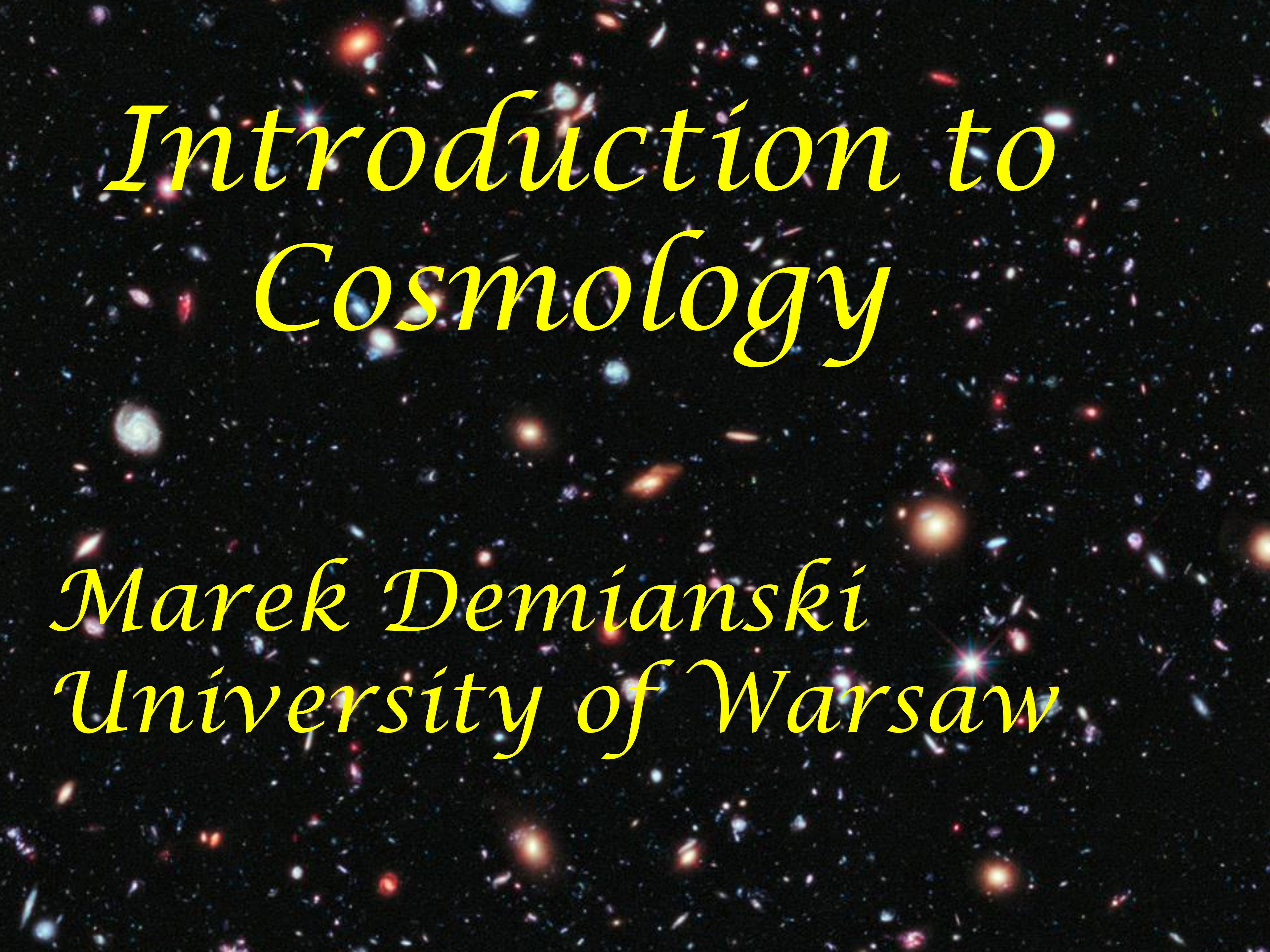


Introduction to Cosmology

Marek Demianski
University of Warsaw

V. M. Slipher

VESTO MELVIN SLIPHER, a pioneer in the field of astronomical spectroscopy during his long career at the Lowell Observatory at Flagstaff, Arizona, probably made more fundamental discoveries than any other observational astronomer of the twentieth century.[1]

He is best known for his discovery in 1913 of the extraordinary radial velocities of the spiral nebulae, as revealed by the enormous "red shifts" of the absorption lines in their spectra.[2] This discovery provided the first evidence for the now widely held theory of an expanding universe,[3] and it was a prerequisite to Edwin P. Hubble's discovery sixteen years later of the relationship between the radial velocities of nebulae and their distances, which has enabled astronomers to gauge the approximate age and dimensions of the known universe.[4]

In the course of this work, Slipher also discovered that the spiral nebulae are rotating,[5] carried out fruitful investigations of the relative motion and distribution of nebulae and globular star clusters,[6] demonstrated the existence of gas and dust in interstellar space, and found that certain nebulae shine only by the reflected light of nearby stars.[7]

M 31 approaches us at 300 km/s
Vesto Melvin Slipher (1912)

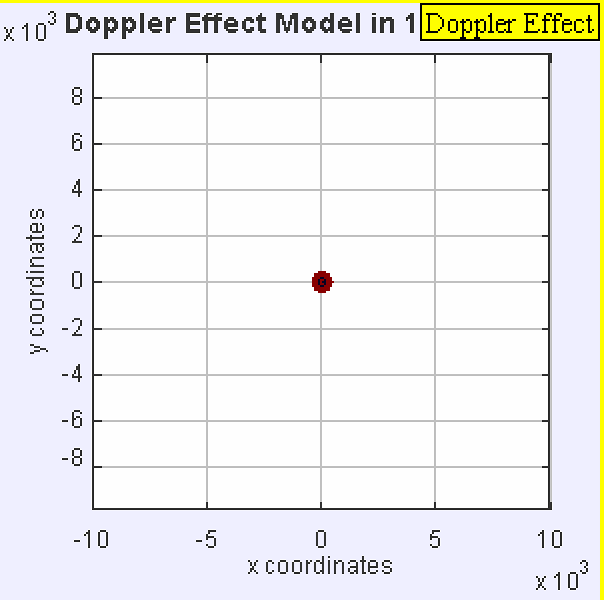
Interpretation of the observed shifts in the position of spectral lines:

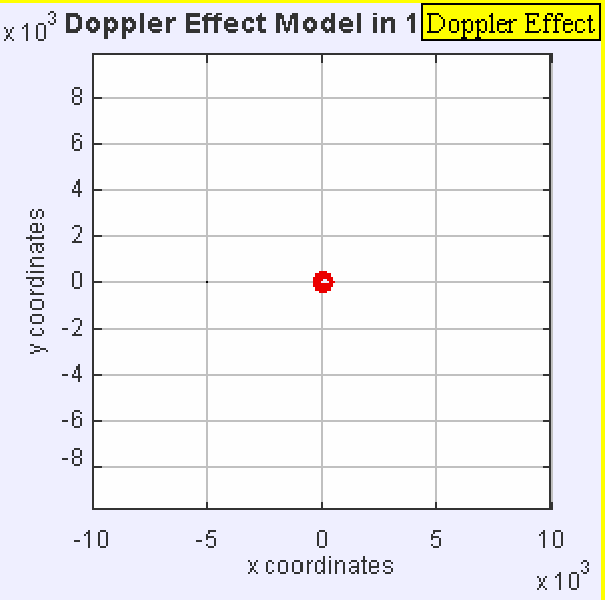
a) Doppler effect

b) Gravitational redshift

$$\frac{\lambda(r_0)}{\lambda(r)} = 1 - \frac{GM}{c^2}\left(\frac{1}{r_0} - \frac{1}{r}\right)$$

Doppler effect

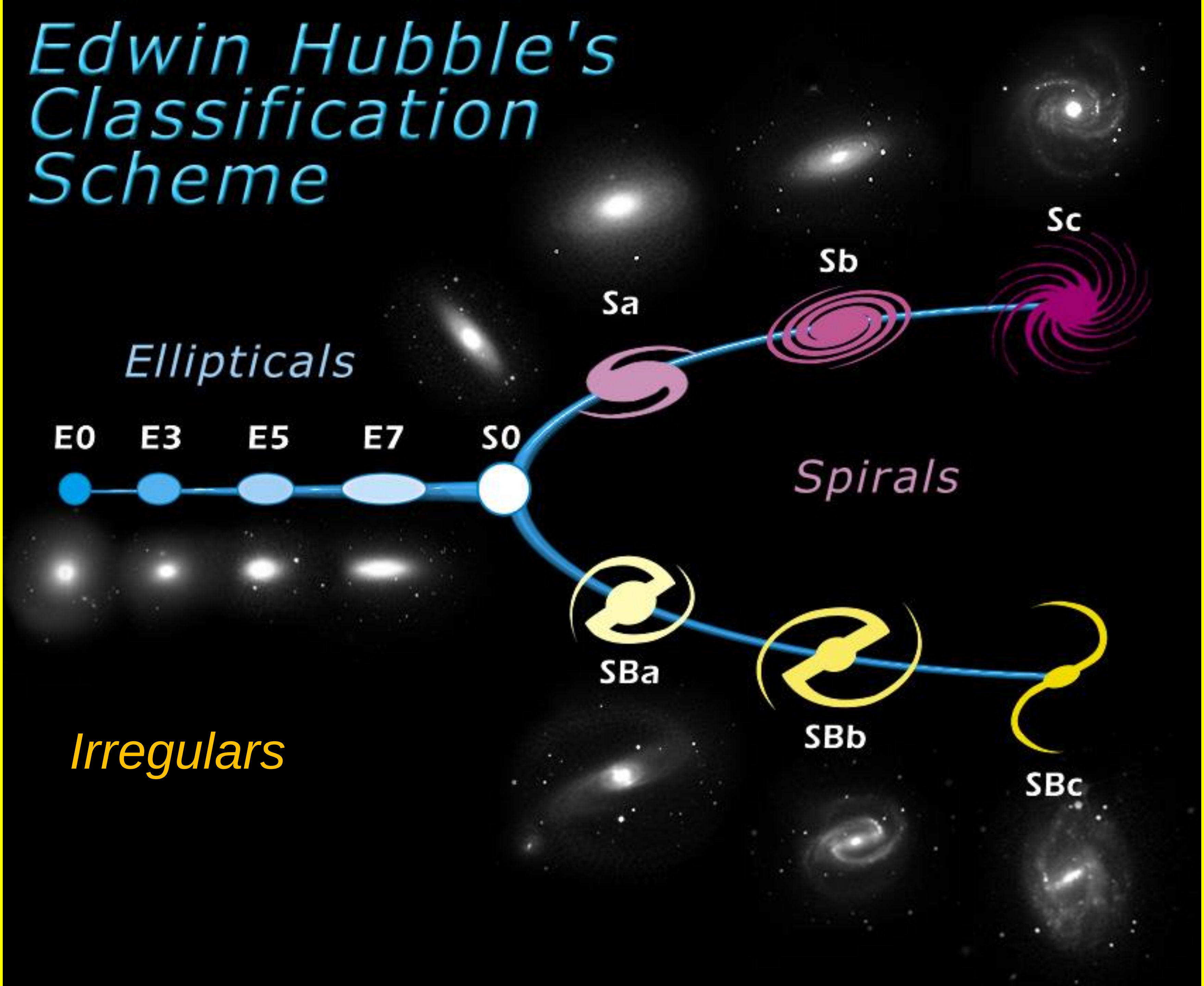




$$(\lambda_o - \lambda_e)/\lambda_e = v/c$$

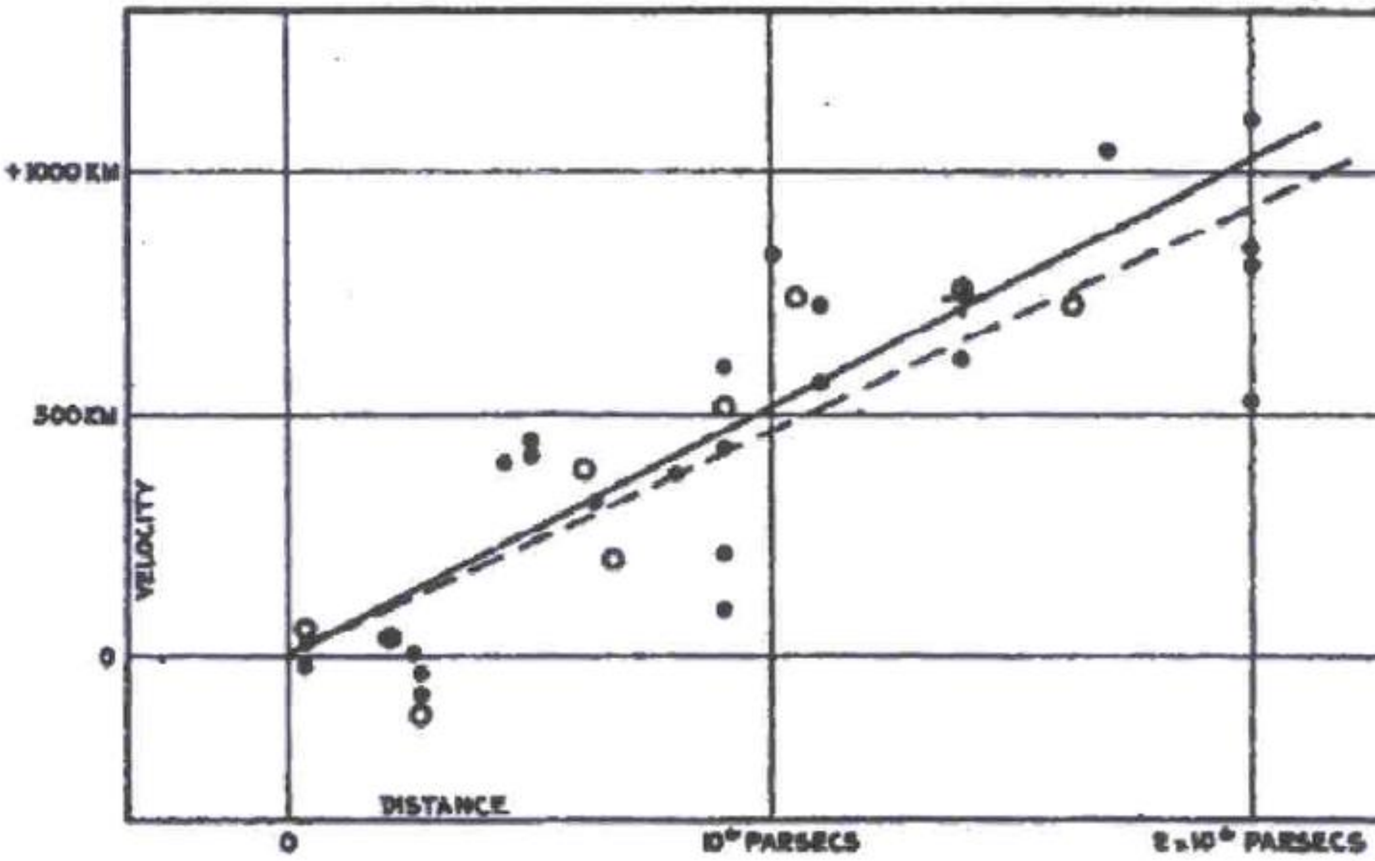
During his stay at the Flagstaff Observatory Vesto Slipher measured about 100 spectral line shifts of different „nebulea“.

Edwin Hubble
1889 - 1953

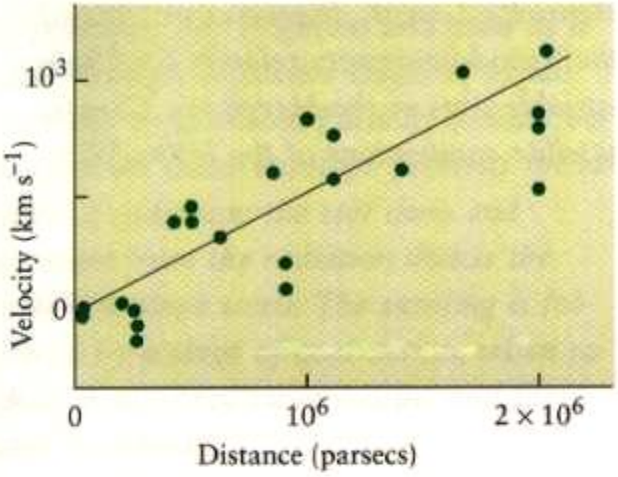

Edwin Hubble's
Classification
Scheme
Ellipticals
E0
E3
E5
E7
S0
Sa
Sb
Sc
Spirals
SBa
SBb
SBc

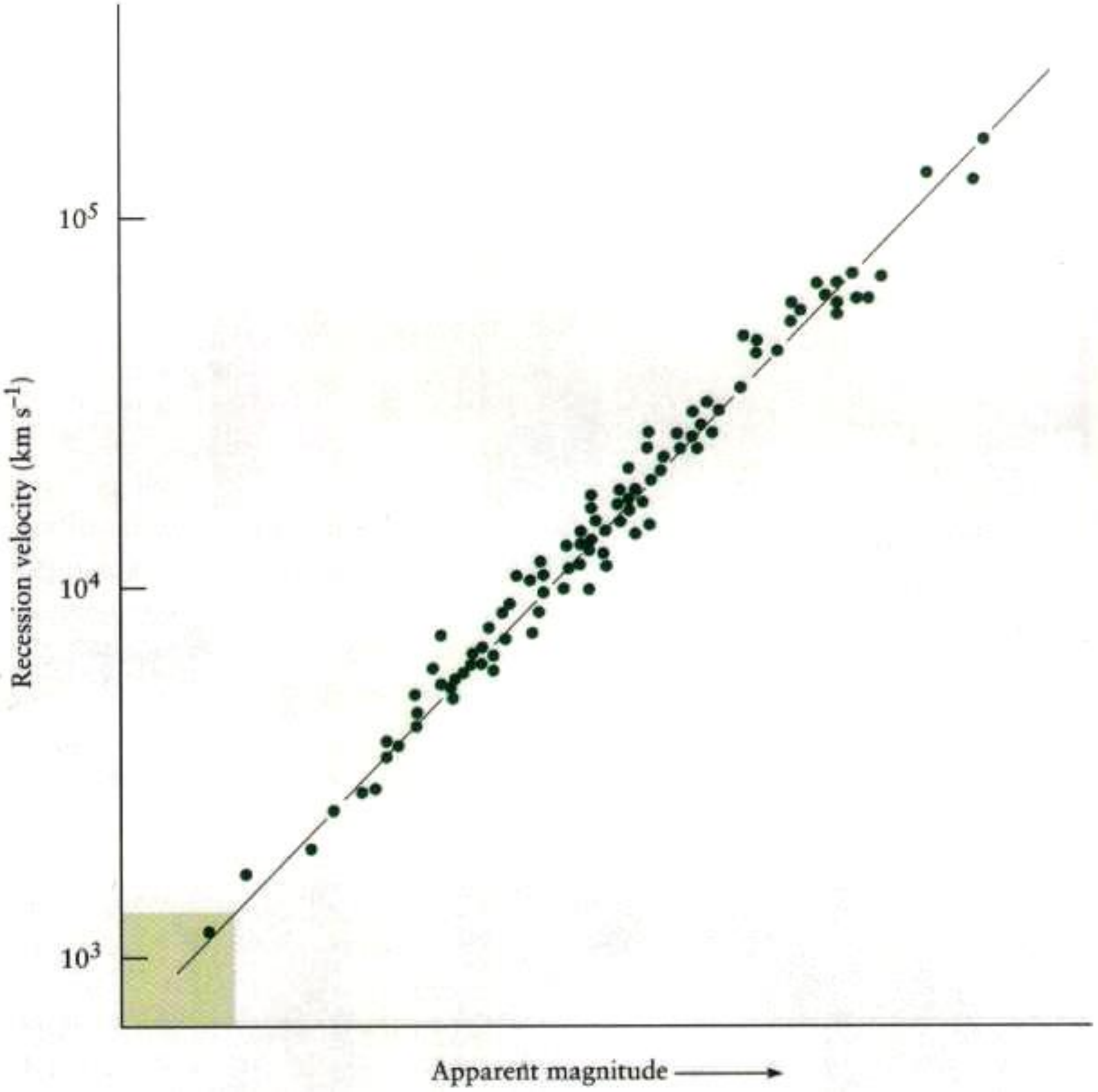
Irregulars

By observing the Cepheid stars Hubble was able to determine distances to several dozens galaxies



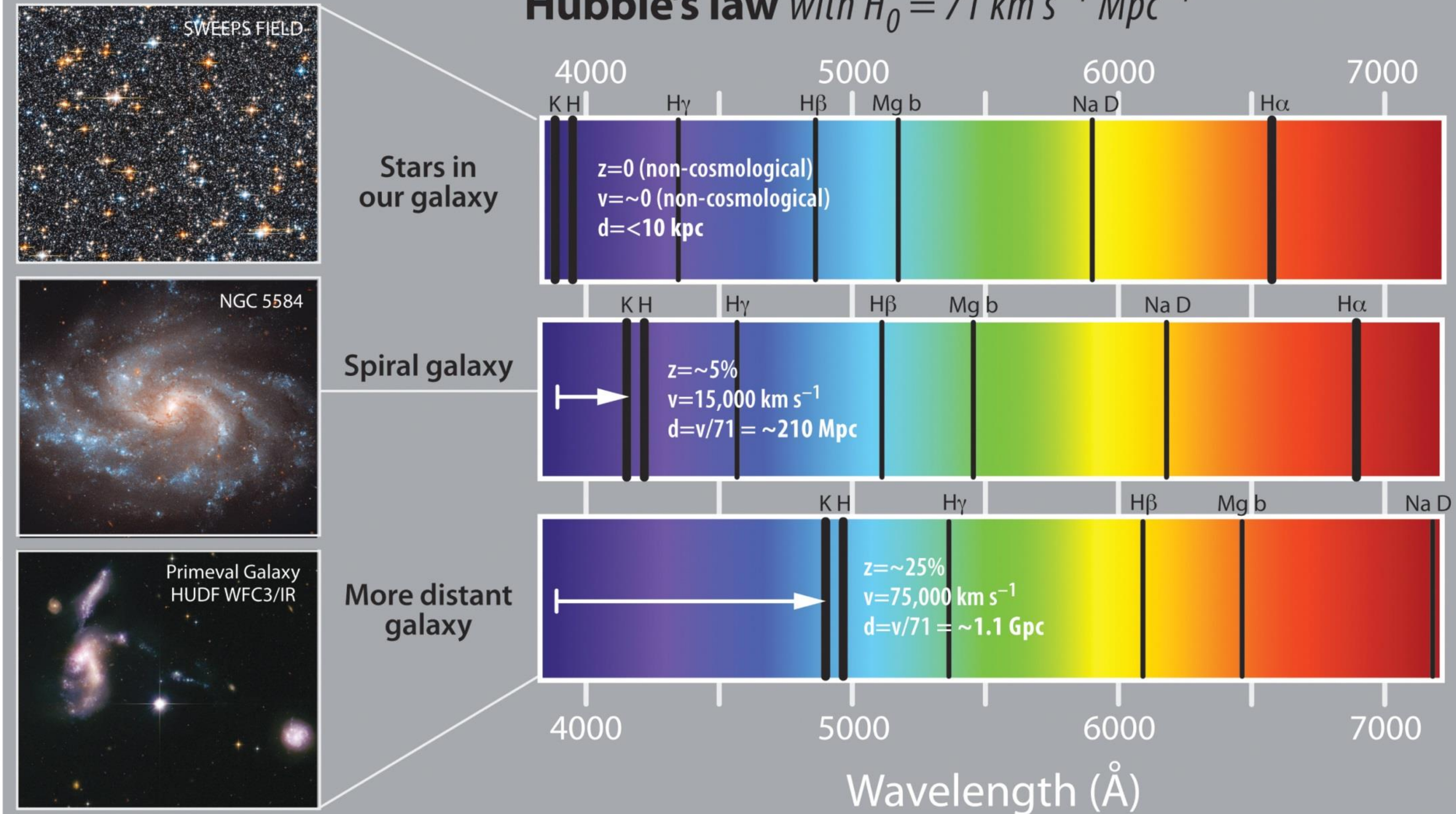
V = H·d, H – Hubble constant





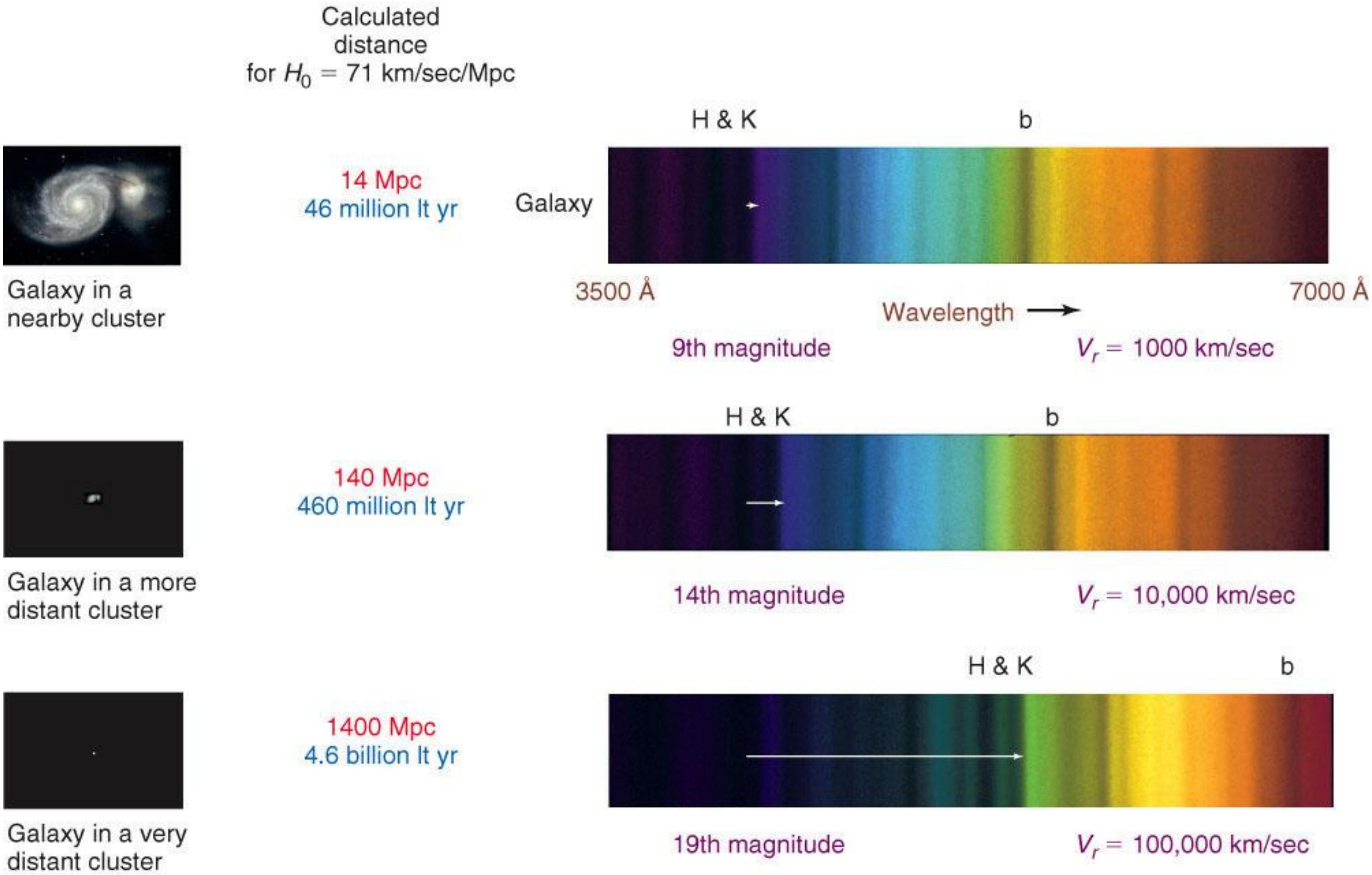
Edwin Hubble made this plot of galaxy velocities versus distances in the 1930s (above left). He only sampled a nearby volume of space, as far as the Virgo cluster. This so-called Hubble diagram was greatly extended by Alan Sandage and his collaborators (right), who compared the recession velocities of the brightest galaxies in galaxy clusters with distances to the clusters as inferred from the apparent magnitudes of these galaxies. A galaxy cluster is so luminous that it can be recognized at a large distance from us. Both plots show that recession velocity increases proportionately to distance.

Hubble's law *with* $H_0 = 71\ km\ s^{-1}\ Mpc^{-1}$



NASA images. Teramura art @kthonhi

Karen Teramura, Institute for Astronomy, University of Hawaii


Calculated distance for H_0 = 71 km/sec/Mpc
H & K
b
14 Mpc
46 million lt yr
Galaxy
3500 Å
7000 Å
Wavelength →
Galaxy in a nearby cluster
9th magnitude
V_r = 1000 km/sec
H & K
b
140 Mpc
460 million lt yr
Galaxy in a more distant cluster
14th magnitude
V_r = 10,000 km/sec
H & K
b
1400 Mpc
4.6 billion lt yr
Galaxy in a very distant cluster
19th magnitude
V_r = 100,000 km/sec

The Hubble law

The measurable quantities:

z – redshift -> v

d – distance

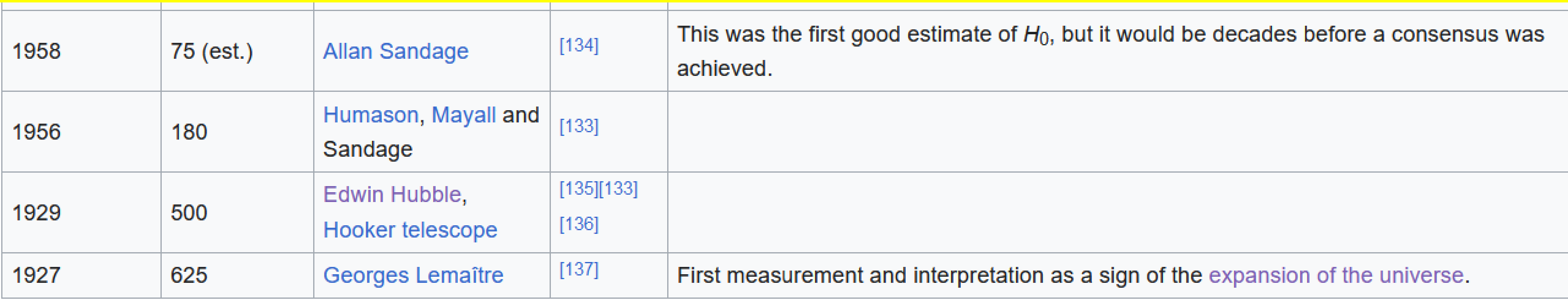
$$V = H \cdot d$$

H is a constant !

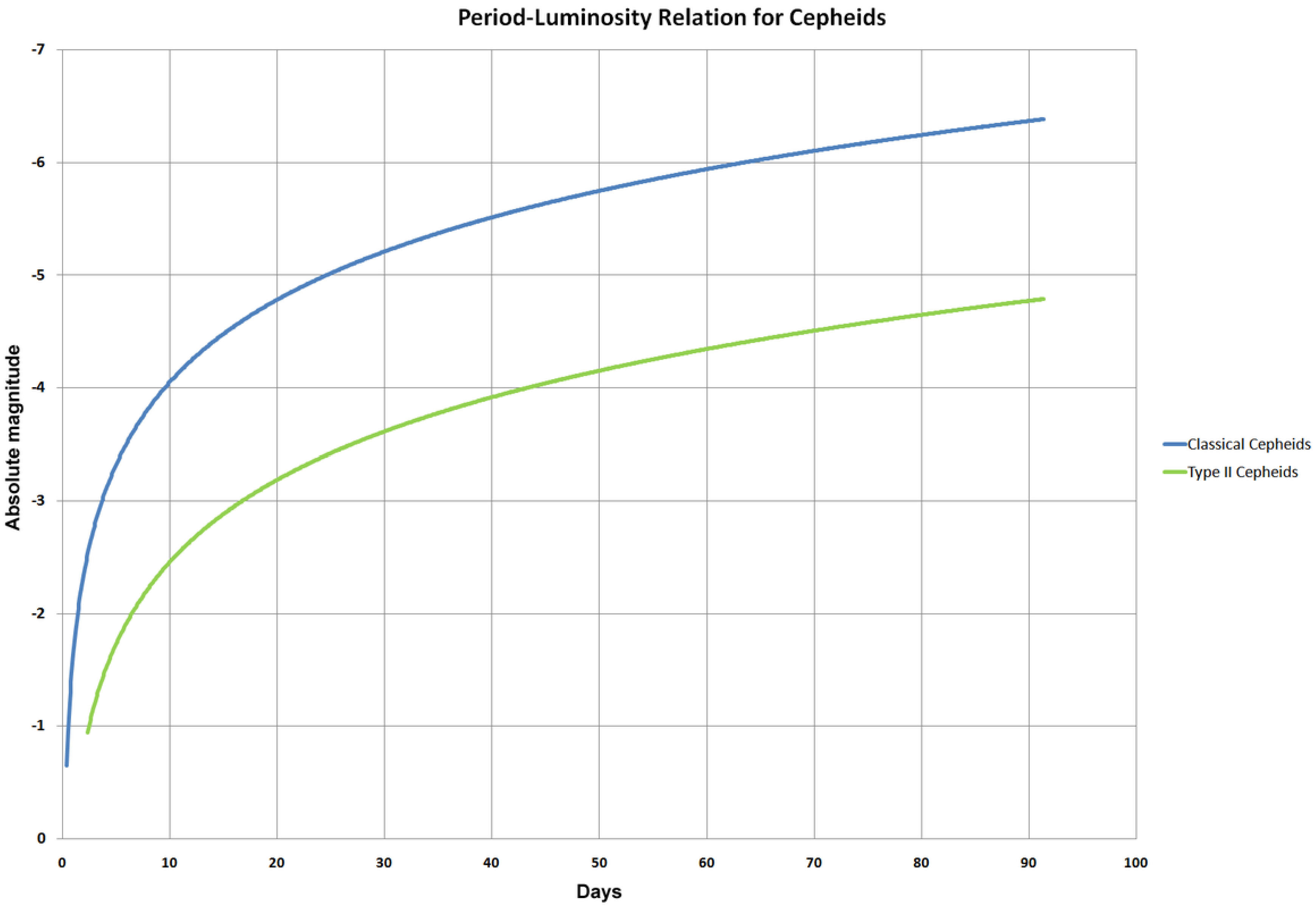
Hint – the Universe could be isotropic

The Universe is expanding !!

Early attempts to measure the Hubble constant

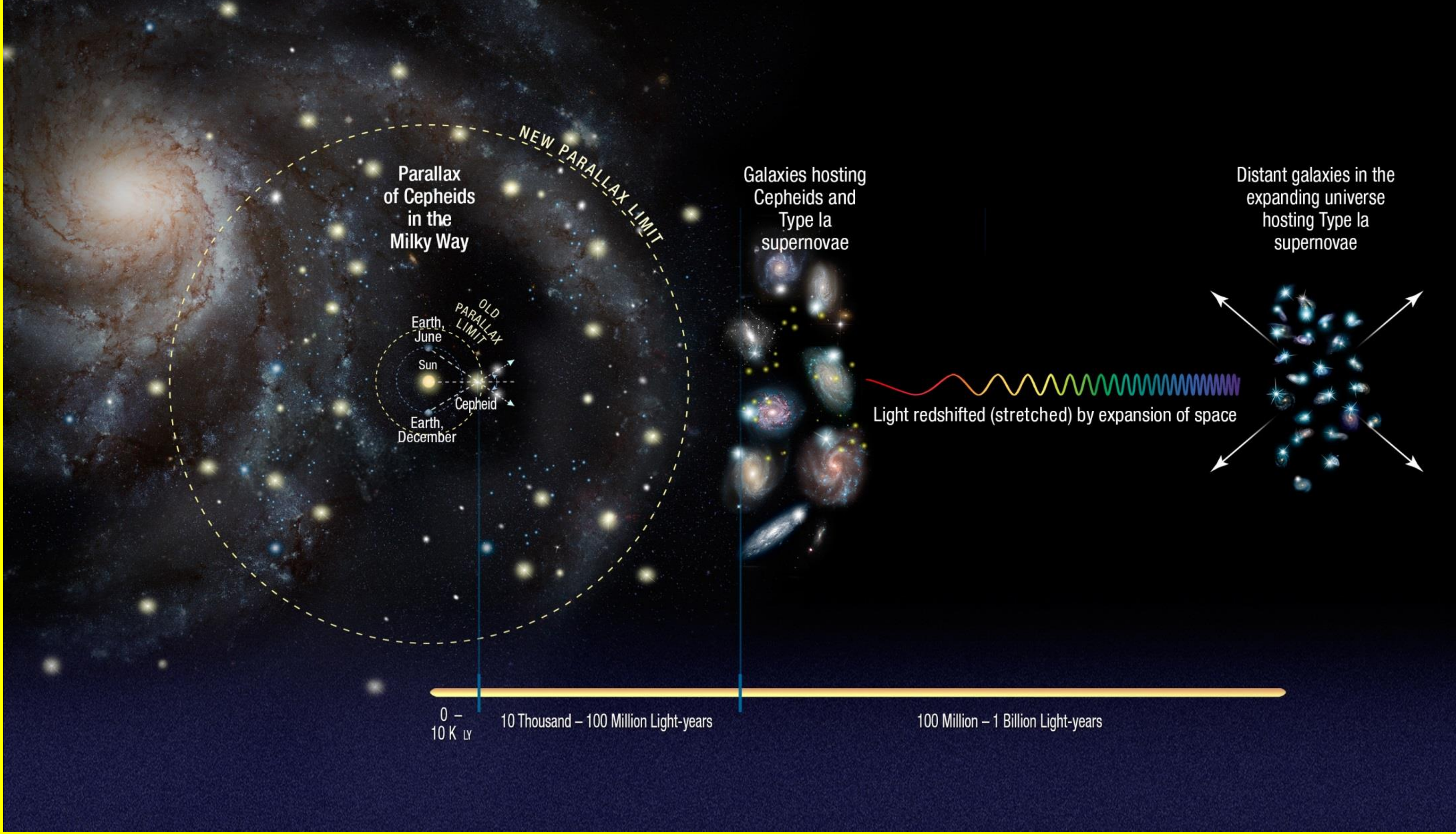


1958	75 (est.)	Allan Sandage	[134]	This was the first good estimate of H_0, but it would be decades before a consensus was achieved.
1956	180	Humason, Mayall and Sandage	[133]	
1929	500	Edwin Hubble, Hooker telescope	[135][133] [136]	
1927	625	Georges Lemaître	[137]	First measurement and interpretation as a sign of the expansion of the universe.


Period-Luminosity Relation for Cepheids
-7
-6
-5
-4
-3
-2
-1
0
Absolute magnitude
0
10
20
30
40
50
60
70
80
90
100
Days
Classical Cepheids
Type II Cepheids

Maarten Schmidt and Allan Sandage

Three steps to the Hubble Constant



Parallax of Cepheids in the Milky Way

Galaxies hosting Cepheids and Type Ia supernovae

Distant galaxies in the expanding universe hosting Type Ia supernovae

Light redshifted (stretched) by expansion of space

0 – 10 K LY

10 Thousand – 100 Million Light-years

100 Million – 1 Billion Light-years

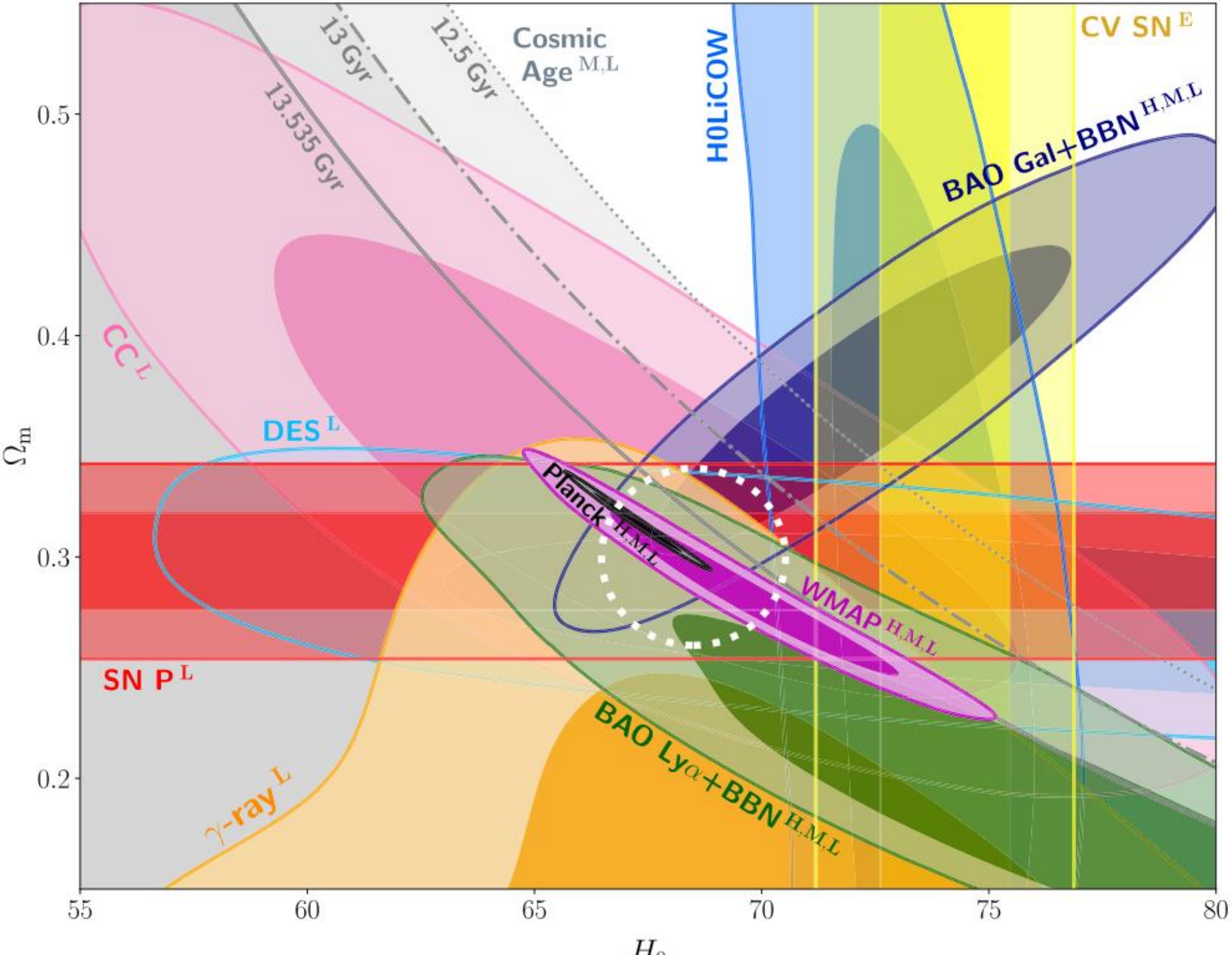
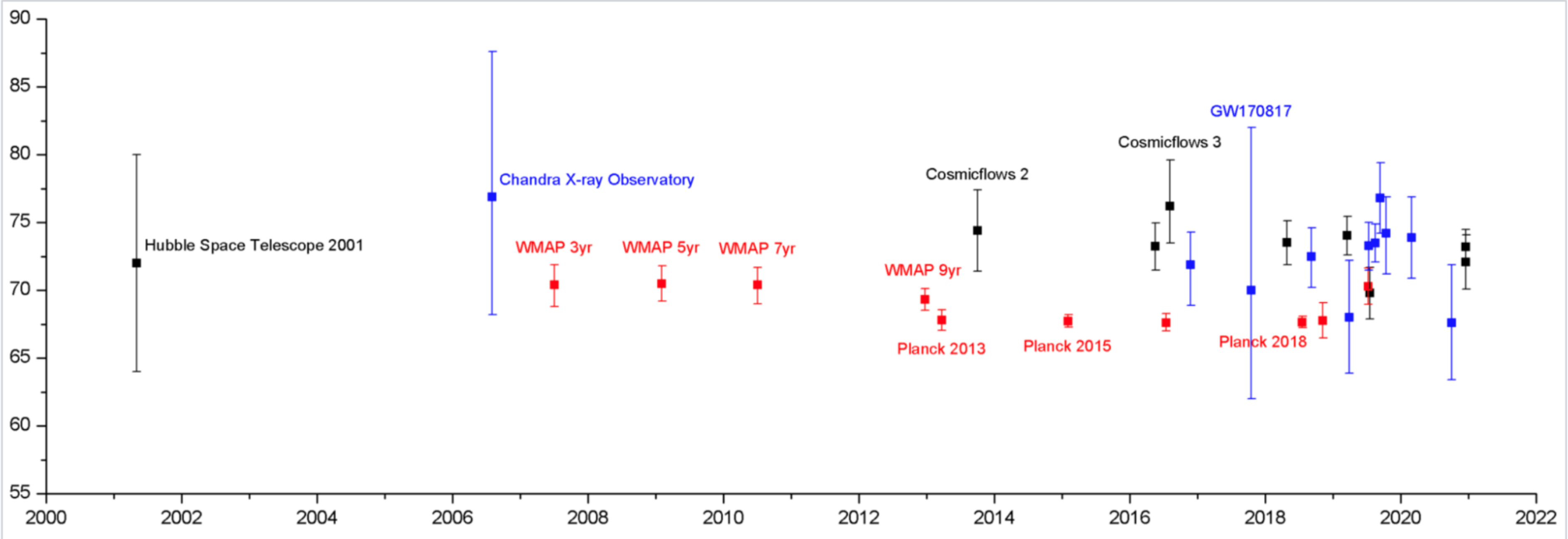

Cosmic Age M,L
13 Gyr
12.5 Gyr
13.535 Gyr
H0LiCOW
CV SN E
BAO Gal+BBN H,M,L
CC L
DES L
Planck H,M,L
WMAP H,M,L
SN P L
BAO Lyα+BBN H,M,L
γ-ray L
Ωm
0.5
0.4
0.3
0.2
55
60
65
70
75
80
H0

Figure 1. Different constraints in the H_0 and Ω_m space based on a flat ΛCDM model. Dark and light contours show the 68% and 95% confidence regions of each posterior, with the exception of the cosmic-age bounds. (For each of those, the parameter space outside the orange regions is excluded if the universe is at least the age given in the label.) Most constraints with different degeneracy directions consistently overlap the region indicated by the guiding white dashed circle. Note that the circle does not represent a joint constraint. Such a common region is, however, not overlapped by the Cepheid-based local determination of H_0 (CV SN) and is only marginally overlapped by the H_0LiCOW constraint. Contours correspond to SN P (red), DES (light blue), CC (pink), H0LiCOW (blue), BAO Gal (navy), BAO Lyα (green), γ-ray (orange), WMAP (magenta), Planck (black), CV SN (yellow), and some guiding cosmic-age constraints (t^* = 13.535, 13, and 12.5 Gyr; orange). Each constraint in the figure is labeled according to whether it can be changed by nonstandard high-z models (H), mid-z models (M), low-z models (L), or local environmental factors (E). See the text for the definition of these model categories. We leave the H_0LiCOW technique without a label because it is relatively insensitive to the underlying cosmological model.

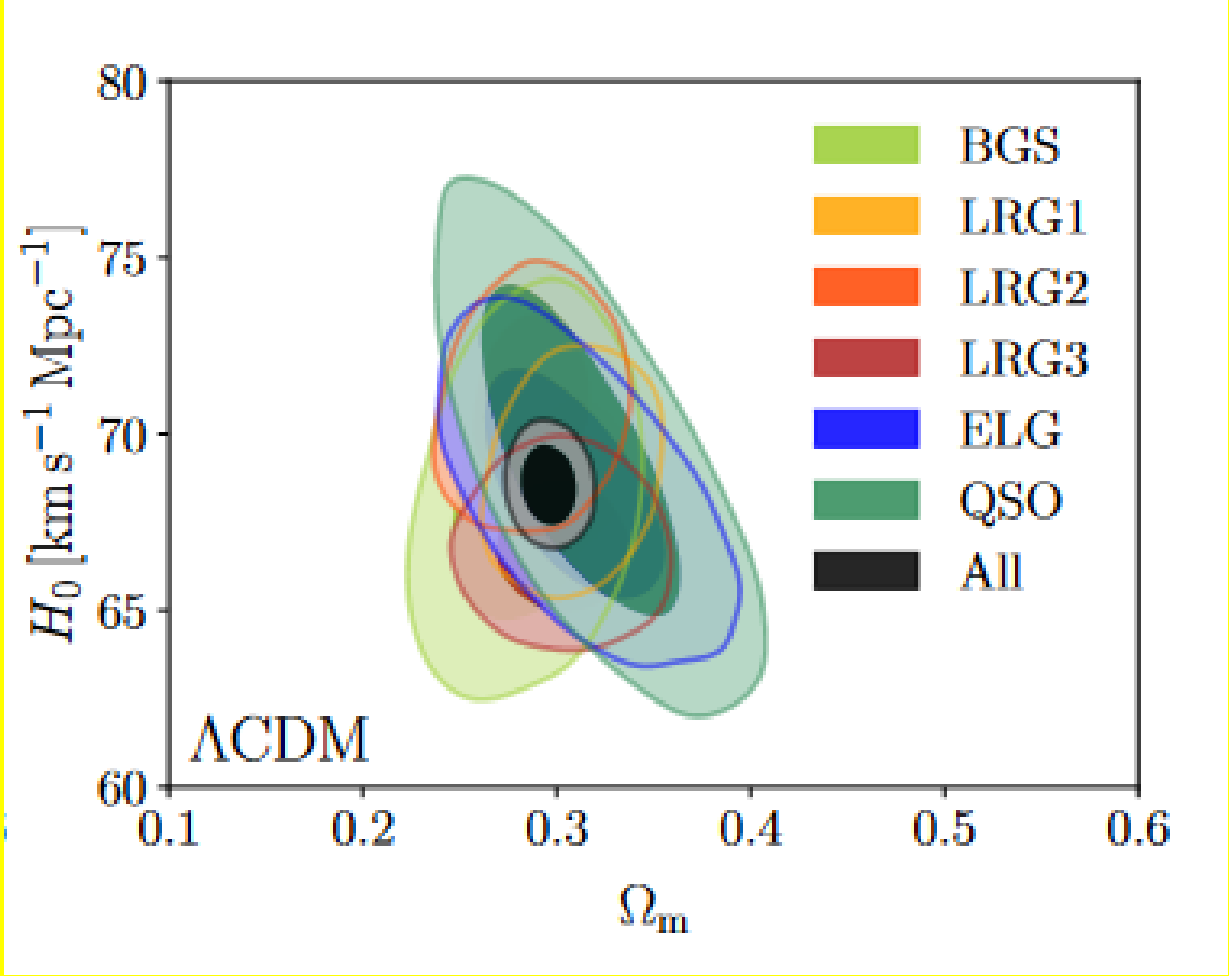
“Investigating the Hubble Constant Tension: Two Numbers in the Standard Cosmological Model”
Weikang Lin, Katherine J. Mack, and Liqiang Hou
Published 2020 November 27 • © 2020. The American Astronomical Society. All rights reserved.
The Astrophysical Journal Letters, Volume 904, Number 2

Hubble-constant “tension”



Estimated values of the Hubble constant, 2001–2020. Estimates in black represent calibrated distance ladder measurements which tend to cluster around 73 km/s/Mpc; red represents early universe CMB/BAO measurements with ΛCDM parameters which show good agreement on a figure near 67 km/s/Mpc, while blue are other techniques, whose uncertainties are not yet small enough to decide between the two.

From Wikipedia: Hubble Constant



Slide from 2411.12022

Immediate conclusions:

Units of H — 1/time

Estimated age of the Universe ≈ 1/H

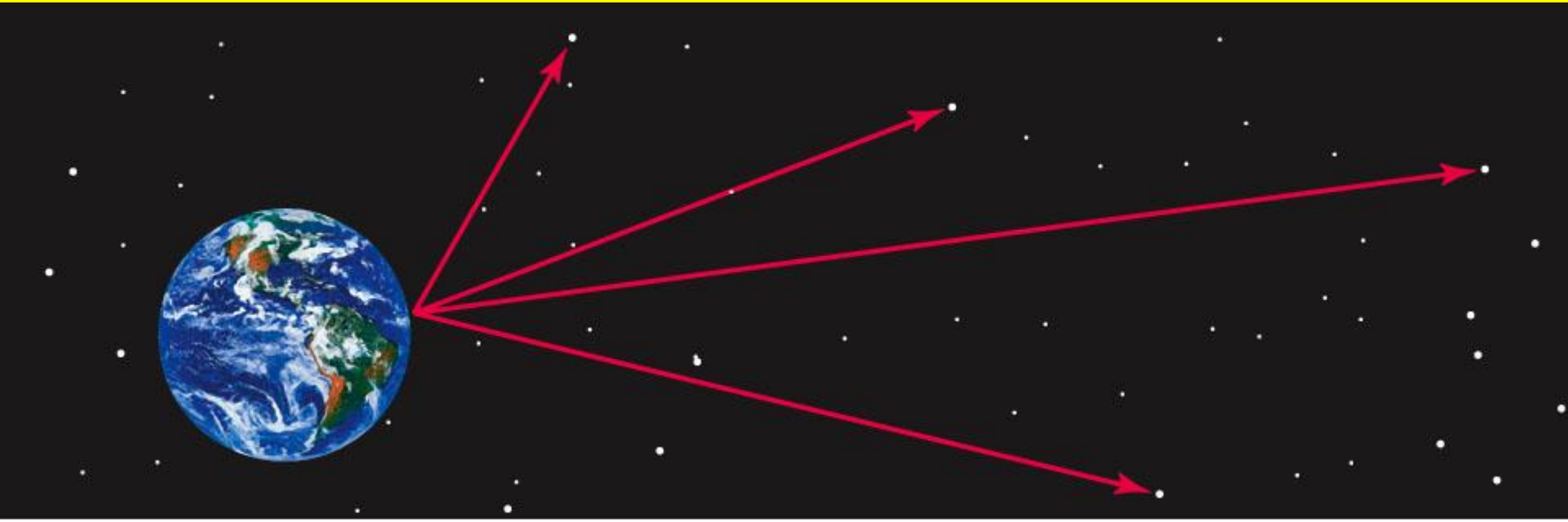
Present value of H ≈ 70 km/sMpc

$1/H \sim 4.2\times10^{17}$ s $\approx 13 \times 10^{9}$ years

$v=H\cdot d$; $c=H\cdot d_{horizon}$

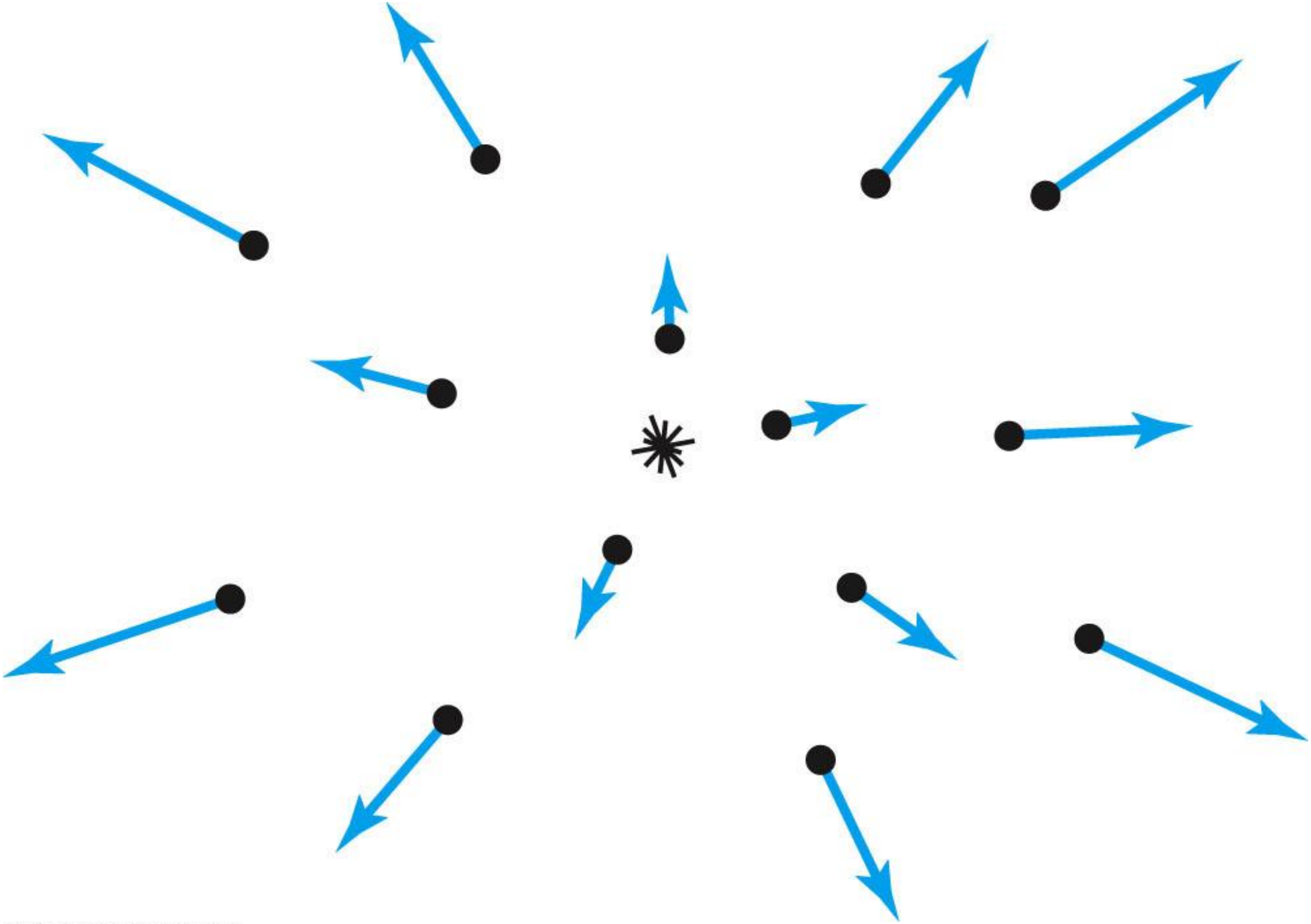
$d_{horizon} = c/H$; $d_{horizon} = 13 \times 10^{9}$ ly!

It is impossible to see anything that is further !

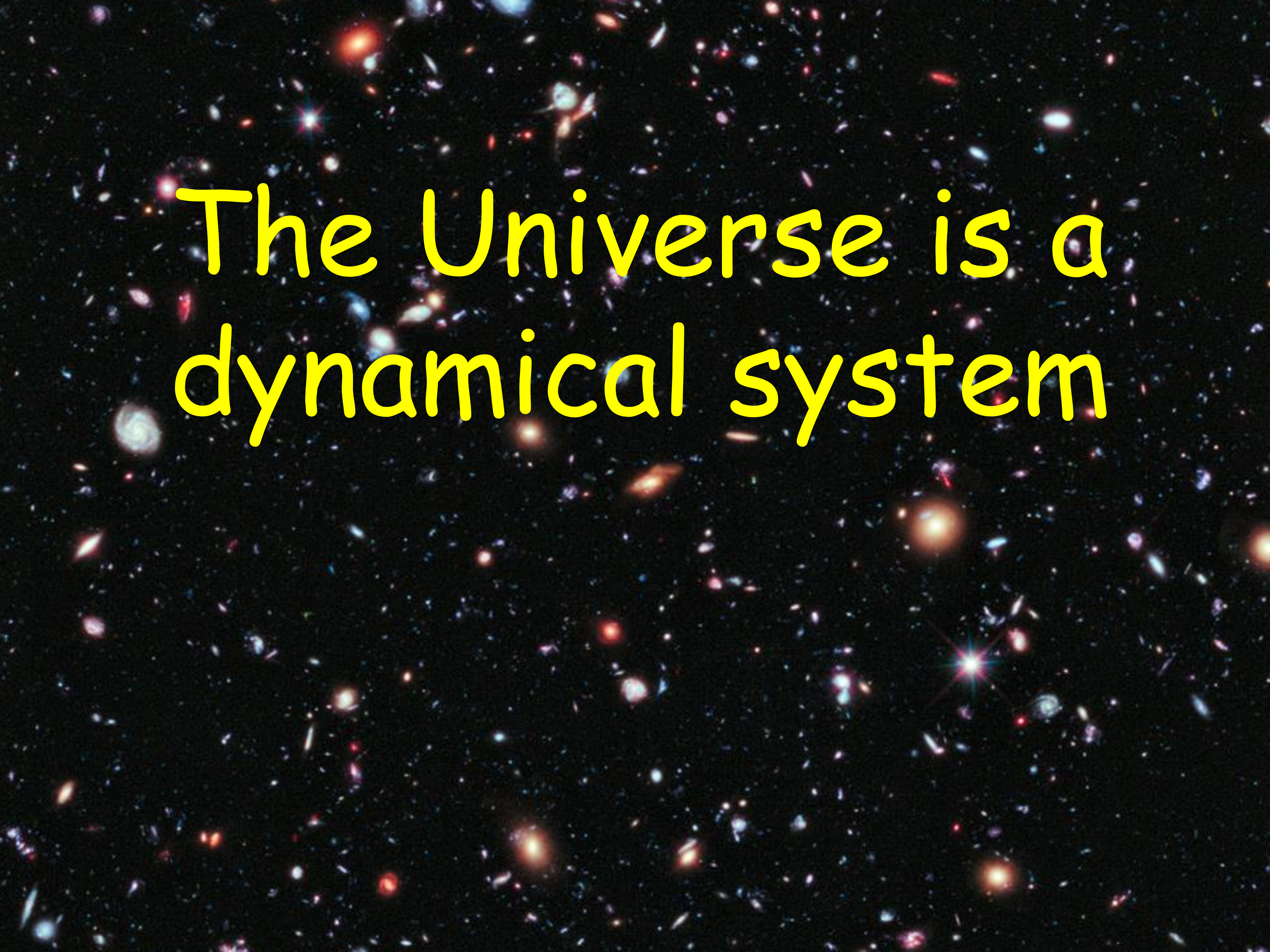


Heinrich Wilhelm Matthias Olbers

Olbers's Paradox

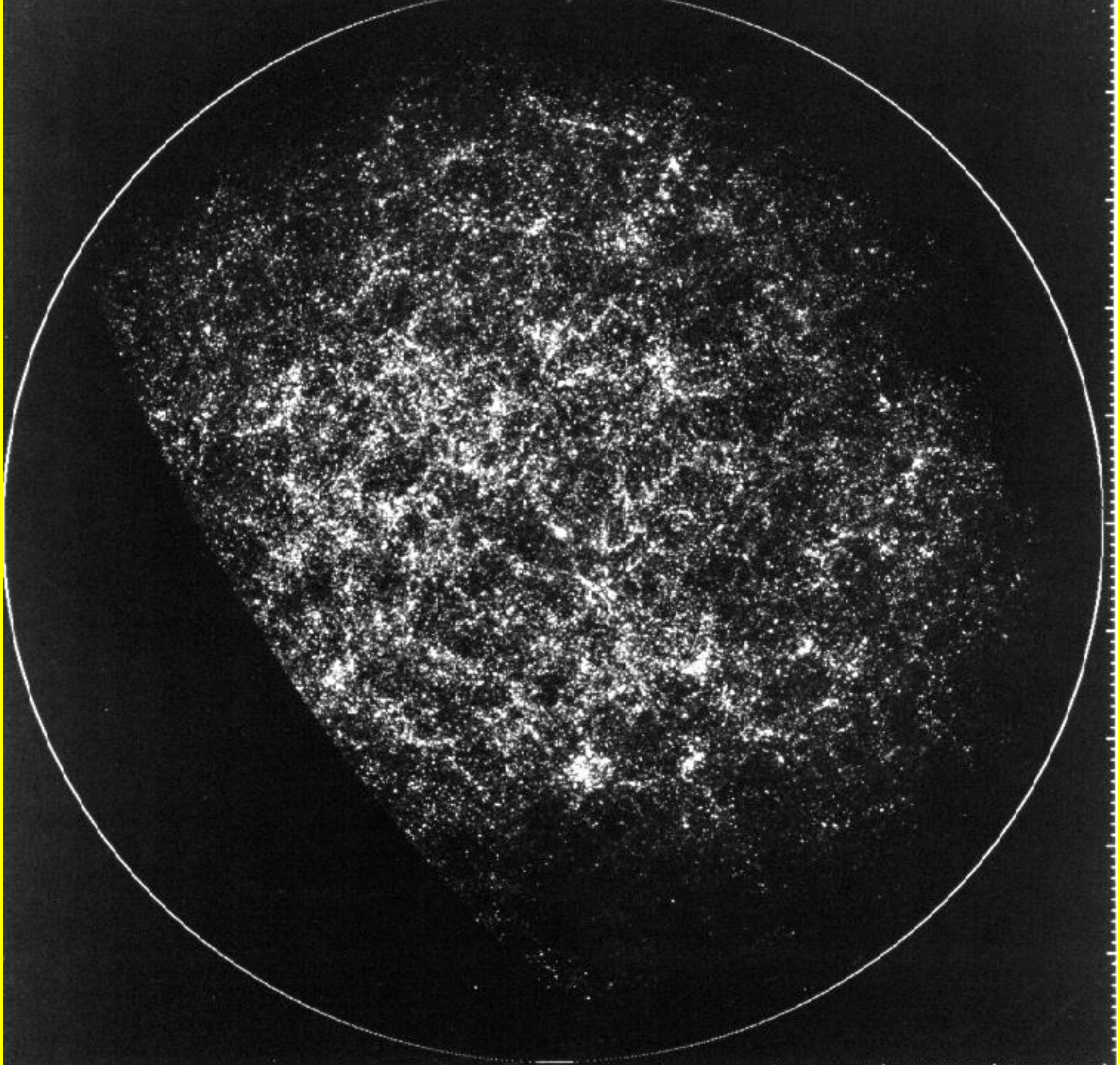


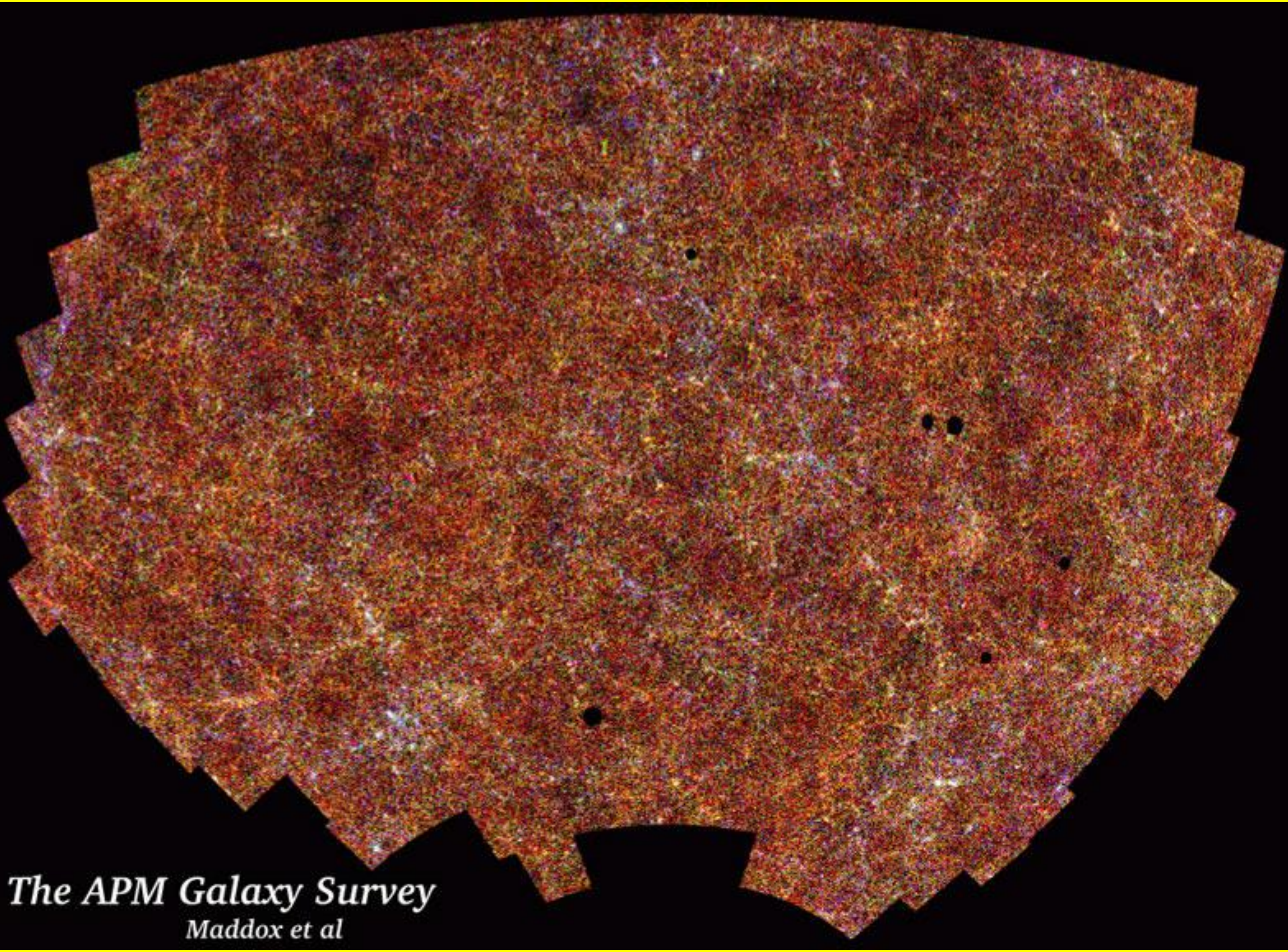
The Universe is a dynamical system



Modeling the Universe

Basic assumption -
the laws of physics and
mathematics hold
everywhere in the Universe





The APM Galaxy Survey
Maddox et al

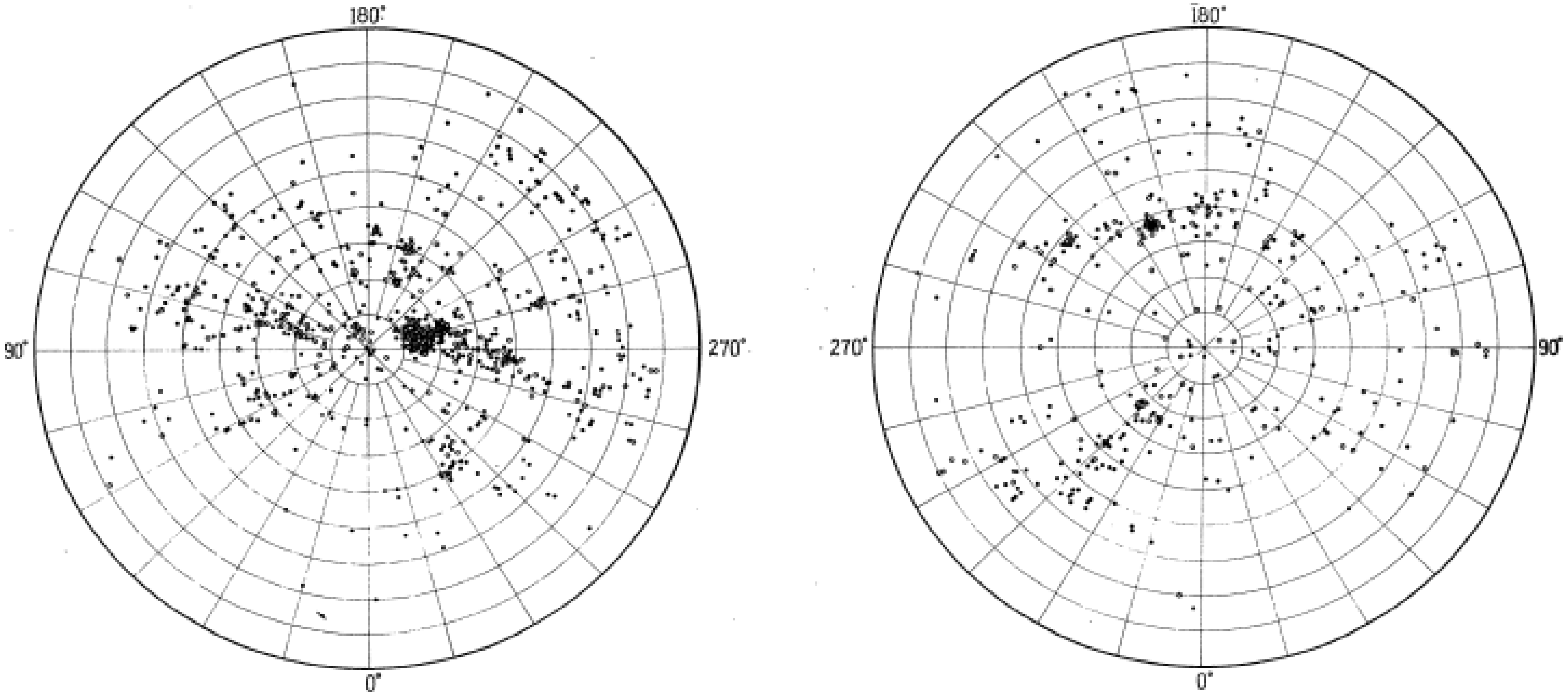


FIGURE 2.2. The Shapley and Ames (1932) map of galaxies brighter than apparent magnitude 13. Courtesy of the John G. Wolbach Library, Harvard College Library.

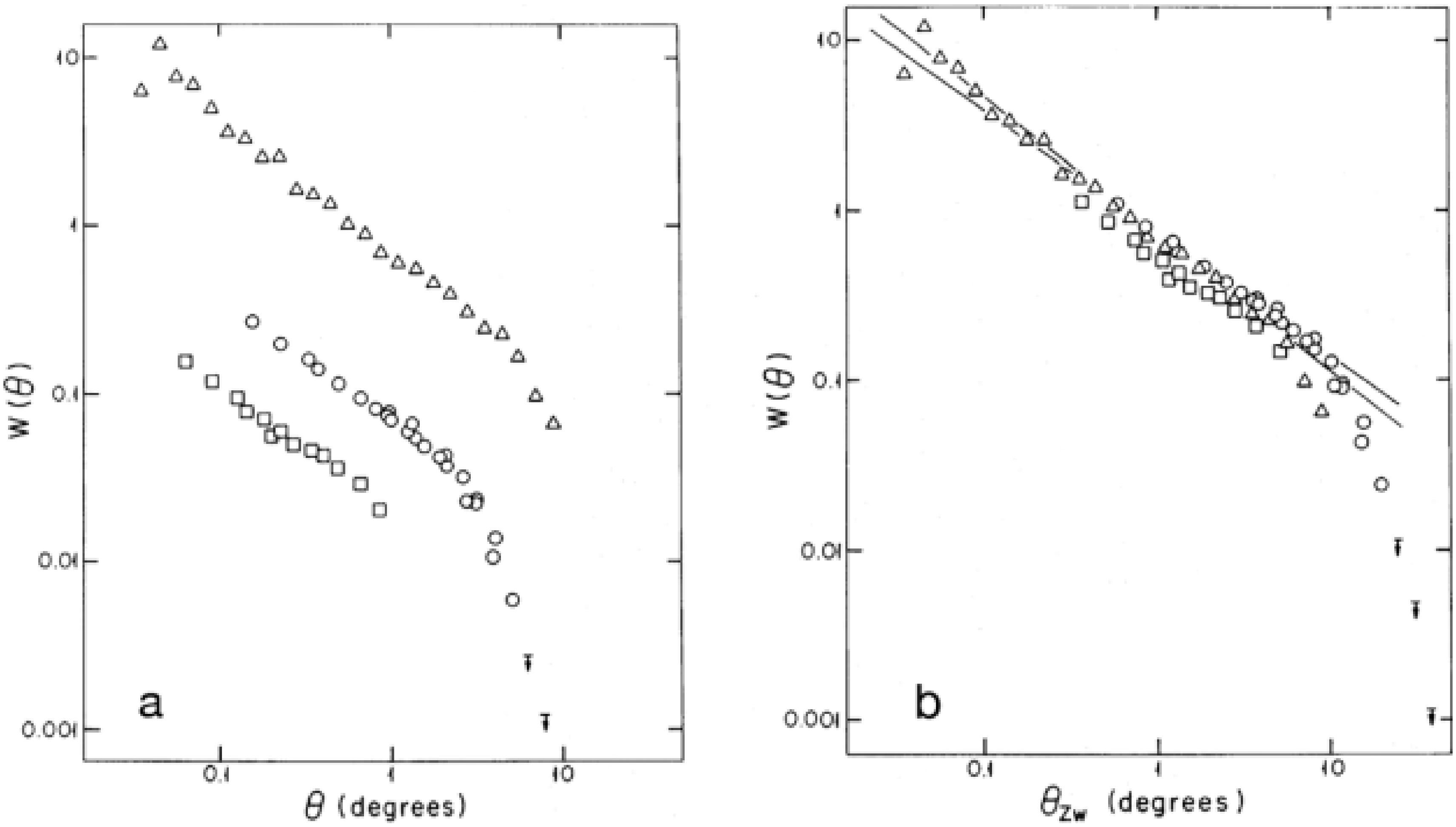


FIGURE 2.5. Scaling test of the galaxy two-point angular correlation functions in Panel (a) for the Zwicky (triangles), Shane-Wirtanen (circles), and Jagellonian (squares) samples. Panel (b) is the result of applying the scaling relation in equation (2.15) to the angular functions (Groth and Peebles 1977). © AAS. Reproduced with permission.

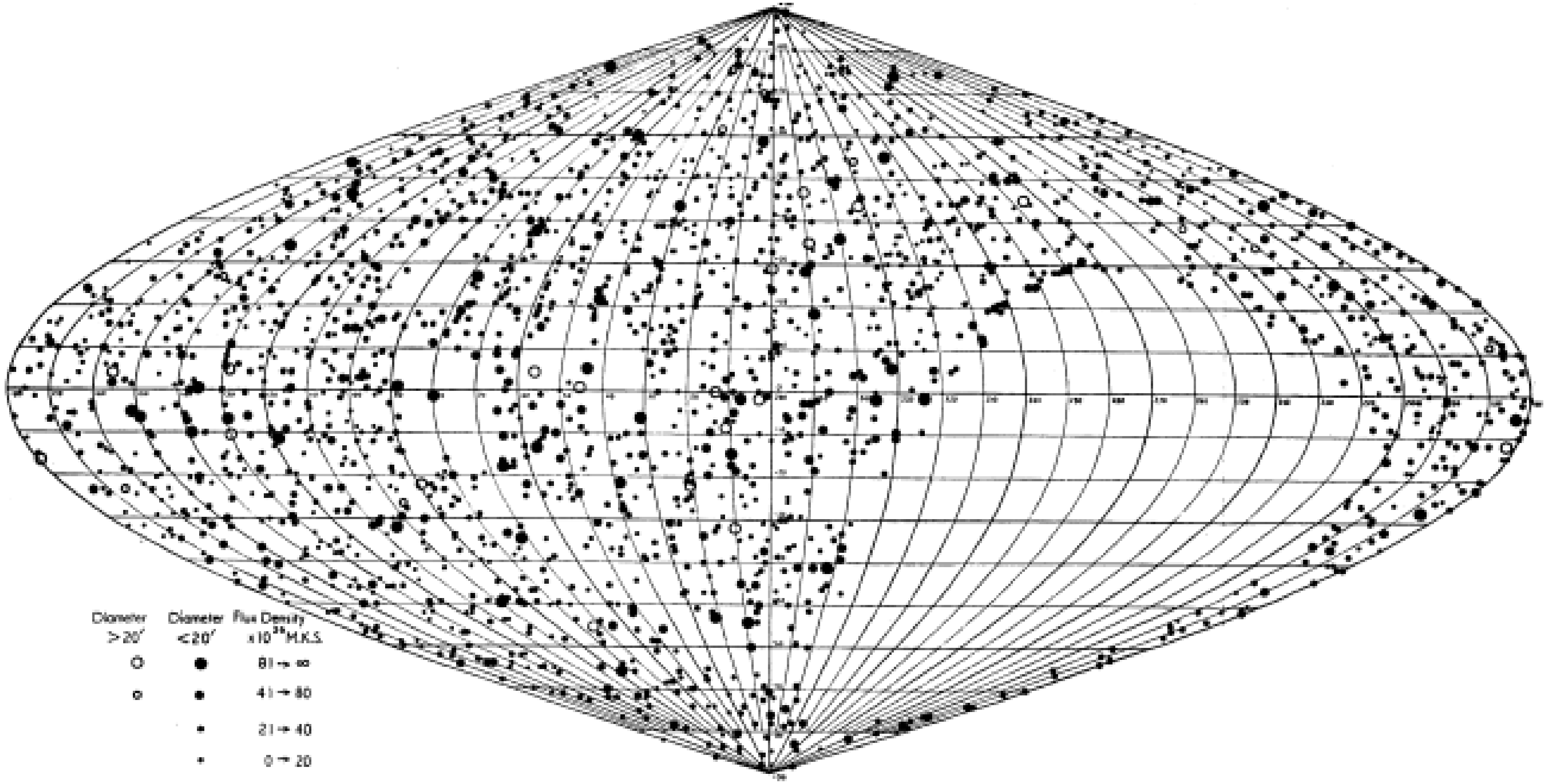
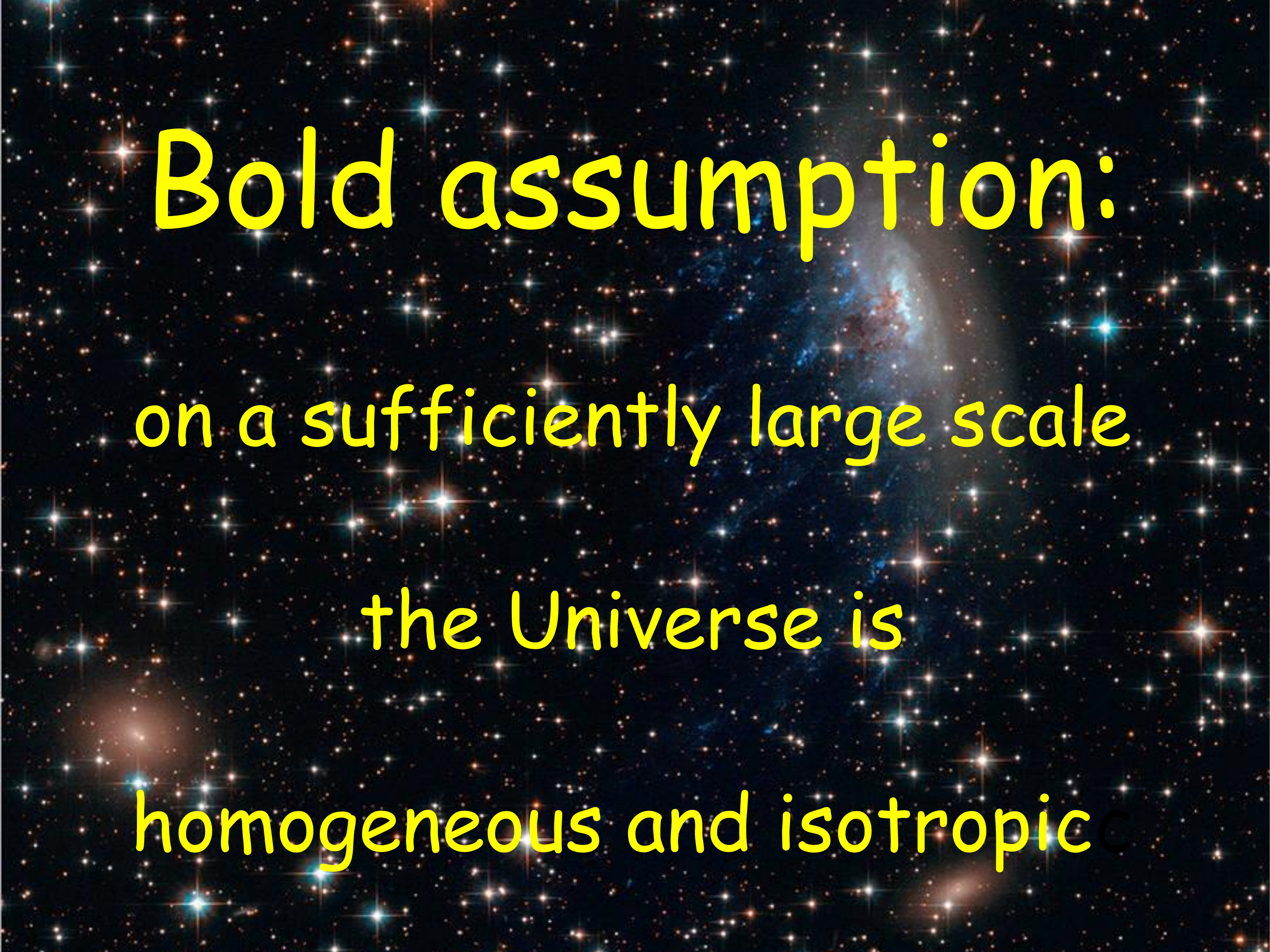


FIGURE 2.4. The Second Cambridge Catalog of Radio Sources (Shakeshaft, Ryle, Baldwin, et al. 1955).

Cosmological Copernican Principle

The Milky Way is just a normal galaxy and it does not occupy a preferred position in the Universe



Bold assumption:

on a sufficiently large scale

the Universe is

homogeneous and isotropicc

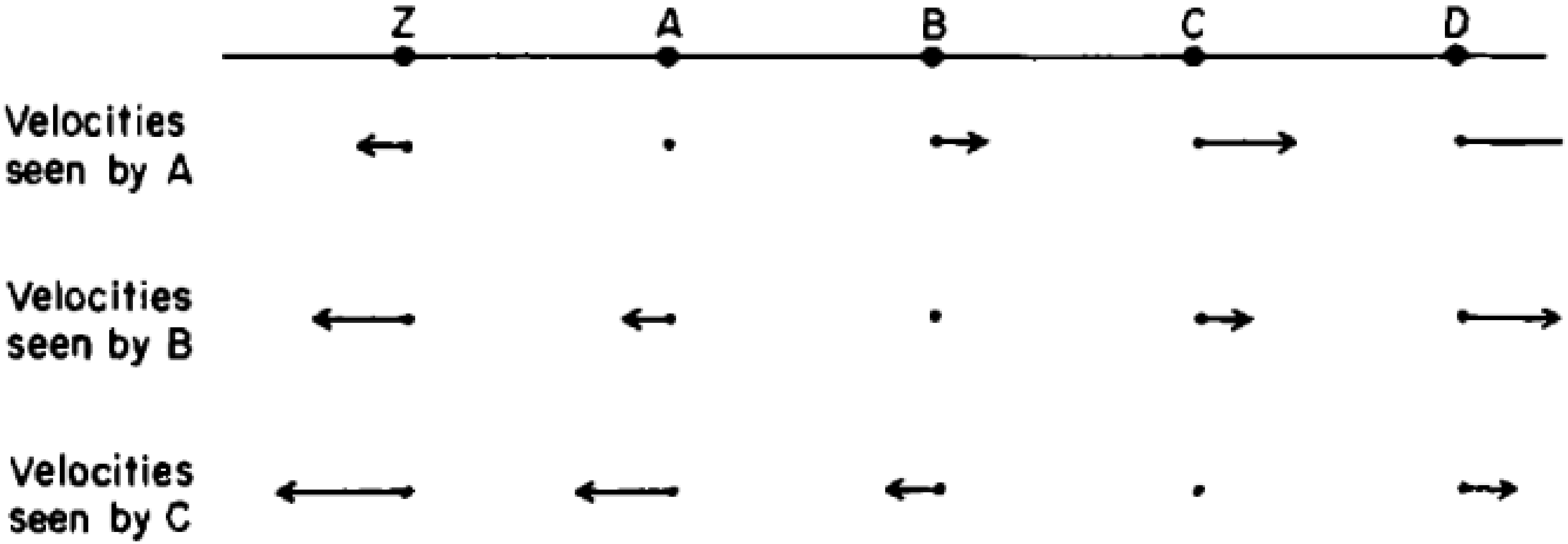


Figure 1. *Homogeneity and the Hubble Law.* A string of equally spaced galaxies Z, A, B, C, . . . are shown, with velocities as measured from A or B or C indicated by the lengths and directions of the attached arrows. The principle of homogeneity requires that the velocity of C as seen by B is equal to the velocity of B as seen by A; adding these two velocities gives the velocity of C as seen by A, indicated by an arrow twice as long. Proceeding in this way, we can fill out the whole pattern of velocities shown in the figure. As can be seen, the velocities obey the Hubble law: the velocity of any galaxy as seen by any other is proportional to the distance between them. This is the only pattern of velocities consistent with the principle of homogeneity.

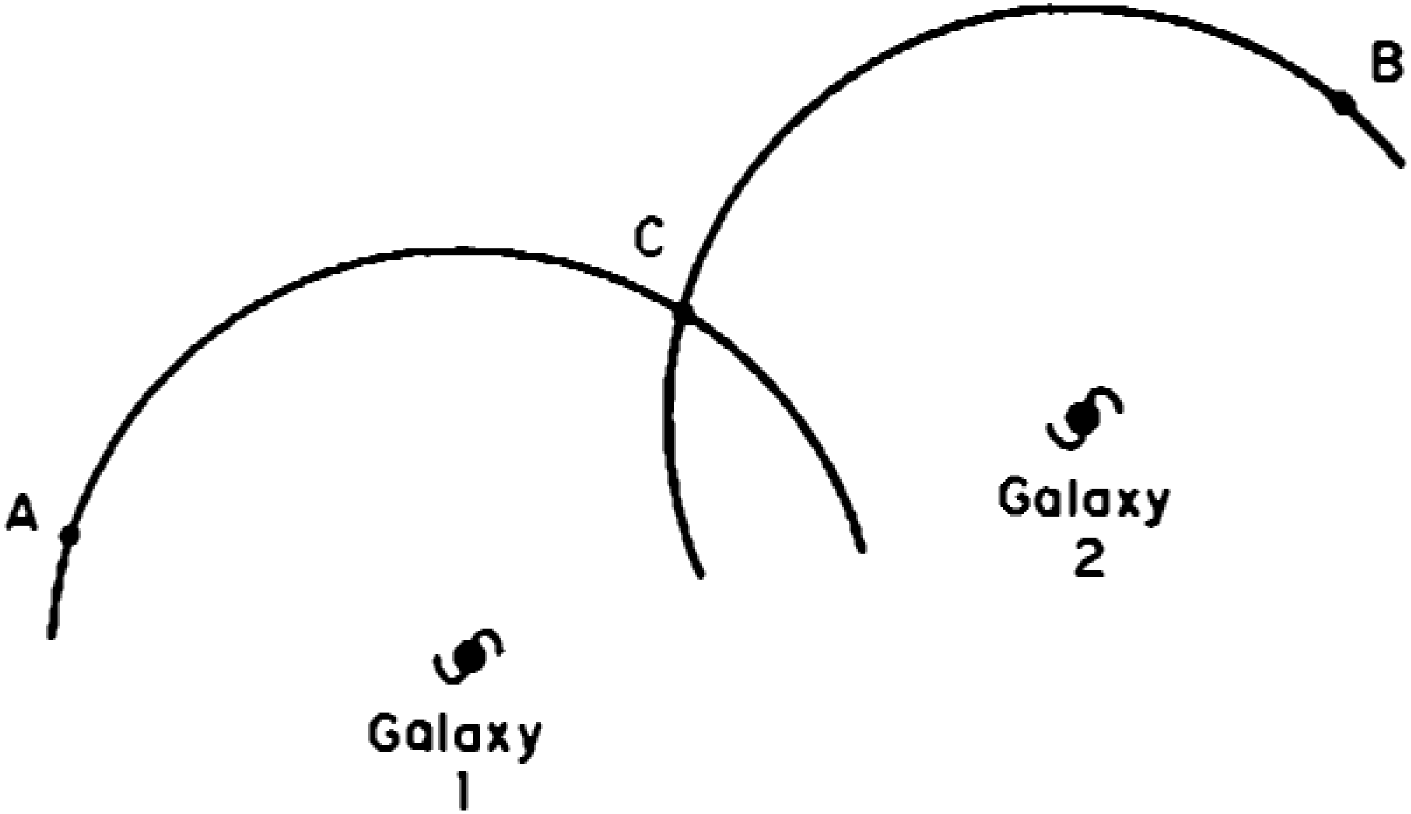
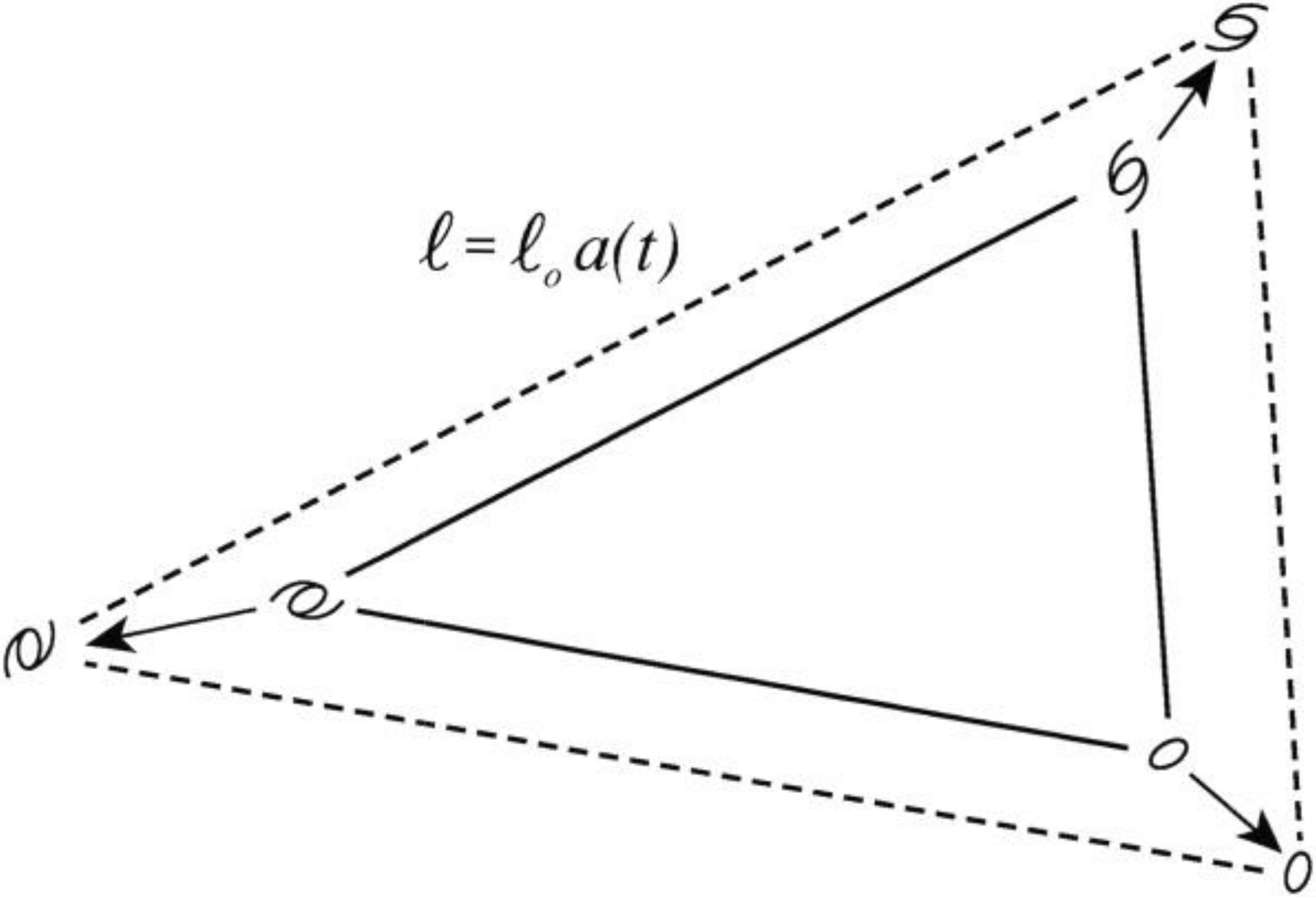


Figure 2. *Isotropy and Homogeneity.* If the universe is isotropic about both galaxy 1 and galaxy 2, then it is homogeneous. In order to show that conditions at two arbitrary points A and B are the same, draw a circle through A around galaxy 1, and another circle through B around galaxy 2. Isotropy around galaxy 1 requires that conditions are the same at A and at the point C where the circles intersect. Likewise, isotropy around galaxy 2 requires that conditions are the same at B and C. Hence they are the same at A and B.



$\ell = \ell_o a(t)$

Homogeneous and isotropic distribution of matter

$$\vec{r}(t) = R(t)\vec{r}_0$$

R(t) – scale factor

$$\frac{d}{dt}\vec{r}(t) = \frac{d}{dt}R(t)\vec{r}_0$$

$$\vec{v}(t) = \frac{\dot{R}(t)}{R(t)}\vec{r}(t)$$

The Hubble constant – $H(t) = \frac{\dot{R}(t)}{R(t)}$

$$\vec{v}(t) = H(t)\vec{r}(t)$$

How to determine $R(t)$?