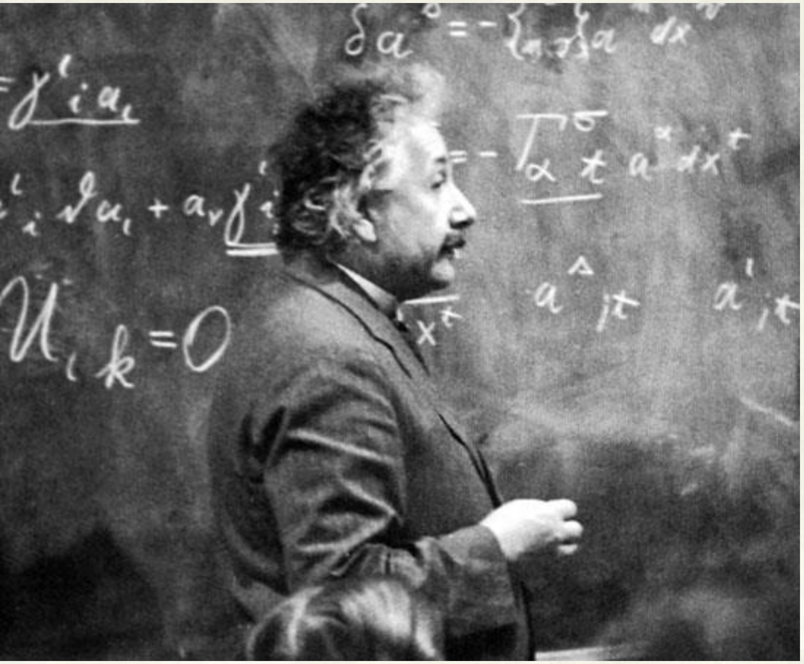
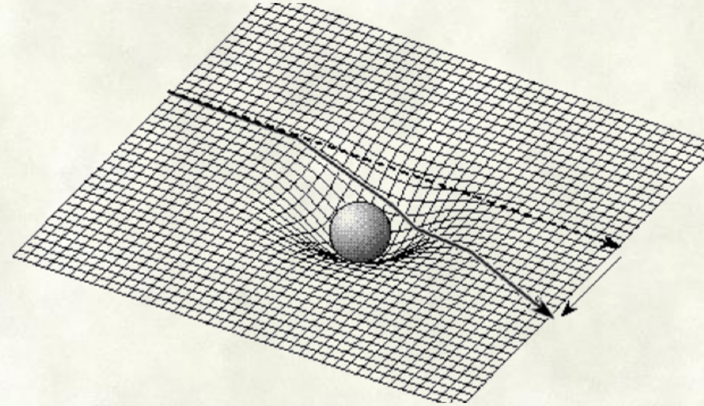
Cosmology

The study of the evolution and structure of the universe.

ASTR 101
11/30/2018

The Evolving Universe





Matter (mass) distorts the space-time around it, path of any moving object is affected by the distorted space-time, which appears as an attractive force, the gravity.

- In the early 20th century the common worldview was that the universe was static and eternal- unchanging with time
- In 1917 Albert Einstein came up with a theory “The General theory of Relativity” which explained gravity in terms of the curvature of space-time.
- But when Einstein tried to model the universe according to general relativity he could not find a stable solution which explained the static universe.
  - instead universe would collapse or expand according to his theory of general relativity.
- Einstein who firmly believed in a static universe, was not ready to accept such dynamic universe yet.
- So he modified the theory, introducing an extra terms to the equations of general relativity. (called gravitational constant) to make the universe static.

Motion of Galaxies

24 inch refractor building at the Lowell observatory in Flagstaff AZ,

TABLE I.

RADIAL VELOCITIES OF TWENTY-FIVE SPIRAL NEBULÆ.

Nebula.	Vel.	Nebula.	Vel.
N.G.C. 221	− 300 km.	N.G.C. 4526	+ 580 km.
224	− 300	4565	+1100
598	− 260	4594	+1100
1023	+ 300	4649	+1090
1068	+1100	4736	+ 290
2683	+ 400	4826	+ 150
3031	− 30	5005	+ 900
3115	+ 600	5055	+ 450
3379	+ 780	5194	+ 270
3521	+ 730	5236	+ 500
3623	+ 800	5866	+ 650
3627	+ 650	7331	+ 500
4258	+ 500		

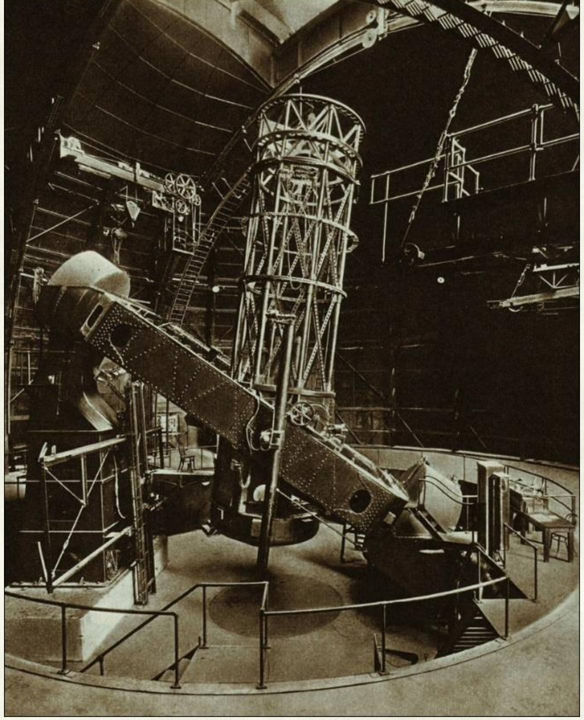
NEBULÆ.

BY V. M. SLIPHER, PH.D.

(Read April 13, 1917.)

A table from Slipher's 1917 presentation at the Amer. Phil. Soc

- In 1909 astronomer Vesto Slipher who worked at the Lowell Observatory measured the spectrum of many spiral Nebulae (as they were called then).
- In 1914 Slipher published radial velocities of 15 spiral nebulae. Some were receding 1100 km/s.
  - Astronomers of that time were not sure what those Doppler shifts really meant.



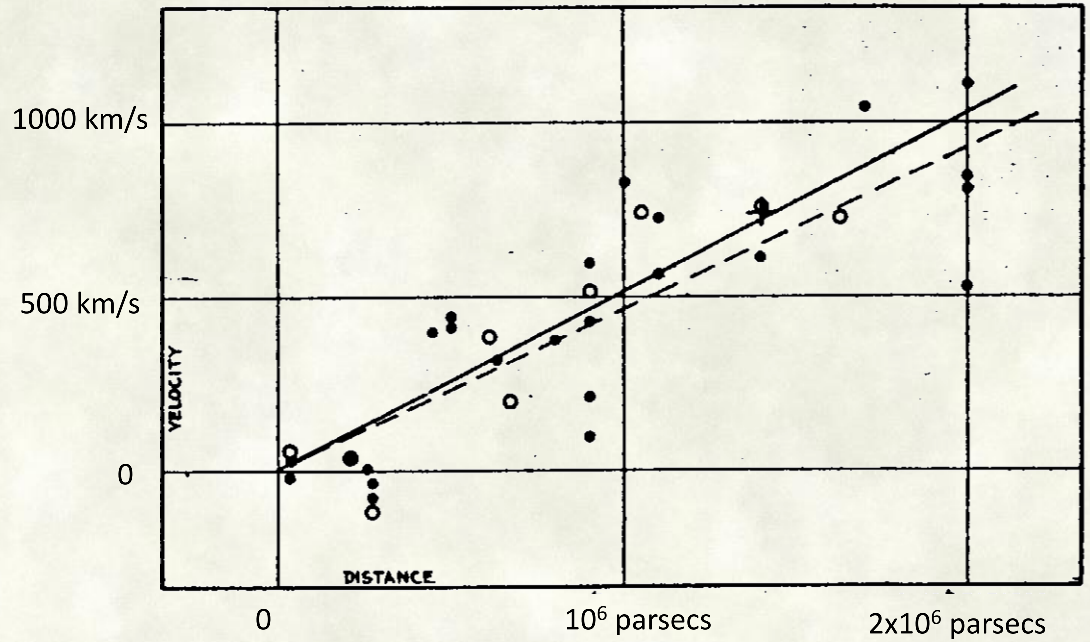
Milton Humason, a high school dropout, joined the Mt Wilson observatory as a janitor, then became a night assistance and later a member of the scientific staff.

Edwin Hubble at the 100 inch telescope

- Slipher was using the 24-inch refractor telescope at the Lowell Observatory. In 1917 a much larger telescope, the 100-inch telescope at Mount Wilson, California was inaugurated (which Edwin Hubble used to find Cephied variables in spiral galaxies).

- 1928 Edwin Hubble with the assistance from Milton Humason measured the spectra of many galaxies,
  - most of them had red shifted spectrums (receding form us).

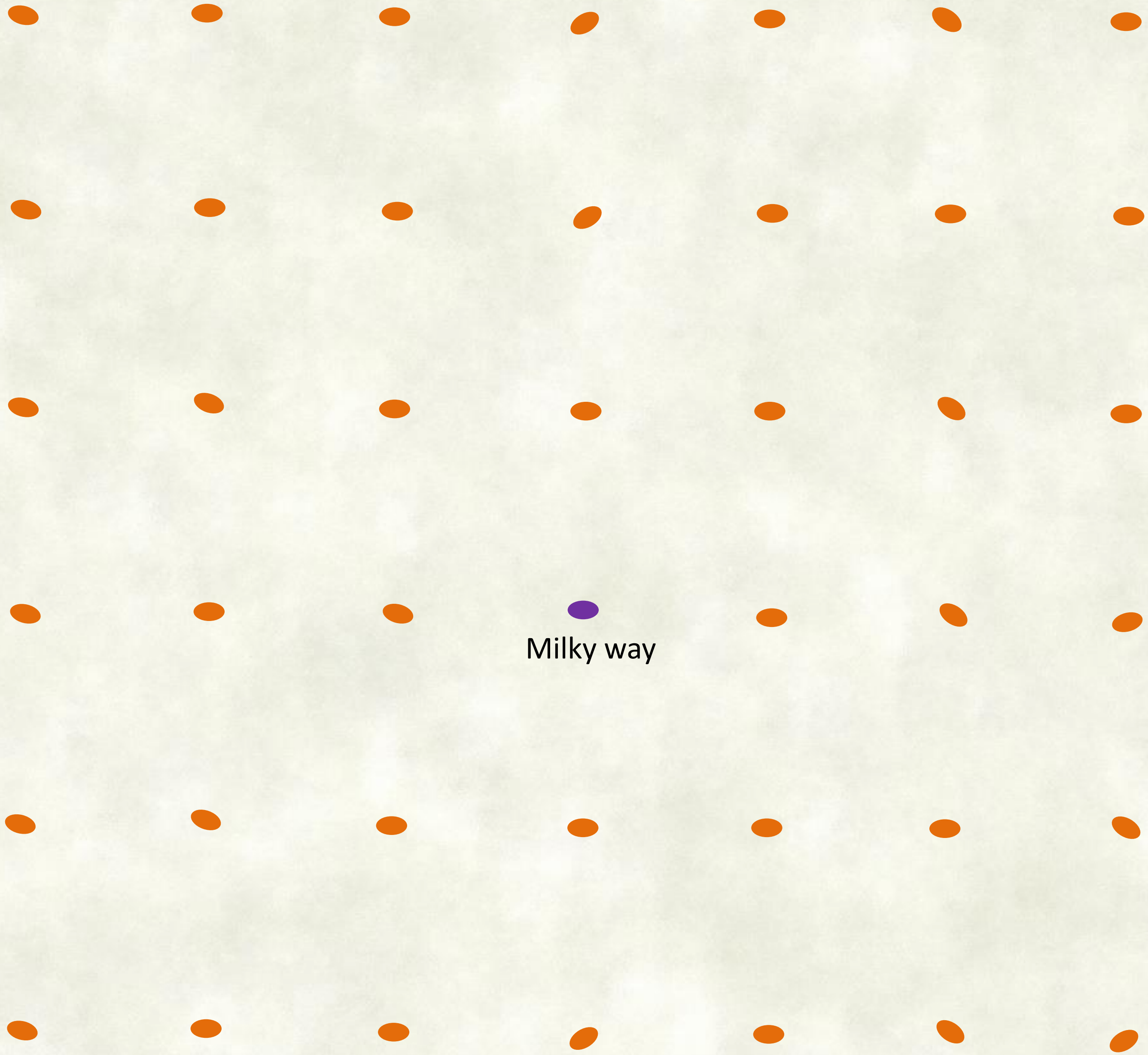
Hubble Law



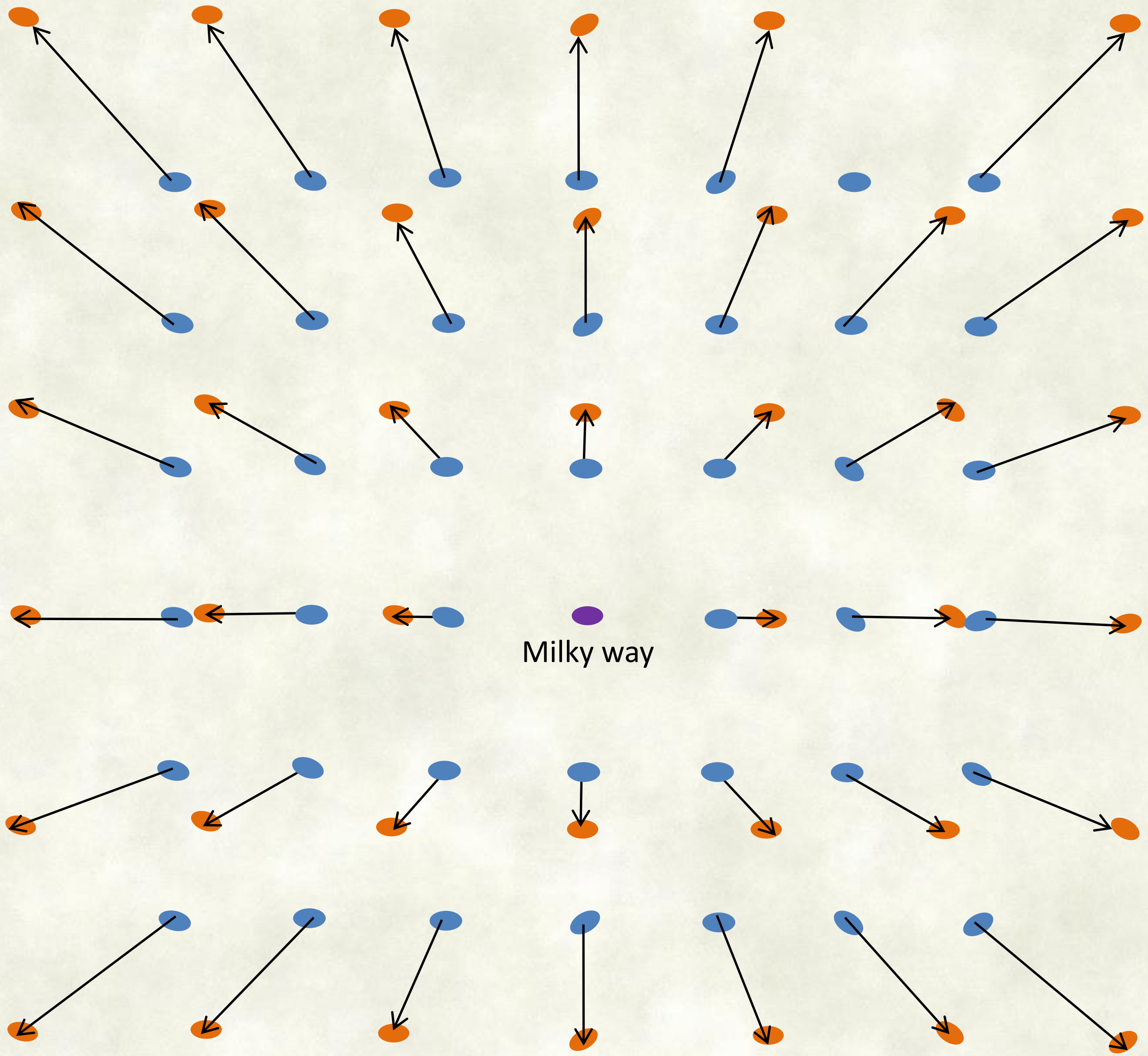
- While Humason was measuring redshifts, Hubble searched for Cepheid variables to determine the distances to them.
- By 1929 Hubble had determined distances to 24 galaxies.
- He saw a direct relation between the speed a galaxy is receding and distance to it.
  - more distance galaxies are receding at a faster velocity, this is known as the **Hubble Law.** **(Hubble-Lemaître law** since October 29**)**
- **That implied the universe was expanding!**

(Even though none, even Hubble believed that the universe was expanding. They thought the observed redshift was due to some effect resulting from light travelling long distance in the universe)

- Distribution of galaxies at a given moment



- Distribution of the same galaxies at a later time, due to expansion of the universe distances between them have increased.

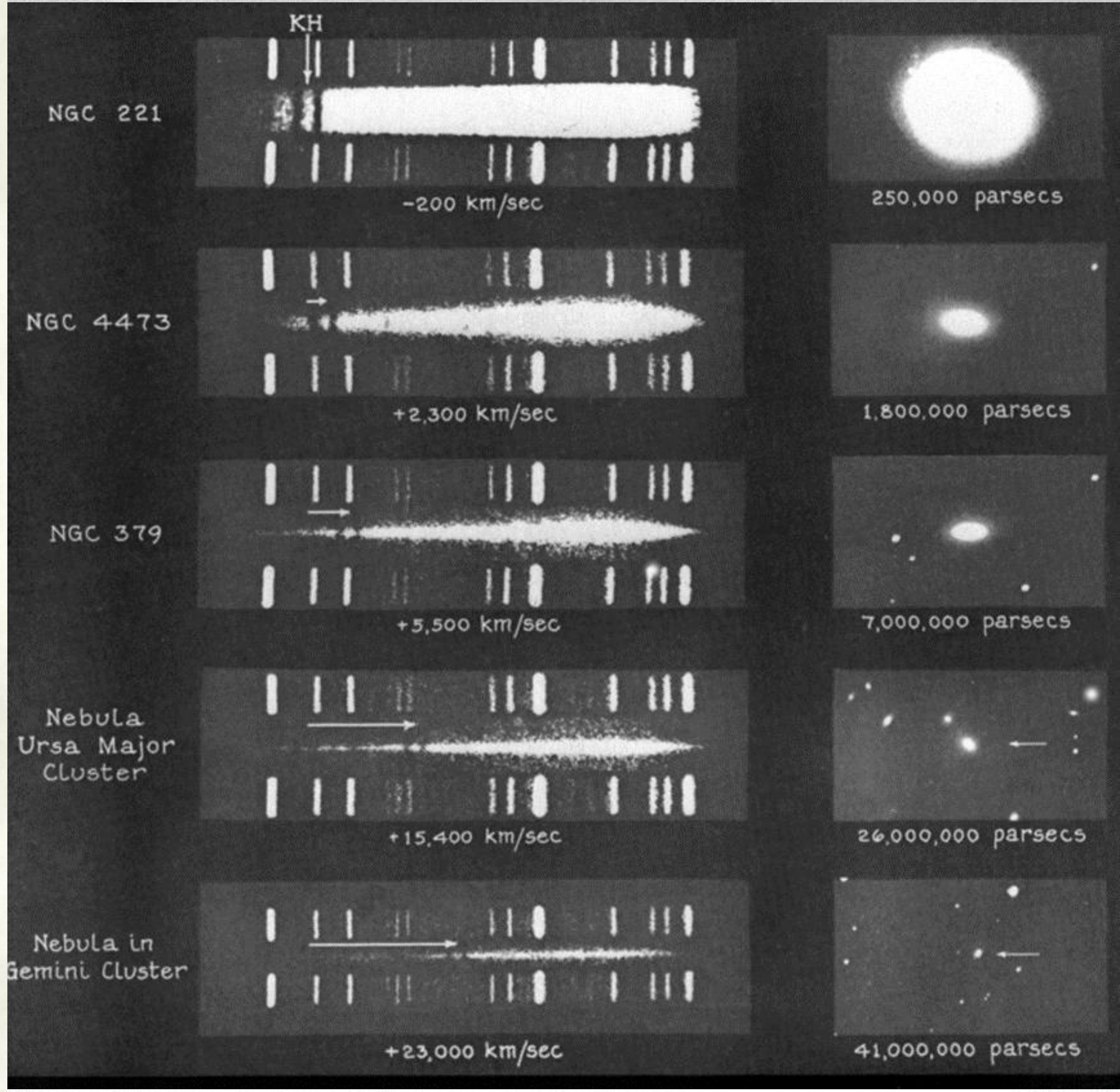


- As the distance increases the distance each galaxy has moved from a given galaxy also increases!
- So speed is proportional to distance ⇒ Hubble law

Taking spectra of galaxies was a tedious task

– Galaxies needed exposure over several nights, and someone has to monitor and guide the telescope during whole process usually in harsh conditions.

A page from Humason's 1936 paper "The Apparent Radial Velocities of 100 Extra-Galactic Nebulae"

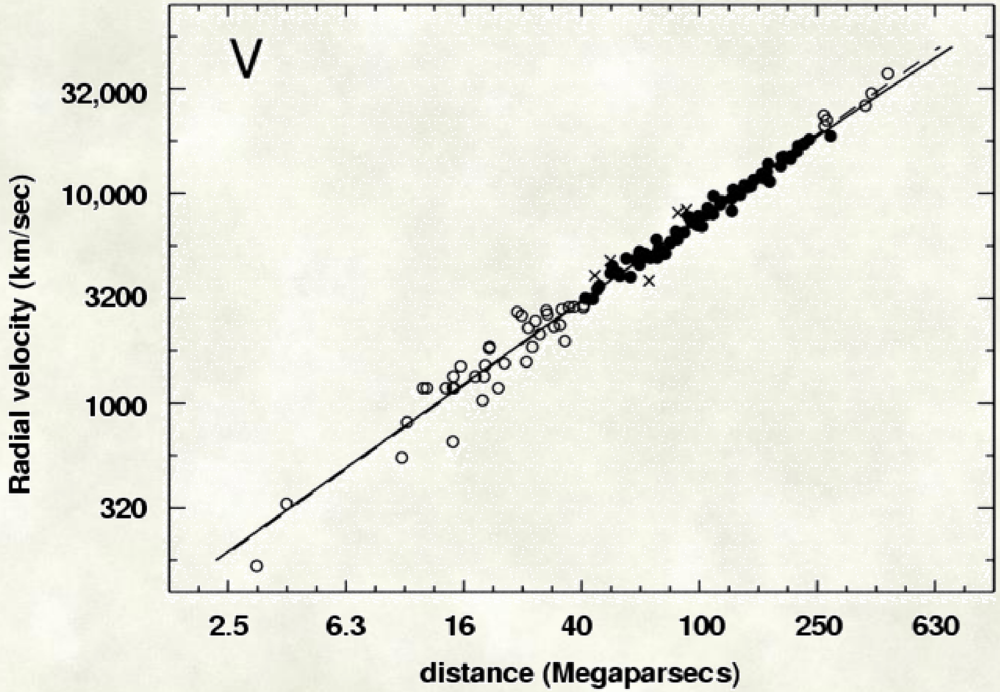


Red-Shifts in the Spectra of Extra-galactic Nebulae

Arrows above the spectra (enlarged twenty times from the original negatives) point to the H and
nes of calcium and show the amounts these lines are displaced toward the red. The comparison spect
re of helium.

The direct photographs (on the same scale and with approximately the same exposure times) illu
rate the decrease in size and brightness with increasing velocity or red-shift.

Hubble Constant



A recent (2005) measurement of Hubble law

- The rate of that increase of the recession velocity with the distance to a galaxy is called the **Hubble constant, H_0**

$$H_0 = \frac{V}{d} \Rightarrow V = H_0 d$$

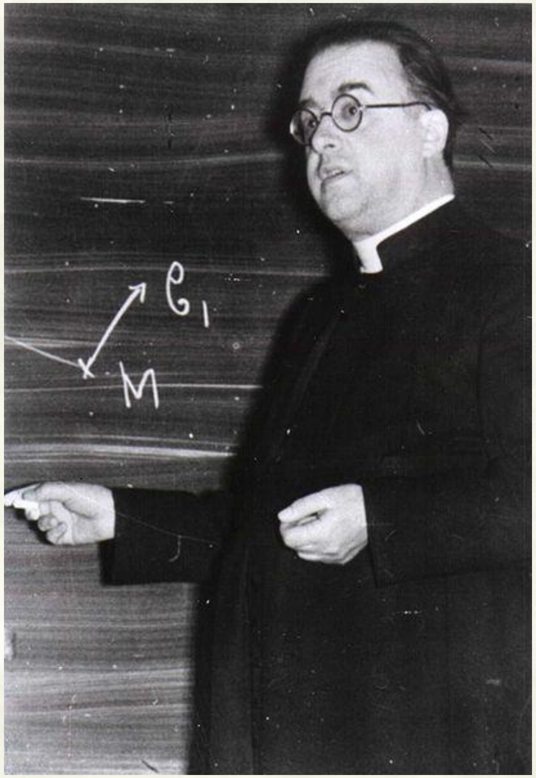
  - V: the velocity in km/sec.
  - D: the distance in millions of parsecs (Mega parsecs).
  - It has units of km/sec per Mpc or km/sec/Mpc .
- Measured value of the Hubble constant is about: H_0 **= 70 km/sec/Mpc**

A galaxy 1 Mpc away is moving 70 km/s

A galaxy 2 Mpc away is moving 140 km/s

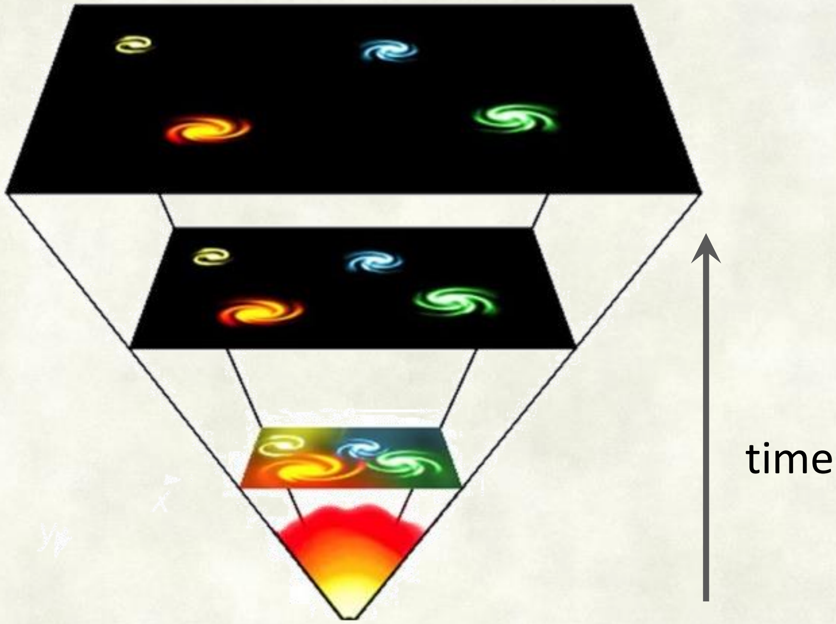
A galaxy 10 Mpc away is moving 700 km/s

The Expanding Universe



- In 1927 Georges LeMaitre (A Belgian astronomer, a Roman Catholic priest, and the professor of physics at the Catholic University of Leuven), came up with a solution to Einstein's general theory of relativity equations.
- The solution he found was of an expanding universe.
- He backed his claim using red shift data published by Slipher in 1914. (which were inadequate).
- In 1927, he published his results in Belgium, explaining *the radial velocity of extra galactic nebulae in terms of an expanding universe.*
- But nobody seems to have agreed, and Einstein who met him at a conference in 1927 had remarked "Your calculations are correct, but your physics are abominable".
- In 1931, Lemaître sent his article to Arthur Eddington, a prominent British astrophysicist and a professor he worked with when he was a student.
- Eddington realized the impotence of LeMaitre solution and what it meant in explaining the redshift distance relation Hubble had discovered.
    - He translated it into English and republished with a commentary.

Big Bang – The primeval atom



A year later in 1933, Lemaître further explored the logical consequences of an expanding universe.

- If the universe is expanding, it had to be smaller in the past.
- extrapolation back in time would lead to an instant when all the matter in the universe was packed together at a single point in an extremely dense state.

- So Lemaître argued that the universe was initially a single particle—the **"primeval atom"** as he called it
  - which disintegrated, giving rise to space and time, which continues to expand to this day.
- This idea marked the birth of what now known as Big Bang theory of cosmology.

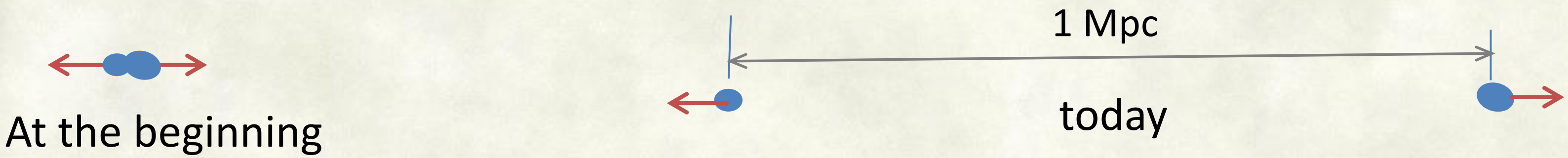
Science and Religion of the Big Bang theory

- Many physicists and astronomers of the time (including Einstein) were skeptical of the idea,

  "a beginning of the universe" proposed by a Catholic priest.

- The idea was too close to the Genesis story in the Bible.
  - It was tempting to think that Lemaître's religious background might have led him to the notion of a beginning of time.
  - Lemaître argued it was just a *scientific* theory and nothing more
  - Lemaitre was against mixing science and religion.
    - He insisted that there was neither a connection nor a conflict between his religion and his science and treated them as different parallel interpretations of the world, both of which he believed with personal conviction.

Age of the universe



- When did the Big Bang happen?

- Current expansion rate is given by the Hubble Constant

$$H_0 = 70 \text{ km/sec per Mpc}$$

⇒ two points (galaxies) in the universe 1 mega parsec apart, they move away from each other at a speed 70 km/s

1 mega parsec = 1000,000 x $3.1\text{x}10^{13}$ km = $3.1\text{x}10^{19}$km

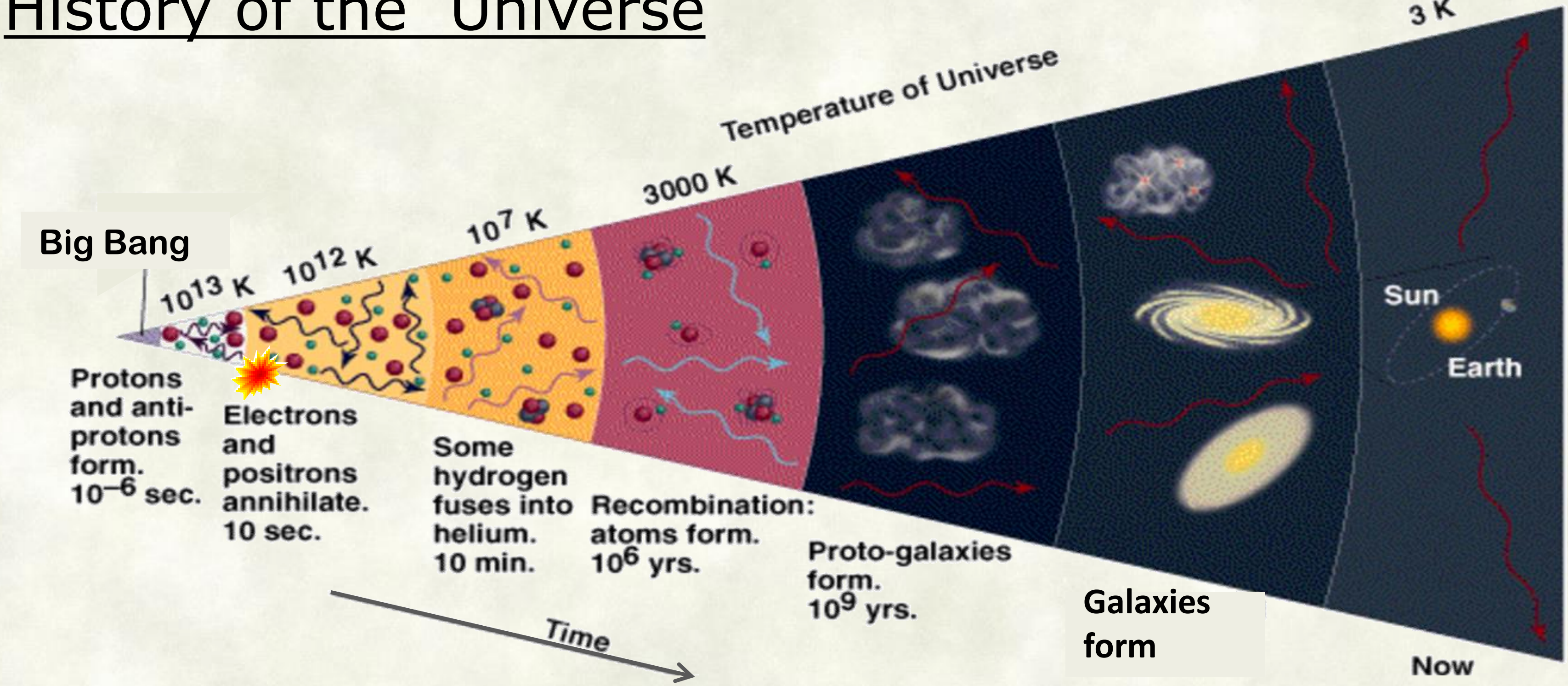
So at 70 km/s rate it would have taken $\frac{3.1\times10^{19}}{70}$ = $4.43\text{x}10^{17}$ seconds

= **14 billion years**

to separate by 1 Mpc, current distance between them.

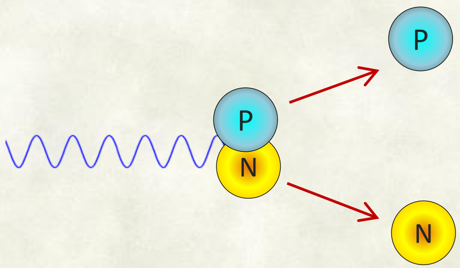
More accurate estimate of the age of the universe give **13.7 billion years**

History of the Universe

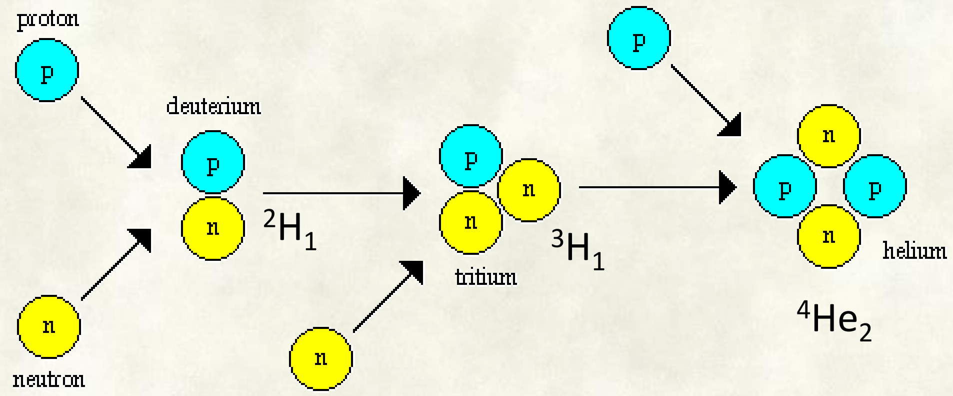


- At the initial moment of the Universe, The Big bang started off with a state of extremely high density and temperature.
  - Universe was filled with energy, dominated by radiation in the form of photons and other energetic particles.
- As the universe expanded, its temperature dropped.
  - energy was converted to elementary particles, elementary particles combined to form protons and neutrons, which combined to form nuclei and then atoms.

Big bang Nucleosynthesis



At higher temperatures nuclei are dissociated to protons and neutrons by radiation (high energy photons)



temperatures below 10^9K protons and neutrons combined to form larger nuclei

- In very early universe (few seconds old) temperature was so great that, all the matter was ionized and dissociated,
  - universe was filled with radiation, protons, neutrons, electrons and neutrinos.
  - No heavier nuclei could exist at such high temperature, any nuclei produced quickly dissociated by high energy radiation
- After about 100 seconds, temperature was about 1 billion K.
- Neutrons and protons combined to form Helium.

Big bang Nucleosynthesis

Helium thus produced underwent further nuclear interactions combining with other helium nuclei and protons:

$^4He + ^4He \rightarrow ^8Be$ (beryllium 8 isotope)

$p + ^4He_2 \rightarrow ^5Li$ (lithium -5 isotope)

but ^8He and ^5Li are highly unstable, and decayed almost instantly before undergo further nuclear interactions.

$^8Be \rightarrow ^4He + ^4He$

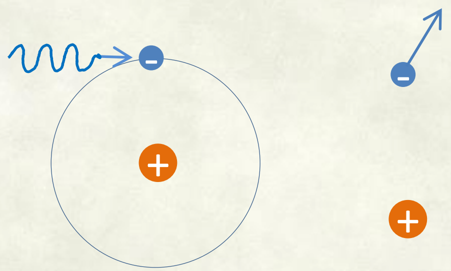
$^5Li \rightarrow p + ^4He_2$

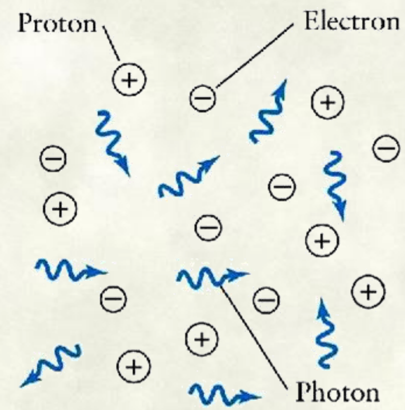
And the temperature was dropping fast, so the Big Bang nucleosynthesis ended at helium after few minutes.

- with a universe containing 76% hydrogen and 24% helium (and trace amounts of lithium and deuterium).

All heavier elements were later synthesized in the cores of stars where conditions were more favorable to form heavier nuclei.

Recombination – primordial photons



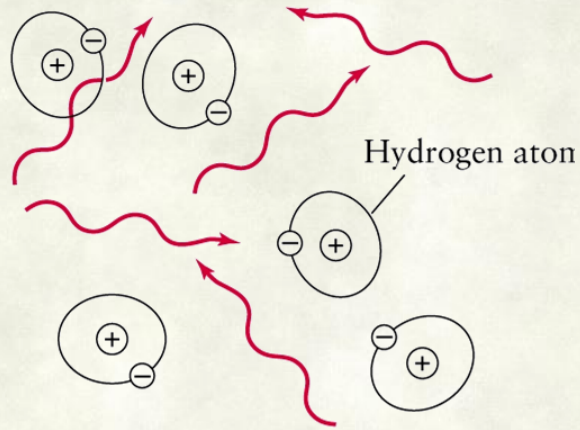


Earlier on in the hot universe radiation (photons) had enough energy , they get absorbed and disassociate atoms

All the matter was ionized, there was a lot of free electrons which scatter protons.

- In the hot early universe matter and radiation have been interacting with each other.
  - elections and protons combine to form atoms
  - photons knocking off electrons from atoms thus dissociating atoms and leaving free electrons.
  - photons are scattered by free electrons
- So photons could not travel too far before being absorbed or scattered. Universe was opaque

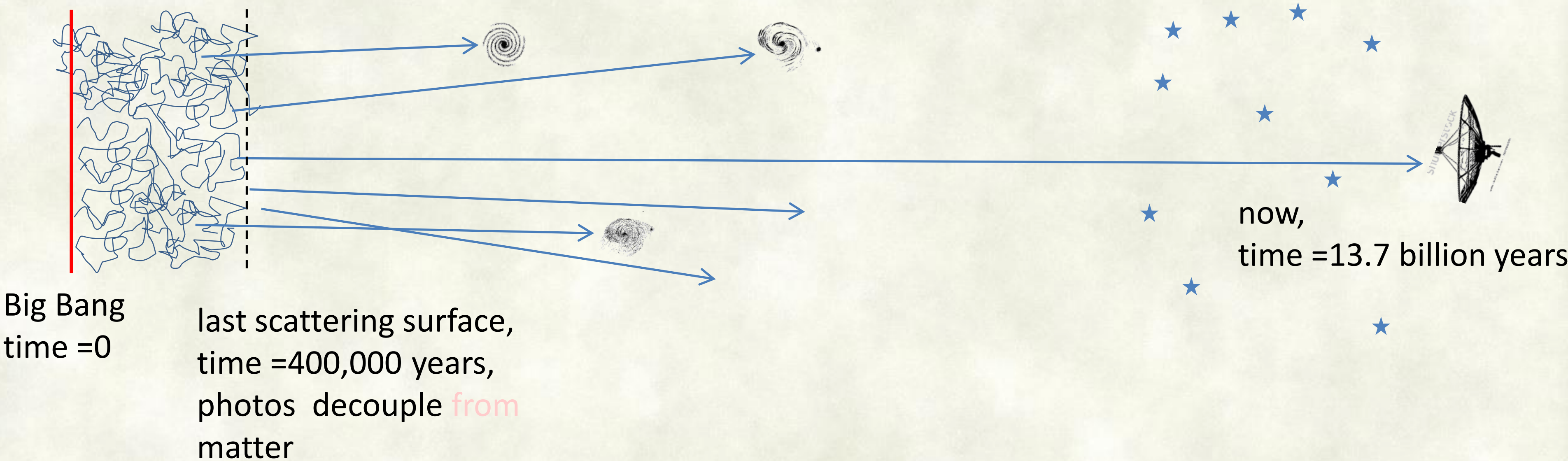
Recombination – primordial photons



After recombination photons not energetic to disassociates atoms, so they move freely

- **Time ~ 400,000 years after the Big bang - temperature 3000K:**
  - Now the temperature has fallen to about 3000 K, photons are not energetic enough to knock off elections form an atom and dissociate them.
  - So electrons combined with nuclei to form atoms remained intact.
  - All free electrons combined with nuclei to form neutral hydrogen and helium atoms and there were no free electrons left. This is called 'recombination'.
  - remaining photons moved freely in space without further interactions with free electrons and atoms.
    - **Universe became transparent: after that light could travel large distances before being absorbed or scattered.**

Relic radiation from the big bang

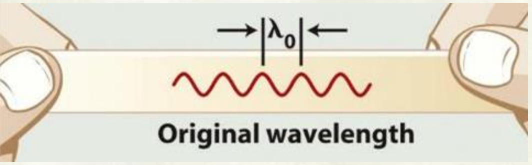


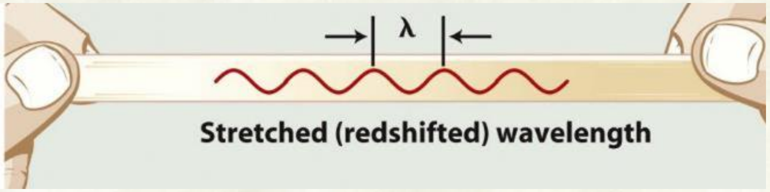
- When they decoupled from matter their temperature was about 3000K
  (filament temperature of a incandescent light bulb)

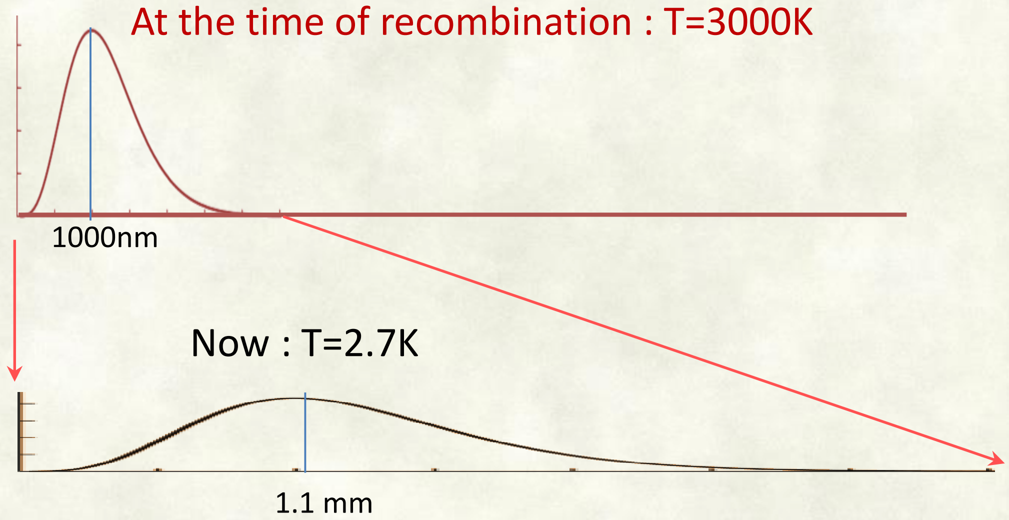
- Those primordial photons have been travelling in all direction in the universe since than.

- Some of them reaching us today. So we should be able to see them.

Cosmic Microwave Background (CMB) radiation

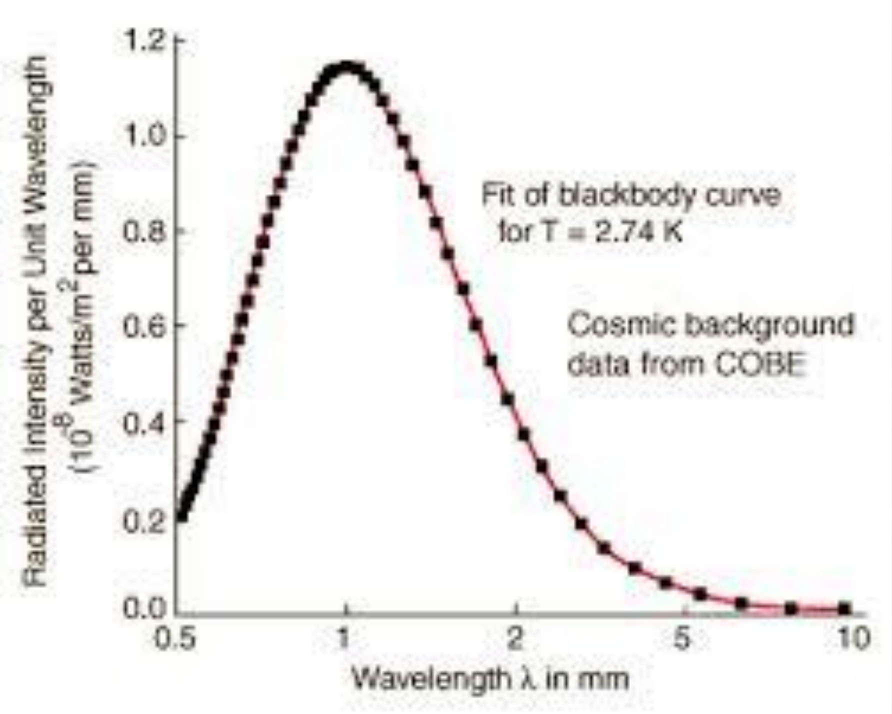




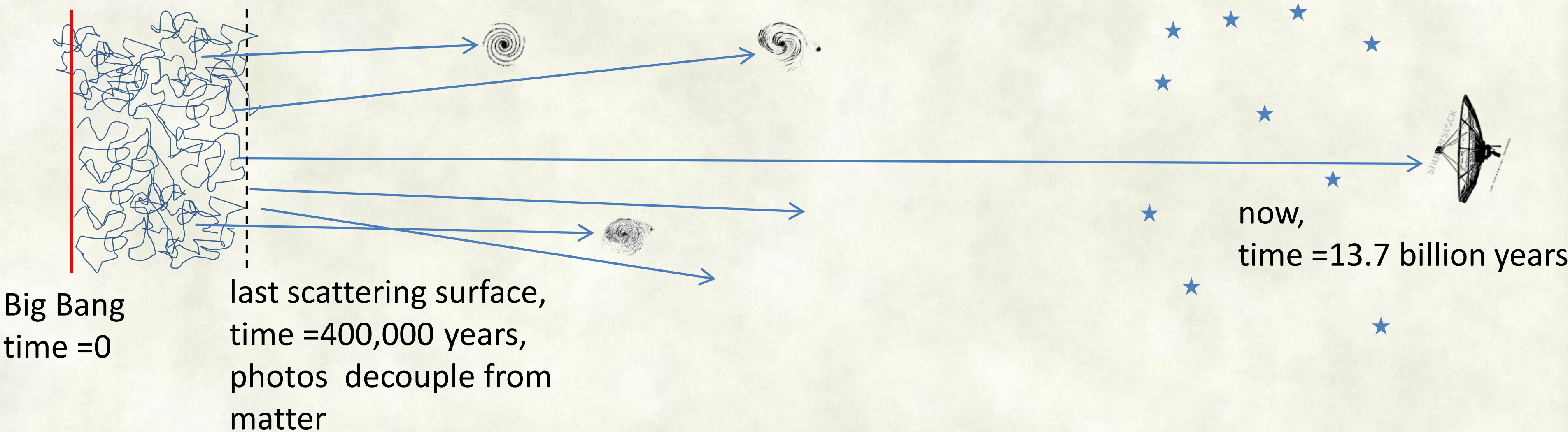


- Primordial photons left from the big ban after 400,000 years have been traveling in the expanding universe:
  - As they travel, space they were travelling was expanding.
  - They get stretched by the expanding space, their wavelengths increased.

- Since then universe has expanded about 1100 times, wavelengths of all those photons has stretched by a factor of 1100,
  - It peaked at 1000nm (infrared) at the time of recombination, now the peak is at 1000x1100 =1100000nm = 1.1mm, in the microwave band.
  - **Corresponding to a thermal radiation of $\frac{3000\ K}{1100}$ = 2.7K**



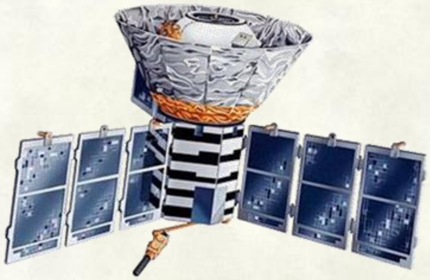
- Today we are receiving this primordial radiation from the Big Bang as microwave radiation from outer space.
- It was predicted by the Big Bang theory in 1950s
  - Discovered inadvertently in 1965 by two engineers, Arno Penzias and Robert Wilson, at the Bell Telephone labs in New Jersey.
- They had built a very sensitive new radio antenna for satellite communication:
  - but there was excess noise in the radio receiver they could not understand or get rid of.
- Coincidentally, researchers at the nearby Princeton University, led by Robert Dicke were devising an experiment to find the CMB. When they heard about the Bell Labs result they immediately realized that the CMB had been found.



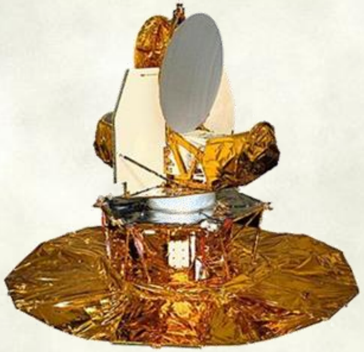
- Cosmic microwave background is the most distance photons (light) we can receive.
- Beyond that photons react and scattered by matter and we cannot see though,
  - like looking at thick fog, since light is scattered by fog we can not see beyond the fog.
- So CMB is the most distant and oldest feature in the universe we can observe with electromagnetic radiation.
- It has been studied extensively since its discovery, using ground based, air bone (balloons) and satellite observations unveiling wealth of knowledge about the universe.

An airborne CMB detector is being readied to launch

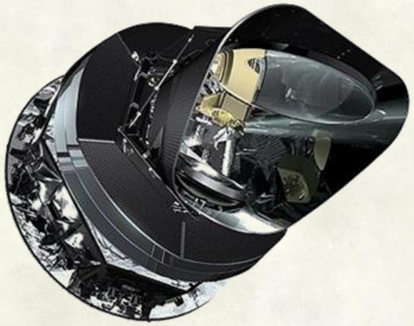
CMB telescopes at the South pole



COBE (1990)



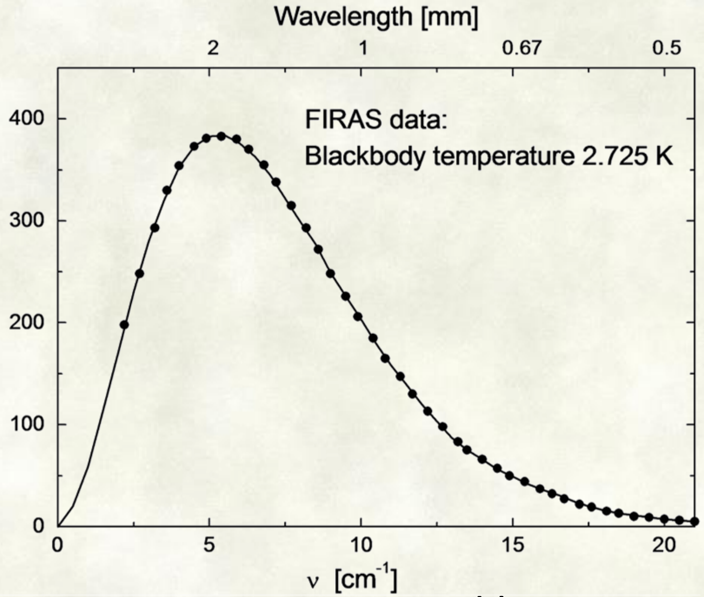
WMAP (2001)



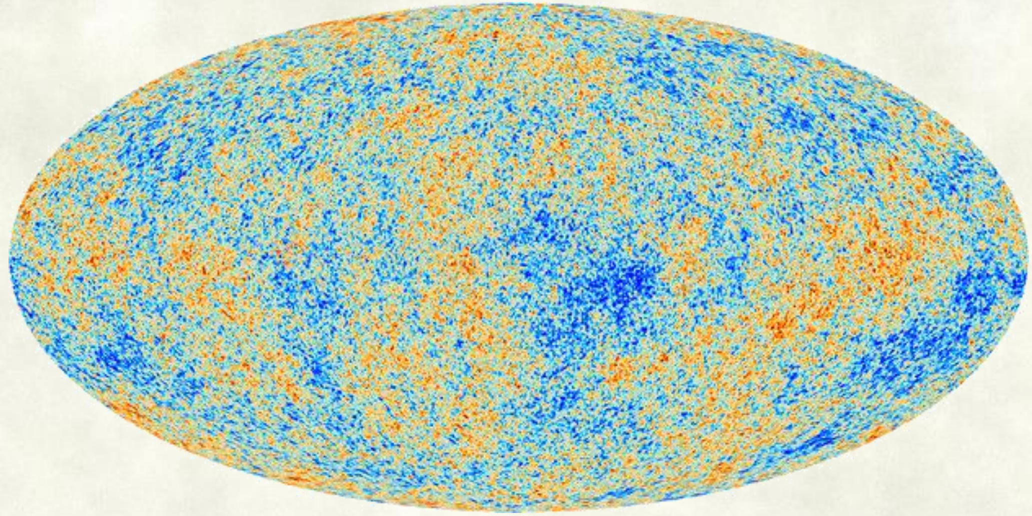
Planck (2009-2013)

Satellite based CMB detectors

Cosmic background anisotropy

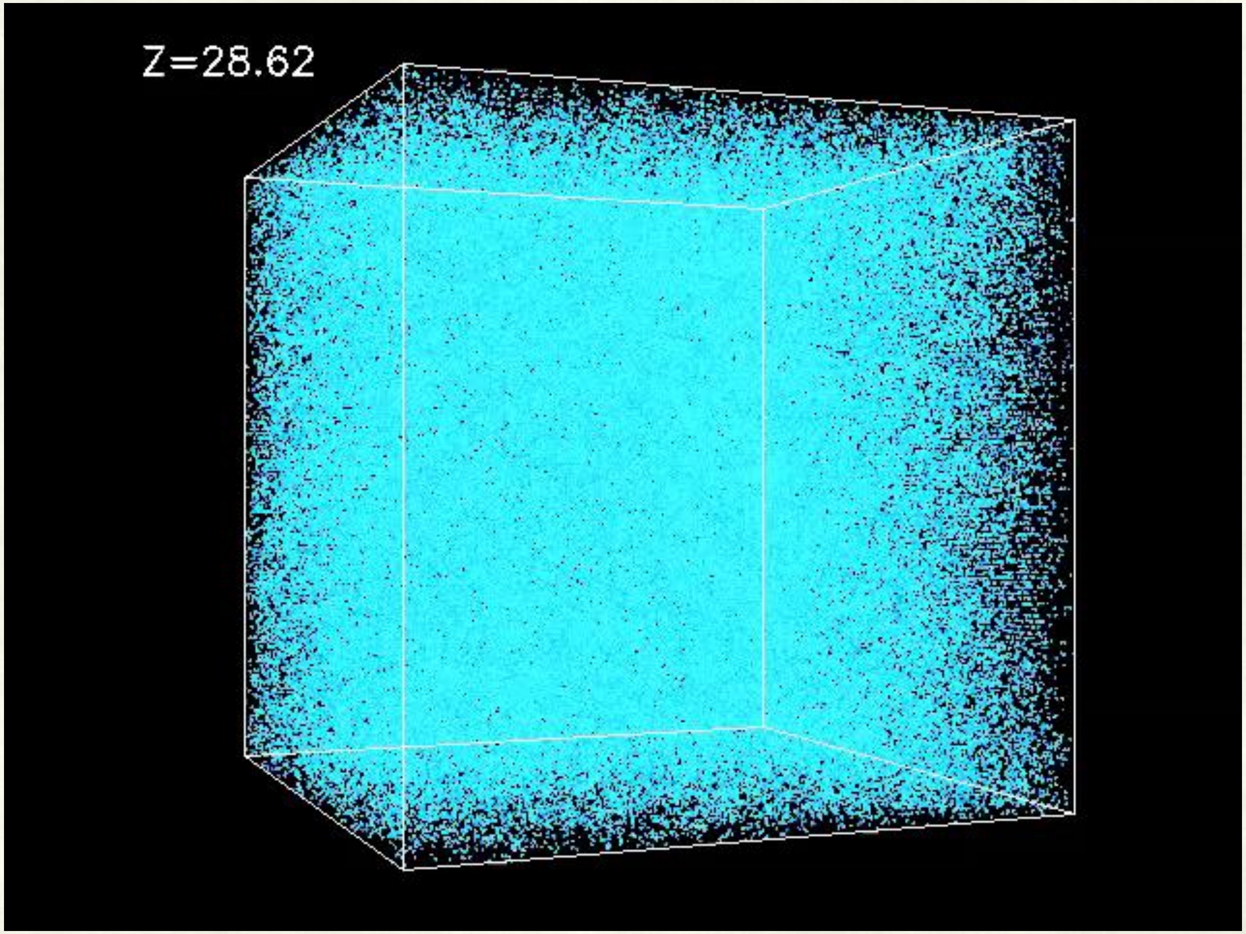


CMB spectrum as measured by COBE



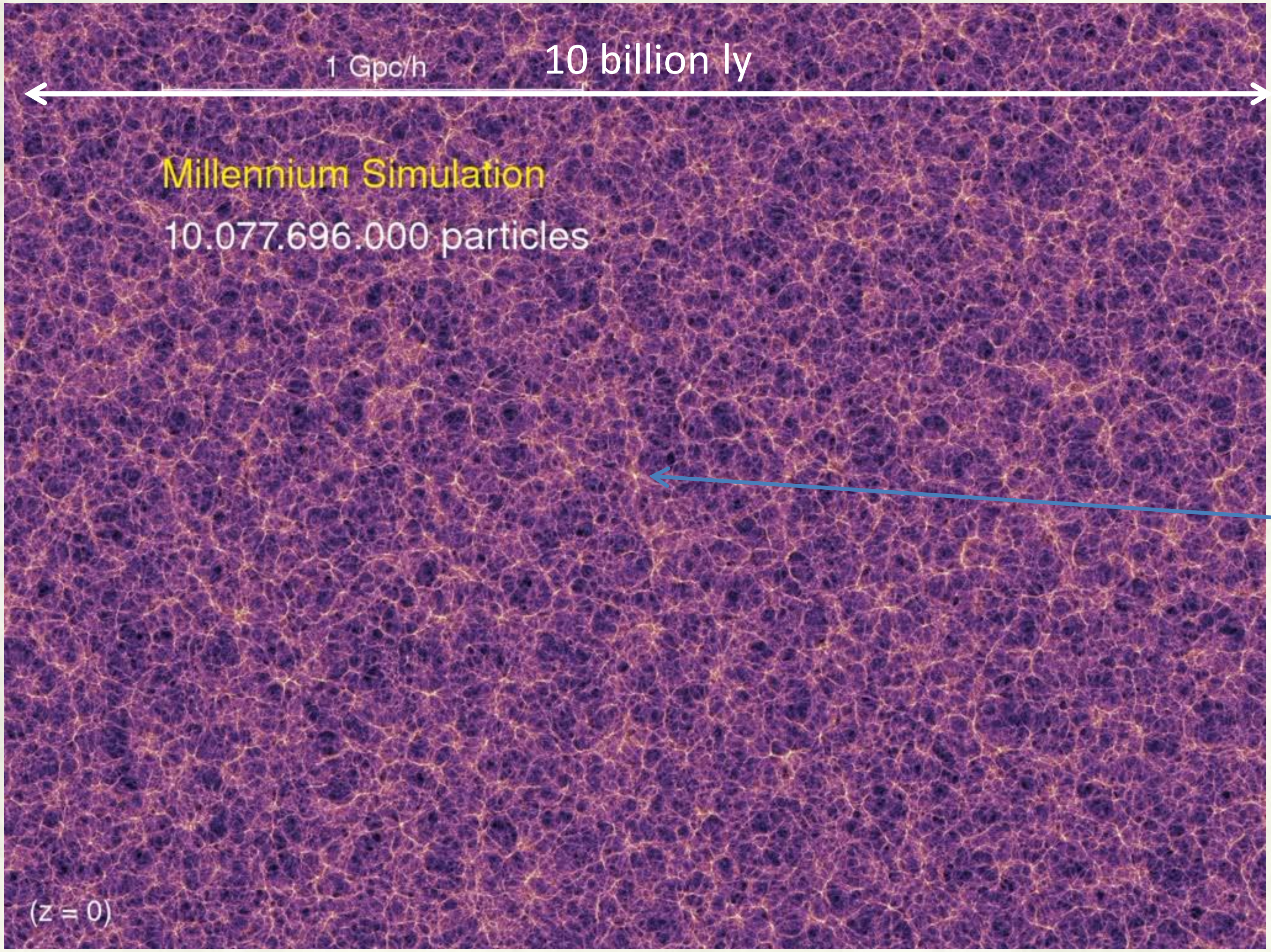
CMB anisotropy map of the sky by Planck. Variation of the temperature from hottest (red) to coldest (blue) is 0.00005K

- The spectrum of the CMB irradiation is the thermal radiation of temperature 2.73K. (original 3000K red shifted by ~ 1100)
- CMB radiation coming from all direction is very uniform. ie. has the same temperature.
- But there are tiny fluctuations $\sim {}^{1}/_{10,000}$
- Those fluctuations represent tiny variations in the matter density of the universe that time.
- Those were the over densities which grew in to galaxies, clusters of galaxies and other structures we see in the universe today.



Evolution of the structure in the Universe from original fluctuations
cosmicweb.uchicago.edu/filaments.html

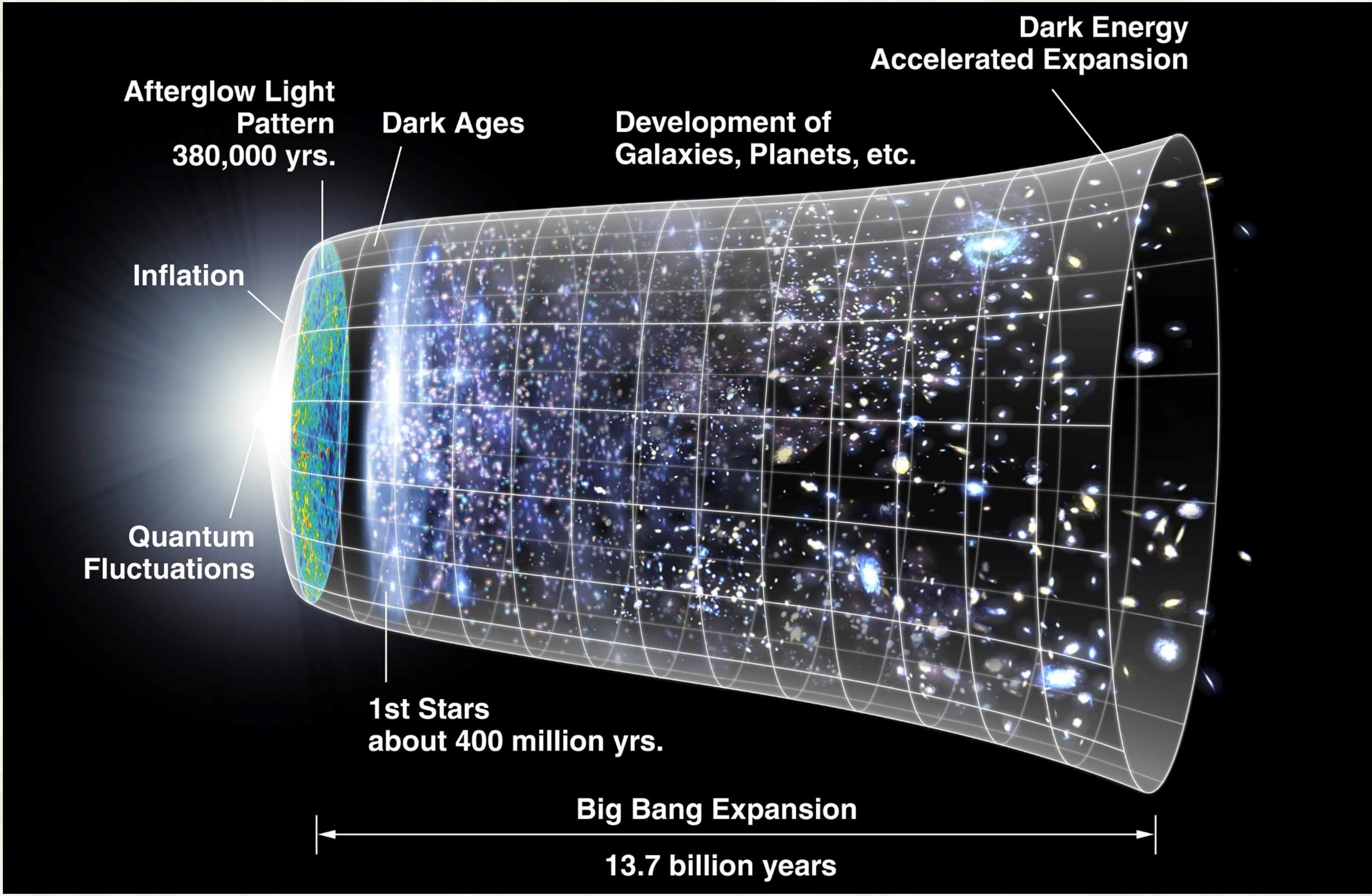
Cosmic Web



cluster of galaxies
(Virgo)

From: www.mpa-garching.mpg.de/galform/virgo/millennium

- This would be the view of the universe in the largest scales, filament, walls, super clusters and voids of galaxies
- Universe is homogeneous and isotropic on scales larger than 500 million light years:
  - no special or preferred place in the universe, same everywhere.

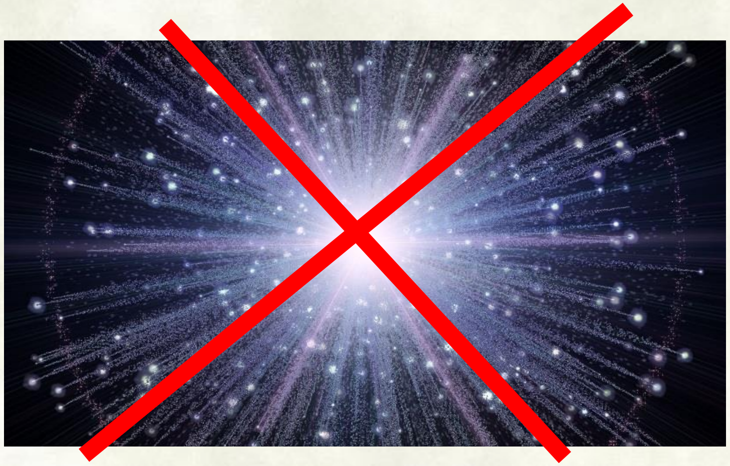

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

- aa

Evidence for the Big bang

- Observational evidence supporting the big bang theory:
  - Redshift of the galaxies: as Hubble found out galaxies are moving away from each other according to Hubble law, showing that universe is expanding.
  - Cosmic microwave background: Relic radiation predicted by the big bang theory and discovered in 1965.
  - Primordial elements: As predicted by the big bang theory, oldest gas clouds in the universe contain 76% hydrogen and 24% helium, with trace amounts of lithium and deuterium.
  - When we look back in time we see older parts of the universe.
    - we can see that galaxies long time ago were quite different from those today, showing that the Universe has evolved over time.

Expanding Universe: Misconceptions



Wrong picture

Galaxies are moving in the space receding from each other, just like debris flung out through space in an explosion:

It is the space, (which originated at Big Bang) that is expanding carrying galaxies with it, not galaxies are moving from each other.

- Just like the distance between dots marked on a balloon increases as it expands.
  - dots are fixed on the surface of the balloon, but they are moving because the surface of the balloon is expanding
- The 2-dimensional surface of the balloon is analogous to the 3 dimensions of space.

  (The balloon is expanding in to 3 dimensional space, for the universe we cannot visualize another dimension it is expanding to, since our experience is limited to only 3D.)

Expanding Universe: Misconceptions

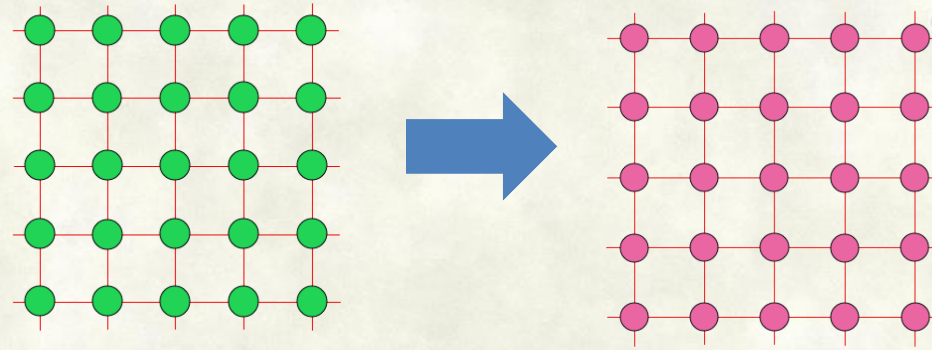
Big bang was a huge violent explosion, which blew away mater in all directions:

- Big Bang is the event that space-time came into existence. Even though initial energy density, temperature and pressure were extremely high, it was not an explosion.

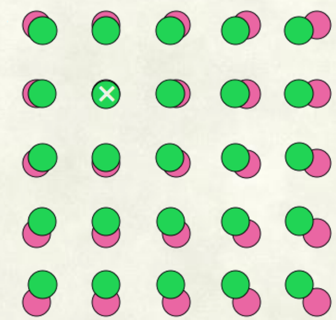
As another 2-dimentional analog, consider bubbles in boiling water:

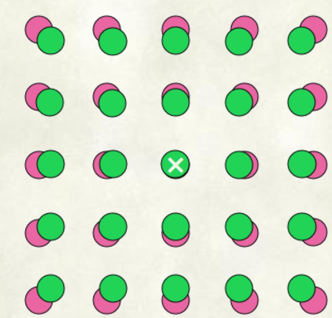
- Bubbles form in the water, which seems suddenly appear, out of nothing and gradually expand and grow in size.
- Surface of the bubble (not its volume) is a close analog of what happened at the Big bang.
- Like the formation of a tiny water bubble which grow in size, formation of space-time at the Big Bang was not an explosion, nothing violent about it.
- In fact it was a smooth, very orderly process.
- As we saw, at the time of recombination (earliest time we can look back and see with light) matter in the universe was so smoothly distributed that any variation in density was less than 0.001% (1/10000).

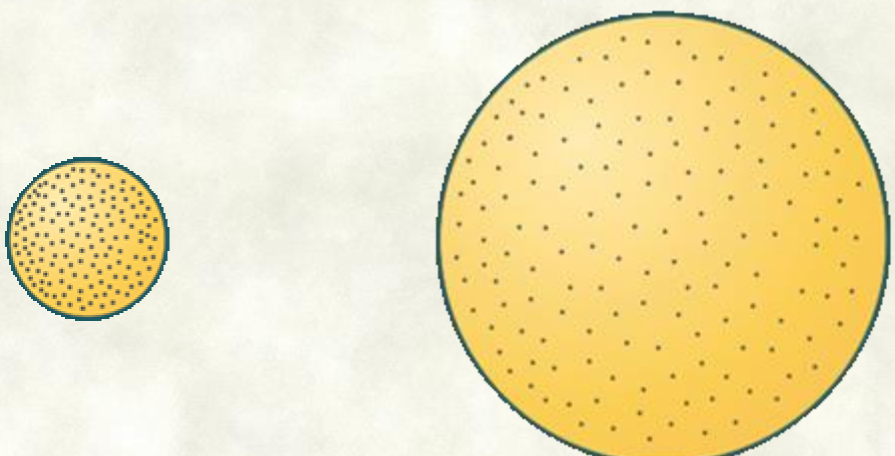
<u>If universe is expanding where is the center?</u>



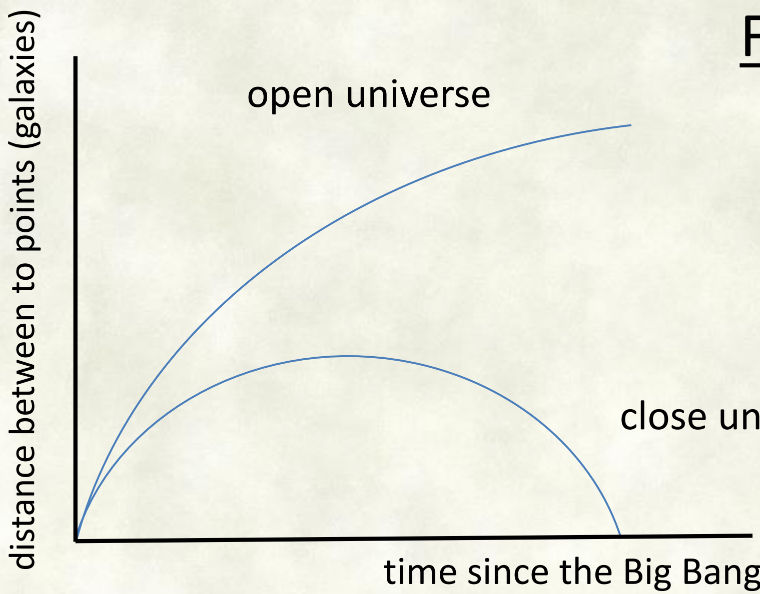
- There is no center to the expansion, it is the same everywhere. It is not like galaxies move in the space starting from some point.
- But the space expanding which happens everywhere.
- At any location in the universe we see everything else moving away from it due to cosmic expansion.
- just like the points on a balloon:
  - From any dot it appears that every other dot is moving away from it. So there is no proffered location, view looks the same from any dot.

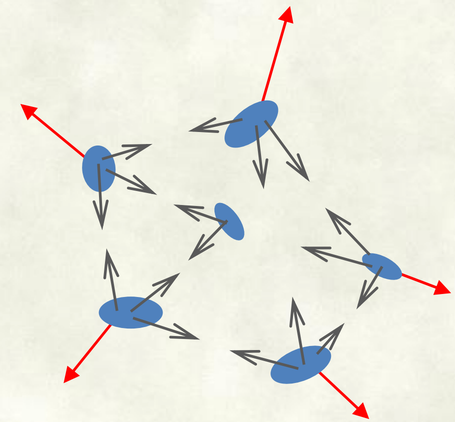






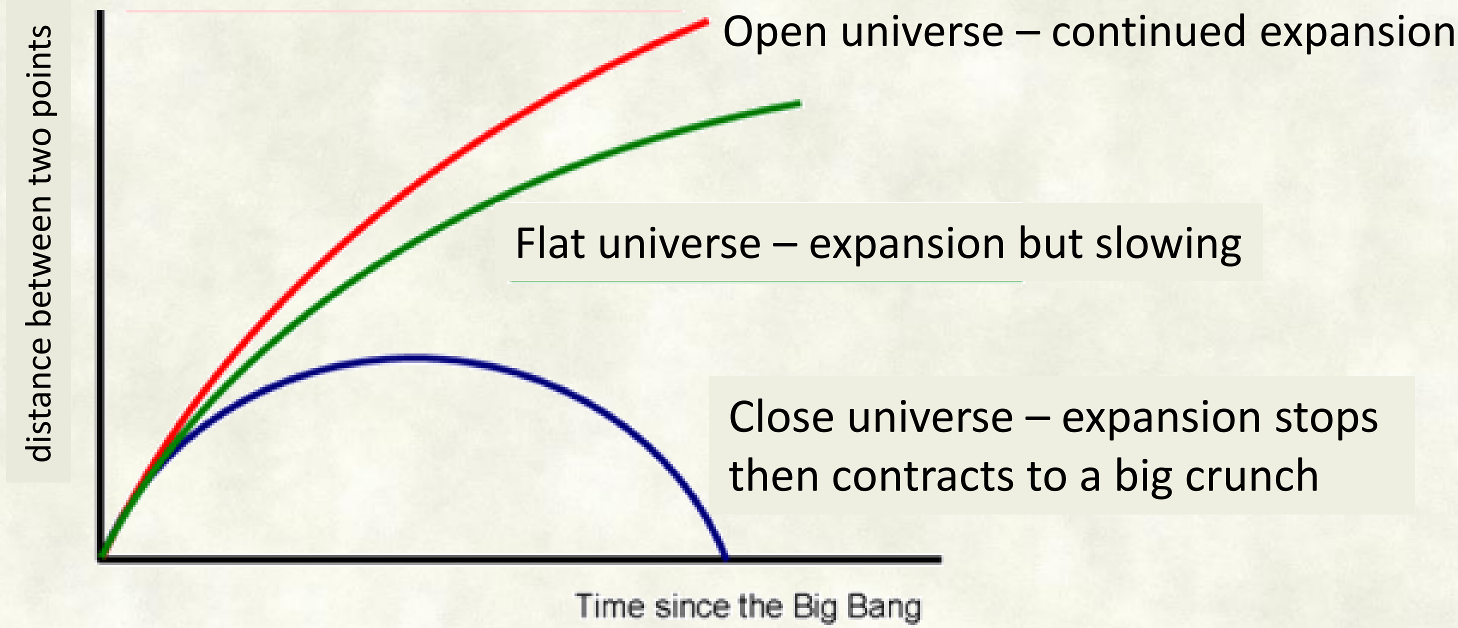
Fate of the Universe





gravitational attraction should deaccelerates the expansion

- Will the Universe expand forever?
  - It depends on the matter density of the universe
  - Just like the an object fall back to the Earth if its speed is less than the Escape velocity, and moving away from the Earth forever if its speed higher than the escape velocity.
  - future state of the expansion of universe depends on its matter content (density) and the rate of expansion (speed).
  - If the density is low, the universe will expand forever. If it is high, expansion will stop at some point in time and the universe will start contract and ultimately collapse to a point "the Big Crunch".

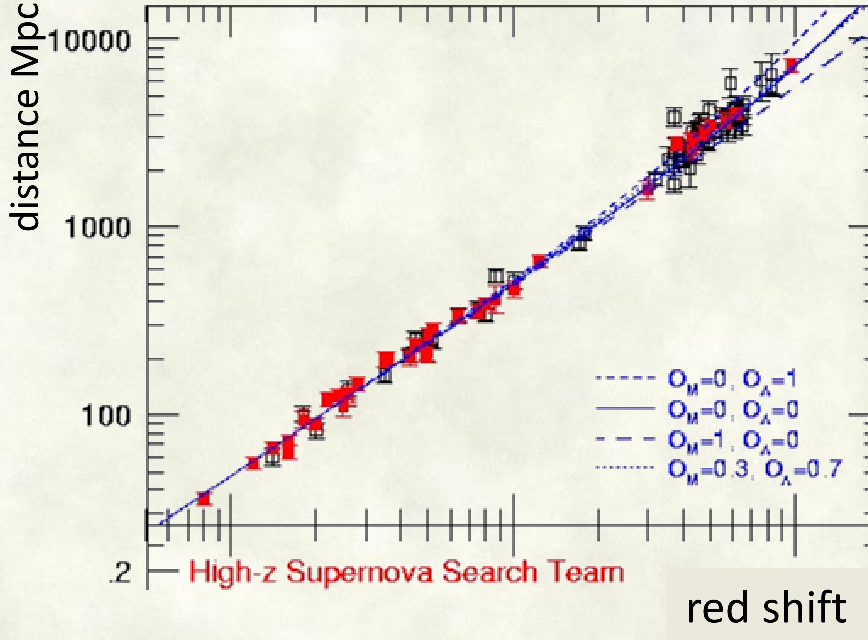


- There is a critical density between final collapse and forever expansion.
  - Density just enough to halt the expansion
  - At this density it will take infinitely long time to the expansion to stop
- Given the current rate of expansion of the universe, that critical density is

about 9×10^{-27} kg/m^3

- This is about five hydrogen atoms per cubic meter
- So there are three possibilities:
  1. Closed: Above the critical density, expansion stops , then contraction and ultimate collapse the "big crunch"
  2. Flat: The critical density, expand forever but ever slowing rates and finally stop
  3. Open: Below critical density expansion slowing down but never stops universe expands forever,

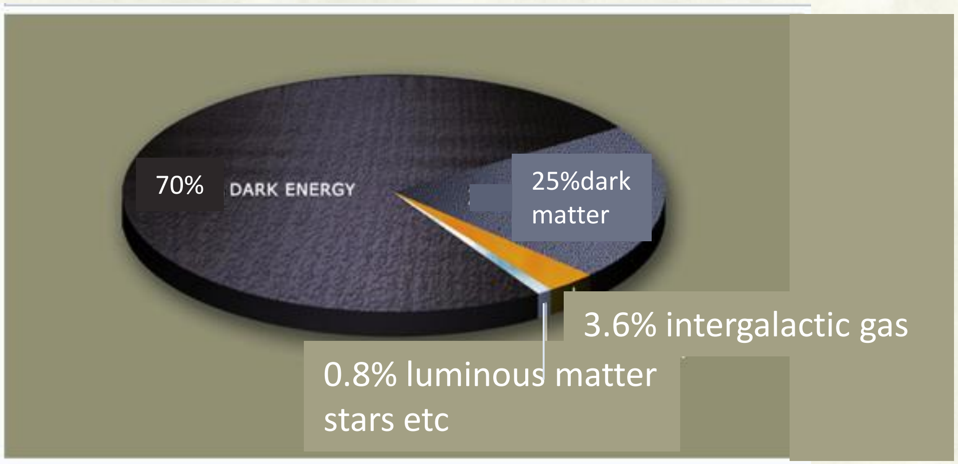
Accelerating Universe



- In mid 1990s astronomers tried to measure the slowing down of the expansion of the universe.
- They used Supernovae 1a explosions in galaxies to estimate distance to them.
  - Supernovae are extremely bright (tens of billions times the sun) so they can be seen at very large distances.
  - Supernova 1A explode at the same mass ($1.4M_\odot$) so all of them has the same brightness wherever it occurs.
  - An ideal standard candle to estimate distances to galaxies far away.

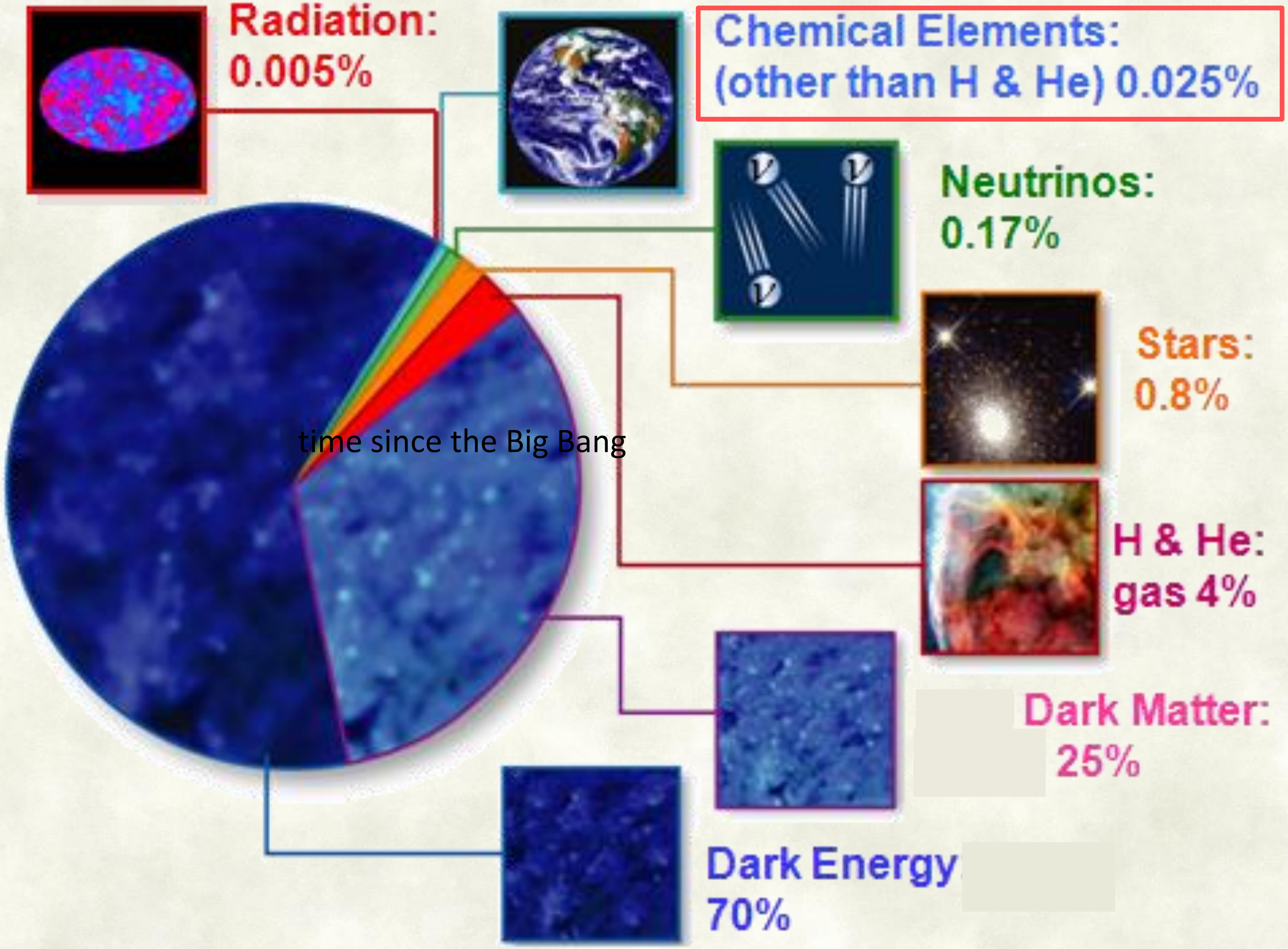
- Astronomers expected to see gravity slowing down the expansion of the universe over time.
- But when they analyzed the results of the measurement in 1998 what they saw was totally unexpected.
  - Expansion of the universe seems to be speeding up over the last 5 billion years.

Dark Energy



- There seem to be some kind of repulsive force which accelerating the universe overcoming the gravitational attraction.
- Ordinary matter always attracts (Newton's law of gravitation) and slows down the expansion.
- So the discovery of cosmic acceleration reveals in addition to the ordinary matter, the presence some other form of matter in the universe, which repulse instead of attracts. It is named as the **dark energy.**
- It turns out the total density of the universe including the density of dark energy is exactly equal to critical density.
- So universe will not only expand forever, but also at ever increasing rates.

Composition of the Universe



- stuff we are made of is only 0.025% of the universe!
- The Ultimate Copernican Revolution.

How our world view has evolved

- Antiquity: earth is the center of the universe everything is there to serve the world (people).
- 3rd C BCE. Earth is spherical, measured the size of the earth, Earth is still at the center
- 16th century: Earth moves around the Sun. Sun was the dominant object in the universe.
- Early 19th Century: Sun is a star in the large star system, sun is at the center of the Milky way Galaxy
- Early 20th Century: Our galaxy just one of many
- 1934-1970 CE: Most of material in the universe is not visible(dark matter)
- 1998 CE: 70% of universe is a mysterious form of matter: "dark energy".
  - Material we see is only 5% of the universe. Stuff we are made is only 0.025%
- 2000s : Multiverse(?), Our universe is just one among infinite number of universes
- How insignificant compared to the universe, the earth, our home in the universe is the only place we have.
- So we have to use its limited resources wisely, protect environment and leave it as a habitable place for the future generations.

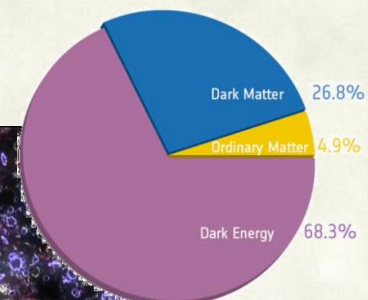
Ancient view:

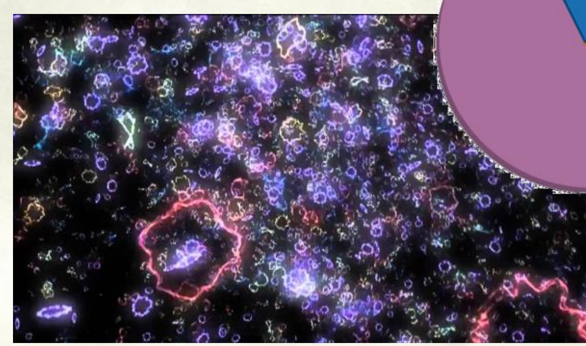
divine creation

commons.wikimedia.org

The Garden of Earthly Delights by Hieronymus Bosch 15th C. (shutters). God overseeing the creation

Must be the book on laws of nature





Review Questions

- What was the most accepted theory of the Universe in early 20th century?
- What convinced them eventually that the universe was evolving?
- How did Hubble and Humason estimated distances and speeds of galaxies?
- What is the Hubble-Lemaitre law? What are its implications?
- According to our current understanding how old is the universe?
- Who proposed the Big bang theory first?
- According to big bang what was the universe filled with at the very beginning?
- Why weren't elements heavier than helium formed in the early universe?
- If somehow Big bang nucleosynthesis went beyond helium and converted most of hydrogen to heavier nuclei what would be the universe look like today.
- What is the most distant event in the universe we can see with electromagnetic radiation (of any kind)?
- What happened during the recombination era of the universe? When did that happen?
- What is the relic radiation from the big bang? Why is it in the microwave region now?
- What are the variations we see in the cosmic microwave background radiation? What did they evolve in to?
- Why do astronomers think 70% of the universe is dark energy?
- What fraction of material in the universe is ordinary matter?
- What are the observational evidence supporting the Big bang theory?
- What is the debris fling out from an explosion the wrong analog to the expansion of the universe? What is the proper explanation of the expansion of the universe?