???
magnetic fields	white dwarf stars	
cosmic rays	neutron stars	

Components of galaxies

- Disk: thin, thick
- Bulge
- Bar
- Spiral arms
- Stellar halo
- Black hole
- Dark matter halo



The structure of the MW



Milky Way is a typical spiral galaxy used for reference, it has all the classic components of a spiral galaxy

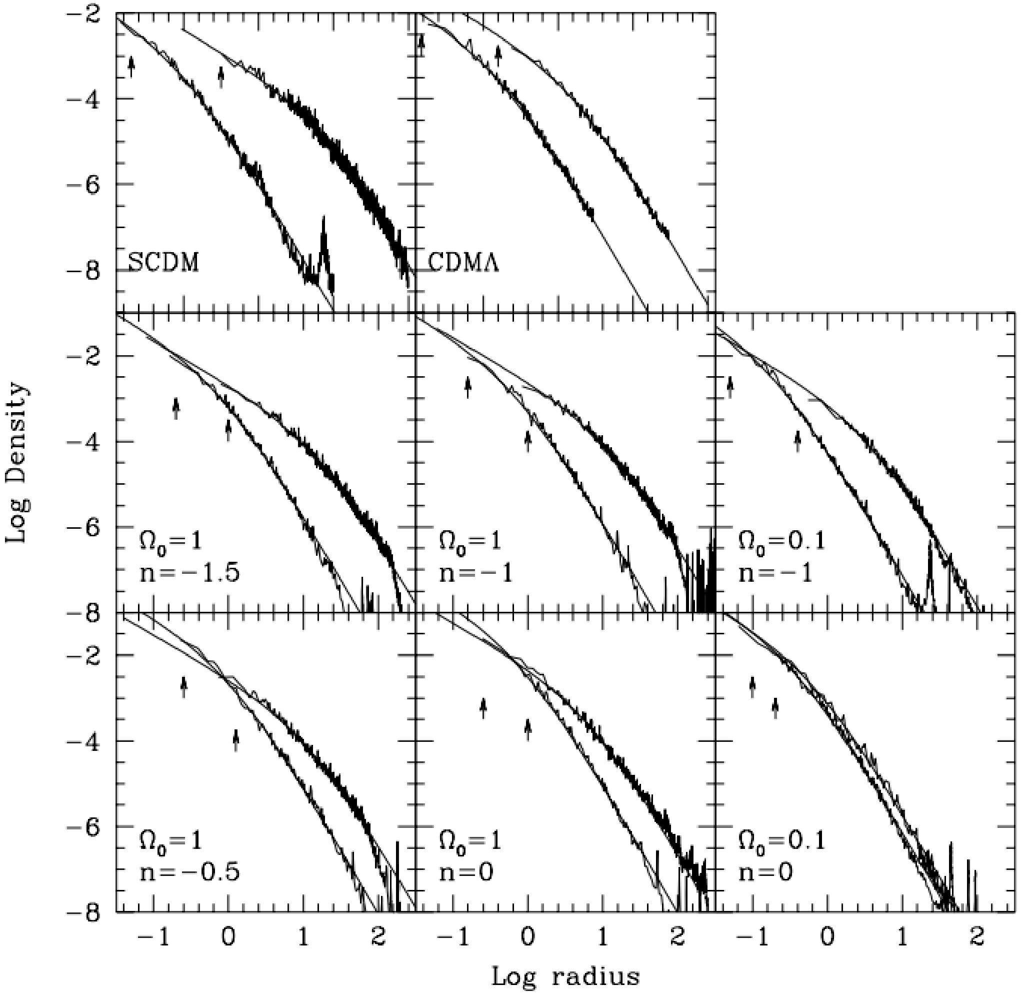
Main components

- When constructing models of galaxies we usually take into account only the most massive components
- The dominant component is the dark matter halo
- The second most important component are the stars

Dark matter haloes

Dark matter haloes forming in cosmological N-body simulations have densities decreasing with radius and a lot of substructure

Fitted profiles

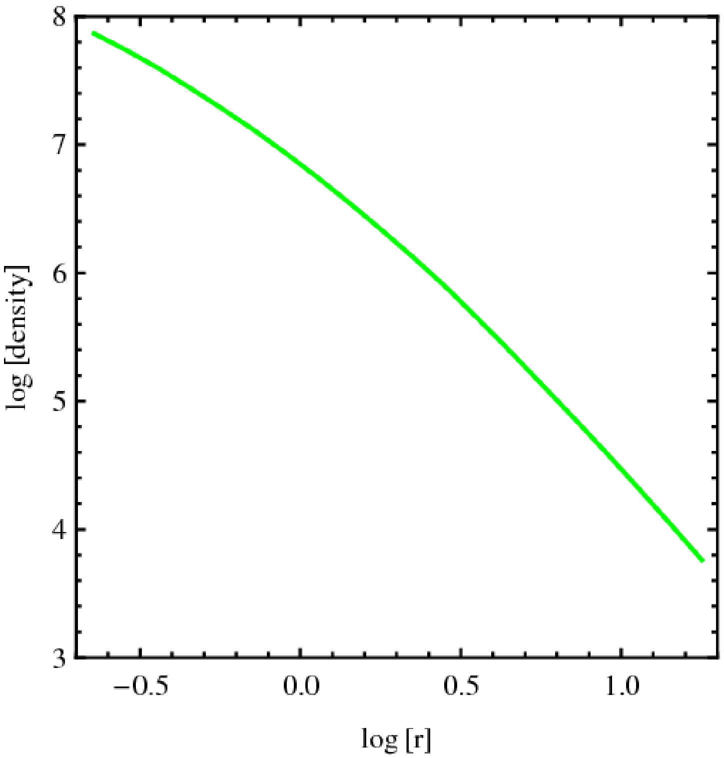


Density profiles for the most and least massive halo in a given simulation

The profiles have similar shapes in different cosmologies and for the whole range of masses

Navarro, Frenk & White 1997

NFW profile

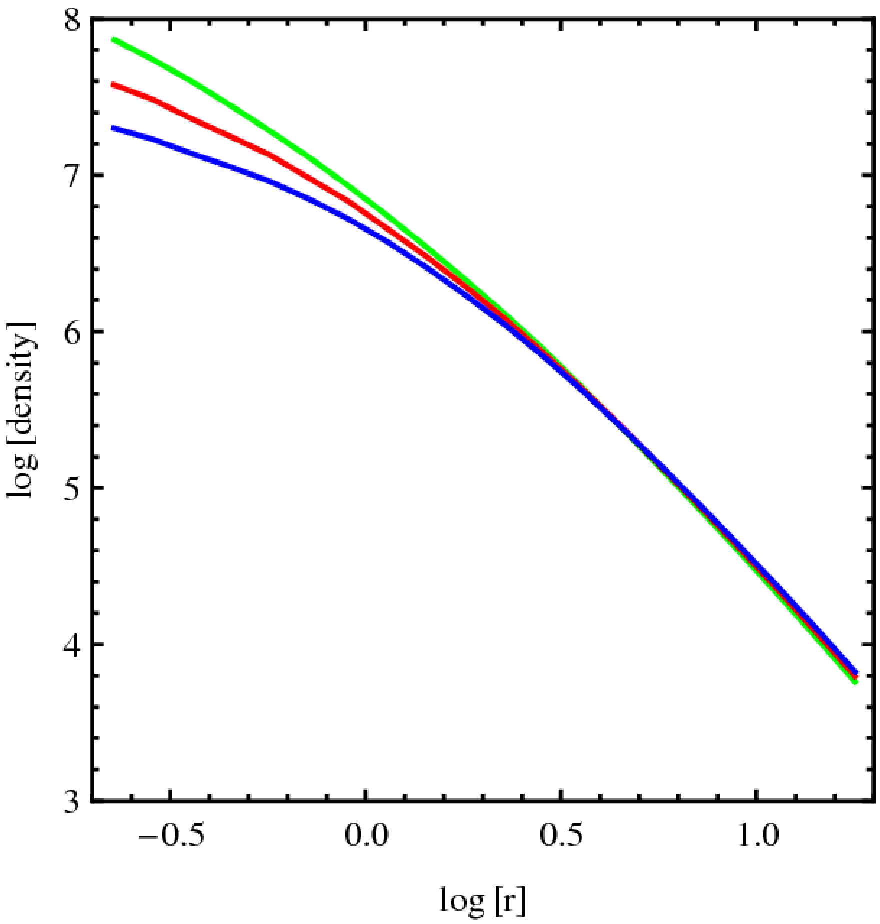


Density distribution in haloes of different mass, from a dwarf galaxy to a galaxy cluster, can be described by a single two-parameter formula
(NFW dark matter profile)

$$\rho = \frac{\rho_{char}}{(r/r_s)(1+r/r_s)^2}$$

Navarro, Frenk & White 1997

Shallower dark matter profiles



α=1, 0.6, 0.2

- The formula can be generalized to include inner slopes of different values, usually between α=1 (cusp) and α=0 (core)
- Shallower slopes have important consequences for the dynamics

$$\rho = \frac{\rho_{char}}{(r/r_s)^{\alpha}(1+r/r_s)^{3-\alpha}}$$

More general profiles

$$\rho = \frac{\rho_{char}}{(r/r_s)^{\alpha}(1+r/r_s)^{\gamma-\alpha}}$$

inner slope α

outer slope γ

α=1, γ=3 NFW profile

α=1, γ=4 Hernquist profile

α=2, γ=4 Jaffe profile

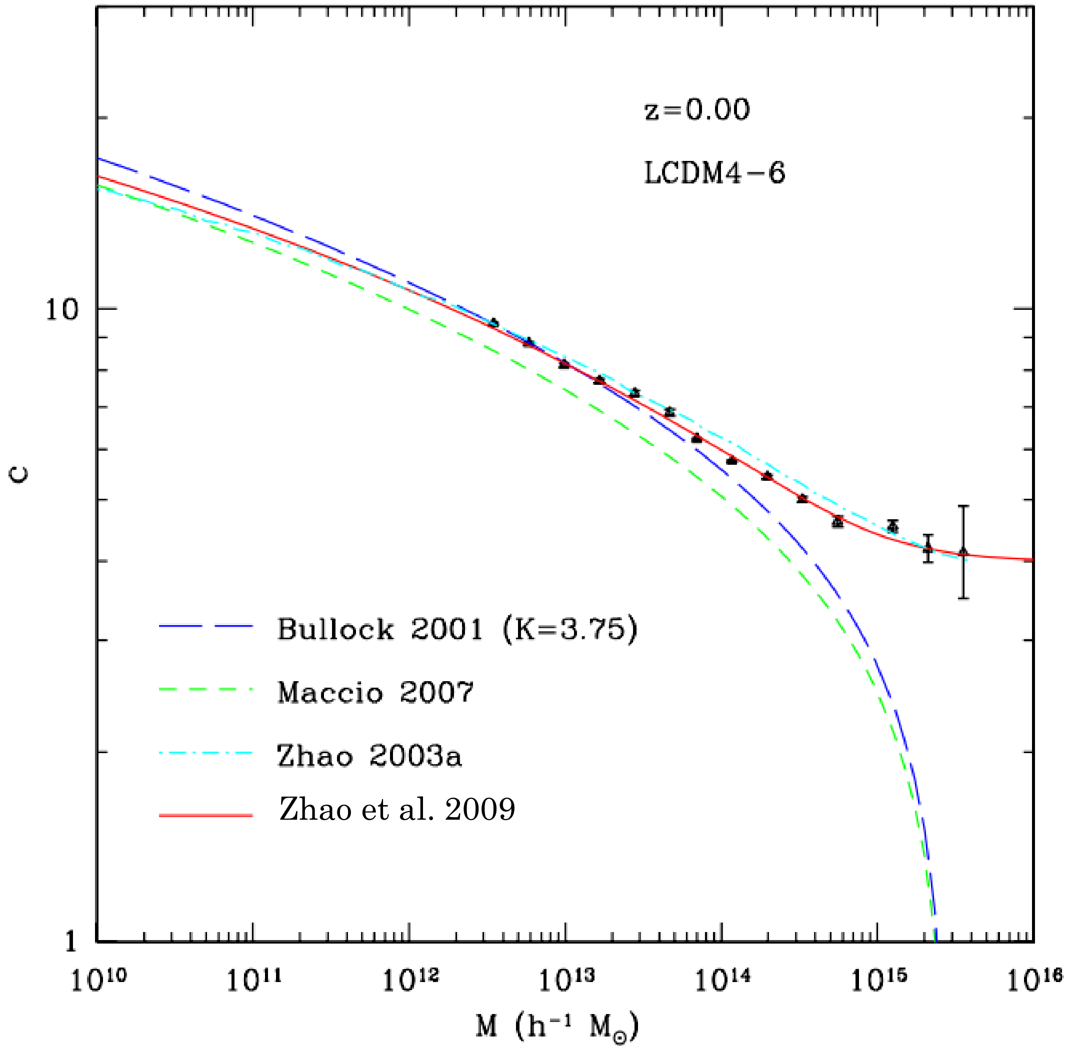
Hernquist model is often used instead of NFW because its total mass is finite and as a model for bulges and elliptical galaxies

Parametrization

- The NFW profile is characterized by 2 parameters: normalization and scale-length or virial mass and concentration
- The virial mass is defined as mass within the virial radius r_v where the mean density is Δ_c times the critical density of the Universe at present
- The virial parameter Δ_c is taken from the spherical collapse model, $\Delta_c = 100\text{-}200$, $\Delta_c = 102$ for LCDM
- The scale radius r_s is where the slope changes and is -2, between the inner and outer slopes
- The concentration parameter is defined as the ratio

  $c = r_v / r_s$, the typical values of c are 5-30

The mass-concentration relation



- Simulated haloes of smaller mass are more concentrated
- Difficult to confirm with observations

Exponential thin disk

$$\Sigma(R) = \Sigma_0 e^{-R/R_d}$$

Surface density distribution

$$M_d = 2\pi\Sigma_0 R_d^2$$

Total mass

$$M(R) = M_d[1 - e^{-R/R_d}(1 + R/R_d)]$$

Mass as function of radius

Surface brightness/density profiles of many galactic disks are approximately exponential in radial direction and can be described in this way, neglecting thickness

Exponential thick disk

$$\rho_d(R,z)=\Sigma(R)\zeta(z)=\frac{M_d}{4\pi R_d^2 z_d}\exp\left(-\frac{R}{R_d}\right)\sec h^2\left(\frac{z}{z_d}\right)$$

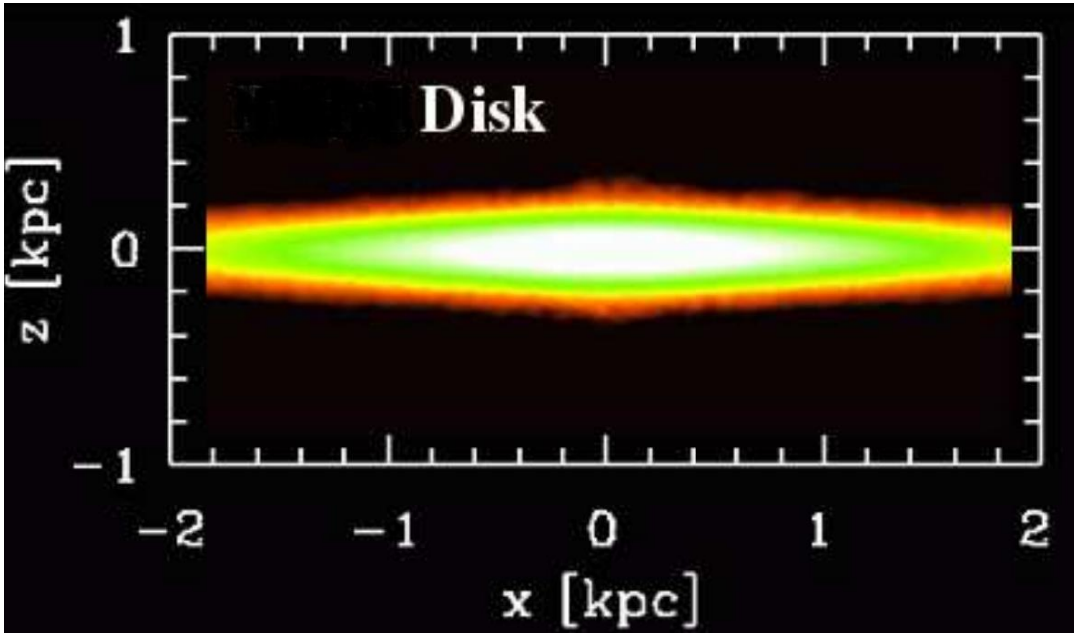
Disk parameters:

mass,

radial scale-length

vertical scale-length

sech x = 2/(e^x + e^{-x})
hyperbolic secant of x



Bulges and ellipticals

- In these structures the surface density of stars can be approximated by Sersic profiles

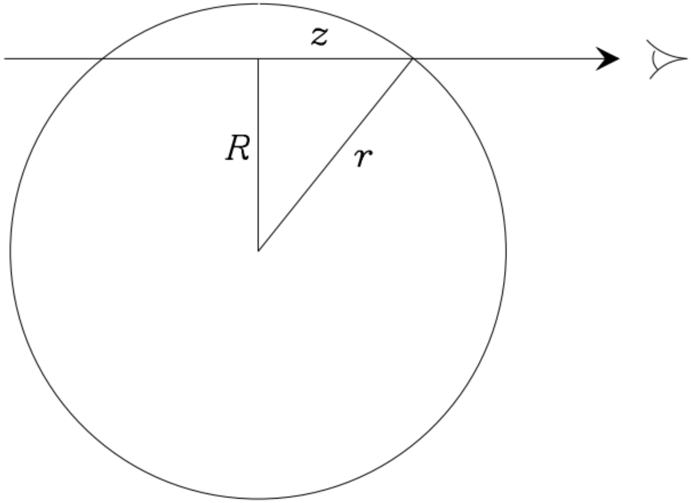
$$I(R) = I_0 \exp[-(R/R_S)^{1/m}]$$

- The Sersic index can have a large range of values $0.5<m<10$, it correlates with the luminosity of the elliptical galaxy, luminous ellipticals having $m\approx6$ and dim ones $m\approx2$.
- It is a generalization of de Vaucouleurs profile for elliptical galaxies which is recovered for $m=4$. Exponential profile corresponds to $m=1$.
- R_S is the characteristic radius or effective radius.

Projection and deprojection

projection

$$I(R) = 2\int_R^\infty \frac{\nu(r)\,r\,dr}{\sqrt{r^2 - R^2}}$$



deprojection

$$\nu(r) = -\frac{1}{\pi}\int_r^\infty \frac{dI}{dR}\frac{dR}{\sqrt{R^2 - r^2}}$$

Abel integrals

Sersic deprojected

$$\nu(r) = \nu_0 (r / R_S)^{-p} \exp[-(r / R_S)^{1/m}]$$

$$\nu_0 = \frac{I_0 \Gamma(2m)}{2 R_S \Gamma[(3-p)m]}$$

$$p = 1.0 - 0.6097 / m + 0.5463 / m^2$$

3D density of stars, a good approximation applicable for the whole range of *m* values

Plummer model for stars

For dSph galaxies the surface distribution of stars can be approximated by a Plummer formula:

$$I(R) = \frac{a^2 M}{\pi (R^2 + a^2)^2}$$

Then the density, potential and mass in 3D:

$$\nu(r) = \frac{3a^2 M}{4\pi (r^2 + a^2)^{5/2}} \qquad \Phi(r) = -\frac{GM}{(r^2 + a^2)^{1/2}} \qquad M(r) = \frac{Mr^3}{(r^2 + a^2)^{3/2}}$$

M – total mass of galaxy

a – characteristic scale of Plummer profile

Circular velocity

Circular velocity is the velocity of a test particle moving on a circular orbit in the potential of the galaxy under the assumption of centrifugal equilibrium

For point mass $$v_c^2(r) = r\frac{d\Phi}{dr} = \frac{GM}{r}$$

For spherical systems $$v_c^2(r) = r\frac{d\Phi}{dr} = \frac{GM(r)}{r}$$

For thin disks $$v_c^2(R) = R\frac{d\Phi}{dR}$$

Circular velocities

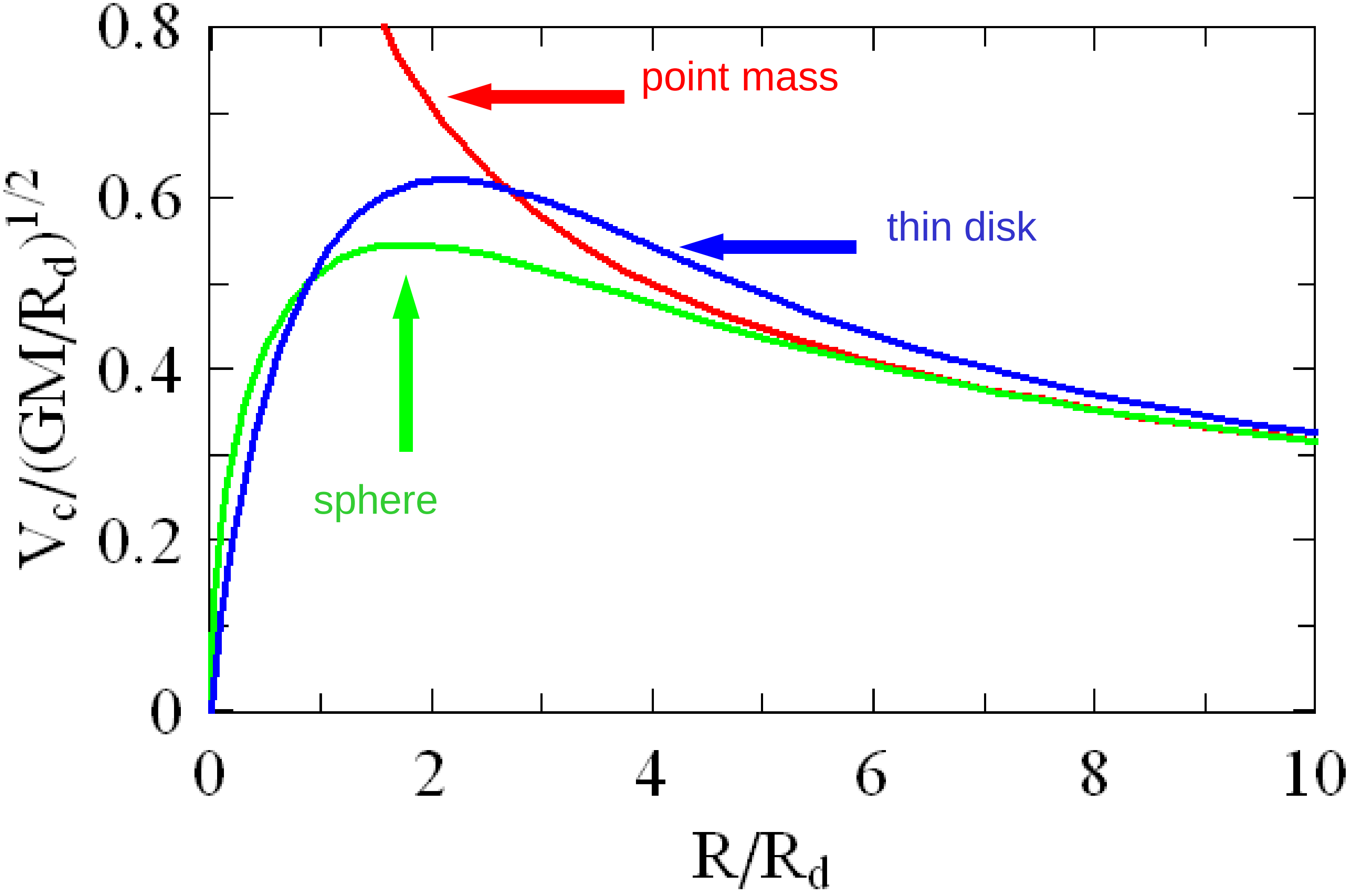
For an exponential disk:

$$v_c^2(R) = \frac{GM_d}{R_d}\frac{(R/R_d)^2}{2}\left[I_0\left(\frac{R}{2R_d}\right)K_0\left(\frac{R}{2R_d}\right) - I_1\left(\frac{R}{2R_d}\right)K_1\left(\frac{R}{2R_d}\right)\right]$$

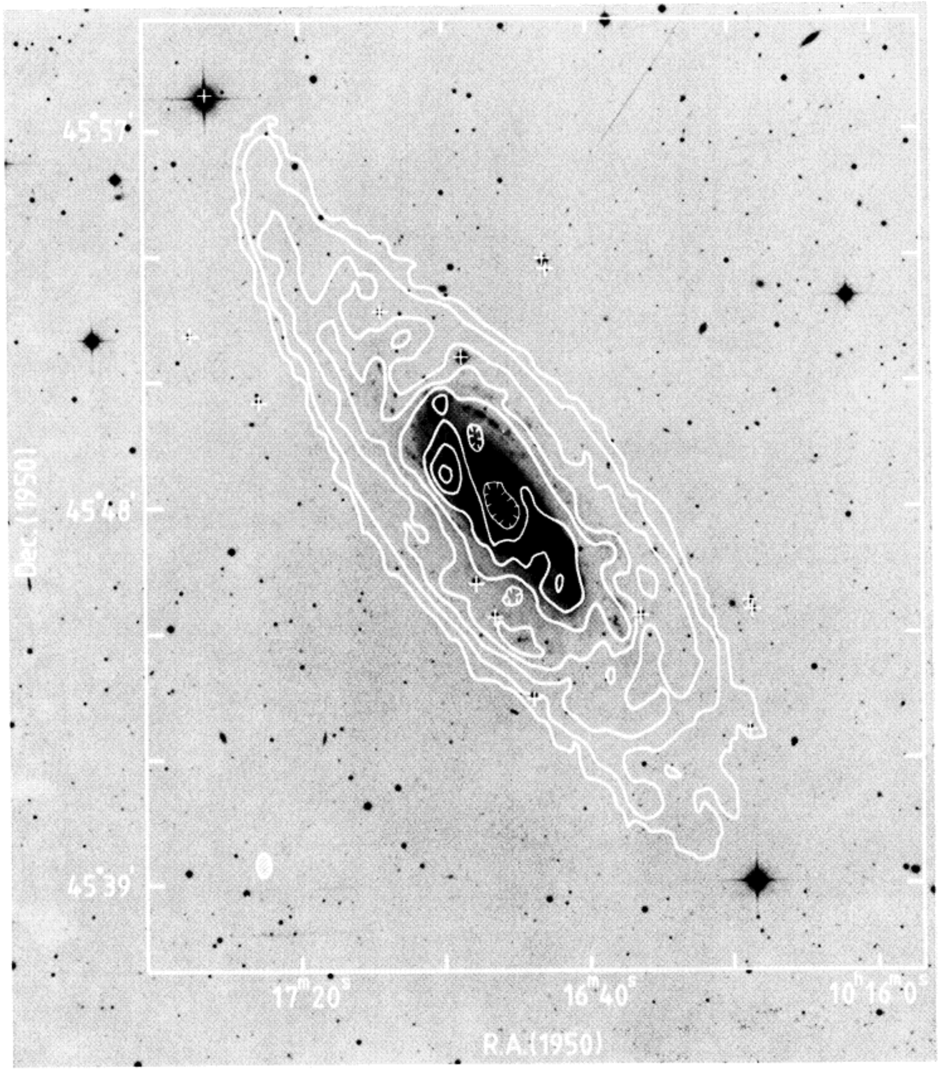
For a spherical distribution with the same mass interior to *r*=*R* as in the disk:

$$v_c^2(r = R) = \frac{GM_d}{R_d}\frac{[1 - e^{-R/R_d}(1 + R/R_d)]}{R/R_d}$$

Circular velocity



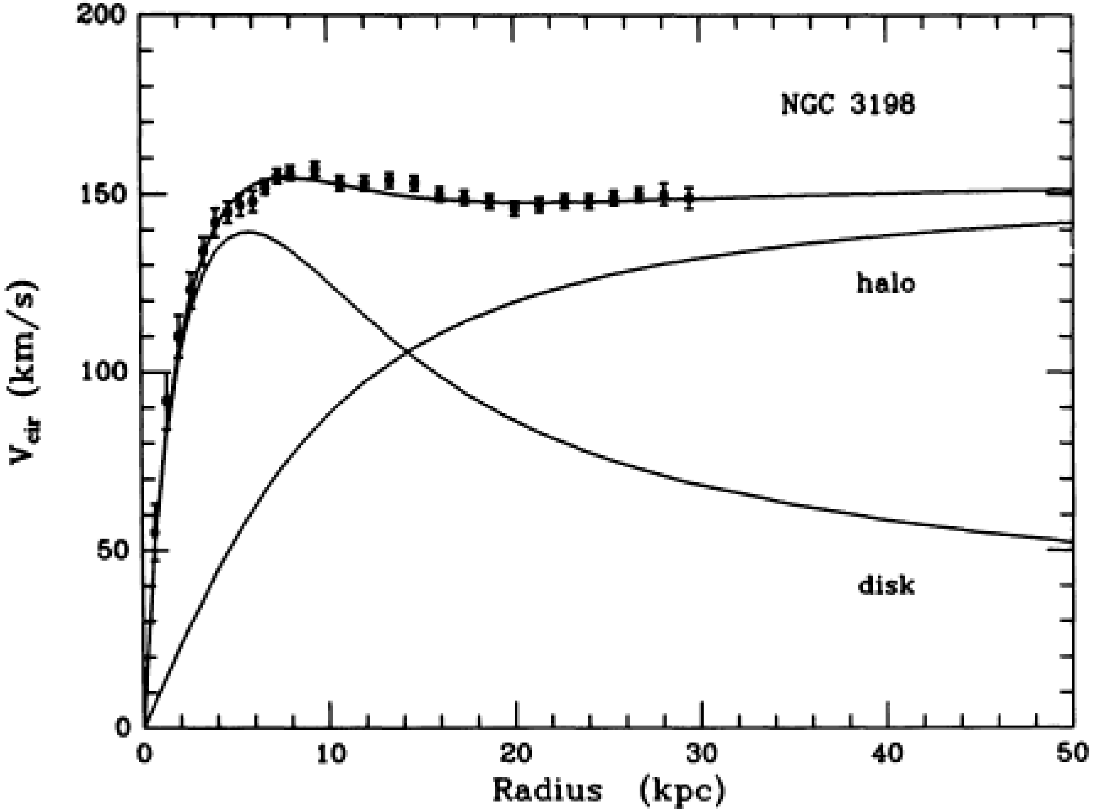
Classic example: NGC 3198



Density contours of neutral hydrogen extending far beyond the optical image

van Albada et al. (1985)

Rotation curve of NGC 3198



Model:
exponential disk
+ spherical halo

Disk scale-length:
$R_d = 2\ h^{-1}$kpc

The mass to light ratio at the last measured point:

$M/L_V = 28\ h\ M_\odot/L_\odot$

Model of the Milky Way

- The surface brightness of the disk can be approximated as

$$I(R) = I_d \exp(-R / R_d)$$

- The scale-length R_d = 2-3 kpc, is difficult to measure because of our position in the disk
- The circular velocity of the star at the distance of the Sun is

$$v_c(R_0) = (220 \pm 20)\mathrm{km/s}$$

Model of the Milky Way

- In the direction perpendicular to the Galactic plane the density distribution can be approximated as

$$\rho(R,z) = \rho(R,0)\exp[-|z|/z_d(R)]$$

- z_d , the scale-height at cylindrical radius R, depends on the stellar population used to estimate it
- Older stellar populations have larger z_d

Thin/thick disk

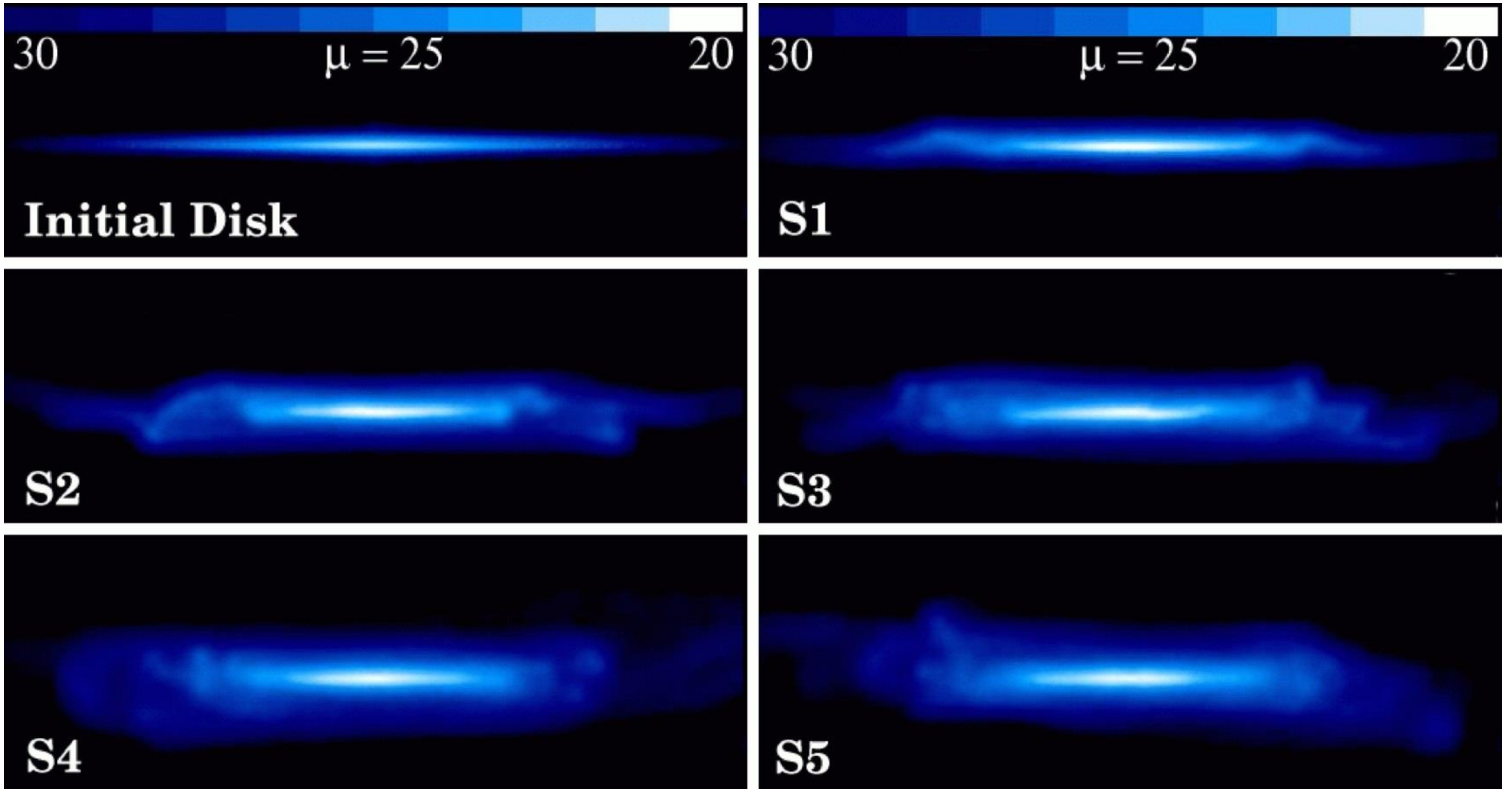
- A more accurate description of the vertical structure of the disk is obtained by a combination of a thin disk with z_0~0.3 kpc, the and thick disk with z_1~1 kpc

$$\rho_d(R,z) = \Sigma_d e^{-R/R_d} \left(\frac{\alpha_0}{2z_0} e^{-|z|/z_0} + \frac{\alpha_1}{2z_1} e^{-|z|/z_1} \right)$$

- Stars of the thick disk are older and more metal poor
- The surface density of the thick disk is only ~7% of the thin disk
- In the mid-plane thin-disk stars dominate strongly

Thickening of the disk

Thick disk was probably created by encounters with smaller galaxies/satellites



Disk thickens as a result of mergers with small satellites S1-S5

Kazantzidis et al. (2008)

The bulge of the Galaxy

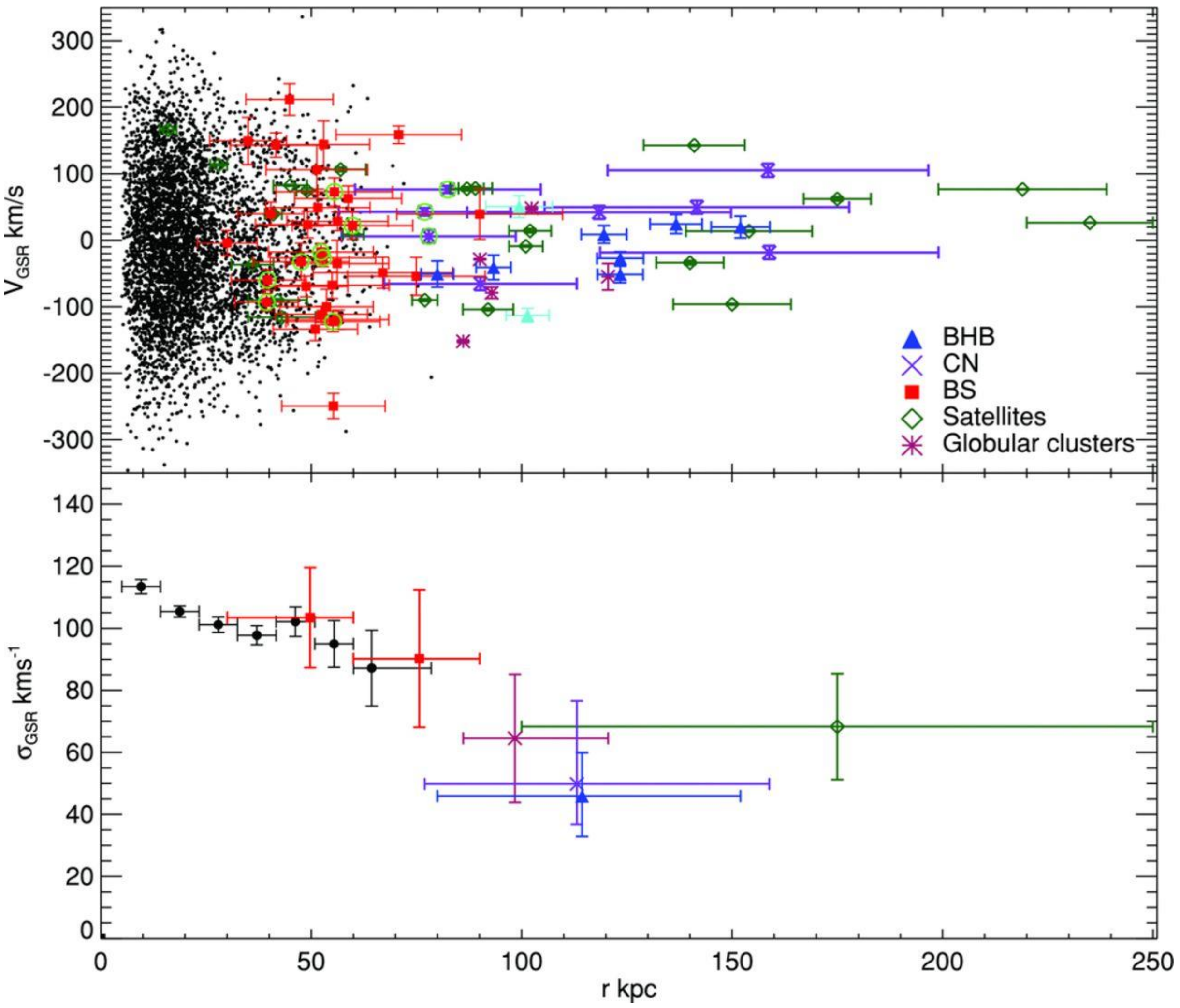
- The next most significant component is the bulge containing old stars contributing ~15% of luminosity with velocity dispersion ~150 km/s
- The bulge is triaxial, brighter on one side when seen from the Sun
- The bulge probably formed from a bar as a result of vertical instabilities that lead to the thickening of the bar (pseudo-bulge)

The bar seen from the Sun

The stellar halo of the Galaxy

- Only about 1% of the stellar mass of the Galaxy is in the stellar halo
- The halo contains mostly old stars of low metallicity
- The stars show little or no mean rotation, random motions dominate
- The density distribution can be approximated as a power-law $\rho \sim r^{-3}$ out to 50 kpc
- The halo hosts many old globular clusters

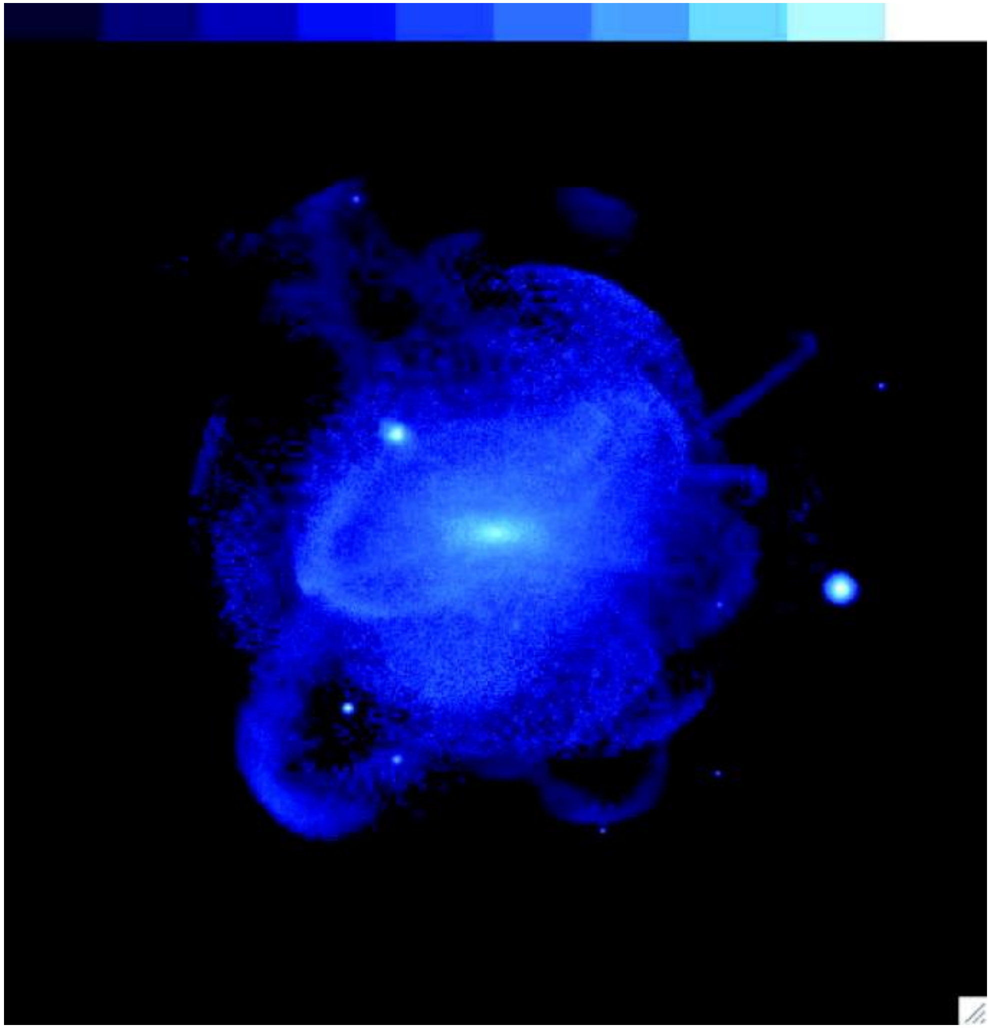
Cold veil of the stellar halo



Velocity dispersion of the stars in the halo decreases and points to a rather low mass of MW

Deason et al. (2012)

Formation of a stellar halo



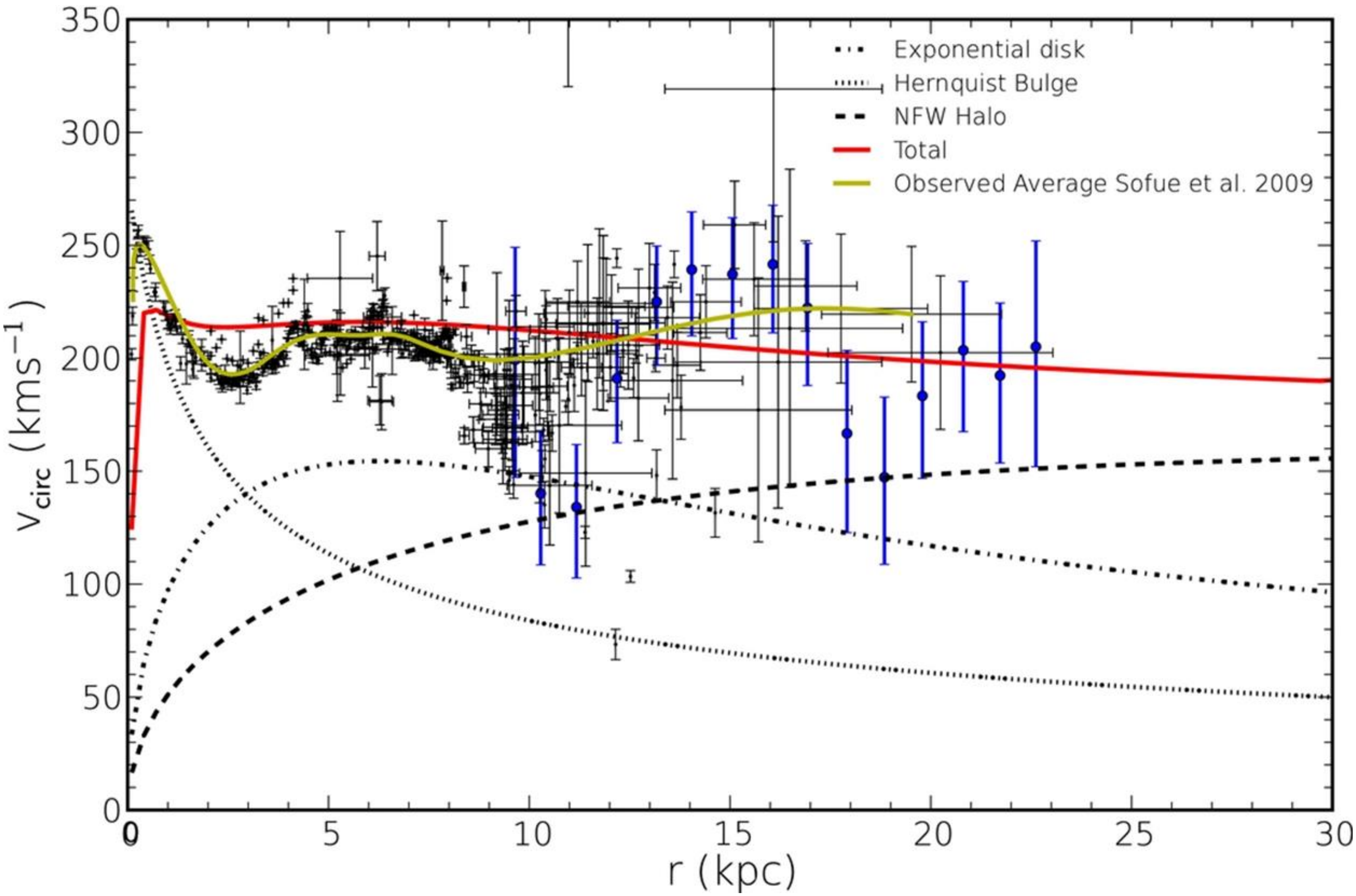
- The halo probably formed from disrupted globular clusters and dwarf galaxies
- Disrupted satellites were accreted early

Bullock & Johnston (2005)

Dark matter halo

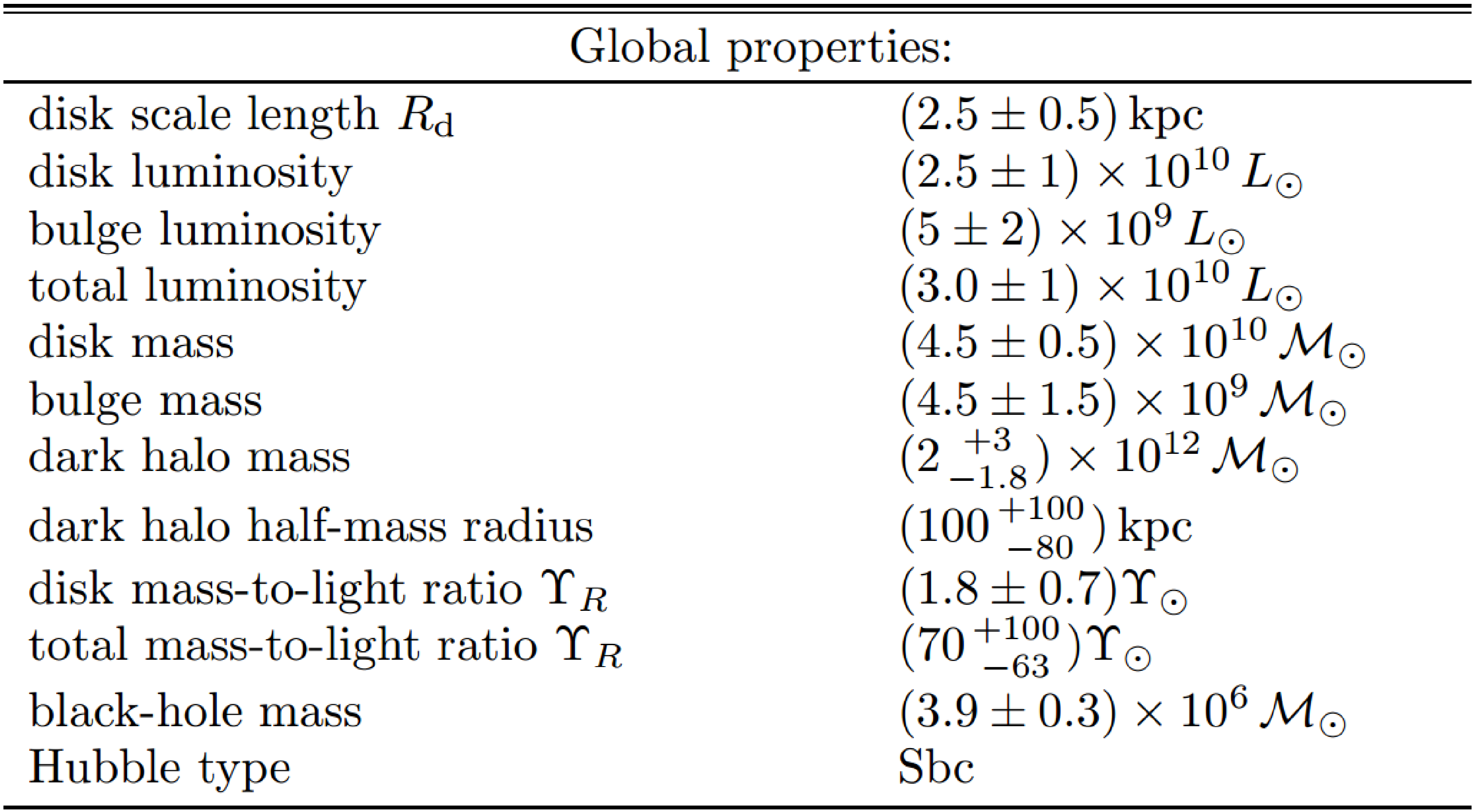
- The properties of the dark matter halo of the Milky Way are the most difficult to constrain
- The total mass of the halo is about 2 x 10^{12} $M_{\odot}$ and the virial radius about 250 kpc
- Both the inner and outer slope of the density profile are poorly constrained

Rotation curve of the MW



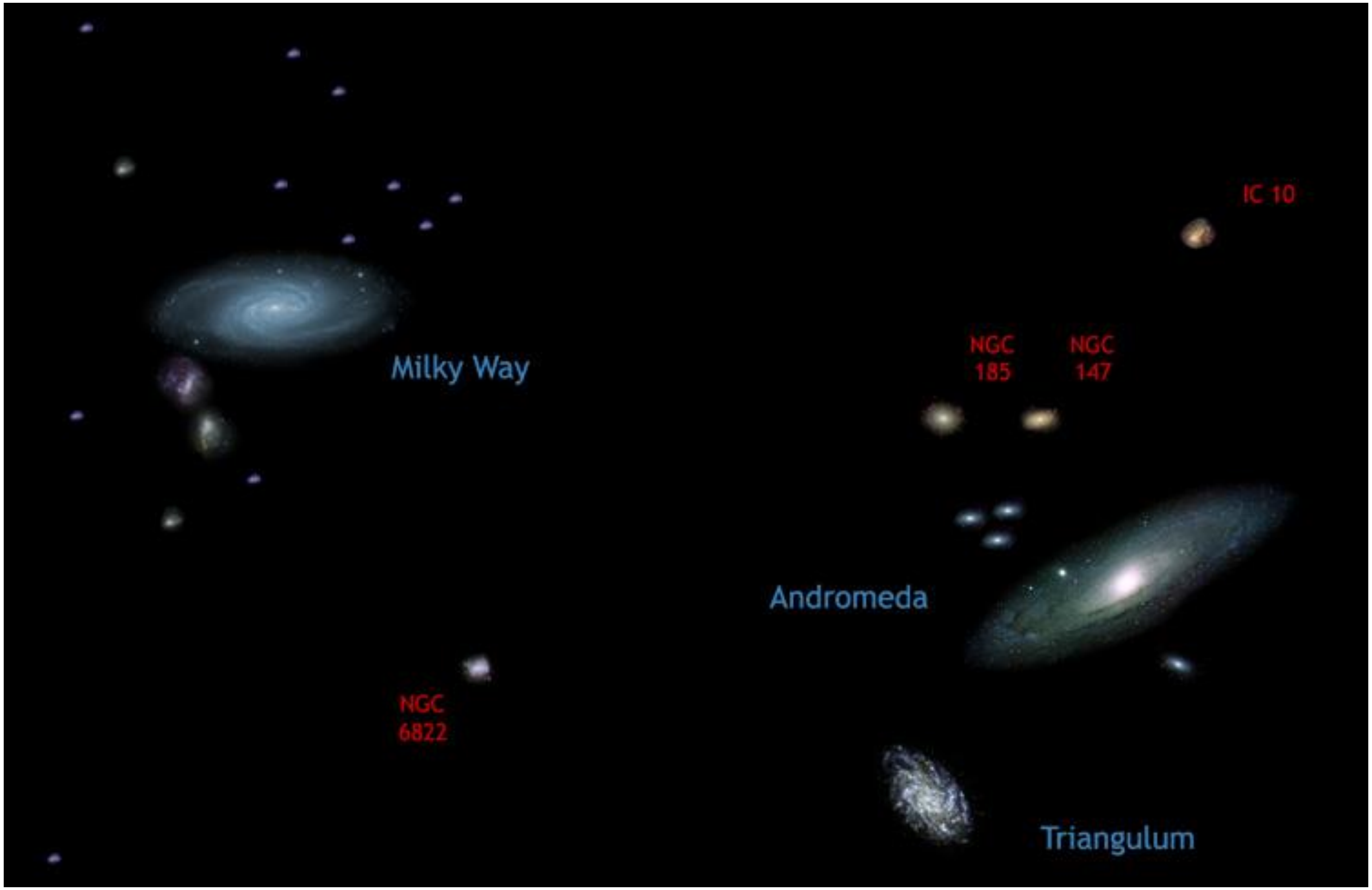
Kafle et al. (2012)

Milky Way: summary of properties



Global properties:	
disk scale length R_d	(2.5 ± 0.5) kpc
disk luminosity	$(2.5 \pm 1) \times 10^{10}\, L_\odot$
bulge luminosity	$(5 \pm 2) \times 10^{9}\, L_\odot$
total luminosity	$(3.0 \pm 1) \times 10^{10}\, L_\odot$
disk mass	$(4.5 \pm 0.5) \times 10^{10}\, \mathcal{M}_\odot$
bulge mass	$(4.5 \pm 1.5) \times 10^{9}\, \mathcal{M}_\odot$
dark halo mass	$(2\,^{+3}_{-1.8}) \times 10^{12}\, \mathcal{M}_\odot$
dark halo half-mass radius	$(100\,^{+100}_{-80})$ kpc
disk mass-to-light ratio Υ_R	$(1.8 \pm 0.7)\Upsilon_\odot$
total mass-to-light ratio Υ_R	$(70\,^{+100}_{-63})\Upsilon_\odot$
black-hole mass	$(3.9 \pm 0.3) \times 10^{6}\, \mathcal{M}_\odot$
Hubble type	Sbc

The Local Group



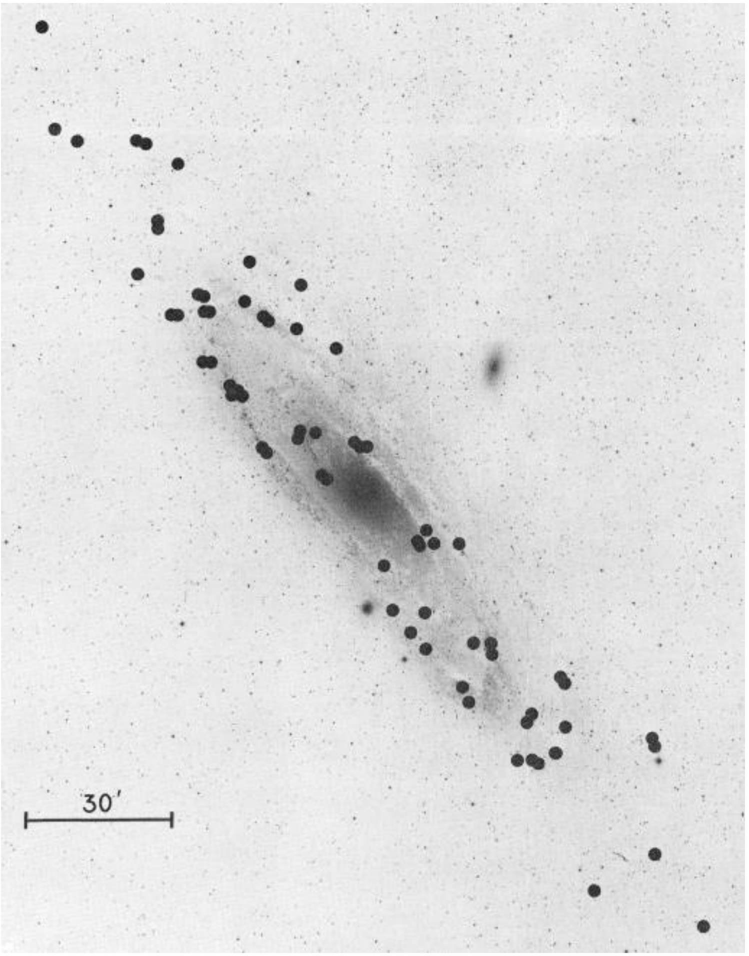
The term „Local Group” was coined by Edwin Hubble and used in his book „The Realm of the Nebulae”, 1936

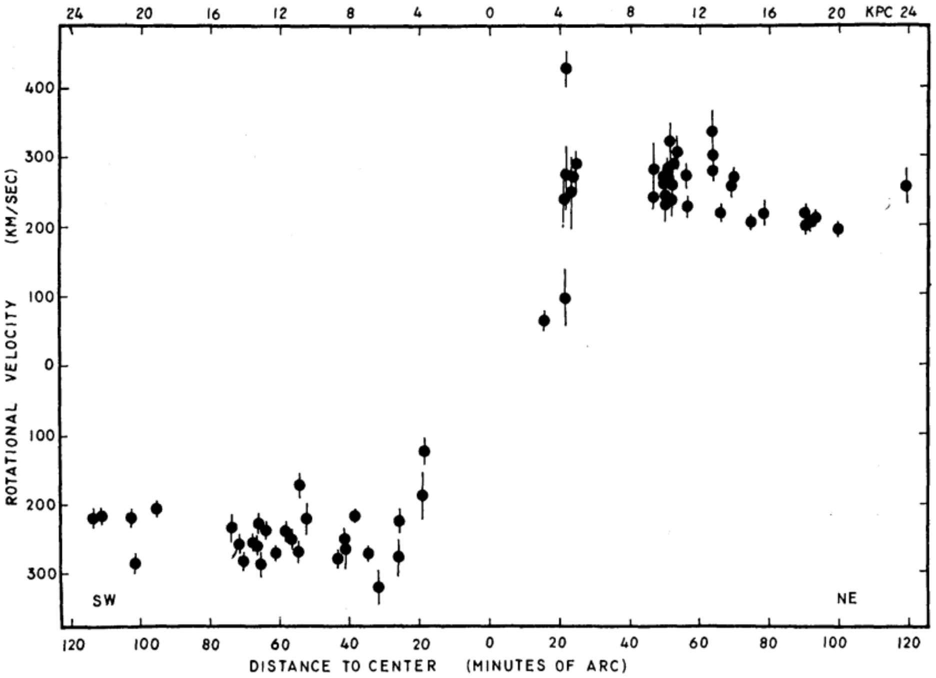
Our neighbour Andromeda

Main properties

- Names: Andromeda Galaxy, M31, NGC 224
- The spiral type galaxy nearest to the Milky Way
- Presently at the distance of 770 kpc
- Large angular size on the sky 190’ x 60’
- Luminosity similar to Milky Way, 4 x 10^{10} $L_\odot$
- Mass around 2 x 10^{12} $M_\odot$ probably a little larger than the Milky Way, mostly from dark matter
- Contains a black hole of mass 10^8 $M_\odot$

Rotation curve





Observations of ionized hydrogen regions provided first evidence for a flat rotation curve in Andromeda

Rubin & Ford 1970

Andromeda’s velocity

- Proper motion measurements performed in 3 fields: disk, spheroid and recently discovered stream
- Stellar positions measurements over 5-7 years were used
- After corrections, the velocity of Andromeda with respect to the center of the Milky Way is:

  $V_{rad} = -109.3$ km/s

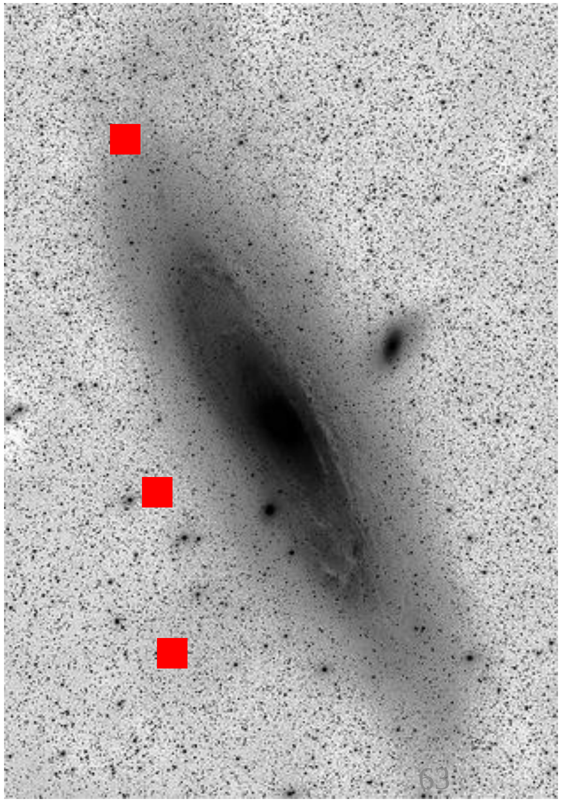
  $V_{tan} = 17.0$ km/s

  van der Marel et al. 2012

- Update from Gaia

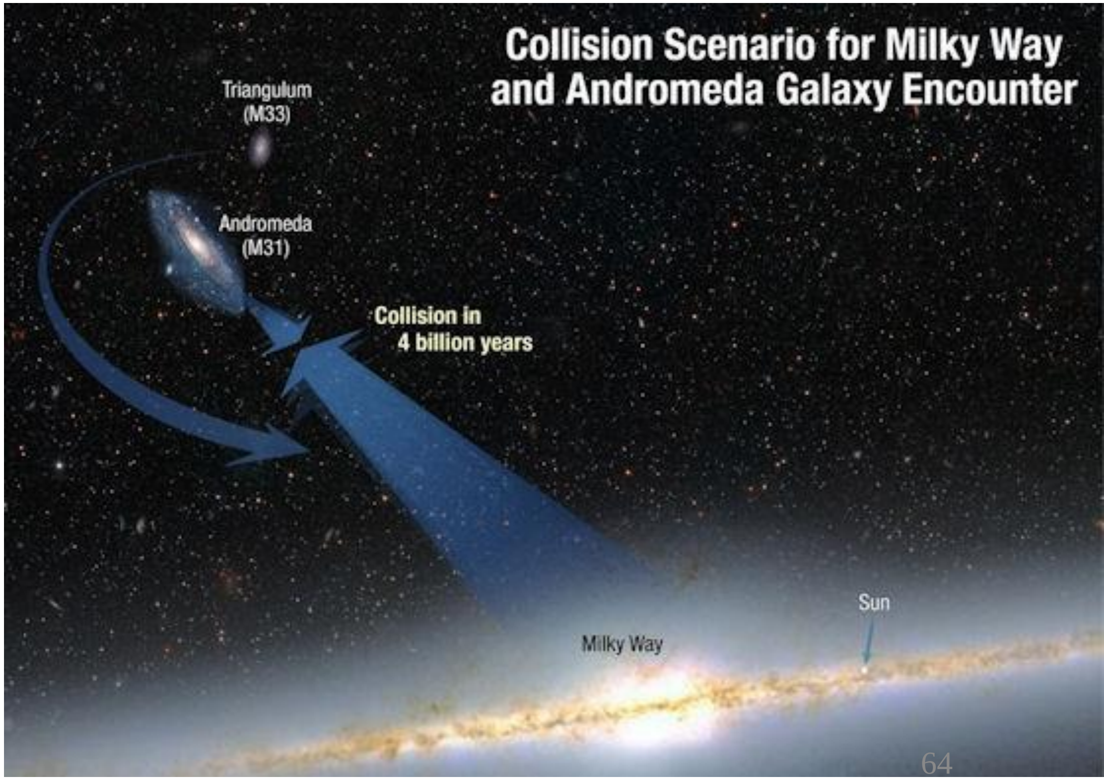
  $V_{tan} = 57 \pm 30$ km/s (less radial)

  van der Marel et al. 2019



Head-on collision

- $V_{rad} < 0$ and $|V_{rad}| >> |V_{tan}|$ so the velocity vector of M31 is statistically consistent with a head-on collision orbit toward the Milky Way
- The collision will take a few Gyrs and the first contact will take place in 4 Gyr
- The galaxies will finally merge in about 6 Gyr



The mass of the LG

- The measurement of the relative velocity between MW nad M31 can be used to estimate the mass of the LG
- We can treat the LG as a system of two point masses
- Then the distance between the two galaxies changes according to the equation

$$\frac{d^2 r}{dt^2} = -\frac{GM}{r^2}, \quad M = M_{MW} + M_{M31}$$

- The equation allows us to estimate the LG mass

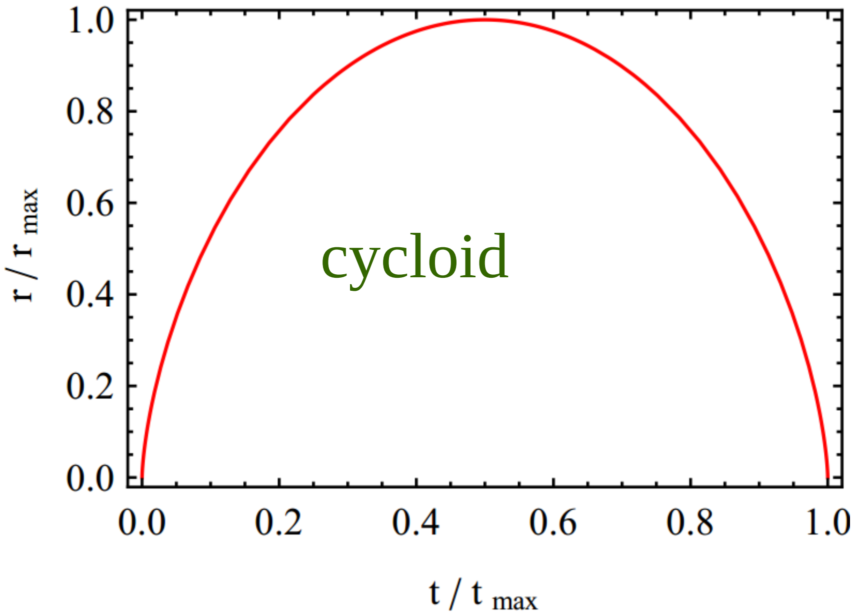
Solution

- The solution for the bound pair is in the parametric form

$$r = \frac{r_{\max}}{2}(1-\cos\theta)$$

$$t = \left(\frac{r_{\max}^3}{8GM}\right)^{1/2}(\theta - \sin\theta)$$

$$0 \le \theta \le 2\pi$$



- The distance *r* increases to the maximum value and then decreases

Relative velocity

- The relative velocity of MW and M31 is

$$v = \frac{dr}{dt} = \frac{dr}{d\theta}\left(\frac{dt}{d\theta}\right)^{-1} = \left(\frac{2GM}{r_{\max}}\right)^{1/2} \frac{\sin\theta}{1-\cos\theta}$$

- Combining the equations for *r*, *t* and *v* we get

$$\frac{v\,t}{r} = \frac{\sin\theta\,(\theta - \sin\theta)}{(1-\cos\theta)^2}$$

- This equation can be solved numerically for θ

Timing the LG

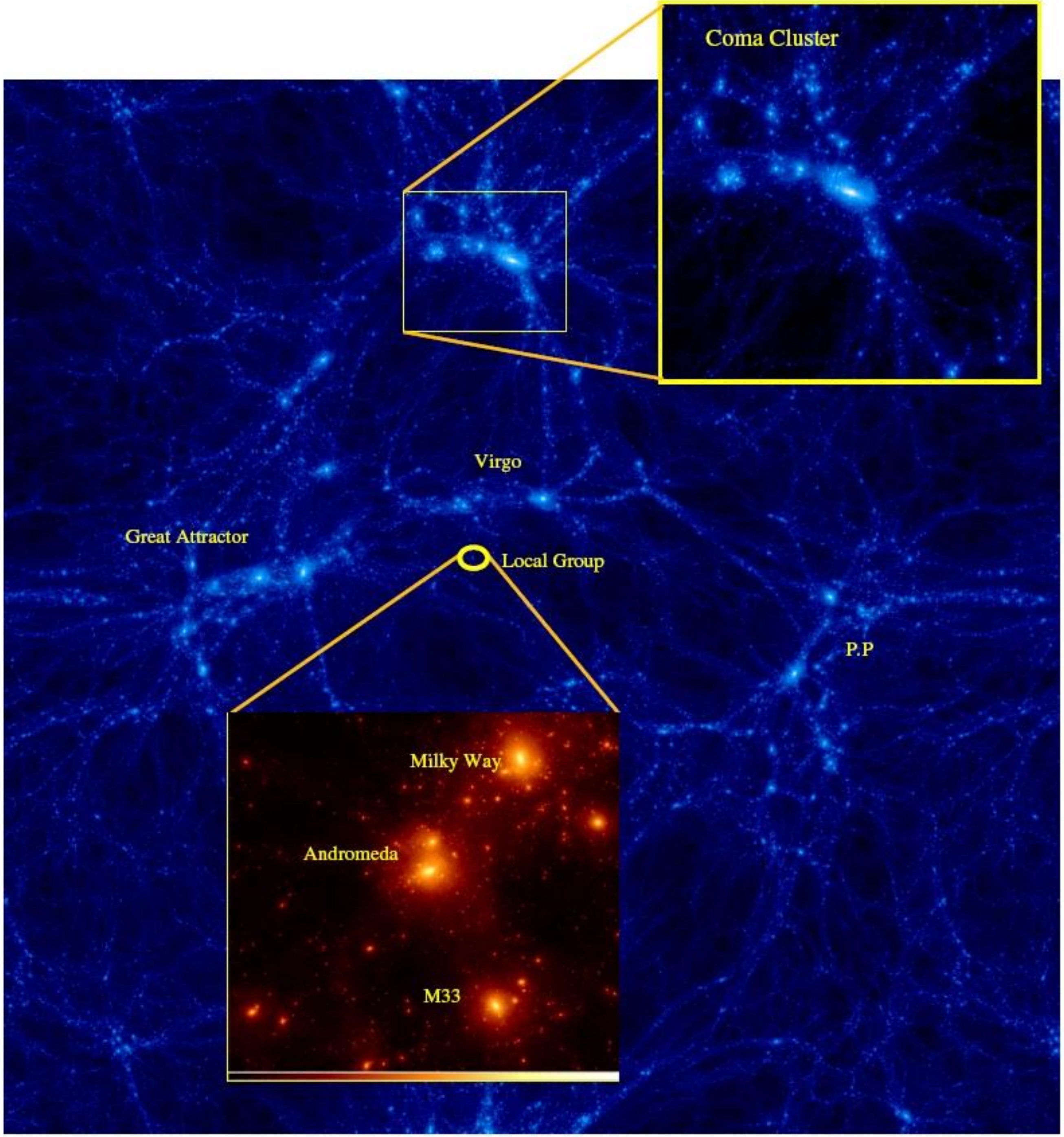
- MW and M31 formed at the Big Bang and originally followed global expansion (r=0 at t=0)
- Due to mutual attraction they stopped at some point and the motion was reversed
- The galaxies now approach for the first time
- For the present we take:

  v = -109.3 (± 4.4) km/s

  r = 770 (± 40) kpc

  t = 13.7 Gyr (the present age of Universe)
- This gives $\theta = 4.2 = 1.33\,\pi$ and $M = 4.2 \times 10^{12}\ M_{\odot}$

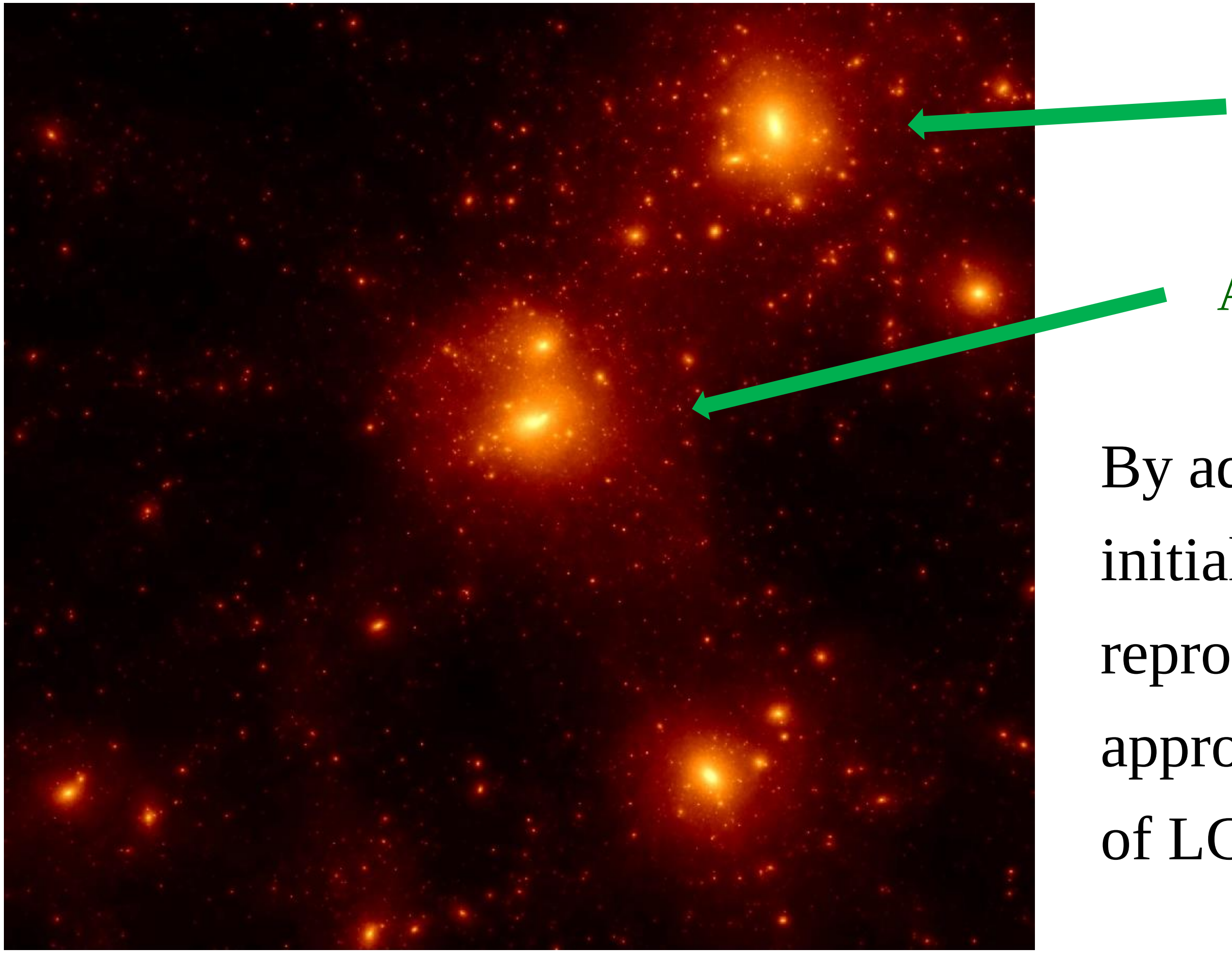
The CLUES project



Constrained simulations of the Local Universe

LG-like objects are not difficult to find

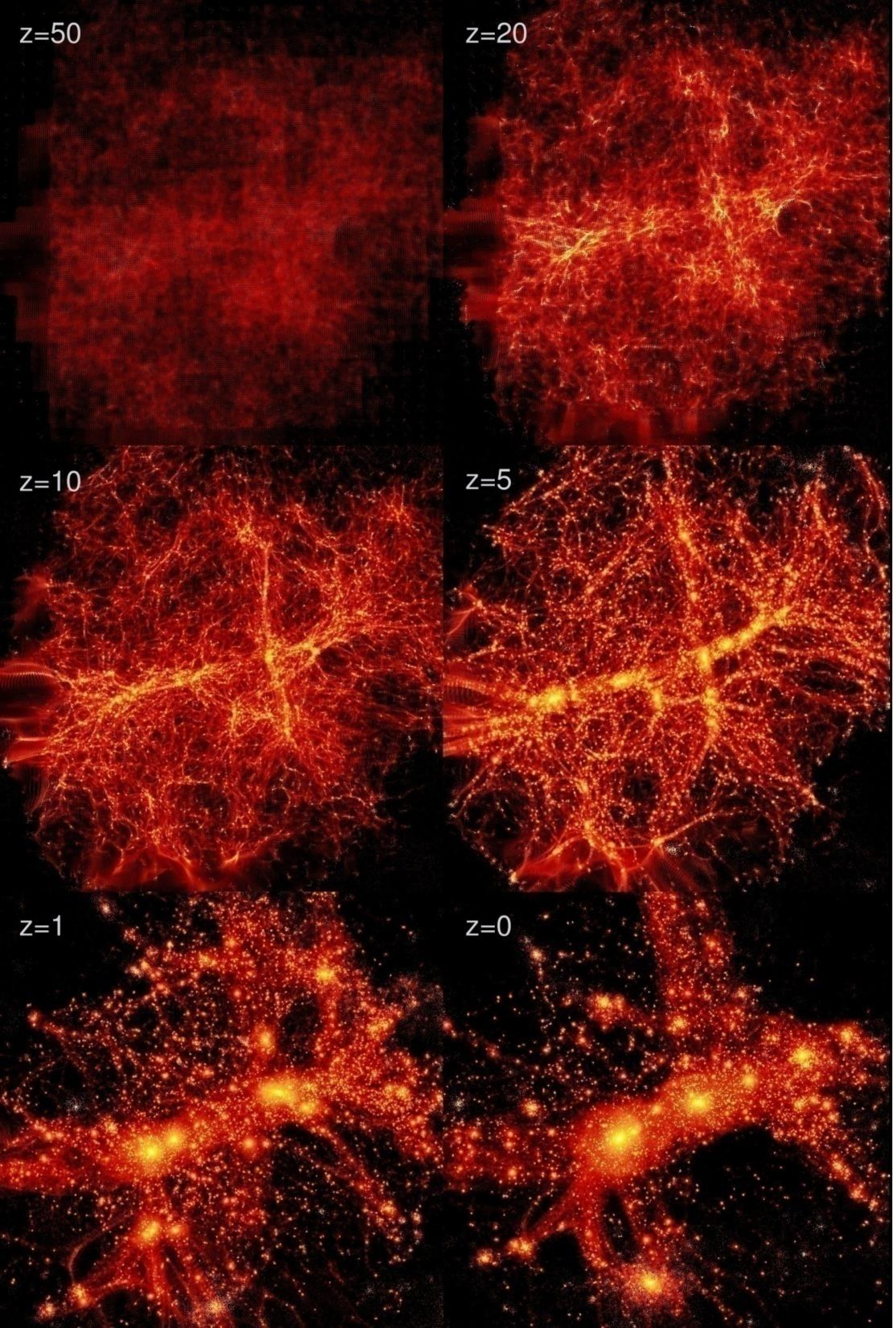
Simulation of the Local Group



By adopting particular initial conditions we can reproduce the approximate distribution of LG members

CLUES
Constrained Local UniversE Simulations

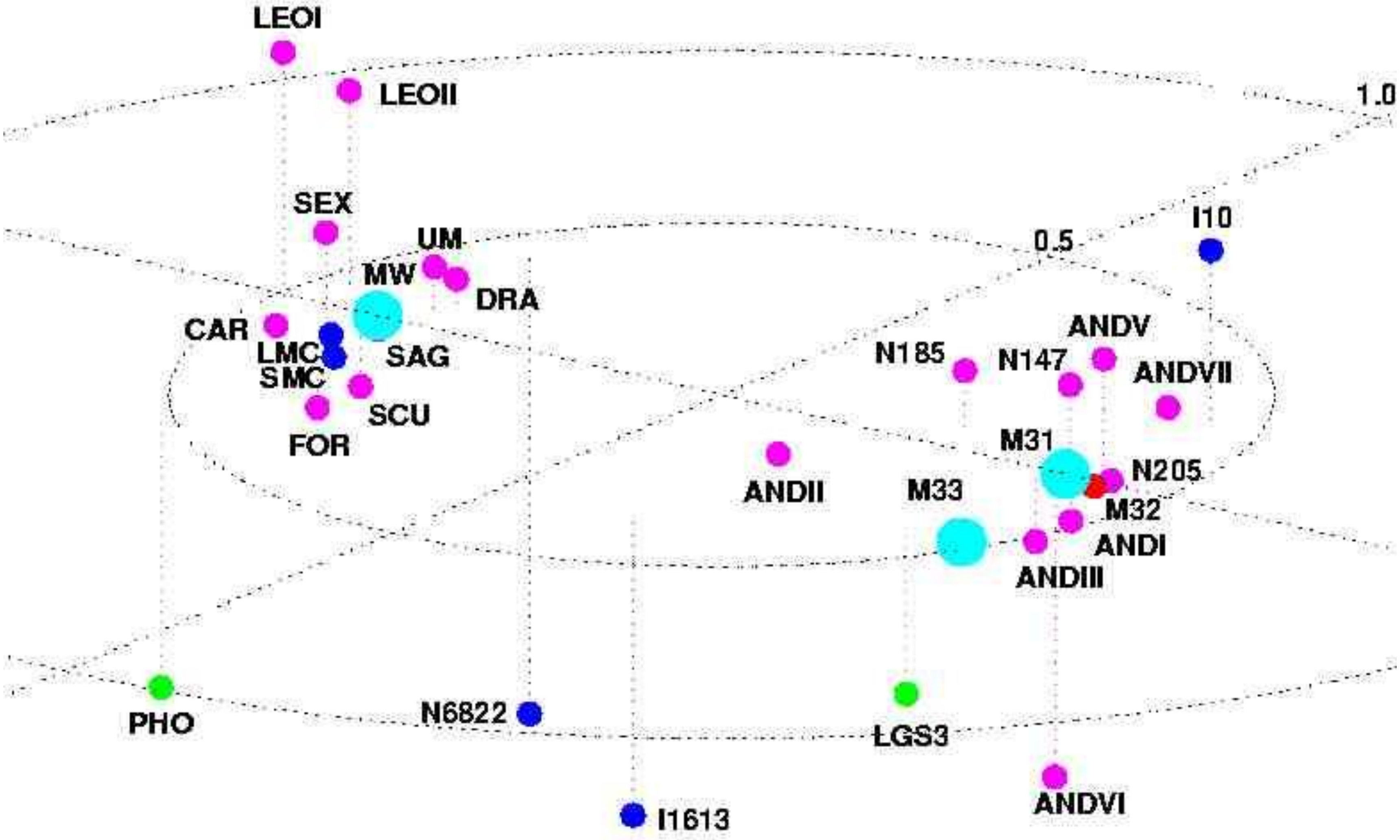
http://www.clues-project.org/



Evolution of the Local Group

Redshift z	Age of Universe t [years]
50	4.7×10^{7}
20	1.8×10^{8}
10	4.7×10^{8}
5	1.2×10^{9}
1	5.8×10^{9}
0	1.3×10^{10}

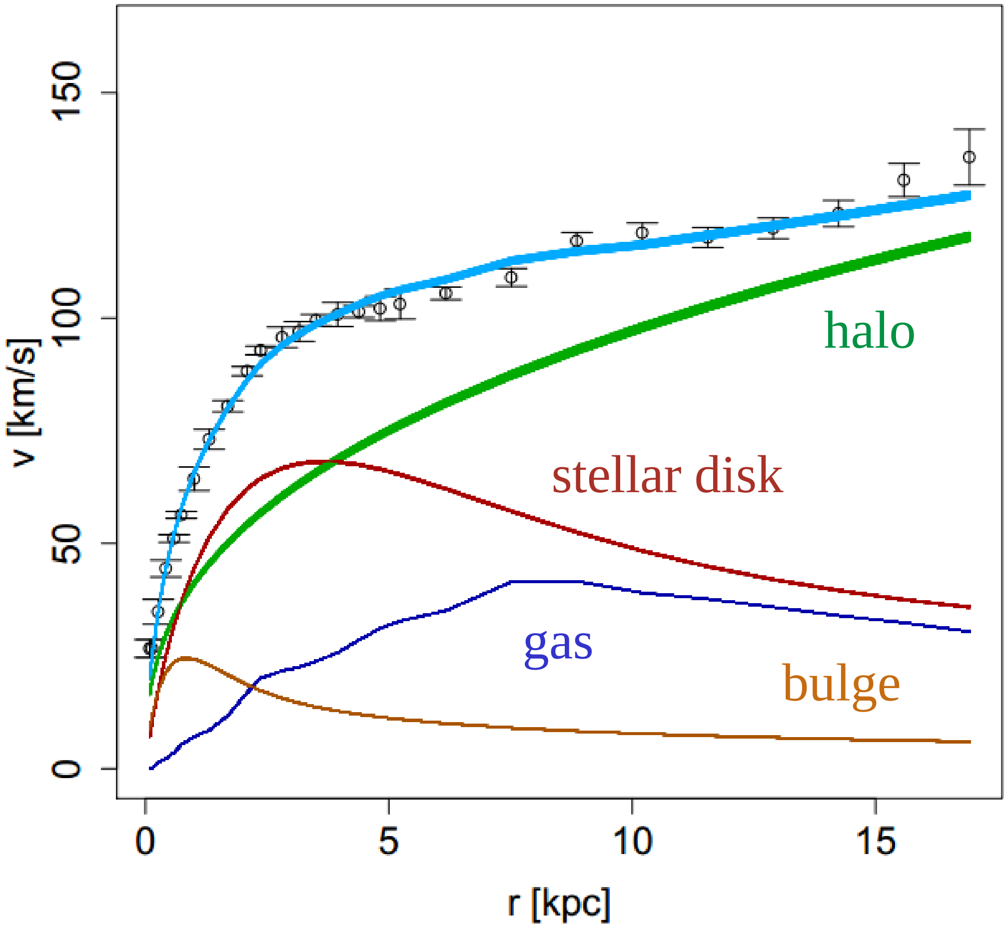
The Local Group



Main galaxies of the LG

- Most massive members: Milky Way, Andromeda and Triangulum galaxy (M33)
- Their mass ratios are 10:10:1 and together they make most of the LG mass
- All three are spirals
- M33 and M31 are at a similar distance to MW (800 kpc)
- M33 is probably gravitationally bound to M31
- M31 & M33 probably interacted in the past

Model for M33



The best model for M33 has a rather steep dark matter density profile in the center (slope -1.2), contrary to what is found in similar, more distant galaxies

Hague & Wilkinson 2014

dIrr versus dSph galaxies

NGC 6822

dIrr

irregular/disky

rotating

contain gas

forming stars

Leo I

dSph

elliptical

non-rotating?

do not contain gas

not forming stars

Morphology-density relation: dSph galaxies are found closer to the big galaxies, while dIrrs occupy isolated regions at the outskirts of the LG

Irregular

Small Magellanic Cloud

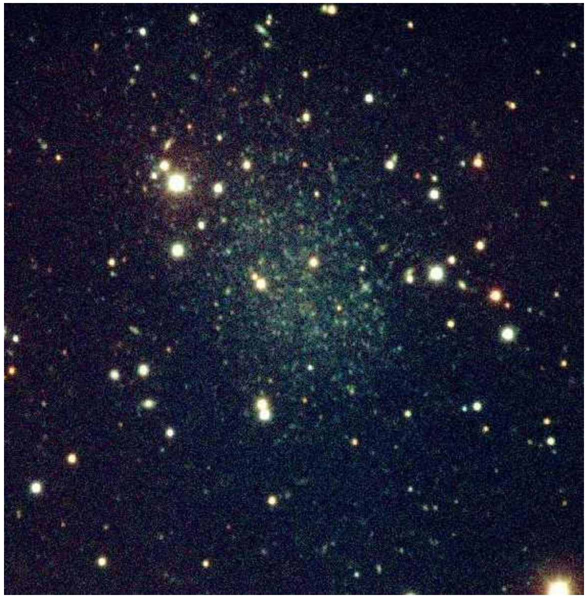
Argo

NGC 6822

Sextans B

Spheroidal

Leo I



Antlia

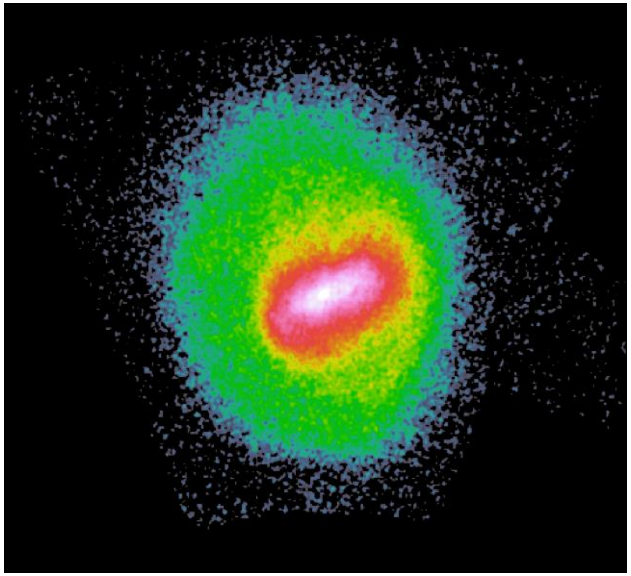
Cetus

Pegasus

The Large Magellanic Cloud

Optical image

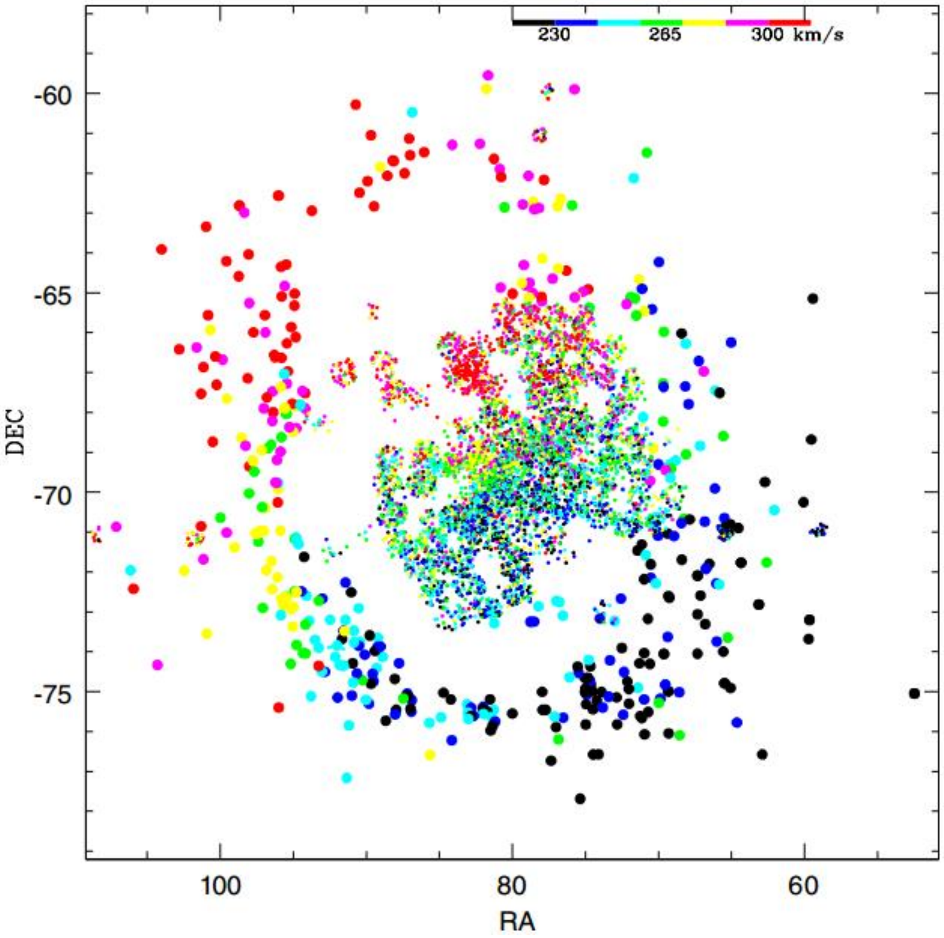
Map of stars



- dIrr galaxy closest to MW (d~50 kpc)
- The brightest part is the bar
- The bar is embedded in a rather thick disk
- The disk is inclined by 35 deg to our line of sight

van der Marel et al. 2002

Motions of the stars



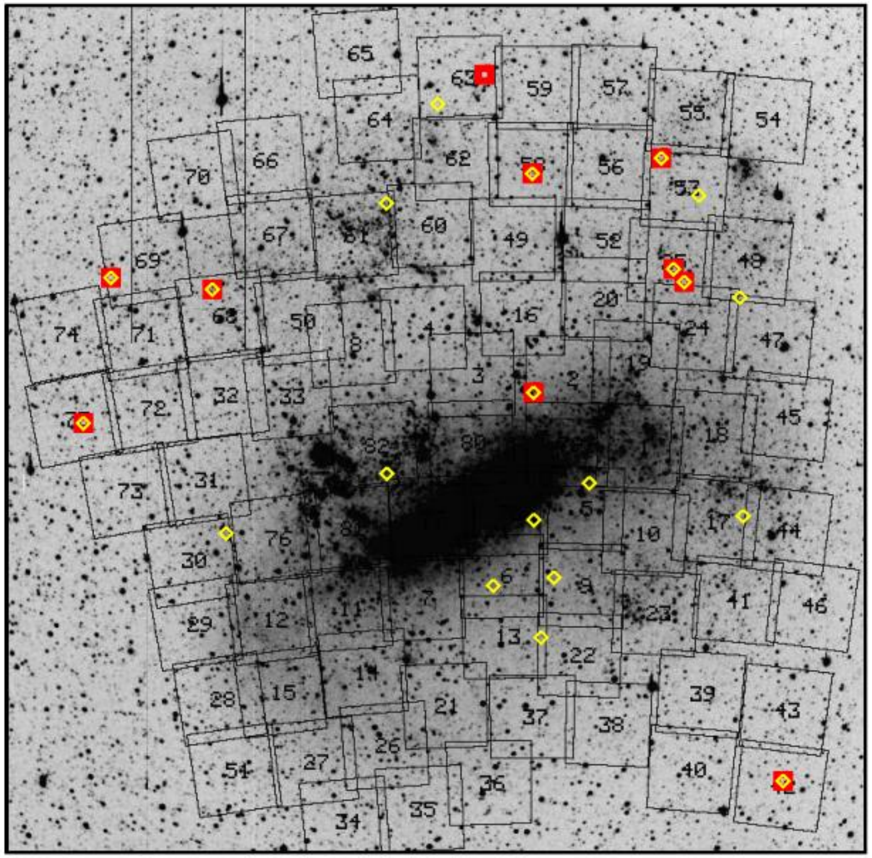
van der Marel & Kallivayalil 2014

- Rotation dominates (young stars rotate faster)
- There is also some contribution from random motions
- Dynamical modelling gives the mass estimate

M(<9 kpc)=
1.7 (± 0.7) x 10^{10} $M_\odot$

M/L = 6 $M_\odot$ /$L_\odot$

Proper motion of LMC



Squares/diamonds: quasars used for reference

Image size: 8° x 8°

- Precise astrometric measurements were performed with HST in time span of 7 years
- 21 quasars were used
- Final results gave:

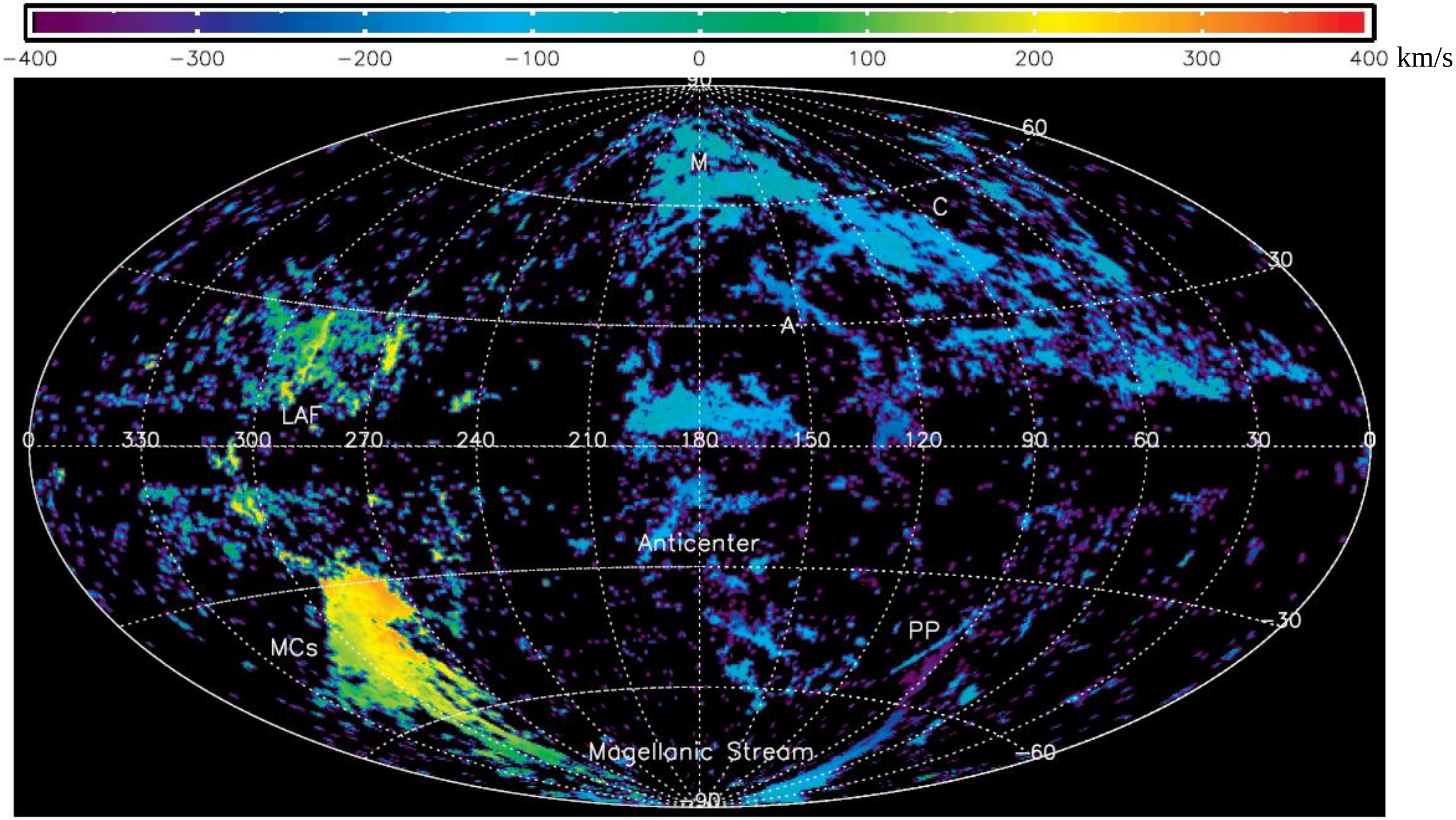
$V = 321\ (\pm 24)$ km/s

$V_{rad} = 64\ (\pm 7)$ km/s

$V_{tan} = 314\ (\pm 24)$ km/s

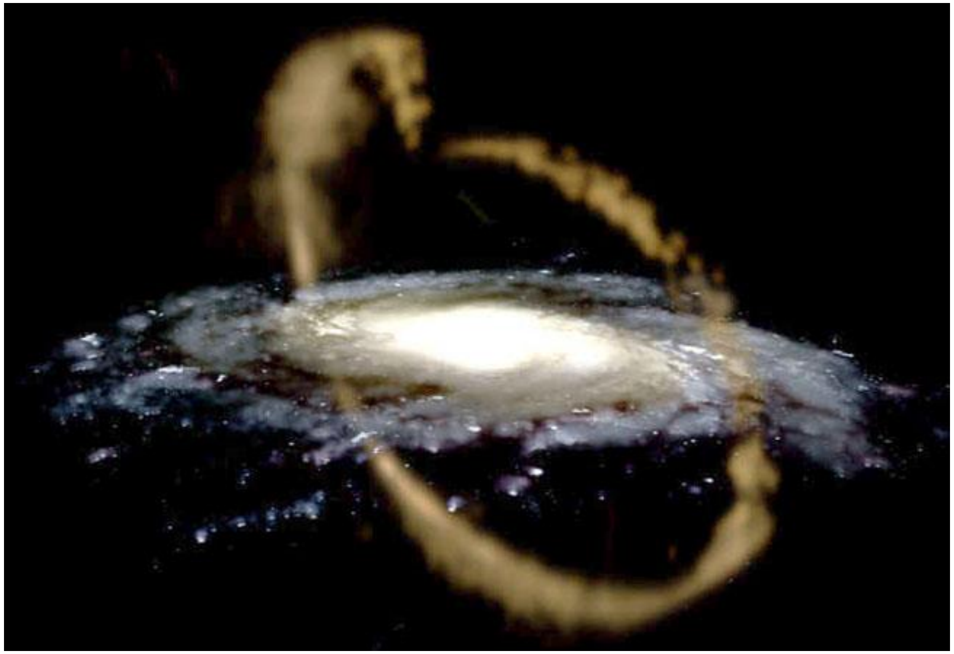
Kallivayalil et al. 2013

Magellanic Stream



Magellanic Clouds are accompanied by a 100°-long stream of gas

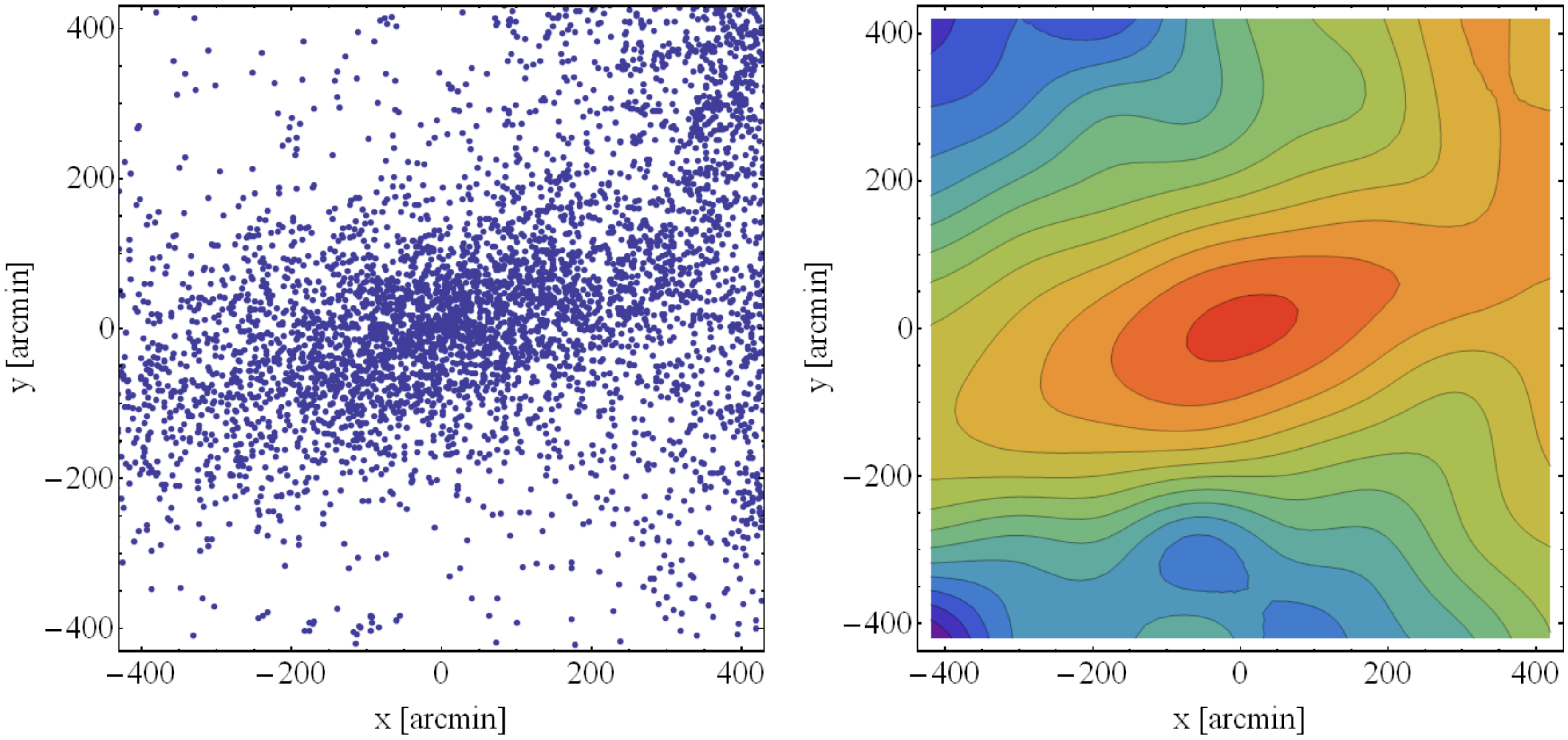
The Sagittarius dwarf



Due to its proximity to the Milky Way Sgr must be strongly affected by tidal forces.

- Distance from the Sun: d=24 kpc,
- Orbital pericenter ~16 kpc, apocenter ~60 kpc
- The stream of Sgr has been mapped in detail
- The stream can be used to constrain the potential of the MW

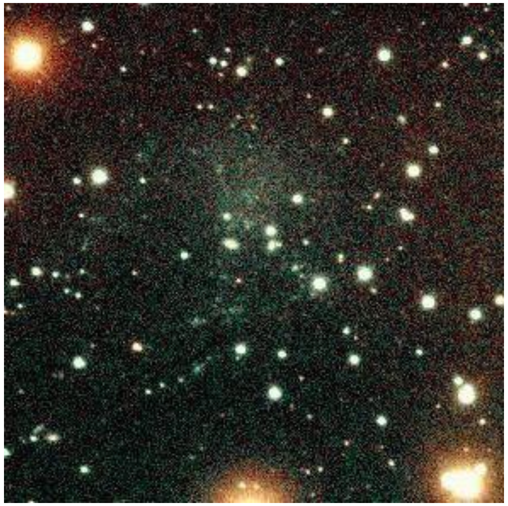
Distribution of stars in Sgr



Majewski et al. 2003

What is the origin of this shape?

Dwarf spheroidals

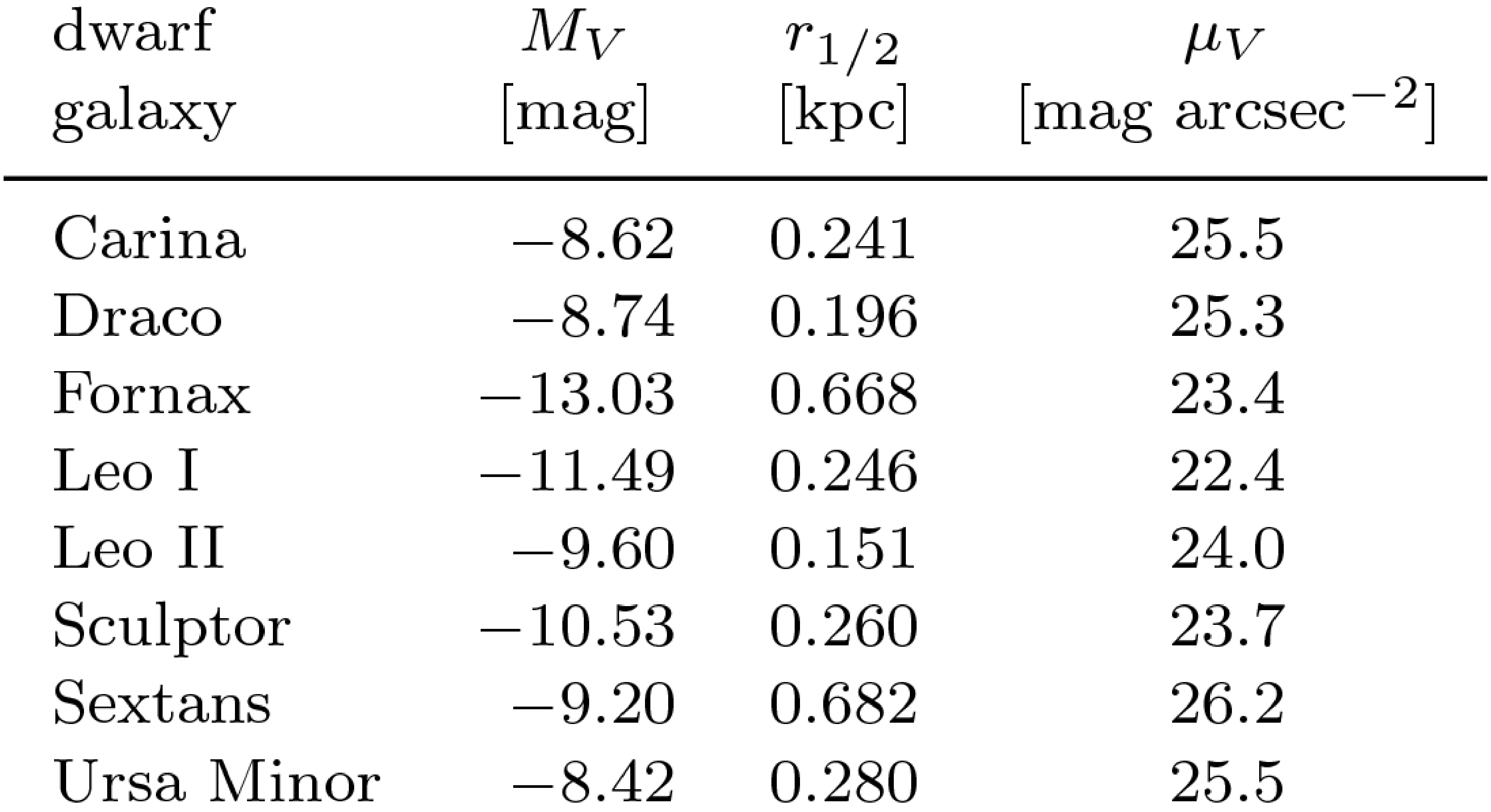


Carina

Fornax

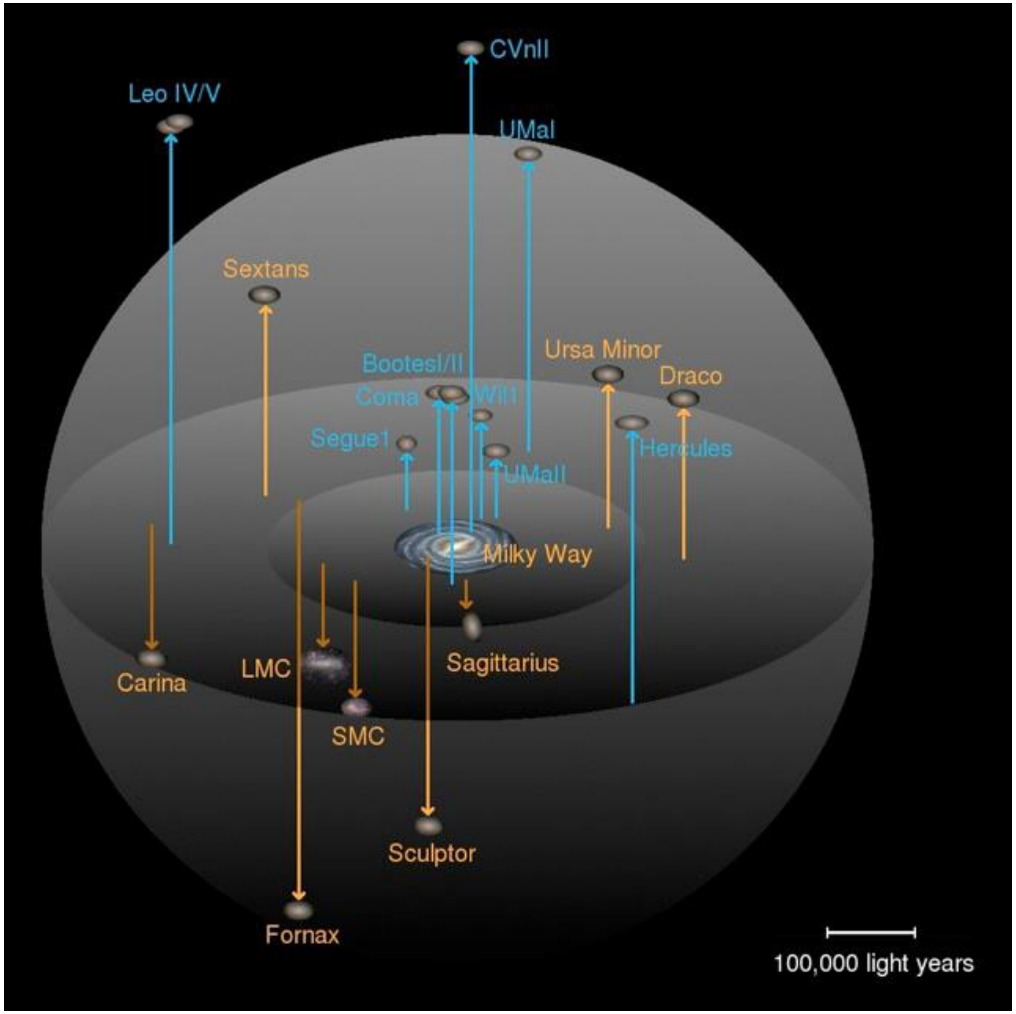
- The only galaxies for which individual stars can be resolved and their velocities measured
- Velocity dispersions are so large that the galaxies are believed to be dominated by dark matter, M/L~10-100
- Observed numbers are too small to agree with theory
- Could be formed by interactions

Classical dSphs of the Milky Way



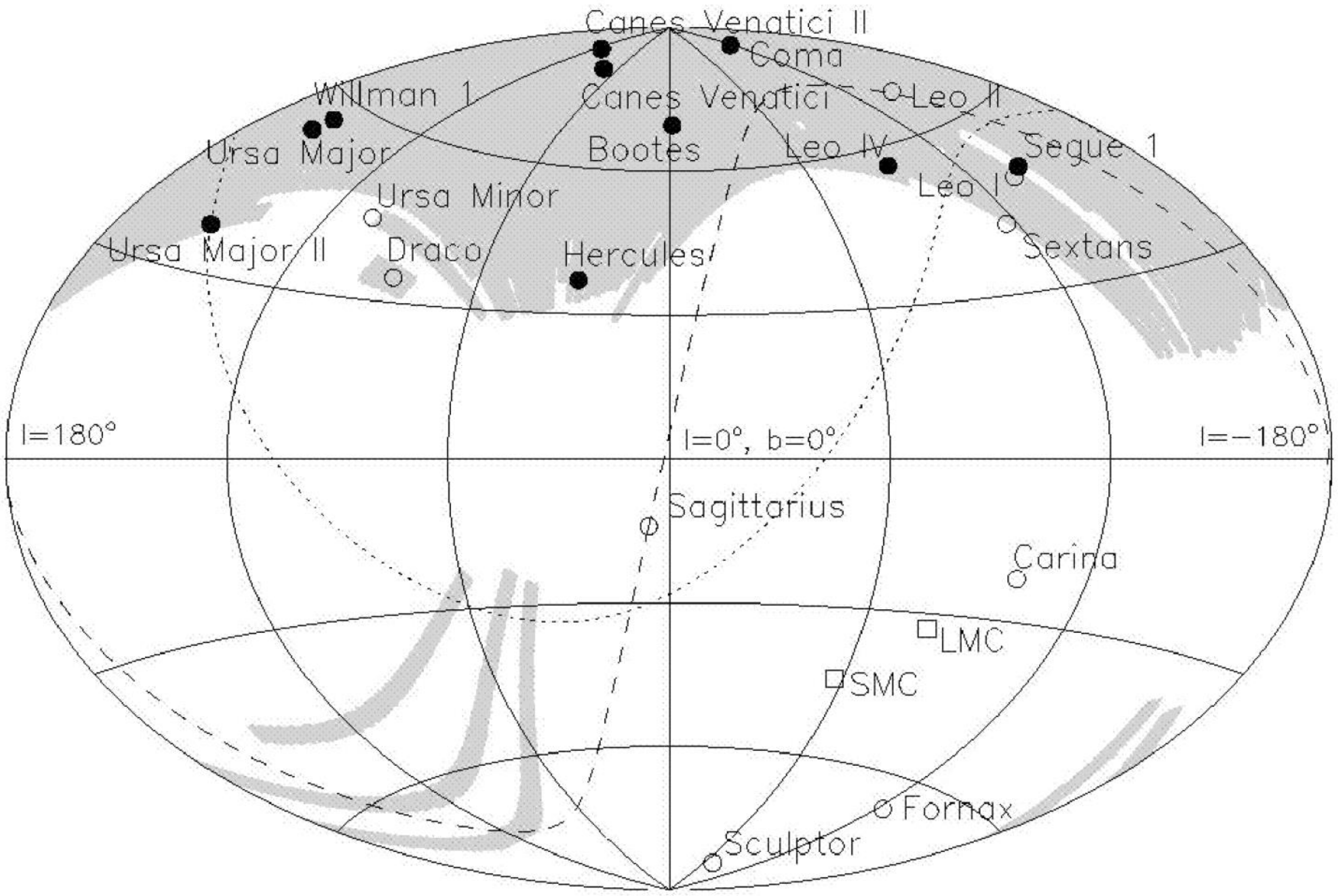
dwarf galaxy	M_V [mag]	$r_{1/2}$ [kpc]	μ_V [mag arcsec^{-2}]
Carina	-8.62	0.241	25.5
Draco	-8.74	0.196	25.3
Fornax	-13.03	0.668	23.4
Leo I	-11.49	0.246	22.4
Leo II	-9.60	0.151	24.0
Sculptor	-10.53	0.260	23.7
Sextans	-9.20	0.682	26.2
Ursa Minor	-8.42	0.280	25.5

New discoveries in SDSS



- Fainter than classical dSph but relatively nearby (40–220 kpc)
- More irregular and metal poor
- More dark matter dominated?
- Believed to be the missing satellites

Ultra-faint satellites



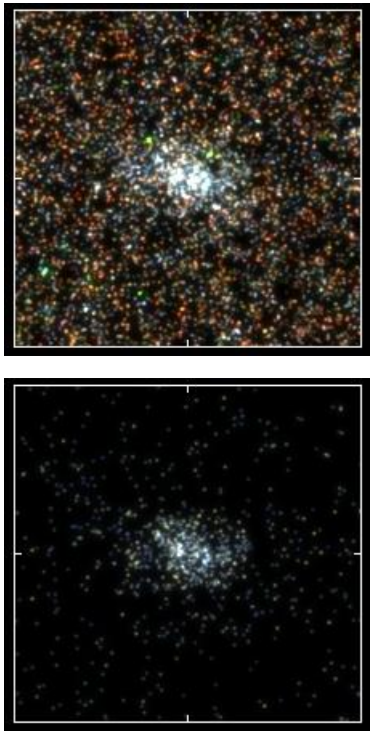
Belokurov et al. (2007), SDSS

● newly discovered

○ known before

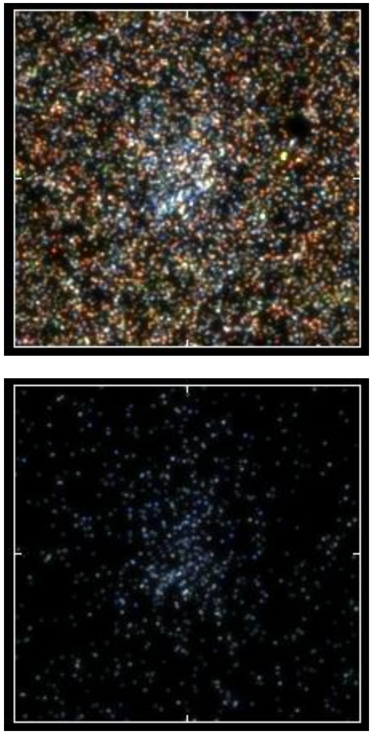
New dwarfs

Canes Venatici I



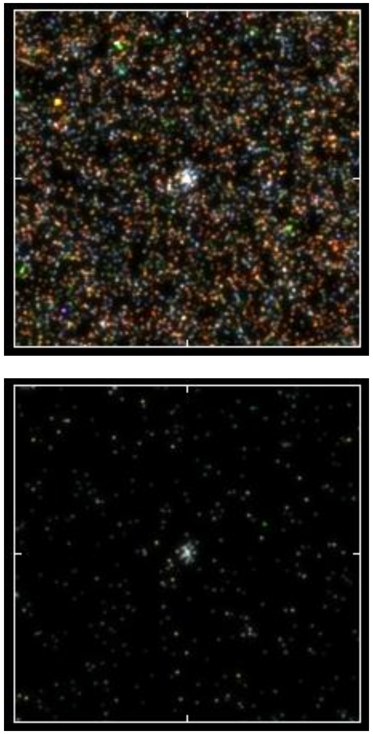
d = 220 kpc

Bootes



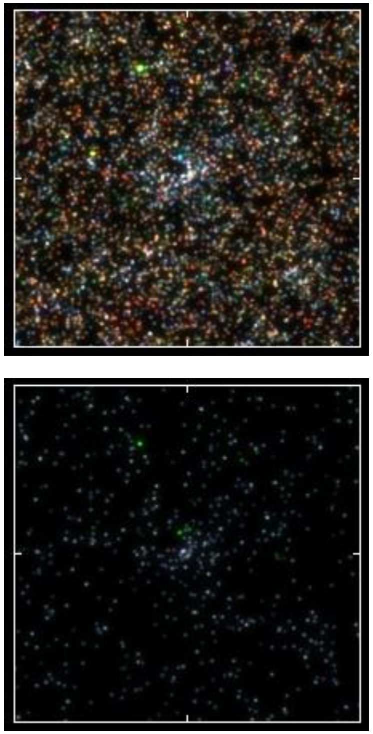
d = 60 kpc

Canes Venatici II



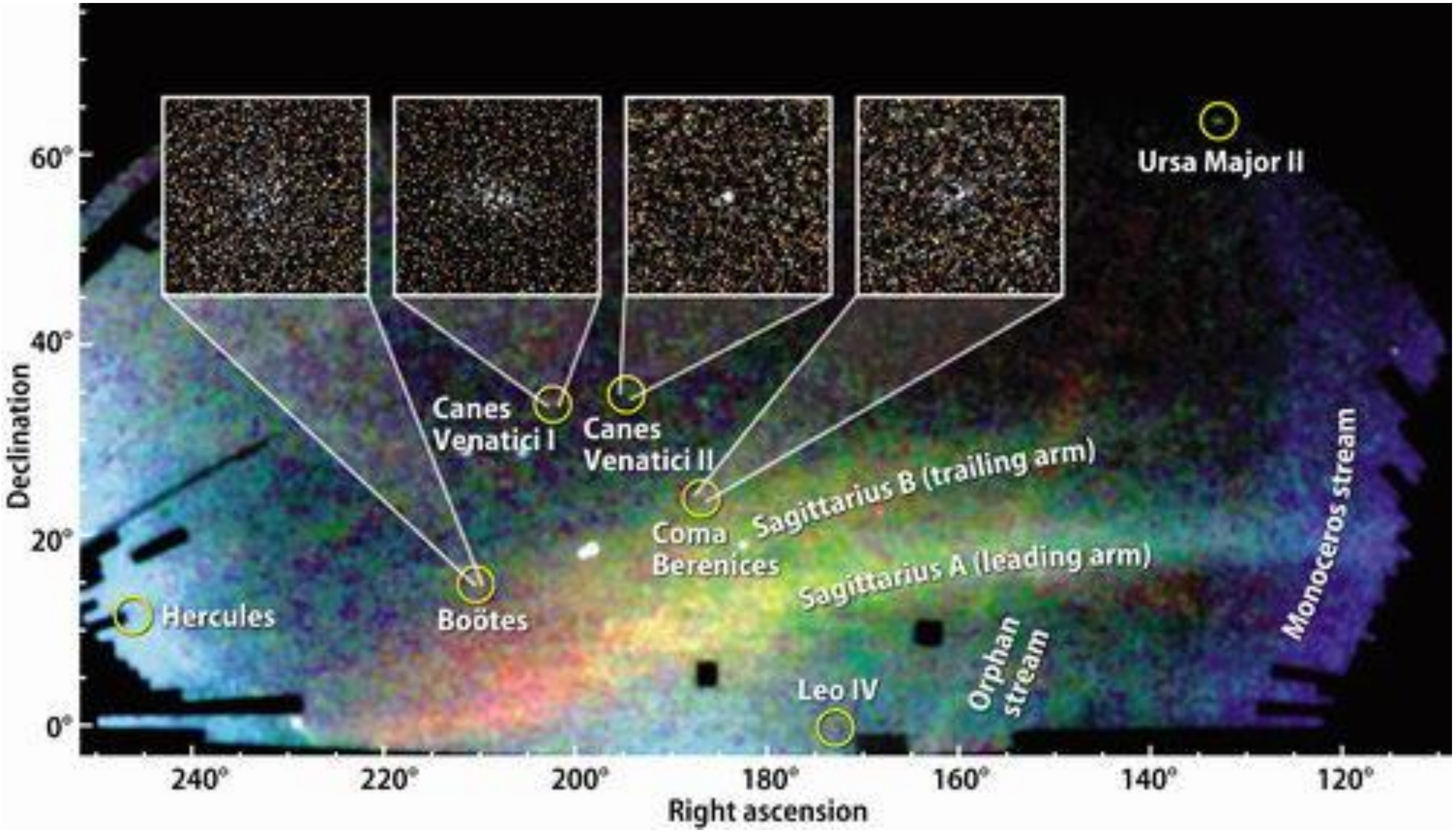
d = 150 kpc

Coma Berenices



d = 44 kpc

„Field of streams”



Belokurov et al. (2006)

The field of streams contains newly discovered dwarfs as well as streams from disrupted satellites

Properties of new dwarfs

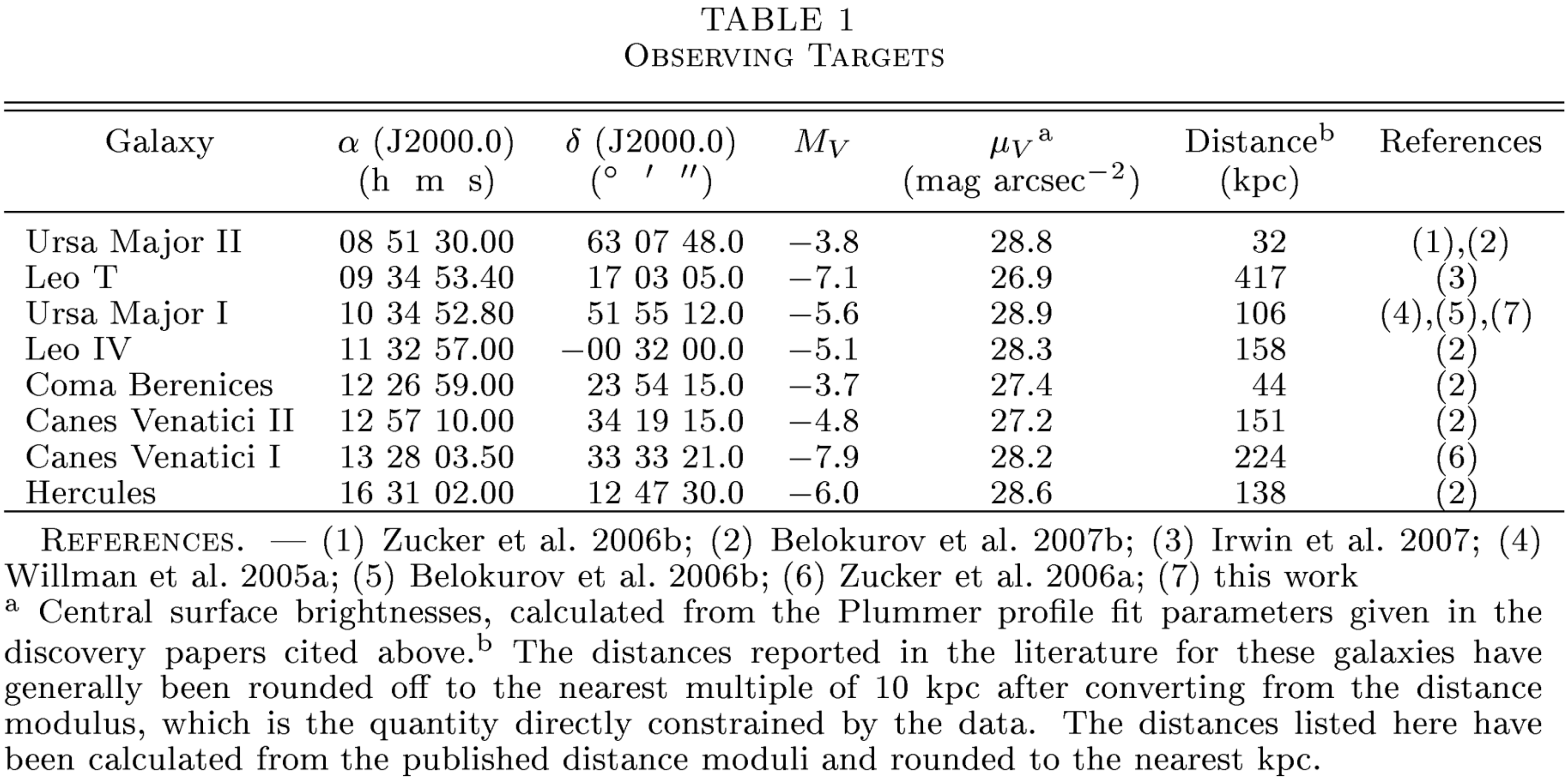


TABLE 1
OBSERVING TARGETS

Galaxy	α (J2000.0) (h m s)	δ (J2000.0) ($^\circ$ $'$ $''$)	M_V	μ_V[a] (mag arcsec^{-2})	Distance[b] (kpc)	References
Ursa Major II	08 51 30.00	63 07 48.0	−3.8	28.8	32	(1),(2)
Leo T	09 34 53.40	17 03 05.0	−7.1	26.9	417	(3)
Ursa Major I	10 34 52.80	51 55 12.0	−5.6	28.9	106	(4),(5),(7)
Leo IV	11 32 57.00	−00 32 00.0	−5.1	28.3	158	(2)
Coma Berenices	12 26 59.00	23 54 15.0	−3.7	27.4	44	(2)
Canes Venatici II	12 57 10.00	34 19 15.0	−4.8	27.2	151	(2)
Canes Venatici I	13 28 03.50	33 33 21.0	−7.9	28.2	224	(6)
Hercules	16 31 02.00	12 47 30.0	−6.0	28.6	138	(2)

REFERENCES. — (1) Zucker et al. 2006b; (2) Belokurov et al. 2007b; (3) Irwin et al. 2007; (4) Willman et al. 2005a; (5) Belokurov et al. 2006b; (6) Zucker et al. 2006a; (7) this work

[a] Central surface brightnesses, calculated from the Plummer profile fit parameters given in the discovery papers cited above.[b] The distances reported in the literature for these galaxies have generally been rounded off to the nearest multiple of 10 kpc after converting from the distance modulus, which is the quantity directly constrained by the data. The distances listed here have been calculated from the published distance moduli and rounded to the nearest kpc.

Simon & Geha 2007

M/L for new dwarfs

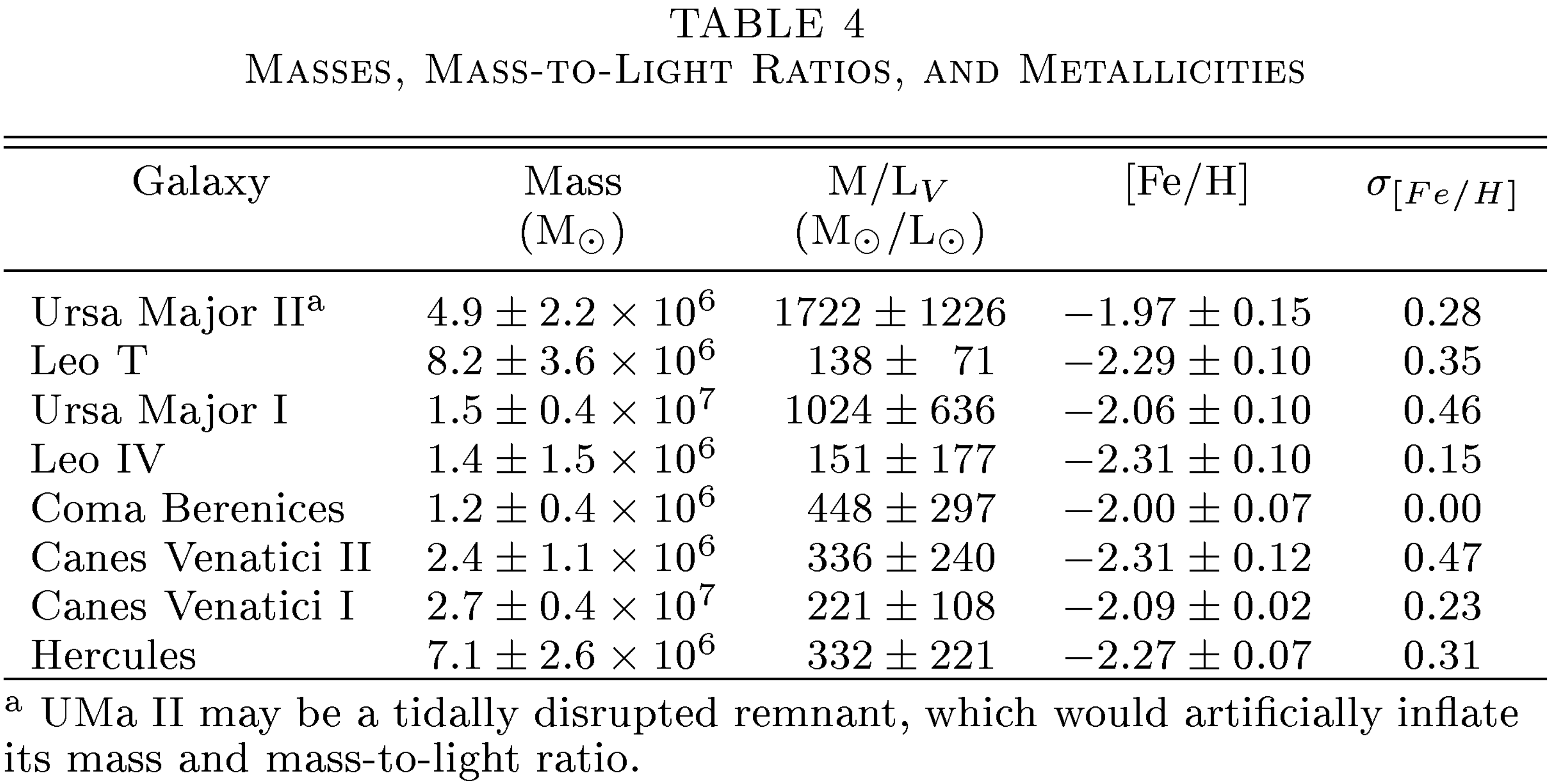


TABLE 4

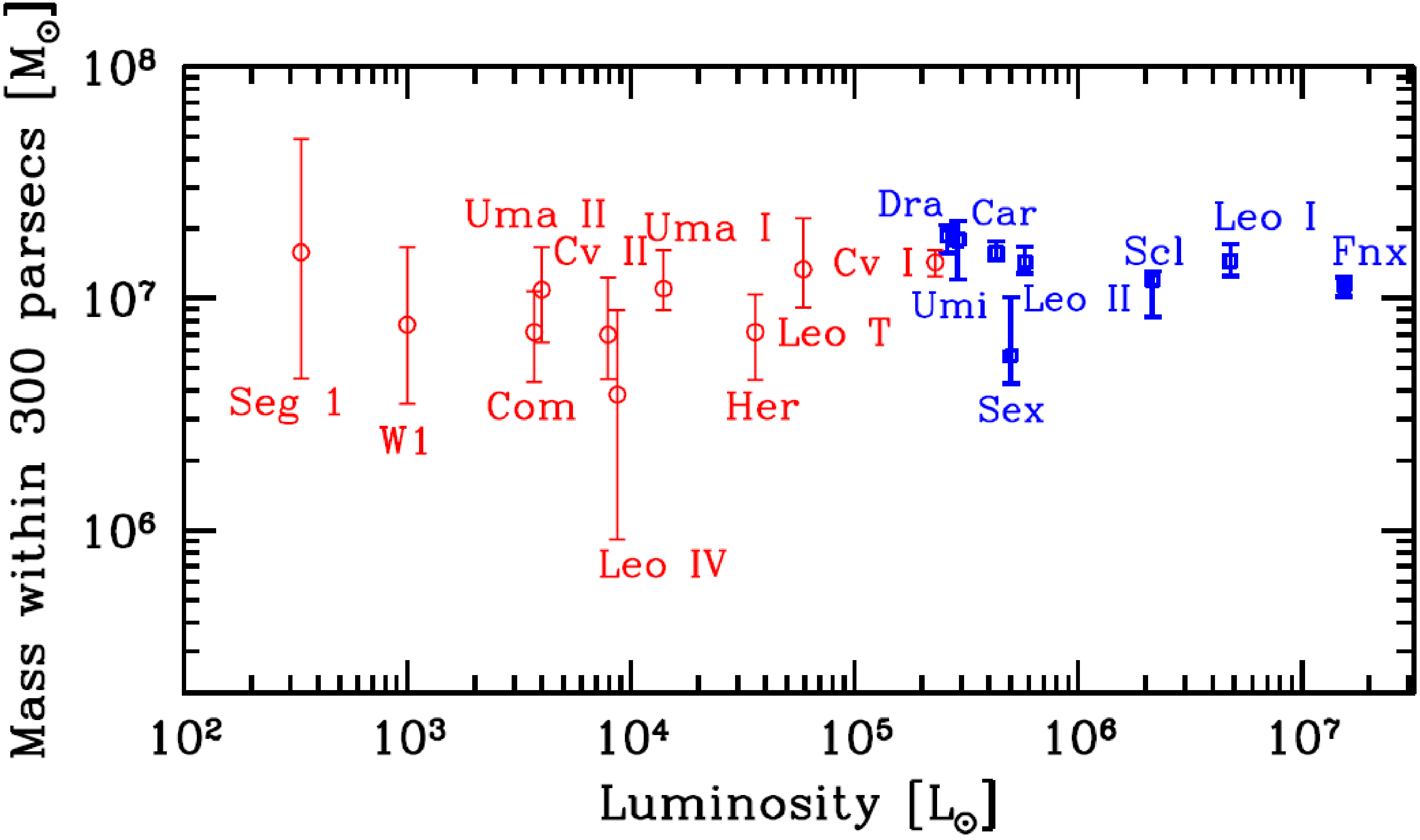
Masses, Mass-to-Light Ratios, and Metallicities

Galaxy	Mass ($M_\odot$)	M/L_V ($M_\odot/L_\odot$)	[Fe/H]	$\sigma_{[Fe/H]}$
Ursa Major II[a]	$4.9 \pm 2.2 \times 10^6$	1722 ± 1226	-1.97 ± 0.15	0.28
Leo T	$8.2 \pm 3.6 \times 10^6$	138 ± 71	-2.29 ± 0.10	0.35
Ursa Major I	$1.5 \pm 0.4 \times 10^7$	1024 ± 636	-2.06 ± 0.10	0.46
Leo IV	$1.4 \pm 1.5 \times 10^6$	151 ± 177	-2.31 ± 0.10	0.15
Coma Berenices	$1.2 \pm 0.4 \times 10^6$	448 ± 297	-2.00 ± 0.07	0.00
Canes Venatici II	$2.4 \pm 1.1 \times 10^6$	336 ± 240	-2.31 ± 0.12	0.47
Canes Venatici I	$2.7 \pm 0.4 \times 10^7$	221 ± 108	-2.09 ± 0.02	0.23
Hercules	$7.1 \pm 2.6 \times 10^6$	332 ± 221	-2.27 ± 0.07	0.31

[a] UMa II may be a tidally disrupted remnant, which would artificially inflate its mass and mass-to-light ratio.

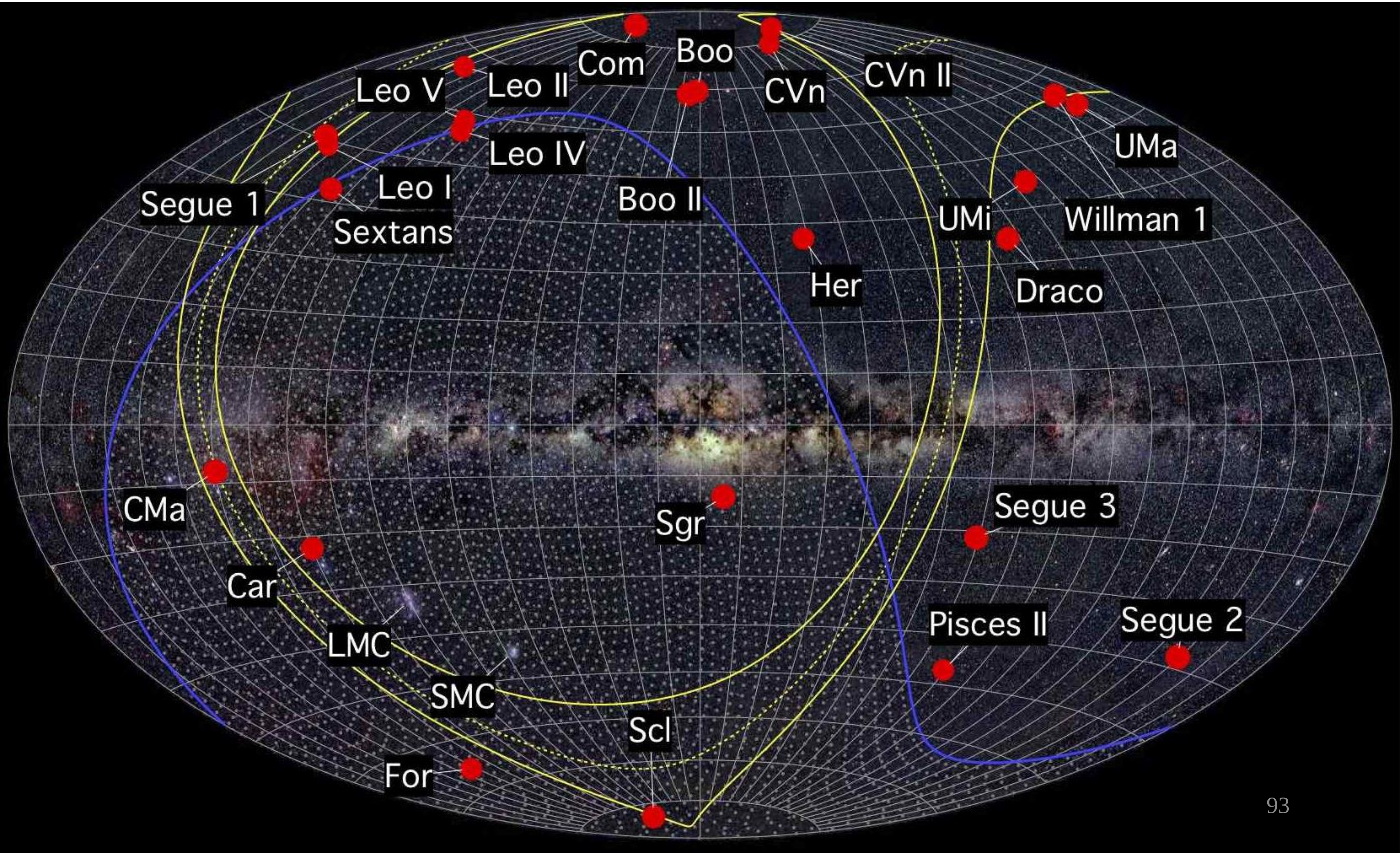
Simon & Geha 2007

Common mass scale?

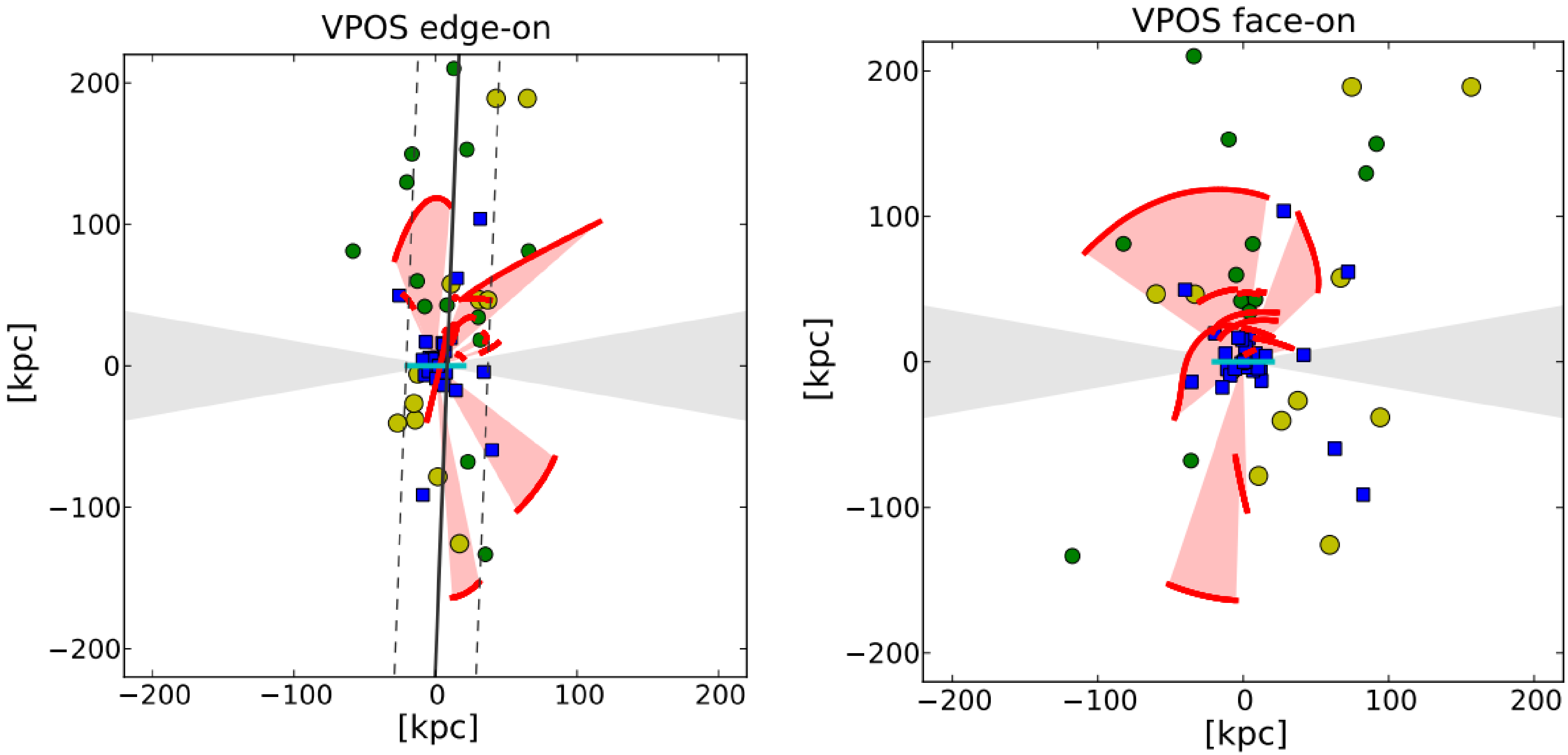


Strigari et al. 2008

Dwarfs of the Milky Way



Vast Polar Structure



The plane formed by classical satellites (yellow dots), new satellites (green dots), GCs (blue squares) and streams (red)

Pawlowski et al. 2012

Neighbourhood of Andromeda

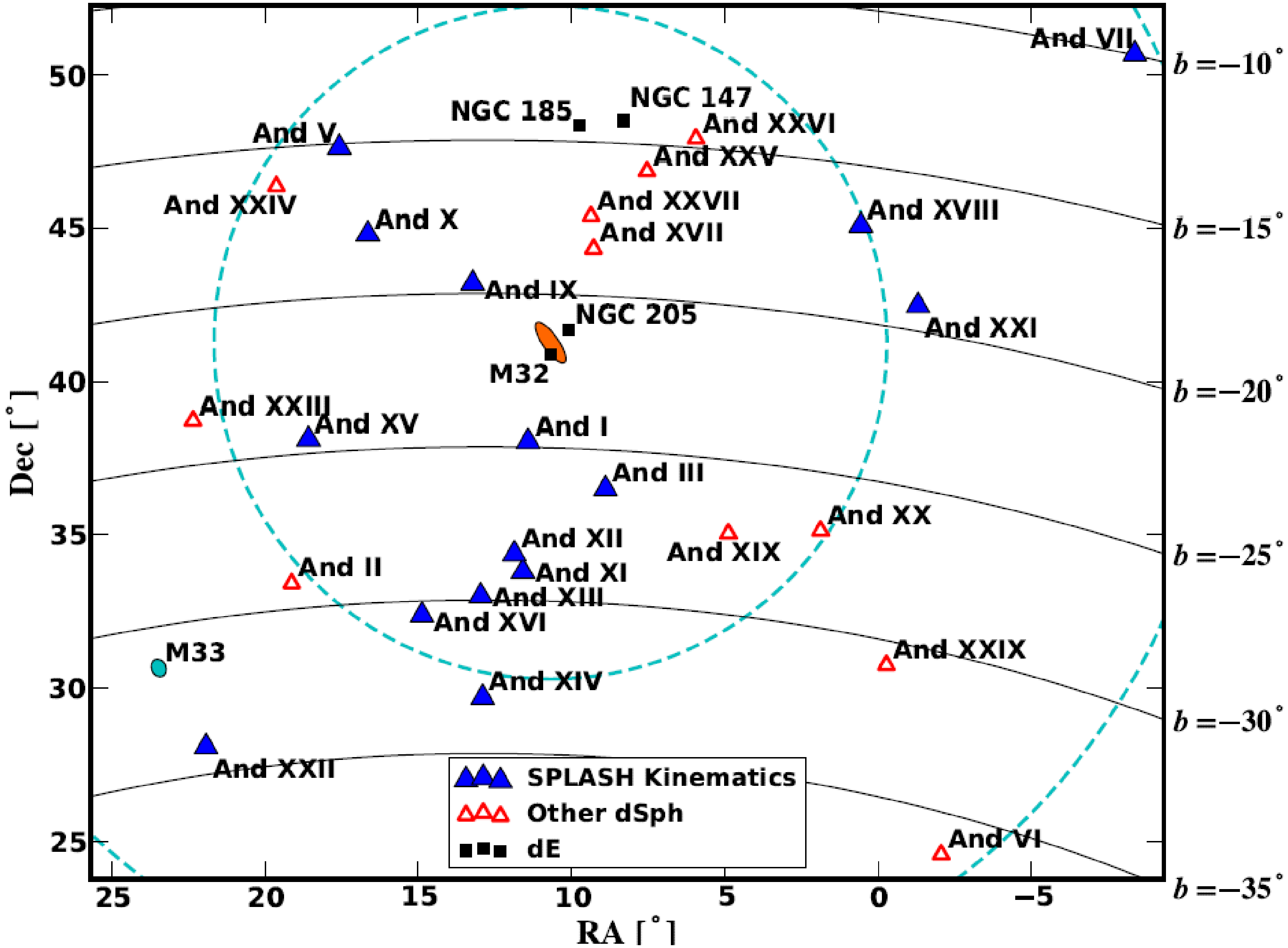
- There is a few tens of dwarf galaxies in the neighbourhood of M31, most of them discovered in recent years
- Some stellar streams have also been found which probably are remnants of dwarf galaxies disrupted by tidal interactions with M31
- Andromeda itself probably formed from mergers of smaller objects
- Such galactic cannibalism is one of the most important processes in the formation of big galaxies

Satellites of Andromeda

Name	Type	Year of discovery
M32	dE2	1749
NGC 205 (M110)	dE5	1773
NGC 185	dE3	1787
NGC 147	dE5	1829
And I-III	dSph	1970
And IV		1972
And V-VII	dSph	1998
And VIII	dSph	2003
And IX	dSph	2004
And X	dSph	2005
And XI-XIII		2006
And XIV-XVI		2007
And XVII-XX		2008
And XXI-XXII		2009
And XXIII-XXIX		2011
And XXX-XXXIII		2013

- Most satellites were discovered in the last decades in different surveys (SDSS, PAndAS)
- Follow-up observations, including the spectroscopy of stars are done by the SPLASH survey

Andromeda's dwarfs



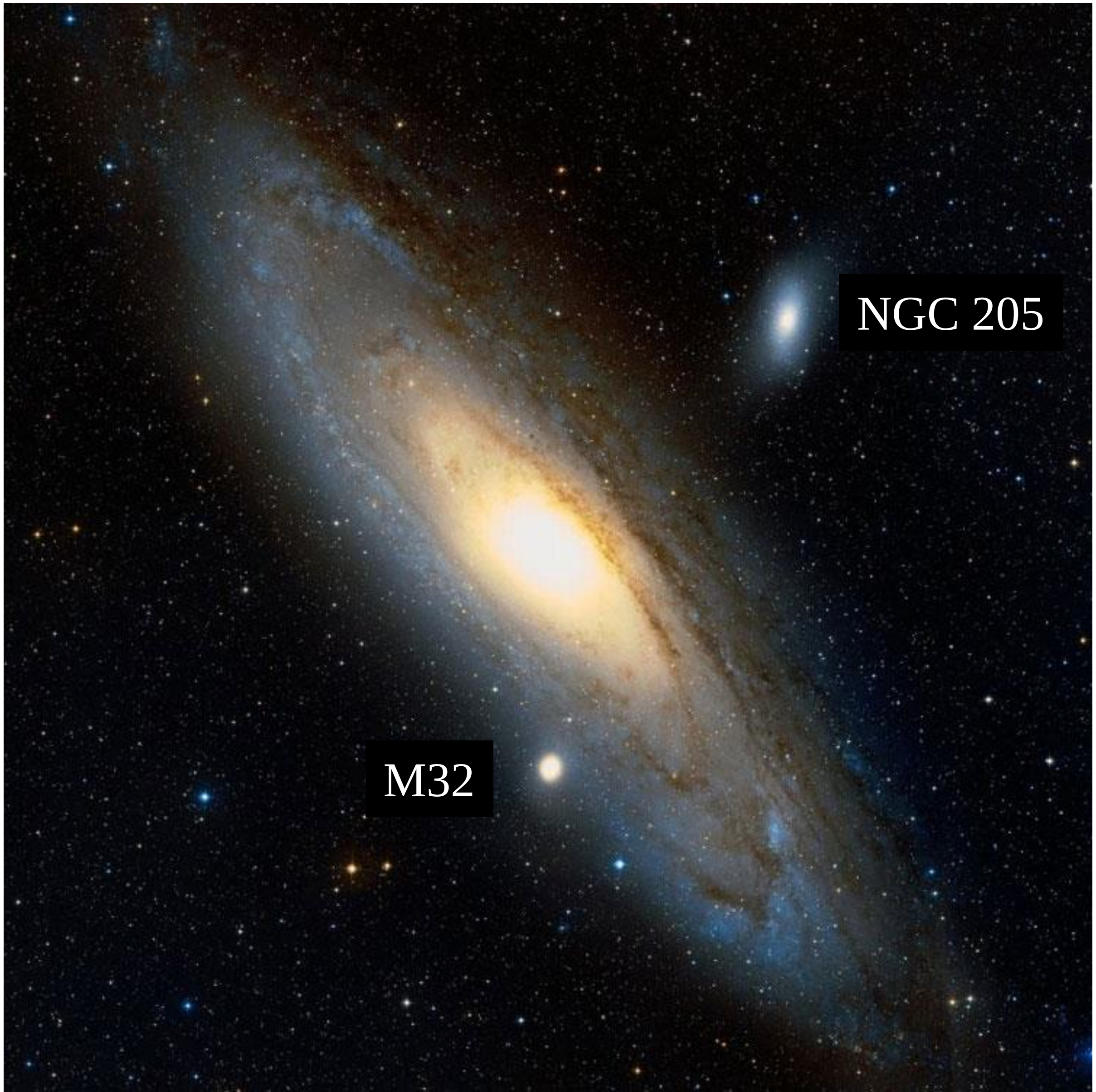
SPLASH = Spectroscopic and Photometric Landscape of Andromeda's Stellar Halo

Tollerud et al. 2012

What about ellipticals?

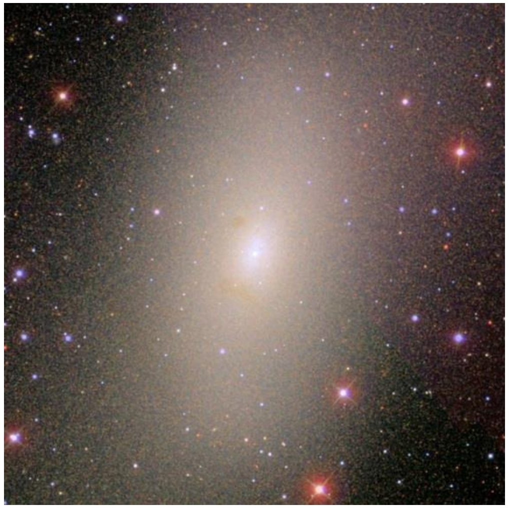
- There are no big elliptical galaxies in the Local Group
- There are no dwarf elliptical galaxies near the Milky Way
- There are 4 dE galaxies near Andromeda

Ellipticals near M31



Ellipticals near M31

M32 (cE2)



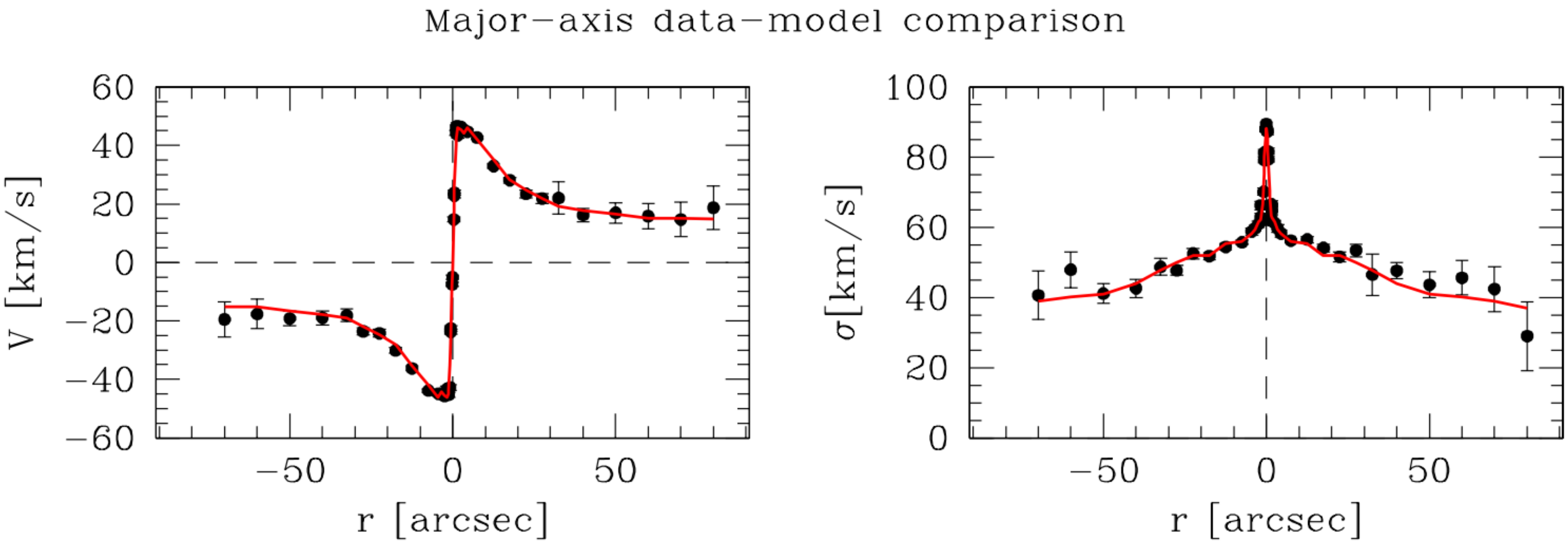
NGC 205 (E5)

NGC 185 (E2)

NGC 147 (E5)

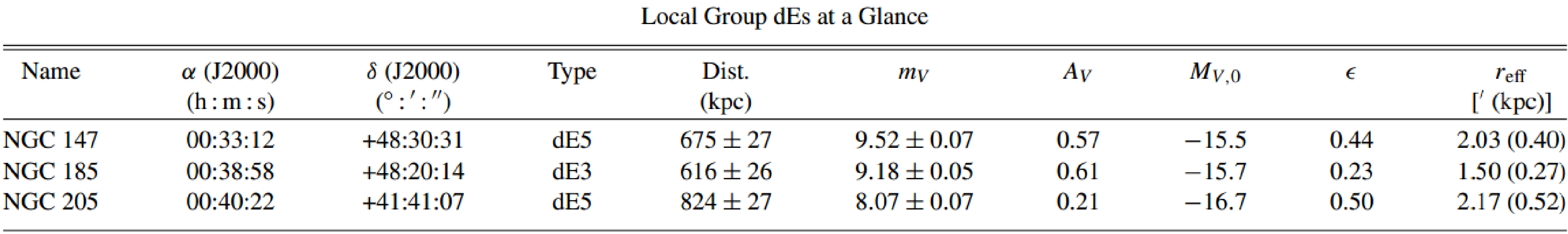
M32

- Kinematics of M32 has been recently measured and modelled in detail
- Constant M/L (=1-2 $M_\odot$ /$L_\odot$) axisymmetric models with a central black hole of mass 2.4 x 10^6 $M_\odot$ reproduce the data well (no dark matter needed out to 3 effective radii!)



Howley et al. 2013, SPLASH survey

Other ellipticals



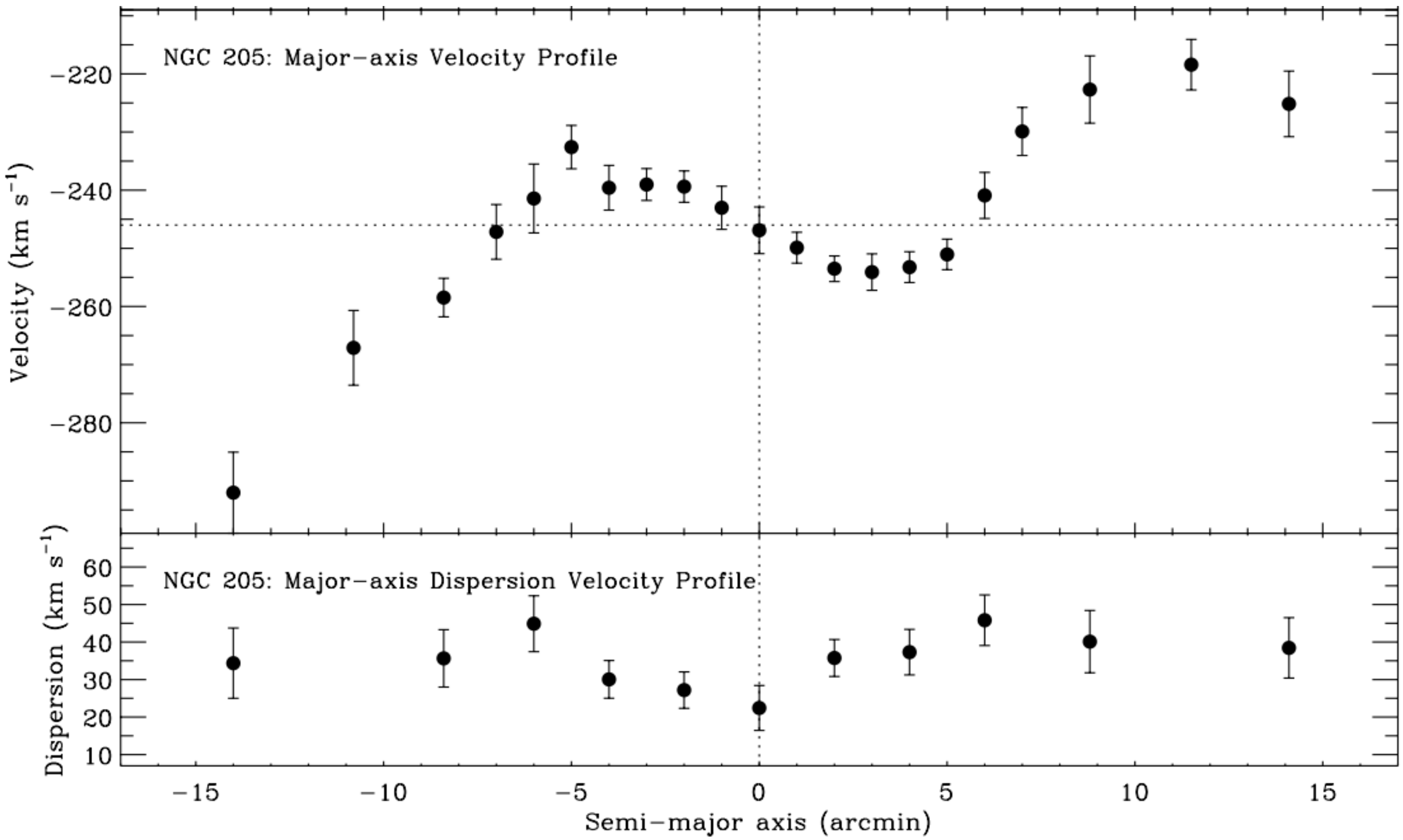
Local Group dEs at a Glance

Name	α (J2000) (h : m : s)	δ (J2000) (° : ′ : ″)	Type	Dist. (kpc)	m_V	A_V	$M_{V,0}$	ϵ	r_{eff} [′ (kpc)]
NGC 147	00:33:12	+48:30:31	dE5	675 ± 27	9.52 ± 0.07	0.57	−15.5	0.44	2.03 (0.40)
NGC 185	00:38:58	+48:20:14	dE3	616 ± 26	9.18 ± 0.05	0.61	−15.7	0.23	1.50 (0.27)
NGC 205	00:40:22	+41:41:07	dE5	824 ± 27	8.07 ± 0.07	0.21	−16.7	0.50	2.17 (0.52)

Geha et al. 2010

- All these galaxies have luminosities of the order of a few times 10^8 $L_\odot$ and masses ~10^9 $M_\odot$
- Their properties are similar to dEs found in nearby galaxy clusters such as Virgo
- However, their dynamics may be different: NGC 205 seems to be affected by M31 while NGC 147 and 185 may form a bound pair

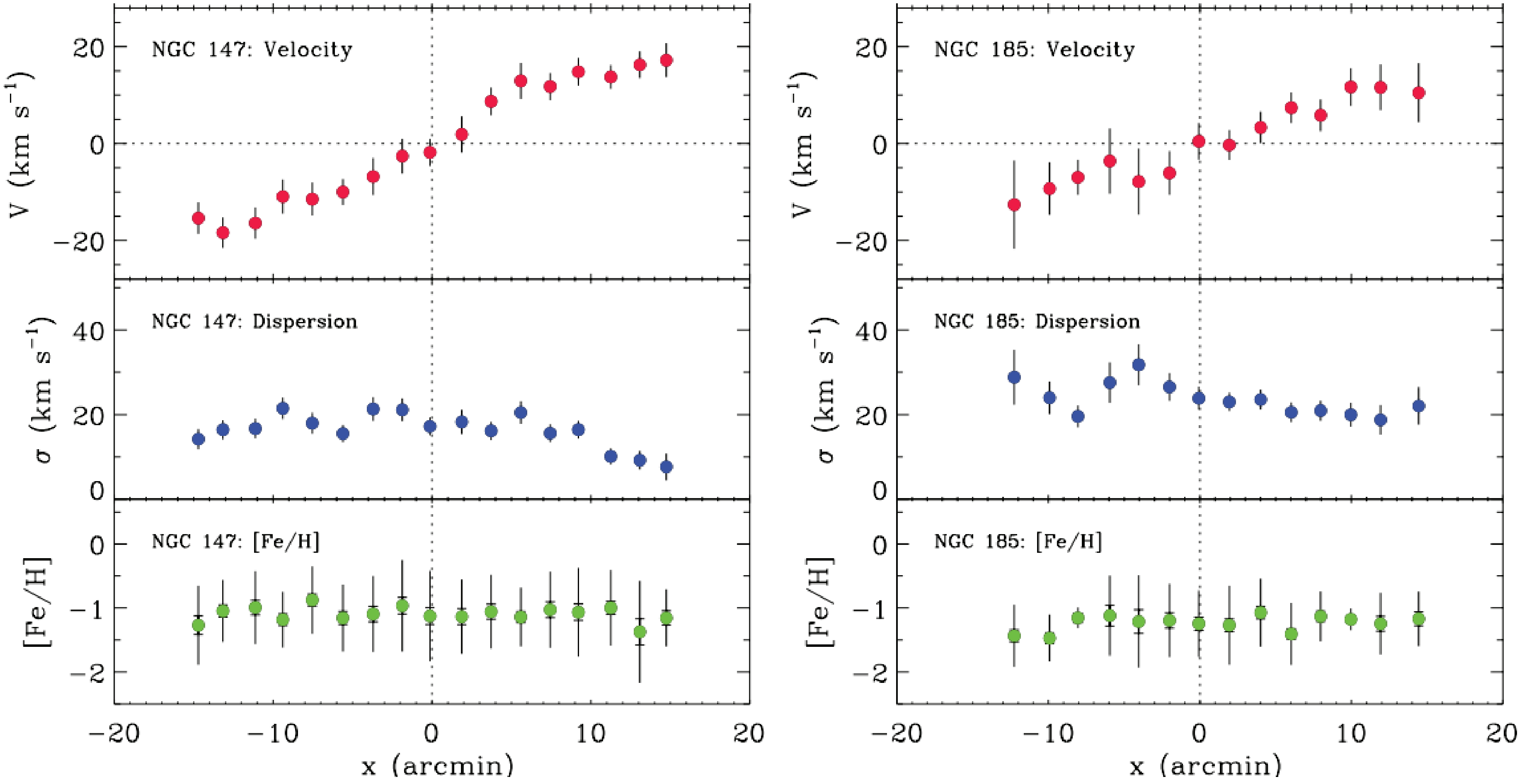
NGC 205



The change of the direction of rotation signifies the transition to tidal tails around 1 kpc, data reproduced with M/L ~ 7

Geha et al. 2006

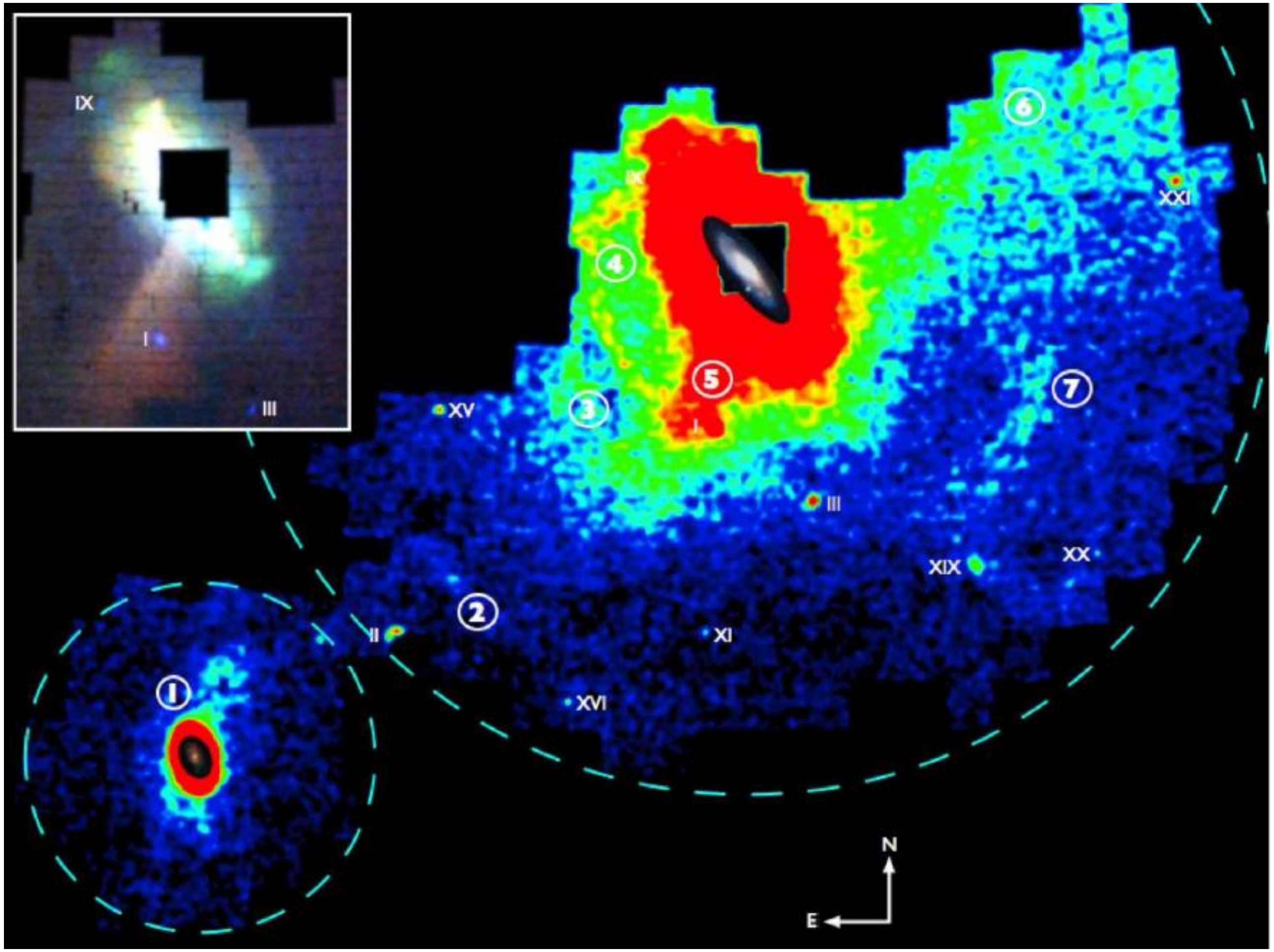
NGC 147 & 185



Both galaxies have similar properties with significant rotation along the major axis, M/L ~ 4-5

Geha et al. 2010

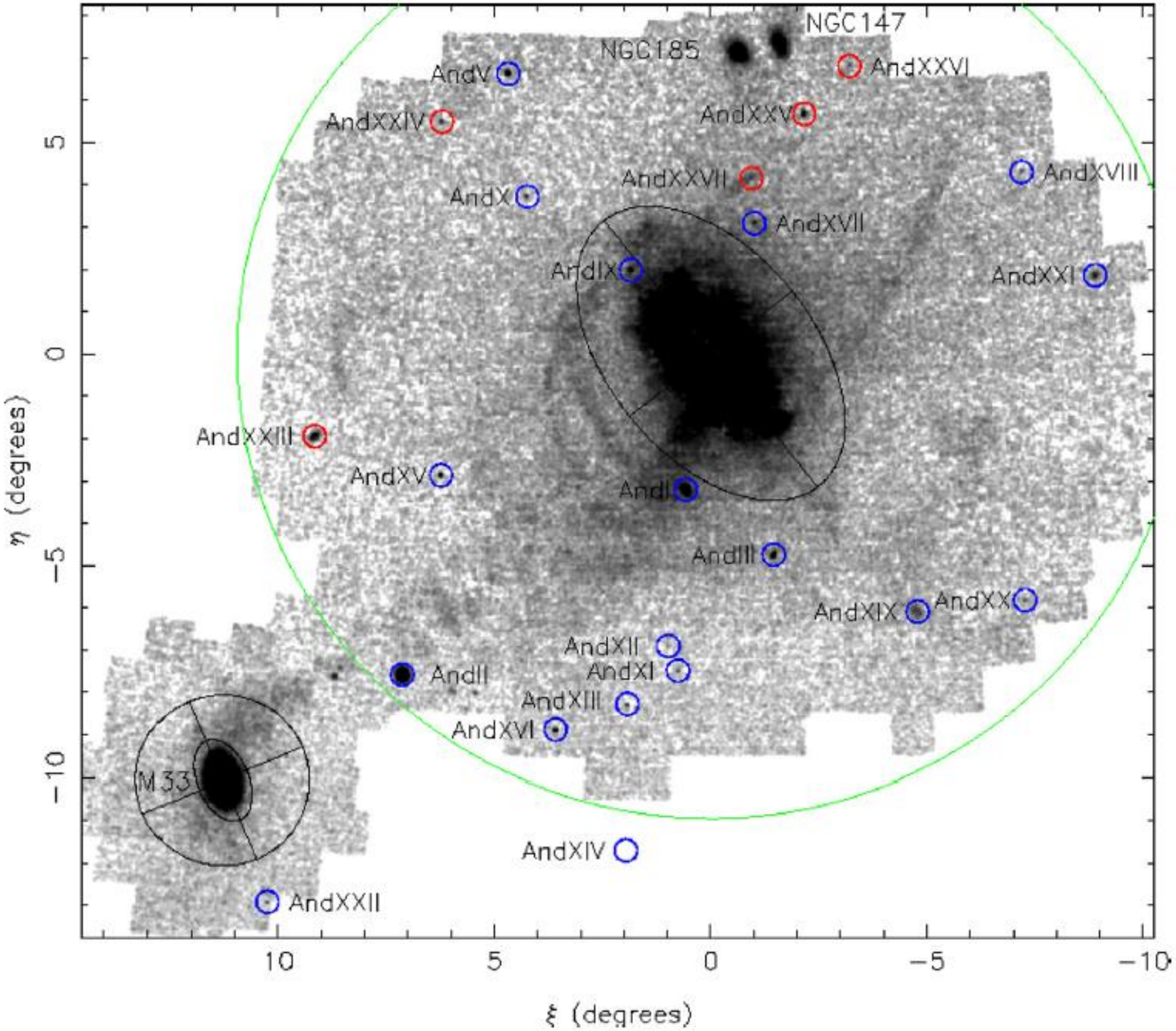
PAndAS Survey



PAndAS = Pan-Andromeda Archaeological Survey

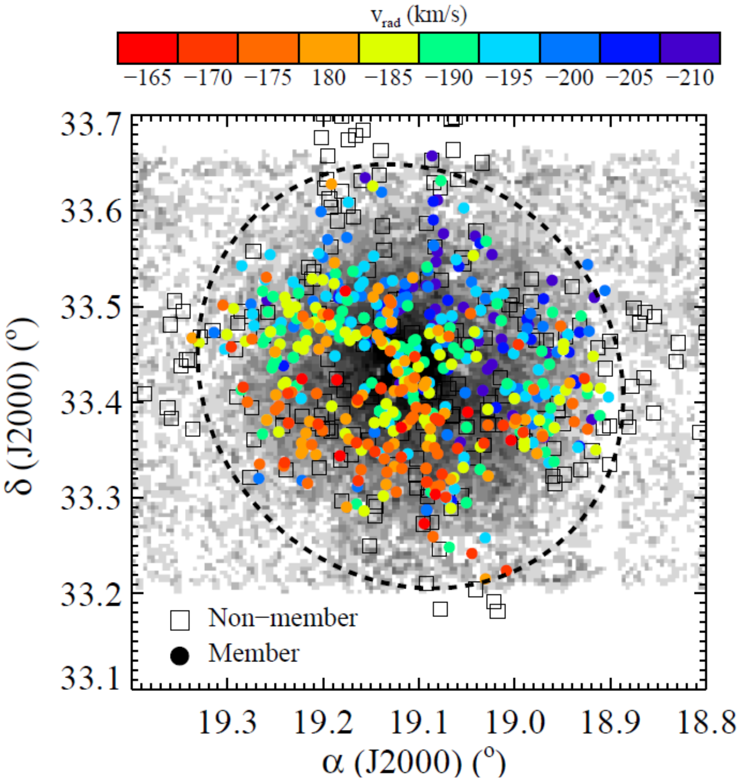
McConnachie et al. 2009

Discovery of And XXIII-XXVII

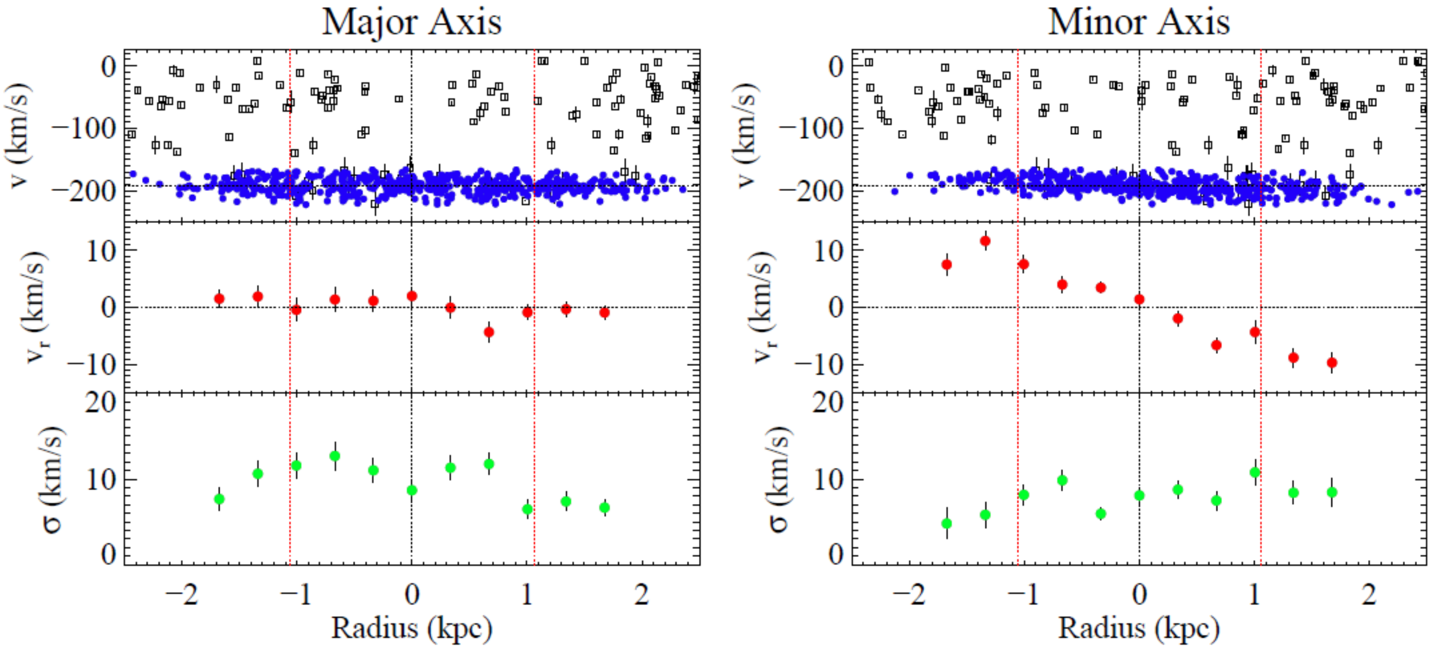


PAndAS, Richardson et al. 2011

Prolate rotation in And II

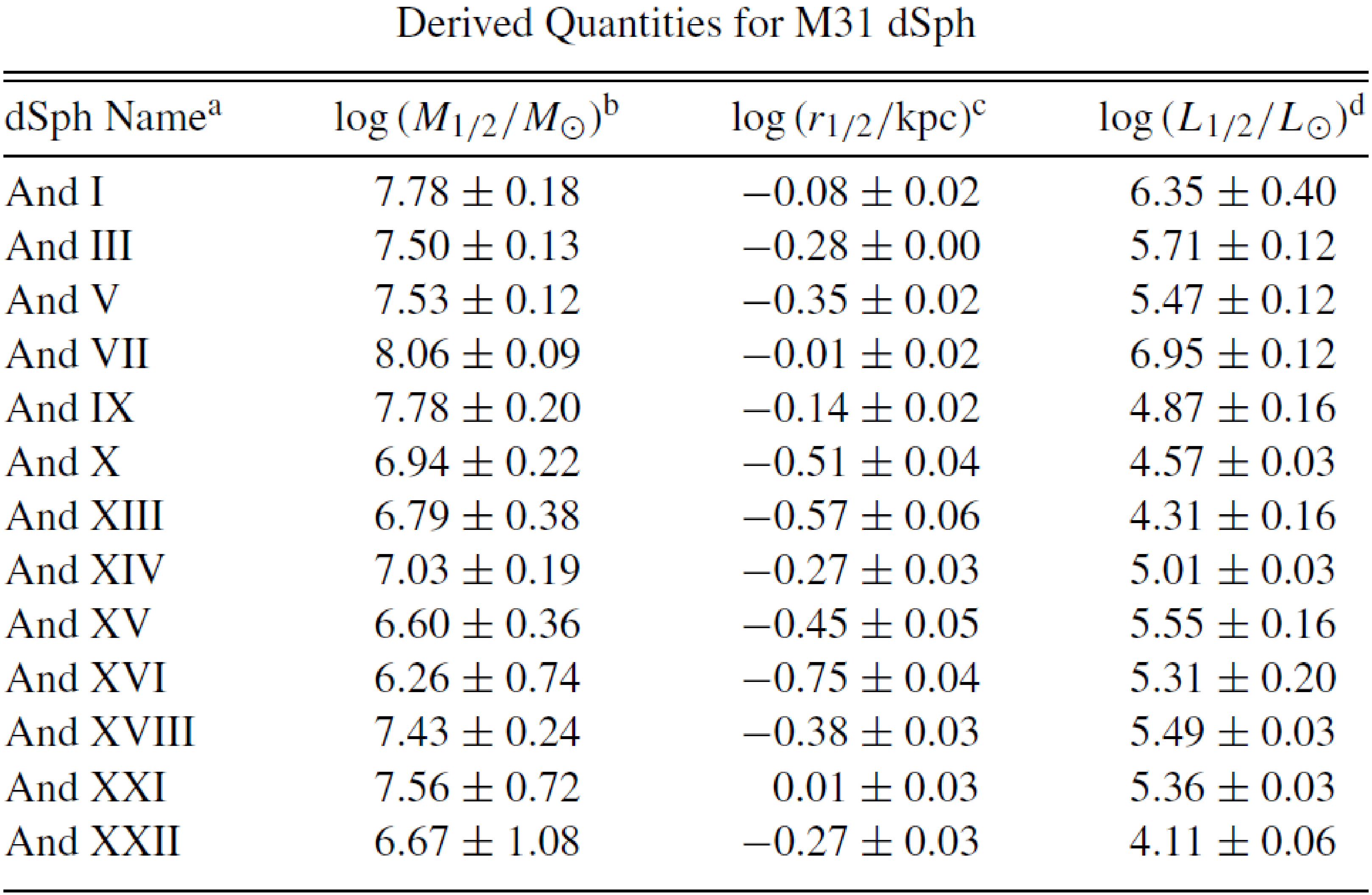


- Kinematics from 531 RGB stars
- First dwarf galaxy to show prolate rotation



Ho et al. 2012

Mass and light estimates

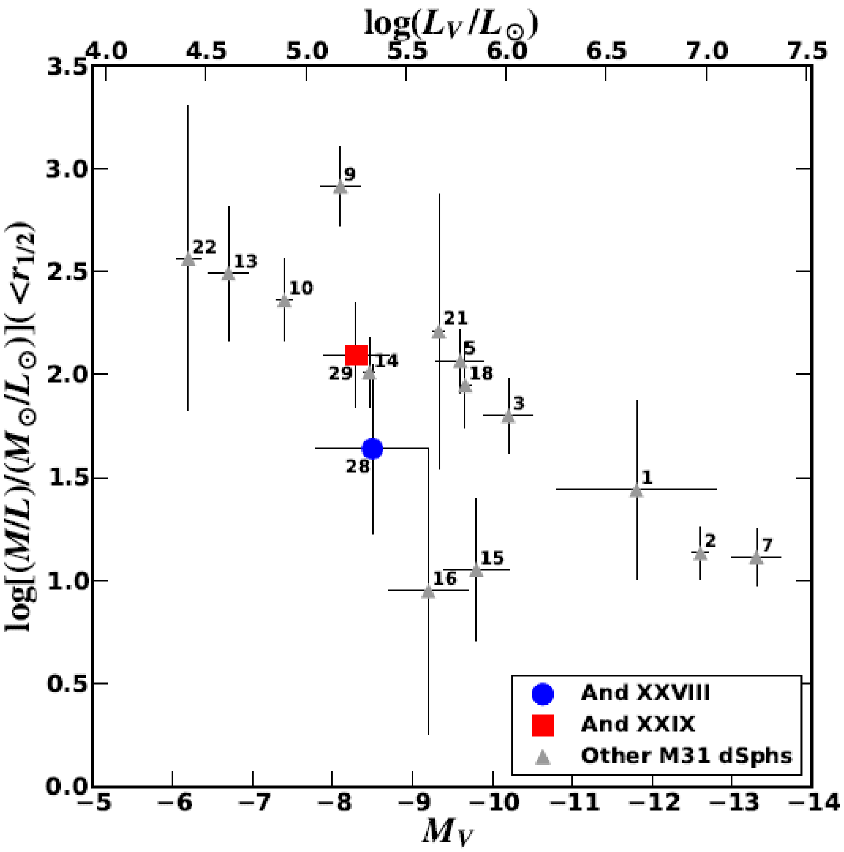


Derived Quantities for M31 dSph

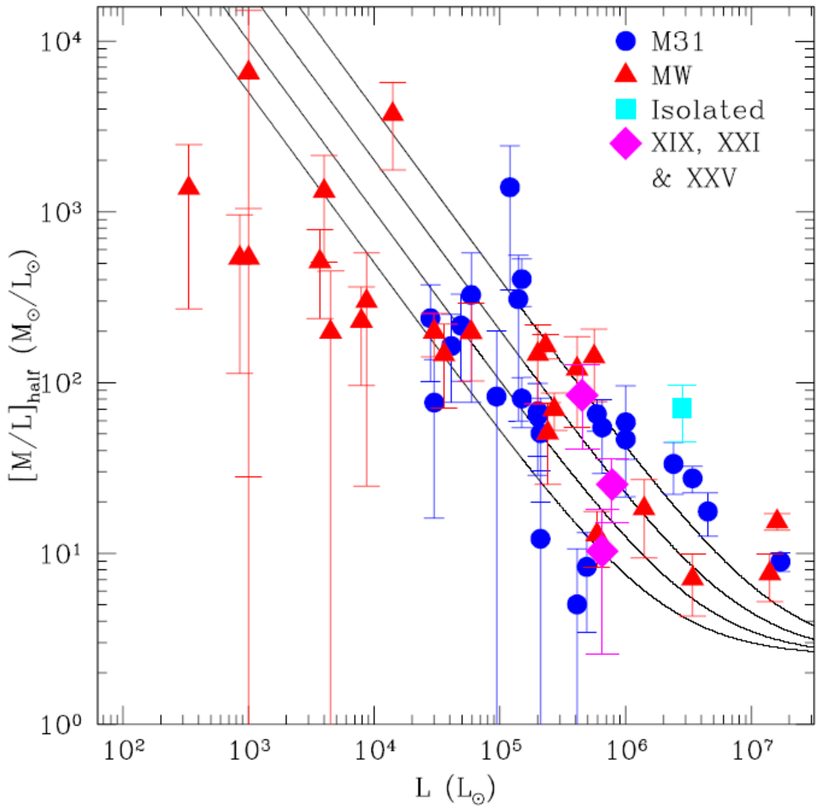
dSph Name[a]	$\log(M_{1/2}/M_\odot)$[b]	$\log(r_{1/2}/\mathrm{kpc})$[c]	$\log(L_{1/2}/L_\odot)$[d]
And I	7.78 ± 0.18	-0.08 ± 0.02	6.35 ± 0.40
And III	7.50 ± 0.13	-0.28 ± 0.00	5.71 ± 0.12
And V	7.53 ± 0.12	-0.35 ± 0.02	5.47 ± 0.12
And VII	8.06 ± 0.09	-0.01 ± 0.02	6.95 ± 0.12
And IX	7.78 ± 0.20	-0.14 ± 0.02	4.87 ± 0.16
And X	6.94 ± 0.22	-0.51 ± 0.04	4.57 ± 0.03
And XIII	6.79 ± 0.38	-0.57 ± 0.06	4.31 ± 0.16
And XIV	7.03 ± 0.19	-0.27 ± 0.03	5.01 ± 0.03
And XV	6.60 ± 0.36	-0.45 ± 0.05	5.55 ± 0.16
And XVI	6.26 ± 0.74	-0.75 ± 0.04	5.31 ± 0.20
And XVIII	7.43 ± 0.24	-0.38 ± 0.03	5.49 ± 0.03
And XXI	7.56 ± 0.72	0.01 ± 0.03	5.36 ± 0.03
And XXII	6.67 ± 1.08	-0.27 ± 0.03	4.11 ± 0.06

Tollerud et al. 2012

Mass-to-light ratios

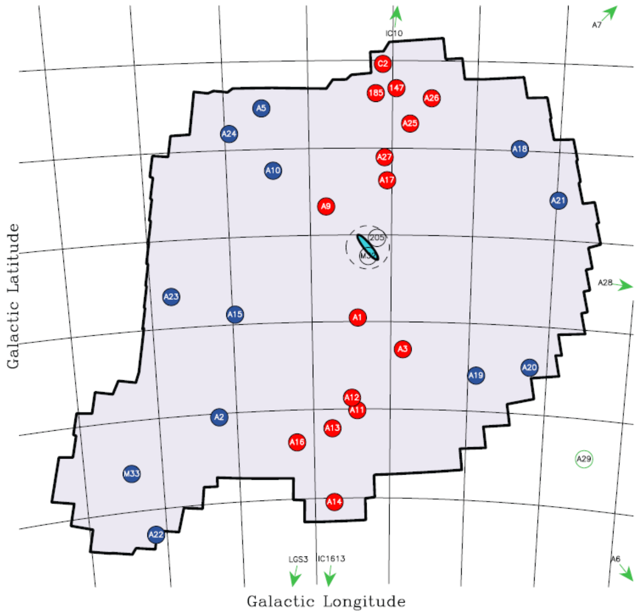


Tollerud et al. 2013



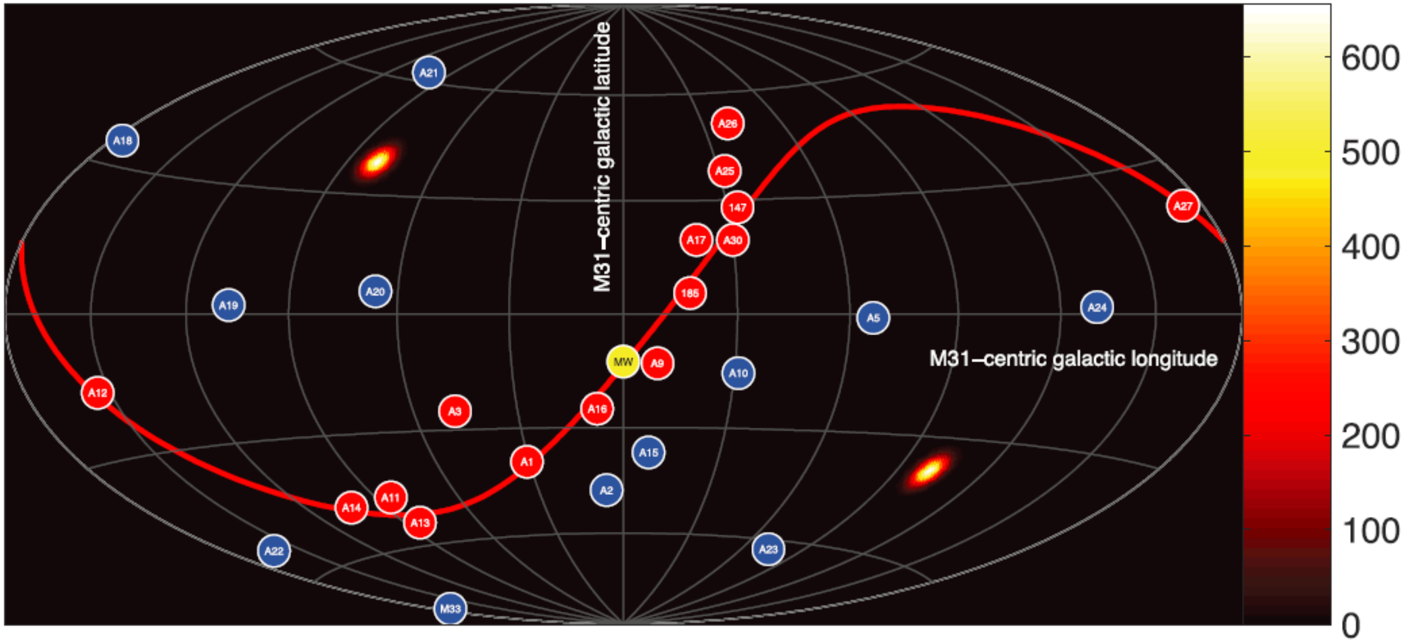
Collins et al. 2013

Andromeda dwarfs are dark matter dominated systems like Milky Way dwarfs



Plane of satellites?

- 15 of 27 satellites of M31 seem to be aligned in a plane perpendicular to the MW disk
- 13 of 15 move in the same direction around M31



Ibata et al. 2013