THE MILKY WAY IN CONTEXT: THE STRUCTURE OF THE LOCAL GROUP OF GALAXIES

Lezione II- Fisica delle Galassie

Cap. 1-2 from THE GALAXIES OF THE LOCAL GROUP

S. VAN DEN BERGH

+

The Laniakea supercluster of galaxies (Tully et al. 2014)

+

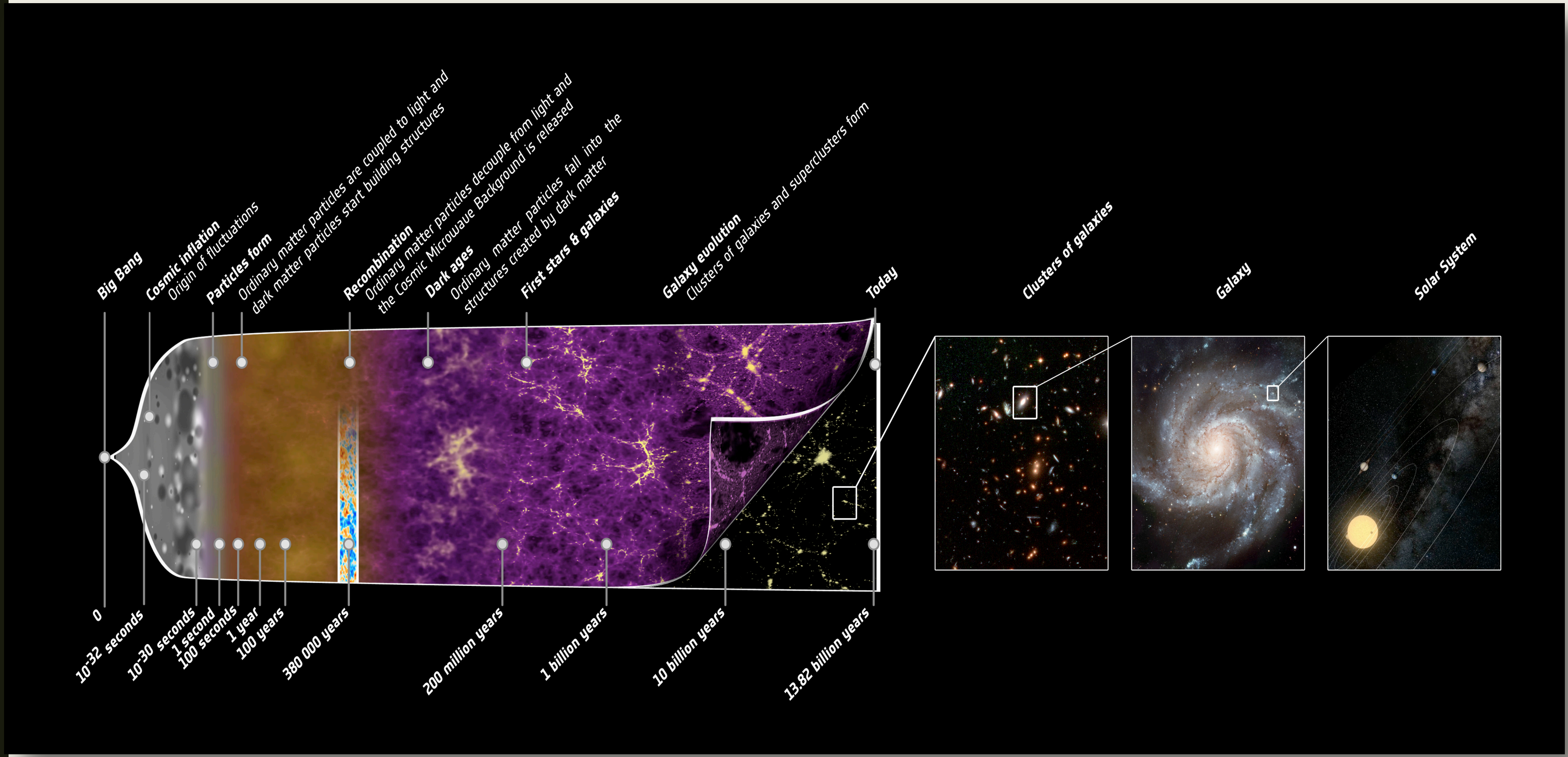
Stellar populations in the Local Group Galaxies (E. Grebel)

+

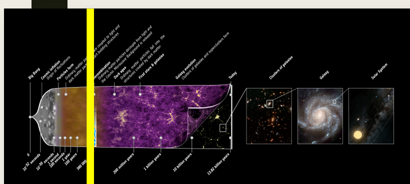
D'Souza & Bell (2018)

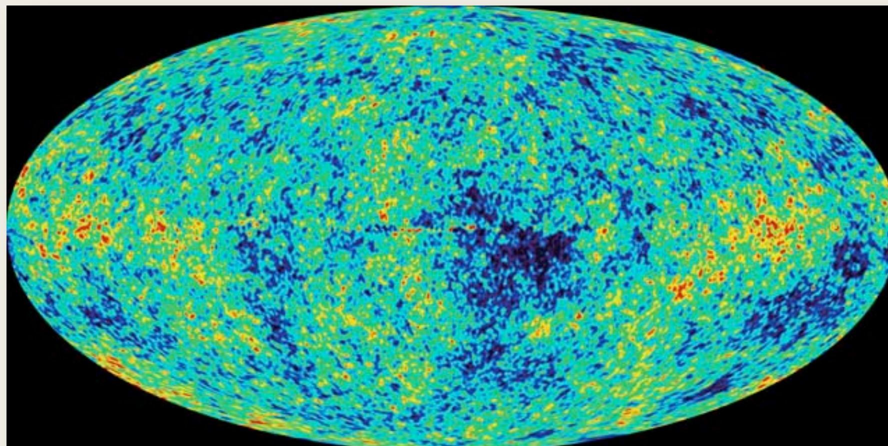
Laura Magrini

History of Cosmic structure formation



The Cosmic Microwave Background



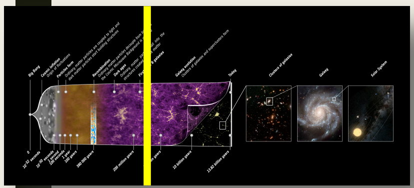


- The cosmic microwave background (CMB) is an almost-uniform background with a temperature of T=2.725 ±0.002 K.

- The CMB was produced 10^5 yr after the Big Bang. At that time, the Universe was filled with a hot, ionized gas. This gas was almost completely uniform, with fluctuations of 10^{-5} in temperature ($\Delta T/T$) [These anisotropies were first detected by the COBE (NASA's COsmic Background Explorer) satellite in 1992]

- These fluctuations are at the origin of the present-time structure, such as **filaments, super-clusters, clusters, and galaxies.**

The re-ionization and structure formation

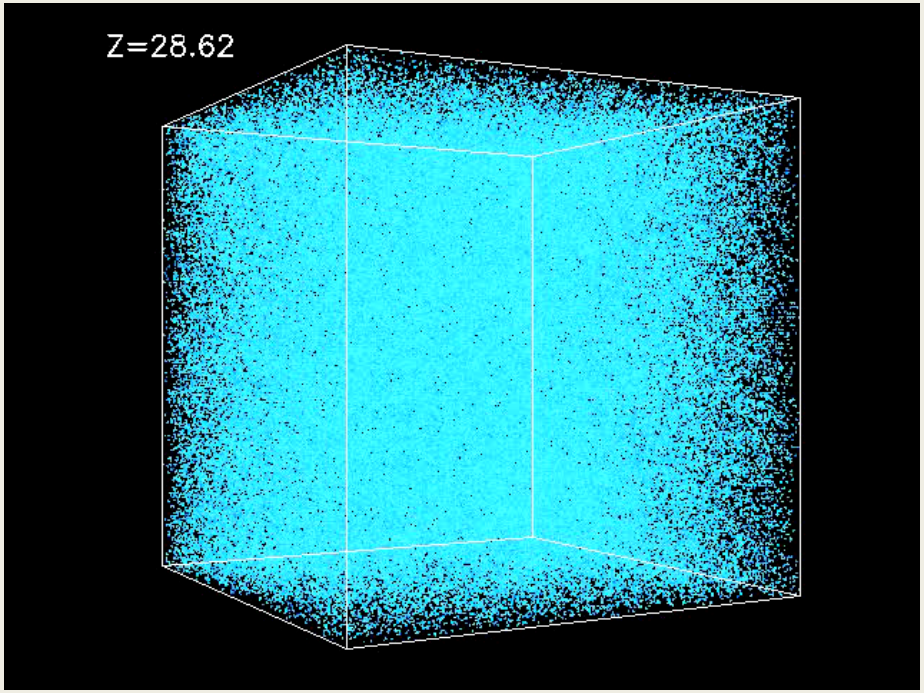


- A critical period in the evolution of the Universe is the **end** of the so-called "**cosmic dark ages**", when the first collapsed structures achieved sufficient temperatures and density to ignite in **nuclear fusion**.

- These sources may have been stars, galaxies, quasars, or some combination of the above.

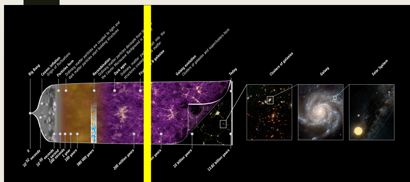
- The simulation:

At the initial epoch (z=30), when the age of the Universe was less than 1% of its current age, distribution of matter appears to be uniform. **This is because the seed fluctuations are still fairly small**. As time goes on, the fluctuations grow: from the smallest bright clumps which have sizes and masses similar to those of **galaxies** to the large **filaments**.



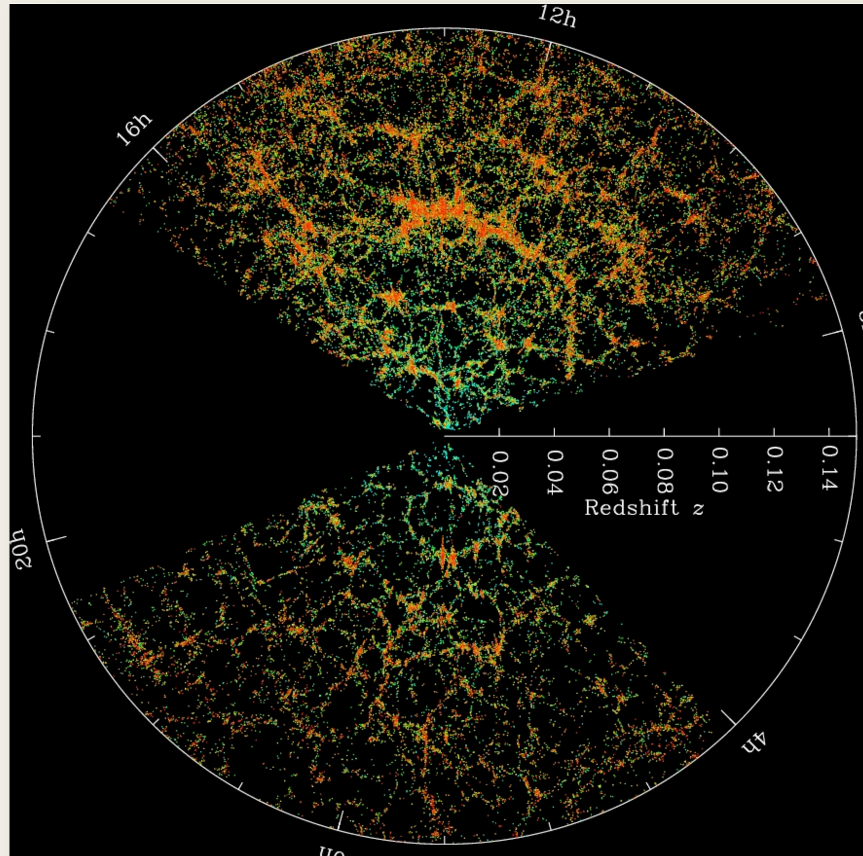
Credits:
simulations were performed at the National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University).
Visualizations by Andrey Kravtsov.

From simulations to observations



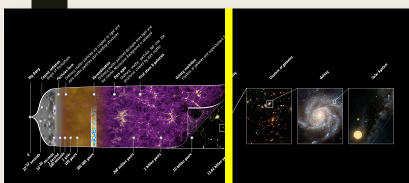
The observations of the Large Scale Structures in the Universe:

- On scales of **10 or 30 Mpc**, the observed variation in the number of galaxies exceeds the random variation expected from counting statistics (√N), an indication of gravitational clustering. On **100 Mpc scale**, the number of galaxies shows only a small fractional variation.
- On a scale of **300 Mpc, the Universe is essentially smooth.** The Universe is isotropic and homogeneous at the largest scales.



2D map of the distribution of galaxies from the Sloan Digital Sky Survey (SDSS) at different redshifts.
Credit: M. Blanton and the SDSS.

Why the our Galaxy and its neighbors, the Local Group



The galaxies of the Local Group drawn to scale (Binggeli 1993)

- Within 1 Mpc
- Resolved into stars
- Laboratory to study individual objects (star clusters, planetary nebulae, SNR, etc.)
- Examples of most major galaxy types (excluding giant ellipticals)

- Fate or Chance?

A giant elliptical galaxy at the distance of the Magellanic Clouds would have disrupted the Milky Way galaxy

Why to study the Local Group

- Hubble (1936) was the first to draw attention to the fact that our Milky Way system belongs to a small cluster of galaxies, which he dubbed "The Local Group".

- Hubble emphasized that the **Local Group was (and is) important** since it:

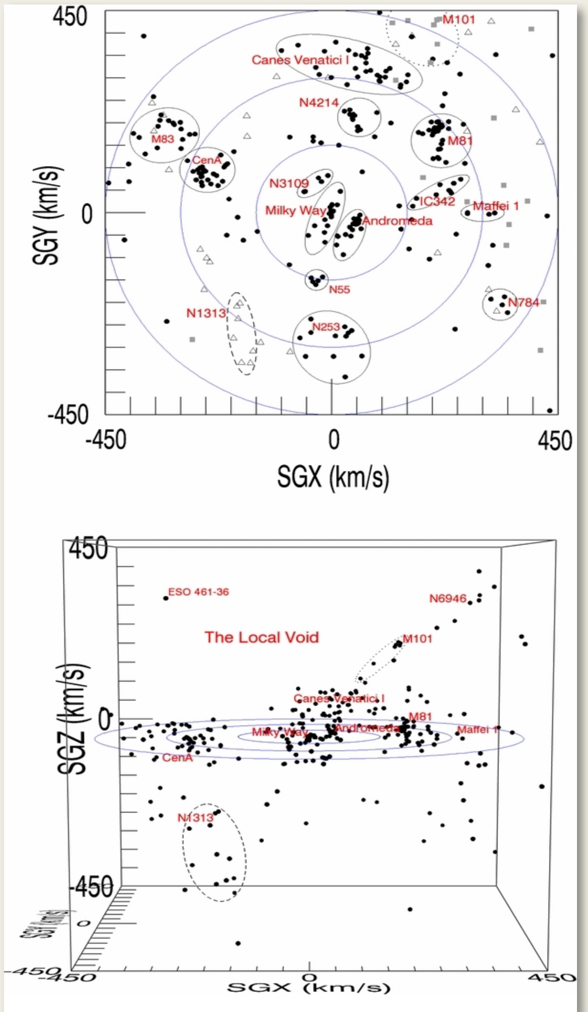
(1) provided an opportunity to study nearby examples of a wide range **of galaxy types** in detail (with photometry and spectroscopy) in a wide range of ages and metallicity **not available** when studying only the Milky Way

(2) enabled astronomers to calibrate the luminosities of "**standard candles**" such as Cepheids, RR Lyrae stars etc., which could then be used to determine the extragalactic distance scale.

(3) The right place to conduct the "near-field cosmology"!

The location in the Local Universe

Form Courtois et al. 2013

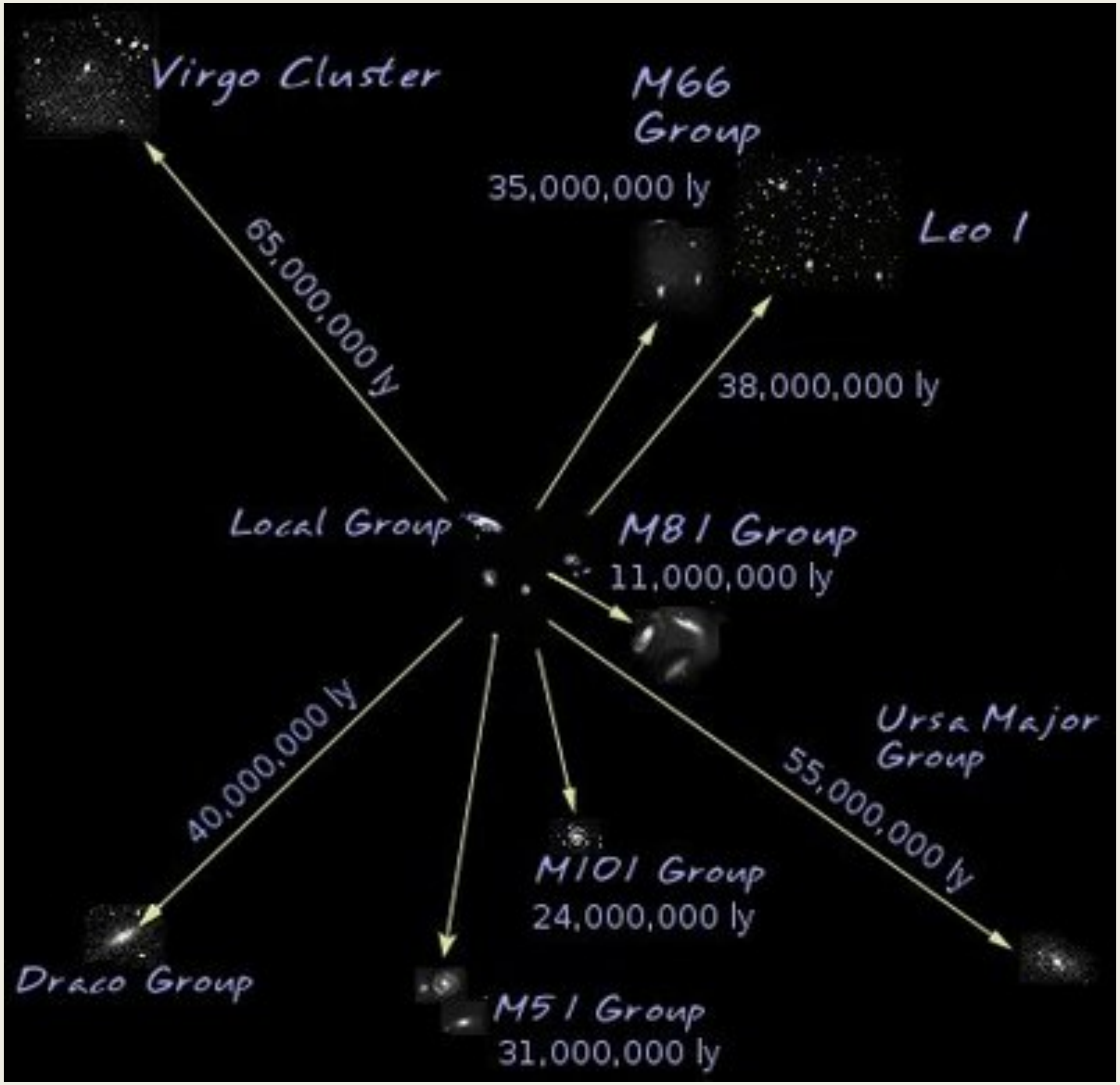


- The Local Group (LG) has a physical radius of ~1.2 Mpc (Van den Bergh 1999), defined as the **radius of its zero-velocity surface, namely the surface which separates the LG from the field expanding with the Hubble flow**.

- The LG is located in a diffuse and warped filament/wall connecting the Virgo Cluster with the Fornax Cluster.

- Some nearby galaxies and group members of this large structure are the Maffei group, NGC 6744, NGC 5128, M101, M81, NGC 1023, and Cen A (Courtois et al. 2013)

The location in the Local Universe



The Laniakea super cluster

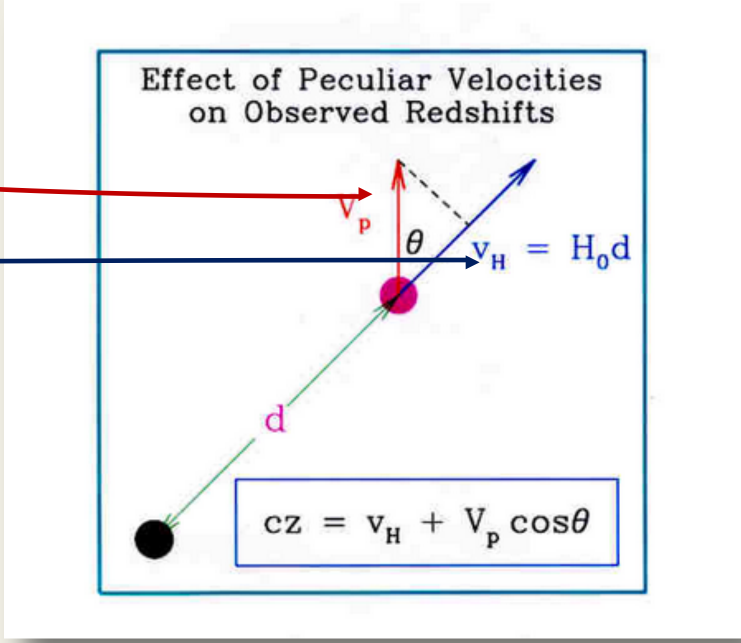
Tully et al. 2014 (*Nature* **volume 513**, pages 71–73)

The distribution of matter can be determined by two independent methods:

1. Distribution of galaxies in projection and redshift
2. **Motions of galaxies.**

If the distance to each galaxy from Earth is directly measured*, then **the peculiar velocity** can be derived from the **subtraction of the mean cosmic expansion**, the product of distance times the Hubble constant, from observed velocity.

The peculiar velocity is the line-of-sight departure from the cosmic expansion and arises from gravitational perturbations; a map of peculiar velocities can be translated into a **map of the distribution of matter**



* With independent methods, see next slide

The Laniakea super cluster

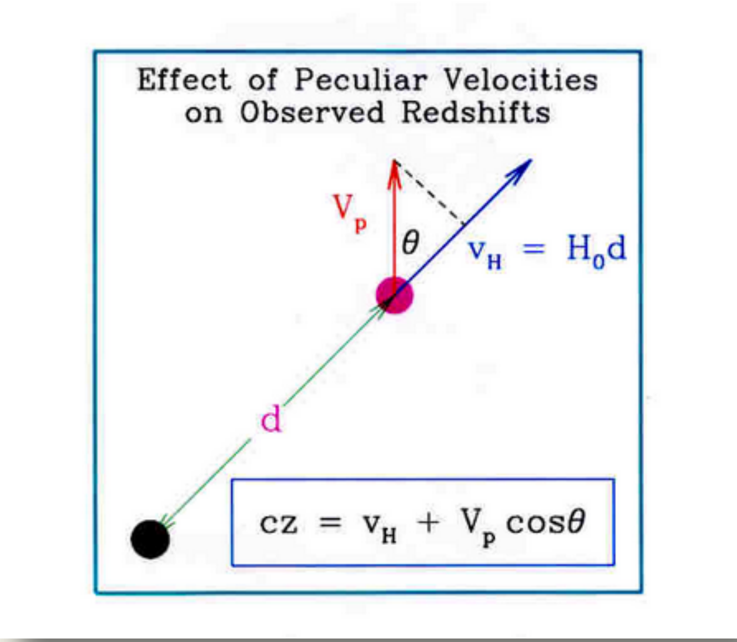
Tully et al. 2014 (*Nature* **volume 513**, pages 71–73)

V_H from H_0 (Hubble constant) and from distance (independently measured)

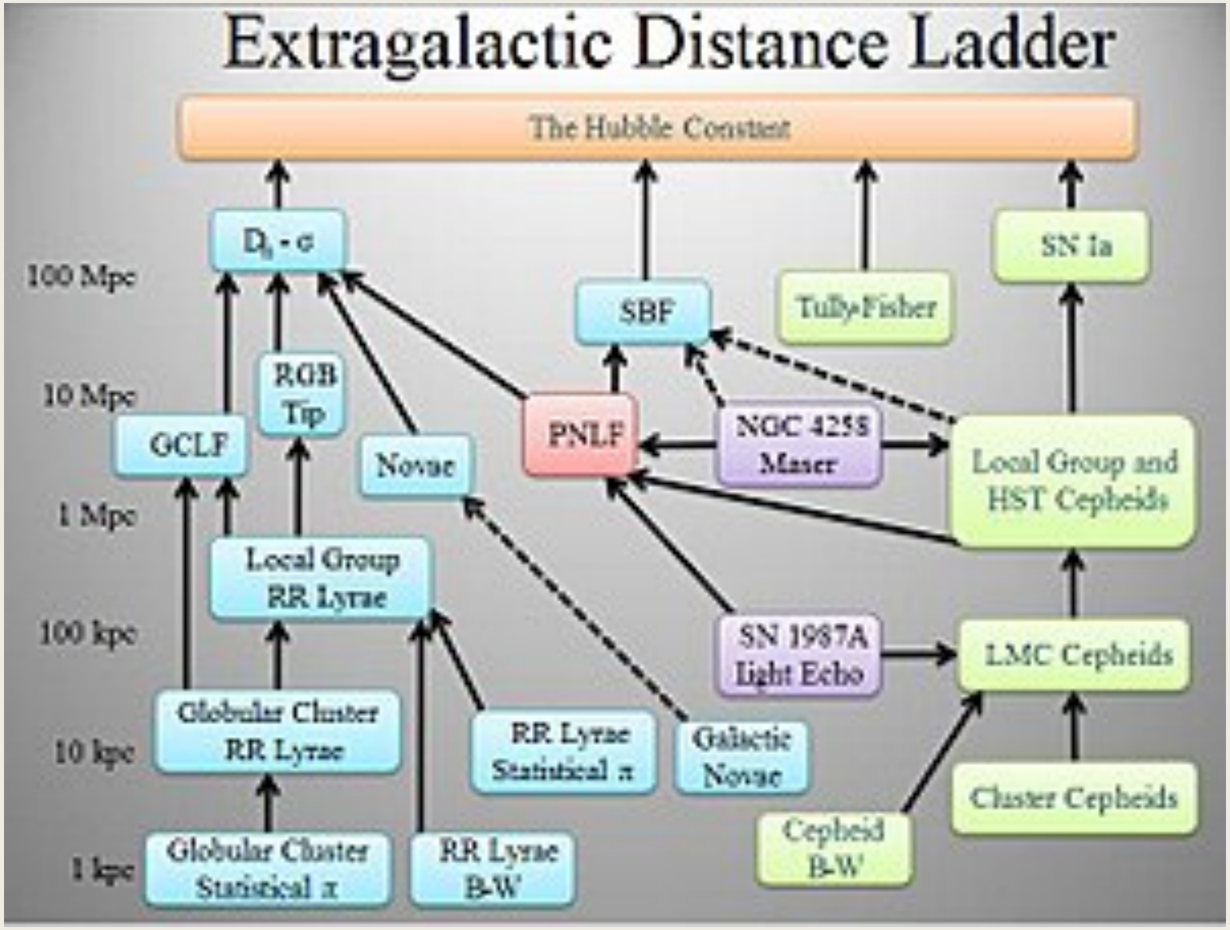
Z (redshift) from spectroscopy (Doppler shift)

C light velocity

→ We can derive $V_p \cos\theta$

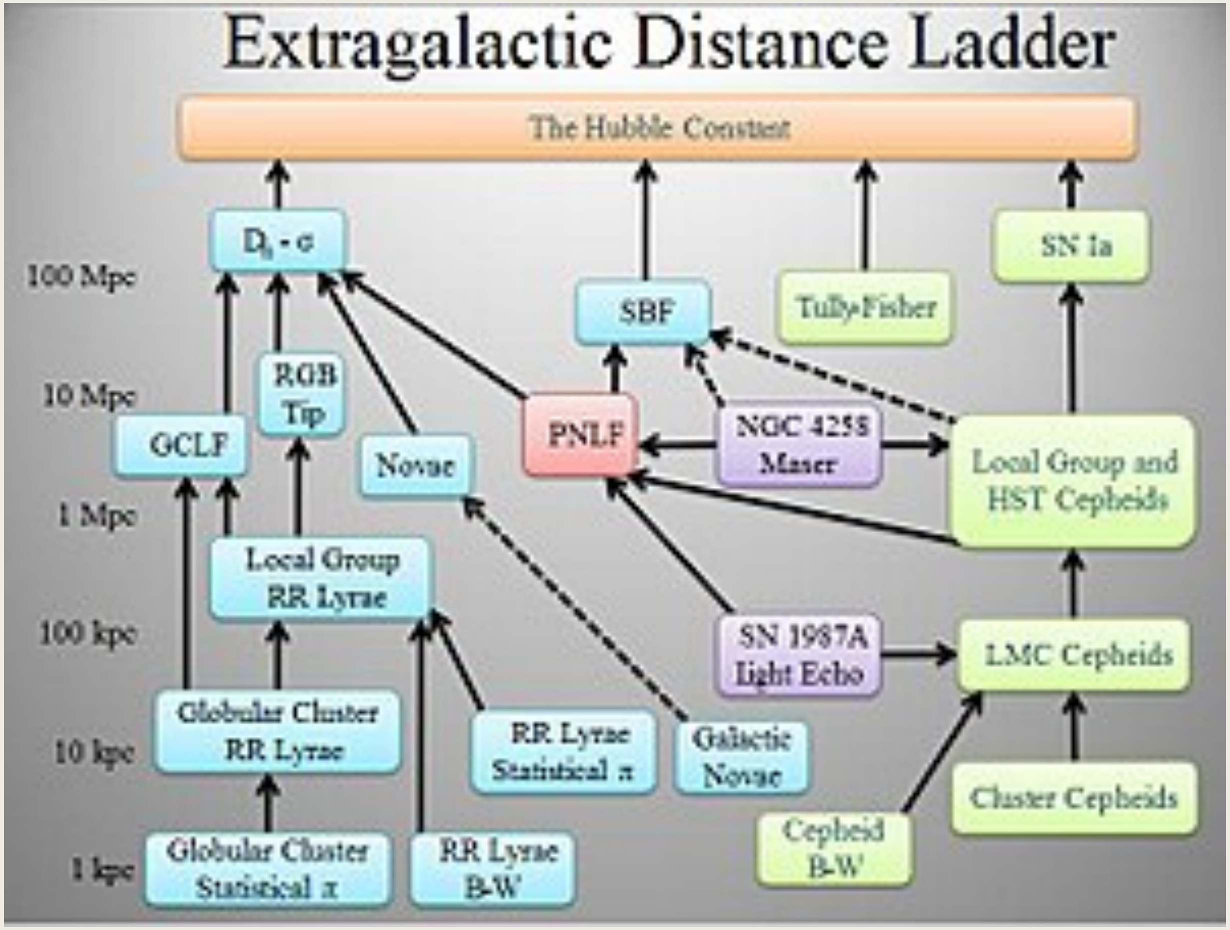


*how to measure extragalactic distances



- Technique applicable to star-forming galaxies.
- Technique applicable to Population II galaxies (old stars).
- Geometric distance technique.
- The planetary nebula luminosity function technique applicable to all populations
- Solid black lines: Well calibrated ladder step.
- Dashed black lines: Uncertain calibration ladder step.

*how to measure extragalactic distances

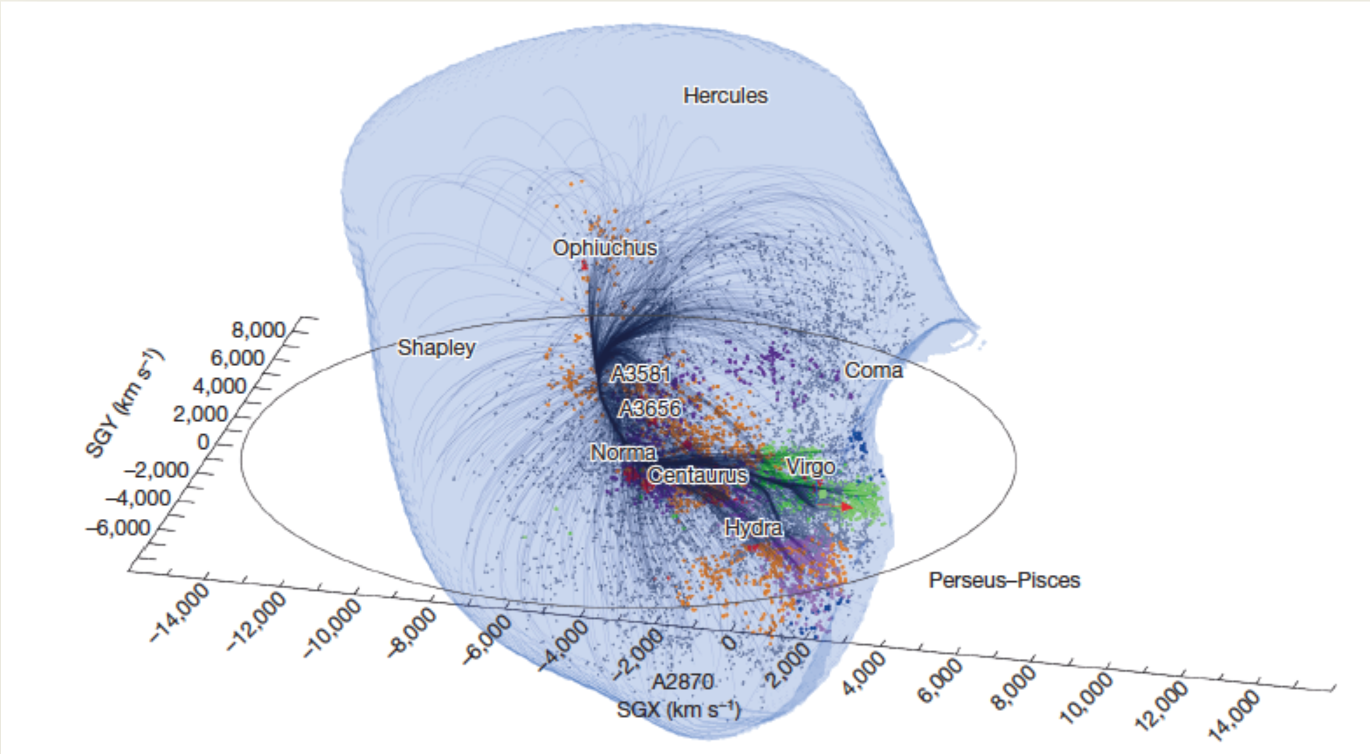


- Use of '**standard candles**'
- Variable stars with well-known period luminosity relationship (in old –RR Lyrae and young –Cepheids- stellar populations)
- **V=H d → last step, for distant galaxies**

- Uncertainties in distances translates → into uncertainties in the peculiar velocities of galaxies
- Many measurements are required to **average several galaxies** in the same region of the sky

The Laniakea super cluster

Tully et al. 2014 (*Nature* **volume 513**, pages 71–73



Map of structure made using not only overdensities (in positions and redshifts) of galaxies but also their peculiar velocities

→ Peculiar velocities obtained for ~8000 galaxies

Video Nature Laniakea

The Laniakea super cluster

Tully et al. 2014 (*Nature* **volume 513**, pages 71–73

The maps derived from spectroscopic survey reveals:

- Galaxies congregates in clusters along filaments
- There are large regions referred as voids
- The structures are inter-connected without clear boundaries

→ **The historical separation in galaxy clusters is overtaken by the new concept of inter-connected filaments and superclusters**

→ The location where peculiar velocity flows diverge trace the surfaces of the supercluster

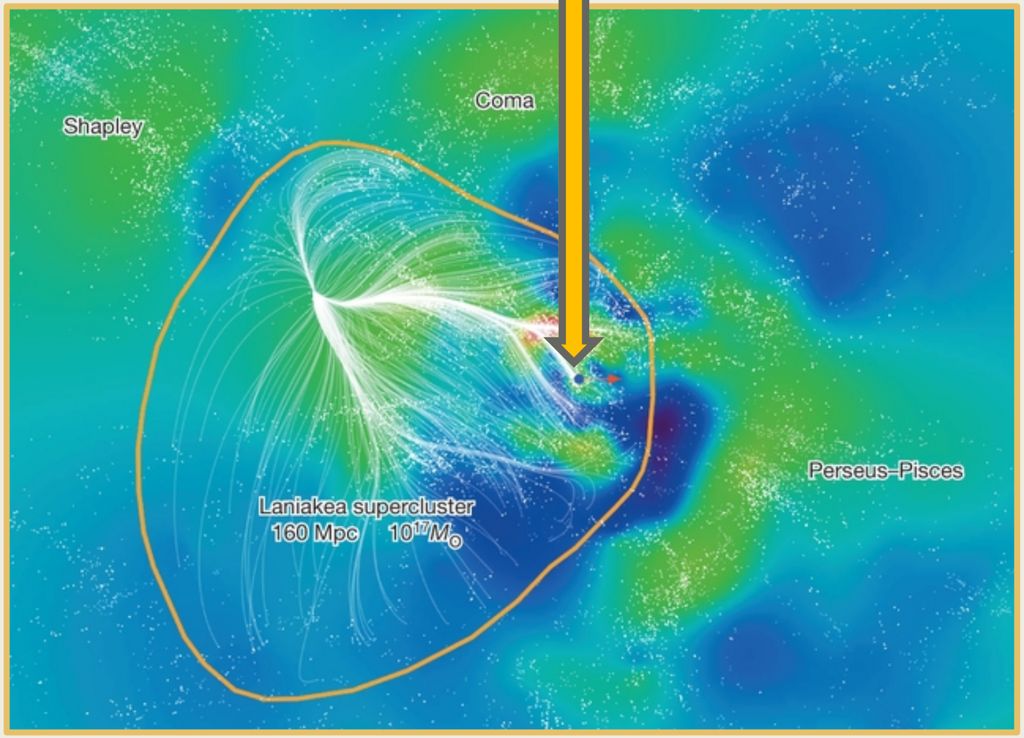
→ **The supercluster in which the MW is located is called Laniakea** (in Hawaiian means ‘Immense heaven', 'open skies', or 'wide horizons’)

The Laniakea super cluster

Tully et al. 2014 (*Nature* **volume 513**, pages 71–73

The characteristics of Laniakea:

- Size Laniakea → 160 Mpc radius → Local Group 1.2 Mpc!!
- Mass 10^{17} $M_{\odot}$ → Local Group 2 10^{12} $M_{\odot}$!!



Going back to our corner of sky….
The galaxies of the LG

Table 2.1. *Observational data on Local Group members*

Name	Alias	Type	α (J2000)	δ	V_r (kms^{-1})	V	$E(B-V)$
WLM	DDO 221	Ir IV–V	$00^h\,01^m\,57^s\!.8$	$-15°27'51''$	−120	10.42	0.02
IC 10	...	Ir IV:	00 20 24	+59 17 30	−344	10.4	≈0.85
NGC 147	...	Sph	00 33 11.6	+48 30 28	−193	9.52	0.17
And III	...	dSph	00 35 17	+36 30 30	...	14.21	0.05
NGC 185	...	Sph	00 38 58.0	+48 20 18	−202	9.13	0.19
NGC 205	...	Sph	00 40 22.5	+41 41 11	−244	8.06	0.04
M32	N 221	E2	00 42 41.9	+40 51 55	−205	8.06	0.06
M31	N 224	Sb I–II	00 42 44.2	+41 16 09	−301	3.38	0.06
And I	...	dSph	00 45 43	+38 00 24	...	12.75	0.04
SMC	...	Ir IV/IV–V	00 52 36	−72 48 00	+148	1.97	0.06
Sculptor	...	dSph	01 00 04.3	−33 42 51	+110	8.8	0.00
Pisces	LGS 3	dIr/dSph	01 03 56.5	+21 53 41	−286	14.26	≃0.03
IC 1613	...	Ir V	01 04 47.3	+02 08 14	−232	9.09	0.03
And V	...	dSph	01 10 17.1	+47 37 41	...	15	0.16
And II	...	dSph	01 16 27	+33 25 42	...	12.71	0.08
M33	N 598	Sc III	01 33 50.9	+30 29 37	−181	5.85	0.07
Phoenix	...	dIr/dSph	01 51 03.3	−44 27 11	...	...	0.02
Fornax	...	dSph	02 39 53.1	−34 30 16	+53	7.3	0.03
LMC	...	Ir III–IV	05 19 36	−69 27 06	+275	0.4	0.13
Carina	...	dSph	06 41 36.7	−50 57 58	+223	10.6	0.05
Leo A	DDO 69	Ir V	09 59 23.0	+30 44 44	+24	12.69	0.02
Leo I	Regulus	dSph	10 08 26.7	+12 18 29	+287	10.2	0.02
Sextans	...	dSph	10 13 02.9	−01 36 52	+226	10.3	0.04
Leo II	DDO 93	dSph	11 13 27.4	+22 09 40	+76	11.62	0.03
Ursa Min.	DDO 199	dSph	15 08 49.2	+67 06 38	−247	10.6	0.03
Draco	DDO 208	dSph	17 20 18.6	+57 55 06	−293	11.0	0.03
Milky Way	...	S(B)bc I–II:	17 45 39.9	−29 00 28	+16	...	...
Sagittarius	...	dSph(t)	18 55 04.3	−30 28 42	+142	...	0.15
SagDIG[a]	...	Ir V	19 29 58.9	−17 40 41	−79	14.2	0.07
N 6822	...	Ir IV–V	19 44 56.0	−14 48 06	−56	8.52	0.25
Aquarius[a]	DDO 210	V	20 46 53	−12 50 58	−131	13.88	0.04
Tucana[a]	...	dSph	22 41 48.9	−64 25 21	...	15.15	0.00
Cassiopeia	And VII	dSph	23 26 31	+50 41 31	...	15.2	0.17
Pegasus	DDO 216	Ir V	23 28 34	+14 44 48	−182	12.59	0.15
Pegasus II	And VI	dSph	23 51 39.0	+24 35 42	...	14.1	0.04

[a] Local Group membership needs to be confirmed.

From Van Den Bergh (2007)

The Local Group contains representatives of the main classes of galaxies, among them:

- early-type spiral (M31)
- late-type spiral (M33)
- luminous irregular (LMC, SMC)
- Dwarf irregular (Leo A, Sextans A&B, NGC3109)
- Spheroidal (NGC 205, NGC147)
- Dwarf spheroidal (Sculptor)
- Dwarf elliptical (M32).

The Local Group does not contain a giant elliptical or or a blue compact galaxy, although IC 10 is, perhaps, a presently rather inactive example of this class.

The galaxies of the Local Group cover 5 order in mass.

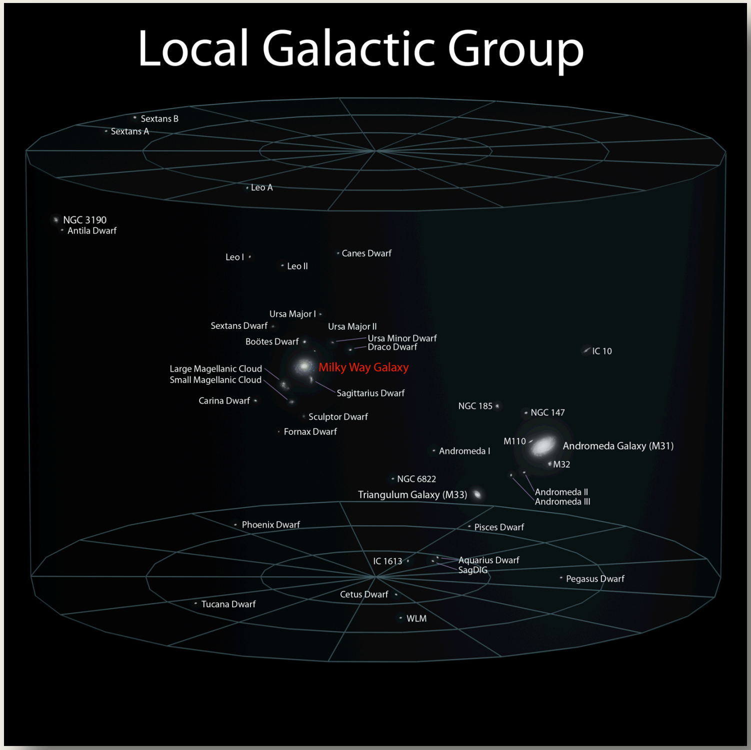
By number the LG is dominated by dwarf galaxies

The structure of the LG

M 31, M 32, NGC 205, NGC 147, NGC 185, M 33	Andromeda subgroup
IC 10	
NGC 6822	
IC 1613	
WLM	
LMC, SMC, Galaxy	Galaxy subgroup

IC 1613 (M_V = −14.9) has been discovered by Dyer (1895). This for indicates that our Local Group sample (at least outside the zone of avoidance at low Galactic latitudes) is almost certainly **complete for objects brighter than MV = −15.**

All known Local Group members **fainter than MV =−9** are satellites of the Galaxy suggests that the sample of more distant faint Local Group galaxies is still incomplete and many **more dwarf satellites have to be discovered.**



The number of dwarf galaxies has been increasing over the years, since fainter and fainter objects are being discovered (e.g. Crater, Belokurov et al. 2014) out of deep and wide area sky surveys (2MASS, SDSS, etc.). The exact number of DG in the LG is unknown. **As of today, they would be ~70 (McConnachie 2012).**

The main characteristics

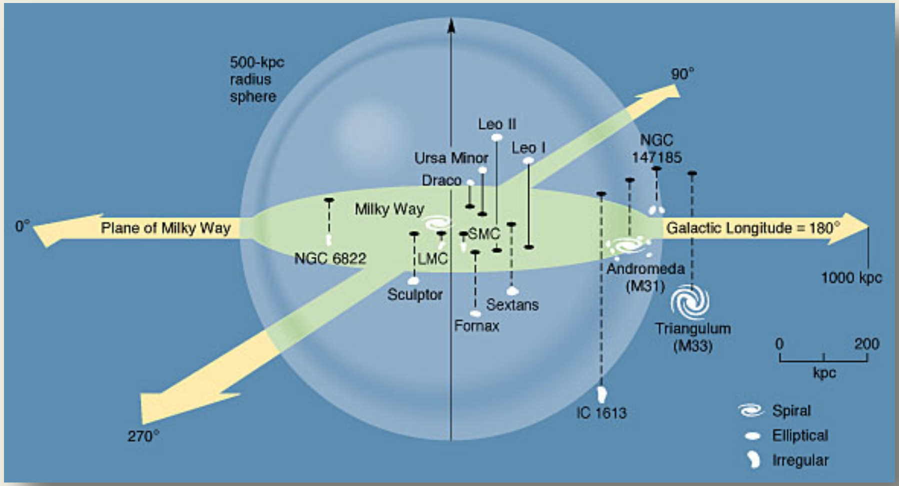


Table 20.1. *Local Group properties*

Radius of zero-velocity surface	$R_o = 1.18 \pm 0.16$ Mpc[a] (1)
Half-mass radius	$R_h \approx 350$ kpc
Total Local Group luminosity	$L_V = 4.2 \times 10^{10} L_\odot$ (2,4)
Radial velocity dispersion	$\sigma = 61 \pm 8$ km s^{-1} (1)
Total Local Group mass	$M = (2.3 \pm 0.6) \times 10^{12} M_\odot$ (1)
Local Group mass-to-light ratio	$M/L_V = 44 \pm 14$ (in solar units) (2)
Mass of Andromeda subgroup	$M(A) = (1.15{-}1.5) \times 10^{12} M_\odot$ (3)
Luminosity of Andromeda subgroup	$L_V = 3.0 \times 10^{10} L_\odot$ (4)
Andromeda subgroup mass-to-light ratio	$M(A)/L_V = 38{-}50$
Mass of Milky Way subgroup[b]	$M(G) = (0.46{-}1.25) \times 10^{12} M_\odot$ (5)
Luminosity of Milky Way subgroup	$L_V = 1.1 \times 10^{10} L_\odot$ (4)
Milky Way subgroup mass-to-light ratio[b]	$M(G)/L_V = 42{-}114$
Bound multiple systems	M31 + M32 + NGC 205, LMC + SMC, NGC 147 + NGC 185

- The total mass of the LG $2.3 \pm 0.6\ 10^{12}\ M_\odot$
- Most of this mass appears to be concentrated in the Andromeda and Milky Way subgroups of the LG.
- The total luminosity of the Local Group is found to be M_V = -22.0 (90% of the luminosity concentrated in the 3 spirals)
- Dwarf spheroidal galaxies are strongly concentrated within the Andromeda and Milky Way sub-clusters, whereas the majority of dwarf irregular galaxies appear to be free-floating members of the LG as a whole.

The main characteristics

Table 20.1. *Local Group properties*

Radius of zero-velocity surface	$R_o = 1.18 \pm 0.16\,\mathrm{Mpc}^a$ (1)
Half-mass radius	$R_h \approx 350$ kpc
Total Local Group luminosity	$L_V = 4.2 \times 10^{10}\,L_\odot$ (2,4)
Radial velocity dispersion	$\sigma = 61 \pm 8\,\mathrm{km\,s^{-1}}$ (1)
Total Local Group mass	$M = (2.3 \pm 0.6) \times 10^{12}\,M_\odot$ (1)
Local Group mass-to-light ratio	$M/L_V = 44 \pm 14$ (in solar units) (2)
Mass of Andromeda subgroup	$M(\mathrm{A}) = (1.15\text{–}1.5) \times 10^{12}\,M_\odot$ (3)
Luminosity of Andromeda subgroup	$L_V = 3.0 \times 10^{10}\,L_\odot$ (4)
Andromeda subgroup mass-to-light ratio	$M(\mathrm{A})/L_V = 38\text{–}50$
Mass of Milky Way subgroup[b]	$M(\mathrm{G}) = (0.46\text{–}1.25) \times 10^{12}\,M_\odot$ (5)
Luminosity of Milky Way subgroup	$L_V = 1.1 \times 10^{10}\,L_\odot$ (4)
Milky Way subgroup mass-to-light ratio[b]	$M(\mathrm{G})/L_V = 42\text{–}114$
Bound multiple systems	M31 + M32 + NGC 205, LMC + SMC, NGC 147 + NGC 185

This shows that dark matter in the Local Group outweighs visible matter by about an order of magnitude!

Is the Local Group typical?

In the past, the Local Group was considered a typical example of a group of galaxies (Van den Bergh, 2000):

- Inspection of the Palomar Sky Survey (Minkowski & Abell 1963) shows (van den Bergh 1962) that only a **small fraction** of all galaxies are isolated objects or members of rich clusters.

- **The majority of galaxies in nearby regions of the Universe are seen to be located in small groups and clusters resembling the Local Group.**

Clustering in the Universe: Groups vs. Clusters

Clusters are part of a continuous range of structures :

galaxies → groups→ clusters→ superclusters→ large scale structure

Very roughly (depending on definitions) the total galaxy content of the Universe is divided :

1-2% in rich clusters

5-10% in clusters

50-90% in "Local Group"s or looser groupings

	Groups	Clusters
# Galaxies	~10	>50
Radius of Core (kpc)	~300	~300
Median radius (kpc)	~1000	~3000
Velocity dispersion (km/s)	~150	~800
M/L ratio	~200	~200

Is the Local Group a typical group of galaxies?

Small groups of galaxies are indeed the most common form of aggregation of galaxies in the Local Universe.

The Local Group has only about **10 significant galaxies ($L>10^8L_\odot$)**, so it belongs to the 'group' category, within 1 Mpc of the Milky Way:

The composition of the LG is thus different from typical large clusters:

in core regions: 10%-40%-50% in spirals-ellipticals-lenticulars

in outer regions: 80%-10%-10% in spirals-ellipticals-lenticulars

Is the Local Group typical?

However recent observations and cosmological simulations are telling us that:

The spatial and kinematic configuration of Local Group (LG) galaxies is very uncommon in the Local Universe as well as in cosmological simulations (Forero-Romero & Gonzalez 2015)

→ only 2%of MW-sized haloes reside in a pair similar to MW-M31 and with similar LG environment.

The LG is dominated by two big spirals: the Milky Way (MW) and M31

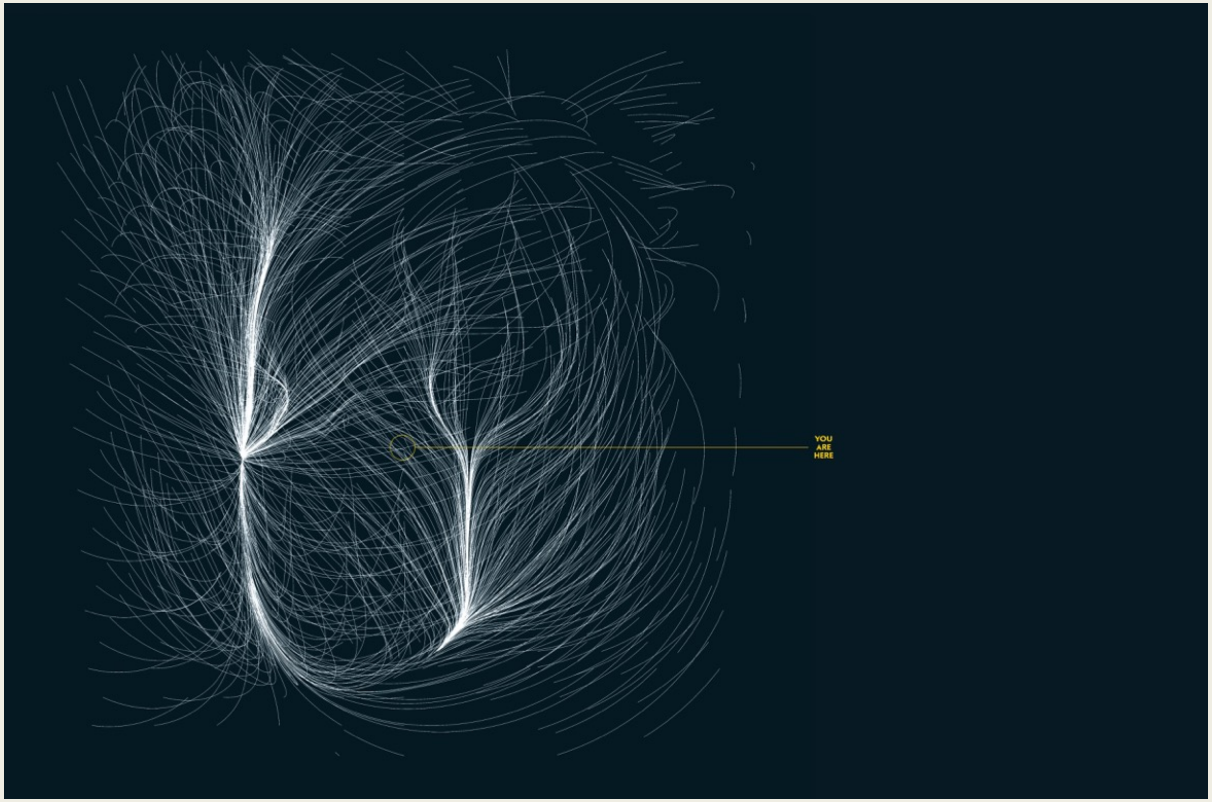
→ the pair configurations in quite rare in group of galaxies

The velocity vector of M31, with a low tangential velocity is consistent with a head-on collision orbit toward the MW (e.g., Sohn et al. 2012).

→ the orbital parameters of the LG are rare among typical pairs, but not sufficiently rare to challenge the ΛCDM model.

Is the Local Group typical?

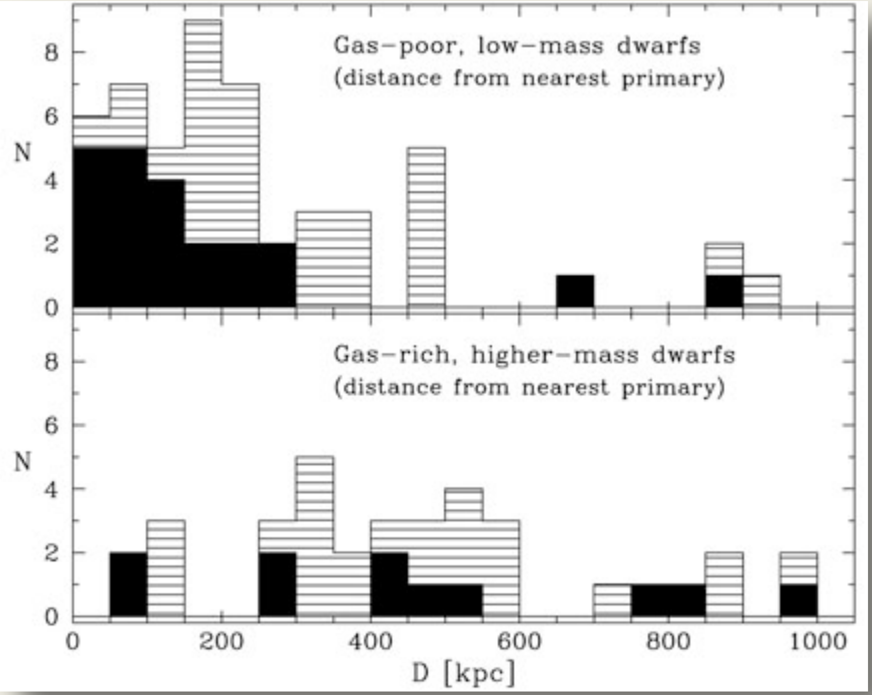
Typical or not, the Local Group is the only small portion of the Laniakea superclusters (and of the whole Universe) that we can analyse in details, resolving its stellar populations, gas and dust content, etc.



Morphological Segregation in the LG

The distribution of the different types of galaxies within the LG is determined by the location of the two most massive spiral galaxies :

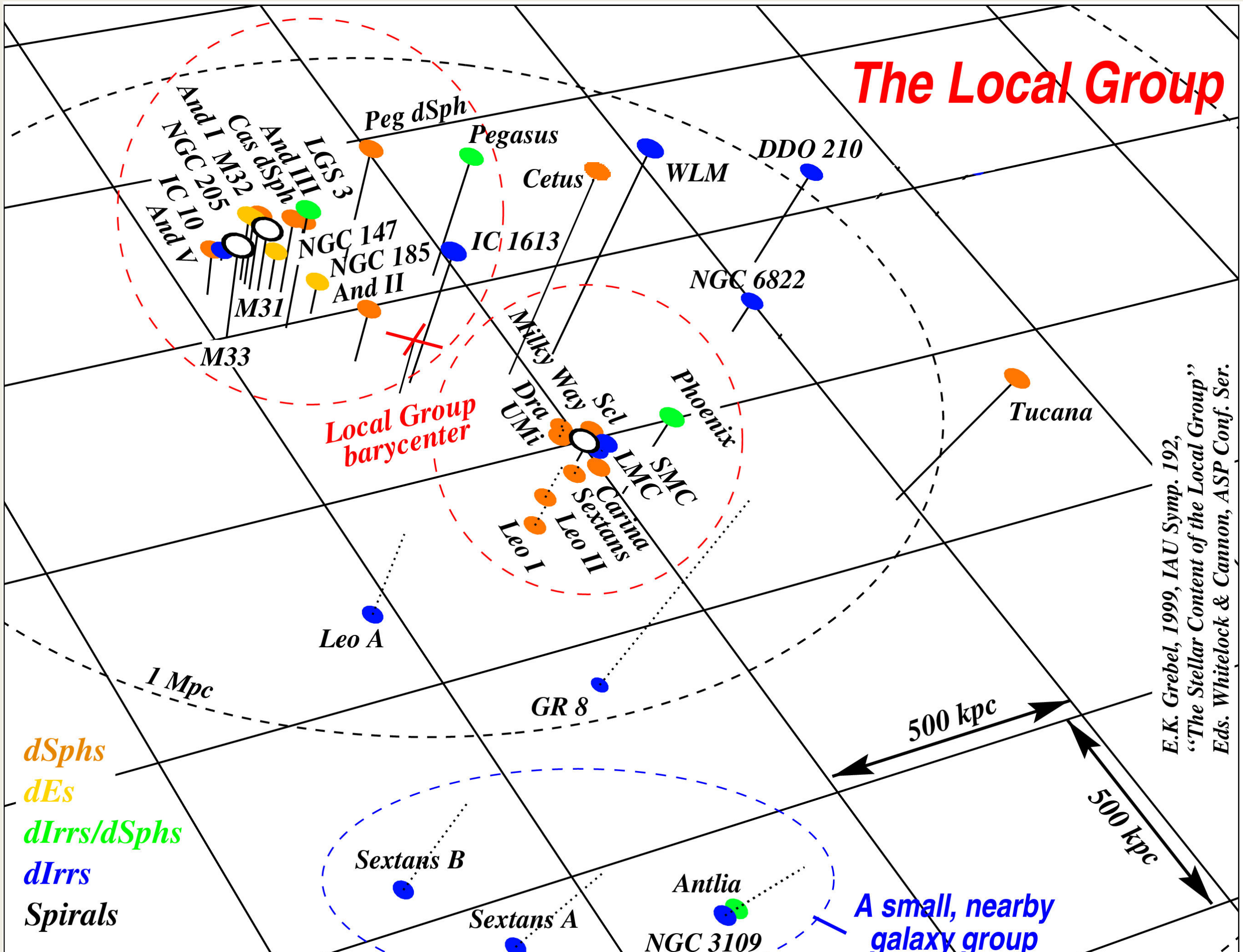
- The gas-poor dwarfs - primarily dSphs - are strongly clustered around the closest massive spiral
- The gas-rich dwarfs (dwarf Irrs) exhibit less of a tendency toward close concentration around massive galaxies and are more widely distributed.



Morphological segregation:

Distribution of different types of galaxies in the Local Group (solid histograms) and in the M81 and CenA (hashed histograms) as a function of distance D to the closest massive primary (from Grebel 2004).

Impact of environment on galaxy evolution, at least on small scales



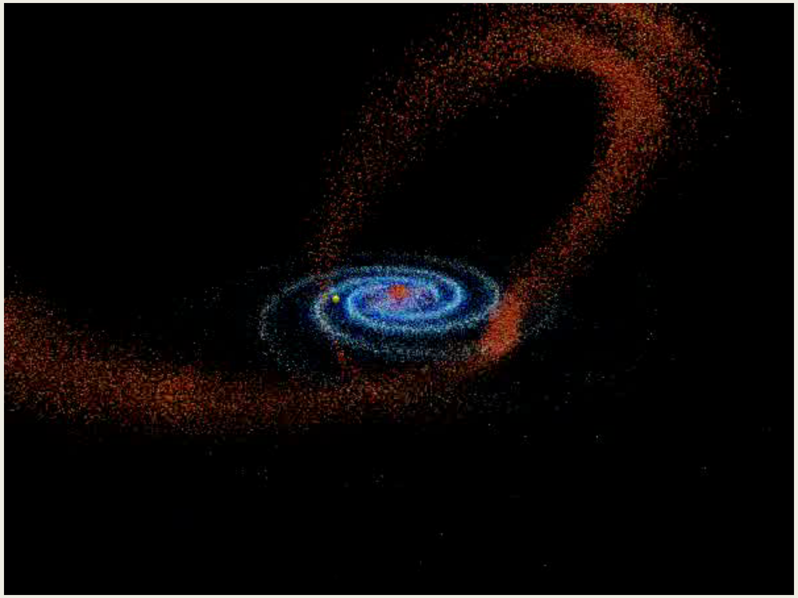
In Blue: dwarf irregular galaxies, which are star forming galaxies

In orange-yellow: dwarf spheroidal galaxies

An ”active” group: effect of the environment on action

Accretion evidence:

- The detection of extra-tidal stars and streams around and within massive galaxies is evidence for **ongoing harassment and accretion events.**
- The stellar content, population properties, and chemistry of nearby galaxies allow us to constrain to what extent these kinds of objects could have contributed as building blocks to more massive galaxies → **remember Gaia-Enceladus!**

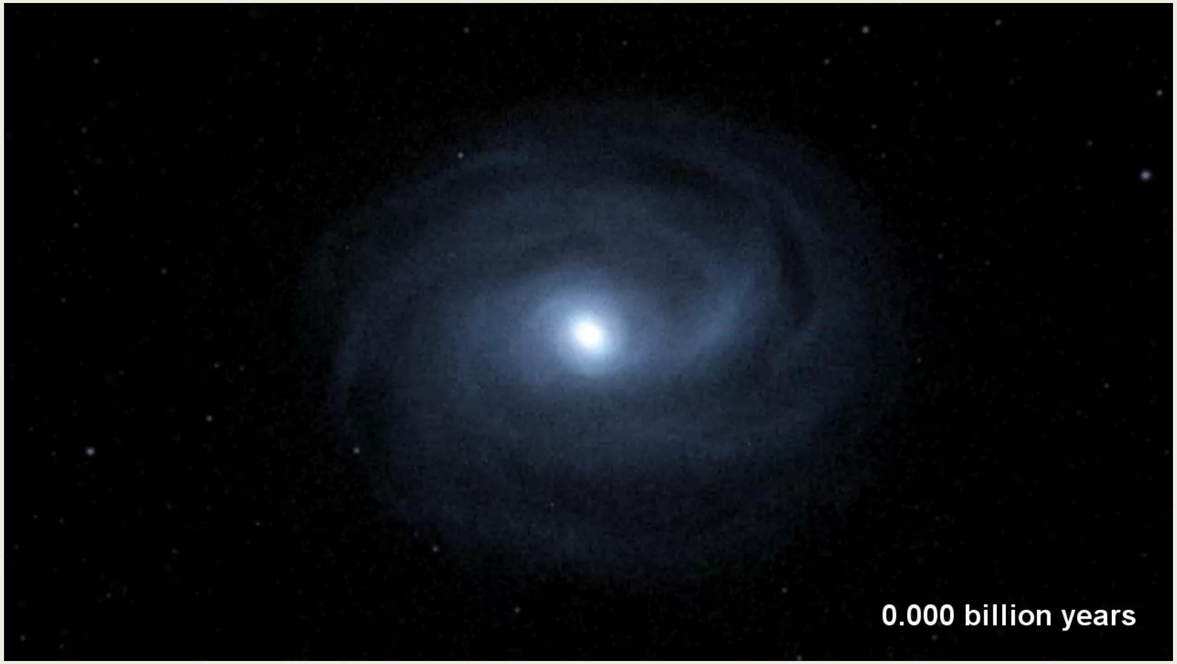


Video by David Law and Steven Majewski, University of Virginia.

- Tidal disruption of a dwarf galaxy
- Formation of the so-called Sagittarius stream (the Sagittarius dwarf galaxy is currently being accreted by the Milky Way)

An ”active” group: predictions for the future of the LG

- MW-M31 close encounter in the next 4 Gyr



Visualization Credit: NASA, ESA, and F. Summers (STScI)

Simulation Credit: NASA, ESA, G. Besla (Columbia University), and R. van der Marel (STScI)

- Joint evolution of the MW, M31, and M33 over the next several Gyr.
- HST observations indicate that M31 and the MW will crash together in a head-on collision about 4 Gyr.
- Around 6 Gyr from now, the two galaxies will merge to form a **single elliptical galaxy.**
- M33 continues to orbit the merged pair

How old is the Local Group?

On the age of LG stellar populations

- According to hiererchical structure formation scenarios, low-mass system should have been the **first sites of star formation in the Universe**
- **Massive galaxies should have formed by hierarchical merger of smaller systems**
- Resolved stellar populations in dwarf galaxies are important to test this scenario, comparing the properties of their old stellar populations with those of massive galaxies as the Milky Way

Do the oldest stellar populations in the MW and in dwarf galaxies show similar properties (e.g. ages and metallicities)?

How old is the Local Group?

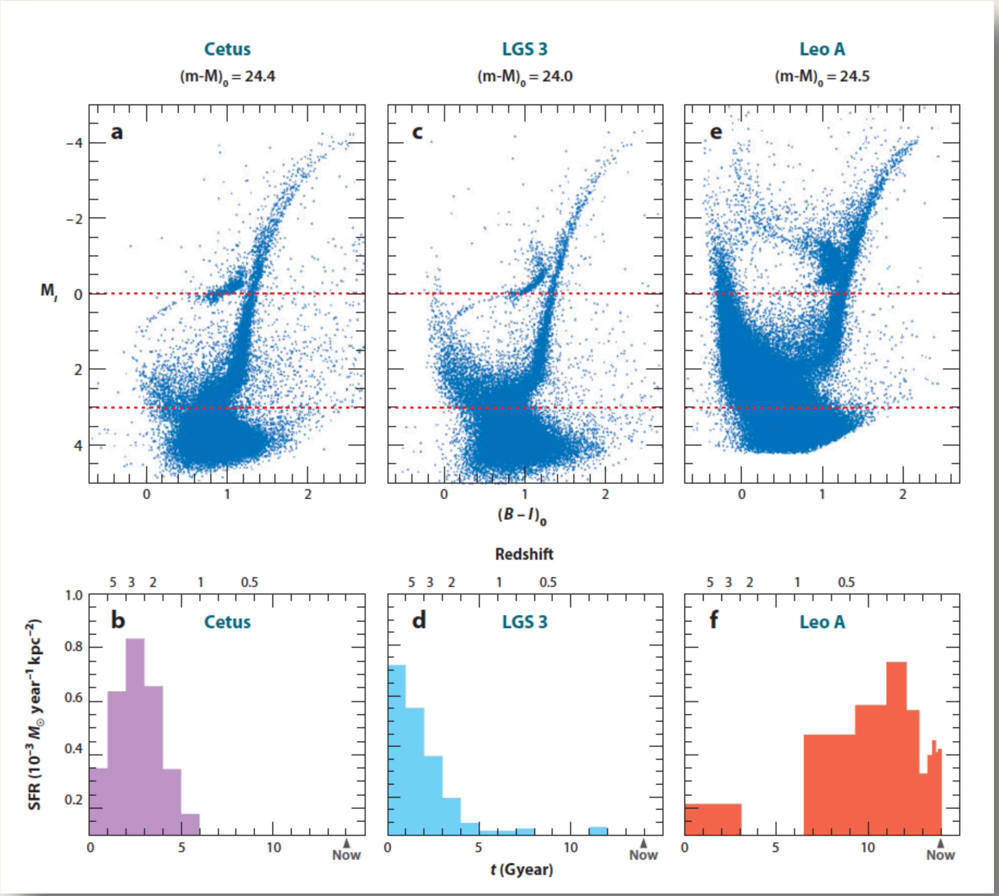
On the age of LG stellar populations

- One of the most interesting results of population studies in individual Local Group galaxies is that all of these objects appear to contain very old stars with ages >10 Gyr

- Furthermore, available evidence indicates that the earliest star formation took place in a **larger** volume than it does at the present time: Local Group galaxies shrank as they evolved **(see also the location of the metal poorest Globular clusters in the halo of the MW)**

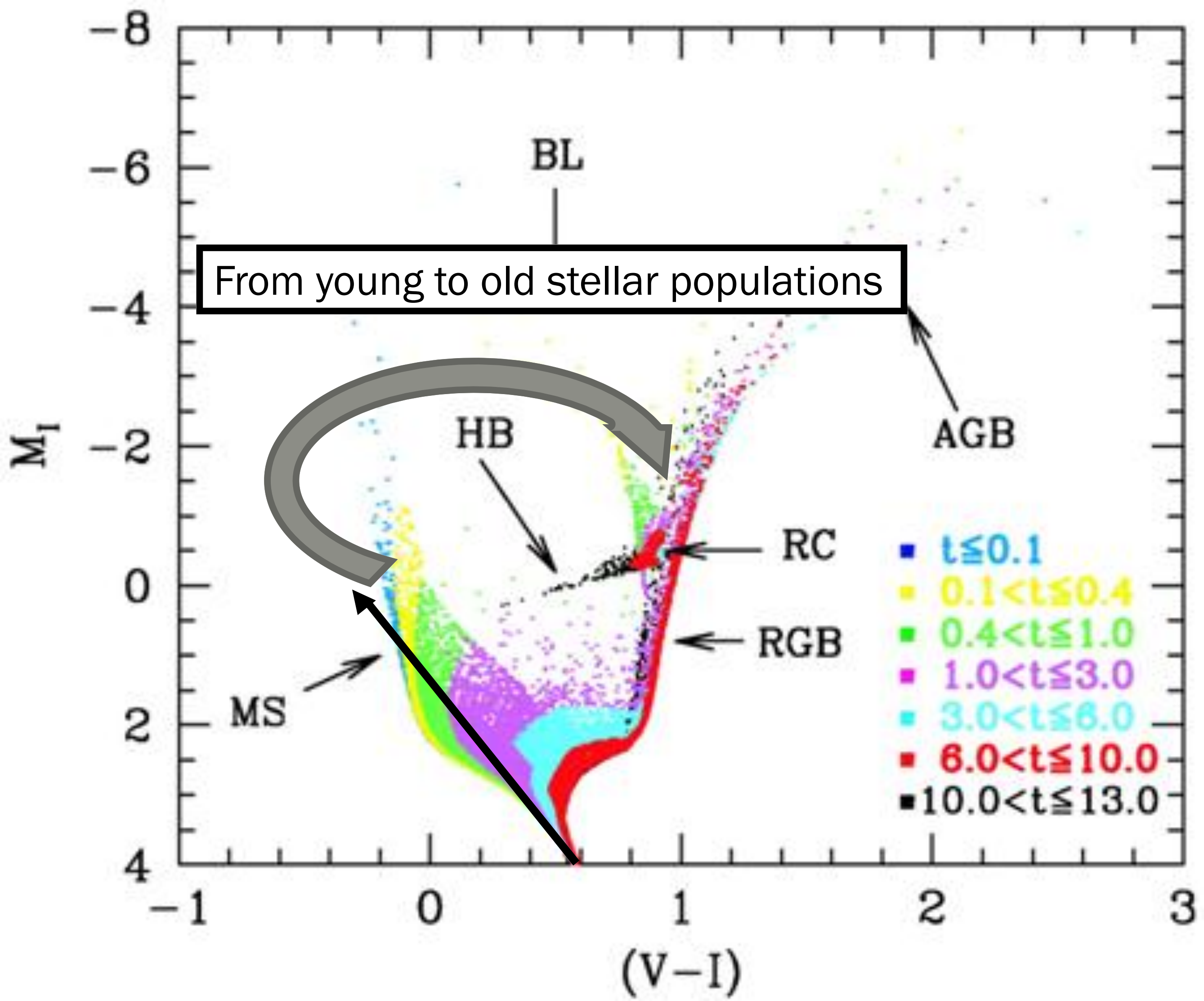
A variety of star formation histories

dSph Transition dIrr



HST CMDs and SFHs for three Local Group dwarf galaxies from Tolstoy et al. (2009)

How to interpret this diagram



Star formation histories

- Detailed star formation histories are derived photometrically through colour-magnitude diagrams (CDMs):

→ Irregular galaxies are characterized by **largely continuous star-formation variation of factor 2-3**, and are more active at present time

→ Transition galaxies are characterized **by very low star formation rates** and may eventually turn into quiescent dSph

→ Dwarf spheroidal galaxies tend to have continuous star formation rates, with **decreasing intensity with time**

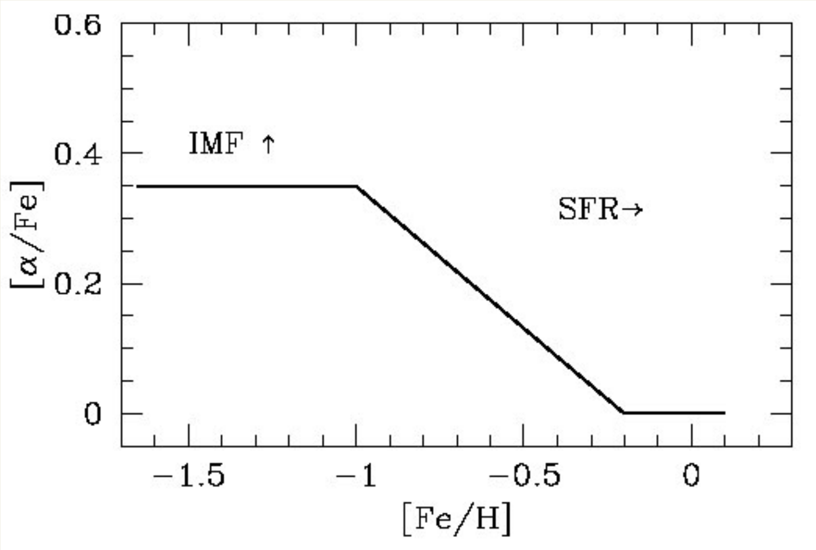
A variety of star formation histories: differences and common aspects

- Old populations are ubiquitous, but their fraction vary from galaxy to galaxy
- Not a single dwarf galaxy without an old stellar population
- In all galaxies, including the MW, there is a common epoch of star formation (**consistent with building block scenario**)
- No cessation of star formation after the re-ionization is observed, but even the least massive galaxies show evidence for star formation extending over many Gyr

  → can be solved assuming that in the past these galaxies were much more massive, and thus the **complete photo-evaporation was prevented**

Resolved chemistry in the Local Group

[α/Fe] traces the star-formation timescale in a system, because it is sensitive to the ratio of SNe II (massive stars) to SNe Ia (intermediate mass binary systems with mass transfer). SNe Ia have a longer timescale than SNe II and as soon as they start to contribute they dominate the iron enrichment and [α/Fe] inevitably decreases.



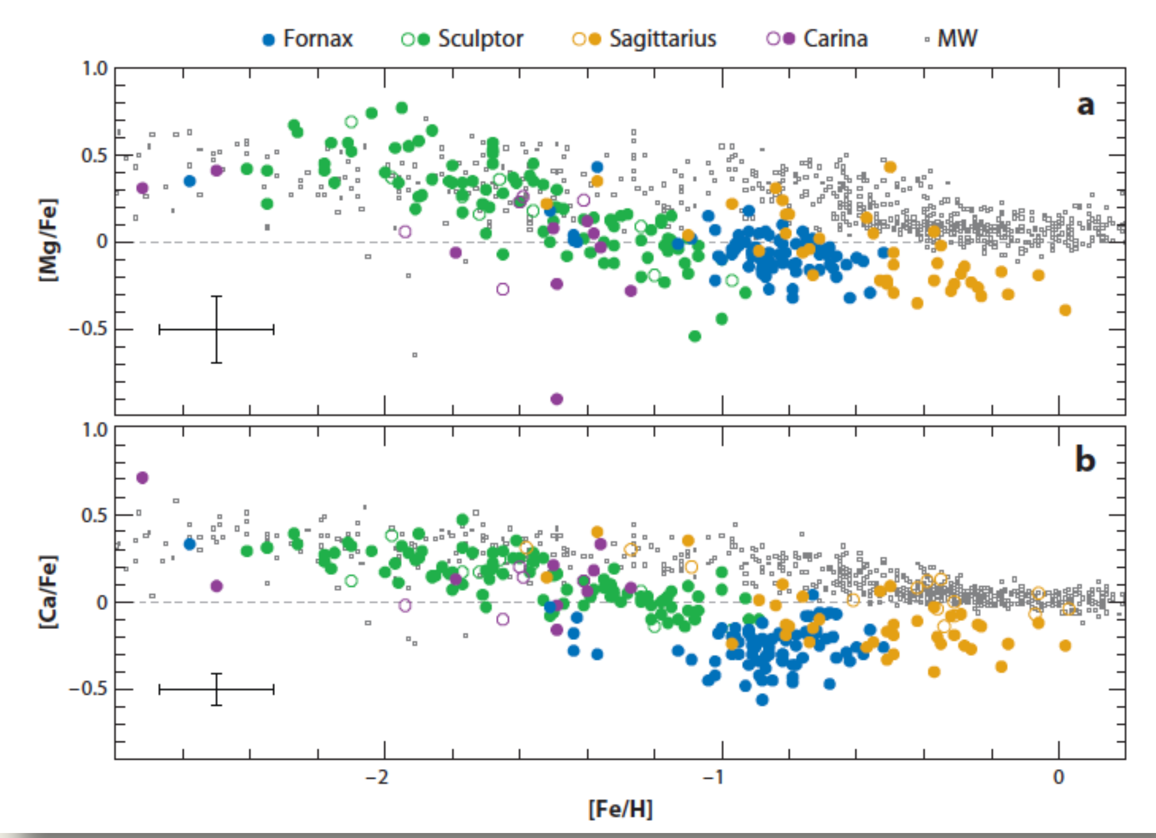
- Star formation history
- Time-scales
- IMF

The knee position indicates the metal-enrichment achieved by a system at the time SNe Ia start to contribute to the chemical evolution, between 10^8 and 10^9 years after the first star-formation episode.

Resolved chemistry in the Local Group

A galaxy that efficiently produces and retains metals **(higher SFR)** will reach a higher metallicity by the time SNe Ia start to contribute than a galaxy that either **loses significant metals in a galactic wind**, or simply **has a low SFR.**

- The position of this knee varies for different galaxies because of the **wide variety of SFHs.**
- At low metallicity stars in dSphs are consistent with the Halo of the MW



Resolved chemistry in the Local Group

The comparison of the abundances of dwarf galaxies and of the Halo of the MW in the [α/Fe] vs [Fe/H] plane gives a strong evidence against ***present-day dSphs*** as the dominant contributors to the building-up of the Galactic Halo.

→ However, it cannot be excluded that the MW halo accreted such dwarf galaxies **early in their evolution**, disrupting them and stopping further evolution involving SNIa.

→ Abundance patterns vary considerably among Local Group galaxies, calling for more complex explanations than those based simply on differences in timescales (e.g. environment, inflow, outflow, etc.)

The halo of M31: tracing back its merger history

From the study of M31, the other large spiral galaxy of the Local Group, we can learn a lot about the formation of spirals, and also of the Milky Way (with important cosmological implications…..)

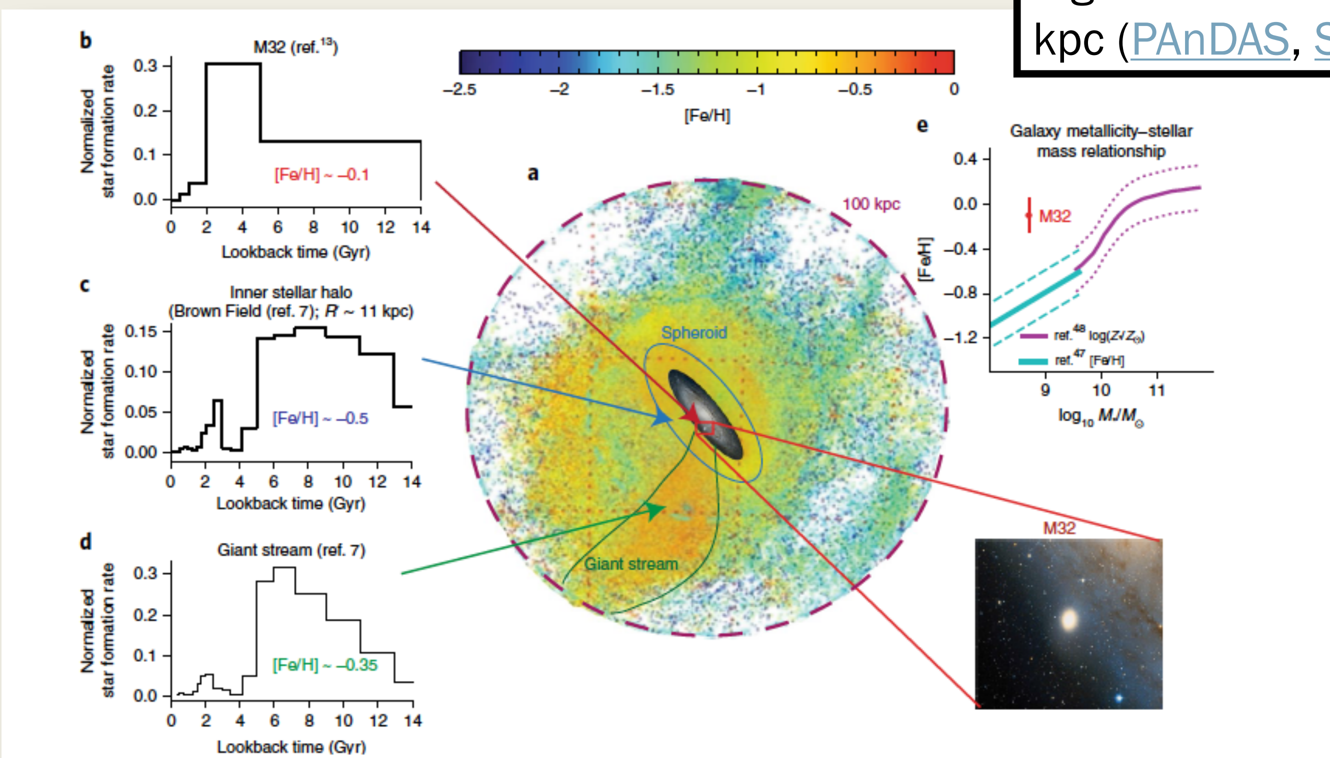
- **Stellar halos of galaxies are built up from the merger debris of accreted and disrupted satellites.**
- As a satellite galaxy is cannibalized by the main galaxy, it leaves **behind a trail of debris.**
- Deciphering the merger history of a galaxy from these debris would enable us to understand how these galaxies build up over time as well as disentangle **which of the galaxies properties were caused by these mergers.**

The halo of M31: tracing back its merger history

M31′s stellar halo is 10 times more metal-rich and 20 times more massive than the Milky Way halo.

The stellar halo of M31 has been mapped to exquisite detail out to a galactocentric distance of 150 kpc ([PAnDAS](), [SPLASH]())

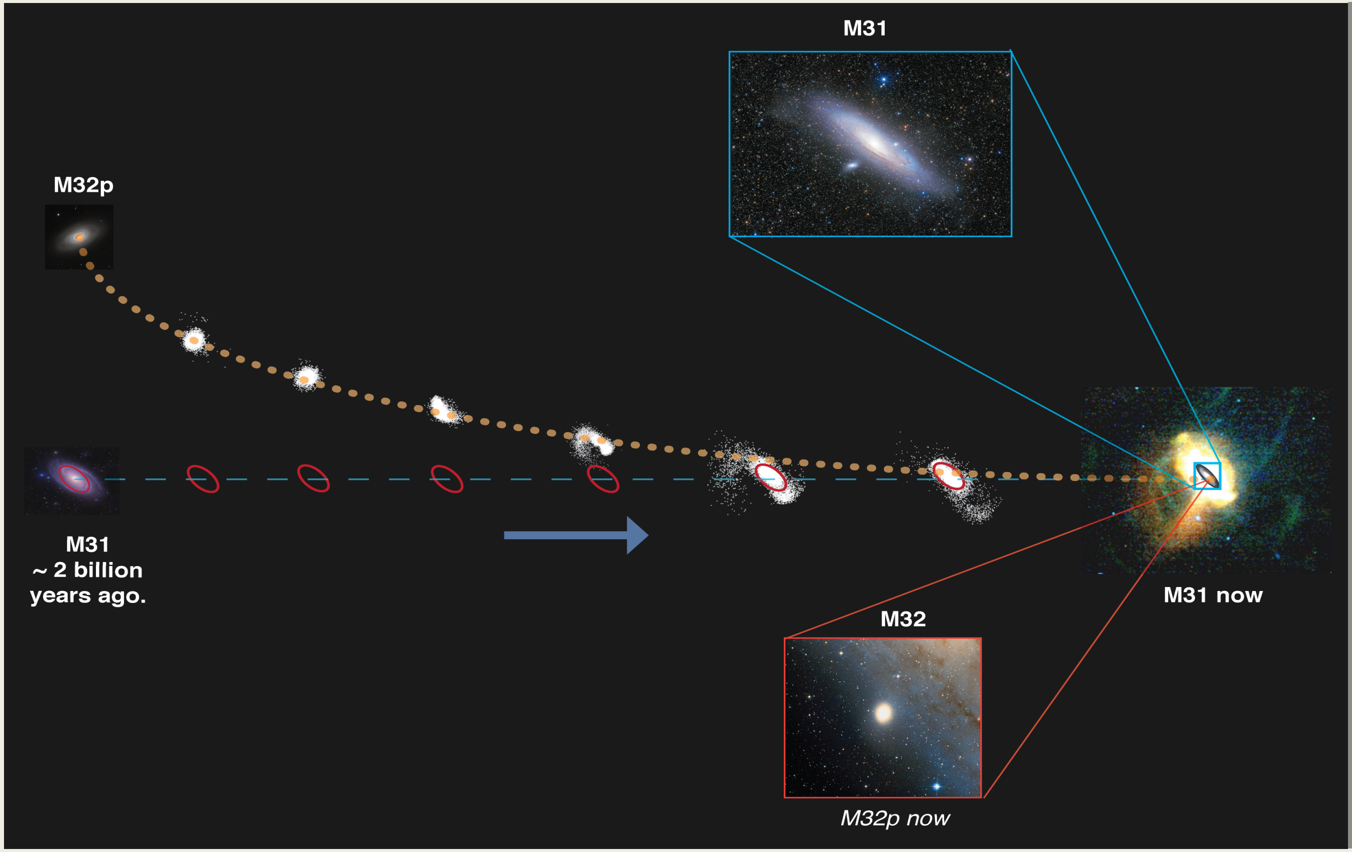
Metallicity map from the Panda Survey



D'Souza & Bell 2018

The halo of M31: tracing back its merger history

The disruption of the most massive progenitor results in a debris field similar to the stellar halo of M31



Simulation of the merger, with the formation of the inner halo and stream.

The model suggests that M31 with its extremely large and **metal-rich stellar halo should be dominated by a single large accretion and recent accretion event**

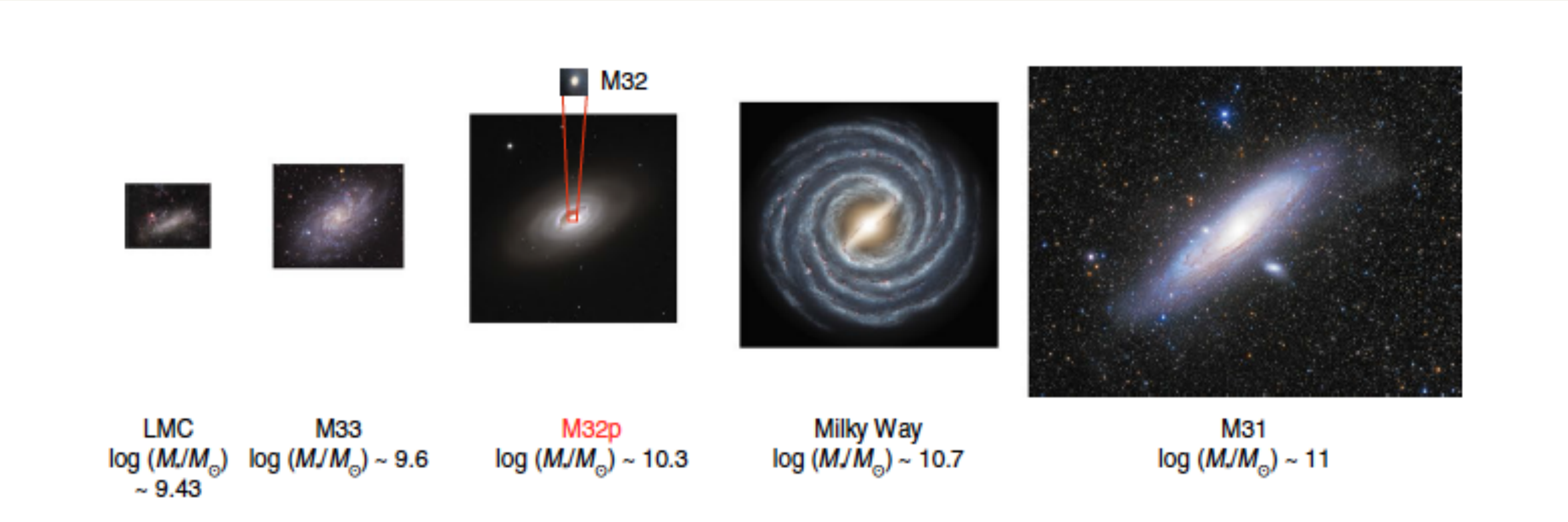
D'Souza & Bell 2018

The halo of M31: tracing back its merger history

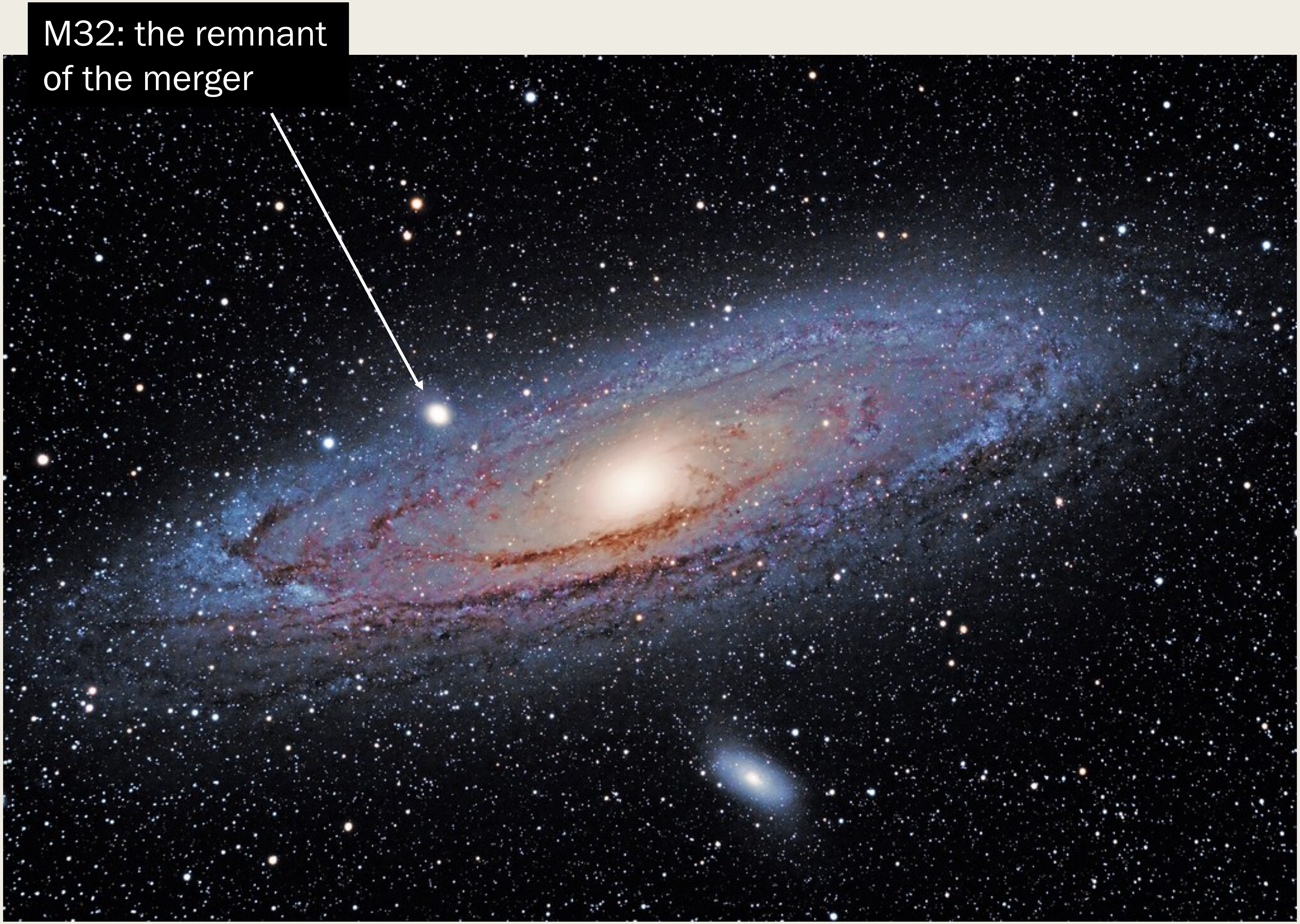
M32p, the most massive progenitor accreted by M31, was the third largest member of the Local Group.

M32p is compared with the largest present-day members of the Local Group: LMC, M33, Milky Way and M31.

M32p is represented using an analogue in the local universe M64.



D'Souza & Bell 2018


M32: the remnant of the merger

Which science in the LG

Although it could not be to most typical aggregation of galaxies in the Local Universe, and it appears as a small structure in the infinity of the Universe, the Local Group remains of paramount importance because of the great detail with which **we can resolve the stellar populations** of its galaxies:

- Photometry→ to reconstruct the star formation history through colour-magnitude diagrams
- Spectroscopy→ ages, chemistry and kinematics of individual stars

Optical/IR spectroscopy

Terminology:

Resolving power: $R = \lambda/\Delta\lambda$

Dispersion – $\Delta\lambda$/pixel

Where:

Λ is the wavelength and $\Delta\lambda$ the wavelength interval to resolve

- "low" resolution → 10 <R < 1000
- "moderate" resolution → 1000 <R < 10,000
- "high" resolution → R> 10,000

Spectrographs

- A ray reflected by grooves in the grating will either interfere constructively or destructively with the ray from the groove next to it, depending on the angle and wavelength, creating a "spectrum".

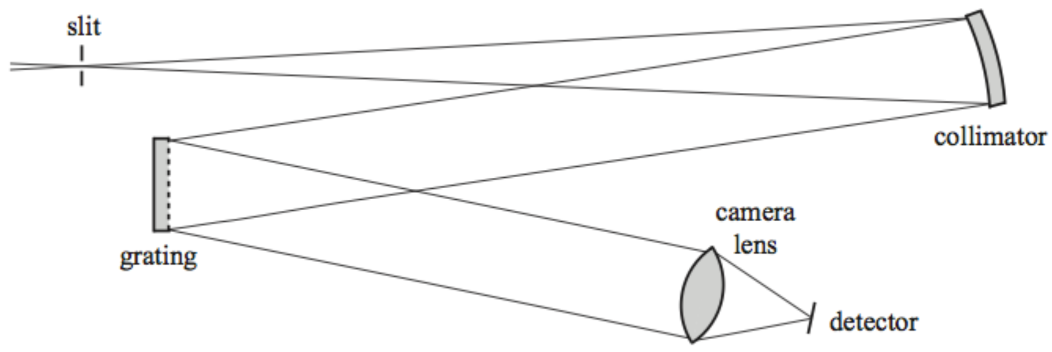


Fig. 1.— The essential components of an astronomical spectrograph.

From Massey, Astronomical Spectroscopy

$$m\lambda = \sigma(\sin i + \sin\theta).$$

i = angle of incidence
Θ =angle of diffraction
m=order of the grating
σ=distance between two adjacent grooves

The advantage of a grating over a prism is that light passing through a prism is absorbed, while a **grating works on reflected light without any transmission.**

High resolution spectra

- Two way to obtain high resolution spectra:

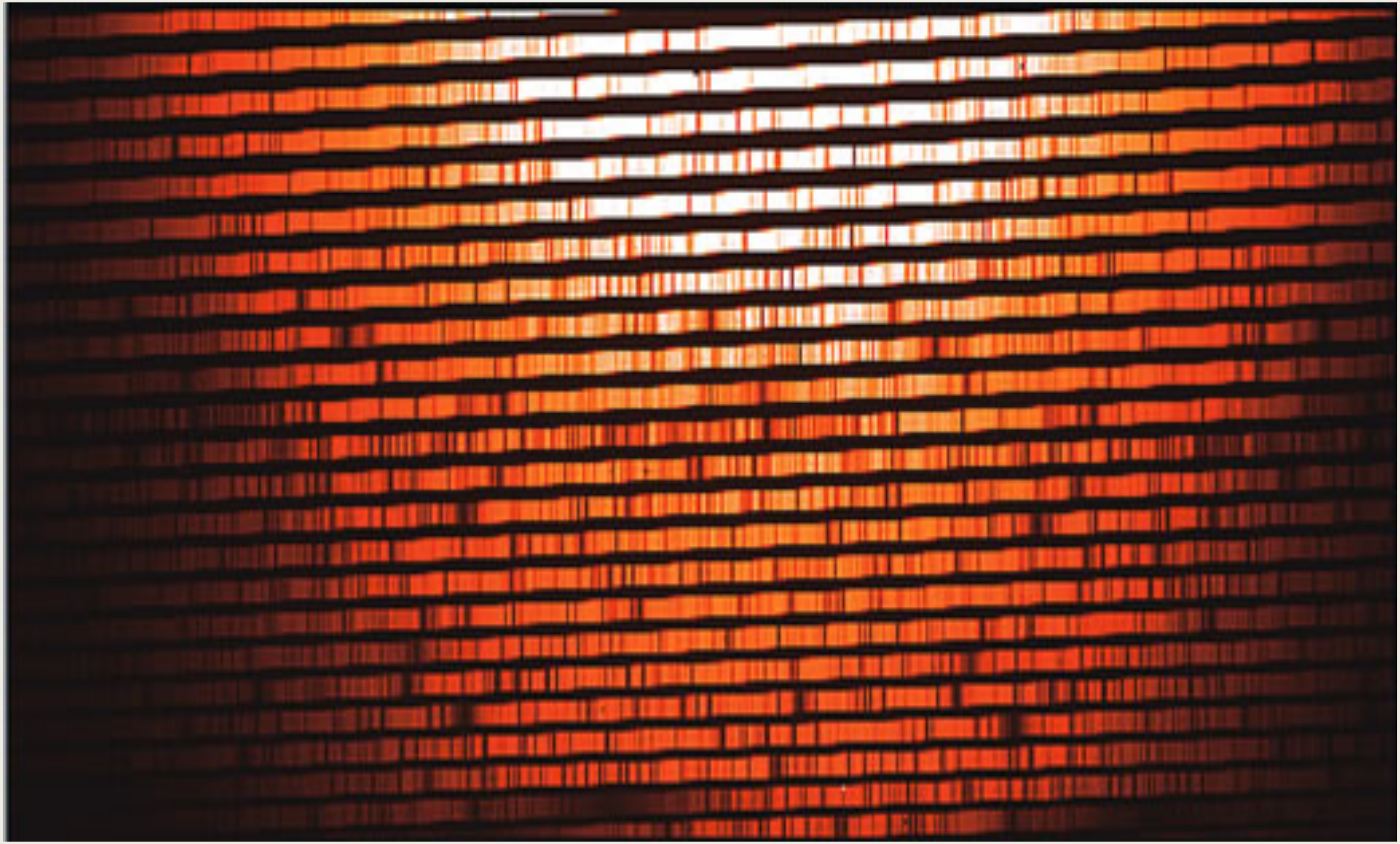
- differentiating the grating equation:

$$d\theta/d\lambda \sim m/\sigma$$

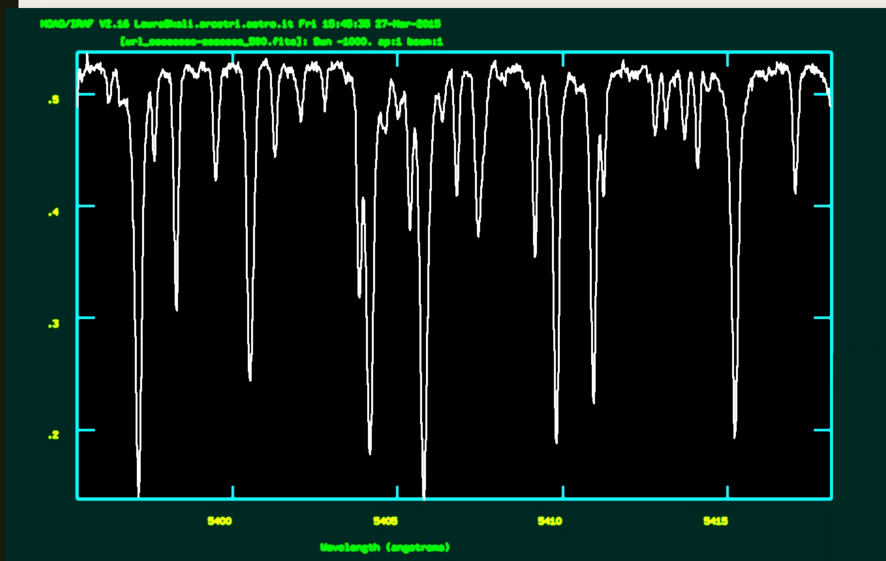
- For small incidence angles [Littrow condition]: grating with many grooves are necessary to reach high resolution (**traditional spectrographs**, max 1800 grooves) → **small sigma (large number of grooves)**

- For high incidence angle: high dispersion con be achieved with a low number of groves per mm by operating in a high order (**echelle spectrographs**, 80 grooves, with typically tanθ ~ 2 or greater) → **large order m**

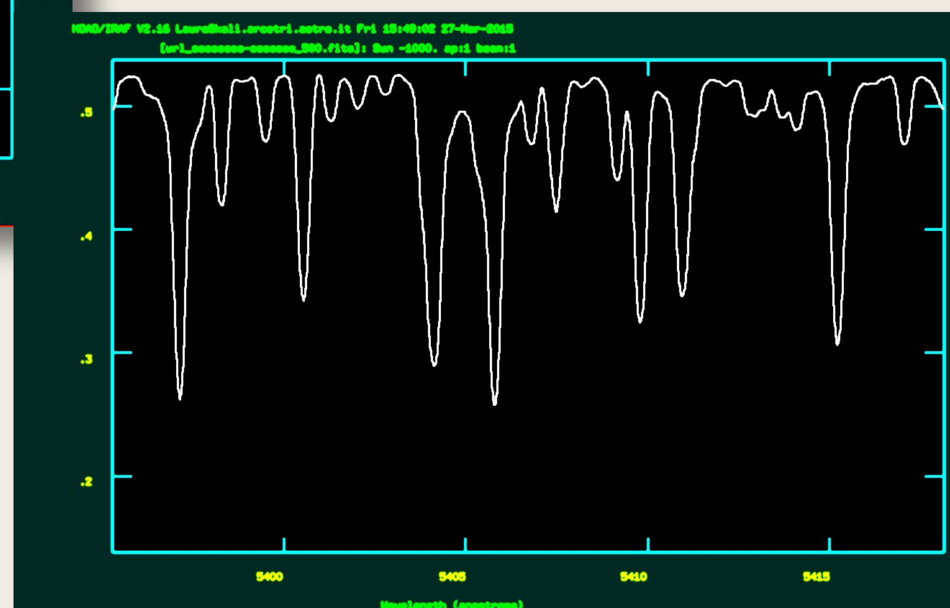
Echelle spectrum



Importance of resolution

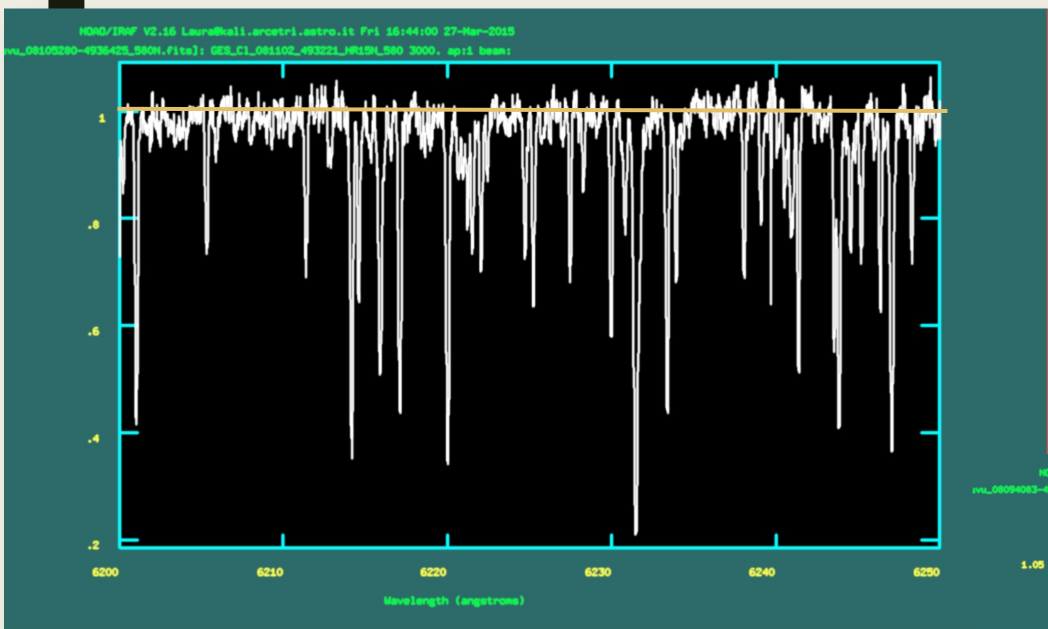


In stellar spectra…



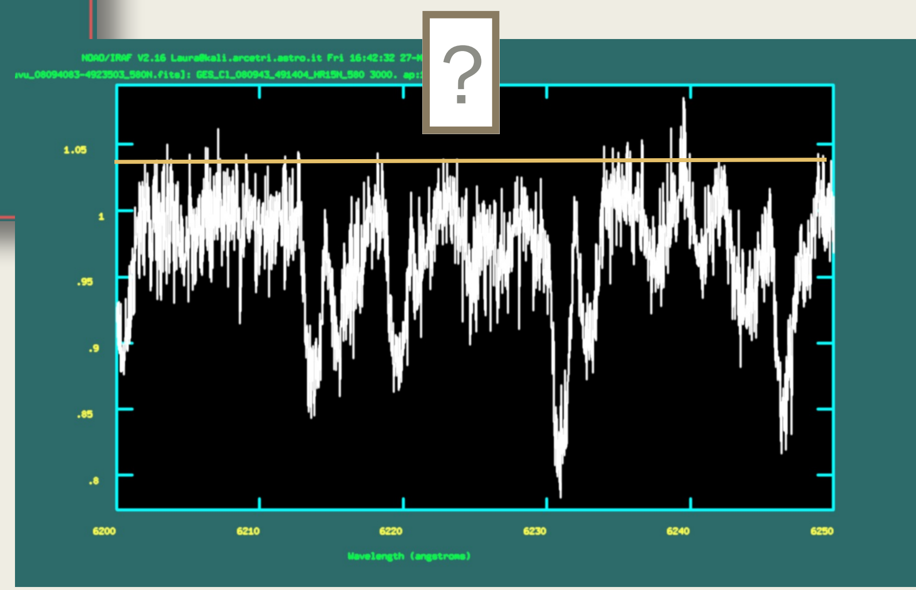
UVES spectrum of the Sun at its original resolution R=47000 and binned to mimic a lower resolution spectrum

Importance of large collecting areas: large telescopes



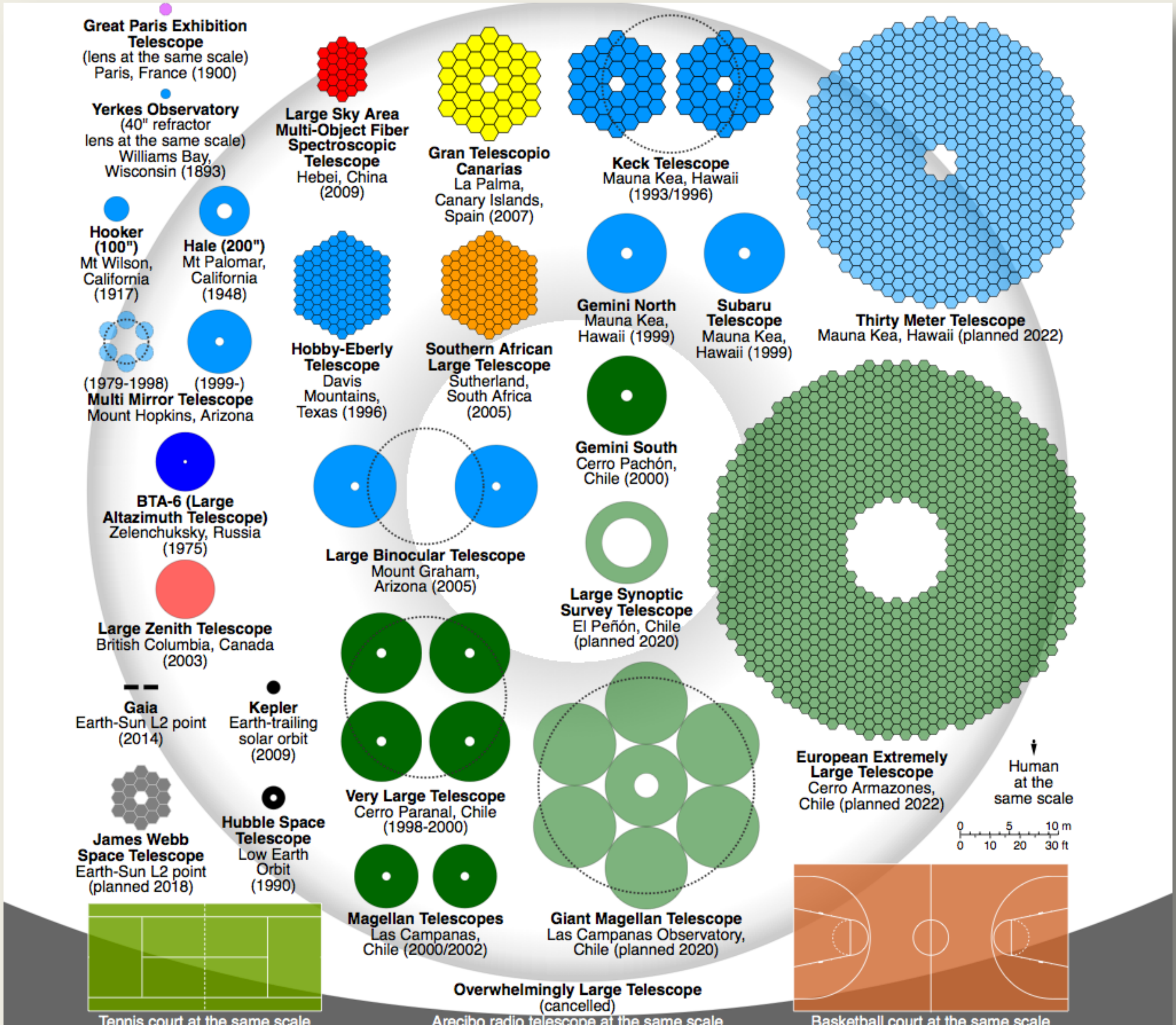
UVES@VLT Spectra of stars in the open clusters NGC2547

High signal-to-noise ratio to define the continuum and to measure faint lines



Low signal-to-noise ratio (+ rotation): impossible to define the continuum and to measure lines

Present and forthcoming telescopes: a comparison of mirror size

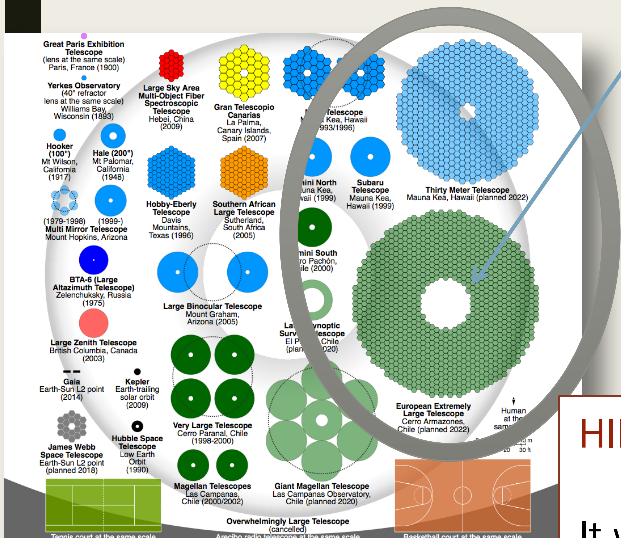


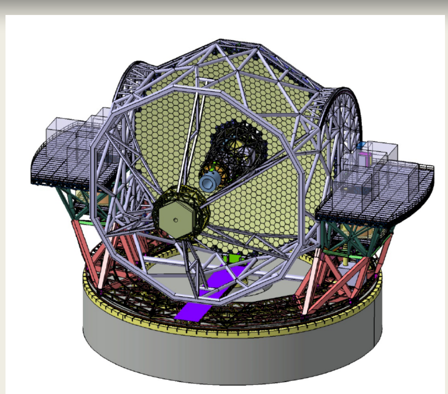
Future telescopes and spectrographs

- Which is the future of resolved stellar population studies?
- Which telescopes/instruments?
- Which science cases?

Future telescopes and spectrographs

https://www.eso.org/public/italy/teles-instr/elt/





ELT — for Extremely Large Telescope — this revolutionary new ground-based telescope concept will have a 39-metre main mirror and will be the largest optical/near-infrared telescope in the world: "the world's biggest eye on the sky".

- The ELT programme was approved in 2012 and green light for construction at Cerro Armazones was given at the end of 2014. The first stone ceremony for the telescope was attended by the President of Chile in May 2017. Dozens of Europe's most cutting-edge companies are participating in the construction. First light is targeted for 2025.

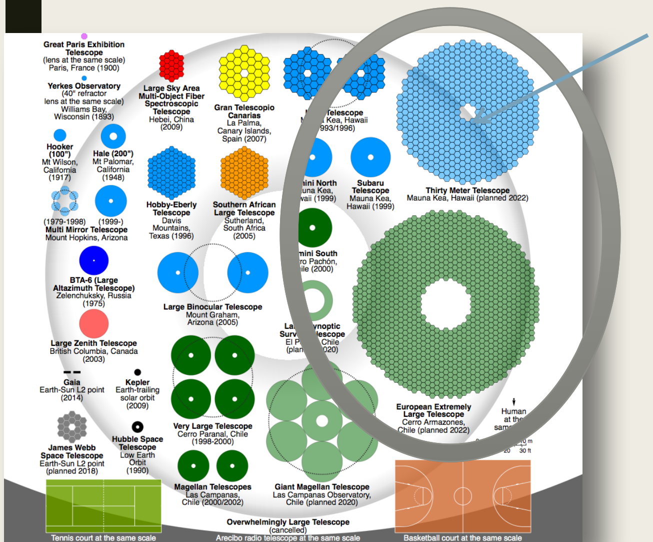
HIRES spectrograph:

It will deliver high-resolution and high-quality spectra (S/N>100) of solar-type and cooler dwarf stars out to distances of several kpc.

HIRES will also be an extremely efficient machine to trace the metal enrichment pattern of extragalactic star clusters and resolved stellar populations, hence tracing the star formation history in other galaxies, if enabled with some multiplexing capability.

Future telescopes and spectrographs

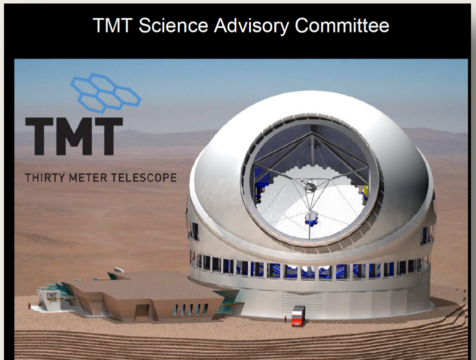
https://www.tmt.org/page/milky-way-and-nearby-galaxies



The Thirty Meter Telescope is a new class of extremely large telescopes that will allow us to see deeper into space and observe cosmic objects with unprecedented sensitivity.

With its 30 m prime mirror diameter, TMT will be three times as wide, with nine times more area, than the largest currently existing visible-light telescope in the world.

This will provide unparalleled resolution with TMT images more than 12 times sharper than those from the Hubble Space Telescope.



With the seeing-limited high-resolution spectrograph HROS, the total improvement relative to VLT/UVES or Keck/HIRES or Subaru/HDS is expected to be 15 – 20.

For example, a 4-hour integration with HROS will enable R = λ/δλ ~ 40 000 spectroscopy with SNR = 100 per spectral resolution element for stars as faint as V ~ 21 in the visible.

Resolved stellar population with new generation telescopes

- Science cases with E-ELT:

The E-ELT offers the exciting prospect of reconstructing the formation and evolution histories of a representative sample of galaxies in the nearby Universe by studying their *resolved* stellar populations.

Studying stellar populations requires the capability of resolving and measuring individual stars and so up until now such studies have been limited to our own Galaxy and its nearest neighbors.

In particular, no examples of large elliptical galaxies are within reach of current telescopes for this type of study.

With its superior resolution and photon collecting power the E-ELT will allow us to perform precise photometry and spectroscopy on the stellar populations of a much more representative sample of galaxies, **reaching out to the nearest giant ellipticals at the distance of the Virgo cluster.**

Thus, the E-ELT will provide detailed information on the star formation, **metal enrichment and kinematic histories of nearby galaxies**, showing us how they were formed and built-up over time.

Resolved stellar population with new generation telescopes

- Science cases with TMT:

In λCDM simulations of the growth of structure, dwarf galaxies play an important role as the building blocks of large galaxies.

However:

- Their chemistry shows very little in common with the chemistry of stars in the Milky Way halo, disk, bulge (Venn et al. 2004; Navarro et al. 2004).
- The number of surviving dwarf galaxies in the immediate neighborhood of the Milky Way is far lower than predicted.

There are a variety of possible solutions to these problems that need to be tested with detailed examination of the kinematics, metallicities, and abundance ratios of stars in dwarf galaxies beyond the Milky Way halo are necessary.

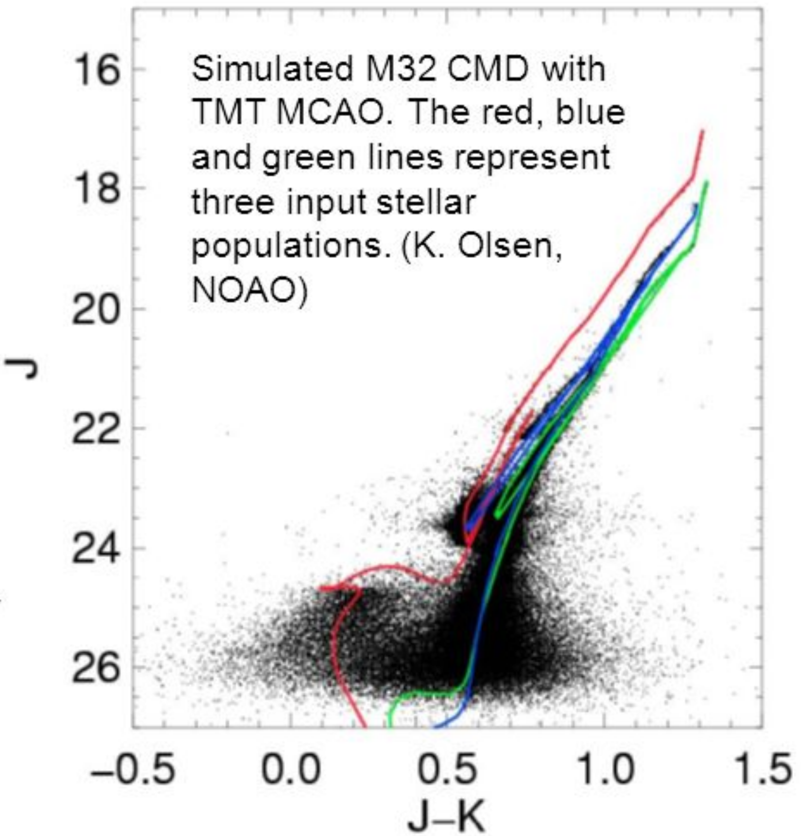
With TMT/HROS, it will be possible to carry out detailed abundance analyses of stars at or just above the tip of the red giant branch throughout the Local Group.

For example, current generation high-resolution spectrographs on 8 – 10m telescopes have been able to study tens of stars in Local Group dwarf spheroidal galaxies at V = 17 – 18 with exposure times up to 14 hours.

Those systems lie as far away as 250 kpc. **TMT/HROS will be able to obtain similar results for stars at V ~ 20 in more distant (~ 400 – 500 kpc) and hence more isolated systems.**

Stellar Populations in the Local Universe - Stellar archaeology

- *IRIS and HROS will determine the star formation history in galaxies out to the Virgo cluster:*
  - Adaptive optics will allow photometry of resolved stellar populations in crowded fields.
  - This will give star-formation history and metallicity in a wide range of environments.
  - High-resolution spectroscopy will provide element abundances.
  - Complimentary to high-z galaxy studies.



….the MW and the LG galaxies

- Near field cosmology
- Constraints on the mechanisms of galaxy assembly and evolution
- MW in the context of the Local Group: dwarf galaxies to assemble the Galactic halo
- Differences and analogies with M31
- The future instrumentation for resolved stellar populations