SECOND COSMOLOGY SCHOOL

Ministry of Science and Higher Education
Republic of Poland

INTRODUCTION TO COSMOLOGY
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Galaxy Clusters

(part I)

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At present we have some key ideas about galaxy clusters

1. Galaxies tend to gather into Groups and Clusters.

2. Galaxy clusters are rare extremes in the galaxy distribution, with local overdence $\Delta\rho/<\rho> \sim 10^3$.

3. Galaxy groups and clusters are not the largest known gravitationally bound objects.

4. Superclusters are largest bound structures identified in the Universe.

5. Galaxy clusters are the element of large-scale structure of Universe.

6. Clusters are part of a continuous range of structures:

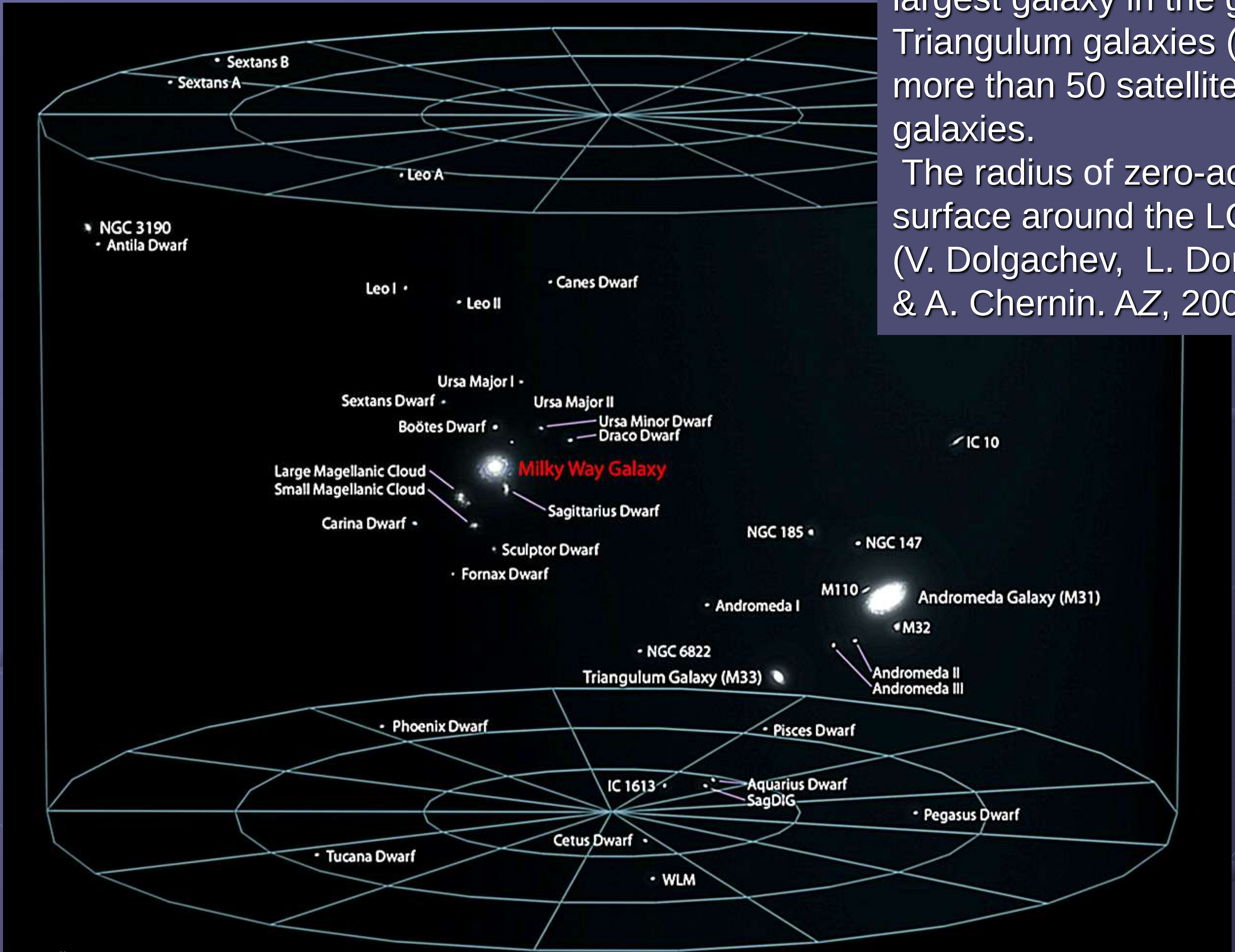
Galaxies ⇨ Groups ⇨ Clusters ⇨ Superclusters ⇨ Large Scale Structure.

Very roughly (depending on definitions) the total galaxy content of the universe is divided: 1-2% in rich clusters, 5-10% in clusters and 50-100% in "Local Group"s and/or looser groupings.

Local Galaxy Grope:

Milky Way, Andromeda (M31, largest galaxy in the group) and Triangulum galaxies (M33) and more than 50 satellite small galaxies.

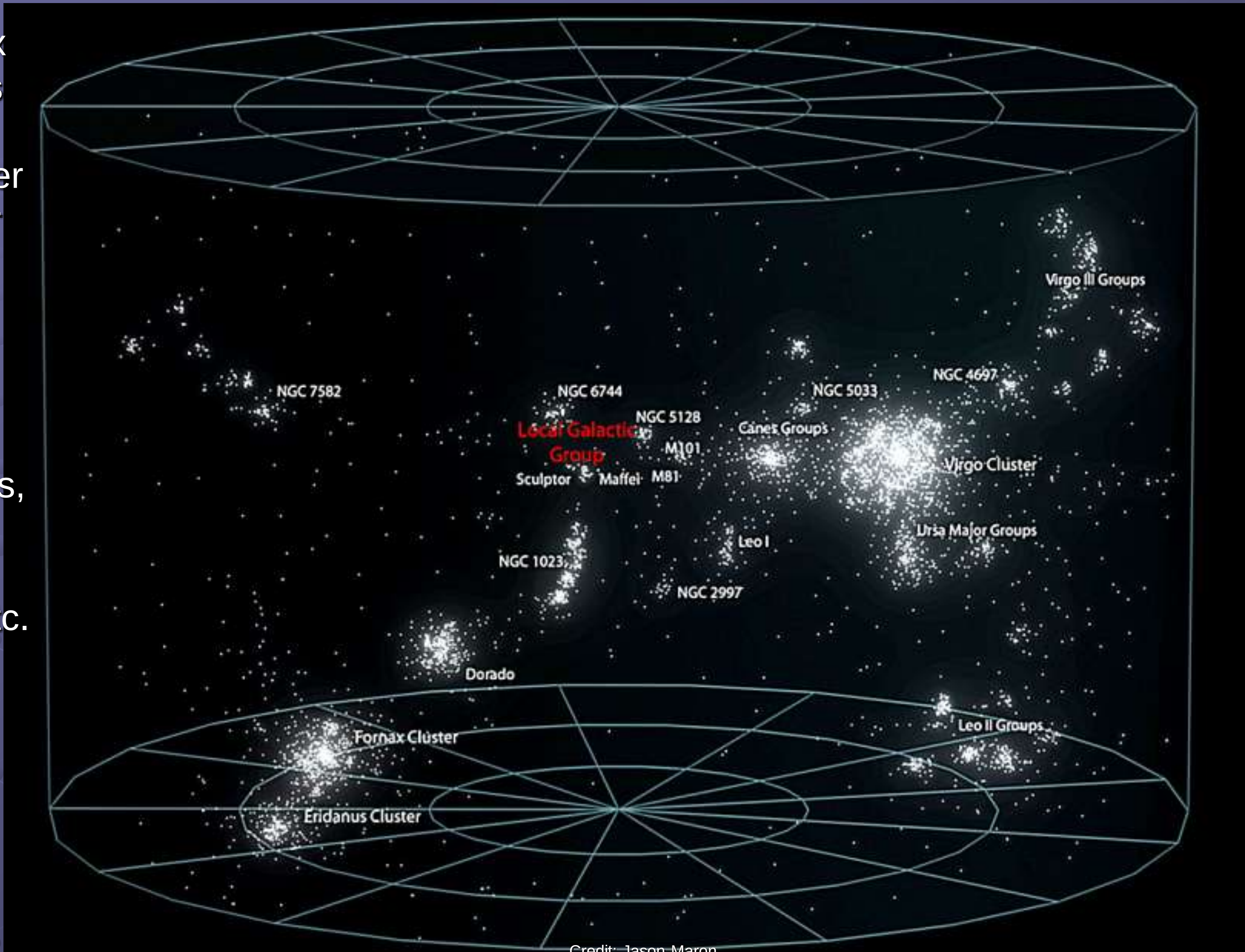
The radius of zero-acceleration surface around the LG ≃2 Mpc (V. Dolgachev, L. Domozhilova & A. Chernin. AZ, 2003, **80**, 792).



Credit: Jason Maron
http://www.jaymaron.com/astro/Earth's_Location_in_the_Universe_SMALLER_(JPEG).jpg

Virgo Supercluster

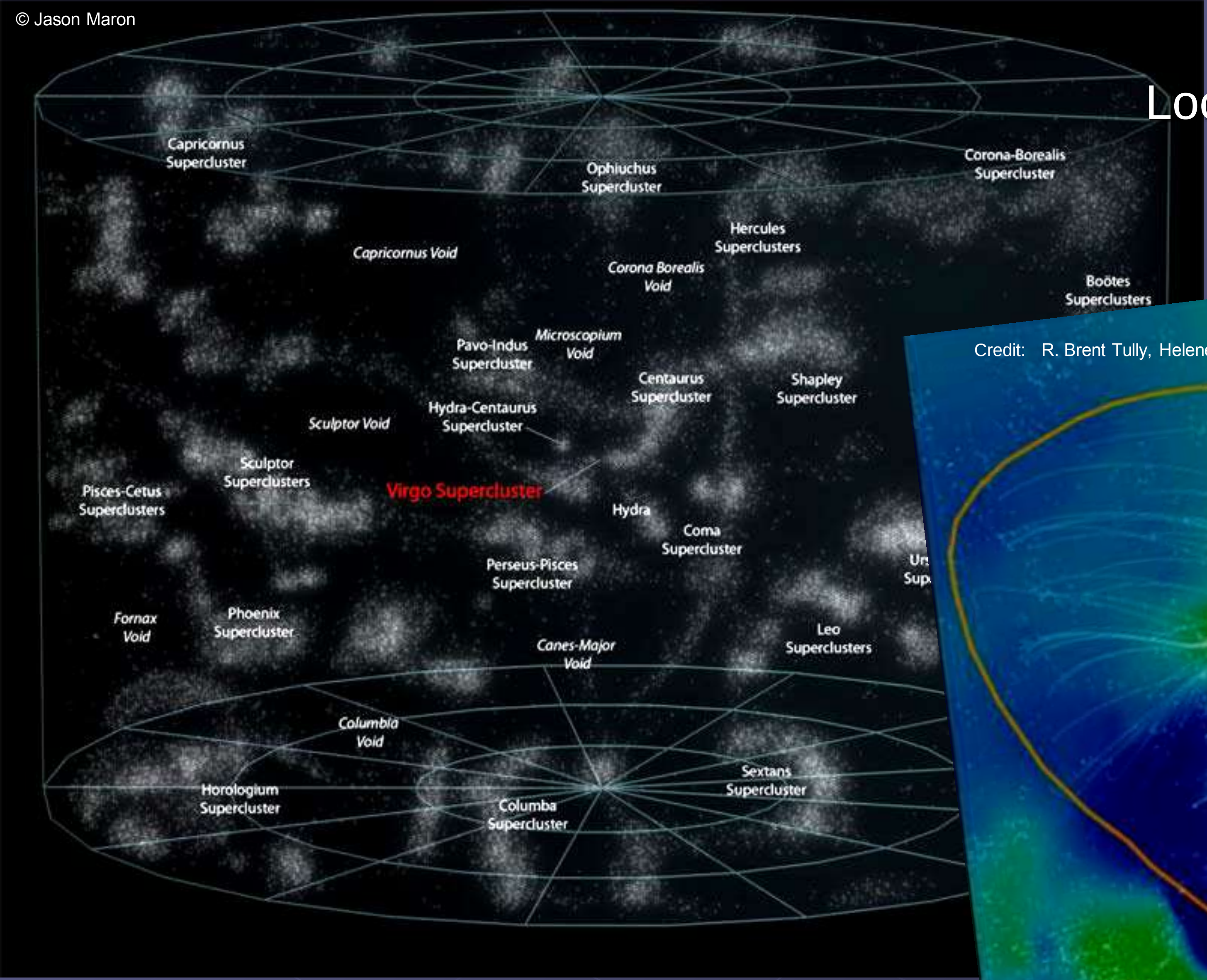
Virgo, Fornax and Eridanus Clusters; Norma Cluster (located near the center of the Great Attractor, not shown), and a lot of galaxy groups, like to LGG, M81 group, Leo Group etc.

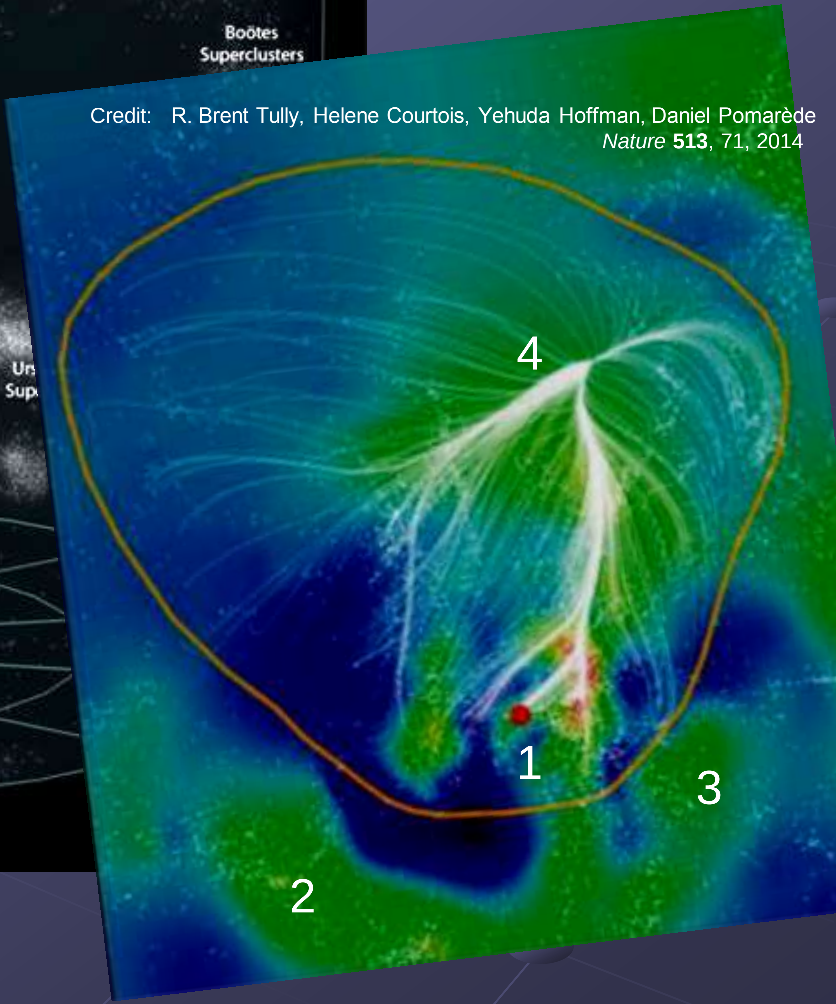


Credit: Jason Maron
http://www.jaymaron.com/astro/Earth's_Location_in_the_Universe_SMALLER_(JPEG).jpg

Local Supercluster:

Laniakea

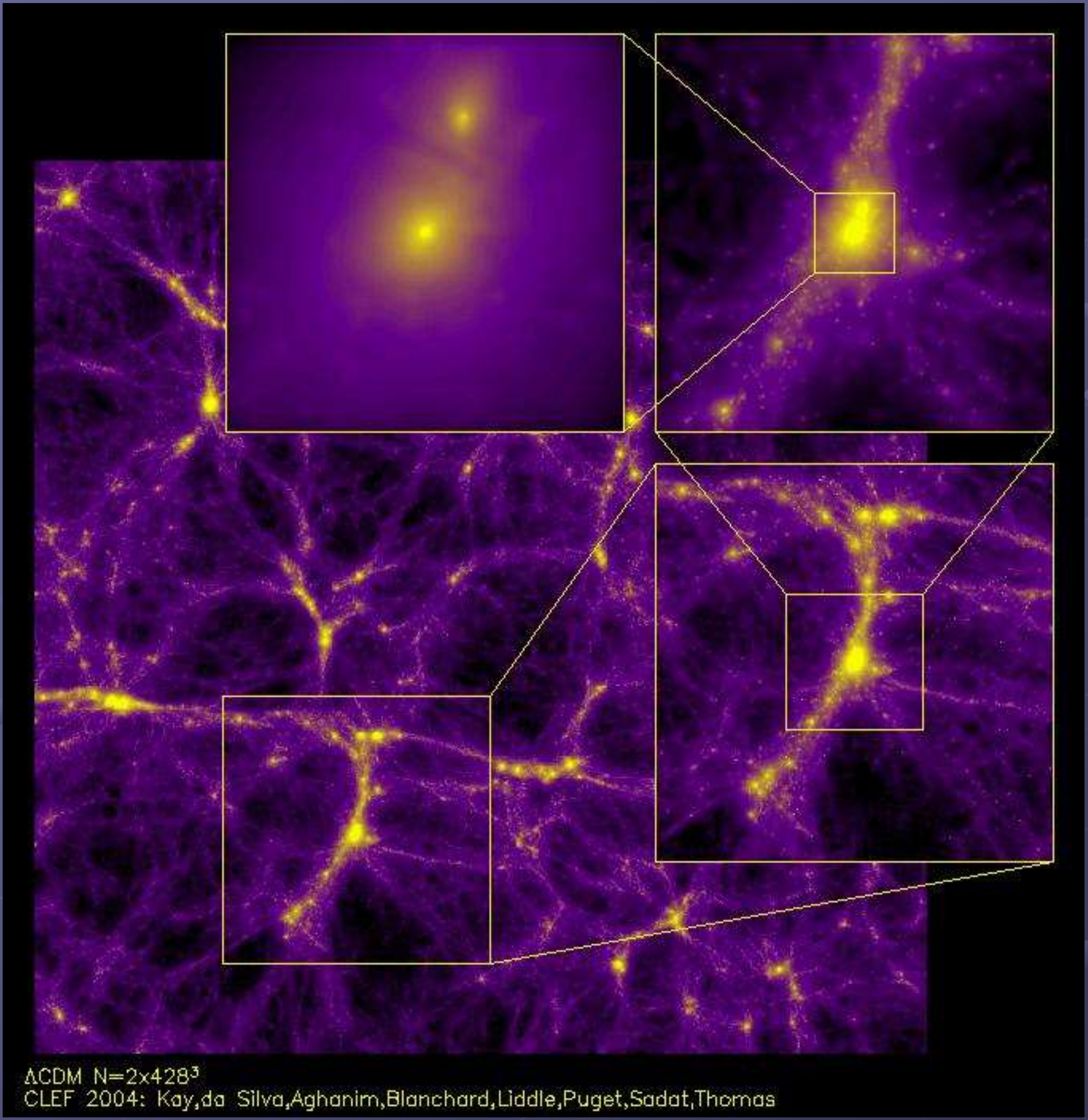




The radius of zero-acceleration surface around the Laniakea ≃80 Mpc.

1 – our position (Virgo); 2 – Perseus-Pisces; 3 – Coma, 4 – the Great Attractor

Hierarchy of Structures:



Groups:
3 to 30 bright galaxies

Clusters:
30 to 300+ bright galaxies

Superclusters:
Clusters of Clusters?

LSC:
Voids, Filaments, & Walls

JWST Science Simulations: Galaxy Evolution tracking animation. This visualization shows galaxies, composed of gas, stars and dark matter, colliding and forming filaments in the large-scale universe providing in a view of the Cosmic Web.

Galaxy clusters are the largest virialized structures in the Universe. Structures larger than clusters have not had time to "turn around", collapse, and virialize.

Galaxies : $t_{virial}=10^8$ yr $\lll$ t_{Hubble}

Clusters : $t_{virial}=10^9$ yr $\ll$ t_{Hubble}

Superclusters : $t_{virial}=10^{10.5}$ yr $>$ t_{Hubble}

Note: clusters are not necessarily the largest bound structures in the universe ⇨ superclusters may be bound, but haven't yet turned around and virialized.

On these large scales, components have not had a chance to separate during collapse ⇨ a cluster is probably a representative sample of the Universe.

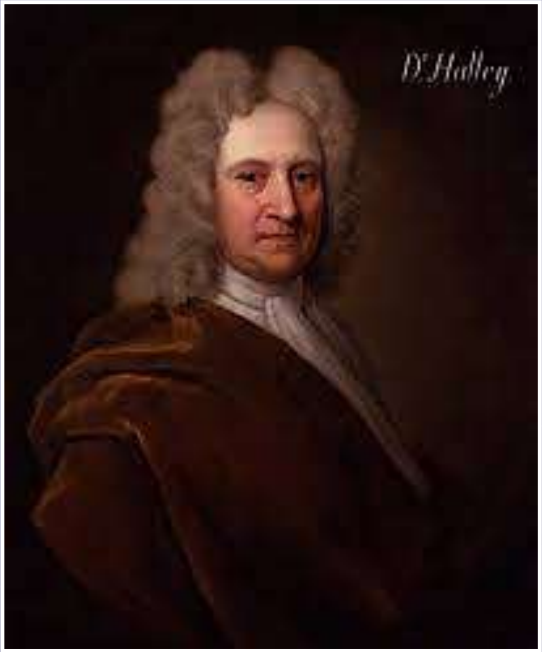
This is important when, for example, we measure their Dark Matter (DM) content : $(M_{DM} / M_{baryons})_{cluster} = (M_{DM} / M_{baryons})_{Universe}$

So a measurement in clusters can be scaled up to derive matter for the universe.

WHAT WE CAN SEE ON THE SKY?

GALAXY CLUSTERS MILESTONES

Non-random distribution of nebulae is known from XVIII century, the time of Friedrich Wilhelm Herschel – the Great Herschel.



The first separate list of 6 nebulae was compiled by Edmond Halley in 1715 ("Of Nebulae or lucid Spots among the Fix't Stars").

Charles Messier and Wilhelm Herschel independently produced catalogues of nebulae, and noticed remarkable concentrations of nebulae on the sky.

30 from 103 objects listed in the famous Messier' "Catalogue des nébuleuses et des amas d'étoiles que l'on découvre parmi les étoiles fixes, sur l'horizon de Paris" (1784) are galaxies.

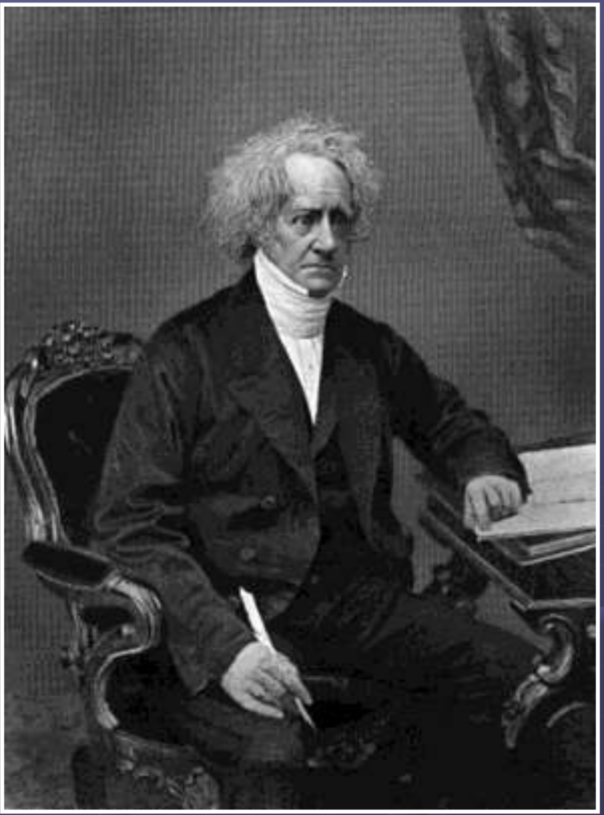
More, Messier at first noted to local concentration of the nebulae in Virgo: 15 ones are placed on the small part of sky.

The central part of Virgo cluster (4°x4°, DSS image). The elliptical galaxy in the center is M87. The two largest elliptical galaxies on the right are M84 and M86. The chain of five galaxies on the left contains M89, M90, M58, M88 and M91.

William and Caroline Herschel

In difference from "comet hunter" Messier, Sir Frederick William Herschel attend all sky wonders. His big refractor (*D*=1.47 m, *F*=12.2 m) allows to find faint nebulae. In 1785 he published "On the Construction of the Heavens", where he suggested that the "sidereal system we inhabit' is a nebula, like to other observed nebulae. W. Herschel classified about 2500 nebulae, including in Coma Berenices. He gives relevant description of the Coma cluster of galaxies: "That remarkable collection of many hundreds if nebulae which are to be seen in what I have called the nebulous stratum of Coma Berenices", and recognized several other nearby clusters and groups of galaxies, such as Leo, Ursa Major, Hydra, etc.

Frederick William Herschel' work was continued by his son, John Frederick William Herschel.
J. Herschel surveyed the southern sky from Cape of Good Hope, and catalogued over 6000 nebulae in the "General Catalogue of Nebulae and Clusters of Stars" (1864).



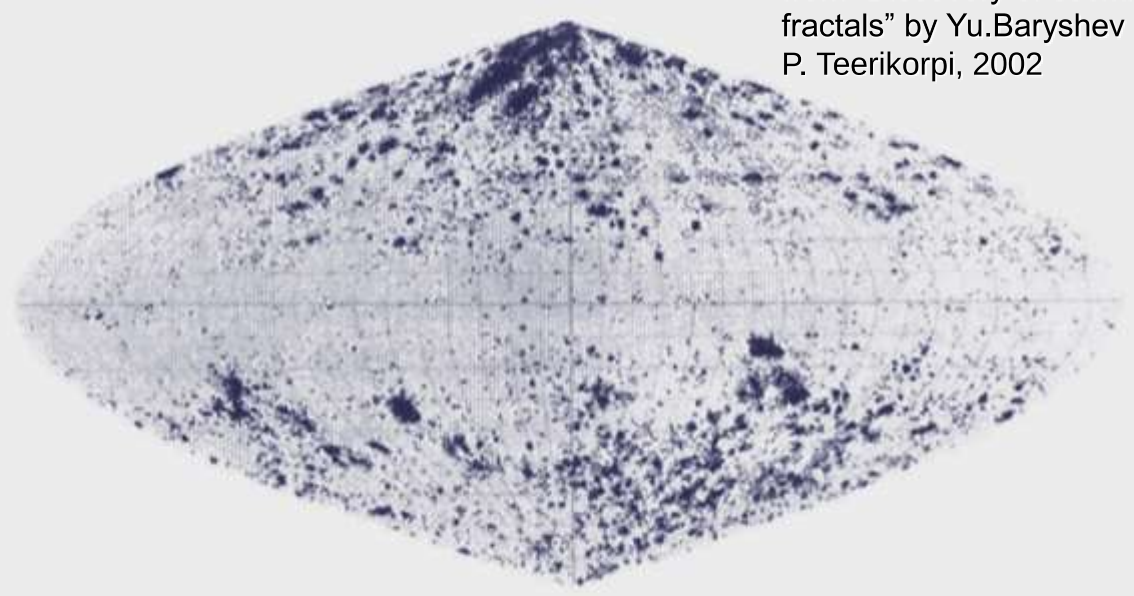
At the beginning of the XIX century J. Herschel noted to the excess of nebulae in the northern Hemisphere with respect to the southern one.

He also recognized several concentrations of nebulae (in Pisces and Fornax, in particular). He already hinted at the existence of the Local Supercluster, with the Virgo concentration "being regarded as the main body of this system", and our own Galaxy "placed somewhat beyond the borders of its densest portion, yet involved among its outlying members".

Later Gérard de Vaucouleurs named the “main body” as Supergalaxy!

Herschel's ideas were further developed only in the XX century when the extragalactic nature of some nebulas was established and astronomers started to consider clusters of galaxies as physical systems. Dreyer' New General Catalogue complemented by the Index Catalogues listed about 13000 nebulae in 1908. It was the next step in galaxy distribution study.

The distribution of 11475 spiral nebulae in the sky map prepared by Carl Vilhelm Ludwig Charlier in the beginning of the 20th century. He noted: “A remarkable property of the image is that the nebulae seem to be piled up in clouds”



from “Discovery of cosmic fractals” by Yu.Baryshev & P. Teerikorpi, 2002

But some astronomers explained the existence of great nebulae clouds as observational selection connected by cosmic extinction.

13

Distance Ladder

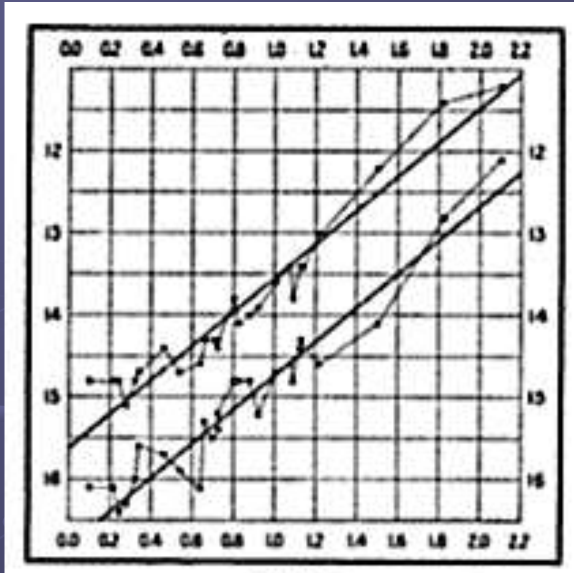
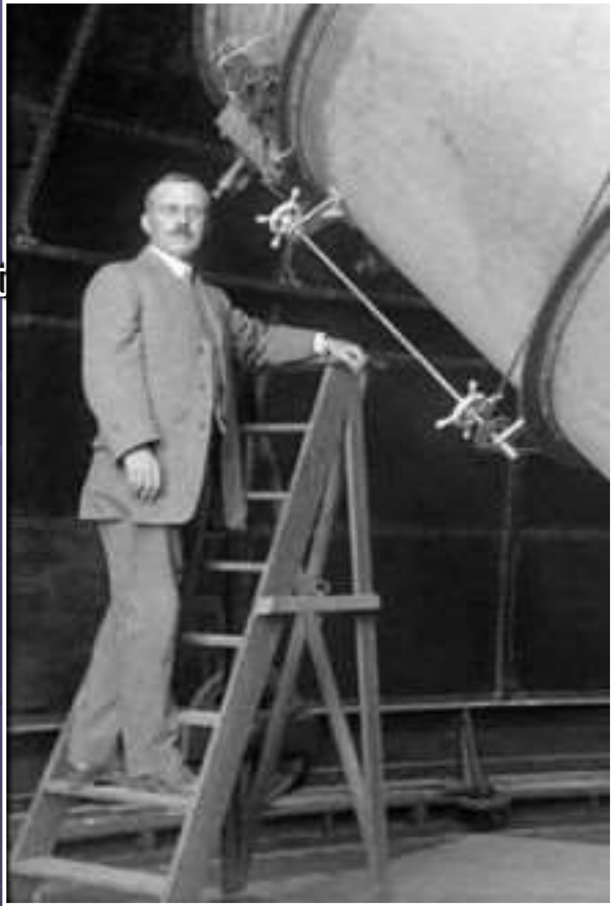


Fig. 2.

From: Harvard College Observatory, Circular 173

Magellanic clouds. In 1908 Henrietta Swan Leavitt based on dataset of 1777 variable, established "period–luminosity relationship" for cepheids. It allows to estimate the distance to nearest galaxies.

Andromeda Galaxy

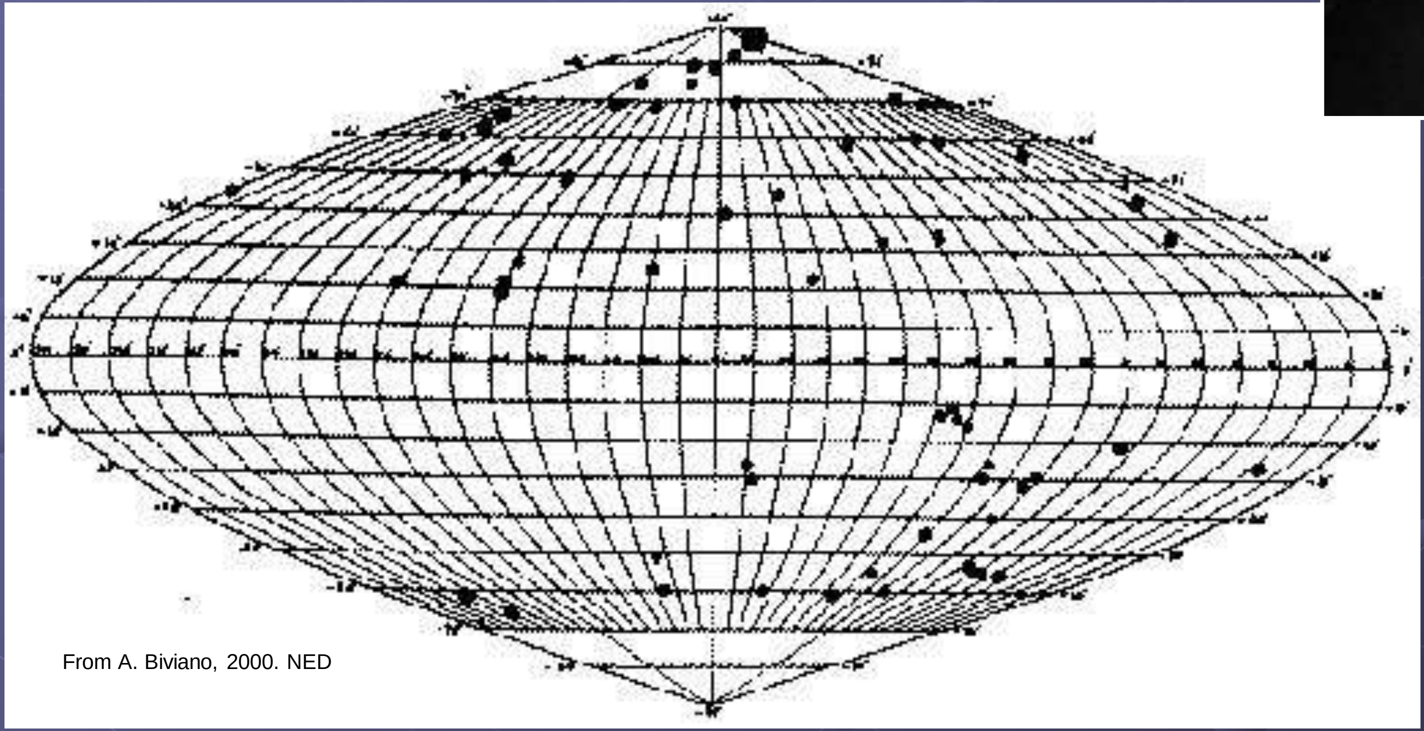


In 1917 Heber Curtis observed a nova within M31 (*Ibid.,* **29**, 206). Searching the photographic record, 11 more novae were discovered. Curtis noticed that these novae were, on average, 10^m fainter than those that occurred elsewhere in the sky.

As a result, he was able to come up with a distance estimate of 500'000 light-years The paper was published only in 1988 (*PASP,* **100**, 6), however the results noted to so-called "island universes" hypothesis, which held that spiral nebulae were actually independent galaxies.

More, the results were base for his position on "The Great Debate" about the nature of MW, spiral nebulae and the dimensions of the universe between Curtis and Shapley (1920). To support his claim of the Great Andromeda Nebula being, in fact, an external galaxy, Curtis also noted the appearance of dark lanes resembling the dust clouds in our own galaxy within Andromeda -- the MW -- as well as the significant Doppler shift that he had observed of Andromeda.

Knut Lundmark (one of the first to suspect that the galaxies are remote stellar systems) plotted on the sky map the positions of "55 clusters of the anagalactic nebulae" in 1927. But he didn't divided galaxy group and clusters.



From A. Biviano, 2000. NED

In 1919 Lundmark estimate the distance (as photometrical parallax) to M31 using magnitudes of novae (*Astronomische Nachrichten*, **209**, 378).

Andromeda Galaxy

Ernst Julius Öpik

In 1922 Ernst Öpik presented a method to estimate the distance of M31 using the measured velocities of its stars. His result placed the Andromeda Nebula far outside our galaxy at a distance of about 450 000 parsecs (1 500 000 LY). It was first published data. He also estimate the mass of Andromeda Nebula (4.5×10^9 solar masses, modern value ~1.5×10^{12} solar masses).

Astrophys. **J**., **55**, **406—410** (1922)

AN ESTIMATE OF THE DISTANCE OF THE ANDROMEDA NEBULA

By E. OEPIK

ABSTRACT

Andromeda Nebula.—Assuming the centripetal acceleration at a distance r from the center is equal to the gravitational acceleration due to the mass inside the sphere of radius r, an expression is derived for the *absolute distance* in terms of the linear speed v_c at an angular distance ρ from the center, the apparent luminosity i, and E, the energy radiated per unit mass. From observations, v_o comes out 157 km/sec. for $\rho=150''$; and giving i a value corresponding to magnitude 6.1, and assuming E the same as for our Galaxy, the distance is computed to be 450,000 parsecs. This result is in agreement with that obtained by several independent methods. If it is correct, the *mass* within 150″ of the center is about 4.5×10^9 times the sun's mass, and the nebula is a stellar universe comparable with our Galaxy. *The ratio of the axes of the central ellipsoid*, whose shape is supposed to be due to rotation, was determined from photographs to be about 0.79.

Various estimates of the distance of the Andromeda Nebula have been made hitherto by H. Shapley,[1] H. D. Curtis,[2] K. Lundmark,[3] Luplau-Janssen and Haarh[4] and others; these estimates

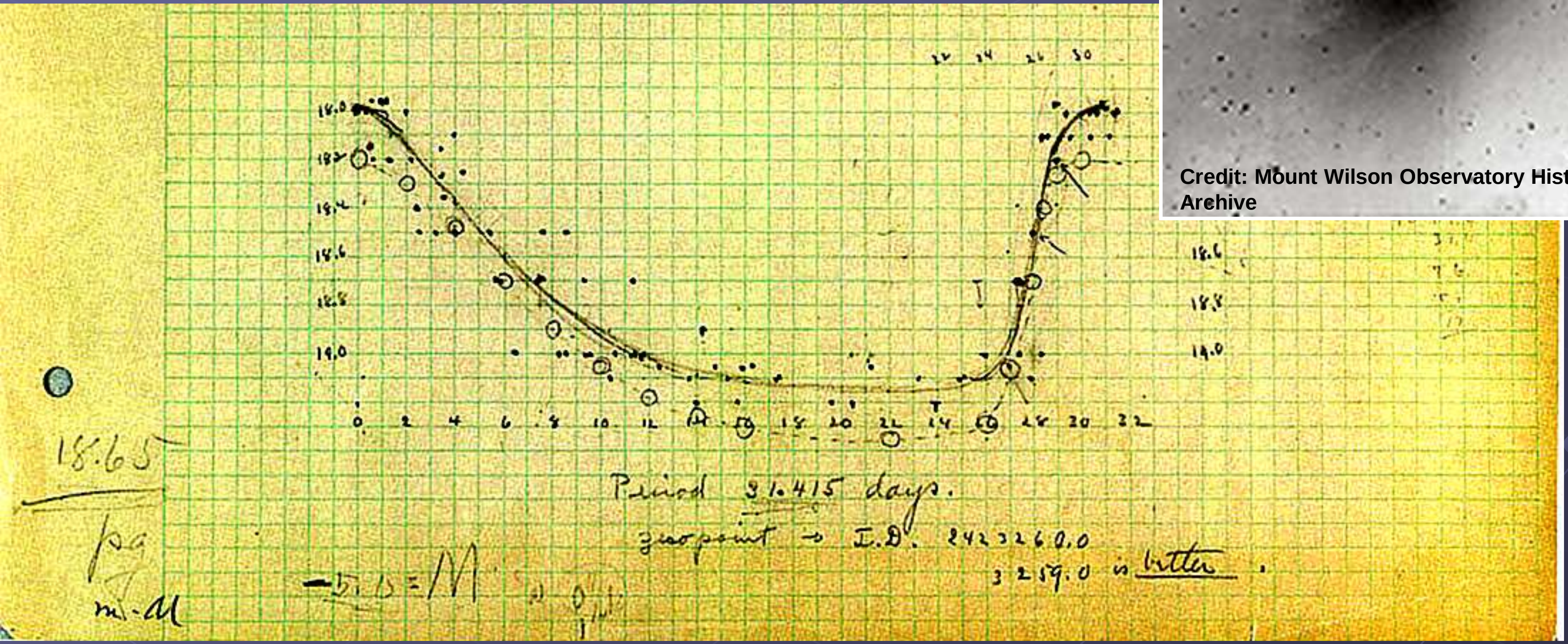

E. Habble stargazes through the Hooker telescope at California’s Mount Wilson Observatory.

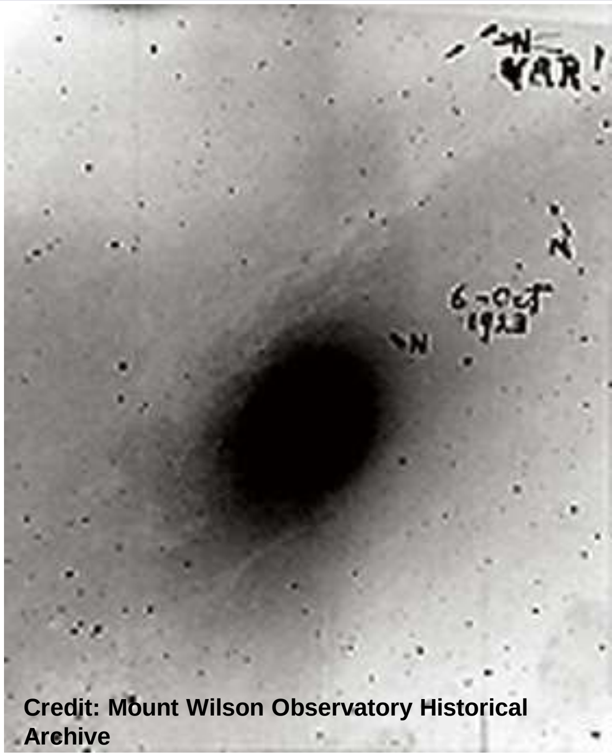
In the early twenties, Edwin Powell Hubble discovered cepheids in the Andromeda Nebula on 100-inch Hooker telescope at California’s Mount Wilson Observatory.
His measurement demonstrated conclusively that this feature was not a cluster of stars and gas within our own Galaxy, but an entirely separate galaxy located a significant distance from the Milky Way

He definitely established the extragalactic nature of M31
and finished "The Great Debate"
in 1925.

On October 6, 1923 Hubble noted *N* for Nova and *Var* for variable star in M31.

Hubble's observatory notebook observations fragment showing the changes in brightness of a star in M31.

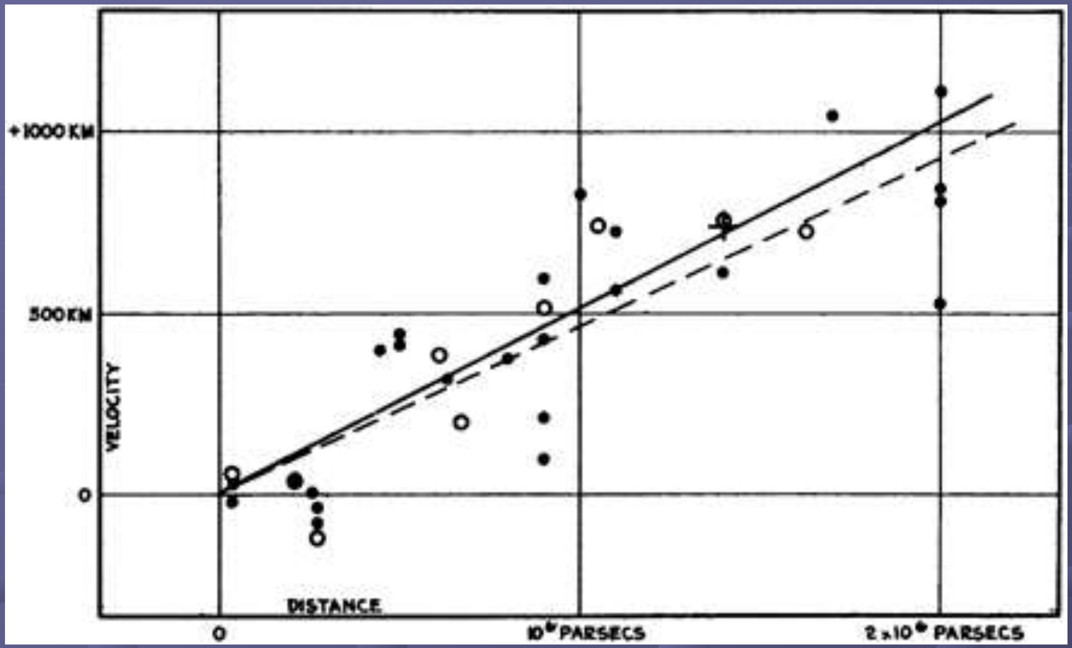




Credit: Mount Wilson Observatory Historical Archive

From:
http://faculty.humanities.uci.edu/bjbecker/ExploringtheCosmos/lecture17.html

A few years later – in 1929 Hubble published work "A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae".



$cz=Hr$ or

$$\frac{\Delta\lambda}{\lambda}=\frac{H}{c}r$$

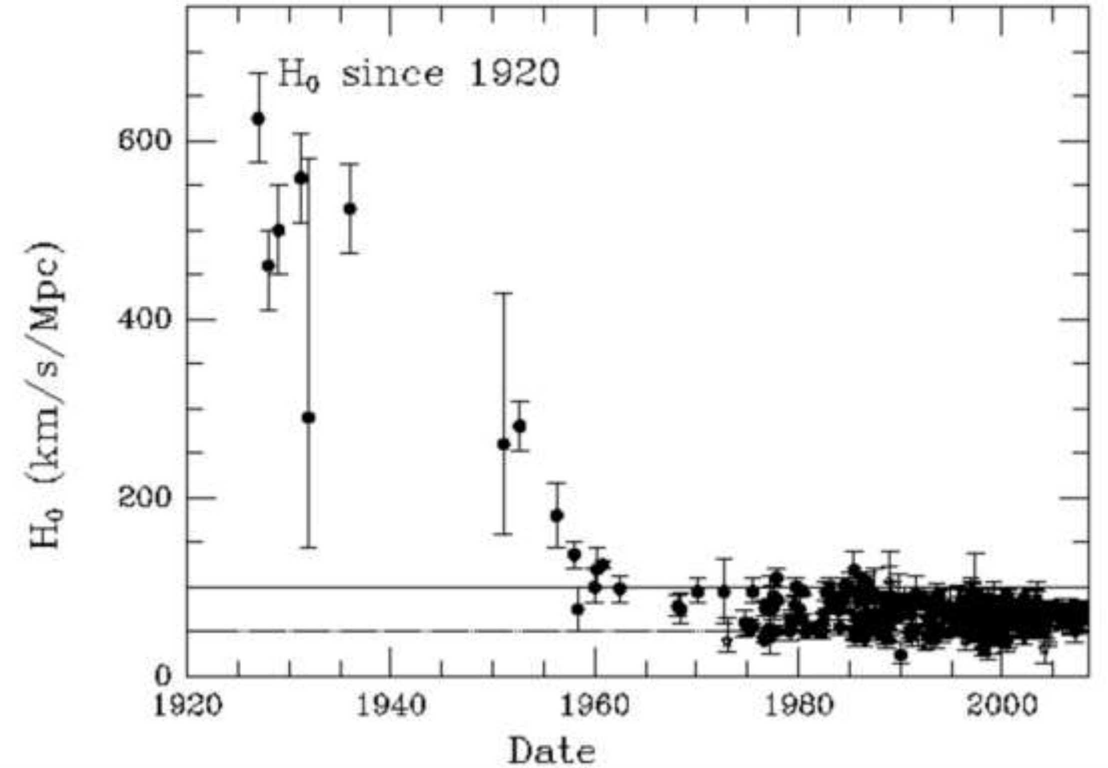
From:

Proceedings of the National Academy of Sciences of the United States of America, Volume 15, p. 168

Publication Date: 03/1929

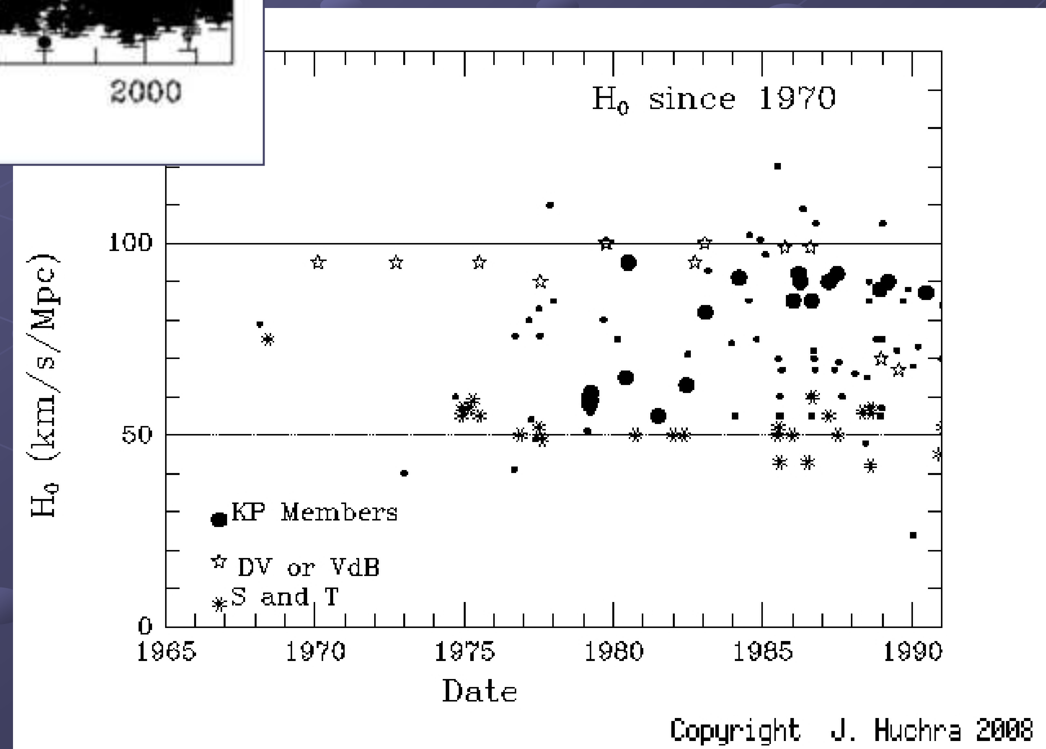
It is a key to distance determination. But we need to establish distance markers for Hubble constant measurement.

The first H value was determined by Lundmark (published in 1925: MNRAS, **85**, 865, line 20 in the Table I)



The evolution of our knowledge of the Hubble Constant, since it was first determined by Lemaitre, Robertson and Hubble in the late 1920's. Lundmark data is not shown.

H and h^{-1}



Communications from the Mount Wilson Observatory, to the National Academy of Sciences, No. 116.

Reprinted from the Proceedings of the National Academy of Sciences, Vol. 20, No. 5, pp. 264–268. May, 1934.

THE VELOCITY-DISTANCE RELATION FOR ISOLATED EXTRA-GALACTIC NEBULAE

By Edwin Hubble and Milton L. Humason

Mount Wilson Observatory, Carnegie Institution of Washington

Read before the Academy, Monday, April 23, 1934

The velocity-distance relation was first established[1] for a few nebulae whose distances were derived from involved stars. With the aid of data from clusters whose relative distances were estimated from the mean apparent magnitudes of the many members of each cluster, the relation was confirmed in the form[2]

$$\log v = 0.2\, m + 0.51,$$

which, since

$$\log d = \frac{m - M + 5}{5},$$

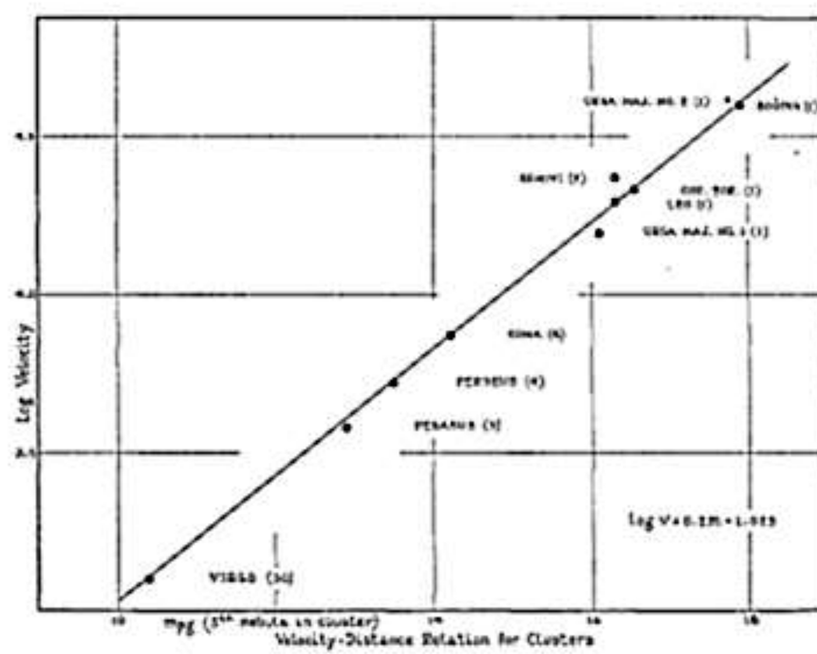


Fig. 2.—Figures in parentheses following the names of the clusters indicate the number of nebulae observed in each cluster.

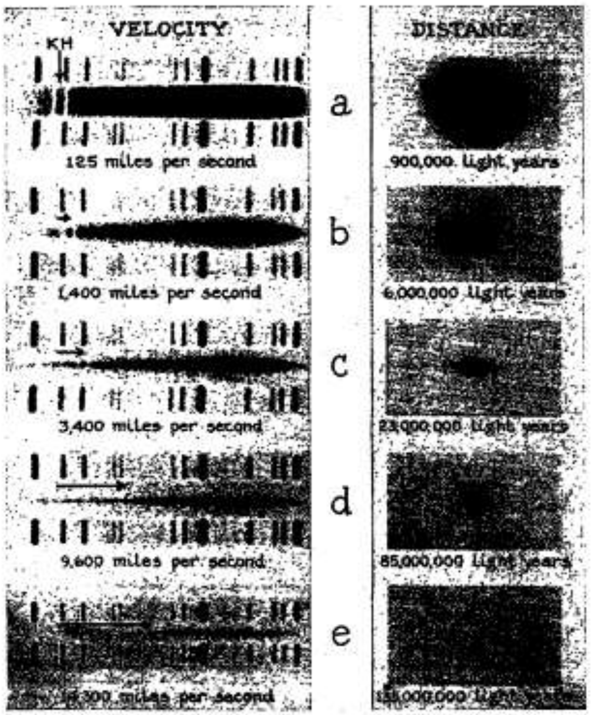
In 1934 and 1936 Milton L. Humason confirmed the Hubble low for galaxies in far clusters. He measured velocities of 39 200 km/s and 42 000 km/s for galaxies in the Bootis and Ursa Major II clusters, making them the most distant clusters known at that time.

Astronomical Society of the Pacific Leaflets, Vol. 2, No. 91, p.161,1936

LEAFLET 91—August, 1936

IS THE UNIVERSE EXPANDING?

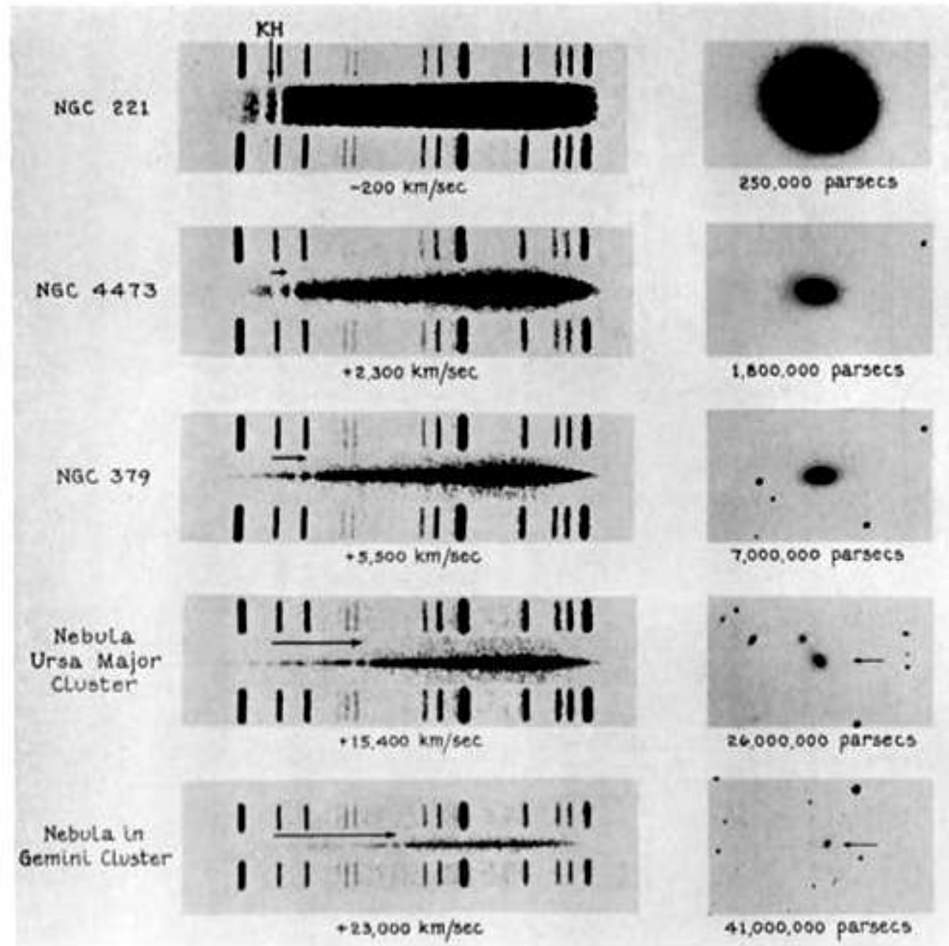
By M. L. Humason
Of the Mount Wilson Observatory
Carnegie Institution of Washington



RED-SHIFTS IN SPECTRA OF EXTRA-GALACTIC NEBULAE
The arrows above the nebular spectra point to the H and K lines of calcium and show the amounts these lines are displaced toward the red end of the spectra. It is these red-shifts (interpreted as velocities of recession) which indicate the universe is expanding. The direct photographs (on the same scale and with approximately the same exposure times) illustrate the decrease in size and brightness with increasing velocity in passing to more and more distant objects. The nebulae illustrated are (a) NGC 221, (b) NGC 4473, (c) NGC 379, (d) nebula in Ursa Major I cluster, and (e) nebula in Gemini I cluster.

Humason, M. L. *ApJ*, **83,** 10, 1936

PLATE III

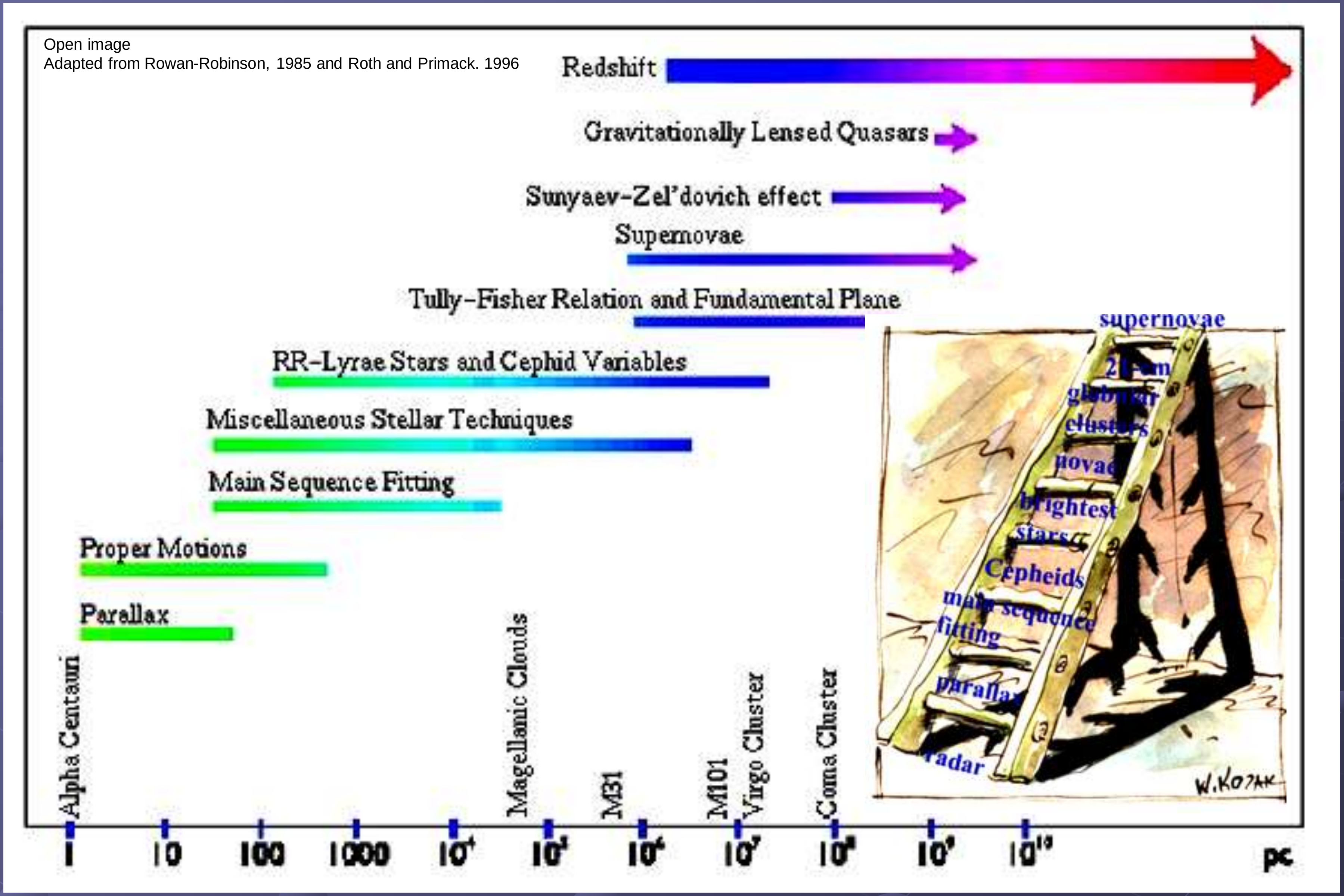


Red-Shifts in the Spectra of Extra-galactic Nebulae

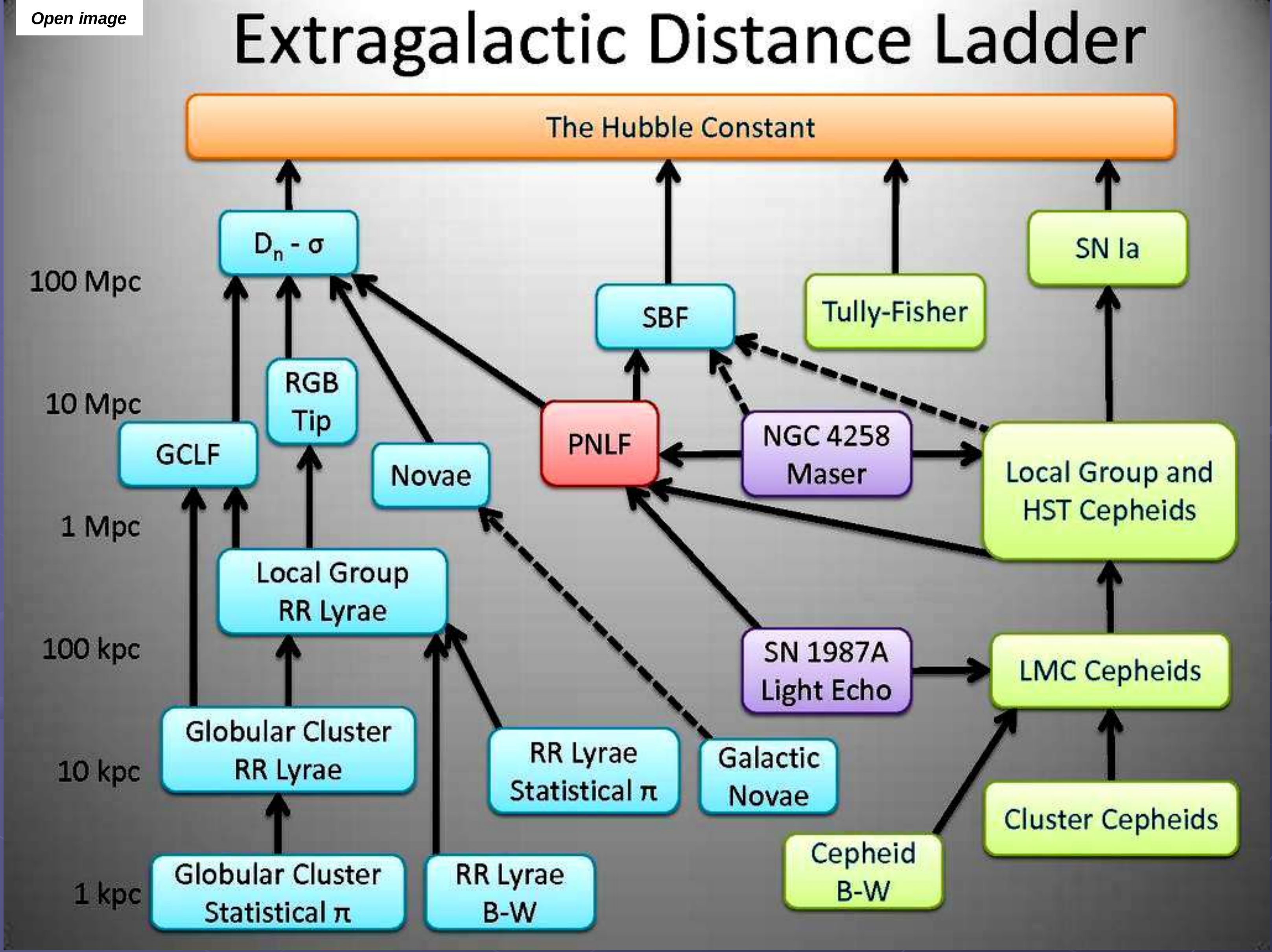
Arrows above the spectra (enlarged twenty times from the original negatives) point to the H and K lines of calcium and show the amounts these lines are displaced toward the red. The comparison spectra are of helium.

The direct photographs (on the same scale and with approximately the same exposure times) illustrate the decrease in size and brightness with increasing velocity or red-shift.

NGC 4473 is a member of the Virgo Cluster; NGC 379 of a group in Pisces.



The different distance estimators.



Green: applicable to star-forming galaxies. Blue: applicable to Population II galaxies. Purple Geometric distance technique. Red: PNLF is applicable to all populations of the Virgo Supercluster. Solid lines: Well calibrated ladder step. Dashed lines: Uncertain calibration ladder step.

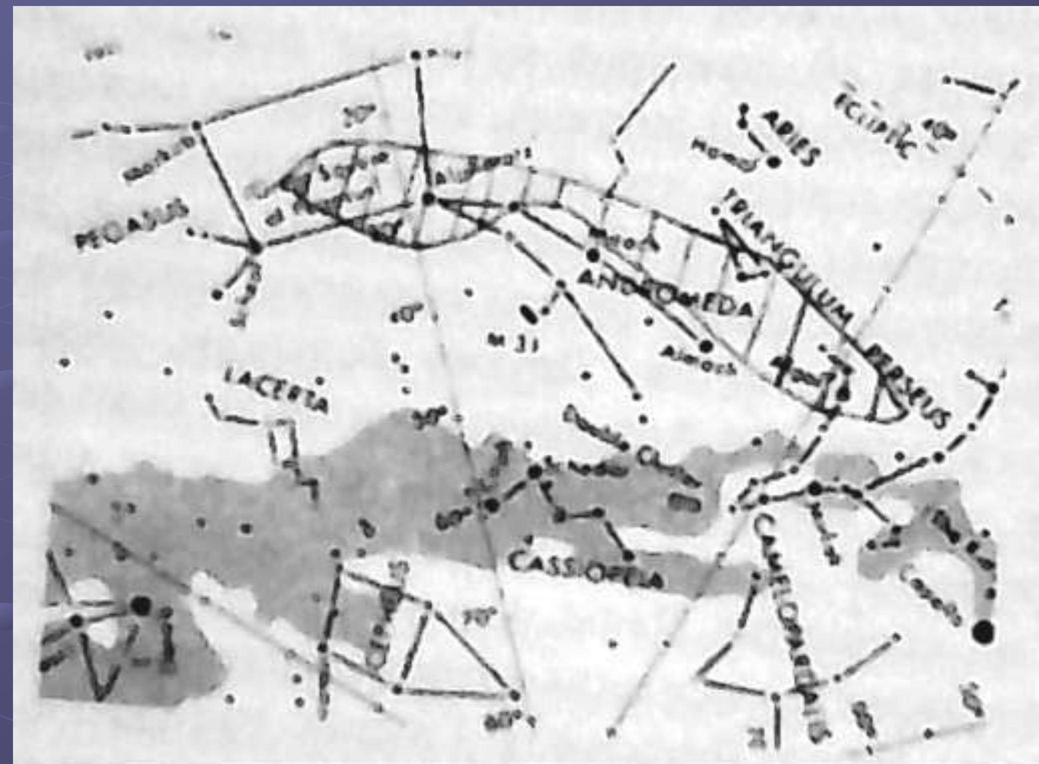
Great Galaxy Clouds on the sky

More galaxy systems were discovered in thirties of the XX century: Cancer, Hercules, Leo, and notably the "Centaurus cloud", today's Shapley concentration. Harlow Shapley correctly estimated it to be 14 times more distant than Virgo, and 10 times as rich in nebulae (1930).

3 years later Shapley published a list of 25 clusters and suggested the existence of "metagalactic clouds" in Coma Berenices, Centaurus and Hercules ("supercluster" term didn't exist), and Fritz Zwicky at first estimated the mass of a galaxy cluster, thus establishing the need for invisible matter – dark matter! He noted the observed dispersion in the radial velocity of the galaxies in the Coma cluster was very large and the gravity provided by the luminous matter in the cluster was not enough to hold the cluster together.

F. Zwicky
at the 18-inch Schmidt

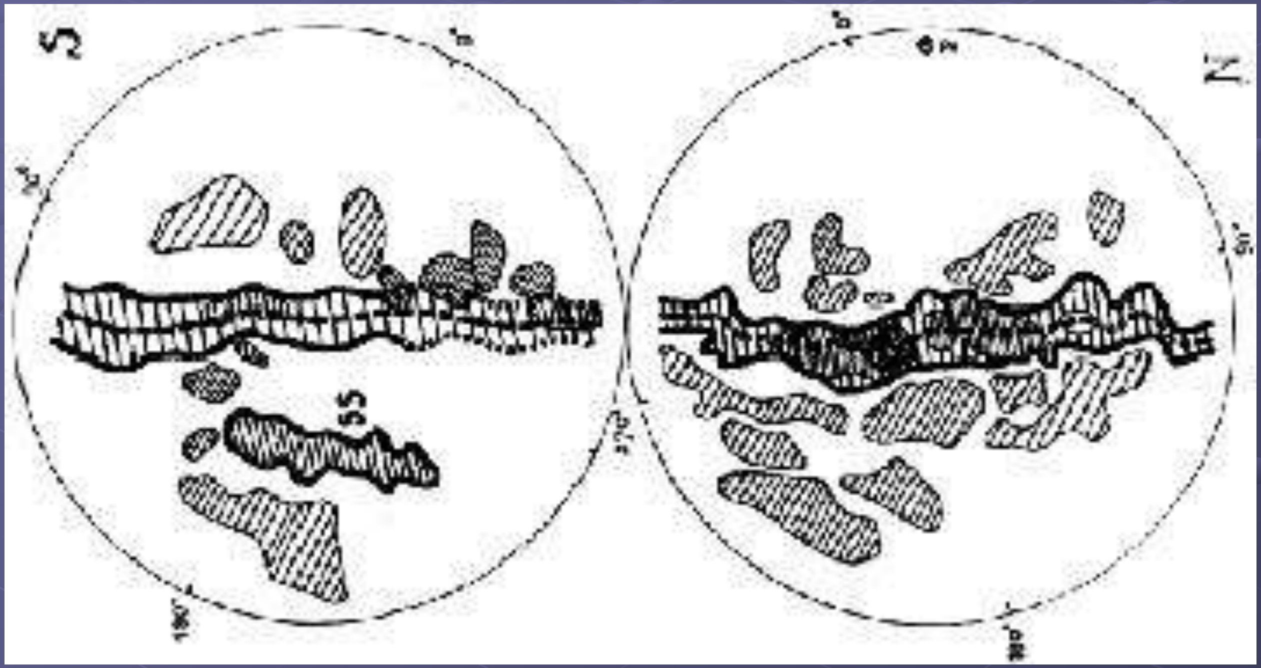
"The Great Perseus-Andromeda Stratum of Extra-Galactic Nebulae as Observed at the Lowell Observatory", Tombaugh, C. W., 1937



In 1937 C. Tombaugh described the Perseus-Pisces stratum – long concentration contains about 1800 galaxies.

In contrast to these works, in 1936 Hubble described the distribution of nebulae as "moderately uniform" and noted that "no organization on a scale larger than the great clusters" was definitely known.
So, the definition of galaxy clusters and existence "clusters of clusters" still waited own researchers.

After the Second World War, the Lick and Palomar sky surveys and the spectroscopic observations provided the essential data-base for the analysis of the distribution of galaxies and superclusters became one more element of Universe.

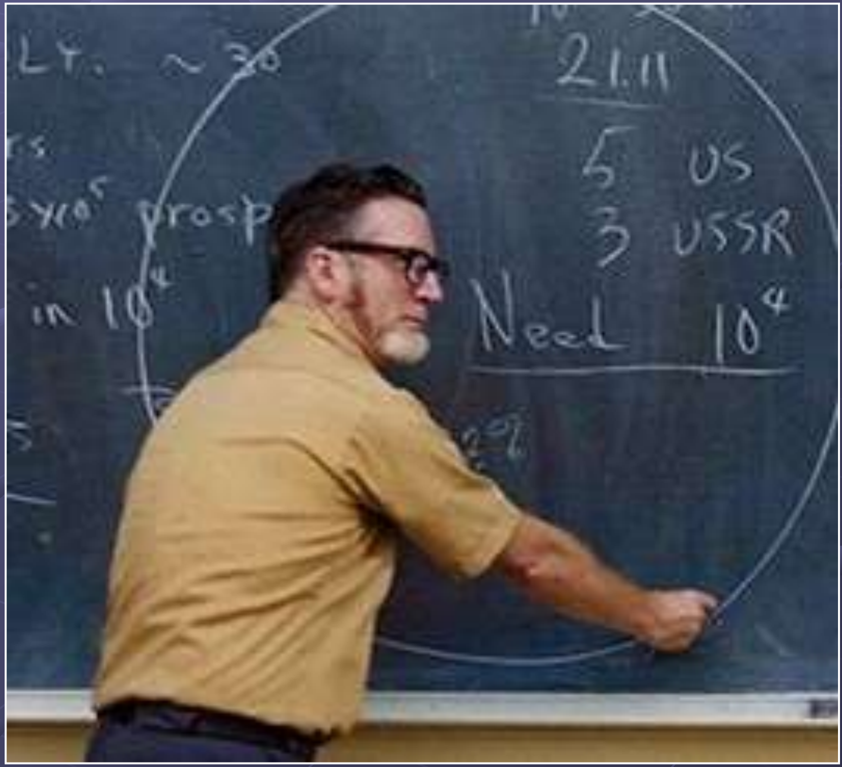


From de Vaucouleurs (1953), NED.

The evidence for the "Local Supergalaxy" and for many other superclusters grew stronger mainly through the works of Gérard Henri de Vaucouleurs, Shane & Wirtanen, van den Bergh, Abell.

New observational data gave the possibility for systematic search of nearby galaxy clusters.

In 1947 Herzog, Wild and Zwicky announced the construction of a "Catalogue of Galaxies and Clusters of Galaxies", however the final CGCG was published only in 1967.



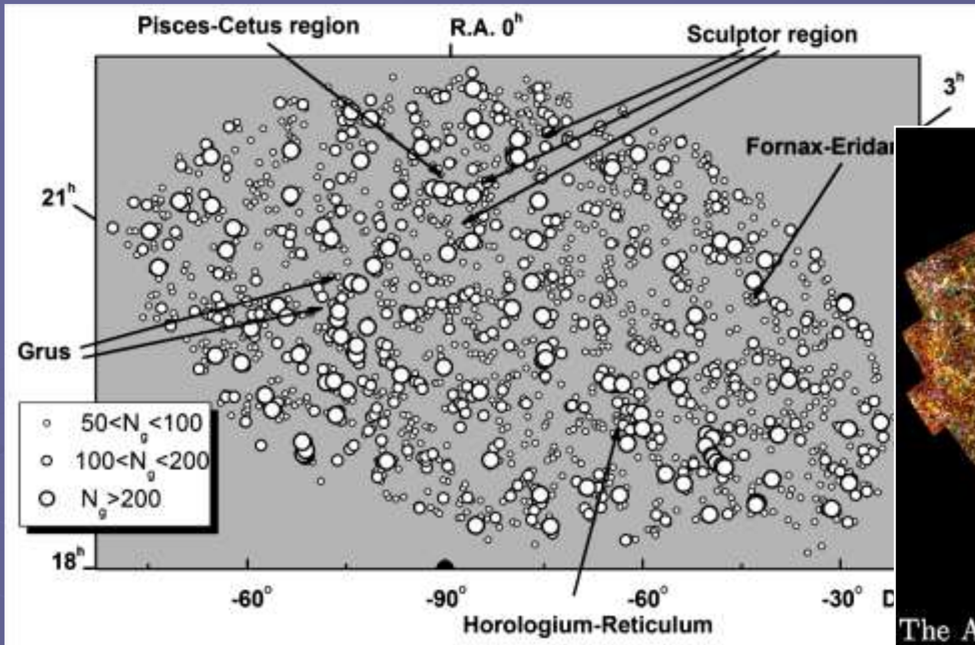
Paper of George Ogden Abell
"The distribution of rich clusters of galaxies" was published in 1958 (ApJS, V.3, P.211).
Citations to the article: 1618!

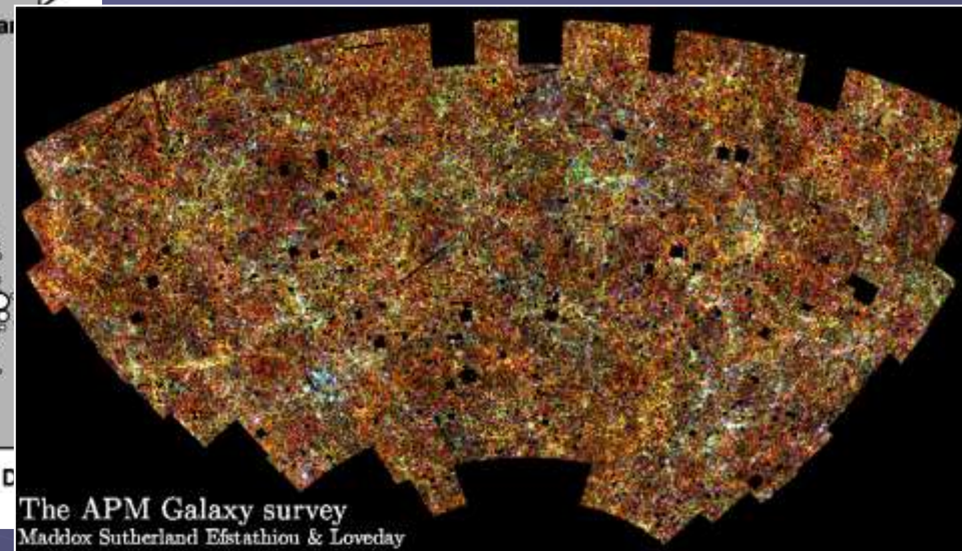
The catalogue collected 2712 north sky galaxy clusters which were selected on red POSS plates.

Abell was the first to study of distribution of cluster richnesses.

Both Abell's catalogue and Abell, Corwin & Olowin paper (contained 1364 south clusters, ApJS, V.70, P. 1, 1989) were much more than a catalogues of clusters. From publication of Abell's catalogue a new era in the investigation of galaxy clusters began. Researchers obtained a catalogue of clusters, and they could start look at them as a population, rather than as individual objects.

The first volume of Zwicky et al. “Catalogue of Galaxies and Clusters of Galaxies” was published only a few years later Abell's paper, but it did not exert such a large influence on the study of clusters. Unfortunately the sizes of Zwicky's clusters were distance-dependent, since they were defined within the isopleth contour that represents twice the field density.





To be continued!