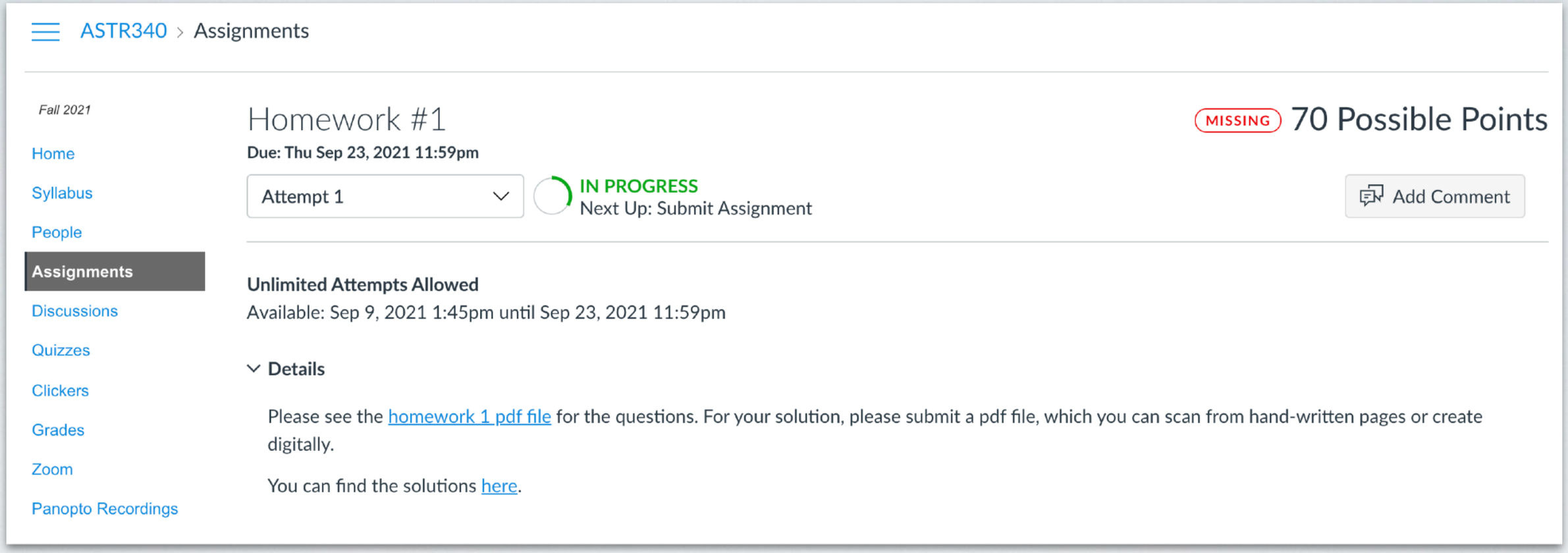
ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 11 • The Universe beyond our Galaxy

10/05/2021

Homework #1


ASTR340 › Assignments
Fall 2021
Home
Syllabus
People
Assignments
Discussions
Quizzes
Clickers
Grades
Zoom
Panopto Recordings
Homework #1
Due: Thu Sep 23, 2021 11:59pm
MISSING
70 Possible Points
Attempt 1
IN PROGRESS
Next Up: Submit Assignment
Add Comment
Unlimited Attempts Allowed
Available: Sep 9, 2021 1:45pm until Sep 23, 2021 11:59pm
Details
Please see the homework 1 pdf file for the questions. For your solution, please submit a pdf file, which you can scan from hand-written pages or create digitally.
You can find the solutions here.

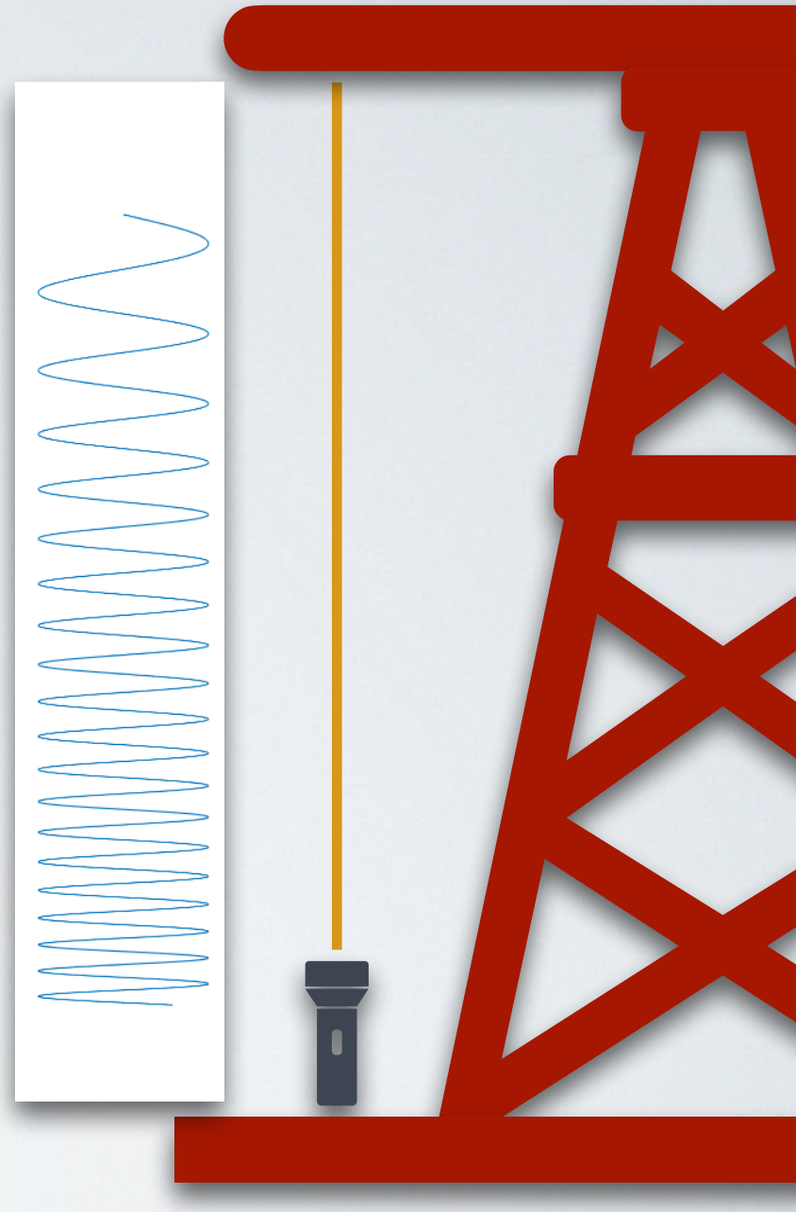
Quiz grades

- No adjusting quiz grades after the fact… sorry!
- Average scores are generally well above 90%
- Two attempts
- Worst grades are not dropped (as for attendance)

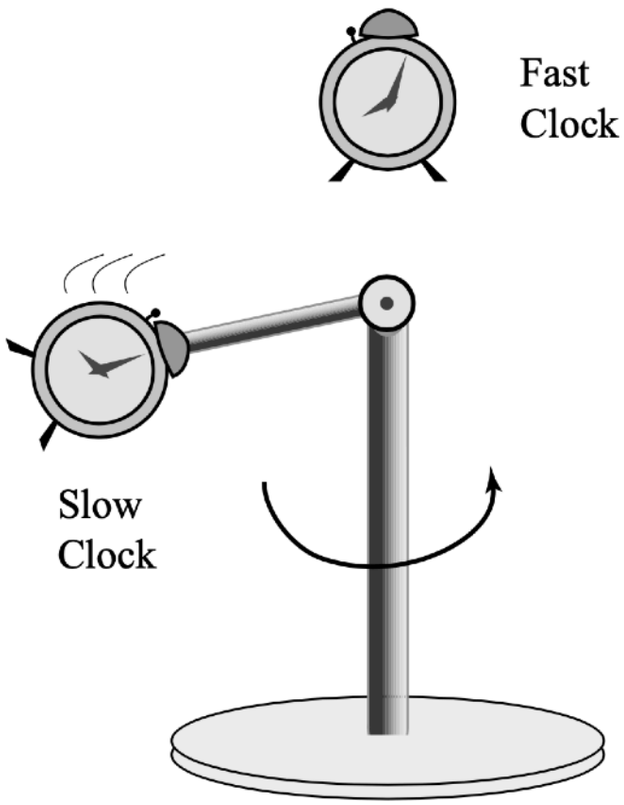
Gravitational time dilation

- Light beam loses energy as it climbs up (gravitational redshifting)
- **Frequency decreases**
- Imagine a **clock based on frequency** of laser light: 1 tick = time taken for fixed number of crests to pass
- Gravitational redshifting **slows down the clock**
- **Clocks in gravitational fields run slower**

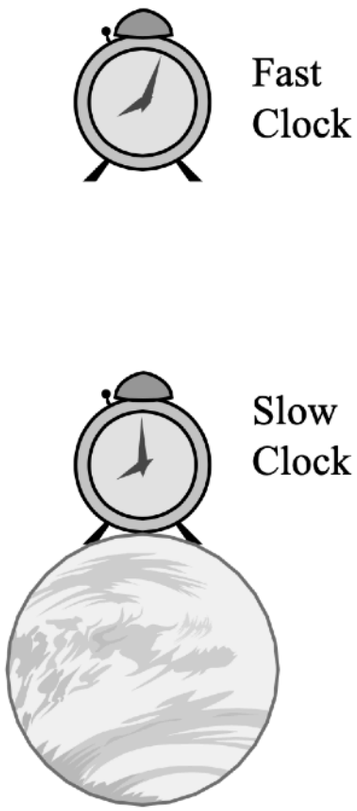
$$\Delta t_{\text{grav}} = \sqrt{1 - \frac{2GM}{c^2 r}}\,\Delta t_{\text{space}}$$



Alternative reasoning: spinning clock



Rotating Centrifuge



High Gravity Planet

- Imaging quickly rotating clock
- Not an inertial frame, so SR doesn't apply directly
- But as it turns out, a stationery observer still sees the clock running more slowly than in its own (proper) frame
- The circular rotation is equal to a constant acceleration
- According to the weak equivalence principle, this acceleration is indistinguishable from gravity
- Thus, clocks must run more slowly in gravitational fields

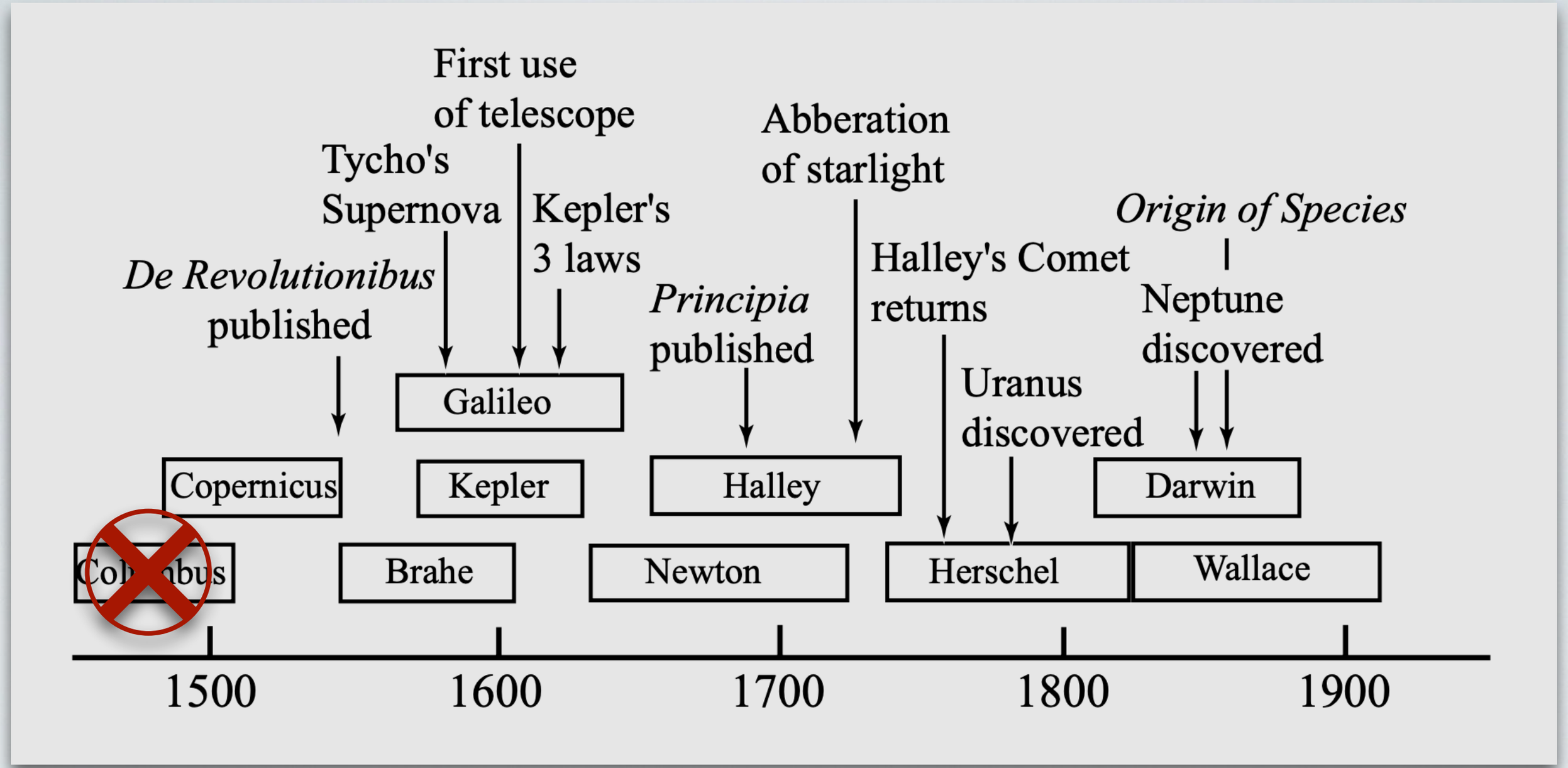
Hawley & Holcomb, Foundations of Modern Cosmology

Today

- Enlightenment Science
- The Great Debate
- The distance ladder
- Hubble & the expanding Universe

Part 1: Enlightenment Science

Today



Hawley & Holcomb, Foundations of Modern Cosmology

Participation: Recap #1

TurningPoint:

At the beginning of the enlightenment era, do we know the scale of the solar system?

Session ID: diemer

30 seconds

Participation: Recap #2

TurningPoint:

At the beginning of the enlightenment era, do we know the distance to the closest stars?

Session ID: diemer

 30 seconds

Participation: Recap #3

TurningPoint:

At the beginning of the enlightenment era, what do we know about the Milky Way?

Session ID: diemer

 30 seconds

Participation: Recap #4

TurningPoint:

At the beginning of the enlightenment era, what do we know about the Universe as a whole?

Session ID: diemer

 30 seconds

History

Classical Greece

Aristarchus, Erathostenes, Aristotle, Ptolemy…

Renaissance

Copernicus, Galileo, Brahe, Kepler…

Englightenment

Newton, Bacon, Halley, Herschel (x2)…

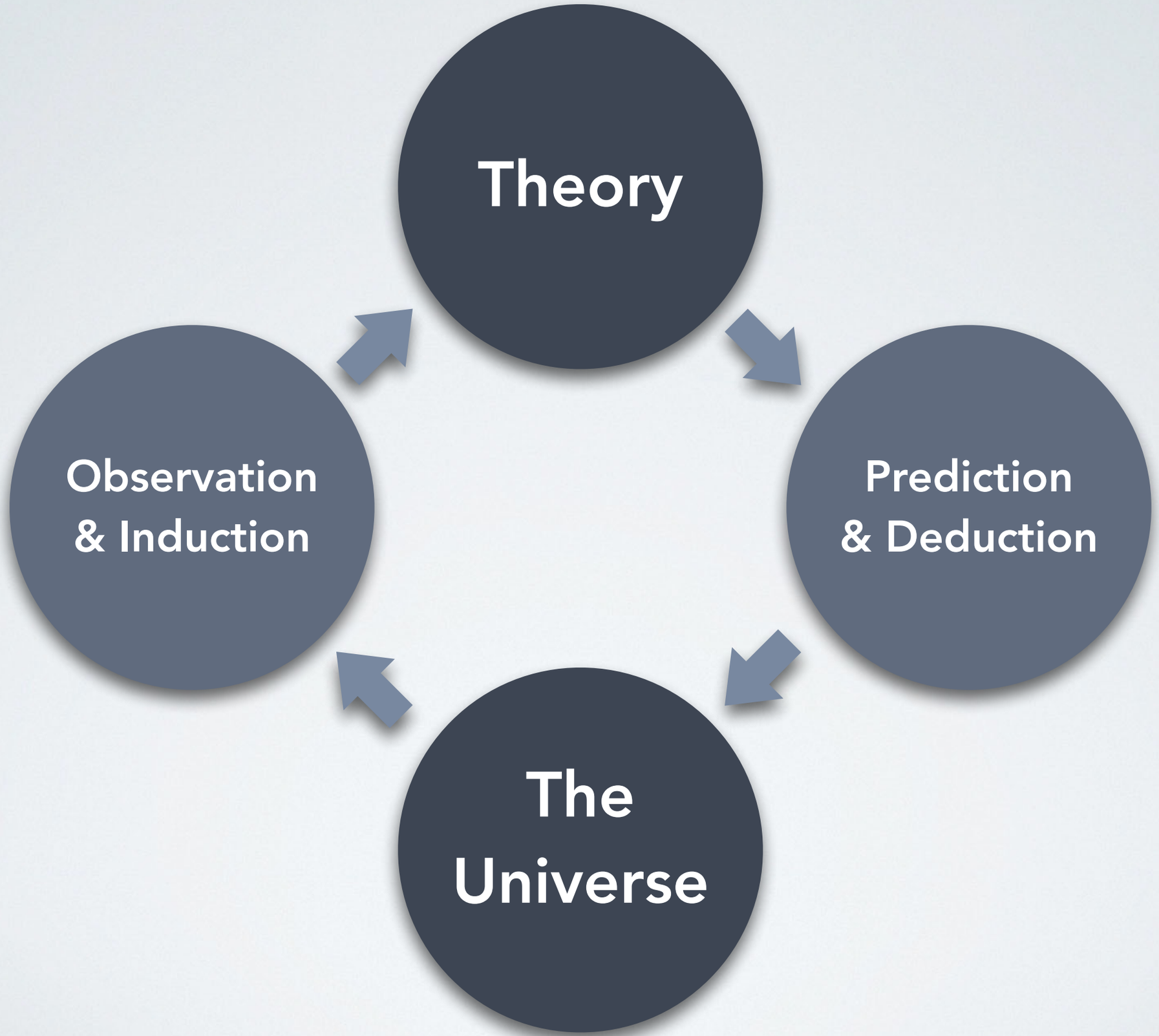
Modern Science

Maxwell, Einstein, Hubble, Shapley/Curtis…

Enlightenment science

- Beginning of enlightenment often credited to…
  - Bacon's scientific method (~1620)
  - Newton's Principia (~1687)
- Important enlightenment philosophers (for this course):
  - Francis Bacon
  - Immanuel Kant
- Important enlightenment scientists (for this course):
  - Messier
  - Halley
  - The Herschels

The scientific method



Charles Messier (1730 - 1817)

- Identified many **nebulae** (fuzzy patches of light)
- Published **Messier Catalogue** in 1780
- Intended as aids to **comet hunters** to reject “uninteresting” objects
- Catalog contains galaxies, star-forming clouds, star clusters…

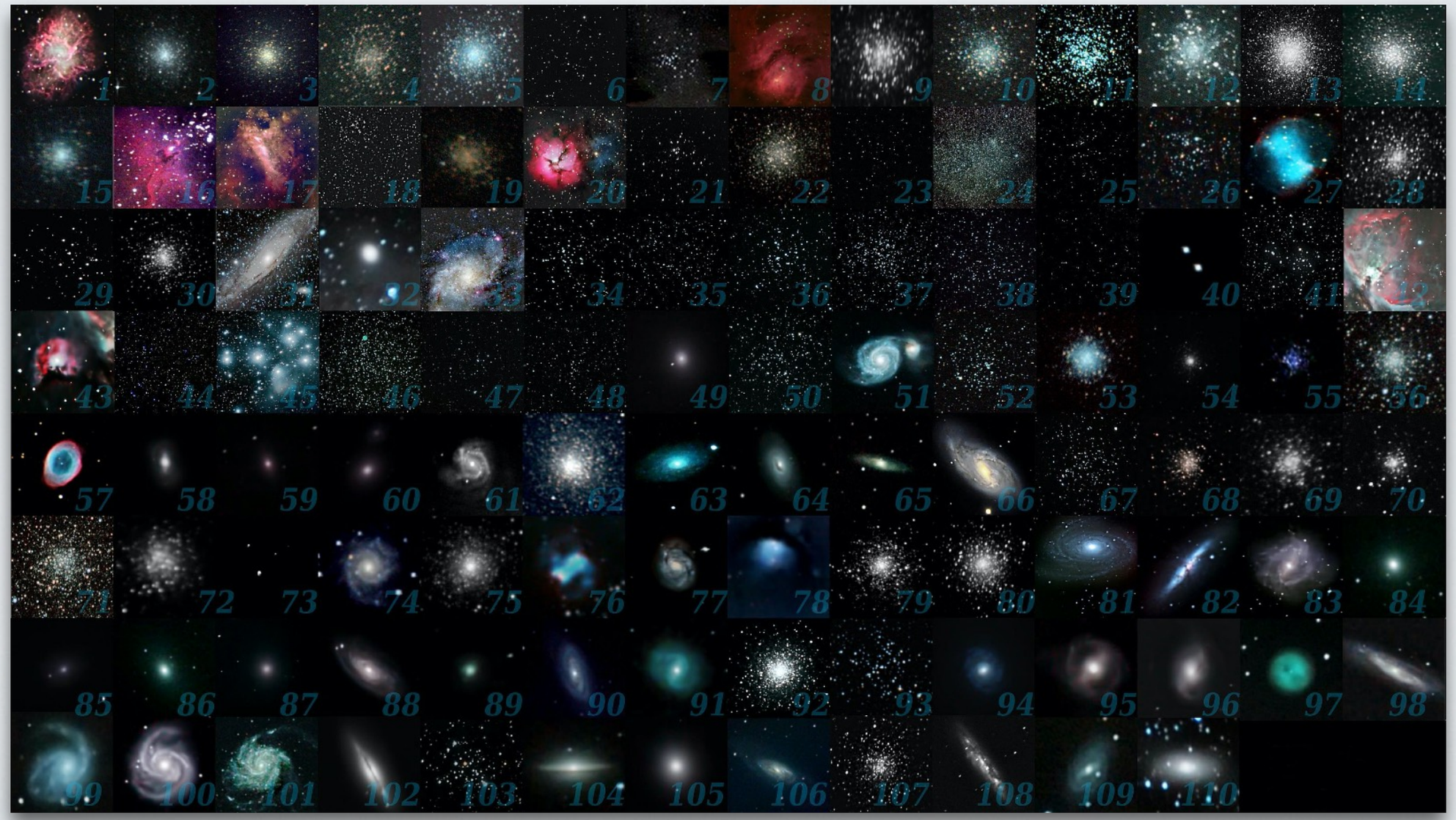
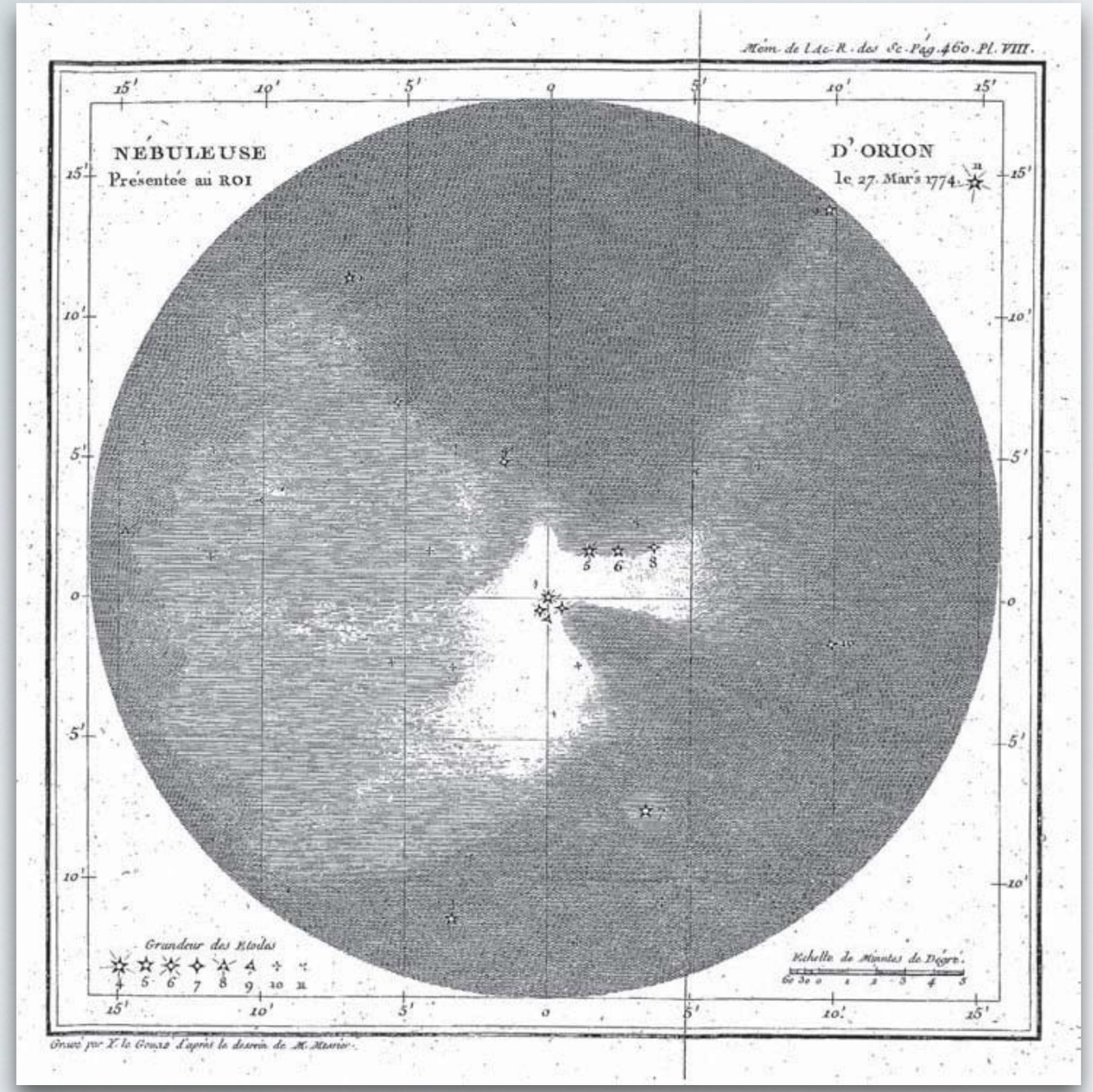
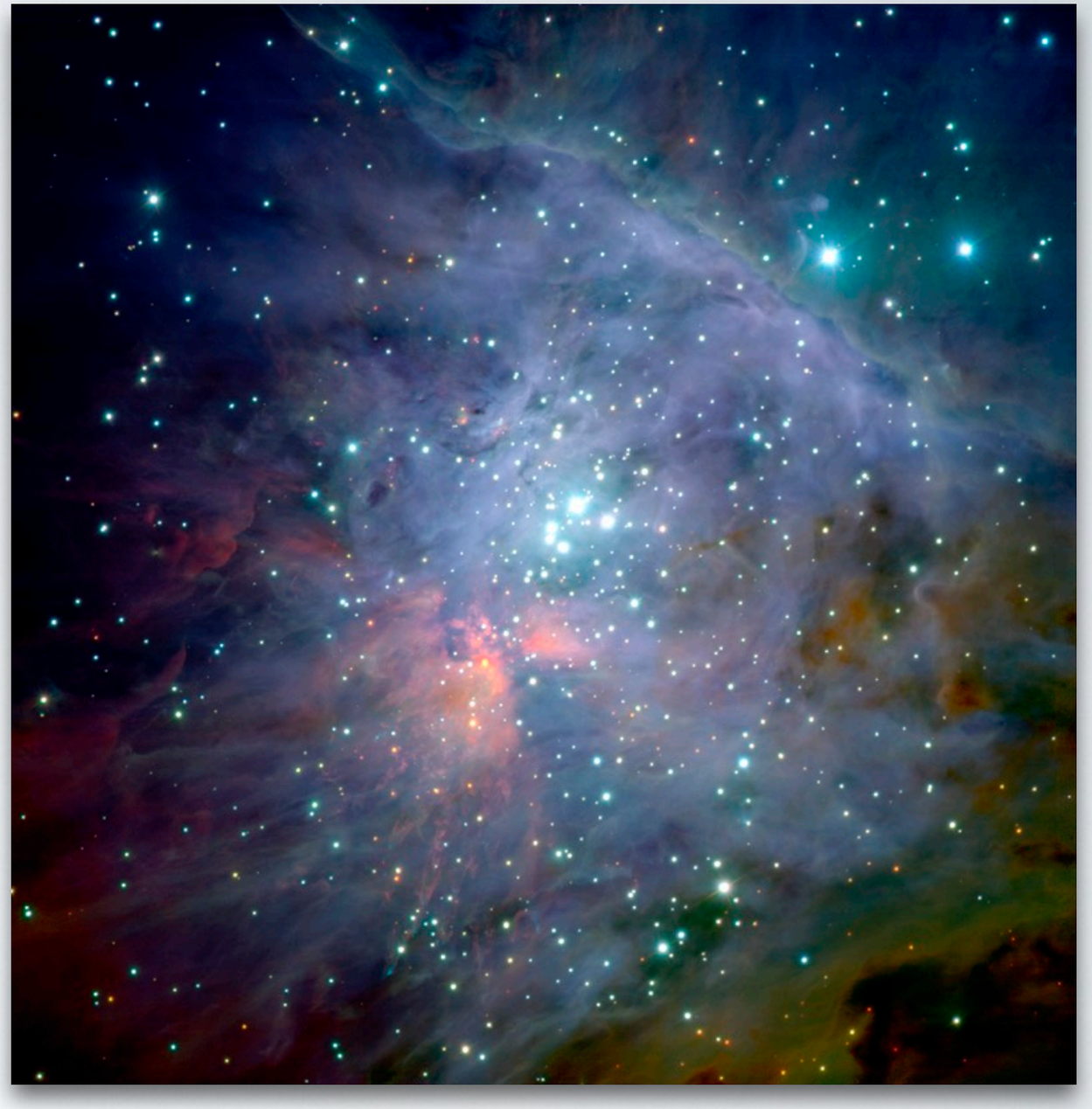


Image: NASA / HST / Wikipedia

Orion Nebula (M42)





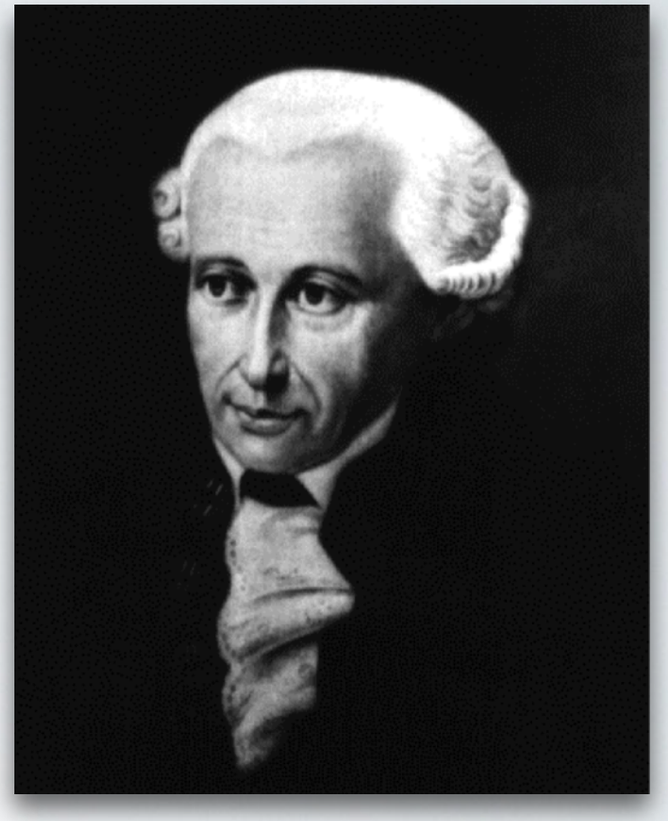
Images: ESO / Wikipedia

Whirlpool Galaxy (M51 a/b)

Drawing by Lord Rosse (1845)

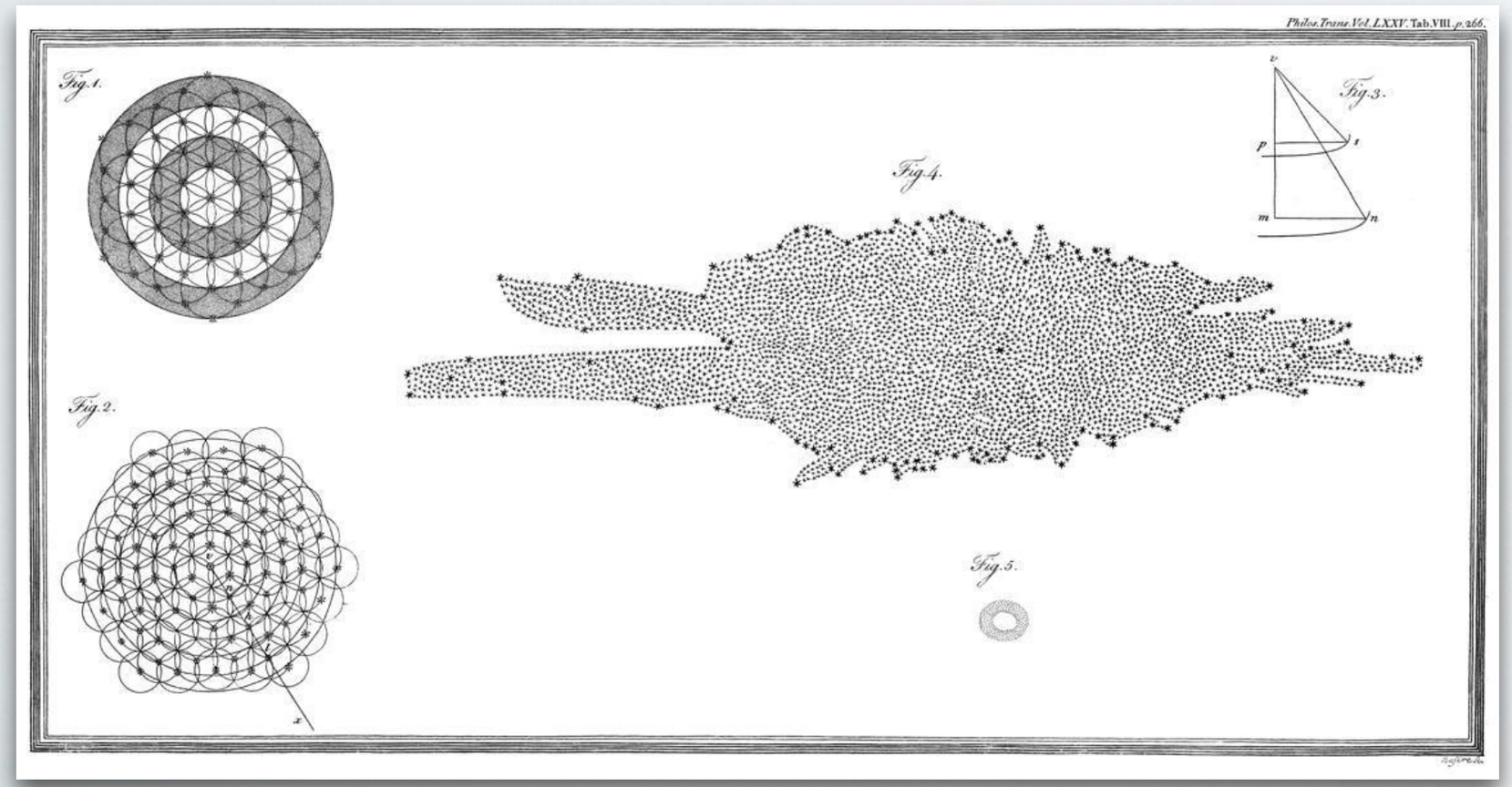
Immanuel Kant and the Island Universe

- **Philosopher** but also interested in astronomy
- Heard about the "nebulae" and postulated that they are separate "worlds" similar to Milky Way
- Called them "**Island Universes**" (1775)
- Views did not take hold becaues there was no direct evidence yet of other galaxies



William & Caroline Herschel

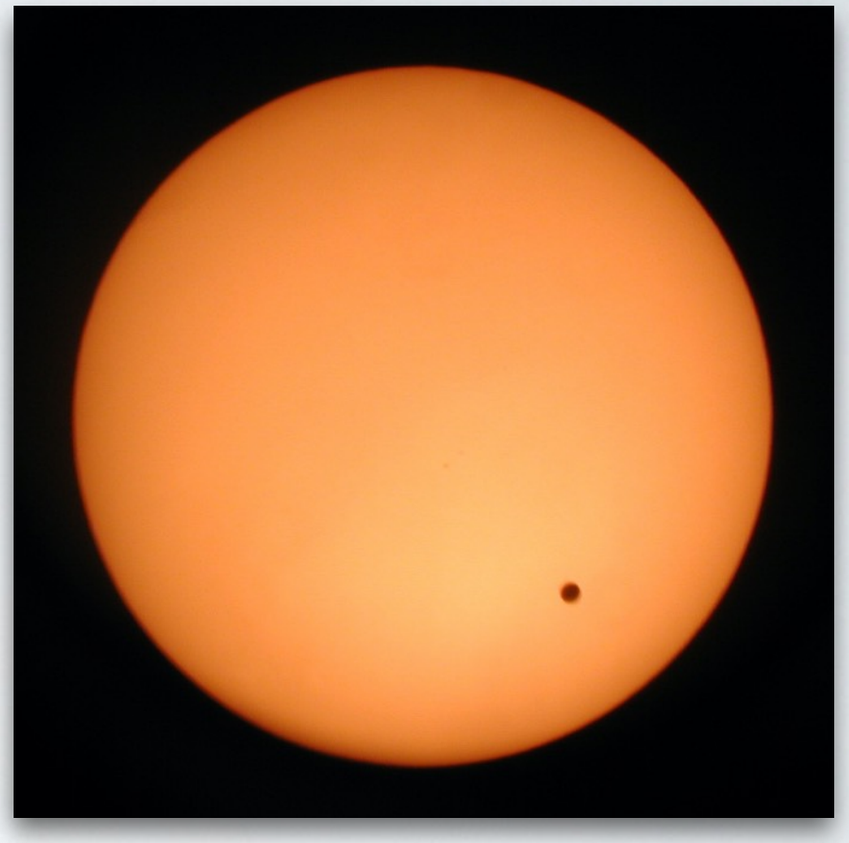
- Discovered Uranus (1781)
- Discovered about 2400 new nebulae
- Thought they could be star collections like MW
- Concluded Milky Way was a disk with the Sun at the center (map from 1785)



Images: Wikipedia

Size of the Solar System

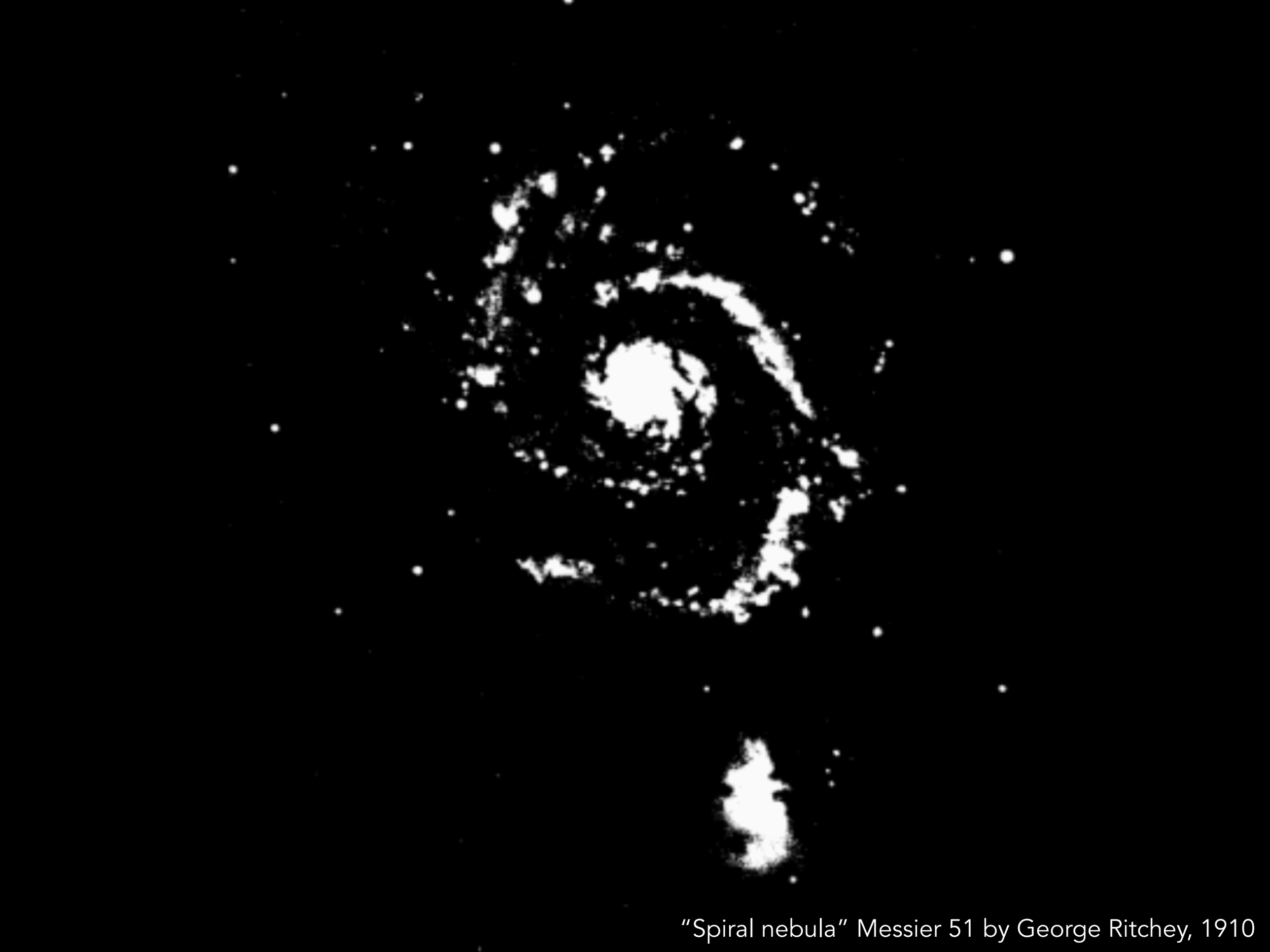
- Many attempts to improve on Aristarchus' measurement
- Gregory / Halley proposed using (rare) **transit of Venus** (as seen from different points on Earth)
- Measured two transits in 1761/1769
- Early example of **collaboration** of many astronomers!
- Got solar parallax of 8.6" **(within 4%)**



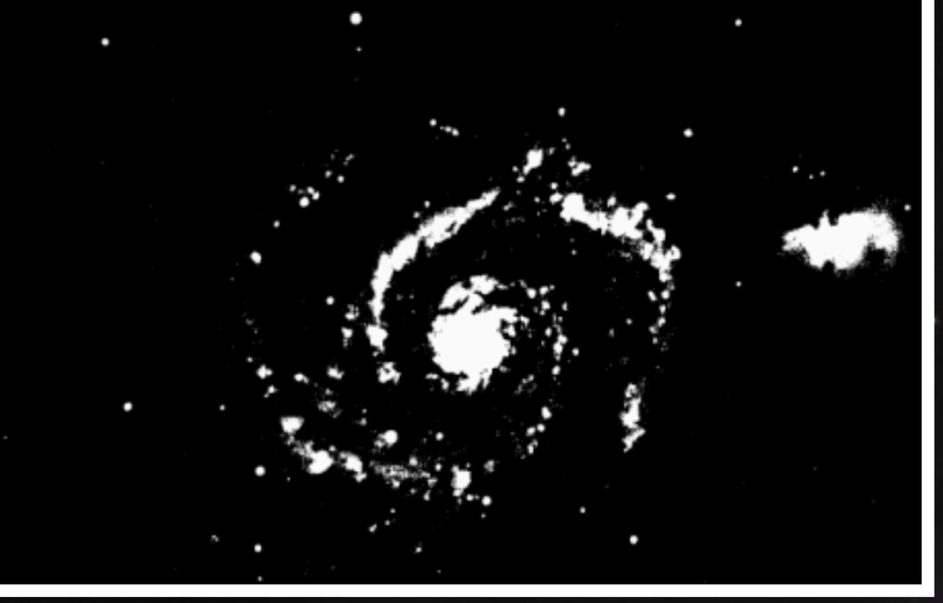
Enlightenment Summary

- **After the enlightenment** (beginning of 19th century), we…
  - have observed thousands of nebulae with different shapes
  - know the scale of the solar system
  - roughly know the shape of Milky Way
- **but…**
  - do not know whether nebulae are in MW or “island universes”
  - do not have a good scale for the Galaxy (no stellar parallax)
  - think the Universe is static

Part 2: The Great Debate of 1920



“Spiral nebula” Messier 51 by George Ritchey, 1910



M51 by Hubble Space Telescope

Additional data about scale of the Universe

- Bessel measured **stellar parallax** of 61 Cygni (1838)
- Heber Curtis (1917) observed novae (strong flares in stars' light) in three spiral nebulae; much fainter than in MW, suggesting **great distance**
- Harlow Shapley showed that Sun is **far out in disk of Milky Way** (but overestimated MW size by factor of three)

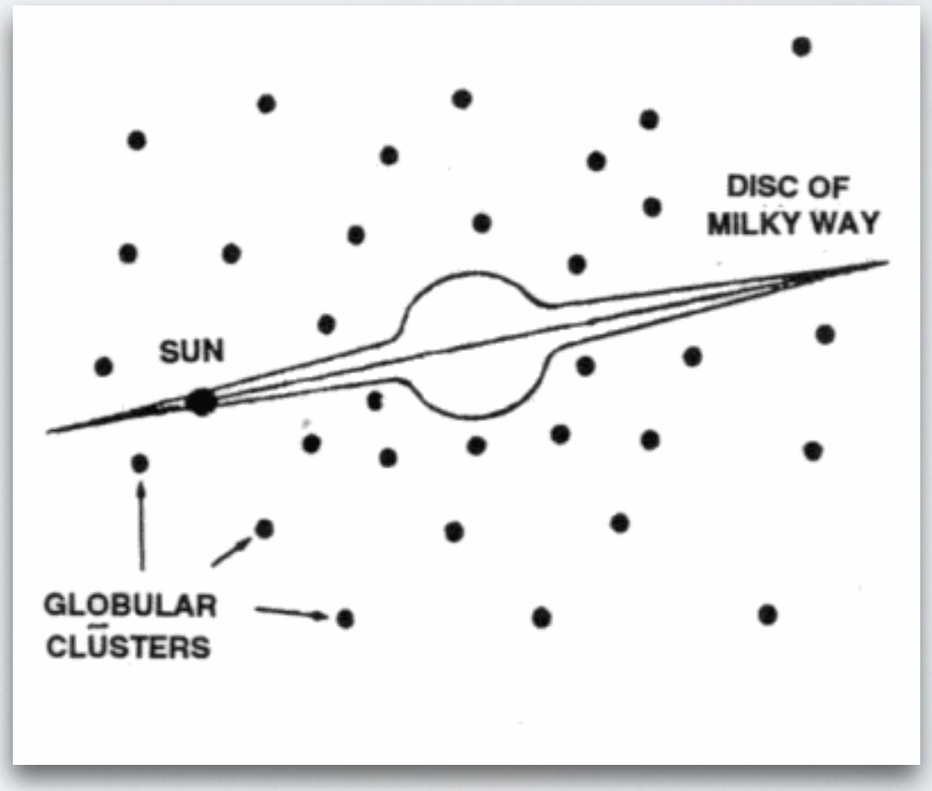
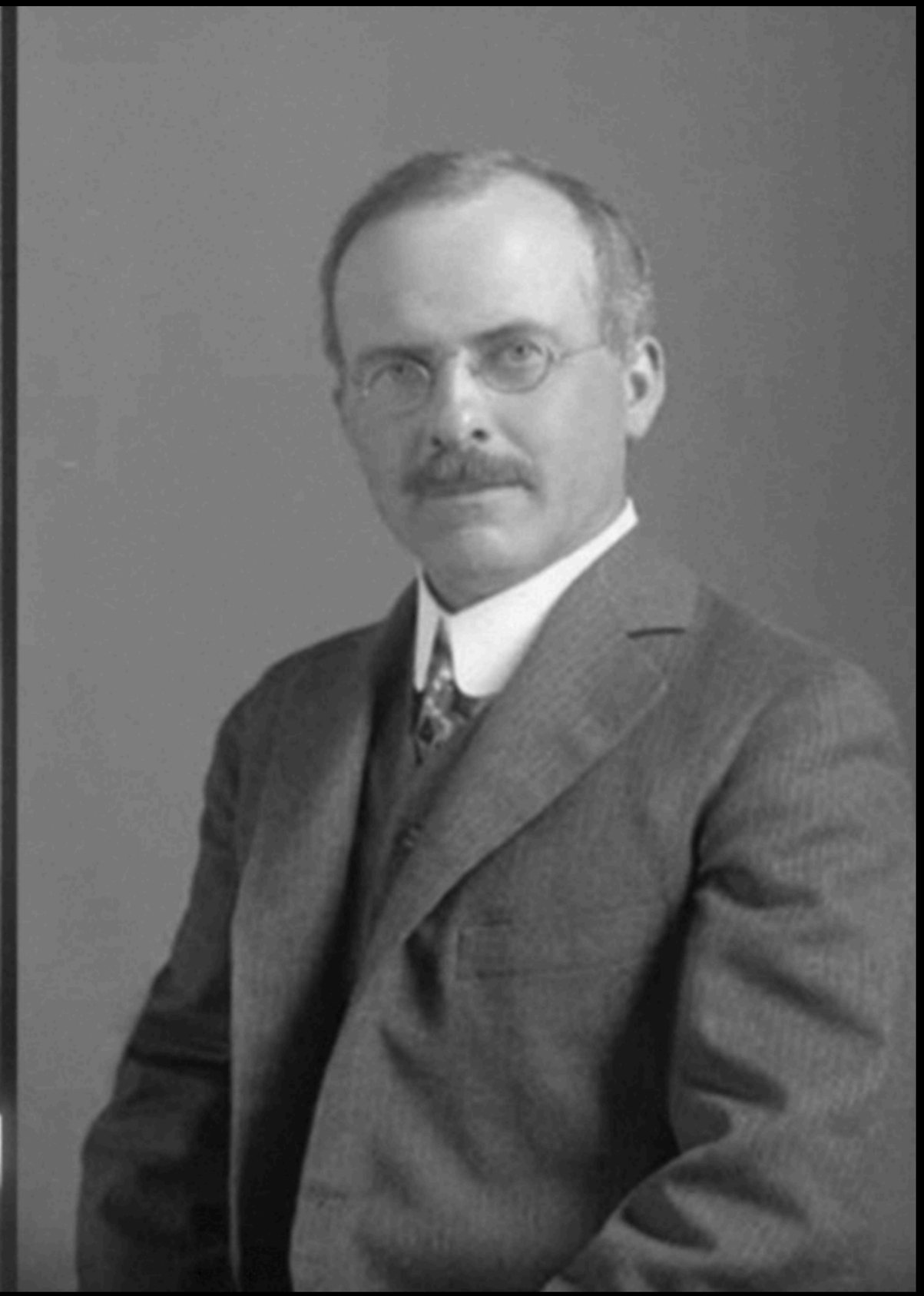


Image: science-frontiers.com

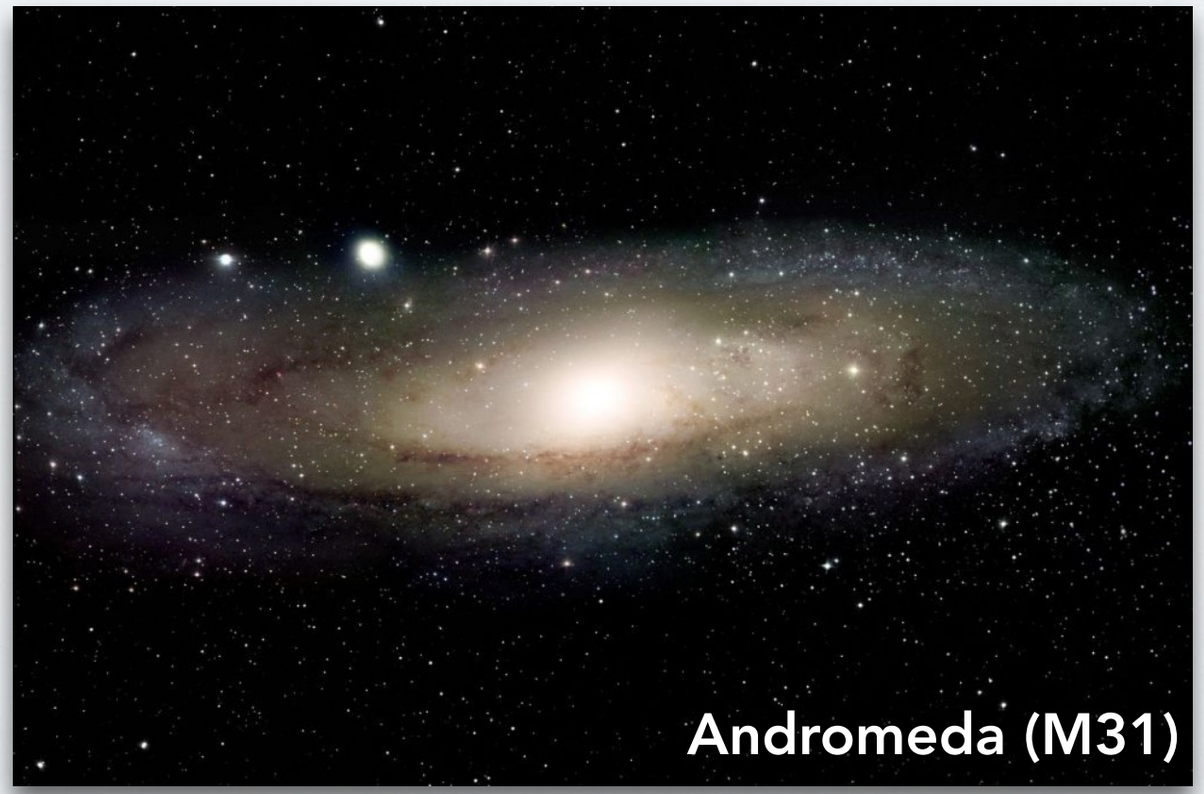
Harlow Shapley



Heber Curtis

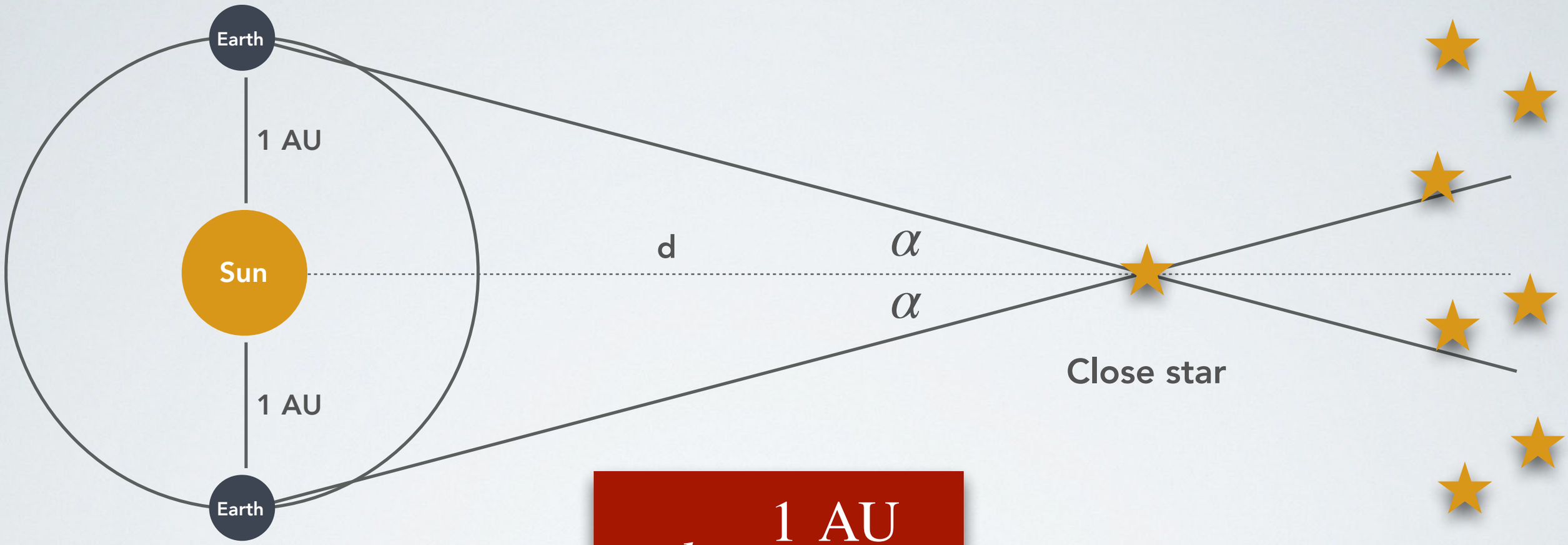
The Great Debate

- **Shapley**
  - If Andromeda not in the MW, must be extremely far away
  - Pinwheel galaxy seen to be rotating (wrong)
- **Curtis**
  - More novae in Andromeda than in MW
  - Novae appear faint in Andromeda (and other nebulae)



Part 3: The distance ladder

Parallax

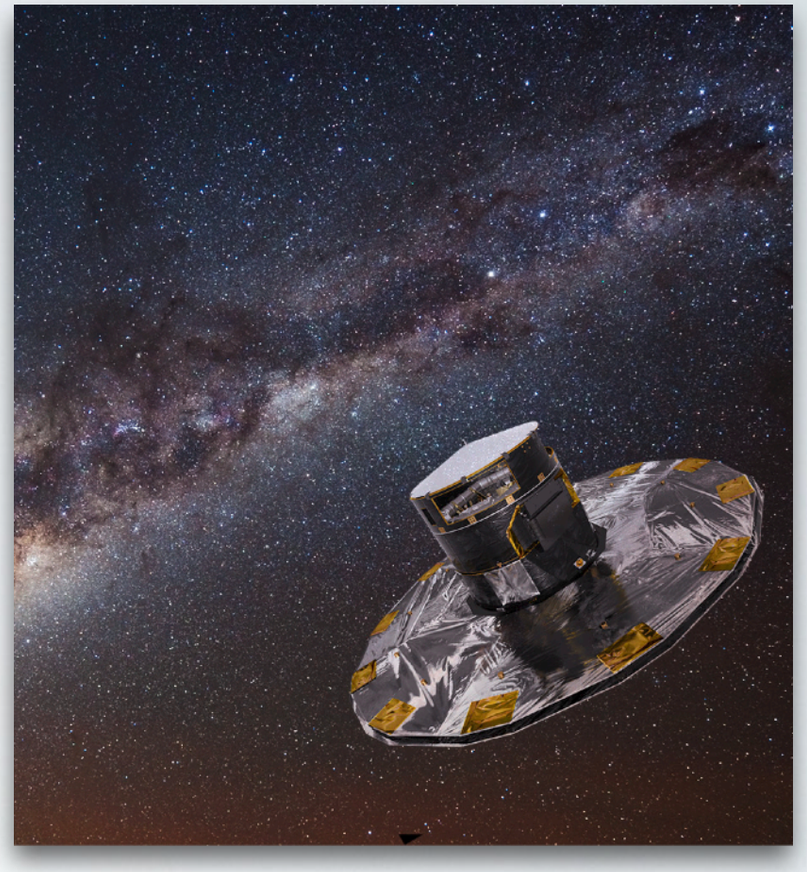


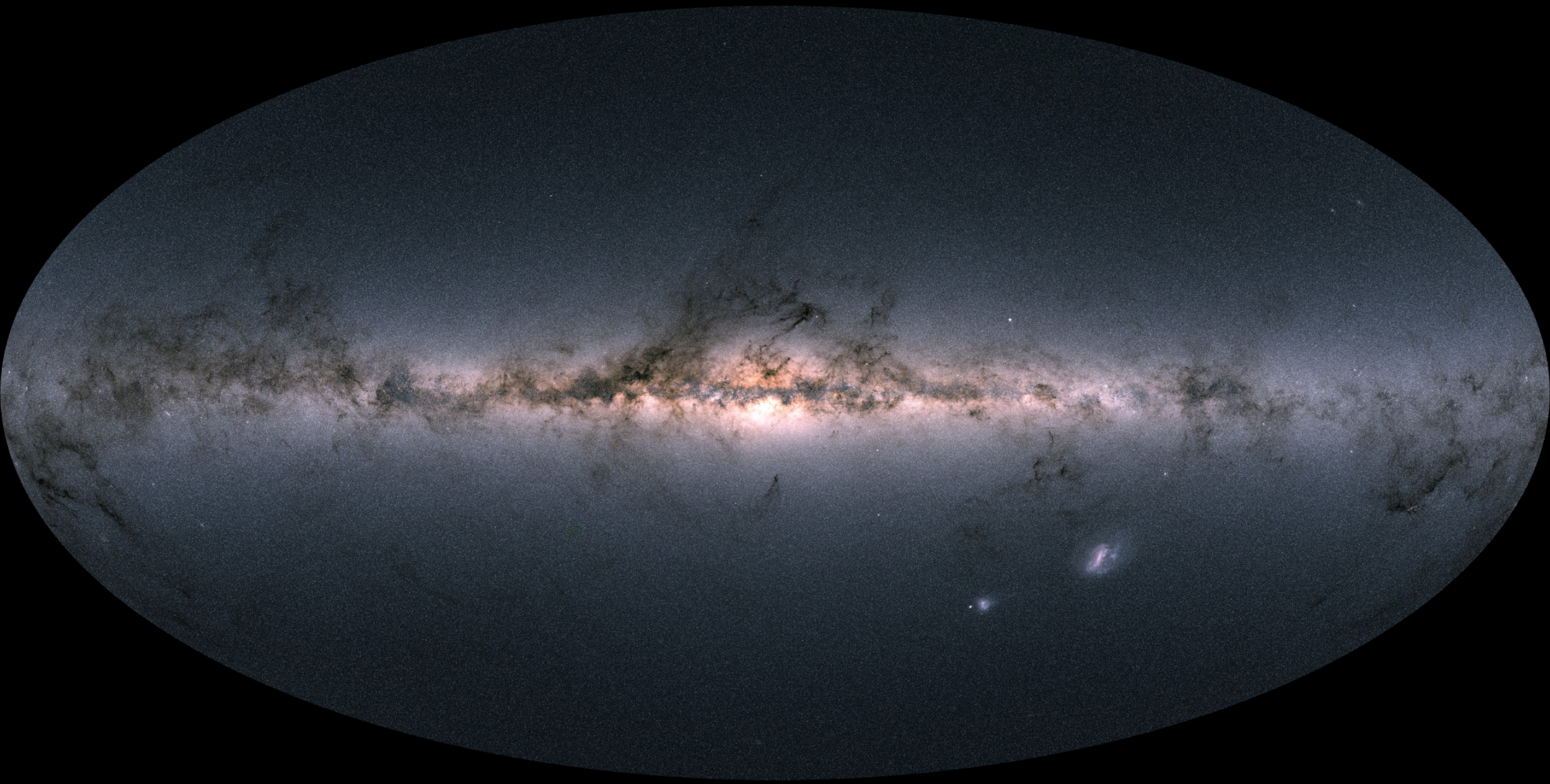
$$d = \frac{1\ \text{AU}}{\alpha}$$

- Angles are expressed in radians
- sin(small angle) ~ small angle

Parallax

- Stellar parallax first measured in 1838 by Friedrich Bessel (0.29″ for the star 61 Cygni)
- Until 1990s, could only detect parallax out to 50 pc
- GAIA satellite (launched 2013) can map out positions and motions of stars **across the whole galaxy** — 1 billion stars!





ESA / GAIA

Participation: Recap #5

TurningPoint:

How far away is the closest galaxy, Andromeda?

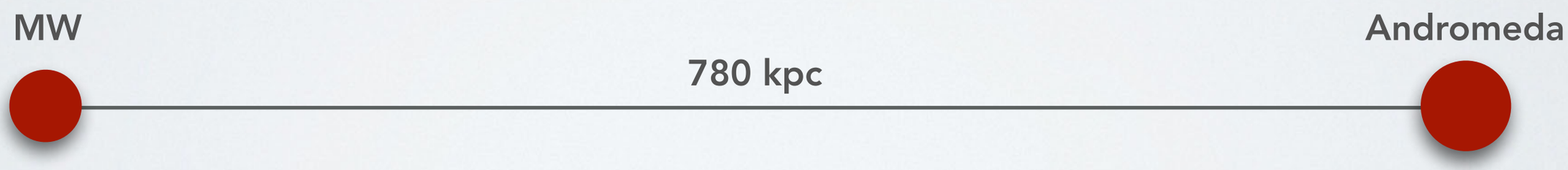
Session ID: diemer

 30 seconds

Parallax to other galaxies?

- Cannot detect parallax in galaxies outside the MW!
- Even for Andromeda (closest neighbor), parallax is

$$\theta = \frac{1''}{780{,}000} = 3 \times 10^{-10} \text{ degrees}$$

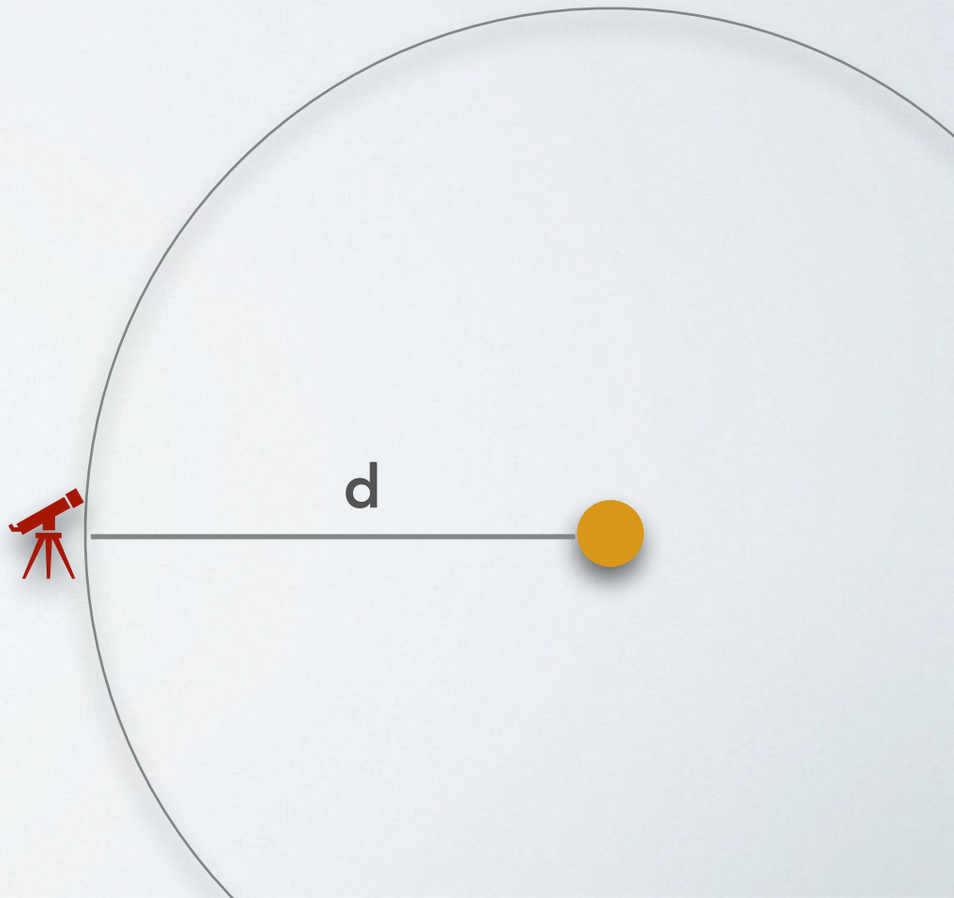


Standard Candles

- Fundamental issue: we cannot discern between an object being **dim** and being **far away**
- Need objects whose **absolute luminosity** we know; then:
  - Total luminosity is L_{std} (energy/time, e.g. erg/s or $L_\odot$)
  - Observed brightness b_{obs} (energy/time/area, e.g. erg/s/cm^2)
  - Distance is d, then

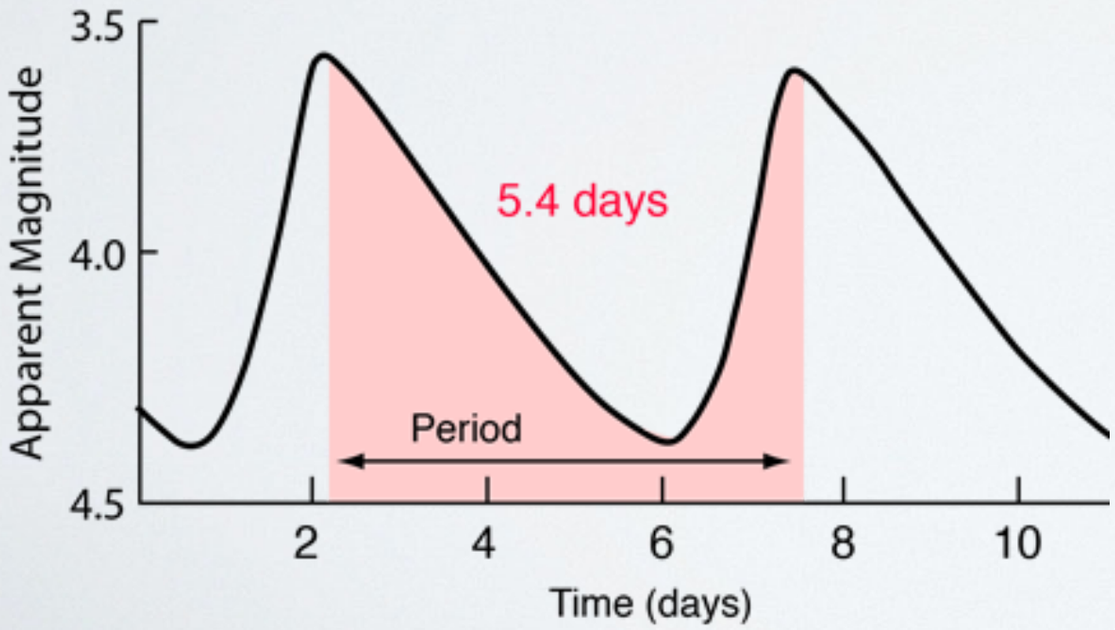
$$b_{\text{obs}} = \frac{L_{\text{std}}}{4\pi d^2}$$

$$\Longrightarrow \quad d = \sqrt{\frac{L_{\text{std}}}{4\pi b_{\text{obs}}}}$$



The first standard candle: Cepheid Variables

- In 1912, Henrietta Swan Leavitt observed a type of **variable star** called Cepheids
- Instrinsic luminosity can then be obtained from apparent brightness and **parallax distance**
- She discovered that Cepheids' total luminosity is related to the **period of fluctuations**
- Cepheids can be used as **standard candles!**



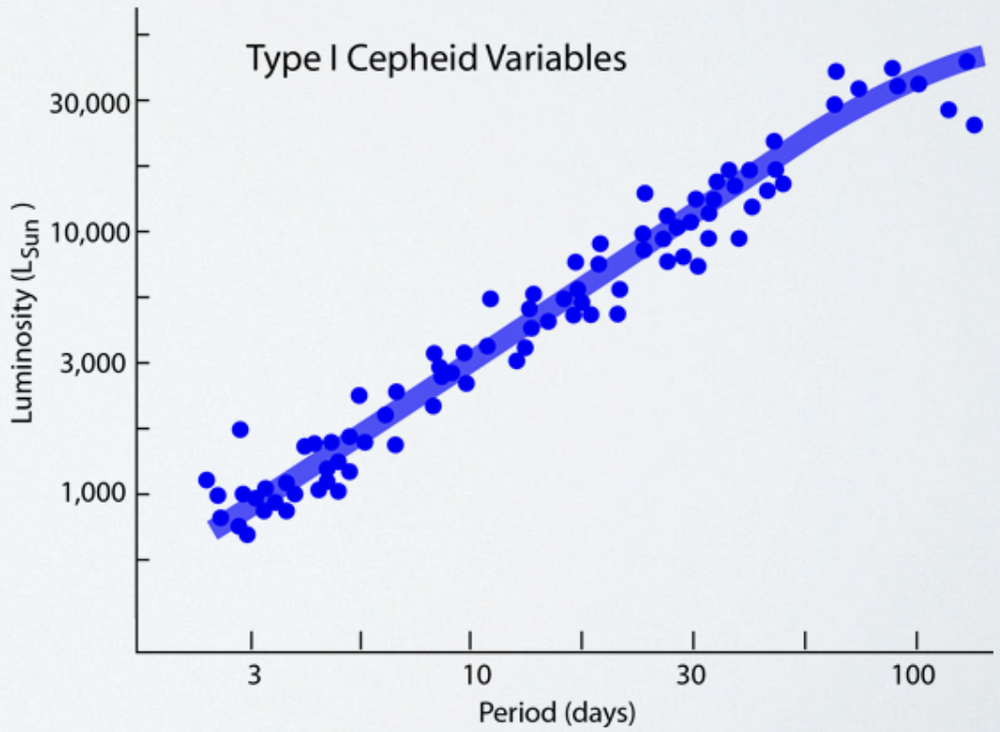
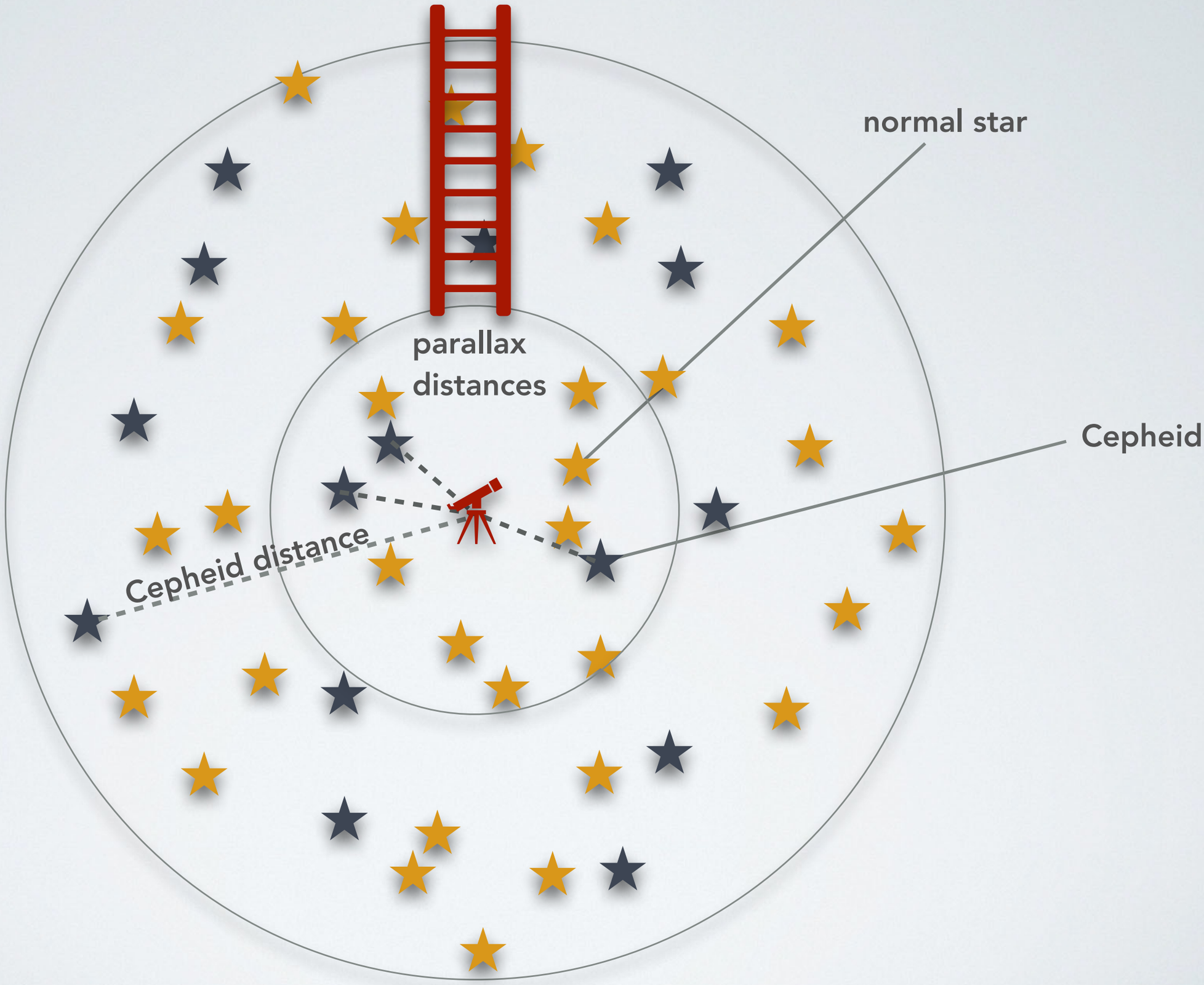


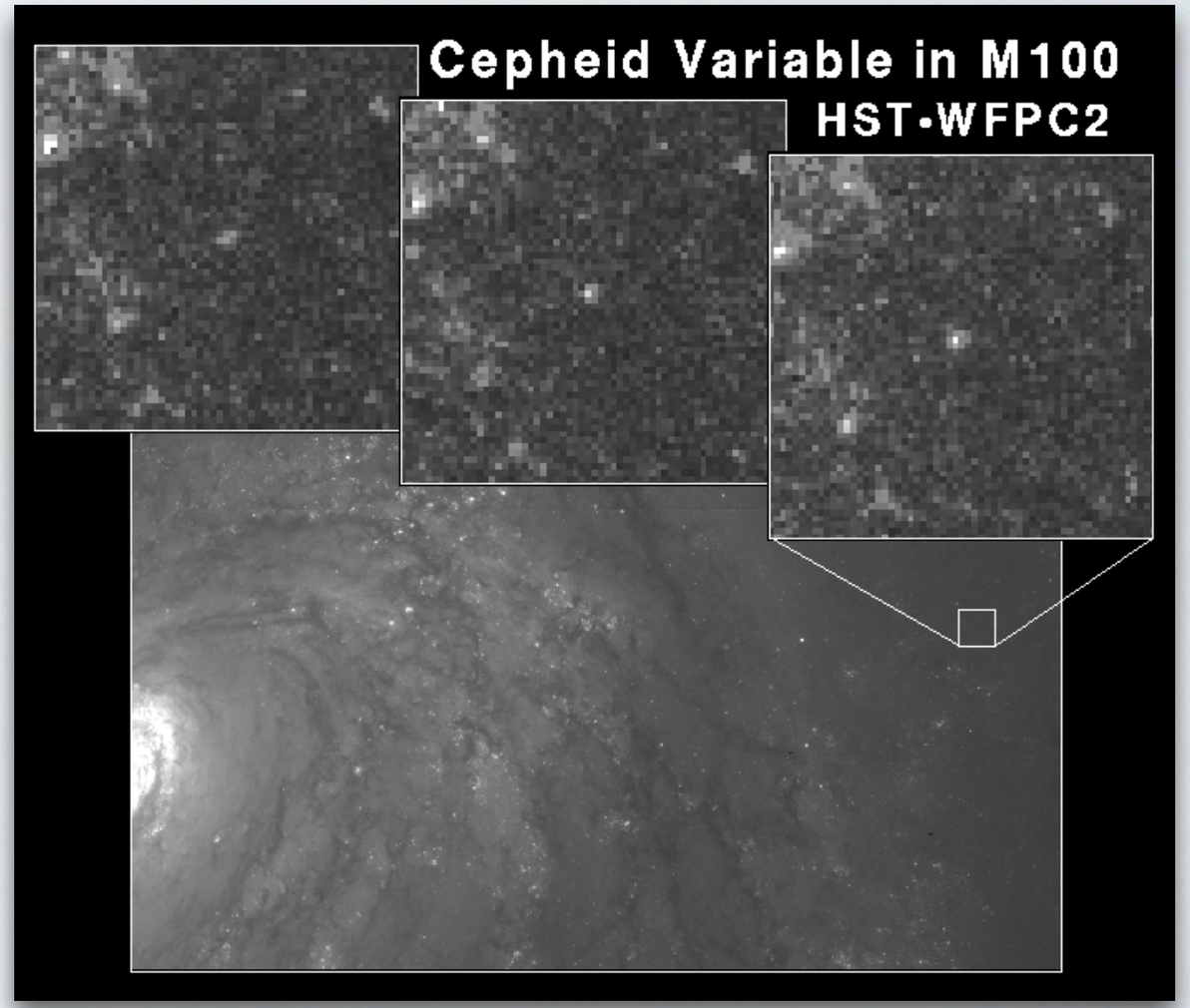
Image: hyperphysics.phy-astr.gsu.edu

Distance “ladder”



Cepheids Today

- In modern times, Cepheids in the Virgo galaxy cluster have been measured with Hubble Space Telescope (16 Mpc away!)



Participation: Group discussion #11

Messier Objects

Without knowing anything about what they are, how many categories would you sort them into?

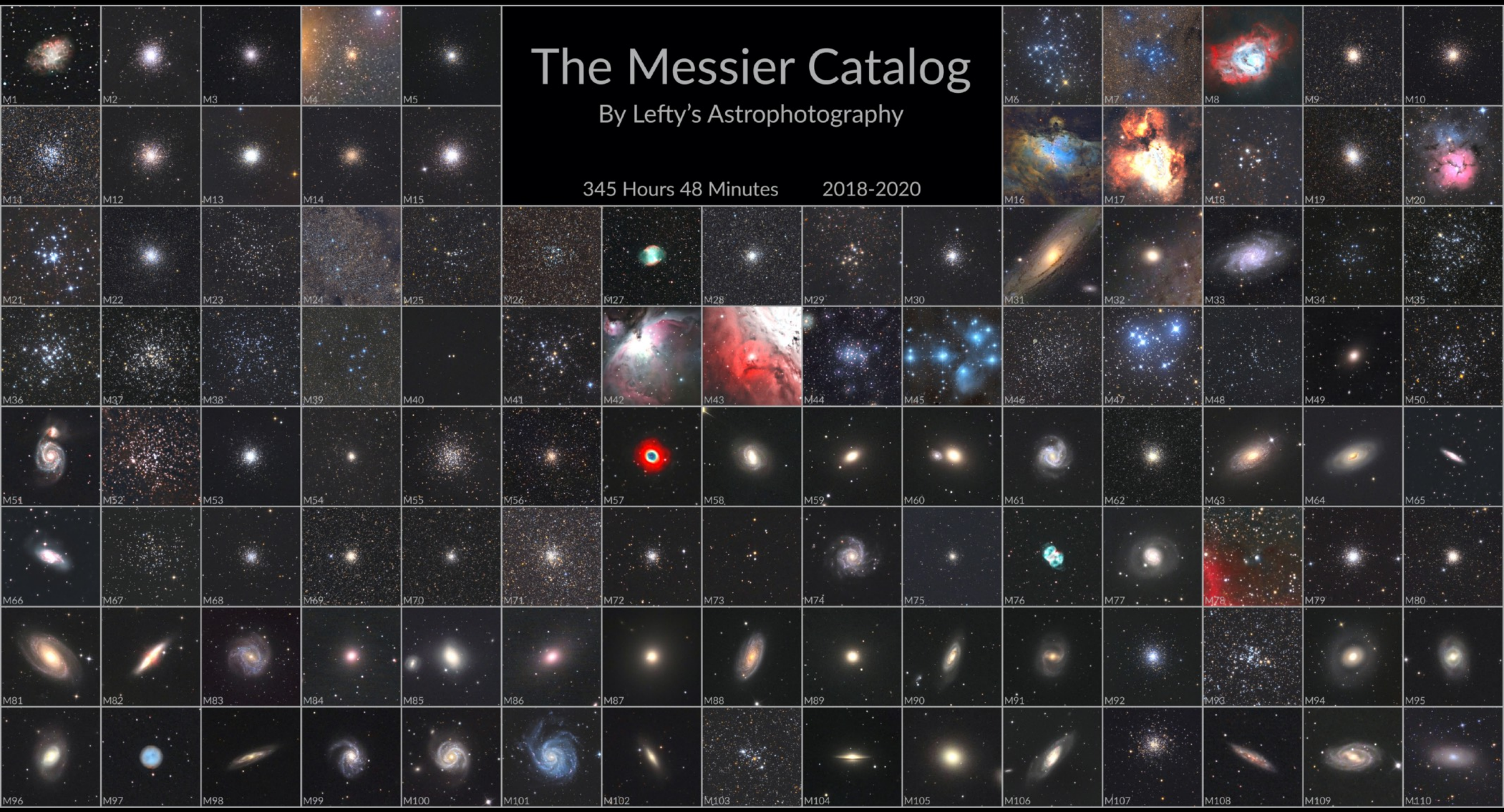
Find a descriptive name for each category ("pink bunnies", "green squares"), write down a few of its characteristics, and list a few objects that would fall into this category. Are there any weirdos that don't fit any group?

 10 minutes

The Messier Catalog

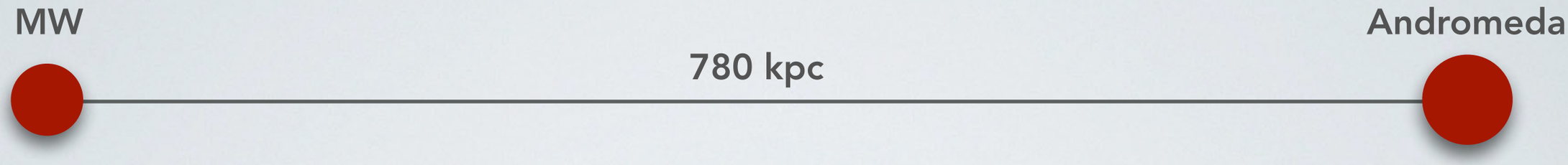
By Lefty's Astrophotography

345 Hours 48 Minutes 2018-2020



Part 4: Hubble and the Expanding Universe

The distance to Andromeda

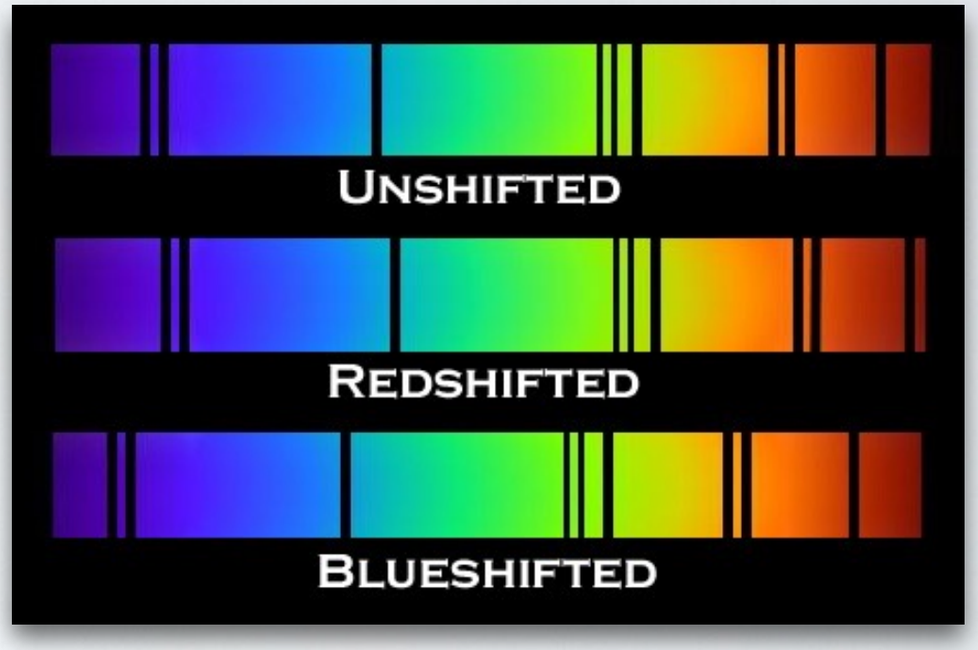


- Studied Andromeda “spiral nebula” with 100-inch telescope on Mount Wilson
- In 1924, Edwin Hubble first observed a variable star with properties of a **Cepheid in Andromeda**
- Determined that Andromeda must be **well outside MW**, settling the Great Debate!

Cosmological Redshift

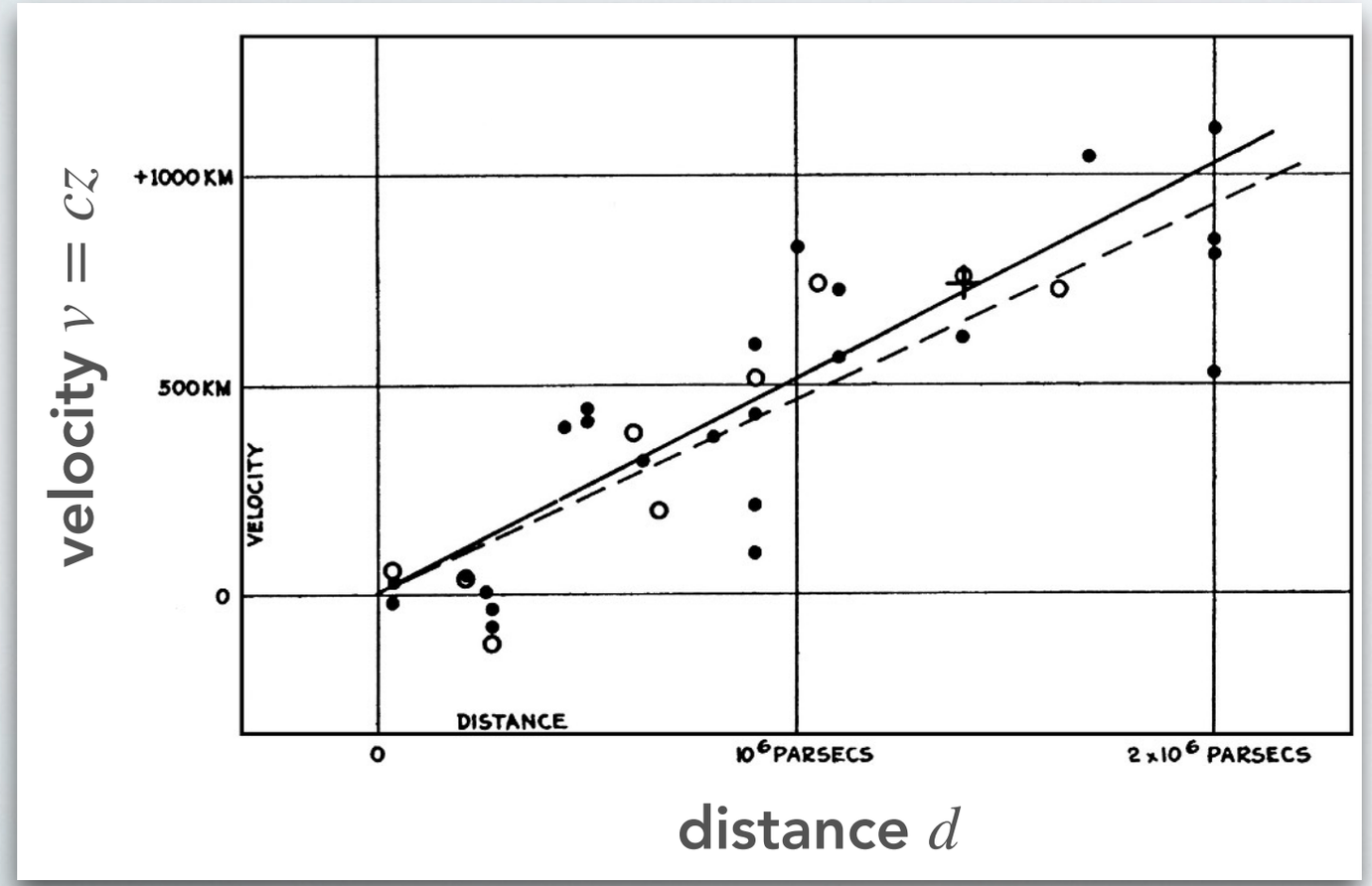
$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{em}}}{\lambda_{\text{em}}}$$

- Defined as the **relative shift in wavelength** between the emitted and observed light
- The "redshift" can be…
  - **z > 0:** redder, longer wavelength
  - **z < 0:** bluer, shorter wavelength
- Approximation $z \approx v/c$ can be used at **low redshift** and small velocities (v << c)



Hubble-Lemaitre law

- Slipher (1912) measured redshifts of some spiral nebulae, found **large velocities** (>1000 km/s) relative to MW
- Hubble and Humason systematically studied galaxies
  - Obtained **redshifts** from stellar spectra
  - Obtained **distances** using Cepheids and other estimates
- Interpreted redshift as Doppler shift, v/c (valid at low redshift)
- **Linear** relationship!
- Published in 1929; Lemaitre published same result in 1927 (in low-impact journal)



$$v = H_0 \times d$$

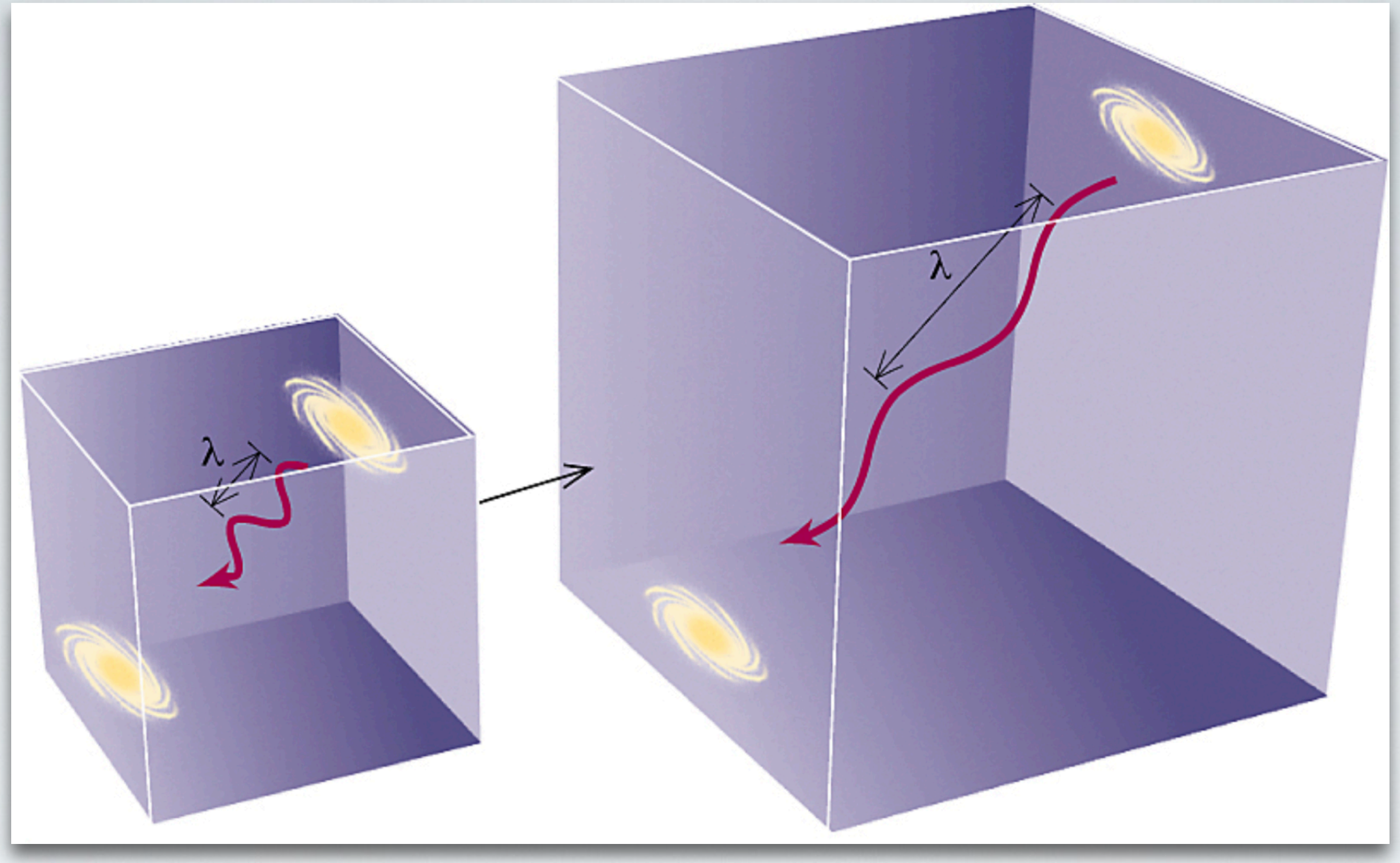
$$H_0 \approx 70 \ \frac{\text{km/s}}{\text{Mpc}}$$


Vesto Slipher


Milton Humason


Georges Lemaitre

Cosmological redshift



Redshift is caused by the expansion of space!

Hubble & The basketball

Images: UChicago / NASA

Take-aways

- The **enlightenment** era was the beginning of **extragalactic** astronomy, but it was unknown whether galaxies ("nebulae") were inside Milky Way or separate objects

- We can use the **distance ladder** technique to calibrate **standard candles** that can be seen from farther away

- Galaxies that are **farther** away **move** away from us **faster**

Next time…

We'll talk about:

- Big Bang Theory & The expanding Universe

Assignments

- Post-lecture quiz (by tomorrow night)
- Homework #2 (by Thursday)

Reading:

- H&H Chapter 11