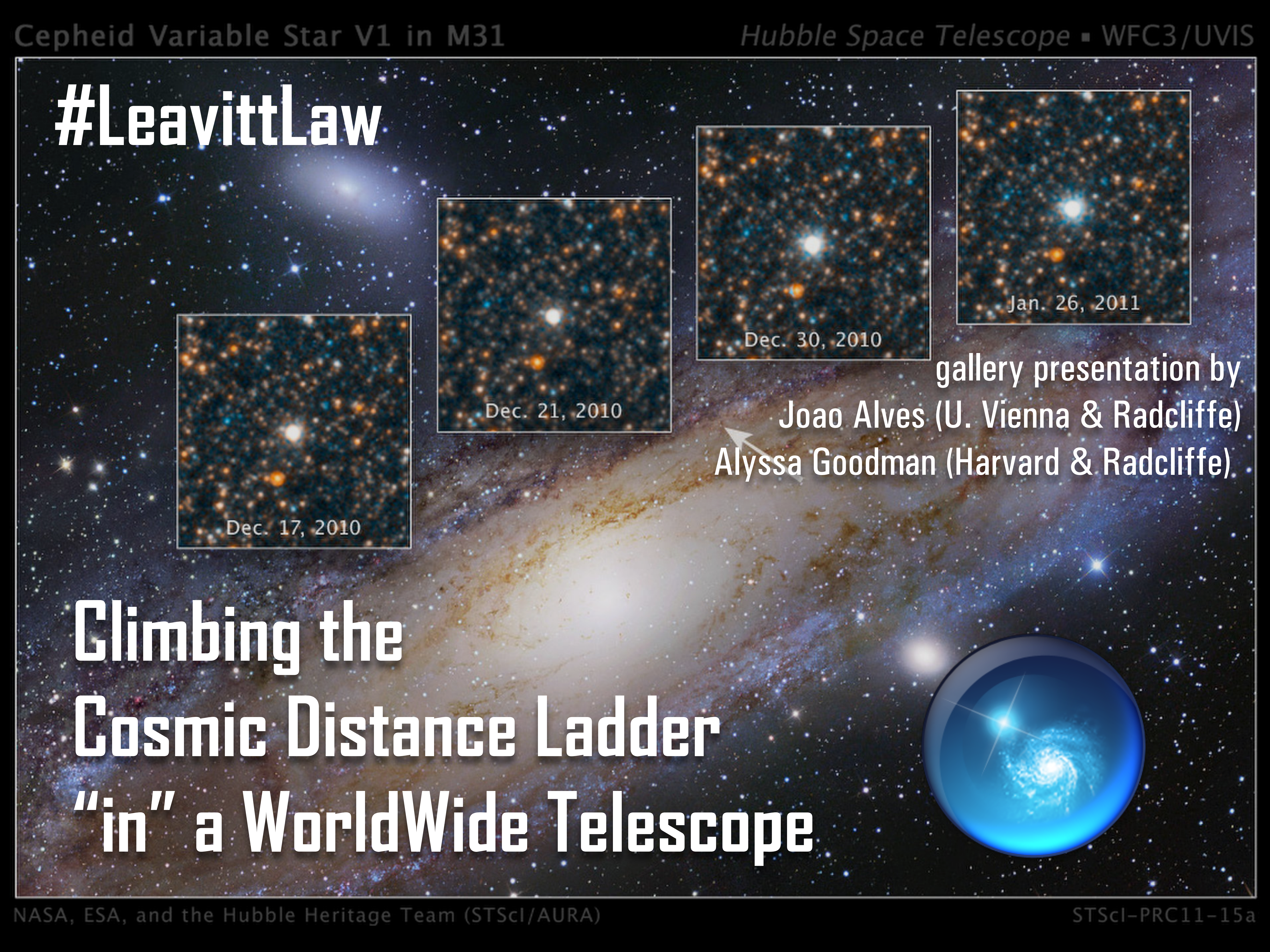
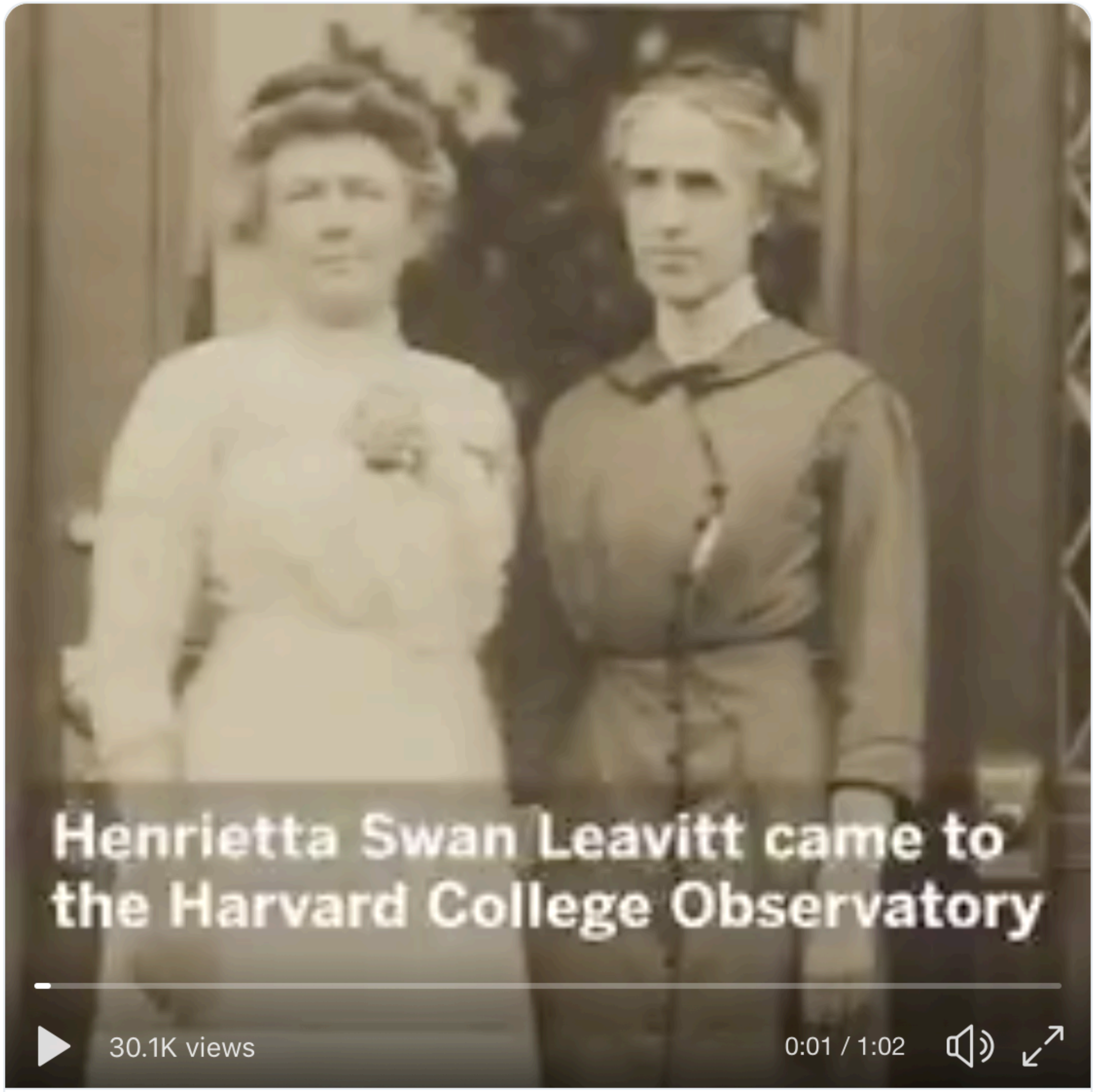

Cephheid Variable Star V1 in M31
Hubble Space Telescope ▪ WFC3/UVIS
#LeavittLaw
Dec. 17, 2010
Dec. 21, 2010
Dec. 30, 2010
Jan. 26, 2011
gallery presentation by
Joao Alves (U. Vienna & Radcliffe)
Alyssa Goodman (Harvard & Radcliffe)
Climbing the
Cosmic Distance Ladder
"in" a WorldWide Telescope
NASA, ESA, and the Hubble Heritage Team (STScI/AURA)
STScI-PRC11-15a

Harvard University
@Harvard

Following

Astronomer Henrietta Swan Leavitt died on this day in 1921. Her groundbreaking work at the Harvard Observatory helped establish some of our fundamental understandings of the universe.



Pioneering astronomer Henrietta Swan Leavitt
The story of the female “computers” at the Harvard Observatory.

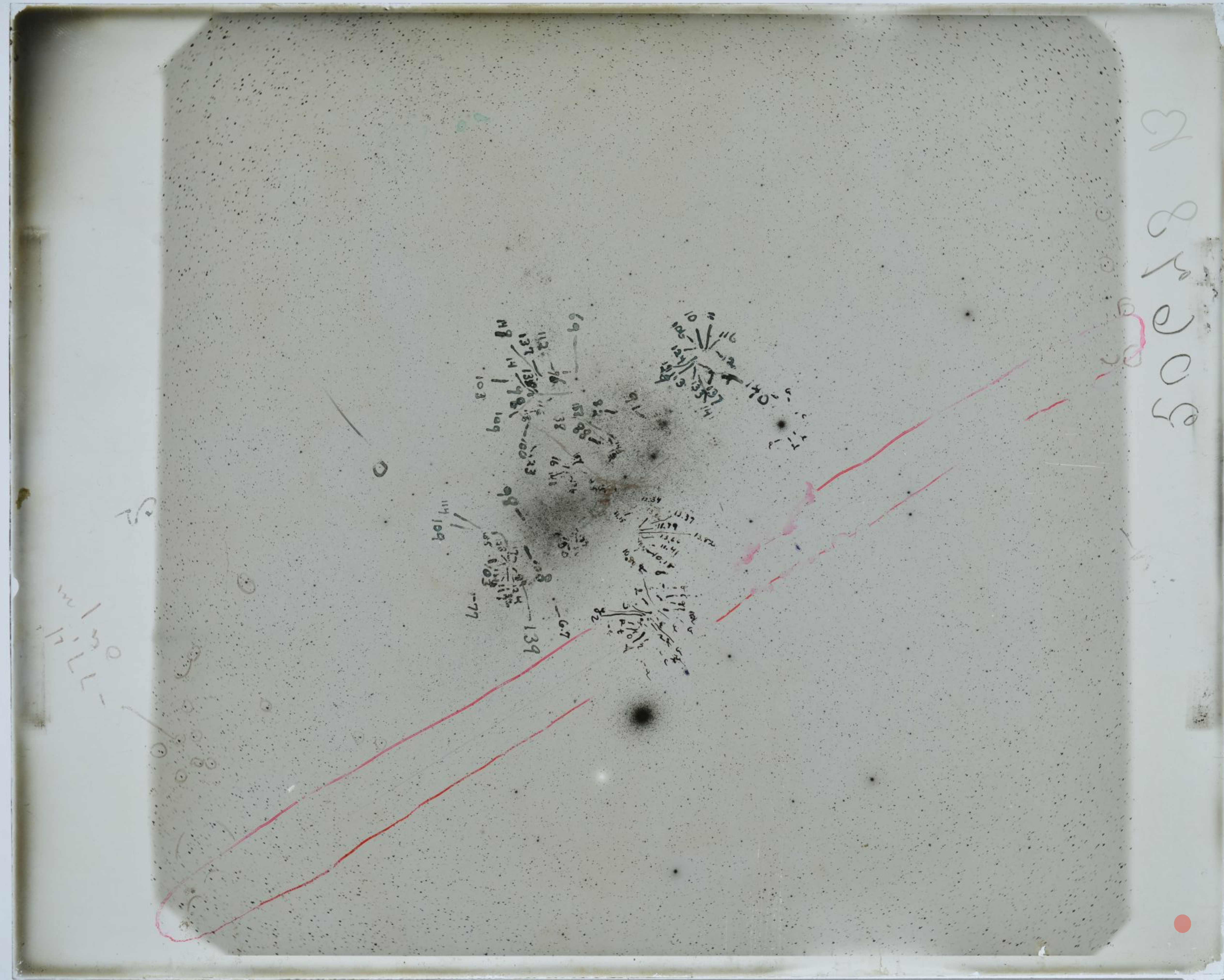
10:34 AM - 12 Dec 2017

#LeavittLaw

How Henrietta Leavitt's insight took the measure of the Universe

Alyssa Goodman
Radcliffe coDirector for Science
Professor, Harvard University
Research Associate, Smithsonian
@AlyssaAGoodman

João Alves
Radcliffe Fellow
Vice Dean & Professor
University of Vienna
@JoaoAlves



A sense of scale

(WorldWide Telescope tour)

1785

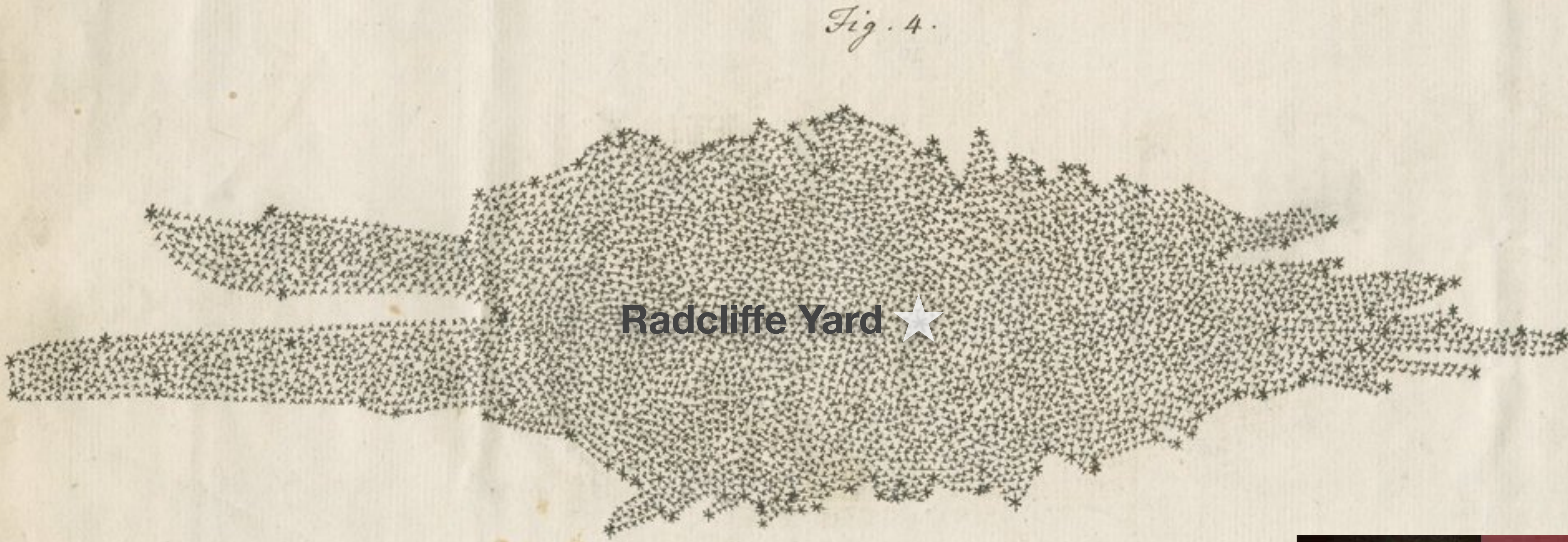
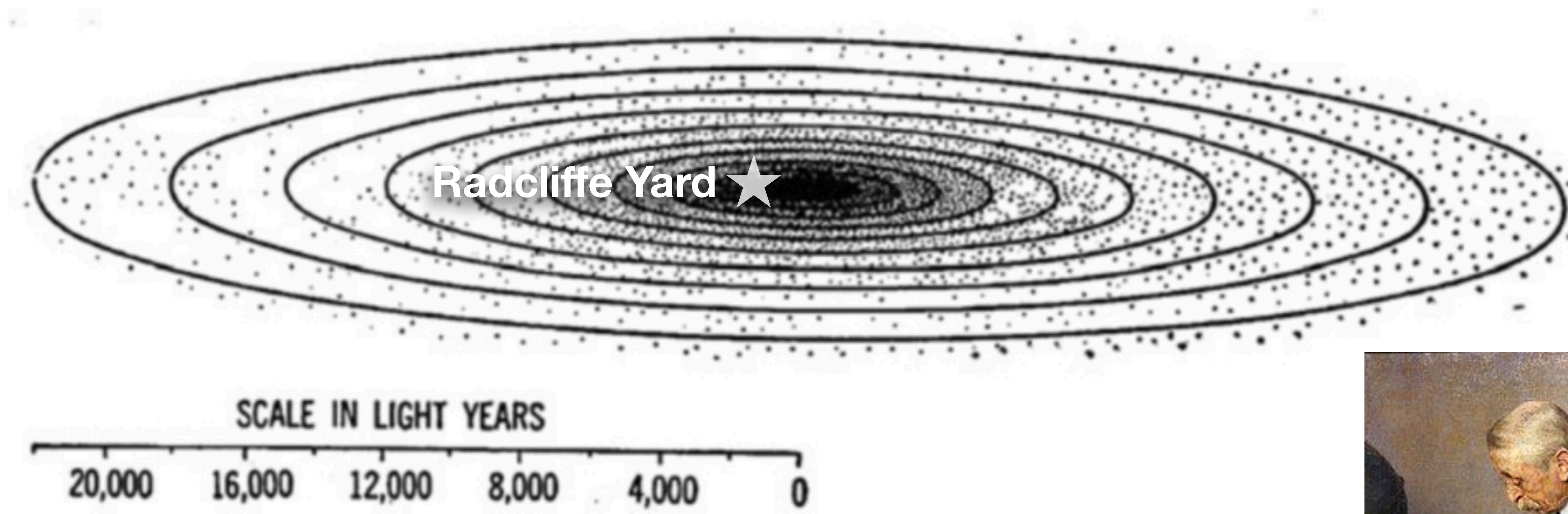


Plate 8 figure 4 from the paper "On the construction of the heavens", by William Herschel, Philosophical Transactions of the Royal Society, vol.75 (1785), pp.213-266.

"our nebula...is of the third form; that is: A very extensive, branching, compound Congeries of many millions of stars."

(assumes star evenly distributed in space)

1901-22



The Kapteyn Universe (Kapteyn Astronomical Institute)

(uses photographs to perform star counts, derives distances statistically, neglects dust extinction. Vertical structure of the Galaxy correct)

Henrietta Swan Leavitt 1868-1921

Radcliffe graduate

Orthochromatic AC 948 Aug 1, 1900
Just off edge

AC 3836 Aug 17, 1903
9.5 9.7

AC 1595 July 1, 1901.
exp. too short.

AM 1287 May 28, 1902
9.4 9.6

AM 1051. Sept 7, 1901
9.4 9.6

AM 1237 May 2, 1902
9.4 9.6

AM 1251 May 15, 1902
9.5 9.7

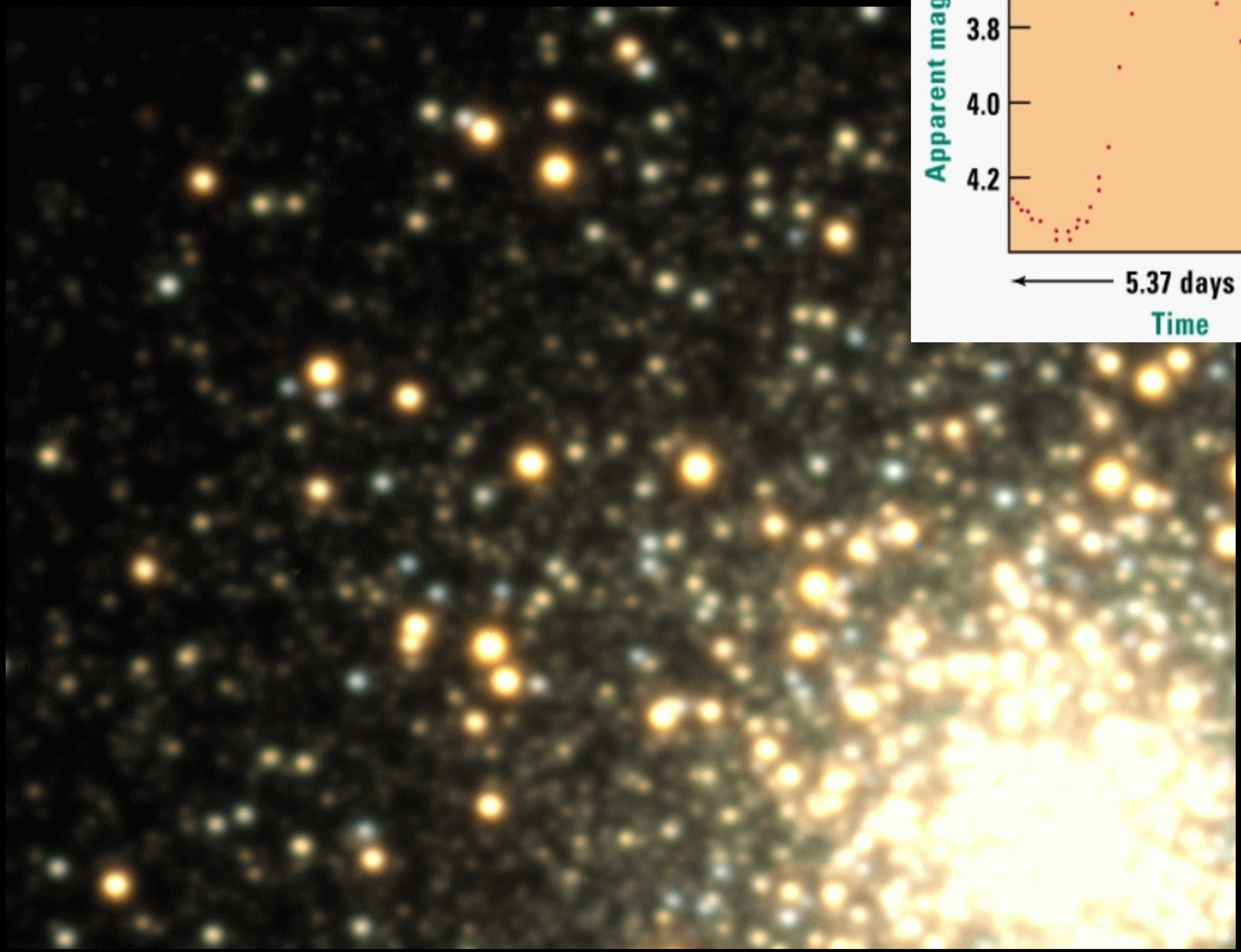
AM 1270 May 26, 1902.
9.4 9.6

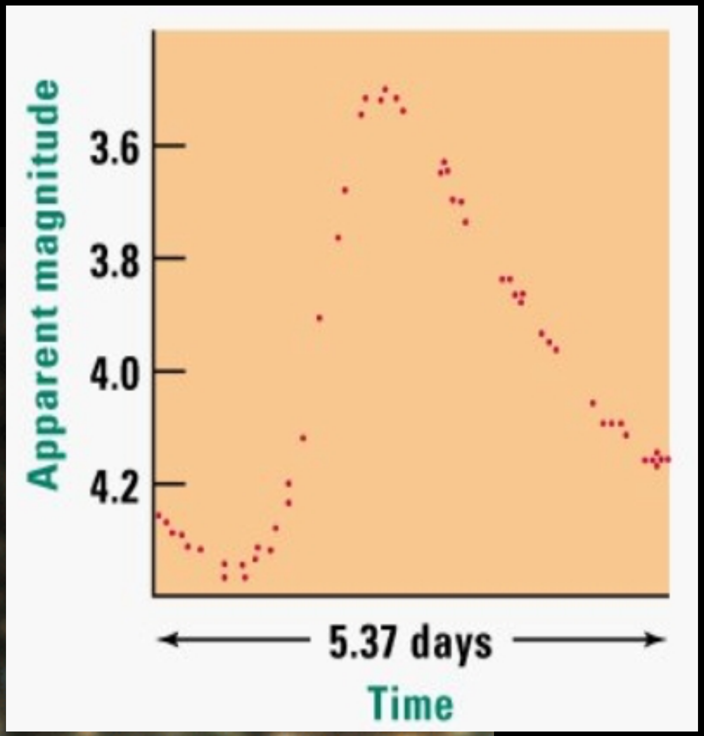
8265

The variables appear to fall into three or four distinct groups. The majority of the light curves have a striking resemblance, in form, to those of cluster variables. As a rule, they are faint during the greater part of the time, the maxima being very brief, while the increase of light usually does not occupy more than from one-sixth to one-tenth of the entire period. It is worthy of notice that in Table VI the brighter variables have the longer periods. It is also noticeable that those having the longest periods appear to be as regular in their variations as those which pass through their changes in a day or two. This is especially striking in the case of No. 821, which has a period of 127 days, as 89 observations with 45 returns of maximum give an average deviation from the light curve of only six hundredths of a magnitude. Six of the sixteen variables are brighter at maximum than the fourteenth magnitude, and have periods longer than eight days. It will be noticed that this proportion is much greater here than in Table II. The number which have been measured up to the present time is 59, and of these the brighter stars were first selected for discussion, as the material for them was more abundant. A few of the fainter variables, selected at random, were then studied, but no attempt has yet been made to determine periods for the remainder. While, therefore, the light curves thus far obtained have characteristics to which the majority of the variables will probably be found to conform, no inference can be drawn with regard to the prevalence of any particular type, until many more of the periods have been determined.

Leavitt 1908

Cepheid stars are variable.

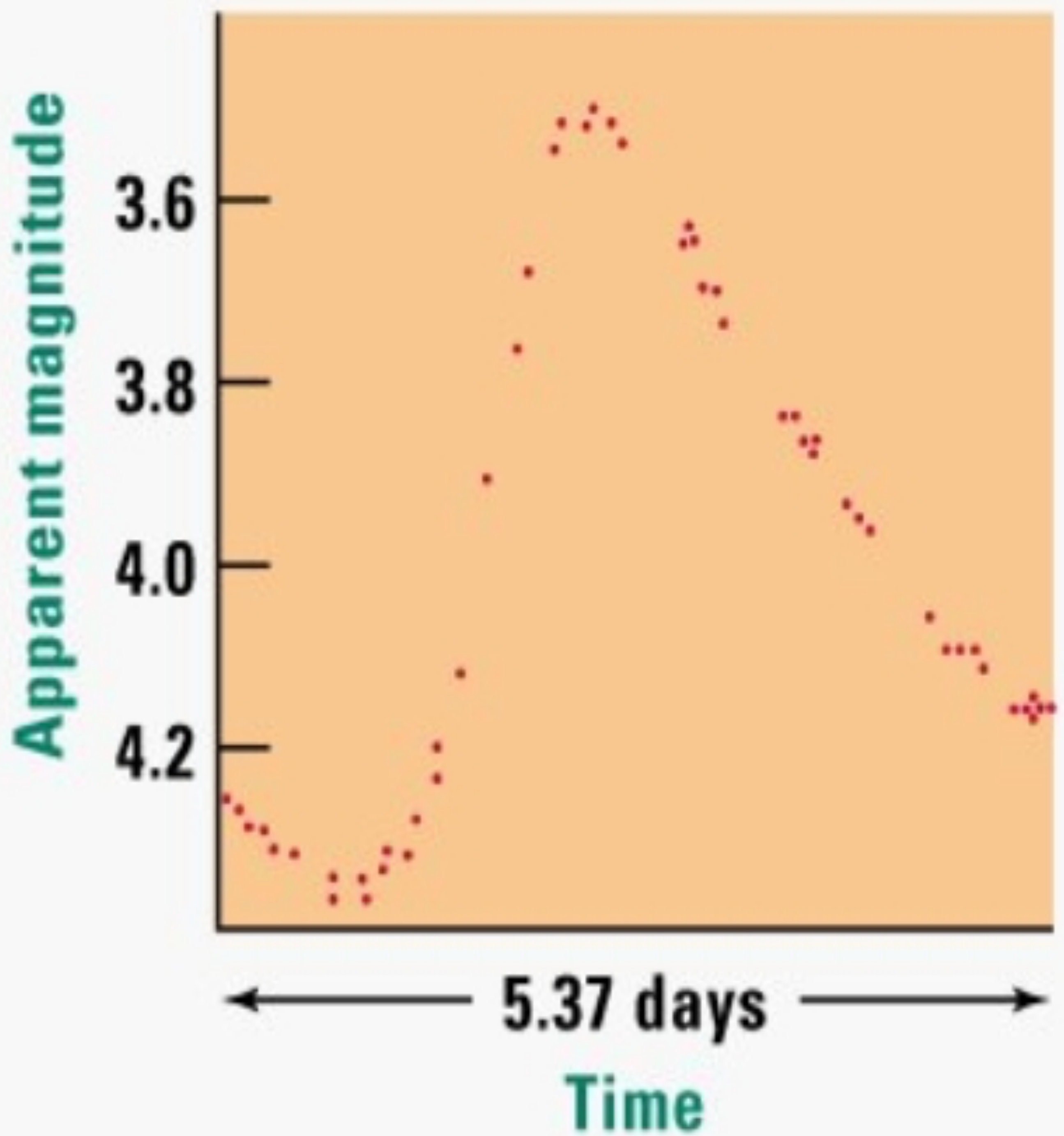




Cepheid stars are variable.

Light curve for one cycle of delta Cephi, a Cepheid variable

Cepheid stars are variable.



Cepheids pulsation period is related to their intrinsic brightness #LeavittLaw.

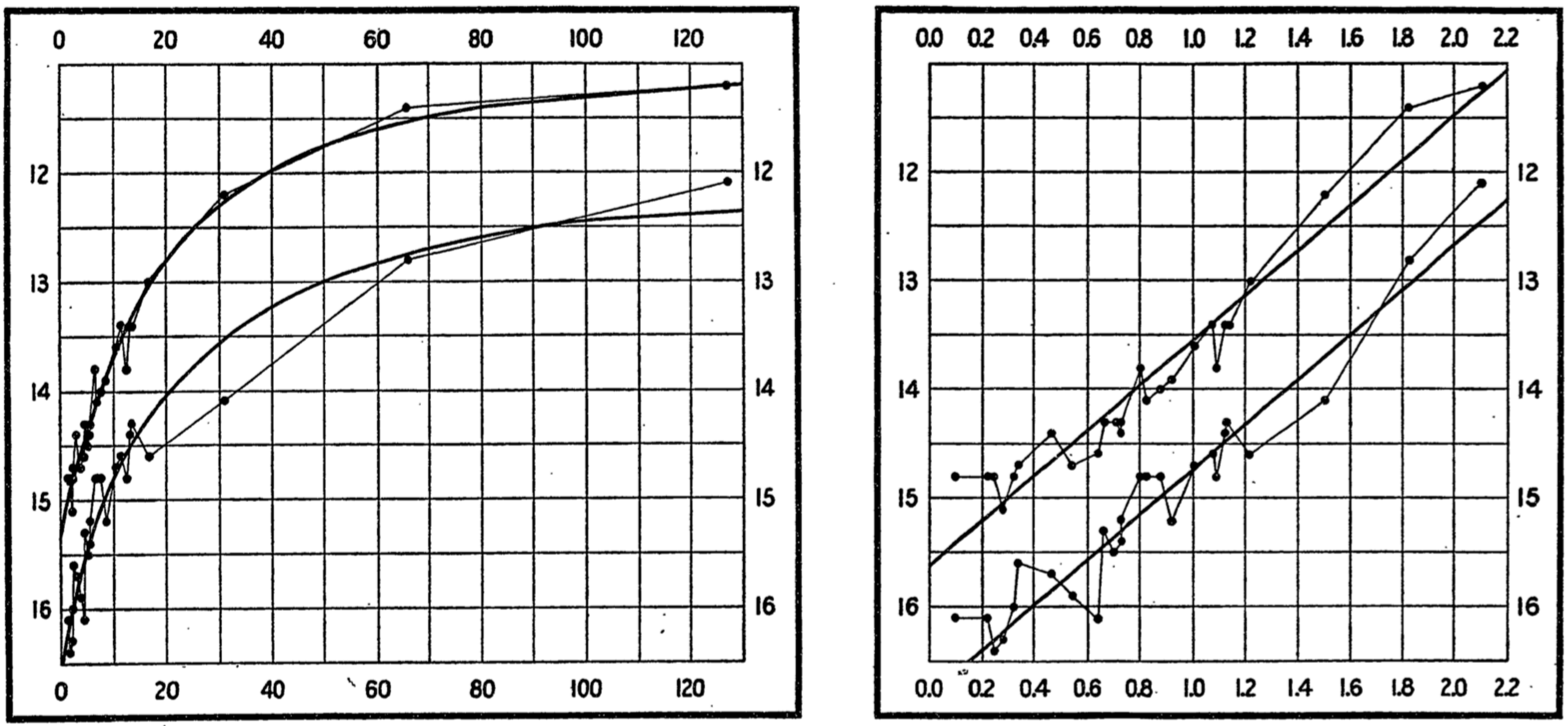
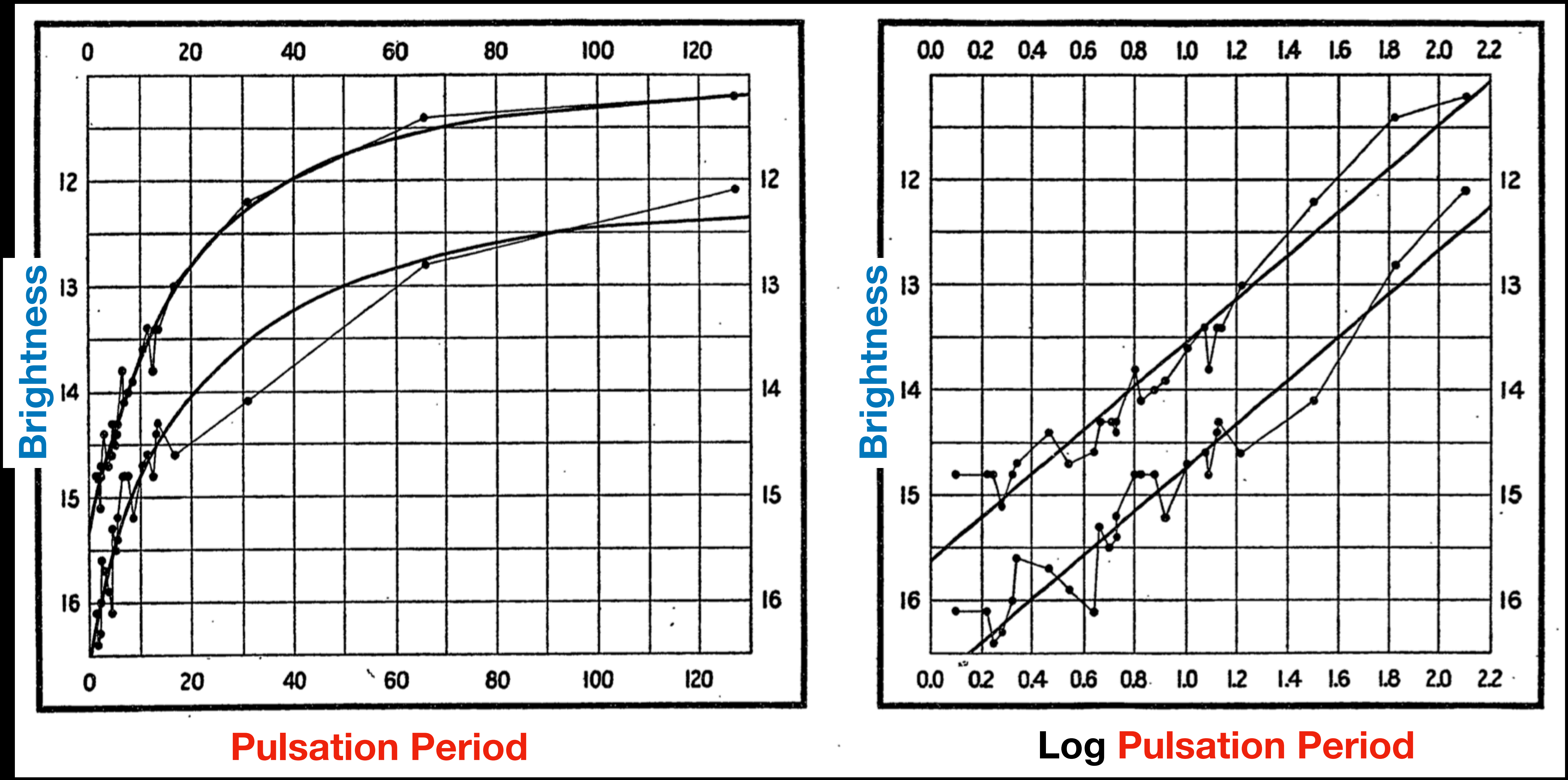


FIG. 1. FIG. 2.

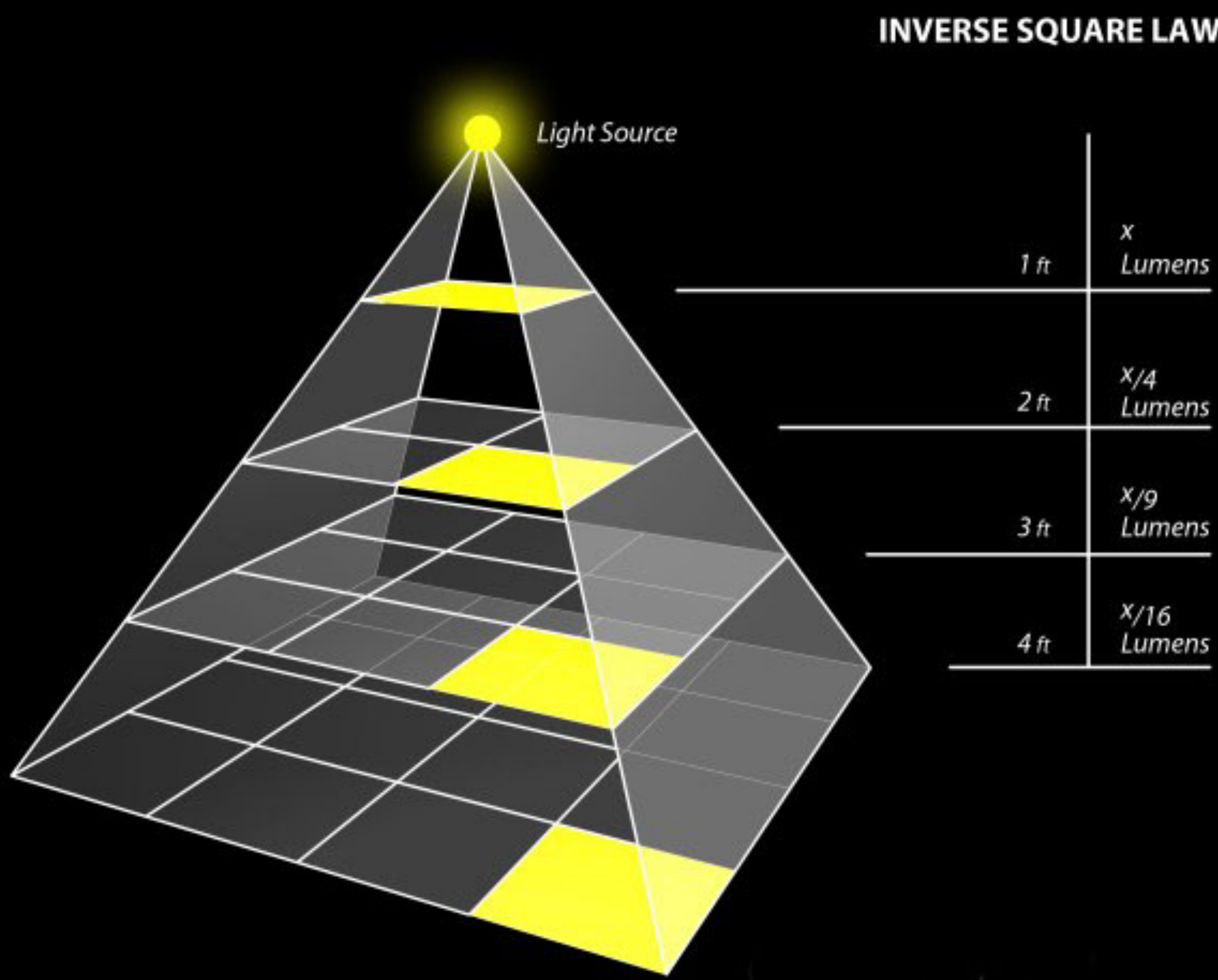
Leavitt & Pickering 1912

Cepheids pulsation period is related to their intrinsic brightness #LeavittLaw.



Leavitt & Pickering 1912

Comparing intrinsic brightness to apparent brightness gives distance, just like looking at a faraway light bulb.



ASTRONOMISCHE NACHRICHTEN.

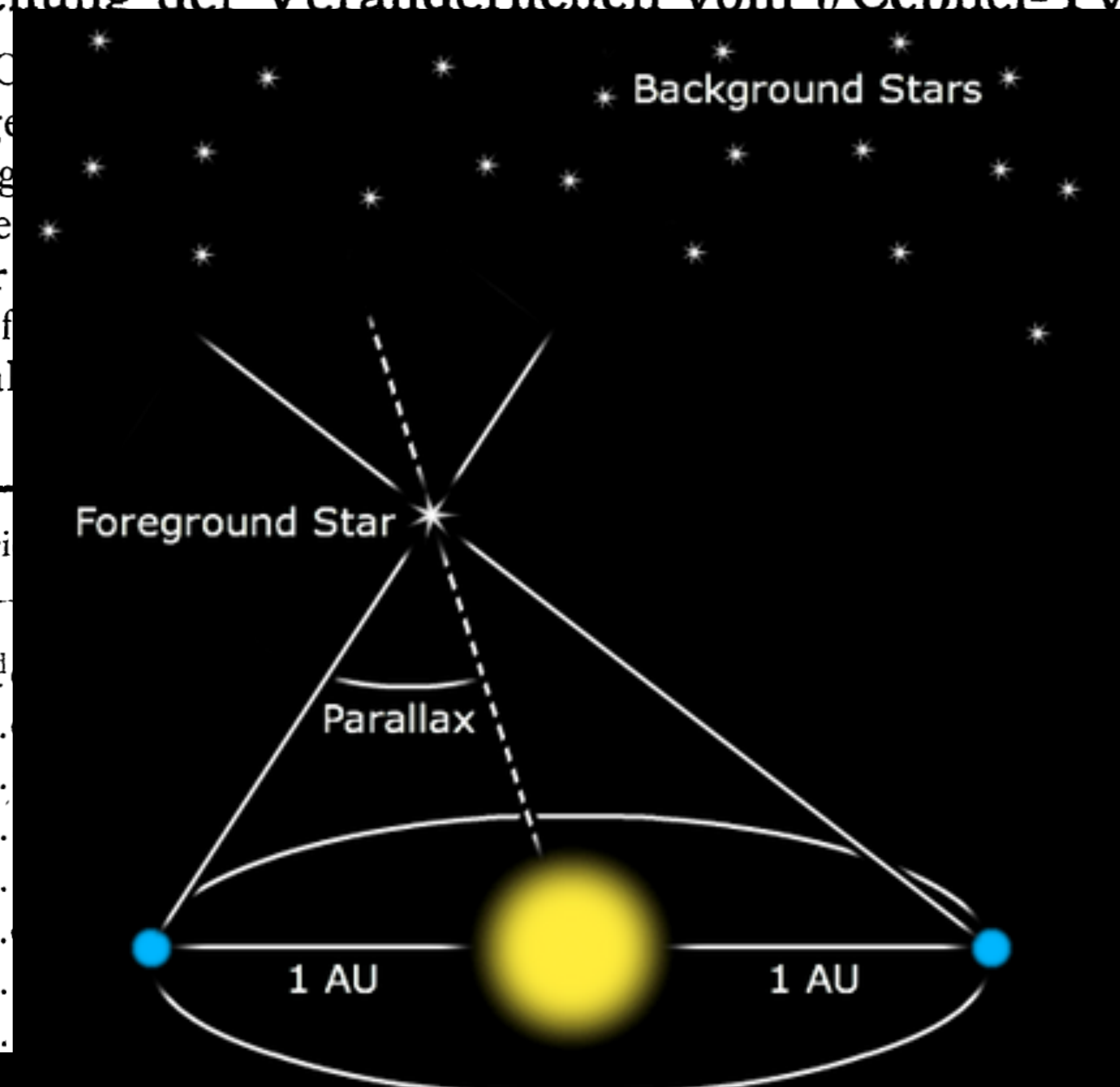
Band 196. Nr. 4692. 12.

Über die räumliche Verteilung der Veränderlichen vom δ Cephei-Typus. Von *E. Hertzsprung*.

Es ist bekannt, daß die δ C … 13 als δ Cephei-Veränderliche
durch sehr kleine Eigenbewegunge … dort gegebenen genauen Eigen-
aber merkliche Radialgeschwindig … e mittlere sekulare Parallaxe für
nicht mit unserer Sonne ein ge … t einer größeren Genauigkeit zu
Raum bewegtes System, vielmehr … nöglich war [2]). Diese 13 Sterne
diese Sterne durchgängig sehr entf … gestellt.

In dem »Preliminary General …

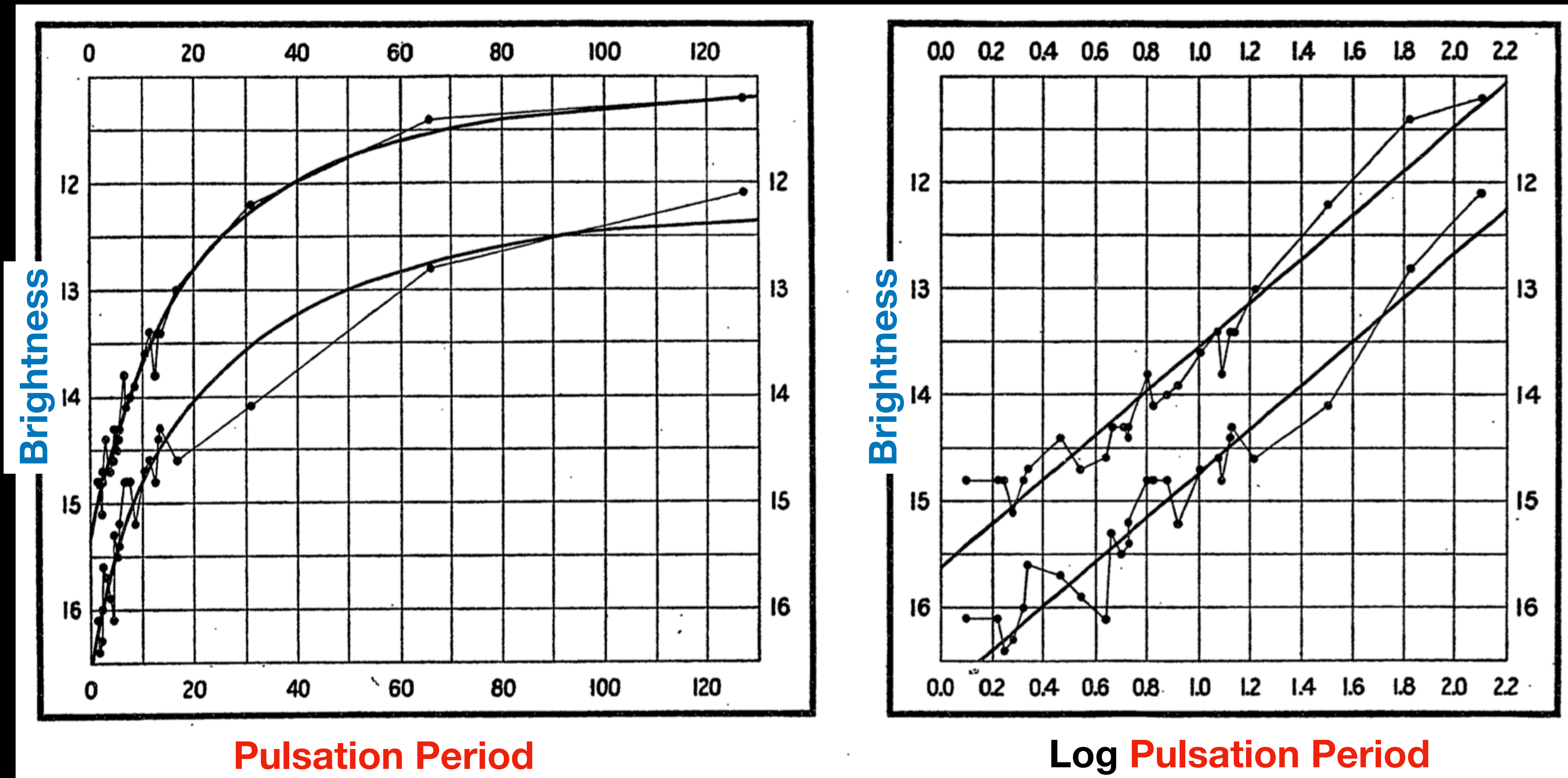
	Nr. Boss	Name	Peri…	$v_0 \sin\lambda$	(m. F.)^2 +.0076
				″/a	(″/a²)
F7	325	α Ursae min.	3.^{d}	+.09	.0076
F2-F9	637	SU Cassiop.	1.	+.24	.209
F1-G5	1629	RT Aurigae	3.	+.25	.127
cG~	1815	ζ Geminor.	10.	+. 5	.78
F8-K0	2628	l Carinae	35.	+.15	.103
F5-G9	4493	X Sagittarii	7.	+.17	.91
F2-G6	4564	W Sagittarii	7.	+.10	.110
F5-G8	4632	Y Sagittarii	5.	+.13	.480



Hertzsprung 1913

Once a cepheid's distance is be known by TWO methods (e.g. parallax and intrinsic-apparent brightness comparison), a "ladder" is established, where Cepheids can give distance *just* from #LeavittLaw (period→distance).

Cepheids pulsation period is related to their intrinsic brightness #LeavittLaw.



Measuring periods accurately is much easier than measuring brightness accurately.

For those who like words...

Cepheid stars are variable.

Cepheids pulsation period is related to their intrinsic brightness #LeavittLaw.

Comparing intrinsic brightness to apparent brightness gives distance, just like looking at a faraway light bulb.

Once a cepheid's distance is be known by TWO methods (e.g. parallax and intrinsic-apparent brightness comparison), a "ladder" is established, where Cepheids can give distance *just* from #LeavittLaw (period→distance).

Measuring periods accurately is much easier than measuring brightness accurately.

Distances for the MOST distant Cepheids (in other galaxies) are tied to another method (e.g. redshifts + #HubbleLaw), to add more rungs to the ladder.

What happened?

590 16 Finale

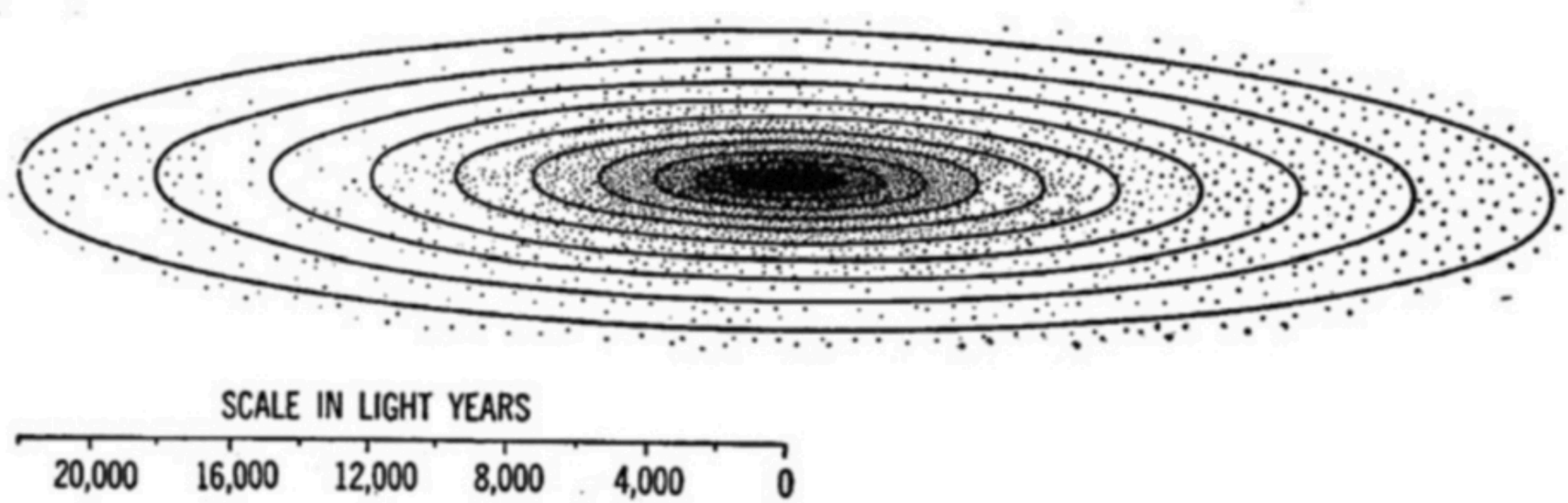


Fig. 16.8 The Kapteyn Universe (Kapteyn Astronomical Institute)

Shapley 1918

Figure from de Sitter's book 'Kosmos', published in 1934 and credited to Jan H. Oort (see P. van der Kruit book on Kapteyn).

From National Academy of Sciences,
Smithsonian Institution, Washington, D. C.
(Carl H. Butman, Representative).

For Release to Afternoon Papers,
Monday, April 26

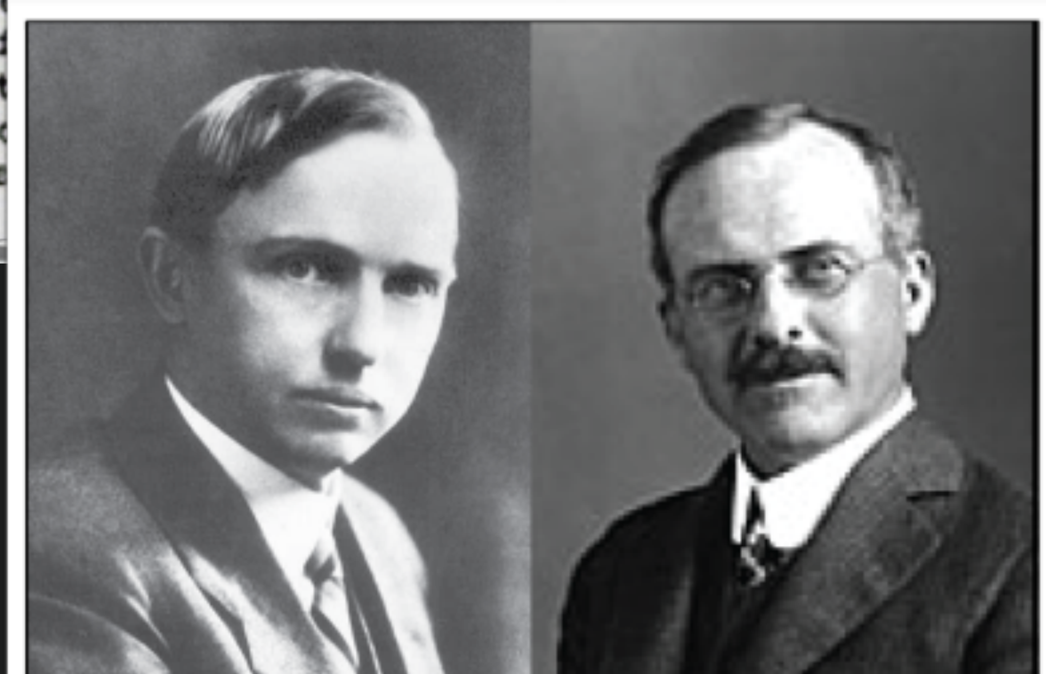
For Files

HOW MANY UNIVERSES ARE THERE?

This evening two California astronomers will discuss the Size of the Universe, and present their views as to whether or not there is only one or several universes, before the National Academy of Sciences, which is now in session in Washington.

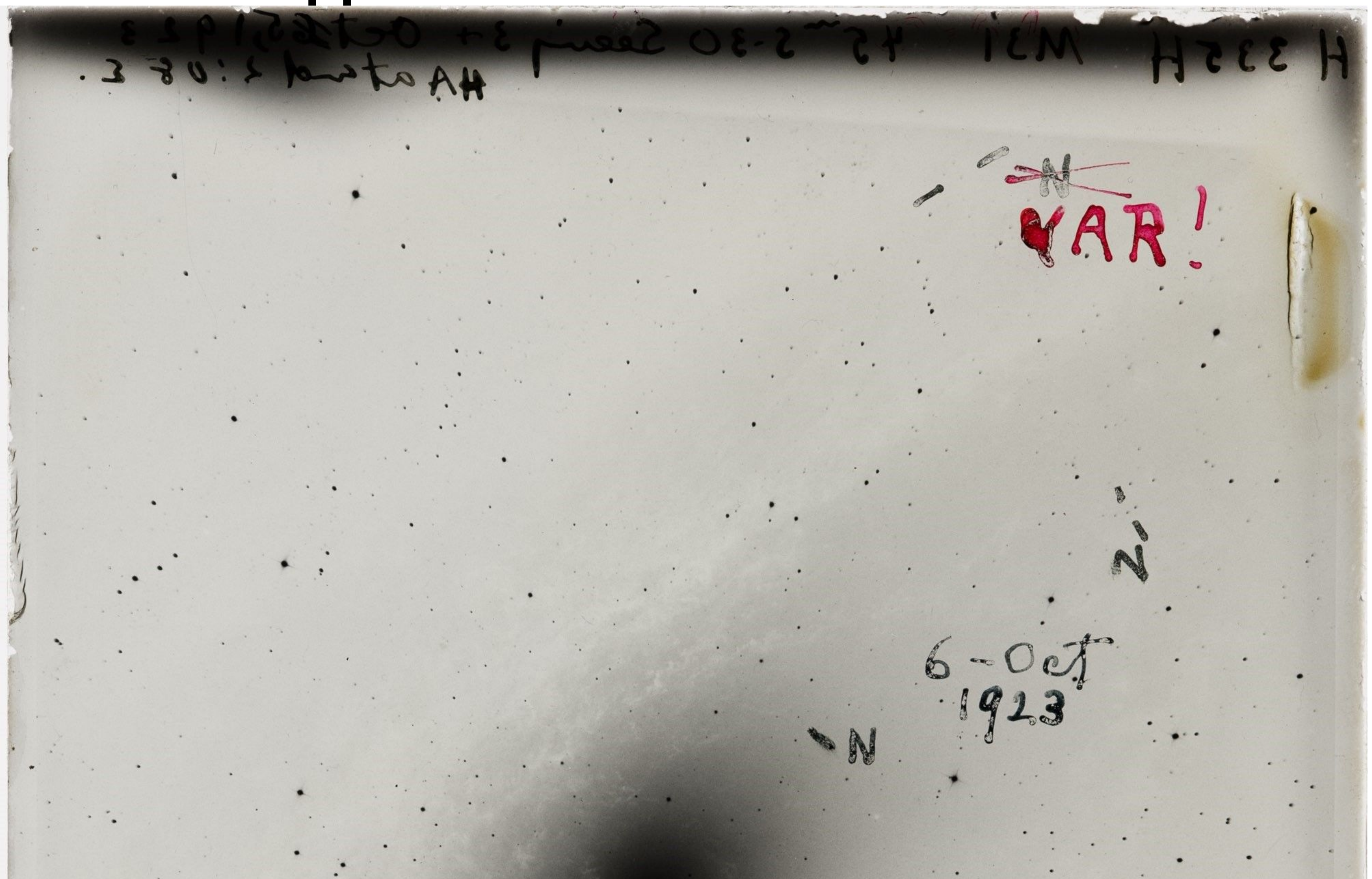
In this public meeting, Dr. Harlow Shapley of the Mt. Wilson Solar Observatory, will discuss recently secured evidence pointing to the dimensions of our galaxy of stars, known popularly as the Milky Way, which he believes to be ten times greater than is held in the older theories concerning the dimensions and compositions of the Milky Way. In other words, he claims that it takes light about three hundred thousands of years to cross from one side to the other of the space occupied by the 3,000,000,000 stars of which our sun is the nearest one. He holds the spiral nebulae, those clam-shell-like cloudy luminous objects seen by great telescopes, to be inside our system.

Doctor Shapley's views will be followed by the discussion of Doctor Heber D. Curtis of the Lick Observatory, who will defend the older view that our Milky Way is approximately of the dimensions suggested by Newcomb, about 30,000 light-years in diameter, with the spiral nebulae regarded as very probably individual galaxies of "island universes", like ours. Thus there may be a million other universes each having 3,000,000,000 stars. Inhabitants of numerous universes would see our Milky Way as a spiral nebula. The lect these two learned astronomers will be followed by a general discussion the auditors present who are interested in the development of this new in scientific research.

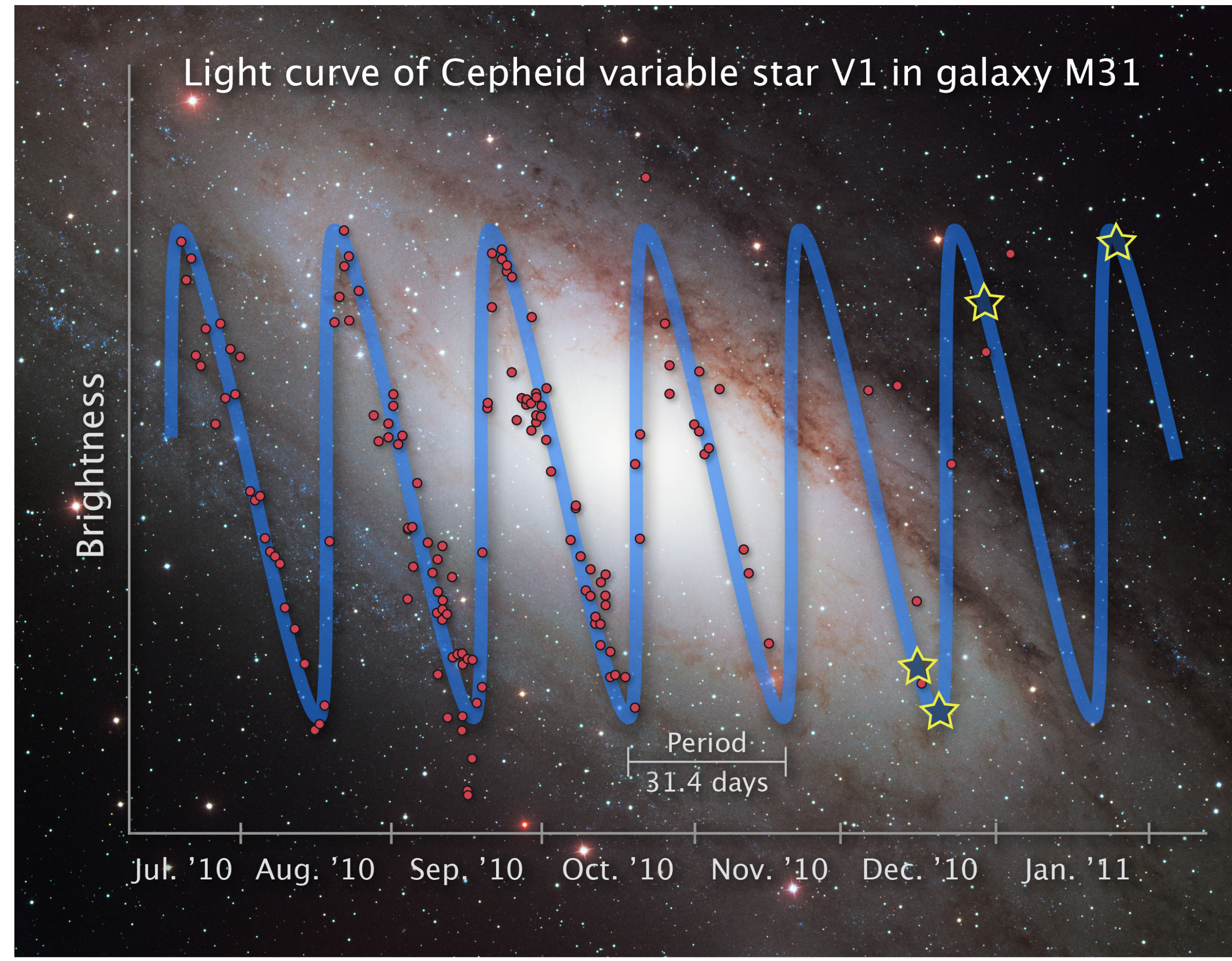


The Shapley-Curtis Debate at the Smithsonian Natural History Museum, 1920

What happened?

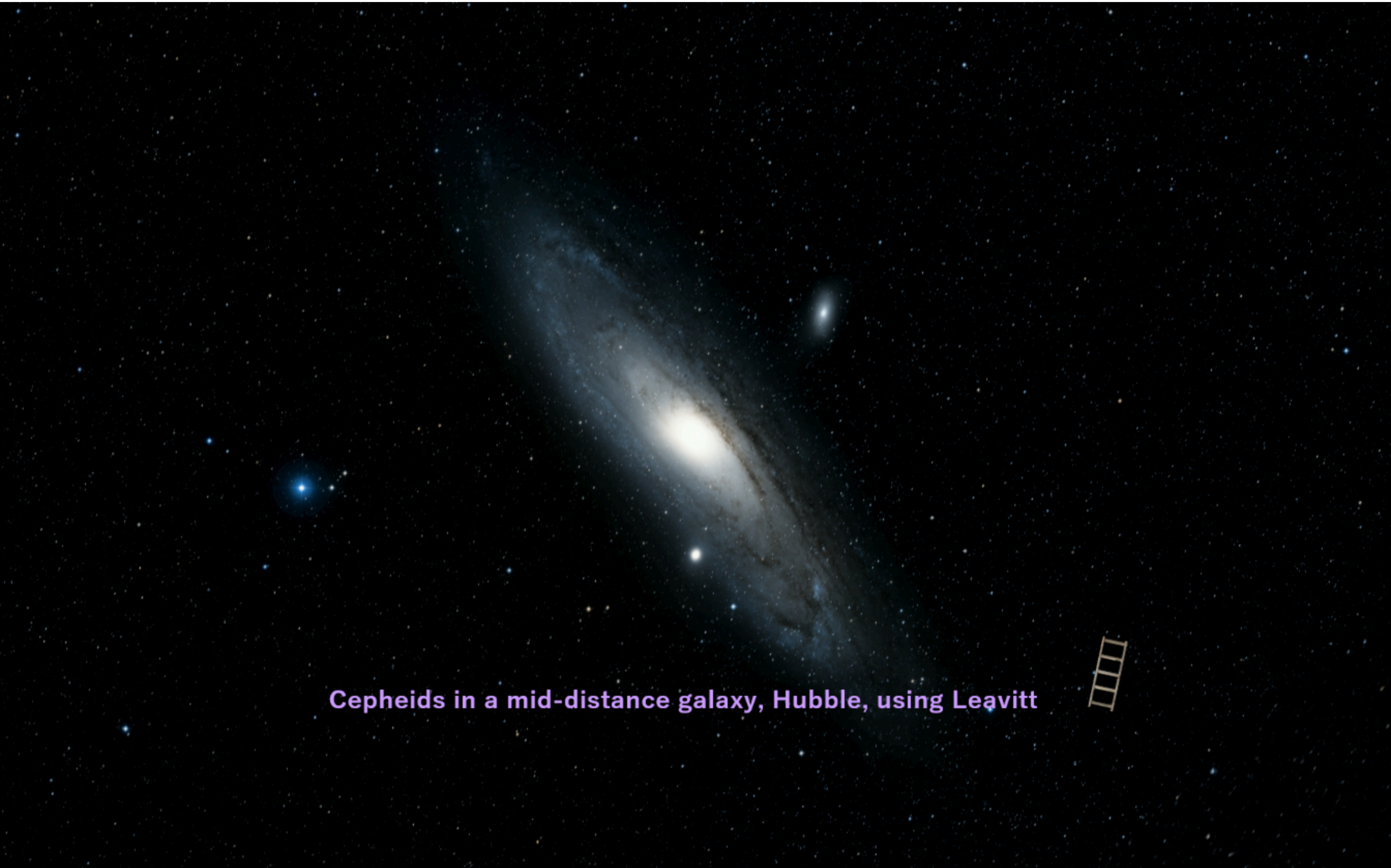


What happened?



Hubble 1925

What happened?



Distances for the MOST distant Cepheids (in other galaxies) are tied to another method (e.g. redshifts + #HubbleLaw), to add more rungs to the ladder.

faraway galaxies using redshift (Hubble 1929)

Cepheids in mid-distance galaxies (Hubble 1925, using Leavitt)

Cepheids in nearby galaxies (Leavitt 1908, 1912)

Milky Way Cepheids nearby (statistical parallax, Hertzsprung 1913)

Sun (geometry)

faraway galaxies using redshift (Hubble)

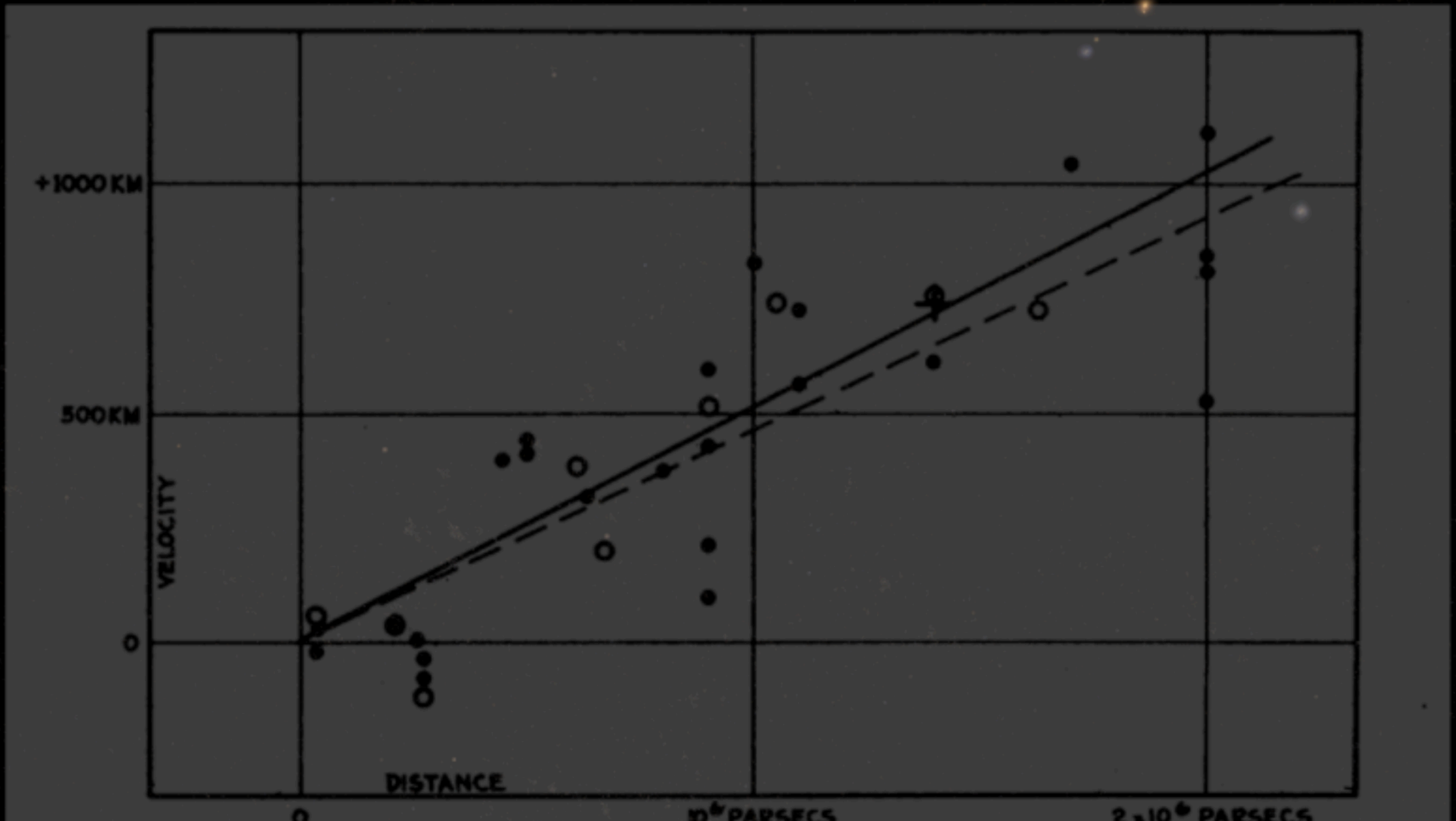
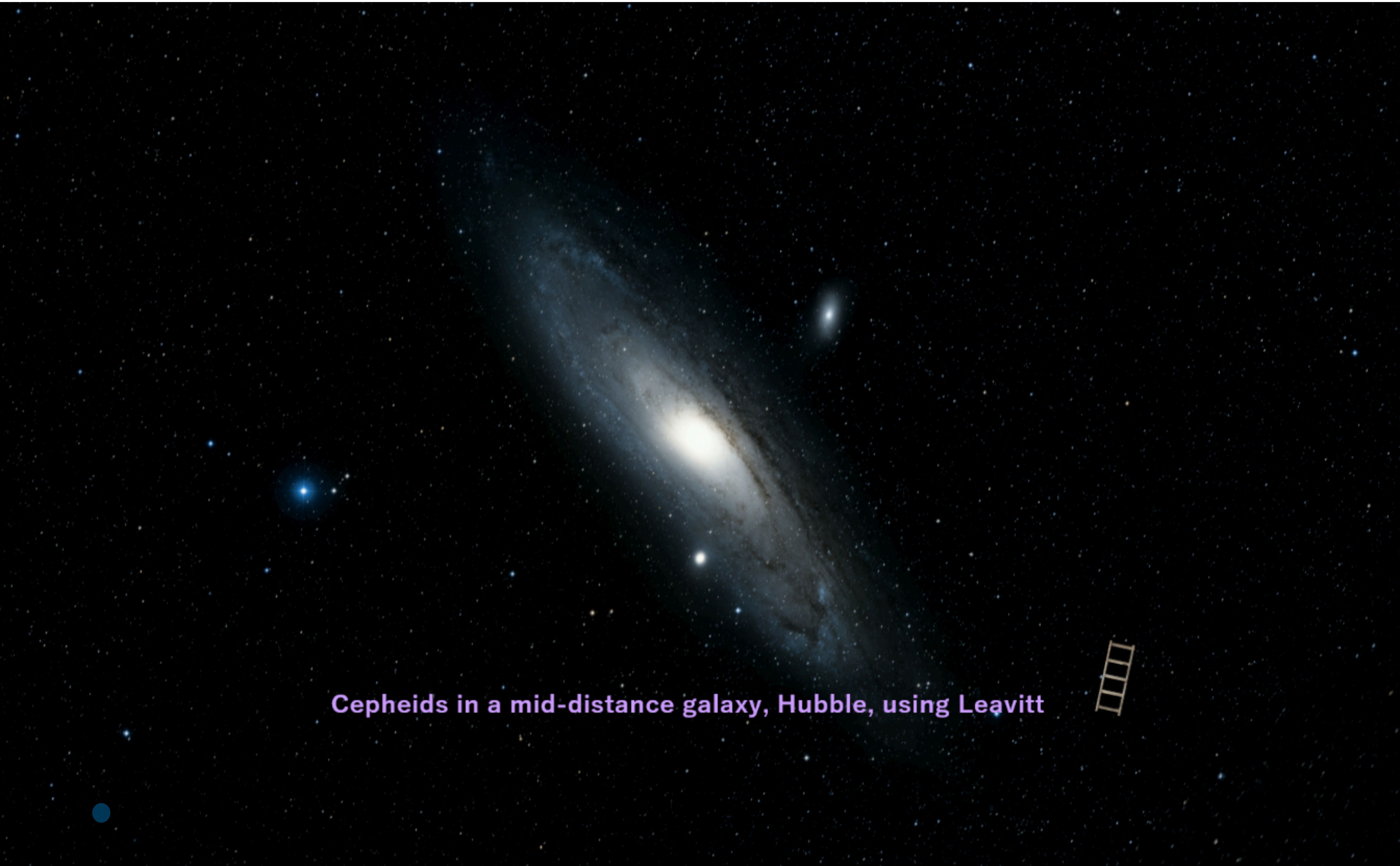


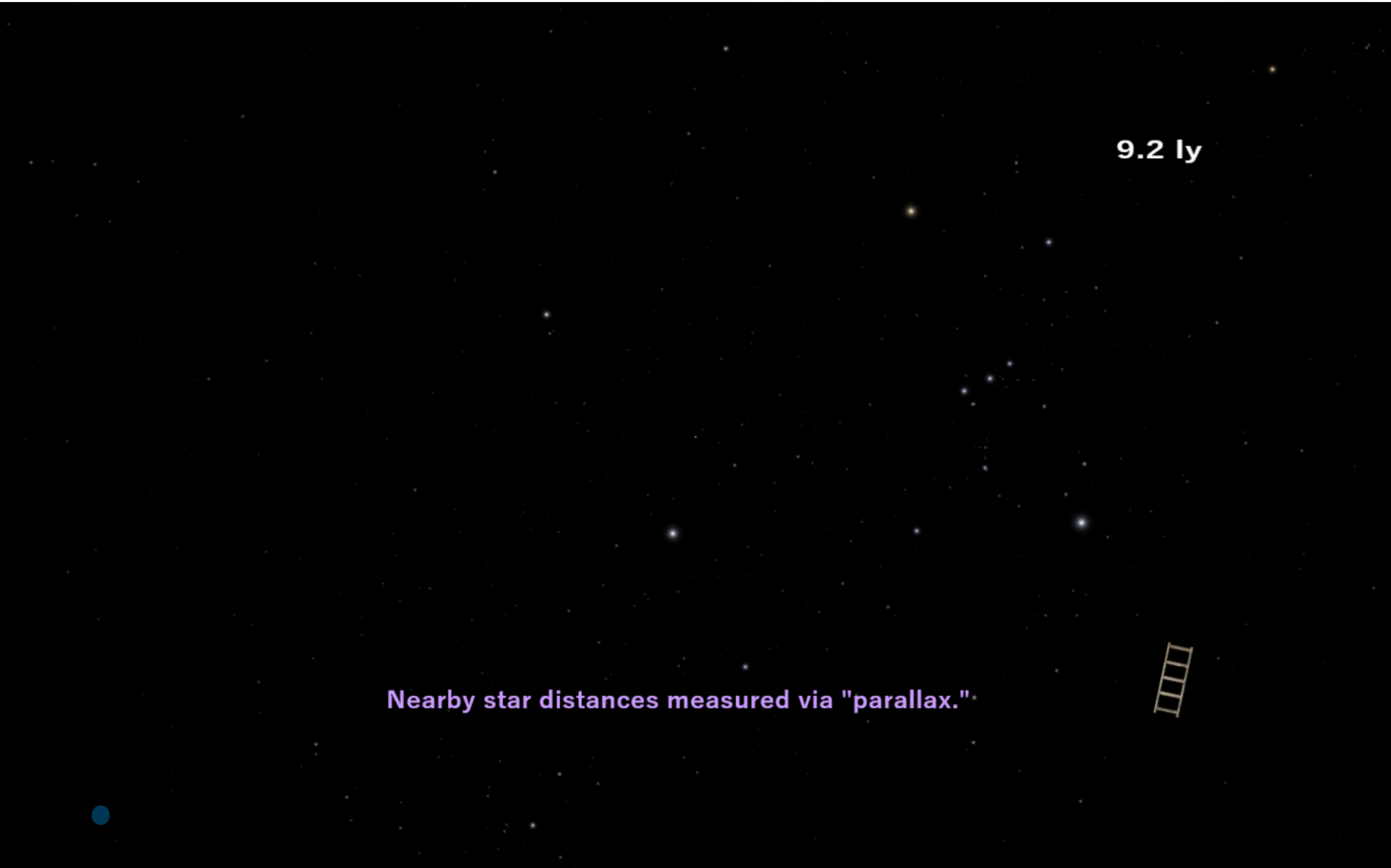
FIGURE 1
Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble Law (redshift)distances to faraway galaxies

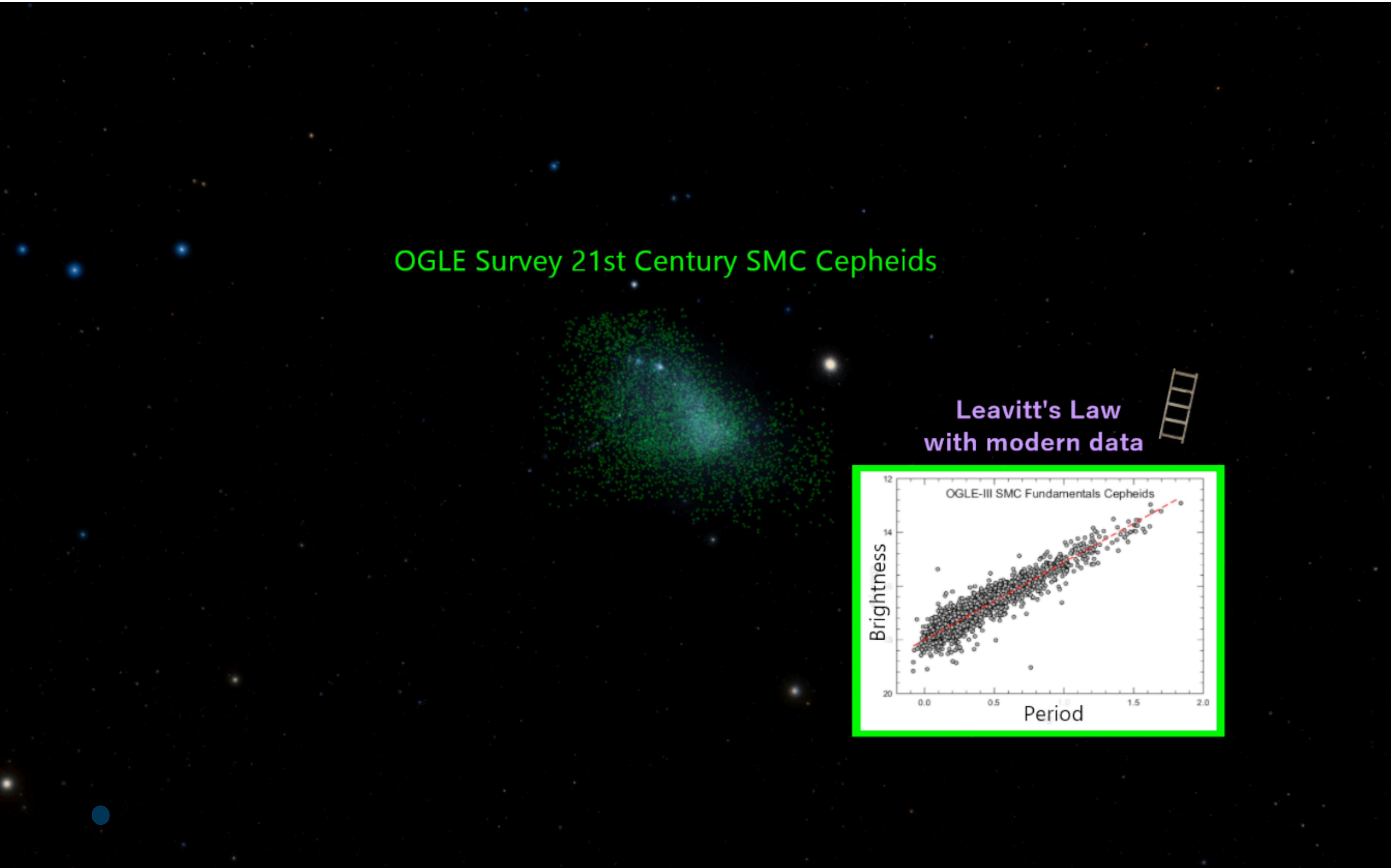
Cepheids in mid-distance galaxies (Hubble, using Leavitt)



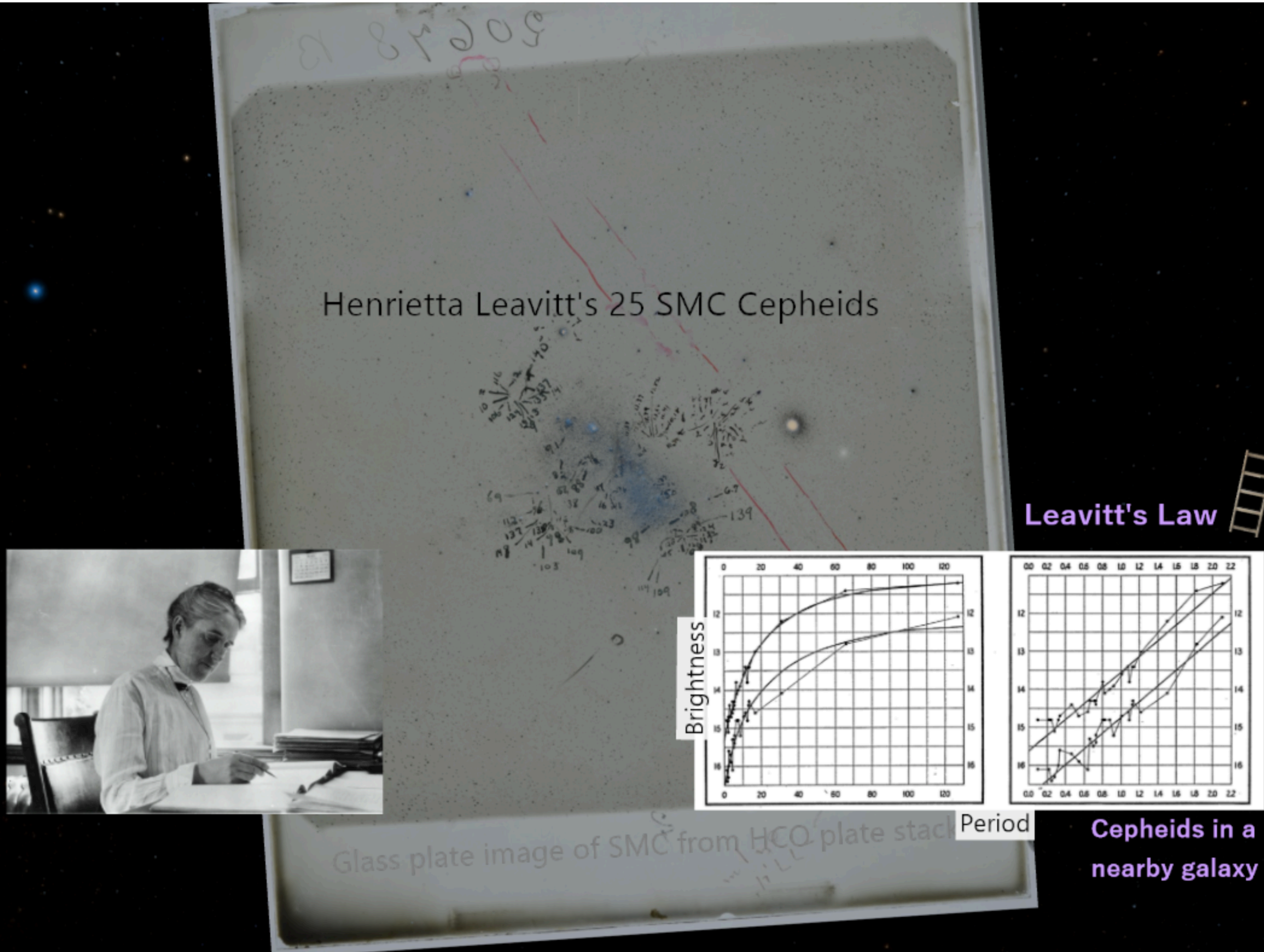
Milky Way Cepheids nearby (parallax, Hertzsprung)



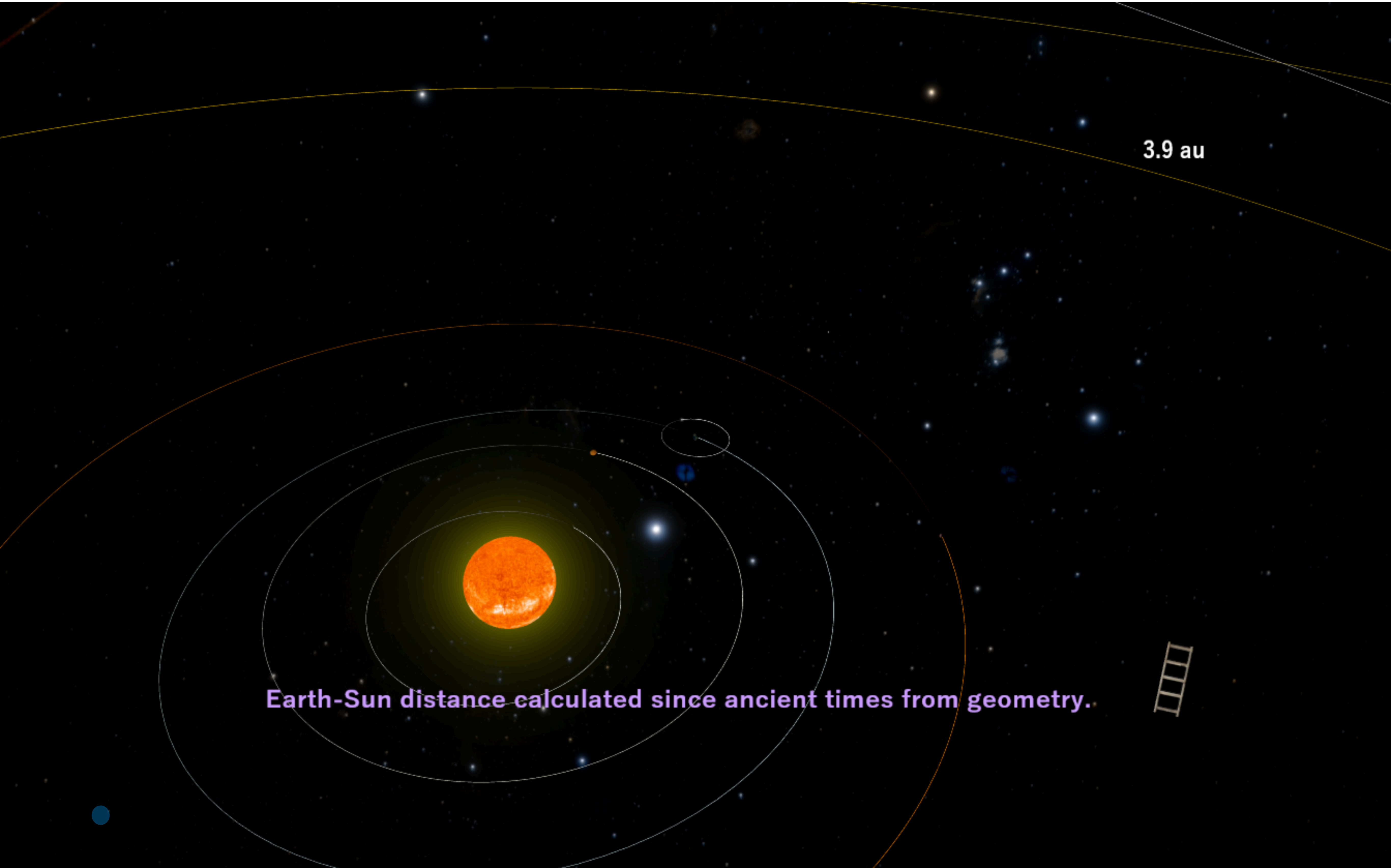
Cepheids in nearby galaxies (Leavitt)



Cepheids in nearby galaxies (Leavitt)



Sun (geometry)



The "Simple" Cosmic Distance Ladder

faraway galaxies using redshift (Hubble 1929)

Cepheids in mid-distance galaxies (Hubble 1925, using Leavitt)

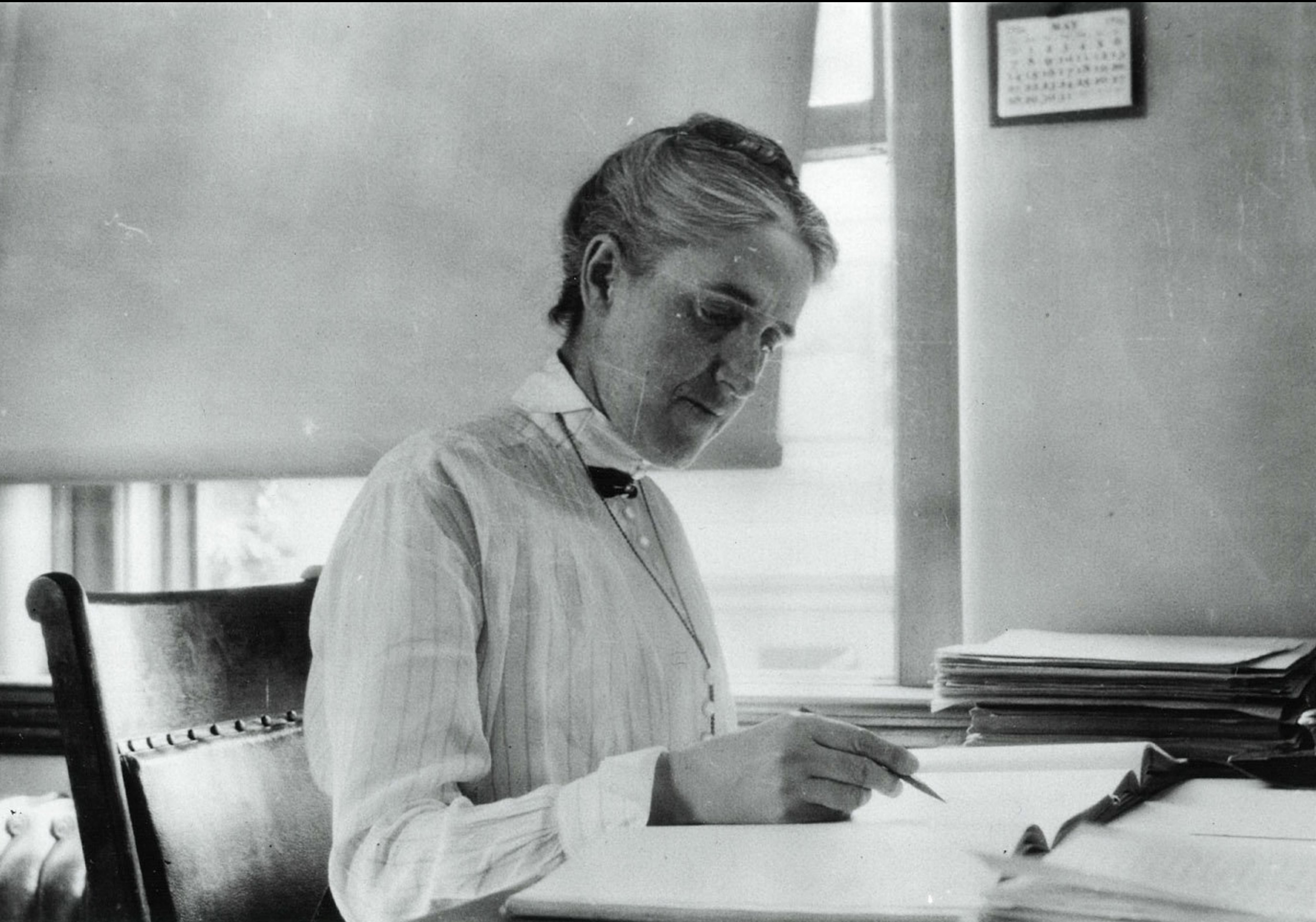
Cepheids in nearby galaxies (Leavitt 1908, 1912)

Milky Way Cepheids nearby (statistical parallax, Hertzsprung 1913)

Sun (geometry)

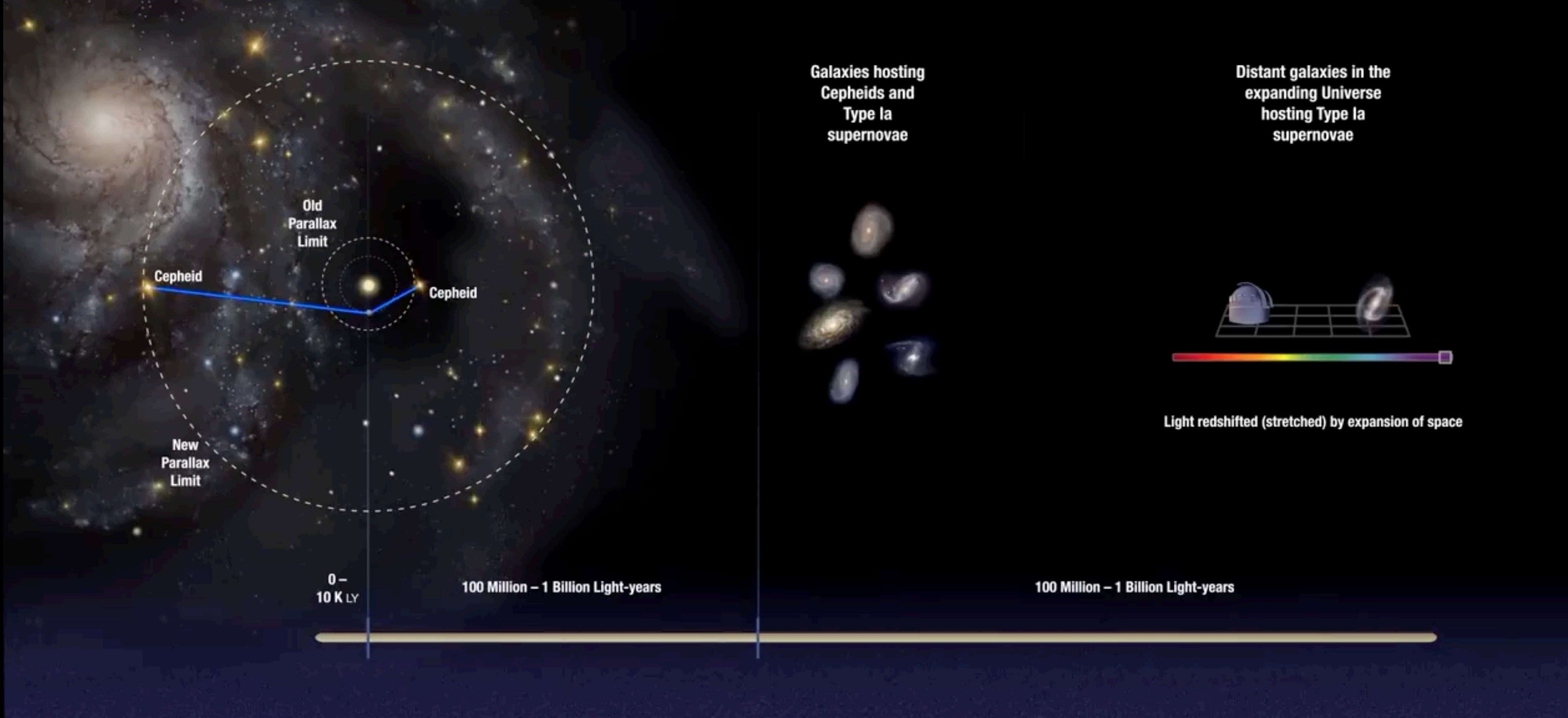
A sense of scale

(WorldWide Telescope tour)

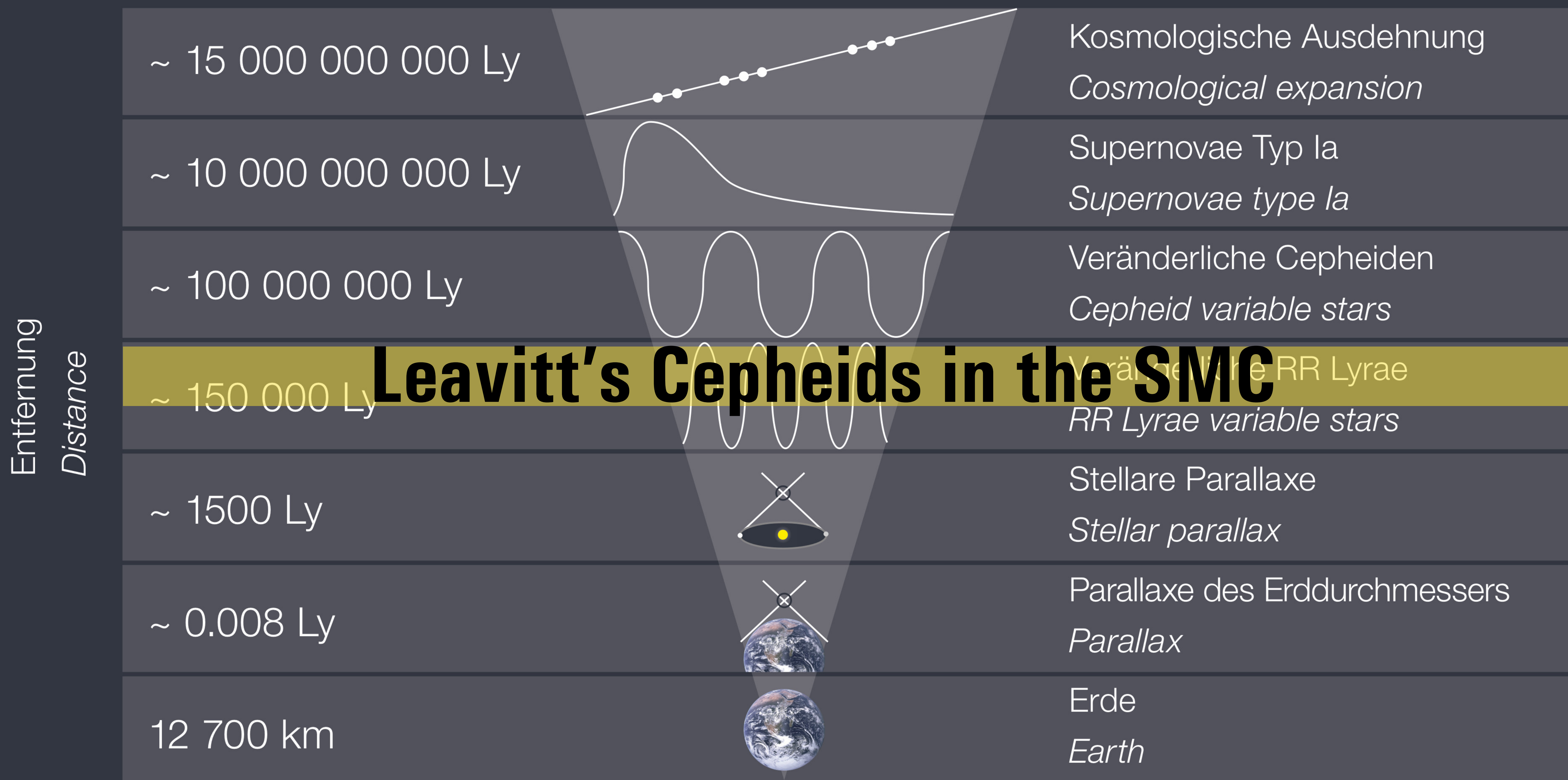

MAY

extra slides (not shown)

Three Steps to Measuring the Expansion Rate of the Universe



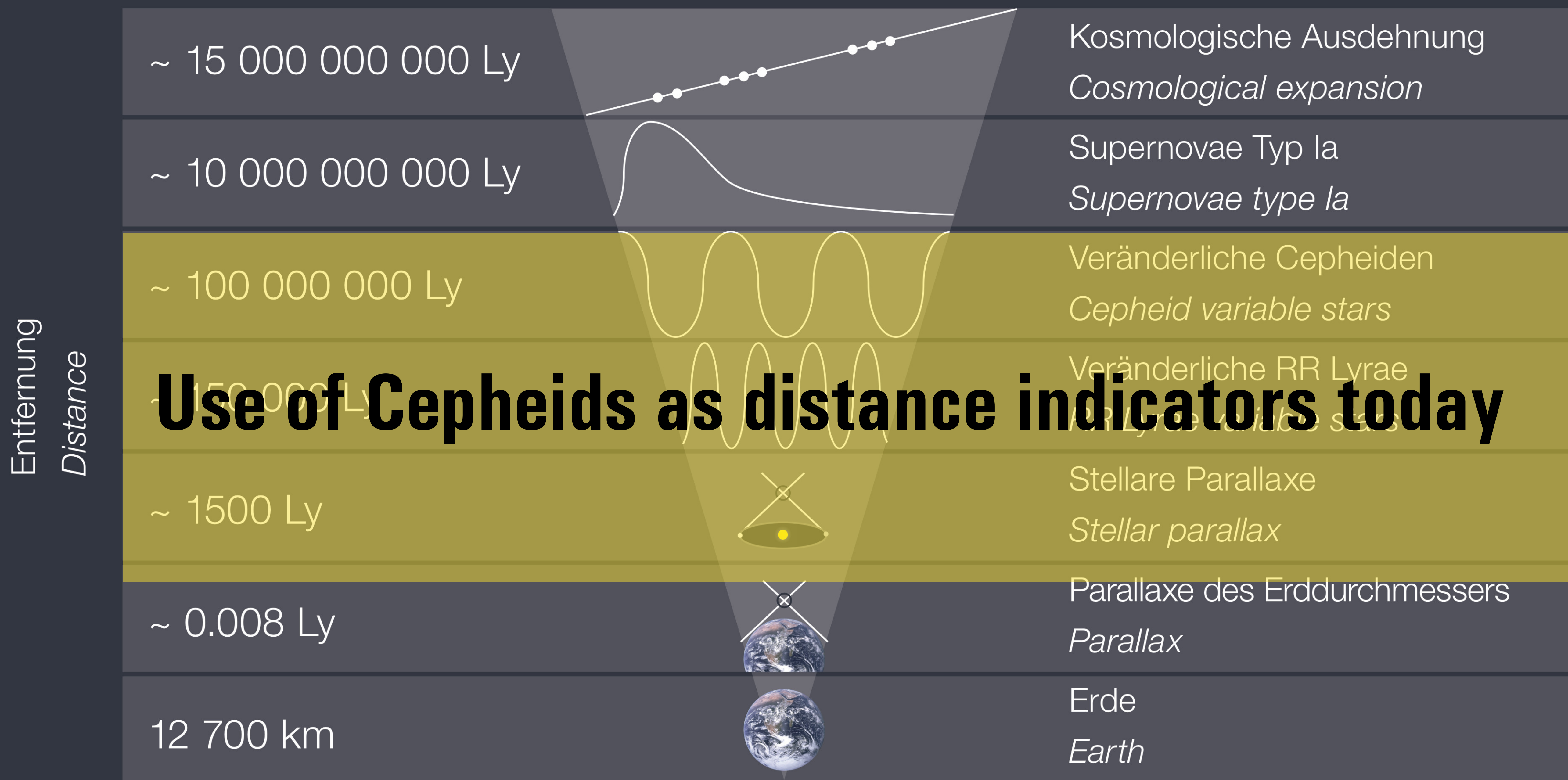
A fully modern “distance ladder”



Leavitt’s Cepheids in the SMC

(courtesy ESO Supernova center)

A fully modern "distance ladder"



Use of Cepheids as distance indicators today

(courtesy ESO Supernova center)

1936: "The Realm of the Nebulae" by Edwin Hubble

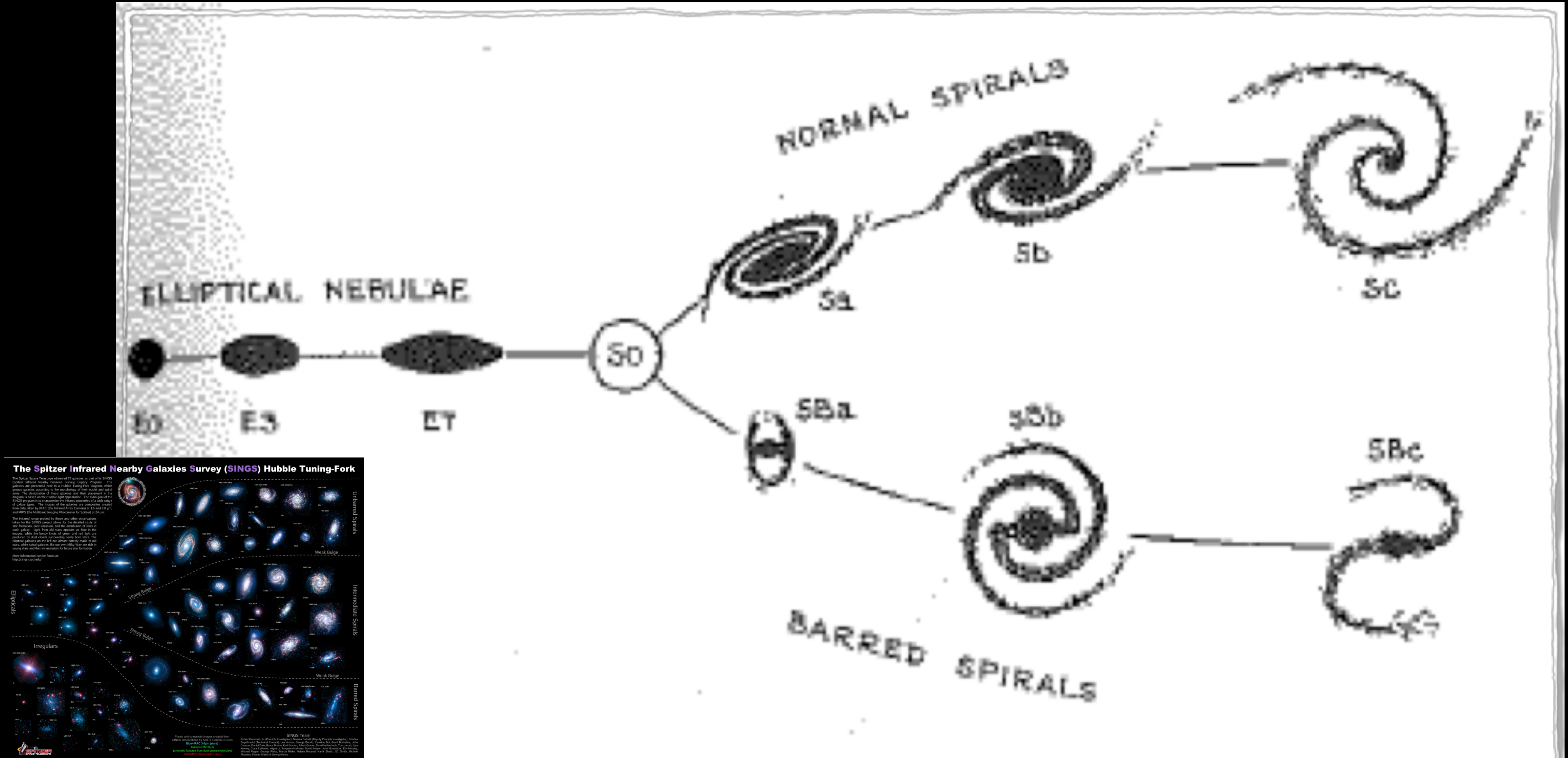


FIG. 1. *The Sequence of Nebular Types.*

The diagram is a schematic representation of the sequences of classification. A few nebulæ of mixed types are found between the two sequences of spirals. The transition stage, S0, is more or less hypothetical. The transition between E7 and SB_a is smooth and continuous. Between E7 and S_a, no nebulæ are definitely recognized.

"Hubble's Tuning Fork Diagram"

The Shapley-Curtis Debate at the
Smithsonian Natural History Museum, 1920

Boyden station - Arequipa, Peru

Extra background links

The Glass Universe (book, 2017) by Dava Sobel: https://www.penguinrandomhouse.com/books/315726/the-glass-universe-by-dava-sobel/9780143111344/

Phil Plait on distances: https://www.youtube.com/watch?v=CWMh61yutjU

Performance of the Story of Henrietta Leavitt (2018): https://thayermemoriallibrary.org/event/luminosity-the-story-of-henrietta-leavitt-astronomer-computer-trailblazer/

The Women Who Mapped The Stars (play by Joyce Van Dyke, 2018): https://starmappers.wordpress.com, http://www.wbur.org/artery/2018/04/26/nora-theatre-women-mapped-stars

Silent Sky (performance 2018): http://www.wbur.org/artery/2017/03/13/silent-sky-harvard-astronomy-women-computers

DASCH project: http://dasch.rc.fas.harvard.edu

The LMC in WWT

SOME HELPFUL BORROWED SLIDES
FROM https://www.harding.edu/lmurray/
LAMBERT E. MURRAY

Note on This Distance Scale

- When Cepheid variables were first utilized, there were no Cepheid variables close enough to measure their distance using direct parallax measurements.
- Distances to the Cepheid variables in our own galaxy were determined using statistical techniques, and were dependent upon these theoretical calculations.
- This situation recently changed with the Hipparcos satellite, and we were able to get a more accurate measure of this important "standard candle". It turns out that the Cepheid variable stars are actually brighter than was initially guessed using the statistical arguments. As a result, we now know that objects are actually about 10% farther away than we previously had thought, i.e., the universe is about 10% larger than we thought.

Hubble's Measurement for M31

- Making use of a Cepheid variable star he observed in M31 (a spiral-shaped nebula), Hubble concluded that this nebula was 2.2 million light years beyond the Milky Way, thus establishing the existence of "island universes", or what we today call galaxies.
- Today we recognize M31 as the Andromeda Galaxy, the only object not part of the Milky Way that can be seen with the naked eye from the Earth's northern hemisphere.

Shapley Uses RR Lyra Variables to Determine our Place in the Milky Way

- Shapley made use of RR Lyra variable stars found in many globular clusters to determine the distances to these clusters.
- RR Lyra variables, like the Cepheid variables also have a period – luminosity relationship.
- By measuring the distances to, and the relative locations of the globular clusters, Shapley determined that these clusters were spherically distributed about a point *not* centered on the Earth.
- He made the correct assumption that these clusters are clustered around the center of the galaxy.

Shapley's Conclusions

- Shapley correctly concluded that the sun lay about 2/3 of the way out from the center of the galactic disk.
- Shapley's distance measurements, however, were wrong, for like many early astronomers, he was unaware of the importance of the Interstellar Medium (or ISM) and the dimming produced by the interstellar dust.
- This same mistake had earlier convinced William Herschel that the earth was at the center of the galaxy. He had argued that the center of the galaxy should have more stars. But when he counted the stars is the Milky Way he found that there were about as many stars is one direction as the other. He did not know about the obscuring gas and dust in the center of our field of view.

Determining Distances to Galaxies

- Cepheid variable stars can be used to measure the distances to galaxies that are within about 60 Mpc (200 million ly).
- Beyond that other *standard candles* must be used – these all depend upon knowing (or at least having some estimate of) the absolute magnitude of the standard candle.
- Other standard candles which are used.
  - Red and Blue Supergiants (out to about 250 Mpc or 800 million ly)
  - Bright Globular clusters (out to 400 Mpc)
  - Bright HII regions (out to 900 Mpc)
  - Supernova explosions (beyond 900 Mpc)

The Tully-Fisher Relation

- Yet another standard candle is the line width of the 21-cm hydrogen emission line.
- The Tully-Fisher relation indicates that the broader the emission line, the brighter the galaxy. Thus the width of the emission line can be used to determine the absolute magnitude of a distant galaxy.
- The reason this works is that the line width is determined by the Doppler shift – red shifted on the receding side and blue shifted on the approaching side of the galaxy. The larger the shift (the wider the line) the faster the rotation of the galaxy, the more mass contained in the galaxy, thus the more stars – giving rise to a brighter galaxy.

The Hubble Law

- As early as 1914, Slipher, working at the Lowell Observatory had observed that a large number of spiral galaxies that he had been studying exhibited a red shift in their spectra – indicating that most of these galaxies were moving away from us.
- During the 1920's Edwin Hubble determined the distances to a number of these galaxies using Cepheid variable stars and noticed a correlation between the distance to the galaxies and the observed red–shift of the spectrum.
- He found that the farther away a galaxy was, the greater the red-shift.

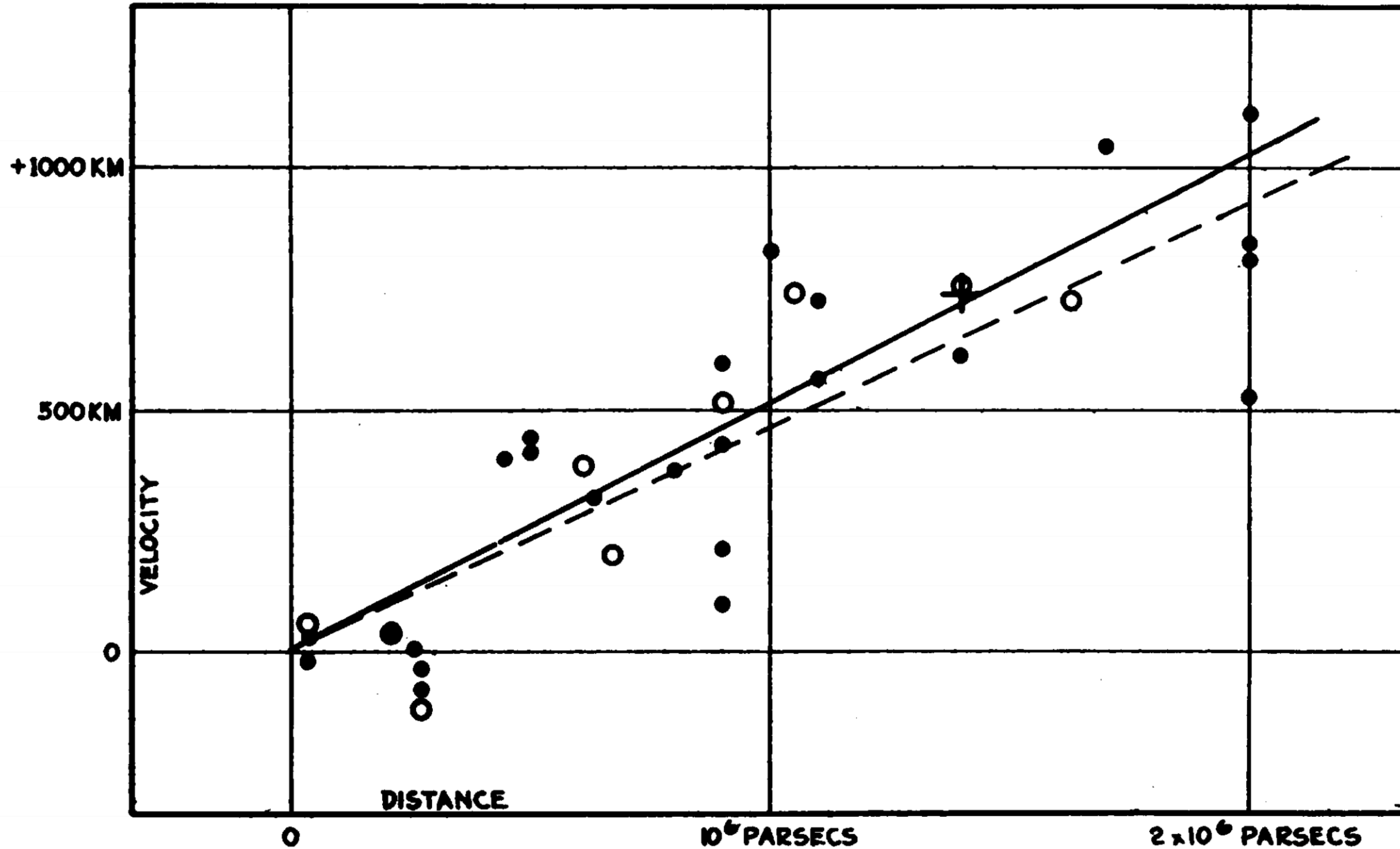


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

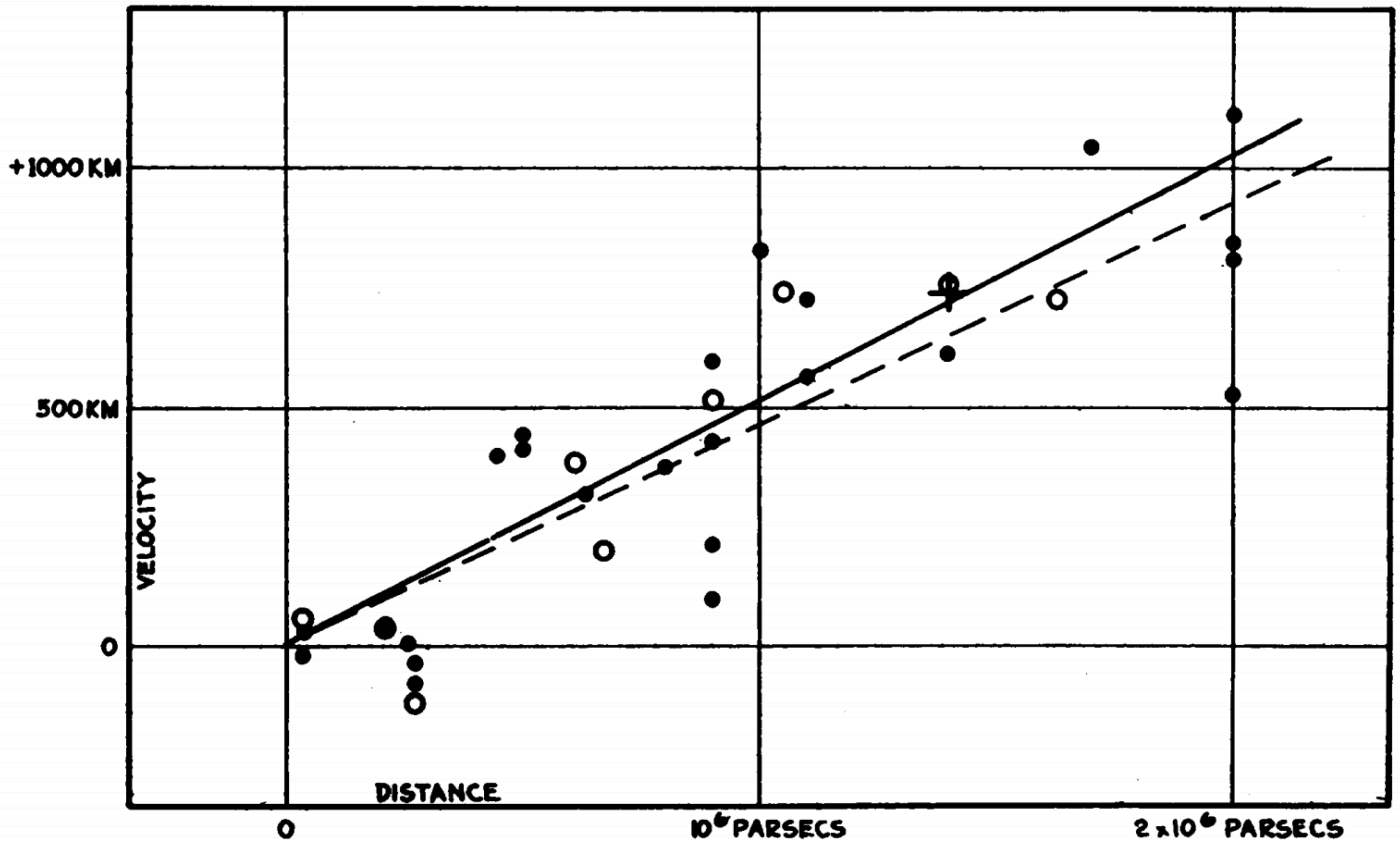


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.