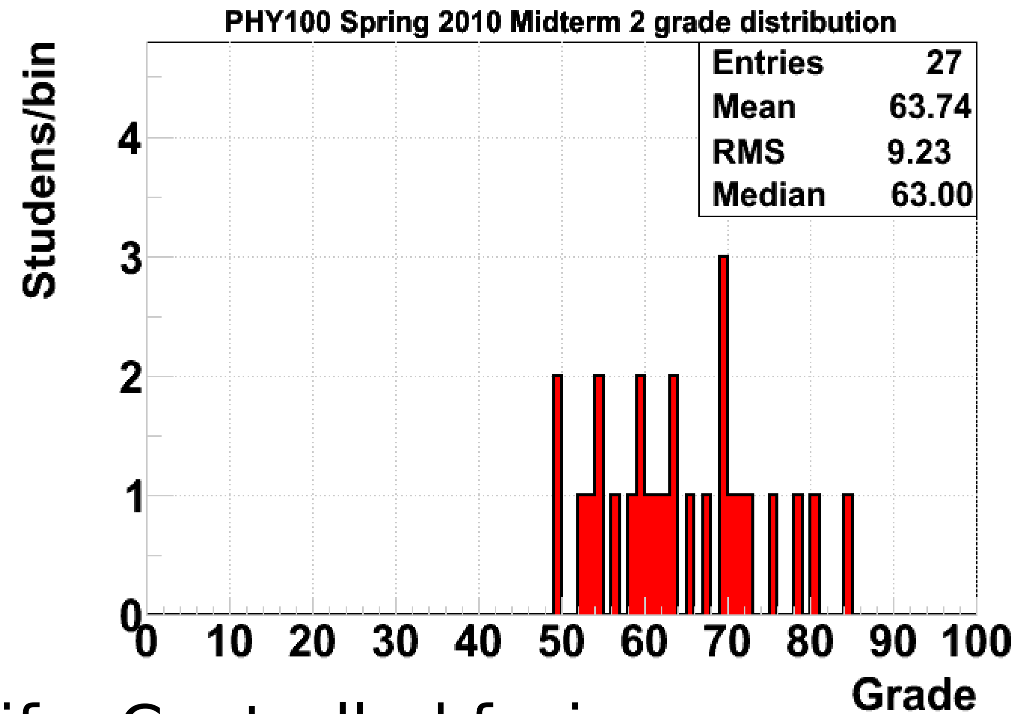
Lecture 19
Big Bang Cosmology

Arán García-Bellido

UNIVERSITY of ROCHESTER

News

- Exam 2: you can do better!



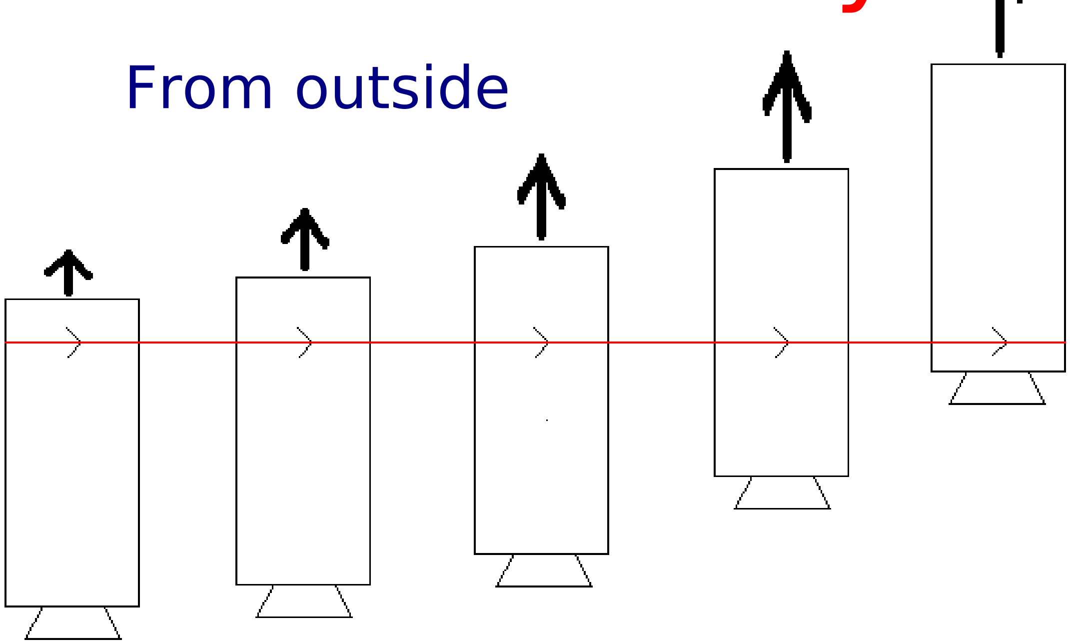
- Presentations
  - April 14: Great Physicist life, Controlled fusion
  - April 19: Nuclear power, Search for ET life
  - April 21: Music, Nuclear terrorism
  - 2 per day 20 min+discussion/Q&A
  - Want to meet with all groups this week
  - Contact me

Cosmology

- Scientific study of the large scale structure of the universe
  - Attempt to understand the origin, evolution and fate of the universe
  - The universe: all matter, space, time and energy
- Remember first lecture:
  - Tycho Brahe (1546-1601): careful observation of sun, moon, planets
  - Johannes Kepler (1571-1630): elliptical orbits, 3 laws of planetary motion
  - Isaac Newton (1643-1727): Universal law of gravitation + laws of motion → explained Kepler's laws of planetary motion
  - Albert Einstein (1879-1955): In an accelerated rocket ship, light would seem to travel on a curved path
    - Gravity = accelerated frame
    - Gravity curves space

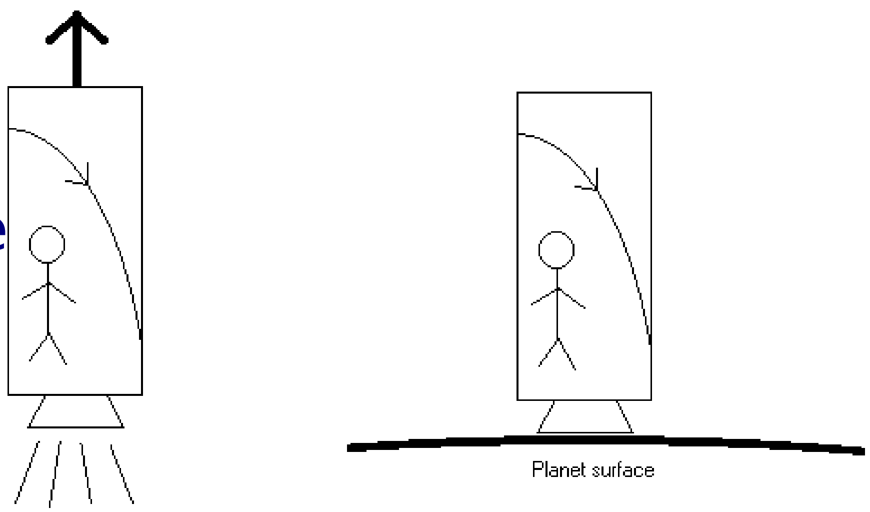
Gravity bends light

From outside



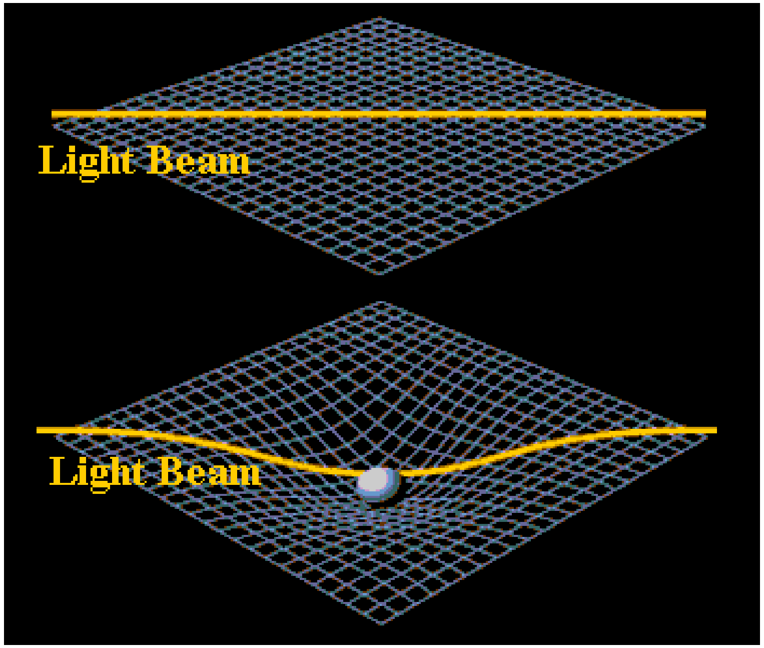
View of our accelerating elevator. The beam of light travels in a straight line (as respresented by the red line); it is the elevator that is accelerating. The time interval between each view of the elevator is the same. We can thus imagine that if we were standing in the elevator, the beam of light would thus appear to follow a curved path, as show below (lower left).

From inside



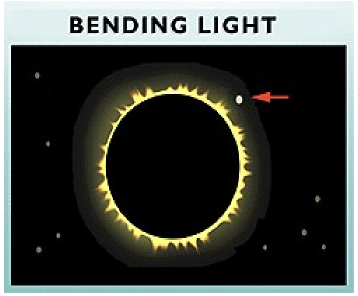
Due to the "equivalence principle," if you were to stand inside the elevator, it would not be possible to tell whether you were accelerating (above left) or whether you were instead placed in a gravitational field, on a planet's surface (above right). And because we know that in an accelerating frame like that in the elevator on the left, a beam of light would appear to follow a bent path, we ought to observe the same bending of light if we were on a planet's surface. (The effect of bending is extremely exaggerated here.) That's how we can conclude that gravity bends light!

- Light is not bent because of the gravitational force 'per se'
- Light moves on a geodesic (=shortest distance between two points)
- So Einstein interprets gravitation as a curvature of spacetime
- Gravity warps spacetime
- Light just follows the curvature of space

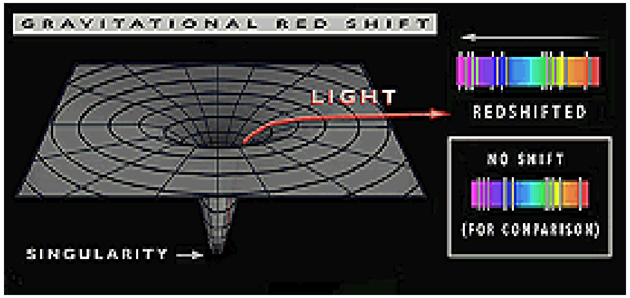


General Relativity: tests

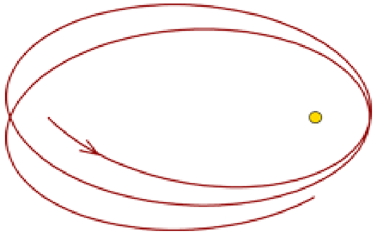
- Bending of light by gravitational field ✔



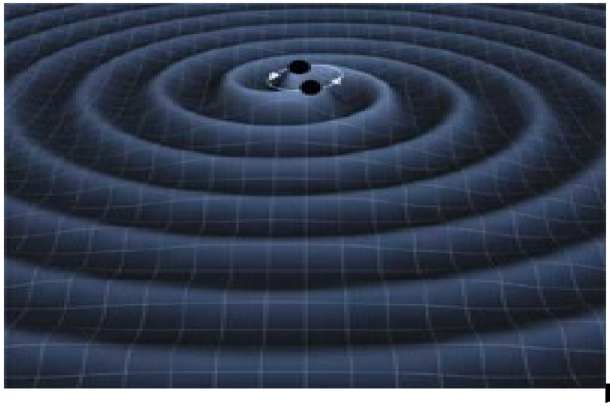
- Gravitational redshift of light ✔



- Perihelion advance of Mercury ✔



- Gravitational waves ?



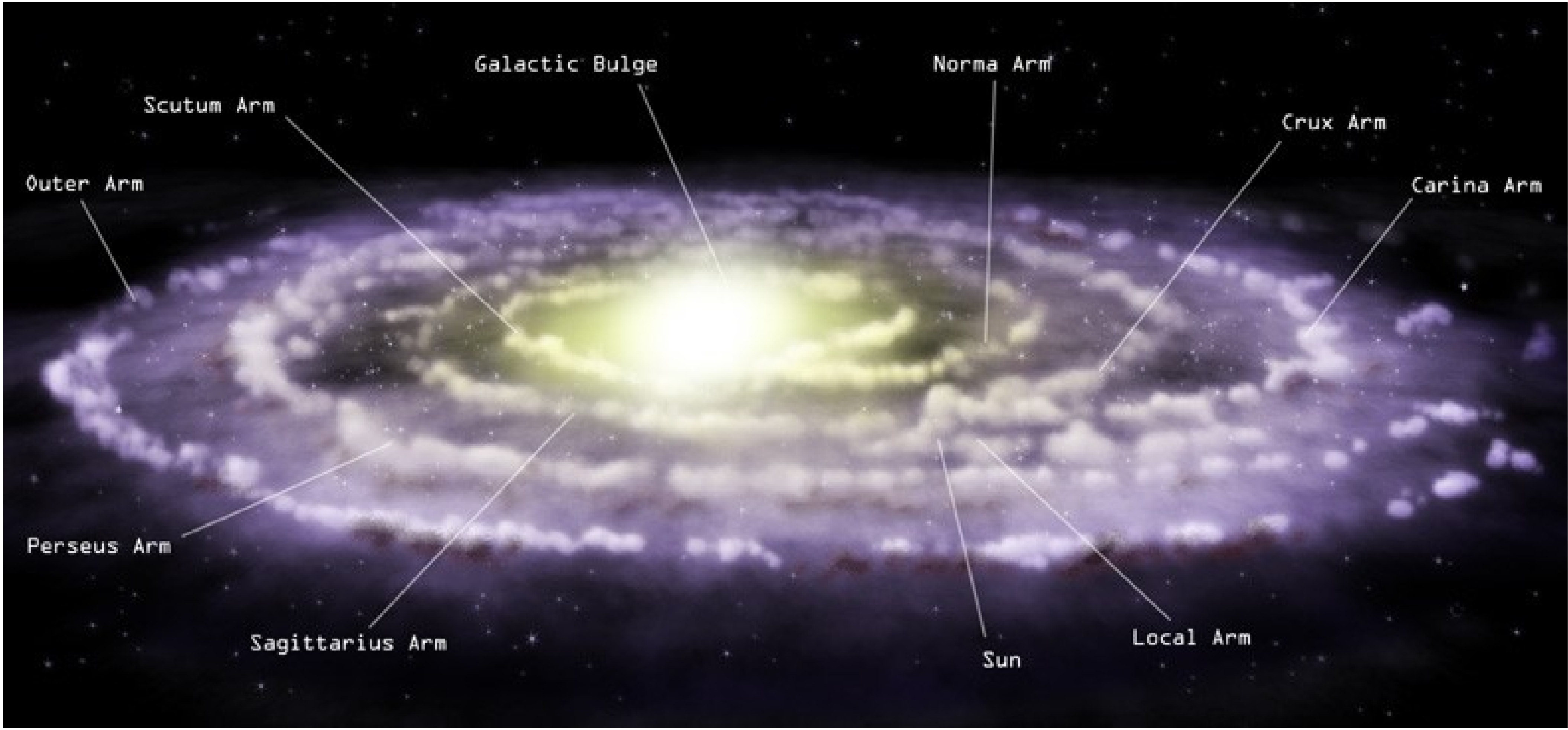
Light travels at a finite speed

Object	Lookback time
Sun	8 minutes
Alpha Centauri	4 years
Andromeda Galaxy	2 million years
Seyfert Galaxy NGC1068	16 million years
Quasar (z=0.158)	2 billion years
Galaxy at z=1	7 billion years
Age of universe	13.7 billion years

- 1 light year: $9x10^{15}$ m
- 1 Mpc = 1 Megaparsec = $3x10^{22}$ m
- Light travels NYC-San Francisco in 1/100 second
- Light travels 1 Mpc in 3 million years
- The farther away the object, the longer ago light was emitted
- Telescopes are time machines!

The milky way

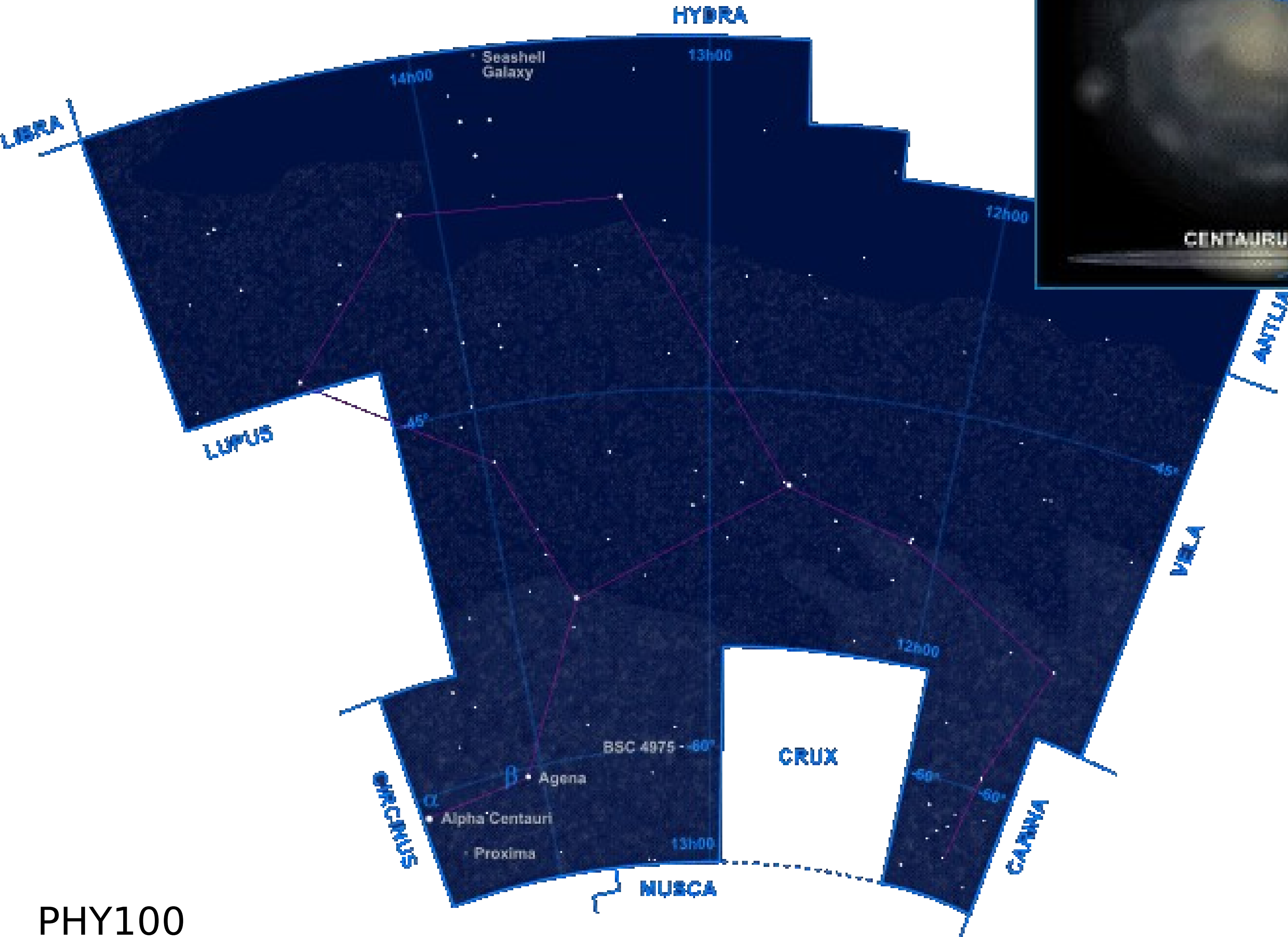
- 200-400 billion stars
- $6x10^{11}$ solar masses
- Sun is 26,000 ly away from center
  - Orbiting at 220 km/s
  - Period of revolution: 225 M years

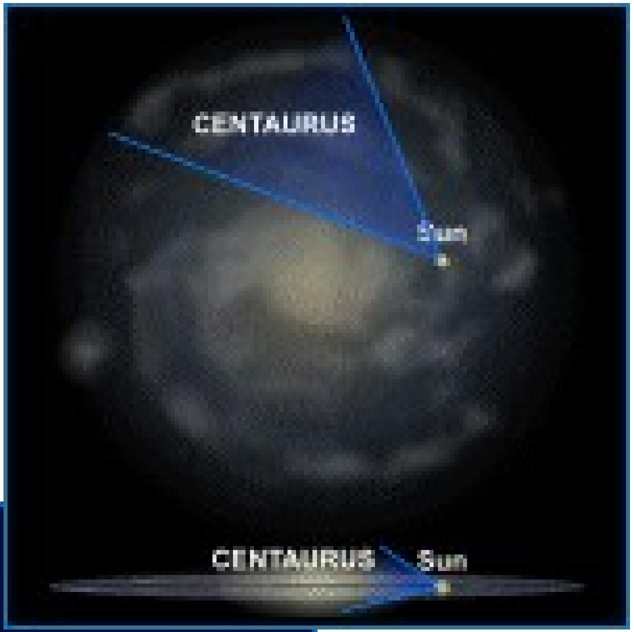


Constellations?

- Centaurus

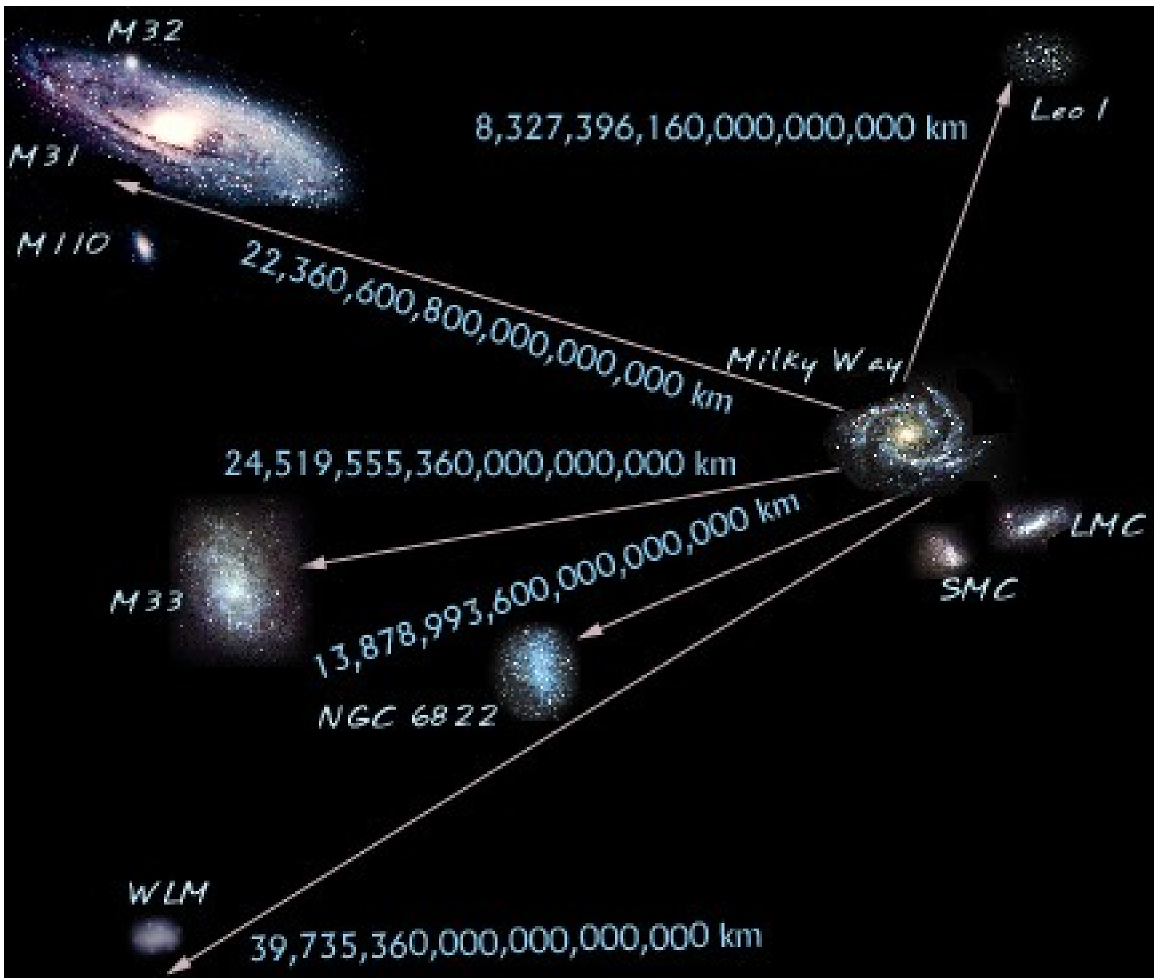
http://www.glyphweb.com/esky/default.htm

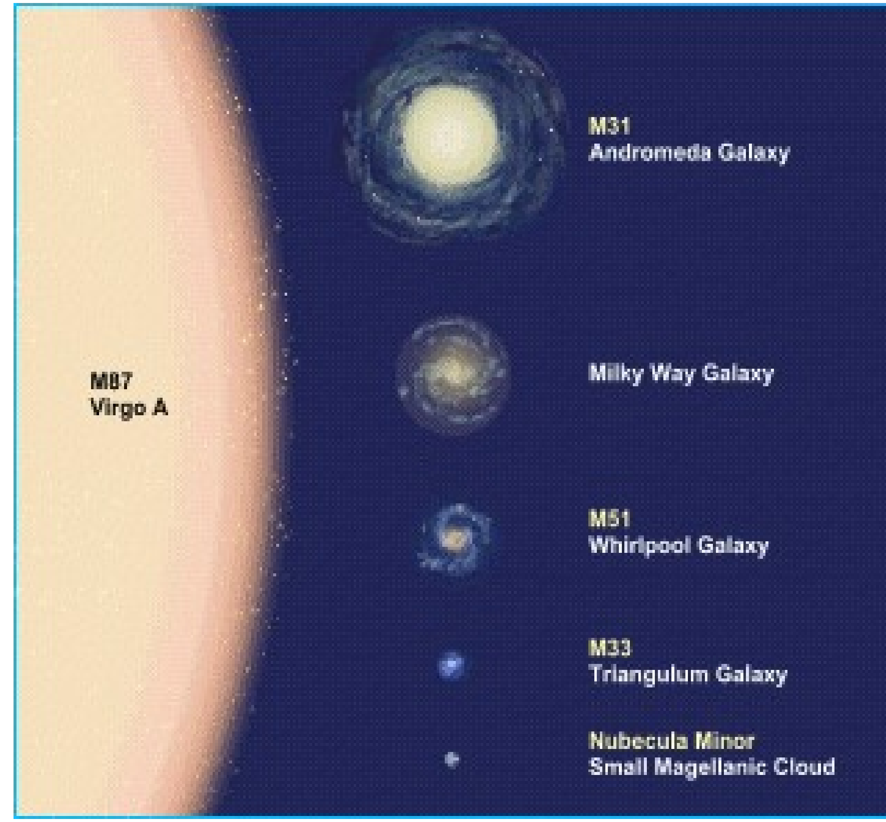




Our local universe

- Local group: 35 galaxies
- 10 million ly diameter
- 10^{12} solar masses
- Part of the Virgo supercluster



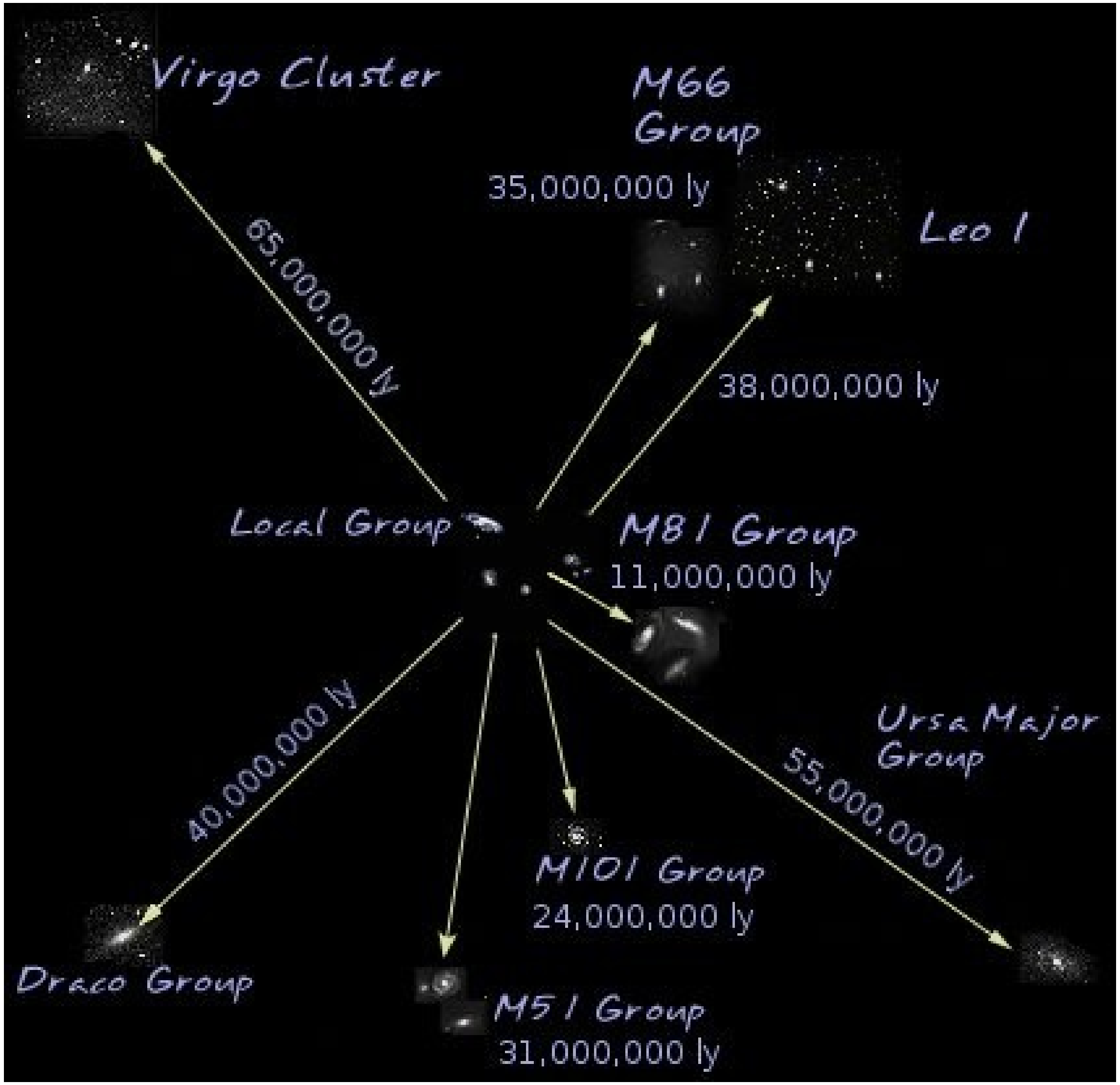


Andromeda could collide with our Milky Way in 2.5 Billion years

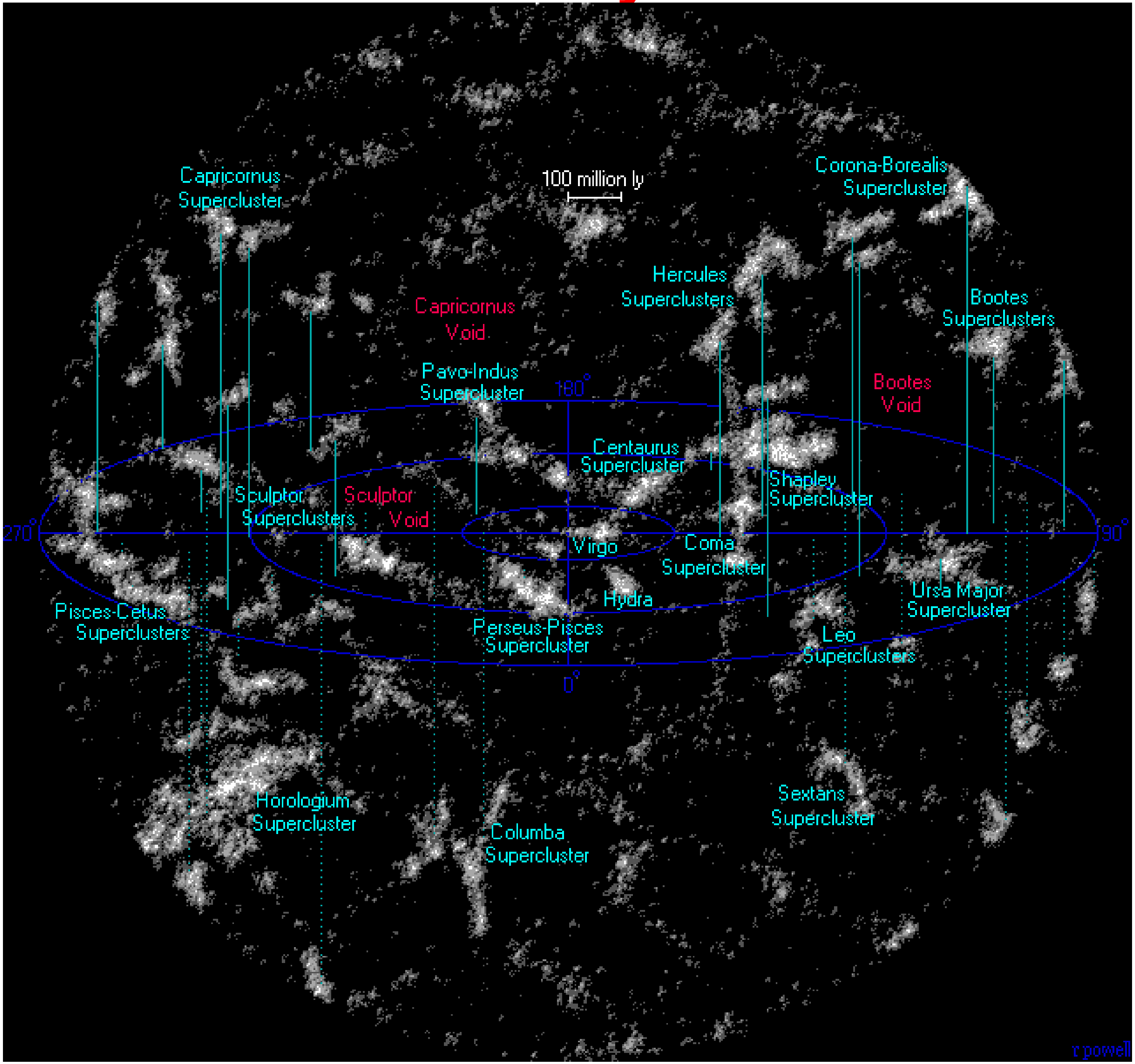
Local group

Local supercluster...

- Contains about 100 groups and clusters of galaxies
- 200 million light years diameter
- 10^{15} solar masses

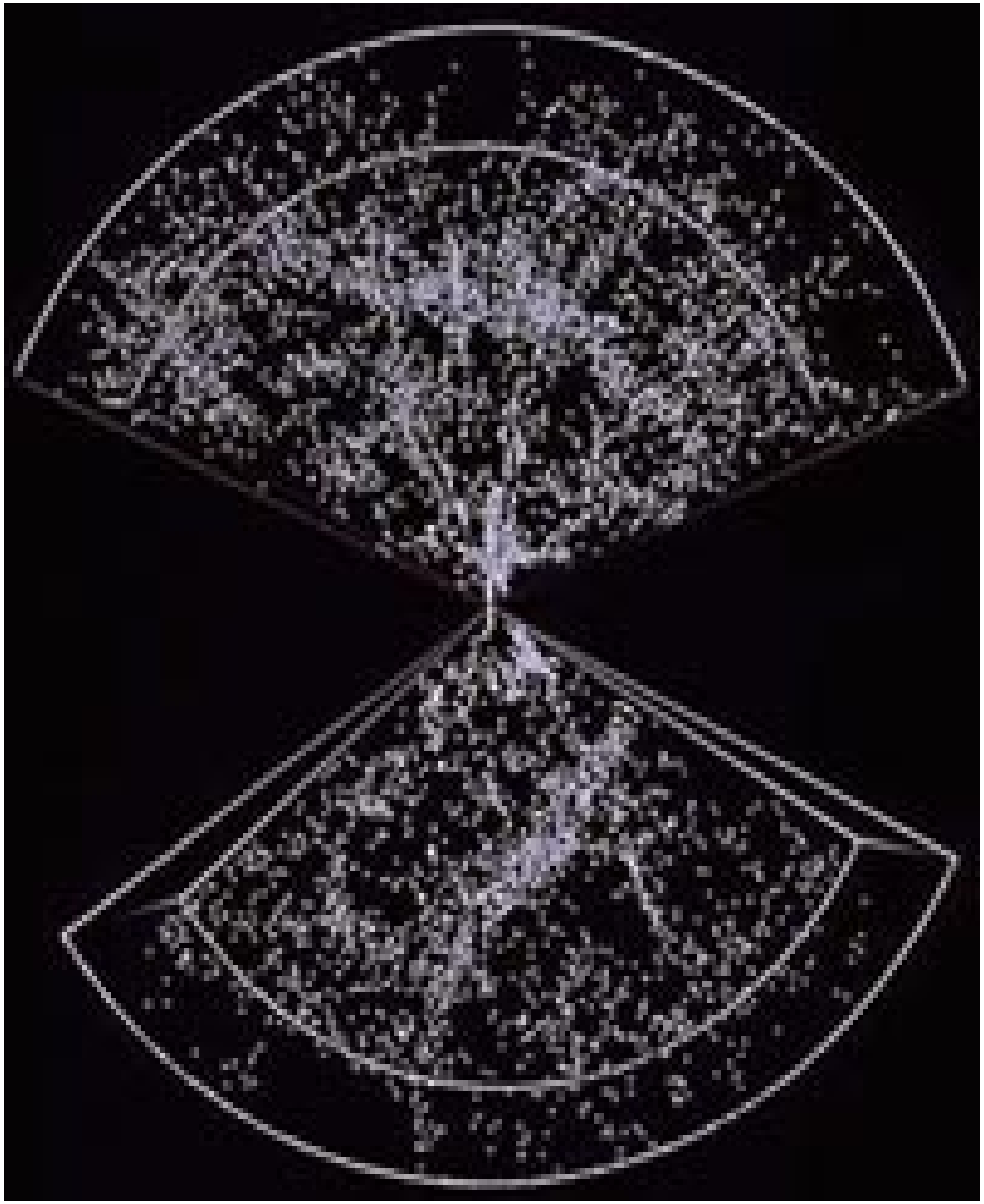


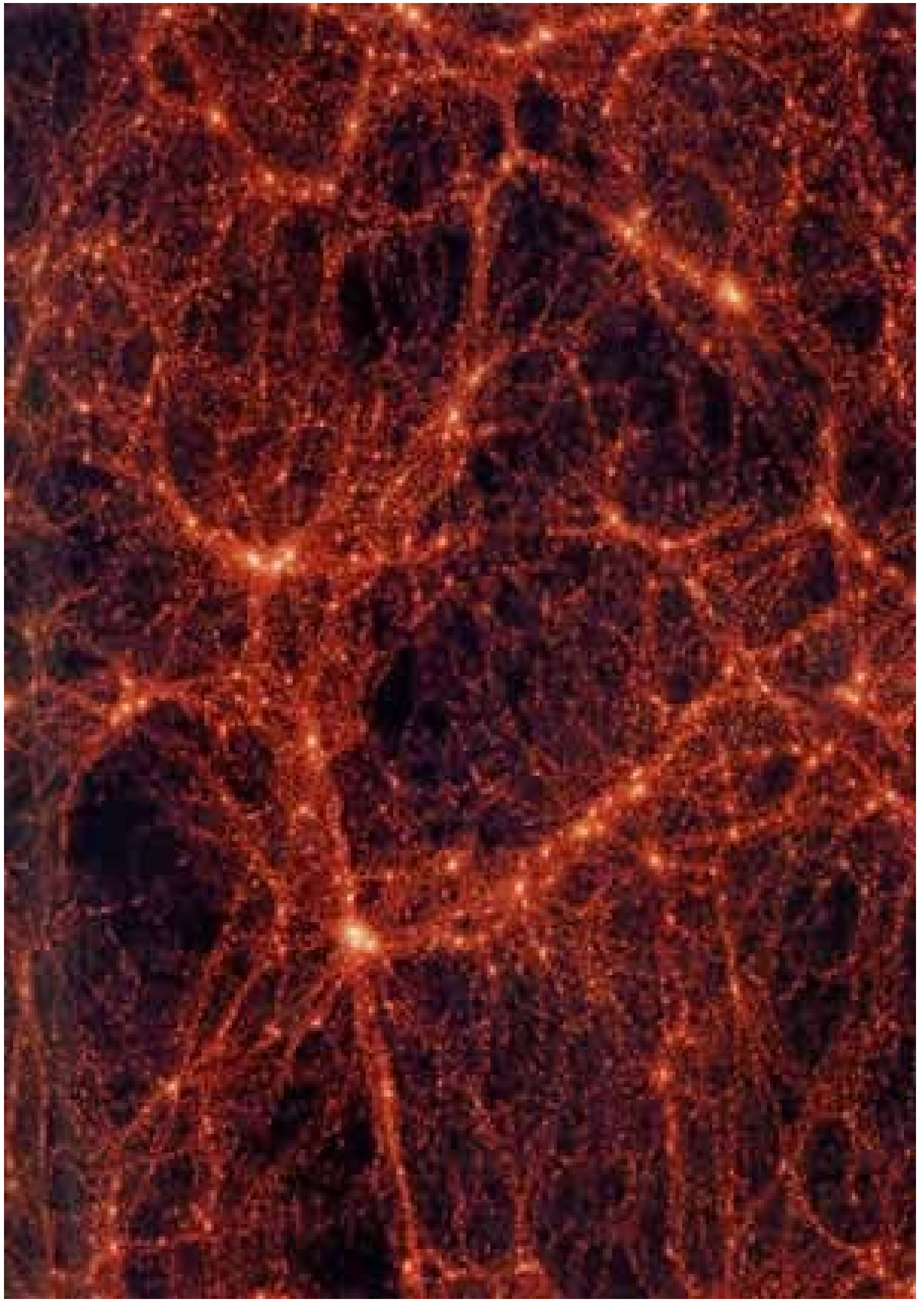
... and beyond



Capricornus Supercluster
100 million ly
Corona-Borealis Supercluster
Hercules Superclusters
Capricornus Void
Bootes Superclusters
Pavo-Indus Supercluster
180°
Bootes Void
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
Virgo
Coma Supercluster
90°
Hydra
Ursa Major Supercluster
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Horologium Supercluster
Columba Supercluster
Sextans Supercluster
r powell

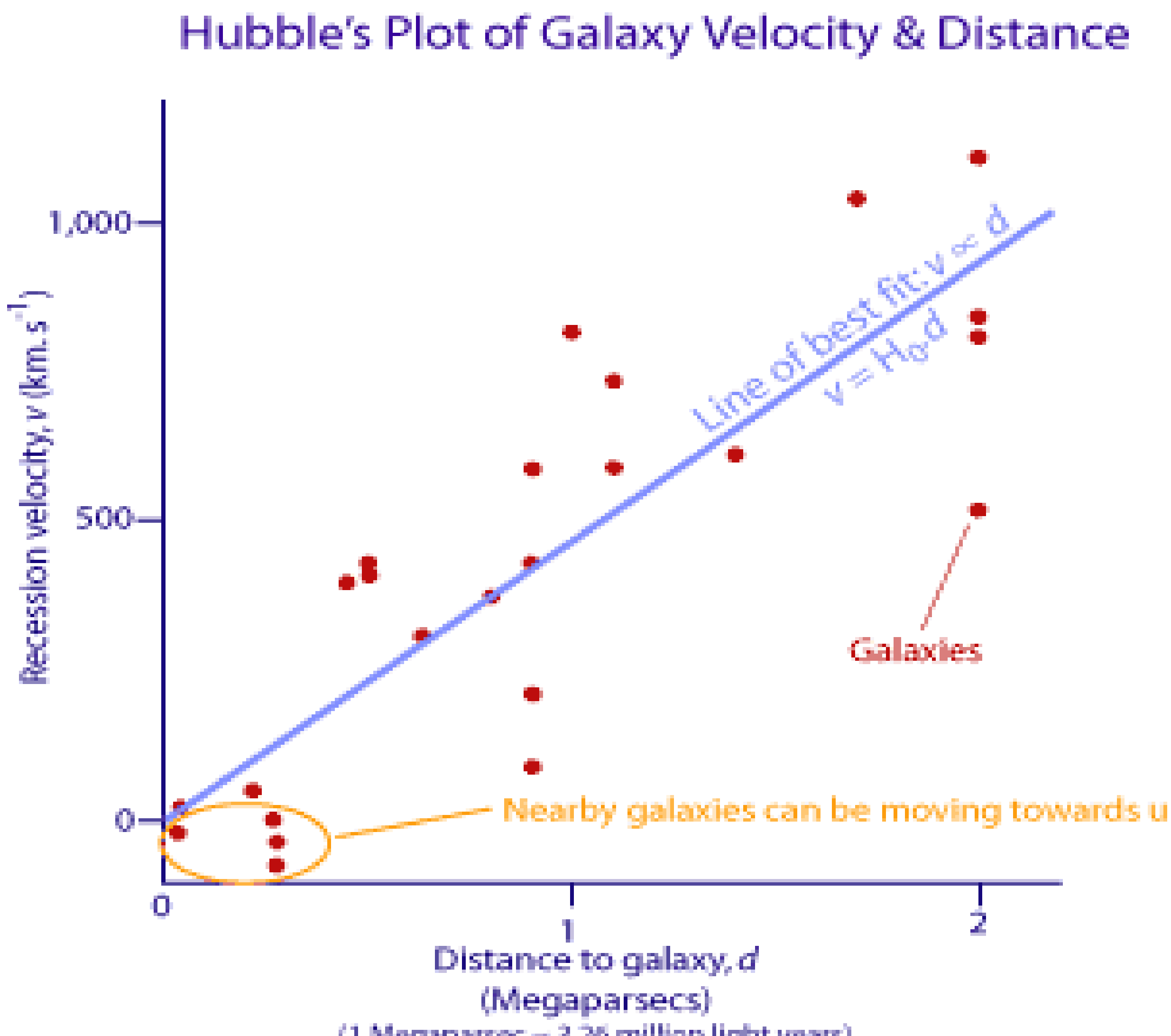
Large scale structure





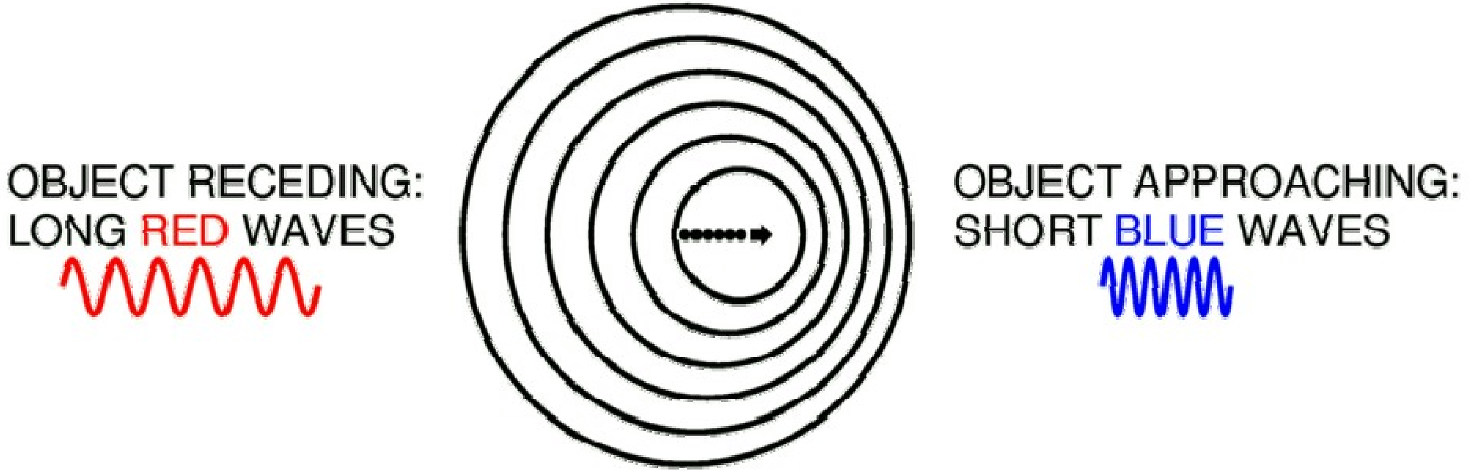
Edwin Hubble

- Discovers a surprise in 1929
- Galaxies that are further away appear redder
- All galaxies recede from us, but more distant galaxies recede from us faster!

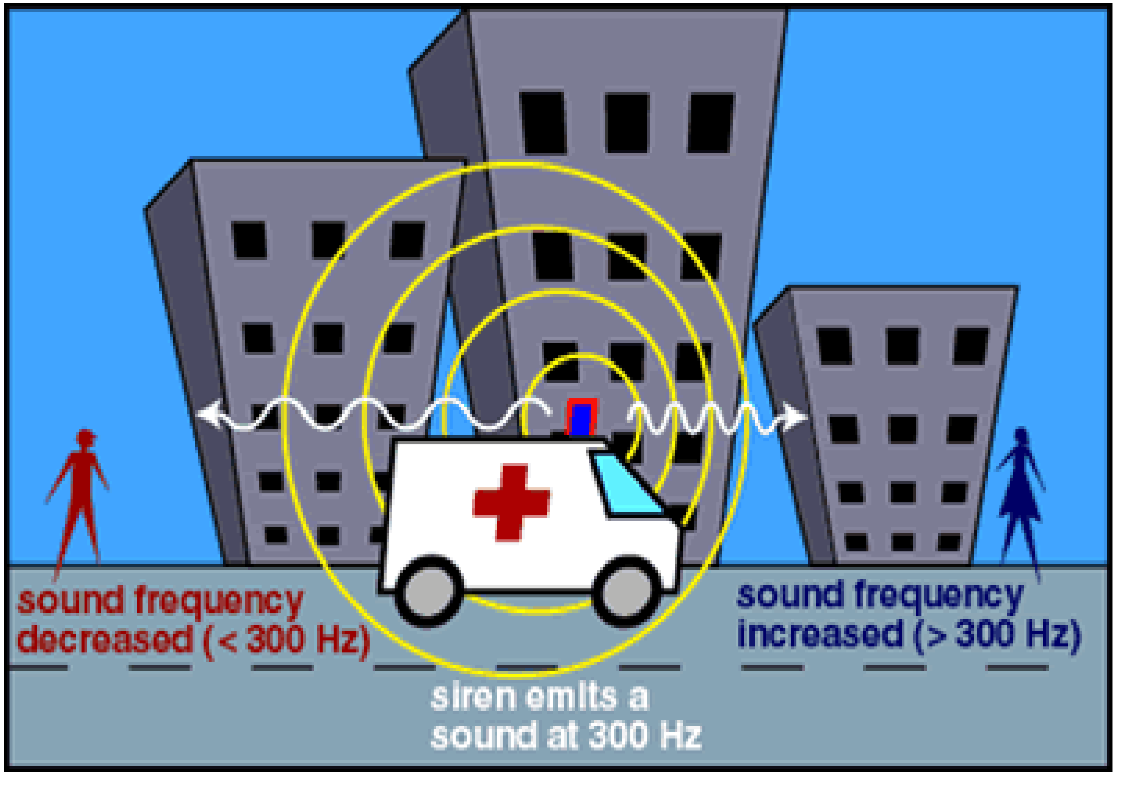


100 inch Hooker telescope at
Mount Wilson Observatory

Doppler effect

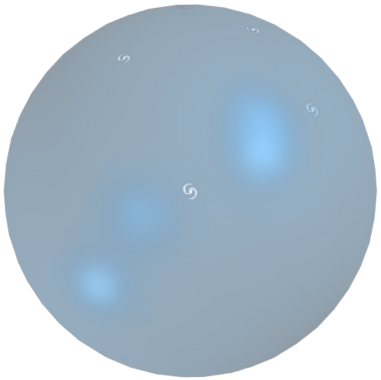


- Frequency appears higher to observers in direction of motion: blueshifted light
- Frequency appears lower to observers in direction away from direction of motion: redshifted light
- Animation

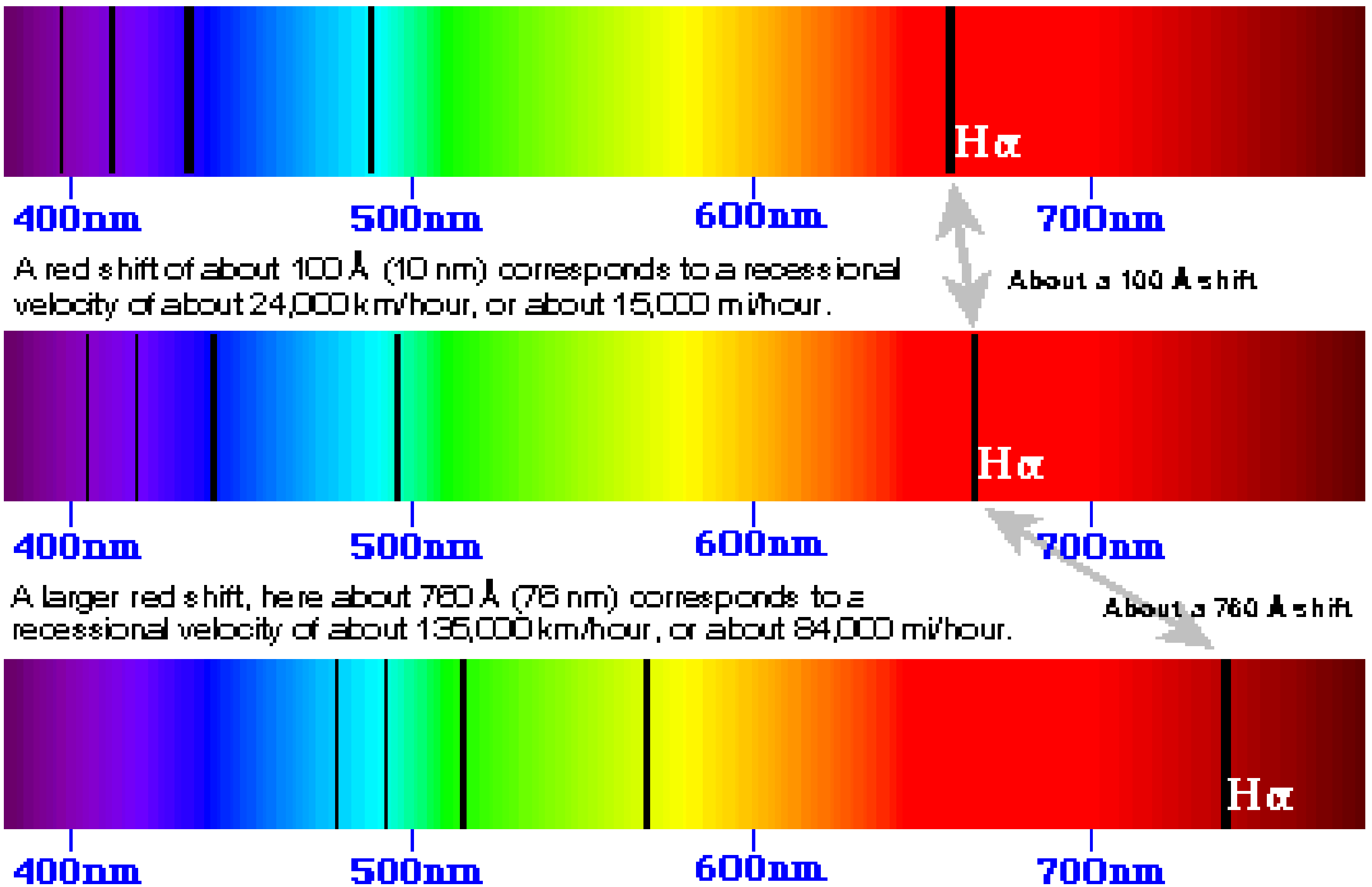


Cosmological redshift

- λ stretches along with the Universe
- Object receding: longer (redder) λ
- Object approaching: shorter (bluer) λ
- Use star spectrum to measure velocity of the source: larger v, larger redshift/blueshift



Demo

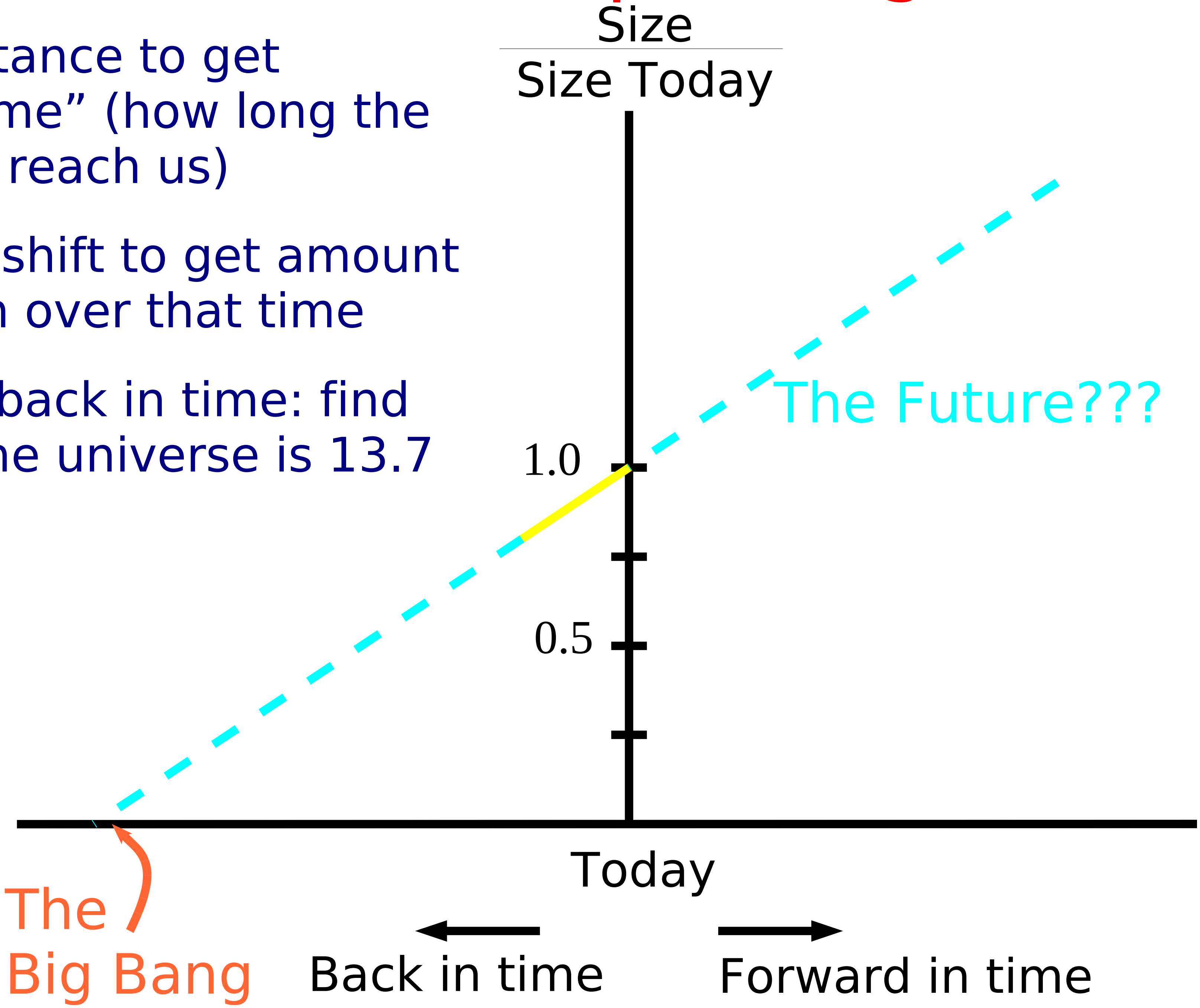


Universe expanding


- Galaxies are receding in all directions
- Same amount in all directions: uniform, except for local exceptions
- It's not that galaxies are moving through space: **space itself is expanding**
- No need to think our galaxy is at the center of universe
- Expansion of space makes effect same to all observers throughout the universe: it is the same seen from another galaxy
- **Cosmological Principle**: the axiom that the universe is isotropic and homogeneous
    - Does not apply to stars within Milky Way Galaxy, or to bright, nearby galaxies
    - Applies to the average distribution of galaxies on the largest scales
    - Implies that we are not a privileged observer

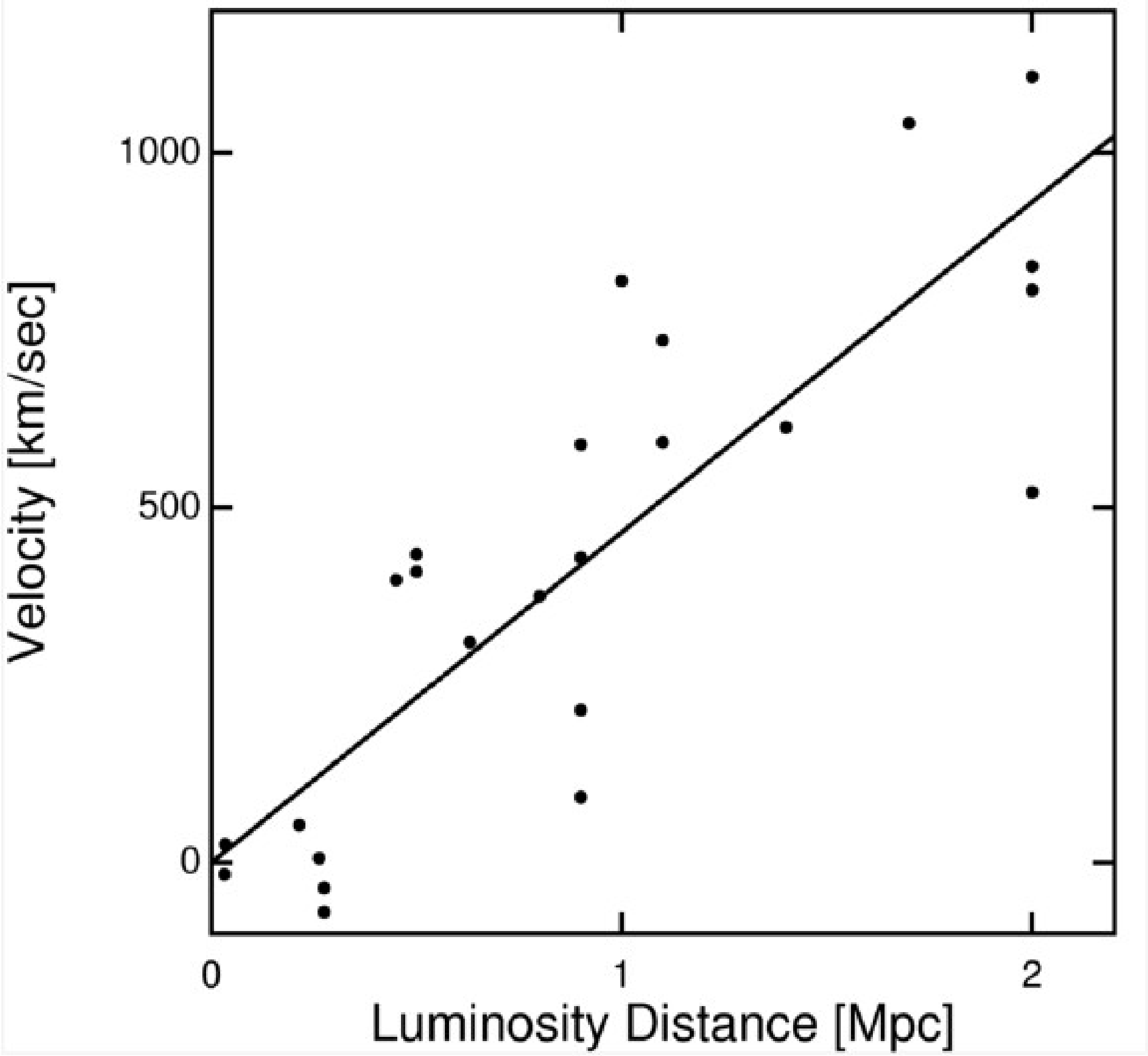
The Universe is expanding!

- Measure distance to get “lookback time” (how long the light took to reach us)
- Measure redshift to get amount of expansion over that time
- Extrapolate back in time: find the age of the universe is 13.7 billion years

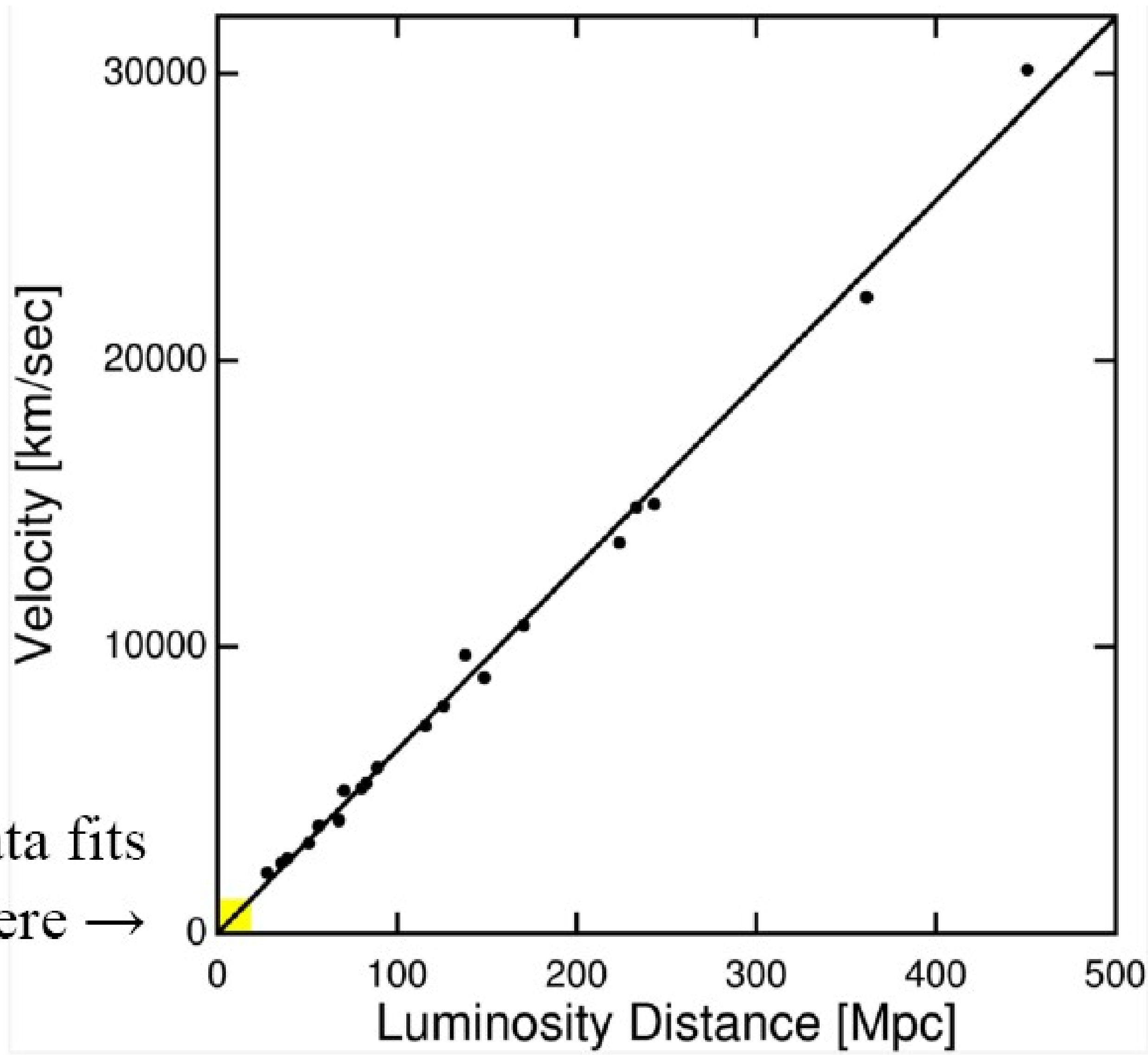


1929

- Hubble's constant: ~70 km/s per Mpc

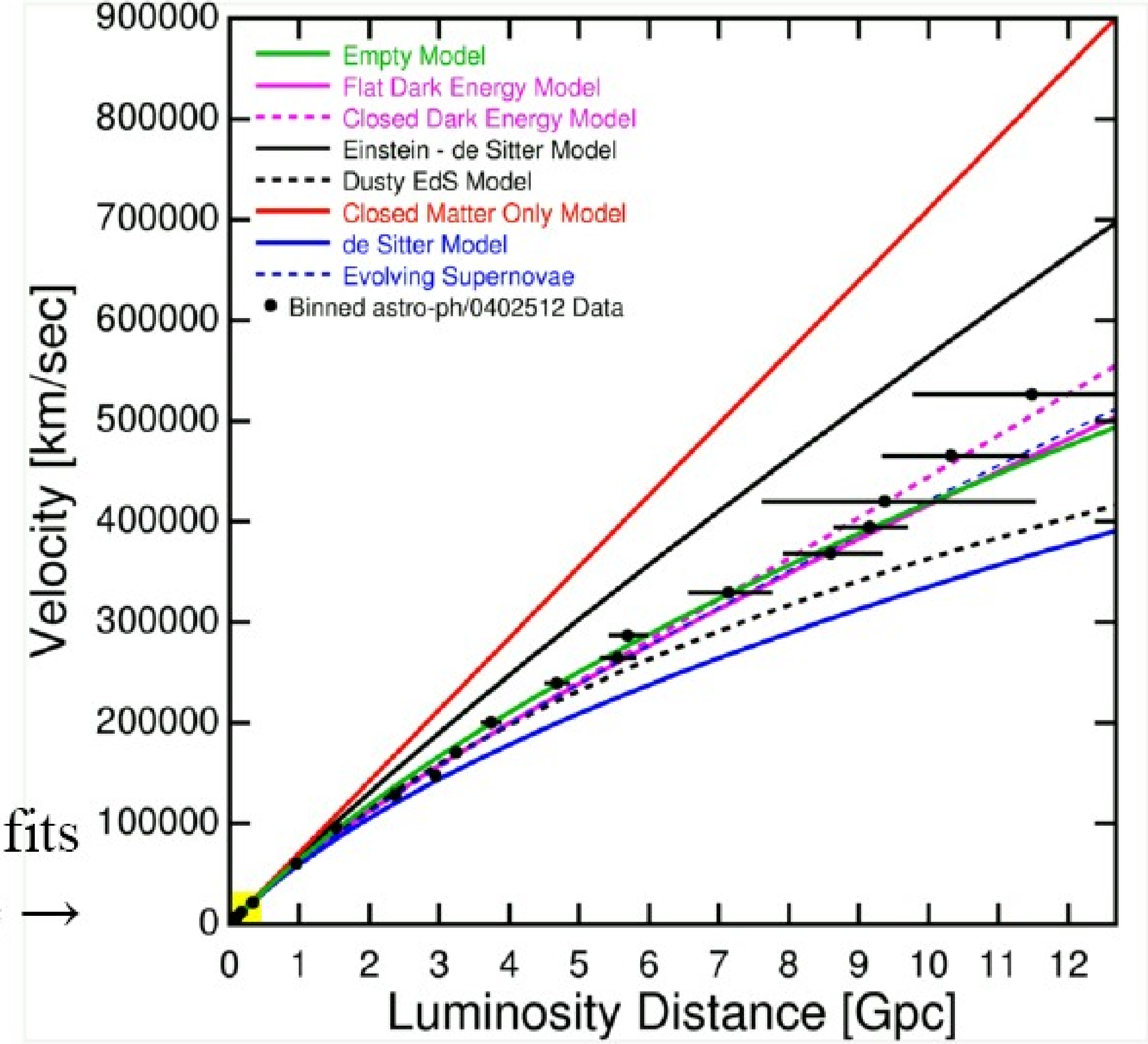


1995



1929 data fits in here →

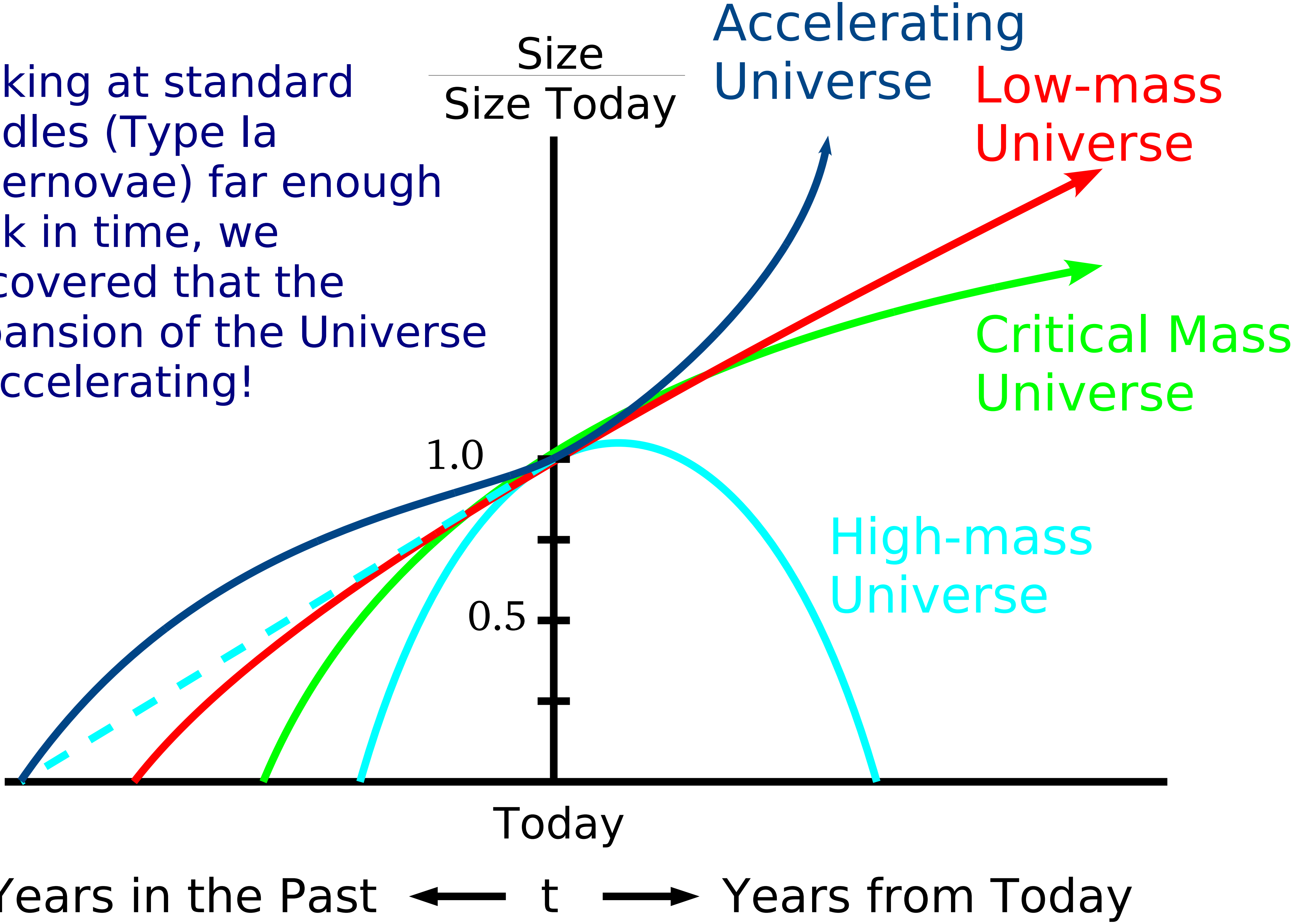
2004

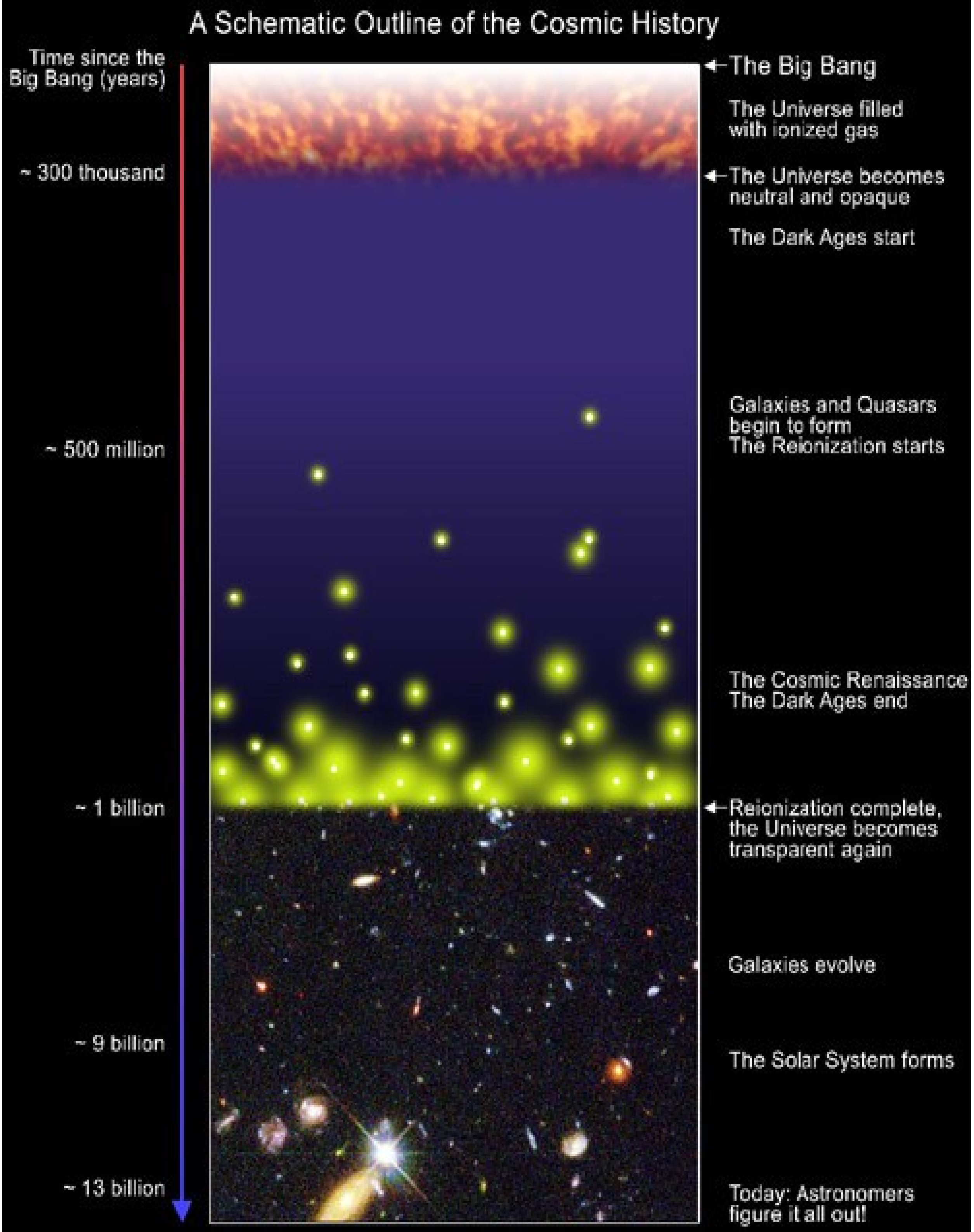


1995 data fits in here ⟶

v = cz

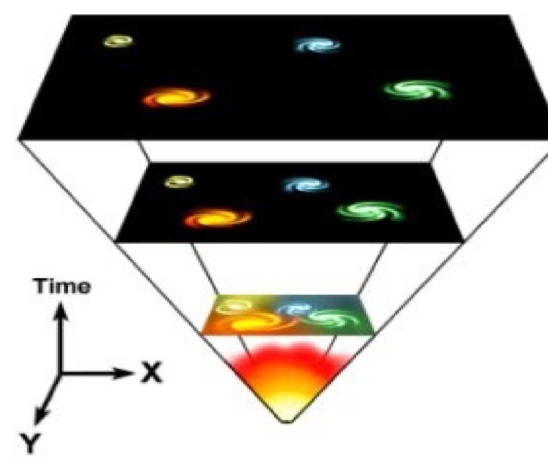
Looking at standard candles (Type Ia supernovae) far enough back in time, we discovered that the expansion of the Universe is accelerating!



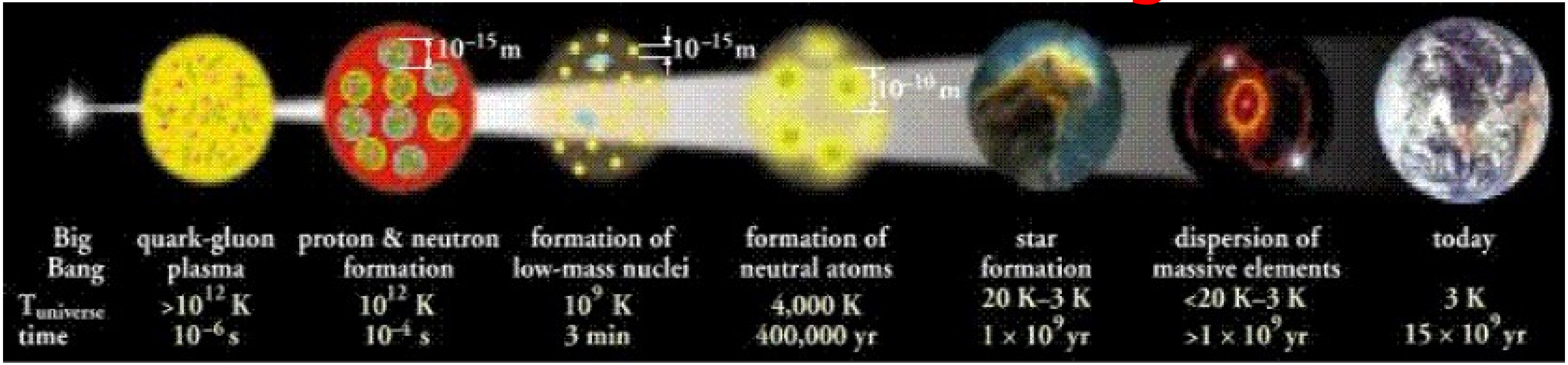


Big Bang

- Expansion implies early Universe was dense and hot
- Further back in time you go, the more uncertain the theory becomes
- Predicts a Microwave Background



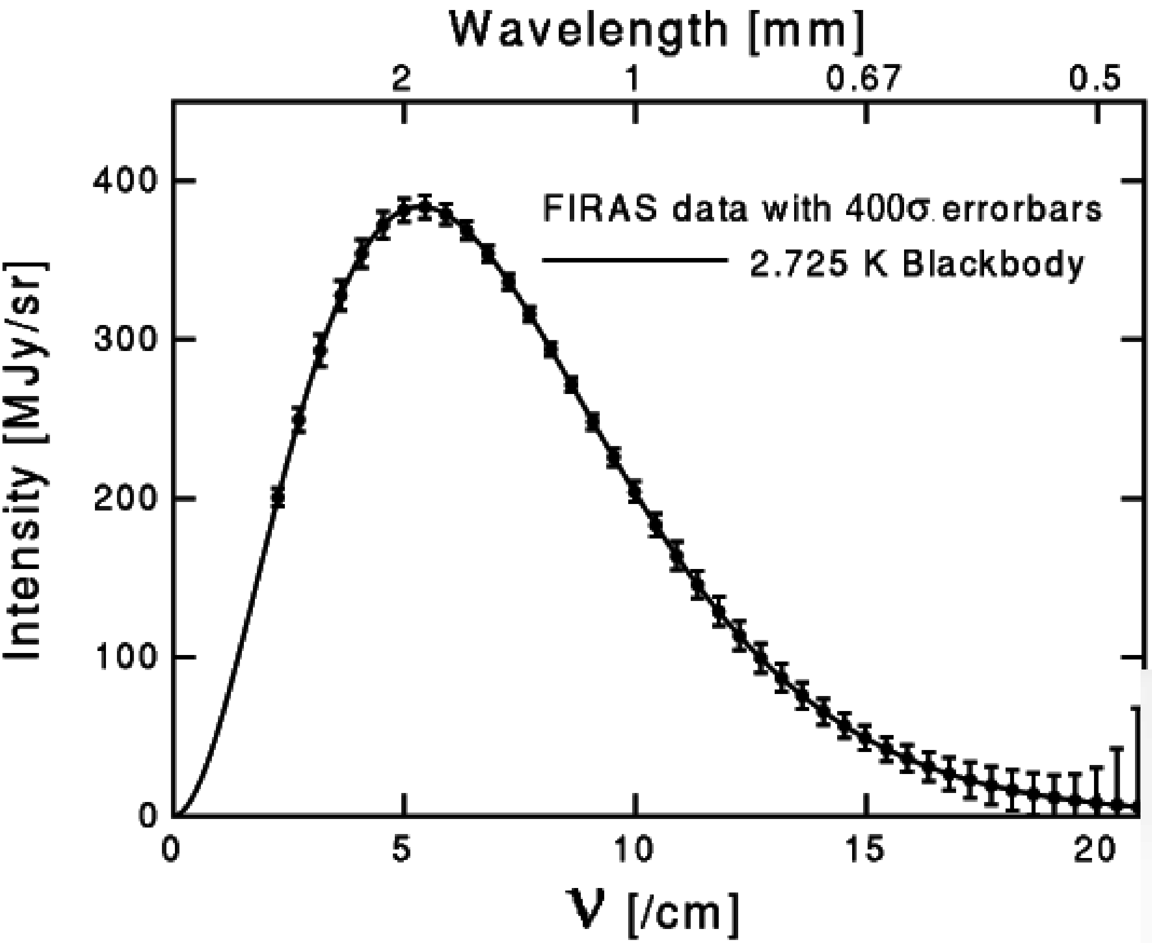
Cosmic Microwave background



Hot Big Bang predicts this evolution:

- Initially hot plasma of protons, neutrons, electrons and photons, like a fog
- When the universe grows, it cools down, when it is cool enough neutral stable atoms can form (4,000 K or after 400,000 years)
- These atoms no longer absorb all the light (thermal radiation)
- The universe becomes transparent instead of a fog
- Those same photons can be seen today as a very cool glow: equally distributed in the sky
- Massive redshift: $T = 4{,}000\text{ K} \rightarrow T_{now} = 3\text{ K}$ (Perfect blackbody)
- Cosmic Microwave Background (“CMB”)

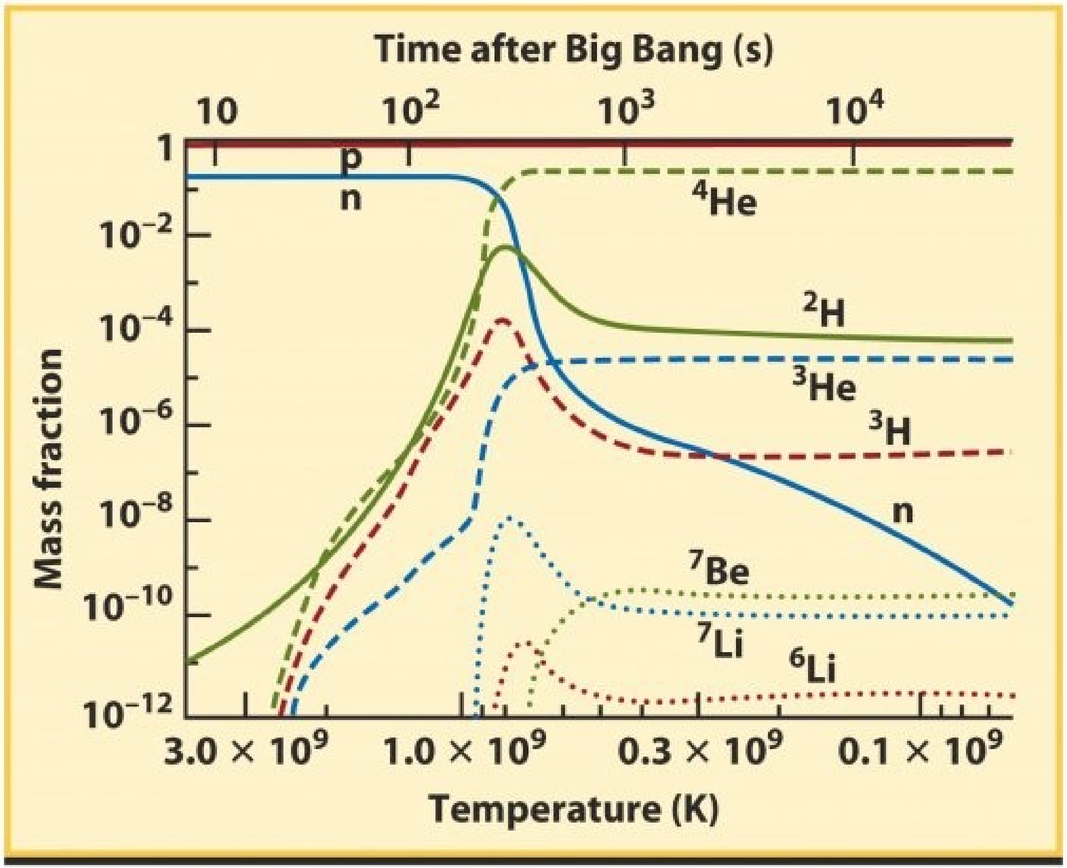
Evidence for Big Bang (1)

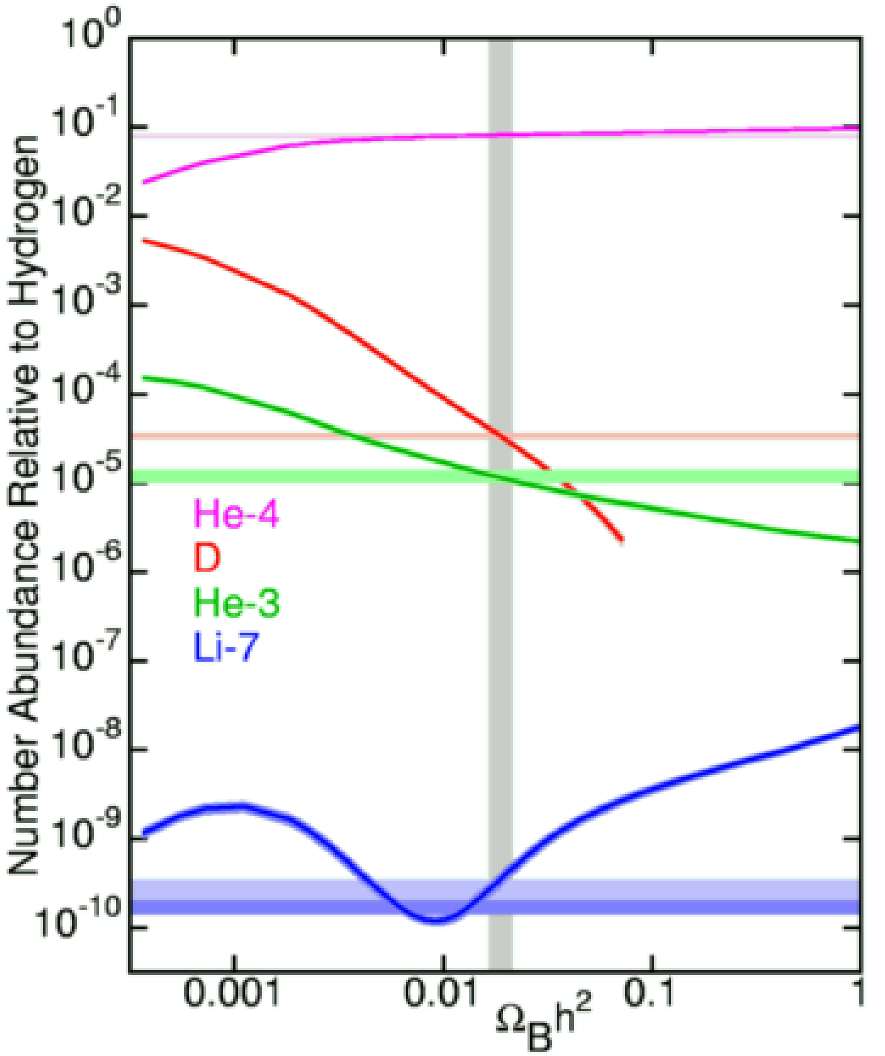


- Cosmic Microwave Background
- Uniform and isotropic signal
- Perfect blackbody
- Penzias and Wilson (1964)
- Nobel 1978

Evidence for Big Bang (2)

- **Nucleosynthesis**: t = 100 seconds
- We see the predicted distribution of light nuclei in the universe





http://www.astro.ucla.edu/~wright/BBNS.html

Evidence for Big Bang (3)

- **Morphology, composition, and distribution of galaxies**
- Galaxies formed 1 billion years after BB
  - Clusters and super clusters have formed later
- Populations of stars have been aging and evolving
  - More distant galaxies (younger) are different from closer (older) galaxies
- Star composition
  - Very distant stars (first generation) are mostly H and He
  - Older stars (like our sun) have traces from heavier elements

Summary

- Big Bang theory: the expansion of the universe began at a finite time in the past, in a state of enormous density and pressure (Weinberg)
  - Tightly constrained by observations
  - Highly successful family of theories with no obvious competitor
- Many unanswerable questions: many based on misconceptions or simply unobservable!
  - Where did the Big Bang occur?
  - What is the Universe expanding into?
  - What happened before the Big Bang?
  - Are there many universes?