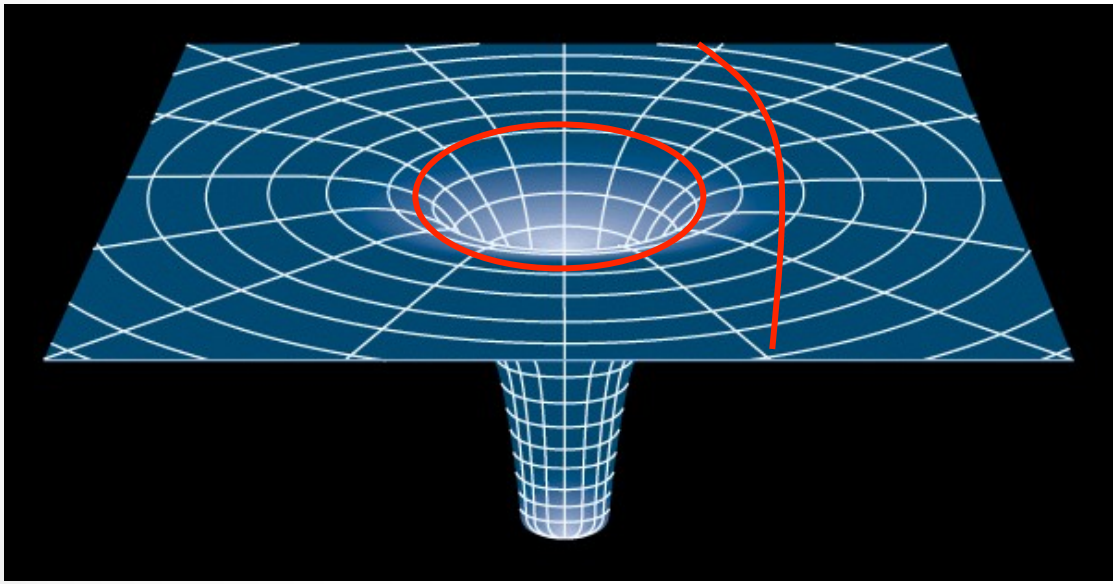
Review of Lecture 10

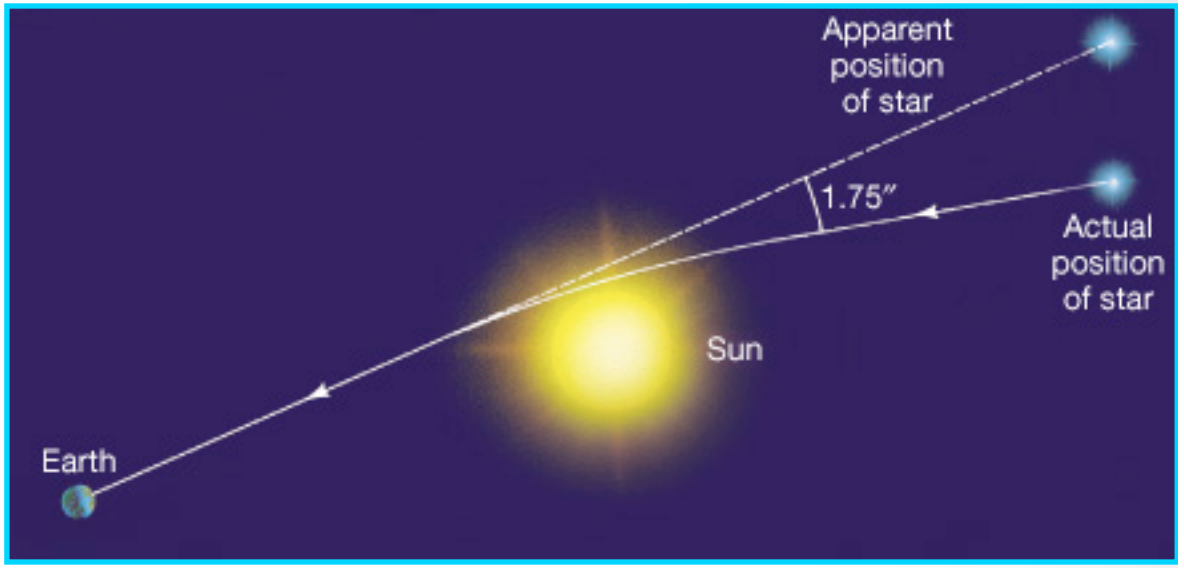
- General Relativity as a replacement for Newtonian gravity. Mass warps spacetime



In this model, orbits are are straight lines in curved spacetime

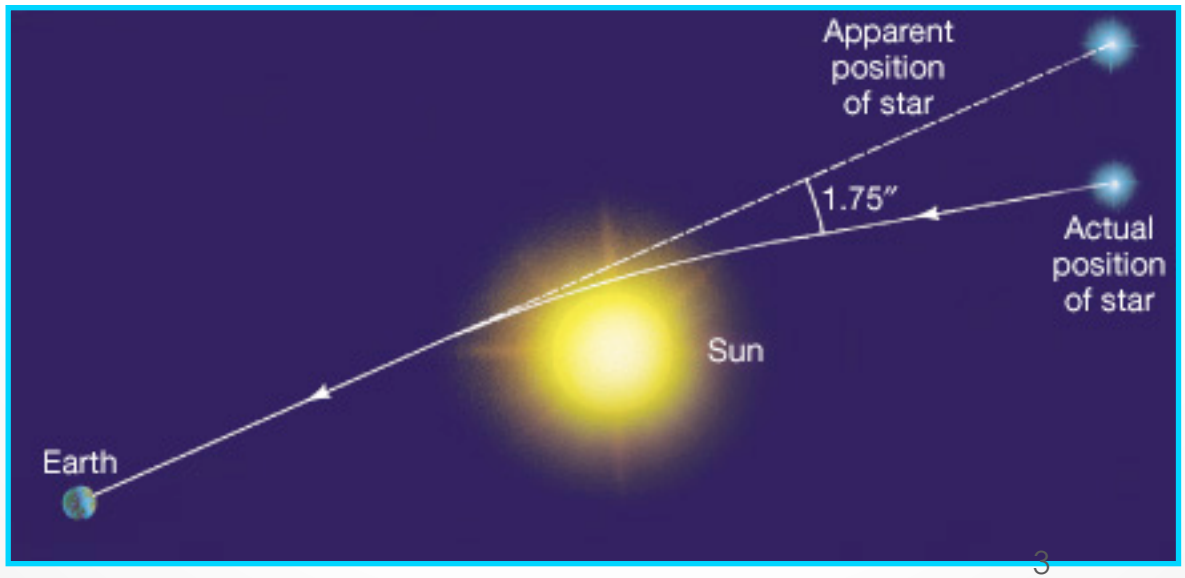
In this model photons follow the same straight lines in curved space and are subject to gravity

GR predictions: lensing

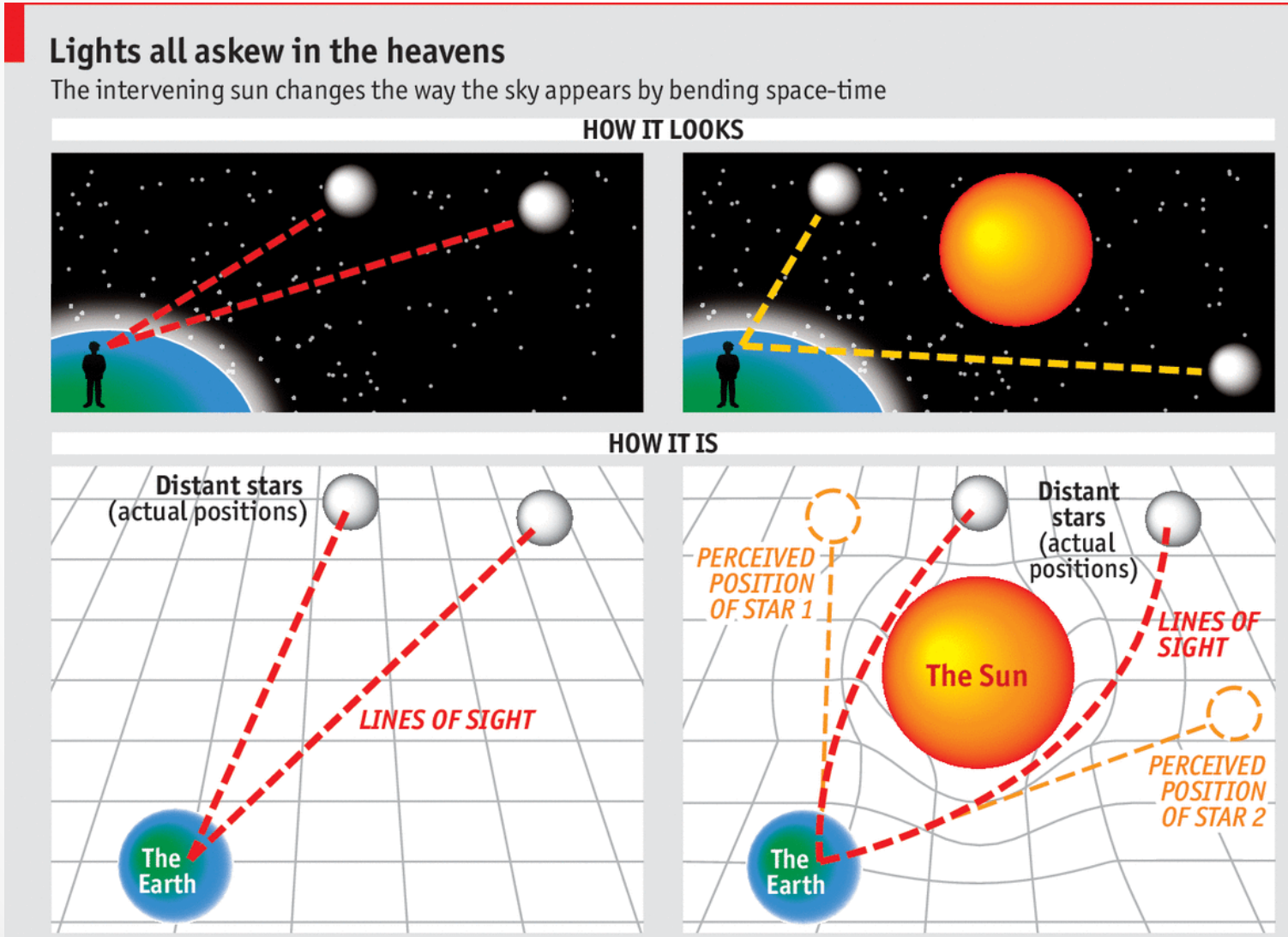


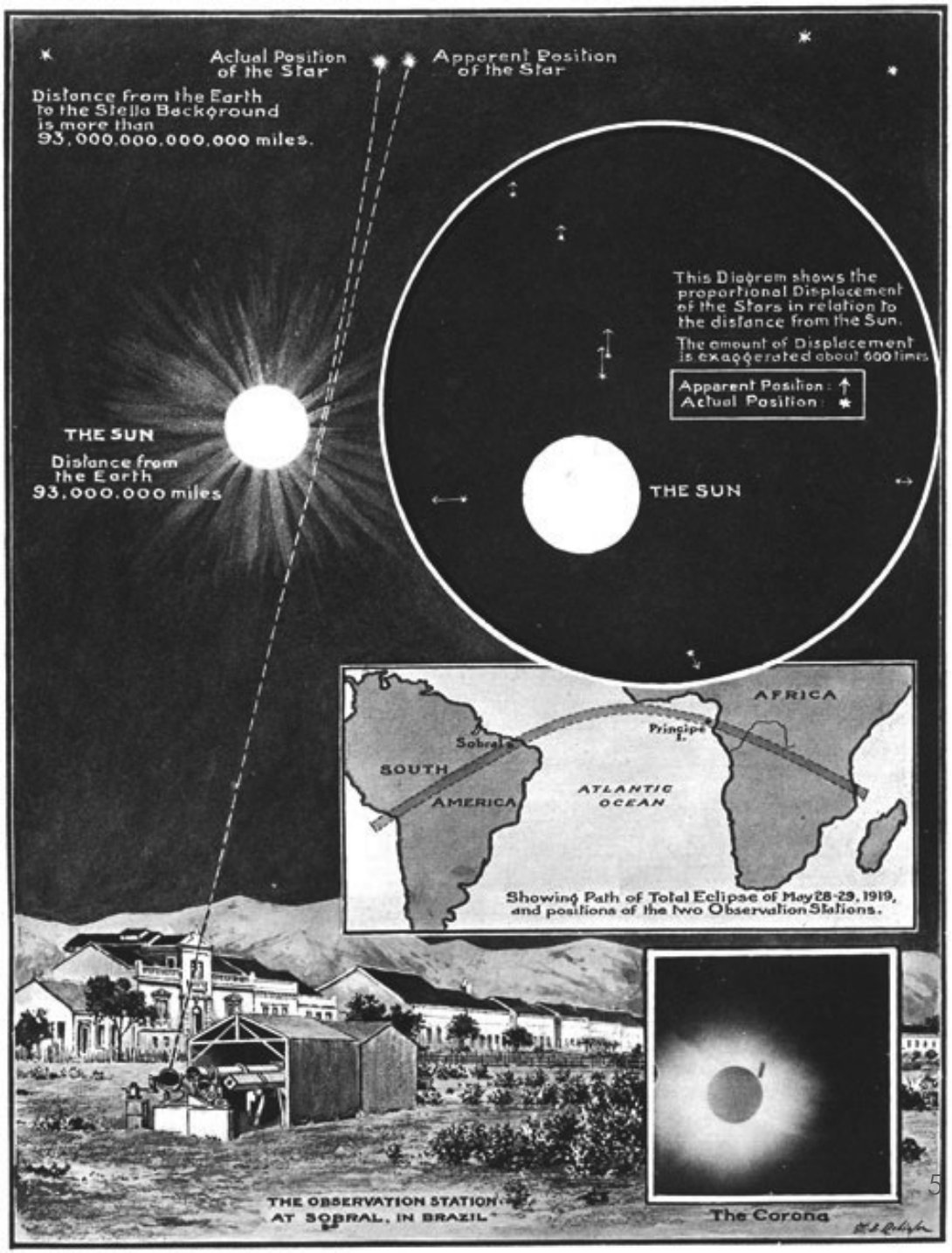
The Deflection of Starlight

- There were several other predictions of GR, one important one was that light rays would also follow straight lines through curved space.



The Einstein Effect




Actual Position of the Star
Apparent Position of the Star
Distance from the Earth to the Stella Background is more than 93,000,000,000,000 miles.
THE SUN
Distance from the Earth 93,000,000 miles
This Diagram shows the proportional Displacement of the Stars in relation to the distance from the Sun.
The amount of Displacement is exaggerated about 600 times
Apparent Position :
Actual Position :
THE SUN
AFRICA
Principe
Sobral
SOUTH AMERICA
ATLANTIC OCEAN
Showing Path of Total Eclipse of May 28-29, 1919, and positions of the two Observation Stations.
THE OBSERVATION STATION AT SOBRAL, IN BRAZIL
The Corona

Escape Speed

- Set v_{escape}=c and that is the Schwarzchild radius. Any object that is compressed to its Schwarzchild radius collapes to become a black hole

Earth you set
ual to kinetic

ass of the
ject from
which you
want to escape

$$\frac{1}{2}mv^2 = \frac{GmM}{R}$$

Mass of the escaping object

$$v_{escape} = \sqrt{\frac{2 \times G \times M}{R}}$$

Radius from which you want to escape

- Inside the volume (inside the Event Horizon or the Schwarzchild radius) where the escape speed is larger than the speed of light, no information can escape the to rest of the Universe. This is a black hole.
- Note that space time has also curved back in itself inside the event horizon
- All objects have a radius at which they become a black hole, but it is very, very difficult to compress and object to that radius

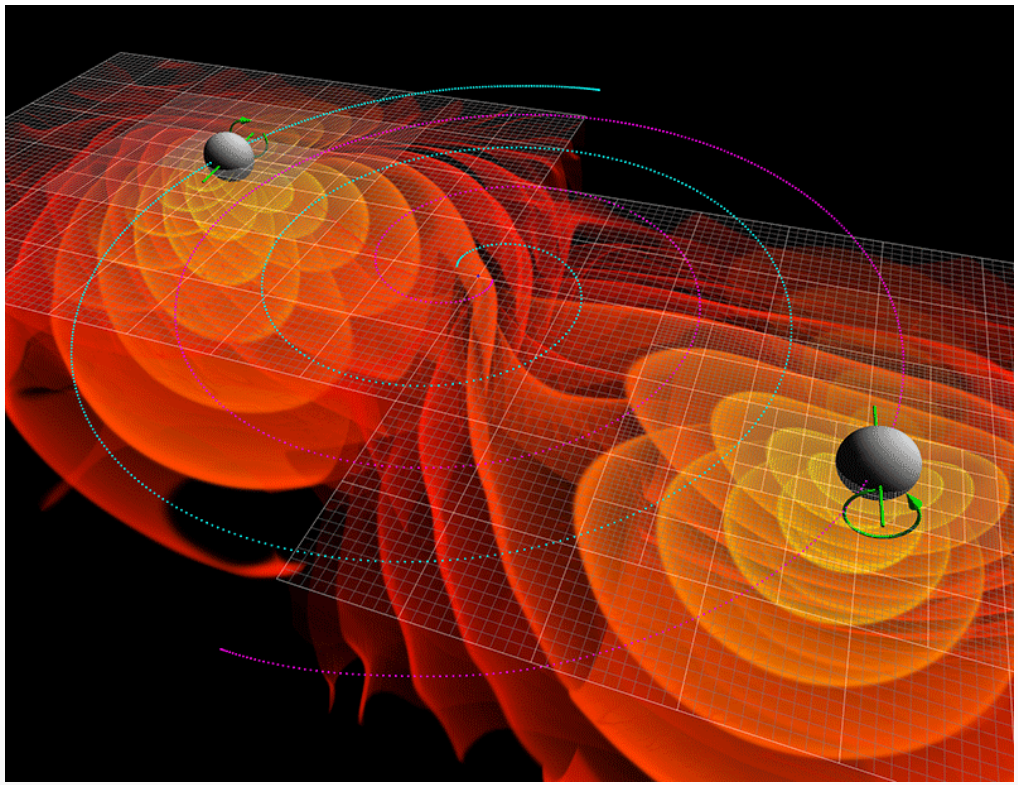
Main-sequence star: Gravity vs thermal pressure

- White dwarf: gravity vs e- degeneracy
  6000km radius
  Upper mass limit: $1.4M_{Sun}$

- Neutron star: gravity vs neutron degeneracy
  Size
  Upper mass limit: $2.5\text{-}3M_{Sun}$

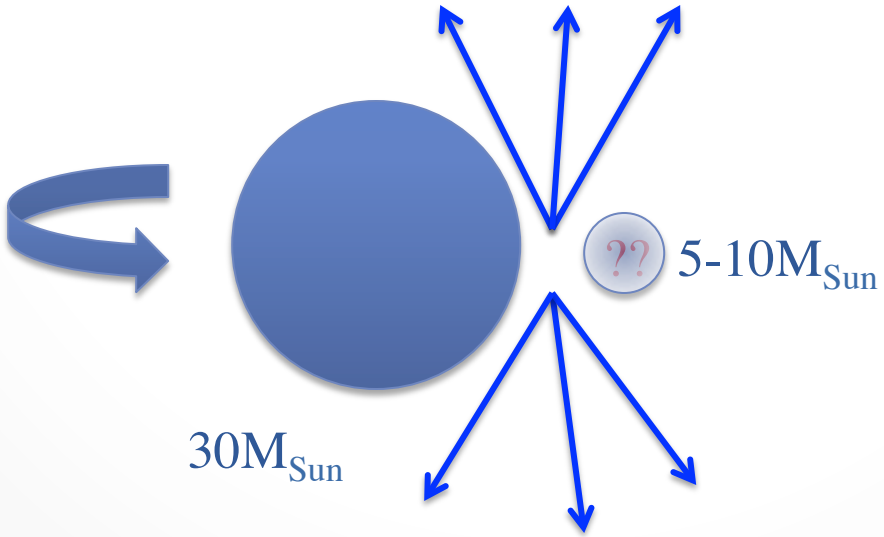
Formation of stellar mass BH

- "fallback" of some material after the formation of a neutron star after core collapse of a massive star
- Merging of two neutron stars



Black Hole Evidence

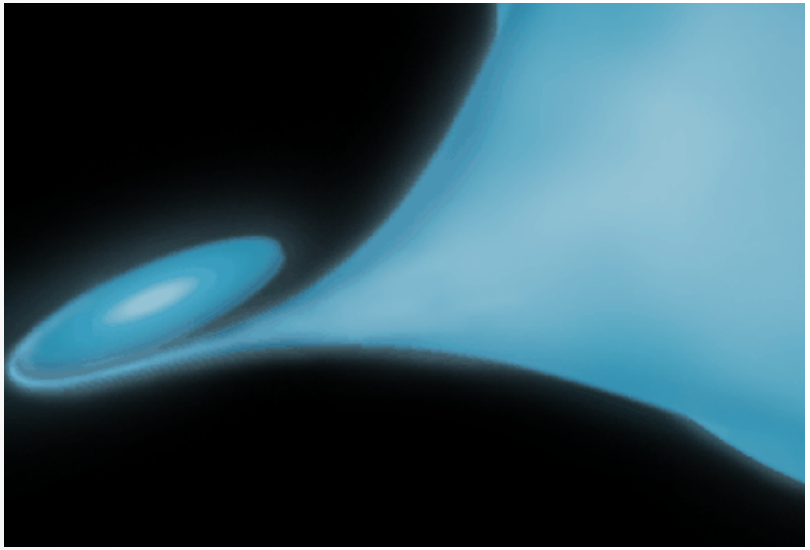
- Cyg X-1 is a bright x-ray source. Look there in the visual part of the spectrum, we see a $30M_{Sun}$ blue main-sequence star which is a spectroscopic binary with a period of 5.6 days.
- The companion has a mass of between 5 and $10M_{Sun}$. What is it?



Cygnus X-1

- There is no sign of the companion at any wavelength (but, remember the x-rays) so what is it?
  1) A red giant would be easily seen
  2) A main-sequence star would be seen with a little effort
  3) Can't be a WD because $M>1.4M_{\odot}$
  4) Can't be a n-star because $M>3M_{\odot}$

Cygnus X-1



- By elimination, we are left with a black hole
- The x-rays back this up. In an accreting WD we see UV radiation, in a neutron-star we see `soft' x-rays, in Cyg X-1 we see `hard' x-rays because the accreting material falls into a deeper potential well.

The equation for the Schwarzschild radius and event horizon radius is:

$$R_S = 2GM/c^2$$

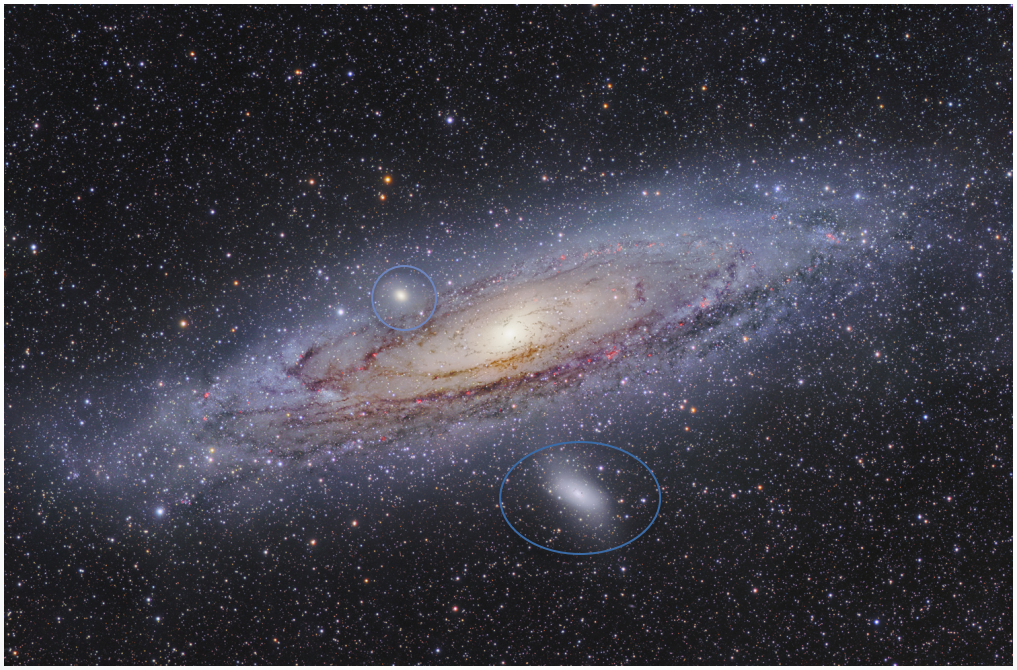
If a black hole of $3M_{Sun}$ merges with a second black hole of $3M_{Sun}$, what happens to the event horizon? (iclicker quiz)

A. It shrinks by a factor of 2 because the gravity is now stronger
B. It increases by a factor of 1, the ratio of the masses
C. It increases by a factor of 2

In formula above, if M goes up by factor 2, so does R_S

Galaxies

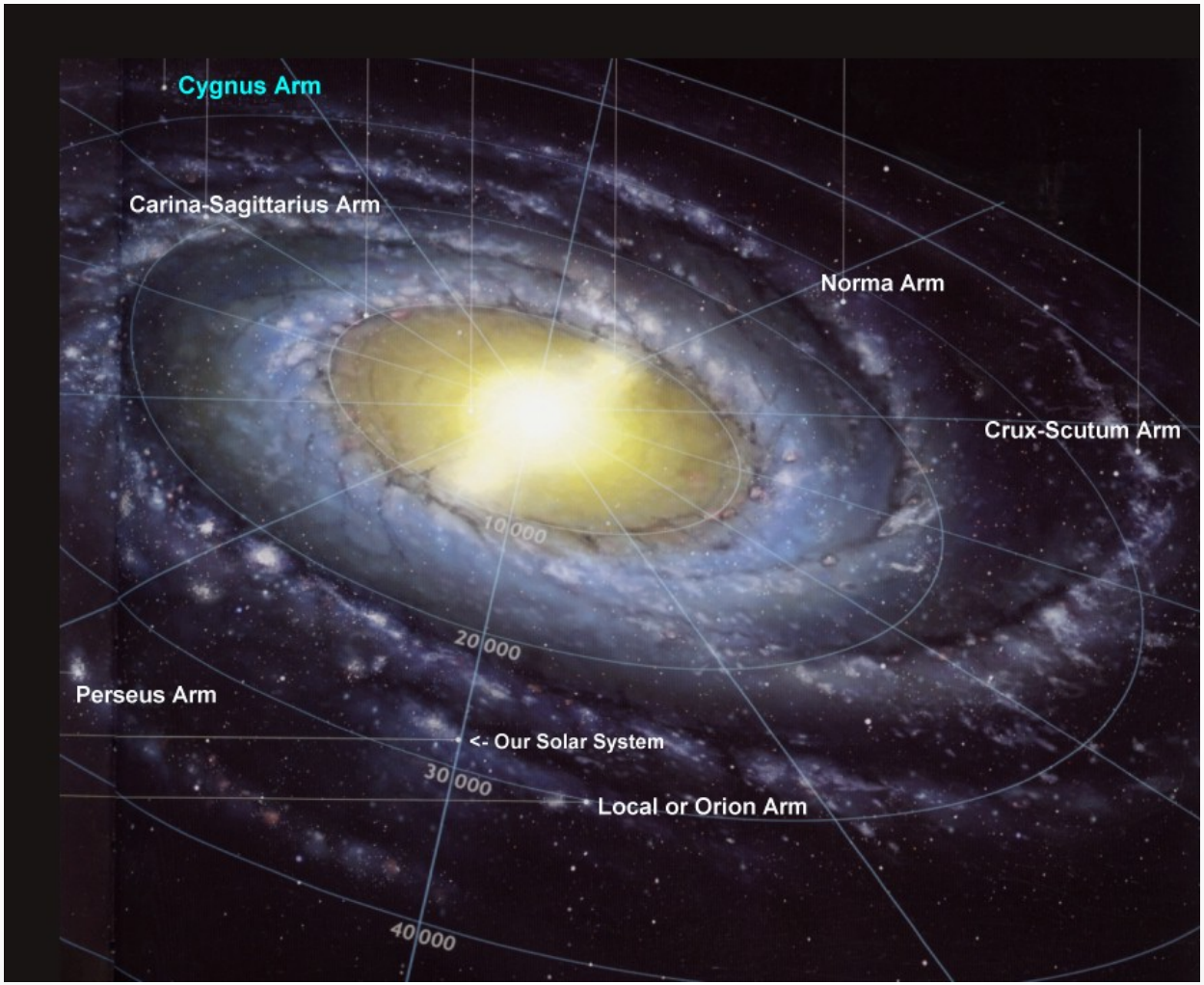
- The Earth, Sun and Solar System live in a system containing stars, planets, gas, dust, white dwarfs, neutron stars, black holes, asteroids, brown dwarfs and more all bound together by gravity (in a curved space time). This is the Milky Way Galaxy.



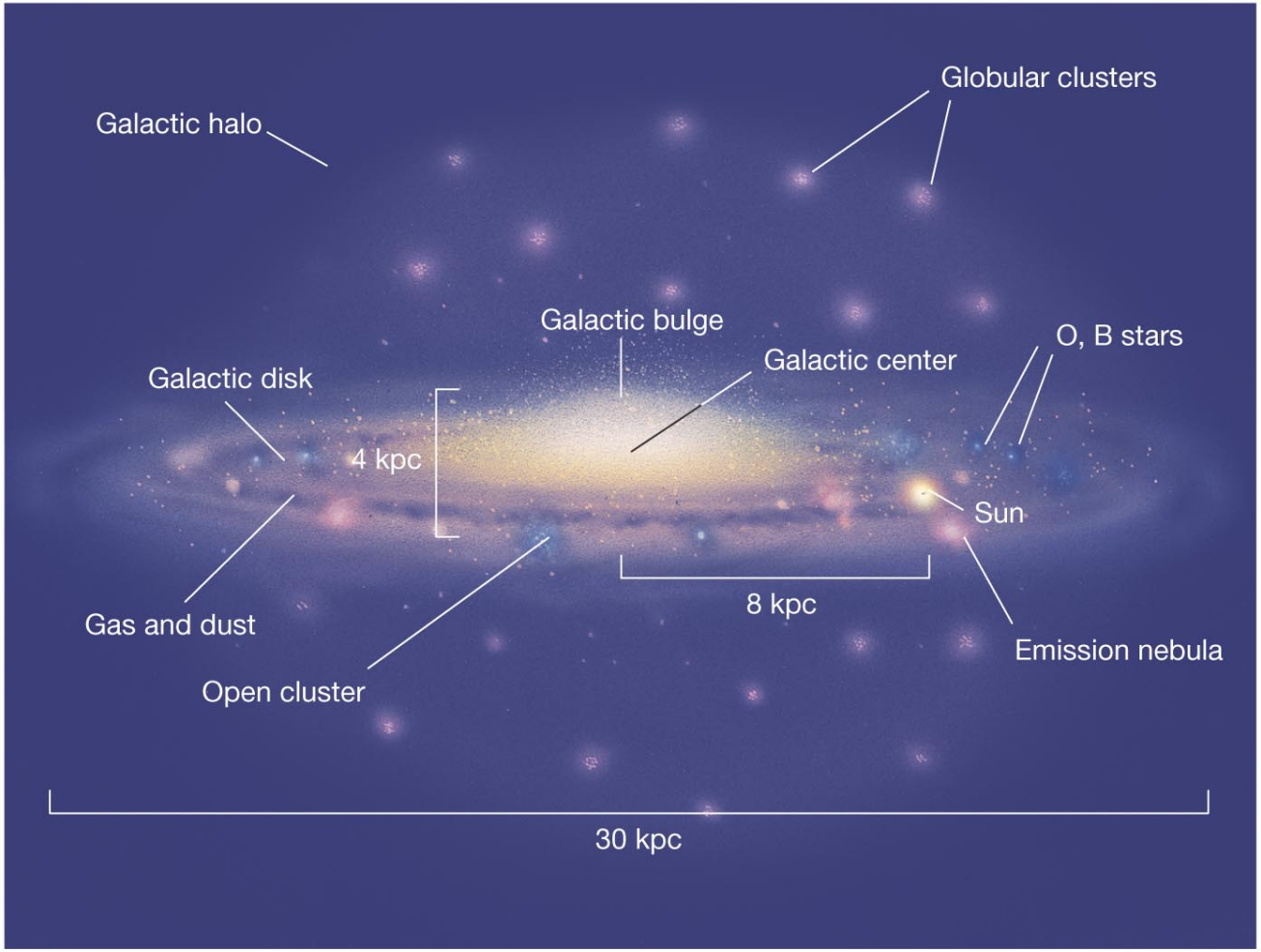
Milky Way Galaxy

Stars	3×10^{11}
Planets	4×10^{11}
Gas	20% by mass
Disk diameter	120,000 LY
Age	12.5×10^{9} years

Milky Way Galaxy Structure



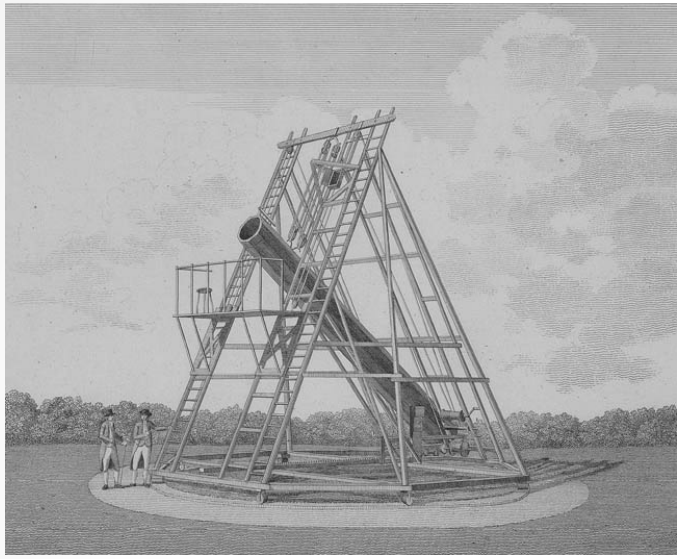
Milky Way Structure II

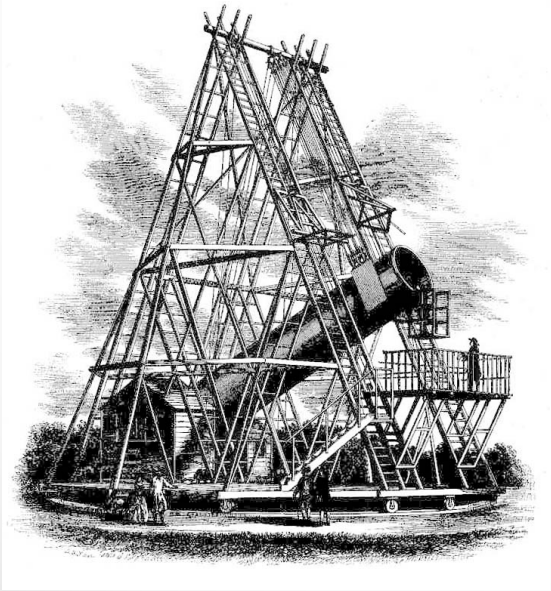


Short History of Understanding the Milky Way Galaxy

Galileo using his 1" telescope was the first to discover the "Milky Way" was composed of individual stars.

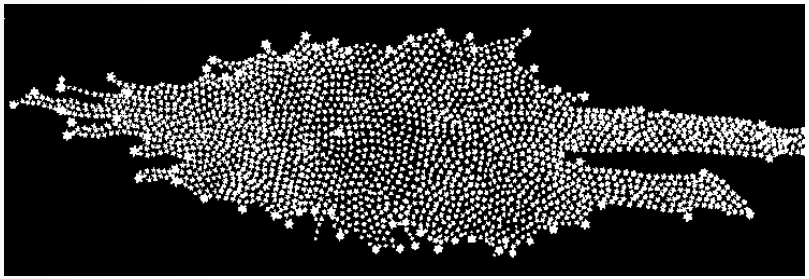
Next 300 years: star counts





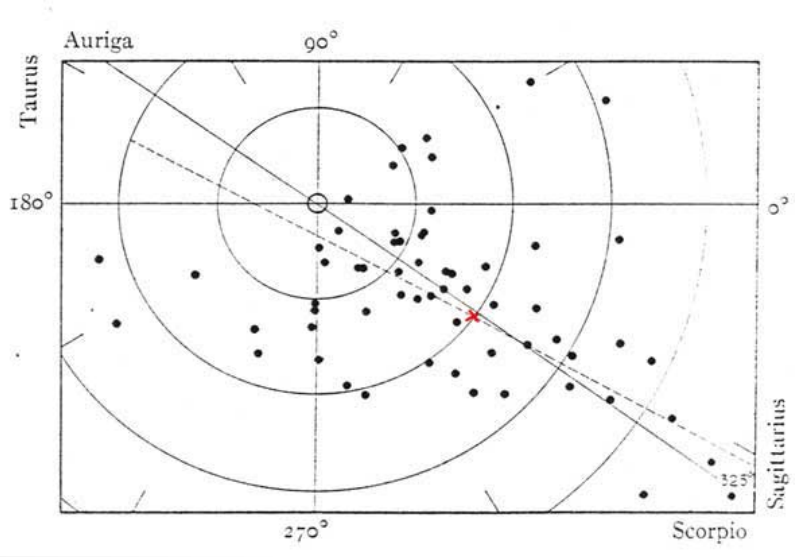
- Star counts were popular and a sense of the stellar system the Sun was a part of started to grow
- But, no knowledge of obscuring dust and no way to get distances to stars

Galactic Model 1781



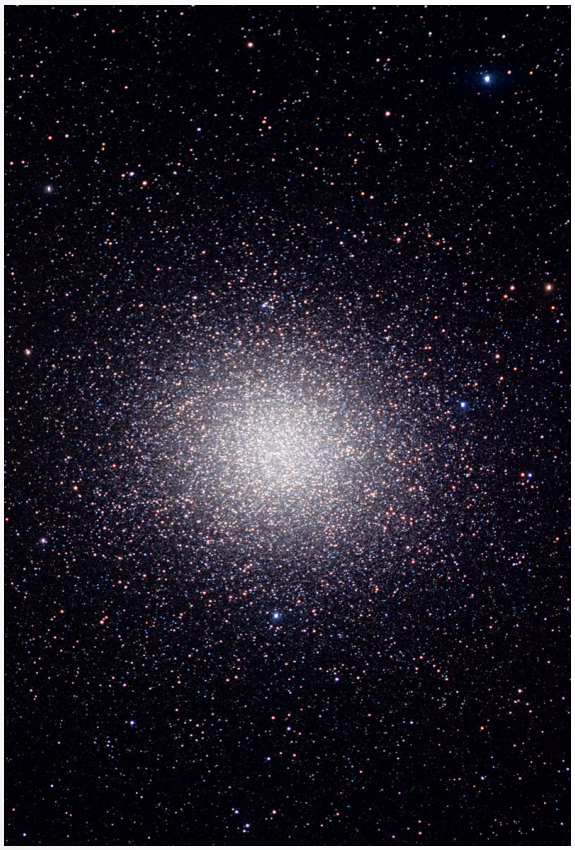
- William and Caroline Herschel built telescopes, observed the sky and made a map of the Galaxy that was the standard for 100 years

Major Progress: 1900-1920



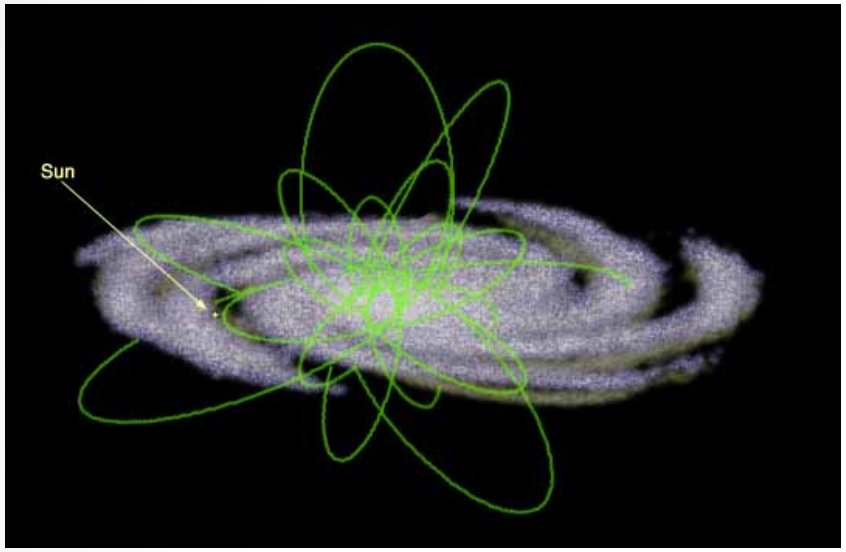
- The distance scale to stars was established via parallax measures and use of variable stars
- The presence of dust was inferred
- Harvard Astronomer Harlow Shapley determined the Galaxy was a factor of 100 larger than previously thought
- The solar system was far from the center

Globular Clusters



- Key to establishing the size of Galaxy was studies of Globular Clusters
- Gravitational bound groups of up to 10^6 stars (very visible)
- 150 in the Galaxy
- Distributed in a large spherical halo around the Galaxy
- Old (12 billion years) and deficient in chemical elements

Globular Clusters

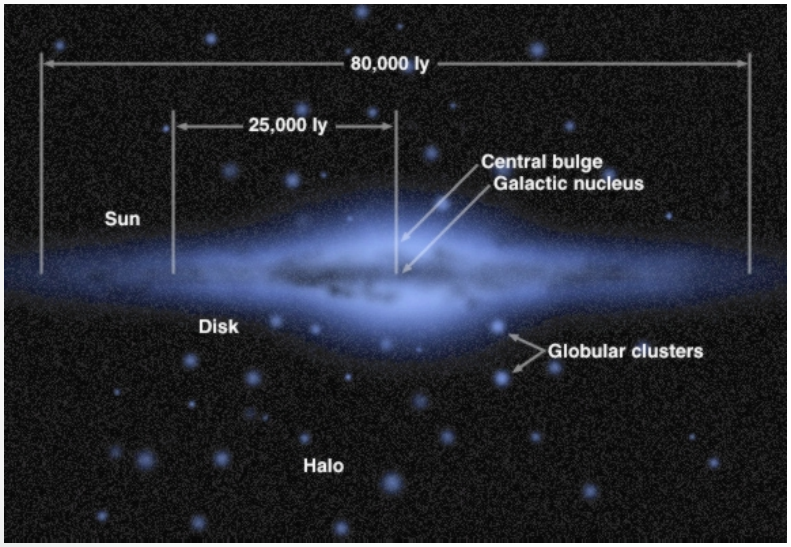


- Distribution is in a halo and the "kinematics" are those of a hot gas
- Low chemical abundances of the stars and "plunging" orbit suggest that the globular clusters were formed very early in the history of the Galaxy

Galactic Halo

- Globular Clusters are most visible component of a large spherical stellar halo of the Galaxy
- Disk and spiral arms are embedded in the halo
- Formation to be discussed in detail later

Galactic Bulge

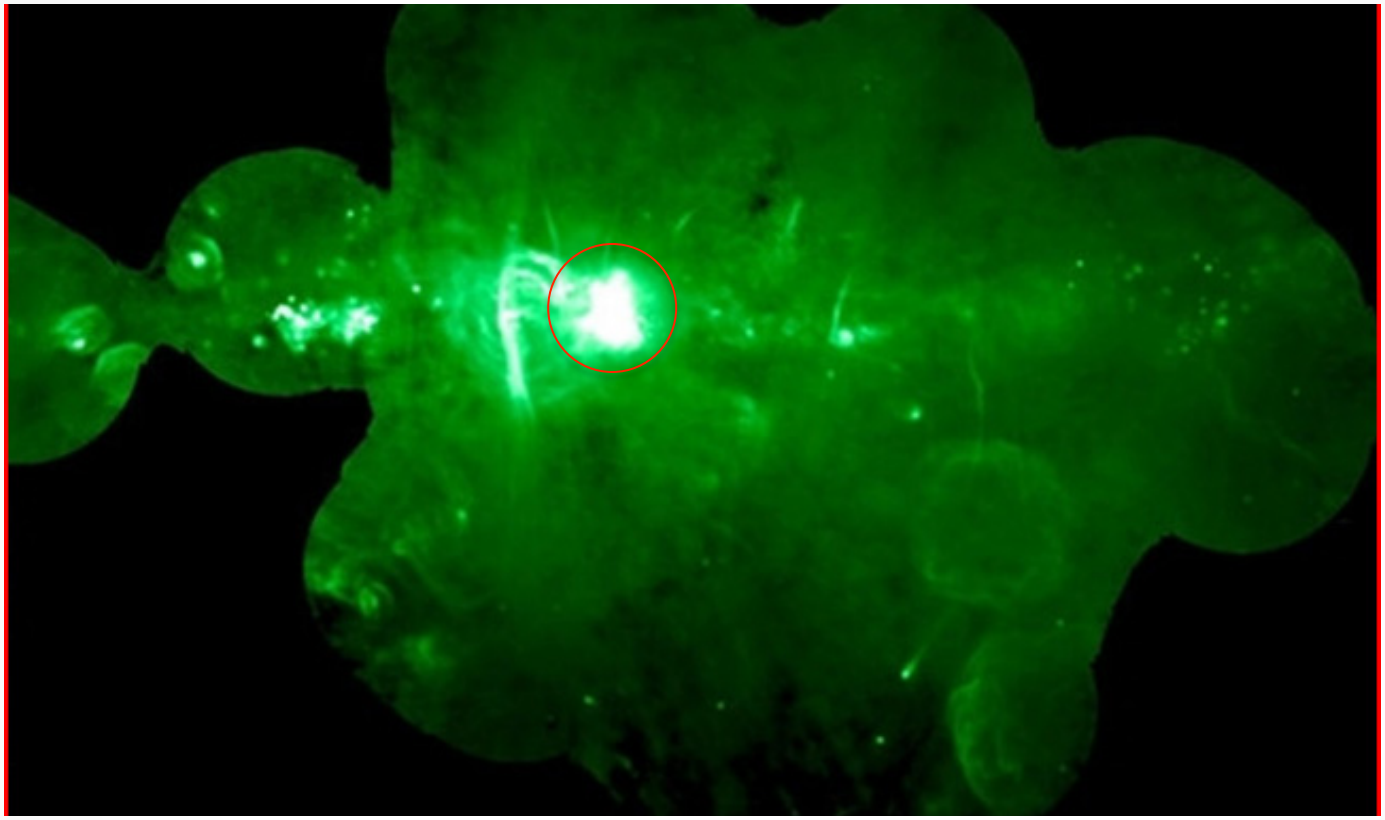


- There is another major component of the Galaxy which is called the Galactic Bulge.
- Also composed of old (12 billion years old) stars, but in the case of the bulge, primarily the same chemical abundances for stars as the Sun

Galactic Center

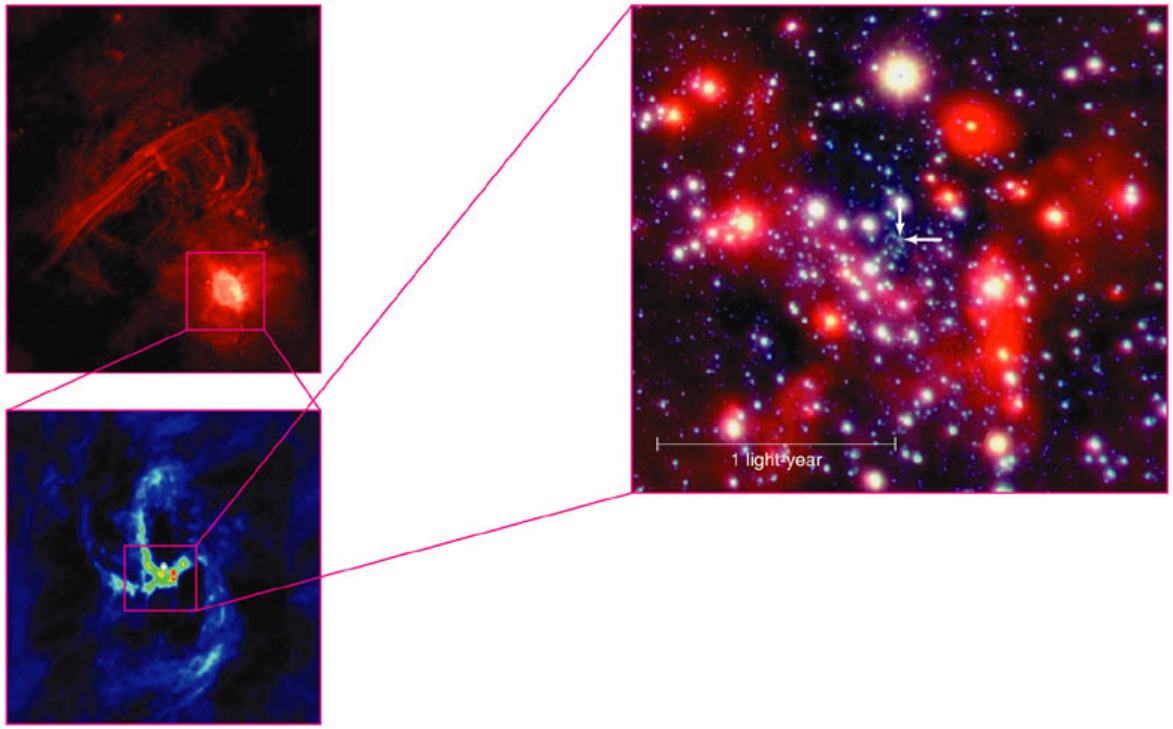
- When Harlow Shapley looked at the globular cluster distribution in the 1920s, he identified a center of the Galaxy.
- In the center of the Milky Way and about 25,000 light years from the Sun
- In the *optical* can hardly see a thing because of dust

Galactic Center

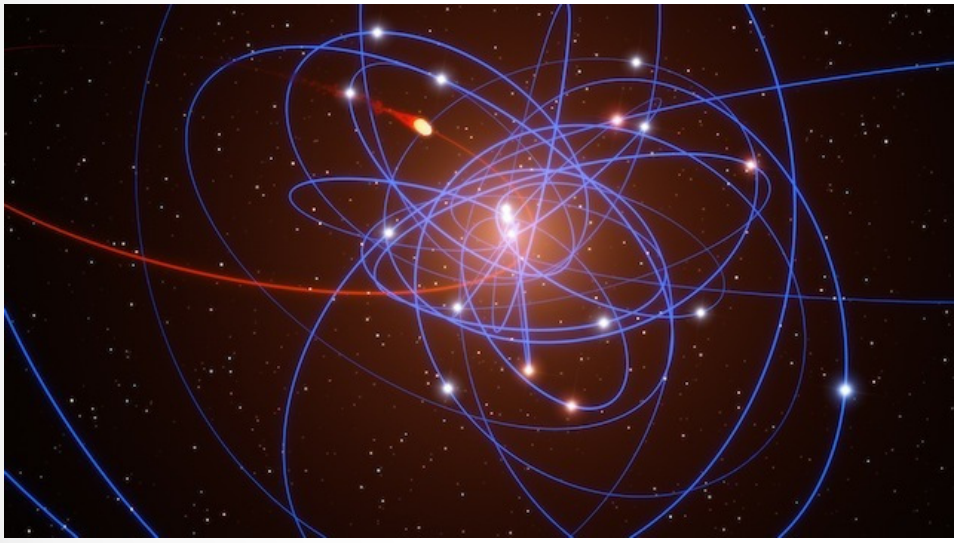


- The true center was identified in 1971via observations at radio wavelengths that identified a dynamical center at a source called “Sagittarius A*”

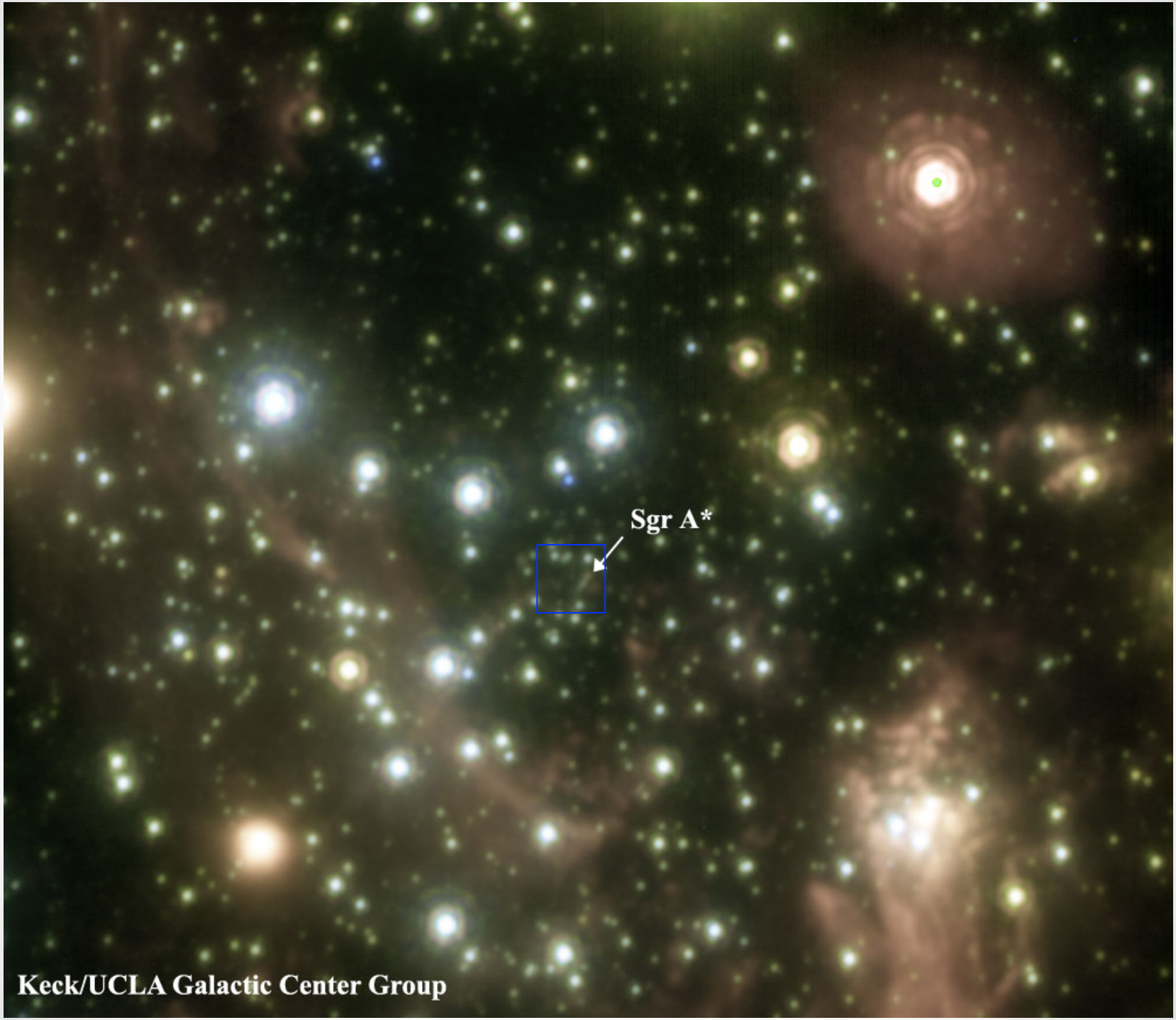
Galactic Center

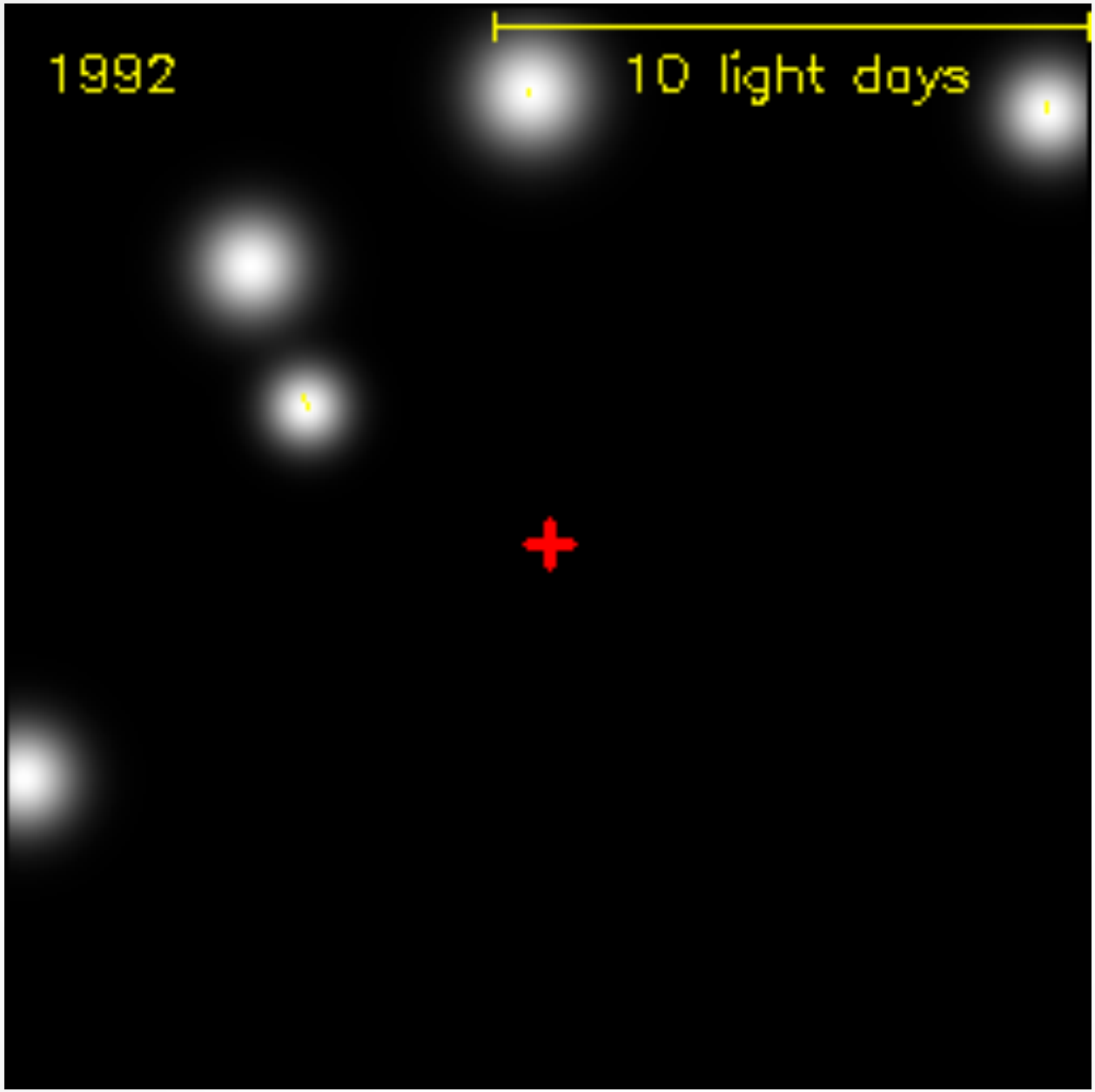


Galactic Center



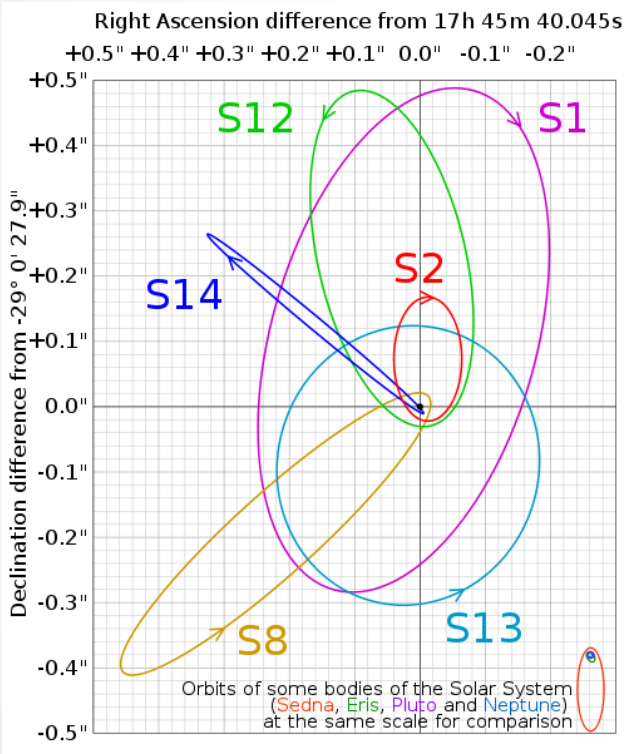
- Group at UCLA started making observations of the Galactic Center at infrared wavelengths
- Initial results suggested that stars at the very center of the Galaxy were moving in unexpected ways
- As adaptive optics improved this became very exciting


Sgr A*
Keck/UCLA Galactic Center Group



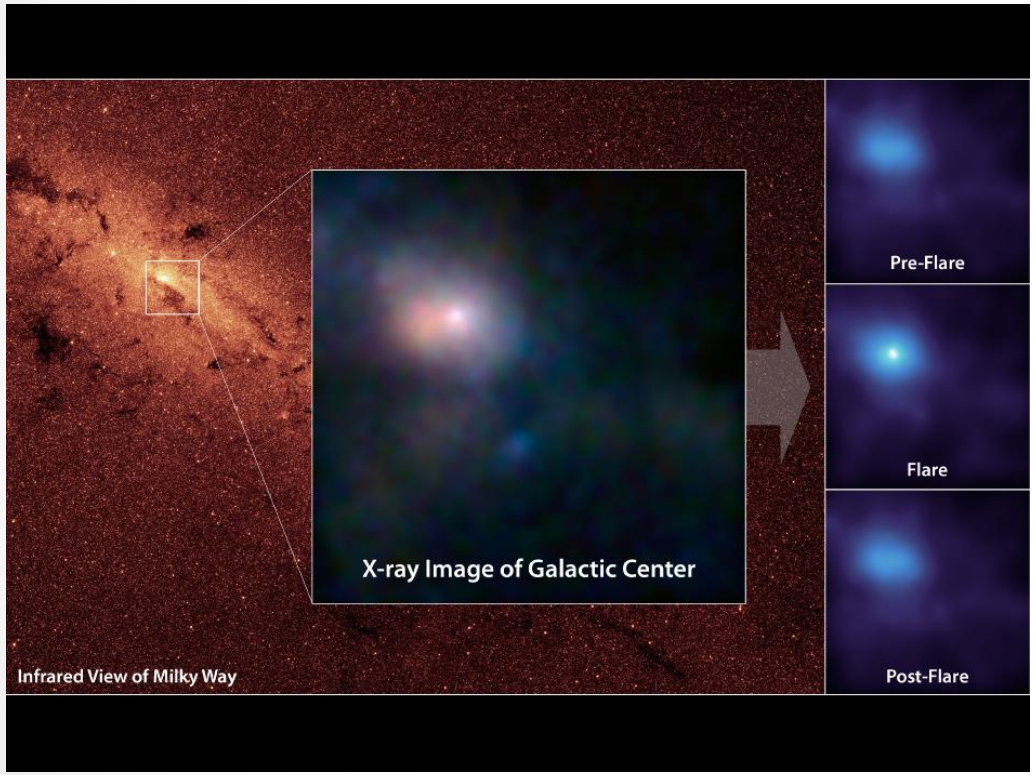
Courtesy of Andrea Ghez, UCLA

Galactic Center



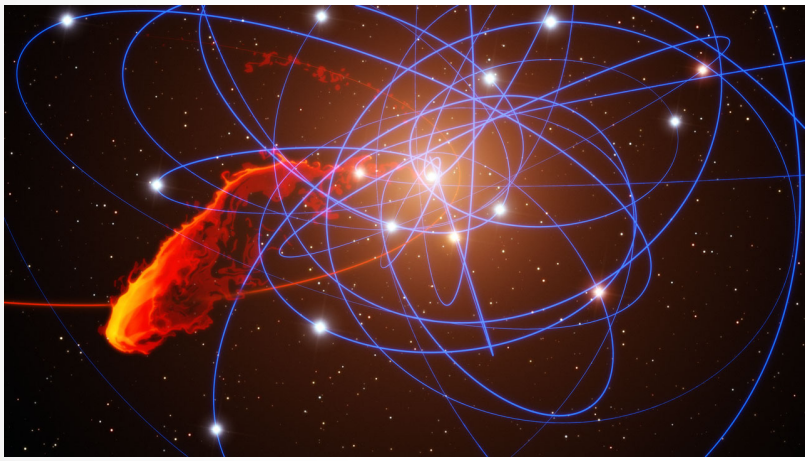
- The orbits of stars at the Galactic Center demonstrate a mass of 4.1 x 10^6 M_{sun} (8.2 x 10^{36} kg) within a volume of less than 0.3AU (r~5 x 10^7km)
- The only object with this mass and density we know of is a supermassive black hole
- Surprisingly quiet

Galactic Center Black Hole



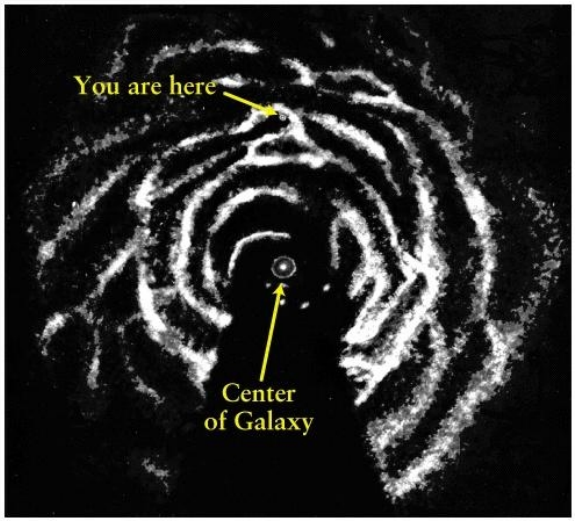
- We see burps and belches sometimes, presumably as some thing gets swallowed by the Black Hole

Galactic Center BH

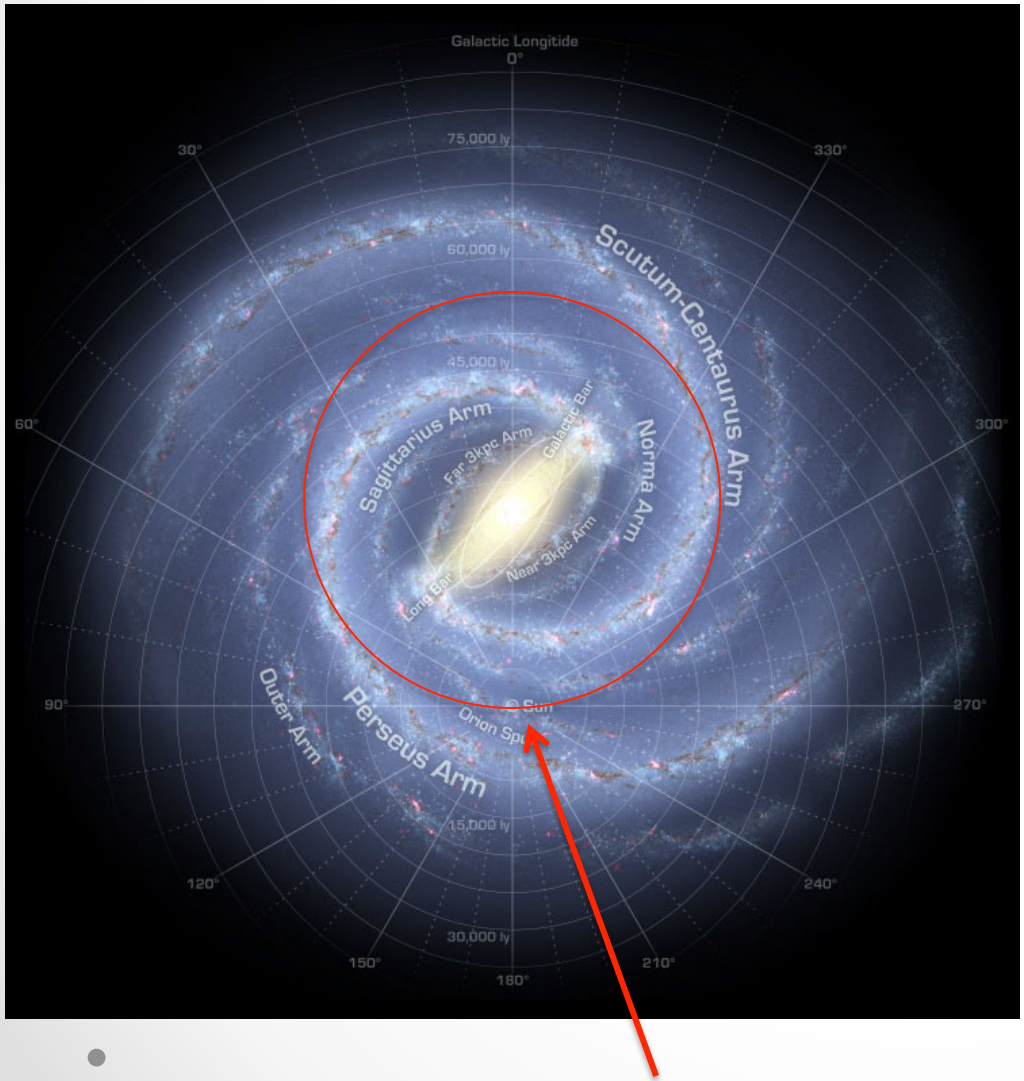


- 3 Earth mass "cloud" in the process of being tidally disrupted and swallowed by the Galactic Center black hole
- Doubled velocity in last seven years (falling in at 13 million mph)
- Fireworks should start later this year

Galactic Disk



- The last major component of the Galaxy is the disk of young stars, gas and dust
- Recognizing that these are arranged in spiral arms was difficult because we are embedded in the disk
- Radio observations of hydrogen gas were the key



- The Sun is in the Galactic disk and orbits the center of the Galaxy once every 240 million years
- 220 km/second wrt the Galactic Center
- Interesting question: why don't the arms wind up tightly after just a few rotation periods?

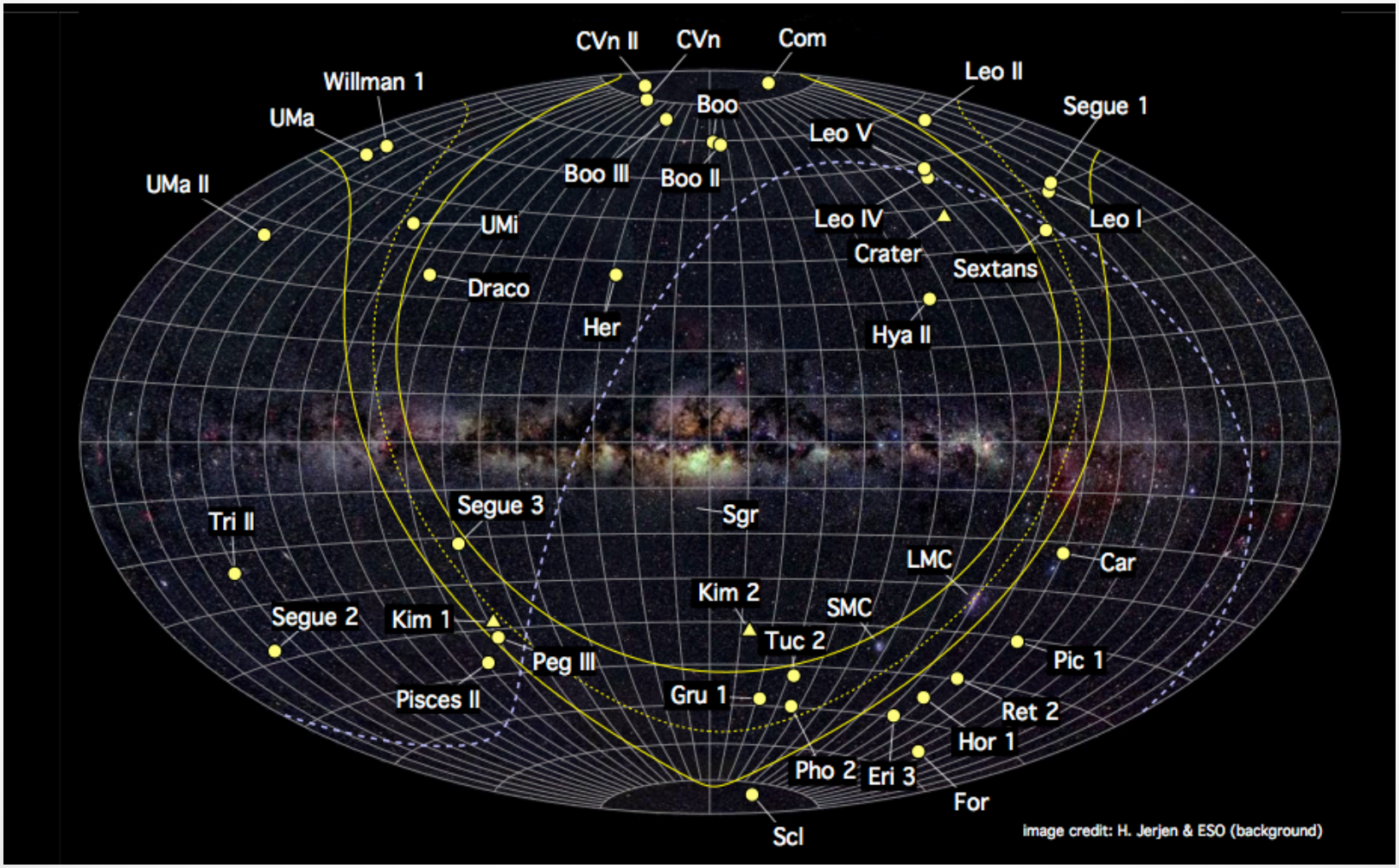
The Dwarfs

- There are 27 (and counting) dwarf galaxy companions to the Galaxy
- A few contain gas and are still forming stars
- Most are very faint, low luminosity, contain little or no gas and are composed of old stars

- Large and Small Magellanic Clouds are nearby Dwarf Irregular galaxies
- LMC is ~1/100th the mass of the Galaxy
- ~160,000 light-years distant
- Contains gas, young stars, old stars

Dwarf Spheroidals

- Most of the Galactic dwarf galaxy companions are "dwarf spheroidal" galaxies
- No gas, old stars, very low luminosity
- Important for models of the formation of galaxies (later)


CVn II
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Segue 1
UMa
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UMa II
Boo III
Boo II
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Leo I
Crater
Sextans
Draco
Her
Hya II
Segue 3
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Tri II
LMC
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Kim 2
SMC
Segue 2
Kim 1
Tuc 2
Peg III
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Gru 1
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Hor 1
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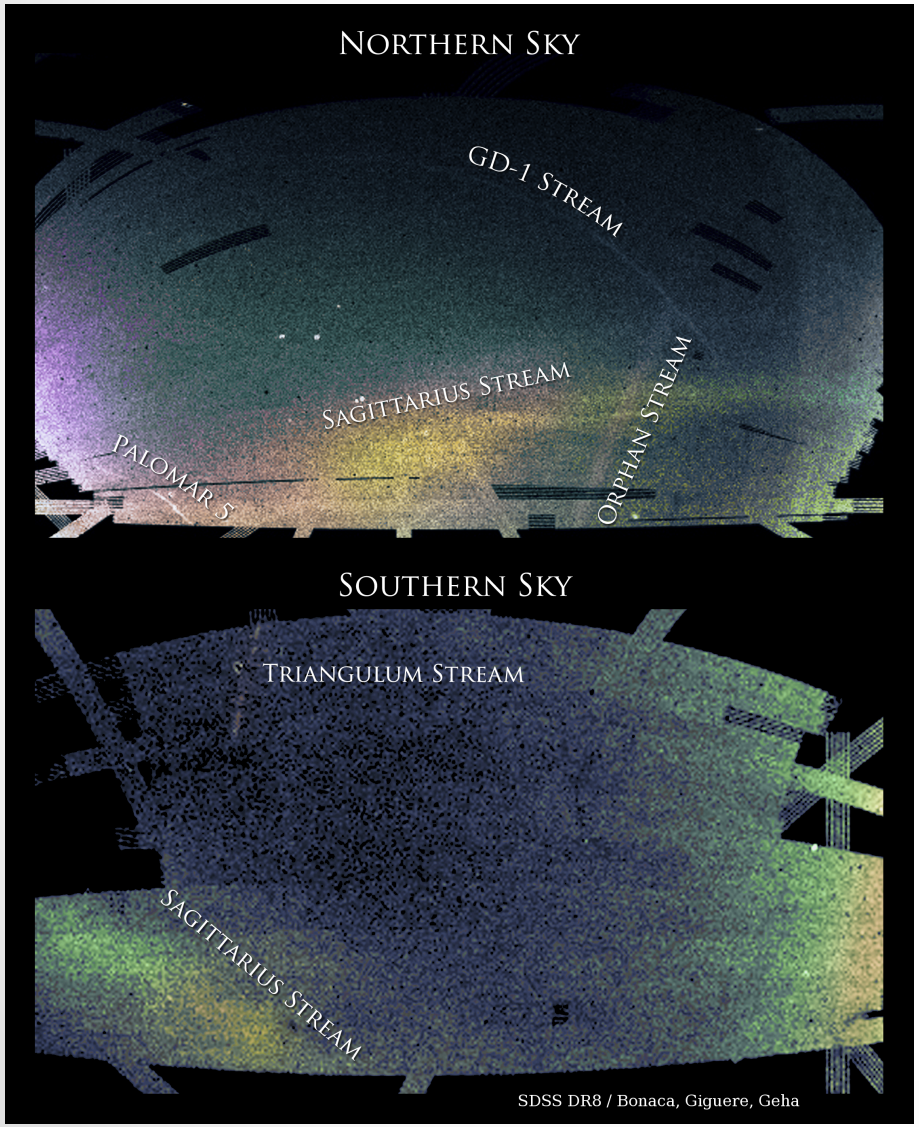
image credit: H. Jerjen & ESO (background)

Galactic Cannibalism

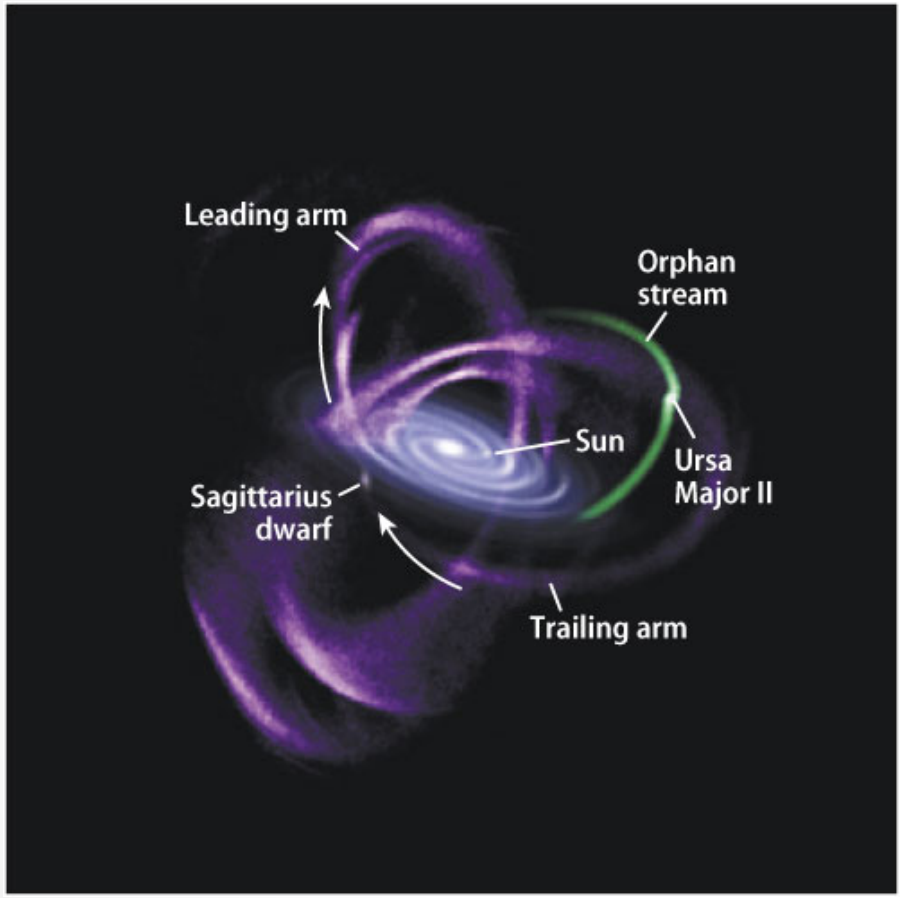
- A third class of companion galaxy is the Sagittarius dwarf which shows up as a "tidal stream"
- Dwarf galaxy in the process of being shredded by the gravitational field of the Galaxy
- Key to understanding how the halo formed

Tidal Streams



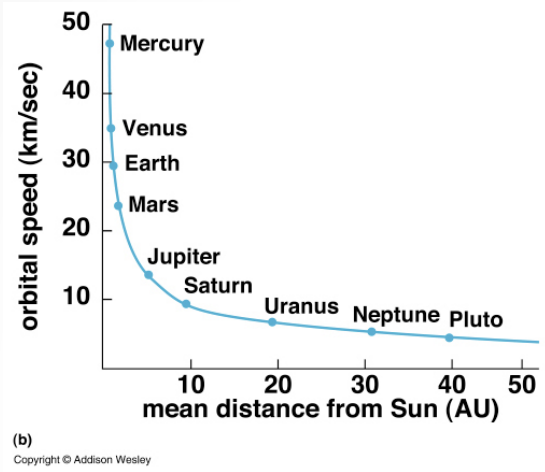
- When a dwarf galaxy or star cluster is tidally disrupted, the stars spread *along* the orbit (at near constant energy) and spread out *around* the stream according to the mass of the galaxy

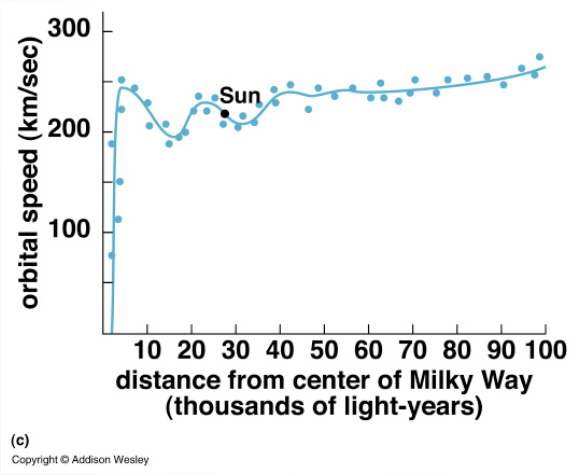
Tidal Streams



- The tidal streams can be very long lived and trace out the orbit of the shredded dwarf/cluster
- We can learn much about the gravitational potential of the Milky Way Galaxy by the behavior of the tidal streams.

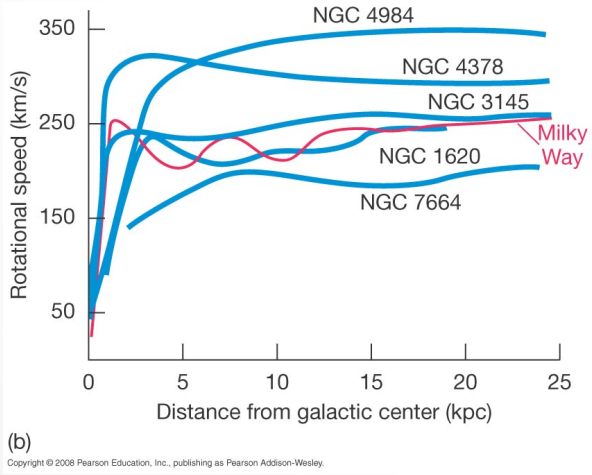
Dark Matter in the Local group





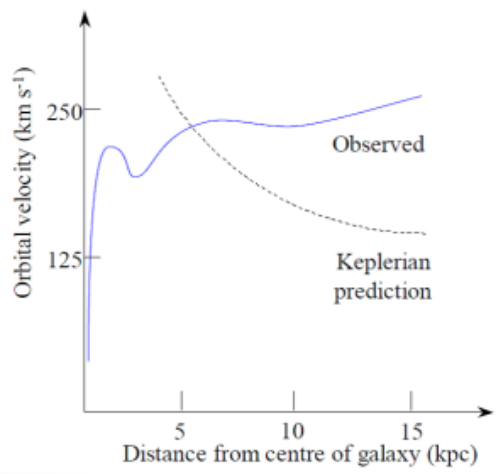
- The orbit speed of the planets follow "Kepler's" Laws for a system with strongly centralized mass
- The orbit speed vs radius plot for the Galaxy was recognized to be very different starting 40 years ago

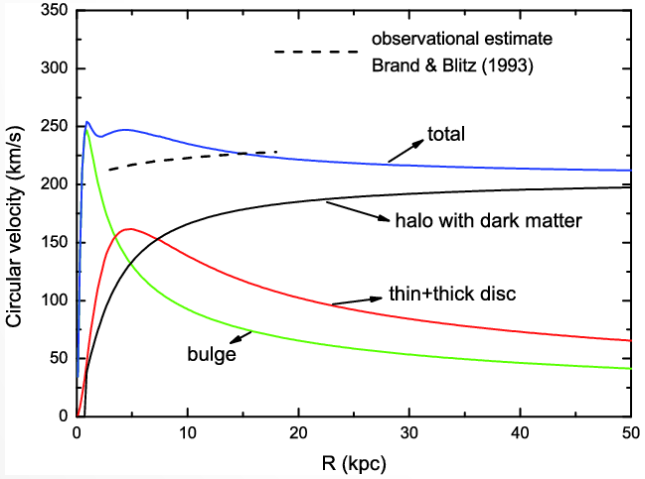
Rotation Curves



- Vera Rubin pioneered the study of rotation curves and the "missing mass" problem
- Not easy to be a woman scientist even 40 years ago

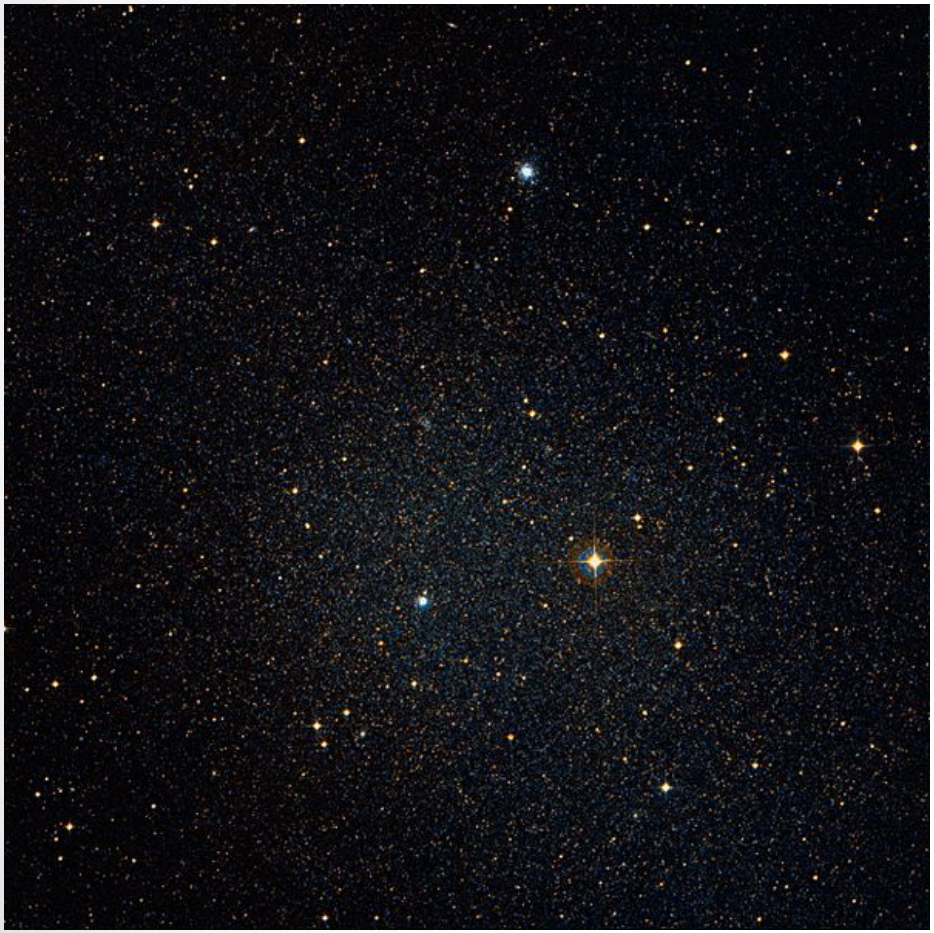
Dark Matter: Spiral Galaxies





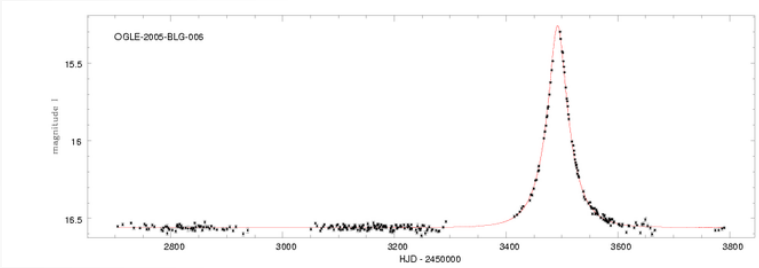
- Galaxy mass distribution is a little more complicated than the Solar system, but it became clear that the Galaxy and all galaxies required a huge amount of "dark matter" to explain the orbits of stars

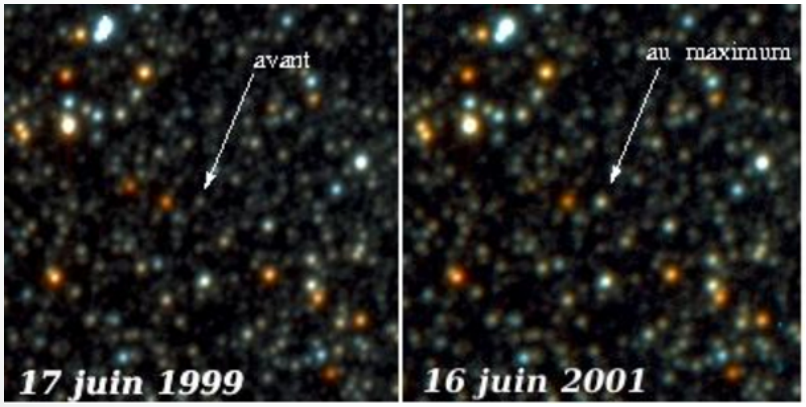
Dark Matter and Dwarfs



- The very low-luminosity dwarf galaxies around the Milky Way Galaxy proved to have even larger ratios of dark to luminous matter and in most cases are strongly dominated by dark matter
- Here, instead of rotation curves, we measure the random speed of the stars and determine the amount of "gravity" required to keep them from flying into space

Dark Matter

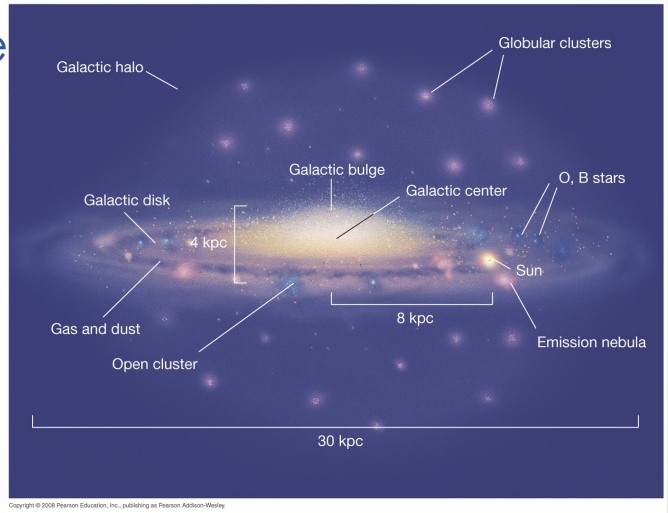




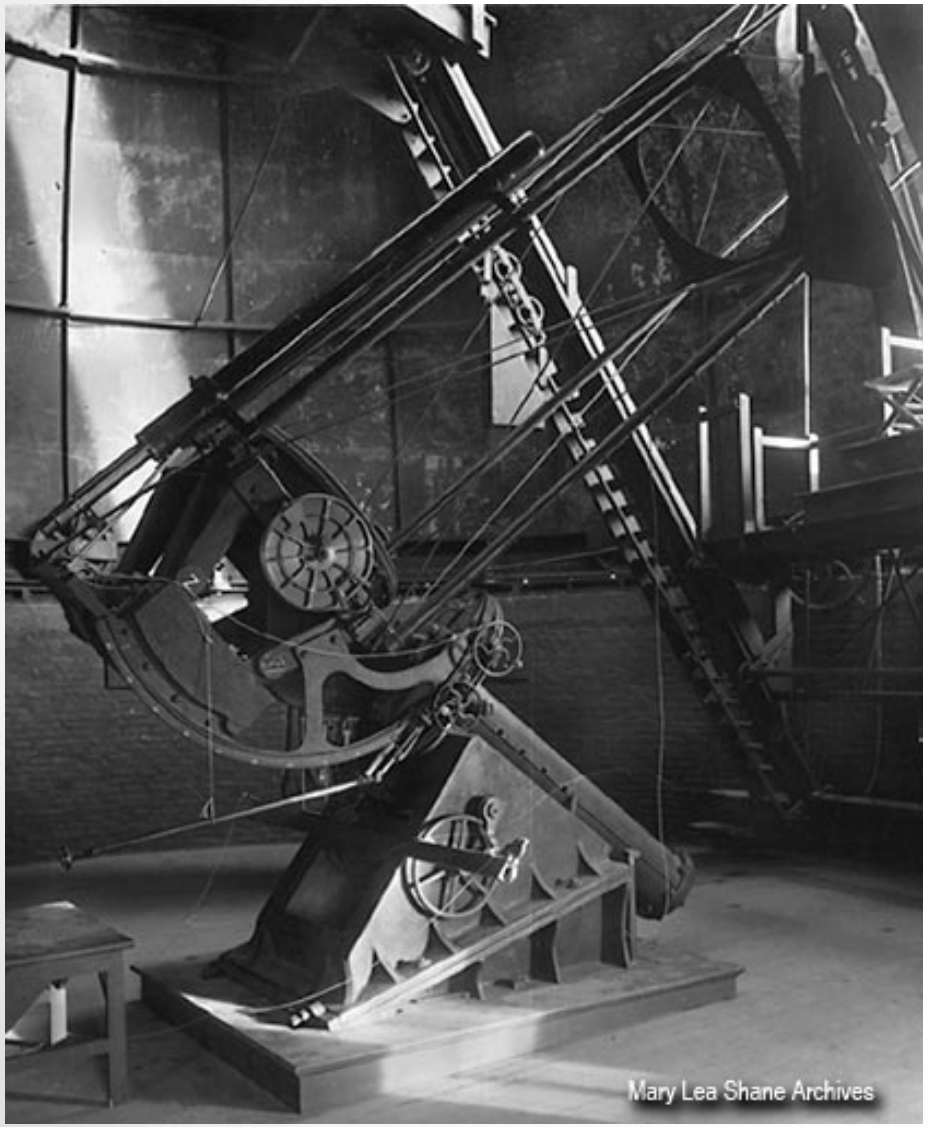
- In the Galaxy, there have been many searches for "baryonic" dark matter (made of ordinary matter like protons and electrons
- Cold white dwarfs, inter-stellar asteroids, very low mass brown dwarfs, mini-black holes etc.
- So far, looks like DM is instead an unknown elementary particle

Milky Way Galaxy

- Galactic Halo: 12 Gyr old stars, star clusters and dwarf galaxies on "plunging" orbits. ~few% of the Galaxy stellar mass. 150,000 light-years in radius
- Galactic Bulge: 12 Gyr old stars and star clusters. ~30% of the Galaxy stellar mass
- Galactic Disk: 0-9 Gyr old stars and star clusters, gas and dust (20% by mass). ~70% of the stellar mass
- Dark Matter Halo: unknown material, 90% of the total mass of the Galaxy!
- Galactic Center: 4 x 10^6 M_{sun} Black Hole

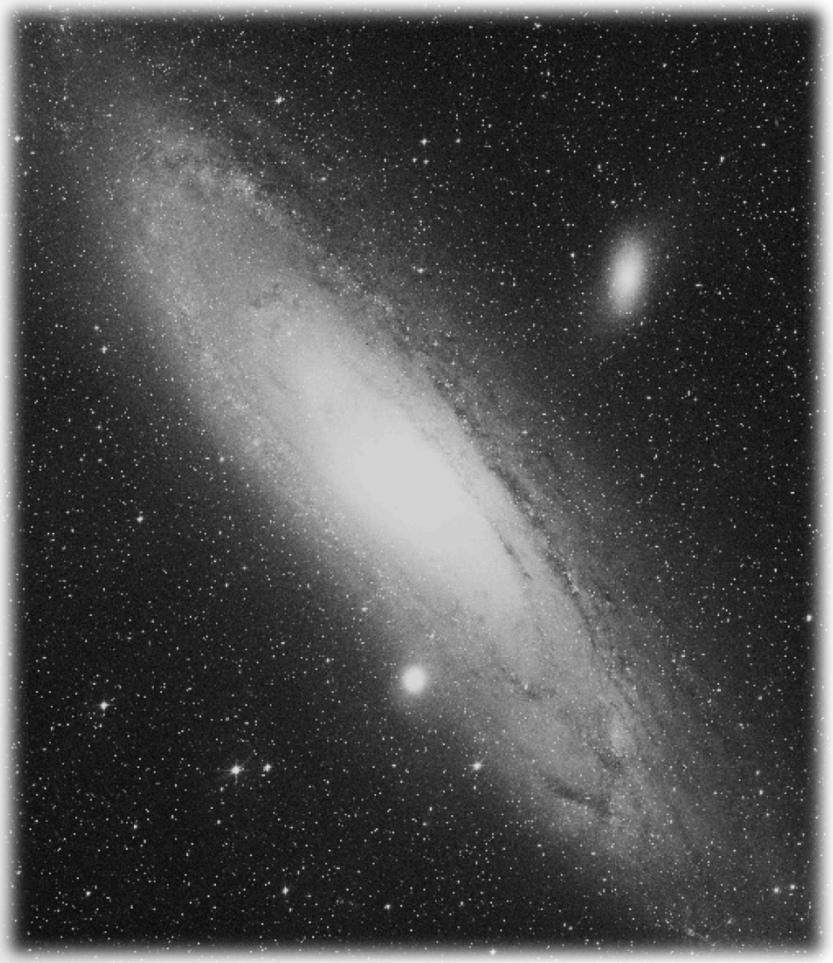


Island Universes

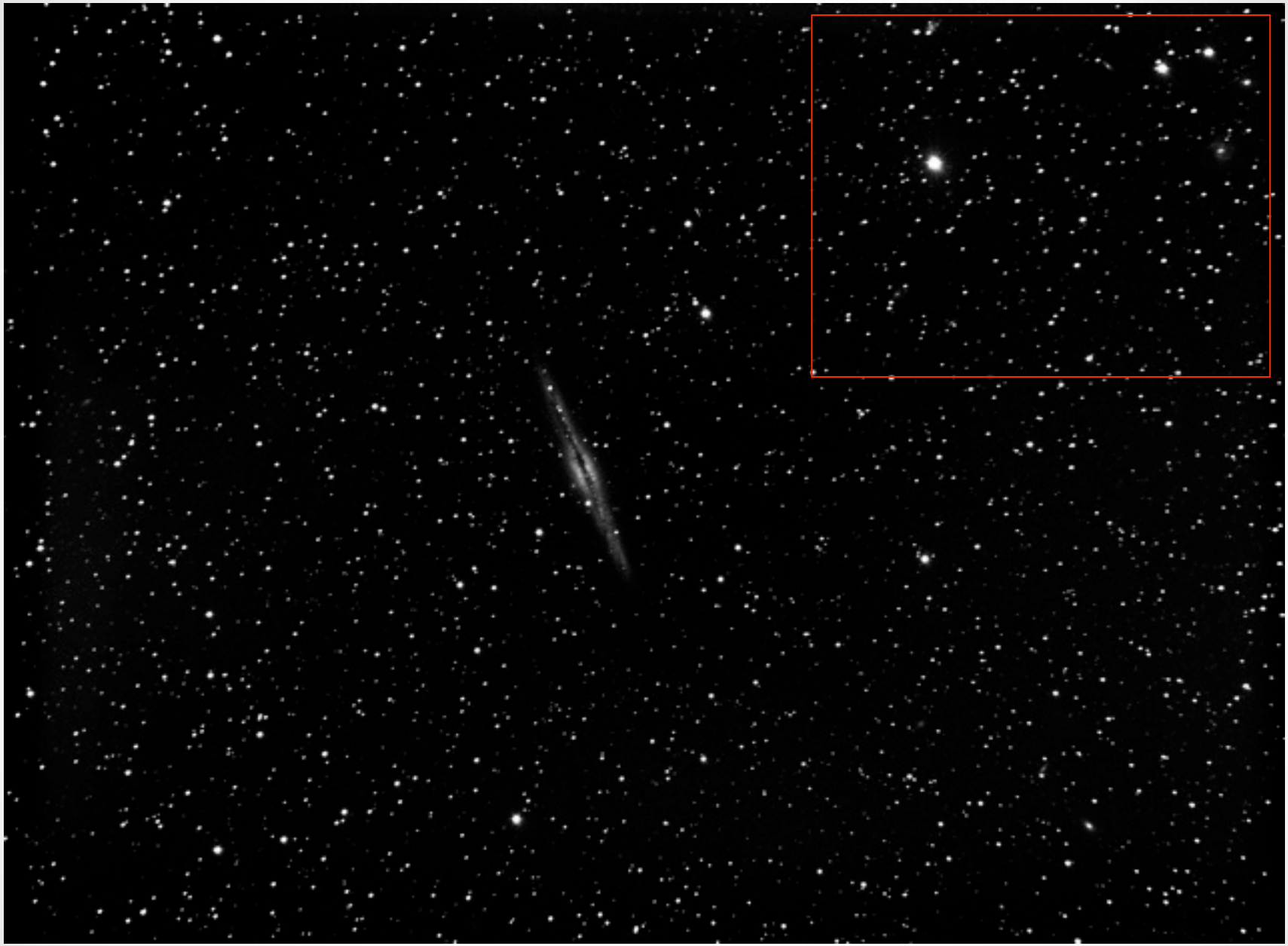


- Up till the early part of the 1900's it was not clear if the Milky Way Galaxy was the entire Universe or if there were other "island universes"
- Lick Observatory Crossley Telescope became devoted to making very deep images of the sky

Spiral Nebulae



- Leading theory of the day was that the "spiral nebulae" were large bodies of gas and dust in the Galaxy that had been spun up by a passing star and would collapse to form a star
- Image of M31 from 1888 and Lick Obs



1899, Nov 6, Crossley

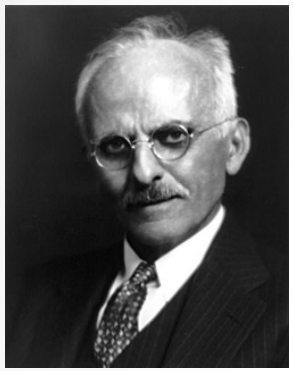
James Keeler

- "With exposures of four hours the Crossley photographs show stars and nebulae far beyond the range of any visual telescopes…the number of new nebulae would be about *120,000*"
- 2nd Lick Director

Keeler's Nebulae

- Keeler's images were a big hit
- The distribution on the sky (away from the obscuring dust in the plane) was uniform, not following the distribution of stars
- This argued for the small nebulae being extra-Galactic and very distant

The Great Debate 1920

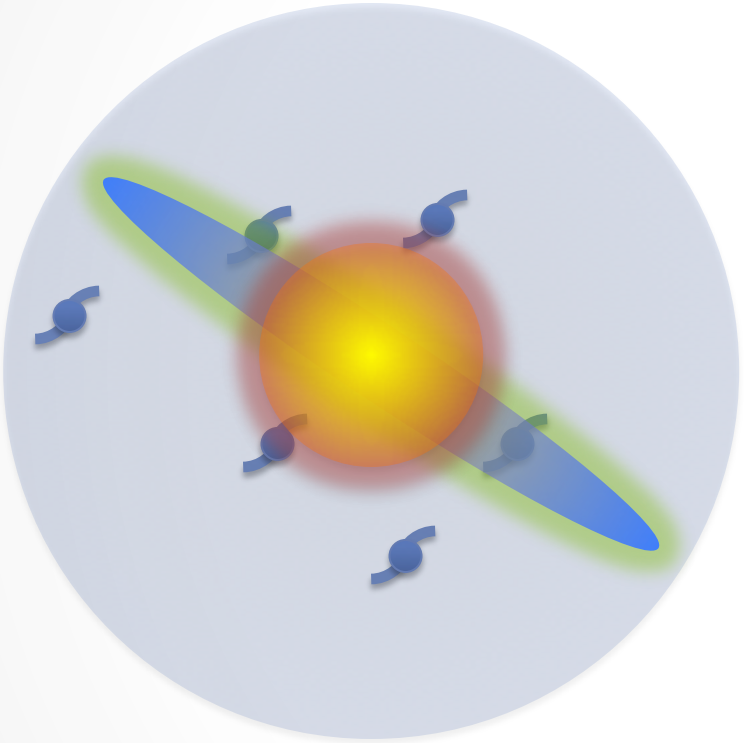


Herber Curtis

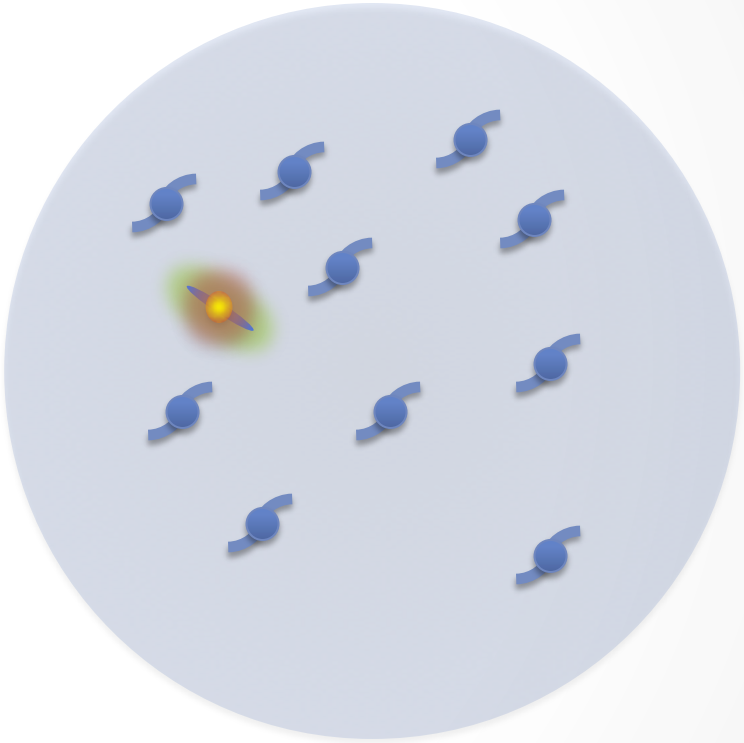
Harlow Shapley

- The question of whether the Galaxy was the entire Universe or just one of millions of "island universes" was the subject of a famous debate in 1920
- Issues were about the distance scale, novae, supernovae and bad data

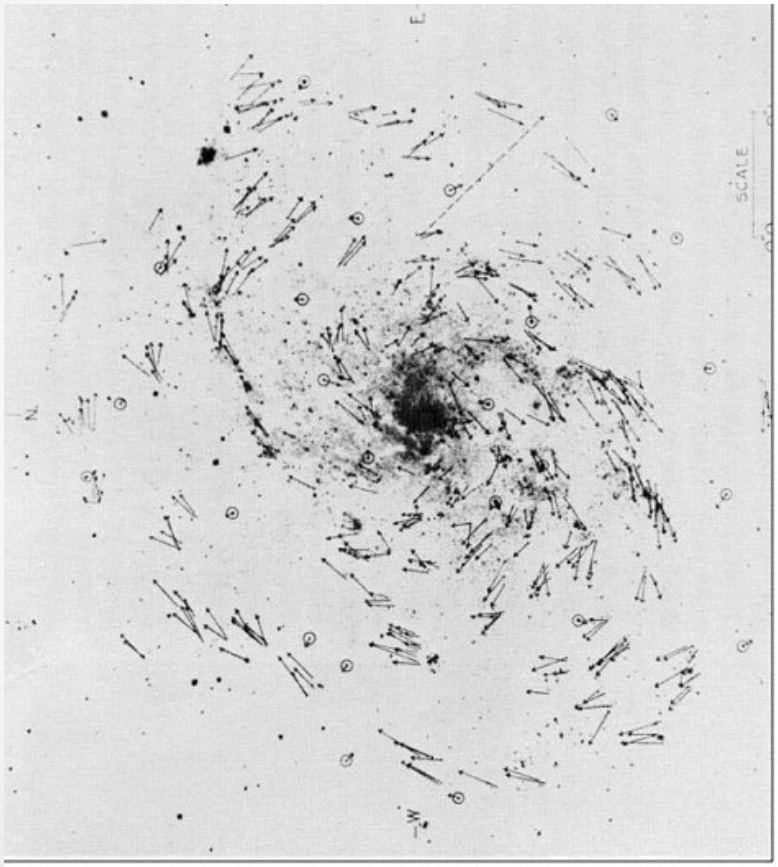
Shapely: Galaxy=Universe



Curtis: Universe is far vaster than Galaxy



Bad data

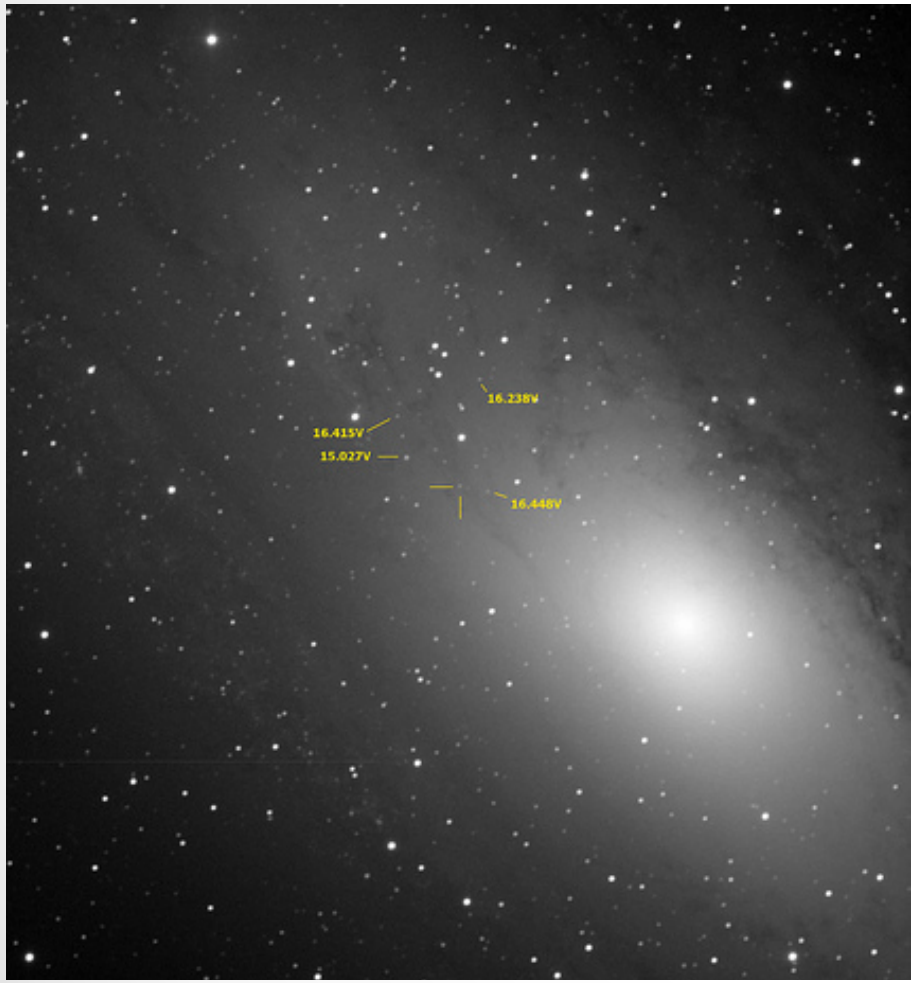


- One of the most striking of the nebulae under discussion was the Pinwheel Nebula (M101)
- Adriaan van Maanen was a respected observer and had reported the measurement of stars moving on orbits in M101

Rotation of Spiral Nebulae

If the van Maanen measurements were accurate and the Pinwheel Nebula was at the great distance implied by Curtis large Universe view, the orbit speed of the stars would be extremely large

Novae and Supernovae

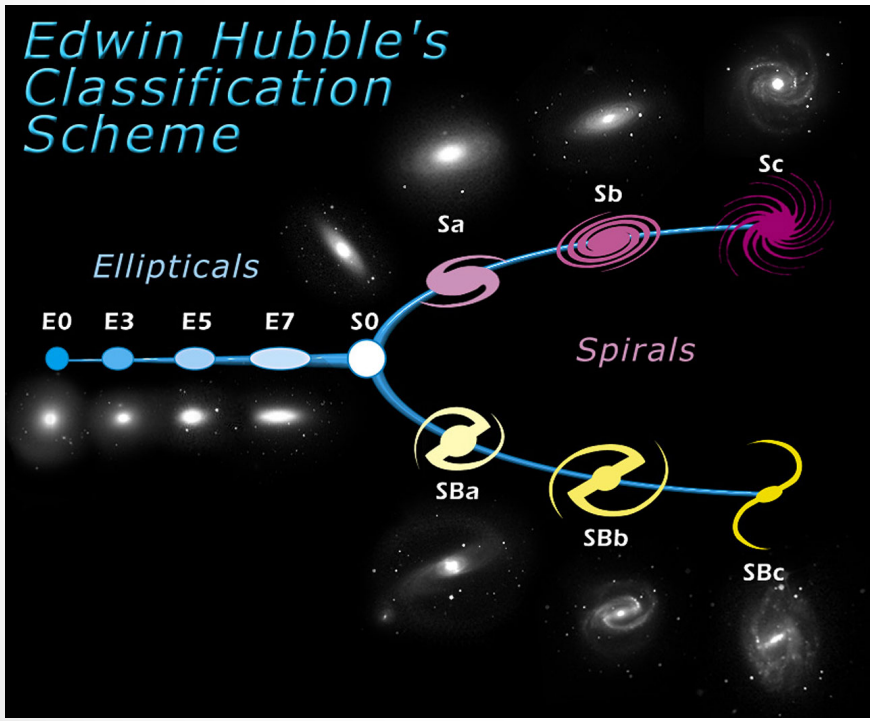


- Another point of confusion was because the difference between novae and supernovae was not recognized
- 1885 a supernova exploded in the Andromeda Galaxy
- Argued that this object would have to be FAR more luminous than Galactic novae if Andromeda was very large and far away
- Of course, the SN *was* far more luminous!

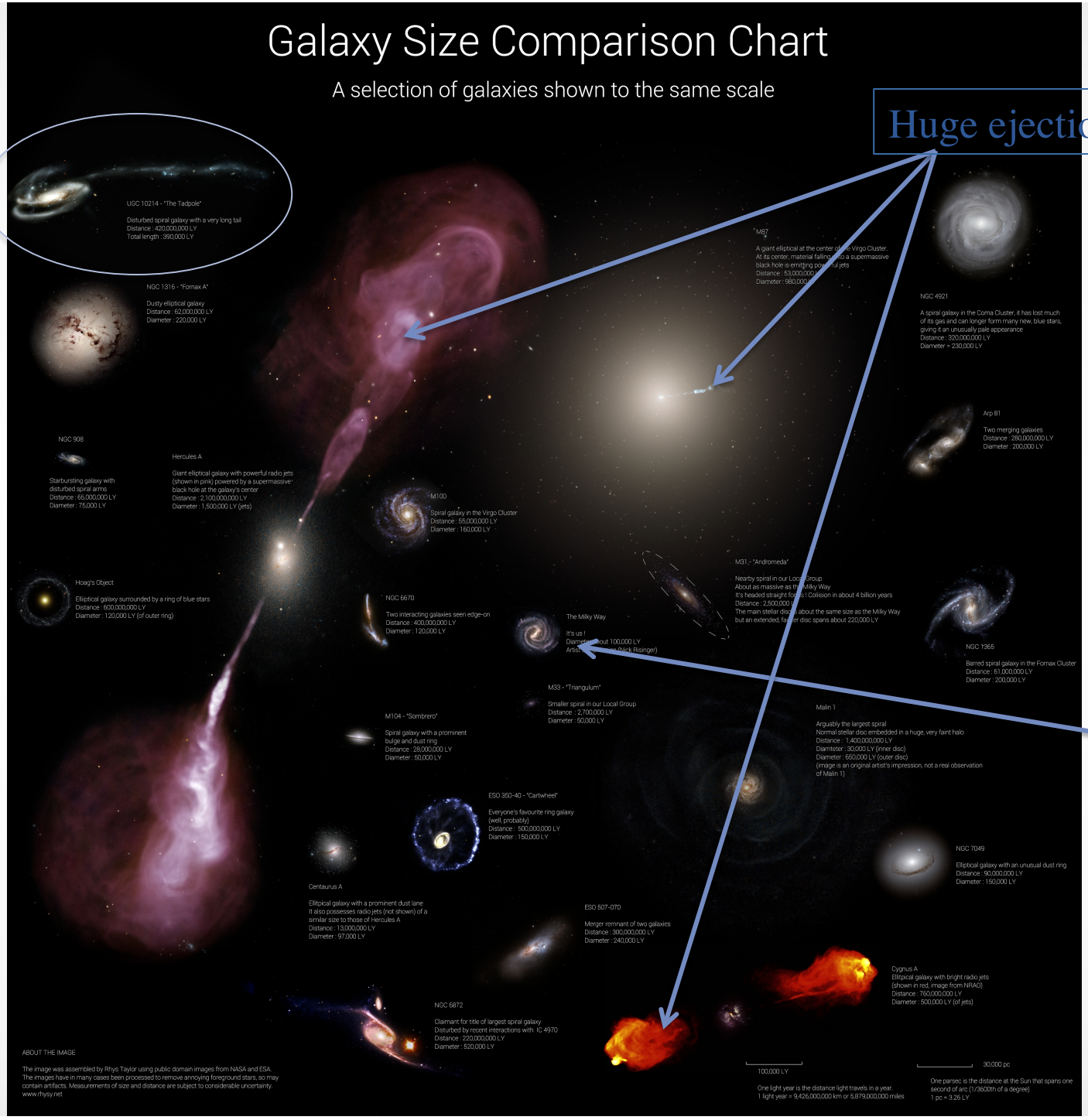
The Great Debate: Winner

- In the end, nobody "won" the debate but improved observations soon settled the issue
  - The van Mannen observations could not be replicated
  - The two classes of novae (novae and supernovae) became accepted
- Within a few years, the Big Universe became the standard model

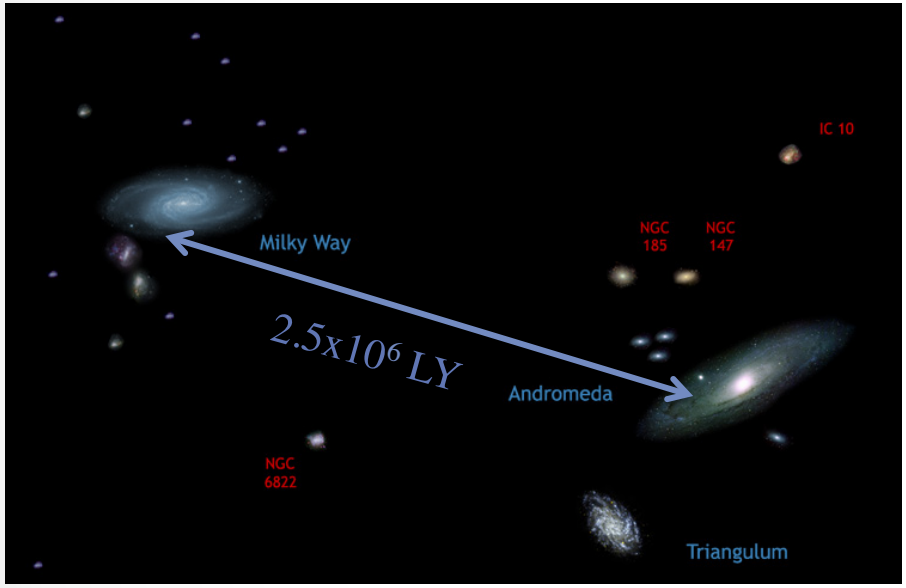
The Galaxy Zoo



- Since the 1920s there has been a huge amount of progress identifying the different kinds of galaxies and their properties
- The formation and evolution of different types of galaxies is an ongoing area of great interest

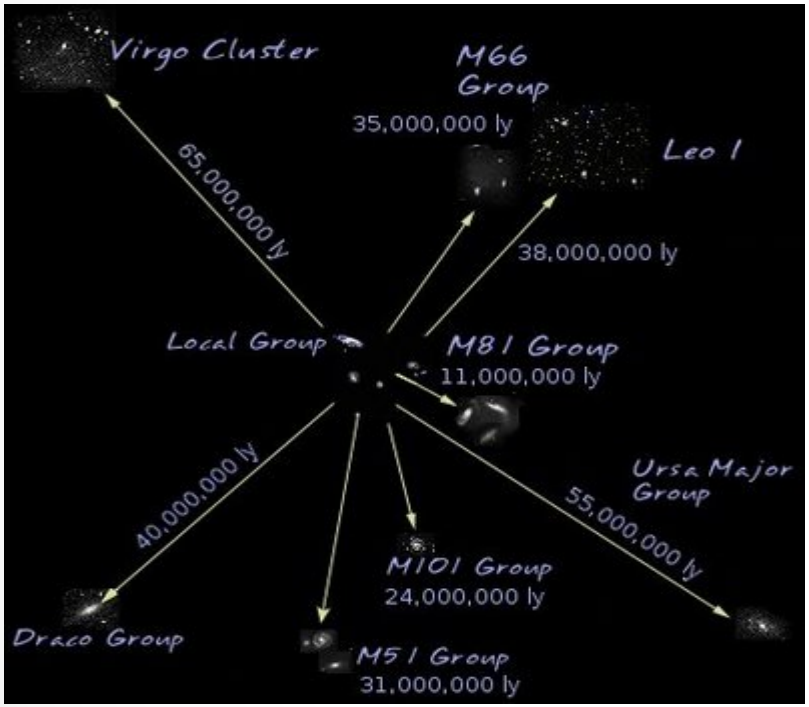

Galaxy Size Comparison Chart
A selection of galaxies shown to the same scale
Huge ejections of gas
Milky Way Galaxy
UGC 10214 - "The Tadpole"
Disturbed spiral galaxy with a very long tail
Distance : 420,000,000 LY
Total length : 390,000 LY
NGC 1316 - "Fornax A"
Dusty elliptical galaxy
Distance : 62,000,000 LY
Diameter : 220,000 LY
M87
A giant elliptical at the center of the Virgo Cluster.
At its center, material falling into a supermassive
black hole is emitting powerful jets
Distance : 53,000,000 LY
Diameter : 980,000 LY
NGC 4921
A spiral galaxy in the Coma Cluster, it has lost much
of its gas and can longer form many new, blue stars,
giving it an unusually pale appearance
Distance : 320,000,000 LY
Diameter = 230,000 LY
NGC 908
Starbursting galaxy with
disturbed spiral arms
Distance : 65,000,000 LY
Diameter : 75,000 LY
Hercules A
Giant elliptical galaxy with powerful radio jets
(shown in pink) powered by a supermassive
black hole at the galaxy's center
Distance : 2,100,000,000 LY
Diameter : 1,500,000 LY (jets)
Arp 81
Two merging galaxies
Distance : 280,000,000 LY
Diameter : 200,000 LY
M100
Spiral galaxy in the Virgo Cluster
Distance : 55,000,000 LY
Diameter : 160,000 LY
Hoag's Object
Elliptical galaxy surrounded by a ring of blue stars
Distance : 600,000,000 LY
Diameter : 120,000 LY (of outer ring)
NGC 6670
Two interacting galaxies seen edge-on
Distance : 400,000,000 LY
Diameter : 120,000 LY
The Milky Way
It's us !
Diameter : about 100,000 LY
M31 - "Andromeda"
Nearby spiral in our Local Group
About as massive as the Milky Way
It's headed straight for us! Collision in about 4 billion years
Distance : 2,500,000 LY
The main stellar disc is about the same size as the Milky Way
but an extended, fainter disc spans about 220,000 LY
NGC 7365
Barred spiral galaxy in the Fornax Cluster
Distance : 61,000,000 LY
Diameter : 200,000 LY
M33 - "Triangulum"
Smaller spiral in our Local Group
Distance : 2,700,000 LY
Diameter : 50,000 LY
M104 - "Sombrero"
Spiral galaxy with a prominent
bulge and dust ring
Distance : 28,000,000 LY
Diameter : 50,000 LY
Malin 1
Arguably the largest spiral
Normal stellar disc embedded in a huge, very faint halo
Distance : 1,400,000,000 LY
Diameter : 300,000 LY (inner disc)
Diameter : 650,000 LY (outer disc)
(image is an original artist's impression, not a real observation
of Malin 1)
ESO 350-40 - "Cartwheel"
Everyone's favourite ring galaxy
(well, probably)
Distance : 500,000,000 LY
Diameter : 150,000 LY
NGC 7049
Elliptical galaxy with an unusual dust ring
Distance : 90,000,000 LY
Diameter : 150,000 LY
Centaurus A
Elliptical galaxy with a prominent dust lane
It also possesses radio jets (not shown) of a
similar size to those of Hercules A
Distance : 13,000,000 LY
Diameter : 97,000 LY
ESO 507-070
Merger remnant of two galaxies
Distance : 300,000,000 LY
Diameter : 240,000 LY
Cygnus A
Elliptical galaxy with bright radio jets
(shown in red, image from NRAO)
Distance : 760,000,000 LY
Diameter : 500,000 LY (of jets)
NGC 6872
Claimant for title of largest spiral galaxy
Disturbed by recent interactions with IC 4970
Distance : 220,000,000 LY
Diameter : 520,000 LY
ABOUT THE IMAGE
The image was assembled by Rhys Taylor using public domain images from NASA and ESA.
The images have in many cases been processed to remove annoying foreground stars, so may
contain artifacts. Measurements of size and distance are subject to considerable uncertainty.
www.rhysy.net
100,000 LY
One light year is the distance light travels in a year.
1 light year = 9,426,000,000 km or 5,879,000,000 miles
30,000 pc
One parsec is the distance at the Sun that spans one
second of arc (1/3600th of a degree)
1 pc = 3.26 LY

Local Group of Galaxies



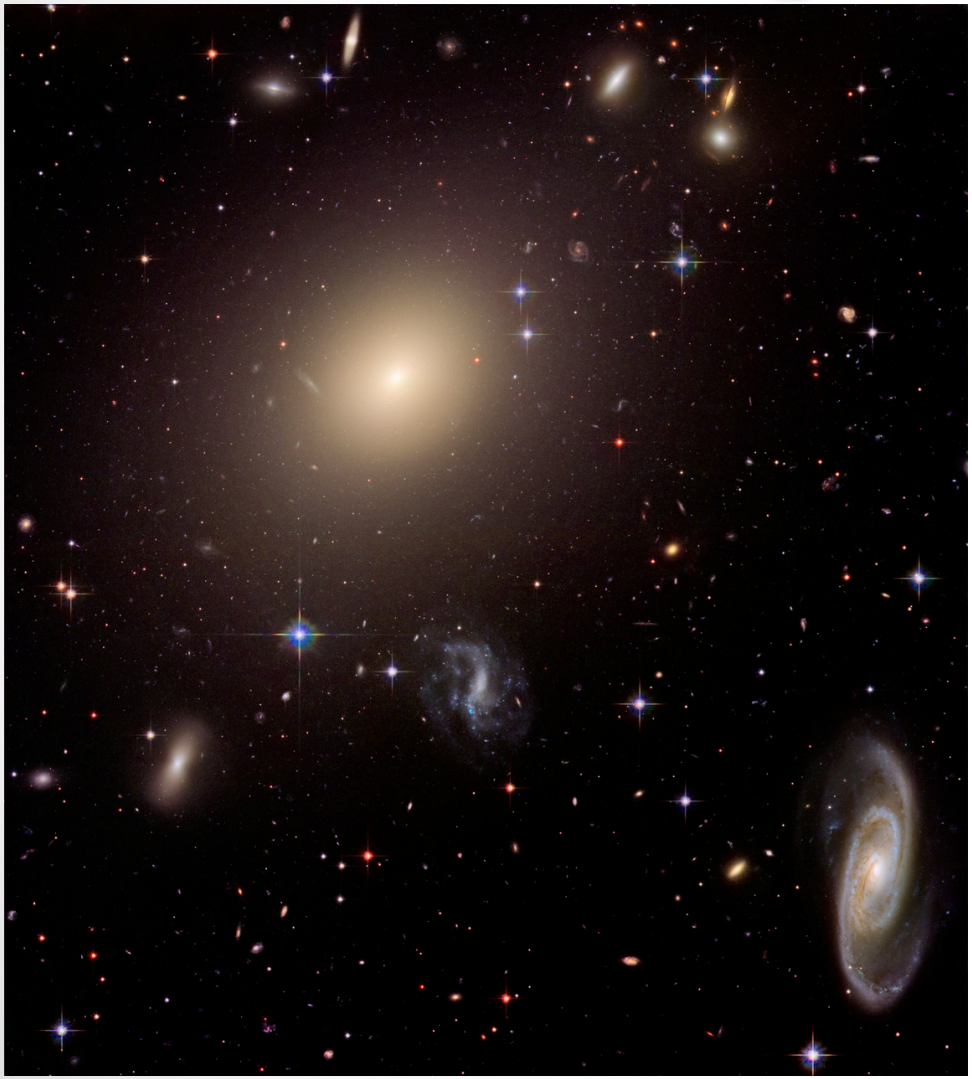
- The Milky Way Galaxy has its small complement of "dwarf" galaxy companions and is a member of the "Local Group" of galaxies.
- Large spiral galaxies, smaller spirals, dwarf irregular, dwarf spherodal and dwarf ellipticals

Galaxy Groups

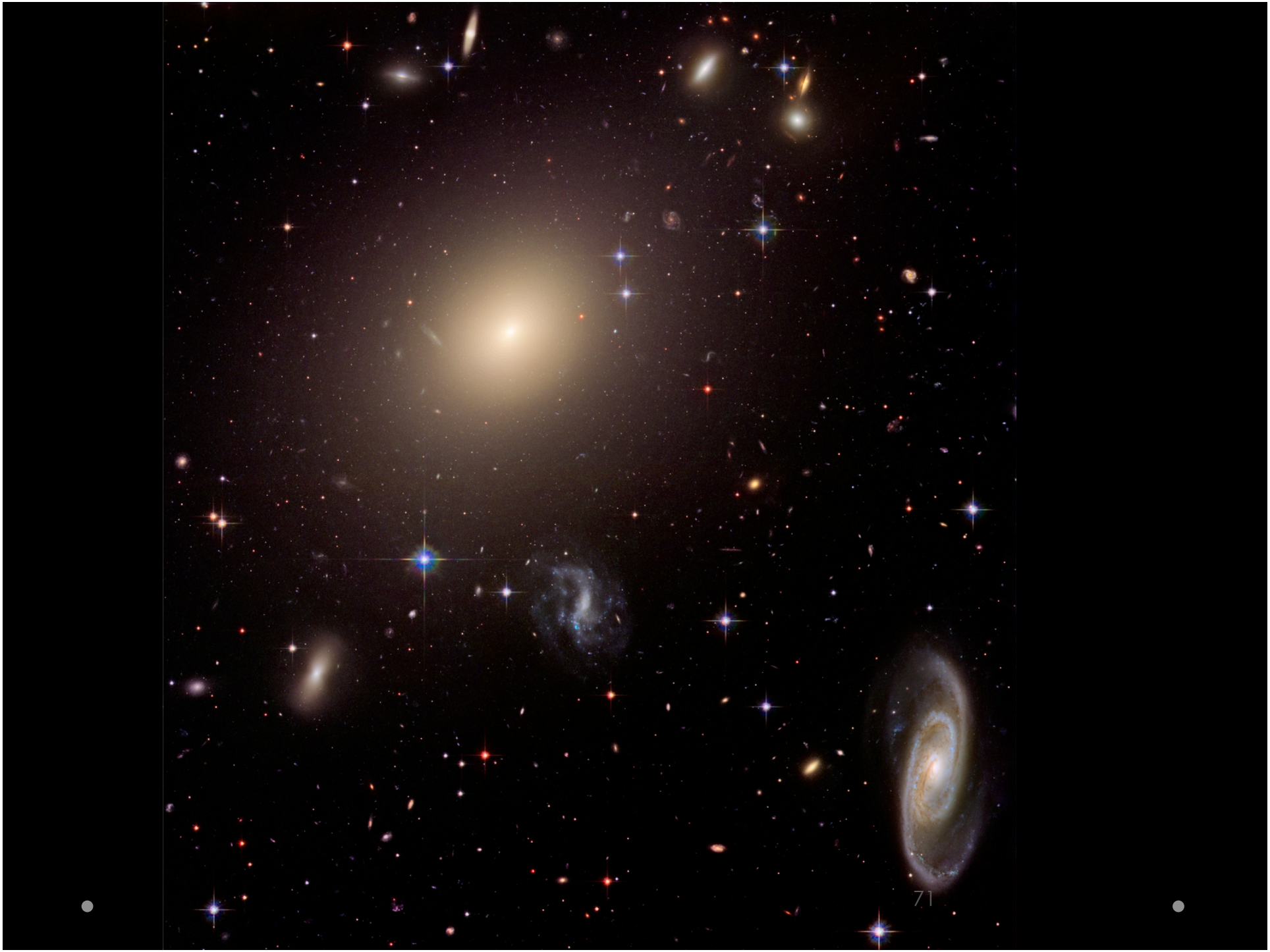


- Local Group is one of many galaxy groups within a radius of ~50 million light years
- Each group is a gravitationally-bound entity
- Most, including the Local Group are flying toward the Virgo Cluster of Galaxies

Giant Elliptical Galaxies



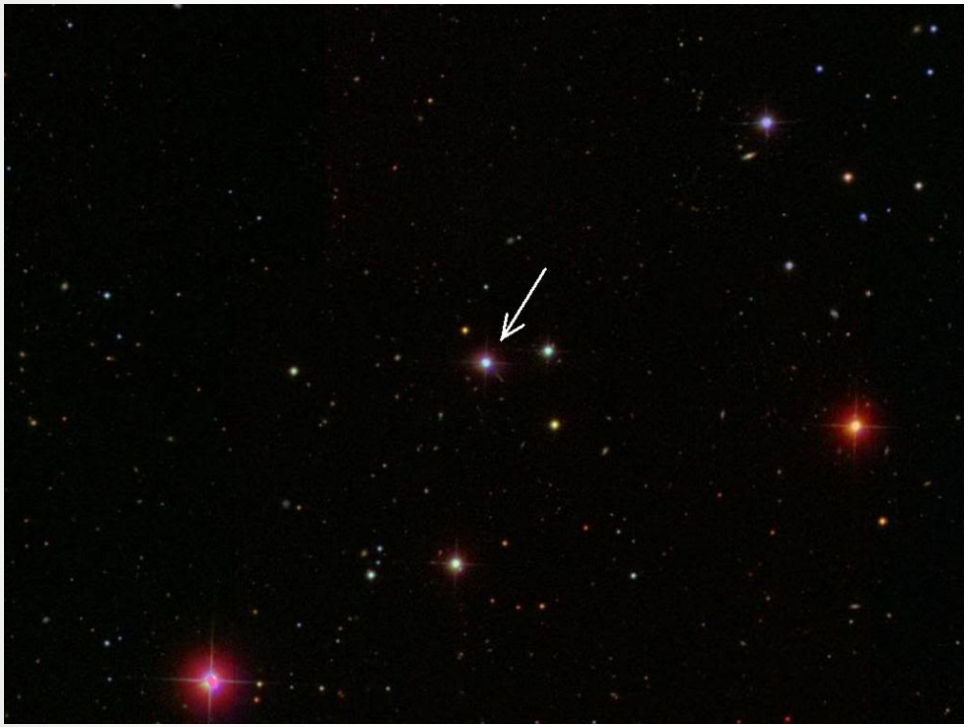
- If we go out 50 million light years from the Galaxy we start to sample a different type of galaxy called a giant elliptical
  - Larger and more massive than the Milky Way Galaxy by up to a factor of 100
  - Gas-poor
  - No star formation



Interacting Galaxies

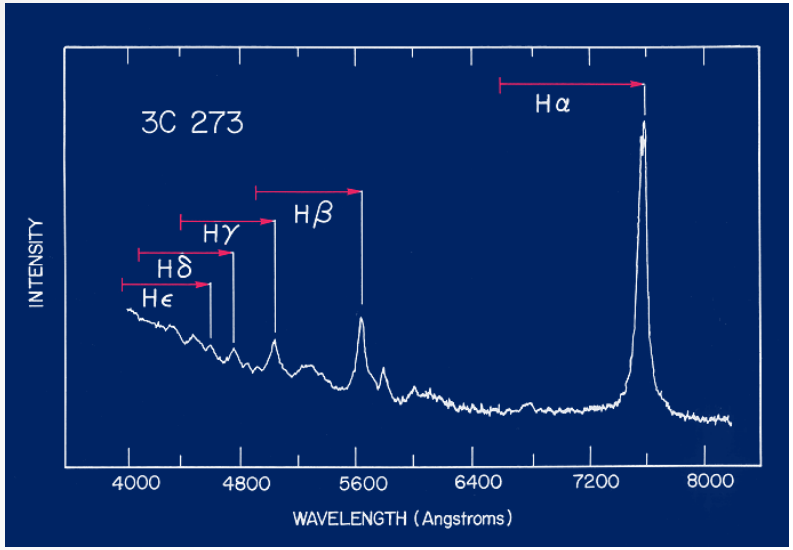
- In the volume within 50Mly there are also a number of galaxies that are in the process of colliding and likely merging
- Mergers of various types are important to galaxy evolution (later)

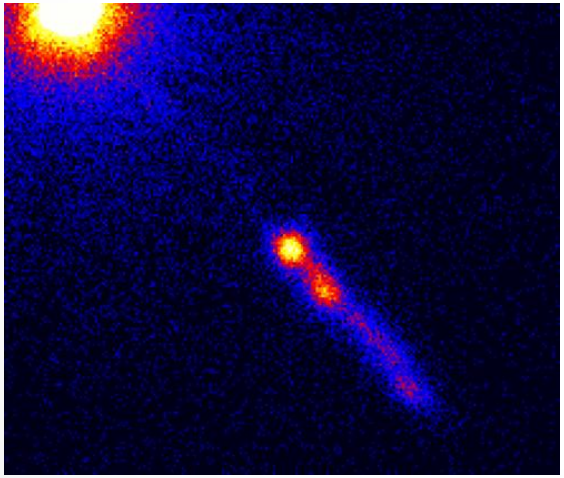
QSO and AGN



- One last type of galaxy in the Zoo
- 1960s point-like radio sources were identified by low-resolution surveys
- Finally identified some of the radio sources with optical counterparts
- 1962 Marteen Schmidt at Caltech obtained a spectrum with strange emission lines

QSO and AGN





- Realized the emission lines were primarily from hydrogen, red-shifted to 50,000 km/sec
- Modern distance to 3C 273 is 2 billion light years
- Implied luminosity was so large that it was judged unbelievable by many
- Subsequently a jet of fast moving material was identified

QSO and AGN

- There are now more than 200,000 QSOs known out to 12 billion light years
- Widely accepted model is that they are supermassive black holes at the centers of galaxies in an "active phase" of mass accretion
- Lower luminosity, more nearby systems have also been identified and are labeled "Active Galactic Nuclei"