The Big Bang and the Structure of the Universe

I. Big Bang
II. Galaxies and Clusters
III. Milky Way Galaxy
IV. Stars and Constellations

Andromeda Galaxy — NASA, Hubble Telescope

iMSS Integrated Middle School Science Partnership
NSF
California State University East Bay
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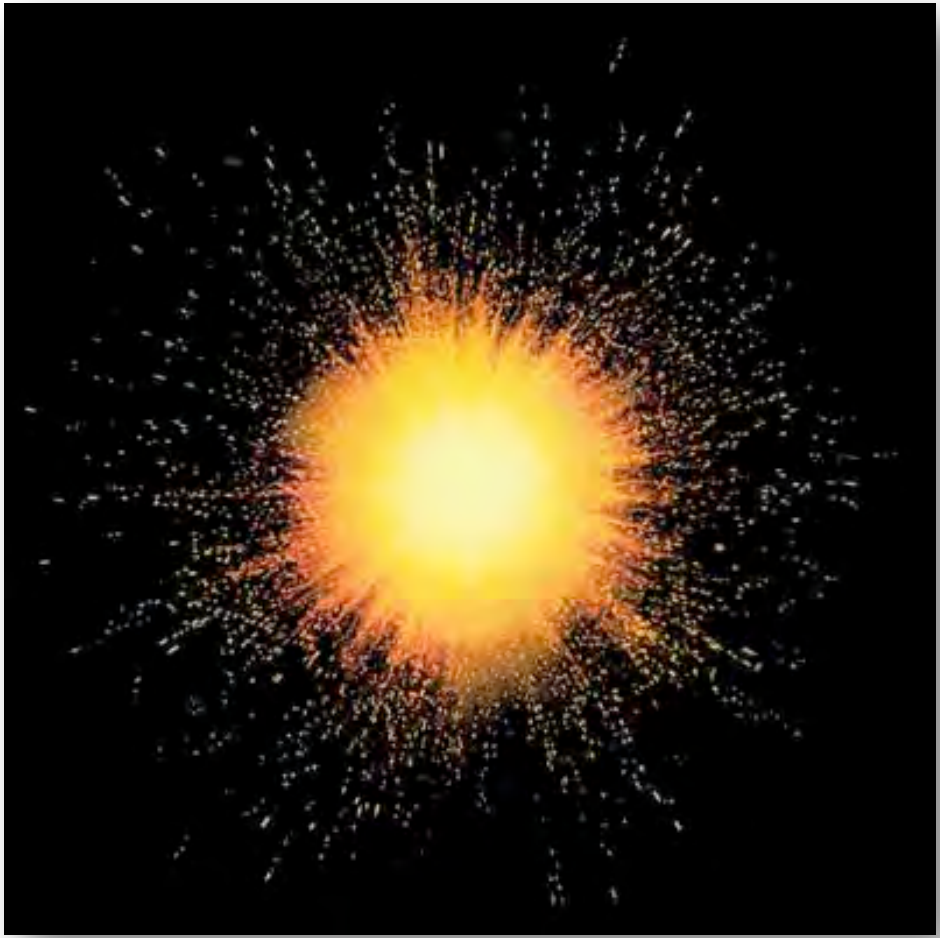
I. The Big Bang and the Origin of the Universe

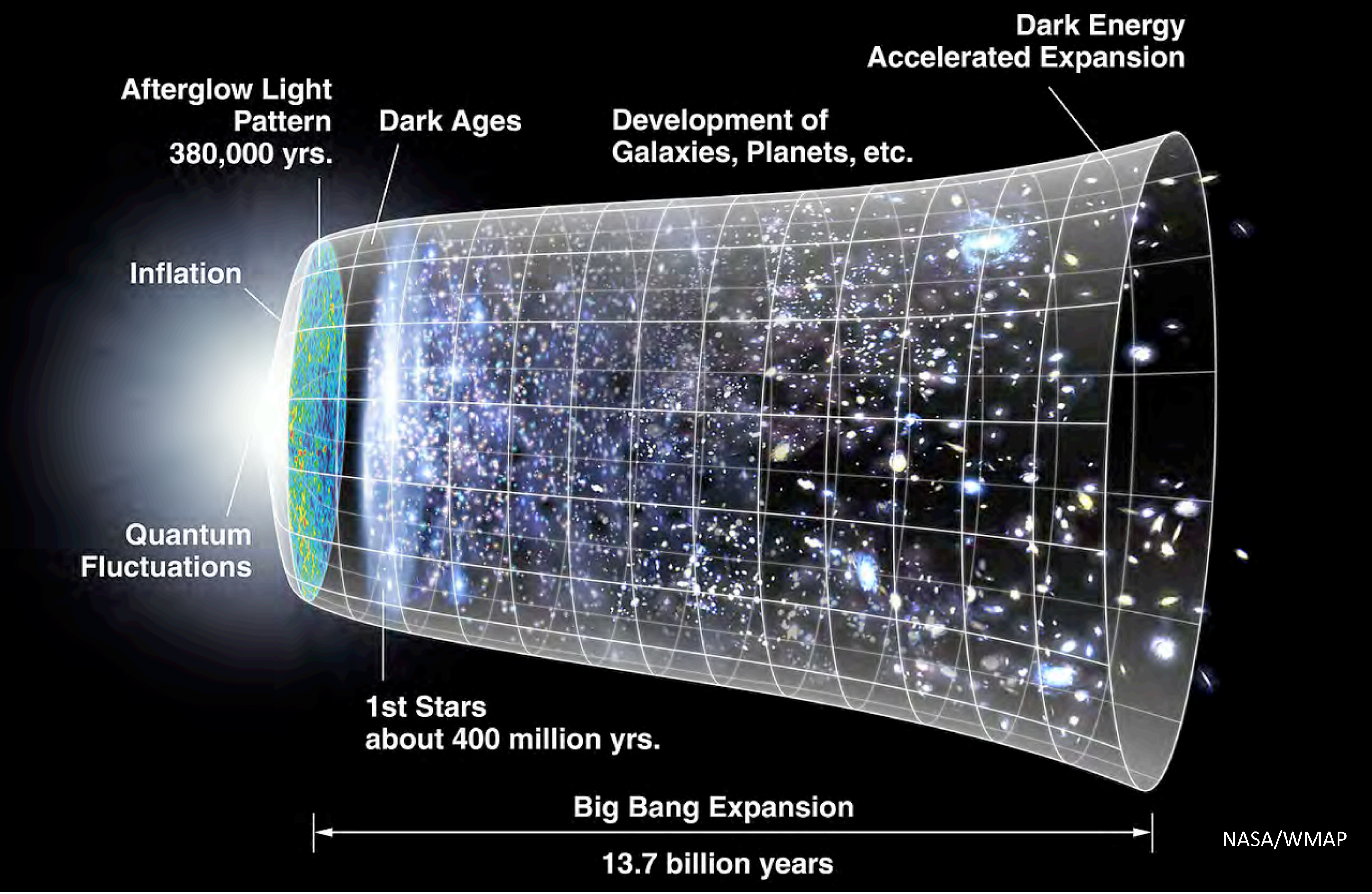


The Big Bang is the prevailing theory for the formation of our universe.

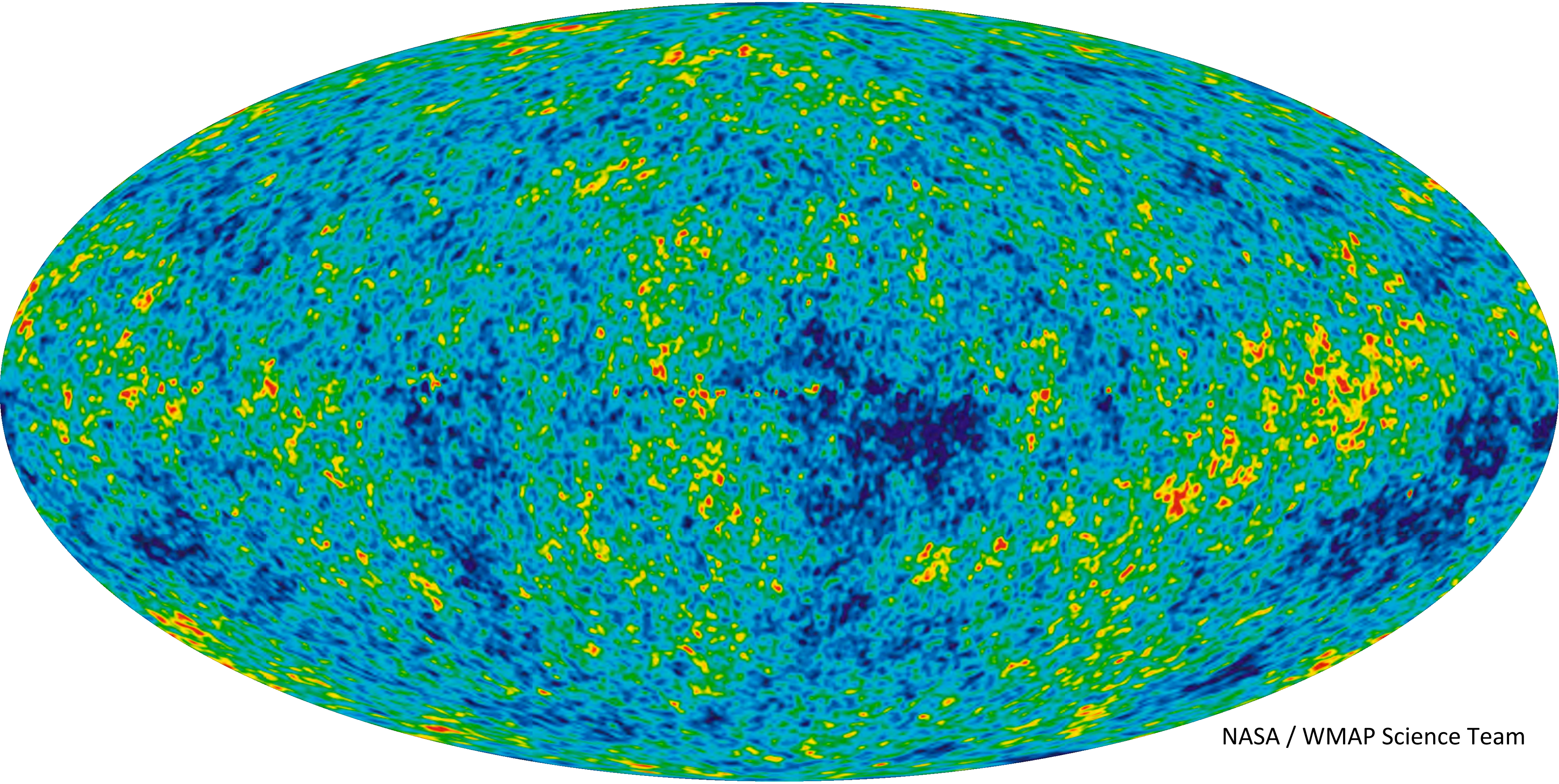
The theory states that the Universe was in a high density state and then began to expand.

The state of the Universe before the expansion is commonly referred to as a *singularity* (a location or state where the properties used to measure gravitational field become infinite).

The best determination of when the Universe initially began to expand (*inflation*) is 13.77 billion years ago.



This is a common artist conception of the expansion and evolution (in time and space) of the Universe.

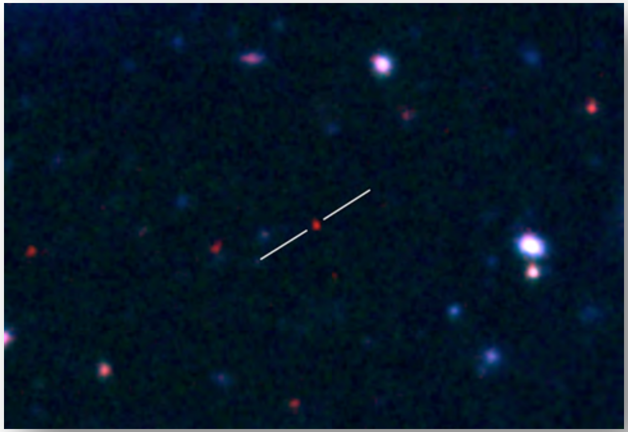


This image shows the cosmic microwave background radiation in our Universe – "echo" of the Big Bang. This is the oldest light in the Universe.
In the microwave portion of the electromagnetic spectrum, this corresponds to a temperature of ~2.7K and is the same in all directions. The temperature is color coded and varies by only ±0.0002K. This radiation represents the thermal radiation left over from the period after the Big Bang when normal matter formed.

One consequence of the expanding Universe and the immense distances is that the further an object, the further back in time you are viewing. Since light travels at a finite speed, the distance to an object indicates how far back in time you are viewing.

For example, it is easy to view the Andromeda galaxy form Earth. The galaxy is 2.5 million light years away and the light that we are viewing took 2.5 million year to get here.

Thus, observing a distant object is the same as looking back in time and provides us with clues about the early evolution of the Universe.

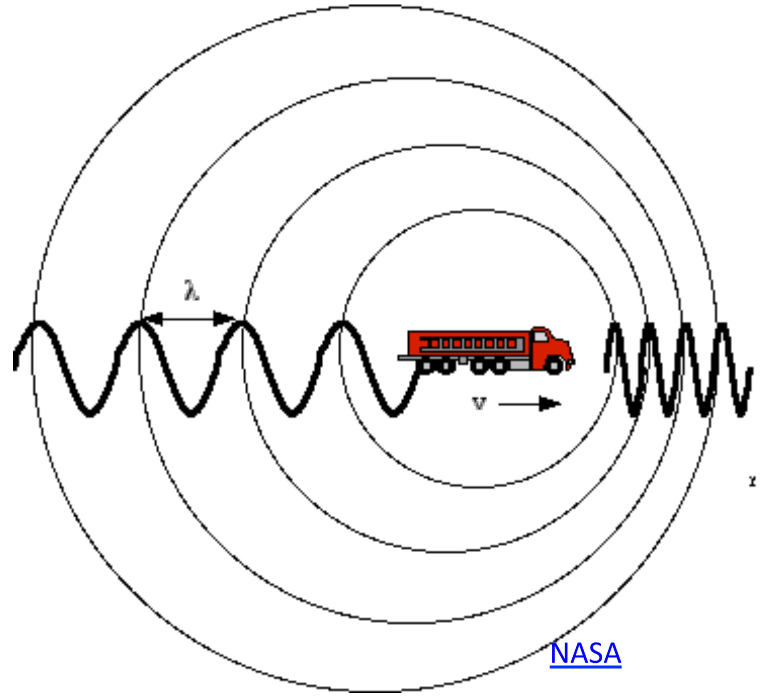


NASA/Swift

The image shows a gamma-ray burst (GRB 090429B) that is the most distant object in the Universe at an estimated distance of 13.14 billion light years. That means that the light that we are observing is 13.14 billion years old.

Doppler Shift

The *Doppler effect* (or *Doppler shift*) is the change in frequency (or wavelength) of a wave when a source (such as a siren) moves relative to an observer.
A common observation is that the tone (pitch) a siren or train whistle changes when the source of the sound moves relative to the observer.



NASA

ClipArtHut

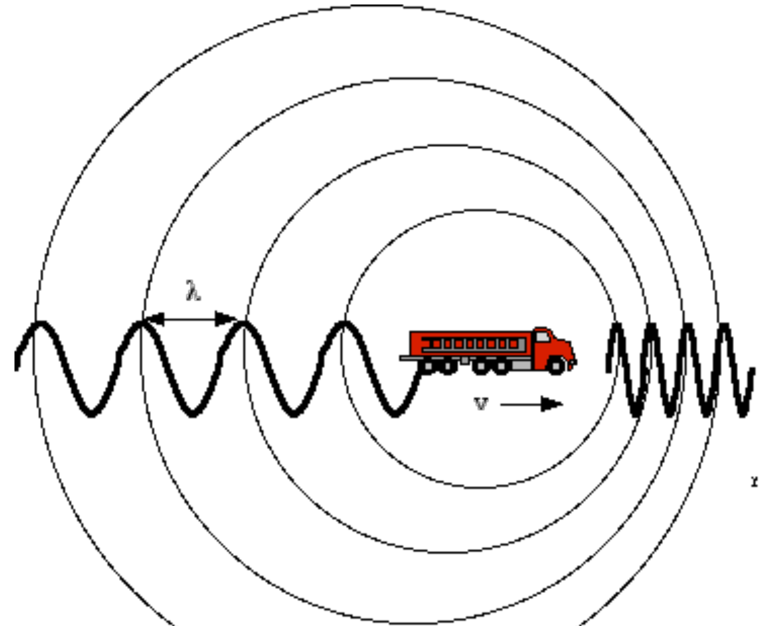
Click the icon to hear a sound file of the doppler shift of siren (arachnoid.com)

If the fire truck is moving toward an observer, the sound is traveling in the same direction as the siren. The sound waves are "compressed" so that the frequency of the sound changes. The wavelength decreases and the siren will have a higher pitch.

If the observer is is behind the fire truck, the truck is moving away and the shift in frequency results in *longer* wavelengths and thus the observer hears a pitch that is lower.

If you were riding on the fire truck, you would hear no change in the pitch of the siren.

ClipArtHut



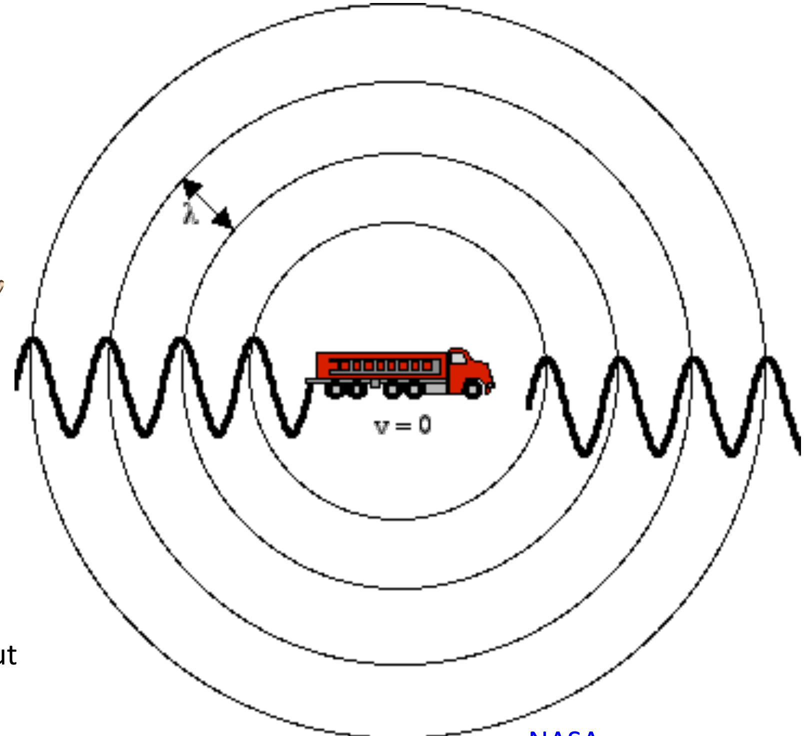
NASA

If you heard a siren or tone that is changing, you could be predict if it is moving toward or away from you:

- If the pitch is increasing (shifting to shorter wavelengths), the source of the sound is moving toward you
- If the pitch is decreasing (shifting to longer wavelengths), the source of the sound is moving away from you

If the fire truck is not moving (v=0), there would be no shift in frequency for stationary observers.

ClipArtHut



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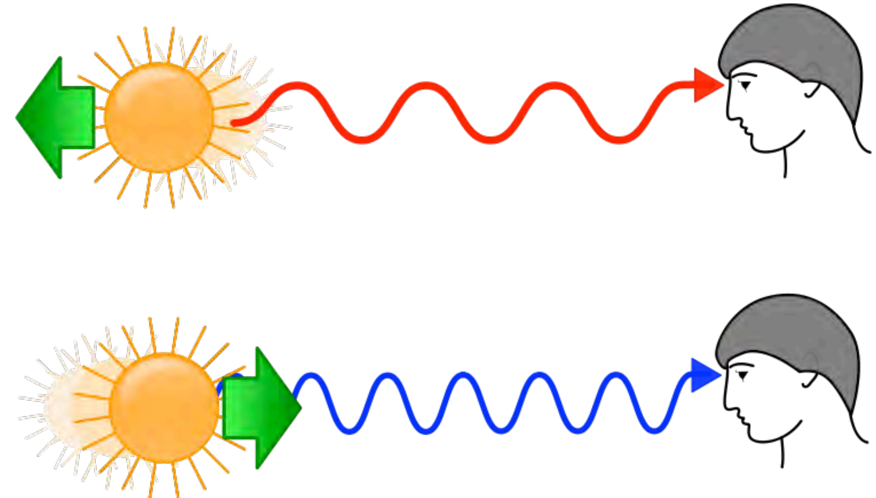
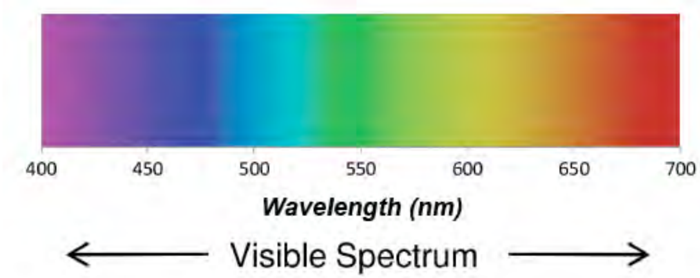
Light is also a wave function and Doppler shifts can be observed in the spectra (light) from stars and galaxies.



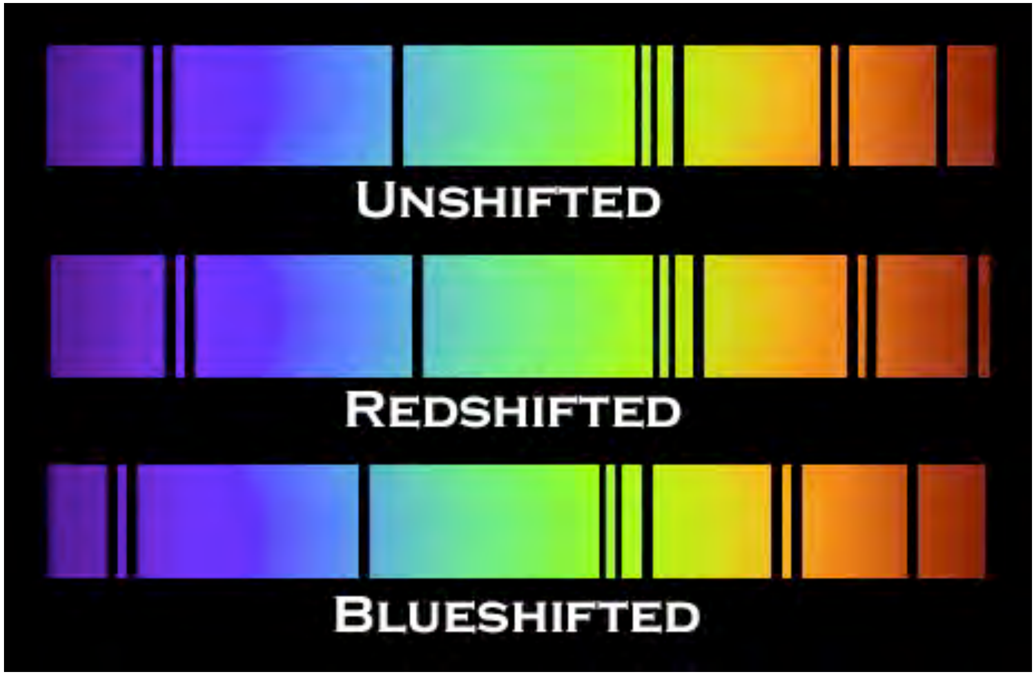
Wikimedia User: Aleš Tošovský

- If a star is moving away from you, it's light will appear to be shifted to longer wavelengths. This is known as *redshift* since red light is at longer wavelengths in the visible portion of the electromagnetic spectrum.



- If a star is moving toward you, it's light will appear to be shifted to shorter wavelengths and is known as *blueshift*. Blue light is at the shorter wavelength portion of visible light.

Objects such as stars that emit spectra (light) with characteristic signatures that may include absorption or emission lines.
In the figure, the dark lines represent absorption by specific elements in or near the source.



MIT

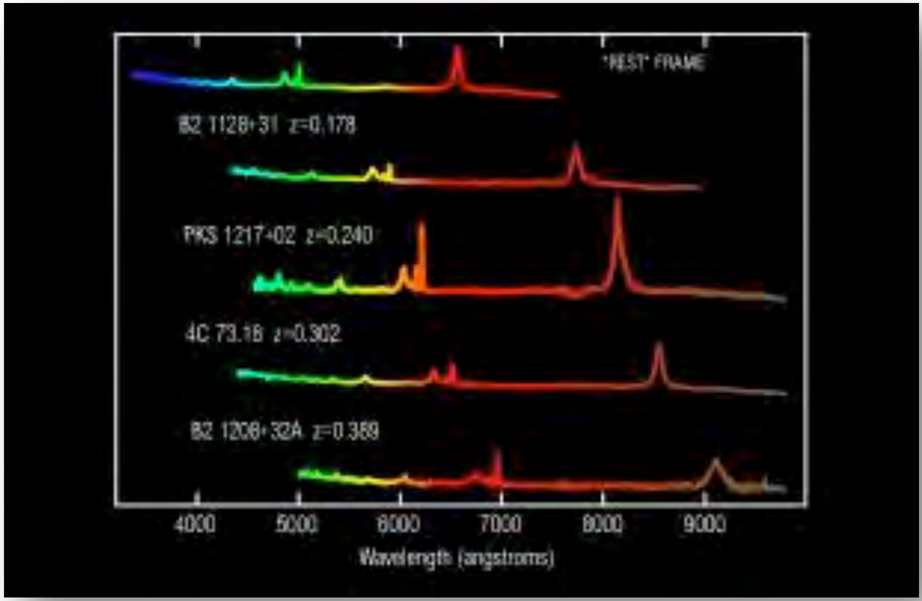
Redshift: note that the absorption lines shift to the longer wavelength (to the red portion) relative to the unshifted spectrum.

Blueshift: note the absorption lines are shifted to shorter wavelengths (toward blue light).

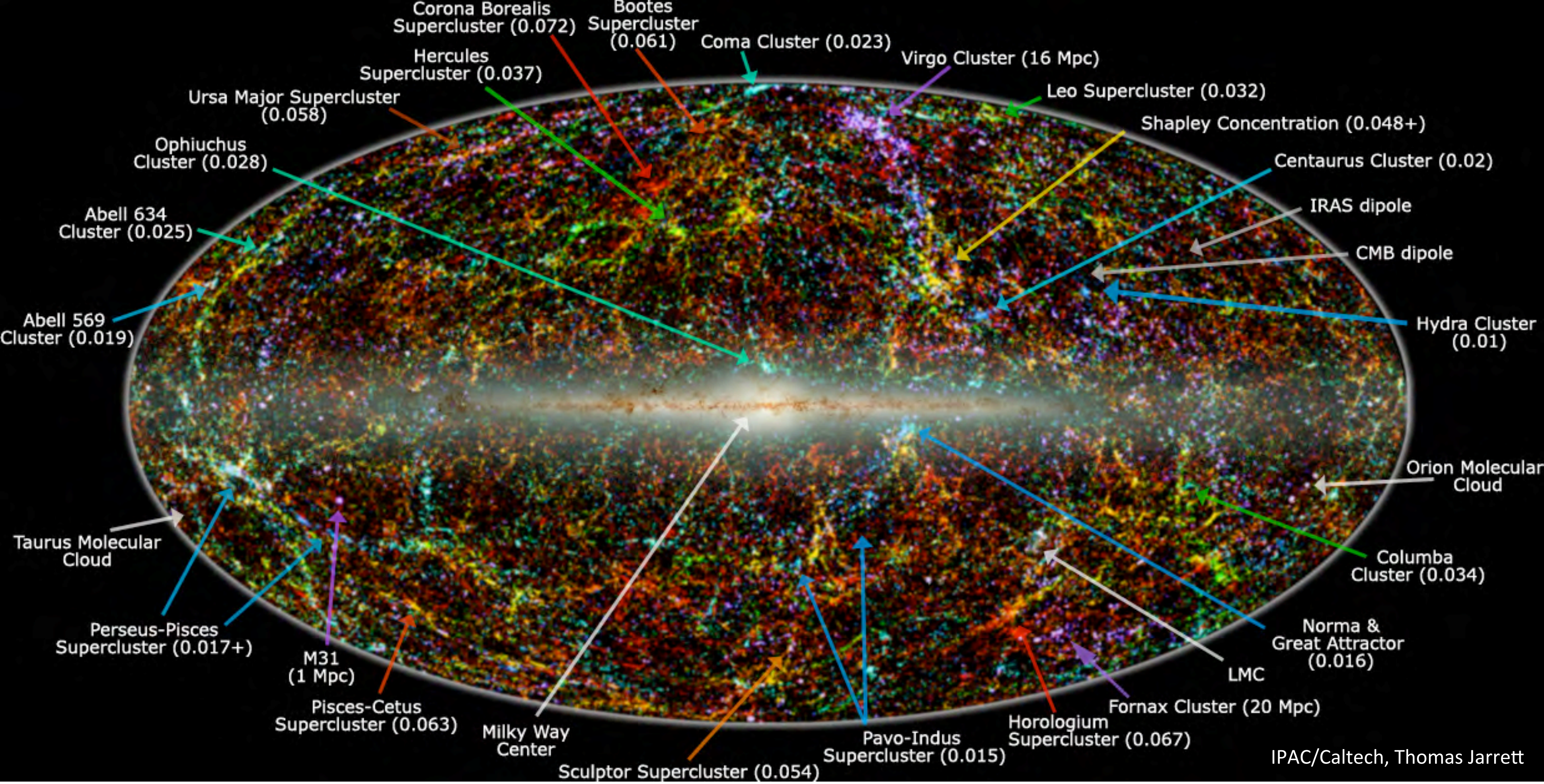
An interesting consequence of the Doppler shift is that the velocity of an object (relative to the observer) can be estimated by the amount of the spectral shift.

The faster that a star is moving away from the observer, the greater the shift toward longer wavelengths.

The figure shows quasi the spectra for 4 different quasi-stellar objects (such as quasars). The top curve shows what the spectra should look like if the objects were not receding (moving away) from Earth. The lower spectra show spectra for objects with progressively greater recession velocities.



National Optical Astronomy Observatory



This figure shows the distribution of >150 million galaxies color coded by redshift (more later). Redshift is a measure of how fast an object is moving away from the observer.

Blue/purple = near objects with lower redshift

Green = objects at moderate distances with intermediate redshift

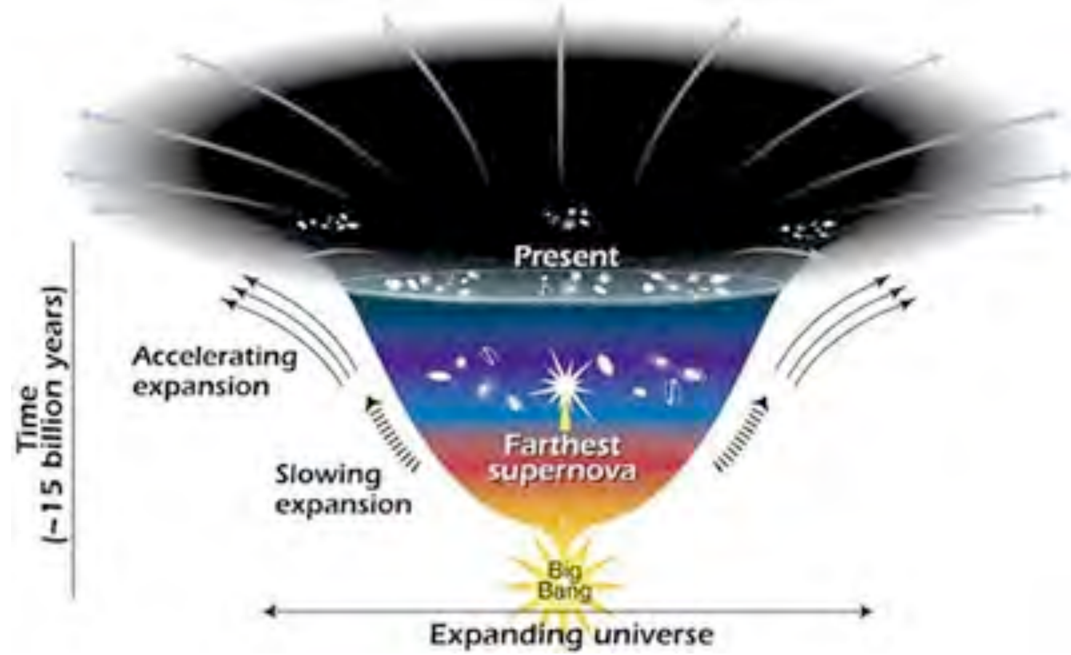
Red = most distant objects with greatest redshift

Bottom line: the Universe is expanding in all directions

Dark Energy

Initially cosmologists expected that the expansion of the Universe would slow down due to gravitation.

However, observations of the most distant objects have indicated that the Universe was actually expanding more slowly in the past than it is today.



NASA/STSci/Ann Feild

Cosmologists have proposed an unknown form of energy known as *dark energy* that permeates space. It is postulated that dark energy is responsible for the increase in the rate of expansion of the Universe.

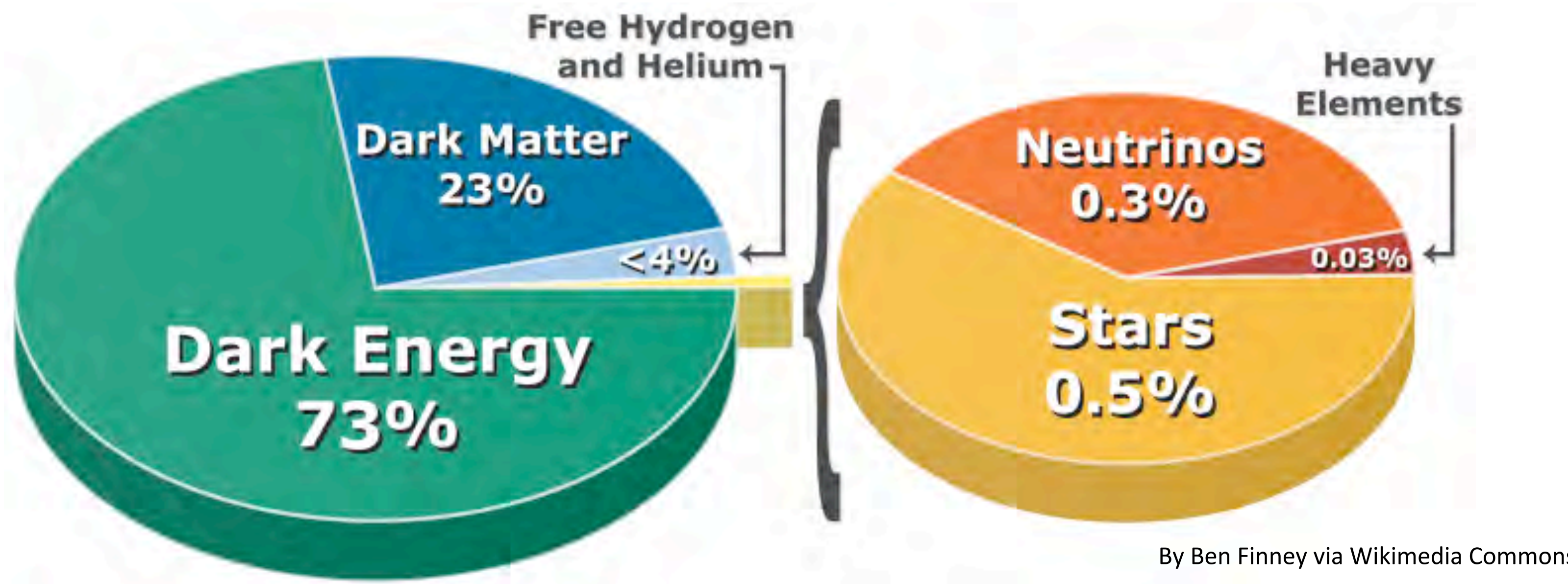
Dark Matter

Analysis of the gravitational interactions of stars and galaxies has led cosmologists to find discrepancies between the mass of the objects determined from their gravitational effects and the mass calculated from the observable matter (stars, gas, and dust) that they can be seen to contain. There does not seem to be enough matter (mass) to account for the observed gravitational interactions.

Cosmologists hypothesize that there is another type of matter that cannot be directly observed – perhaps a type of elementary particle that pervades the universe.

The image shows a galaxy cluster (CL 0024+17) where the blue ring represents dark matter. The presence of dark matter was inferred (not directly observed) from gravitational lensing.

NASA/Hubble



The figures show that ~96% of the Universe is composed of dark energy and dark matter.

- Dark energy is the responsible for the accelerated expansion of the Universe.
- Dark matter is mass in the Universe that directly affects the gravitational interactions between stars and galaxies.

Dark energy and dark energy cannot be directly observed but can be inferred from a variety of observations.

Less than 4% of the Universe is composed of "normal" (baryonic) matter. "Normal" matter is more the exception than the rule.

The Big Bang Theory explains a range of observations about the Universe:

1. Abundance of H and He
2. Cosmic microwave background
3. Observed expansion of the Universe (redshift)
4. The most distant galaxies are receding the fastest

II. Galaxies and Clusters

A galaxy is a gravitationally bound system consisting of stars, stellar remnants, interstellar gas and dark matter.

Galaxies range in size from dwarf galaxies containing a few thousand stars to giants containing more than 100 trillion stars.

The stars in a galaxy orbit around the center of mass for the galaxy.

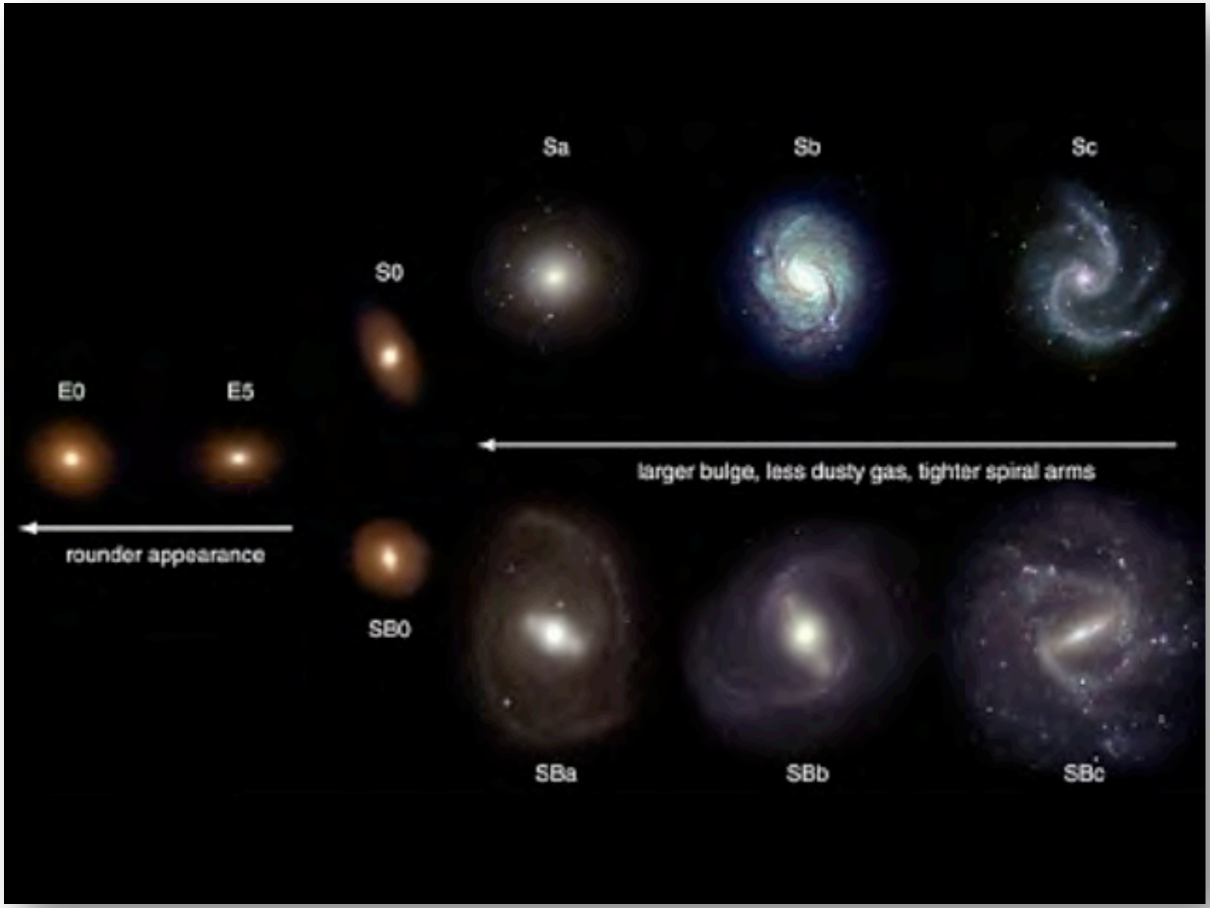
Many galaxies are thought have a massive black hole in its center.

There are ~170 billion galaxies in the observable universe.

The space between galaxies is empty and may contain gas with an average density less than one atom/m^3.

Galaxy Classification

Galaxies show a variety of different morphologies. The Hubble classification scheme is based on the visual appearance.



Keith J. Rowan

Most galaxies fall into one of 3 categories:

- *Elliptical galaxies* (E) appear as smooth featureless ellipses;
- *Lenticular galaxies* (S0) have a bright central bulge and disk-like structure (without spirals);
- *Spiral galaxies* (S) have a central bulge and flatten disk with a spiral arm structure. *Barred spiral galaxies* (SB) are a type of spiral galaxy with two spiral arms.

Galaxies interact with one another where they can collide, merge, or pass through one another.

NASA/Hubble

Galaxy Groups

Galaxies commonly occur in groups or clusters. Solitary galaxies are relatively scare (~5%).

Galaxy groups are the smallest type of association where galaxies are gravitationally bound to one another. Most *galaxy groups* contain less than 50 galaxies.

The image shows a compact galaxy group known as Stephan's quintet. The 4 yellowish galaxies are in the group and the bluish galaxy is closer but not part of this group.

The galaxies in the group have had many interactions in the past and have distorted shapes.

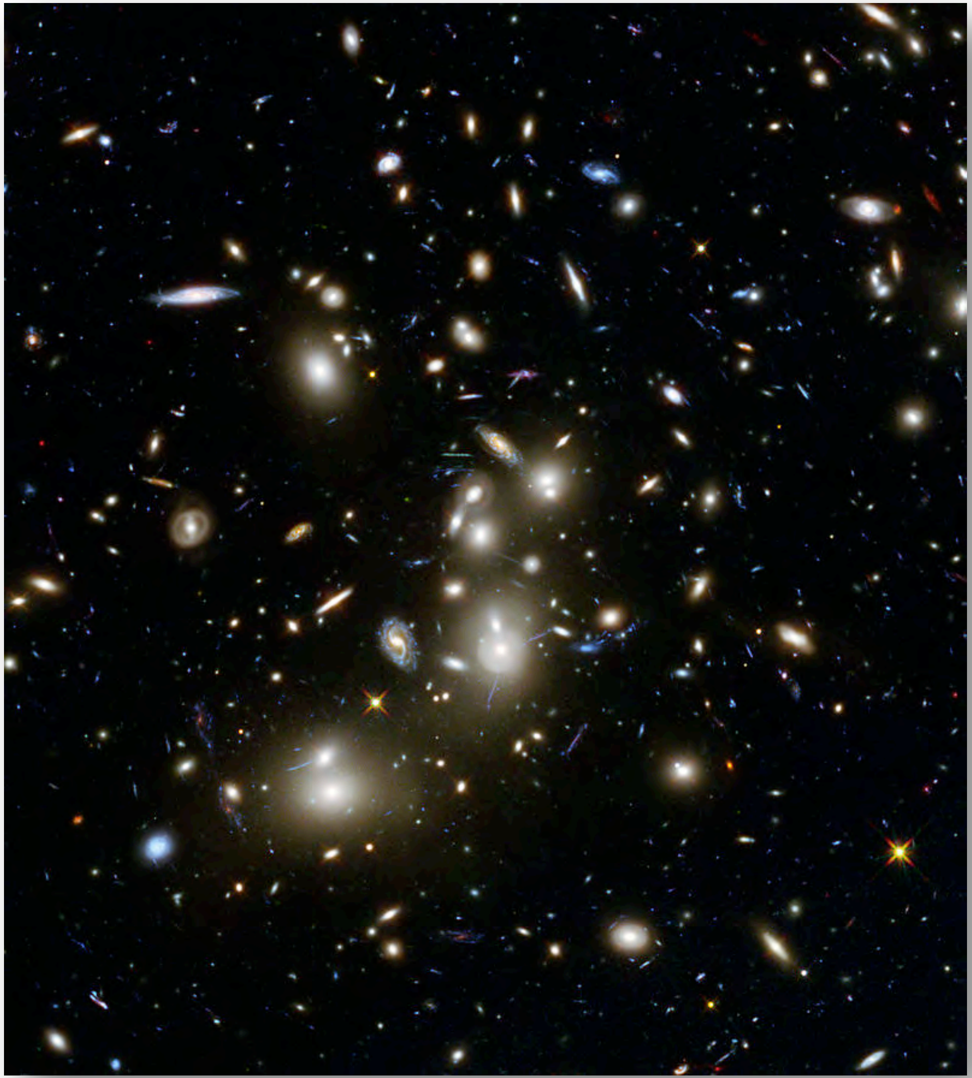
NASA/Hubble

Galaxy Clusters

Galaxy clusters consist of hundreds to thousands of galaxies that are gravitationally interacting

This image is the Abell 2744 cluster (Pandora's Cluster) that resulted from the merging of at least four separate smaller galaxy clusters that took place over a period of ~350 million years.

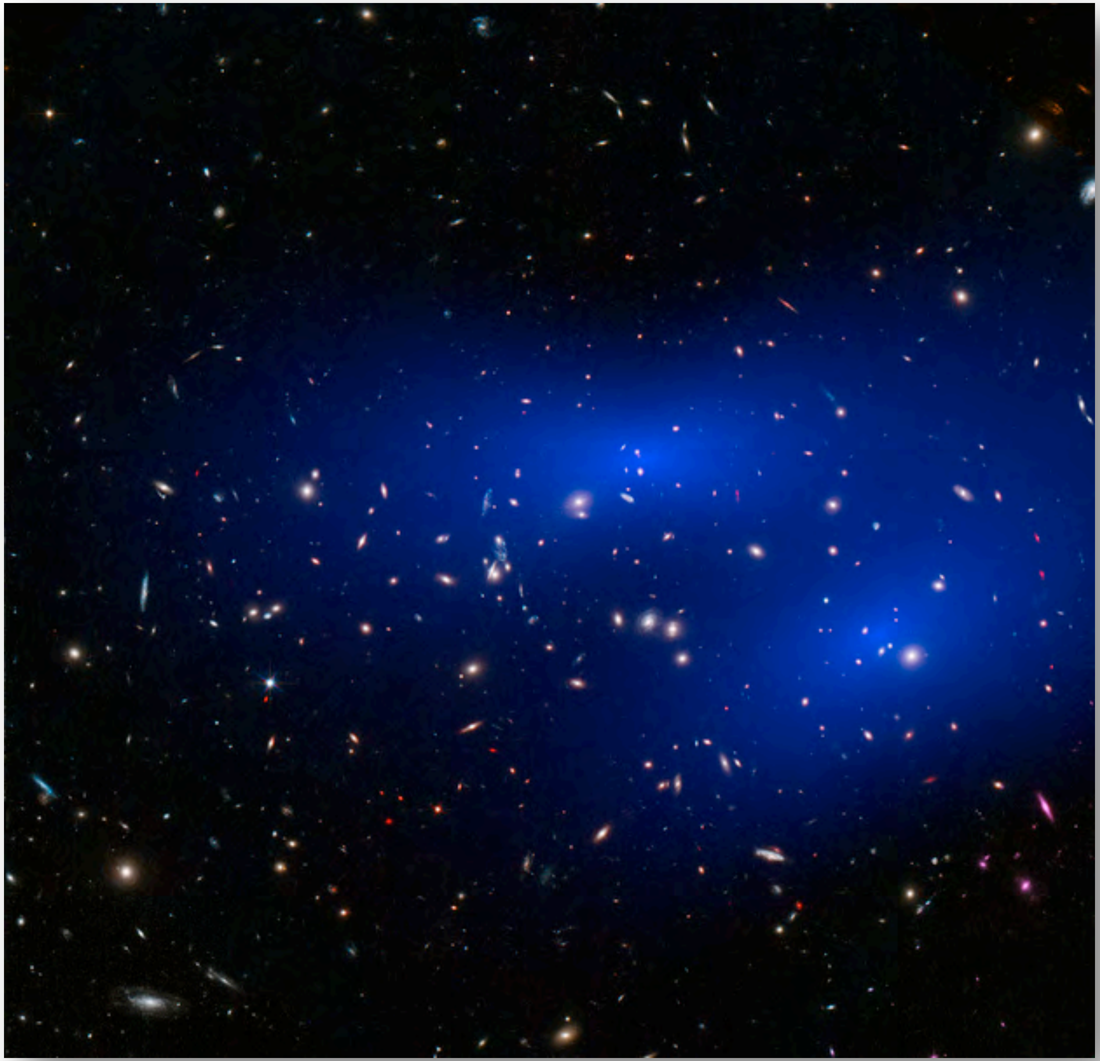
In the cluster, stars make up <5% of the mass and the gases ~20%. Dark matter makes up ~75% of the cluster's mass.



NASA/ESA/HFF

The image shows the massive *galaxy cluster* MACS J0152.5-2852 where nearly every object is a galaxy.

The blue on the image is a map of dark matter inferred from an analysis of the gravitation in the group.



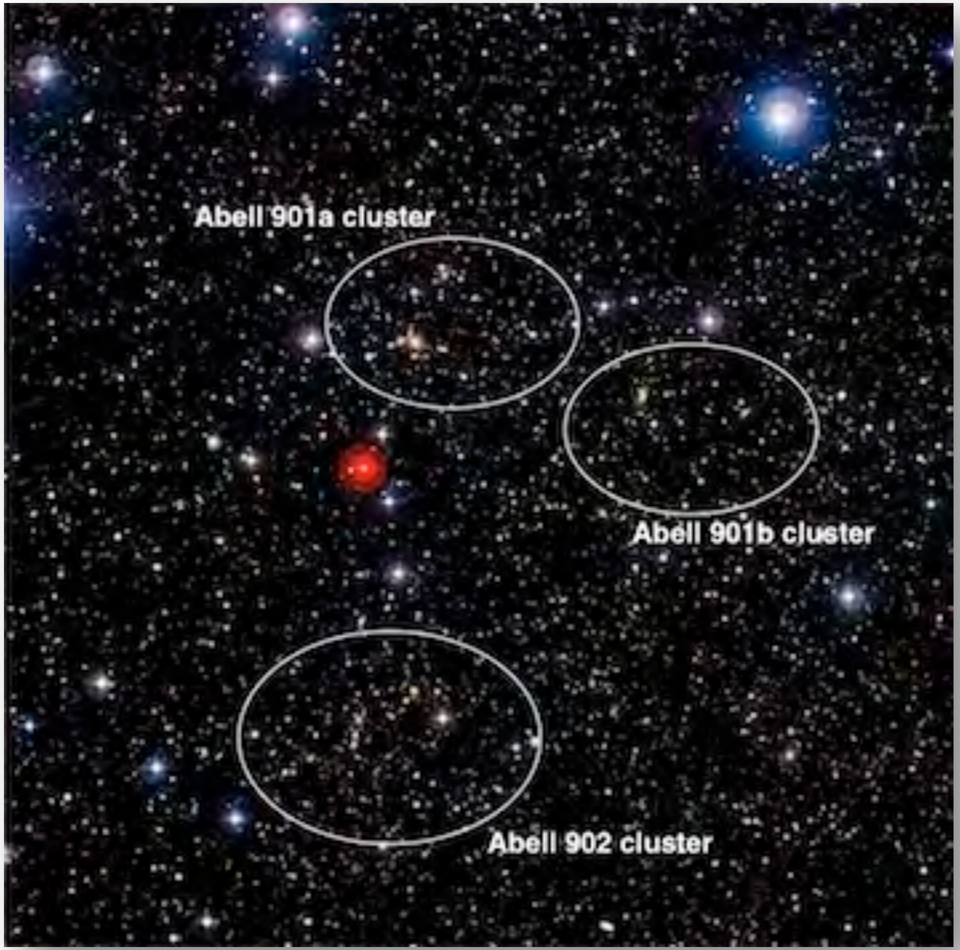
NASA/Hubble/ESA

Galaxy Supercluster

Superclusters are large groups of smaller galaxy clusters and *galaxy groups* and are the largest structures in the Universe.

The image shows the Abell 901/902 supercluster and comprises three separate main galaxy clusters (and filaments of galaxies).

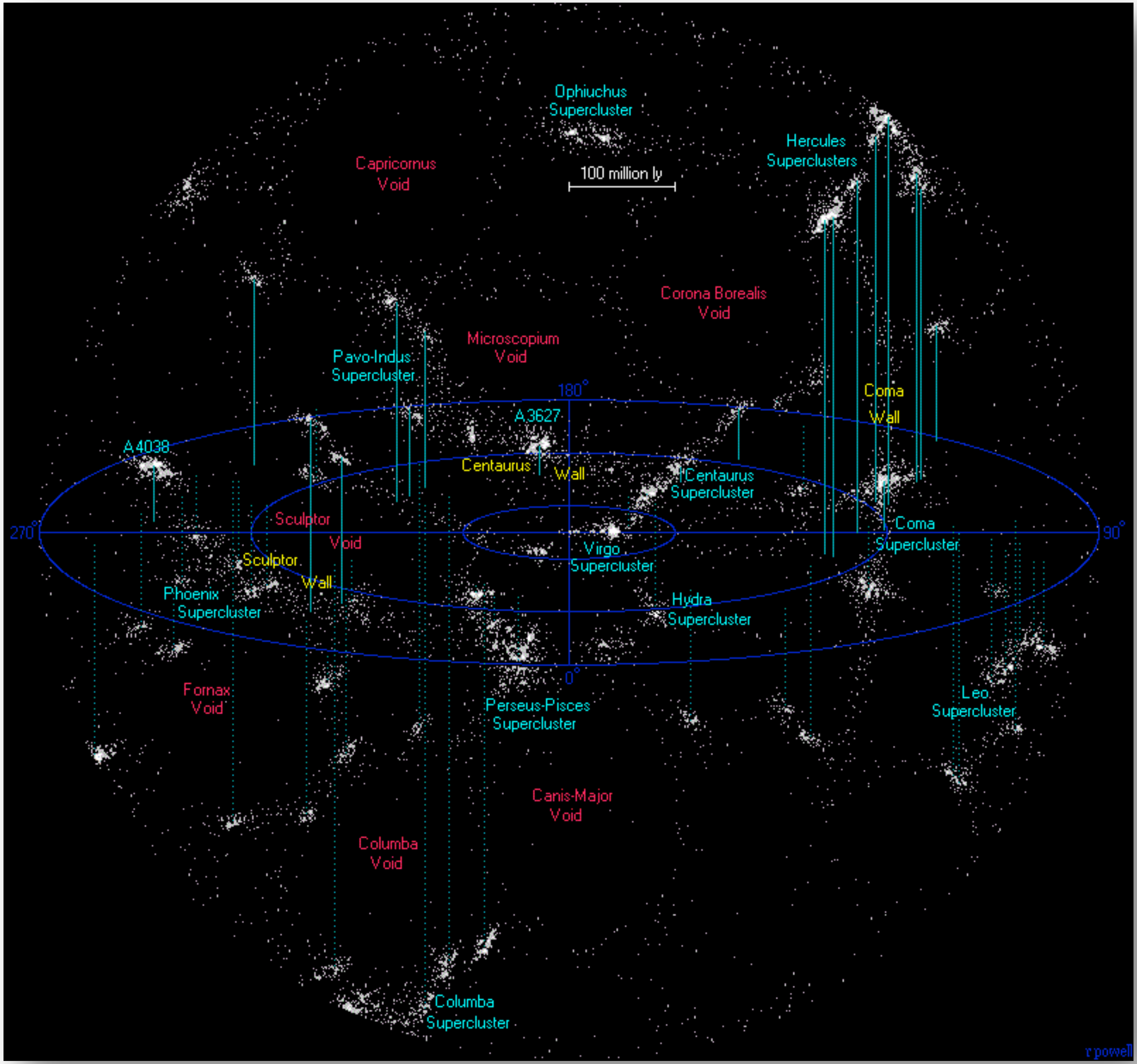
The location



NASA/ESA/Hubble

The image shows a map of voids and superclusters within 500 million light years from the Milky Way.

Clearly, galaxies are not evenly distributed through the Universe.



Richard Powell

III. Milky Way Galaxy

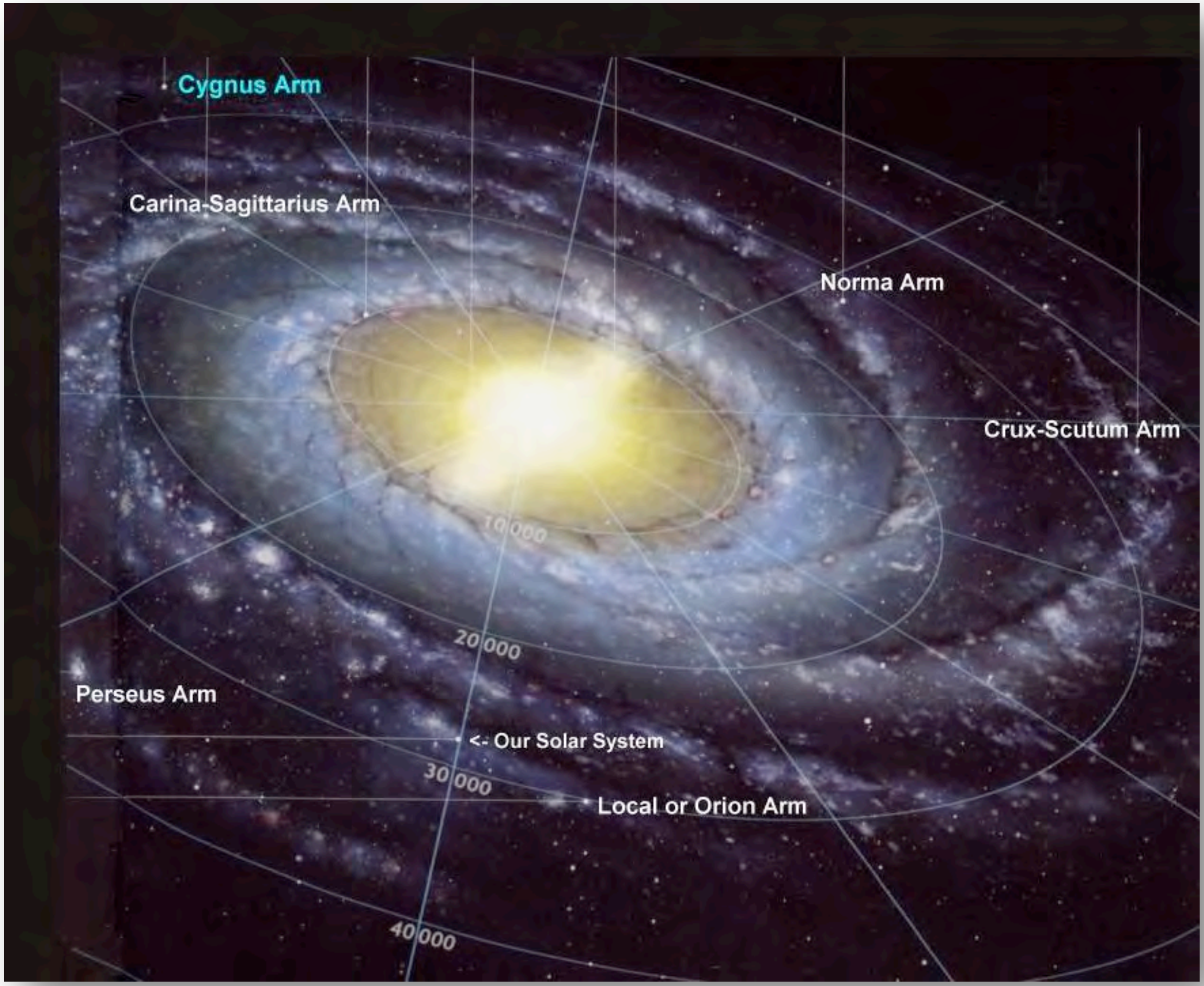
Our solar system is located in the Milky Way galaxy. The Milky Way is a *barred spiral galaxy* that has a diameter ~100,000–120,000 light-years. It is estimated that it may contain 100–400 billion stars, although the number may be as high as one trillion.

ESA

The center of the Milky Way contains an intense radio source, named Sagittarius A*, which is likely to be a supermassive black hole.

The Milky Way rotates around its center and the rotational period is about 240 million years at the position of the Sun.

The Solar System is located within the disk, about 27,000 light-years from the Galactic Center, on the inner edge of one of the spiral-shaped concentrations of gas and dust called the Orion Arm.



Universe Today

IV. Stars and Constellations

Spinelli / NASA

With the unaided eye, we are able to observe only ~9000 individual stars across the entire sky (as seen in every direction).

The nearest star to our solar system is Proxima Centauri; it is 4.2 light years away. Although it is the closest, it is too faint to be observed with the naked eye (red dwarf star that is much fainter than our own Sun).

The most distant star visible to the unaided eye is rho Cassiopeia and is ~8-10 thousand light years away. It it appears as a fairly faint star, but is a supergiant star with a luminosity that is 100,000 times greater than our Sun.

The most distant object that is visible to the naked eye is the Andromeda Galaxy and is 2.5 million light years away.

It is the closest major galaxy to our own Milky Way galaxy.

Andromeda Galaxy NASA

Constellations

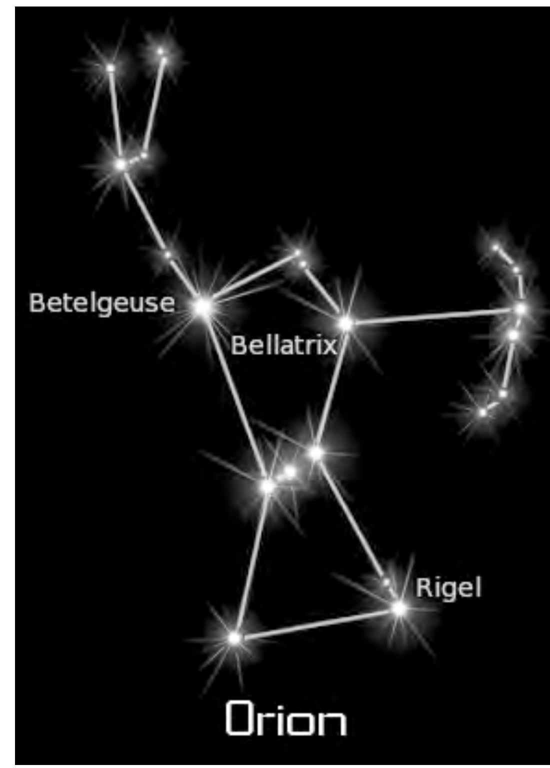
A *constellation* is the arrangement of stars in a specific portion of the sky.

Different cultures through human history have developed different constellations to describe the arrangement of stars in the sky.

There are officially 88 recognized constellations (IAU) that cover the sky as observed from Earth.

The images show the constellation Orion (the Hunter).

wikia



wpclipart

A common and easily recognizable group of stars from the Big Dipper.

However, the Big Dipper is not an official constellation but is part of the constellation Ursa Major.

The Big Dipper is an arrangement of stars known as an *asterism*.

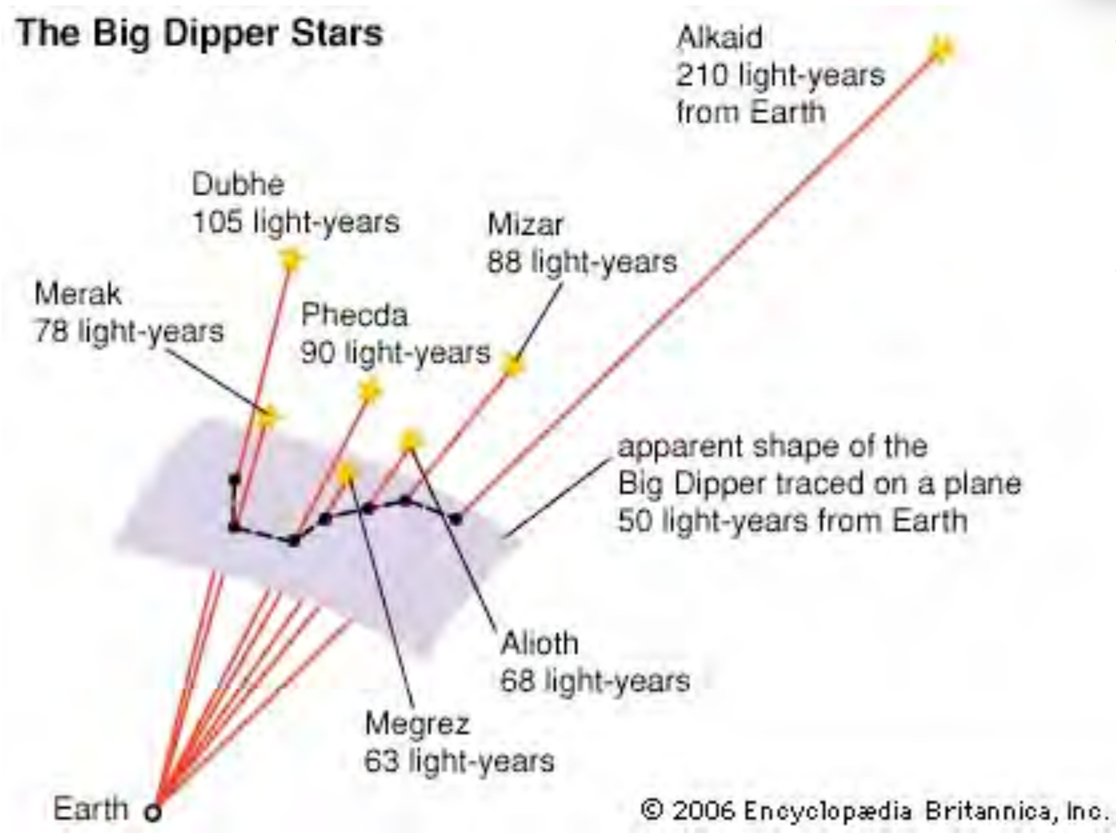
An *asterism* is a prominent pattern of stars with a popular name but are generally smaller than a constellation.

Can you see the Big Dipper in Ursa Major?

flickr User: VincentJames21

Constellations (and asterisms) consist of stars that are unrelated to one another. The configuration of a constellation is based on the apparent positions of stars

flickr User: VincentJames21

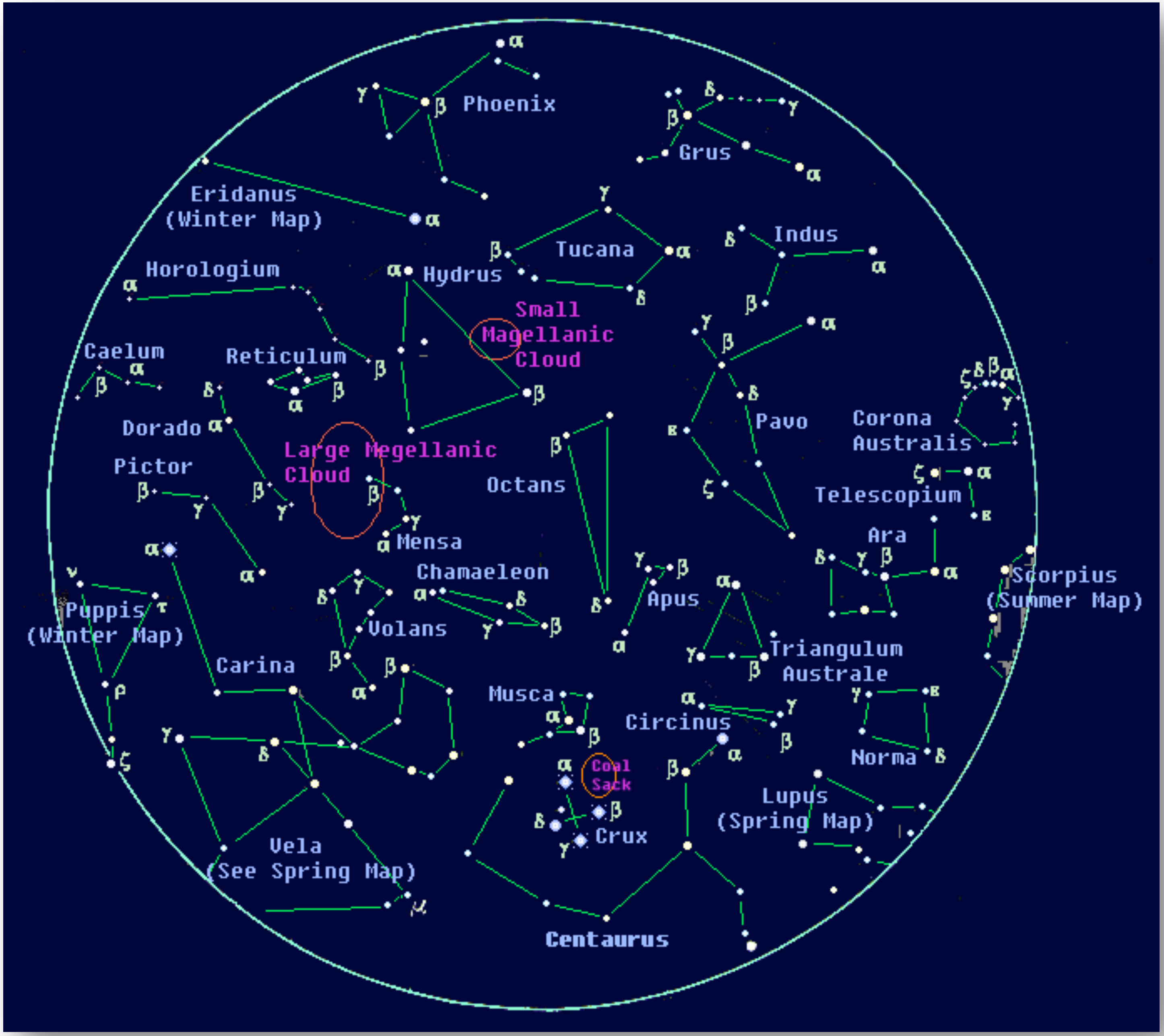


The figure shows the distances of the stars in the Big Dipper from the Earth. The pattern that they form is only from the Earth's perspective. If you observed the same stars from a different part of the galaxy, there would be a different pattern.

This figure shows constellations that are visible in the northern hemisphere.

[starryskies](#)

This figure shows constellations that are visible in the southern hemisphere.



[starryskies](https://www.starryskies.com)

Zodiac

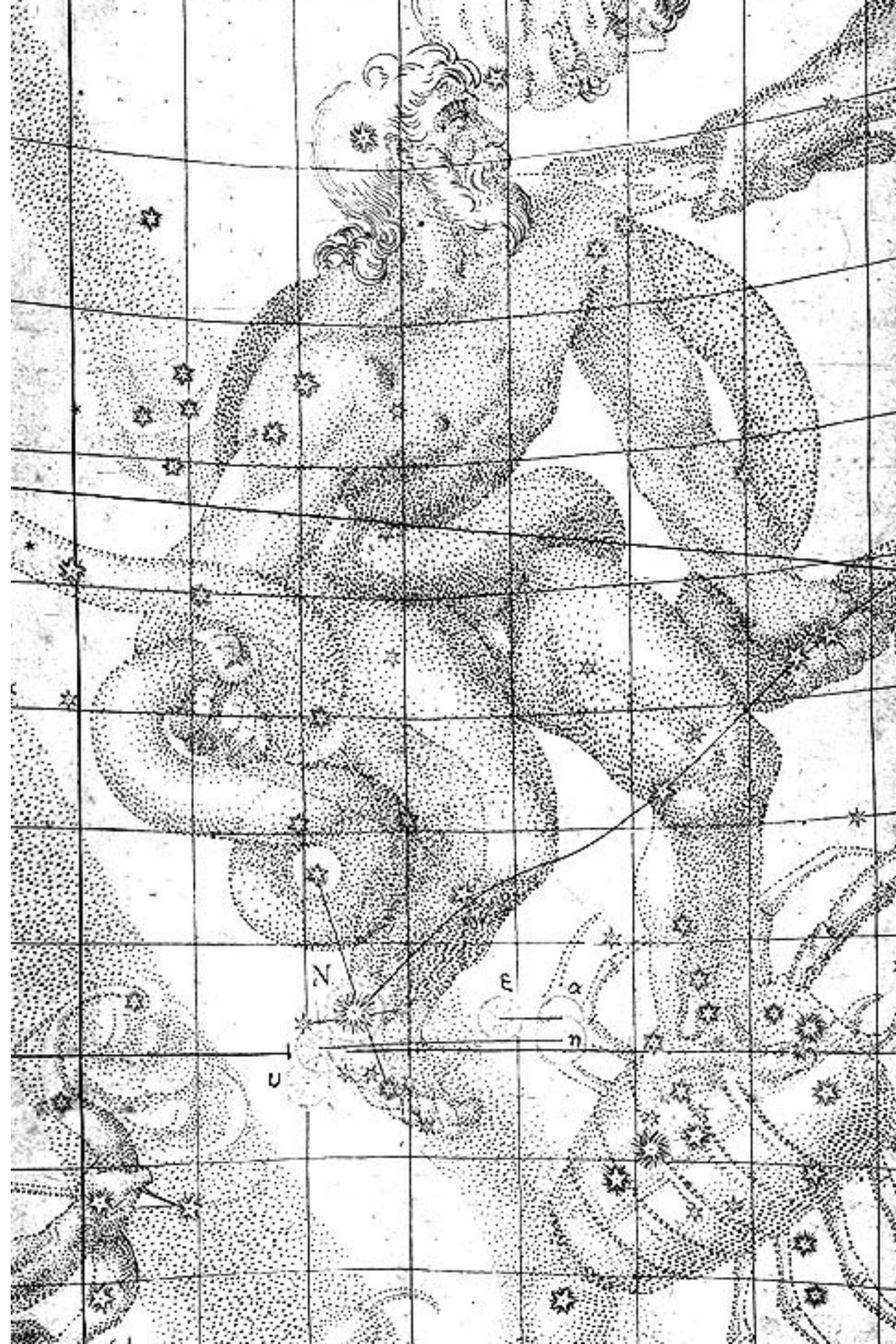
Historically, the zodiac is a circle of 12 constellations that occur along the plane of the ecliptic (planetary plane of our solar system and close to the Earth's equator).

The "ecliptic constellations" include the 12 historic zodiac constellations plus Ophiochus. Ophiochus was established in the 1930's.

NASA

The constellations that are visible from Earth change with the seasons.

Ophiocus is the "serpent bearer" and is an ancient documented as early as the second century BCE. The figure shows Johannes Kepler's illustration of Ophiochus.



Wikimedia

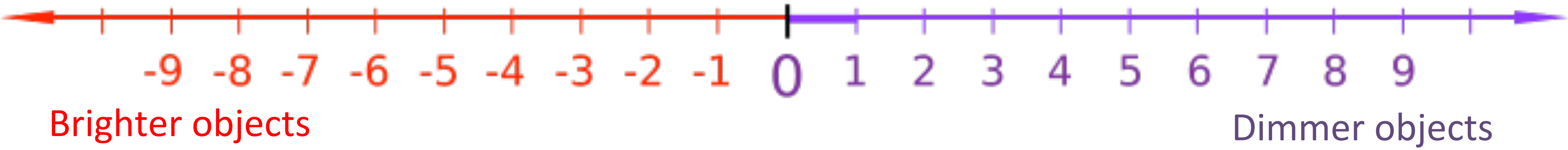
Luminosity and Magnitude

The *luminosity* of a star is the total amount of energy emitted by the star. The amount of light emitted is due to the size, temperature, life-stage of a star. Luminosity is an intrinsic property of a star and is not dependent on the distance.

Spinelli / NASA

The *magnitude* of a star is a measure of the apparent 'brightness' and is dependent on its luminosity and its distance.

With all things being equal (stars of the same luminosity), the more distant a star, the dimmer it appears.



The *magnitude* is a logarithmic scale where it appears to work 'in reverse.' Objects with a negative *magnitude* being brighter than those with a positive *magnitude*. The 'larger' the negative value, the brighter the object.

A change in *magnitude* of one equates to a change in brightness of about two and half times. First magnitude stars are ~100 times brighter than magnitude six stars.

The unaided human eye is only able to see magnitude 6 stars and brighter.

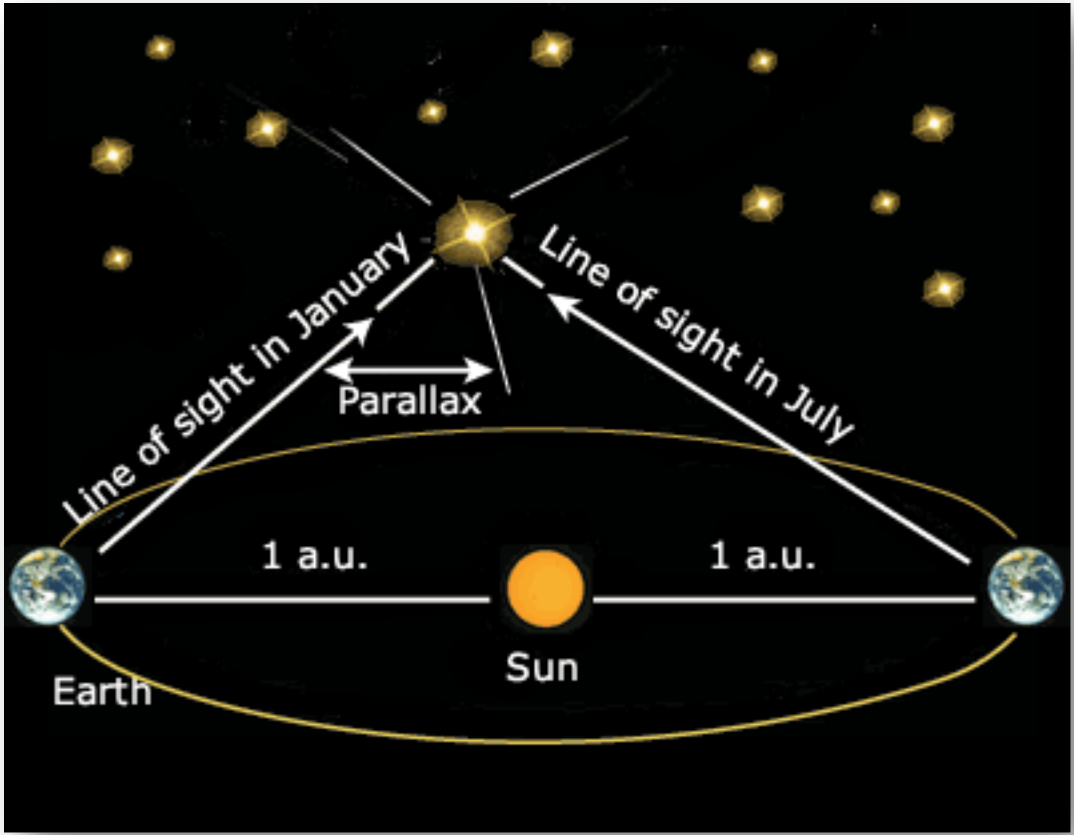
Object	Apparent Magnitude
Sun	-27
Full moon	-13
Venus	-5
Vega	1
Andromeda galaxy	3.4
Rho Cassiopeia	~5
Proxima Centauri	11.5
Pluto	14

How do we determine distances to stars?

1. Parallax. As the Earth orbits the Sun, an observer may see an apparent movement of the star compared to more distant stars in the background.

The distance to the star can be determined from its apparent shift.

The closer a star is to the Earth, the greater the observed parallax.



ESA

Stellar distances further than ~500 light years cannot be measured by this method.

How do we determine distances to stars?

2. Apparent Magnitude and Luminosity.

The color of a star indicates its size and its amount of light that it is emitting (luminosity).

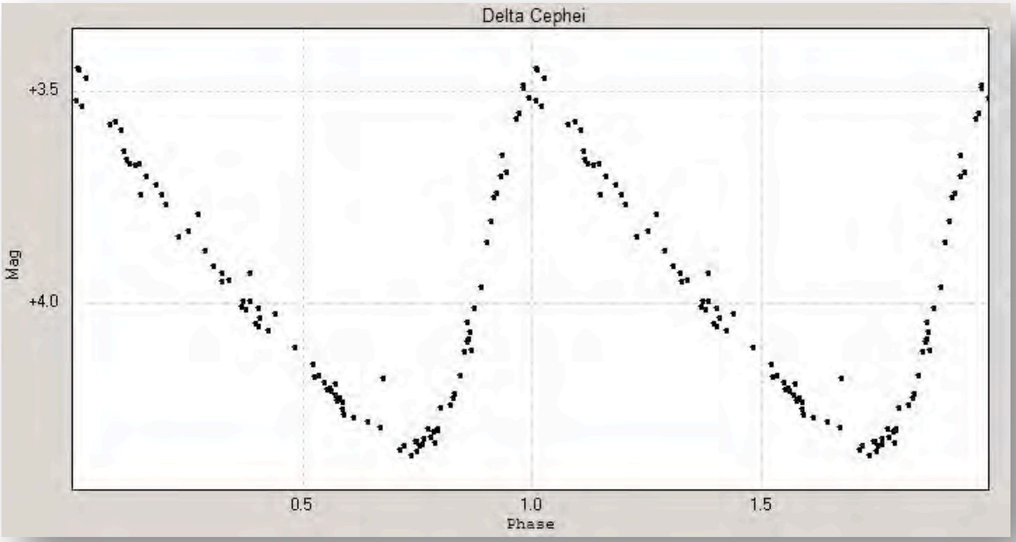
In constellation Orion, the red star at the top (Betelgeuse) is a red supergiant and its luminosity is 90,000–150,000 times greater than the Sun.

Spinelli / NASA

The bright blue star, Rigel, is a blue-white supergiant and has a luminosity 120,000 greater than the Sun.
The distance to the star can be determined by the observed magnitude (amount of light observed). Generally, the more dim that a star appears, the more distant it is.

How do we determine distances to stars?

3. Cepheid Variables
A Cepheid variable is a star that pulsates (periodic changes in temperature and diameter) that produce changes in its observed brightness with periods of about 1 – 70 days. The figure shows a light curve for a Cepheid variable.



Wikimedia User: ThomasK Vbg

There is a strong direct relationship between a Cepheid variable's luminosity and observed pulsation period. By measuring its pulsation period and its luminosity, the distance to the star can be determined from its observed brightness (apparent magnitude).

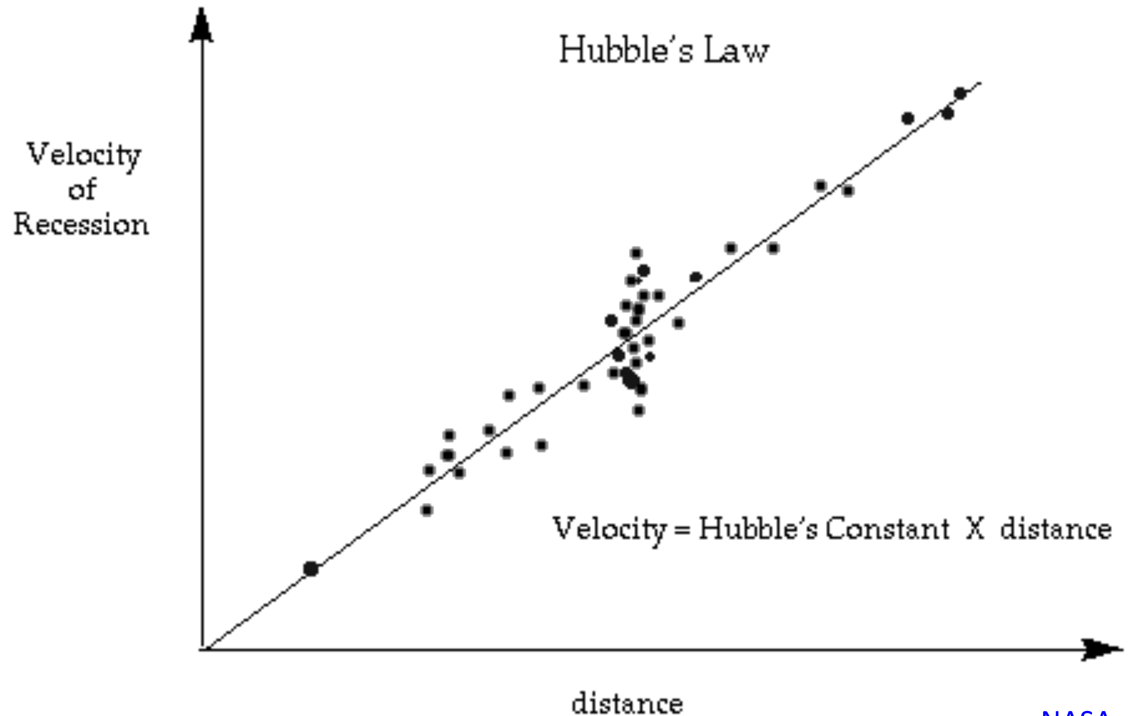
Cepheid variables can be observed in other galaxies, and thus the distance to the galaxy can be determined.

How do we determine distances to stars?

4. Hubble's Law

Distant galaxies observed in deep space are moving away from Earth in all directions as (redshift). This is known as Hubble's law.

The rate at which they are moving away from the Earth (velocity of recession) is proportional to their distance from the Earth.



NASA