The formation and evolution of the Universe

Content expectations

E5.1 The Earth in Space

Scientific evidence indicates the universe is orderly in structure, finite, and contains all matter and energy. Information from the entire light spectrum tells us about the composition and motion of objects in the universe. Early in the history of the universe, matter clumped together by gravitational attraction to form stars and galaxies. According to the Big Bang theory, the universe has been continually expanding at an increasing rate since its formation about 13.7 billion years ago.

E5.1A Describe the position and motion of our solar system in our galaxy and the overall scale, structure, and age of the universe.

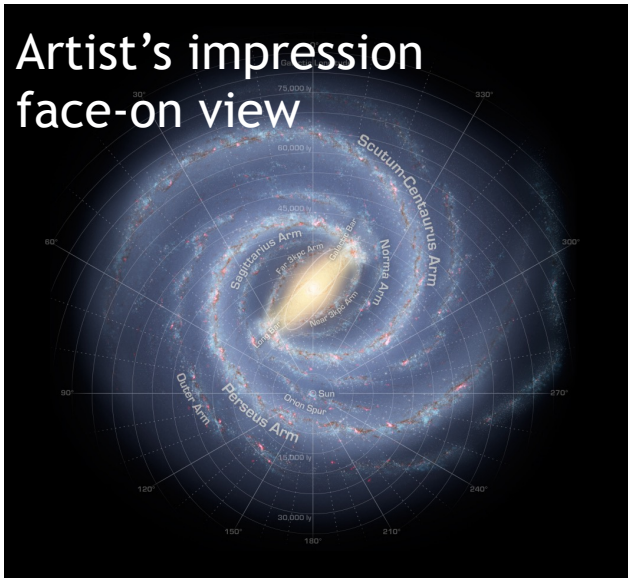
E5.1b Describe how the Big Bang theory accounts for the formation of the universe.

E5.1c Explain how observations of the cosmic microwave background have helped determine the age of the universe.

E5.1d Differentiate between the cosmological and Doppler red shift.

The Milky Way Galaxy

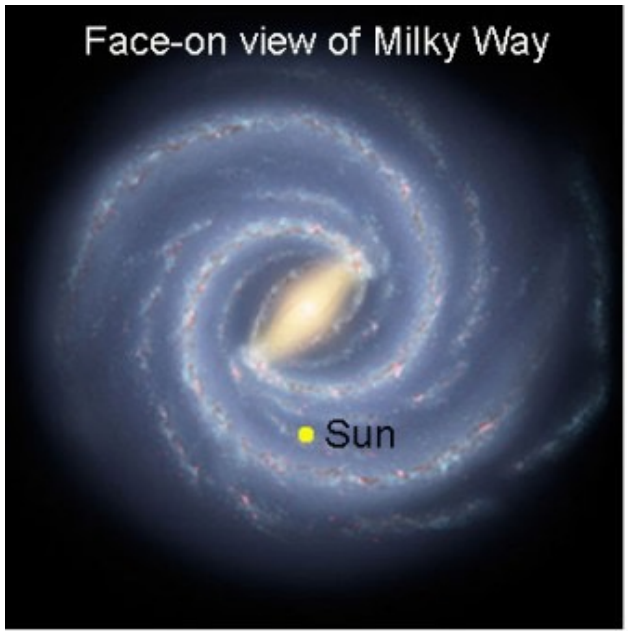

A side-view of the Milky Way from the 2MASS survey

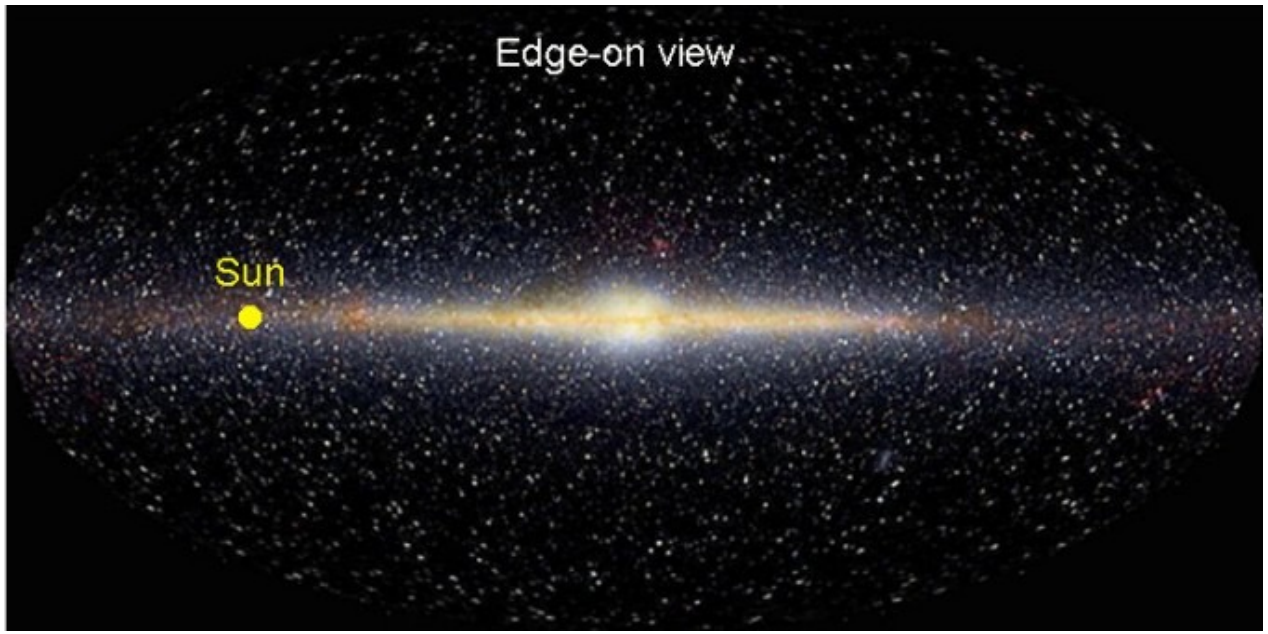


- We live in a spiral galaxy called the Milky Way
  - a vast disk-shaped structure 100,000 LY across
  - contains between 200 and 400 billion stars
- Every star in the night sky is part of the M.W.

The Sun in the Milky Way

The Sun orbits 28,000 LY from the center of the MW





Galaxy clusters and beyond….

- Our galaxy is not unique.
- Most are at enormous distances.
- The nearest large galaxy is M31 in Andromeda.
  - ~2.5 million light years distant
- The M.W. and M31 are the largest galaxies in the ***Local Group***.
  - Cluster of ~30 galaxies
  - ~3 million light years across
  - Also contains many smaller galaxies including “satellite galaxies”.

Beyond the Local Group

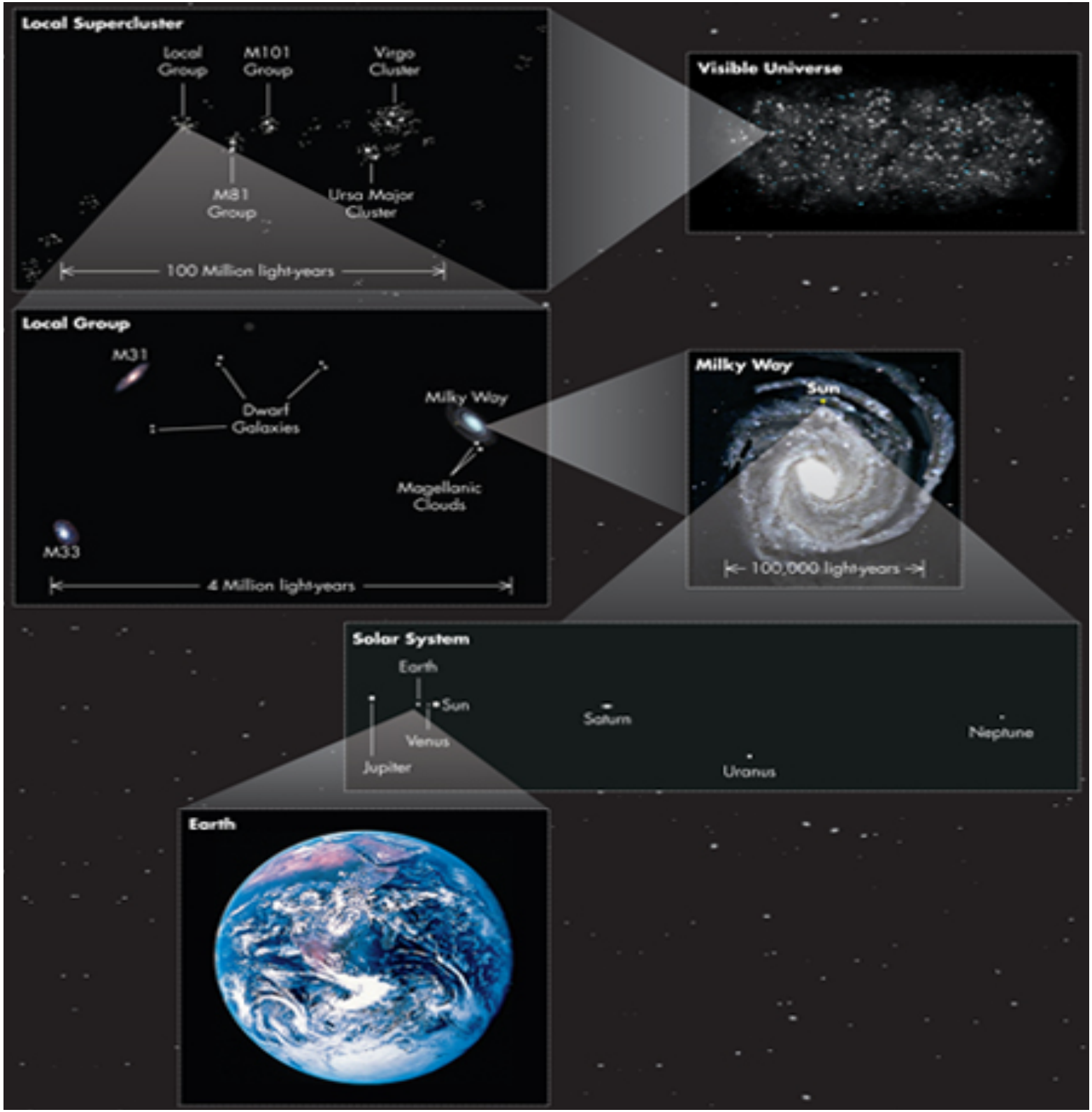
- Dozens of galaxy clusters surround the Virgo Cluster
  - The Local Group is one of them.
  - V.C. is about 50 million LY away
  - Contains 1000s of galaxies
- This larger structure is called the ***Local Supercluster***.
  - ~80 million light years across

The center of the Virgo cluster

Beyond the Local Supercluster

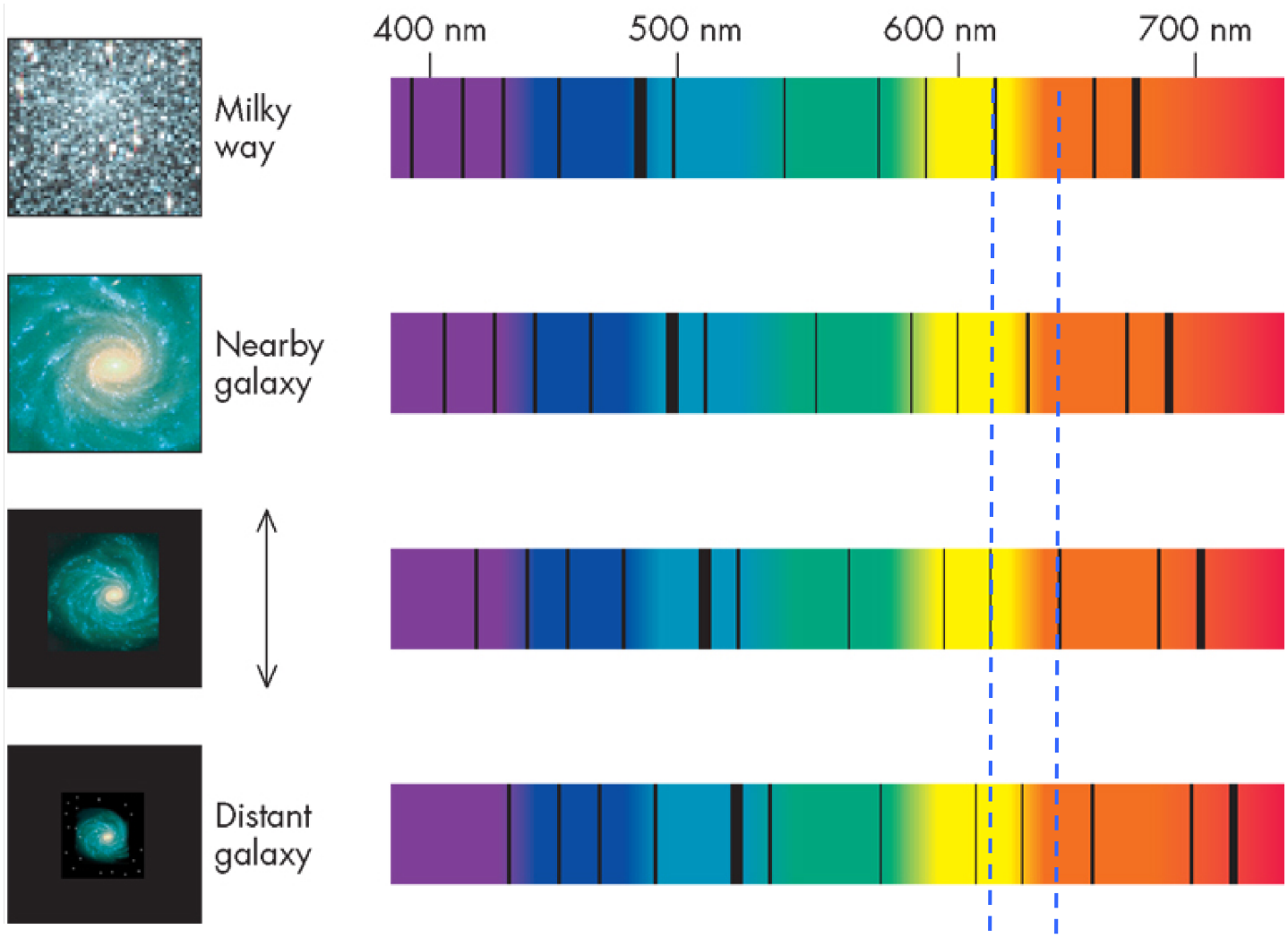
- Many other superclusters exist.
- Superclusters tend to arrange themselves in weblike structures.
  - surrounding vast expanses of empty space
- At larger scales, the Universe appears to be fairly uniform.
- The reason is not understood

The most distant galaxy discovered. It is 13.3 billion LY away


Local Supercluster
Local Group
M101 Group
Virgo Cluster
M81 Group
Ursa Major Cluster
100 Million light-years
Visible Universe
Local Group
M31
Dwarf Galaxies
Milky Way
Magellanic Clouds
M33
4 Million light-years
Milky Way
Sun
100,000 light-years
Solar System
Earth
Sun
Venus
Jupiter
Saturn
Uranus
Neptune
Earth

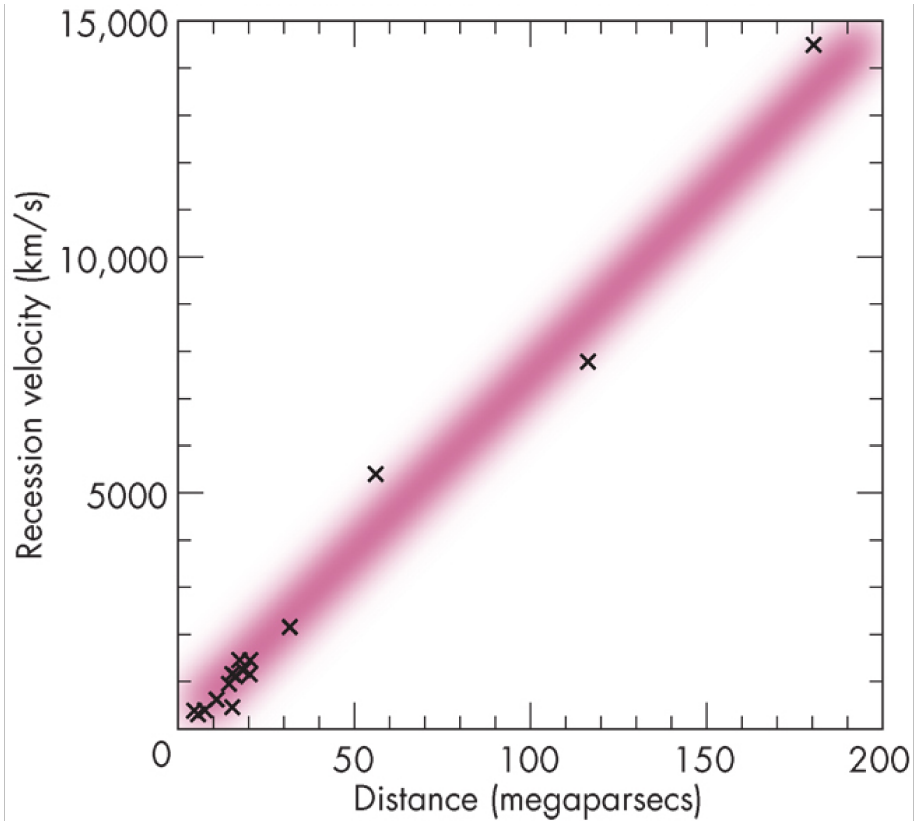
Galaxy Redshift

- Vesto Slipher (1912) observed spectral lines of nearly all observed galaxies are strongly shifted.
  - Mostly ***redshifted***.



Hubble's Law

- Edwin Hubble and Milton Humason realized that the farther away galaxies are, the larger the redshift is.
- Interpreted as galaxies moving away from us (Doppler shift).
- ***The faster a galaxy recedes, the farther away it is***
- The Universe is expanding!



Graph is a straight line through origin:

velocity = constant x distance

constant known as Hubble's constant, H

$v = H d$

Big Bang Theory

- Today:
  - Universe is cold and low density
  - As it expands, it cools
  - Matter (galaxies) gets further apart
- In the past:
  - Universe was smaller, hotter, denser
- In the beginning: unimaginably small and hot!
  - A “primeval atom” (G. Lemaitre)

Cosmic Abundances

- Early success: expanding U picture can match observed abundances, especially ^{4}He

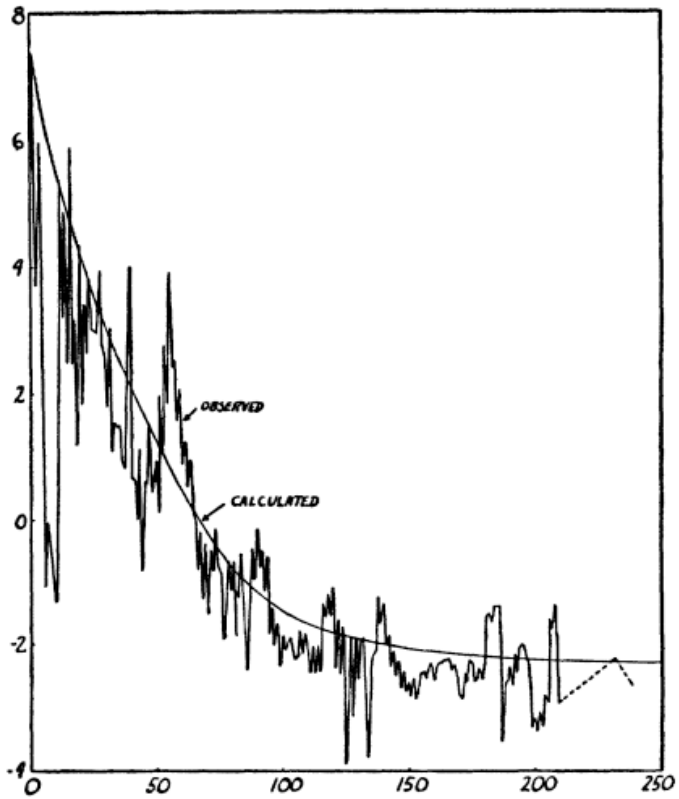


FIG. 1.

Log of relative abundance

Atomic weight

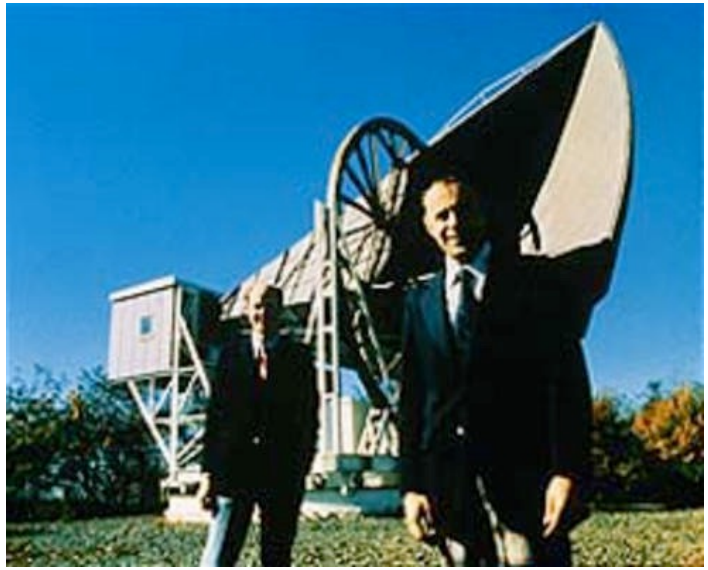
From the now famous Alpher, Bethe, Gamow (1948) paper aka αβγ

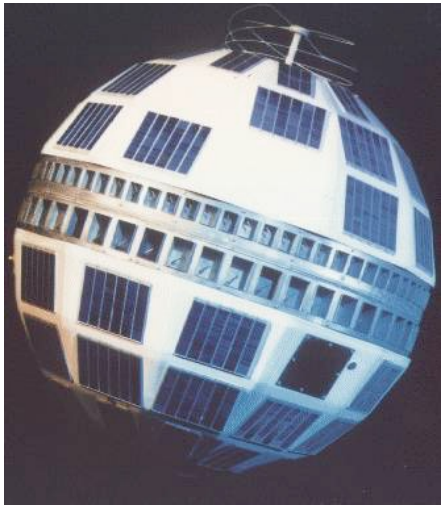
Cosmic Microwave Background (CMB)

- U was extremely hot & dense at early times (as demonstrated by αβγ)
- Alpher & Herman (1948) and later Peebles & Dicke (1964) predicted radiation left over from Big Bang should be about 5 - 10 K

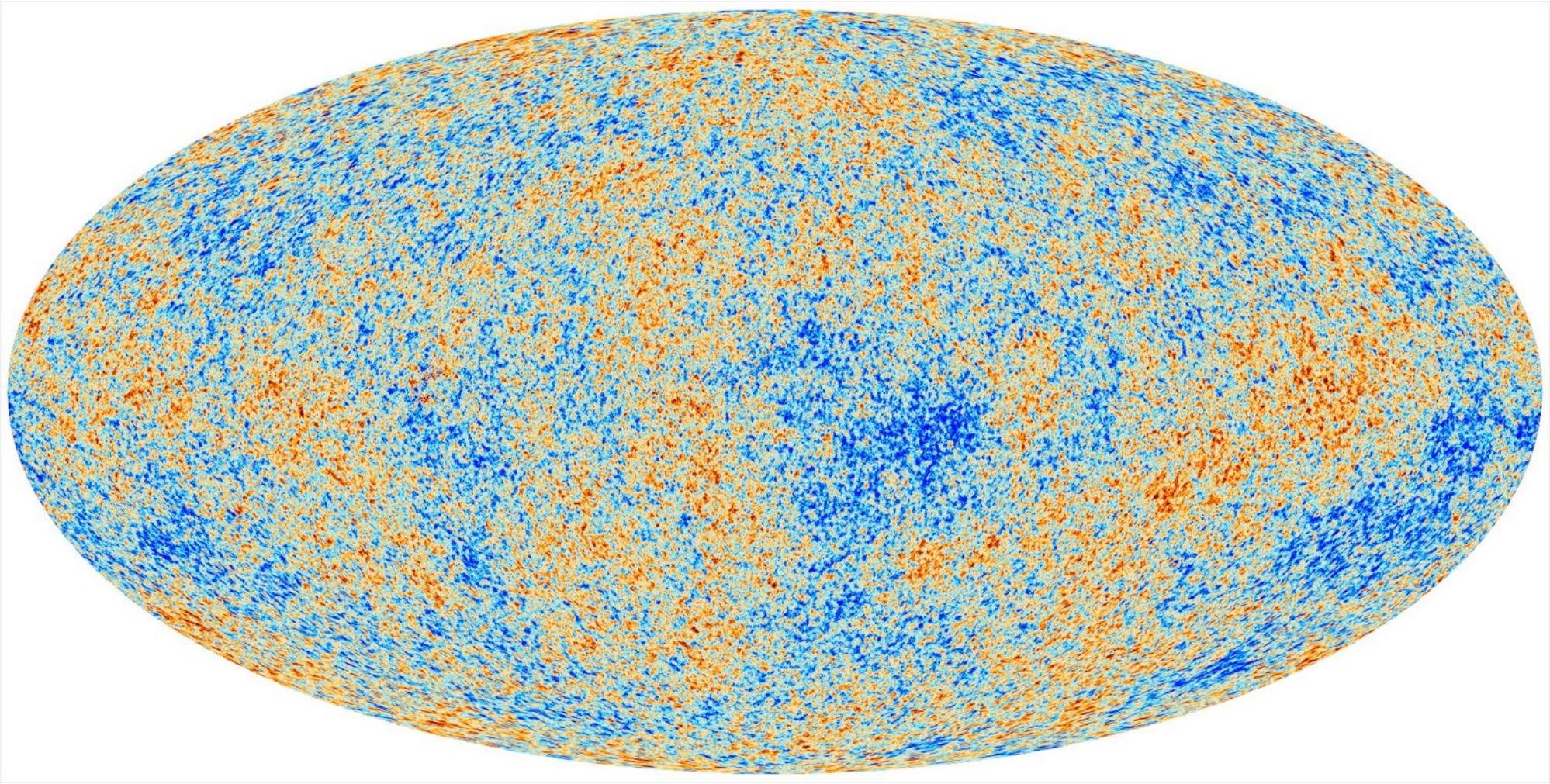
First detection of CMB

- ***Penzias & Wilson (1965)***, Bell Labs - horn reflector antenna used for communicating with Telstar satellite
- Persistent hiss in signal from everywhere in sky
- Learnt of Peebles & Dicke calculation and realized it was the CMB!
- 1978 Nobel Prize





Temperature Fluctuations in CMB



Extremely smooth!!
Fluctuations shown above are 1 part in 100,000

The fate of the Universe

- Depends on the average **density,** ρ
- Define *critical density* ρ_c (balance between gravity and expansion)

- If $\rho > \rho_c$:
  - *Gravity* dominates
  - The Universe will eventually collapse back to a black hole singularity (the "*Big Crunch*").

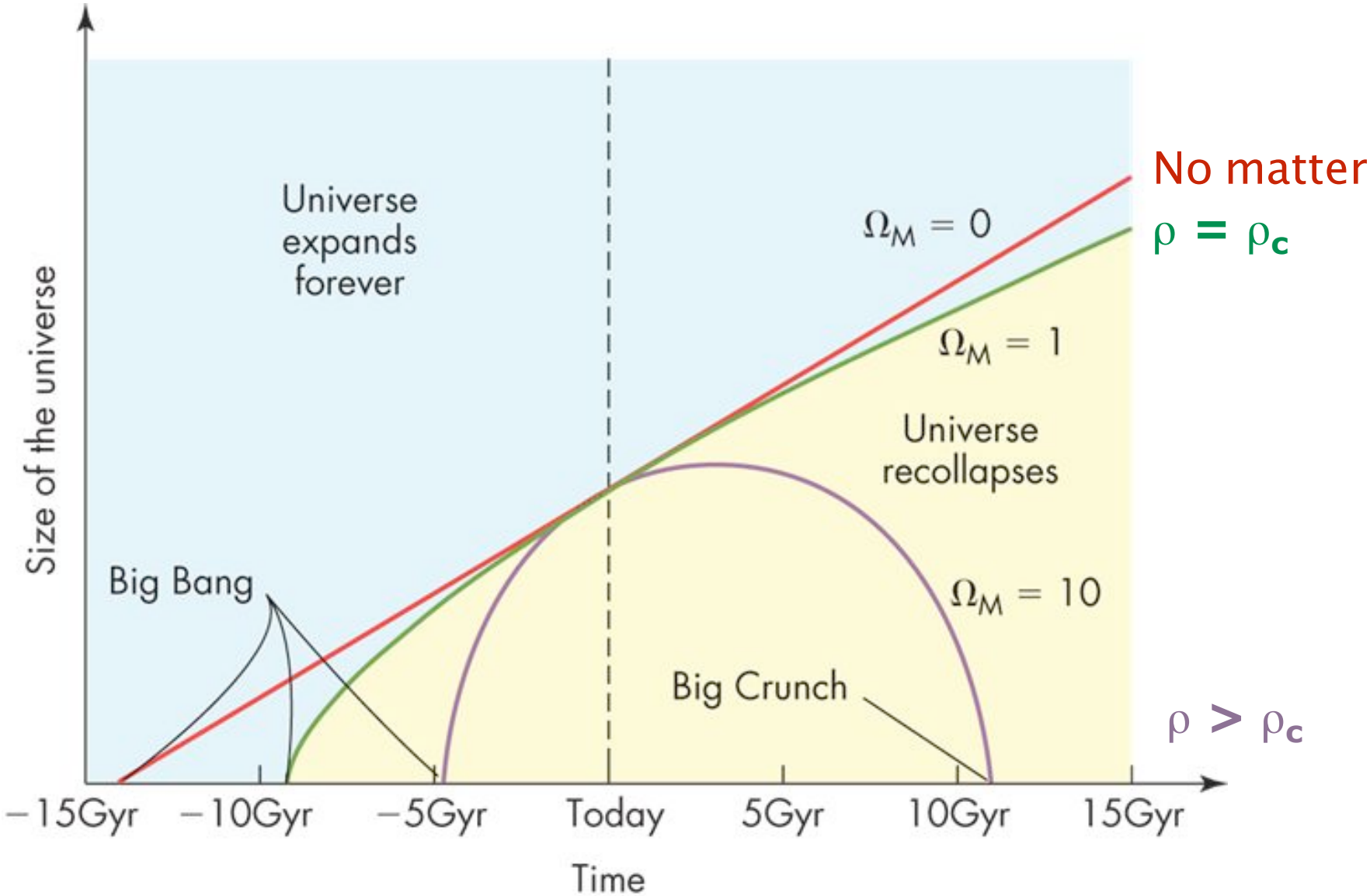
- If $\rho < \rho_c$:
  - *Expansion* dominates
  - The Universe will expand forever.

Omega: Fate of the Universe

- For convenience: cosmologists define a quantity ***Omega***:

$$\Omega_M = \rho / \rho_c$$

- Then plot size of the Universe over time for different values of Ω_M.
  - adjusting slope of each curve to match present rate of expansion.



- Blue region: universe expands forever.
- Yellow region: universe eventually recollapses.

What's the answer?

- From study distances to supernovae and the CMB, find that the expansion of the Universe is accelerating!
- Need repulsive force - **dark energy**
- From studies of galaxy rotation, galaxy clusters and the CMB require extra matter in the Universe that we cannot see - **dark matter**