Scale of the Universe: The Big Picture

ASTR 101

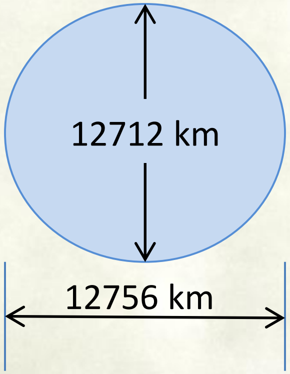
August 24, 2018

- The Solar system
- The Milky way and other galaxies
- Local group of galaxies
- Clusters and superclusters of galaxies
- The cosmic web
- Origin and evolution of the universe

Universe – An outline of what we know

The Earth – our home in the universe

- a planet – 3rd from the Sun in the solar system
- Spherical in shape – somewhat flattened
  - diameter 12756 km at equator
  - 12715 km pole to pole
  - mass 6×10^{24} kg



- It spins: period 23h 56m 4 s
- and revolves around the Sun (at a speed 30 km/s)
  - period 365.25 days (24 hour days)
  - mean distance to the Sun 150 million (1.5×10^{8}) km(=1AU)

The Moon

- Earth has a companion – a satellite – the Moon
  - diameter 3476 km (~ ¼ of earth)
  - mass 7.2×10^{22} kg (~$1/80\ M_{\oplus}$)
  - Moon revolves around the Earth
    - period 27 d 7 h 43 m
    - at a mean distance 384,000 km from the Earth (30 times the Earth's diameter)

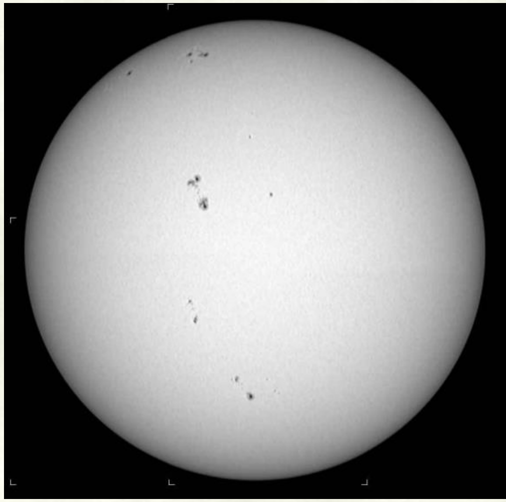
An image taken by the NASA's Deep Space Climate Observatory satellite from 1 million miles away

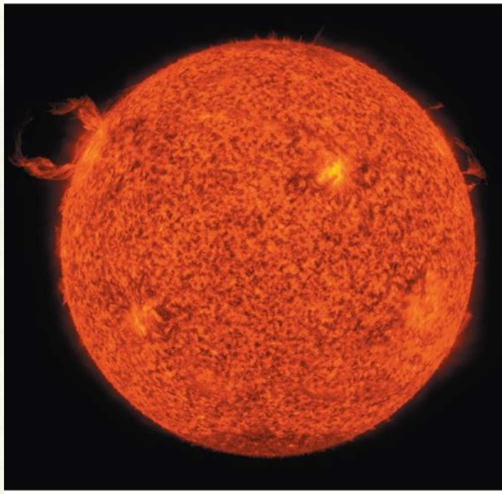
Scaled diagram showing relative sizes of the Earth, Moon and their separation.

- Images taken by the NASA's Deep Space Climate Observatory satellite from 1 million miles away

The Sun

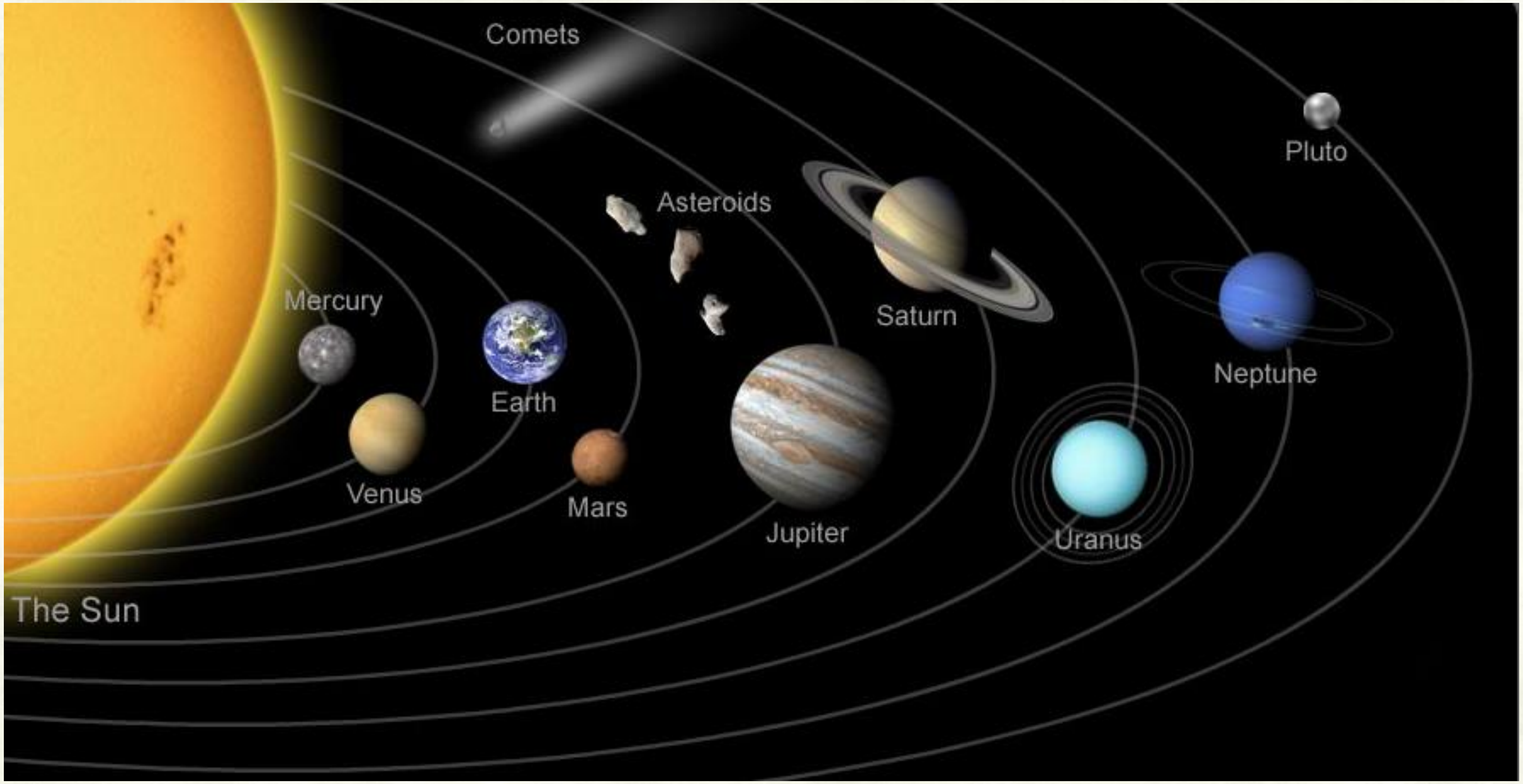
- Sun is a star:
  - A huge ball of hot gases - ~1,390,000 km in diameter (110 times the Earth)
  - mainly hydrogen (H 75%) and helium(He 25%)
  - Mass 2×10^{30} kg ~ 330,000 $M_{\oplus}$
  - Surface temperature 6000K, core 20 million K
  - produces energy by nuclear reactions in the core:
    - by converting hydrogen to helium
    - 4 million tons of hydrogen (4×10^{9}kg) is converted into helium each second,
      - like in a hydrogen bomb, 100 billion H bombs/second
  - Sun has enough hydrogen to burn for another 6-8 billion years





Next nearest star is 4.3 light years away! - Space is mostly empty!!

The Solar System

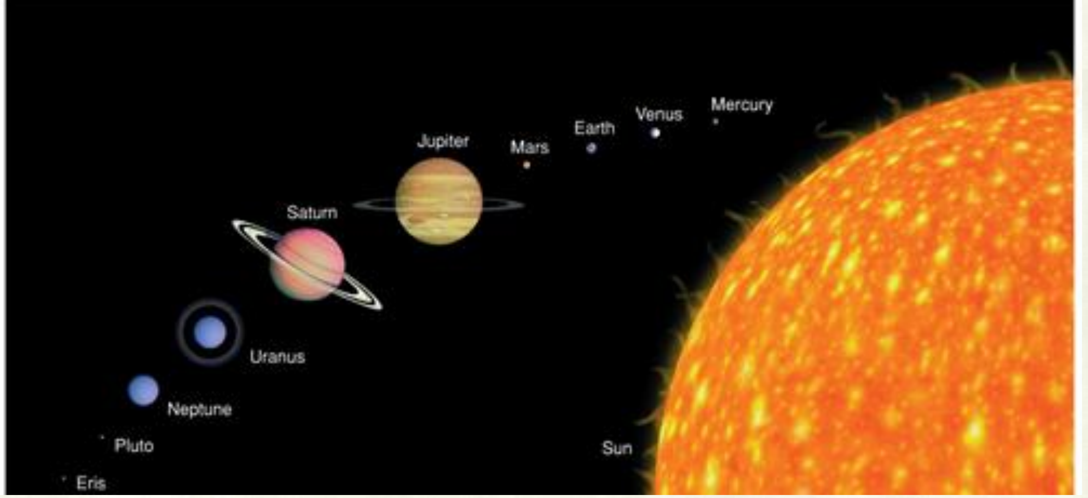


Not to scale

- Earth is only one of the planets in the solar system
- There are 7 other major planets, most of them have satellites (moons)
- Dwarf planets, asteroids, comets…
- All orbiting the Sun.

The Solar system: facts

Sun:
- diameter 1,390,000km
- mass: 2×10^{30}kg
- 99% of the mass of the solar system

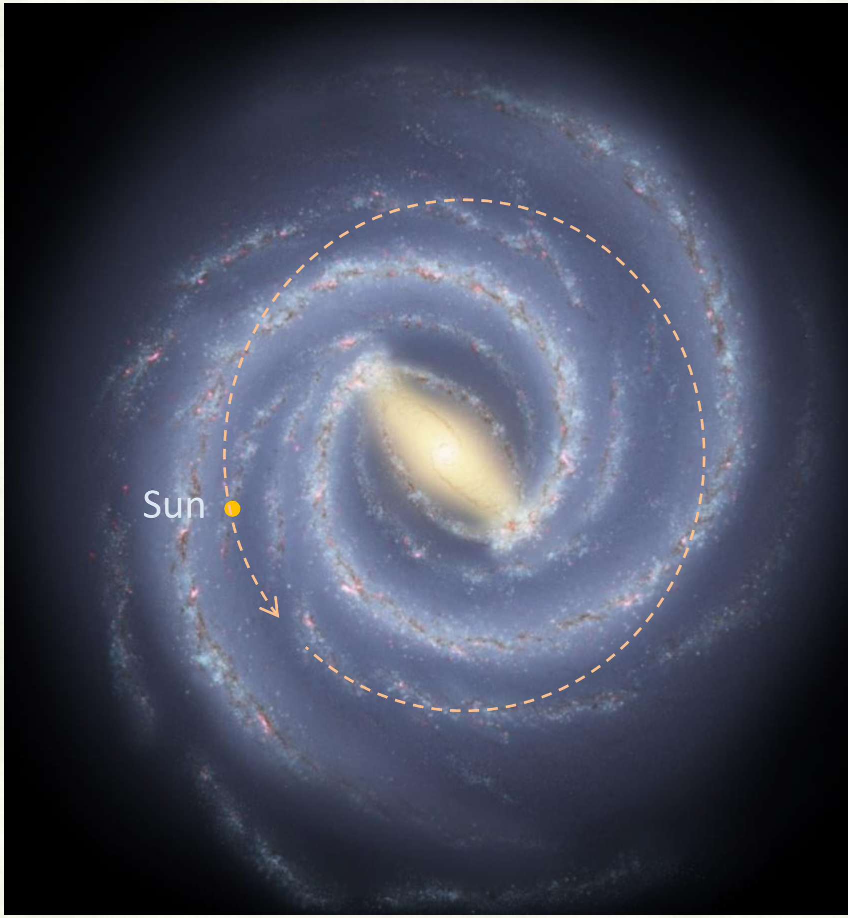


Sizes of the solar system objects to scale

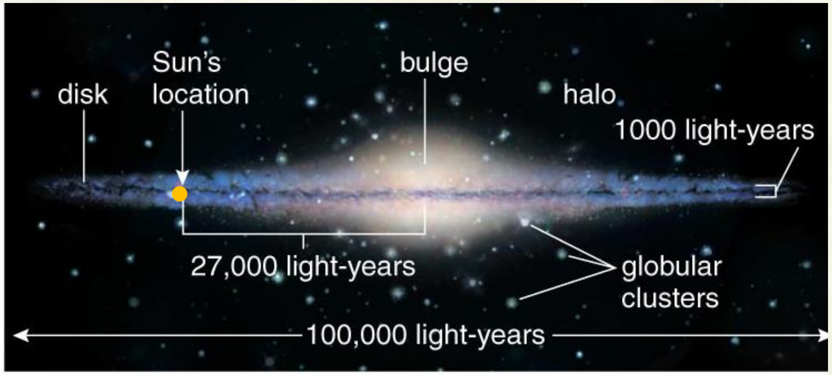
planet	Distance to Sun(AU)	Diameter (Earth =1)	mass (Earth=1)	Density gcm^{-3}	Orbital period	rotation period	number of moons
Sun		109	330000	1.41		24.5 d	
Mercury	0.387	0.38	0.055	5.42	87.9 d	58.6 d	0
Venus	0.723	0.95	0.82	5.24	225 d	243 d	0
Earth	1.00	1	1.00	5.5	1.00 y	23.93 h	1
Mars	1.52	0.53	0.11	3.9	687 d	24.6 h	2
Jupiter	5.20	11.2	318	1.33	11.9 y	9.93 h	67
Saturn	9.54	9.44	95.2	0.69	29.5 y	10.6 h	62
Uranus	19.2	4.01	14.5	1.27	83.8 y	17.2 h	27
Neptune	30.1	3.88	17.1	1.64	165 y	16.1 h	13
Pluto (dwarf planet)	39.5	0.18	0.0022	2.1	248 y	6.4 d	5

The Milky Way Galaxy

- Sun is just one star in a large stellar system, which has over 100 billion stars – a galaxy
- Our galaxy is “the Galaxy” or the Milky way galaxy.
- Shape of a flattened disk with a central spherical bulge.
- 100,000 light years in diameter
- Sun is located half way out from the center.
- All objects in the Milky way are orbiting around its center.
- Sun (and the solar system) moves at a speed of about 230 km/s, and takes about 225 million years to complete one orbit.
- Milky way moves in space 630 km/s



an illustration of the Milky way: credit NASA



The Milky way galaxy contains, stars, gas clouds (nebulae), debris of dead stars …

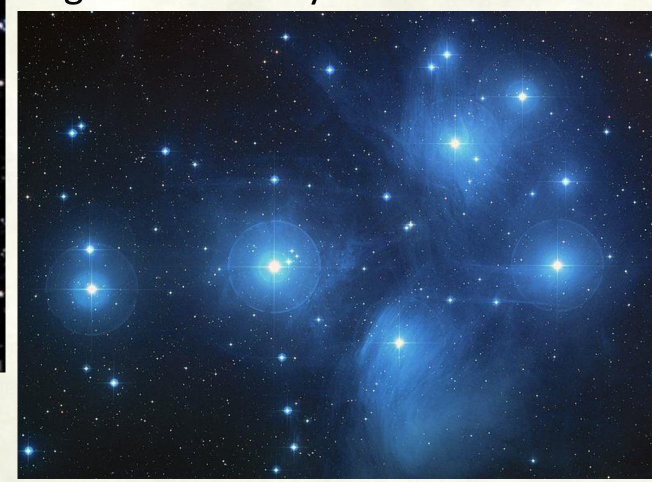
–Many stars are associated with star clusters, rather than isolated

- Two types of star clusters:
  - globular clusters (up to few million stars)
  - open clusters (100-1000s stars)

open cluster : M 25
size 19 ly, 3~000 stars
distance: 2000 ly,   mass: 5000 $M_\odot$
age: 90 million years

globular cluster: M3
size 180 ly, ~500,000 stars
mass: $4.5\times10^5 M_\odot$
distance: 34000 ly
age: 11.4 billion years

globular cluster: M13
size 160 ly, ~300,000 stars
mass: $6\times10^5\ M_\odot$,
distance: 25000 ly
age 11.6 billion years



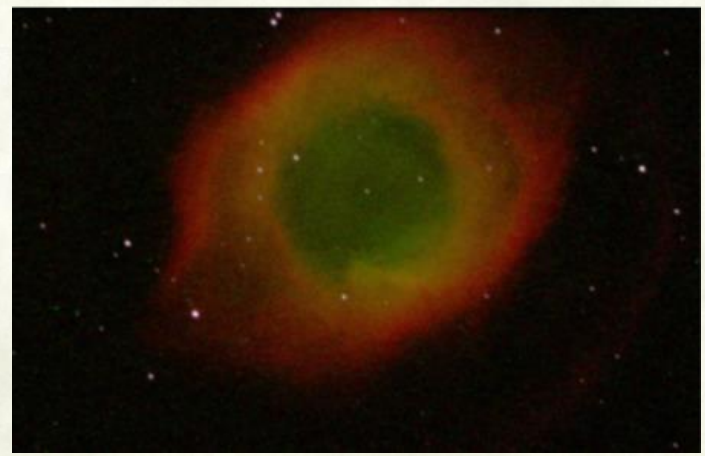
Pleiades (Seven Sisters, M45)
size: 10 ly, ~1000 stars
Distance: 400 ly
age: ~100 million years

M: Messier catalog number

M43: (Orion nebula). A gas cloud 1300 light years away. 20 light years across, mass 2000 $M_\odot$

Horse head nebula, a dust cloud

M1 (Crab Nebula)
A supernova remnant
(a star exploded 1000 years ago)
size: 11 ly
Distance 1650 ly



M57 (Ring Nebula)
(gas escaped from a star)

- Most of the material in galaxies are in the from of interstellar gas clouds, they could be gas clouds yet to form stars or debris of old stars
- In addition: neutron stars, black holes (all debris of dead stars)

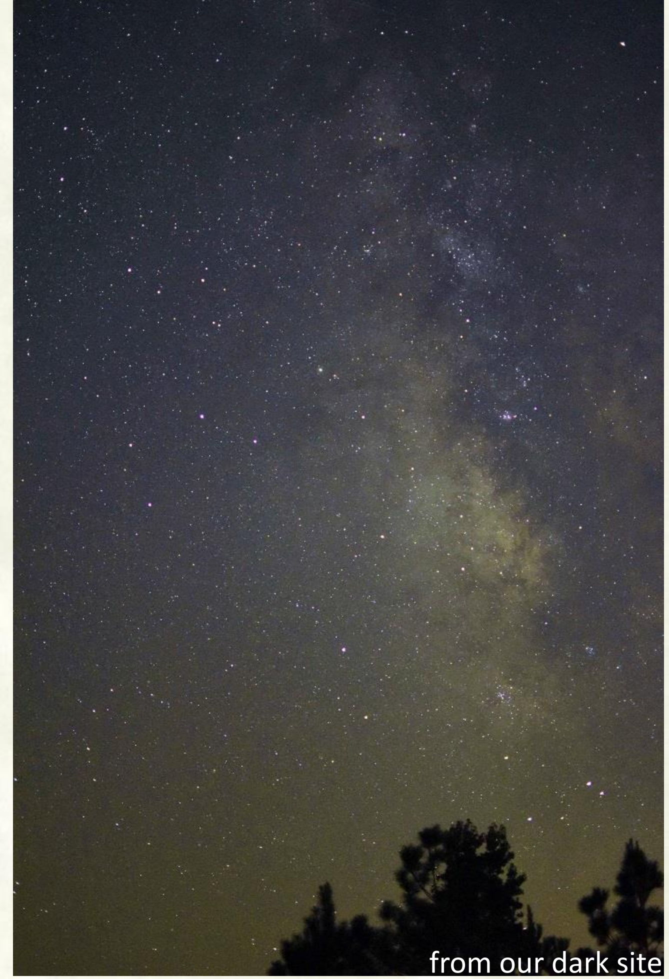
The Milky Way galaxy

- All stars we see in the night sky are in the Milky way, within few thousand light years (farthest star visible to naked eye is about 4000ly away).
- Since we are in the Milky way galaxy, we can not see its actual shape
- Like the view of a large stadium from a seat there.
  - See near by individual people, see their faces, can recognize them.
  - Hard to see individual people seated other side of the stadium. Only see a large crowd.

- Our view of the milky way is somewhat similar to that view of the stadium within.
- Most of the stars we see in the night sky are nearby stars.
- To the naked eye, far away regions of the Milky way are not visible as separate stars.

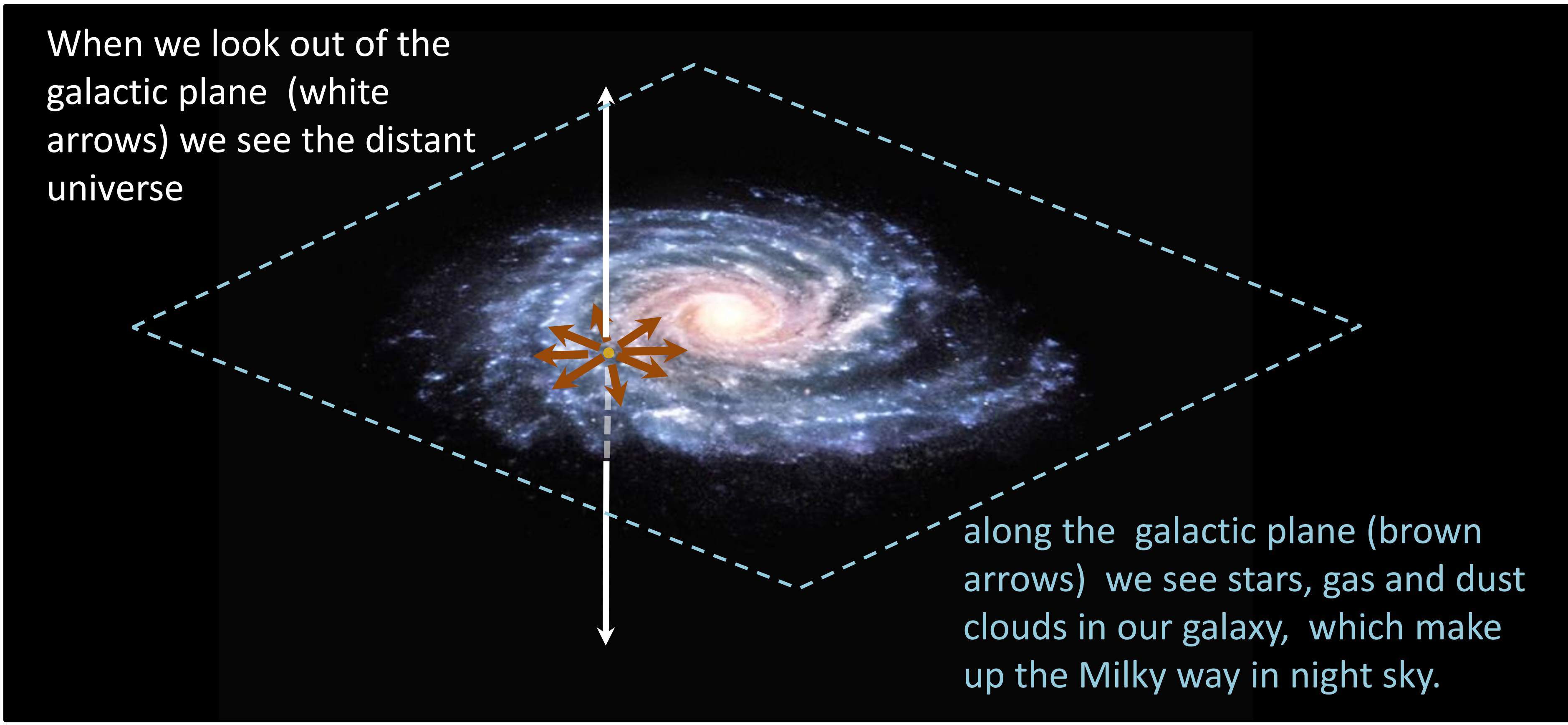
The Milky way galaxy

Views of the Milky way, (these days visible in the predawn sky)

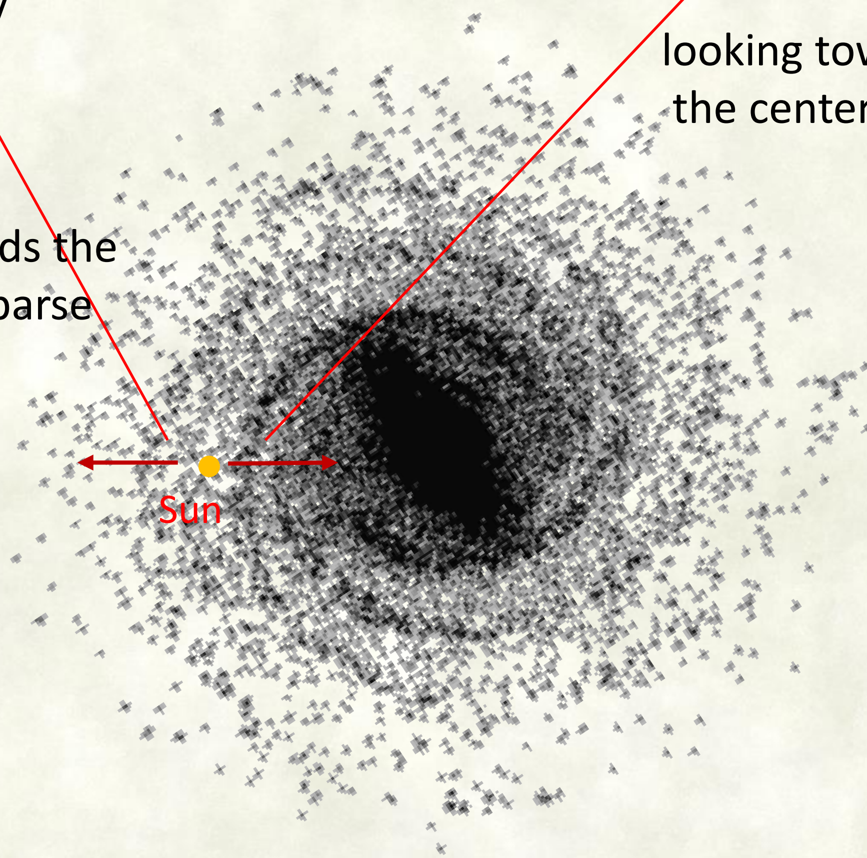


- Our view of the milky way is somewhat similar to that view of the stadium within.
- Most of the stars we see in the night sky are nearby stars.
- To the naked eye, far away regions of the Milky way are not visible as separate stars.
  - There are so many of them far away, we see all of them together as a luminous cloud, stretching across the sky.


looking away
fewer stars
looking towards the
outer edge, sparse
SUN
looking towards
the center, dense


When we look out of the galactic plane (white arrows) we see the distant universe
along the galactic plane (brown arrows) we see stars, gas and dust clouds in our galaxy, which make up the Milky way in night sky.

Milky way stretching across the sky
(arc shape due to wide field lens)



Credit: http://astrophoto.com/JonTalbotandMilkyWay.htm

- Towards the center of the galaxy more stars, so brighter in that direction.
- Also many dust clouds appear as dark patches. They block the view of objects in the central region and beyond.

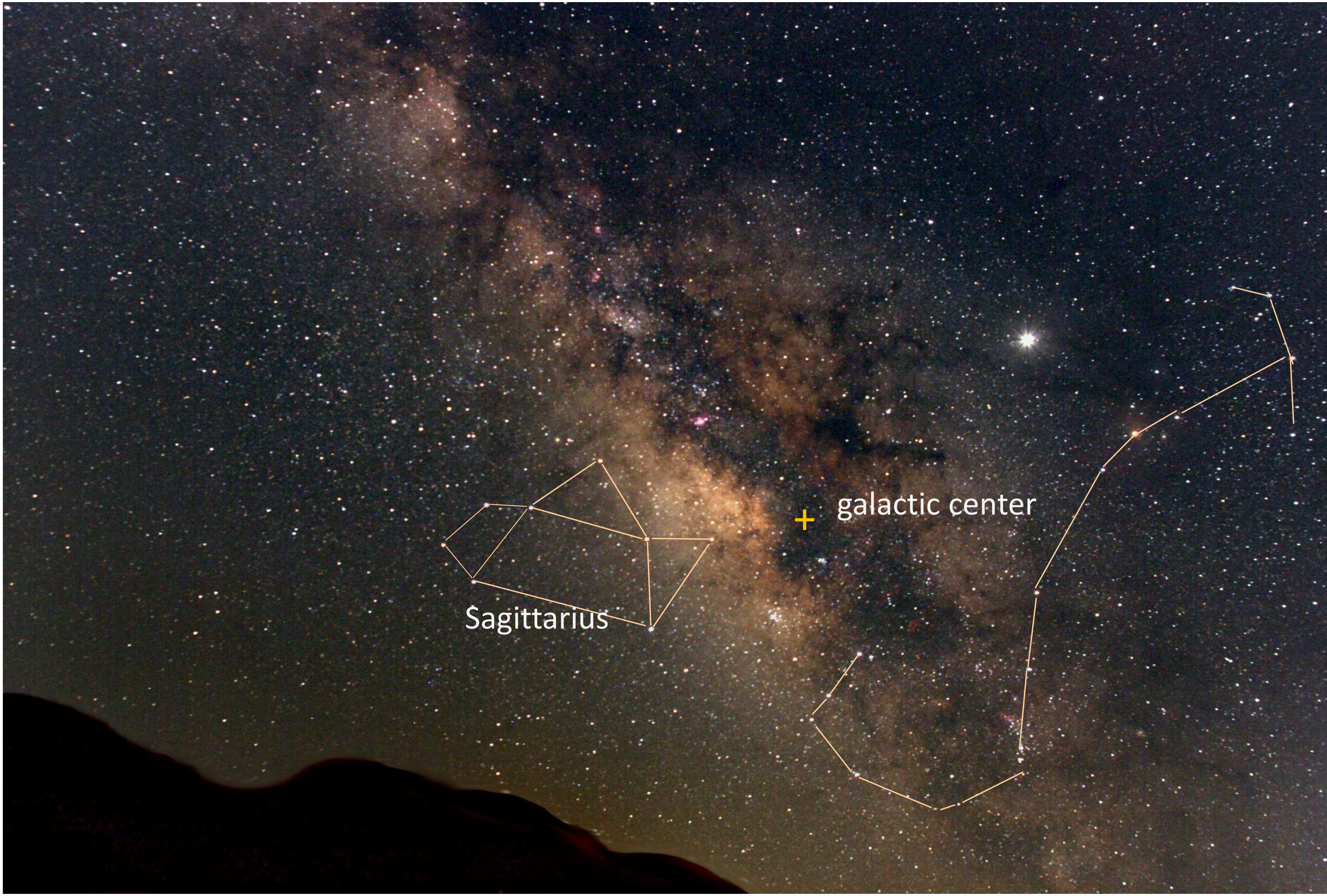
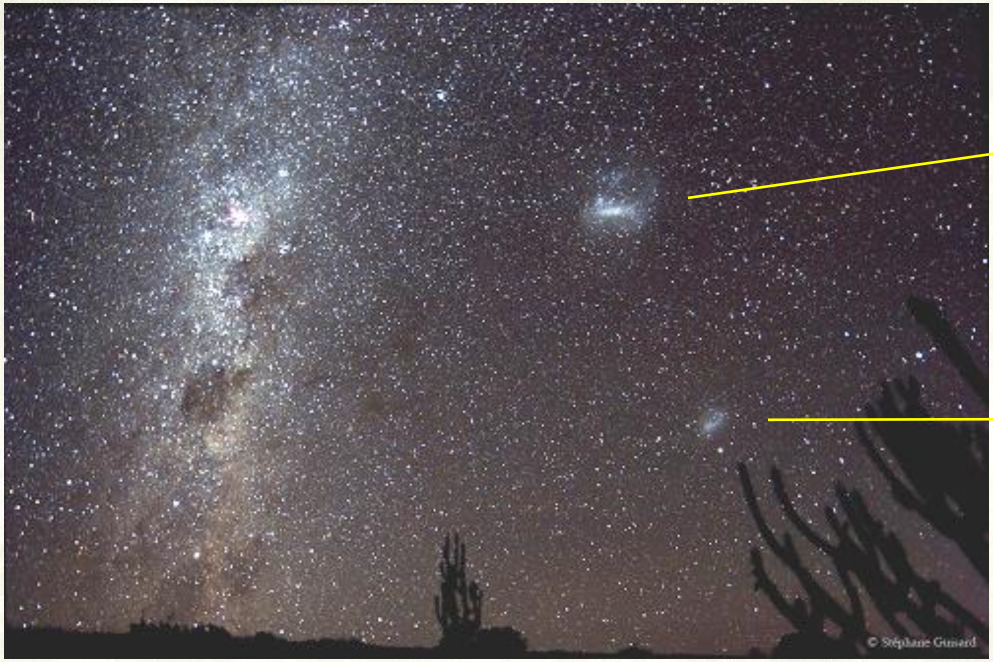


Photo Credit: Derek Rowley.

Magellanic Clouds



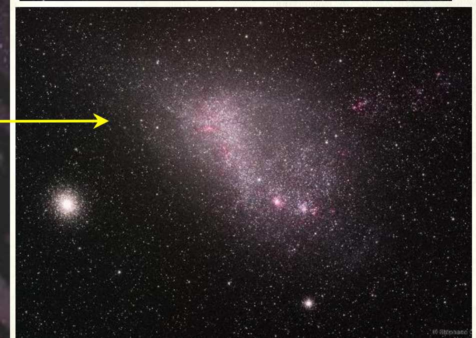
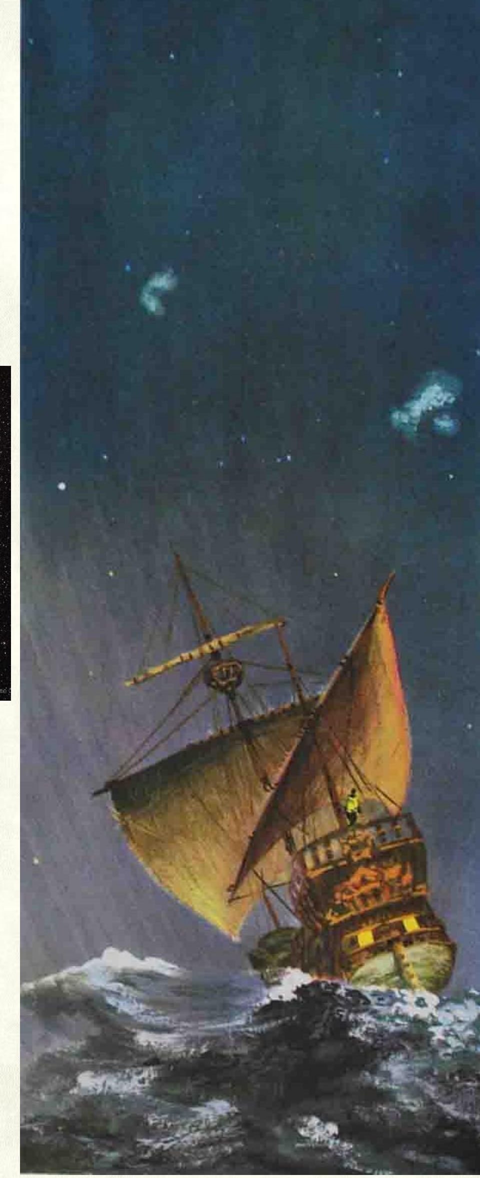


Photo credit: sguisard.astrosurf.com



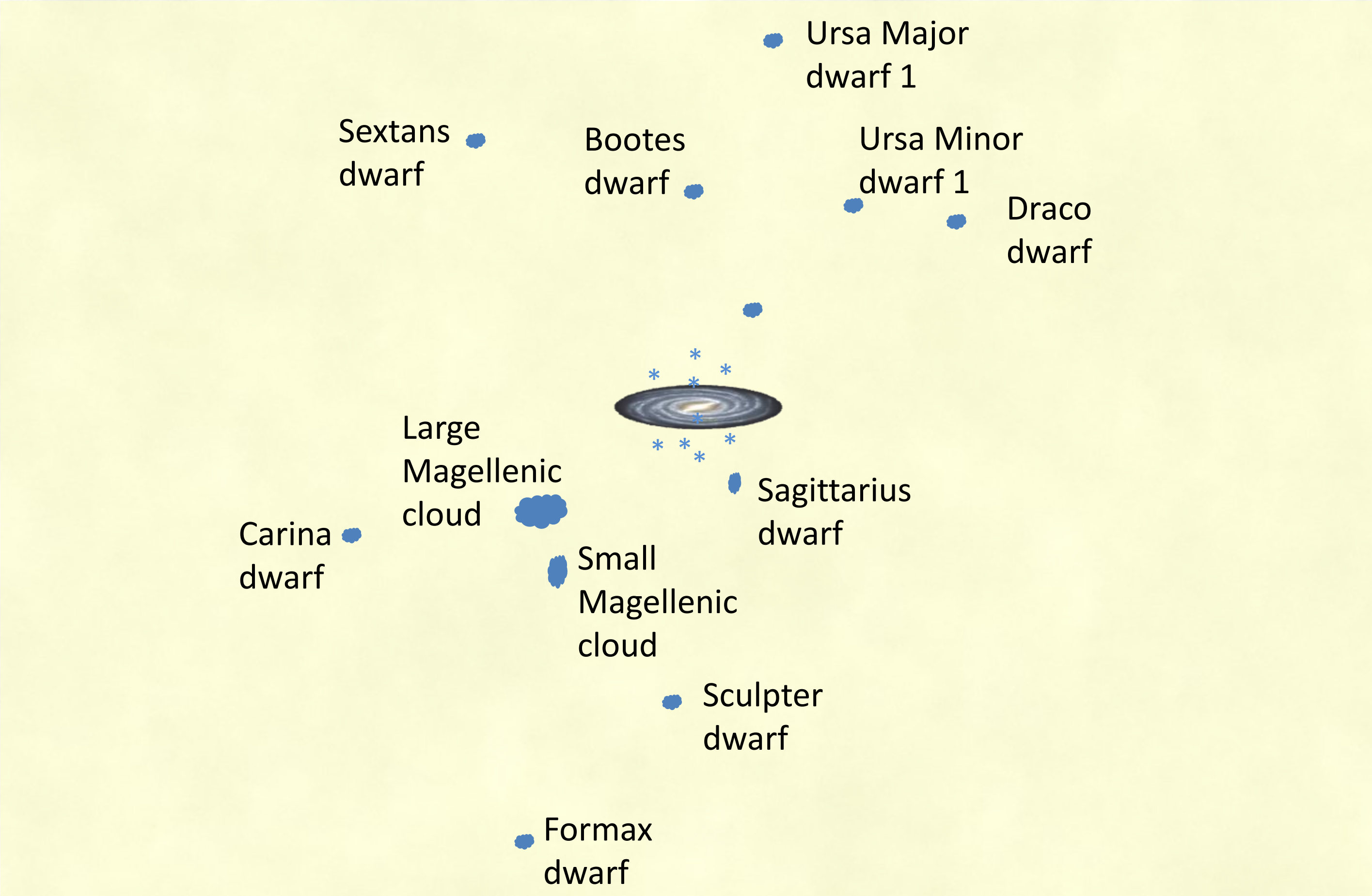
- Magellanic Clouds are companion galaxies of the Milky way,
  - Irregular shaped dwarf galaxies.
- Nearest extragalactic (outside milky way) objects
  - Large Magellanic Cloud: nearest galaxy 170,000 ly away, 14,000ly in size, ~30 billion stars
  - Small Magellanic Cloud : second nearest 240,000 ly away, 7,000ly in size, ~ 3 billion stars
- Located in the southern sky,
  not visible from the US, have to be at least in the tropics to see them.
- Named after Magellan who saw them on his voyage

Magellanic clouds are named after Ferdinand Magellan, who saw them on his voyage, even though he was not the first European to see them.

Credit: Greg Bradley vimeo.com/49963140

Milky way and Magellanic clouds as seen from new Zealand

Companion (satellite) Galaxies of the Milky way



- Milky way has many satellite galaxies
- About 30 have been discovered.
- They are small (dwarf) galaxies with few billion stars.
- Largest of them are the Magellanic clouds.

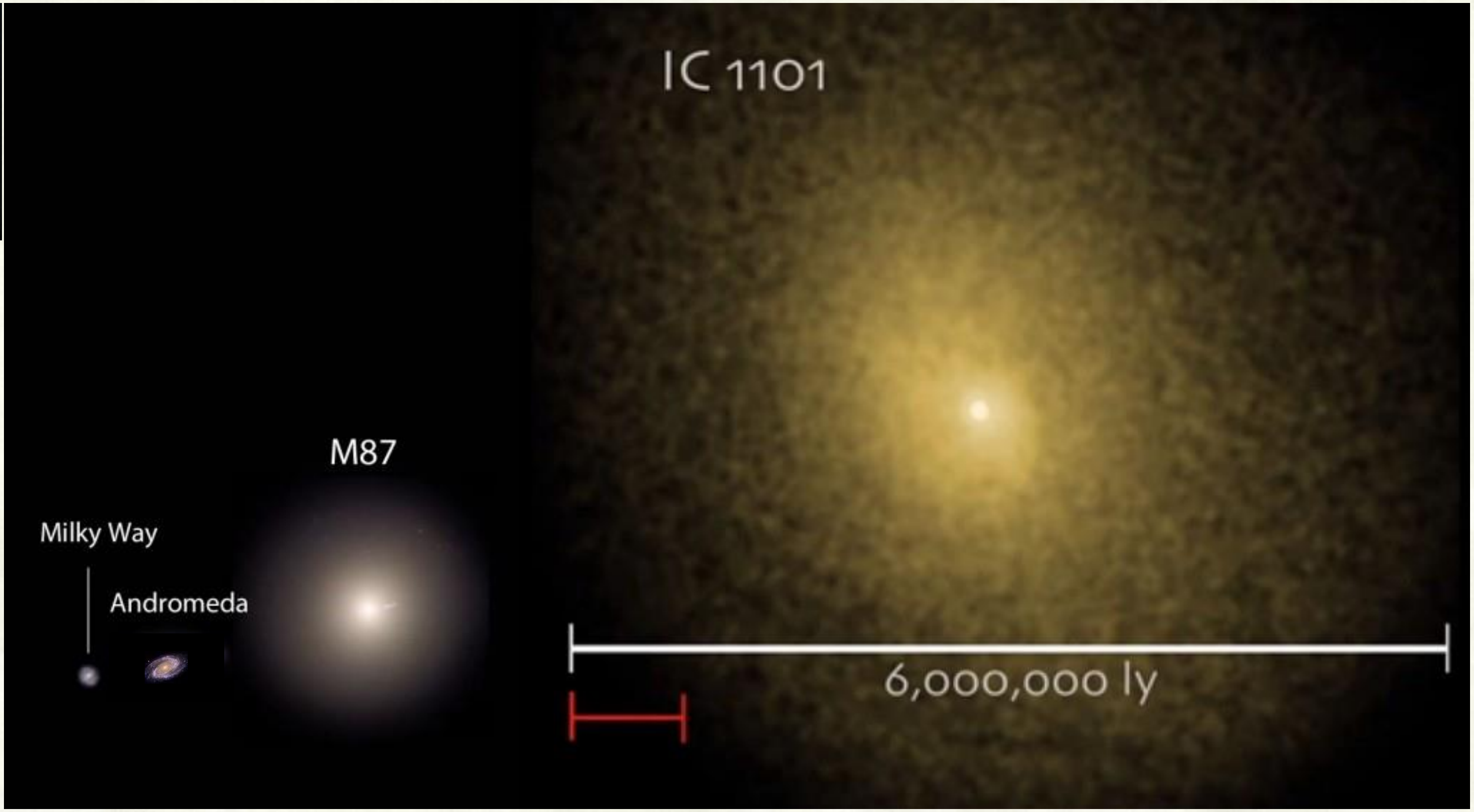
Galaxies: Building blocks of the universe

- Milky way is just one of the galaxies. Universe is full of galaxies, over 100 billion of them in the observable universe.
- Galaxies come in different shapes and sizes:
  - spherical, elliptical, spiral, irregular
  - Dwarf galaxies hundreds of million stars to giant galaxies with hundreds of trillions starts
  - Tens of thousand light years to millions of light years in diameter

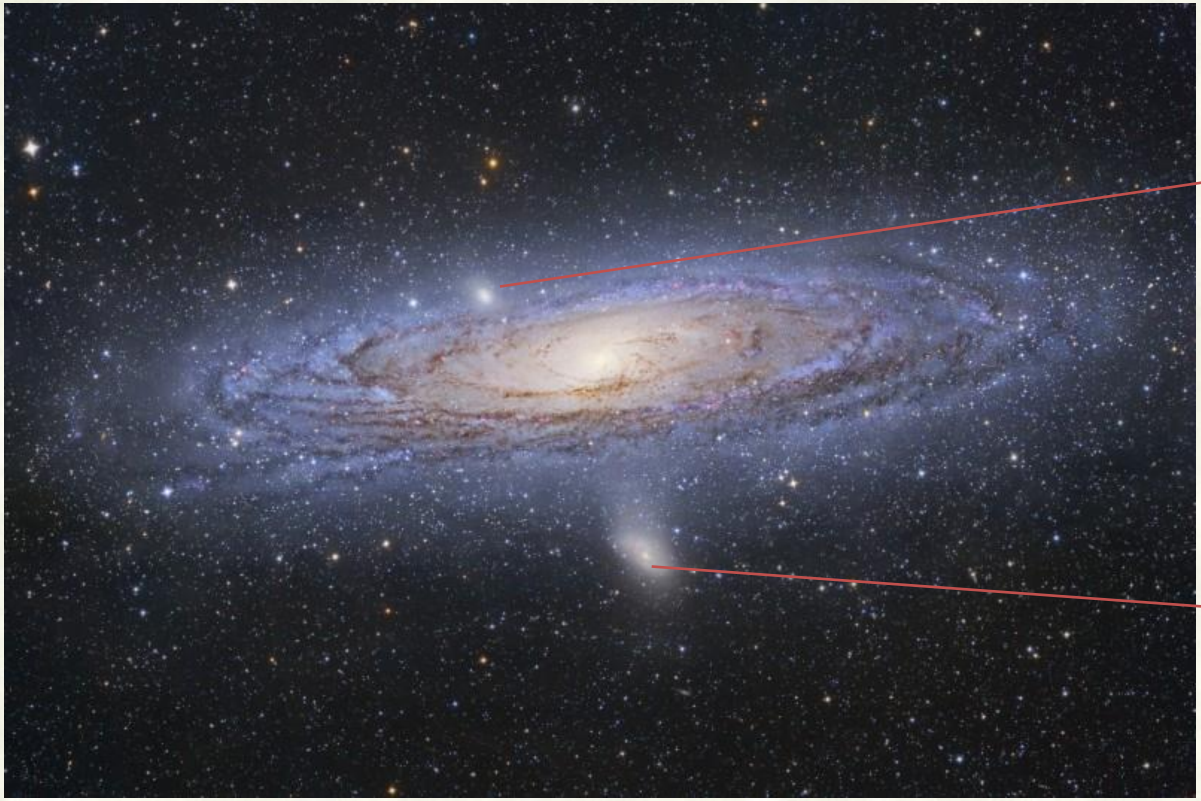
NGC 4150, elliptical

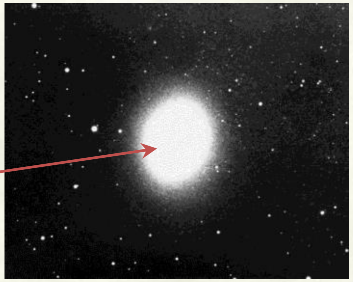
NGC 1232, spiral

NGC 4449, irregular



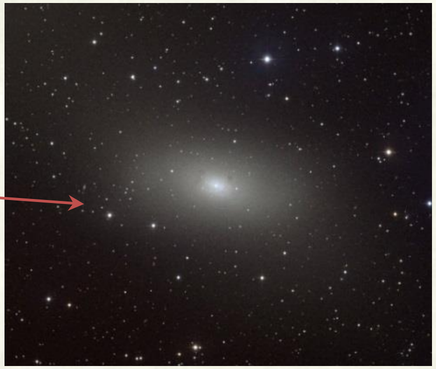
The Andromeda Galaxy





M32

Largest satellites of Andromeda



M110

- Nearest large galaxy to us is the Andromeda galaxy, 2.5 million ly away
- It is larger than the Milky way
  - 220,000 ly in diameter, 1 trillion (10^{12}) stars
  - Many small satellite galaxies (14 known)
  - Visible to the naked eye,
    - most distant object visible without a telescope

Credit: http://hubblesite.org/newscenter/archive/releases/2015/02/video

- Zooming into the Andromeda Galaxy

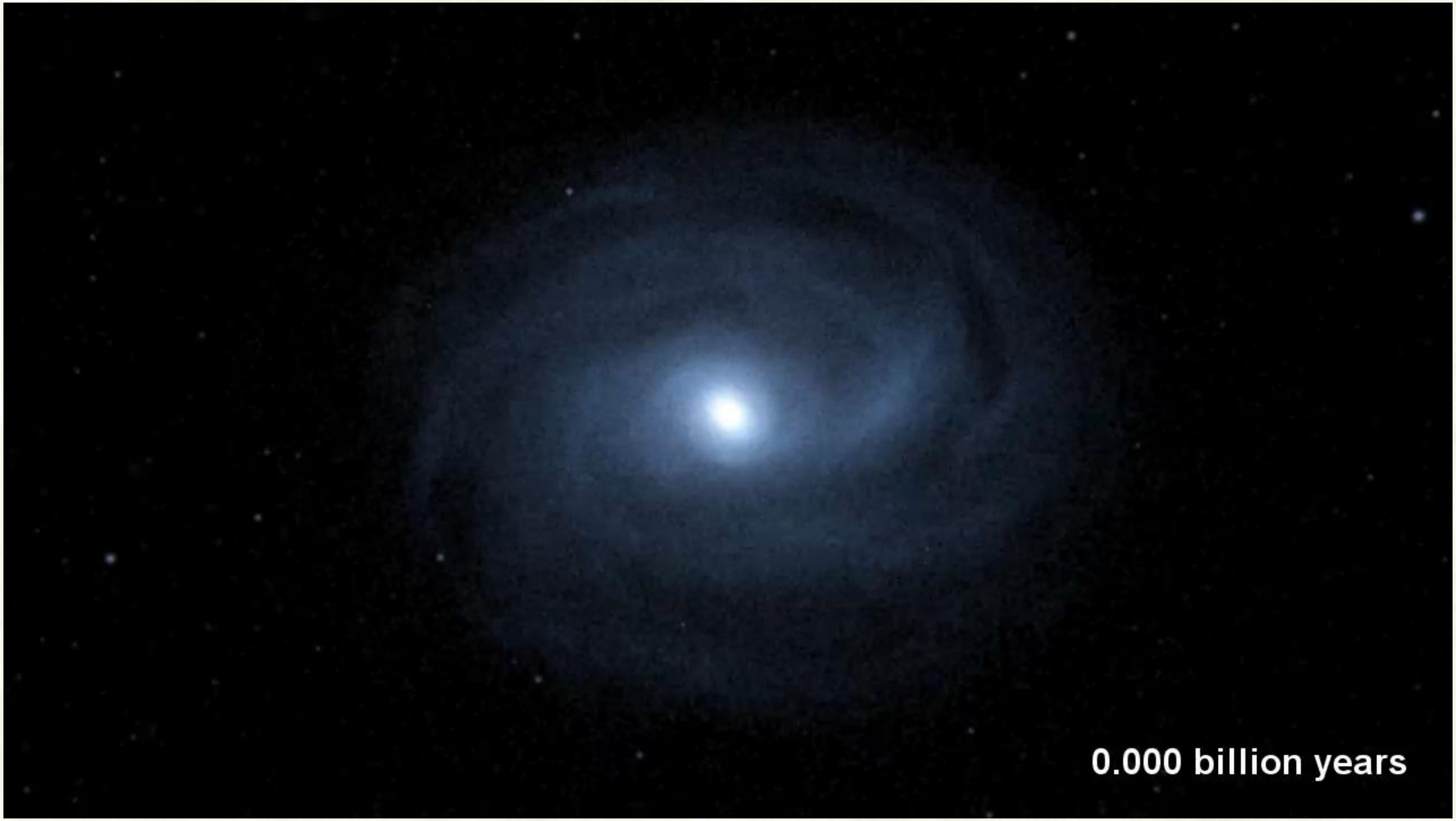
Two other nearby galaxies

Pinwheel galaxy
- Next nearest large galaxy
- 21 million light years away
- 170,000 light years in diameter

Whirlpool galaxy
- 25 million light years away

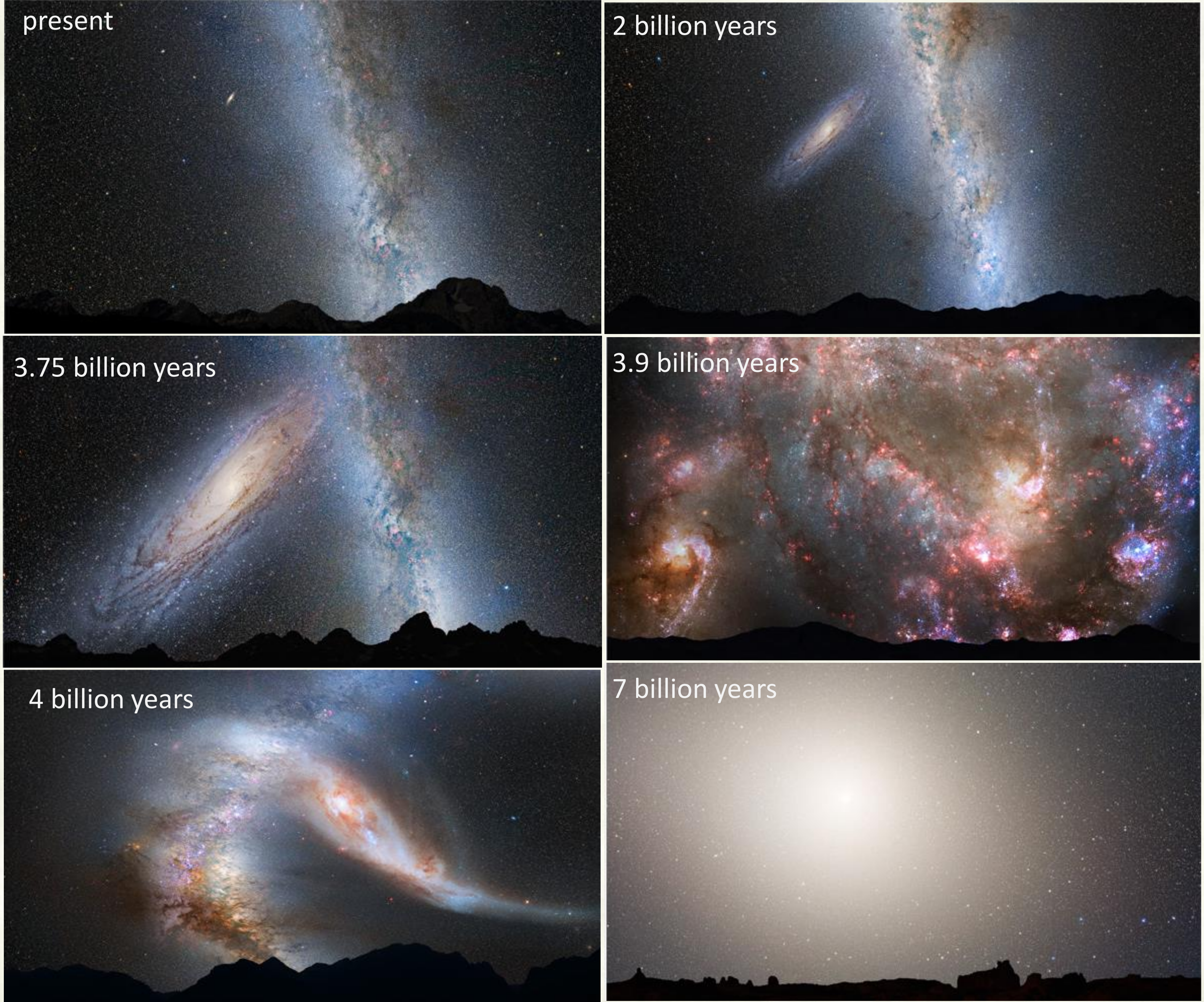
- Spiral arms are areas where stars had formed, whole galaxy is filled with matter (gas). We do not see them since they don't emit light.

Andromeda - Milky way Collision

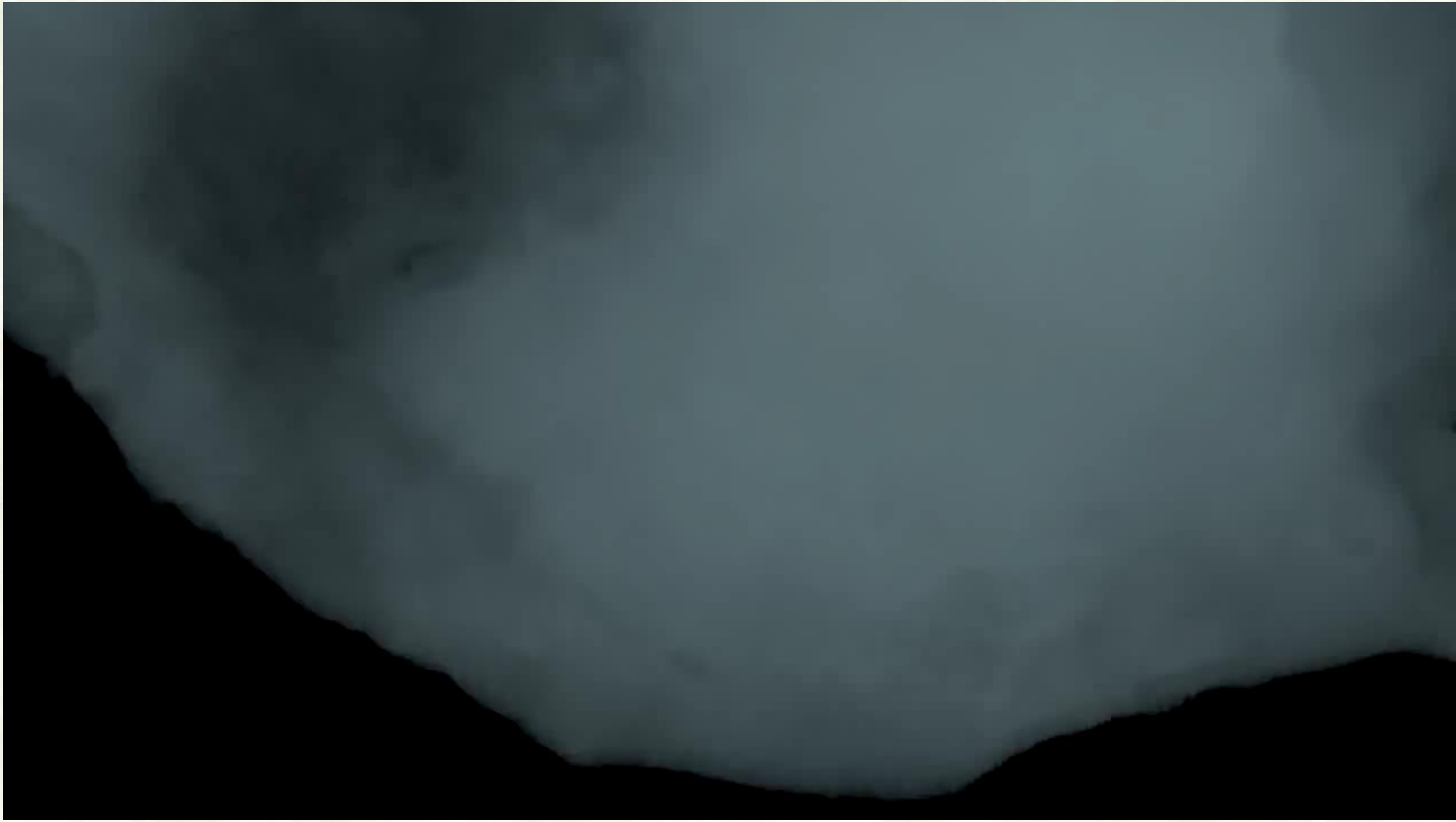


Simulation from: www.nasa.gov/mission_pages/hubble/science/milky-way-collide.html

- Milky way and Andromeda galaxy are moving towards each other (~120km/s).
- They are expected to collide in 4 billion years and merge to form a large elliptical galaxy.


present
2 billion years
3.75 billion years
3.9 billion years
4 billion years
7 billion years

After the merger an elliptical galaxy is formed (in 7 billion years).
The solar system will probably be flung into outer region of the galaxy, much farther from the galactic core than it is today.



https://www.youtube.com/watch?v=_Ssc1GsqHd

Formation of a large spiral galaxy simulation

- Region of the size 10 million light years, has more than 54 galaxies, most of them are dwarf galaxies.
- They are a gravitationally bound group, and is called **the Local group of Galaxies**

Clustering of Galaxies

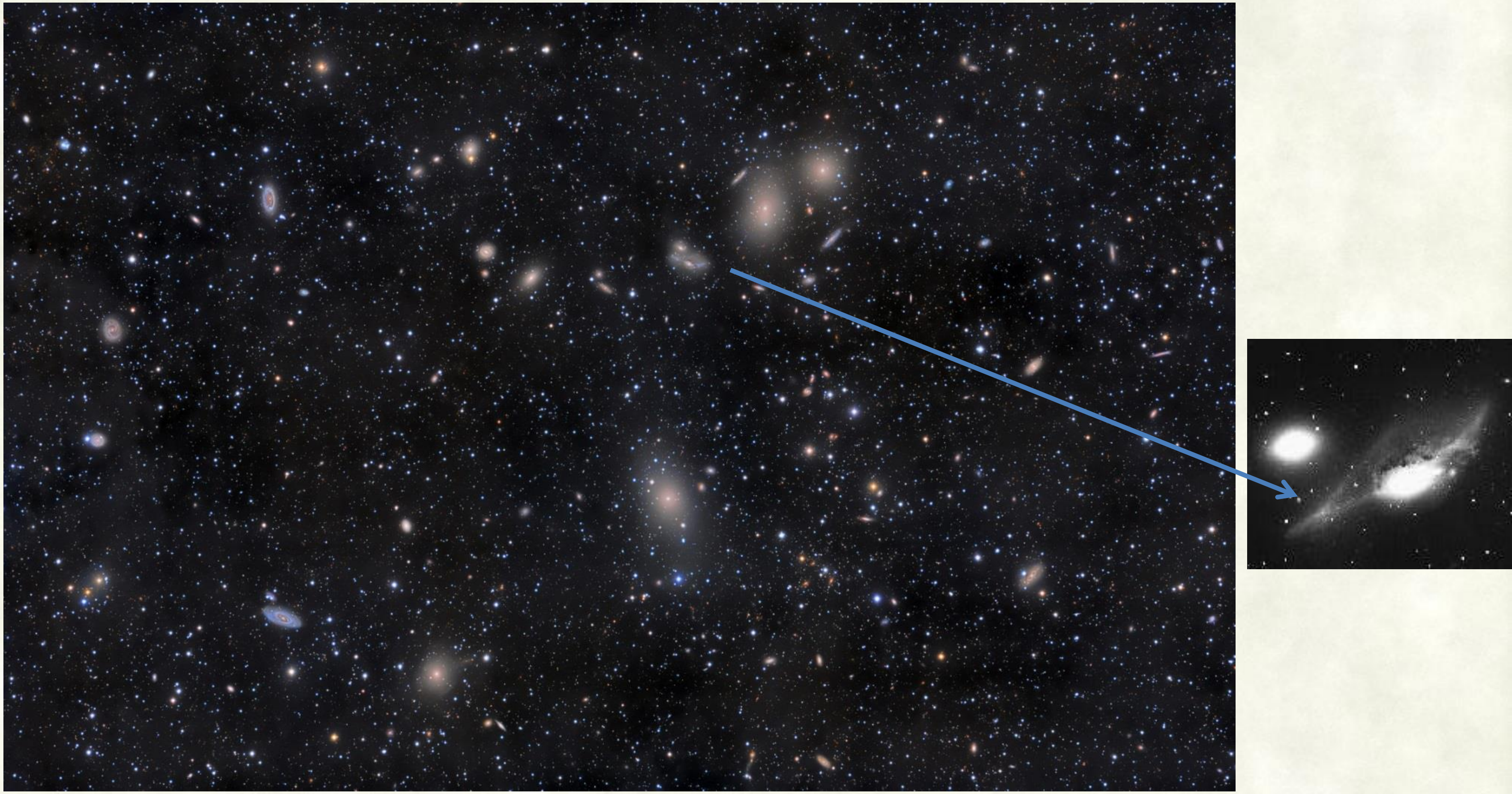
- Milky way, Andromeda, and other nearby dwarf galaxies form a group of galaxies called the local group
- This way of galaxies forming groups is common
- Some groups are large. There are clusters consisting of thousands of galaxies
- Which in turn form even larger structures like super clusters of galaxies, filaments, walls
- They together form the large scale structure of the universe.

galaxies → clusters of galaxies → super clusters of galaxies → cosmic web

Virgo Cluster of Galaxies

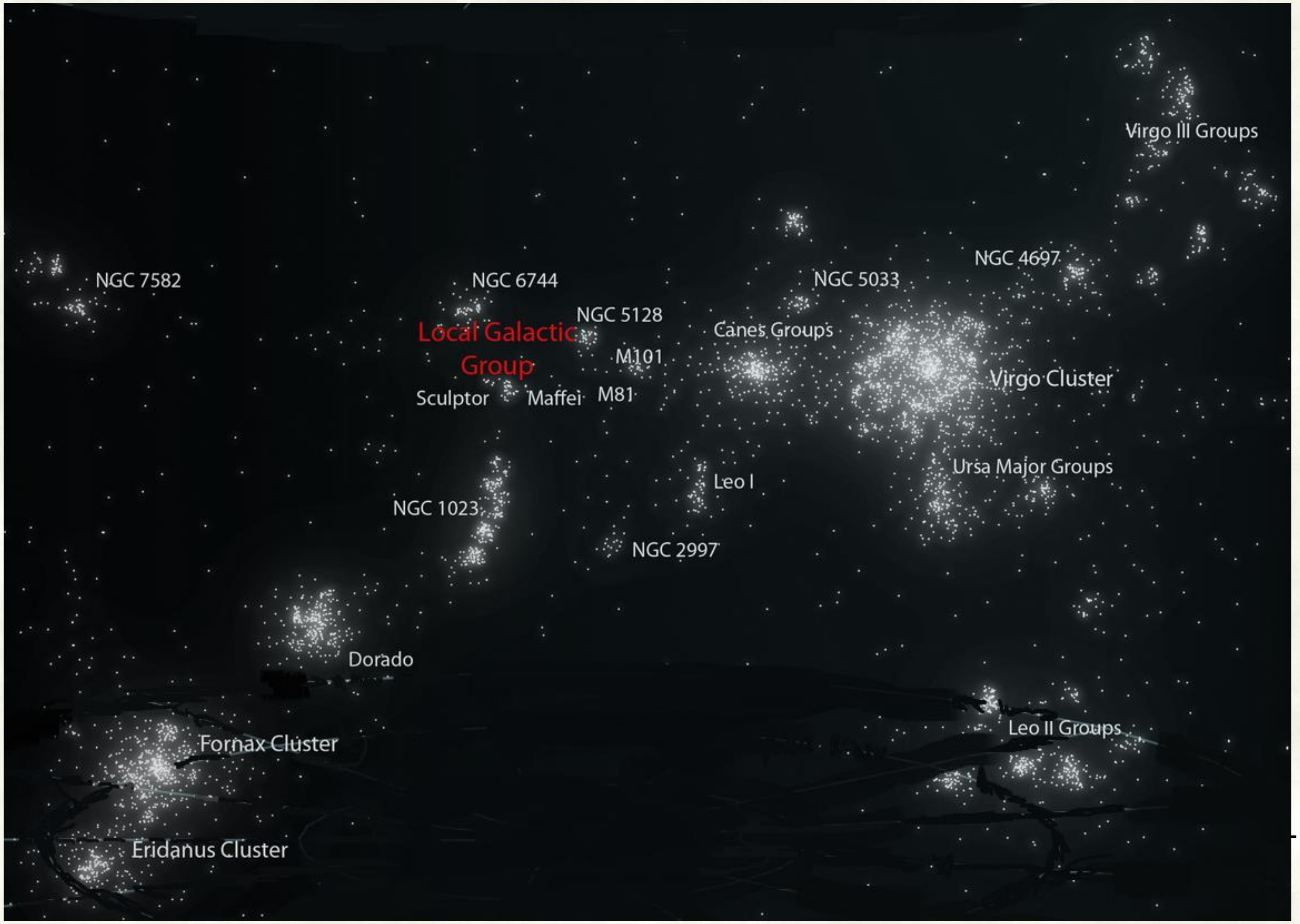
View towards the center of the Virgo Cluster, (angular size $5^{o}x3^{o}$) apod.nasa.gov/apod/ap110422.htm

- A cluster of galaxies may have anywhere from hundreds to thousands of galaxies.
- Nearest large cluster is the Virgo cluster of galaxies.
  - 54 million light years away, 20 million light years in size. more than 1300 galaxies.



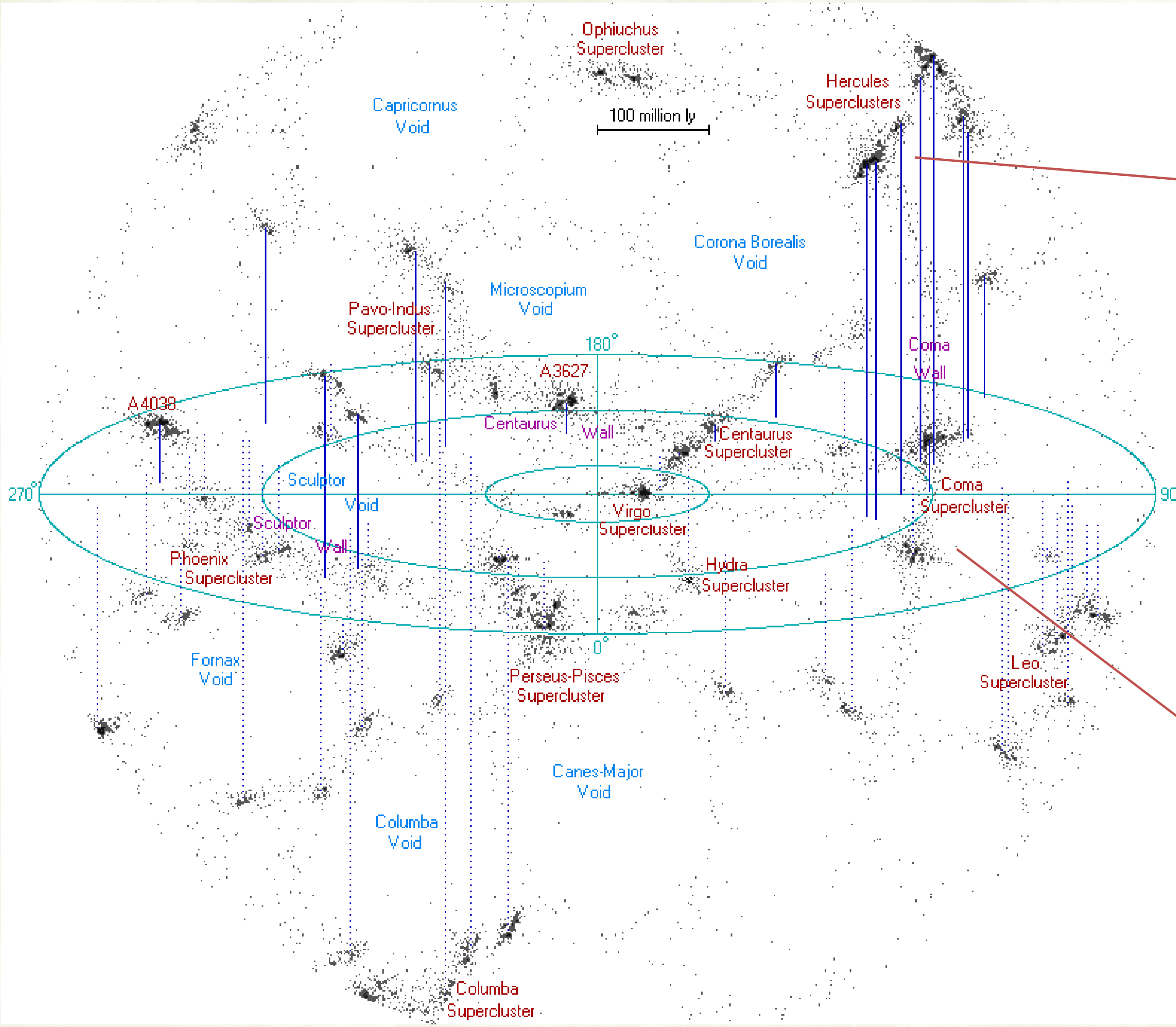
- So many galaxies in close proximity, some are colliding (as seen in the image)

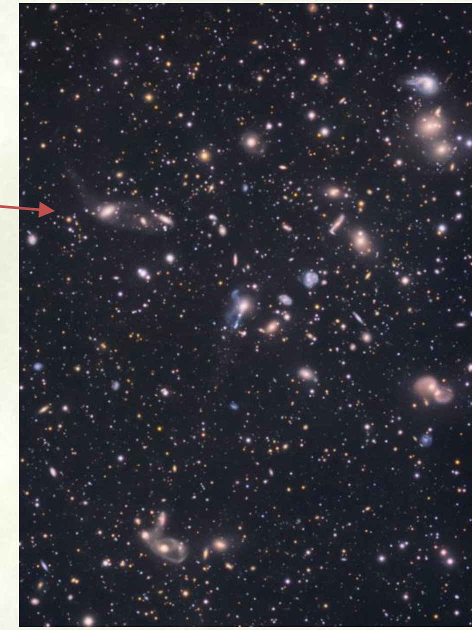
Virgo Super cluster of Galaxies

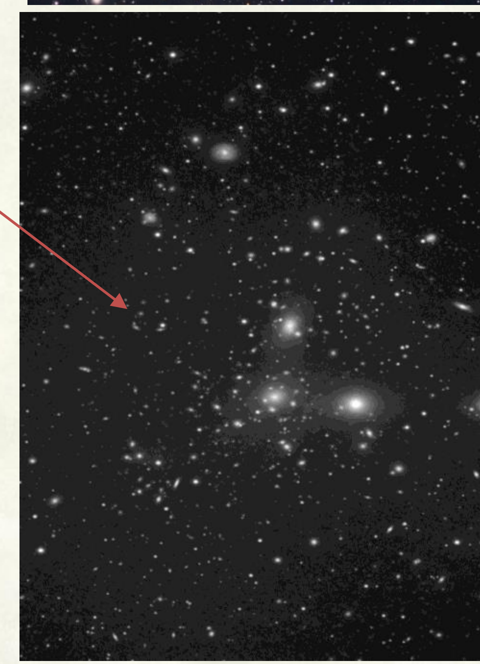


- Our local group of galaxies and the Virgo cluster are part of a larger concentration of galaxies called the Virgo supercluster of galaxies.
  - A collection of nearly 100 groups and clusters of galaxies
  - stretches across a 100 million light-years, total mass about 10^{15} $M_{\odot}$

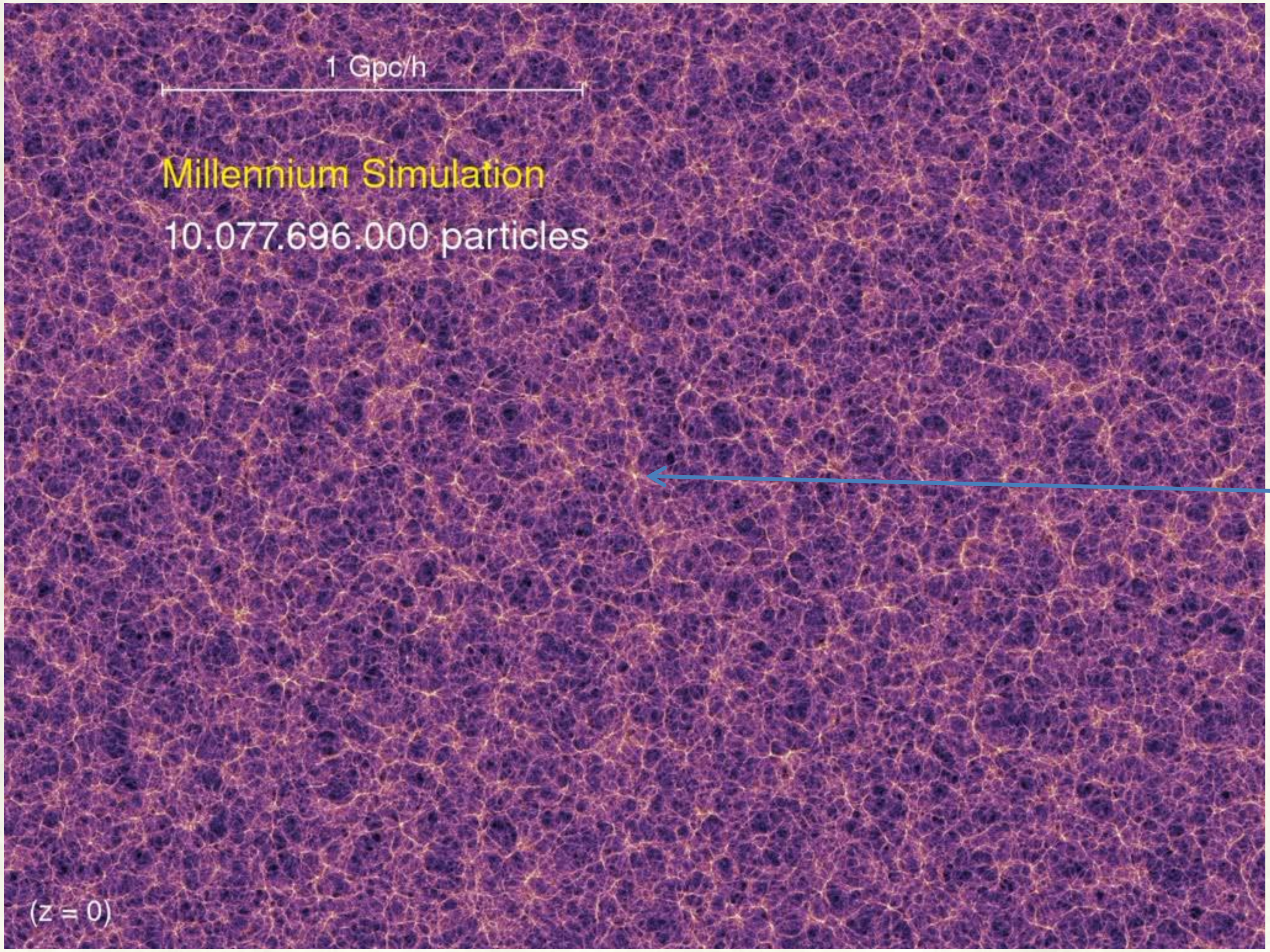
Our neighborhood of 500 million light years







The Cosmic Web



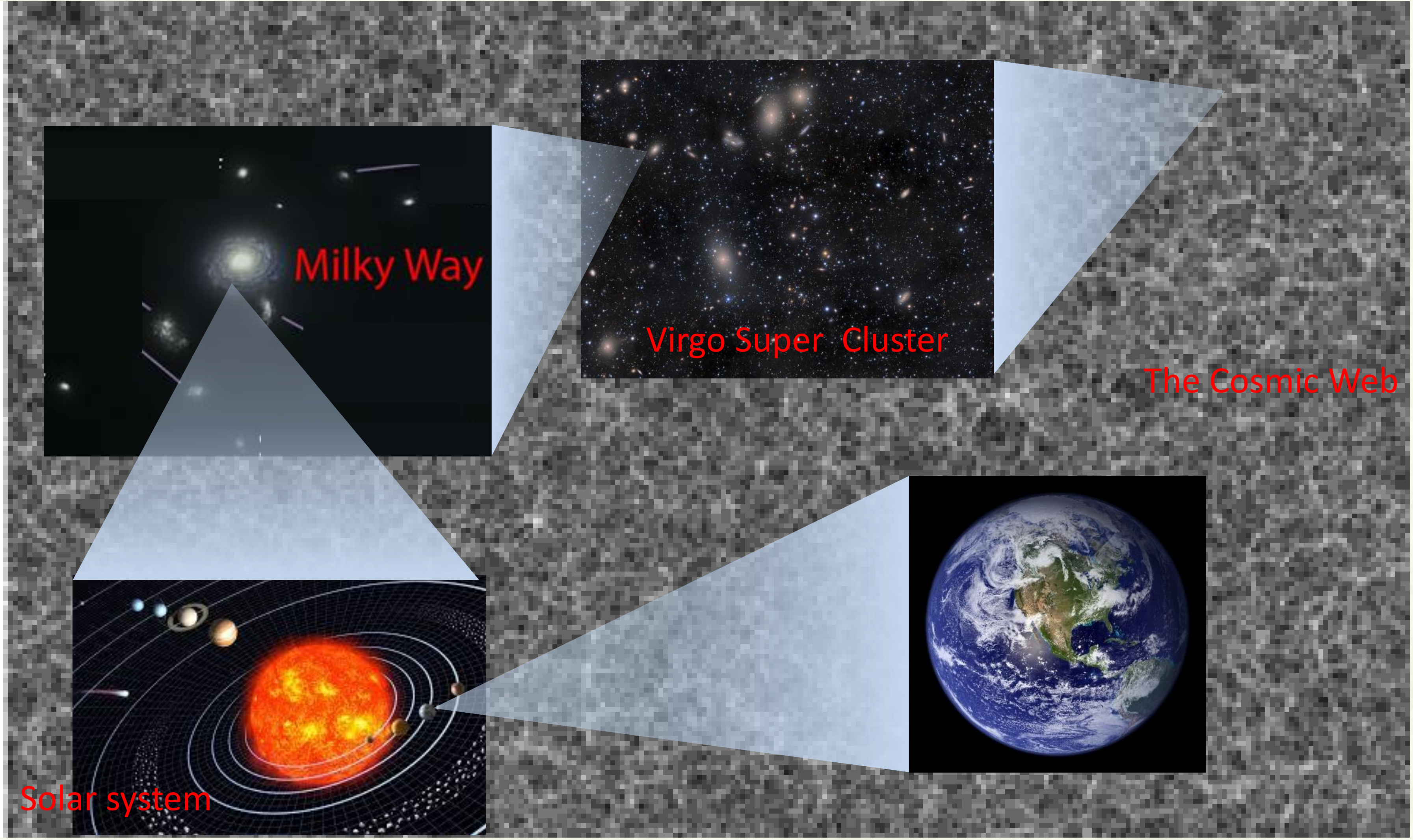
A super cluster of galaxies

- This would be the view of the universe in the largest scales, filaments, walls, superclusters and voids of galaxies
- No further hierarchical structures.
- It is uniform on scales larger than 500 million light years
  - homogeneous (same everywhere)
  - and isotropic (same in all directions)

Hubble eXtreme Field

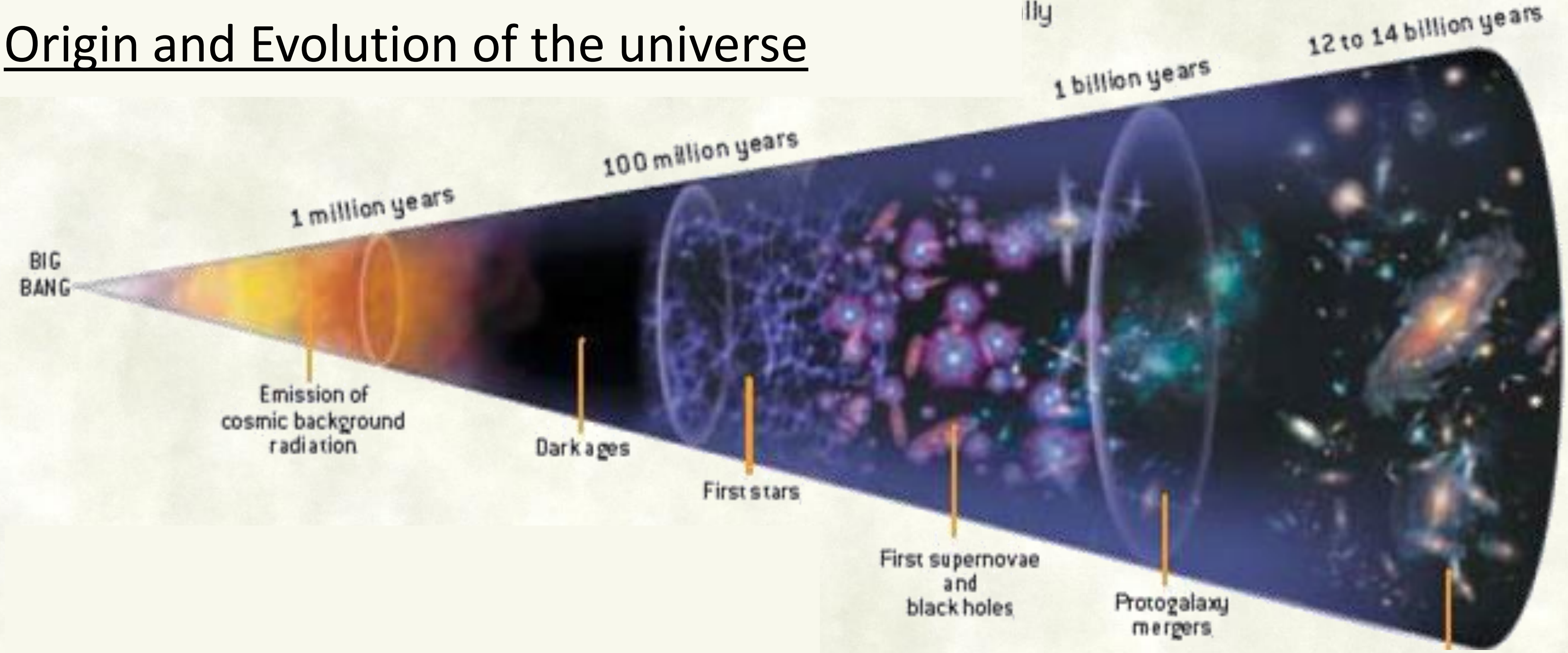
- Image of a tiny patch of the sky, ~2 arc minutes in size
– 35 millionth of the sky
– size of a quarter at 40 feet

- Over 5000 galaxies
- Farthest galaxies in the image are about 13 billion light years away, almost at the edge of the observable universe.



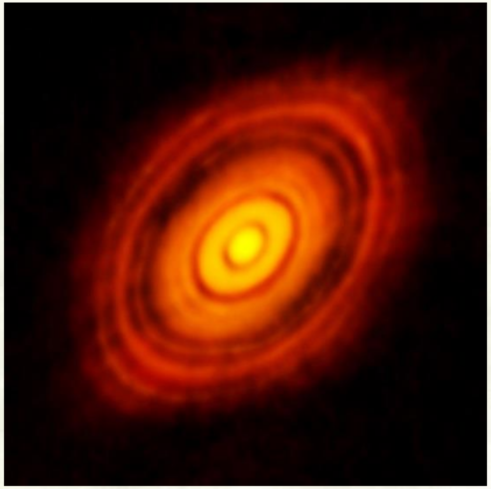
- Cosmic address of the Earth: Cosmic Web → Virgo super cluster → Local group of clusters → Milky way→ Solar System → Earth
- Our ancestors thought Earth was at the center and rest of the universe revolved around it.
- Now we know we are so insignificant compared to the Universe!

Origin and Evolution of the universe



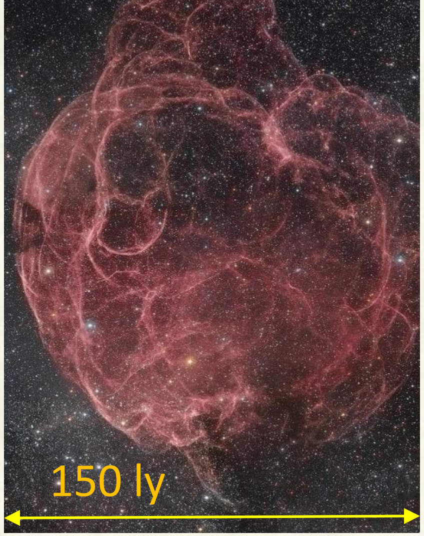
- According to observational evidence, universe had originated about 13.8 billion years ago.
- This event, in which the Universe (space and time) emerged is called the **Big Bang.**
- At the beginning, size of the universe was extremely small, smaller than a single atom, filled with energy, extremely hot (over 10^{32}K) and dense.
- Universe expanded and evolved from this initial state of the Big Bang to the current state, and continues to expand.

Newly formed stars
in a nebula



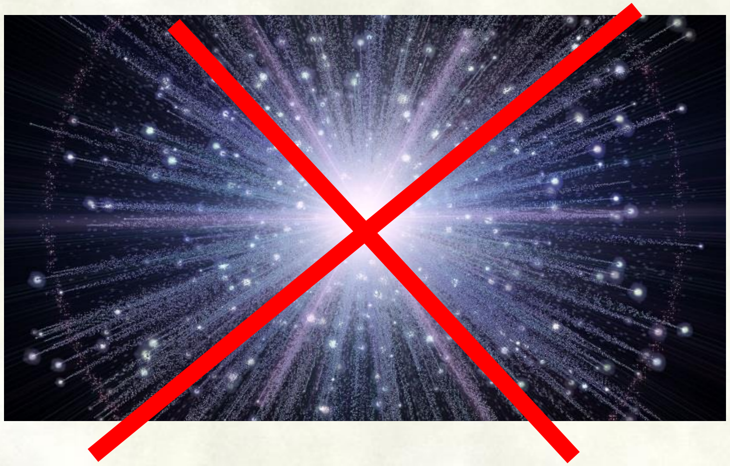
HL-Tauri : a newly formed
Star, with a proto planetary
System, still under formation.

Crab-nebula (10 ly).
a star exploded
1000 years ago.



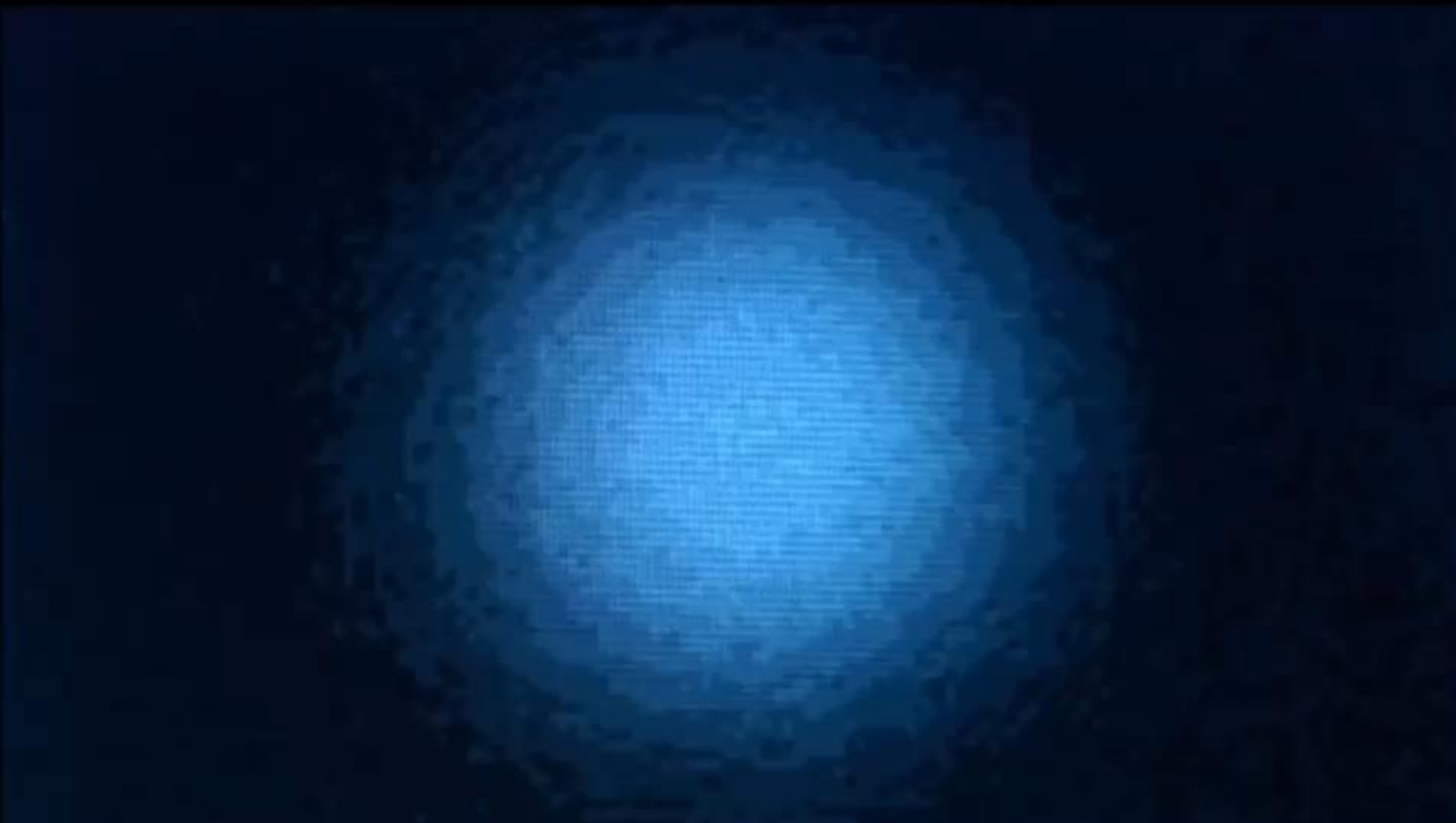
A star exploded
40,000 years ago.

- From the hot radiation filled initial state, Hydrogen(75%) and Helium (25%) formed (in first few minutes). Those primordial elements filled the early universe.
- As the universe expanded it cooled, primordial gases collapsed under gravity to smaller chunks to foam galaxies, and then stars.
- All elements other than hydrogen and helium were formed by nuclear reactions in stars.
- Heavier elements formed in stars were dispersed in space, when stars exploded at the end of their lives, enriching the interstellar space with heavy elements.
- From those debris new stars and planets formed, and the cycle continues, recycling material from one generation of stars to the next.



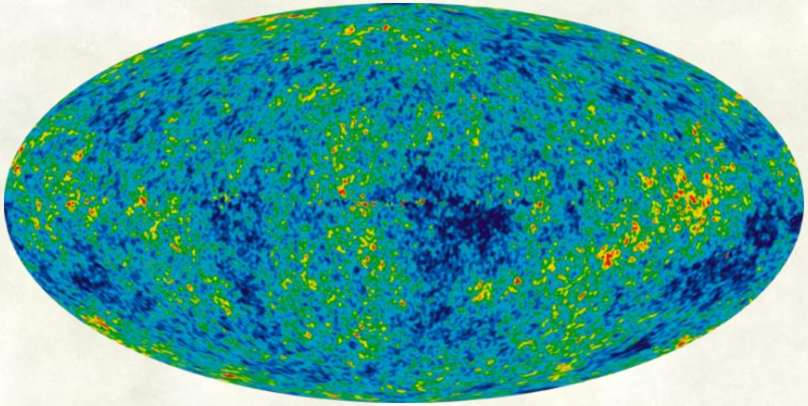
Wrong picture

- Big Ban was not a violent explosion (as often depicted in media, even by some scientists)
- It was the event space and time came into existence. A smooth and orderly event (like bubbles forming in boiling water).
- Space is expanding since then, making the matter (galaxies) move away from each other in the process.
- Matter (galaxies) is not flying away from a single point, they just follow the expansion of the space between them.

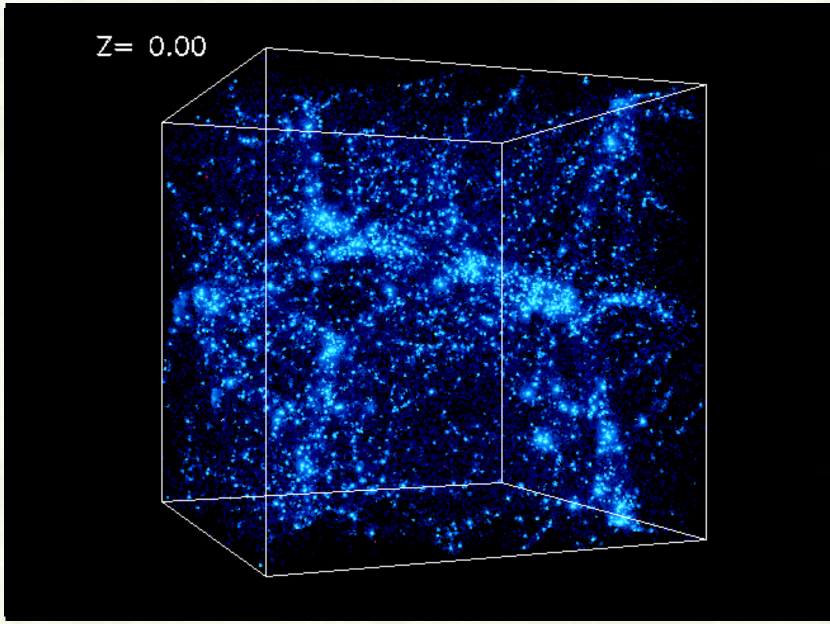


A clip from NOVA “making things cold”. Wrong picture about the Big Bang

Evidence for the Big Bang Cosmology



The Universe, 400,000 years after the Big Bang (from CMB)
temperature ~3000K, no stars of galaxies yet, filled with hot gases
color represents: temperature/density fluctuations



Universe today (simulation)

- We see the universe is expanding, galaxies are moving away from each other.
- We see the radiation from the hot early stages of the universe (called the **cosmic microwave background** (CMB) radiation)
- We can look back in time (look at very distant galaxies) and can see that universe had evolved over time.
- Universe is mostly Hydrogen and Helium as the Big Bang cosmology predicts.
  - Abundance of primordial elements 75% Hydrogen and 25% Helium.
- We can explain how the large scale structure of the universe we see today formed according to Big Bang cosmology.

The Observable Universe

- Since universe is only 13.8 billion years old, we can only see regions of the universe where light can reach us in 13.8 billion years.
  - Light from regions of the universe beyond that has not reached us yet, so we cannot see them.
  - This part of the universe where light had time to reach us is called
    "the observable universe"
  - As the universe ages, we will be able to see more distant parts of the universe.

Review Questions

- What is the shape of the Milky way? Where is the Sun located in it?
- What is the estimated number of stars in the Milky way, what is its diameter?
- Can we see all of the Milky way galaxy from the Earth?
- What is the reason we see Milky way as a luminous cloud?
- What is most distant object in the universe can be seen with the unaided eye?
- What are the dark areas in the Milky way, devoid of any stars?
- What are the Magellanic clouds? Are they visible from the US? Why?
- What is the size of the Andromeda galaxy compared to our galaxy?
- What are the dark areas visible in images of galaxies.
- What are the largest structures in the universe?
- How old is the universe?
- What is the observable universe?
- What are the most abundant elements in the universe? When did they formed?
- How did the heavier elements formed?
- What is meant by the universe is homogeneous and isotropic?
- What is the Big Bang.
- Why do galaxies seems to move away from each other?
- What are the evidence for Big Bang?