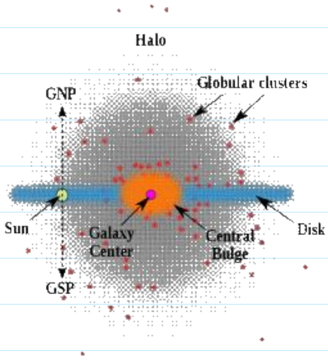
2022 12 23 Galaxy

2022년 12월 23일 금요일 오전 9:27

The Galaxy(Milky Way), galaxy ,
Group/Cluster of galaxies Supercluster of galaxies

Large Scale Structures :
filaments, walls, voids, etc



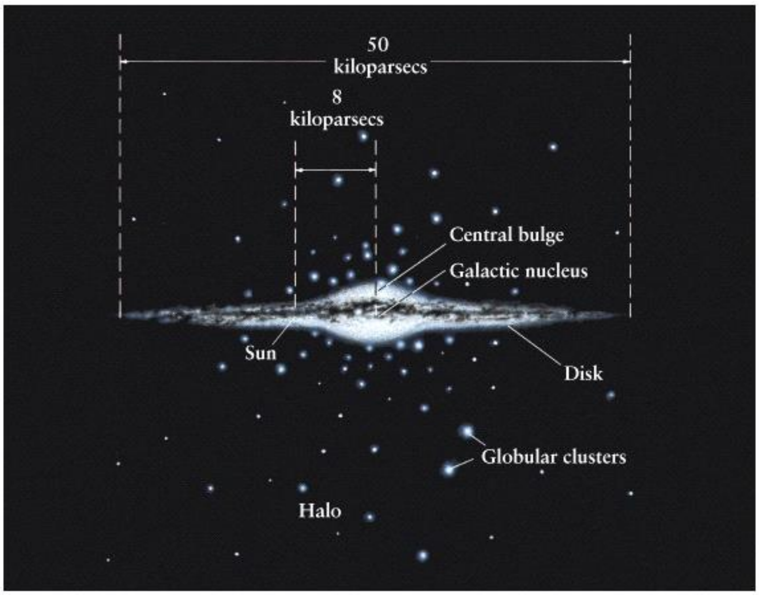
1. The Milky Way Galaxy (The Galaxy)

Galaxy Center
direction : Sagittarius
Distance : 25–27 kly (7.8–8.3 kpc)

Size

- Bulge : a bar-shaped core
  - Size ~10kyr

출처: <https://ko.wikipedia.org/wiki/%EC%9D%80%ED%95%98%EC%88%98>



출처: <https://sites.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect1/lecture1.html>

- Stellar disk
  (gas, dust & stars
  surrounding the core)
  - diameter
    ≈ 170–200 kly ≈ 52–61 kpc
    (DM halo ≈ 500 kpc
    relatively uniformly
  - Thickness ≈ 1kly ≈ 0.3 kpc

- Galactic Halo :
  - Spherical, limited in size by the orbits of LMC &SMC, two Milky Way satellites (180kly (55 kpc) away)
  - Old stars and globular clusters
  - 90% within 30kpc of the Galactic Center
  - The integrated absolute visual magnitude of the Milky Way ≈ −20.9.

Note

- Type Sbc (the Hubble classification
  - spiral galaxies with relatively loosely wound arms.
  - confirmed by the Spitzer Space Telescope in 2005.
- 2nd-largest galaxy in the Local Group (after the Andromeda Galaxy)

Mass

\# of stars = 1~4 x10^{11}
$M_{MilkyWay}$ ≈ 1.29 x10^{12} $M_\odot$
Dark Matter M_{DM} = 1~1.5 x10^{12} $M_\odot$

Mass M≈ (0.8–1.5)×10^{12} $M_\odot$

Milky Way Galaxy **Observation data**

Constellation	Sagittarius
Right ascension	$17^h\ 45^m\ 40.0409^s$[1]
Declination	−29° 00′ 28.118″[1]
Distance	25.6–27.1kly (7.86–8.32kpc)
Type	Sb, Sbc, or SB(rs)bc (barred spiral)
Diameter	Stellar disk: 170–200 kly DarkMatHalo≈1.9Mly(580±120kpc)
Thickness of thin stellar disk	≈2 kly (0.6 kpc)
Number of stars	100-400 billion
Mass	(0.8–1.5)×10^{12} $M_\odot$
Angular momentum	≈1×10^{67} J s
⊙ distan to Gal Center	25.6–27.1 kly (7.86–8.32 kpc)

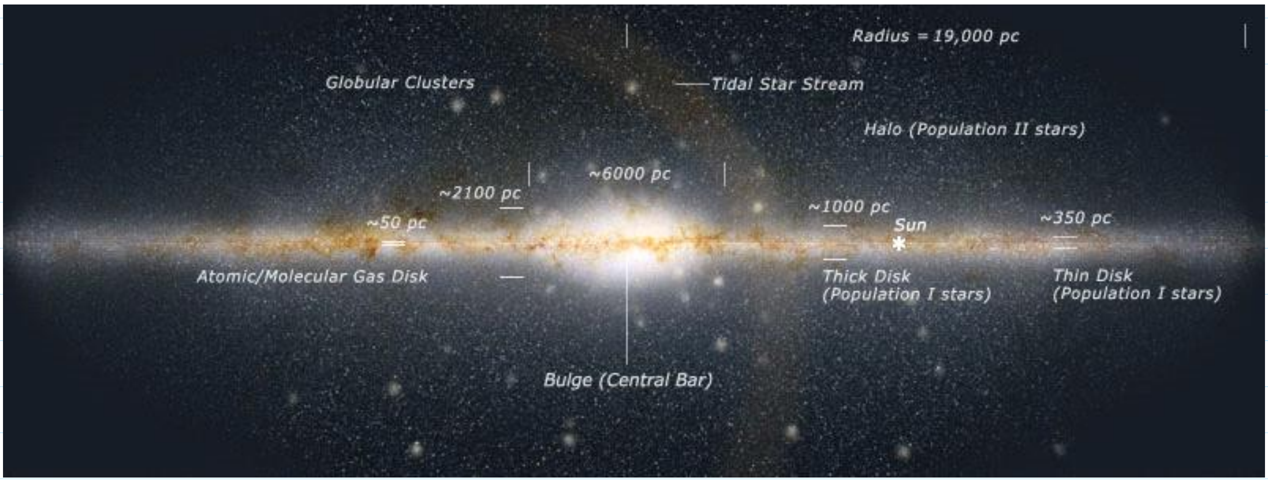
Dark Matter M_{DM} = 1~1.5 x10^{12} $M_\odot$

Mass M≈ (0.8–1.5)×10^{12} $M_\odot$
- Visible
  - $M_{Visible}$ = 5.8 x10^{11} $M_\odot$
- Stars
  - M_{Stars} = 4.6 ~ 6.43 x10^{10} $M_\odot$
- The interstellar gas
  - The mass
    $M_{IS\ gas}$ = 10% ~ 15% M_{Stars}
  - Interstellar gas consists of
    - 90% H (2/3 H atom, 1/3 H_2),
    - 10% He by mass
- Interstellar dust :
  - 1% of the total mass of the gas.
- dark matter
  - ~ 90% of the galaxy mass may be DM.

Angular momentum	≈1×10^{67} J s
⊙ distan to Gal Center	25.6–27.1 kly (7.86–8.32 kpc)
Sun's Gal rot period	240 Myr
Spiral rot period	220–360 Myr
Bar rot period	100–120 Myr
v rel to CMB rest fr	552.2±5.5 km/s[17]
Esca vel at ⊙ position	550 km/s[11]
Dark matter density at Sun's position	0.0088 $M_\odot$$Pc^{-3}$ or 0.35+0.08–0.07 GeV cm^{-3}

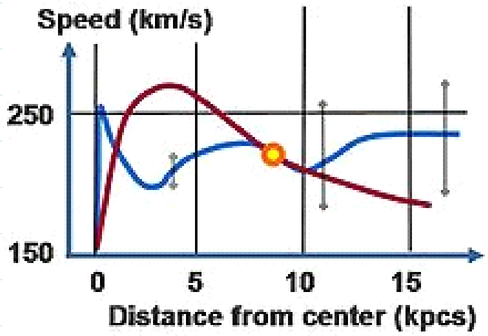
출처: <https://en.wikipedia.org/wiki/Milky_Way>

- Super massive BH at Center
  3.7x$10^6$$M_\odot$(cf at M31, 1~2x$10^8$$M_\odot$
- The Milky Way may contain
  - 10^{10} WD ten billion white dwarfs
    10^9 NS a billion neutron stars, 10^8 BH ~100M stellar BH
  - # planets ≈ # stars
  - # rogue planets ≳ # stars
  - Up up 40 billion Earth-sized planets orbiting in the habitable zones of Sun-like stars and red dwarfs within the Milky Way
  - 11 billion of these planets may be orbiting Sun-like stars.



출처: <http://www.handprint.com/ASTRO/galaxy.html#dimensions>

The interstellar medium
- Filling the space between the stars
- a disk of gas and dust
- The disk has at least a comparable extent in radius to the stars,
- whereas the thickness of the gas layer ranges from hundreds of light-years for the colder gas to thousands of light-years for warmer gas.
- beyond a radius of roughly 40kly (13 kpc) from the center, the number of stars per cubic parsec drops much faster with radius.



Galaxy rotation curve for the Milky Way
Blue is the observed curve;
Red is the predicted curve by stellar mass & gas;
the difference is due to dark matter

Velocities

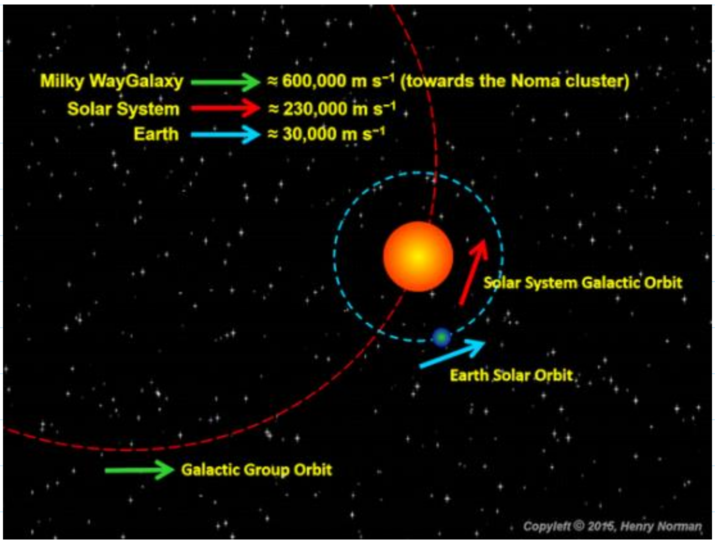
Velocities

Star revolution 200~250km/sec
Sun : 220 km/sec
towards Vega;
with 60° from the galactic center

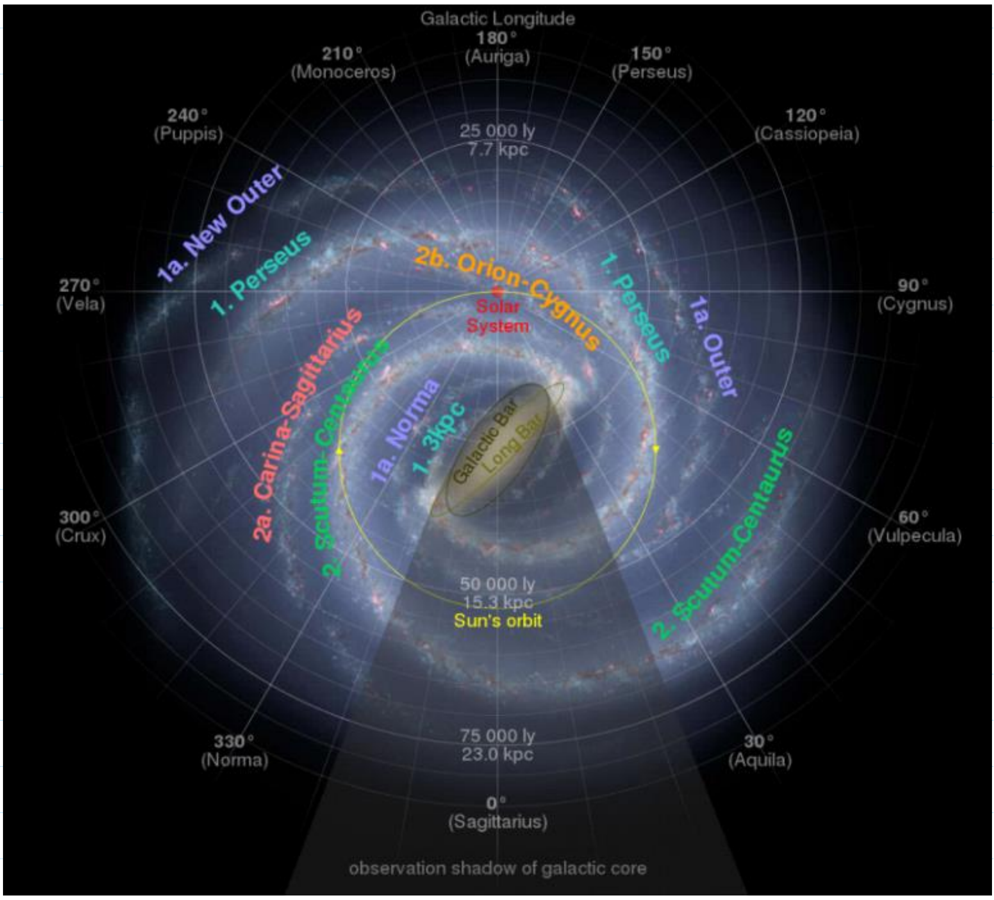
Milky Way speed relative to CMB rest frame
= 552.2 ± 5.5 km/s

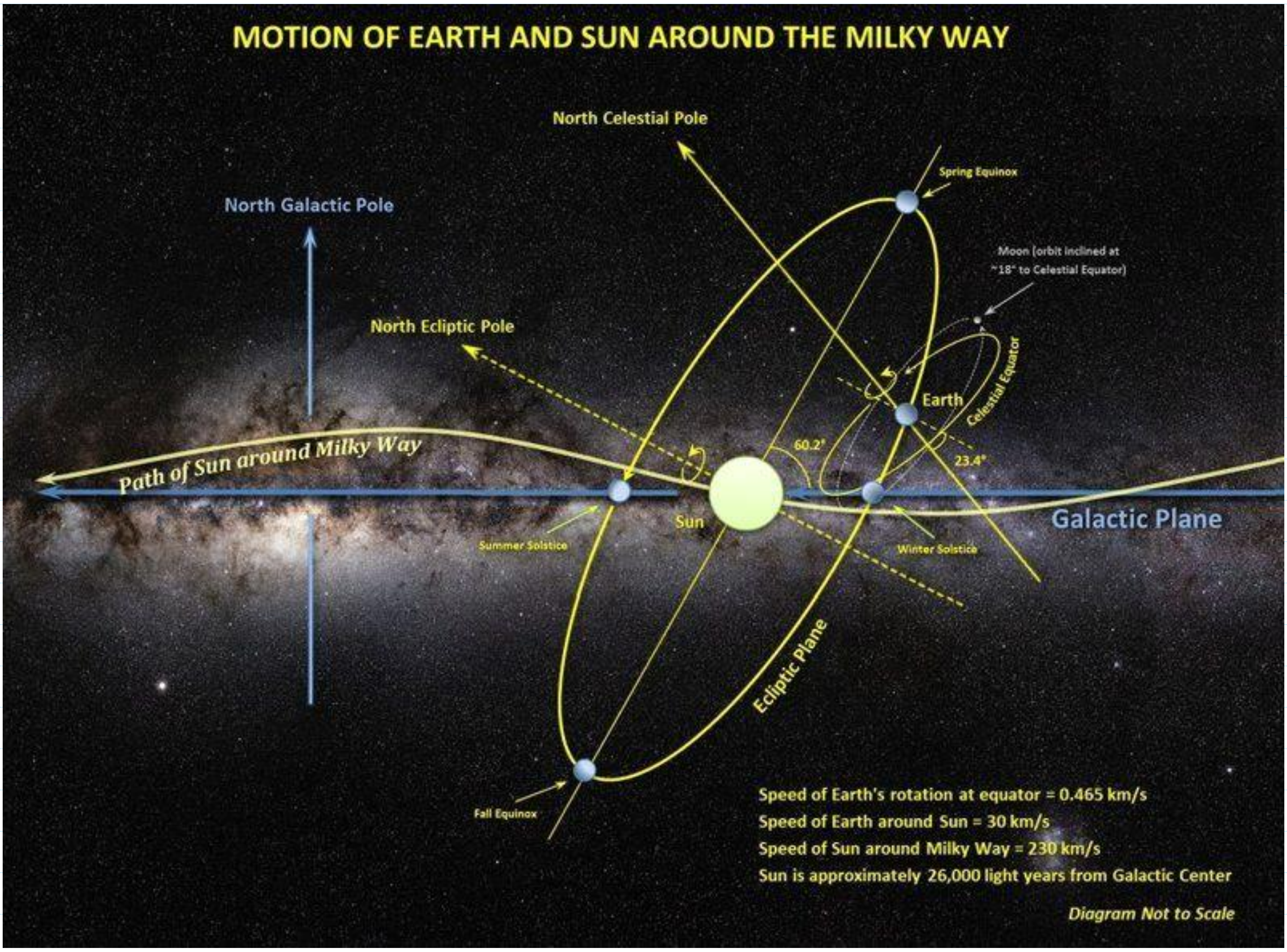
Escape velocity at Sun's position
= 550 km/s

The rotational period at the radius of the sun
= 240Myr



- The Sun's Galactic motion is towards the star Vega, at roughly 60° to the direction of the Galactic Center.
- The Sun's orbit about the Milky Way is roughly elliptical with perturbations due to the Galactic spiral arms and non-uniform mass distributions.
- The Sun passes through the Galactic plane approximately 2.7 times per orbit, very similar to a simple harmonic oscillator with no damping term.
- About 240 Myr takes for the Solar System to complete one orbit of the Milky Way (a galactic year), so the Sun has completed 18–20 orbits during its lifetime and 1/1250 of a revolution since the origin of humans.
- The orbital speed of the Solar System about the center of the Milky Way ≈ 220 km/s.
- The Sun moves through the heliosphere at 84,000 km/h. At this speed, it takes around 1,400 years for the Solar System to travel a distance of 1 ly, or 8 days to travel 1 AU.
- The Solar System is headed in the direction of the zodiacal constellation Scorpius, which follows the ecliptic.



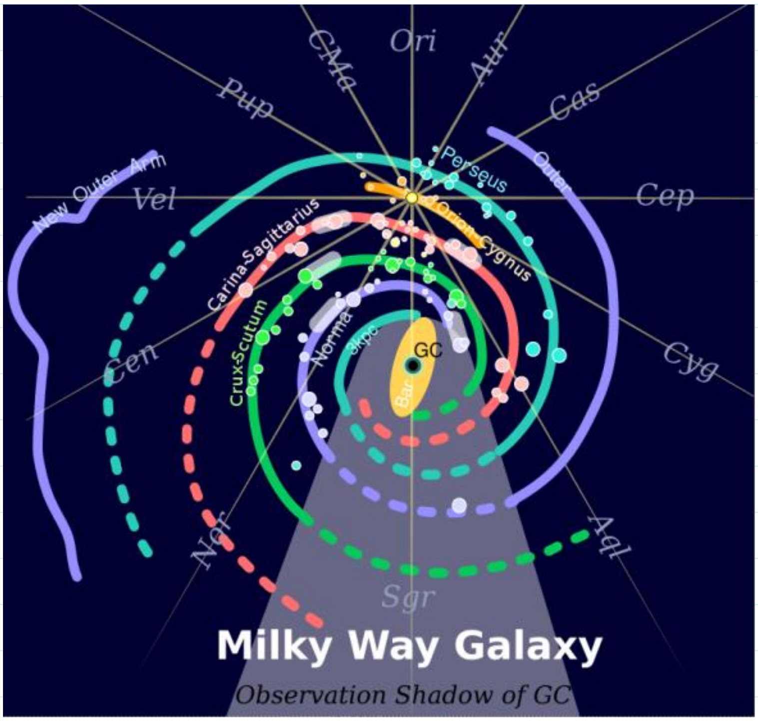


Structure

- Galactic center :
  - in the direction of Sagittarius, where the Milky Way is brightest.
  - ∃ Sagittarius A*
    an intense radio source, harboring a supermassive black hole
    4.1~4.5 x$10^6 M_\odot$

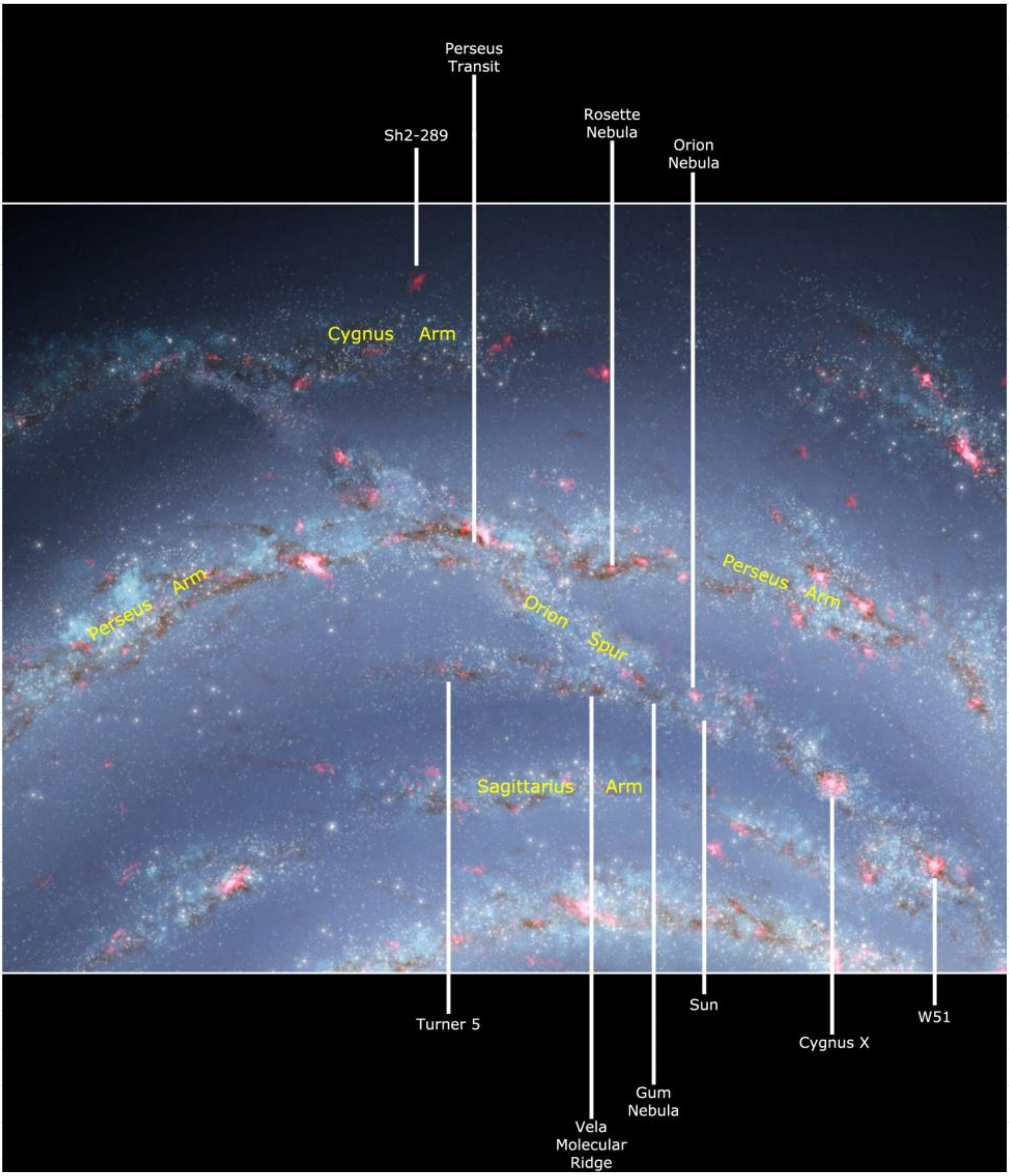
- galactic anticenter
  - in Auriga

- The galactic plane
  - inclined by about 60° to the ecliptic (the plane of Earth's orbit).
  - Relative to the celestial equator, passes as far north as the constellation of Cassiopeia
  - and as far south as the constellation of Crux,
- The north galactic pole



- at RA12h 49m, dec +27.4°
  near β Comae Berenices

- the south galactic pole
  - near α Sculptoris.



The solar system

- Near the inner rim of the Orion Arm,within the Local Fluff of the Local Bubble, and in the Gould Belt.
- 27 kly (8.3 kpc) away from the Galactic Center,
  currently 5–30 parsecs (16–98 ly) above, or north of, the central plane of the Galactic disk.
- The distance between the local arm & the next arm out, the Perseus Arm≈ 2kpc (6.5kly).
- The Solar System, is located in the Milky Way's galactic habitable zone.
- There are far more faint stars than bright stars:

In the entire sky,
about 500 stars brighter than apparent magnitude 4
but 15.5 million stars brighter than apparent magnitude 14.

- Bright star density : one star/ 69 pc^3 , or one star/ 2,360 ly^3
  (from List of nearest bright stars, about 208 stars brighter than absol mag 8.5 within a sphere with a radius of 15 pc (49 ly) from the Sun,
- Star density : about one star / 8.2 pc^3, or one / 284 ly^3
  (from List of nearest stars, there are 64 known stars (of any magnitude, not counting 4 brown dwarfs, within 5 pc (16 ly) of the Sun)

출처: <https://en.wikipedia.org/wiki/Milky_Way>

The surroundings of the Galactic center (Top view map).

출처: <https://en.wikipedia.org/wiki/Galactic_Center>

The **Local Bubble**, or **Local Cavity**

- is a relative cavity in the interstellar medium (ISM) of the Orion Arm in the Milky Way.
- It contains the closest of celestial neighbours and among others,
  the Local Interstellar Cloud (which contains the Solar System),
  the neighbouring G-Cloud, Ursa Major Moving Group (the closest stellar moving group) and
  the Hyades (the nearest open cluster).
- at least 300ly across,
- its neutral-hydrogen density ≈ 0.05 atoms/cm^3,
  Cf) the average for the ISM in the Milky Way ≈0.5 atoms/cm^3,
  the Local Interstellar Cloud ≈ 0.3 atoms/cm^3.
- The exceptionally sparse gas is the result of SN within the past 10~20Myrs.
  The gas remains in an excited state, emitting in the X-ray band.
- Geminga, a pulsar in the constellation Gemini, was once thought to be the remnant of a single supernova that created the Local Bubble, but now multiple supernovae in subgroup B1 of the Pleiades moving group are thought to have been responsible, becoming a remnant supershell.

Description

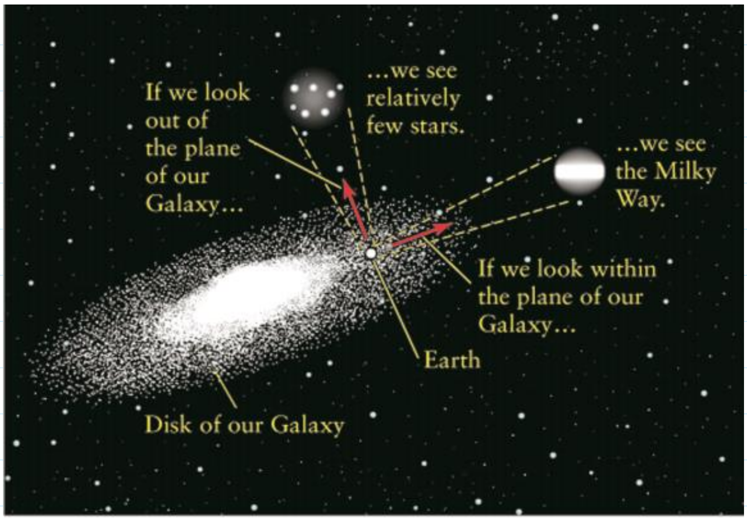
The Solar System has been traveling through the region currently occupied by the Local Bubble for the last five to ten million years.
Its current location lies in the Local Interstellar Cloud (LIC), a minor region of denser material within the Bubble.

- The LIC formed where the Local Bubble and the Loop I Bubble met.
  * The gas within the LIC has a density of approximately 0.3 atoms/cm^3.

- The Local Bubble is not spherical, but seems to be narrower in the galactic plane, becoming somewhat egg-shaped or elliptical, and may widen above and below the galactic plane, becoming shaped like an hourglass.
- It abuts other bubbles of less dense interstellar medium (ISM), including, in particular, the Loop I Bubble.
- The Loop I Bubble was cleared, heated and maintained by supernovae and stellar winds in the Scorpius–Centaurus Association, some 500 light years from the Sun.
- The Loop I Bubble contains the star Antares (also known as α Sco, or Alpha Scorpii). Several tunnels connect the cavities of the Local Bubble with the Loop I Bubble, called the "Lupus Tunnel".[9]
- Other bubbles which are adjacent to the Local Bubble are the Loop II Bubble and the Loop III Bubble.
- In 2019, researchers found interstellar iron in Antarctica which they relate to the Local Interstellar Cloud, which might be related to the formation of the Local Bubble.

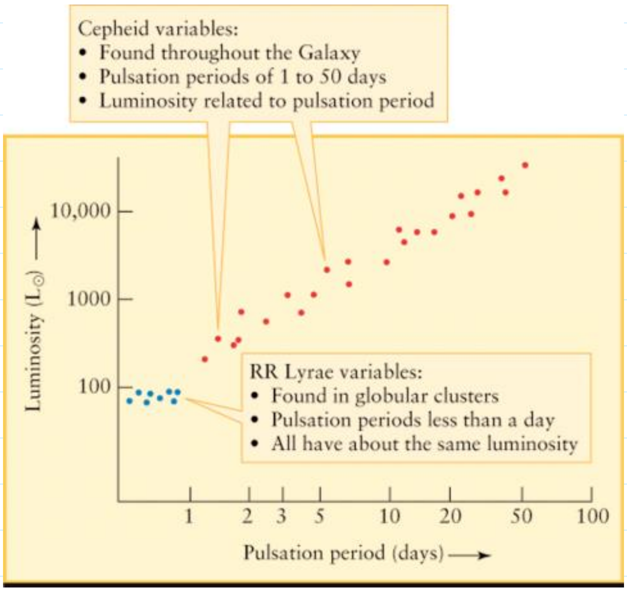
Observation

- Launched in February 2003 and active until April 2008, a small space observatory called Cosmic Hot Interstellar Plasma Spectrometer (CHIPS or CHIPSat) examined the hot gas within the Local Bubble.
- The Local Bubble was also the region of interest for the Extreme Ultraviolet Explorer mission (1992–2001), which examined hot EUV sources within the bubble.
- Sources beyond the edge of the bubble were identified but attenuated by the denser interstellar medium.
- In 2019, the first 3D map of the Local Bubble has been reported using the observations of diffuse interstellar bands.[12]



(a)

Distance
to Globular Clusters, some other objects, even nearby galaxies by variable stars (Cepheids and RR Lyrae stars)



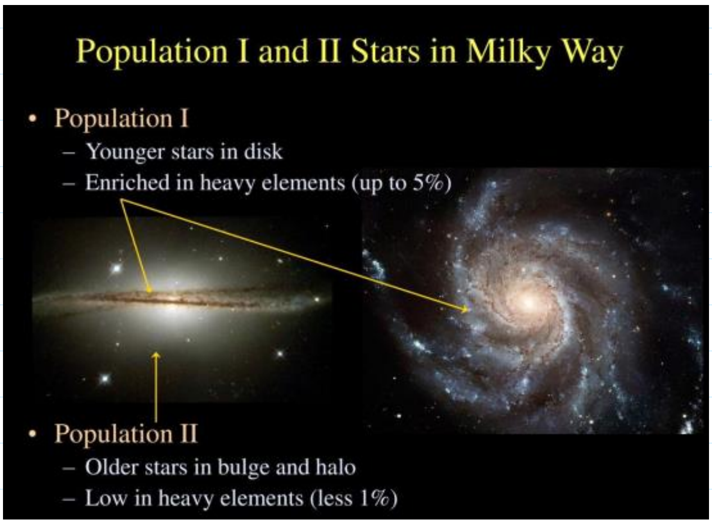
The stars in the Galaxy

pretty different, on average,

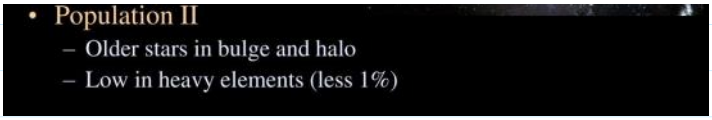
in different parts of the Galaxy

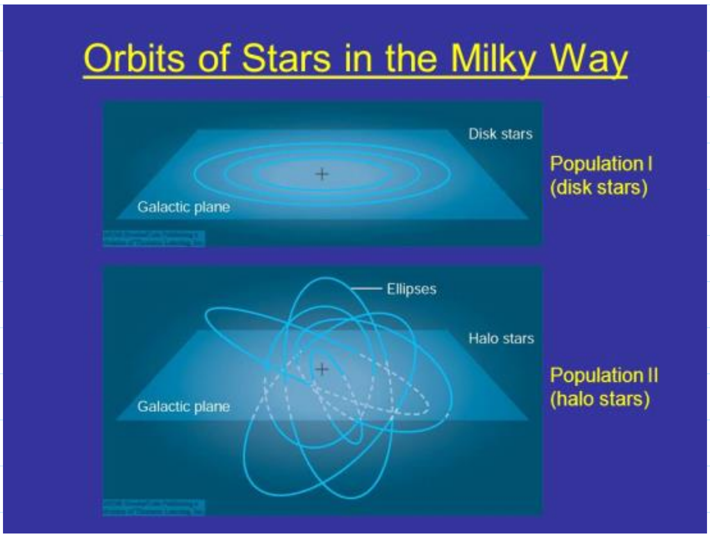
- Halo stars
  - predominantly old
  - metal-poor (~0.01% metals)
  - Globular clusters
  - RR Lyrae Stars
  - (**Population II stars)**

    In Spheroid &Globular clusters
  - Gas poor, no star formation
  - formed long ago from relatively pristine material
  - Orbit : disordered, ellipse, all inclinations, prograde & retrograde, wide range of orbital speeds.



- formed long ago from relatively pristine material
- Orbit : disordered, ellipse, all inclinations, prograde & retrograde, wide range of orbital speeds.
- Central bulge
- contain (both **Pop I** &) **Pop II** stars
- no young luminous O & B stars - no current star formation there.
- Many RR Lyrae stars
- A little gas & dust





- Stars in the disk
  - Age: Mix of young &old,
    are mostly young,
  - metal rich (roughly solar)
    70% H, 28% He, ~2%"metals"
  - Often very gas rich, especially for the young stars
  - (**Population I)**
    in the disk & Open cluster,
  - stars formed from material of previous generation).
  - the place of star formation !
  - Orbit : ordered, ~circular,in the same direction

  - Thick Disk of Stars (1kpc thick)
    - A mix of young & old stars
    - Open Clusters &
      loose Associations of stars
    - Cepheid Stars in young clusters
  - Thin disk of Gas & Dust (~100 pc thick)
    - Mostly cold atomic Hydrogen gas
    - Dusty Giant Molecular Hydrogen (H_2) Clouds
    - This gas and dust is the raw material for the on-going formation of new stars.

Formation (smaller to larger scale structure : (globular) cluster of stars → Galaxy

- The Milky Way began as one or several small overdensities in the mass distribution in the Universe shortly after the Big Bang.
- Some of these overdensities were the seeds of globular clusters in which the oldest remaining stars in what is now the Milky Way formed.
- Nearly half the matter in the Milky Way may have come from other distant galaxies.
- Nonetheless, these stars and clusters now comprise the stellar halo of the Milky Way.
- Within a few billion years of the birth of the first stars, the mass of the Milky Way was large enough so that it was spinning relatively quickly.

- Due to conservation of angular momentum, this led the gaseous interstellar medium to collapse from a roughly spheroidal shape to a disk.

- Therefore, later generations of stars formed in this spiral disk.
- Most younger stars, including the Sun, are observed to be in the disk.

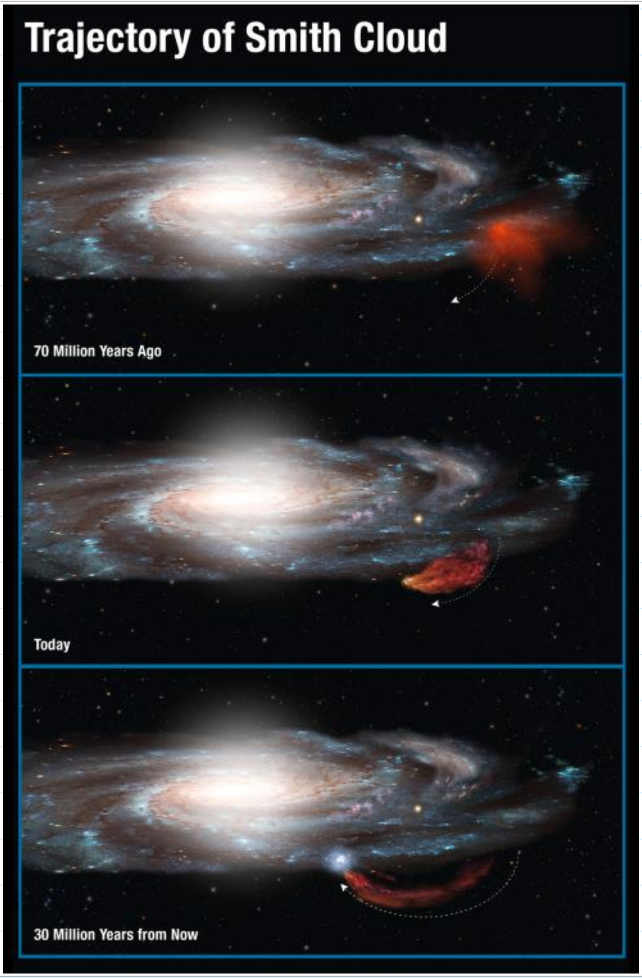
- (galaxy megers & accretion of gas)
  Since the first stars began to form, the Milky Way has grown through both galaxy mergers (particularly early in the Milky Way's growth) and accretion of gas directly from the Galactic halo.

- The Milky Way is currently accreting material from several small galaxies, including two of its largest satellite galaxies, the Large and Small Magellanic Clouds, through the Magellanic Stream.

- Direct accretion of gas is observed in high-velocity clouds like the Smith Cloud.
- **Smith's Cloud**

  - is a high-velocity cloud of hydrogen gas located in the constellation Aquila
  - at least one million solar masses and measures 3 kpc long by 1kpc wide in projection. The cloud is between 11kpc and 13.7kpc from Earth and has an angular diameter of 10° ~ 12°,
  - The cloud is apparently moving towards the disk of the Milky Way at 73 ± 26 km/s.
  - Smith's Cloud is expected to merge with the Milky Way in 27 Myr at a point in the Perseus arm. Its impact may produce a burst of star formation or a supershell of neutral hydrogen.
  - it had passed through the disk of the Milky Way some 70 million years ago.

  출처: <https://en.wikipedia.org/wiki/Smith%27s_Cloud>



- However, properties of the Milky Way such as stellar mass, angular momentum, and metallicity in its outermost regions suggest it has undergone no mergers with large galaxies in the last 10 billion years.
- This lack of recent major mergers is unusual among similar spiral galaxies; its neighbour the Andromeda Galaxy appears to have a more typical history shaped by more recent mergers with relatively large galaxies.
- According to recent studies, the Milky Way as well as the Andromeda Galaxy lie in what in the galaxy color–magnitude diagram is known as the "green valley", a region populated by galaxies in transition from the "blue cloud" (galaxies actively forming new stars) to the "red sequence" (galaxies that lack star formation).
- Star-formation activity in green valley galaxies is slowing as they run out of star-forming gas in the interstellar medium.
- In simulated galaxies with similar properties, star formation will typically have been extinguished within about five billion years from now, even accounting for the expected, short-term increase in the rate of star formation due to the collision between both the Milky Way and the Andromeda Galaxy.[176]
- In fact, measurements of other galaxies similar to the Milky Way suggest it is among the reddest and brightest spiral galaxies that are still forming new stars and it is just slightly bluer than the bluest red sequence galaxies.

Age and cosmological history

- Globular clusters are among the oldest objects in the Milky Way, which thus set a lower limit on the age of the Milky Way.
- The ages of individual stars in the Milky Way can be estimated by measuring the abundance of long-lived radioactive elements such as thorium-232 and uranium-238, then comparing the results to estimates of their original abundance, a technique called nucleocosmochronology.

- These yield values of
  about 12.5 ± 3 billion years for CS 31082-001[179]
  and 13.8 ± 4 billion years for BD +17° 3248.[180]

- Once a white dwarf is formed, it begins to undergo radiative cooling and the surface temperature steadily drops. By measuring the temperatures of the coolest of these white dwarfs and comparing them to their expected initial temperature, an age estimate can be made. With this technique,
- the age of the globular cluster M4 was estimated as 12.7 ± 0.7 billion years.
- Age estimates of the oldest of these clusters gives a best fit estimate of 12.6 billion years, and a 95% confidence upper limit of 16 billion years.[181]

- The discovery of the star in the Milky Way galaxy suggests that the galaxy may be at least 3 billion years older than previously thought.
- Several individual stars have been found in the Milky Way's halo with measured ages very close to the 13.80-billion-year age of the Universe.
- In 2007, a star in the galactic halo, HE 1523-0901, was estimated to be about 13.2 billion years old.

- As the oldest known object in the Milky Way at that time, this measurement placed a lower limit on the age of the Milky Way.
- Another star, HD 140283, is 14.5 ± 0.7 billion years old.[34][186]
- According to observations utilizing adaptive optics to correct for Earth's atmospheric distortion, stars in the galaxy's bulge date to about 12.8 billion years old.[187]

- The age of stars in the galactic thin disk has also been estimated using nucleocosmochronology.
- Measurements of thin disk stars yield an estimate that the thin disk formed 8.8 ± 1.7 billion years ago.
- These measurements suggest there was a hiatus of almost 5 billion years between the formation of the galactic halo and the thin disk.[188]
- Recent analysis of the chemical signatures of thousands of stars suggests that stellar formation might have dropped by an order of magnitude at the time of disk formation, 10 to 8 billion years ago, when interstellar gas was too hot to form new stars at the same rate as before.[189]

- The satellite galaxies surrounding the Milky way are not randomly distributed but seemed to be the result of a break-up of some larger system producing a ring structure 500,000 light-years in diameter and 50,000 light-years wide.[190]
- Close encounters between galaxies, like that expected in 4 billion years with the Andromeda Galaxy rips off huge tails of gas, which, over time can coalesce to form dwarf galaxies in a ring at an arbitrary angle to the main disc.[191]

출처: <https://en.wikipedia.org/wiki/Milky_Way>

galaxy

Ex) The Galaxy (Milky Way;은하수), Andromeda galaxy (M31), ...

# of stars : $10^7 \sim 10^{14}$ ($\sim\ 10^{11}$)

항성계, 성단, 성간 운, 성간 물질 (interstellar medium)

암흑물질이 질량의 90%

은하 중심에 초대질량 블랙홀 존재

형태 분류 : 타원은하, 나선은하, 불규칙은하

# of galaxies ~ 1.7×10^{11} 개

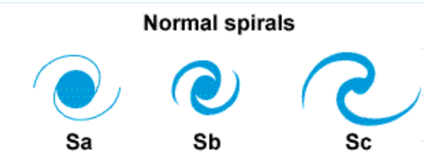
galaxy diameter $10^3 \sim 10^5\ pc$ (~10 kpc)

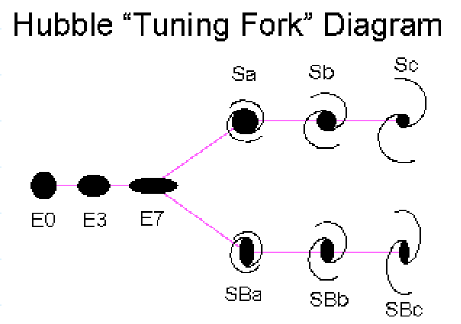
은하간(intergalactic) 공간 밀도 $\lesssim$ 1 atoms/ m^3

Hubble Classification of Galaxies (1926 & 1936)

- Spiral Galaxies (~75%)
  (w/ or w/o bars)
- Elliptical Galaxies (20%)
- Irregular Galaxies (5%)

Dwarf Galaxies





M 65: Type Sa

M 63: Type Sb

NGC 2997: Type Sc

(Ordinary) Spirals (S)

-the central bulge(spheroid)

& the spiral arms (disk)

-relatively rapid rotation

Types: Sa, Sb, and Sc

- **Sa**: strong bulge & tight, indistinct arms
  - the brightest central bulges, $I_{bulge}/I_{disk} \sim 0.3$
  - very tightly wound arms, often not very prominent.
- **Sb**: intermediate type
  - less bright central bulges than Sa galaxies
  - more prominent arms than Sa galaxies.
- **Sc**: small bulge & loose, well-defined arms
  - the dimmest central bulges, $I_{bulge}/I_{disk} \sim 0.05$
  - have loosly wound arms which are very prominent.

Barred Spirals (SB)

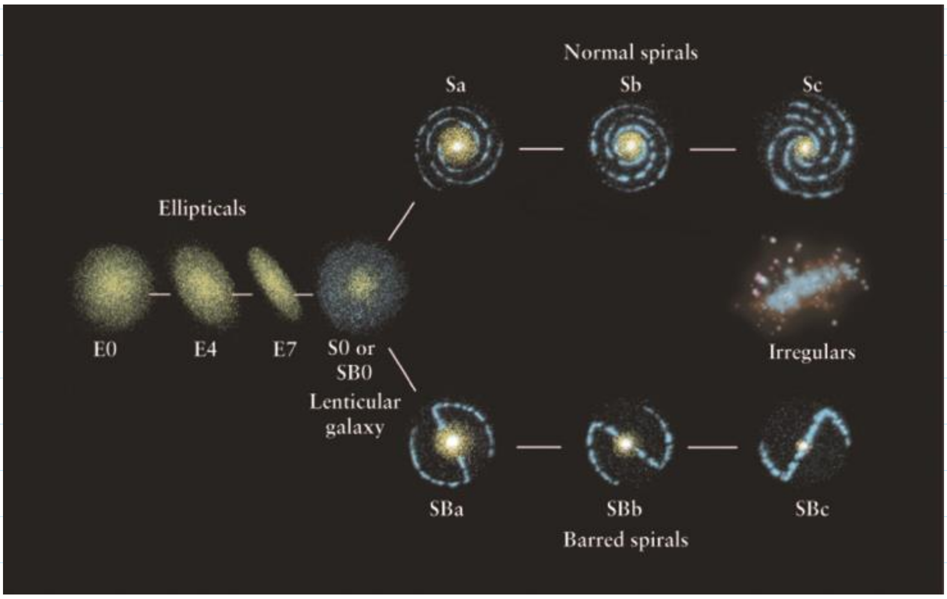
- SBa galaxies have the brightest nuclear bulges.
- SBc galaxies have the least bright nuclear bulges.
- In order of brightest nuclear bulge to least bright: SBa, SBab, SBb, SBbc, SBc.
- About half of all spiral galaxies are barred

spirals.

- All spirals (barred or regular) have young stars and signs of star formation in the arms of the galaxy.
- The star formation makes the arms look sort of blue in colour.
- The nuclear bulges typically have older stars which are redder in colour.

Ex) The Milky Way : SBbc (btw SBb & SBc).

(a) SBa (NGC 4650) (b) SBb (M83) (c) SBc (NGC 1365)



Ellipticals (E)

Show little internal structure:

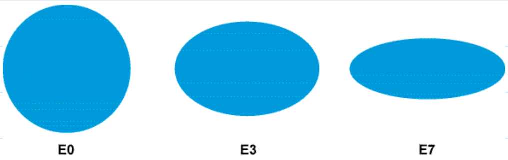
- Elliptical in shape
- No disks, spiral arms, or dust lanes
- Brightest stars are red

Classified by the degree of apparent flatness, denoted by: E followed by a number (from 0 to 9) given by 10x(1-b/a) where

b = the apparent size of the short axis

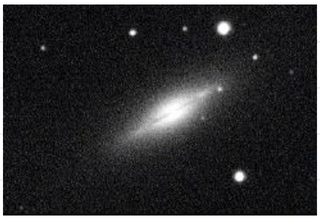
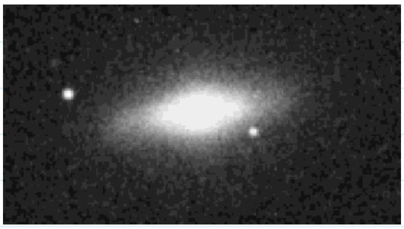
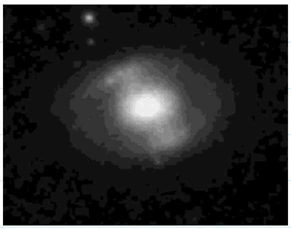
a = the apparent size of the long axis

- E0 is circular
- E7 is flattest (~3:1 aspect ratio)



- Elliptical galaxies have much less gas and dust than spiral galaxies.
- Elliptical galaxies have very few young stars.
- Most stars in ellipticals are old red stars.
- The stars in elliptical galaxies formed long ago, and there has not been a new episode of star formation.

Lenticular Galaxies

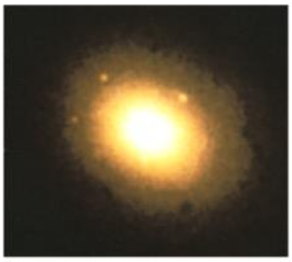




NGC 5866: Type S0 NGC 4251: Type S0 NGC 4340: Type SB0

- Lenticular galaxies are disk-like galaxies with no obvious spiral structure.
- S0 denotes a regular lenticular.
- SB0 denotes a barred lenticular.

Spheroid of old stars with little gas or dust


(a) E0 (M105)


(b) E3 (NGC 4365)


(c) E6 (NGC 3377)

Irregular Galaxies (I)

Chaotic structure, lots of young blue stars

Little evidence of systematic rotation.

Large Magellenic Cloud: Type Irr I

Small Magellenic Cloud: Type Irr I


The Cigar Galaxy: Type Irr II

- Any galaxy that isn't a spiral, barred spiral, elliptical or lenticular is called irregular.
- Type I irregulars are denoted: Irr I and have a hint of spiral structure.
- Type II irregulars are denoted: Irr II and correspond to everything else.
- The irregular galaxies often show signs of star formation.
- The Large and Small Magellenic clouds are nearby galaxies which orbit the Milky Way.
- The tides caused by the Milky Way might be deforming the Magellenic clouds.
- The Magellenic clouds can be seen without a telescope from the Southern hemisphere.

Dwarf Galaxies

- is a small galaxy composed of about 1000 up to several billion stars.

- Most common type of galaxy by number
- Low-luminosity Ellipticals & Irregulars.
- There are no (convincing) Dwarf Spirals.
- **Note** : Significant **dwarf irregular** population, classified as "dI"
- formation & activity are thought to be heavily influenced by interactions with larger galaxies.

Ex) The Large Magellanic Cloud closely orbits the Milky Way & contains over 3x10^{10}0 stars : sometimes classified as a dwarf galaxy;

출처: <https://en.wikipedia.org/wiki/Dwarf_galaxy>

출처: <http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit4/types.html>

Spirals	Ellipticals	Irregulars	Dwarf Irregulars
Range is ~10-20% gas	Very little or no gas or dust	Can range up to 90% gas	Very metal poor (<1% solar)
On-going star formation in the disks	Star formation ended billions of years ago	Often a great deal of on-going star formation	10^{18} kg/m^3
Mix of Pop I and Pop II stars	See only old Pop II stars	Dominated by young Pop I stars	Forming stars for the **first** time only now.
10^9 - 10^{12} M_{sun} 5 - 50 kpc	10^5 - 10^{13} M_{sun} 1 - 200 kpc	10^6 - 10^{11} M_{sun} 1 - 10 kpc	
10^8 - 10^{11} L_{sun}	10^6 - 10^{12} L_{sun}	10^6 - few x 10^9 L_{sun}	

출처: <http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit4/types.html>

INTERACTIVE EXERCISE 24.1

Table 24-1 Some Properties of Galaxies

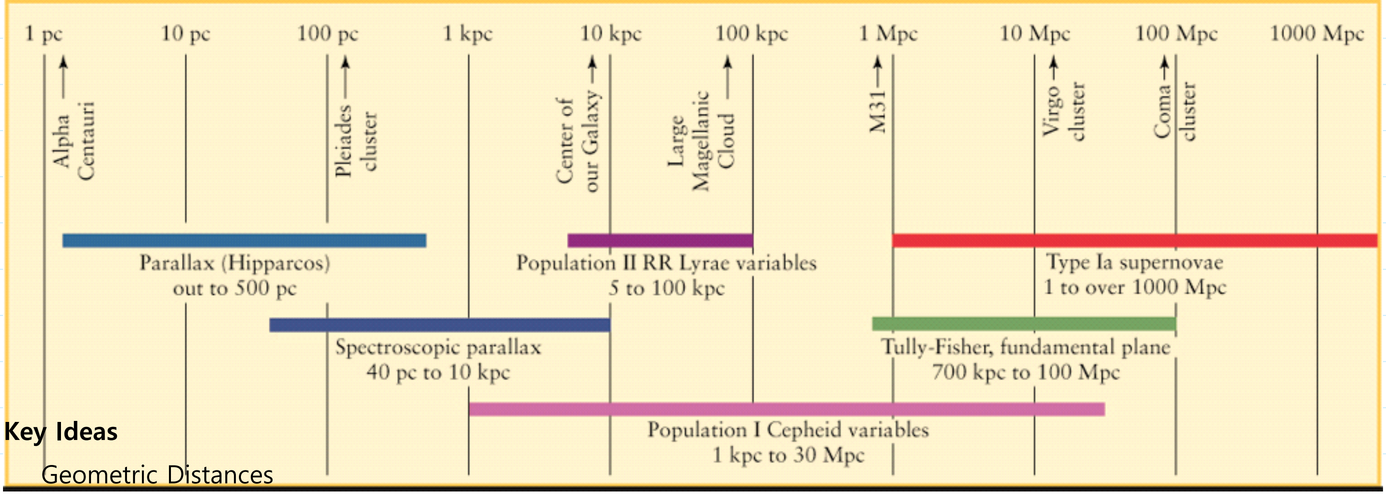
	Spiral (S) and barred spiral (SB) galaxies	Elliptical galaxies (E)	Irregular galaxies (Irr)
Mass ($M_\odot$)	10^9 to 4×10^{11}	10^5 to 10^{13}	10^8 to 3×10^{10}
Luminosity ($L_\odot$)	10^8 to 2×10^{10}	3×10^5 to 10^{11}	10^7 to 10^9
Diameter (kpc)	5 to 250	1 to 200	1 to 10
Stellar populations	Spiral arms: young Population I Nucleus and throughout disk: Population II and old Population I	Population II and old Population I	mostly Population I
Percentage of observed galaxies	77%	20%*	3%

This percentage does not include dwarf elliptical galaxies that are as yet too dim and distant to detect. Hence, the actual percentage of galaxies that are ellipticals may be higher than shown here.

Distances to the Galaxies

- Determinning distance to far away object requires **sequence** of steps of using "standard sticks", "standard candles" or established relation between properties that depended on distance.
- We speak about **distance ladder**
  For the Galaxies:
  1. Determine distance to **nearby stars** using **parallax**.
  2. Identify one which can serve as standard candles – e.g variable stars
  3. Calibrate **period – luminosity relation** for nearby Cepheids and RR-Lyrae by establishing their absolute luminosity, since distance have been measured.
  4. Use **RR Lyrae** to determine distance to **globular clusters**
  5. Use **Cepheids** (much rarer) to establish distance to **nearby galaxies**
  6. Having distance to nearby galaxies, calibrate **Tully-Fisher relation** – **proportionality between luminosity of spiral Galaxies and how fast spiral galaxy rotates**
  7. Measure **rotation of far away spiral galaxies** (Doppler shift) and use Tully-Fisher relation to find their absolute luminosity, and therefore the **distance from brightness**.
  8. Use theoretical knowledge of **SNIa** as standard candles, calibrate luminosity – decay time based on nearby (very rare) supernovae, and use SNIa to measure **very far distances**.
- Errors in early steps propagate throughout the ladder. E.g error in parallaxes of 10% means

we will know all the distances in the Universe only up to 10%.



Key Ideas

Geometric Distances

Trigonometric Parallaxes

Luminosity Distances

"Standard Candles"

Spectroscopic Parallaxes

Cepheid Variables

RR Lyrae Variables

Geometric Distances

Direct measurements of distances using geometry.

Solar System Distances:

- Orbit Geometry (Copernicus)
- Radar Measurements

Stellar Distances:

- Method of Trigonometric Parallax

Parallax Limits

Ground-based parallaxes are measured to ~0.01-arcsec

- good distances out to 100 pc
- < 1000 stars this close

Hipparcos satellite measures parallaxes to ~0.001-arcsec

- good distances out to 1000 pc
- ~100,000 stars

Luminosity Distances

Indirect distance estimate:

- **Measure** the object's **Apparent Brightness**, B
- **Assume** the object's **Luminosity**, L
- **Solve** for the object's **Luminosity Distance**, d_L,

$$B = \frac{L}{4\pi d^2} \rightarrow d_L = \sqrt{\frac{L}{4\pi B}}$$

We call this the **Luminosity Distance** (d_L) to distinguish it from distances estimated by other means (e.g. geometric distances from parallaxes).

The only **observable** is the object's Apparent Brightness, B. The missing piece is the luminosity, (L), which must be inferred in some way.

Standard Candles

Any object whose Luminosity you know ahead of time ("*a priori*") is known as a **Standard Candle**. Once you have a calibration of a set of standard candles, you can then apply them to measuring distances to objects that are too far away for geometric methods like parallaxes.

Spectroscopic "Parallaxes"

Distance-Independent Property:

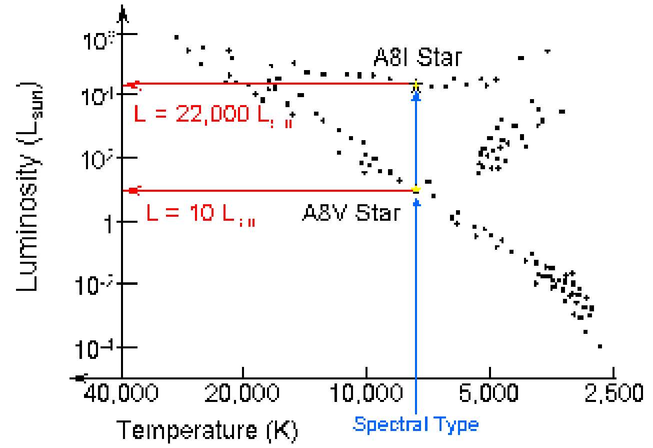
- The observed spectrum of the star.

Physics:

- The Spectral Type (OBAFGKML) tells you the star's Temperature.
- The Luminosity Class (I..V) tells you which region of the H-R Diagram the star belongs in.
- Together, they give the star a unique location on a calibrated H-R Diagram.

Method:

- Build up a calibrated H-R Diagram for nearby stars with good parallax distances.
- Get Spectral Type & Luminosity Class of the distant star from its spectrum.
- Locate the star in the calibrated H-R Diagram
- Read off the Luminosity
- Compute the **Luminosity Distance** (d_L) from is measured Apparent Brightness.



NOTE: Despite the name, the method has nothing to do with measuring geometric "parallaxes".

Distance Limit:

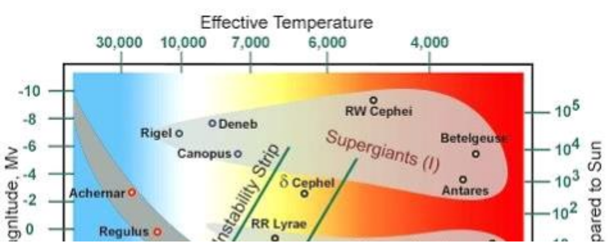
- Practical limit few 100,000 pc.
- Works best for star clusters.

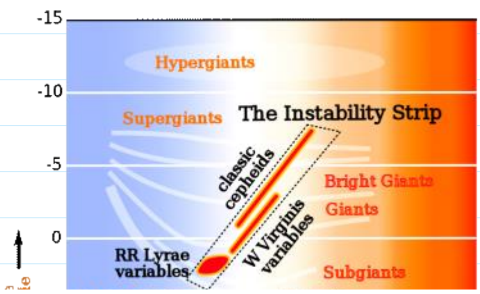
Problems:

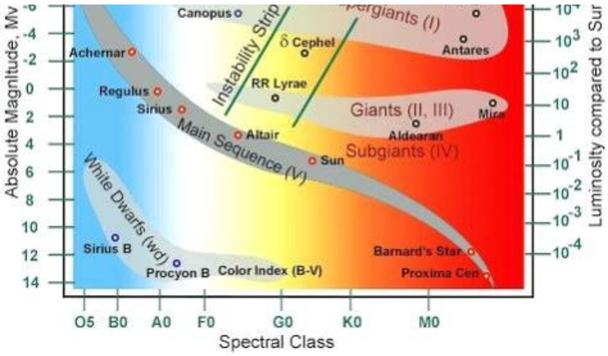
- Luminosity Classes are only roughly defined.
- H-R diagram location depends on **composition**.
- Faint spectra give poor classifications.

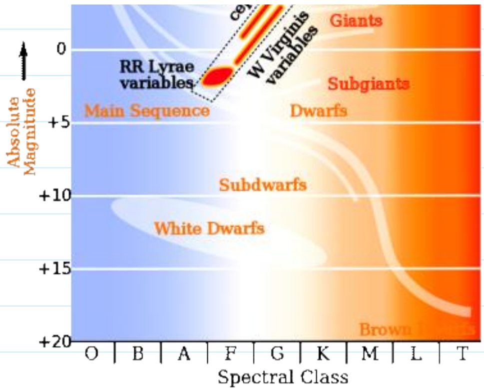
While somewhat difficult to use accurately for individual stars, the method of spectroscopic parallaxes works best for clusters of stars where you can average over many measurements.

Periodic Variable Stars









Periodic Variable Stars

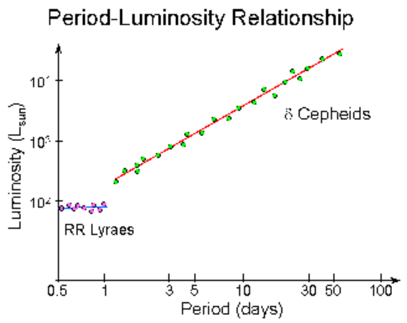
Stars whose brightness varies regularly with a characteristic, periodic (repeating) pattern.

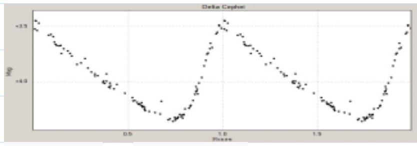
Distance-Independent Property:

- **Period** (repetition time) of their cycle of brightness variations.

Physics:

- **Period-Luminosity Relations** exist for certain classes of periodic variable stars.
- Measuring the Period gives the Luminosity.





[Light curve](https://en.wikipedia.org/wiki/Light_curve) of [Delta Cephei](https://en.wikipedia.org/wiki/Delta_Cephei), the prototype of classical cepheids, showing the regular variations produced by intrinsic stellar pulsations

출처: <https://en.wikipedia.org/wiki/Cepheid_variable>

- **Longer** Period = **Higher** Luminosity

  P = 3 days, L ~ 10^3 L_{sun}

  P = 30 days, L ~ 10^4 L_{sun}

Cepheid Variables

Two types with different P-L relations

(δ Cephei and W Virginis stars).

1) **Classical Cepheids** (Population I Cepheids, type I Cepheids, δ Cepheid variables)

- very regular pulsation
- periods

  1 day up to ~50 days
- in young star clusters :

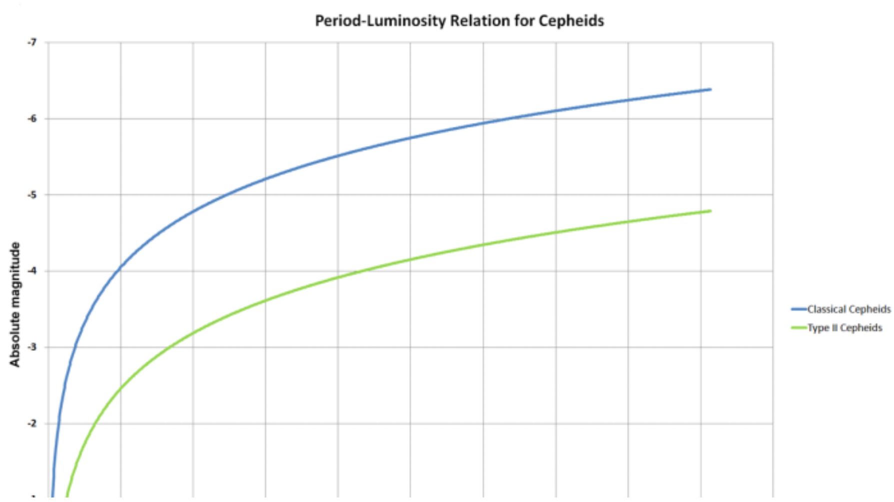
  Popula I variable stars
- M≈ (4–20) $M_{\odot}$
- L~ $10^{3\text{-}4}$ $L_{sun} \lesssim 10^5$ $L_{\odot}$
- yellow

  bright giants

  & supergiants

  of spectral class

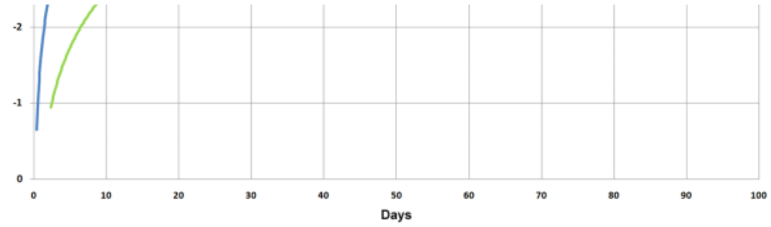
  F6 – K2



- Brightness Range:

of [spectral class](#)
F6 – K2

- Brightness Range:
  few %~a factor 2-3
- radii change
  by (~25% for the
  longer-period l Carinae)
  millions of km.
- are used to determine
  distances to galaxies
  within the Local Group
  and beyond, and are a means
  determininig the Hubble constant.
- have also been used to clarify many characteristics of our galaxy,



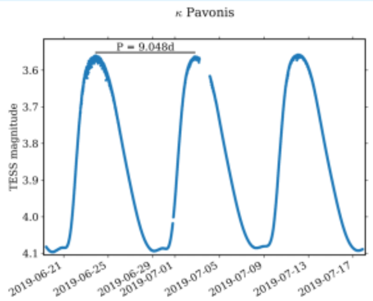
출처: <https://en.wikipedia.org/wiki/Cepheid_variable>

2) **W Virginis variables**

- are a subclass of Type II Cepheids
- pulsation periods between 10–20 days,
- of spectral class F6 – K2.

  출처: <https://en.wikipedia.org/wiki/W_Virginis_variable>

- are old helium shell burning stars
- M < $M_\odot$
- supergiant spectral luminosity classes despite
  their modest masses and actual luminosities,
  because they are highly inflated evolved stars with very low surface gravities.

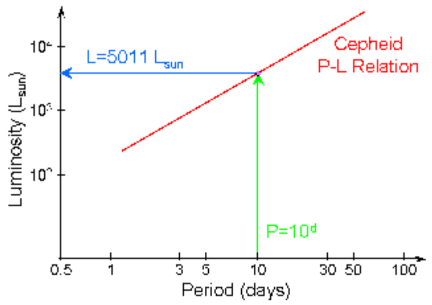


Lightcurve of the W Virginis (Type II Cepheid) variable κ Pavonis recorded by NASA's Transiting Exoplanet Survey Satellite (TESS).

출처: <https://en.wikipedia.org/wiki/W_Virginis_variable>

Method:

- Measure the pulsation period (P)
- Using the P-L relation, read off the Luminosity (L)
- Compute the Luminosity Distance (d_L) from the **Apparent Brightness** and inferred Luminosity.



Distance Limit:

- 30-40 Megaparsecs (Hubble Space Telescope)
- Crucial for measuring distances to galaxies.

Problems:

- No Cepheids with precise parallaxes (a few now have low-quality parallaxes measured by Hipparcos, but are just at the edge of what Hipparcos can do).

Despite the limitations and problems, Cepheid Variable Stars (specifically delta Cephei stars) are one of the most important Standard Candles we use to measure cosmic distances.

RR Lyrae Variables

Rhythmically pulsating Horizontal-Branch stars:

- Found in old clusters, Galactic bulge & halo
- Luminosity of ~50 L_{sun}
- Brightness Range: factor of ~ 2-3
- Period Range: few hours to ~ 1 day.
- Relatives of Cepheid Variables
- This type of low-mass star has consumed the H at its core, evolved and passed through the red giant stage.
- Energy is now being produced by the thermonuclear fusion of He at its core, and the star has entered the horizontal branch (HB).
- The effective temperature of an HB star's outer envelope will gradually increase over time.
- When its resulting stellar classification enters a range known as the instability strip—typically at stellar class A—the outer envelope can begin to pulsate.

Period-Luminosity Relation:

- Less strong than for Cepheids

Method:

- Same as for Cepheids, but using the RR Lyrae P-L Relation to get an estimate of the Luminosity.

Distance Limit:

- ~1 Megaparsec (Hubble)
- Limited to our Galaxy & Andromeda

Problems:

- No RR Lyrae stars with precision parallaxes
- RR Lyrae stars are fainter than Cepheids, so they are only useful as standard candles relatively nearby.

The Cosmic Distance Scale

No single method will provide distances on all cosmic scales. Instead, we have to rely on a multi-step approach that is carefully calibrated at each step.

This makes the Cosmic Distance Scale look like a ladder with a series of steps going from near to far:

- Calibrate Parallaxes using the Astronomical Unit (orbit of the Earth)
- Calibrate H-R diagram methods using stars with measured Parallaxes.
- Calibrate Cepheid and RR Lyrae star distances using H-R diagrams.

Inaccuracy and imprecision at each step carries forward into the next, making each subsequent step less accurate.

Part of the challenge is to understand the sources of these inaccuracies and taking them into account.

출처: <http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit4/cosdist.html>

Satellite galaxies

- The Milky way has
  Several satellite galaxies
  - Large Magellanic Clouds (LMC
  - Small Magellanic Clouds (SMC)

    6th largest in the local group

    with mass of 7.5~8× 10^9 $M_\odot$.
  - etc
  - ∊ the Local Group of galaxies,
    ∊ the Virgo Supercluster,
    ∊ the Laniakea Supercluster.
  - The Milky Way and the LMC are predicted to collide in approximately 2.4 billion years

    출처: <https://en.wikipedia.org/wiki/Large_Magellanic_Cloud>

  - Satellite galaxies that orbit from 1kly (310 pc) of the edge of the disc of the Milky Way Galaxy to the edge of the dark matter halo of the Milky Way at 980kly (300 kpc) from the galaxy center,
    - are generally depleted in hydrogen gas compared to those that orbit more distantly.
    - This is because of their interactions with the dense hot gas halo of the Milky Way that strip cold gas from the satellites.
    - Satellites beyond that region still retain copious quantities of gas.

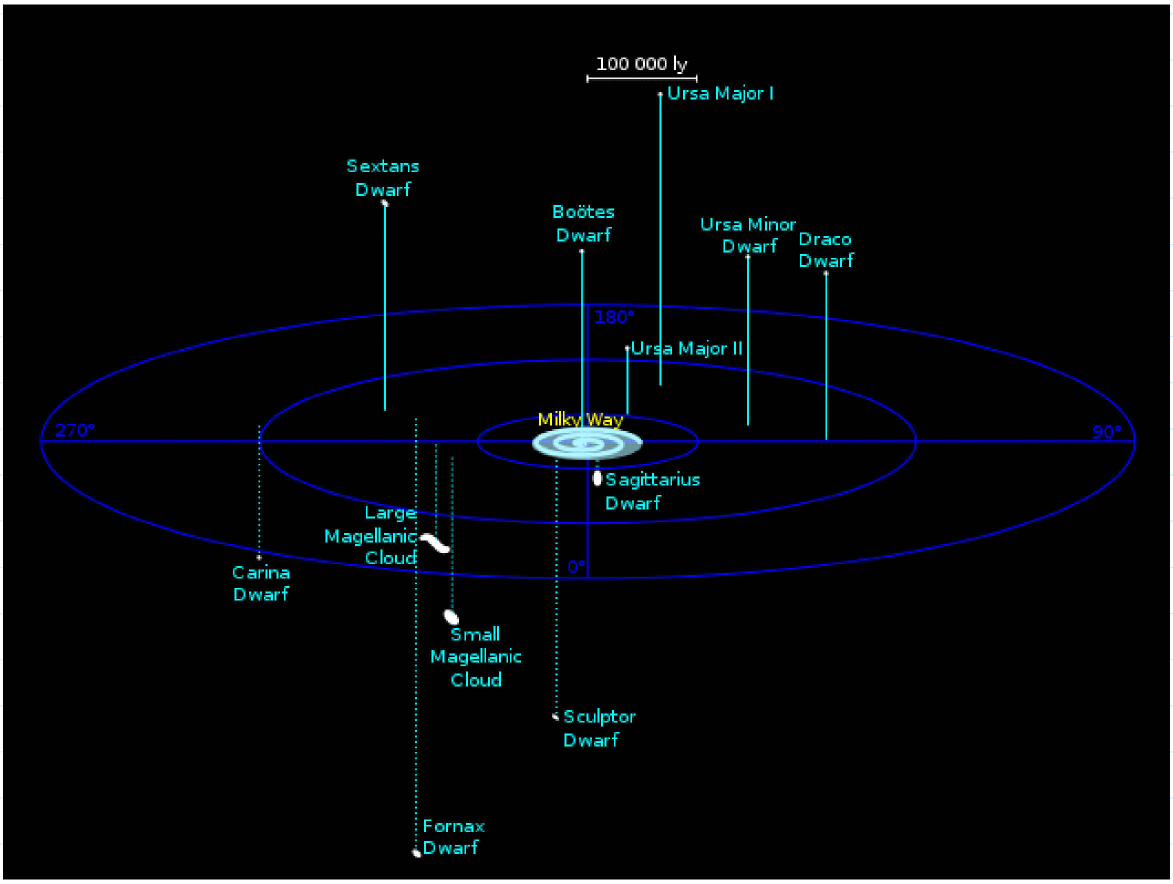
출처: <https://en.wikipedia.org/wiki/Satellite_galaxies_of_the_Milky_Way>

Ex) Large Magellanic Cloud (LMC)

- the 2nd- or 3rd-closest galaxy to the Milky Way, after the Sagittarius Dwarf Spheroidal (~16 kpc) & the possible dwarf irreg gal (the Canis Major Overdensity).
- the 4th-largest galaxy in the Local Group, after the Andromeda Galaxy (M31), the Milky Way, and the Triangulum Galaxy (M33).
- The Milky Way and the LMC are predicted to collide in approximately 2.4 billion years.

출처: <https://en.wikipedia.org/wiki/Large_Magellanic_Cloud>

Milky Way's satellite galaxies



출처: <https://en.wikipedia.org/wiki/Satellite_galaxies_of_the_Milky_Way>

Overview : Structures

Hierarchy of Structure:

Groups: 3 to 30 bright galaxies

Clusters: 30 to 300+ bright galaxies

Superclusters: Clusters of Clusters

Voids, Filaments, & Walls

	Size(Mpc)	# galaxies	Mass	velocity spread	intra cluster medium
Group	**1~2**	**several ≲ #≲50**	**10^{13} $M_\odot$**	**150km/s**	
Local	3	80 ≲ #	2×10^{12} $M_\odot$		
Cluster	**2-3 (1-5)**	**100 ≲ #≲1,000**	**10^{14}–10^{15} $M_\odot$**	**800–1000 km/s**	**T=2–15 keV**
Virgo	3	1,300 ≲ #≲2,000	1.2×10^{15}		
Supercluster					
Walls	200Mpc~3Gpc				

Groups and Clusters of Galaxies

- Galaxies do not exist in isolation.

- A **galaxy group** or **group of galaxies** (**GrG**)
  - the smallest aggregates of galaxies, typically several ≲# galaxies ≲50
  - 1 ≲diameter≲2 Mpc. gravitationally bound

- mass ≈ 10^{13} $M_{\odot}$.
- The spread of velocities for the individual galaxies ≈ 150 km/s.
- the most common structures, comprising at least 50% of the galaxies.

출처: <https://en.wikipedia.org/wiki/Galaxy_group>

- **galaxy clusters** :

  collections of galaxies larger than groups, .

  A **galaxy cluster**, or **cluster of galaxies**,
  - (100 ≲) # galaxies ≲1,000
  - (1~)2 ≲diameter≲3(*or* 5) Mpc, .
  - 10^{14}≲ mass ≲10^{15} $M_{\odot}$,
  - They are the largest structure bound under gravity
  - were believed to be the largest known structures in the universe until the 1980s, when superclusters were discovered.
  - The intracluster medium (ICM) between the galaxies
  - consists of hot X-ray emitting gas with T between 2–15 keV, and large amounts of dark matter.
  - The ICM is composed primarily of ordinary baryons, mainly ionised hydrogen and helium. Due to the gravitational field of clusters, metal-enriched gas ejected from supernovae remains gravitationally bound to the cluster as part of the ICM.
  - Roughly 10% of a galaxy cluster's mass resides in the ICM. The stars and galaxies may contribute only 1% to the total mass.
  - 90% consists of dark matter and not baryonic matter.
  - Density ~ 10^{-3} particles/cm^3. The mean free path of the particles is roughly 10^{16} m, or about one lightyear.

    출처: <https://en.wikipedia.org/wiki/Intracluster_medium>
  - The spread of velocities for the individual galaxies is about 800–1000 km/s.
  - Notable galaxy clusters in the relatively nearby Universe include the Virgo Cluster, Fornax Cluster, Hercules Cluster, and the Coma Cluster.

  출처: <https://en.wikipedia.org/wiki/Galaxy_cluster>

  About 3000 clusters have been cataloged to date.

superclusters of galaxies :

- A **supercluster** consists of groups, clusters and additional isolated galaxies
  - it is among the largest known structures of the universe.
  - they, unlike clusters, expand with the Hubble expansion (The large size & low density)
  - The number of superclusters in the observable universe is estimated to be 10 million.

- "filaments", "supercluster complexes", "walls" or "sheets", voids
  - Superclusters form massive structures of galaxies, called "filaments", "supercluster complexes", "walls" or "sheets",
  - may spanning several x100 Mly ~ 10 Gly, covering more than 5% of the observable universe.
  - Interspersed among superclusters are large voids of space where few galaxies exist.

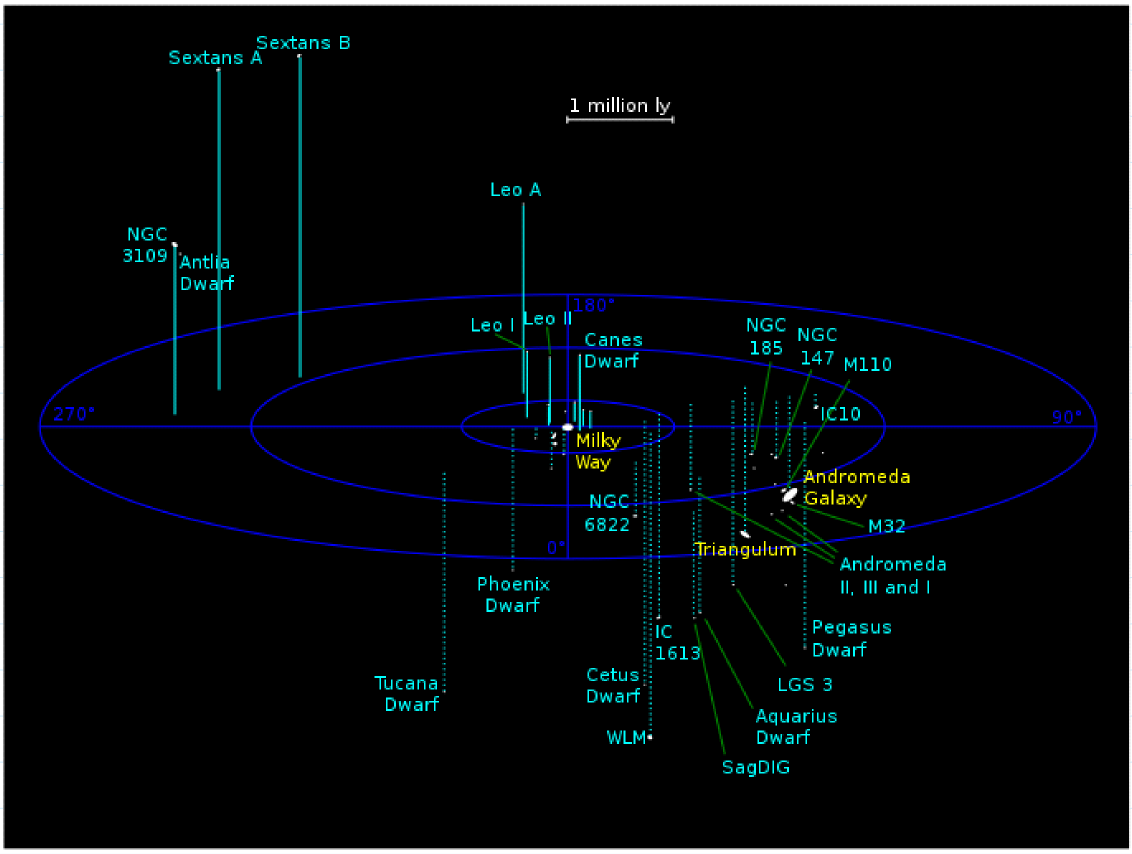
    Ex) The Milky Way ∊ the Local Group ∊ the Virgo Supercluster ∊ the Laniakea Supercluster.

출처: <https://en.wikipedia.org/wiki/Supercluster>

Examples)

The **Local Group** is the galaxy group that includes the Milky Way.

- diameter ~1 Mpc,
- The total # of galaxies : at least 80 (mostly dwarf galaxies).
- a total mass ≈ 2×10^{12} $M_{\odot}$ (4.0×10^{42} kg).
- 5 bright galaxies
  Three Major galaxies :
  the Milky Way, M31(the Andromeda Galaxy), the Triangulum Galaxy(M33)
  The other two :
  LMC, IC10
- a "dumbbell" shape:
  - [the Milky Way (spiral galaxy) & its satellites] : one lobe,
    [the Andromeda Galaxy(M31) (spiral galaxy) & its satellites] : the other.
  - The distance of the two ≈ 0.8 Mpc, moving toward one another with123 km/s.
  - 3 Spirals (MW, M31, & M33)
  - 22 Ellipticals (4 small Es & 18 dEs)
  - 14 Irregulars of various sizes
  - Total Mass ~5×10^{12} M_{sun}



Local Group

출처: <https://en.wikipedia.org/wiki/Local_Group>

- The **Andromeda–Milky Way collision**
  - to occur in about 4.5 billion years. The stars are sufficiently far apart that it will not individually collide. Some stars will be ejected.
  - Galaxy collisions are relatively common.
    - Andromeda, for example, has collided with at least one other galaxy in the past,
    - several dwarf galaxies such as Sgr dSph are currently colliding with and being merged into the Milky Way.
  - M33, the Triangulum Galaxy will participate in the collision ending up orbiting the merger remnant of the Milky Way and Andromeda galaxies and finally to merge with it.

출처: <https://en.wikipedia.org/wiki/Andromeda%E2%80%93Milky_Way_collision>

- The Triangulum Galaxy (**M 33** or **NGC 598**) is the 3rd-largest member.
  - (mass ≈ 5×10^{10} M⊙;spiral galaxy), The distance to M31 is 750kly. Diameter 60kly
  - A close passage 2–4 Gyr ago with M31 triggered star formation across M31's disk.
- The Local Group ∈ the Virgo Supercluster ∈ the Laniakea Supercluster.

출처: <https://en.wikipedia.org/wiki/Local_Group>

The **Virgo Cluster** : a cluster of galaxies

- Nearest sizable cluster to the Local Group
- Relatively loose cluster, centered on 2 bright Ellipticals: M87 & M84

  Properties:

- Distance: ~18 Mpc
- Size: ~ 2 Mpc
- 2500 galaxies (mostly dwarfs); heterogeneous mixture of spiral and elliptical galaxies.
- Mass: ~10^{14} M_{sun}

- The center is 53.8 ± 0.3 Mly (16.5 ± 0.1 Mpc) away
- # galaxies≈ 1300 (up to 2000) ,
- mass ≈1.2×10^{15} M⊙.
- diameter ≈ 4.4 Mpc.
- subtends a maximum arc of ~8°
- at least three separate subclumps: (Virgo A : dominant)

  Virgo A, centered on the giant elliptical M87 (a supermassive BH's event horizon observed (Event Horizon Telescope in 2019)

  a second centered on M86, (M84; M100, etc.)

  Virgo B, centered on M49, - elliptical, the brightest

  Virgo C centered on M60 as well as
- the main cluster of the larger Virgo Supercluster.
- The Local Group experiences the mass of the Virgo Supercluster as the Virgocentric flow (peculiar velocity= 100~400km/s)

출처: <https://en.wikipedia.org/wiki/Virgo_Cluster>

The Coma Cluster of Galaxies (Abell 1656)

- 100 Mpc away, within a few ° of the North Galactic Pole.
- # galaxies ≳1,000
- The radius of the cluster ≈ 1 Mpc
- is much denser than the Local Group

- one of the two major clusters comprising the Coma Supercluster, along with the Leo Cluster (Abell 1367), .
- Its 10 brightest spiral galaxies have apparent mag of 12–14, observable with amateur telescopes larger than 20 cm.
- The central region is dominated by two supergiant elliptical galaxies: NGC 4874 and NGC 4889.

- Most of the galaxies in the central portion are ellipticals.
  Both dwarf and giant ellipticals are found in abundance in the Coma Cluster.

- As is usual for clusters of this richness, the galaxies are overwhelmingly elliptical and S0 galaxies, with only a few spirals of younger age, and many of them probably near the outskirts of the cluster.

Dark matter

- The Coma Cluster is one of the first places where observed gravitational anomalies were considered to be indicative of unobserved mass.
- In 1933 Fritz Zwicky showed that the galaxies of the Coma Cluster were moving too fast for the cluster to be bound together by the visible matter of its galaxies. Though the idea of dark matter would not be accepted for another fifty years, Zwicky wrote that the galaxies must be held together by "...some *dunkle Materie*."[19]
- About 90% of the mass of the Coma cluster is believed to be in the form of dark matter. The distribution of dark matter throughout the cluster, however, is poorly constrained.

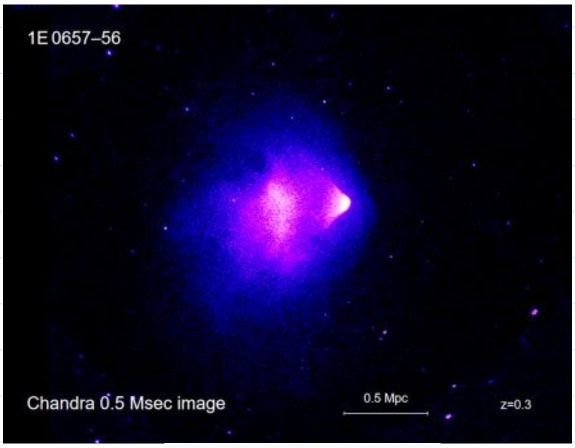
출처: <https://en.wikipedia.org/wiki/Coma_Cluster>

The **Bullet Cluster** (**1E 0657-56**)

- consists of two colliding clusters of galaxies.
  Strictly speaking, the name *Bullet Cluster* refers to the smaller subcluster, moving away from the larger one.
- It is at a comoving radial distance of 1.141 Gpc (3.72 billion light-years).
- Gravitational lensing studies of the Bullet Cluster are claimed to provide the best evidence to date for the existence of dark matter.
- Observations of other galaxy cluster collisions, such as MACS J0025.4-1222, similarly support the existence of dark matter.

Overview

- The major components of the cluster pair—stars, gas and the putative dark matter—behave differently during collision, allowing them to be studied separately.
- The stars of the galaxies, observable in visible light, were not greatly affected by the collision, and most passed right through, gravitationally slowed but not otherwise altered.
- The hot gas of the two colliding components, seen in X-rays, represents most of the baryonic, or "ordinary", matter in the cluster pair. The gases interact electromagnetically, causing the gases of both clusters to slow much more than the stars.
- The third component, the dark matter, was detected indirectly by the gravitational lensing of background objects.
- the lensing is strongest in two separated regions near



X-ray photo by Chandra X-ray Observatory. Exposure time was 140 hours. The scale is shown in megaparsecs. Redshift (*z*) = 0.3, meaning its light has wavelengths stretched by a factor of 1.3.

출처: <https://en.wikipedia.org/wiki/Bullet_Cluster>

Bullet Cluster

Constellation(s)	Carina
Right ascension	$06^h\ 58^m\ 37.9^s$
Declination	−55° 57′ 0″
# of galaxies	~40
Redshift	0.296
거리 (co-moving)	1.141Gpc (3.7Gly).
ICM temperature	17.4 ± 2.5 keV
X-ray luminosity	$1.4 \pm 0.3 \times 10^{39}\ h_{50}^{-2}$ joule/s (bolometric)
X-ray flux	5.6×10^{19} watt/cm^2 (0.1–2.4 keV)
Other designations	
1E 0657-56,	1E 0657-558

objects.

- the lensing is strongest in two separated regions near (possibly coincident with) the visible galaxies. This provides support for the idea that most of the gravitation in the cluster pair is in the form of two regions of dark matter, which bypassed the gas regions during the collision. This accords with predictions of dark matter as only gravitationally interacting, other than weakly interacting.
- The Bullet Cluster is one of the hottest-known clusters of galaxies.
- It provides an observable constraint for cosmological models, which may diverge at temperatures beyond their predicted critical cluster temperature. the subcluster passed through the cluster center 150 million years ago, creating a "bow-shaped shock wave located near the right side of the cluster" formed as "70 MK gas in the sub-cluster plowed through 100MK gas in the main cluster at a speed of about nearly 10 million km/h". The bow shock radiation output is equivalent to the energy of 10 typical quasars.

Significance to dark matter

- The Bullet Cluster provides the best current evidence for the nature of dark matter and provides "evidence against some of the more popular versions of Modified Newtonian dynamics (MOND)" as applied to large galactic clusters.[9] At a statistical significance of 8σ, the spatial offset of the center of the total mass from the center of the baryonic mass peaks cannot be explained with an alteration of the gravitational force law alone.[10]

출처: <https://en.wikipedia.org/wiki/Bullet_Cluster>

Other designations	
1E 0657-56,	1E 0657-558

출처: <https://en.wikipedia.org/wiki/Bullet_Cluster>

Rich Clusters

Contain 1000's of galaxies:

- Extend for 5-10 Mpc
- Masses up to ~10^{15} M_{sun}
- One or more giant Elliptical Galaxies at center.
- Ellipticals found near the center.
- Spirals found at the outskirts.
- 10-20% of their mass is in the form of very hot (10^{7-8}K) intracluster gas seen only at X-ray wavelengths.

Superclusters

Clusters of Clusters

Properties:

- Sizes up to 50 Mpc
- Masses of 10^{15} to 10^{16} M_{sun}
- 90-95% empty space (voids)
- Often long and filamentary in shape

Superclusters are the largest coherent structures seen in the Universe.

The **Virgo Supercluster** (**Virgo SC**) or the **Local Supercluster** (**LSC** or **LS**)

- containing the Virgo Cluster and Local Group.

Local Supercluster (Virgo Supercluster)

centered on the Virgo Cluster

- Size: ~20 Mpc

Supercluster (**LSC** or **LS**)

- containing the Virgo Cluster and Local Group.
- At least 100 galaxy groups and clusters
- within its diameter of 33 Mpc (110 Mly).
- It is thought to contain over 47,000 galaxies.
- The Virgo SC is one of about 10M superclusters in the observable universe
- is in the Pisces–Cetus Supercluster Complex, a galaxy filament.
- the Virgo Supercluster is only a lobe of an even greater supercluster, Laniakea, centered on the Great Attractor.[2]

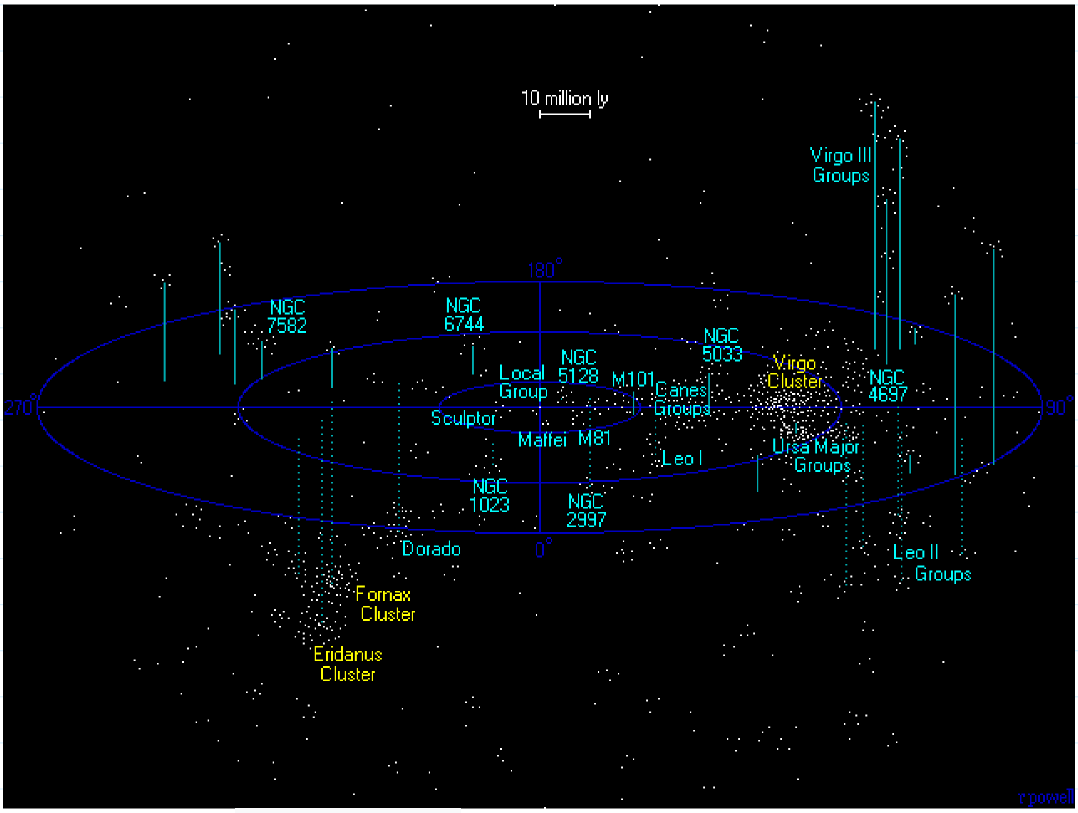
출처: <https://en.wikipedia.org/wiki/Virgo_Supercluster>

Local Supercluster (Virgo Supercluster)

centered on the Virgo Cluster

- Size: ~20 Mpc
- Mass: ~10^{15} M_{sun}
- only ~5% of the volume occupied by galaxies

The Local Group is on the outskirts of the Local Supercluster, and falling into the Virgo Cluster at about 250 km/sec.



The Virgo Supercluster in supergalactic coordinates (click on feature names for more information)

출처: <https://en.wikipedia.org/wiki/Virgo_Supercluster>

The **Coma Supercluster** (**SCl 117**)

- Distance : 300 Mly, a nearby supercluster, located in the constellation Coma Berenices.
- about 20 Mly in diameter, It is roughly spherical,
- is the nearest massive cluster of galaxies to our own Virgo Supercluster.
- comprising the Coma Cluster (Abell 1656) & the Leo Cluster (Abell 1367). contains more than 3,000 galaxies,
- it is in the center of the Great Wall and a part of the Coma Filament.

The **Hydra-Centaurus Supercluster** (**SCl 128**, the **Hydra** and **Centaurus Superclusters**)

- is a supercluster in two parts,
- the closest neighbour of Virgo Supercluster.
- 150 to 200Mly away, several smaller clusters belong to the group.

Hydra-Centaurus

The cluster includes four large galaxy clusters in the Centaurus part

- Abell 3526 (Centaurus Cluster)

contains more than 3,000 galaxies,

- it is in the center of the Great Wall and a part of the Coma Filament.

출처: <https://en.wikipedia.org/wiki/Coma_Supercluster>

- Within the proximity of the Hydra-Centaurus supercluster lies the Great Attractor, dominated by the Norma Cluster (Abell 3627).
  - This massive cluster of galaxies exerts a large gravitational force, causing all matter within 50 Mpc to experience a bulk flow of 600 km/s toward the Norma Cluster[1]

Laniakea[edit]

A 2014 announcement says that the Centaurus Supercluster (Hydra-Centaurus) is just a lobe in a greater supercluster, Laniakea, that is centered on the Great Attractor.

That supercluster would include the Virgo Supercluster, therefore including the Milky Way where Earth resides.[2]

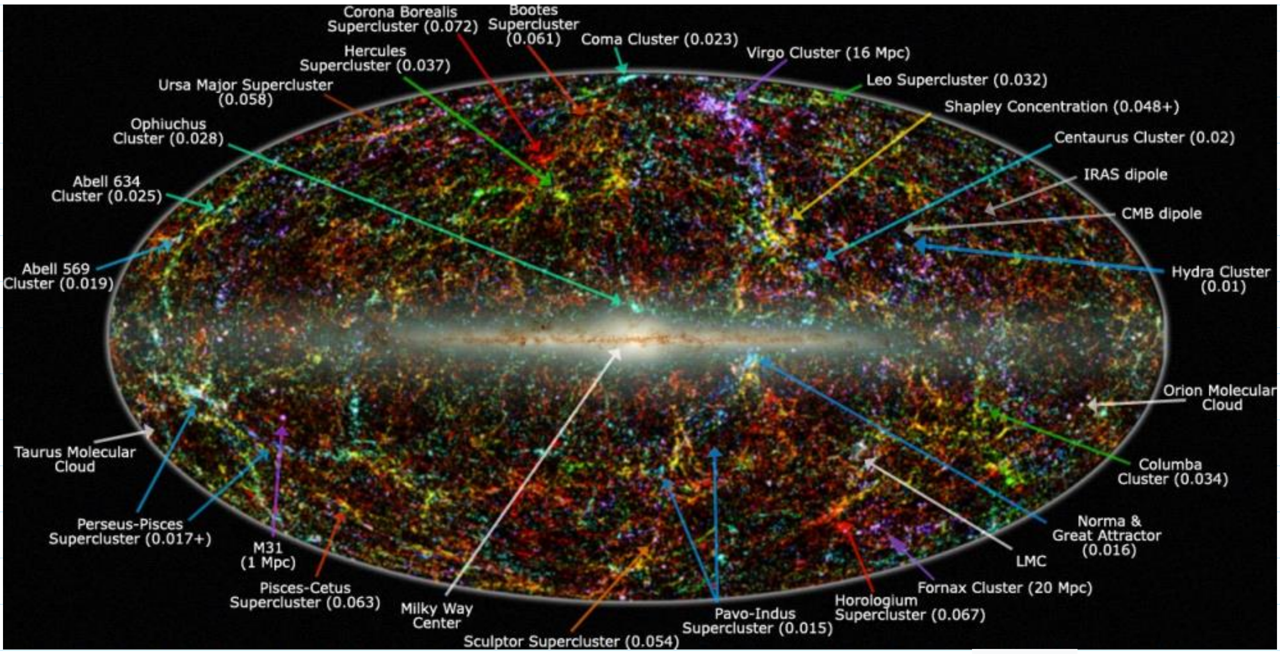
출처: <https://en.wikipedia.org/wiki/Hydra%E2%80%93Centaurus_Supercluster>

The cluster includes four large galaxy clusters in the Centaurus part

- Abell 3526 (Centaurus Cluster)
- Abell 3565
- Abell 3574
- Abell 3581

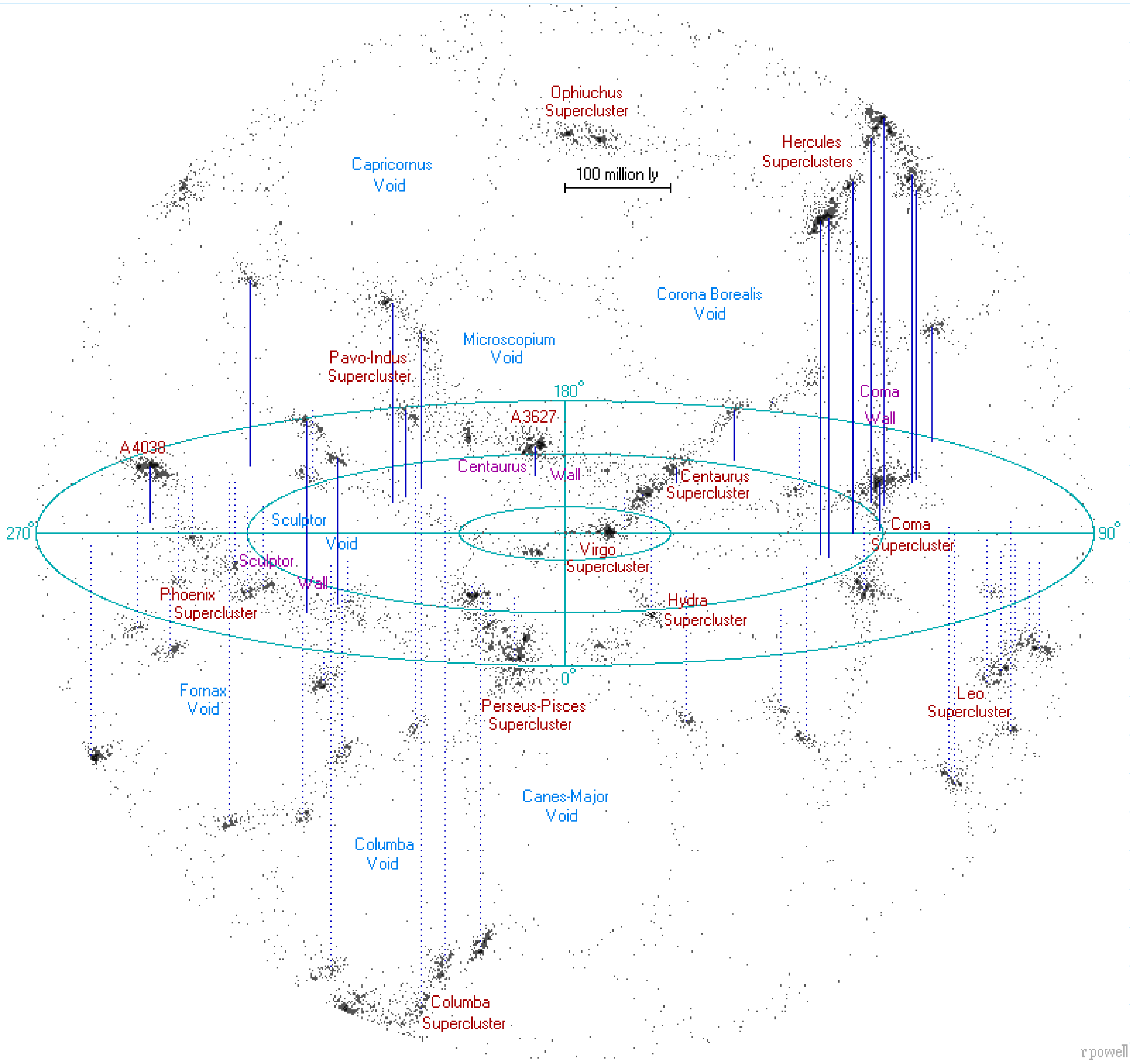
and the proximate

- Hydra Cluster (A1060)
- Antlia Cluster (AS0636)



"Panoramic view of the entire near-infrared sky reveals the distribution of galaxies beyond the Milky Way. The galaxies are color-coded by 'redshift'. Blue are the nearest sources (z < 0.01); green are at moderate distances (0.01 < z < 0.04) and red are the most distant sources that 2MASS resolves (0.04 < z < 0.1). "

출처: <https://en.wikipedia.org/wiki/Observable_universe#Large-scale_structure>



the CfA2 Great Wall ~ Hercules Superclusters + Coma Supercluster + Leo Supercluster

The **Great Attractor**

- is a gravitational anomaly in intergalactic space and
- the apparent central gravitational point of the Laniakea Supercluster.
- The observed anomalies suggest a localized concentration of mass millions of times more massive than the Milky Way.
- However, it is inconveniently obscured by our own Milky Way's galactic plane, lying behind the Zone of Avoidance (ZOA), so that, in visible light wavelengths, the Great Attractor is difficult to observe directly.

- The anomaly is observable by its effect on the motion of galaxies and their associated clusters over a region of hundreds of Mly across the universe.
- These galaxies are observable above and below the ZOA; all are redshifted in accordance with the Hubble Flow, indicating that they are receding relative to us and to each other, but the variations in their redshifts are large enough and regular enough to reveal that they are slightly drawn towards the anomaly.
- The variations in their redshifts are known as *peculiar velocities*, and cover a range from about +

700 km/s to −700 km/s, depending on the angular deviation from the direction to the Great Attractor.

- The Great Attractor itself is moving towards the Shapley Supercluster.[1]
- a supercluster of galaxies, termed the Vela Supercluster, in the Great Attractor's theorized location.

Location

- It is situated at a distance of somewhere between 150 and 250 Mly (million light-years) (47–79 Mpc) (the larger being the most recent estimate) away from the Milky Way, in the direction of the constellations Triangulum Australe (The Southern Triangle) and Norma (The Carpenter's Square).
- While objects in that direction lie in the Zone of Avoidance difficult to study with visible wavelengths, X-ray observations have revealed that the region of space is dominated by the Norma Cluster (ACO 3627), a massive cluster of galaxies containing a preponderance of large, old galaxies, many of which are colliding with their neighbours and radiating large amounts of radio waves.

Debate over apparent mass

the Great Attractor was actually only one tenth the mass that scientists had originally estimated.
The survey also confirmed earlier theories that the Milky Way galaxy is in fact being pulled towards a much more massive cluster of galaxies near the Shapley Supercluster, which lies beyond the Great Attractor, and which is called the Shapley Attractor.

Laniakea Supercluster[edit]

The proposed Laniakea Supercluster is defined as the Great Attractor's basin, encompassing the former superclusters of Virgo and Hydra-Centaurus. Thus the Great Attractor would be the core of the new supercluster.

Vela Supercluster[edit]

In 2016, a multinational team of South African, European and Australian researchers headed by South African astronomer Renée C. Kraan-Korteweg announced the discovery of a supercluster of galaxies that would largely explain the mysterious Great Attractor. Astronomers detected a region of galactic overdensity consistent with the "supercluster" designation, which provides the requisite explanation for a gravitational anomaly in the Shapley Supercluster neighborhood where the Great Attractor was theorized to be located.

출처: <https://en.wikipedia.org/wiki/Great_Attractor>

Voids, Filaments & Walls

The Universe looks foamy on large scales

Filaments:

- Vast chains of superclusters
- Occupy ~10% of the Universe

Voids: Empty bubbles

- 25-50 Mpc in diameter
- 5-10x fewer galaxies than in superclusters

Map of the Local Universe

The "Great Wall"

Found in a large-scale galaxy survey.

Sheet of superclusters:

- 150 Mpc long
- 60 Mpc "high"
- 5 Mpc thick

Mass is ~2×10^{16} M_{sun}

One of the largest structures known.

Implications

The existence of "Large Scale Structure" tells us something about how galaxies formed.

- Large structures sculpted by gravity
- Concentrations of matter where galaxies form

(Representative) Unanswered Questions:

- Why do galaxies form only in particular places?
- How "empty" are the voids?
- Which formed first, galaxies or clusters?

출처: <http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit4/groups.html

The **Perseus–Pegasus Filament**

- is a galaxy filament
- containing the Perseus-Pisces Supercluster
- and stretching for roughly a billion light years (or over 300/h Mpc).
- Currently, it is considered to be one of the largest known structures in the universe.
- This filament is adjacent to the Pisces–Cetus Supercluster Complex.

Contents

Discovery[edit]

- The Perseus–Pegasus Filament was discovered by David Batuski and Jack Burns of New Mexico State University in 1985.
- It is likely that Clyde W. Tombaugh, of the Lowell Observatory, discovered its existence in 1936 while conducting his search for trans-Saturnian planets.
- He reported it as the **Great Perseus-Andromeda stratum of Extra-Galactic Nebulae**.
- Earlier still, parts of this clustering had been reported by Walter E. Bernheimer [de].

See also[edit]

- Abell catalogue
- Large-scale structure of the universe
- Supercluster

Notes[edit]

1. ^ The reference cited claims the Perseus-Pisces Filament as the largest known structure in the universe. However, various reports cite the Hercules-Corona Borealis Great Wall as the largest at 10,000,000,000 light-years (3.1×10^9 pc) across.

출처: <https://en.wikipedia.org/wiki/Perseus%E2%80%93Pegasus_Filament>

The **Sloan Great Wall** (**SGW**)

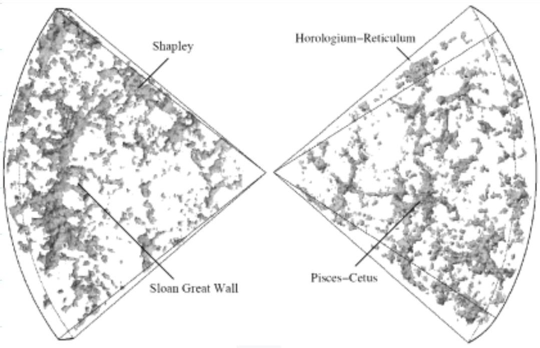
- is a cosmic structure formed by a giant wall of galaxies (a galaxy filament).

- Its discovery was announced from Princeton University on October 20, 2003, by J. Richard Gott III, Mario Jurić, and their colleagues, based on data from the Sloan Digital Sky Survey.

Size

- The wall measures 1.37 billion light-years (1.30×10^{25} m) in length,
- located approximately one billion light-years away.
- In the sky, it is located within the region of the constellations Corvus, Hydra and Centaurus.
- It is approximately 1/60 of the diameter of the observable universe, making it the sixth largest known object after the large quasar groups Clowes–Campusano LQG, U1.11, Huge-LQG, the Giant GRB Ring and the galaxy filament Hercules–Corona Borealis Great Wall (Her-CrB GW), respectively.
- The Sloan Great Wall is between 1.8-2.7 times longer than the CfA2 Great Wall of galaxies (discovered by Margaret Geller and John Huchra of Harvard in 1989).
- It also contains several galactic superclusters, the largest and richest of which is named **SCl 126**. This is located in the highest density region of the structure.
- In 2011, it was suggested that the SGW is a chance alignment of three structures, and not a structure in itself.

출처: <https://en.wikipedia.org/wiki/Sloan_Great_Wall>



The Sloan Great Wall in a DTFE reconstruction of the inner parts of the 2dF Galaxy Redshift Survey

출처: <https://en.wikipedia.org/wiki/Sloan_Great_Wall>