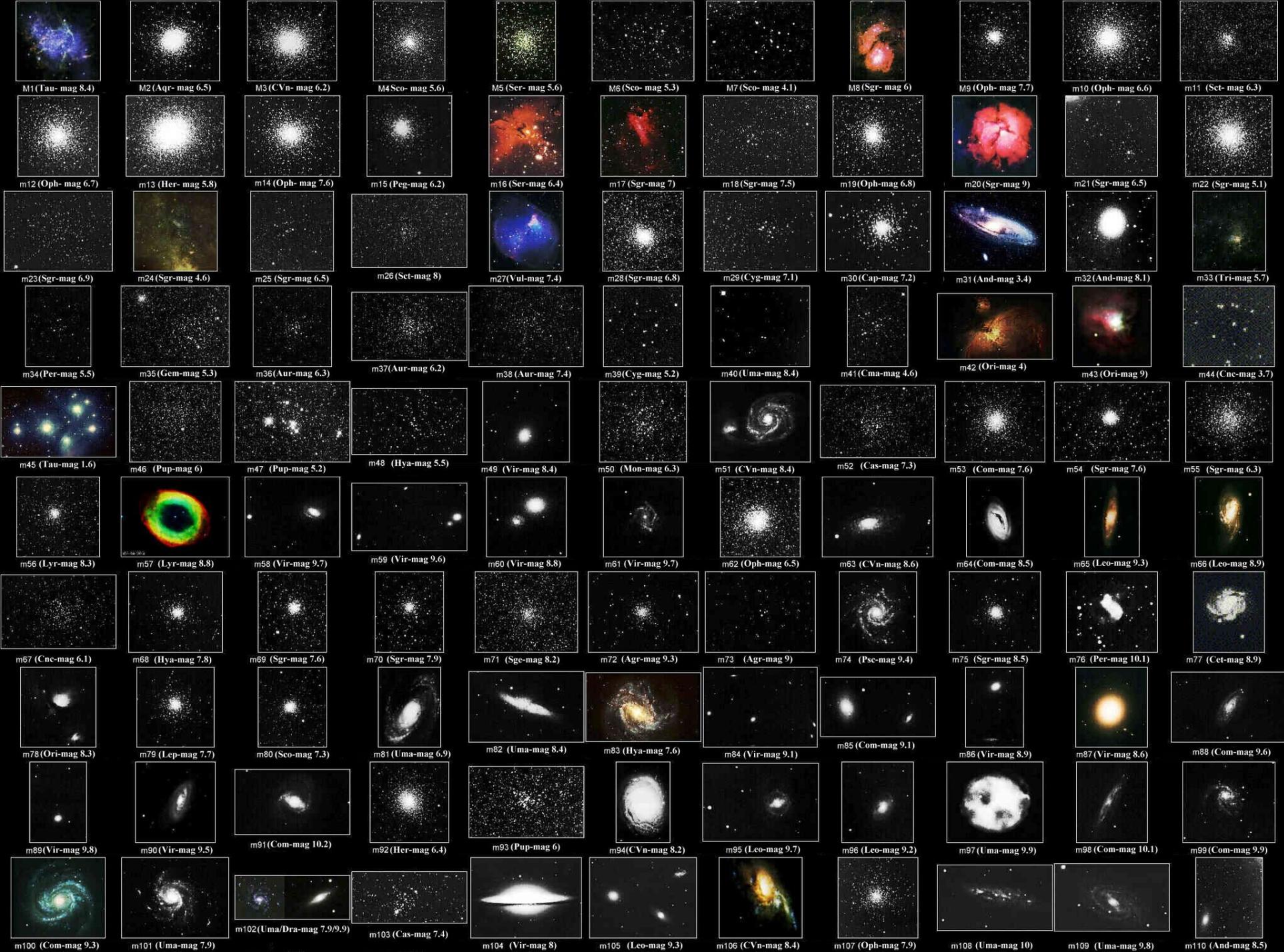


Expanding Universe



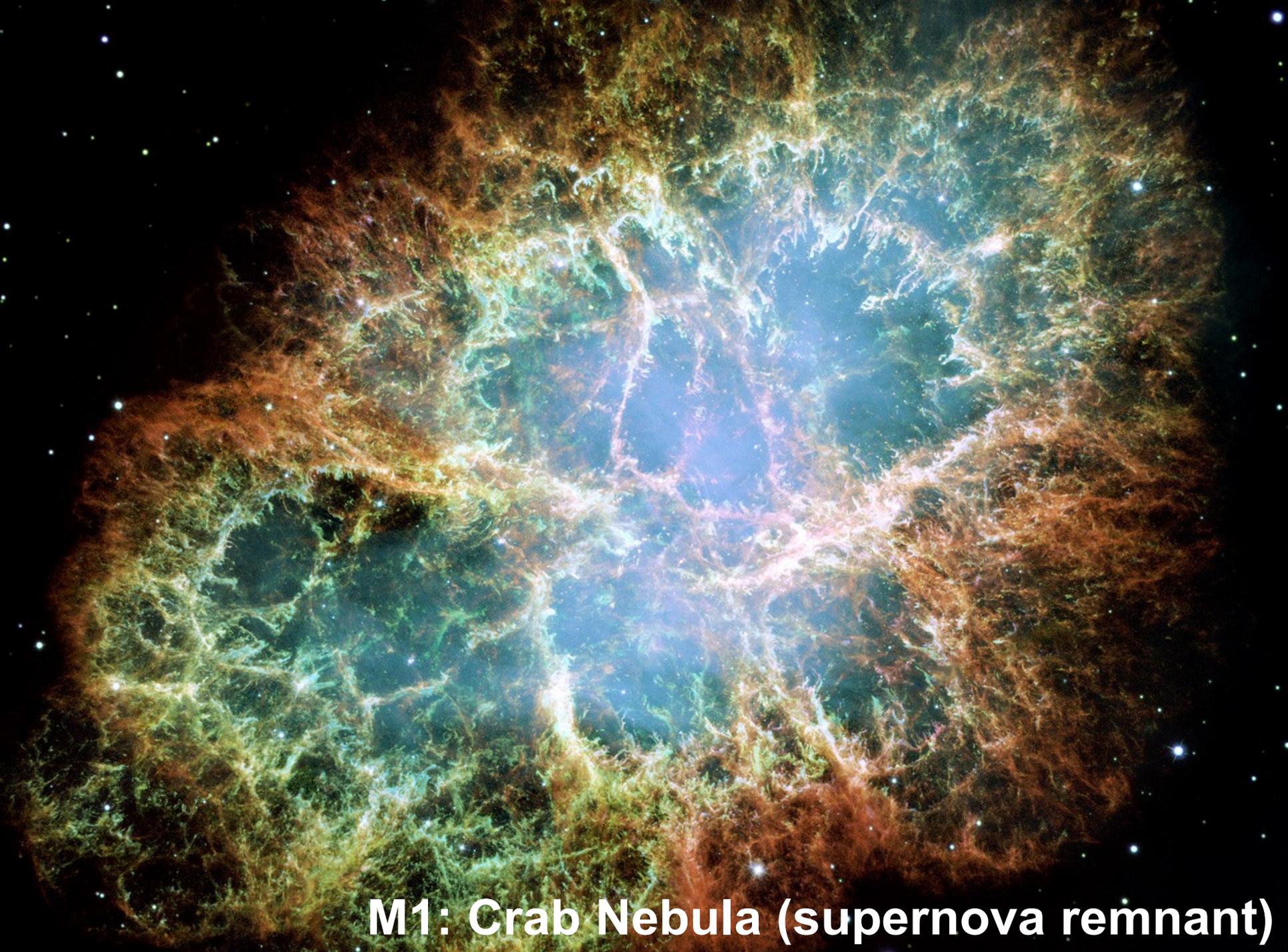
Charles Messier (1730-1817)

- He was a comet hunter, so he needed to know all non-stellar objects on the sky that were *not* comets.
- From 1774 to 1781, he published a list of such objects. We still label objects from his catalog as M1, M2, ..., M110.
- Messier catalog is a mixed-bag collection. It includes stellar clusters, gaseous nebulae, and external galaxies.





M13: Globular cluster (cluster of stars)



M1: Crab Nebula (supernova remnant)



M42: Orion Nebula (star-forming region)



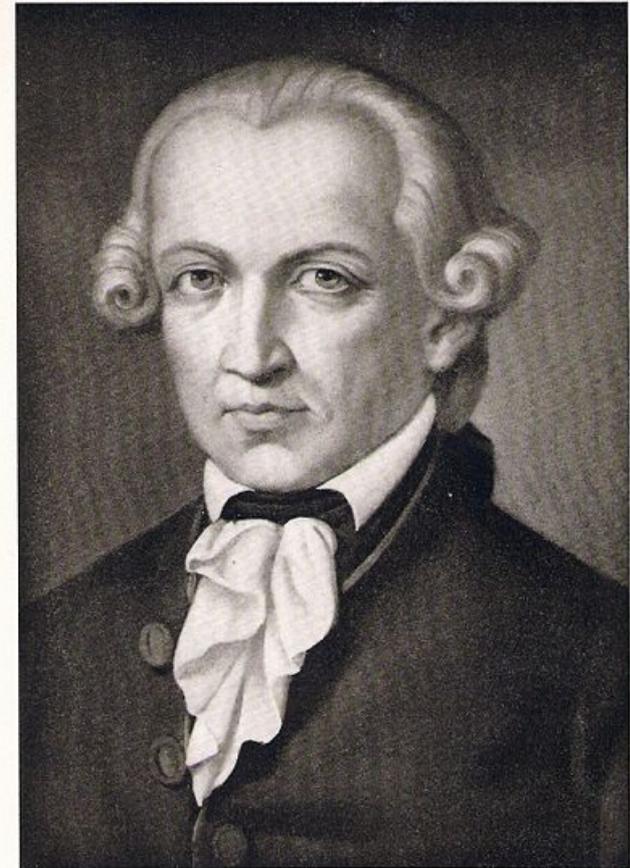
M57: Ring Nebula (planetary nebula)



M51: Whirlpool Galaxy (spiral galaxy)

Immanuel Kant (1724-1804)

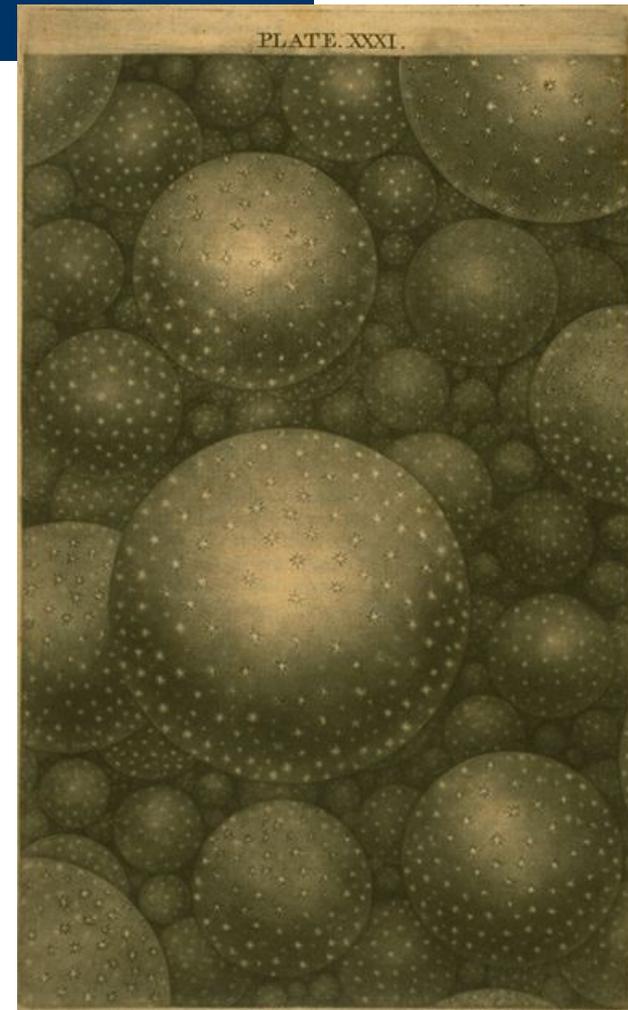
- He was first and foremost a philosopher, but he also proposed interesting astronomical ideas.
- In 1755, he proposed that Solar System formed from a rotating nebula (cloud) of gas and dust, which collapsed under the force of gravity, flattening on the way.



IMMANUEL KANT
From a painting

Kant and Wright

- In 1750 an English astronomer, Thomas Wright, published “*An Original Theory of the Universe*”, in which he explains the Milky Way as a spherical shell of stars, with Sun being just one star in it.
- He created many other models of the universe.
- He also considered the Earth to be a living organism.



Kant and Wright

- Kant read a (highly) distorted review of Wright's book in a newspaper. It looked remarkably similar to his ideas about the formation of the Solar system.
- He proposed that:
 - Stars are mostly located in a plane, just like planets in the Solar system.
 - Stars go around a common center far away.

Kant's Universe

- He realized that disky-shaped round galaxies would appear as faint elliptical blobs of light, if observed from very far way.
- He proposed that numerous elliptical nebulae seen in the sky are other Milky Ways.

“The fixed stars, as we know, are all connected to a common plane and thus create a coordinated totality, a world of worlds. We see that in the immeasurable distances there are more such star systems and that creation in the entirety of its infinite extent is everywhere systematic and interconnected.”

William Herschel (1738 – 1832)

- German immigrant to England, he began his career as an organist in a chapel, but got bored really soon.
- Founded Royal Astronomical Society.
- Got himself into building telescopes (could not get a good enough one at a local Target).



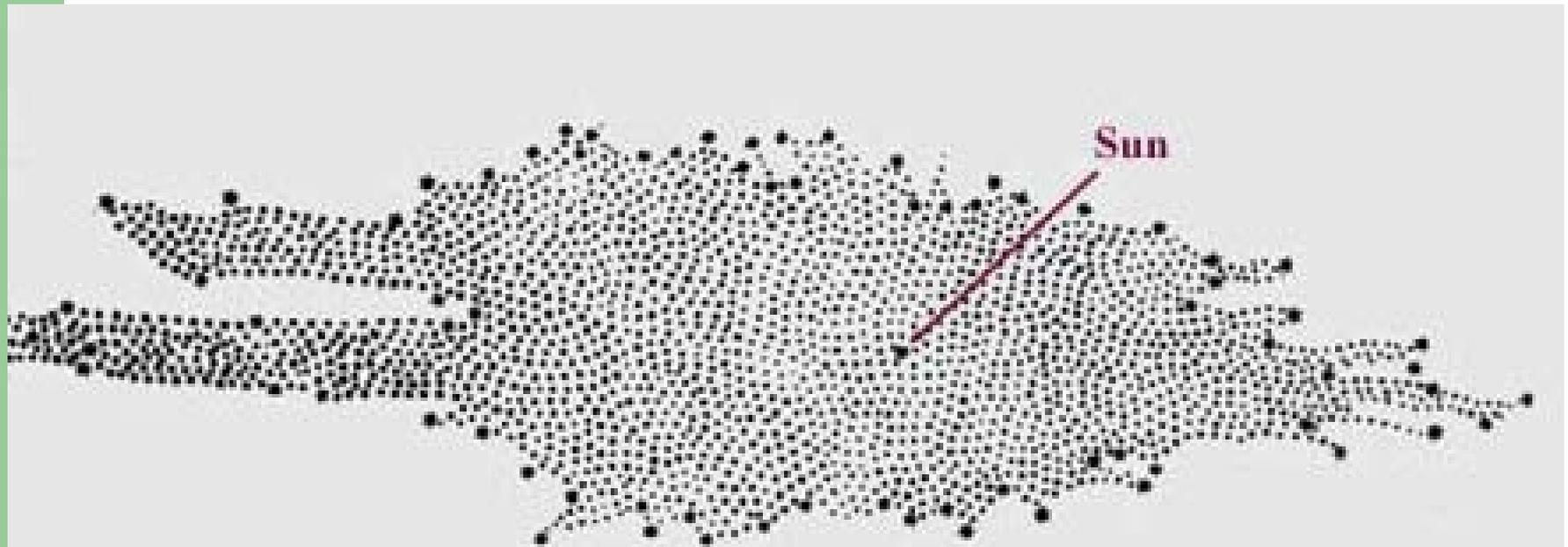
Question

- What do telescopes do?
 - **A** They move distant objects closer.
 - **B** They magnify views of celestial objects.
 - **C** They gather more light from celestial objects.

Herschel's Milky Way

- One of his many undertakings was to map the Milky Way.
- He found that the Milky Way was rather small (according to modern standards), with the Sun close to its center.
- Later, Dutch astronomer Jacobus Kapteyn (1851 – 1922) followed up on Herschel's work. He confirmed his map.

Herschel's Milky Way



William Herschel's Drawing of the Milky Way Galaxy

Herschel's & Kapteyn's Milky Way



Herschel's & Kapteyn's Milky Way

- They both misestimated the size of the Milky Way by a factor of 10.
- They both got it wrong, because
 - Space between stars not empty.
 - Dark interstellar clouds block most of the visible view of our galaxy.



Returning to XIX Century

- By the end of XIX century most astronomers believed that:
 - The Milky Way (galaxy) was small (about 2 kpc across), as Herschel found.
 - In addition to stars, space contained “nebulae”. Small spiral nebulae were by far the most common kind of nebulae.
 - All nebulae were glowing blobs of gas.
- Most physicists believed that the universe was infinite in space and time and more-or-less uniformly filled with stars.

Sky Photography in 1900



Plate 1

THE GREAT NEBULA IN ANDROMEDA



Plate 10

THE GREAT NEBULA IN ORION

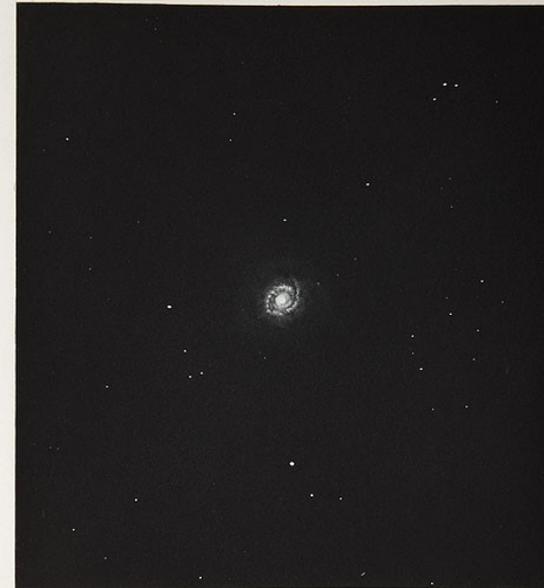


Plate 43

THE SPIRAL NEBULA M 94, CANUM VENATICORUM

The Great Nebula
in Adromeda

The Great Nebula
in Orion

The Spiral Nebula M94.
Canum Venaticorum

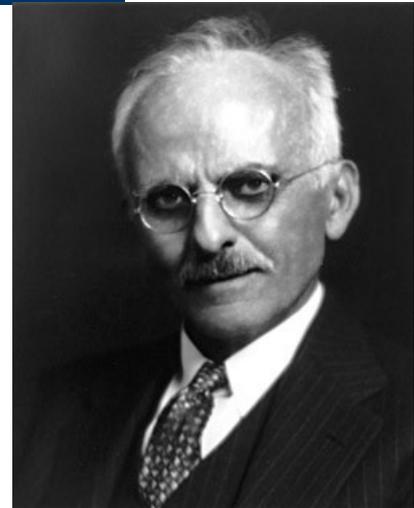
Vesto Slipher (1887 – 1969)

- In 1912 - 1917 he measured Doppler redshifts for some of the spiral nebulae. He found that many of them have velocities much larger than the velocities of stars in the Milky Way.
- He found that out of 25 nebulae, 21 were redshifted, moving away from the Sun. He paid no attention to that fact.
- He suggested that they were “stellar systems seen at great distances”.



A Battle for Galaxies: Attack

- In 1917 Heber Curtis (1872 – 1942) discovered three faint *novae* in Andromeda Nebula. From that he was able to conclude that Andromeda Nebula was about 200 kpc away.
- “Way too far”, said the others.
- He was too short by a factor of 4.



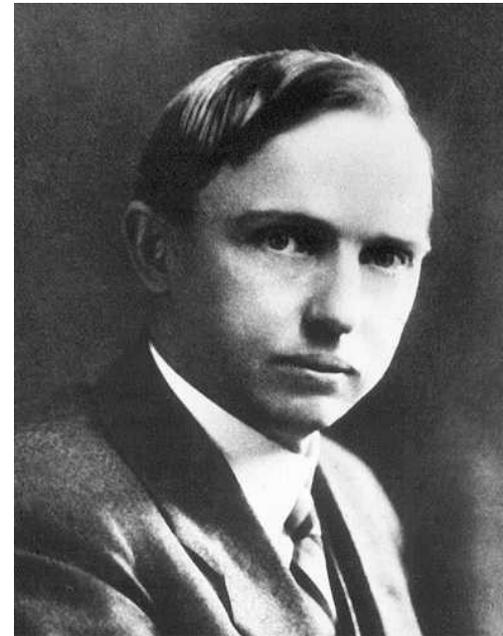
A Battle for Galaxies: Defense

- In 1916 Adriaan van Maanen (1884 – 1926) from the Mount Wilson Observatory (near LA) directly observed the rotational motion of the spiral nebula M100.
- He was a highly respected observer, everyone believed him.
- That was the death blow to the island-universe hypothesis.



Harlow Shapley (1885 – 1962)

- At the same time Harlow Shapley from the same Mount Wilson Observatory measured the size of the Milky Way using **globular clusters**. He found that the Milky Way is about 100 kpc in size – 20 times the size of Herschel’s – Kapteyn’s model.
- He was off by a factor of 3.



Layover: Globular Clusters

- Large balls of stars.
- Contain anywhere from 100,000 to 3 million stars.
- They are distributed spherically in the Milky Way. Shapley guessed (correctly) that the center of the Milky Way = the center of the GC distribution.



Great Debate of 1920

- Took place at the Museum of Natural History in Washington, DC, between Shapley & Curtis, on April 26.
- Topic: "The Scale of the Universe".



Great Debate of 1920

- Shapley argued that:
 - The Milky Way was large, 100 kpc across, with the Sun far from the center.
 - Other spiral nebulae were inside it.
- Curtis argued that:
 - The Milky Way was small, with the Sun close to the center.
 - Other spiral nebulae were separate galaxies, like the Milky Way.

Who was right?

- **A:** Shapley
- **B:** Curtis

Irony of the Great Debate

- Both were right in their revolutionary ideas, and both were wrong in their conservative beliefs.
- If the Milky Way was so enormous as Shapley found, and other spiral nebulae were similar to the Milky Way, then they should be at such large distances, which seem totally unreasonable. So, the Aristotelian prejudice appeared again.
- Now we know that the Milky Way is about 30 kpc across, and the Andromeda galaxy is 780 kpc away from it.



Edwin Hubble (1889 – 1953)

- UofC undergraduate (1910) and graduate student (1917). Worked as a basketball coach at a high school in between.
- Served in both World Wars as a major; got the Legion of Merit.
- In 1919 began his career at Mount Wilson Observatory.



Hubble as Astronomer

- Using ***Cepheid variables***, he measured the distance to the Andromeda galaxy and found that it was 200 kpc, thus settling the debate. This distance was later revised to 800 kpc.
- He developed a classification scheme for galaxies, which still has his name.
- Measured redshifts and distances to galaxies, and discovered the ***Hubble Law***.

Hubble Law

- Hubble found that most galaxies move away from the Milky Way (have positive redshifts). The recession velocity is *approximately* proportional to the distance to the galaxy.

$$v = H_0 d$$

- H_0 is called the ***Hubble constant***, it is the same for all galaxies.

Hubble Constant

- It is measured in km/s per Mpc (km/s/Mpc).
- This is a weird unit:
 - 1 Mpc = 3.086×10^{19} km
 - 1 km/s/Mpc = 3.24×10^{-20} Hz (Hz = 1/s)
- The best current value:

$$H_0 = 67.3 \pm 1.3 \text{ km/s/Mpc}$$

(from cosmological observations).

Hubble Diagram: Then ...

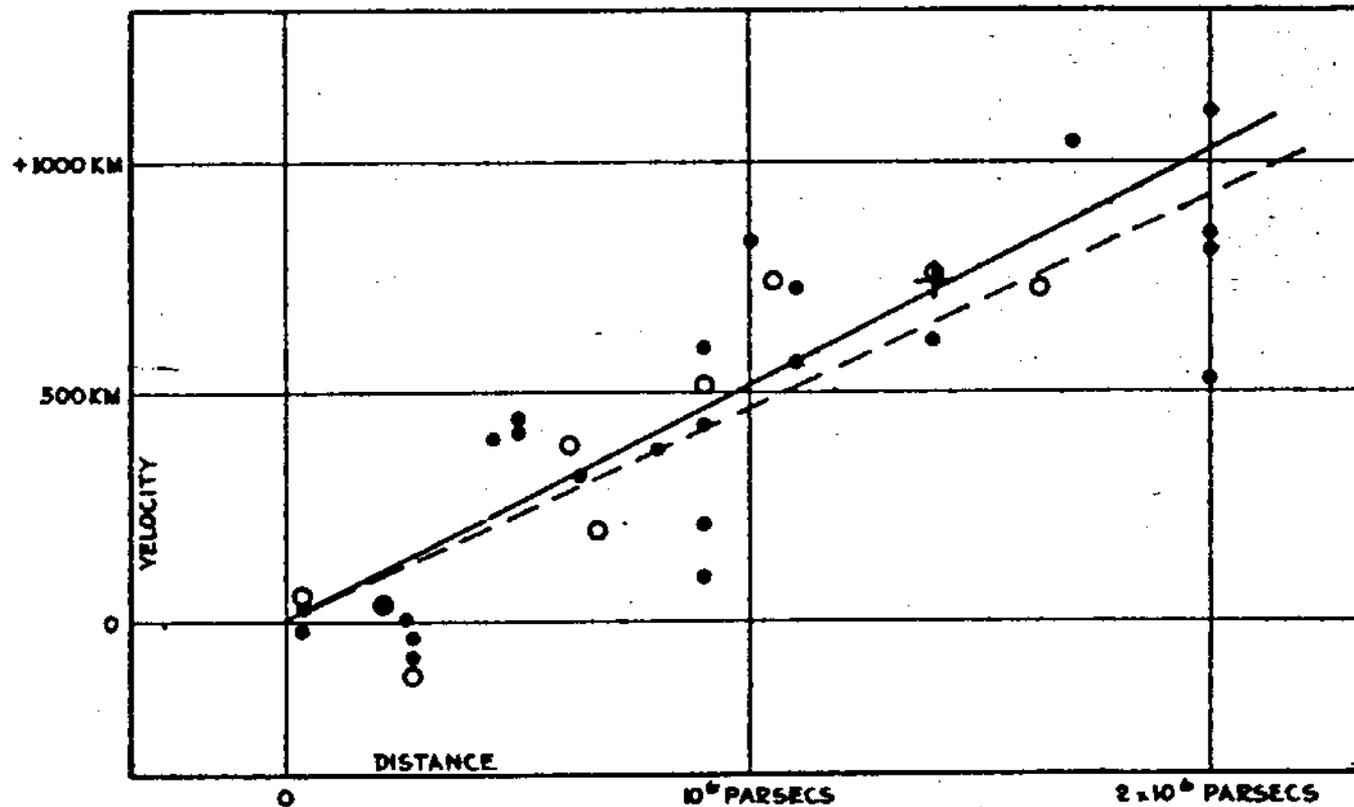
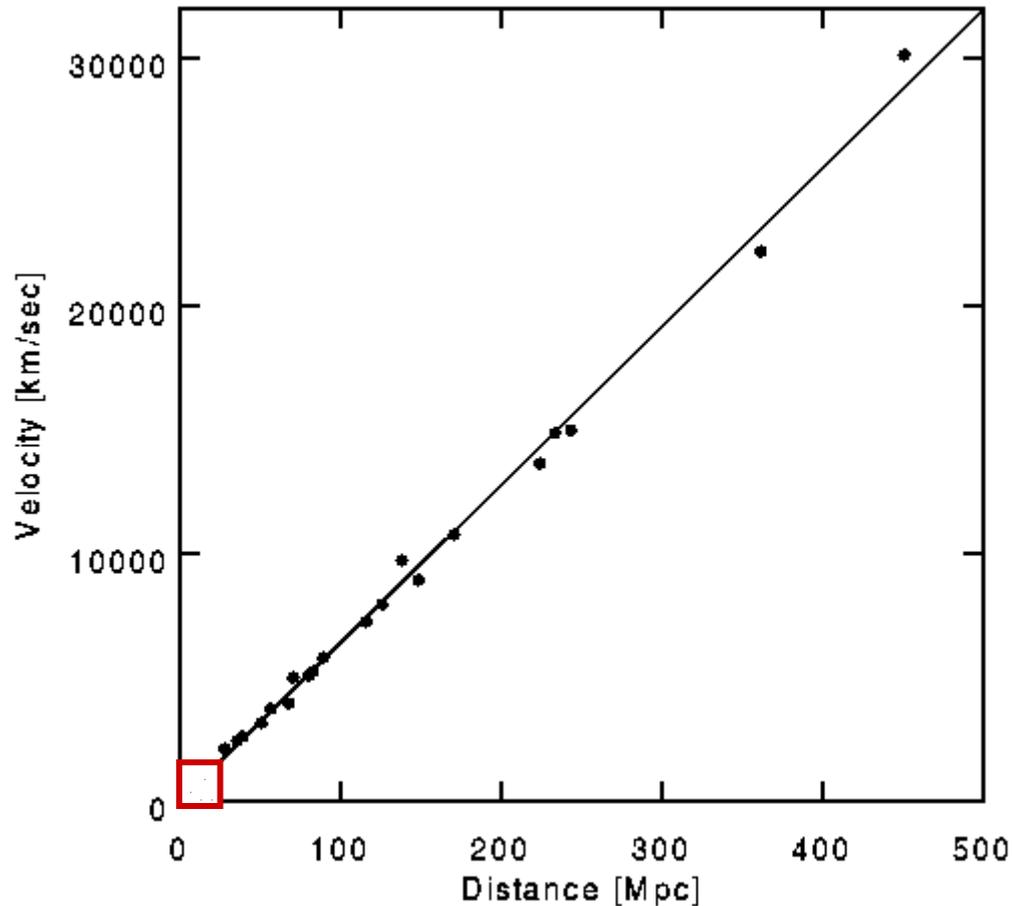


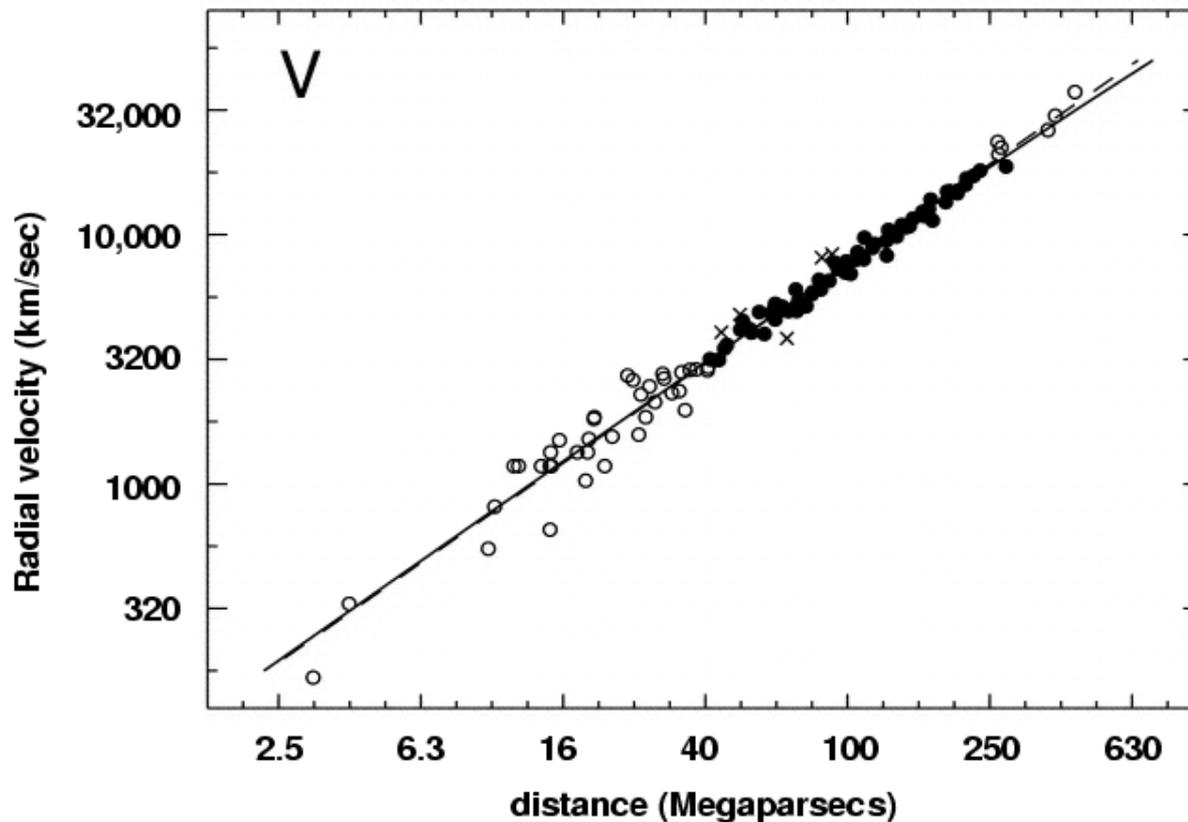
FIGURE 1

Hubble Diagram: ... And Now



Hubble Diagram: The Best

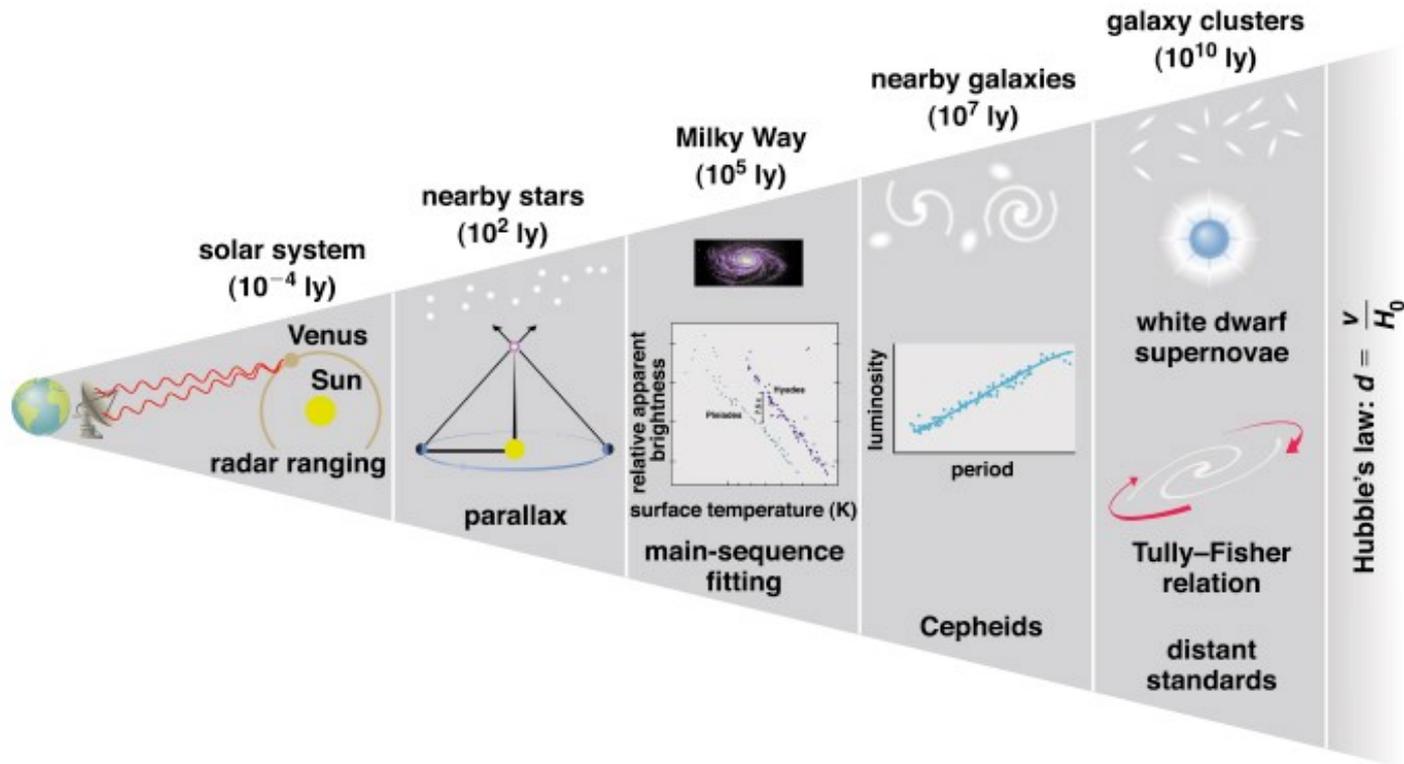
Hubble diagram for Type Ia SNe



Cosmic Distance Ladder



Distance Ladder At A Glance



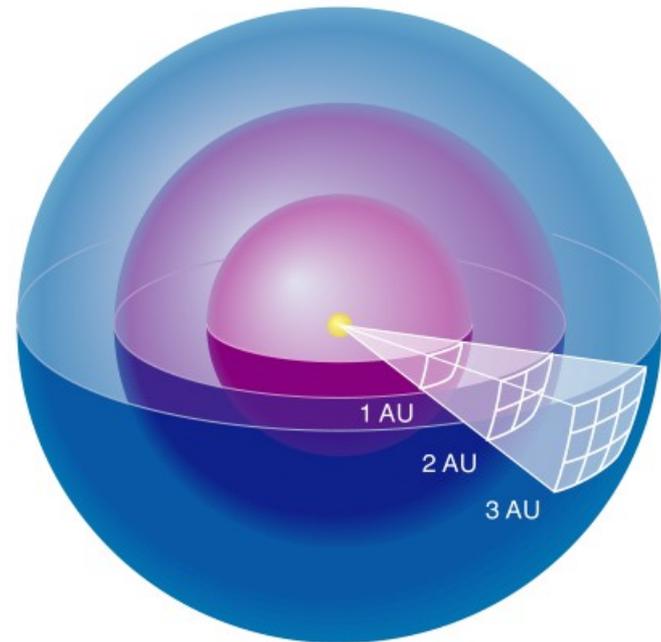
Why Do We Need A Ladder?

- To measure distances accurately to remote astronomical objects like other galaxies is still a very difficult task. We do it by using different methods at different distance (like rungs in the ladder), and then trying to tie the rungs together whenever they meet.
- Distances to nearby stars can be measured by the parallax. Beyond that we need to use the ***luminosity distance*** of a ***standard candle***.

Luminosity, Brightness, Distance

- Observed brightness of an astronomical object (apparent magnitude), its luminosity (absolute magnitude), and the distance to the object are related.

$$B = \frac{L}{4\pi D^2}$$



Cepheid Variables

- The best standard candle available to astronomers today is a ***Cepheid Variable*** star.
- This type of stars change their brightness with a fixed period, and the brighter the star, the longer the period. Thus, by measuring the period of a Cepheid variable, we can determine its luminosity and thus the distance.
- Cepheids allow astronomers to measure distance to about 20 Mpc.

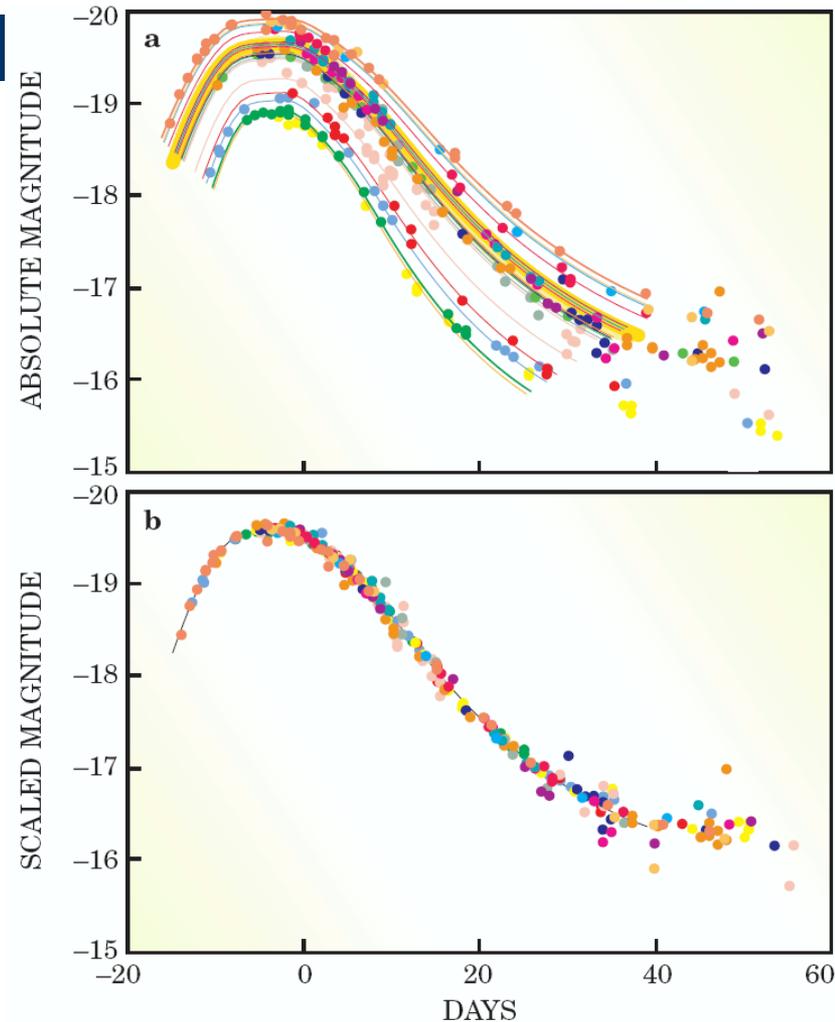
Henrietta Leavitt (1868 – 1921)

- Worked at Harvard College Observatory as a “human computer” since 1893.
- In 1908 - 1912 discovered the ***period – luminosity relation*** for Cepheids.
- The relation was ***calibrated*** by Ejnar Hertzsprung in 1913.
- She died of cancer the year Shapley became the Director. Shapley later refused to nominate her for the Nobel Prize, claiming all credit to himself.



SN Ia As Standard Candles

- Thermonuclear supernovae can also be used as standard candles, because they have a *luminosity – decay rate relation* (similar to Cepheids).



SNIa: Hunting for the Dark Energy

