DARK MATTER
IN ASTROPHYSICAL STRUCTURES

CLUSTERS | GALAXIES | MILKY WAY

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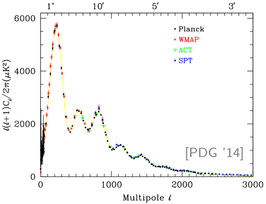
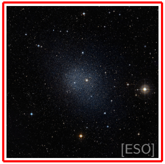
OUTLINE



[– this Lecture –]



time

redshift

big bang nucleosynthesis

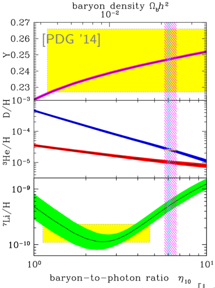
cosmic microwave background

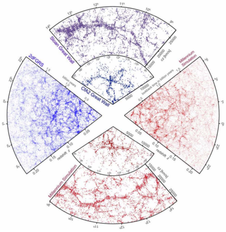
large scale structure

dwarfs

galaxies

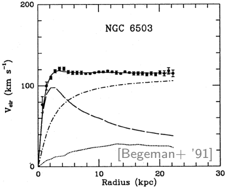
galaxy clusters

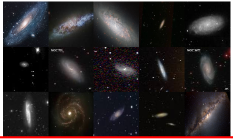




[Springel+ '06]

[Lectures: Serpico, Sheth]





OUTLINE

DARK MATTER IN ASTROPHYSICAL STRUCTURES

Part I. Clusters

- Virial estimates
- Hot gas emission
- Sunyaev-Zeldovich effect
- Gravitational lensing
- Merging clusters

Part II. Galaxies

- Hubble sequence
- Ellipticals
- Spirals
- Dwarfs

Part III. Milky Way

- Tour of the Galaxy
- Kinematics
- Dark matter content
- State of the art and future

II. GALAXIES 101

Let us start with the very basics: the notion of stellar system. A stellar system is a collection of point masses (stars, gas clouds, dark matter, etc) that is gravitationally bound. The behaviour of these systems is entirely determined by Newtonian gravity.

There is a wide variety of stellar systems: binary stars, star clusters, galaxies and galaxy clusters.

To gain some feeling for the physics of stellar systems, consider the typical example of our Galaxy. Roughly:

$N_\star \simeq 10^{11}$ stars
stellar disc: $R_d \simeq 10\,\mathrm{kpc}$, $h_d \simeq 0.5\,\mathrm{kpc}$
Sun: $R_0 \simeq 8\,\mathrm{kpc}$, $v_{\mathrm{orb}} \simeq 200\,\mathrm{km/s}$

It is reasonable to assume that this stellar system is:

- in steady state. A typical star like the Sun has an orbital time

$$t_{\mathrm{orb}} = \frac{2\pi R_0}{v_{\mathrm{orb}}} \sim 246\,\mathrm{Myr} \ll t_{\mathrm{MW}} \sim 10\,\mathrm{Gyr}\,.$$

  That is, a typical star has had time to complete $t_{\mathrm{MW}}/t_{\mathrm{orb}} \sim 41$ orbits, which justifies the steady state (i.e., equilibrium) assumption.

- collisionless.

Problem 3: Justify that our Galaxy is a collisionless system.

Look at the board!

II. GALAXIES 101

There are three other important timescales for galaxy formation:

- free fall time, i.e. the time it takes a structure of mass M and radius R to collapse under its own gravity:

Homework 3: Free fall time.

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32 G\rho}} = \sqrt{\frac{\pi^2 R^3}{8GM}}\,.$$

- cosmic time, e.g. for an Einstein-de Sitter universe (for ΛCDM is just a factor $\mathcal{O}(1)$ different):

$$t(z) = \frac{2}{3H_0}(1+z)^{-3/2} \simeq 9.3(1+z)^{-3/2}\,\mathrm{Gyr}\,.$$

- cooling time, i.e. the time it takes baryons to cool (e.g. by thermal bremsstrahlung):

$$t_{\rm cool} \propto \frac{R^{5/2}}{M^{1/2}}\,.$$

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One can get a grip on the formation time of a structure of mass M and radius R by comparing $t_{\rm ff}$ with $t(z)$:

$$t_{\rm ff} \lesssim t(z) \Rightarrow \begin{cases} z \lesssim 6 & \text{for} \quad R = 100\,\mathrm{kpc},\, M = 10^{12}\,\mathrm{M}_\odot \\ z \lesssim 2 & \text{for} \quad R = 10\,\mathrm{Mpc},\, M = 10^{15}\,\mathrm{M}_\odot \end{cases} \,.$$

For galaxies to actually form the baryons need to cool and sink to the centre of the gravitational potentials, so:

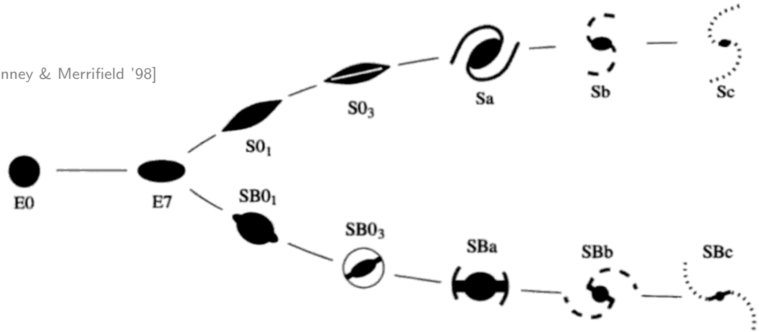
$$t_{\rm cool} \lesssim t_{\rm ff} \Rightarrow R \lesssim 74\,\mathrm{kpc}\,.$$

That is, structures of initial radii $R \lesssim \mathcal{O}(100)$ kpc have enough time to cool and eventually form galaxies. This is in fact the ballpark of most galaxies we observe. On that note, let us now review the observational facts...

II. HUBBLE SEQUENCE

The variety of galaxies in the universe is enormous, so the first step in studying galaxies is their classification. It was Hubble that set in 1936 the main scheme for the classification of galaxies.

[Binney & Merrifield '98]



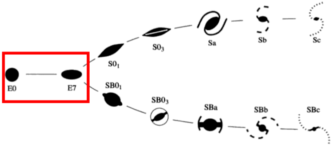
early-type late-type

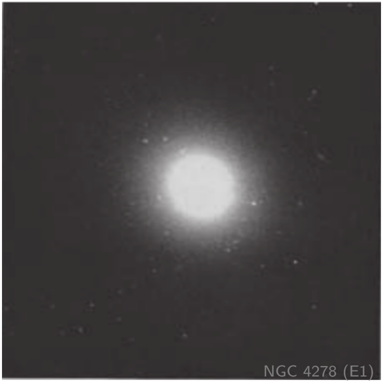
Hubble believed his sequence actually represented a time evolution from early-type to late-type galaxies:

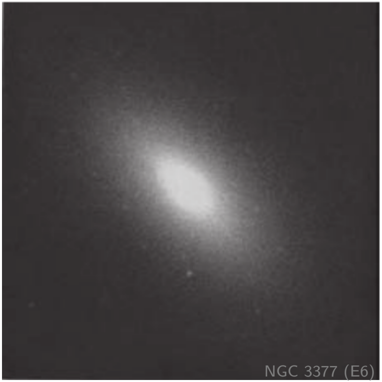
$$E \rightarrow S0,SB0 \rightarrow S,SB \rightarrow Irr$$

Although this belief is not supported nowadays, the nomenclature stuck.

II. ELLIPTICALS



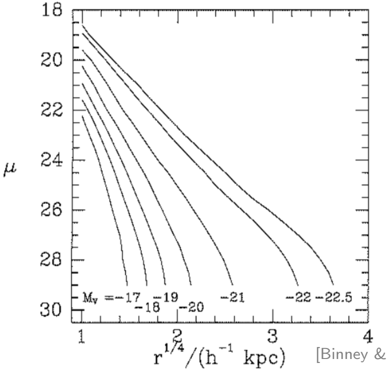




- smooth and spheroidal
- En: axis ratio $b/a = 1 - n/10$; E0–E7
- dE: dwarf elliptical; dSph: dwarf spheroidal

II. ELLIPTICALS

Besides their recognisable morphology, ellipticals are characterised by their photometry and kinematics. Photometrically, the surface brightness along the major axis follows closely a power-law exponential profile. Kinematically, ellipticals show little ordered motion but significant velocity dispersions.



[Binney & Merrifield '98]

photometry

kinematics

Sérsic law: $I(R) \propto \exp\left(-b_n (R/R_e)^{1/n}\right)$, $n = 2 - 6$

central velocity dispersion σ_0

total luminosity $L = \int_0^\infty dR\, I(R) 2\pi R$

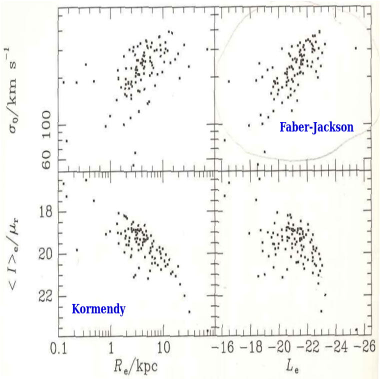
effective radius R_e : $L_e \equiv L(< R_e) = L/2$

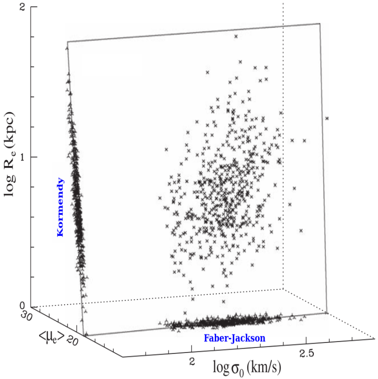
mean surface brightness $\langle I_e \rangle = L_e / \pi R_e^2$

II. ELLIPTICALS

The four observables describing an elliptical $(L, R_e, \langle I_e \rangle, \sigma_0)$ exhibit 3 correlations:

Faber-Jackson law:	$L \propto \sigma_0^4$
Kormendy relation:	$R_e \propto \langle I_e \rangle^{-0.83}$
Fundamental plane:	$R_e \propto \sigma_0^{1.24} \langle I_e \rangle^{-0.82}$

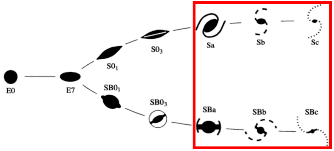


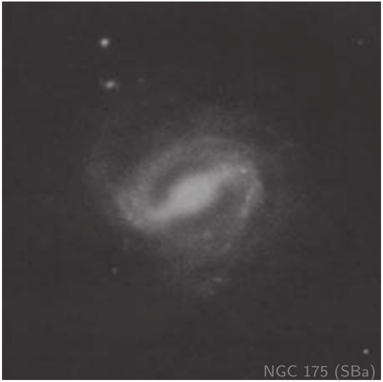


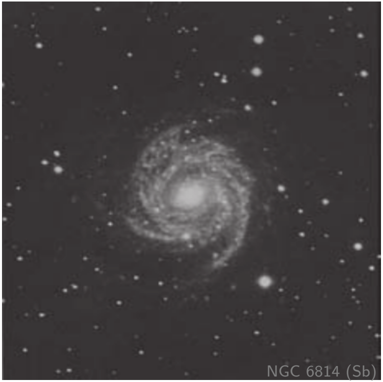
[Binney & Merrifield '98, Mo, van den Bosch & White '10]

The relevance of these correlations is that we can simply measure the photometry (i.e. $R_e, \langle I_e \rangle$) and/or kinematics (i.e. σ_0) of an elliptical to infer its luminosity L, which can be combined with the measured flux density to get an estimate of the distance.

II. SPIRALS



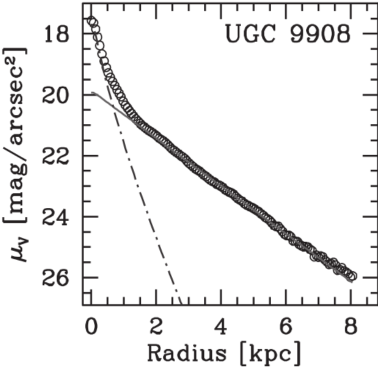




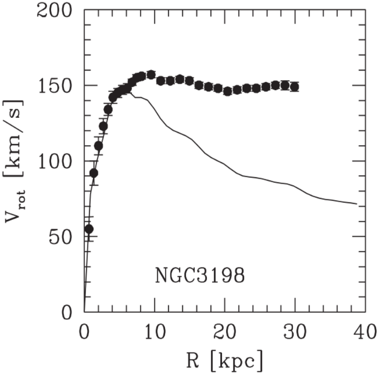
- disc-like with spiral arms
- S (normal): spheroidal bulge; SB (barred): barred bulge
- Sa−d, SBa−d: arm windness and resolution, bulge/disc ratio

II. SPIRALS

Also spirals are defined by their photometry and kinematics. Photometrically, the surface brightness profile has two distinct components, a bulge and a disc. Kinematically, spirals show a very ordered motion featuring a fast disc rotation.



photometry



[Mo, van den Bosch & White '10]

kinematics

exponential disc:
$I(R) \propto \exp(-R/R_d)\,,\ R_d = 1 - 10\,\mathrm{kpc}$

$L = \int_0^\infty dR\, I(R) 2\pi R$

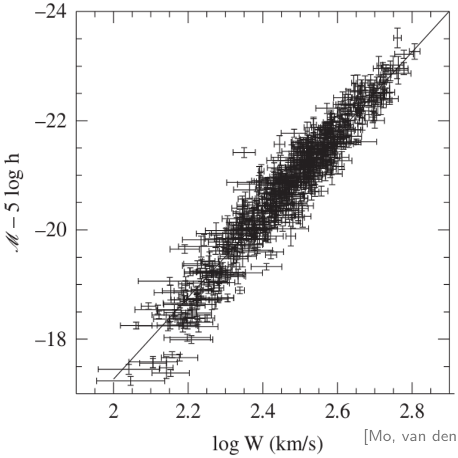
circular velocity:
$V_c^2(R) = GM(< R)/R$

$V_{\mathrm{max}} = \max V_c(R)$

II. SPIRALS

The two key properties of a spiral galaxy (L, $V_{\rm max}$) are inherently correlated:

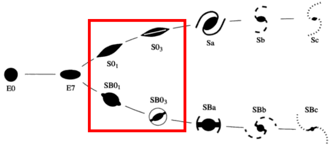
Tully-Fischer relation: $L \propto V_{\rm max}^4$



[Mo, van den Bosch & White '10]

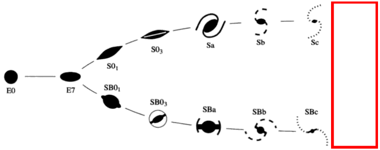
The importance of the Tully-Fisher relation is two-fold: (i) it allows the use of kinematics only (i.e. $V_{\rm max}$) to infer the luminosity L of the galaxy and thus estimate its distance; and (ii) it provides a link between the luminosity of a galaxy and its dynamical mass (through $V_{\rm max}$).

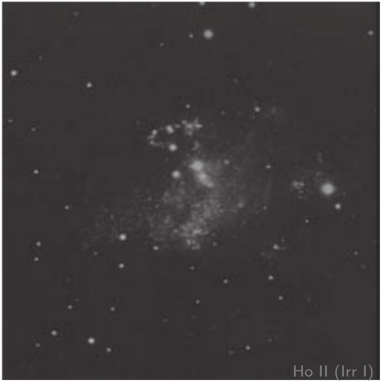
II. LENTICULARS



- smooth as E and disc-like as S
- S0 (normal): spheroidal bulge; SB0 (barred): barred bulge
- S0_{1-3}: dust absorption, SB0_{1-3}: prominence of bar

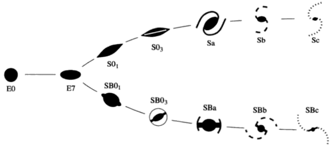
II. IRREGULARS

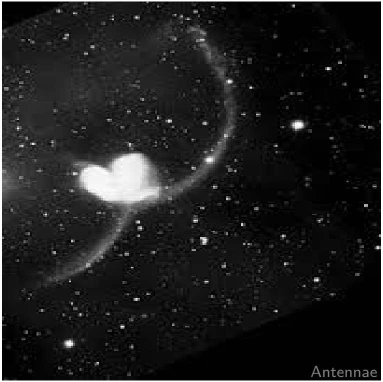




- lack of symmetry
- Irr I: patchy; Irr II: smooth
- both Magellanic Clouds are irregular

II. PECULIAR/INTERACTING

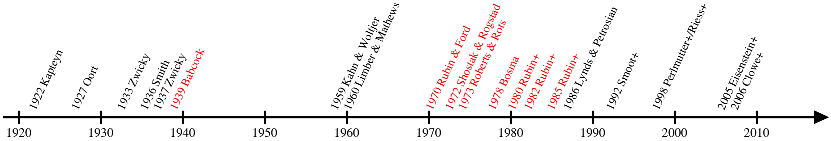




- do not fit any of the Hubble categories
- usually interacting galaxies
- Antennae: probably collision of two spirals

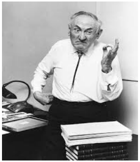
II. DARK MATTER IN GALAXIES

The evidence for dark matter gradually mounted throughout the 20th century, and by now we are convinced that our universe is filled with dark matter at various scales. Note that all evidence for dark matter is of gravitational origin; non-gravitational evidence is yet to be discovered.



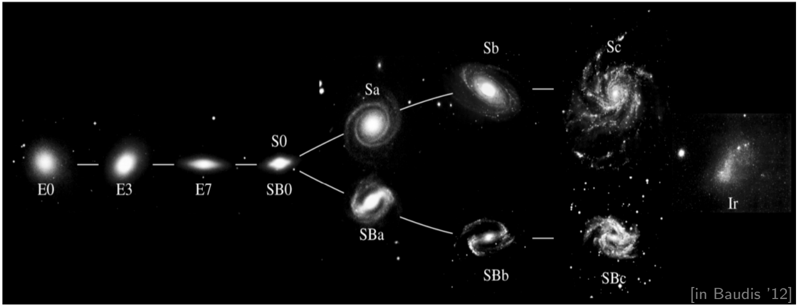
We can identify four key revolutions in the history of dark matter:

1. dark matter is first mentioned by Kapteyn;
2. dark matter is found in the Coma cluster by Zwicky;
3. dark matter is found in spiral galaxies by Rubin & Ford; and
4. dark matter is found at cosmological scales by many.



II. DARK MATTER IN GALAXIES

It was Hubble that set in 1936 the main scheme for the classification of galaxies in the universe.

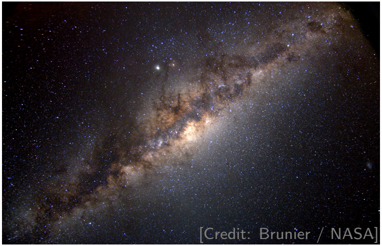


[in Baudis '12]

The (revised) Hubble sequence contains:

- ellipticals: smooth and spheroidal
- spirals: disk-like with spiral arms
- lenticulars: smooth and disk-like
- irregular: lack of symmetry

Our Galaxy is an SBb.


[Credit: Brunier / NASA]

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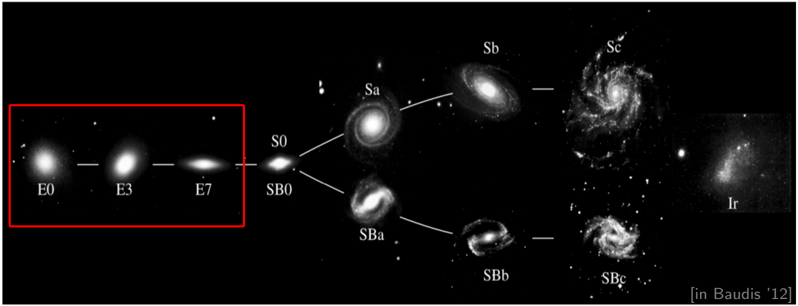

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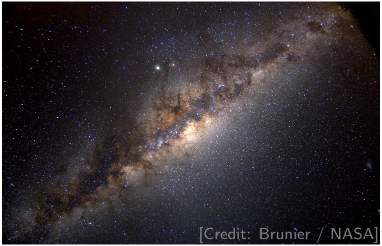
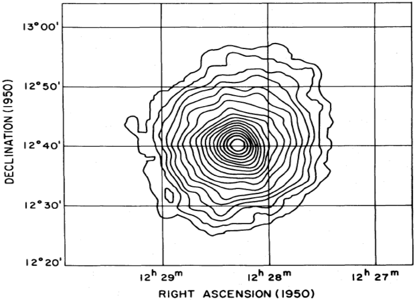

[Credit: Brunier / NASA]

II. DARK MATTER IN ELLIPTICALS

Many ellipticals were found to shine in X rays, pretty much like clusters of galaxies. This is evidence for hot gas emitting bremsstrahlung, and the measured density and temperature profiles can be used to track the total mass.

$$M_{\rm tot}(< r) = -\frac{k_B T_g r}{G \mu m_{\rm H}} \left(\frac{{\rm d} \ln \rho_g}{{\rm d} \ln r} + \frac{{\rm d} \ln T_g}{{\rm d} \ln r} \right)$$



[Fabricant & Gorenstein '83]

Perhaps the most notable example is M87, where $M_{\rm tot}(< 300\,{\rm kpc}) = 3 \times 10^{13}\,{\rm M}_\odot$, or $M/L = 750\,{\rm M}_\odot/{\rm L}_\odot$. Dark matter contributes $> 99\%$ of the mass budget of this giant elliptical.

Other evidence for dark matter from galaxies: [see e.g. Bertone+ '04]

- kinematics of ellipticals
- kinematics of Magellanic stream
- lensing by ellipticals
- lensing of distant galaxies

II. DARK MATTER IN GALAXIES

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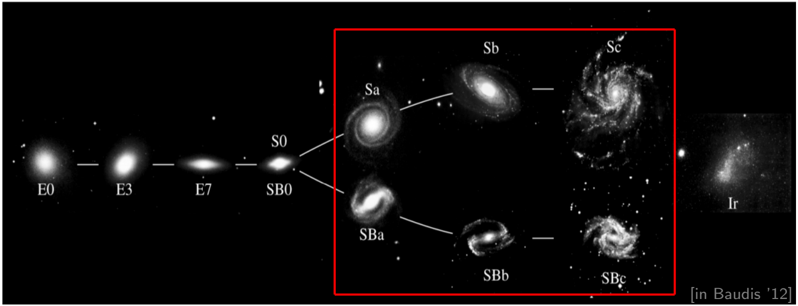

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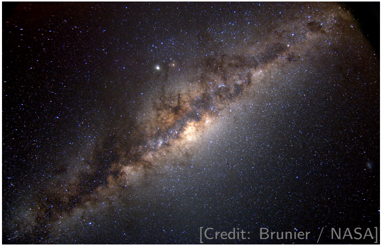
[Credit: Brunier / NASA]

II. DARK MATTER IN SPIRALS

Let us start the journey in our sister galaxy Andromeda (or M31), the closest spiral.

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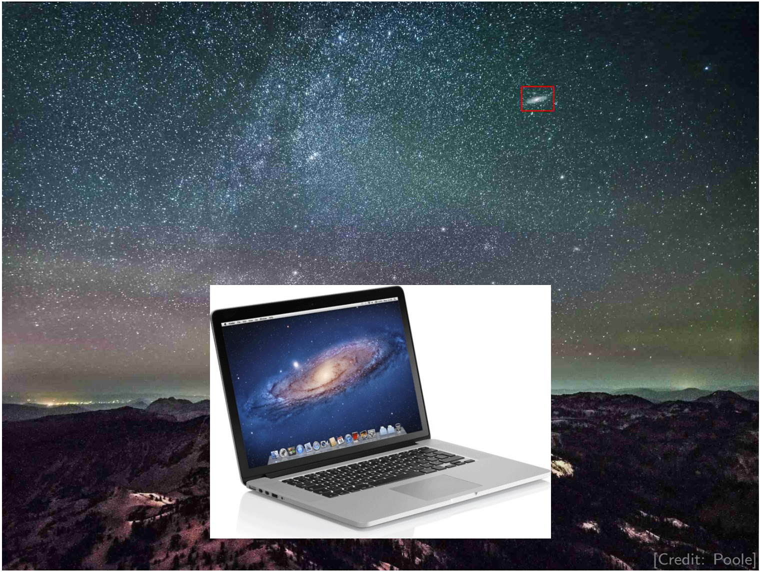
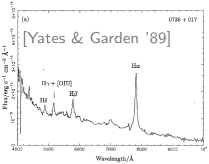


[Credit: Poole]

II. DARK MATTER IN SPIRALS

The kinematics of an object is a prime tool to learn about its mass.



Kinematic measurements can be obtained through the Doppler shift of spectral lines.

$$\Delta\nu = -\frac{v_{\rm los}}{c}\nu_0$$

In a seminal article from 1939, Horace Babcock used emission and absorption gas lines to study the rotation of Andromeda.

LICK OBSERVATORY BULLETIN

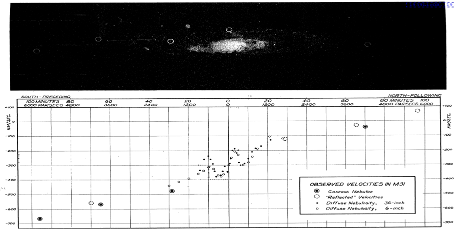
NUMBER 498

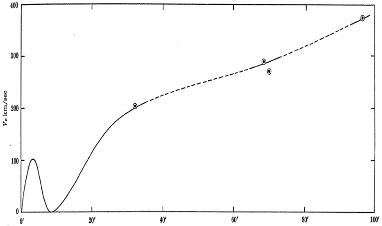
THE ROTATION OF THE ANDROMEDA NEBULA*

BY

Horace W. Babcock

He found surprisingly high velocities across the galactic plane...





II. DARK MATTER IN SPIRALS

… and correspondingly large mass-to-light ratios.

Imagine a column of cross-section one square parsec

The coefficients for the mass-luminosity relation given

TABLE 5

MASS-LUMINOSITY RELATIONS IN M31

x (distance from nucleus)	0′	0′.5	15′	50′	80′
Mass of column (⊙)		11000	7900	4100	2200
Volume (cu. psc.)		5400	5300	4500	2400
Mass density (⊙/cu. psc.)		2.1	1.5	0.9	0.9
Log I (Redman and Shirley)	(2.00)	1.29	0.10	9.44	9.00
I	(100)	19.5	1.26	0.276	0.100
Luminosity density (⊙/cu. psc.)		1.25	0.0827	0.021	0.0144
M/L	0.001 (Hubble)	1.6	18	43	62

in the table evidently indicate little more than orders of magnitude. The mass densities are especially uncertain in the central core, where they are probably too small, so that the corresponding mass-luminosity coefficients near the nucleus may be considered minimum values. Nevertheless, the great range in the calculated ratio of mass to luminosity in proceeding outward from the nucleus suggests that absorption plays a very important rôle in the outer portions of the spiral, or, perhaps, that new dynamical considerations are required, which will permit of a smaller relative mass in the outer parts.

strate that, in a wide region around the sun, circular velocities of the stars decrease with distance from the center.

The Andromeda Nebula and the Galaxy have many well-known features in common, but one outstanding discrepancy between the two systems has hitherto been in their diameters. The spiral arms of M31 can hardly be traced to a radius of more than 1°.6 or 6 kiloparsecs. Beyond this radius, no stars, comparable to the brighter stars in the vicinity of the sun, have been reported, although Hubble has discovered some outlying globular

However, a confirmation of this hint had to wait for over 3 decades.

II. DARK MATTER IN SPIRALS

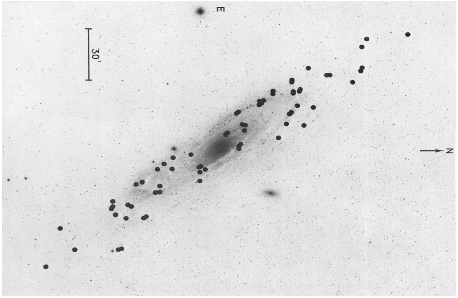
In 1970, Vera Rubin and Kent Ford measured Hα shifts across Andromeda.

THE ASTROPHYSICAL JOURNAL, Vol. 159, February 1970

ROTATION OF THE ANDROMEDA NEBULA FROM A SPECTROSCOPIC SURVEY OF EMISSION REGIONS*

VERA C. RUBIN† AND W. KENT FORD, JR.†
Department of Terrestrial Magnetism, Carnegie Institution of Washington and Lowell Observatory, and Kitt Peak National Observatory‡
Received 1969 July 7; revised 1969 August 21

They found a flat rotation curve up to 24 kpc, way beyond the luminous matter:



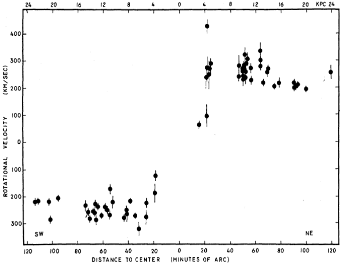


FIG. 3.—Rotational velocities for sixty-seven emission regions in M31, as a function of distance fr the center. Error bars indicate average error of rotational velocities.

This paper was the turning point for the dark matter paradigm. Soon afterwards, the same result was confirmed by 21 cm line observations (Rogstad & Shostak '72).

II. DARK MATTER IN SPIRALS

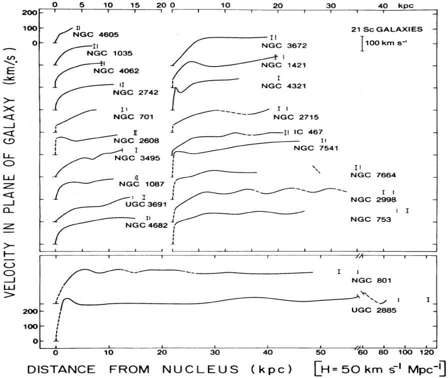
The 1970s and 1980s witnessed a steady growth in the number of spirals with flat rotation curves. Several authors contributed to this effort...

THE ASTROPHYSICAL JOURNAL, **238**:471–487, 1980 June 1

ROTATIONAL PROPERTIES OF 21 Sc GALAXIES WITH A LARGE RANGE OF LUMINOSITIES AND RADII, FROM NGC 4605 ($R = 4$ kpc) TO UGC 2885 ($R = 122$ kpc)

VERA C. RUBIN,[1,2] W. KENT FORD, JR.,[1] AND NORBERT THONNARD
Department of Terrestrial Magnetism, Carnegie Institution of Washington

Received 1979 October 11; accepted 1979 November 29



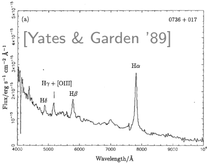
VIII. DISCUSSION AND CONCLUSIONS

We have obtained spectra and determined rotation curves to the faint outer limits of 21 Sc galaxies of high inclination. The galaxies span a range in luminosity from 3×10^9 to 2×10^{11} $L_\odot$, a range in mass from 10^{10} to 2×10^{12} $M_\odot$, and a range in radius from 4 to 122 kpc. In general, velocities are obtained over 83% of the optical image (defined by 25 mag arcsec^{-2}), a greater distance than previously observed. The major conclusions are intended to apply only to Sc galaxies.

1. Most galaxies exhibit rising rotational velocities at the last measured velocity; only for the very largest galaxies are the rotation curves flat. Thus the smallest Sc's (i.e., lowest luminosity) exhibit the same lack of a Keplerian velocity decrease at large R as do the high-luminosity spirals. This form for the rotation curves implies that the mass is not centrally condensed, but that significant mass is located at large R. The integral mass is increasing at least as fast as R. The mass is not converging to a limiting mass at the edge of the optical image. The conclusion is inescapable that non-luminous matter exists beyond the optical galaxy.

II. DARK MATTER IN SPIRALS

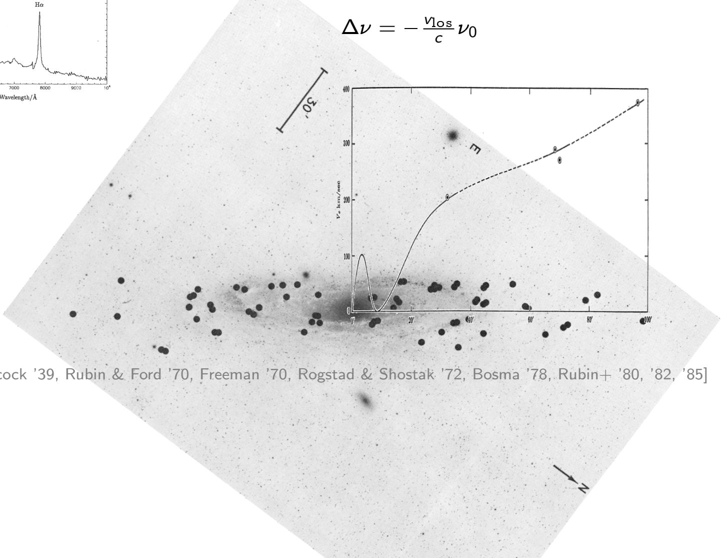
The kinematics of an object is a prime tool to learn about its mass.



[Yates & Garden '89]

The kinematics of Andromeda has been studied since the 1930s through the Doppler shift of spectral lines.

$$\Delta\nu = -\frac{v_{\rm los}}{c}\nu_0$$



[Babcock '39, Rubin & Ford '70, Freeman '70, Rogstad & Shostak '72, Bosma '78, Rubin+ '80, '82, '85]

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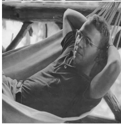

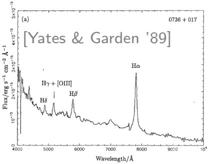

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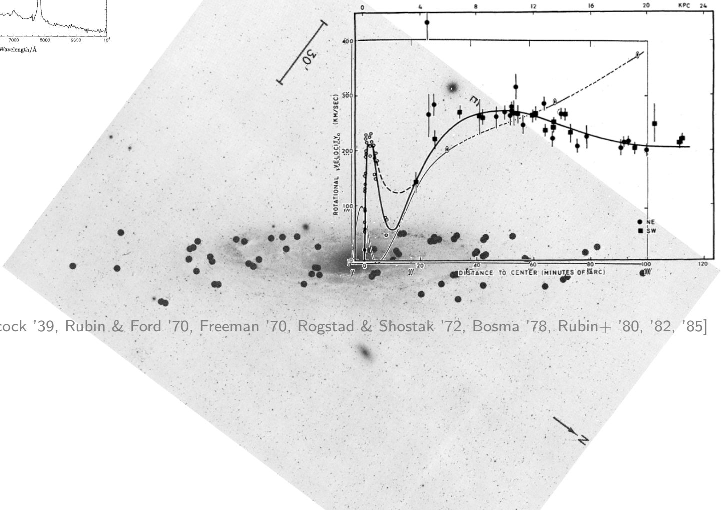

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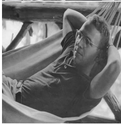
II. DARK MATTER IN SPIRALS



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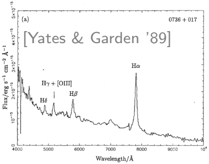

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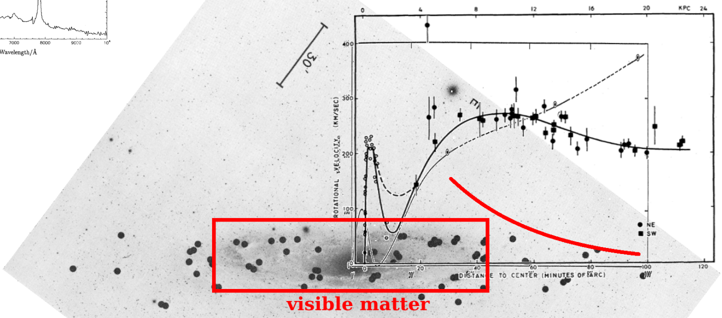


[Babcock '39, Rubin & Ford '70, Freeman '70, Rogstad & Shostak '72, Bosma '78, Rubin+ '80, '82, '85]

Under Newtonian gravity, a spherical mass induces $\boxed{v_c^2 = \frac{GM(<r)}{r}}$.

The rotation provided by the visible mass falls off as $v_c \propto 1/\sqrt{r}$ at large r. A flat rotation curve implies* a dark matter halo with $M(<r) \propto r$.

* Modifications of gravity at galactic scales are also feasible. [Milgrom x3 '83]

II. DARK MATTER IN SPIRALS

Let us go one step back to Newton's laws. Consider the motion of a test particle under the influence of a point mass (e.g., the Sun-Earth system). The gravitational potential per unit mass reads

$$\phi = -\frac{GM}{r}\,.$$

The force per unit mass acted upon the particle in a circular orbit is

$$|F| = \frac{v_c^2}{r} = \frac{\mathrm{d}\phi}{\mathrm{d}r} = \frac{GM}{r^2} \quad \Rightarrow \quad \boxed{v_c^2 = \frac{GM}{r}}\,. \text{ circular speed}$$

But a galaxy cannot really be approximated by a point-like distribution of matter.

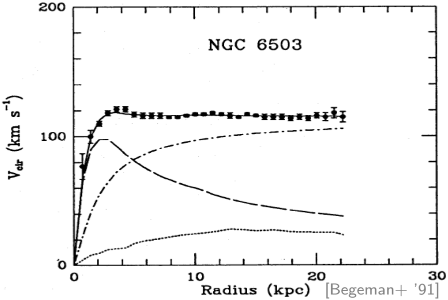
Homework 4: Spherical body dynamics.

II. DARK MATTER IN SPIRALS

point-like: $\boxed{v_c^2 = \frac{GM}{r}}$ spherical: $\boxed{v_c^2 = \frac{GM(<r)}{r}}$

We learn that:

1. for a point mass or for $M(<r) \simeq \text{const}$, $v_c \propto r^{-1/2}$ (Keplerian fall-off); and
2. $v_c \simeq \text{const}$ implies $M(<r) \propto r$.



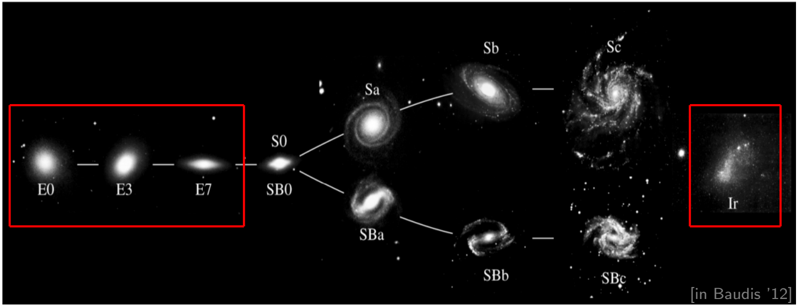
[Begeman+ '91]

Therefore, the flat rotation curves observed in spiral galaxies indicate $M(<r) \propto r$ in a region where the luminous mass enclosed is barely increasing. This is striking evidence for dark matter.

Note: virtually in no spiral has a Keplerian fall-off been observed, which means we are not able to actually infer the total mass of these systems...

II. DARK MATTER IN GALAXIES

It was Hubble that set in 1936 the main scheme for the classification of galaxies in the universe.

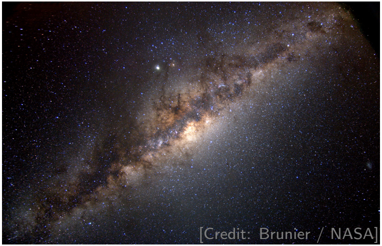


[in Baudis '12]

The (revised) Hubble sequence contains:

- ellipticals: smooth and spheroidal
- spirals: disk-like with spiral arms
- lenticulars: smooth and disk-like
- irregular: lack of symmetry

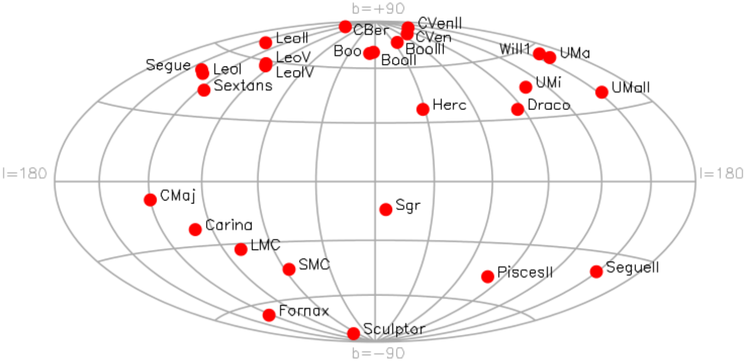
Our Galaxy is an SBb.


[Credit: Brunier / NASA]

II. DARK MATTER IN DWARFS

Although they contribute little to the total luminosity, dwarfs are by far the most abundant galaxies in the universe. They usually fall in the categories of dwarf irregulars (dIrr), dwarf ellipticals (dE) or dwarf spheroidals (dSph).

Just in the Local Group there are over 100 dwarfs, 49 of which are satellites of our own Galaxy. These are very faint objects, usually detected at high latitudes where the emission of the Milky Way is less problematic. It is highly likely that more dwarfs are discovered over the next years.



[McConnachie '14]

II. DARK MATTER IN DWARFS

The variety of existing dwarf galaxies is rather remarkable.

Galaxy		Original Publication	Comments
The Galaxy	S(B)bc	...	Position refers to Sgr A*
Canis Major	????	Martin et al. (2004a)	MW disk substructure?
Sagittarius dSph	dSph	Ibata et al. (1994)	Tidally disrupting
Segue (I)	dSph	Belokurov et al. (2007)	
Ursa Major II	dSph	Zucker et al. (2006a)	
Bootes II	dSph	Walsh et al. (2007)	
Segue II	dSph	Belokurov et al. (2009)	
Willman 1	dSph	Willman et al. (2005a)	Cluster?
Coma Berenices	dSph	Belokurov et al. (2007)	
Bootes III	dSph?	Grillmair (2009)	Very diffuse. Tidal remnant?
LMC	Irr	...	
SMC	dIrr	...	
Bootes (I)	dSph	Belokurov et al. (2006)	
Draco	dSph	Wilson (1955)	
Ursa Minor	dSph	Wilson (1955)	
Sculptor	dSph	Shapley (1938a)	The prototypical dSph
Sextans (I)	dSph	Irwin et al. (1990)	
Ursa Major (I)	dSph	Willman et al. (2005b)	
Carina	dSph	Cannon et al. (1977)	
Hercules	dSph	Belokurov et al. (2007)	Tidally disrupting? Remnant? Cluster?
Fornax	dSph	Shapley (1938b)	
Leo IV	dSph	Belokurov et al. (2007)	Binary w/ Leo V?
Canes Venatici II	dSph	Sakamoto & Hasegawa (2006)	
Leo V	dSph	Belokurov et al. (2008)	Cluster? Binary w/ Leo IV?
Pisces II	dSph	Belokurov et al. (2010)	Awaiting spectr. confirmation
Canes Venatici (I)	dSph	Zucker et al. (2006b)	
Leo II	dSph	Harrington & Wilson (1950)	
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[adapted from McConnachie '14]

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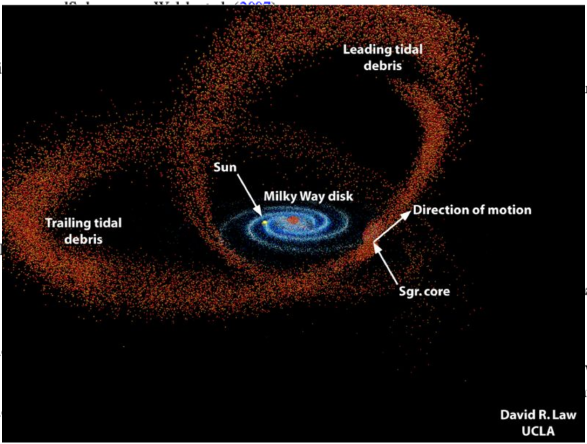

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Draco	dSp		
Ursa Minor	dSp		
Sculptor	dSp		ical dSph
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Leo IV	dSp		eo V?
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Canes Venatici (I)	dSp		
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[By ESO/S. Brunier (ESO) [CC BY 4.0 (http://creativecommons.org/licenses/by/4.0)], via Wikimedia Commons]

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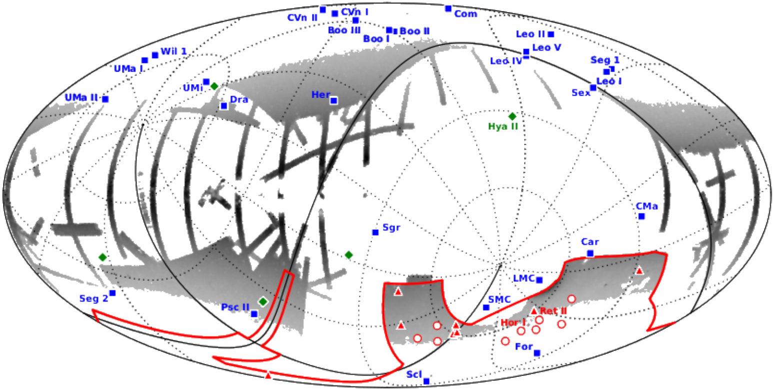
[adapted from McConnachie '14]

II. DARK MATTER IN DWARF SPHEROIDALS

Apart from the Magellanic Clouds, all Milky Way satellites are dwarf spheroidals (dSph), several of which have been discovered in the last year or so.



[Drlica-Wagner et al '15]

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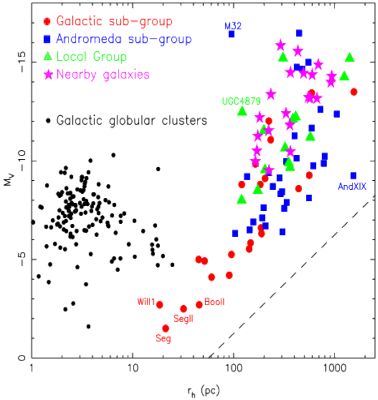

[McConnachie '14]

Fact sheet of Milky Way dSph:

$r_h \simeq 20 - 1000\,\mathrm{pc}$ $\quad D_\odot \simeq 20 - 200\,\mathrm{kpc}$

$M_{\rm tot} \simeq 10^5 - 10^8\,\mathrm{M}_\odot$ $\quad M_\star \simeq 10^2 - 10^7\,\mathrm{M}_\odot$ $\quad M_{\rm gas} \simeq 0$

What is so special about dSph?

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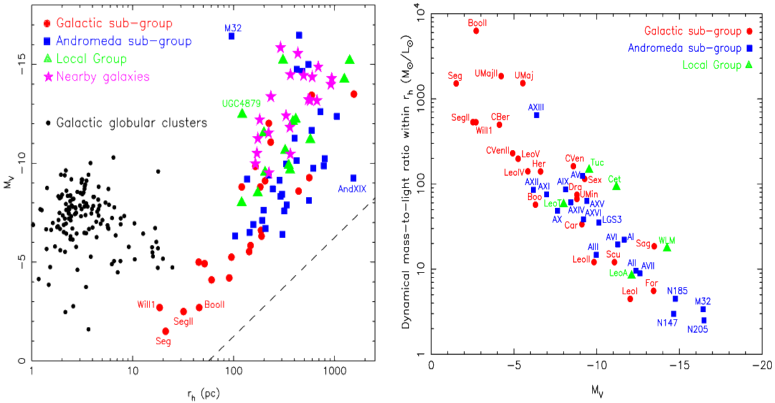

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What is so special about dSph? It turns out that are the most dark matter dominated objects in the universe, with mass-to-light ratios sometimes exceeding 1000.

II. DARK MATTER IN DWARF SPHEROIDALS

Let us see how to derive the dark matter content of a dwarf spheroidal. Since these objects are collisionless, in equilibrium and roughly spherical, the Jeans equations simplify to

$$\frac{1}{\nu}\frac{\mathrm{d}(\nu\sigma_r^2)}{\mathrm{d}r} + \frac{2\beta\sigma_r^2}{r} = -\frac{\mathrm{d}\phi}{\mathrm{d}r} = -\frac{GM(< r)}{r^2}\,,$$

where ν is the density of stars, σ_r^2 the radial velocity dispersion and $\beta = 1 - \sigma_\theta^2/\sigma_r^2$ is the anispotropy parameter. For $\beta = \mathrm{const}$, we can solve for σ_r^2 as

$$\nu\sigma_r^2 = Gr^{-2\beta}\int_r^\infty ds\, s^{2\beta-2}\nu(s)M(< s)\,.$$

Now, the observables are the projected stellar density $I(R)$ and the projected line-of-sight velocity dispersion σ_p^2, which are related with the mass modelling through:

$$I\sigma_p^2 = 2\int_R^\infty dr\left(1-\beta\frac{R^2}{r^2}\right)\frac{\nu\sigma_r^2 r}{\sqrt{r^2-R^2}}\,.$$

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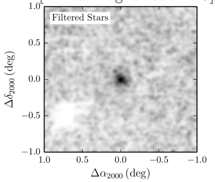
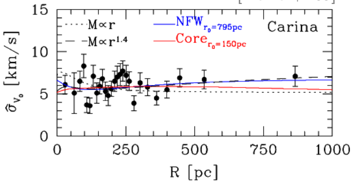
1. Measure $I(R)$ and $\sigma_p(R)$.

[Drlica-Wagner et al '15]



[Walker+ '09]



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$$\nu\sigma_r^2 = Gr^{-2\beta}\int_r^\infty ds\, s^{2\beta-2}\nu(s)M(<s)\,.$$

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$$I\sigma_p^2 = 2\int_R^\infty dr\left(1-\beta\frac{R^2}{r^2}\right)\frac{\nu\sigma_r^2 r}{\sqrt{r^2-R^2}}\,.$$

1. Measure $I(R)$ and $\sigma_p(R)$.
2. Infer $\nu(r)$ from $I(R)$ (Abel integral). [see Binney & Tremaine '08]
3. Fix β and the parameters of your mass model to compute $M(<r)$.

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Let us see how to derive the dark matter content of a dwarf spheroidal. Since these objects are collisionless, in equilibrium and roughly spherical, the Jeans equations simplify to

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where ν is the density of stars, σ_r^2 the radial velocity dispersion and $\beta = 1 - \sigma_\theta^2/\sigma_r^2$ is the anispotropy parameter. For $\beta = \mathrm{const}$, we can solve for σ_r^2 as

$$\nu\sigma_r^2 = Gr^{-2\beta}\int_r^\infty ds\, s^{2\beta-2}\nu(s)M(<s)\,.$$

Now, the observables are the projected stellar density $I(R)$ and the projected line-of-sight velocity dispersion σ_p^2, which are related with the mass modelling through:

$$I\sigma_p^2 = 2\int_R^\infty dr\left(1-\beta\frac{R^2}{r^2}\right)\frac{\nu\sigma_r^2 r}{\sqrt{r^2-R^2}}\,.$$

1. Measure $I(R)$ and $\sigma_p(R)$.
2. Infer $\nu(r)$ from $I(R)$ (Abel integral). [see Binney & Tremaine '08]
3. Fix β and the parameters of your mass model to compute $M(<r)$.
4. Infer $\nu\sigma_r^2$ using $\nu(r)$ and $M(<r)$.

II. DARK MATTER IN DWARF SPHEROIDALS

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5. Fit $I\sigma_p^2$ and find the best-fit parameters of the mass model.

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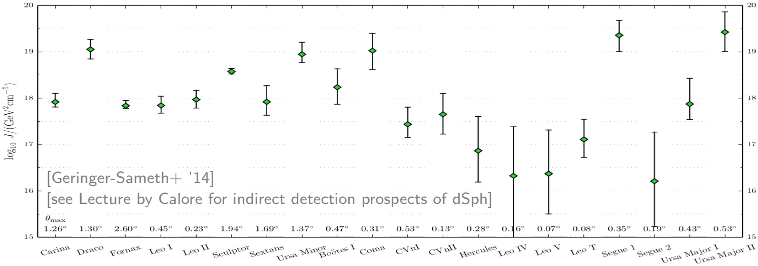
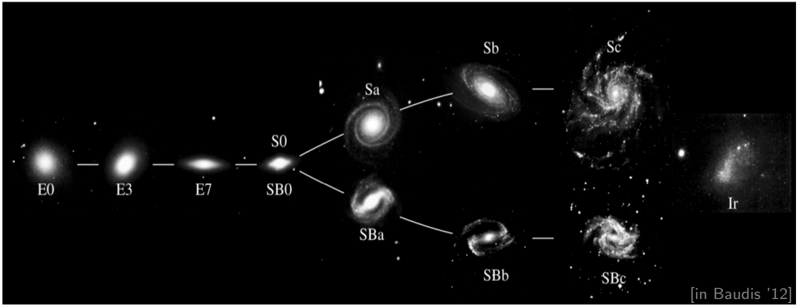


II. DARK MATTER IN GALAXIES

It was Hubble that set in 1936 the main scheme for the classification of galaxies in the universe.



The (revised) Hubble sequence contains:

- ellipticals: smooth and spheroidal
- spirals: disk-like with spiral arms
- lenticulars: smooth and disk-like
- irregular: lack of symmetry

Our Galaxy is an SBb.