

For Recitation Tomorrow: read about Dark Matter using link on Canvas

Reading: Chapter 19, Sect. 19.3, Chapter 26, Sect. 26.4-26.5

Reading for next time: Chapter 28, Section 28.2, Chapter 27

Last time: Galaxy Morphologies



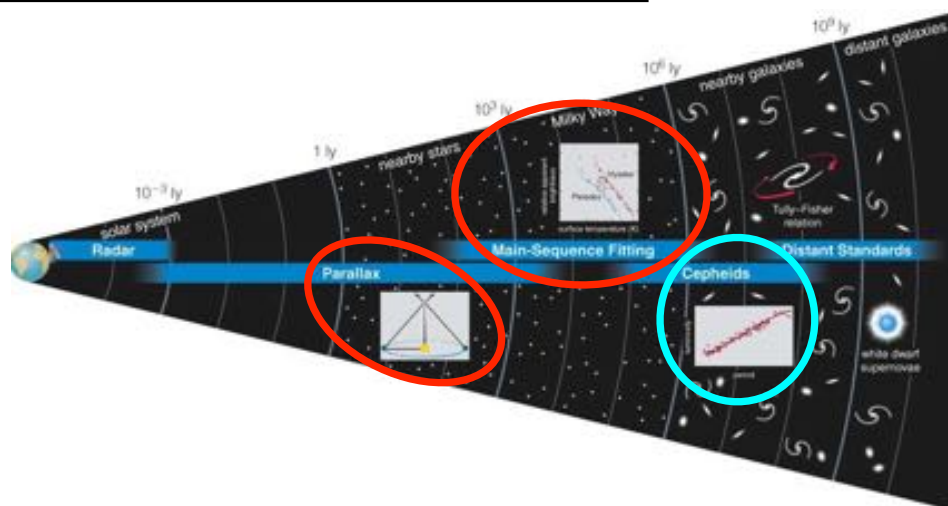
- dozens of galaxies lie near the Milky Way in our “local group”
- Spirals come in many forms, but most galaxies are not spirals, but ellipticals or irregular
- Galaxy mergers and collisions are responsible for making ellipticals and irregulars from spirals

Today: Galaxy Distances and Motions

- By using variable stars and other “standard candles” we can measure the distance to other galaxies across the known Universe
- The ‘Hubble Law’ - we live in an expanding universe

Galaxy Distances:

The Cosmic Distance “Ladder”



Galaxy Distances:

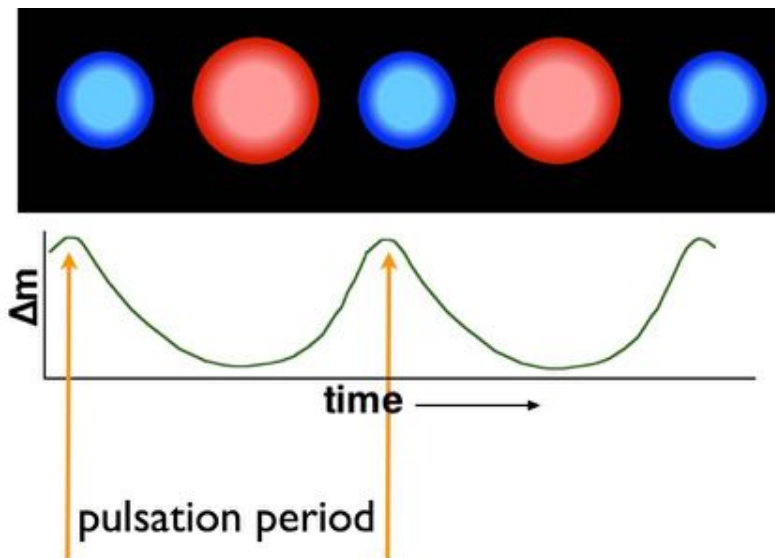
The Cosmic Distance “Ladder”

- **Step 1: Nearby stars and clusters - to ~1000 pc**
 - trig. parallax - to ~ 1000 pc (Hipparcos)
 - main sequence fitting / stat. parallax to ~ 30,000 pc
- **Step 2: “Nearby” Galaxies**
 - **Cepheid Variable Stars**
 - luminous core He- burning stars that pulsate
 - Pulsation period proportional to luminosity:
 - **Period-Luminosity Relation for Cepheids:**
 - longer period \leftrightarrow higher luminosity

Period \rightarrow Luminosity

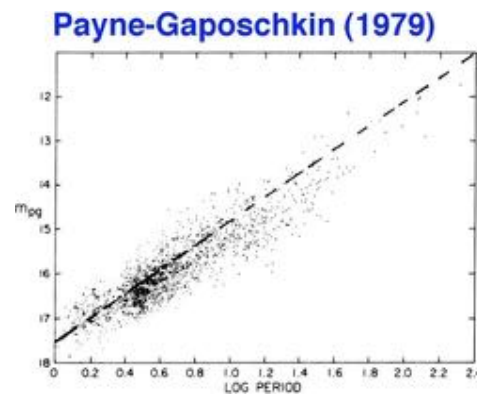
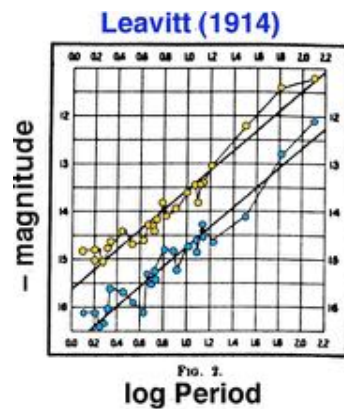
+ apparent magnitude \rightarrow distance

accurate to ~ 20% or better out to 20 Mpc!

Cepheid variable stars

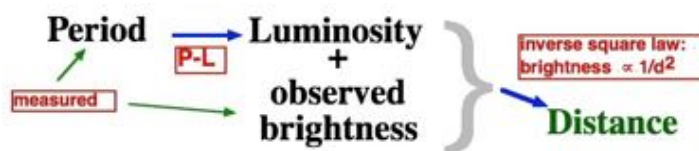
The P-L relation

- 1912: **Henrietta Leavitt** finds [the “Period-Luminosity Relation”](#)
- Cepheids are **intrinsically very bright**
 - visible in **distant galaxies**
 - in SMC - all at ~same distance
 - plot brightness (m) vs. Period (P)...



Cepheids as “Standard Candles”

- intrinsic brightness depends only on period!



$$d \text{ parsecs} = 16.1 \times P_d^{0.55} \times 10^{0.2m}$$

- **accurate to ~20% or better out to 20 Mpc**
- **Examples:**
 - 4 d period Cepheid in U Mi. $m=2.24$ (96.8 pc) POLARIS
 - 20 d period Cepheid in Andromeda: $m= 19.8$ (0.75 Mpc)
 - 20 d Cepheid in NGC 3351 (Virgo clust): $m= 25.5$ (10 Mpc)

"I am constant as the Northern Star.."

Julius Caesar Act III, Scene 1, line 60

Shakespeare, 1599



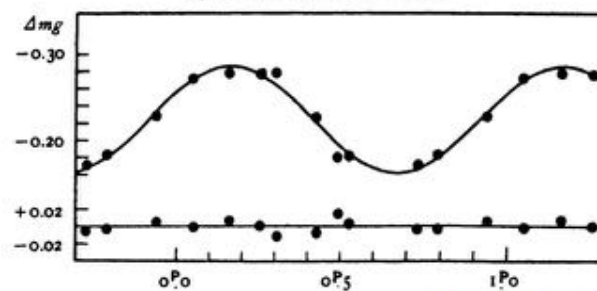
"I am constant as the Northern Star.."

Julius Caesar Act III, Scene 1, line 60

Shakespeare, 1599

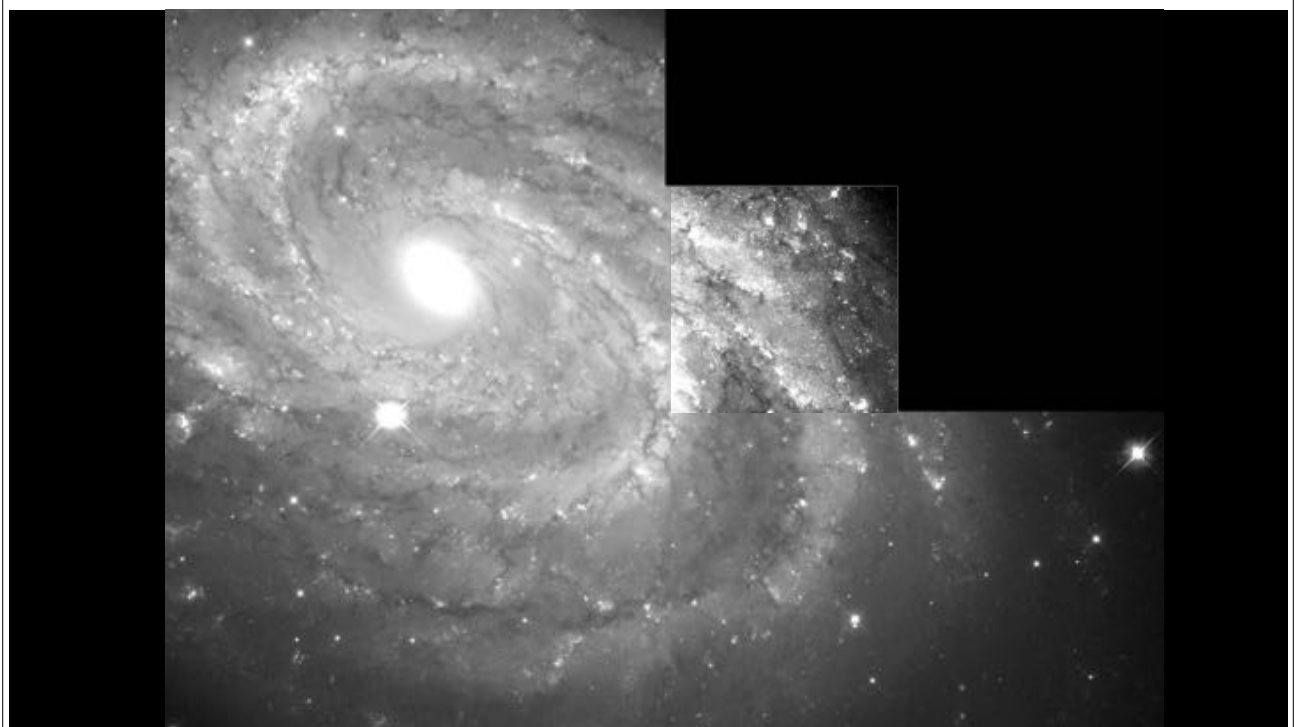
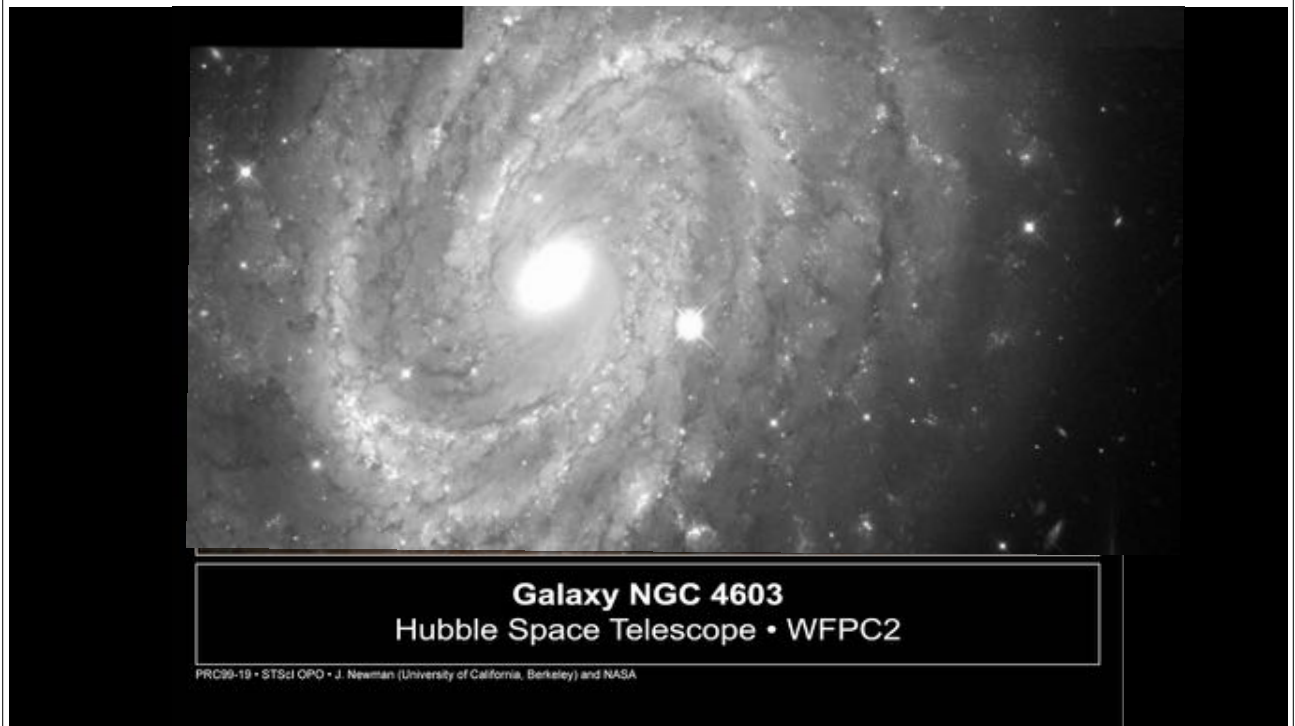
- but... the North Star (Polaris) is a Cepheid!
- 314 years after Shakespeare:

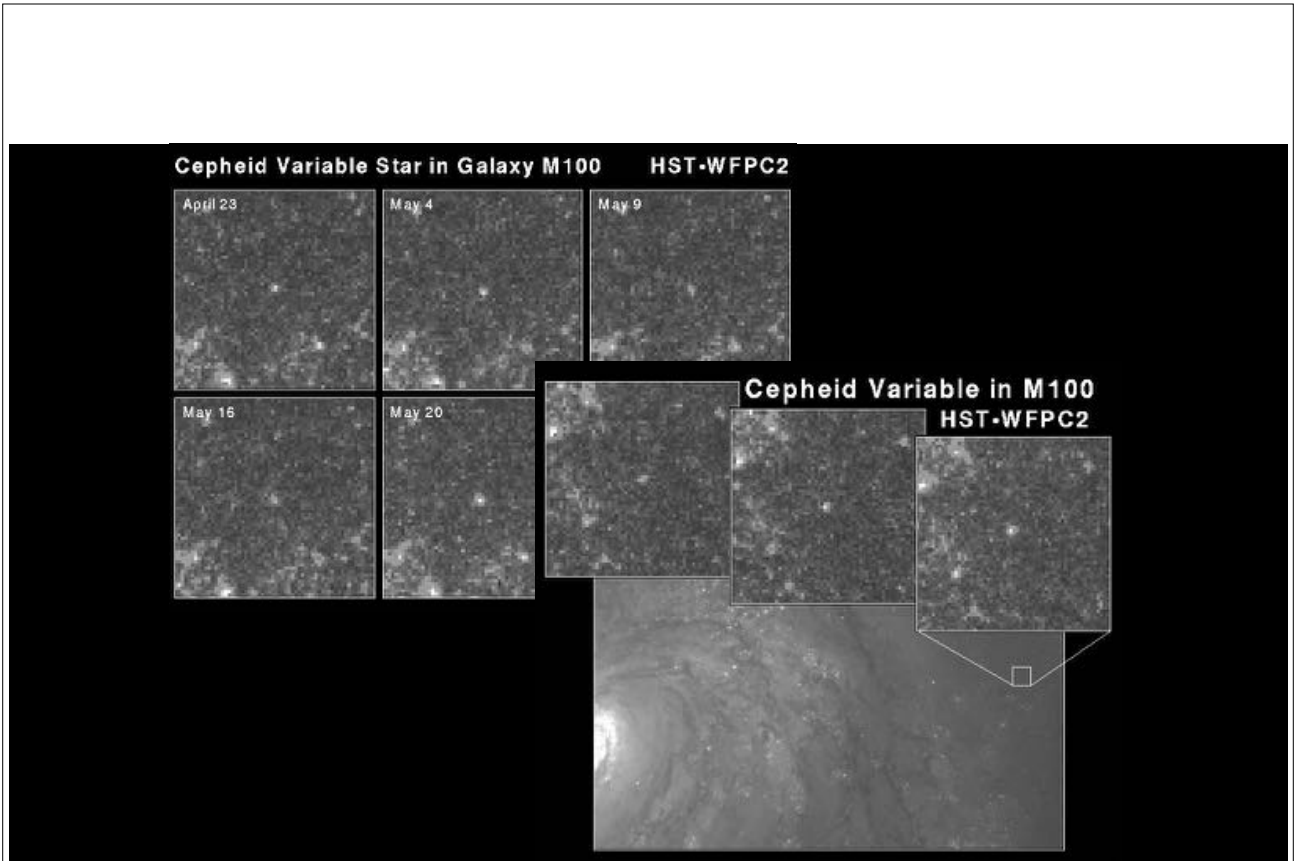
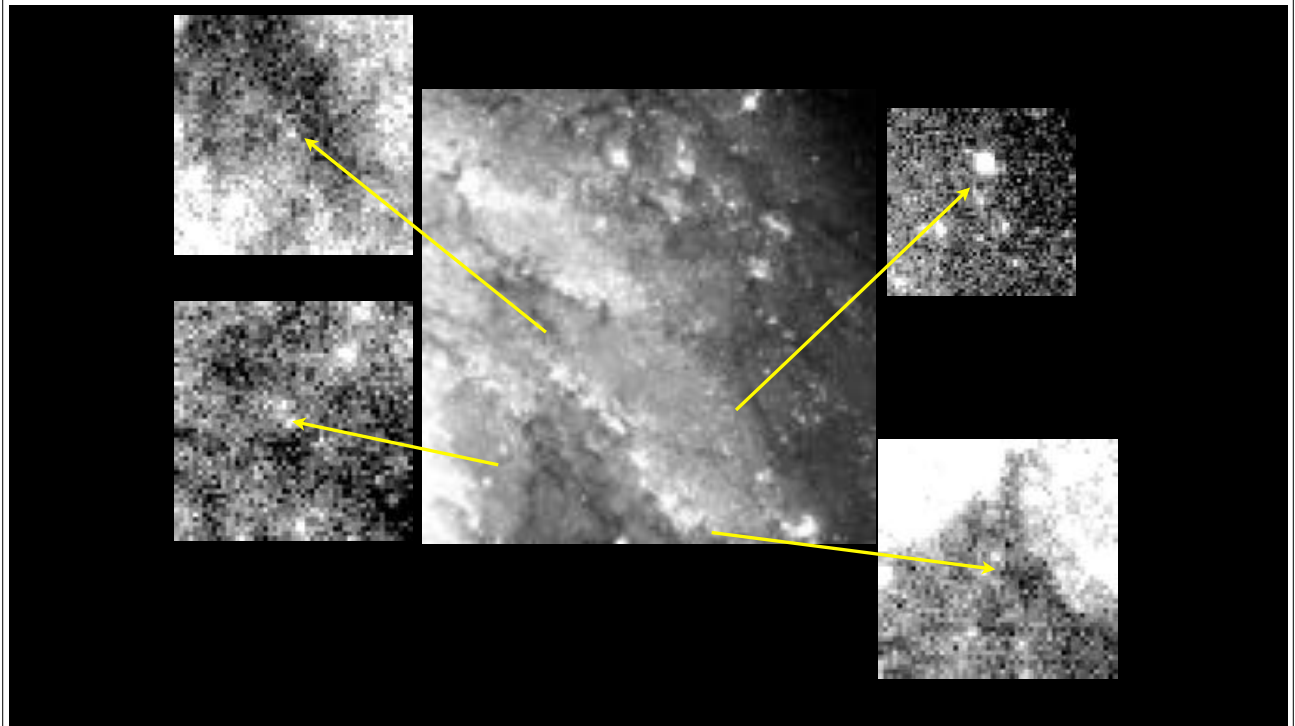
Fig. 4. Lichtkurve von Polaris.

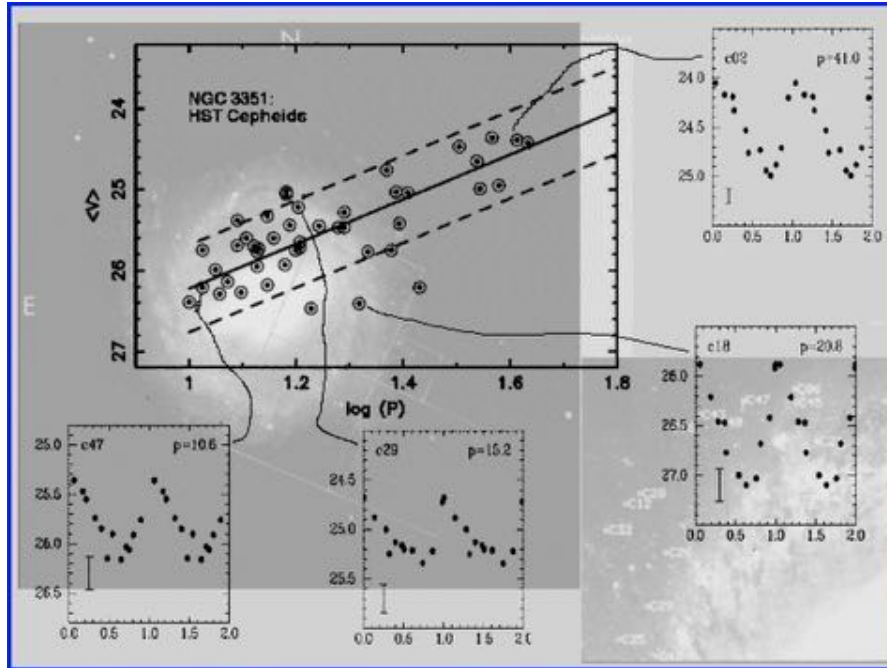


Panekoek, 1913

- P-L relation distance for Polaris = 314 light years!

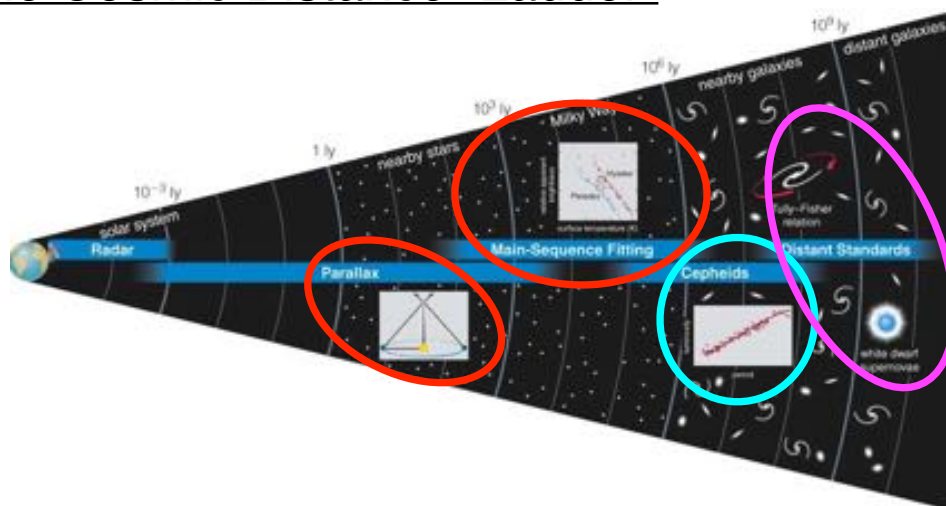






Galaxy Distances:

The Cosmic Distance “Ladder”



Step 3: Beyond Cepheids (20 Mpc - 1000 Mpc)

• Tully-Fisher Relation

- width of spectral lines → mass of galaxy

→ Luminosity → Distance

• Average Galaxy Characteristics

- luminosity of brightest HII region
- luminosity of planetary nebulae
- luminosity/size of galaxy type

Step 4: Beyond 1000 Mpc

- Type Ia Supernovae (out to 3000 Mpc)
- brightest galaxy in cluster (???)

Type Ia Supernovae as distance indicators

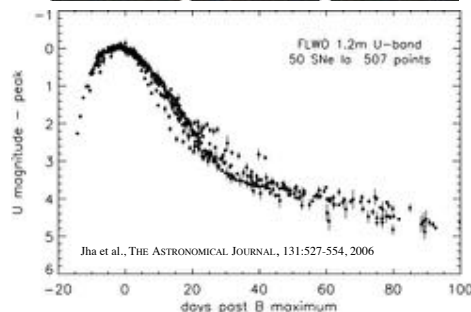
Distant galaxies before supernova explosions

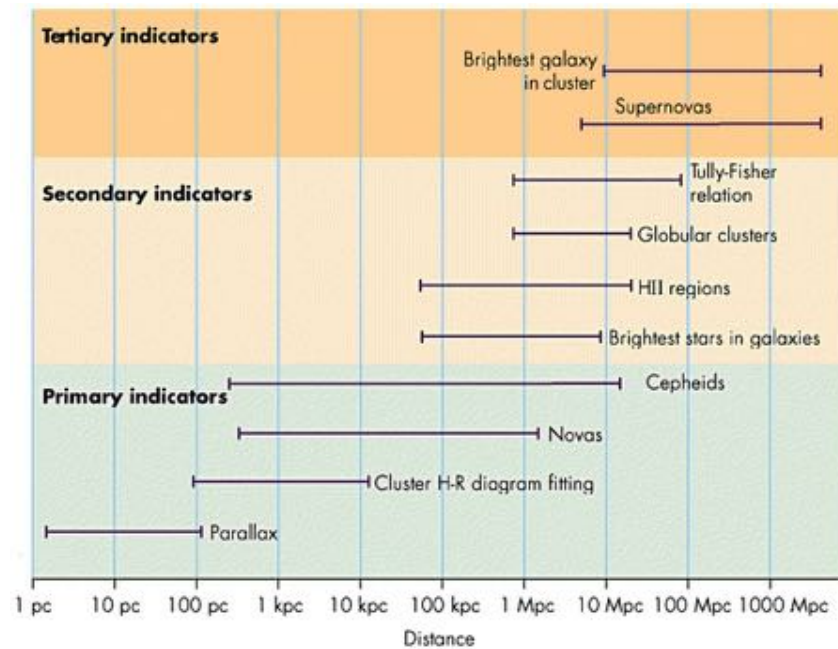


The same galaxies after supernova explosions



- white dwarfs tipped over $1.4M_{\odot}$
- very uniform explosion properties
- visible to very large distances





Galaxy Motions (radial velocity only)

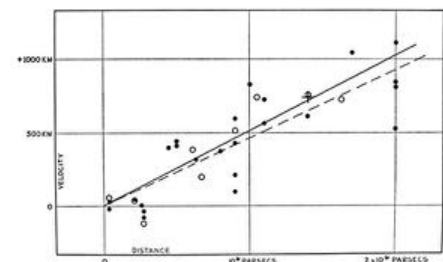
• 1920s: Hubble & Slipher

- survey of galaxy distances and radial velocities
- most galaxies show red shifts
- **larger redshift** →
more distant galaxy



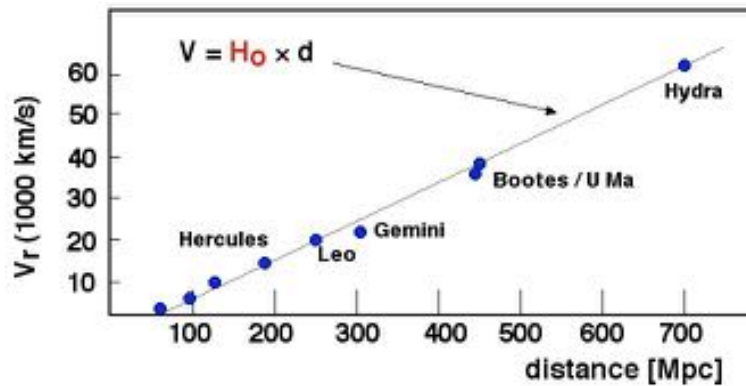
• The Hubble Law

- Velocity = $H_0 \times \text{distance}$
- H_0 = the Hubble Constant [units of km/s/Mpc]



The Hubble Law

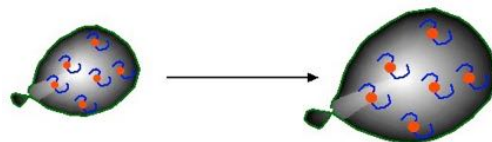
- H_0 is the “Holy Grail” of modern astronomy:
 - sets the **scale** of the Universe
 - reflects the **age** of the Universe
 - hints at the **future** of the Universe



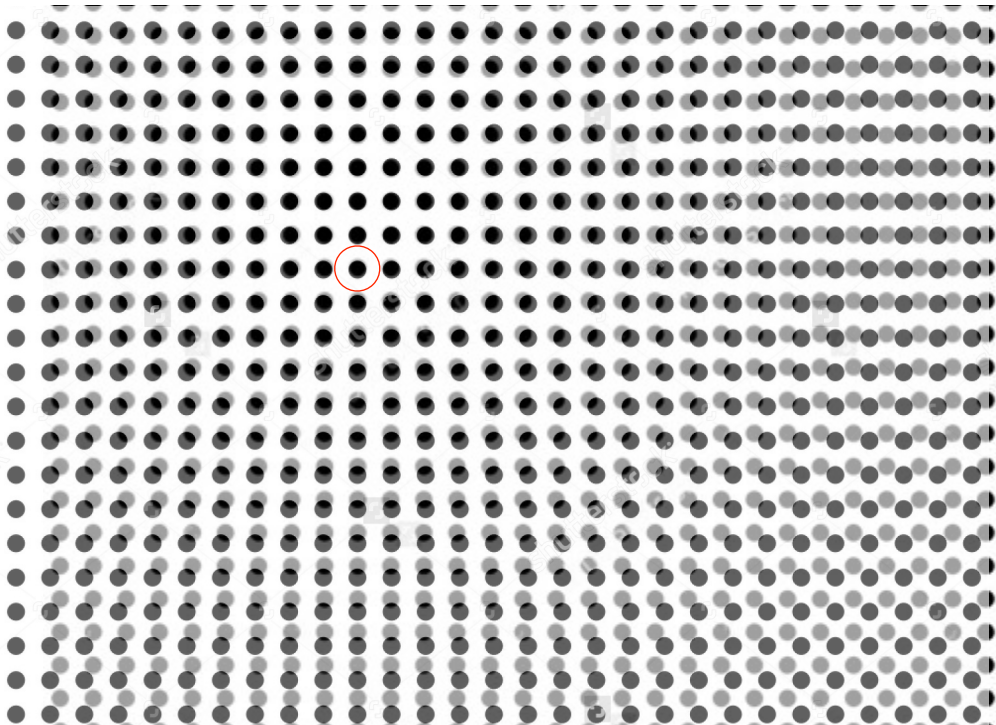
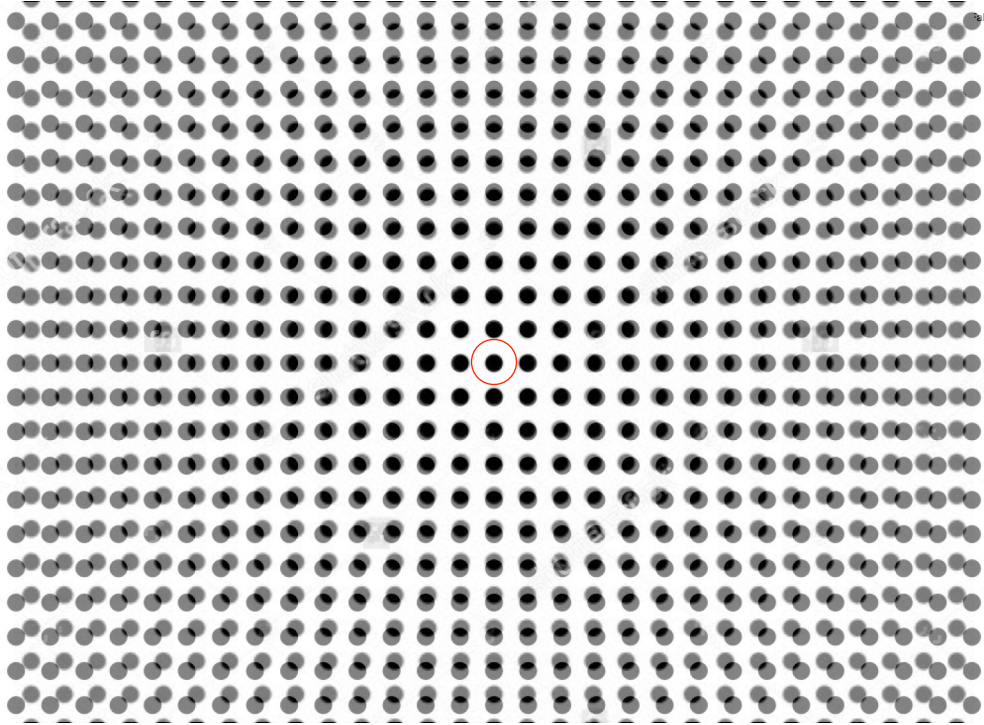
if **ALL** distant galaxies are moving away from us,
are we at the center of the Universe?

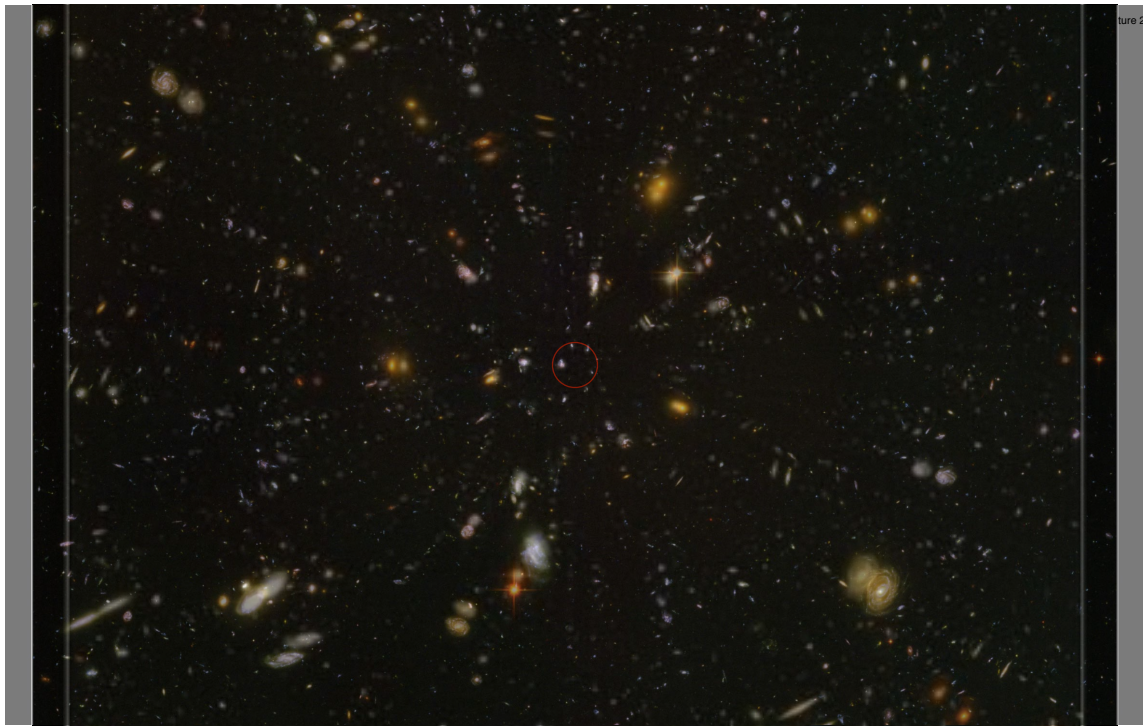
NO!

- in an **Expanding Universe**
 - all galaxies move away from each other
 - farther galaxies move faster ($V \propto d$)



- *Expansion gentle on small scales:*
 Andromeda shows **blue** shift





“Brooklyn is not expanding”

- the Hubble expansion is an observational consequence of an expanding Universe
- space *itself* is expanding, carrying galaxies along with it
- this expansion is (locally) gentle, and small compared to gravity on Galactic scales:
 - Between us and Sirius, $v_{\text{exp}} \sim 0.6$ mph
 - between Andromeda and the Milky Way, it is only 45 km/s outwards
 - gravitational force between Andromeda & Milky Way easily overwhelms Universe expansion

