# <u>The Milky Way</u>

{**Abstract** – *In this segment of our "How far away is it" video book, we cover the structure of the Milky Way galaxy.*

*We start with a high-level description of the three main components: the galactic center with its black hole, the galactic disk with its spiral arms, and the galactic halo stretching far out in all directions using the European Space Agency spacecraft Gaia's findings. We also show how full images of the Milky Way can be created from within the galaxy.*

*Using the full power of the Hubble, Spitzer, and Chandra space telescopes, we take a deep dive into the center of our galaxy with its central bulge. We detail the evidence for the existence of a supermassive black hole, Sagittarius A*, at the very center of the galaxy's core. We cover and illustrate the work done by the UCLA Galactic Centre Group in conjunction with the new Keck observatory on top of the Mauna Kea volcano in Hawaii, and the Max Plank Institute for Extraterrestrial Physics in Germany and more recently* and the European Southern Observatory with its array of Very Large Telescopes in Chile. *This includes a look at how close the star S2 approached Sgr A* and what that black hole might look like. In addition, we cover stellar interferometry with ducks on a pond to see how these measurements were done.*

*Next, we go a level deeper into the nature of a Black Hole singularity. We cover the Schwarzschild radius, event horizon, accretion disk, gravitational lensing, and gamma-ray jets. We then actually build Sgr A*. In addition to the supermassive black hole, we take a look at a solar mass black hole.*

*We then cover the structure of the galactic disk including: the bar core, the two 3 Parsec arms, Scutum-Centaurus, Perseus, Sagittarius with its Orion Spur, Norma and the Outer Arm. We review the locations of various celestial objects we've seen in previous Milky Way segments, to show how close to us they are. We also cover the disk's rotation and the Sun's orbit. We look at our solar system's Ecliptic Plane with respect to the galactic plane. And we cover the galaxy's dust clouds and how we see them with radio astronomy. We also cover the galaxy's rotation curve and its connection with dark matter.*

*Next, we cover the galactic halo. We start with Shapley's globular cluster map that first showed that we were not at the center of the galaxy. We cover the size of the halo, the inner and outer halos orbital motion, and the newly discovered galaxy within our galaxy called Gaia-Enceladus. We end with recent discoveries of massive amounts of Hydrogen in the halo and this findings impact on the Dark Matter debate. And we end with a calculation of the entire Milky Way's mass.*

*We end our galaxy coverage by illustrating how far one would have to go to take a picture that would include what we see in our illustrations. We conclude the chapter with another look at the distance ladder that took us across the galaxy.*}

## Introduction

> **[Music:** *Beethoven - Symphony No.9, 'Choral' _ III – Completed in 1824, this was Beethoven's last and best symphony. Accompanied by the poem "Ode to Joy" written by Friedrich Schiller in 1785 and adjusted by Beethoven for his 9th. This most wonderful of symphonies is most appropriate for covering the scope and structure of our magnificent Milky Way galaxy.***]**

Welcome to our final segment on the Milky Way. In this segment:

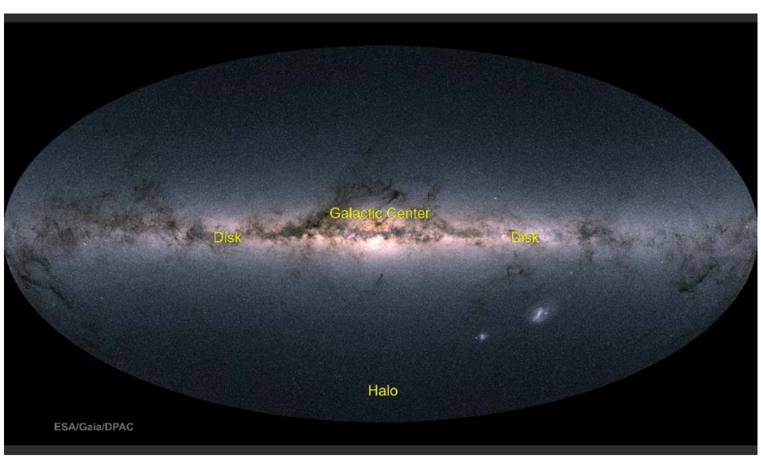
- We'll go over our current understanding about the structure and size of the Milky Way as a whole, and our place in it.
- We'll examine the galactic center with its supermassive black hole. We'll go a little deeper into the nature of a black hole and show a few of the black hole candidates we have found.
- We'll explore the galactic disk with its spiral arms.
- And we'll cover the latest information on the galactic halo.

And, as usual, we'll discuss how we came to know these things from our viewpoint deep inside the galaxy itself.

### Galaxy Overview

On January 1st, 1990, from its orbit around Earth, the Goddard Space Flight Center's Cosmic Background Explorer created this edge-on view of our Milky Way galaxy in infrared light.

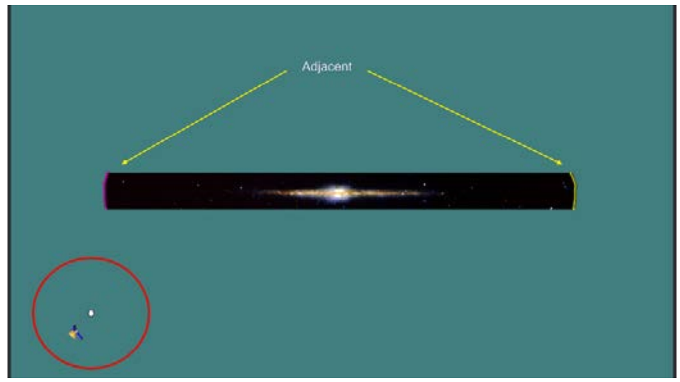
Here's a newer inside image of our galaxy. In fact, it's the most detailed map ever made. It was released in 2018 by Gaia the European Space Agency spacecraft that recorded the position and brightness of 1.7 billion stars, as well as the parallax, proper motion and color of more than 1.3 billion stars. The map shows the density of stars in each portion of the sky. The galaxy has a center with a central bulge, a disk of rotating stars and dust and a halo without dust clouds, and peppered with globular star clusters. The disk is at least 100,000 light years in diameter, and the halo is much larger than that. We'll go into each of these galaxy components, starting with the galactic center.



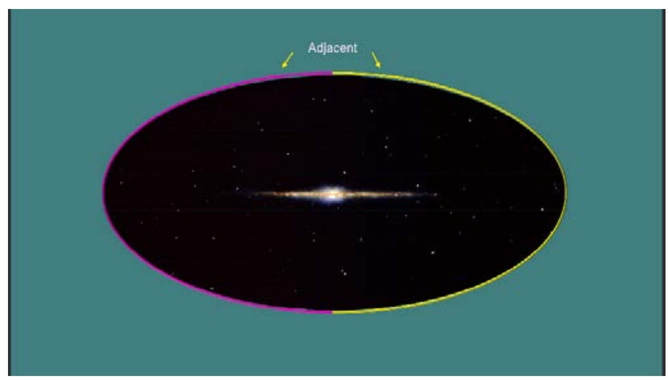
## How to photograph our galaxy from the inside

But first let's take a closer look at how an image like this is created.

From orbit, we point the camera at the center of the galaxy, and turn it 180 degrees to face away from the center. We're now looking through the plane of the galaxy away from the center. Then we scan the camera clockwise taking hundreds of pictures along the way. We continue the rotation through the center and all the way back to the starting point. Note that the stars on the right edge of the image, taken at the end of the rotation, are adjacent to the stars on the left edge of the image, taken at the beginning. In other words, the entire right side of the image borders on the left.




Now we rotate the camera up a bit and repeat the process. We do this over and over until the entire northern sky is covered. The last shot is taken with the camera pointing straight up perpendicular to the galactic plane. We then repeat the process for the southern sky and we have the entire picture.




Once we have all the pictures covering the spherical surface of the sky all around us, we map it to a flat surface. There are a number of ways to do this. Astronomers use the elliptical projection method, because it maintains the relative size and distance between celestial objects. You may have seen maps of the Earth that use this technique.

**Galactic Center - 26,000 light years**

The world's Great Space Observatories — the Hubble Space Telescope, the Spitzer Space Telescope, and the Chandra X-ray Observatory — have collaborated to produce this unprecedented look at the central region of our galaxy.

- Hubble documented vast arches of gas, heated by stellar winds from very large stars.
- Spitzer's infrared picked up the pervasive heat signals of all these stars.
- Chandra detected x-ray sources from ultra dense neutron stars and small black holes.

Together, they produced this spectacular image.

**[Additional info:** Observations using infrared light and X-ray light see through the obscuring dust and reveal the intense activity near the galactic core.

Note that the center of the galaxy is located within the bright white region to the right of and just below the middle of the image.

Each telescope's contribution is presented in a different color:

- Yellow represents the near-infrared observations of Hubble.

- Red represents the infrared observations of Spitzer.

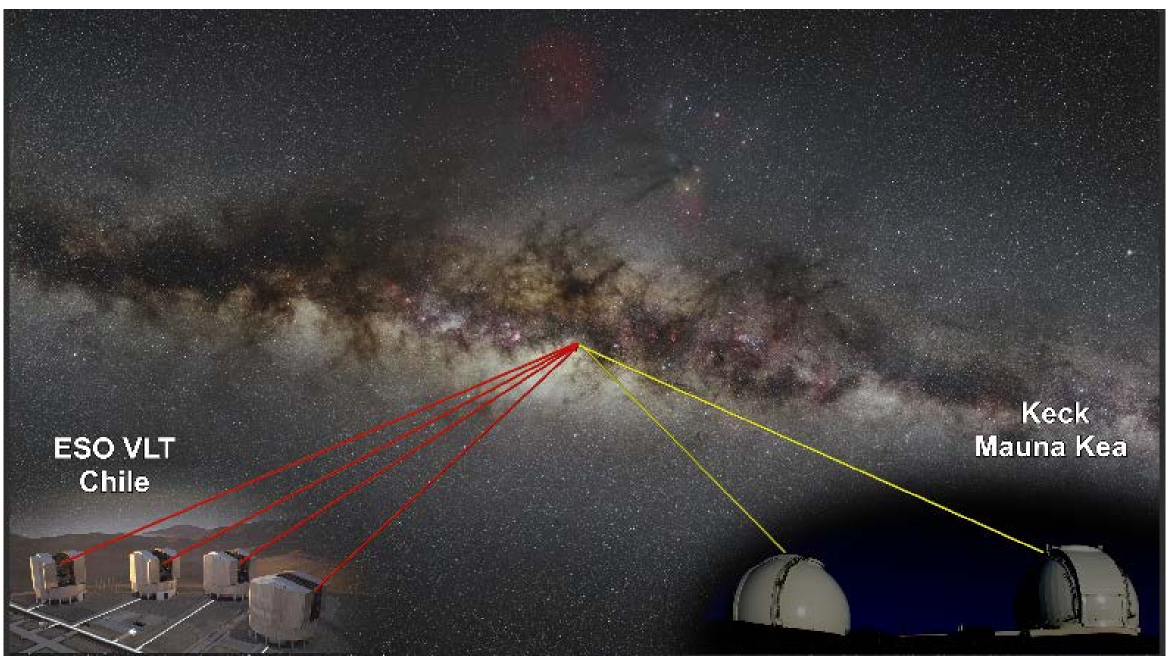
- Blue and violet represent the X-ray observations of Chandra.

When these views are brought together, this composite image provides one of the most detailed views ever of our galaxy's core.**]**


The central object in the Milky Way is known as Sagittarius A* or Sgr A* for short. It lies approximately 26,000 light-years away. It is surrounded by so many stars and gas and dust that it is extremely difficult to see.

**[Additional info:** Our first look at Sgr A* came with the advent of broadcast radio in the 1930s. Karl Jansky was asked to locate the radio interference to Bell Labs early trans-Atlantic transmissions. He built the first radio antenna and located the source at the center of the galaxy. He named it Sagittarius and is credited with starting the entire field of radio astronomy. Flashing forward – we now have the Hubble space telescope which was designed in part to study what we now call Sagittarius A*.**]**

Teams of astronomers and astrophysicists have been working on understanding Sgr A* for over 25 years. The UCLA Galactic Centre Group along with the Keck observatory on top of the Mauna Kea volcano in Hawaii, and the European Southern Observatory with its array of Very Large Telescopes in Chile, and the Max Plank Institute for Extraterrestrial Physics in Germany and many others have made dramatic progress in advancing our understanding of this critically important part of our galaxy.

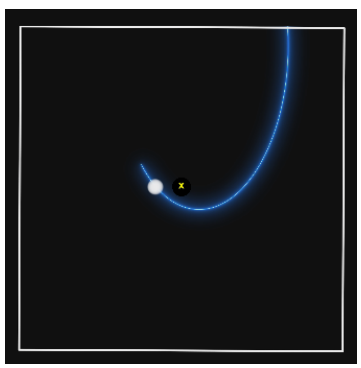


After decades of carful observations, the speeds and orbits of around 45 stars around Sgr A* have been calculated. This enabled measuring the precise location of the point they are all orbiting around. The measured orbits also identified the gravitational pull from this point which in turn gave us its mass at 4 million times the mass of our Sun.

But, when we look at this point, we don't see anything. This was strong evidence that Sgr A* was a black hole because stars are known to be unstable at much smaller masses.

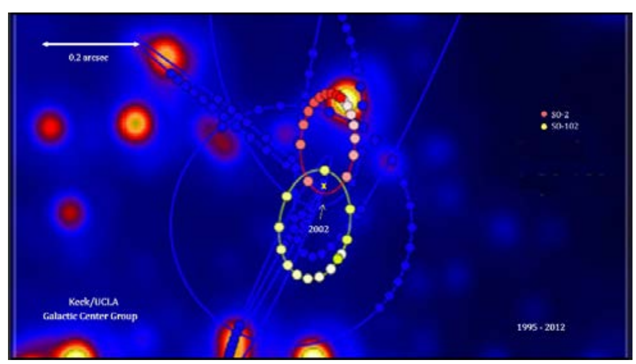
The star S2 is of particular interest because it passes closer to Sgr A* than any other. It's a single main sequence star with 10 to 15 times the mass of our Sun.

Observations of the star showed that its orbit took it to within 20 light hours of Sgr A* in 2002 without bumping into anything. That puts Sgr A*'s 4 million solar mass into a very small place.

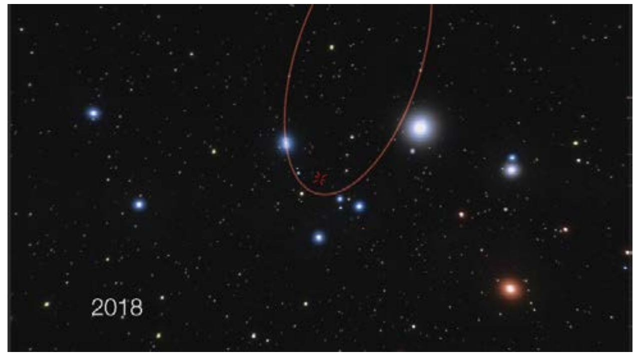


For many astrophysicists, this constituted proof that it was indeed a supermassive black hole. But others pointed out that an extremely dense dim star cluster could produce these results.

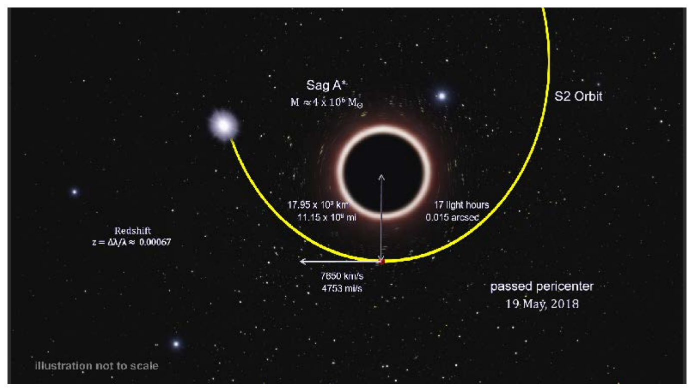
But if Sgr A* were a cluster, S2's orbit would have wobbled. It did not wobble. This was persuasive evidence that the object S2 is orbiting is a Super Massive Black Hole (or SMBH for short). 500 years after Copernicus put the sun at the center of our solar system, we have identified Sagittarius A* as a supermassive black hole at the center of our galaxy.



But we weren't done with S2. Its orbital period is 16 years. Following the 2002 passing, a major effort was mounted to upgrade ESO's VLT array of telescopes to enable the precision needed to reveal the true geometry of space and time near this object and test Einstein's theory of general relativity.




These new instruments followed S2 very closely. At the start of 2018 it was accelerating towards Sgr A* reaching relativistic speeds. On May 19th, it reached its closest approach. At that point, it was traveling at 7650 km/s (or 4753 mi/s). That's almost 3% of the speed of light. Its distance from the black hole was just 18 billion kilometers (or 11 billion miles). That's only 120 times our distance from the Sun. The separation on the sky between the two points was just 15 mas. It was also reddening in color as the black hole's gravitational field stretched its light to longer wavelengths. The color change in this illustration is exaggerated for effect. The reddening is quite small and would not be visible to the naked eye.

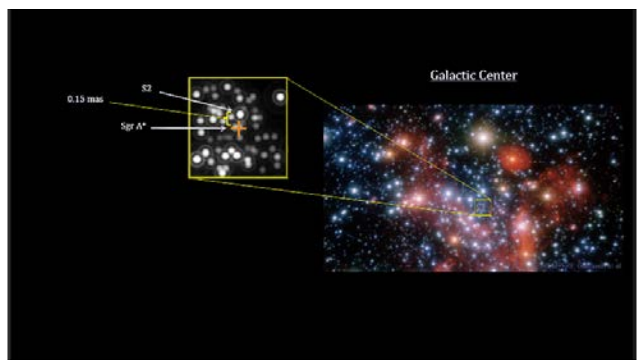



S2's velocity changes close to the black hole were in excellent agreement with the predictions of general relativity. In addition, the change in the light wavelength agreed precisely with what Einstein's theory predicted. But understanding what is happening this far away is always prone to errors. I remember when we thought there was a gas cloud G2 that would be entering the black hole in 2014. This never materialized. In our current case, some astronomers point out that massive, non-luminous objects, such as stellar mass black holes, might be present and could affect the orbital dynamics of S2. More research is needed to rule out this possibility.

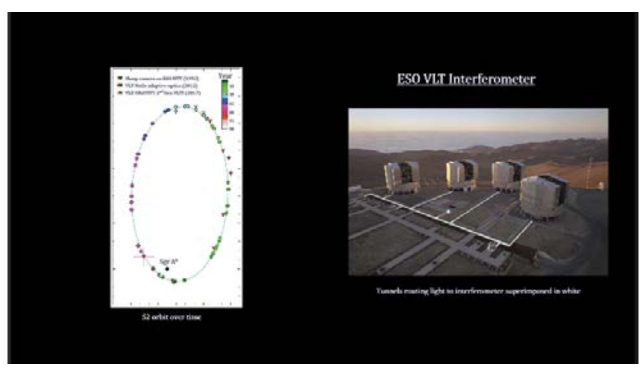
Here's a Fulldome illustration that shows how Sgr A* might look to viewers on a planet orbiting S2 as it orbits the black hole. We'll cover black holes and why our super massive black hole might look like this, but first we'll cover how the ESO VLT actually measured the minute distances associated with S2 and Sgr A* 26,000 light years away.

**Stellar Interferometers**

The Hubble space telescope can resolve angles on the sky as small as 50 milliarcsec. The angular distance between S2 and Sgr A* at pericenter was just 15 milliarcsec. That's 42 billionths of one degree and 3 times smaller than Hubble can resolve.

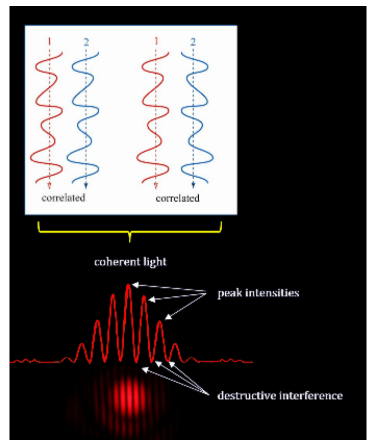



To follow S2 as closely as they did, astronomers had to use a stellar interferometer. These kinds of telescopes can resolve images 30 to 40 times smaller than optical telescopes. This makes them extremely important tools for studying the galactic center as well as exoplanets. They can even resolve sunspots on nearby stars. So to understand how we know how close S2 got to Sgr A*, we need to understand how these stellar interferometer telescopes work.



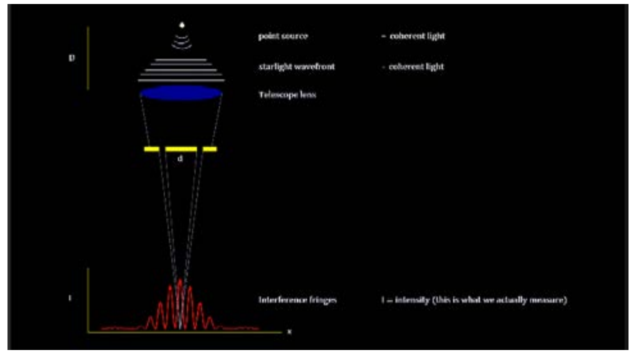
In the “Speed of light” chapter of the “How fast is it” video book, we covered the Michelson Interferometer used to measure minute distances in a lab. Interferometers can measure distances on the order of a few nanometers. Michelson and Morley used it to show that the speed of light was a constant.

In order to create light interference, Michelson illuminated his interferometer with fully coherent light. Coherent light has a common frequency and phase. It always produces interference patterns on the far side of a double slit. Fully coherent light (like the kind that lasers create) will produce regions of fully destructive interference. That is, the dark regions have no light falling on them. Partially coherent light will produce regions of partially destructive interference – meaning some light falls in the dark regions. And incoherent light will not produce interference patterns at all.

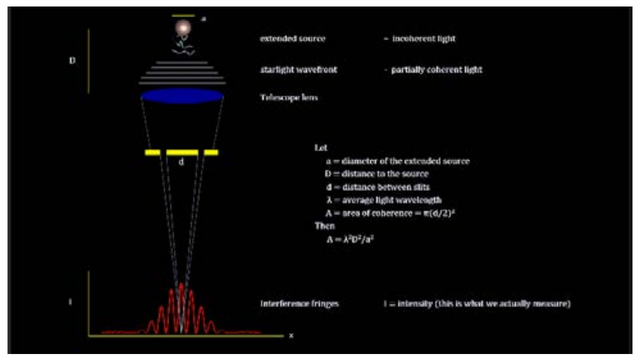



We find in nature that waves can start out as incoherent and become partially coherent as the waves spread out. Watch how these ducks start with a chaotic mix of water waves as they enter the pond. But as the waves move out, they become quite orderly. This is a geometrical effect. The farther away one travels from the source, the less significant the distance between the individual wave generators becomes.

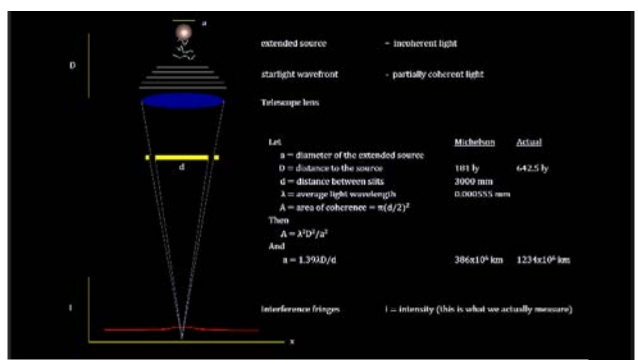
A point source for starlight would produce coherent light. And at any distance from the source, the light would create interference patterns. But there are no point sources in nature.




Stars have a diameter on the sky. An extended thermal light source would start out with incoherent light. But as the light moves away from the source, its coherence increases just like with the ducks on the pond. The relationship between the diameter of the source, its distance from the interferometer, and the distance between the two slits was determined in the lab. [The area of coherence is the area at the telescope that contains coherent enough light from the source to create interference patterns. It goes up with the distance from the source and it goes down with the diameter of the source.]




Michelson used this property to measure the diameter of Betelgeuse in 1921. [He added optics to make an interferometer on the Mt. Wilson 100” Hooker Telescope. He determined the aperture spacing that produced fringes (2,000 mm or 6 feet) and the largest spacing that didn't (3,000 mm or 10 feet). That gave him the area of coherence. In his day, they thought Betelgeuse was 181 ly away. So from that he calculated the diameter of the star to be 386 million km or 240 million miles. Today we know that Betelgeuse is 642 ly away with a diameter 3 times larger than Michelson calculated. But it was a good start for stellar interferometry.

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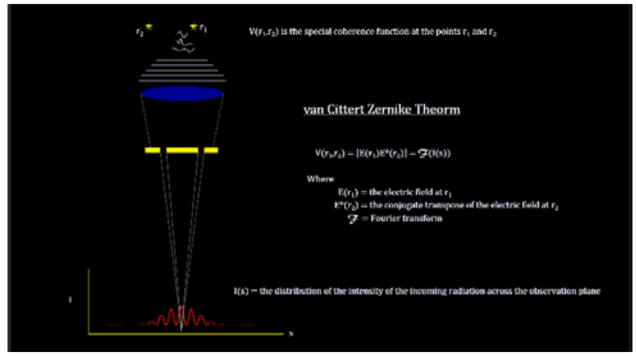
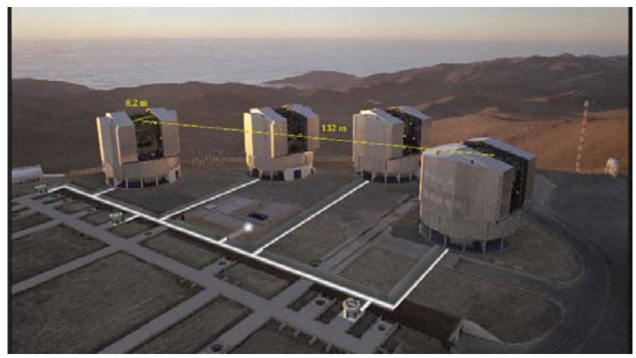
It is fascinating to note that incoherent light waves created by exited atoms in stars 20 billion km apart can travel for 26,000 years and still carry the remnants of that starting condition. A large enough stellar interferometer can use the visibility dimming of the interference patterns created by that light to detect the original star separation. See how the amount the image fads is greater the further apart the two stars are. The math involved was developed independently by Dutch physicists P.H. van Cittert in 1934 and F. Zernike in 1939. It's known as the van Cittert-Zernike theorem.



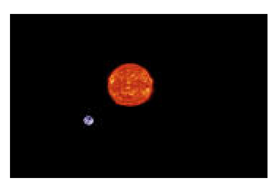

It has taken 80 years to extrapolate the basic physics of interferometry into the working instruments we have today. There are currently over 20 stellar interferometers in operation around the globe. It was the four 8.2 meter ESO VLT optical telescopes with an attached 4-way interferometer called GRAVITY that covered the S2 pericenter passage around Sgr A*. The diameter of the observation baseline is the 130 meters between the two outermost telescopes, not the 8.2 meters on any one of the telescopes. This gives the interferometer over 15 times the telescopes' resolving power.




## Black Holes

From antiquity into the eighteenth century, it was believed that the idea of empty space is a conceptual impossibility.

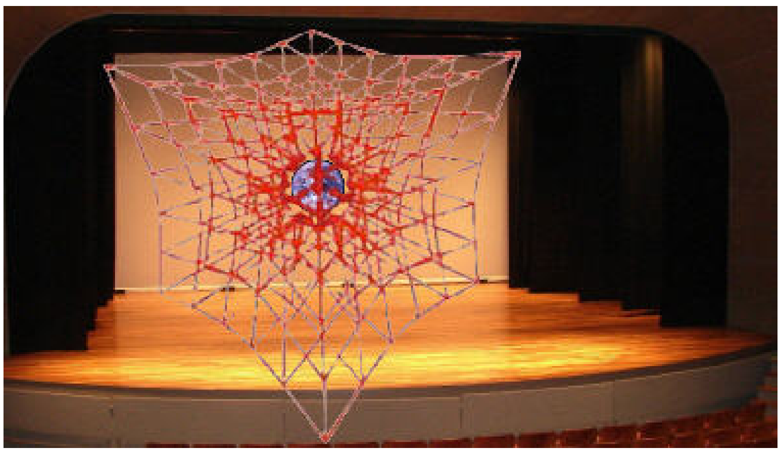
Space is nothing but an abstraction we use to compare different arrangements of the objects. Concerning time, it was believed that there can be no lapse of time without change occurring somewhere. Time is merely a measure of cycles of change within the world.



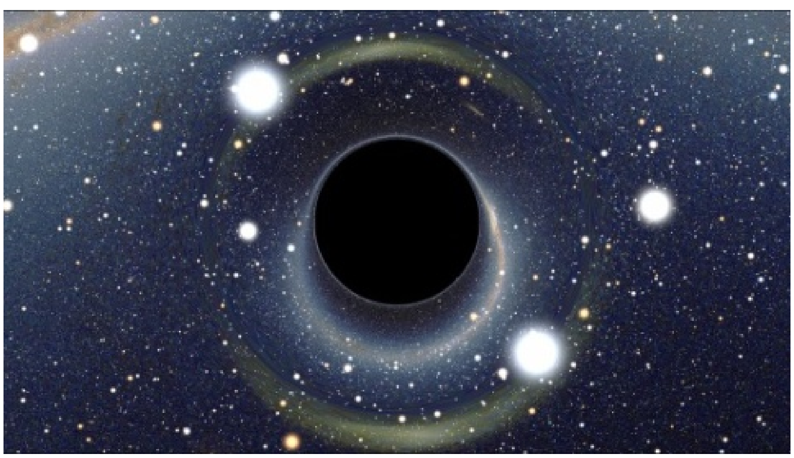
Then, in 1686, Isaac Newton founded classical mechanics on the view that *space* is real and distinct from objects and that *time* is real and passes uniformly without regard to whether anything moves in the world.

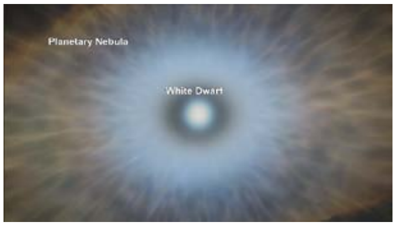
He spoke of *absolute space* and *absolute time* as a stage within which matter existed and moved as time flowed at a constant rate. It was understood that space and time tell matter how to move, but matter has no effect on space and time.

The idea that space and time act on matter, but that matter does **not** act on space and time, troubled Einstein. Noting that light curved in a gravitational field, Einstein proposed that the mass of an object does indeed act on the space and time it exists in. Specifically, he proposed that the presence of matter curves space-time.

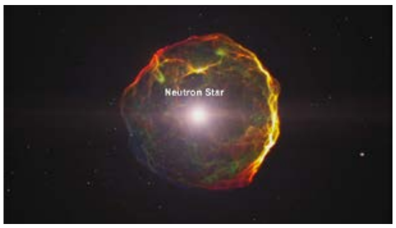


This lead Einstein to his theory of general relativity which predicts the existence of black holes as objects so massive that light itself cannot escape their gravity. [The star goes dark for distant observers – hence the name Black Hole.]





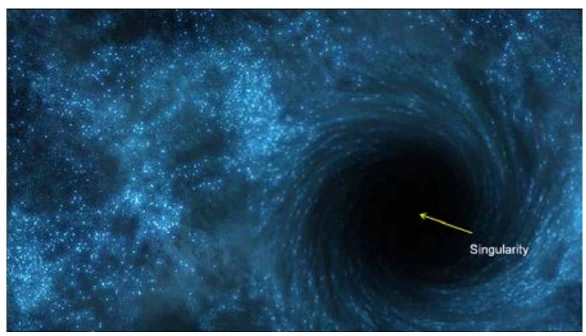

You'll recall that explosions at the end of life for stars less than 5 times the mass of the sun create planetary nebula and leave behind white dwarfs. In these stars, electron exclusion pressure is enough to counteract the inward force of gravity.



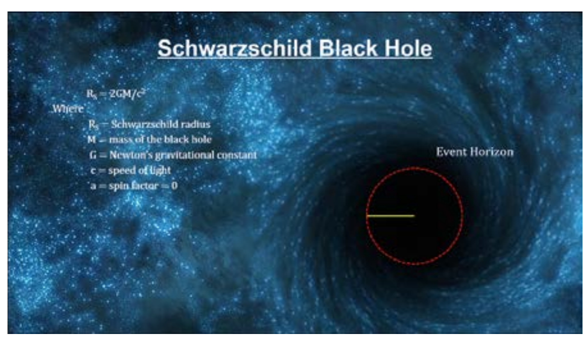

Supernova explosions at the end of life of stars more than 5 times the mass of the sun leave behind a neutron star. In these stars, electron pressure is insufficient to overcome the force of gravity, but neutron exclusion pressure is.

But if a star is greater than 30 times the mass of the sun, even neutron exclusion pressure won't do the trick. In fact, there is no known force that will counteract the inward force of gravity for such a supernova or hyper nova exploding star.

According to Albert Einstein's general theory of relativity, the star will collapse into zero volume and infinite density – called a singularity. This defines a black hole. It gets its name from the fact that such a singularity would create a gravitational pull that not even light could escape. The object literally becomes invisible.

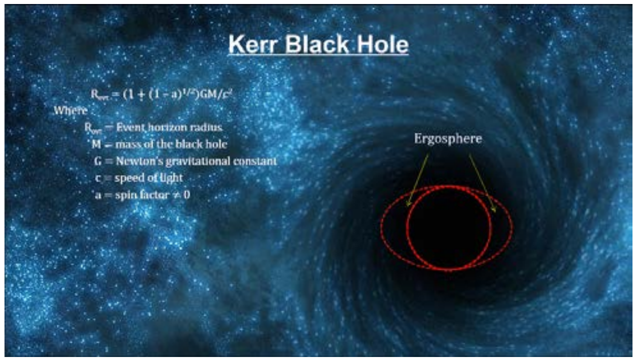



In 1916, Karl Schwarzschild, a contemporary of Einstein, solved his equation for the special case of a non-rotating sphere. He found that although the diameter of the singularity is zero, the radius at which light would be captured depends entirely on the mass of the black hole. This is called the Schwarzschild radius and it defines the Event Horizon.

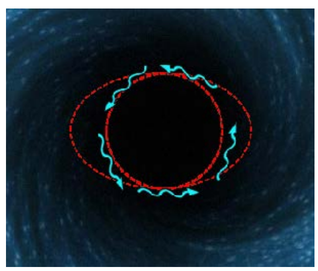



[For the Sun, the Schwarzschild radius is 3 km or 1.8 mile. That means that if the Sun were to shrink to a 6 km or 3.6 mile diameter, it would disappear!]

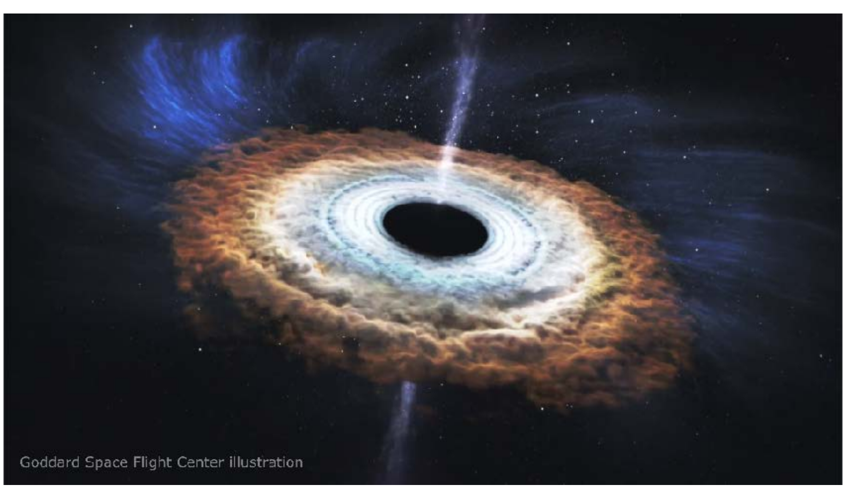
But it would be the rare black hole that doesn't spin. In 1963, Roy Kerr developed the general solution for spinning black holes. It showed that there is a second region beyond the event horizon that defines a volume around the black hole called the ergosphere.




In this region, space itself is dragged around by a black hole's spin. (It's called frame dragging.) Also, in this region, light can enter stable orbits around the black hole. This would produce a photon sphere shell incasing the black hole with light from all the stars in the universe accumulated over the entire age of the black hole. It would be a sight to see.

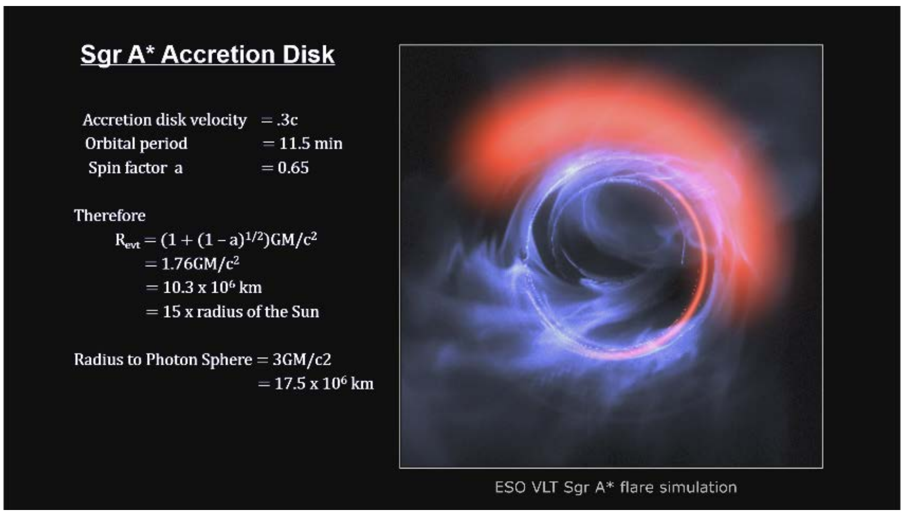


One thing all rotating black holes have in common besides the fact that we can't see them, is that matter flows in via an accretion disk. The exact mechanism is not yet fully understood, but we know that gamma-ray jets shoot out at the polls carrying a percentage of the falling matter with it at speeds approaching the speed of light.


Goddard Space Flight Center illustration

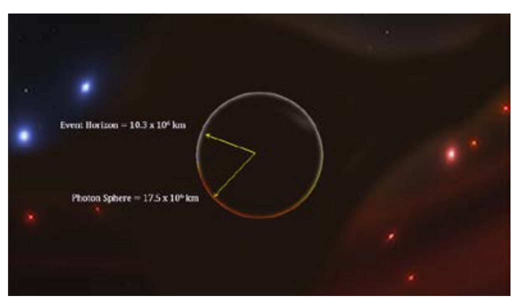
## Black Hole Sagittarius A*

In late 2018, ESO's GRAVITY instrument observed flares of infrared radiation coming from the accretion disc around Sgr A*. These flares came from clumps of gas swirling around at about 30% of the speed of light on a circular orbit just outside its event horizon. [Light from objects moving closer to and across the event horizon is stretched into and beyond infrared wavelengths. This will create what looks like a flare.] They indicate that Sgr A* is spinning with a full rotation every 11.5 minutes. This makes the 4 million solar masses Sgr A* a supermassive Kerr black hole. This new information also enabled calculating the distance from Sgr A*'s center to its event horizon at round 10 million km or 15 times the radius of our Sun, and the distance to the photon sphere at around 17 million km.

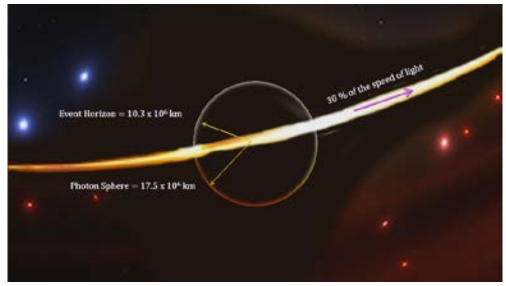



To illustrate how a black hole might look, we'll build Sgr A*. Here we are viewing it from the equatorial plane and the object is rotating in on the left an out on the right. Its center is dark out to the event horizon.

This thin ring around the black hole, just outside the event horizon, represents the cross section of Sgr A*'s ergosphere with shell of orbiting light. What we'd see is the light that leaks out in our direction.



The observed flares indicate that Sgr A* has the remnants of an accretion disk that is no longer feeding the black hole on a regular basis. If the disk were not gravitational lensed, the black hole would have looked like this.

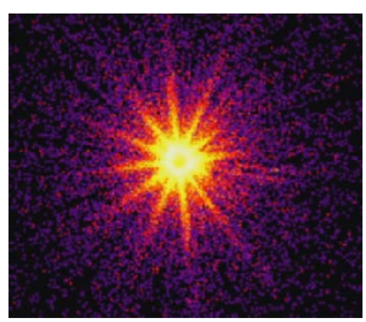



But, because of gravitationally lensing, the massive amount of light rays emitted from the disk's top face travel up and over the black hole, and light rays emitted from the disk's bottom face travel down and under the black hole. This combination gives us the full image of how the black hole would actually look.

## Stellar Mass Black Hole MAXI J1820+070 – 10,000 ly

There are three classifications for black holes based on their mass: stellar - with masses up to ten times the mass of our sun; supermassive - with millions or even billions of times the mass of our sun; and intermediate - with masses somewhere in between. Sgr A*, the black hole at the center of our galaxy is a supermassive black hole.

Stellar-mass black holes form when the most massive stars supernova. Here's one called J1820 discovered by accident. In March, 2018, the Japanese's instrument MAXI aboard the international space station recorded an extremely strong x-ray outburst.



NASA's NICER neutron star instrument, also on the space station, focused on the outburst for days and watched it fade. In addition, the Gaia mission was able to locate the x-ray source companion star and determine its distance at 10,000 light years. Analysis showed that the x-ray object is a black hole with the mass of around 10 suns. The x-rays are generated as matter from the stare feeds the accretion disk around the black hole.

Some astronomers calculate that there are as many as 100 million stellar-mass black holes like this one in our galaxy. Most of these are invisible to us, and only about a dozen have been identified. For more information on Black Holes, see the "General Relativity Effects" segment of the "How fast is it" video book.

## The Galactic Disk

The number of star in the Milky Way is very difficult to determine. But, based on detailed analysis of star distances, star motions, neutral hydrogen radiation from spiral arms, galaxy rotation curves and mass (including dark matter) astronomers currently believe that the galaxy has a relatively flat rotating 100,000 to 120,000 light years wide and 1,000 ly deep disk of some 100 to 400 billion stars.

This image, out of the Spitzer Science Center and the University of Wisconsin, represents an attempt to synthesize over a half-century of work on the Galactic Disk's structure based on data obtained from the literature at radio, infrared, and visible wavelengths.

**[Additional info:** The Milky Way was dubbed as a spiral galaxy in 1951 when William Morgan of the Yerkes Observatory presented his results showing the galaxy's three arms of hot stars, which he named Perseus, Orion and Sagittarius.

There were three methods traditionally used to map the disk structure of our Galaxy.

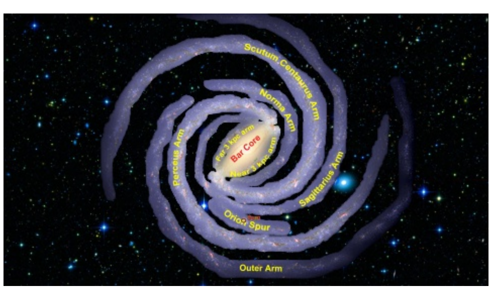
- Starting in 1958, the first method studied the density of the neutral hydrogen in the plane of the Galaxy.
- Starting in the 1960s the second method used radio astronomy to map out the Milky Way's structure.
- Starting in 1976, the third method plotted the giant HII regions. These were usually formed in the spiral arms.]


The galactic center itself, with the supermassive black hole that we discussed earlier, is shaped like a bar. Although most parts of the Milky Way galaxy are relatively uncrowded, roughly 10 million stars are known to orbit within just a single light-year of the galactic center in a region known as the central bulge.


Recent surveys discovered the two 3-kpc Arms, named for their length. They are now generally thought to be associated with gas flow roughly parallel to the central bar.

Using infrared images from Spitzer, scientists have discovered that the Milky Way's elegant spiral structure is dominated by just two arms wrapping off the ends of a central bar of stars. One is named Scutum-Centaurus and the other is named Perseus.

Each of these major arms consists of billions of both young and old stars.




Three thinner arms spiral out between the two giant main arms called Sagittarius, Norma and the Outer Arm. These are primarily filled with gas and pockets of star-forming activity.

There is also a spur off the Sagittarius arm called the Orion Spur.

- It's 3,500 light-years across; and approximately 10,000 light-years long.
- We are located on the inner edge half-way along this spur around 26,000 light years from the galactic center.

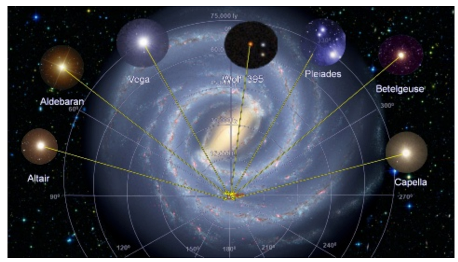
When we fill in the space between the arms, we get the full picture.

It's interesting to note that the number of stars per unit volume of space in the regions between arms is the same as the number in the arms themselves. What distinguished the arms is that they have a far greater number of younger stars. In fact, all the known H II star forming regions in the galaxy exist inside the arms. We don't find any in the area between the arms.

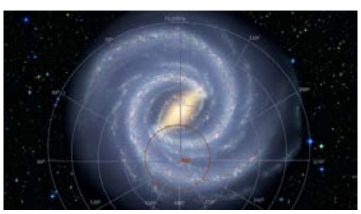
**Our place in the Milky Way**

If we lay a grid over the galaxy, we can locate some of the stars, nebula and H II regions we have seen in this chapter.

Actually, all the local neighborhood stars would fit into the red circle I used to locate our Solar System. That would be stars like Wolf 395, Altair, Vega, Polaris, Capella, Aldebaran, the Pleiades, and Betelgeuse. They are all with us in the **Orion Spur**, as is the Orion, Horsehead, Cone, Witch's Head, Veil and many other Nebulae.

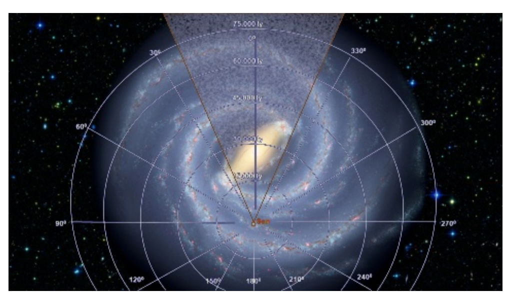



In **Sagittarius**, we see the Jewel Box star cluster and the Trifid, Omega, Lagoon, Eagle, and Cat's Paw nebulas among other. In **Perseus**, we see the Rosette, Heart and Soul Nebulae as well as the Crab Supernova to name just a few.

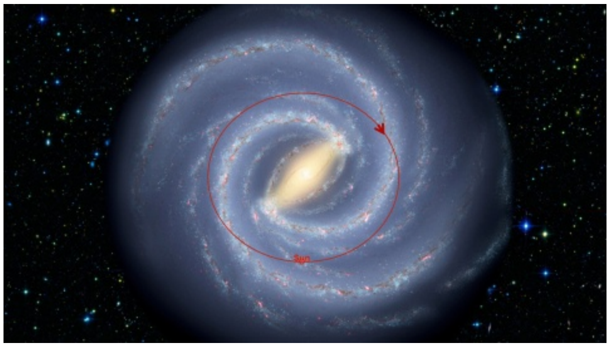


In fact, except for the hyper-velocity stars and a few of the supernova remnants, everything we have seen in this chapter is within this circle. As vast an area as we have covered, it is only a fraction of the Milky Way galaxy.

Another point that ought to be covered is that we cannot see through the galactic core into the other side. The core is simply too dense with stars and gas and dust to penetrate. So this slice of the disk has not been seen or analyzed. But our understanding of spiral galaxies is that they are symmetric, so this picture makes that assumption and fills in the blanks accordingly.

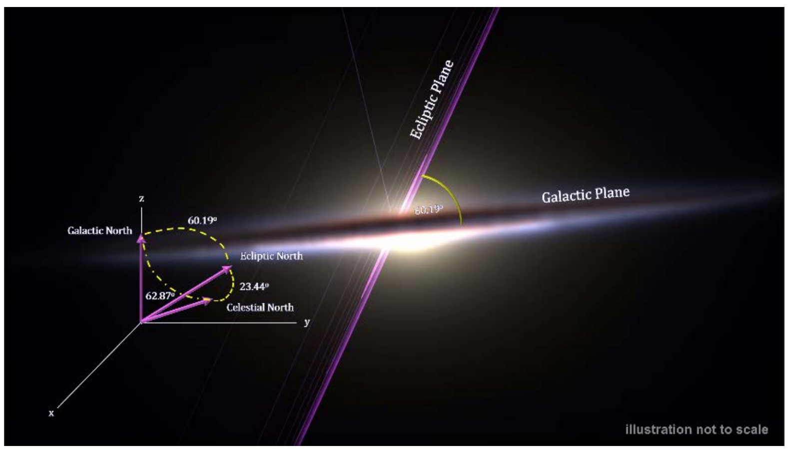


Viewed from "above" – what would be North on Earth – the Milky Way spins in the counter-clockwise direction. Of course, if you were to view it from the other side, it would spin clockwise.

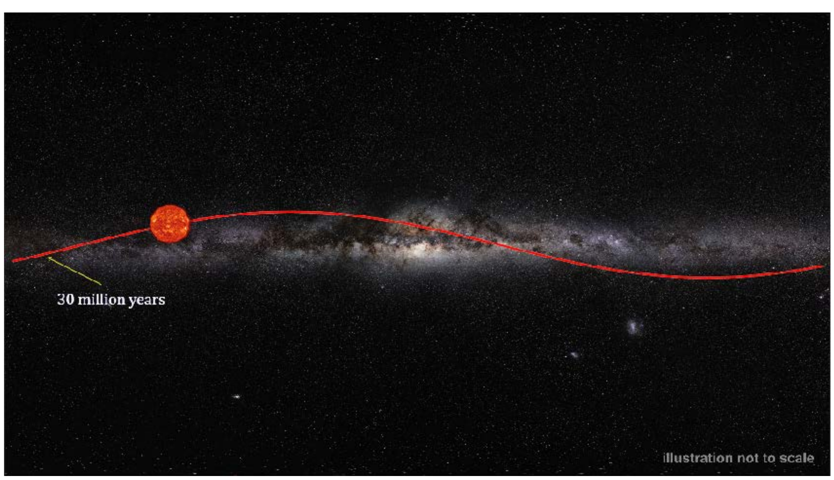


Here we see the Sun's orbit around the galactic center. Our orbital speed is approximately 230 km/s or 143 miles per sec. That's fast, but it takes us around 213 million years to complete one orbit around the galactic center. The last time we were in the same place in our orbit, dinosaurs were just starting to appear on the Earth. We have traveled around 1/1000th of a revolution since the origin of humans.

Here's a look at our solar system's Ecliptic Plane with respect to the galactic plane. It's just over 60 degrees off. We see that the solar system is quite out of alignment with the galaxy's disk. Earth's 23 degree tilt to the solar plane puts us at an almost 63 degree tilt from the galactic plane. This is why the Milky Way appears at such a strange angle across the night sky.



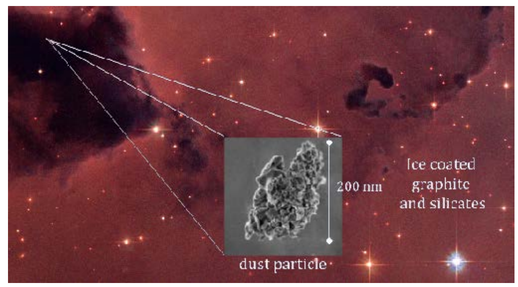

Also, as the Sun orbits the galaxy, it oscillates up and down relative to the plane of the galaxy. It does this approximately 2.7 times each time around. Astronomers estimate that we are currently at around 75 to 100 light years above the galactic plane and moving down. This estimate has us crossing the plane in approximately 30 million years!



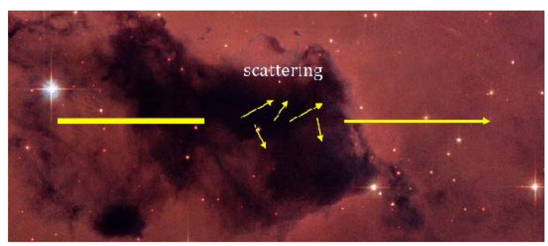
## Dust

Before we leave the galaxy's dusty disk we'll take a closer look at the dust itself. It's critically important for calculating intrinsic star luminosity, and it's the only galaxy content that we can use to accurately calculate the galaxy's rotation curve - that's star velocities as a function of their distance from the galactic center. The Milky Way's rotation curve is one of the reasons scientist have proposed the existence of dark matter.

The dust is made of thin, highly flattened flakes of graphite and silicate (that's carbon and rock-like minerals) coated with water ice. Each dust flake is roughly the size of the wavelength of blue light or smaller. The dust is probably formed in the cool outer layers of red giant stars and dispersed in the red giant winds and planetary nebulae.

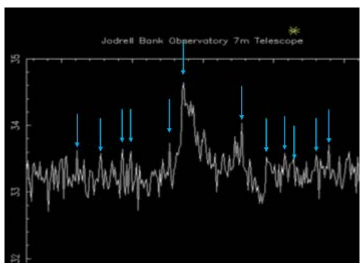


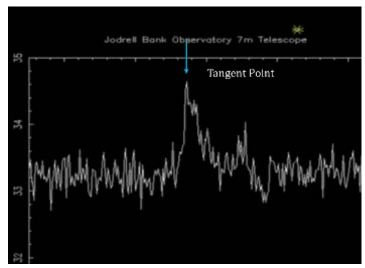

The dust absorbs and scatters the light that passes through it. The further the light has to travel, the more of this dust it encounters, and the dimmer it gets. Astronomers call this 'extinction'. Due to this extinction effect, stars in the galactic disc can lose half their luminosity every 3,000 light years. [It wasn't until we could measure the amount of dust between us and the stars that we could accurately use standard candles to determine how far away they were. It was the astronomer Robert Trumpler who first quantified this phenomenon in the 1930s.]




These clouds are best viewed using radio astronomy. This is because gas clouds radiate radio waves. And radio waves pass through dust particles untouched because their wavelength is much larger than the size of these particles. We can see these clouds all across the galaxy, including the hidden area behind the central bulge. What's more, the hydrogen in these regions emit a spectral line in the radio frequency band. And this spectral line exhibits Doppler shifts enabling us to measure the cloud's radial velocity relative to us.

In this line of sight reading, we see a number of peaks. Each one represents a cloud. The peaks have different frequencies because the clouds have different radial velocities. The maximum peak is from a cloud that's radial velocity is close to its total orbital velocity. **[Additional info:** In particular, in HI regions, neutral hydrogen has one at 21 cm from neutral hydrogen, and in HII regions, carbon monoxide has one at 2.6 and 1.3 mm.**]**



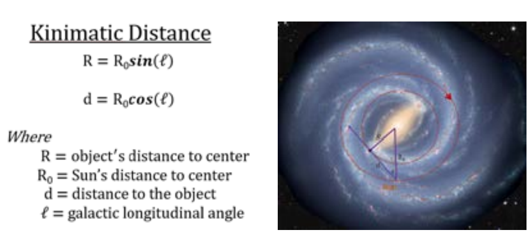



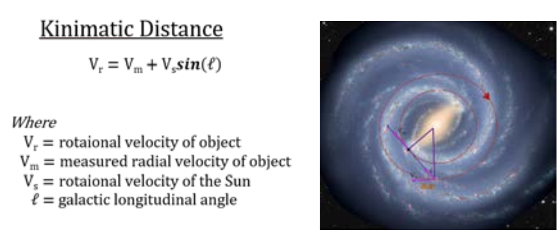

**[Kinematic Distance**

We can use the Doppler shift of dust clouds to find the kinematic distance to the object and calculate how fast it is rotating around the center of the galaxy. Kinematic distance is the distance to an object based on its motion.

**[Additional Info:** Motion around the galactic center is generally circular, but all stars, including our own, have orbits that are perturbed by the presence of other stars. To calculate a baseline motion we use a Local Standard of Rest (LSR) based on the average motion of all the stars in our vicinity. It is currently set at 220 km/s ($V_0$) at 26,100 ly ($R_0$) from the center. In addition, based on several Palomar Observatory Sky Surveys, we are 65.2 light years above the galactic plane.**]**

In order to convert this radial velocity information into rotational velocity and distance from the center of the galaxy, we use a technique called the Tangent Point Method. First, we take a line of sight look for clouds. Having found one, we adjust the longitude to get the maximum radial velocity based on the Doppler shift. This will mark the clouds closet approach to the center. At this tangent point, a line to the center will be perpendicular to the line of sight. Here, the radial velocity of the cloud will be equal to its rotational velocity around the center of the galaxy. We can calculate its distance from the center and its distance from us with a little trigonometry.



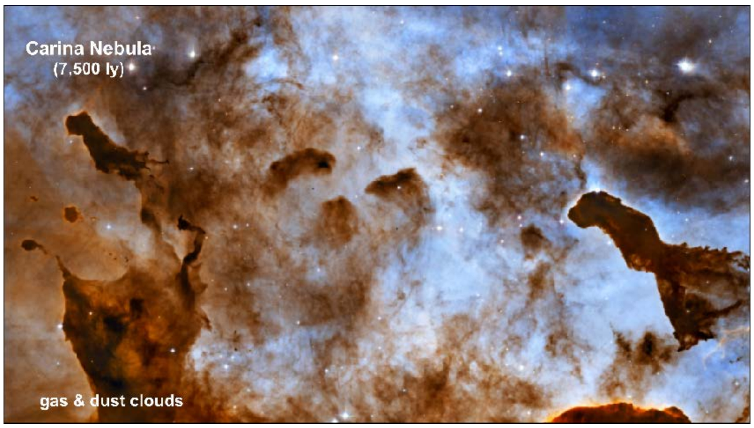




**]**

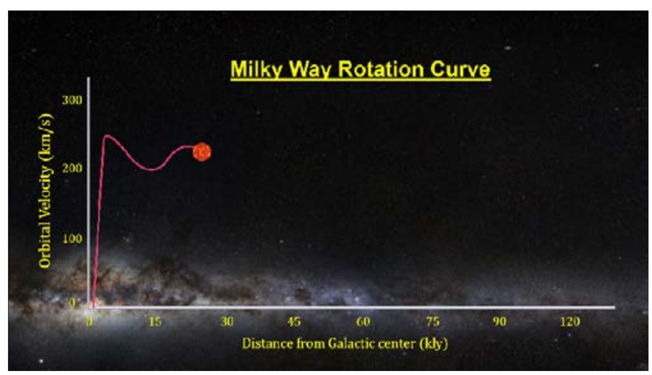
## Milky Way Rotation Curve

The best way to map out the rotation curve for the galaxy's disk is to measure the orbital velocities and distances of gas clouds and star forming regions across the galaxy. These are the HI, HII, and molecular clouds we covered in our segment on "Star Birth Nebula". These are the best objects to analyze for three reasons:

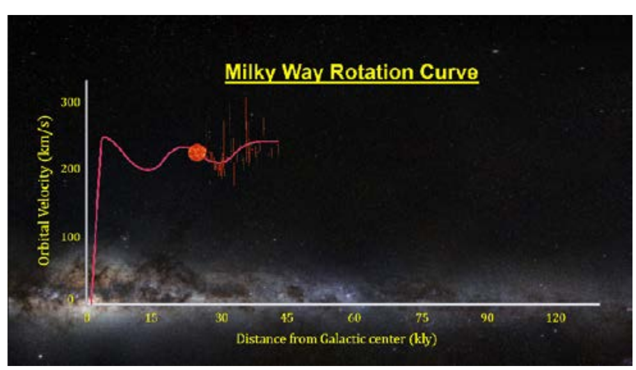
1) They trace out the spiral arms;
2) We can see them clearly at great distances using radio astronomy; and
3) There is a good way to calculate their distance for the inner part of the galaxy.



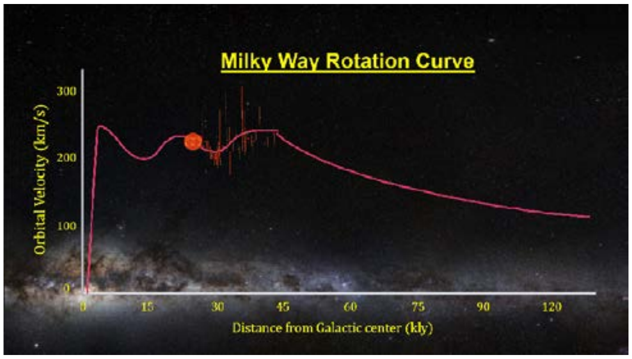

So for clouds closer to the center than we are, we can scan the sky, bit by bit and create a map of the rotation velocity and distance for the inner galaxy. This map can then be used to find distances to all the clouds and the stars they contain as long as they are closer to the center of the galaxy than we are.



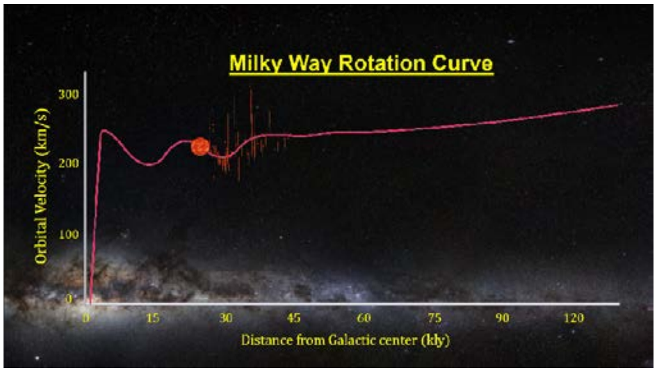

For clouds further out, there are no tangent points. For these, we have to use weaker methods for determining distance and rotational velocity. We then do a best fit line from the collected data. Here is a graphic superimposed on our galaxy curve that indicates the accuracy of methods used to provide the included data points. The vertical lines through each point represent the range of possible velocities for any given distance. Notice that these lines are quite long.



Rotation curves give us a measure of a system's mass. And, at the outer edges of the disk, the star mass density drops off dramatically. That's why, in the 1970s, everyone expected to see a rotation curve that looked like this.



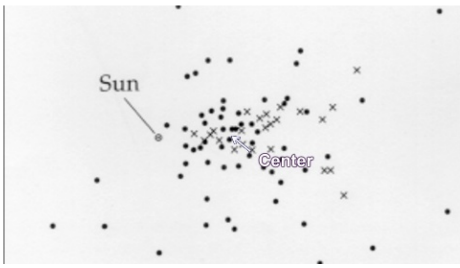

But what we found is that, where the velocities were expected to fall off, they remained relatively constant. If our current theory of gravity holds up over galactic distances, then this curve tells us that our model of the Milky Way is missing something. In order for objects far from the center of the Galaxy to be moving faster than predicted, there must be significant additional mass far from the Galactic Center exerting gravitational pulls on those stars.

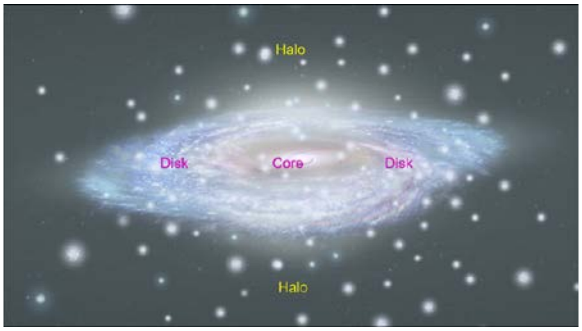



This means that the Milky Way must include an unseen component that is very massive and much larger than the galaxy's visible disk. Not knowing what it is, we call it Dark Matter and it extends way into the galaxy's halo.

## The Milky Way Halo

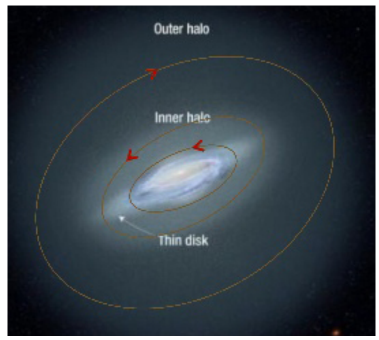
At the turn of the 20th century, astronomer Harlow Sharpley, studying a large number of RR Lyrae stars inside globular clusters, found that the center of the galaxy was far from the Sun. He mapped 93 globular clusters. They formed a spheroidal shape with their own center – not near the Sun. He concluded that these giant clusters formed the "bony frame" of the galaxy.



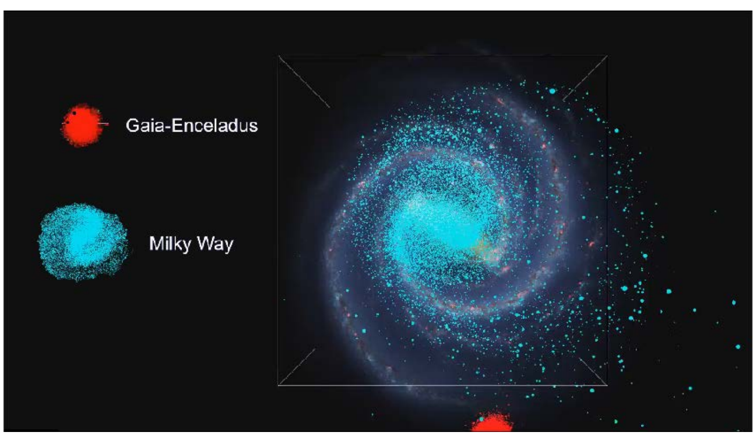



This area around the disk is called the galactic halo or corona. It holds a large number of old stars and 158 globular clusters. The Galactic halo itself has a diameter of at least 600,000 light years based on the locations of the globular clusters, although it may extend much further. [There is no star formation out in the halo.

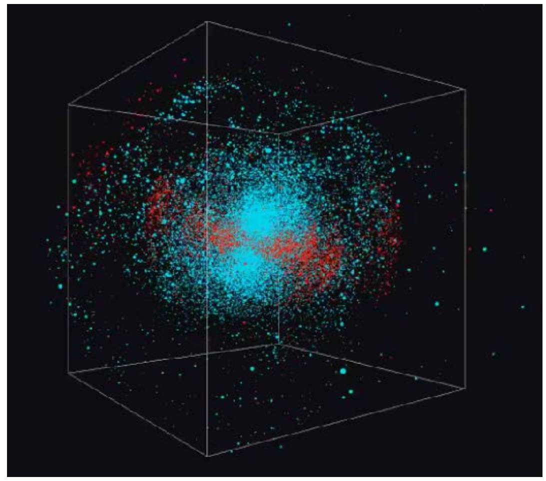
In 2007, using 20,000 stars observed by the Sloan Digital Sky Survey, an international team of astronomers discovered that the Milky Way halo is a mix of two distinct components rotating in opposite directions: the outer halo and the inner halo.



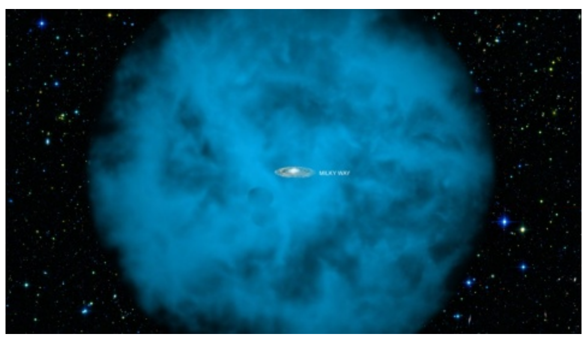

Then, in 2018, a team of astronomers analyzed seven million stars from the Gaia mission, and found that 30,000 of them were moving counter to the normal Milky Way flow. Star motion and composition profiles indicated that they came from a different galaxy. They called this new galaxy Gaia-Enceladus. Using computer models for galaxy collisions, they estimated that it collided with the Milky Way around 10 billion years ago.



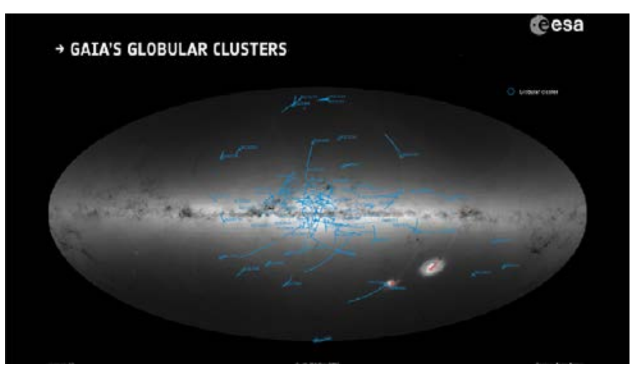
This is a computer simulation of the merger. Here we see that Gaia-Enceladus is now our galaxy's inner halo.



On September 24, 2012, Chandra found evidence that the Milky Way Galaxy is embedded with a large amount of hot gas in the halo. Counting this vast amount of gas, the mass of the halo is estimated to equal the mass of the stars in the galaxy! But, as massive as it is, the amount of matter in this hot gas is not nearly enough to explain the galaxy's rotation curves. Dark Matter or a new theory of gravity is still needed.

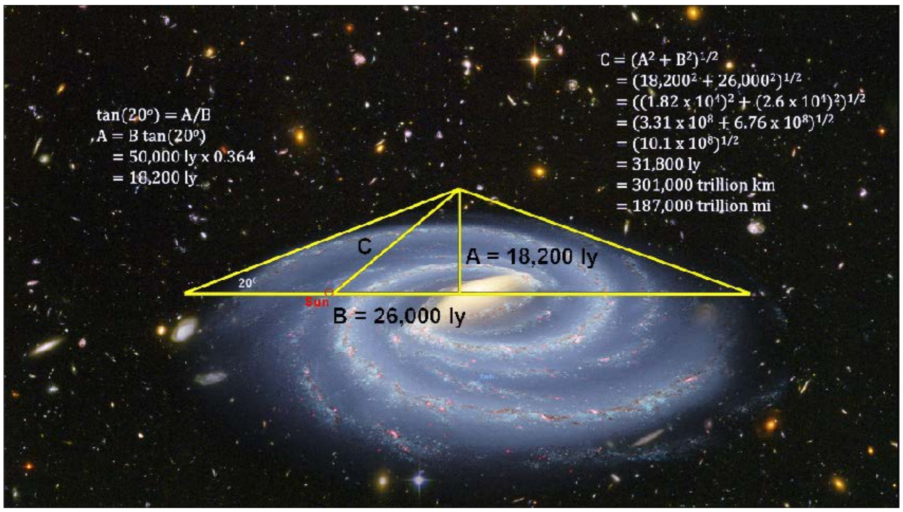


In 2018, using both Hubble and Gaia data on globular cluster sizes and velocities, the mass of our galaxy was estimated to be at least 1.5 trillion times the mass of our sun. This is more than previous estimates and indicates that the Milky Way is among the universe's larger galaxies.

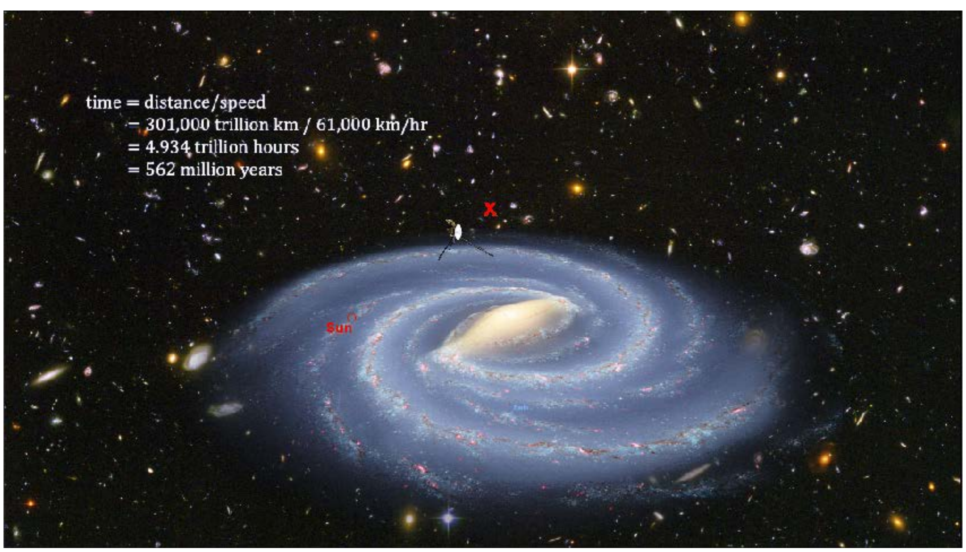


## Milky Way Photo Point

We started with an image of the Milky Way constructed from within the galaxy. Whenever you see any picture of the whole Milky Way from outside the galaxy, remember that it is an artist drawing. The size of the galaxy is so large, that the distance one must travel to see it all is way too far. Here's what I mean. If we assume that our field of view is 140 degrees, we can use trigonometry to find the distance to a point where such a picture could be taken. That point is approximately 301,000 trillion km or 187,000 trillion miles from the Sun's current location.



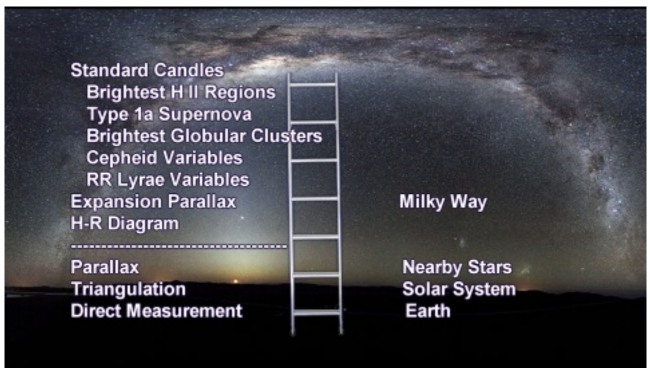

Voyager I left on its journey in 1977 and is traveling at 61,000 km/hr or 38,000 miles per hour. It has already gone 21.2 billion km or 13.2 billion miles. If we aim it at the photographic point, at its current velocity, Voyager won't reach this point for another 562 million years. If some future generation were to ever take such a picture, they would see our entire solar system as little more than a single pixel.



## Chapter Conclusion

In our chapter on the Milky Way:

- We studied the nearby stars were parallax told us how far away they were.
- We developed the H-R diagram as a way to calculate luminosity based on temperature and spectral analysis.
- We covered key standard candles such as Cepheid and RR Lyrae Variables as well as Type 1a Supernovae
- And we examined star clusters; planetary nebula; and emission nebula for their beauty and value as standard candles.




This distance ladder took us all the way across the galaxy. In our next chapter, we'll use all these techniques to move out into intergalactic space.

Greek letters:
- α β γ δ ε ζ η θ ι κ λ μ ν ξ ο π ρ σ τ υ φ χ ψ ω
- Α Β Γ Δ Ε Ζ Η Θ Ι Κ Λ Μ Ν Ξ Ο Π Ρ Σ Τ Υ Φ Χ Ψ Ω

⇒ → ± ⊙ ∞ ↛ ∃ ∄ ∈ ∉ ∬ ∫ ≅ ≥ ≤ ≈ ≠ ≡ √ ∛ ~ ∝ ħ ÷