Discovery of the Milky Way

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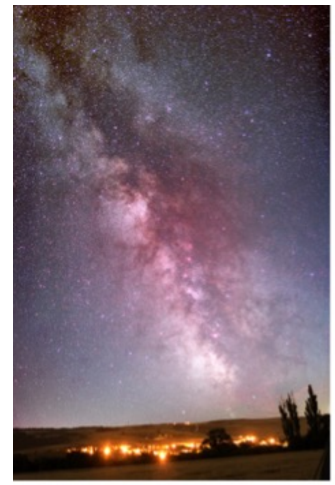
On to galaxies…

Monty Python's "Galaxy Song"

Discovery of the Milky Way

Before the 20th century, we thought that the Milky Way was the entire Universe.



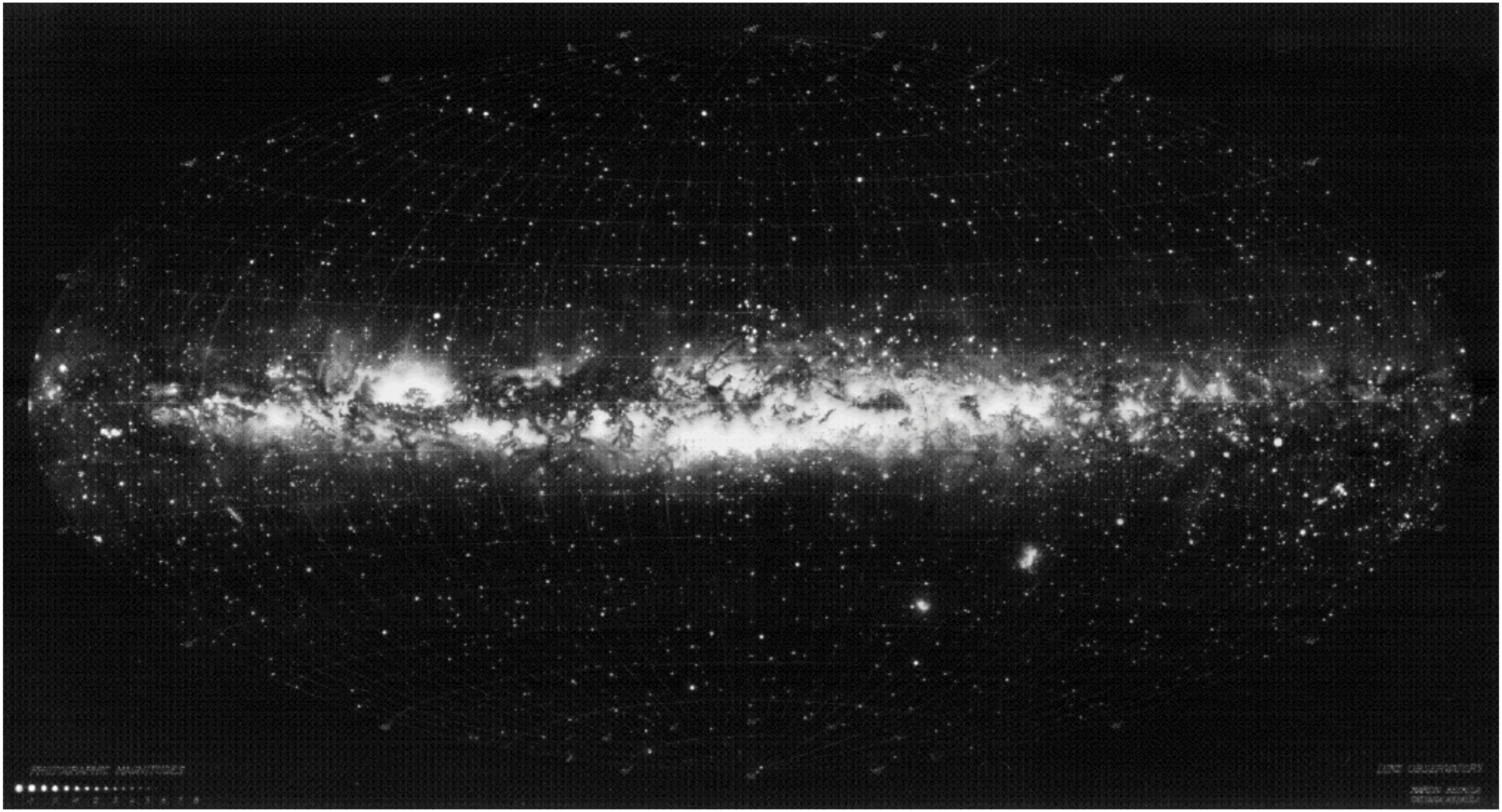
How did we figure out that it wasn't?

Statistics!

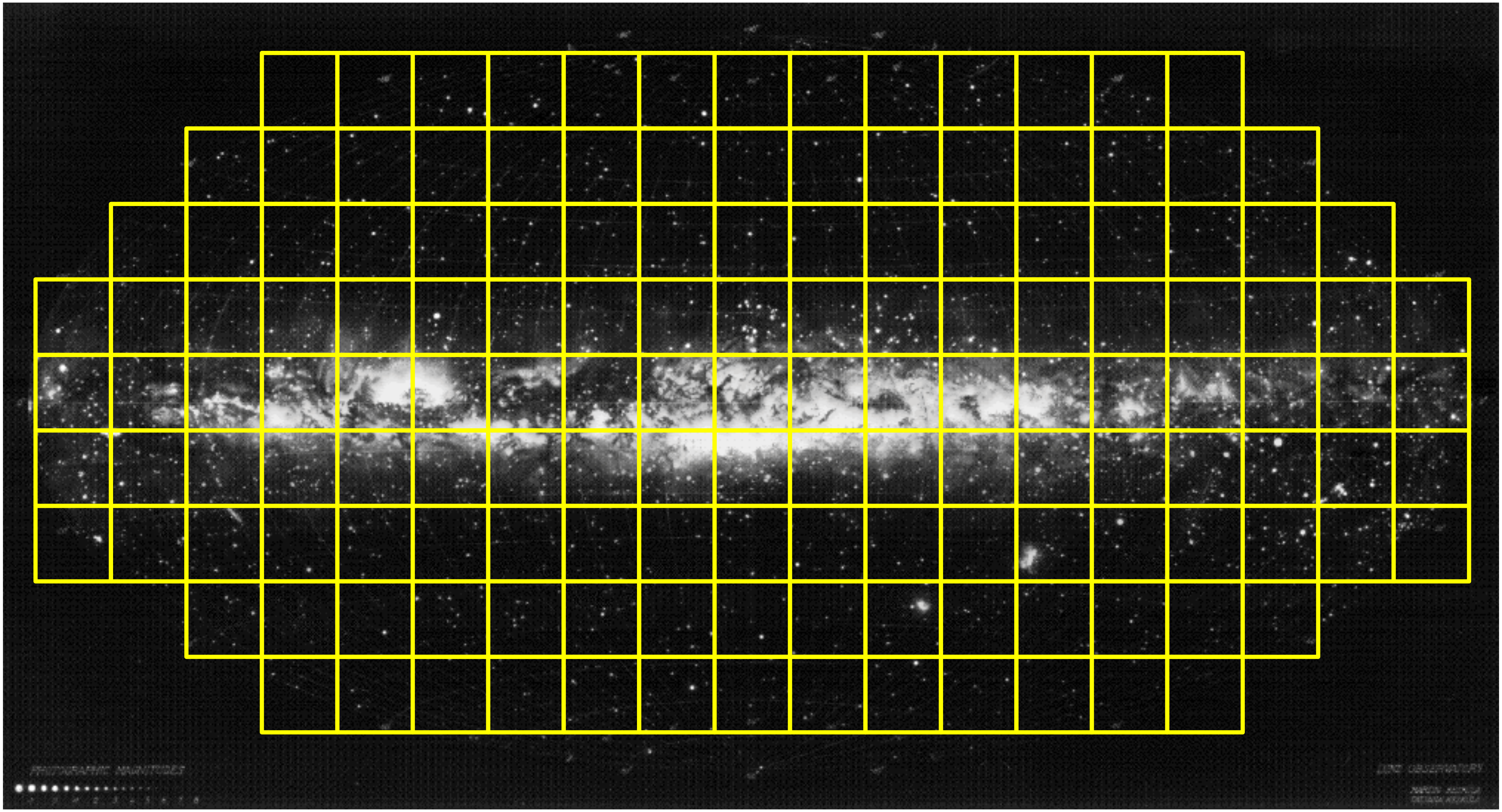
William and Caroline Herschel

- Brother and sister German/English astronomers in the 1700 and 1800s.
- William was also a musician, and discovered Uranus as well as moons in the solar system.
- Caroline worked with him and discovered many comets.
- They cataloged many nebulae in the night sky. A version of their catalog (from William's son) is still used today.
- They made the first attempt to determine the size and shape of the Milky Way by counting stars in 1785.
- How did this work?

An all-sky view of the Milky Way

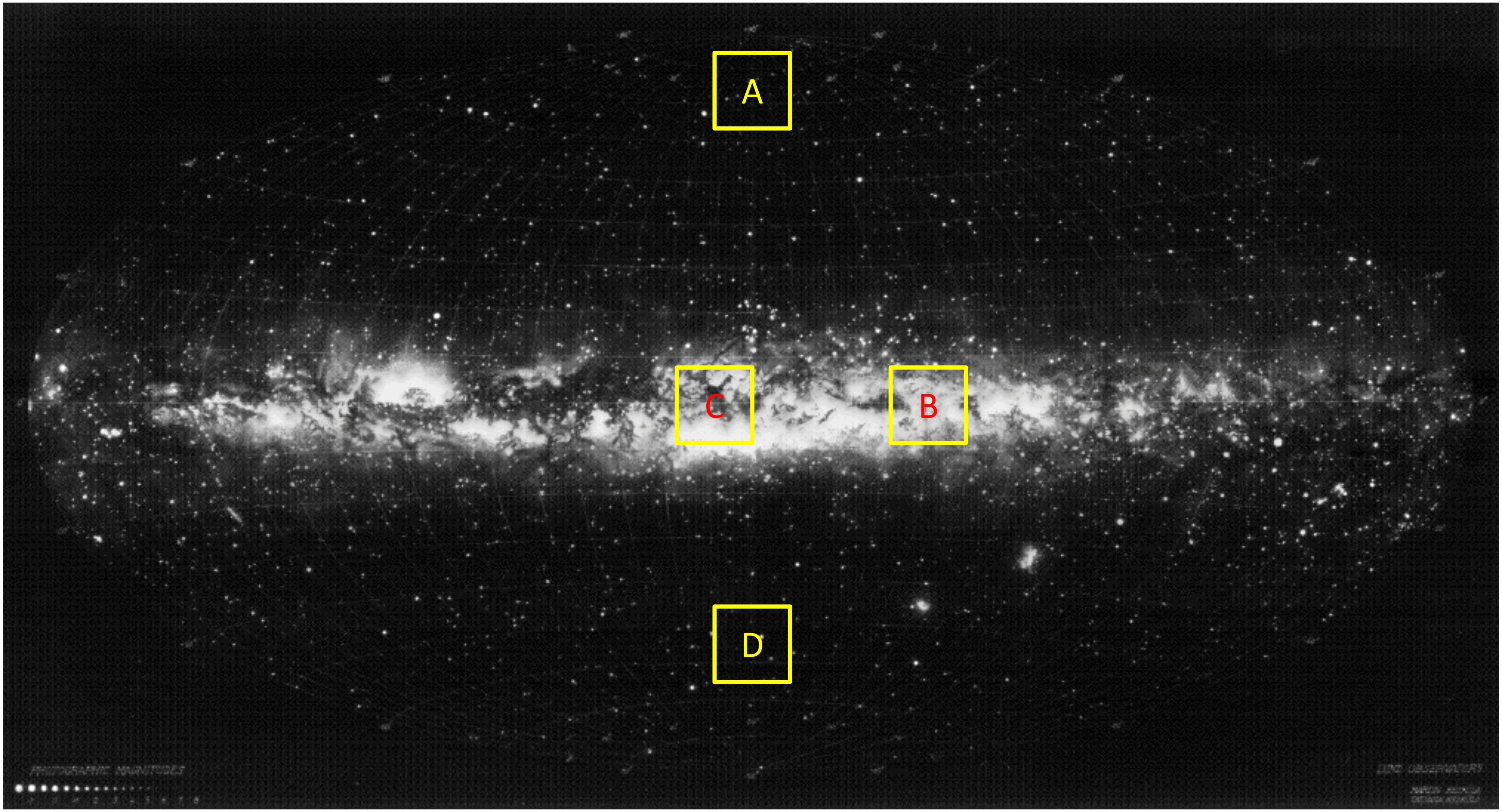


Count the stars in different directions.



Brighter = More stars = Larger distance to edge of Galaxy

Which direction has more stars?



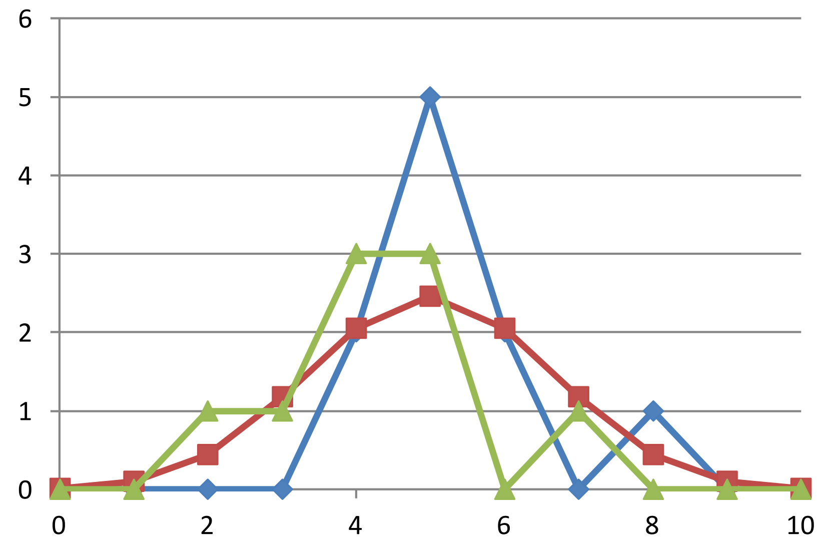
Star counts

- How can you tell if two regions have *significantly* different numbers of stars?
- Need to understand statistics.

- Let’s do an experiment: coin flipping.

Coin Flip results

- The results of your coin flips are shown below (green) along with a simulation (blue) and the prediction (red).
- Pretty good agreement?



- A total of XX heads were flipped during 100 coin flips (XX%). Were the coins fair?

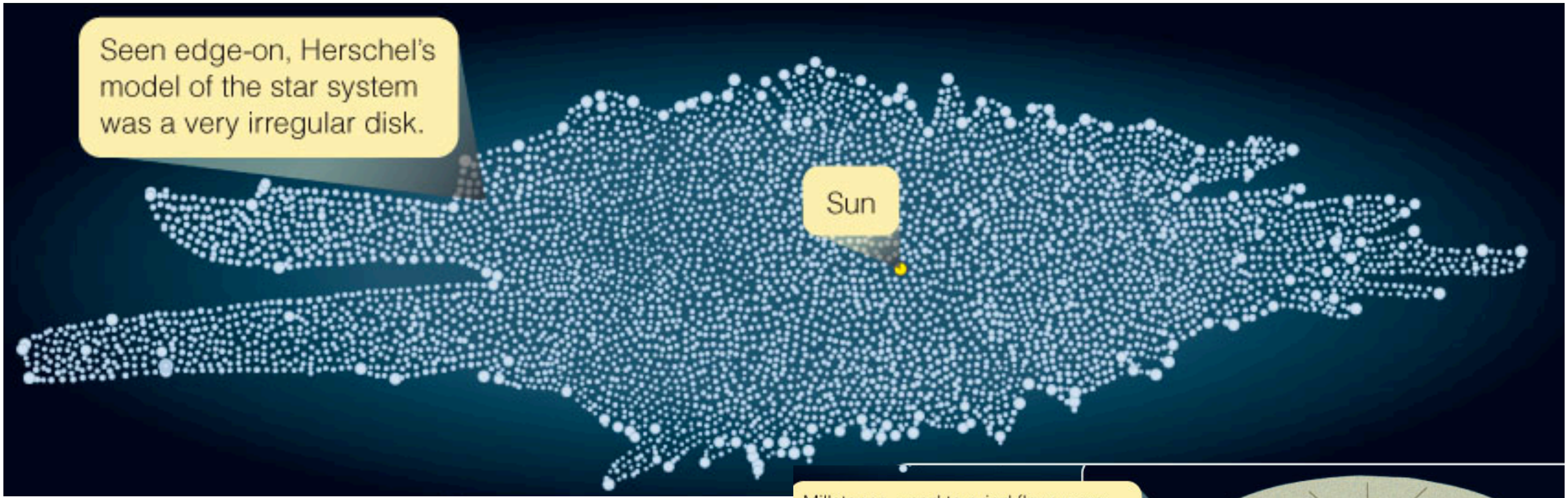
How can you tell if two regions have *significantly* different numbers of stars?

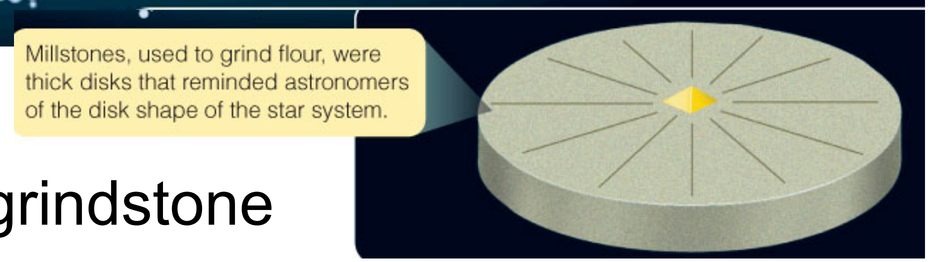
- Consider boxes A, B, C, and D.
- Let's assume that A has 9 stars in it, B has 55 stars, C has 49 stars, and D has 12.
- B and C are consistent with each having the same number of stars, while A and D are *significantly* less (deviate by more than $\sqrt{N}$).

Therefore, the galaxy is larger in the direction of B and C than it is toward A or D.

This same principle is how polls and surveys determine margin of error.

The Herschels' results





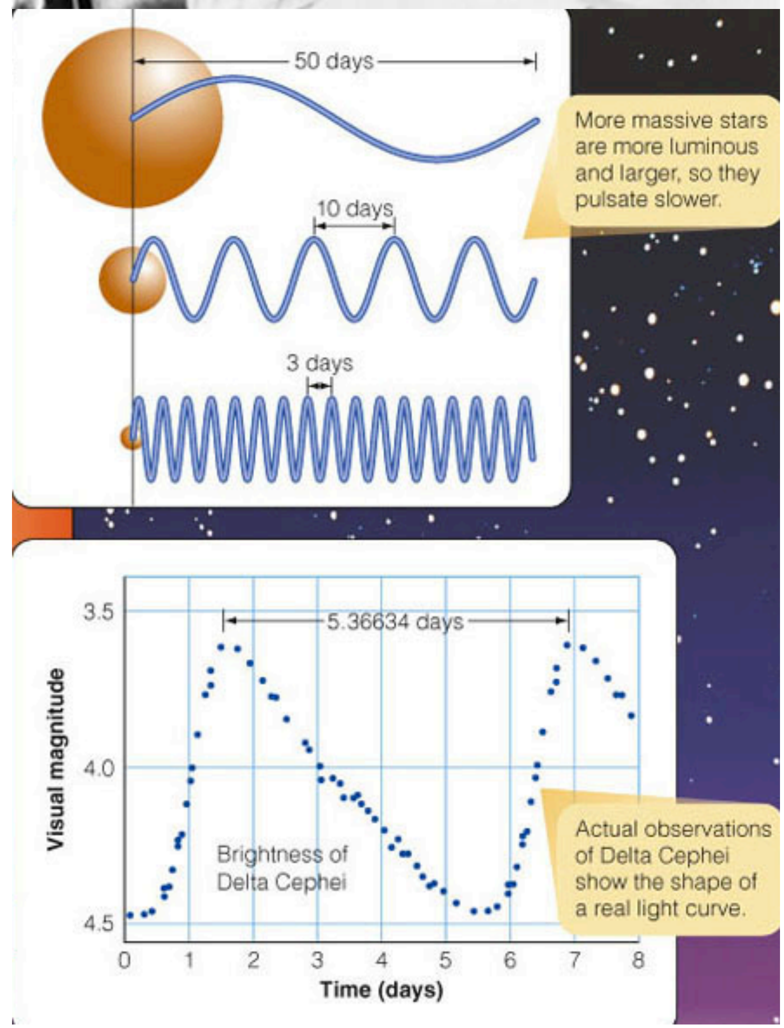
- They found that the Milky Way was shaped something like a grindstone (or frisbee) 15,000 light-years across with the Sun in the center.
- Irregular edge due to lack of observed stars in certain directions.
- **Problem: Stars cluster in space and dust absorbs light from distant stars.**

Size of the Milky Way

- A better way to determine the size of the Milky Way and the location of our Sun in it is by measuring distances to objects in the Galaxy.
- Parallax only works for relatively close objects (within 100s of parsecs).
- Need to observe bright objects that can be seen across the entire Milky Way.

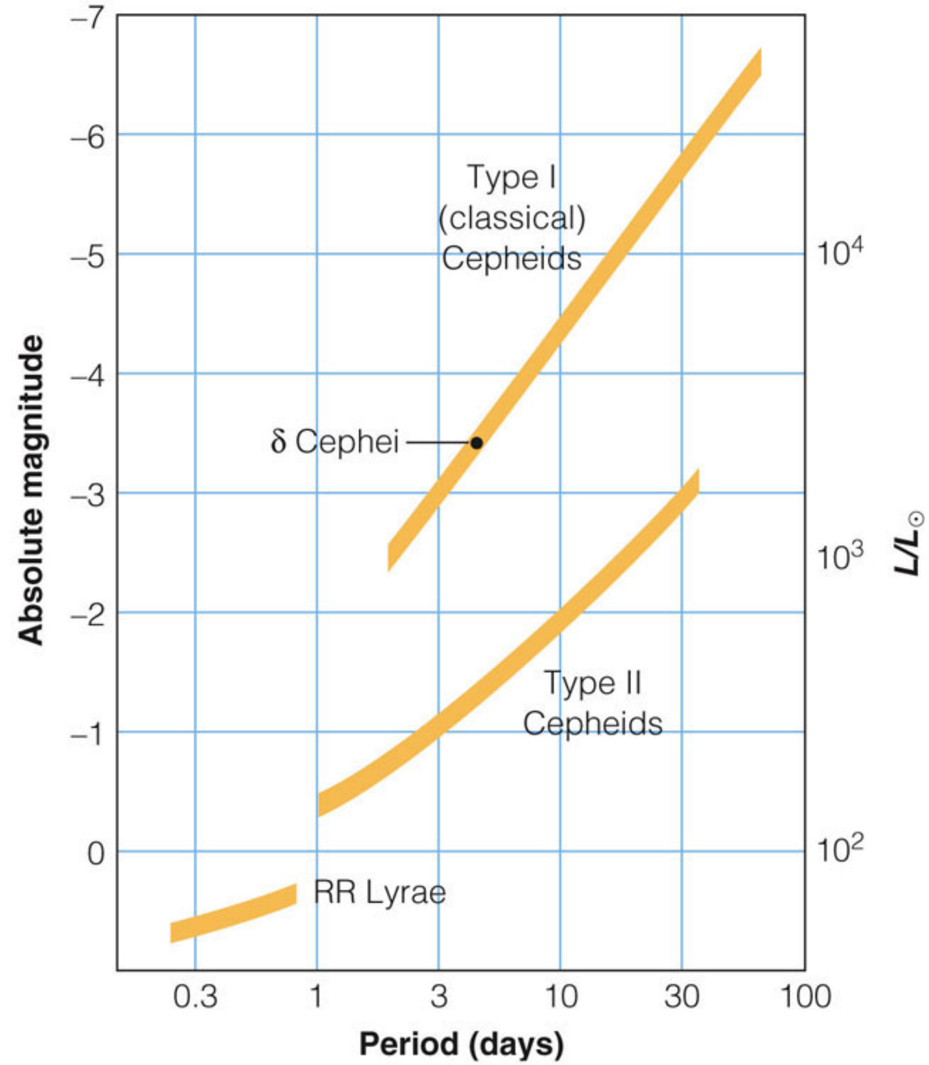
Cepheids

- Henrietta Leavitt (1868-1921) discovered a relation between the **period** and **luminosity** (or **absolute magnitude**) of Cepheid stars.
- Cepheids are stars that vary in luminosity (by growing and shrinking) over periods of days to months.
- **The *longer* the period the *brighter* the star.**



Distances from the Period-Luminosity Relation

- Measure the period of a Cepheid
- This gives you the absolute magnitude of the star.
- Measure the apparent magnitude of the star
- You can use these two magnitudes to calculate the distance to the Cepheid.
- You can do this with other types of variable stars too.

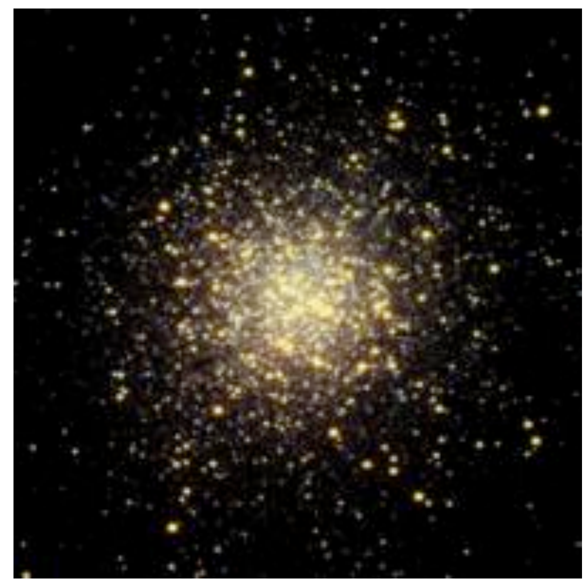


Harlow Shapley (1885-1972)

- Calibrated Leavitt's period-luminosity relation by measuring distances to nearby Cepheids.
- Used this relation to measure distances to globular clusters.
- Found that globular clusters are not centered on the Sun. **Therefore, the Sun is not at the center of the Milky way!**

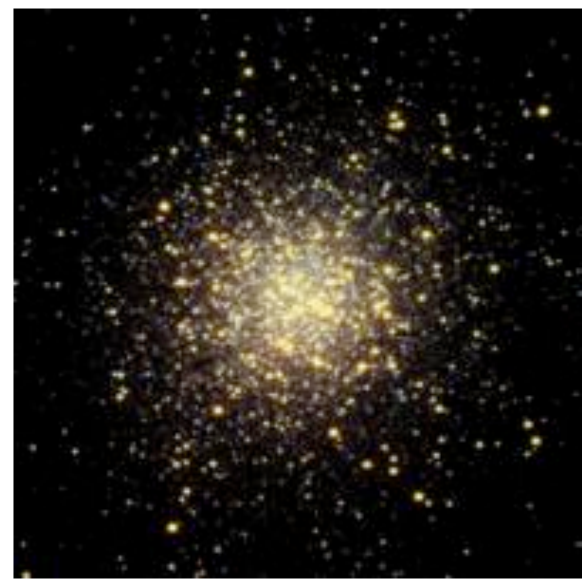
Using star clusters to measure the size of the Milky Way

- Open Clusters
  - young clusters of recently formed stars located in the disk of the Milky Way (with lots of dust).
- Globular Clusters
  - old (about 10 billion years) centrally-concentrated clusters of stars located in the halo of the Milky Way (away from obscuring dust).



Using star clusters to measure the size of the Milky Way

You will be repeating the work of Shapley by locating the center of the Milky Way using open and globular clusters.



Globular Clusters

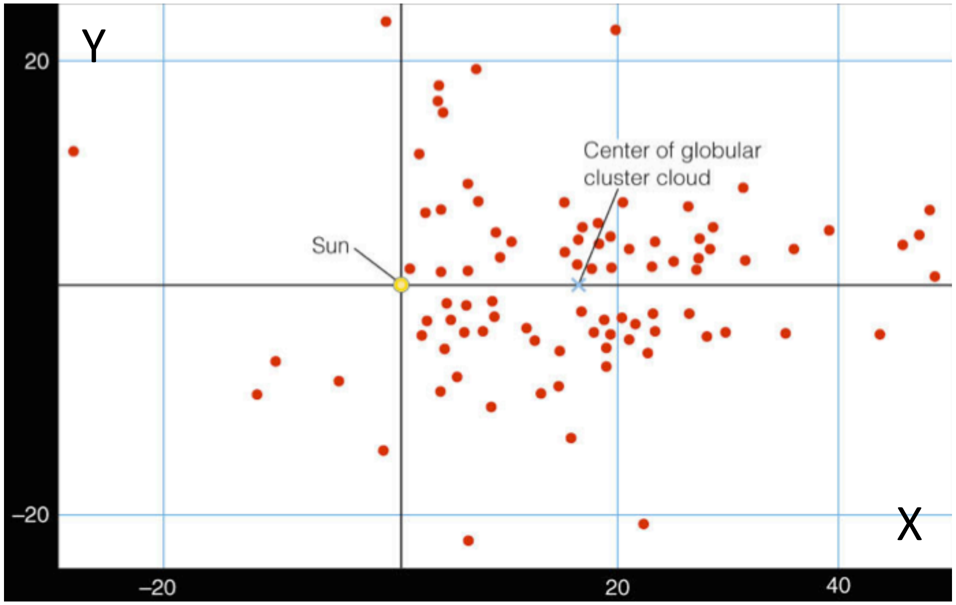
Name	x (kpc)	y (kpc)	z (kpc)
Pal 6	6	0	0
NGC 2419	-76	-1	36
NGC 6342	8	1	1
NGC 6380	11	-2	-1
NGC 6229	7	22	20
NGC 6760	6	4	-1
NGC 6981	12	8	-9
NGC 6205	3	5	5
Pal 1	-7	8	4
NGC 6401	10	1	1
NGC 6256	8	-2	0
NGC 5986	9	-4	2
Pal 10	4	5	0
Lynga 7	6	-4	0
NGC 6809	5	1	-2
NGC 6624	8	0	-1
NGC 5904	5	0	5
NGC 6441	12	-1	-1
NGC 5024	3	-1	18
Terzan 7	22	1	-8
NGC 2808	2	-9	-2
NGC 7099	5	2	-6
NGC 1904	-8	-8	-6
NGC 6266	7	-1	1

Open Clusters

Name	x (pc)	y (pc)	z (pc)
Stock 14	1011	-2148	-29
NGC 5138	1151	-1500	116
NGC 6940	268	732	-98
NGC 2547	-40	-420	-63
NGC 1746	-515	9	-97
NGC 4755	1181	-1804	94
NGC 6531	1242	168	-9
NGC 1857	-1863	382	43
Col 107	-1529	-786	-27
Tr 16	843	-2658	-34
Col 228	722	-2290	-42
NGC 2324	-2796	-1843	193
NGC 6208	904	-335	-98
NGC 6604	1584	524	50
IC 2602	53	-150	-14
NGC 6530	1458	156	-36
NGC 2232	-310	-212	-50
NGC 2467	-1077	-2123	17
NGC 2670	-48	-1090	-69
NGC 6613	1210	306	-22
NGC 6025	647	-461	-84
NGC 7160	-203	815	94
NGC 2264	-653	-277	27
NGC 2353	-789	-781	8
NGC 457	-1555	2093	-196
Mel 71	-1952	-2238	234
NGC 1245	-2135	1408	-401
NGC 6834	899	1990	46
NGC 6830	775	1348	-49

Plot x vs. y and x vs. z for both populations

Shapley's results

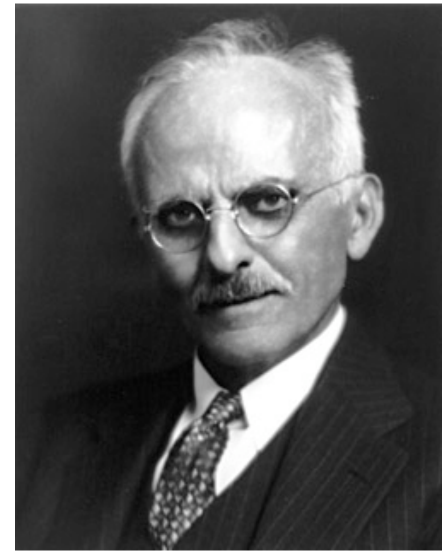


- Shapley found that globular clusters were clumped around a point about 20,000 parsecs from Sun.
- Shapley's result showed that the Milky Way was much, much bigger than previously thought!
- This value turns out to be about twice as far as the currently accepted value of the distance from the Sun to the Galactic Center (8500 parsecs).

Discovery of Spiral Nebulae

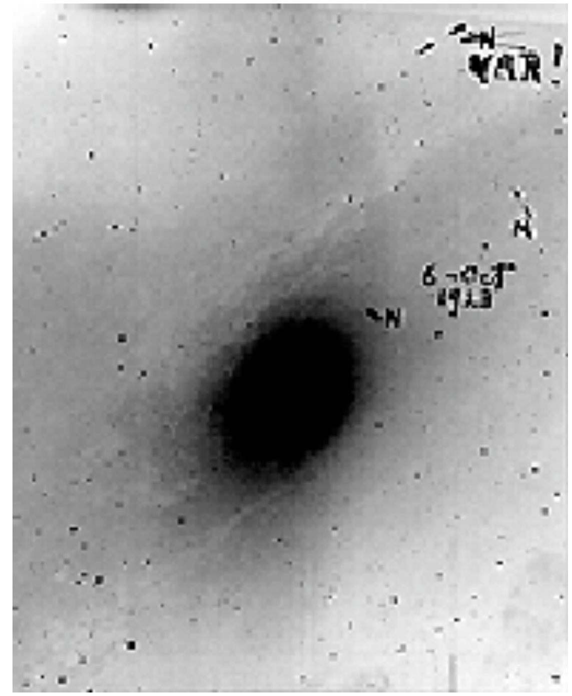
- In 1845, Lord Rosse used his 72-inch telescope to discover the first nebula with spiral structure.
- Were these “spiral nebulae” distant versions of our galaxy?
- This was a matter of debate for almost 80 years.

The Great Debate (1921)



- Shapley versus Heber Curtis
- Shapley argued that the Milky Way was the entire universe, but that the Sun was not in the center.
- Curtis said the Sun was at the center of the Milky Way, but that our galaxy was one of many.
- They were both partially correct.

Edwin Hubble

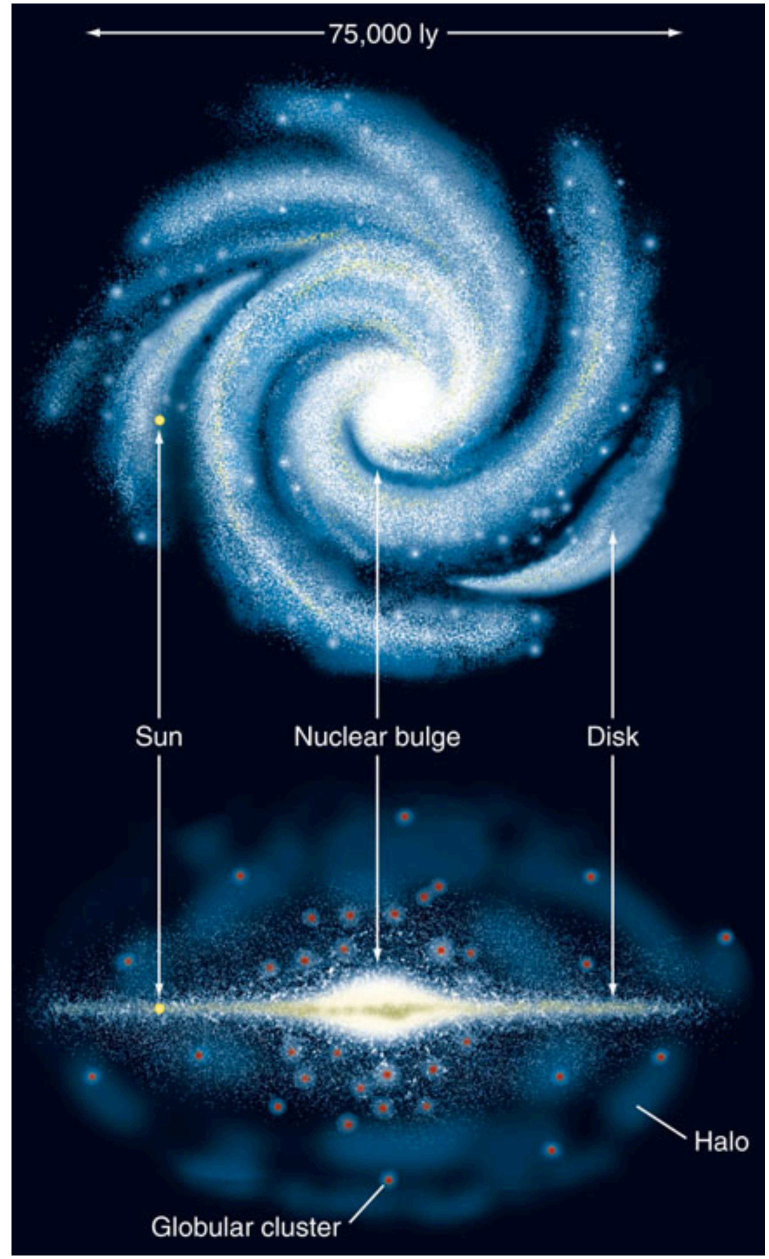


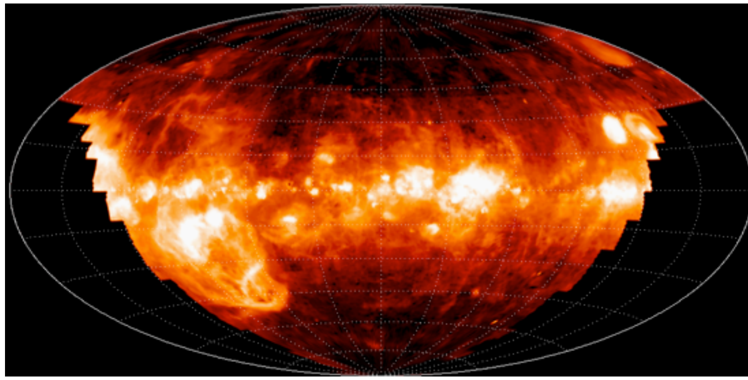
- In 1923, Hubble found a Cepheid variable in Andromeda using the largest telescope of the day, the 100-inch reflector on Mt. Wilson near Los Angeles.
- The distance he measured proved that Andromeda was clearly beyond the Milky Way.
- Current distance to Andromeda is 780 kiloparsecs.

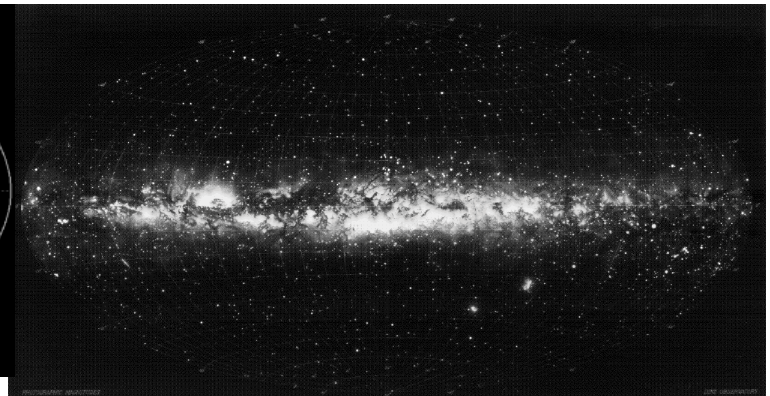
The structure of the Milky Way

The structure of Milky Way

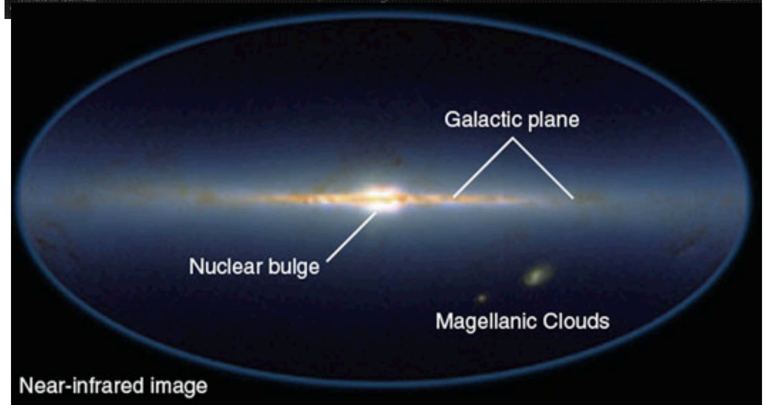
- The *disk* contains stars, open clusters, and lots of gas and **dust**. It is characterized by its spiral arms and lots of star formation.
- The disk is about 30 kiloparsecs (kpc) across and less than 1 kpc thick near the Sun.
- The Sun is in the disk, 8.5 kiloparsecs from the Galactic Center.

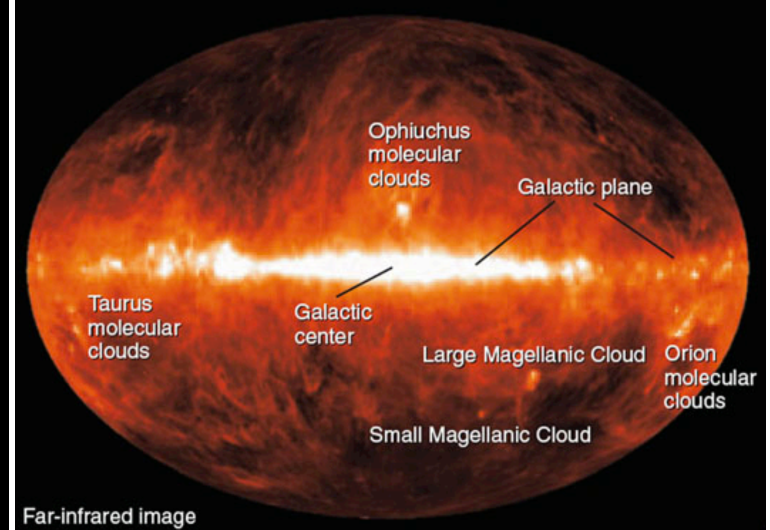


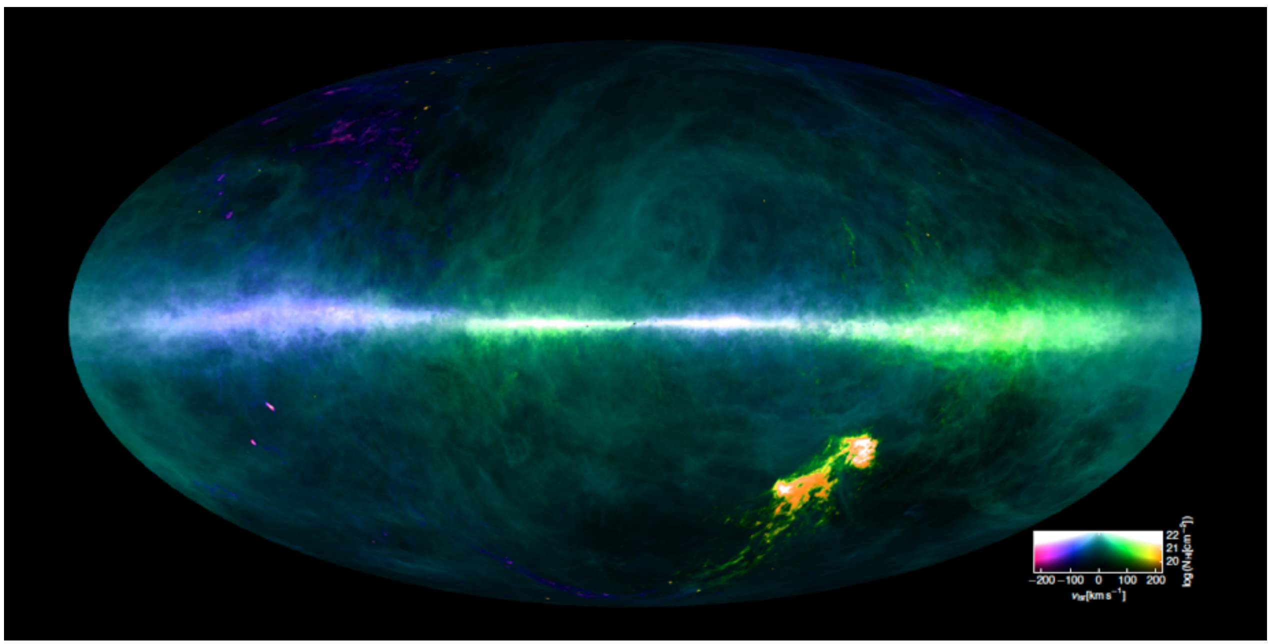




The disk is visible in (clockwise from above) forming stars, young stars, old stars, dust and molecular gas, and cool gas.

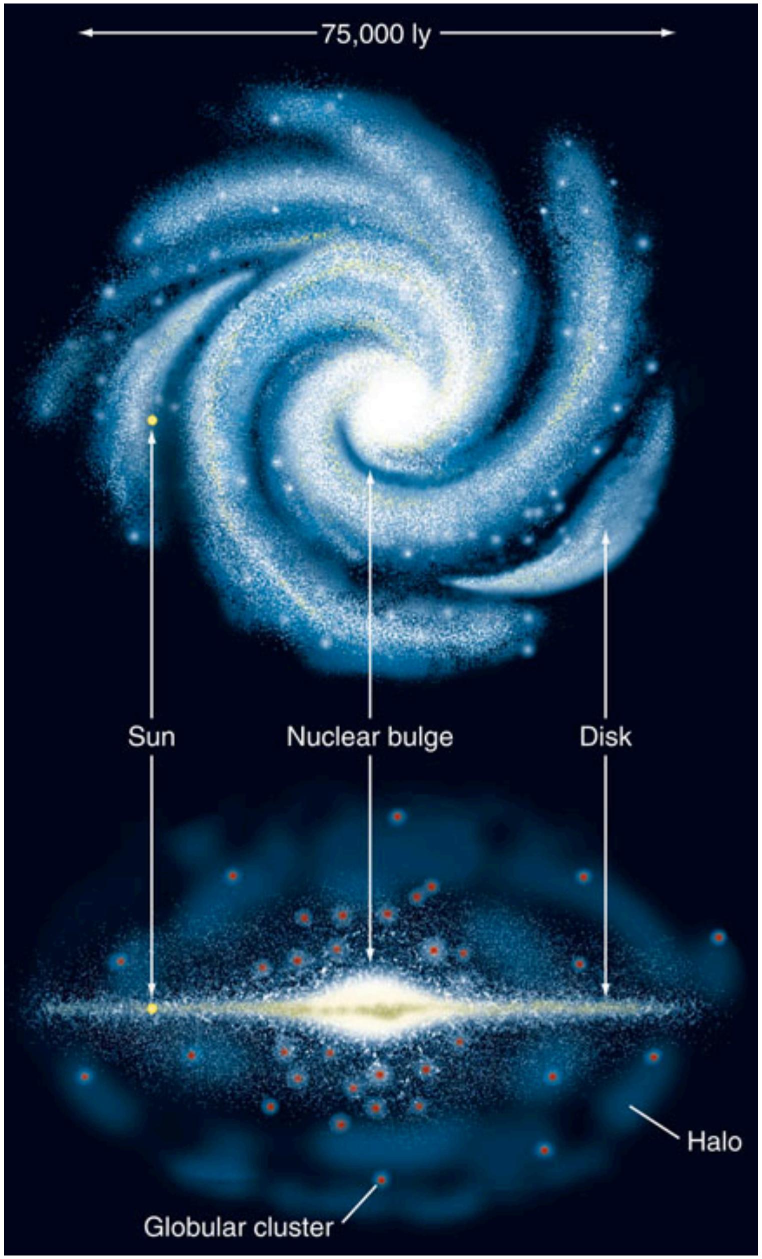






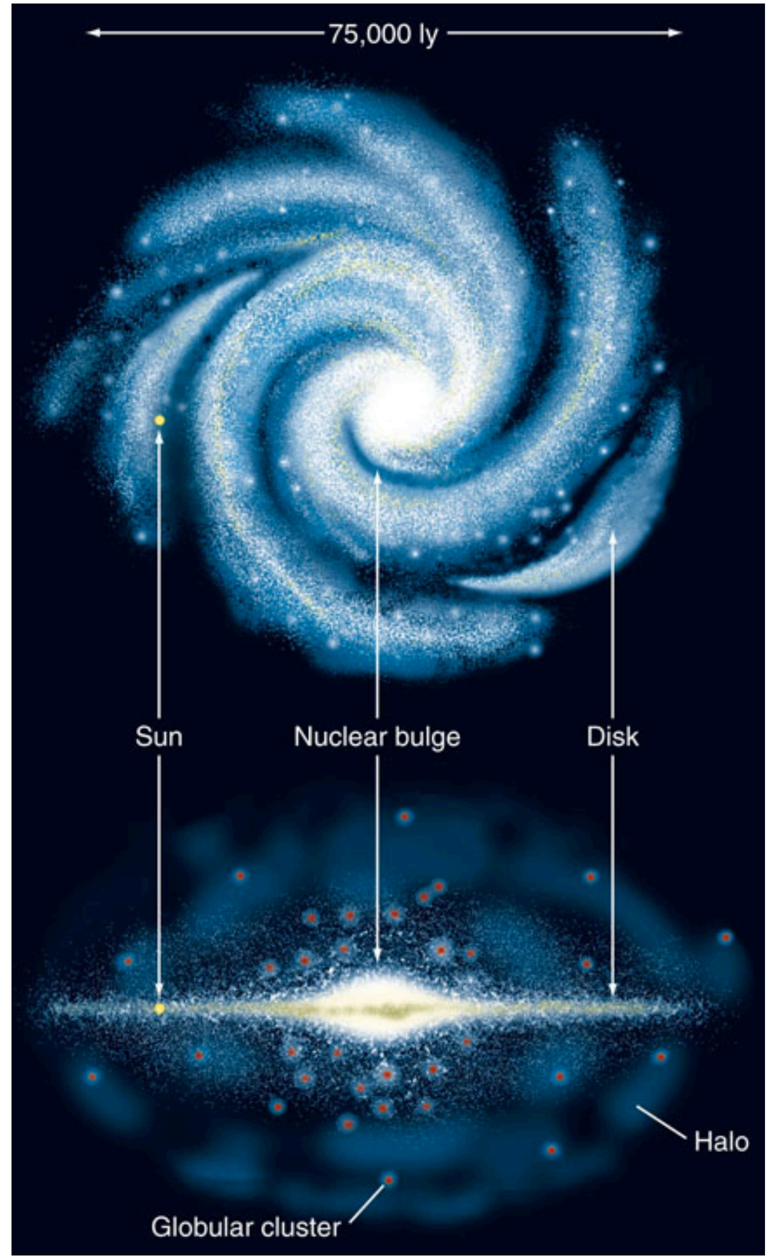
The structure of Milky Way

- The *halo* is spherical. It contains globular clusters, hot gas, very few stars, very little cool gas, and lots of *dark matter*. The halo only has 2% of the stars as the disk and bulge.
- The halo extends beyond the disk out to, perhaps, 100 or more kpc.
- There is little star formation in the halo.

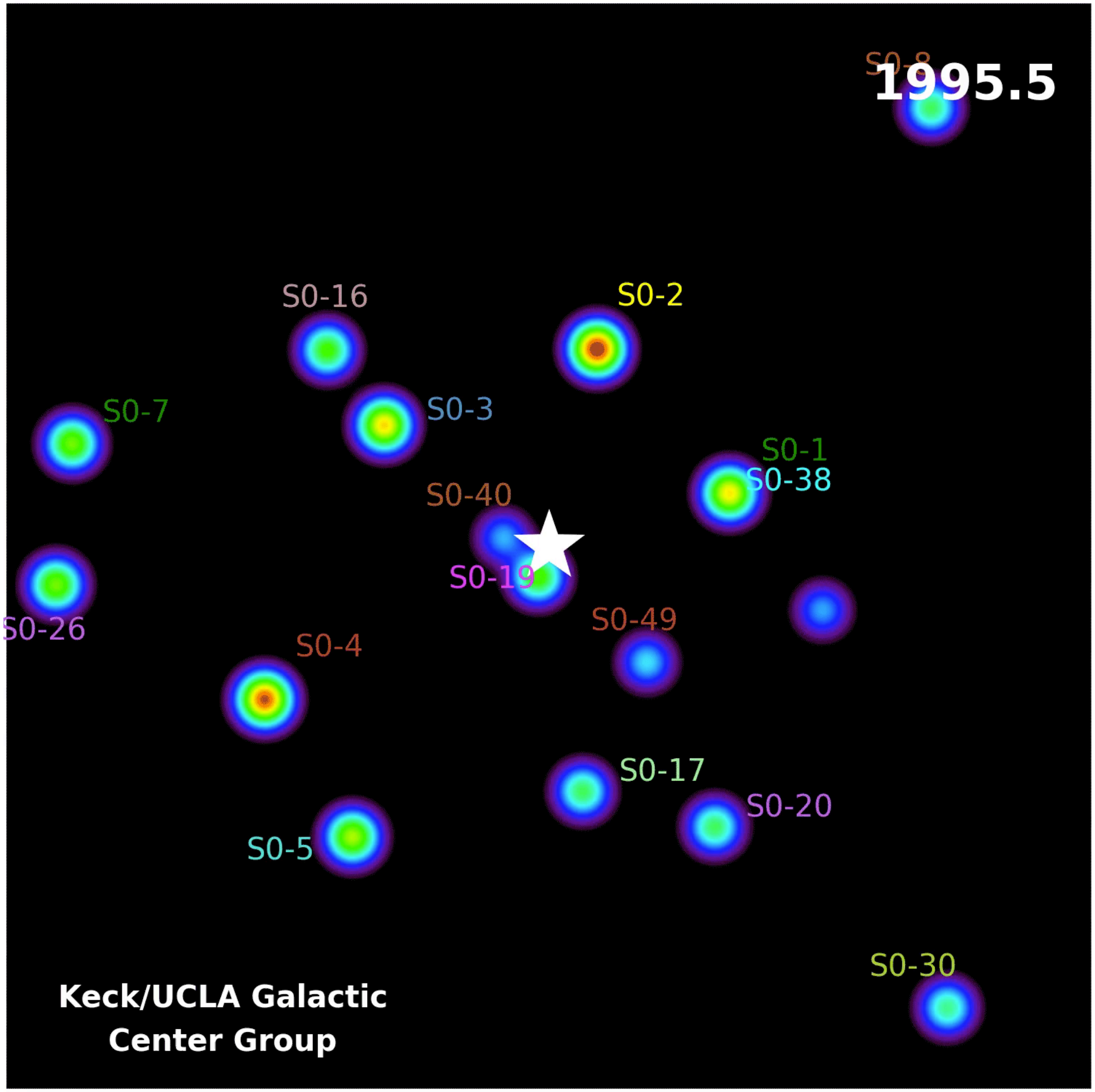


The structure of Milky Way

- The *bulge* is spherical, but is concentrated in the center of the galaxy.
- The bulge is mostly stars. It has a diameter of 4 kpc.
- There is a bar (not shown) composed of stars, gas, and dust that extends 6 kpc through the center of the galaxy
- In the center of the Galaxy, the *nucleus,* there is a *supermassive black hole*, about 4 million solar masses.



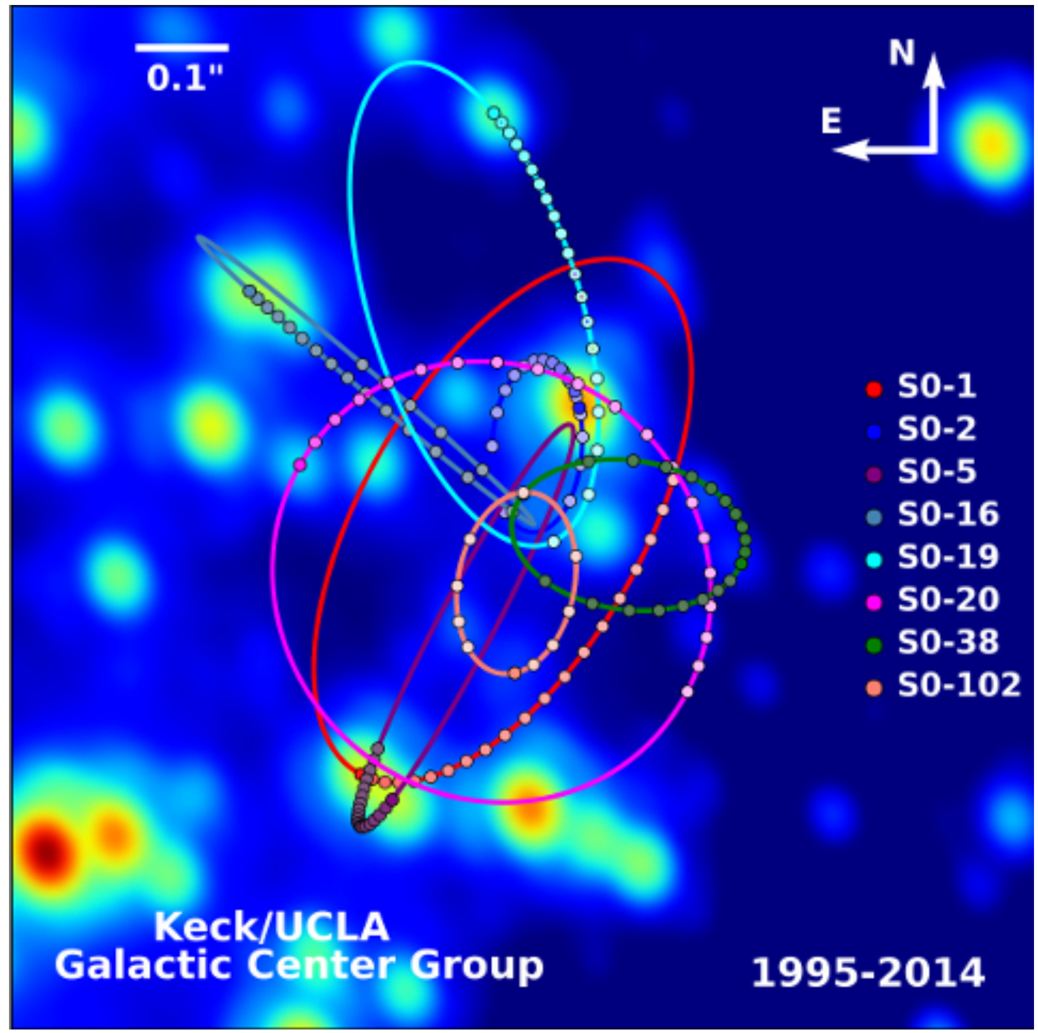
What's at the center of the Milky Way?



The Black Hole at the center of the Milky Way

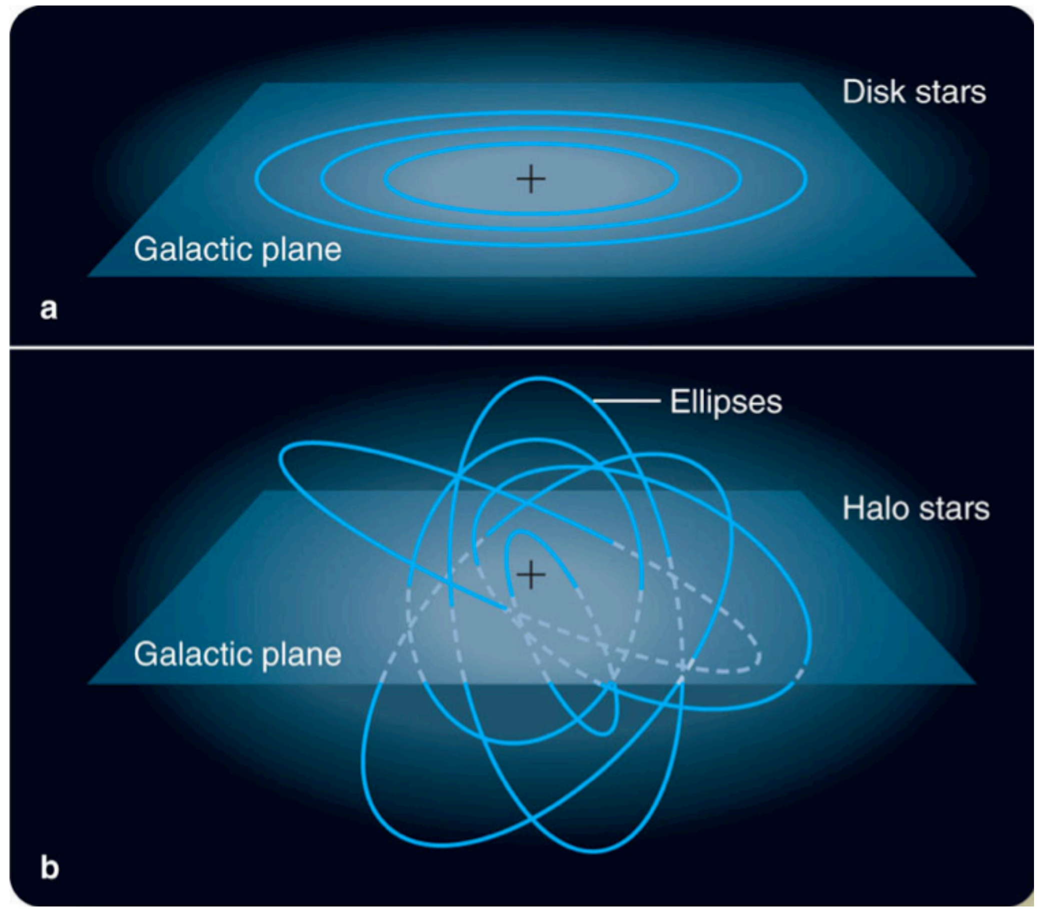
Using Kepler's and Newton's laws, we can relate the size and the period of the stellar orbits to derive the mass of the Milky Way's black hole.

$M_{\bullet} \sim$ 4 million solar masses



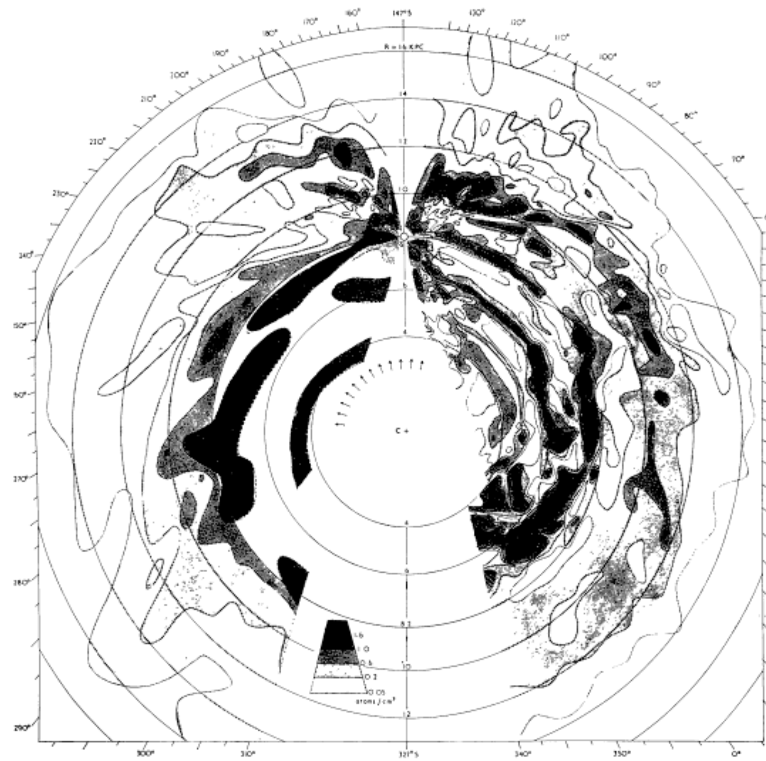
Disk vs. Halo and Bulge

- Stars and gas in the disk are all rotating together in the same general direction in the plane of the disk
- Stars in the halo and bulge orbit in different planes with no general sense of rotation.



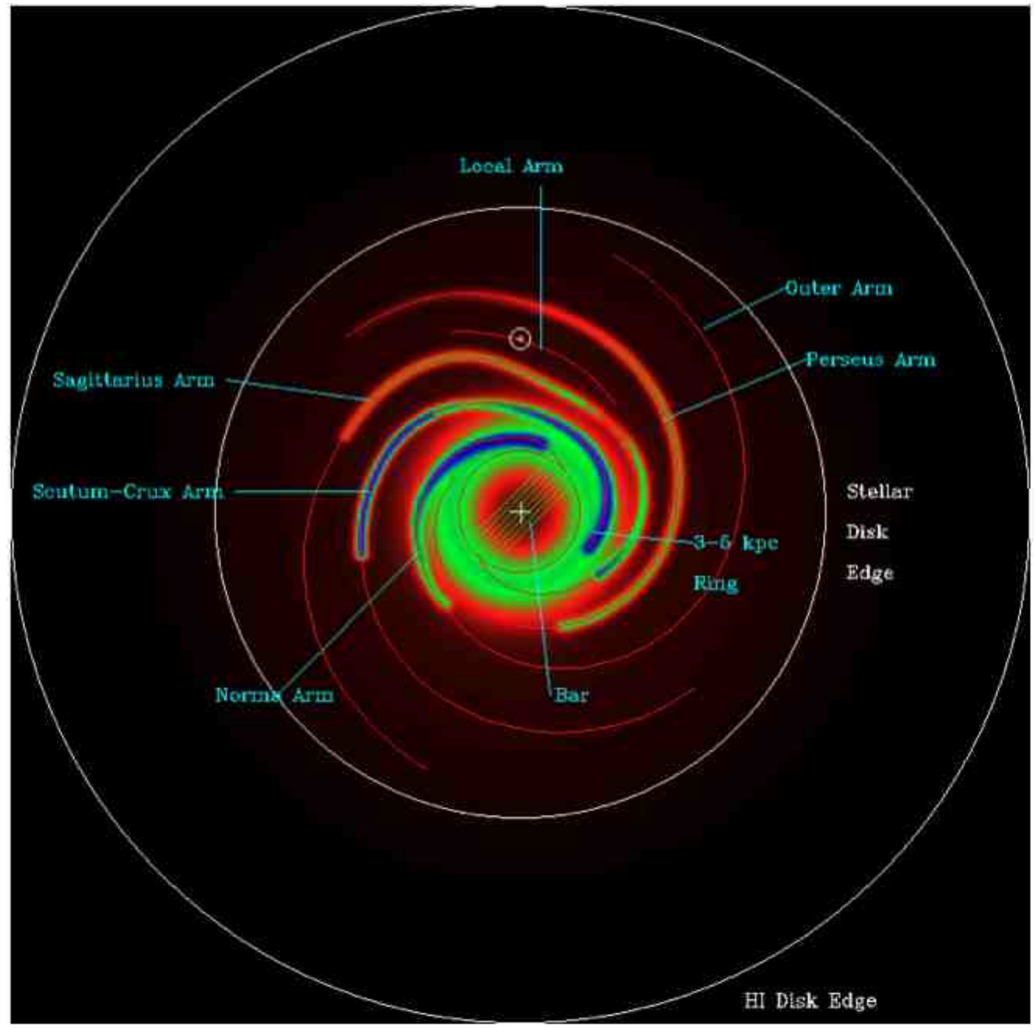
Spiral Arms

- If you measure the amount of gas as a function of distance at different positions, you can make a map of the spiral arms of the Milky Way.
- This is an early map in neutral hydrogen.



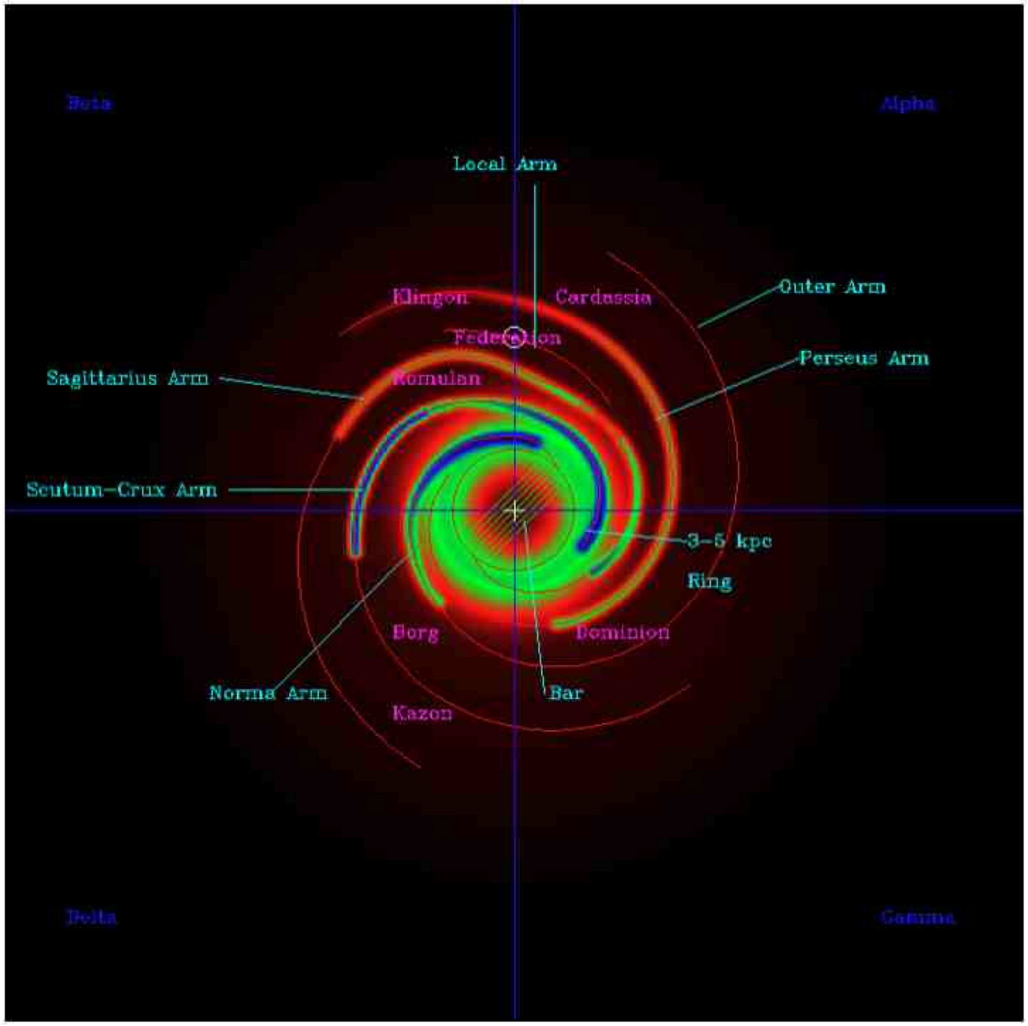
Spiral Arms

This is a more recent map using just electrons with various features labeled.



Spiral Arms

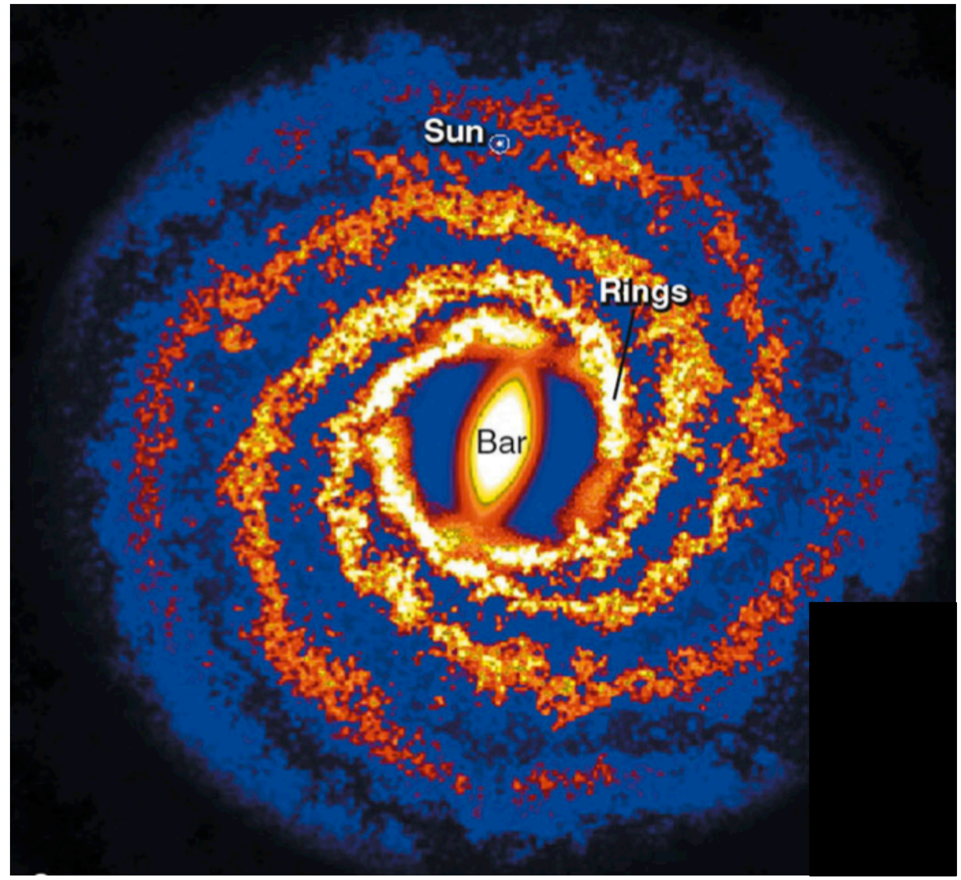
The same map as before, but with additional fictional labels.



Spiral Arms

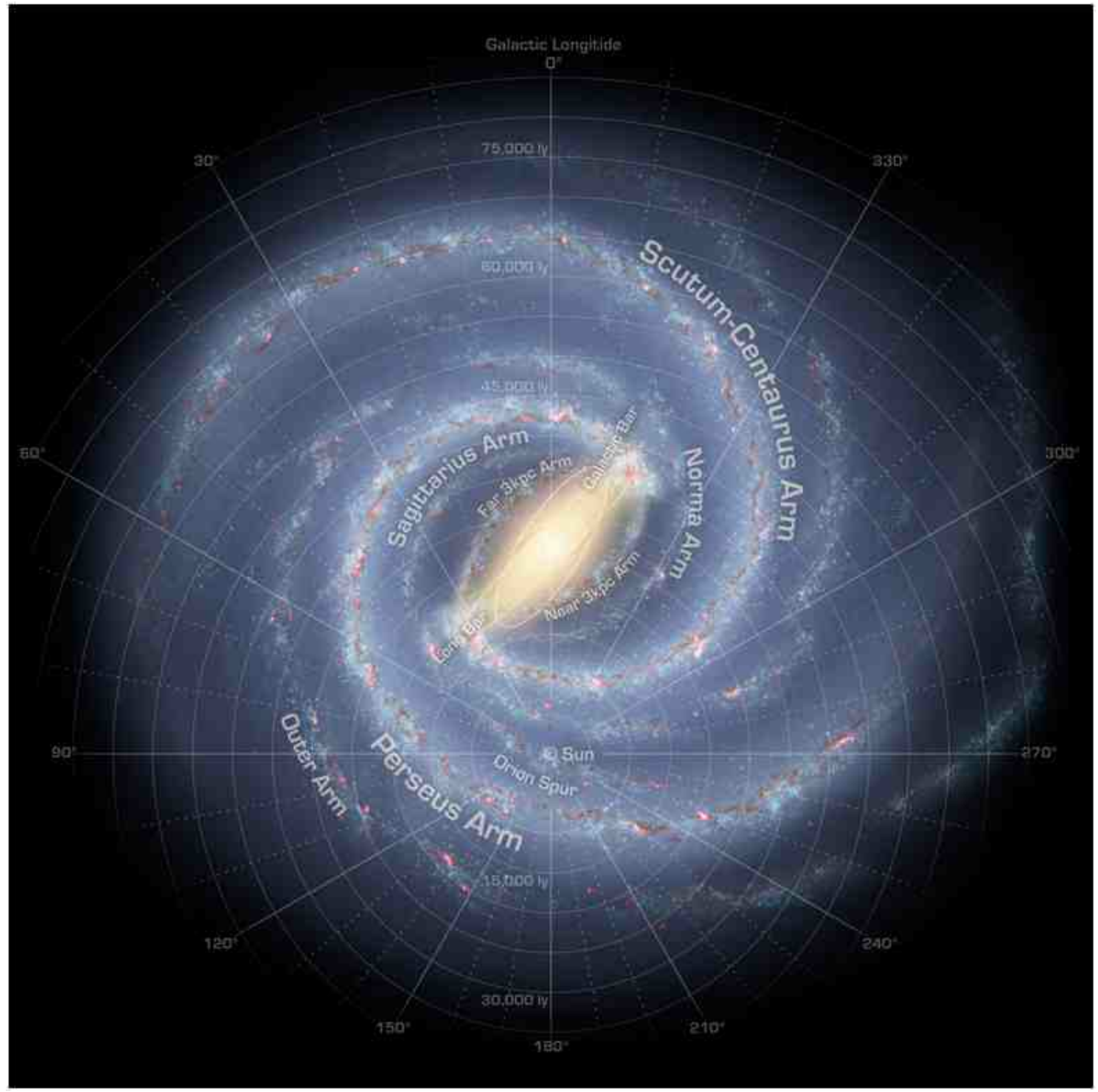
Another recent map using the distribution of dust to trace the spiral arms.

Notice that this is the first map that shows the bar.

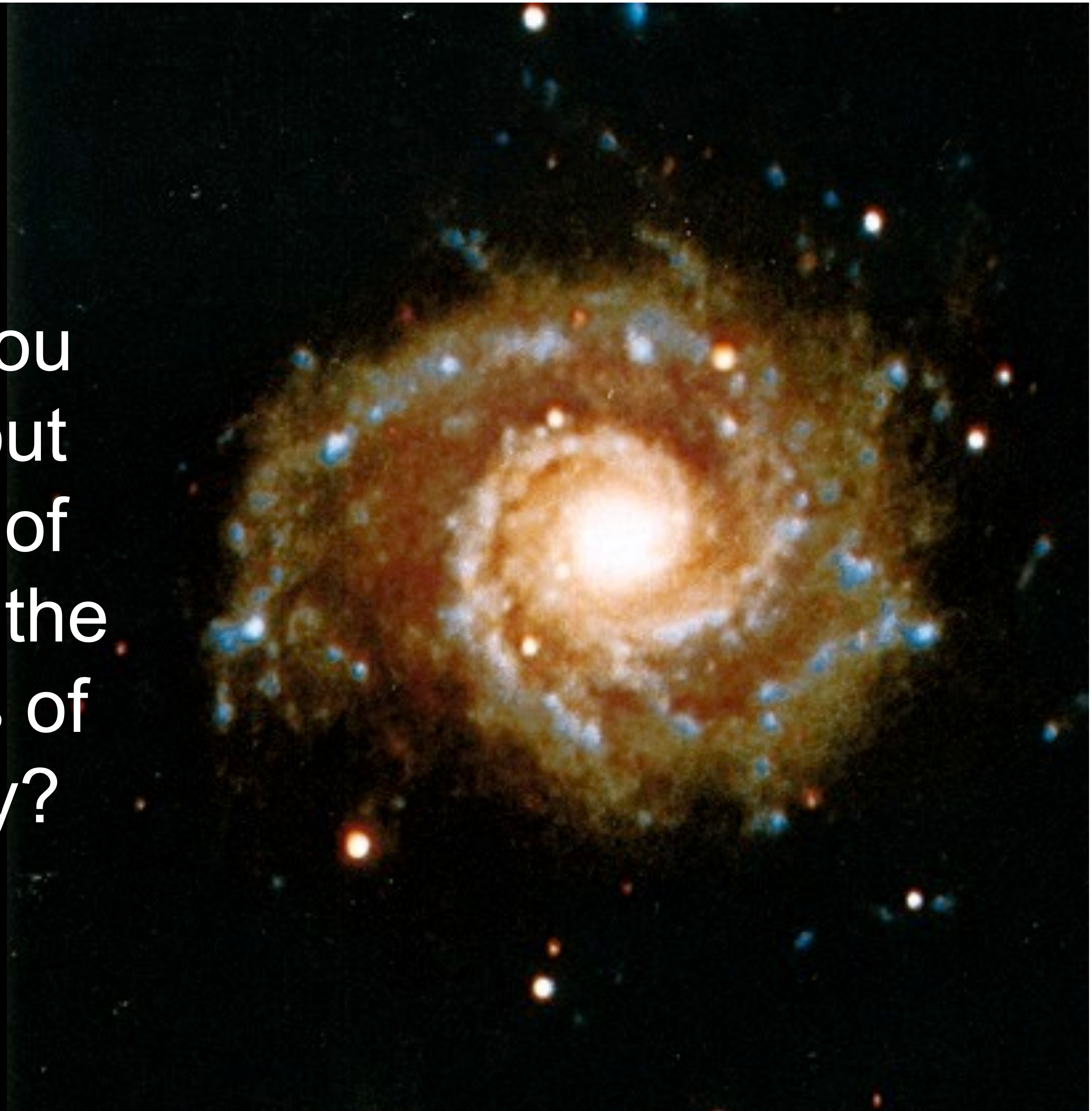


Spiral Arms

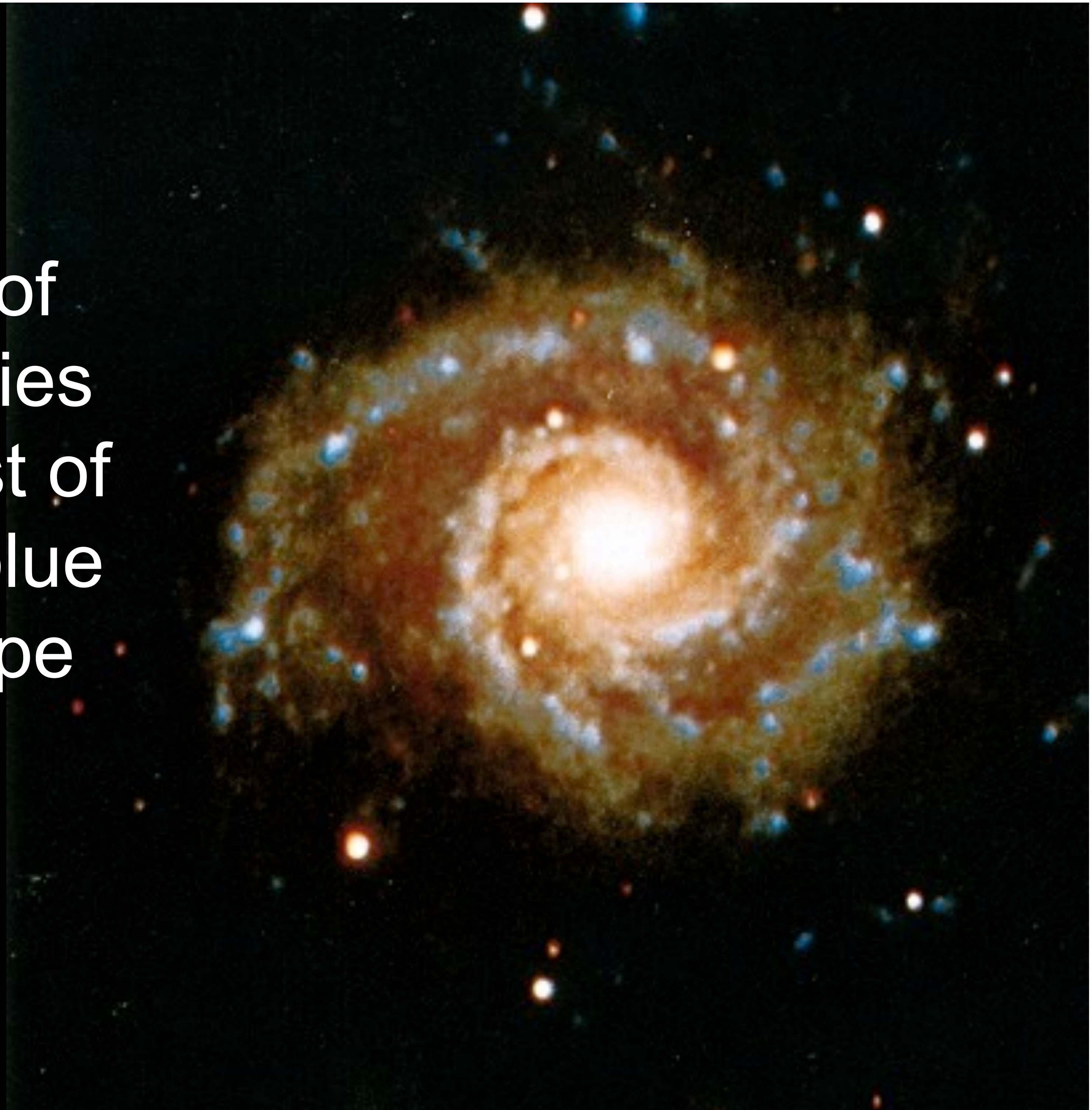
Artist's conception based on recent measurements of stellar distances in the infrared

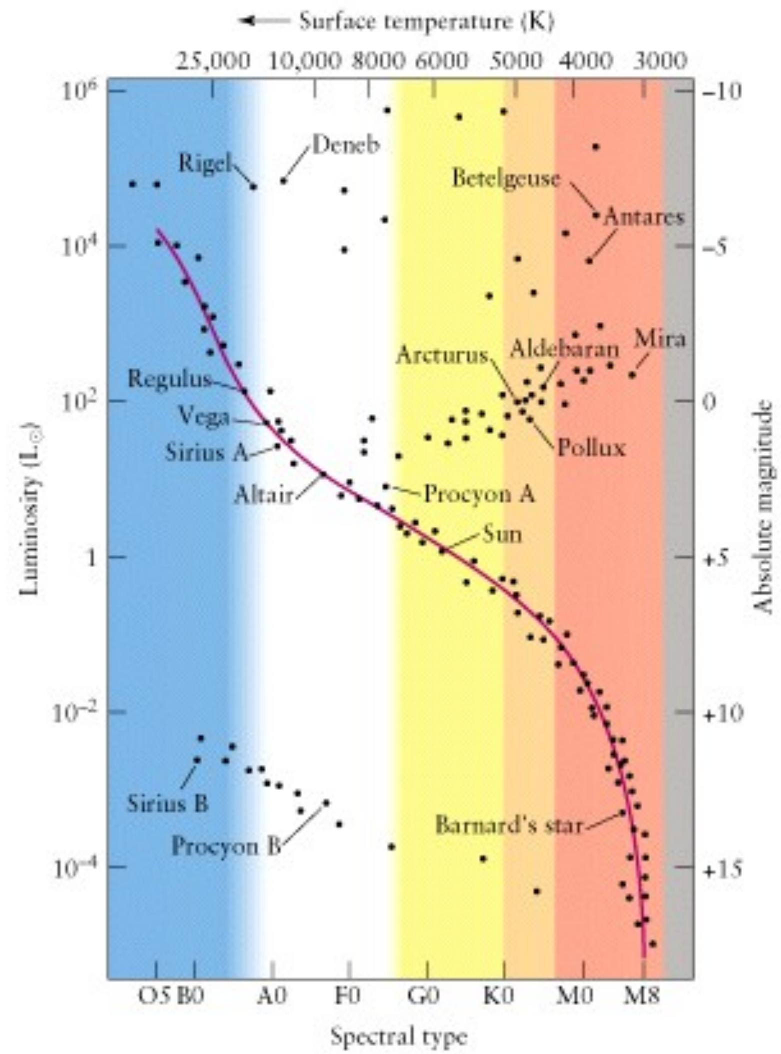


What do you notice about the colors of the stars in the spiral arms of this galaxy?



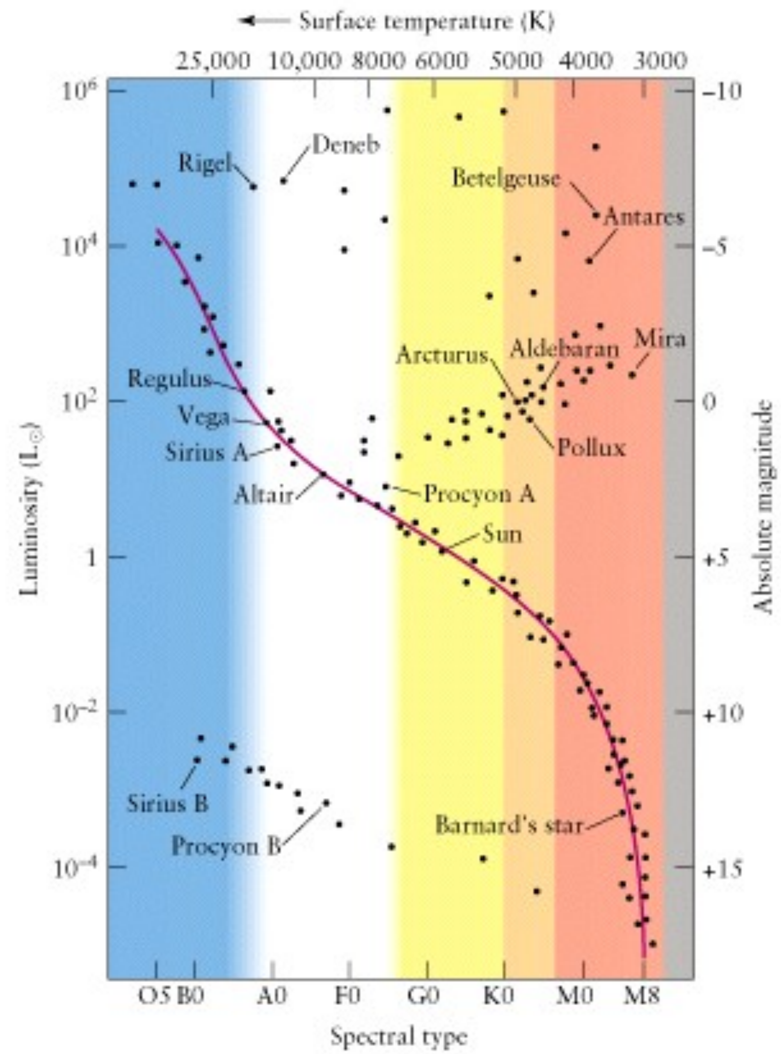
The arms of spiral galaxies contain most of the bright, blue O and B type stars.





Stellar Lifetimes

- Which live longer, Red or Blue stars?



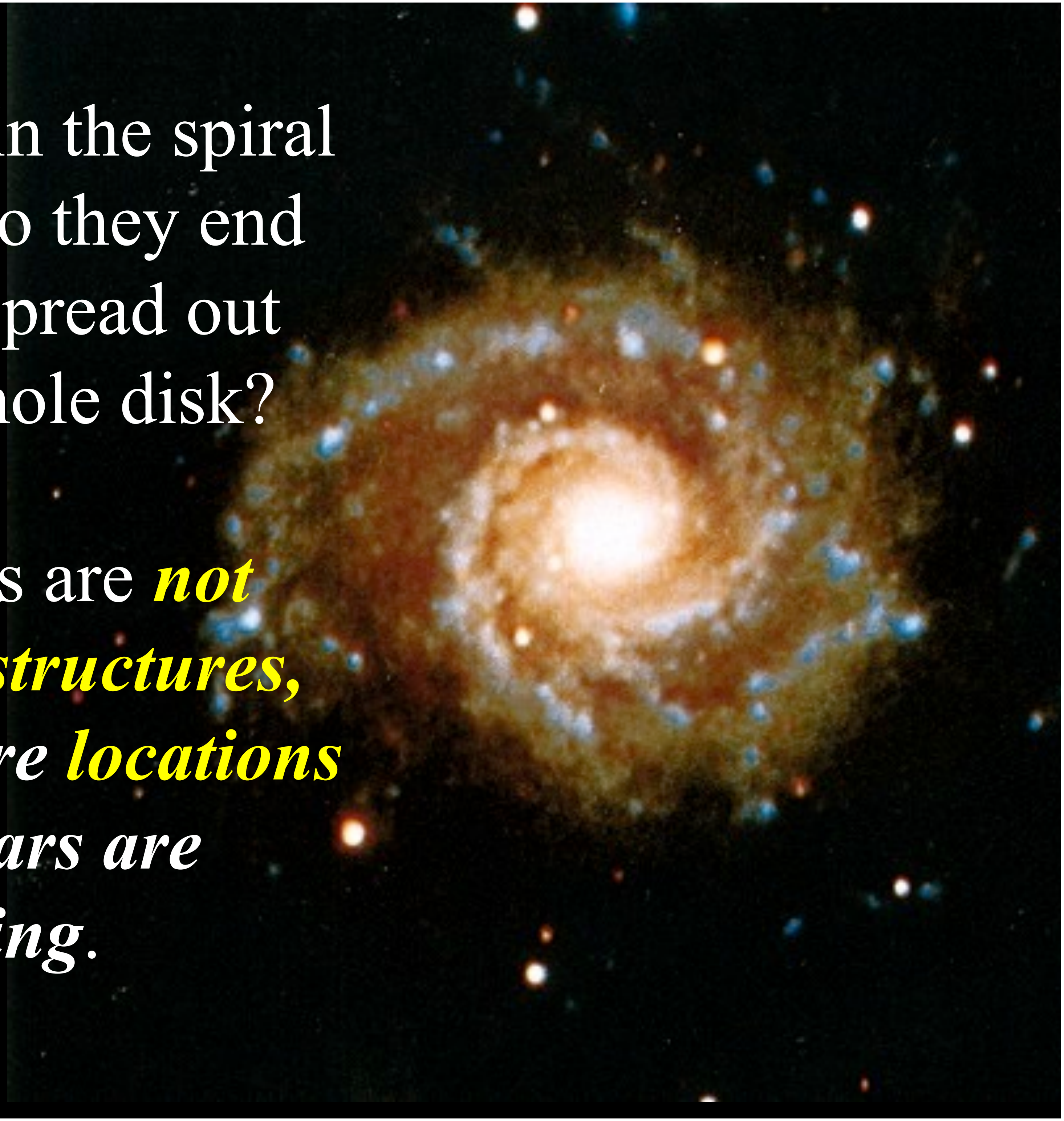
Stellar Lifetimes

- So the stars in the spiral arms are mostly bright, hot, and young stars!

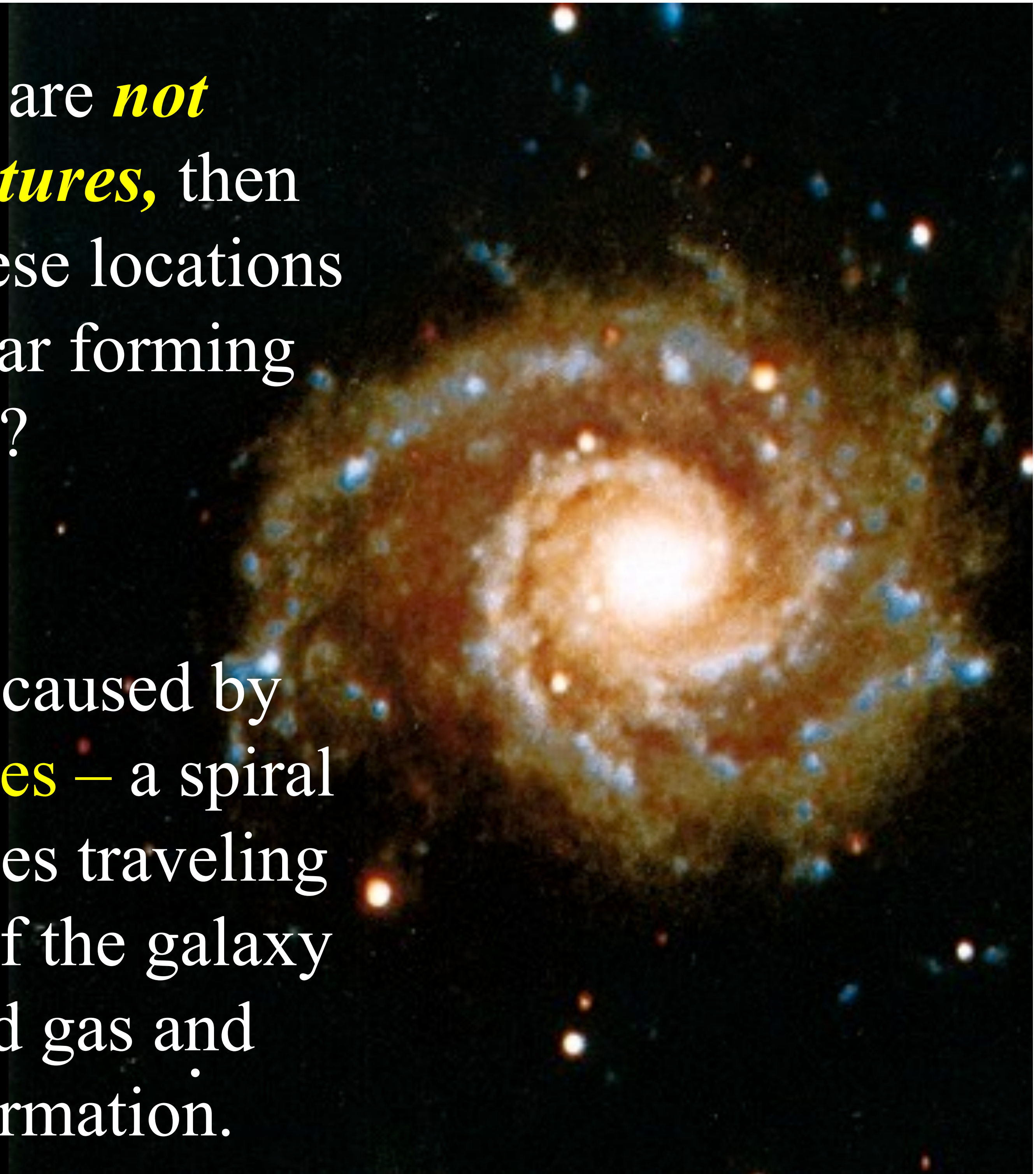
Since O stars have such a short lifetime, it must be that: the arms of spiral galaxies are where star formation happens!

If stars form in the spiral arms, how do they end up getting spread out over the whole disk?

Spiral arms are ***not permanent structures,*** ***rather they are locations where stars are forming***.



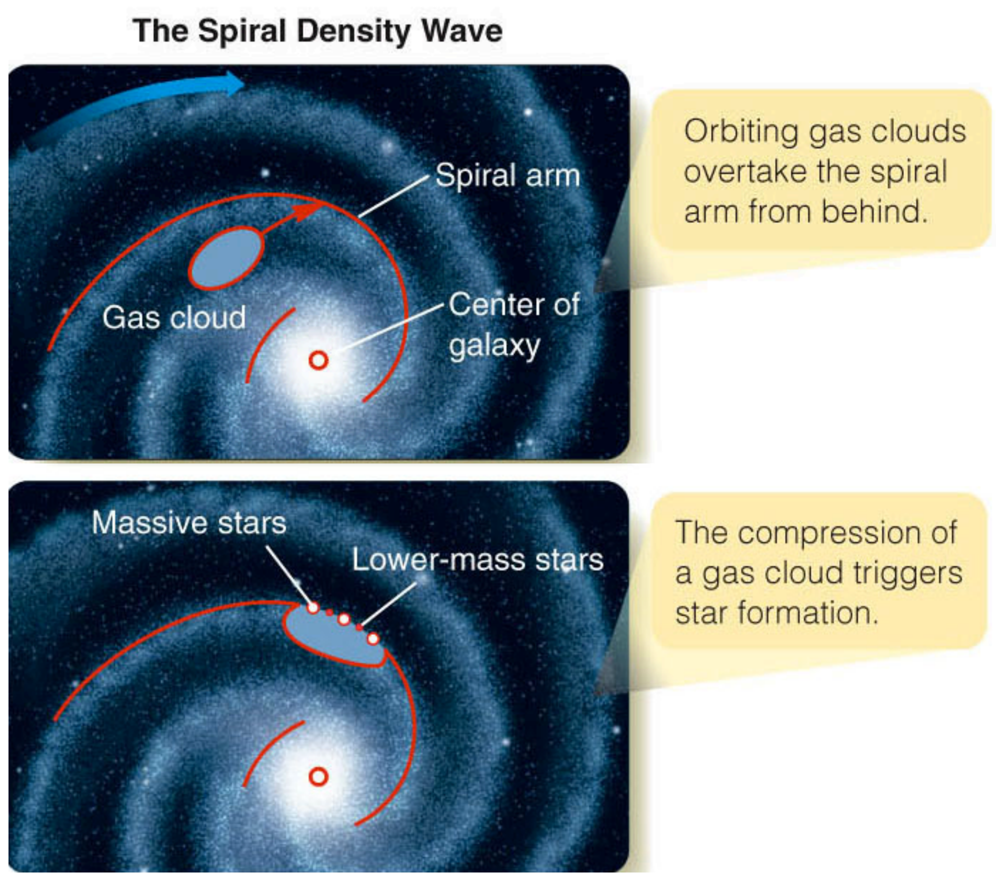
If spiral arms are ***not permanent structures,*** then what is making these locations become active star forming regions?



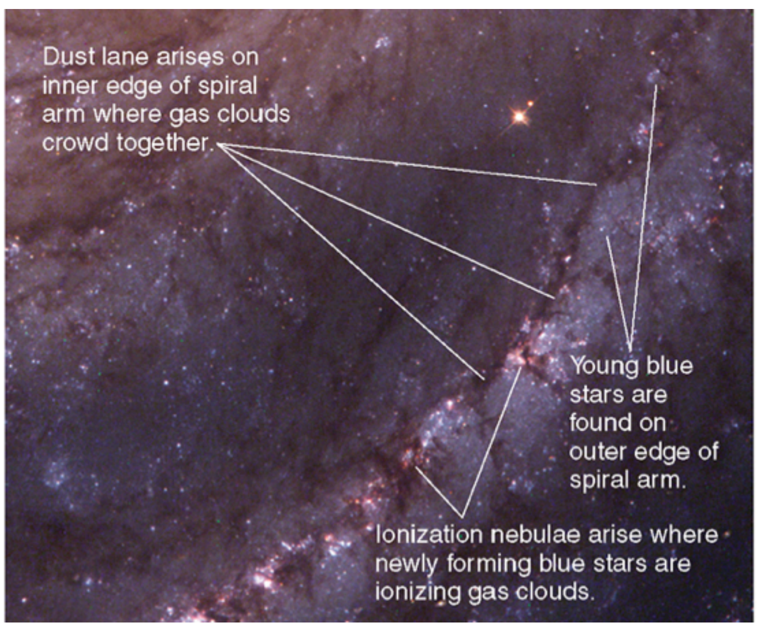
Spiral arms are caused by spiral density waves – a spiral shaped disturbances traveling through the disk of the galaxy that compressed gas and triggers star formation.

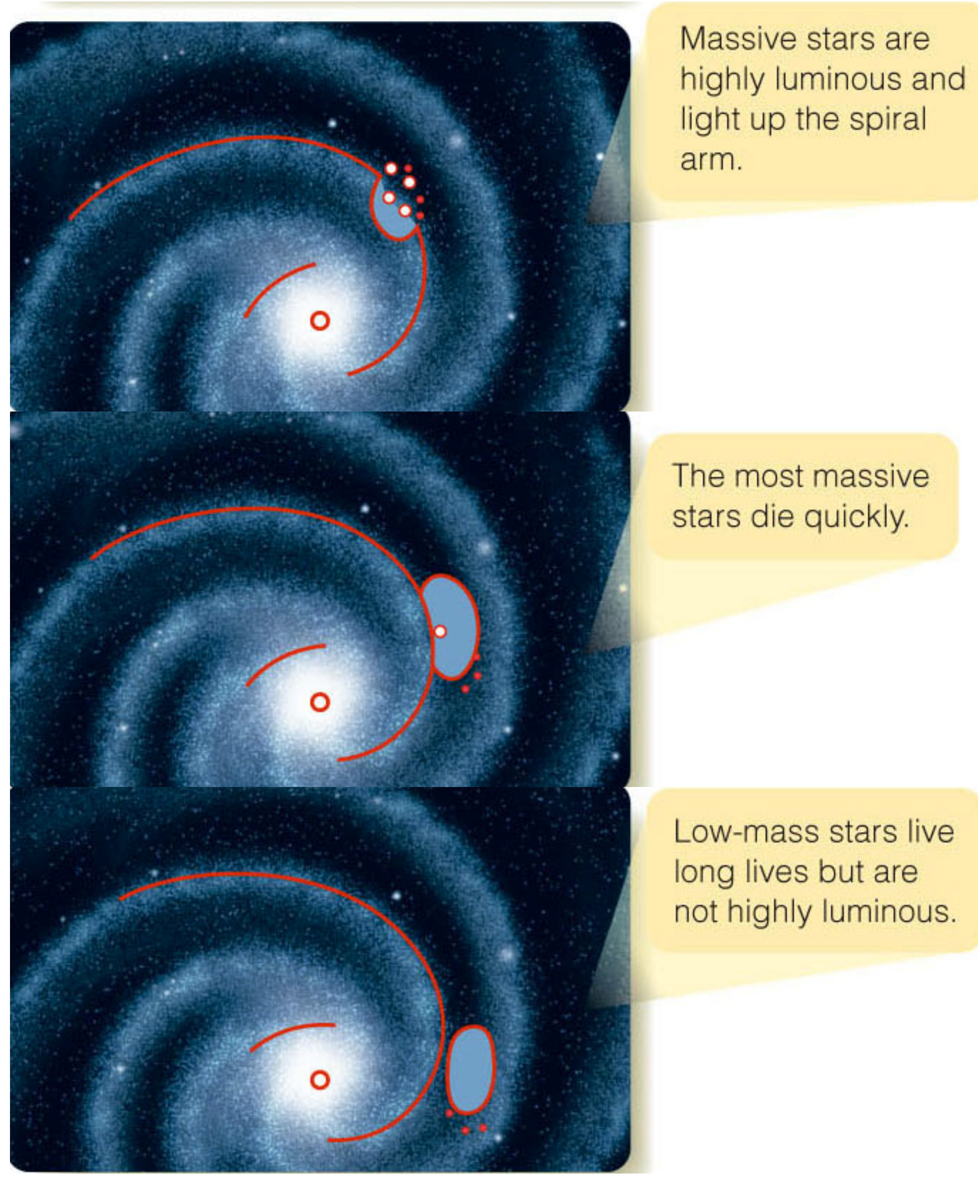
Spiral Density Waves

- Spiral arms are like traffic jams: stars and gas bunch up as they move through them.
- As the gas compresses, star formation is triggered.



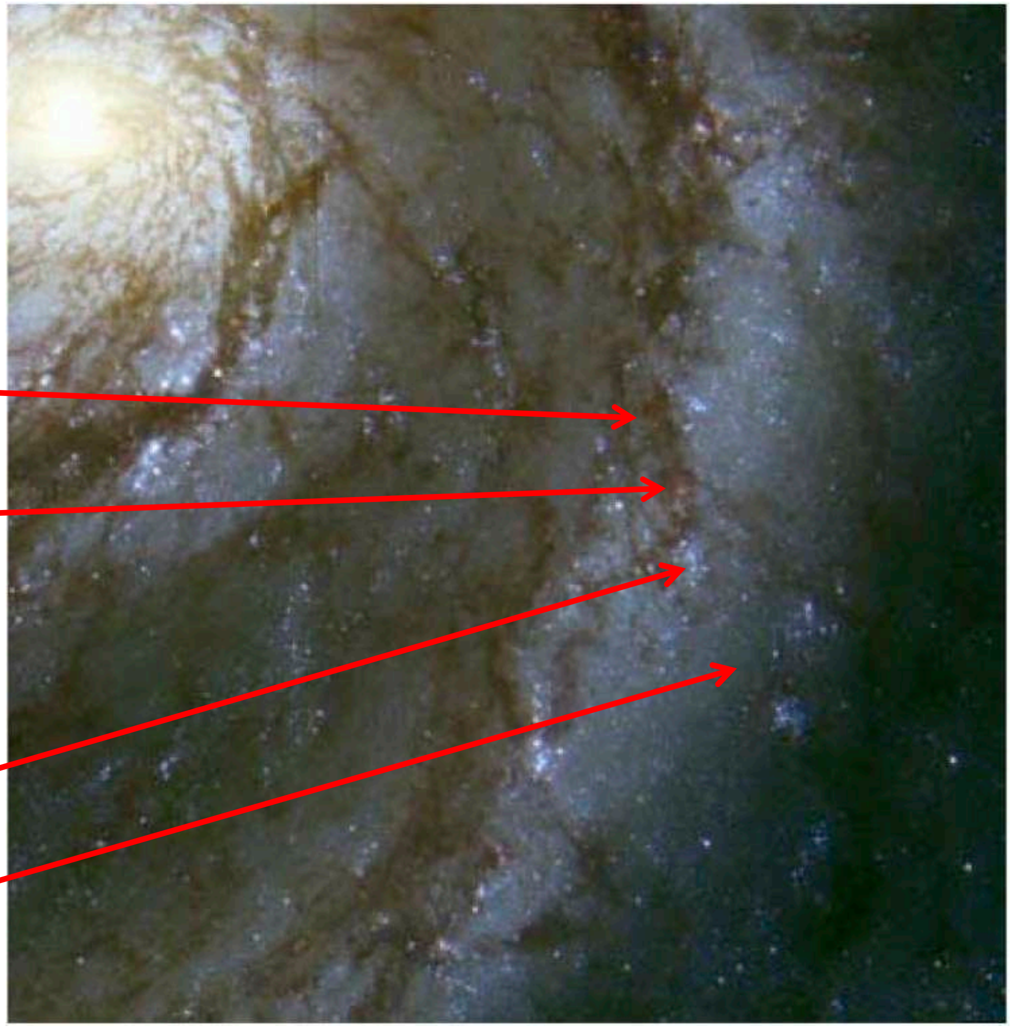
- Massive, luminous, blue stars are only seen close to the spiral arm.
- Longer-lived, fainter, low-mass stars (like our Sun) continue on through many spiral arms.





Star Formation across spiral arms

- We can see many of the stages of star formation across a spiral arm.
- Molecular clouds
- ionization nebulae (reddish; associated with protostars)
- Main Sequence O Stars (blue)
- lower mass main sequence stars (red)



Stars in the bulge

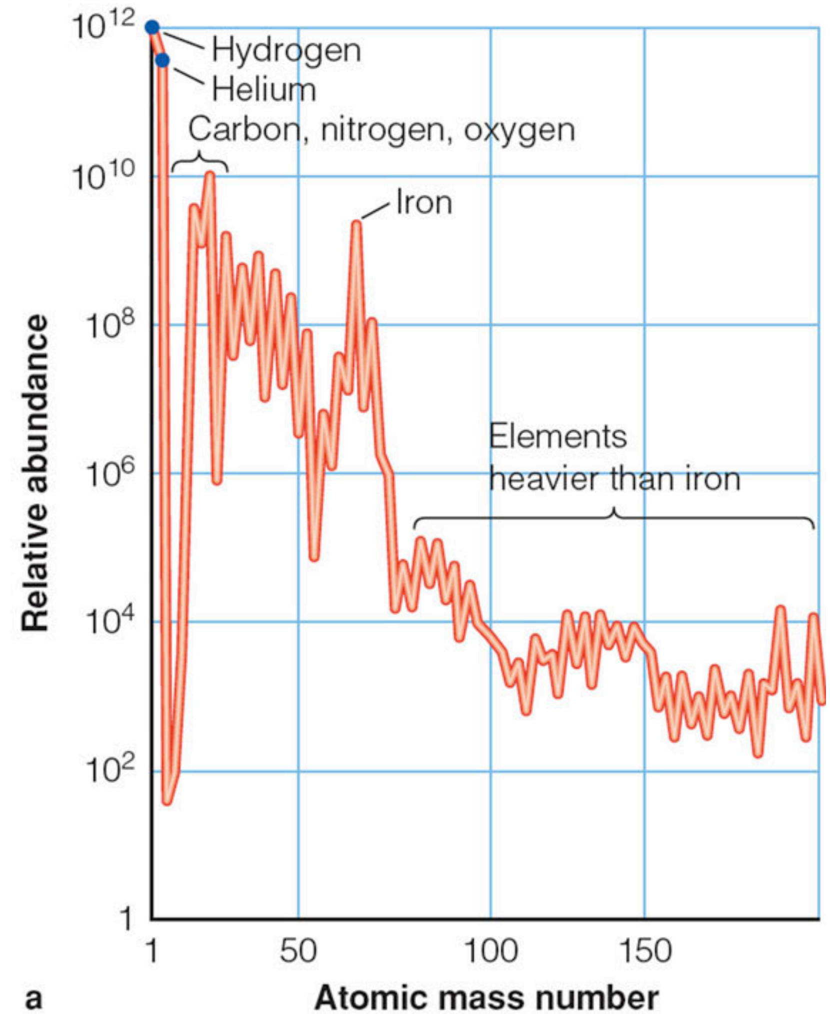
What color is the center of the galaxy?

Stars in the bulge

- Stars in the bulge of our galaxy are *redder* than stars in the disk.
- Are they low or high mass stars?
- Are they younger or older?

Metals (astronomically speaking)

- Any element more massive than hydrogen and helium is called a *metal* (but only by astronomers).
- “Metals” are elements that can only be formed in stars.
- Hydrogen and Helium were produced when the Universe formed.
- **The more metals in a star, the more generations of stars that formed before it.**
- **The amount of metals in a star serves as clock for star formation**



Populations of stars

Stars in galaxies can be divided into two populations:

- Population I
- Population II

Population I stars are in the *disk.* They are younger, bluer and contain more *metals.*

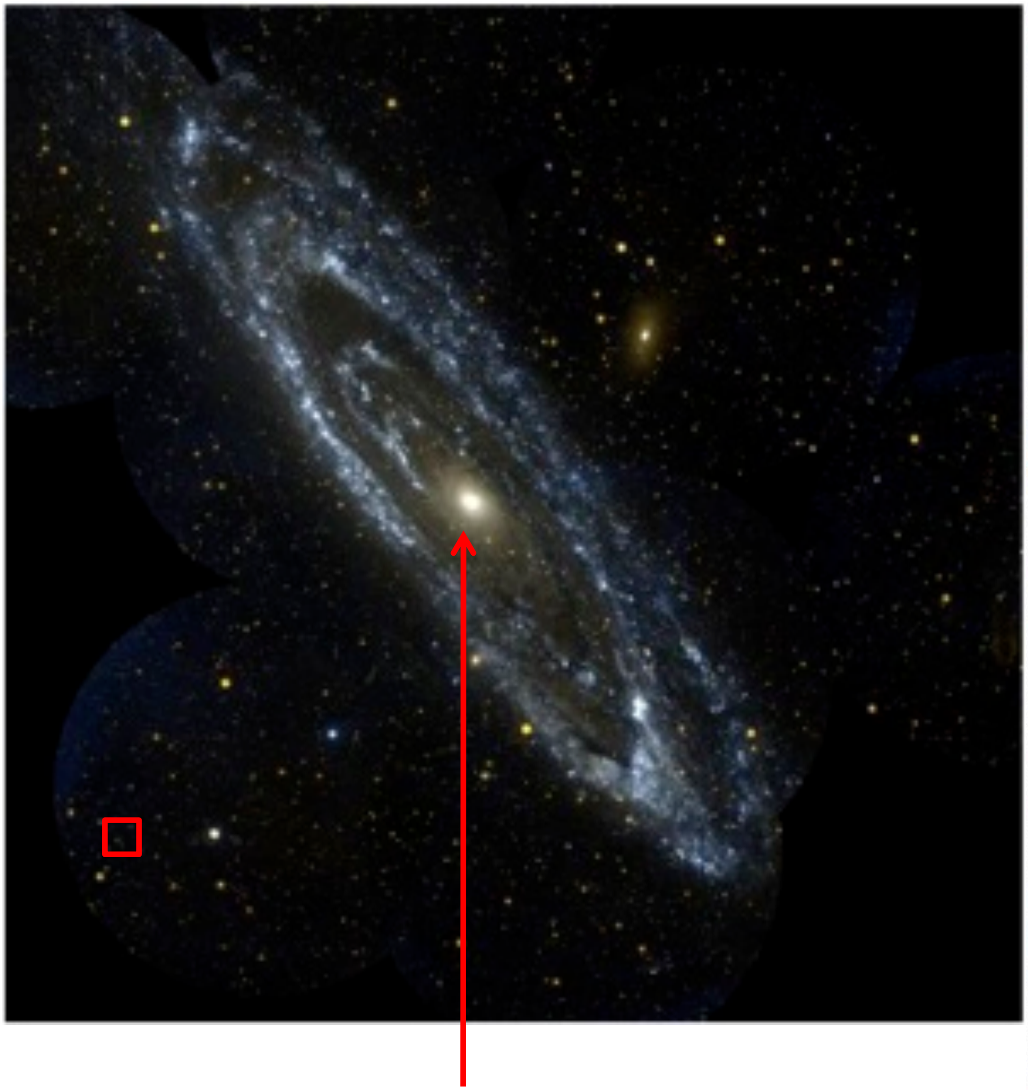
Population II stars are in the *halo* and *bulge*. They are older, redder, and contain fewer metals.

<u>For the bulge & halo:</u>

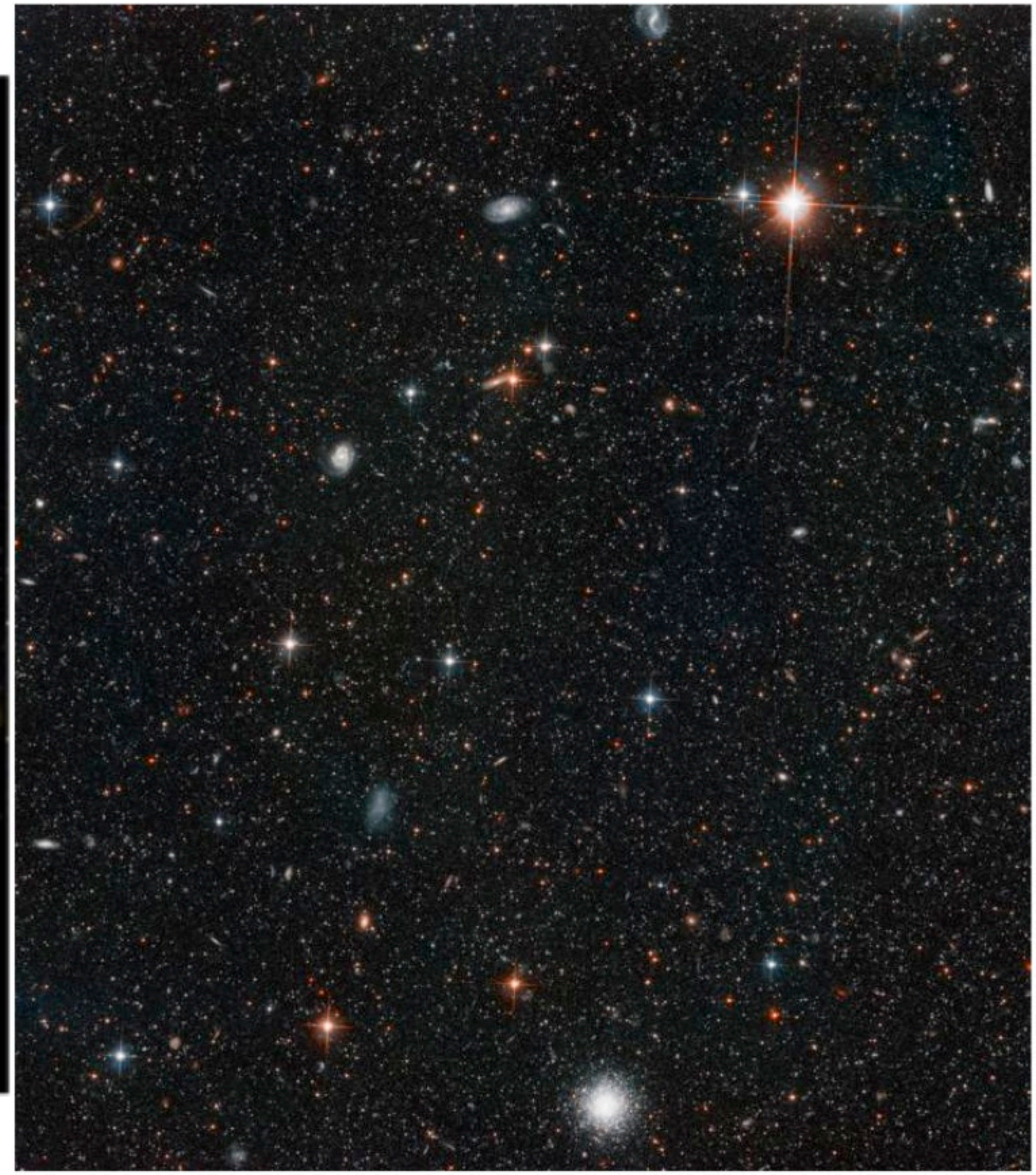
Are they red or blue?

Are the stars lower or higher mass than the disk?

Are the stars younger or older than the disk stars?



Bulge



Halo stars

Milky Way Structure

- Disk
  - diameter of 30 kpc and 1 kpc thick near the Sun
  - Sun is located 8.5 kpc from center of Milky Way in the disk
  - active star formation in disk
- Bulge
  - diameter of 4 kpc located at the center of the galaxy
  - more spherical than disk
  - supermassive black hole at the center (in nucleus)
- Bar
  - seen in stars and dust, extends 6 kpc through center of galaxy
- Halo
  - 100s of kpc in diameter, only contains 2% of stars in galaxy
  - includes globular clusters and *dark matter* composing most of the mass of galaxy.

Ages of stars in the Milky Way

- Disk stars: 0-10 billion years old, metal-rich (Population I)
  - Spiral arms have stars < 100 million years old
  - stars in the rest of the disk, 0.2-10 billion years old
- Bulge stars: 2-10 billion years old, metal-poor (Population II)
- Halo stars: 10-13 billion years old, very metal-poor (Population II)

So what about other galaxies?