The Milky Way Galaxy

General Information

Structures in the Universe

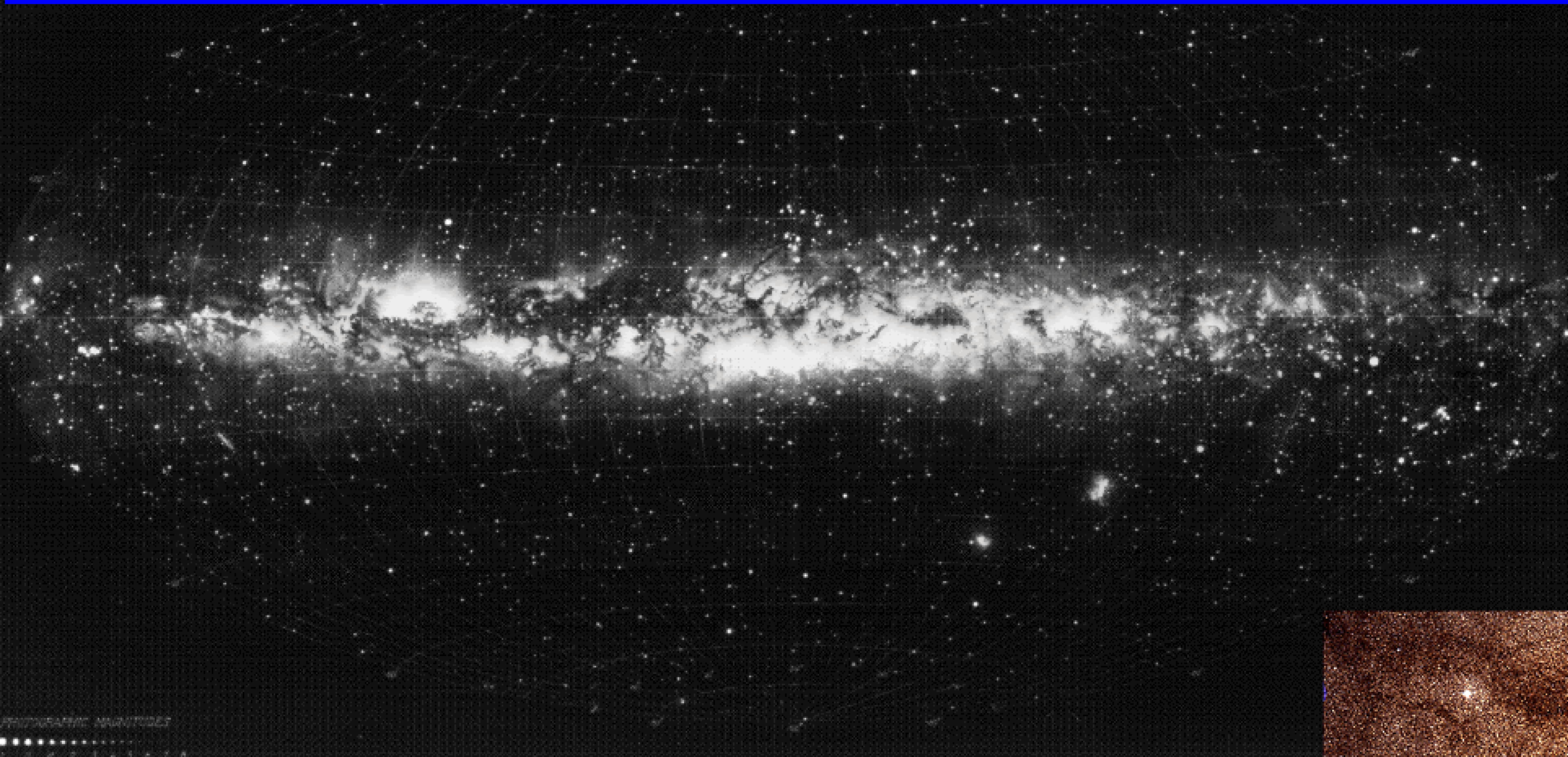
Levels of organization:

- Stellar Systems
- Stellar Clusters
- Galaxies
- Galaxy Clusters
- Galaxy Superclusters
- The Universe

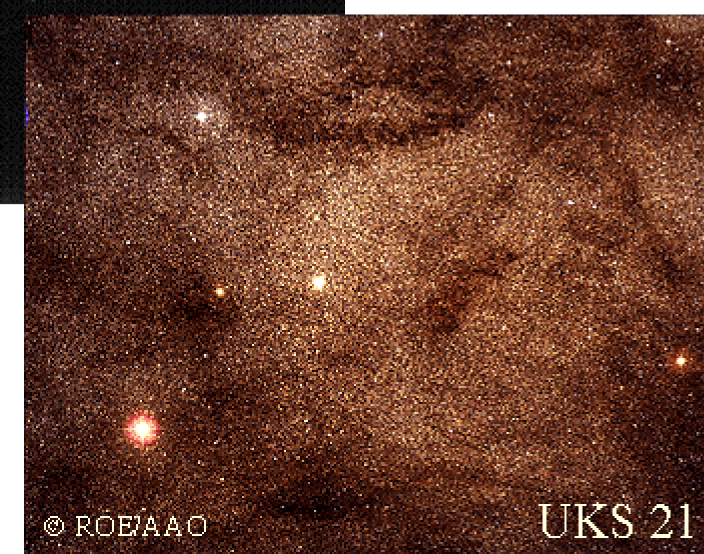
Everyone should know where they live:

- The Solar System
- (we don’t live in a cluster)
- The Milky Way Galaxy
- The Local Group
- Laniakea Supercluster
- The Universe

Milky Way as We See It



Closeup view:



Milky Way from Outside

Tilted view:

Edge on view:

Studying Galaxies

We cannot get outside our galaxy

- The distances are too great – we cannot send a spacecraft even to the nearest stars
- The “outside” views are of other galaxies, probably similar to our own

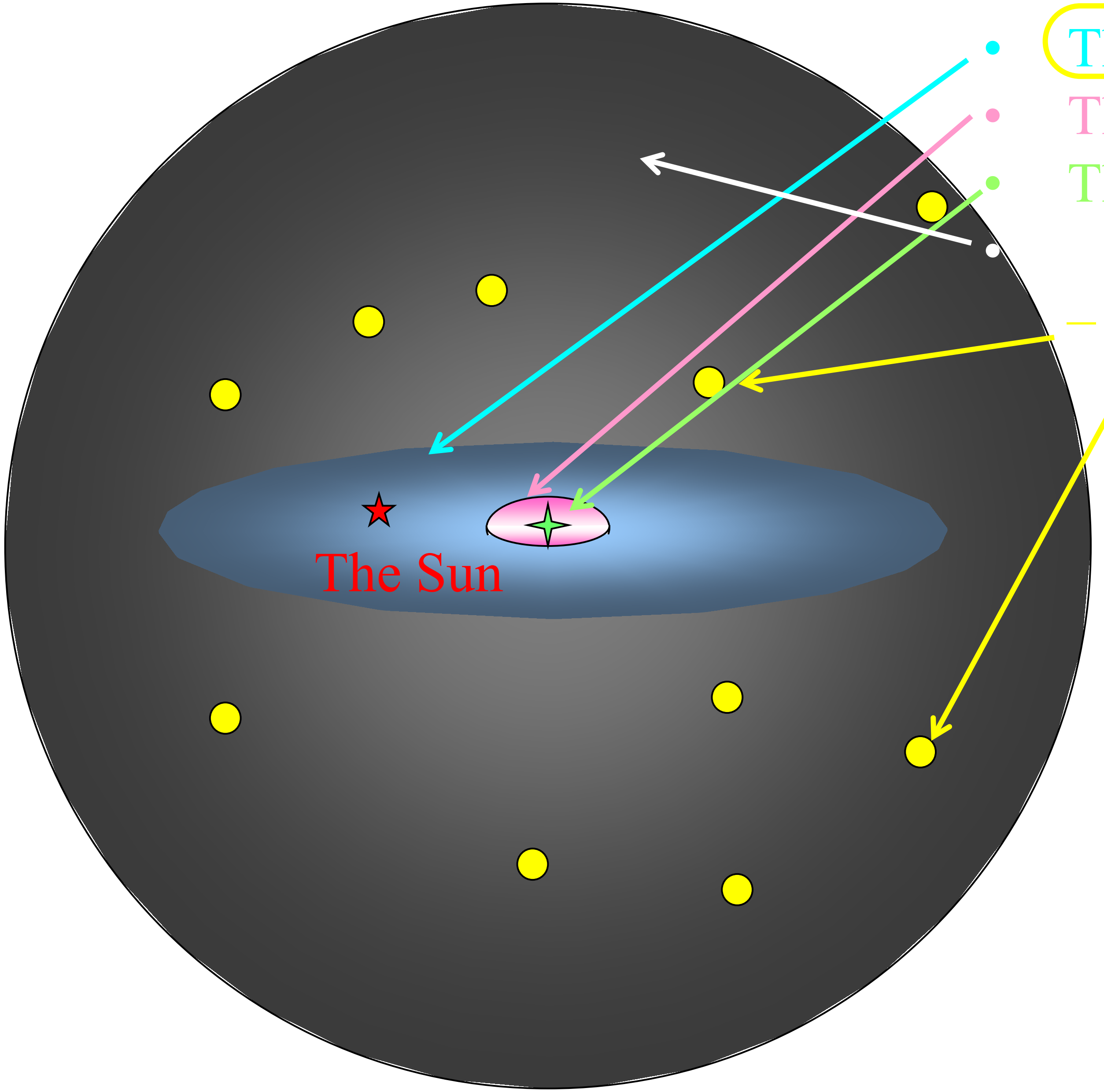
We are inside our galaxy

- This lets us see details of our galaxy with unparalleled precision

- However, there is dust in the plane of the galaxy – makes it hard to study within the plane of our galaxy
- It makes it very difficult to see the overall shape and distribution of our galaxy

- We infer other galaxies have many details similar to ours
- We infer our galaxy has an overall shape and structure similar to others

The Milky Way – Basic Structure



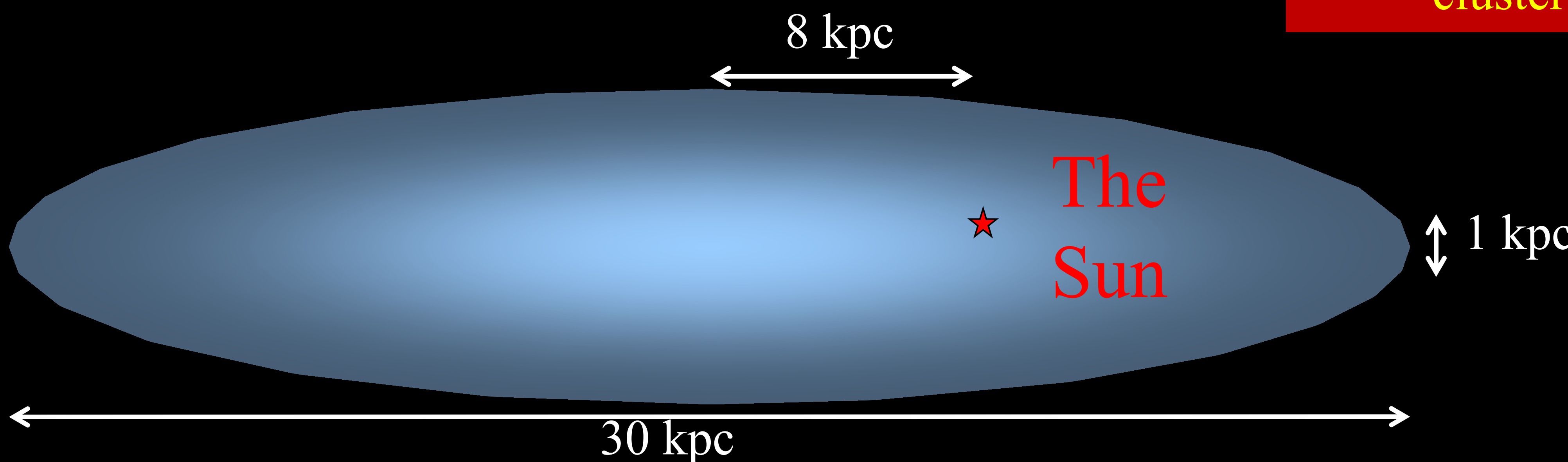
- The disk
- The bulge
- The nucleus
-
  – Globular clusters

The Disk

Dimensions and Structure

- A large, flat disk, shaped like a pancake
  - About 30 kpc in diameter
  - About 1 kpc thick
- We are about half way out (8 kpc)
- Has prominent spiral structure

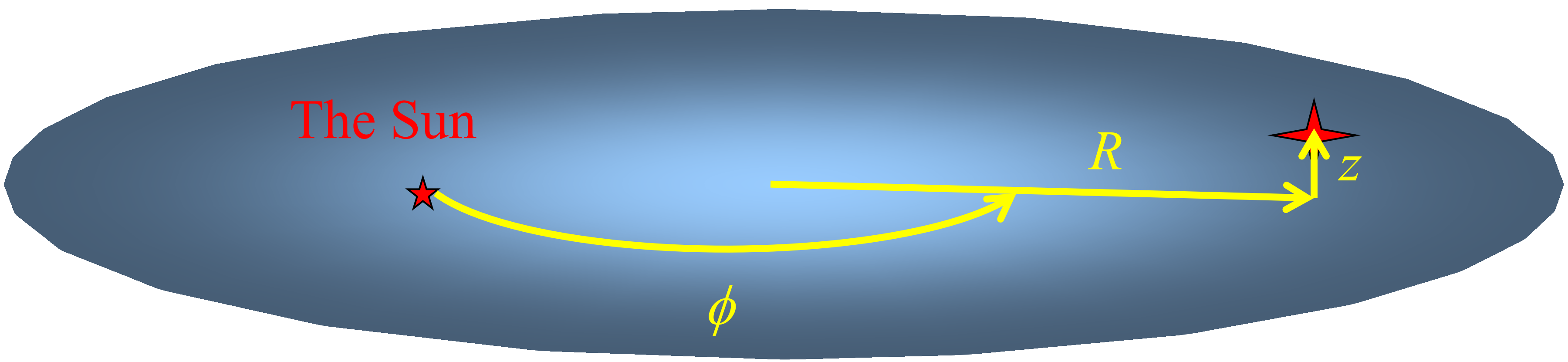
- The disk
- The bulge
- The nucleus
- The halo
  - Globular clusters



Characterizing Locations

The position of any object can be described in our galaxy using cylindrical coordinates:

- How far out they are from the center (R)
- How high (vertically) they are from the disk (z)
- The azimuthal angle (ϕ) of the star compared to our Sun

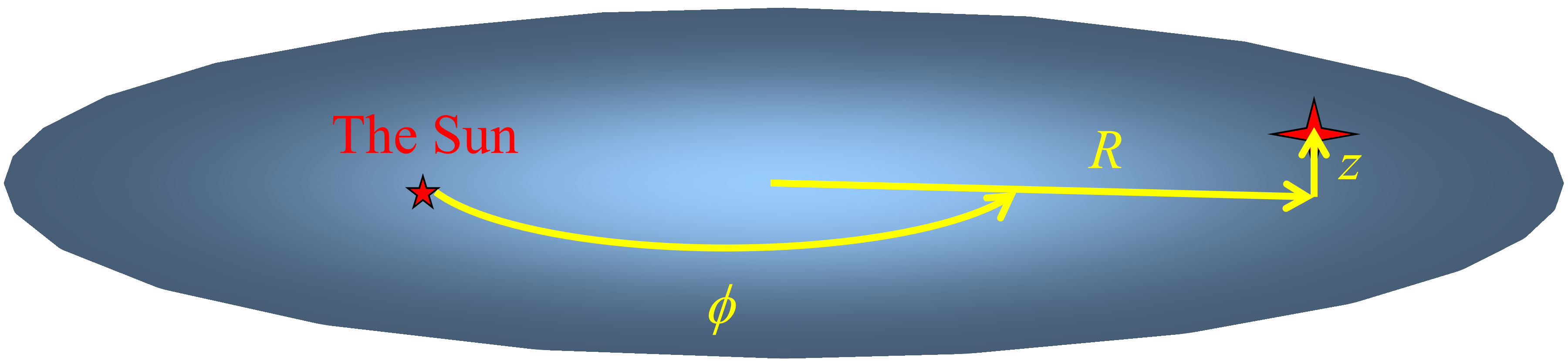


For example, the Sun's position is approximately:

- $R = 8.23 \pm 0.12$ kpc (out pretty far)
- $z = 10 \pm 10$ pc
- $\phi = 0$ (by definition)

Characterizing Distributions

- The disk is (roughly) rotationally symmetric
  - Everything is independent of ϕ
- Therefore the density of any object within it will depend only on the radius R and the height z



- In general, the distribution will look something like $n(R,z) = n_0 e^{-R/h_R} e^{-|z|/h_z}$
- The *scale height* h_z tells us how far things stray from the disk
- The *scale length* h_R tells us how things fall off with distance from the center

The Disk – Composition

- Stars
  - Thin disk stars
    - Sometimes in *Open Clusters*
  - Thick disk stars

- Gas
  - Molecular Clouds
    - Hydrogen is in H_2 molecules
  - HI regions*
    - Neutral hydrogen atoms
  - HII regions
    - Hydrogen is ionized

- Dust

*When an element is followed by a roman numeral, the roman numeral is one greater than the charge

Stars in the Disk

- Stars in the disk orbit the center in roughly circular orbits
- Near the Sun, they orbit at about 200 km/s
  - Probably comparable at larger/smaller radii
- They are more concentrated near the middle
  - Scale length ~ 3 or 4 kpc
- They fall into two groups: *thin disk* and *thick disk*

Thin disk stars

- Common (90 – 95% of disk stars)
- 98 – 99% of nearby stars
- Metallicity 0.4% to 2%
- Scale height ~ 300 to 400 pc
- Masses 0.1 to 100 $M_\odot$
- Stars are 0 to 8 Gyr in age
- Small deviations from circular orbits

Thick disk stars

- Rare (5 – 10% of disk stars)
- 1 – 2% of nearby stars
- Metallicity 0.1% to 0.4%
- Scale height ~ 1 to 1.5 kpc
- Masses from 0.1 to 1 $M_\odot$
- Stars are 8+ Gyr in age
- Large deviations from circular orbits

Thin vs. Thick Disk Stars

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- How can we account for these differences?
- Stars form in a relatively small region near the center (thin disk)
- About 8 Gyr ago, something disturbed the stars in the disk at the time
  - Probably collision with another galaxy
  - Eventually they settle down and form the thick disk
- Relatively little metals in these early stars
  - Metals come from previous stars that died
- New stars made since then comprise our current thin disk

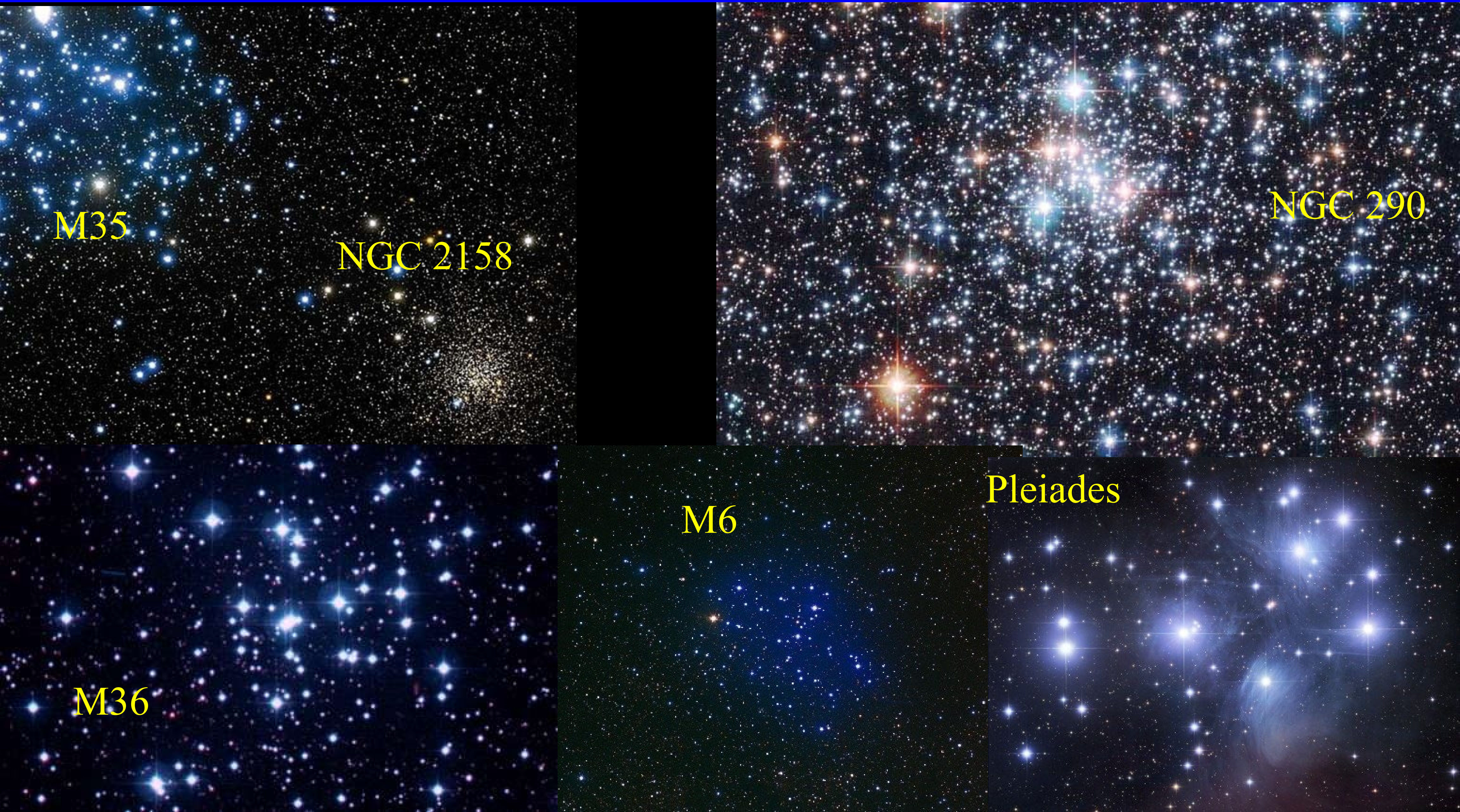
Number of Stars in the Disk

- Density of stars in the neighborhood of the Sun is about $0.1/\text{pc}^3$
- The total number of stars in the disk is of order 100×10^9
  - Total mass about $60\times10^9\ M_\odot$
  - Total luminosity about $20\times10^9\ L_\odot$
- Note that this suggests a typical star is less massive than the Sun
- Also less luminous than the Sun

Clusters of Stars in the Disk: Open Clusters

- The youngest stars are often in loose associations called *stellar clusters*
- These are recently born collections of stars that are still together
- Not surprisingly, they are in the thin disk
- Over time, stars probably wander away from the clusters where they were born
- These clusters are called *open clusters*
- Range in size from 100 to 30,000 $M_\odot$

Open Clusters



The Interstellar Medium

- Interstellar space is not quite empty
  - It contains thin gas and dust, generally mixed together
  - Total mass about $10\times10^9\ M_\odot$
- The gas is concentrated with a scale height ~ 100 pc
  - Compare thin disk ~ 300 pc and thick disk ~ 1000 pc
- The gas comes in a variety of temperatures
  - HII regions contain ionized hydrogen
    - Heated by bright stars, supernovae, and other violent events
    - Can be detected by their recombination radiation
  - HI regions contain atomic hydrogen
    - Not sufficiently cooled to make molecules
    - Detected mostly using the 21 cm line
  - Molecular clouds contain hydrogen molecules H_2
    - Detected using emissions from other molecules, like CO
- The dust annoyingly makes everything difficult to see
  - Especially in the disk!

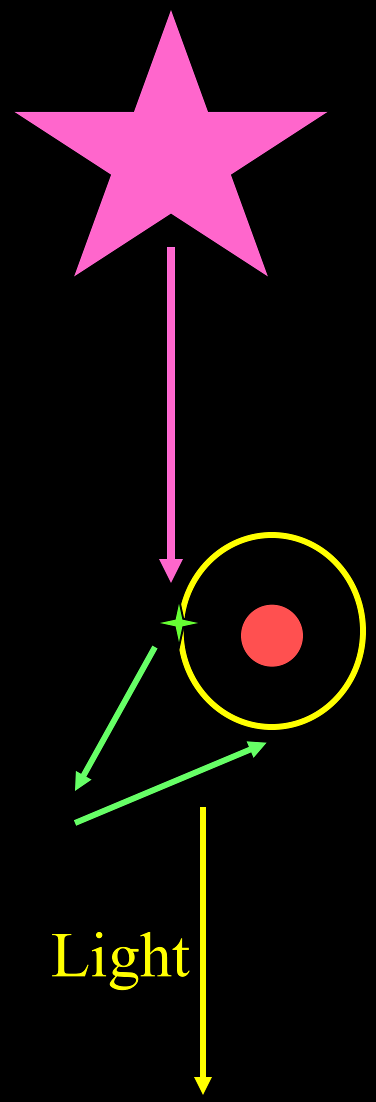
HII Regions

- Interstellar gas gets heated by light from various sources
  - High mass stars
  - Supernovae

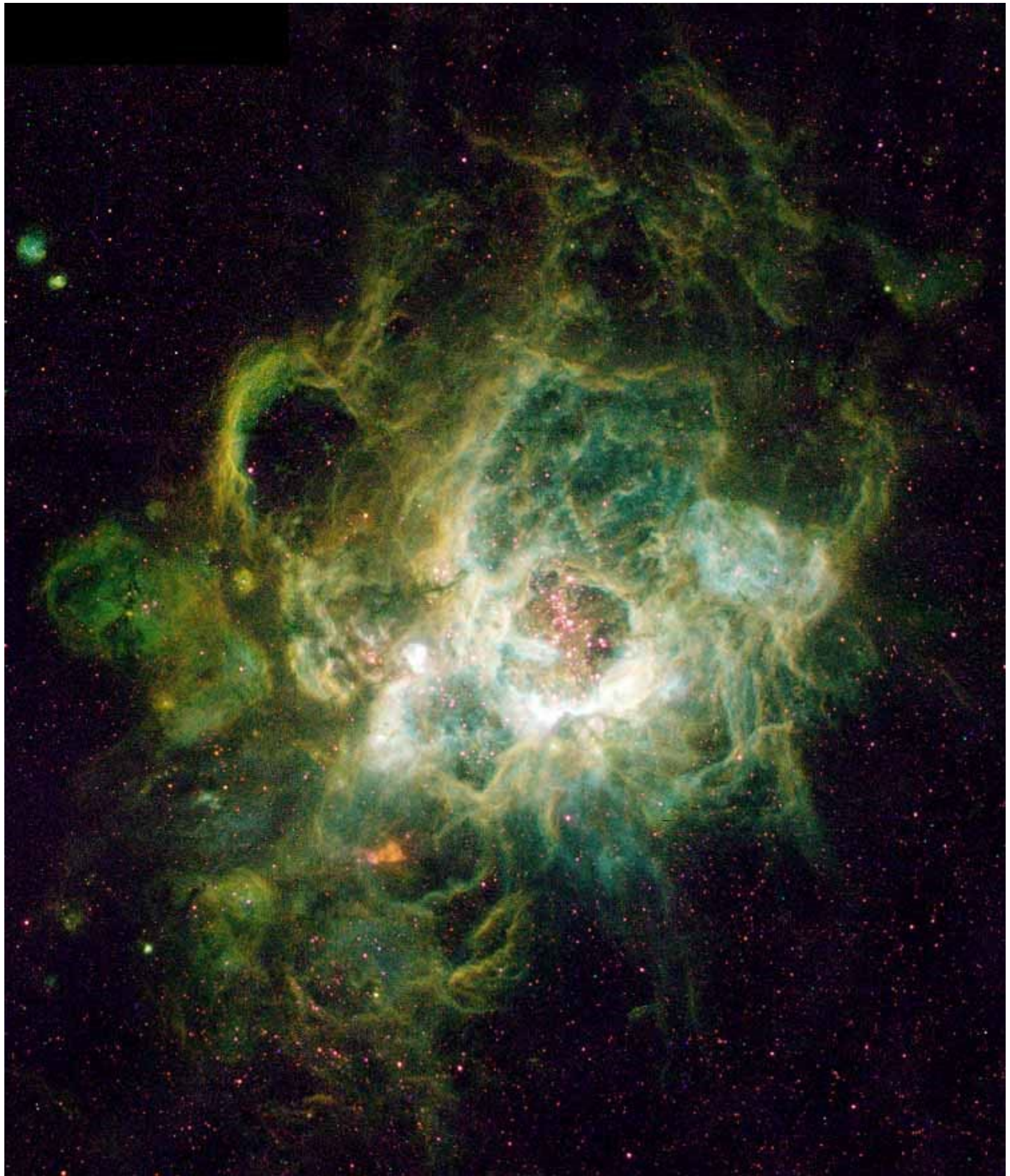
- If the density is high enough, and the temperature not too high, you can get *recombination radiation* from atoms getting ionized and then recombining
- Light from the star knocks an electron free
- The electron finds an unbound nucleus and settles back in
- As it goes from one level to another, it emits light

- Typical light from hydrogen will be visible or near ultraviolet
- At high temperatures, light from elements like Fe^{+24} will be X-rays

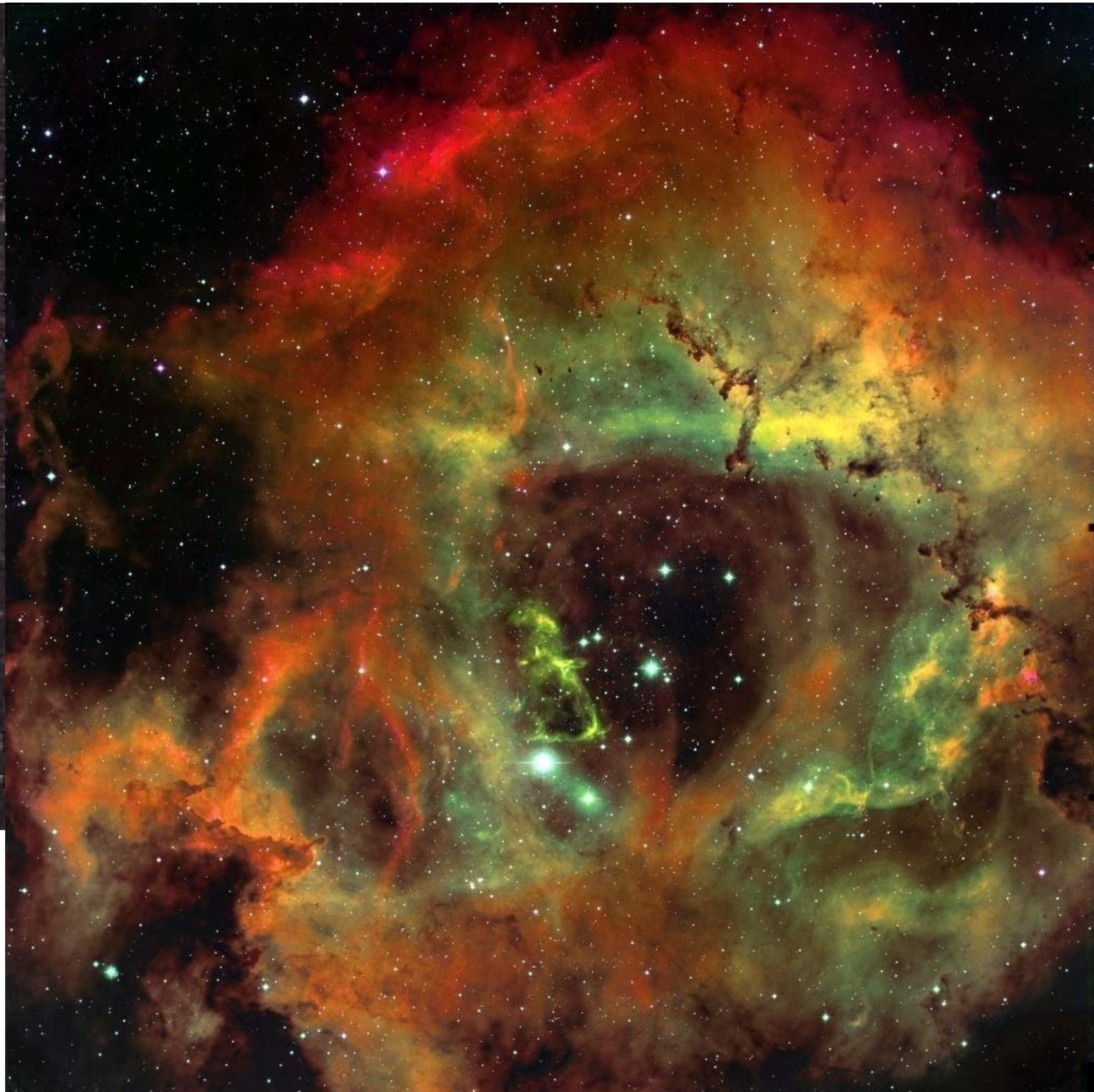
- At extremely high temperatures and low densities, you can still get light from electron-electron collisions



Ionization (Emission) Nebulae (1)



Ionization (Emission) Nebulae (2)



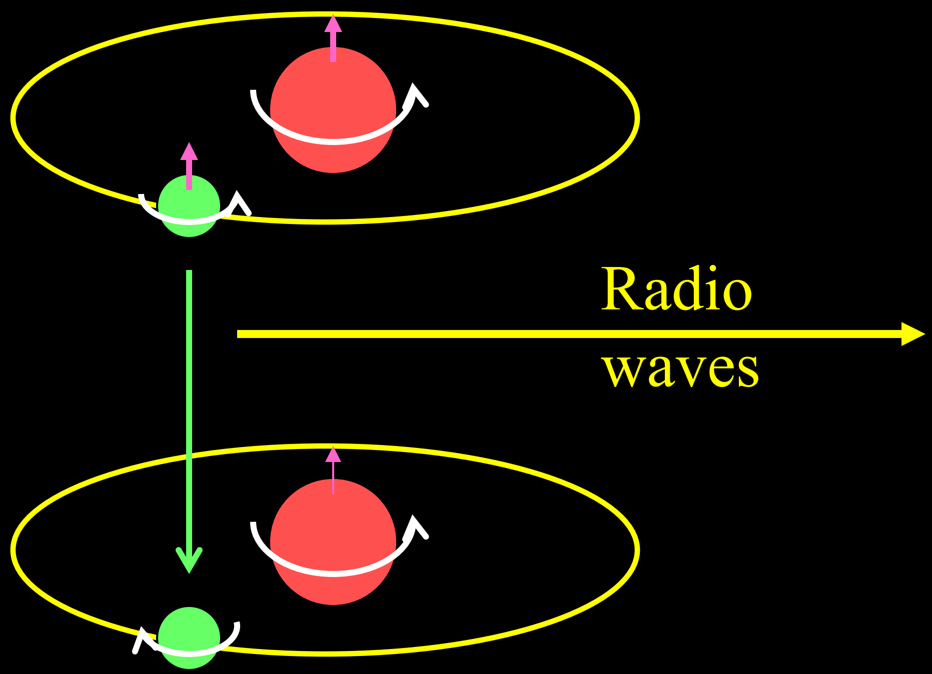
HI Regions

- At intermediate temperatures/densities, hydrogen (and other elements) will be bound into atoms
  - But not molecules

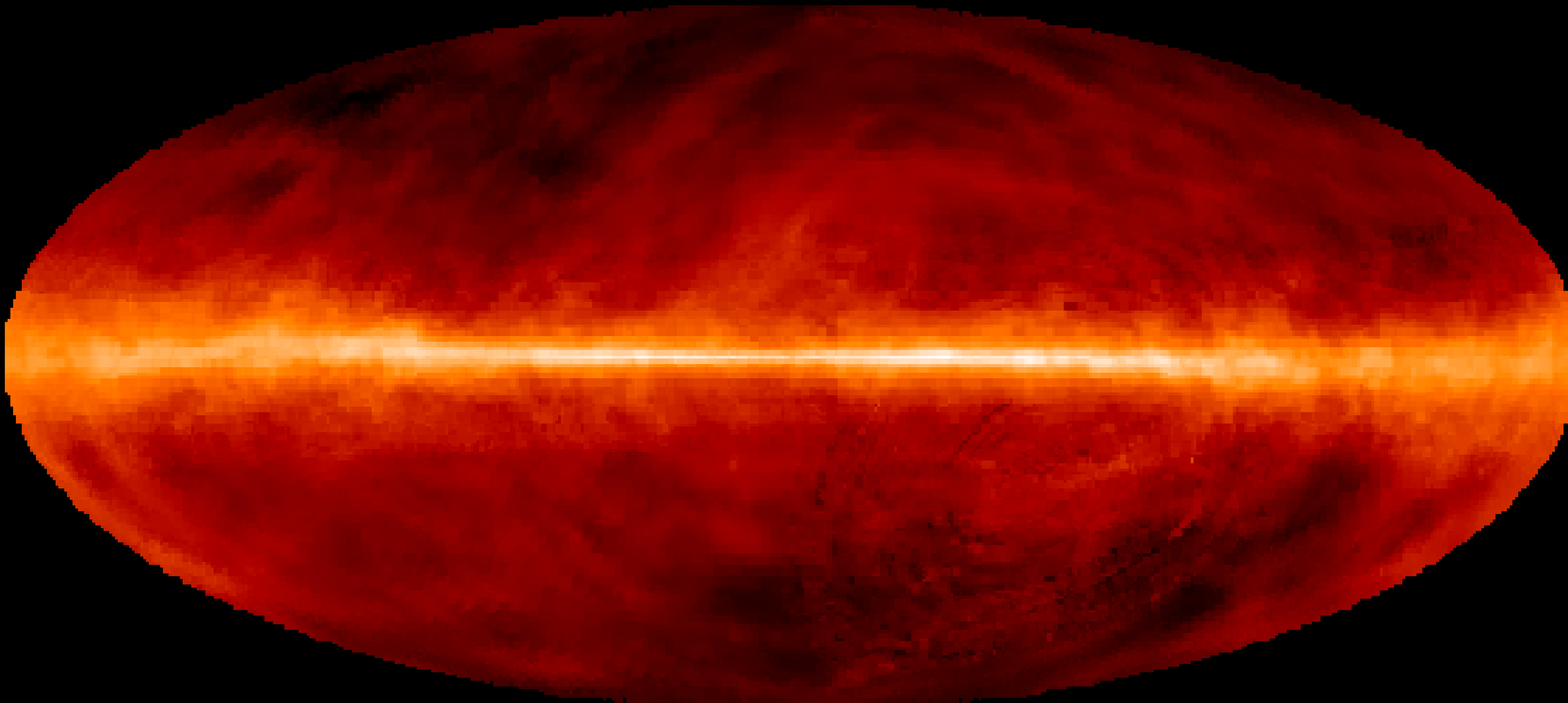
- The nucleus and the electron both have spin
- Spinning charges produce magnetic fields
- The atom has lower energy when spins cancel

- Because of collisions between atoms, they nonetheless often end up aligned
- The atom then makes a transition when the electron spin flips over
- The release of energy is emitted in a photon with wavelength 21 cm

- Takes on the average about 10 Myr
- We can not only detect hydrogen this way, we can use Doppler shift to get the velocity



The 21 cm line

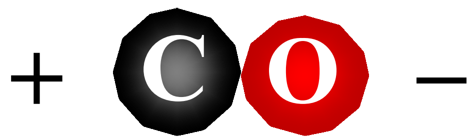


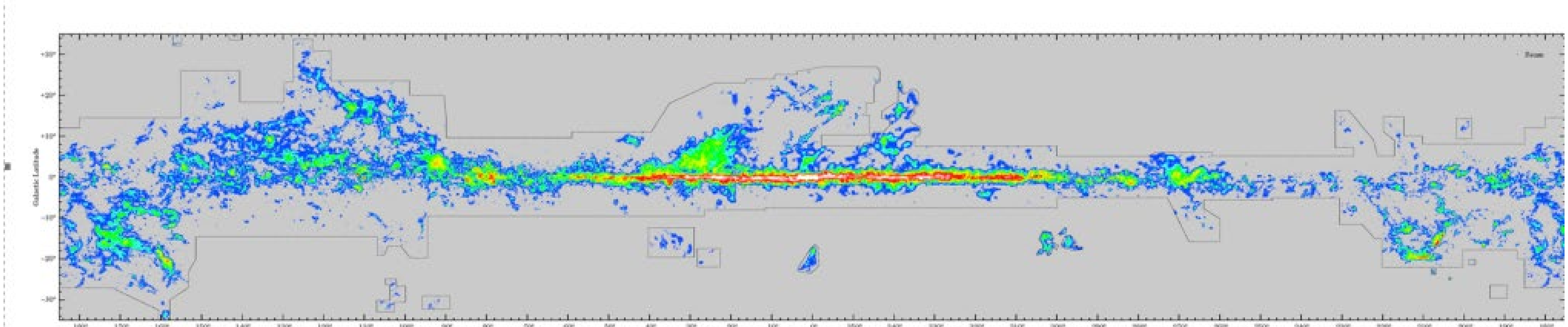
Molecular Clouds

- At low temperatures (and/or high densities), the hydrogen atoms bond together to make H_2 molecules
- Molecular hydrogen is very difficult to detect directly

- Fortunately, there are small amounts of other gasses that are easier
  - CO, HCN, OH, NH_3, H_2O, etc.
- These molecules all have *dipole moments* that make them more efficient at radiating energy.
  - More positive on one side, more negative on the other

- They produce electromagnetic waves efficiently when they vibrate
- And when they rotate

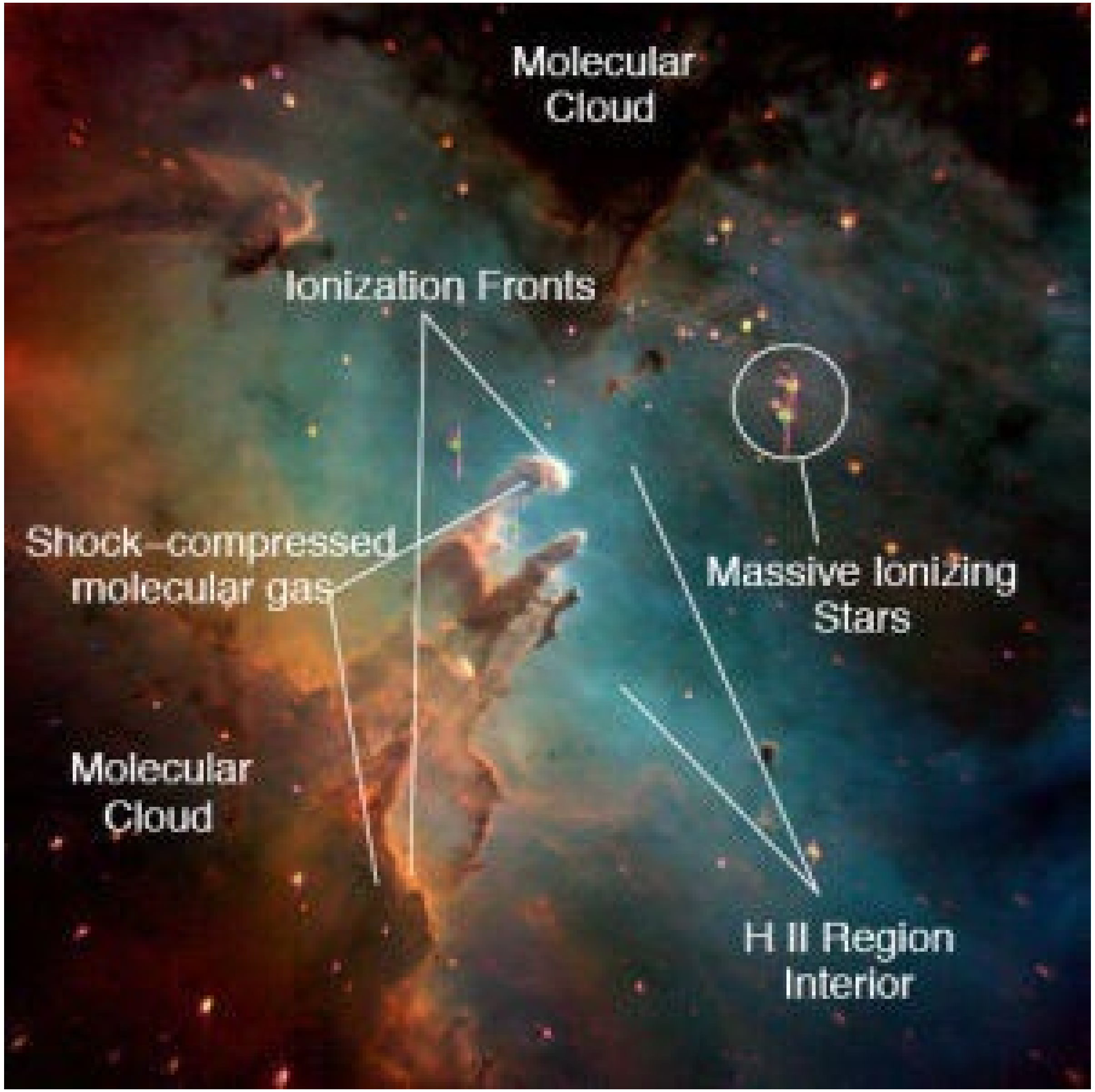




Molecular Clouds and Star Formation

- Molecular clouds are cool and dense enough that gravity can overcome pressure
- Over time, they slowly contract and form new stars
- The gas tends to be very close to the galactic plane
- Stars tend to form very close to the galactic plane

Labeled Eagle Nebula



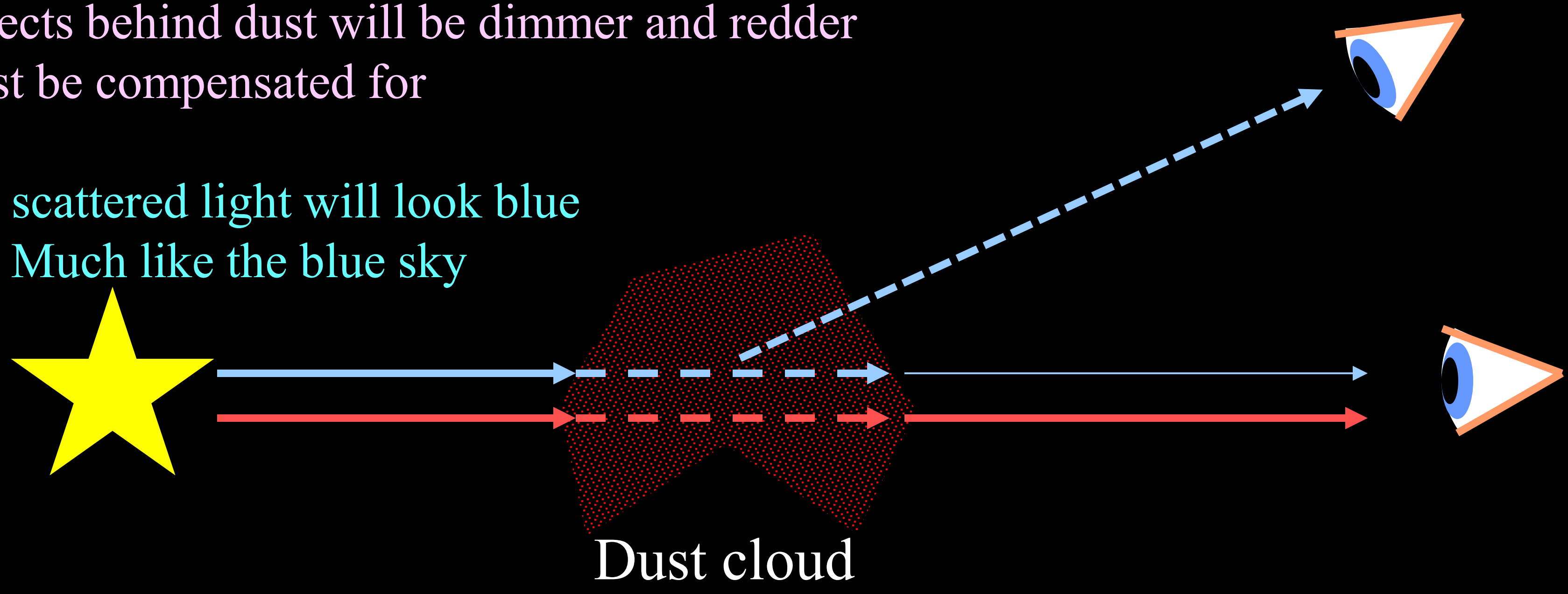
Dust (1)

- Galaxies like ours have a lot of dust in the disk
  - For us, about 1% of the mass
- Consists mostly of carbon compounds and silicates

- Size of dust particles range from 0.01 μm to 1 μm
- These are efficient at scattering and absorbing light
  - The probability of scattering or absorbing roughly proportional to $1/\lambda$

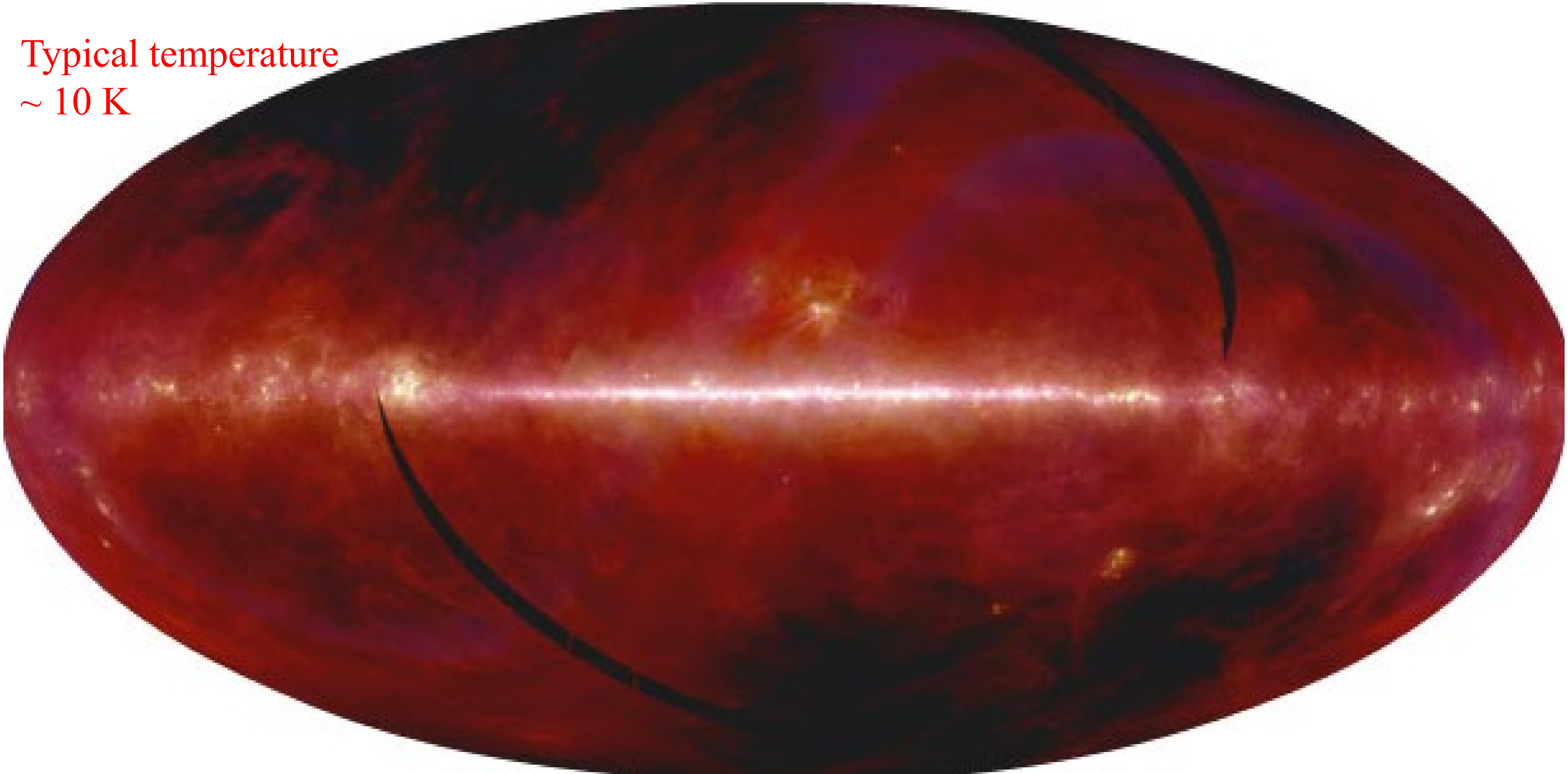
- Short wavelengths are scattered the most
- Objects behind dust will be dimmer and redder
- Must be compensated for

- The scattered light will look blue
  - Much like the blue sky



Dust (2)

- Dust is warmed by absorbing light from stars
- It glows in the infrared
- Typical temperature ~ 10 K

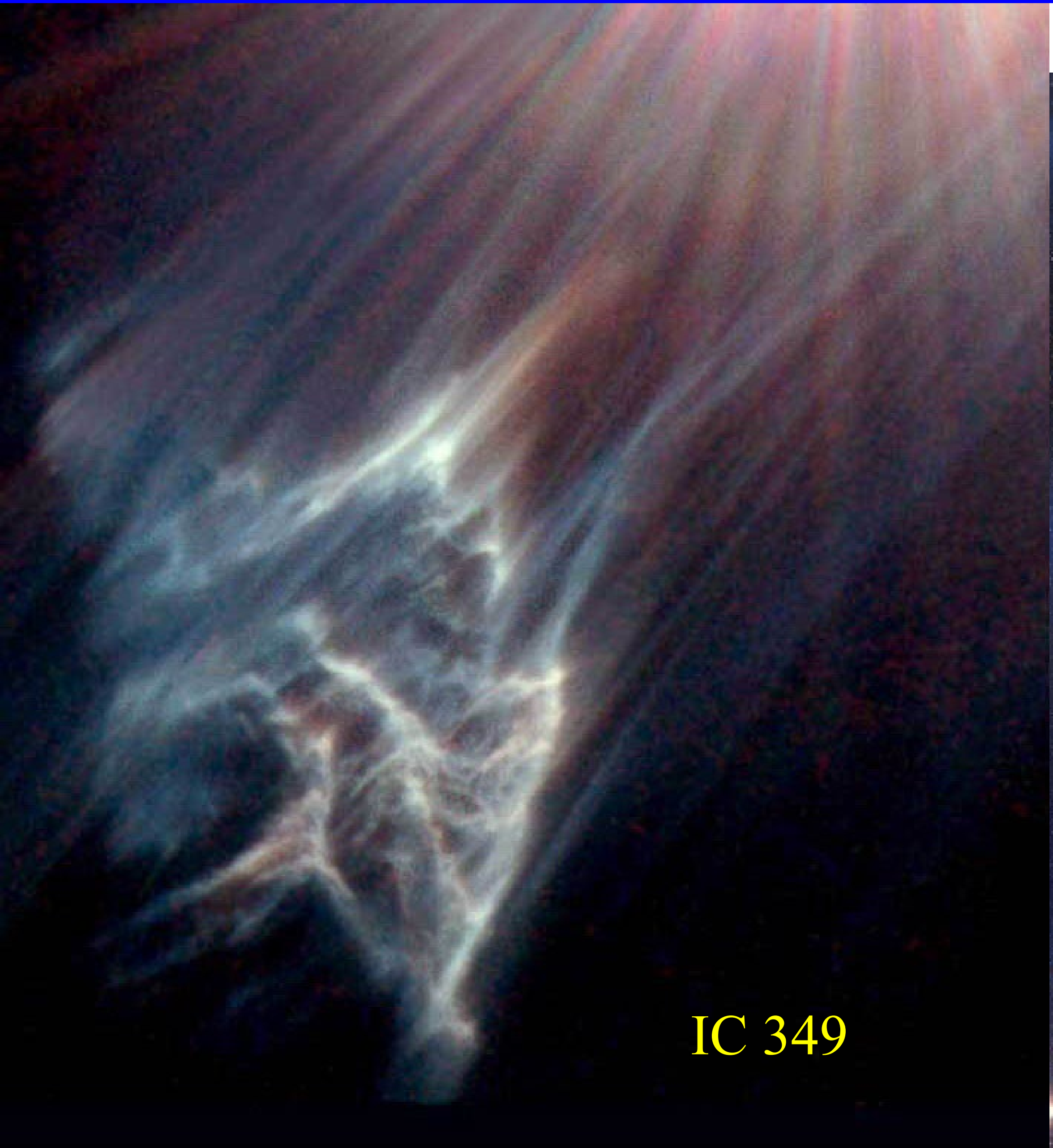


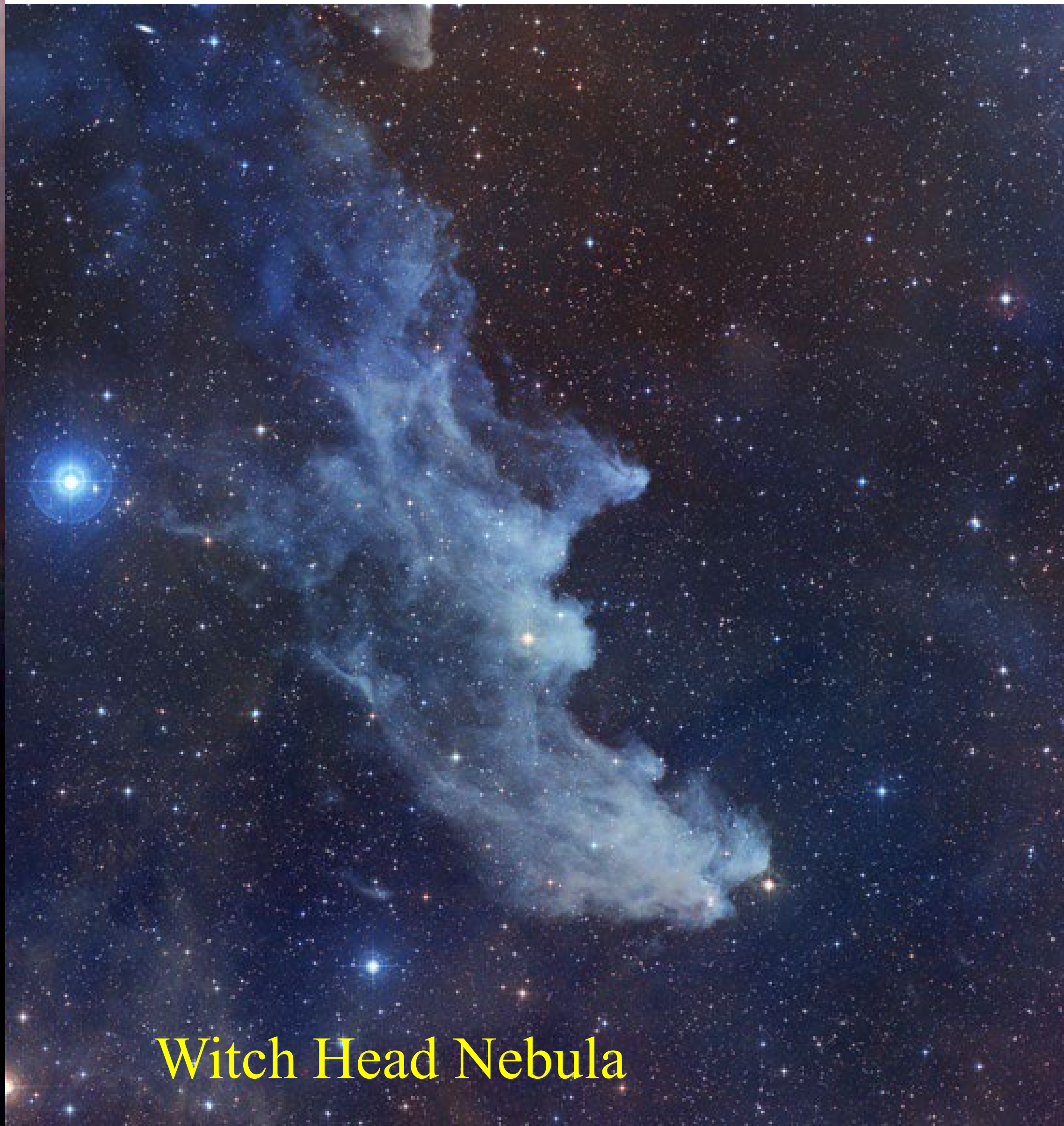
Reflection Nebula: The Pleiades

- The light reflected from nearby stars causes the dust to look blue

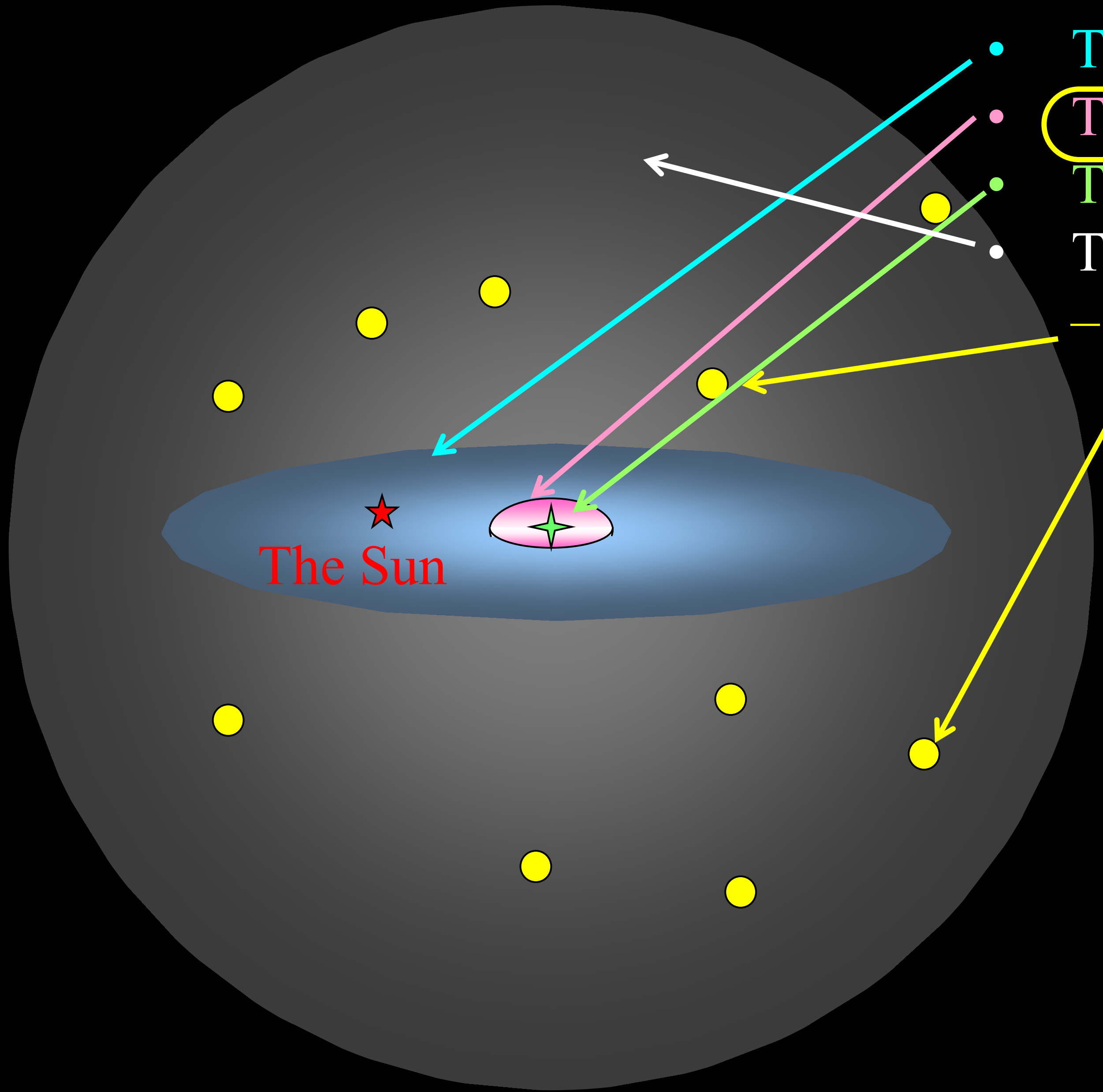
Reflection Nebula: Merope Nebula

More Reflection Nebulae





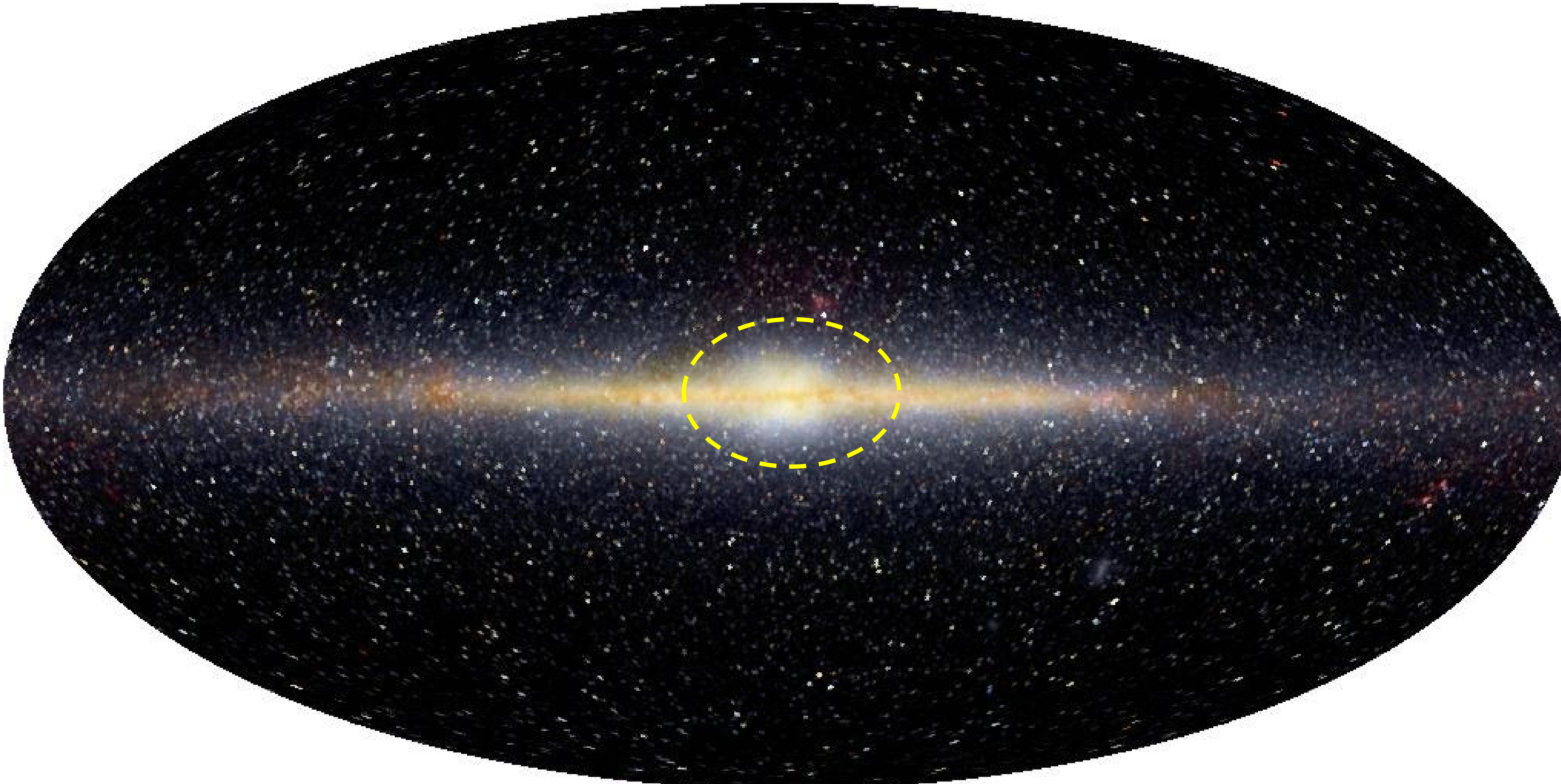
The Milky Way – Basic Structure



- The disk
- The bulge
- The nucleus
- The halo
  - Globular clusters

The Bulge

As Viewed in Infrared



General Information About the Bulge

- Must be studied via infrared, because view blocked by gas and dust

- High metallicity stars, comparable to the Sun (1.6%) , some as high as 5%
  - Probably production of metals got an earlier start or proceeded more quickly in this region
- Almost all older stars, 1 Gyr or more
- Little or no gas and dust
  - Without free gas, no current star formation

- Rotating around the center, same direction as disk, but slower
  - Typical speeds 100 km/s (compare $v_\odot = 220$ km/s)
- Much more elliptical orbits
- Lots of up and down motion as well

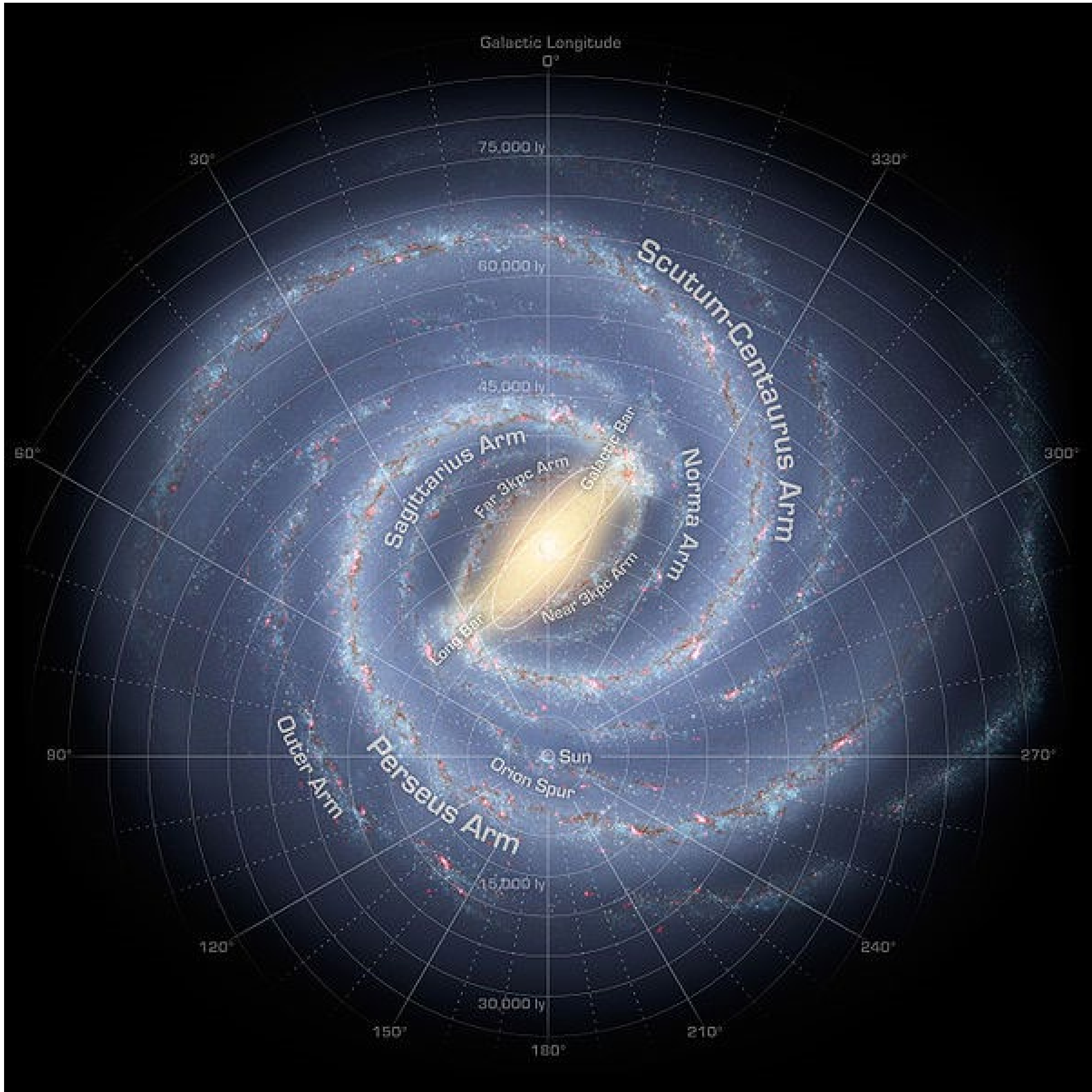
- Total mass in bulge about $20\times10^9\, M_\odot$

Color of the Bulge

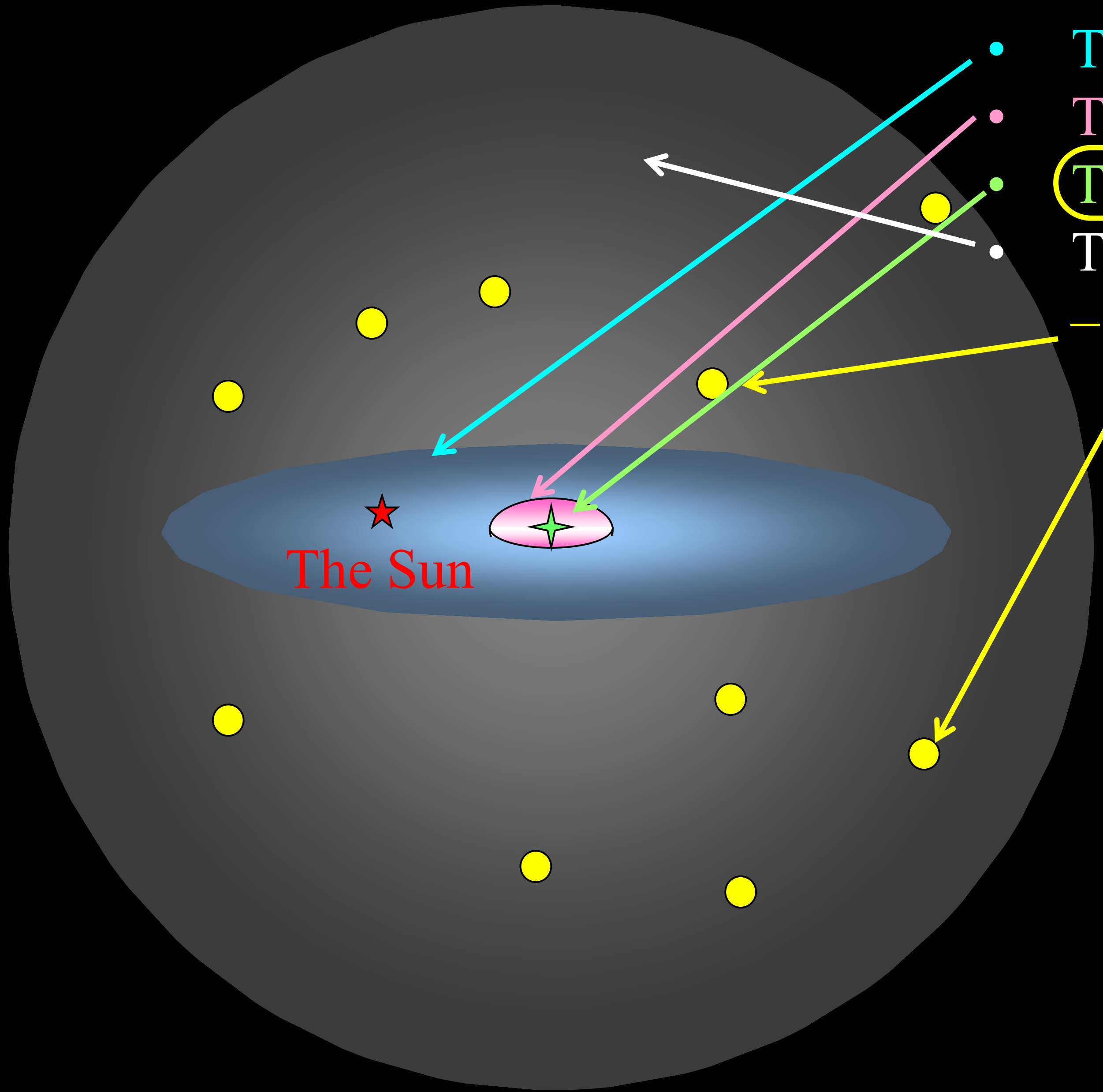
- Disk appears blue from young stars
- Bulge appears red from old stars

The Shape of the Milky Way's Bulge

- The bulge is approximately 2 kpc in radius and 1 kpc thick
  - Flattened sphere?
- One side of the bulge looks thicker than the other
  - Best guess – this side is closer to us
- This implies our galaxy is a *barred spiral galaxy*
  - Bulge is bar shaped



The Milky Way – Basic Structure



- The disk
- The bulge
- The nucleus
- The halo
  - Globular clusters

The Nucleus

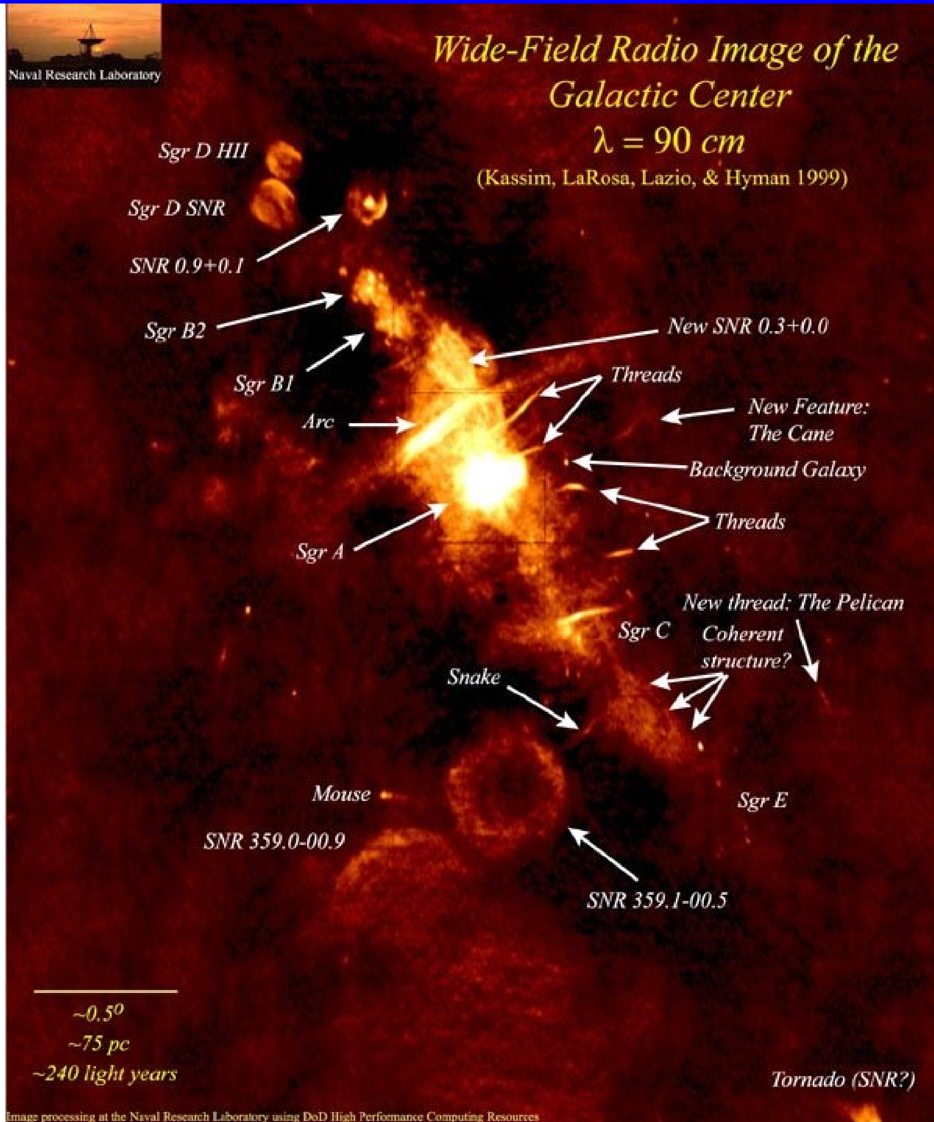
General Description

- Near the center of our galaxy lies the *nucleus*
- Density of stars ~ 2×10^6 /pc^3
  - compare 0.1/pc^3 near us
- Total mass about $10^7\ M_\odot$

- Many high mass stars
  - Must be young
  - Some more luminous than $10^6\ L_\odot$
- Several recent Type II supernova remnants
  - Suggests current star formation

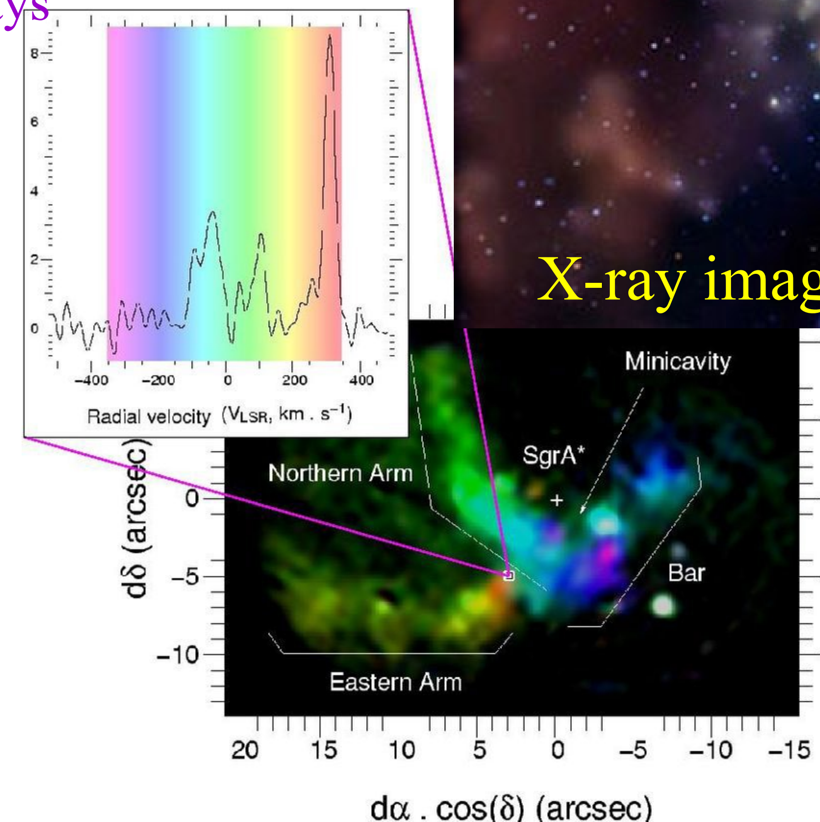
- Lots of gas
  - Much of it at high temperatures
  - Moving in many cases at high velocities

- Intense radio sources can penetrate gas and dust



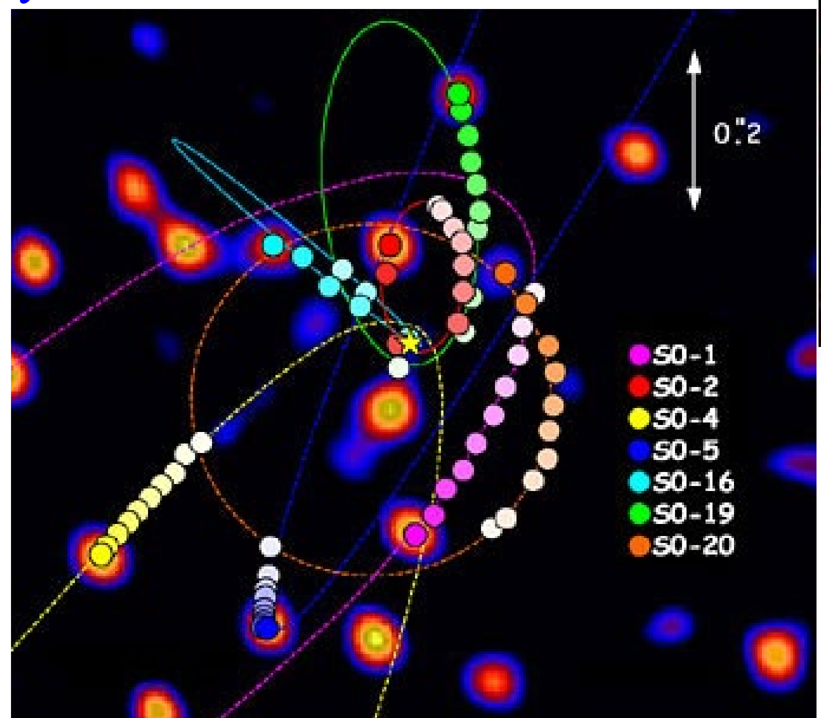
Details Near the Center

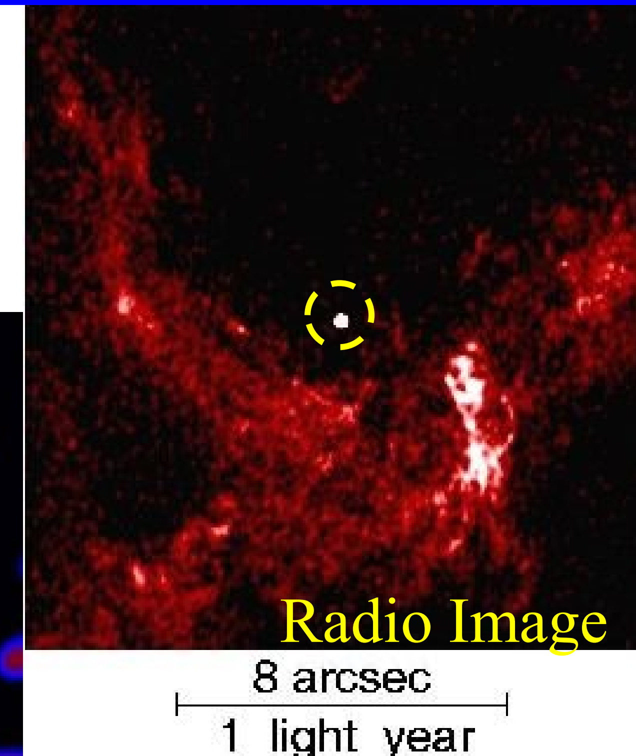
- We see gas heated by super-hot stars
  - More than 100 O and B stars
- We see gas streaming into the center at speeds as high as 1000 km/s
- We see gas producing large amounts of X-rays
  - Very near the center
- A strong radio source: Sgr A*
  - This seems to be the center of our galaxy

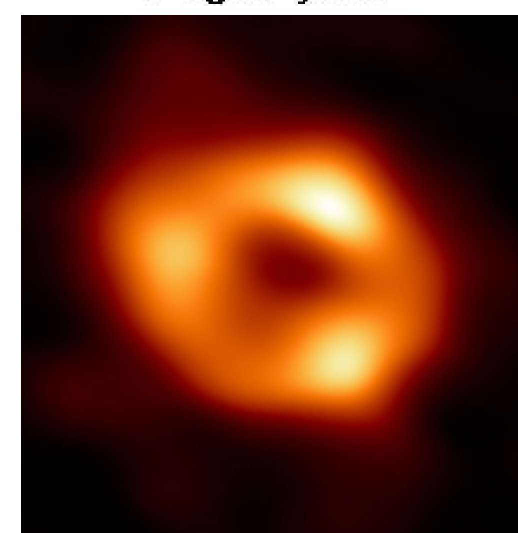


Stars Near the Center

- We see stars orbiting very quickly
- S2 is a star that completes an orbit every 15 years
  - Compare: Sun orbits in 250 Myr
  - Speeds up to 5000 km/s
- By studying orbits of these close stars, we can get an estimate of the mass of the central object
- Mass about $4.15\times10^{6}\ M_{\odot}$
- Quite small size
  - Diameter of ring is 0.4 AU
- Only object we can imagine is a black hole
  - Radius 0.09 AU







The Monster in the Middle

We can use the motion to find the distance

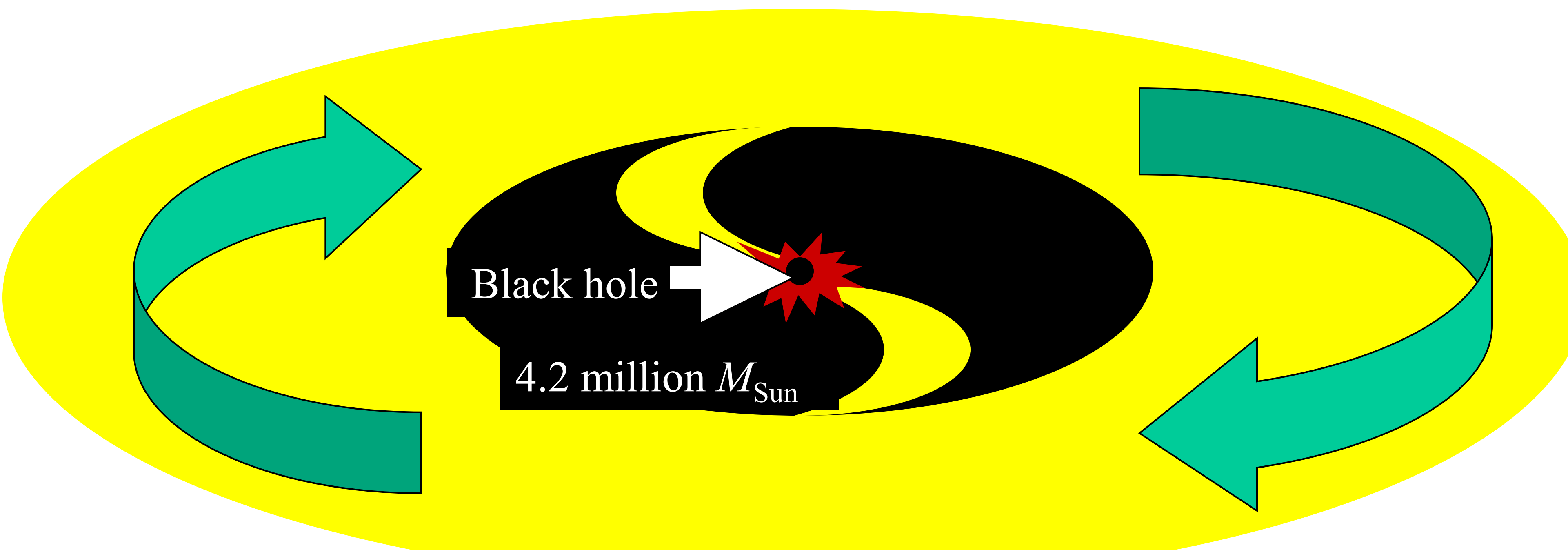
- Doppler shift tells us the velocity
- Period & velocity tells us the radius
- Apparent size tells us the distance
  - 7.9 ± 0.4 kpc

Radio waves can't come from black hole itself

- Gas from nearby attracted by gravity
- Accelerates to near light speed
- Friction creates heat/X-rays/etc.
- More efficient than any other power source

We can also determine the mass of Sagittarius A*

- About 4.15 million $M_{\odot}$



Black Holes in Galaxies

- Our galaxy contains a $4.15\times10^6\ M_\odot$ black hole
  - Far too large to have formed from a single star
- Most guesses are that they started as one or a few normal black holes
  - Though the earliest black holes were probably pretty massive
- Over time, black holes merged to form a larger black hole
- Black hole also swallowed gas and stars to grow
- Our black hole is not atypical!
- Many galaxies have black holes
  - Probably most galaxies
  - Maybe all galaxies
- Some galactic black holes are smaller, and some are MUCH larger
  - Some more than $41\times10^9\ M_\odot$

The Halo

General Description

The halo is the largest part of the galaxy

- Roughly spherical in shape (not well measured)
- Extends out to ~ 50 kpc in radius (not well measured)
  - Disk ~ 15 kpc

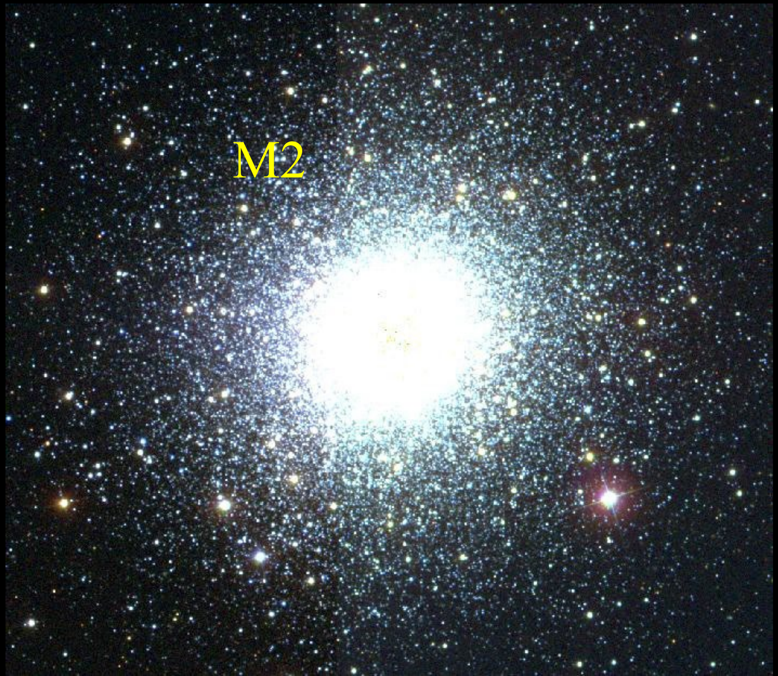
It is made of:

- Individual stars
- Globular clusters
- Thin clouds of gas
- Dark matter!
  - The nature of the dark matter is not known

Halo Stars

- Halo stars are very low metallicity
  - Typically $Z < 0.04\%$ (sun $Z = 1.6\%$, thick disk 0.1% to 0.4%)
- Average velocity compared to the Sun of ~ – 200 km/s
  - Recall Sun has velocity 220 km/s
  - This means on average they are as likely to be going around the wrong way as the right way
- They have additional random velocities in all three dimensions
  - Order 100 km/s in every direction
  - Indicates they are in all kinds of crazy orbits
- Scale height probably several kpc
  - Probably not well described by the same distribution for disk stars
- Local density is about 0.1% of local disk stars
  - But much thicker layer, so not as rare as you would think
- Total mass of halo stars plus globular clusters around $10^9\ M_\odot$

Globular Clusters - Images



Globular Clusters - Information

In addition to open clusters, there are also *globular clusters*

- They have masses in the range $10^4 – 10^7\, M_\odot$
- They usually appear to be permanently gravitationally bound
  - Although some of them are slowly falling apart
- They have metallicity much lower than the Sun (Sun = 1.6%)
  - Metal rich globular clusters have $0.1\% < Z < 0.4\%$
  - Metal poor globular clusters have $Z < 0.1\%$

Metal Rich vs. Metal Poor Globulars

Metal rich $Z = 0.1\%$ to 0.4%

- Orbits similar to thick disk stars
- Metal rich globular clusters are very old (commonly > several Gyr)

Metal poor $Z = 0.004\%$ to 0.1%

- Orbits similar to halo stars
- Halo stars are probably stars that escaped from globular clusters
- Metal poor globular clusters are the oldest known stars

- Oldest stars known are globular clusters and halo stars
- Best estimate 13 ± 1 Gyr
  - Comparable to best guess of age of universe
- Certainly > 11 Gyr
  - This puts constraints on age of the universe

Distribution of Globular Clusters

- The globular clusters (especially the metal-poor ones) are distributed throughout the halo
  - Very few of them crossing through the disk

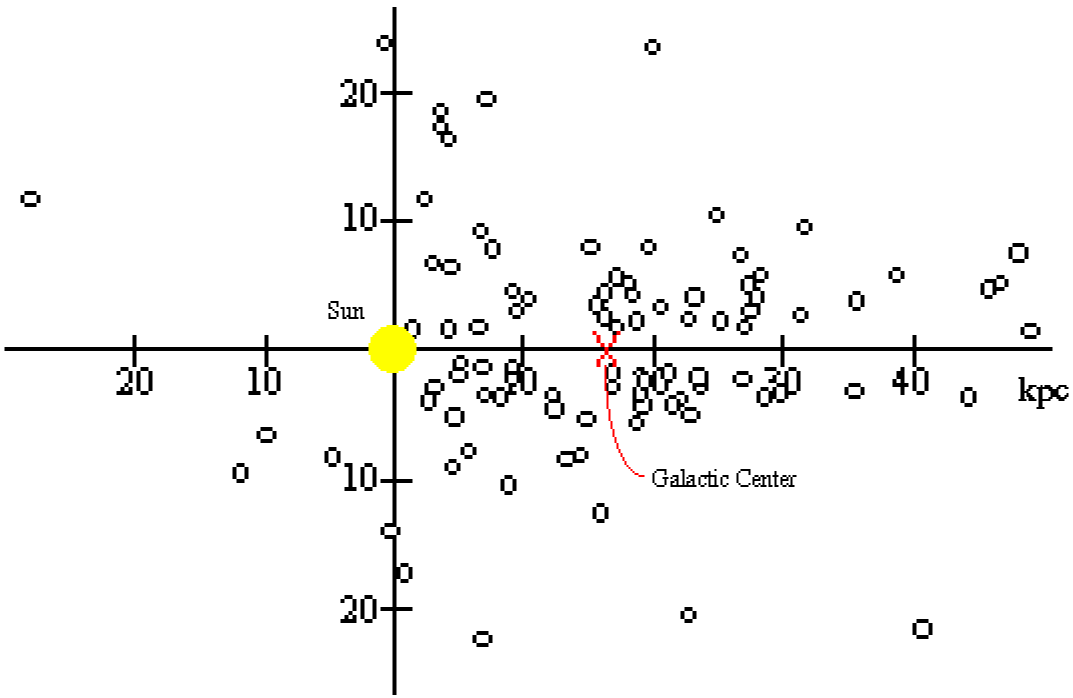
- Therefore, we don't have a lot of gas and dust blocking our observations of them

- We can therefore find all their 3D positions pretty well

- It is observed that they are *not* centered on us, but instead on a point about 8 kpc away in the direction of Sagittarius

- This was the first clue of the direction and distance to the center of our galaxy

- We now use other, more accurate measures



Gas in the Halo

- There is a small amount of gas in our halo
  - Elliptical galaxies can have a lot more gas

- Some of this gas is thin and very hot
  - Probably heated by supernovas
  - Expelled from the Milky Way

- But some of it is cold
  - Probably flowing into the galaxy from intergalactic space
  - Probably renews the disk gas

Total Mass of the Galaxy (?)

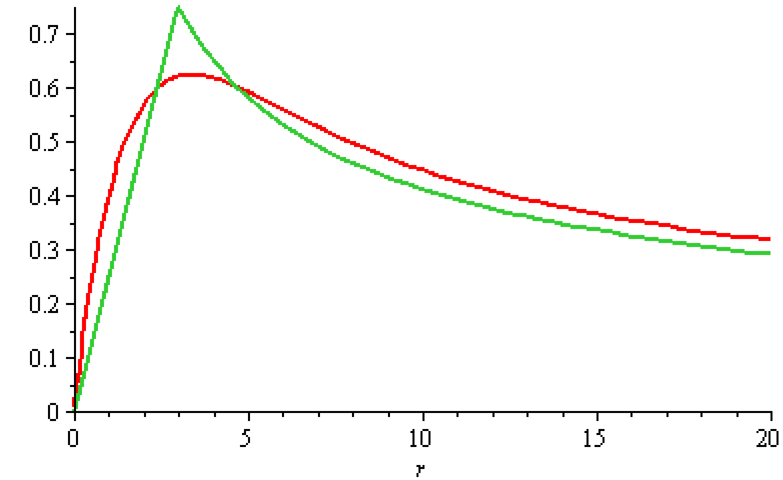
How much mass is there in the whole galaxy?

- Method #1: Count stars and measure gas
- Method #2: Measure Orbits
- Counting stars and gas indicates a total mass of about 100 billion $M_\odot$. Maybe a little bit more
- Almost all of this mass is closer than the Sun

Object	Mass ($M_\odot$)
Disk Stars	60×10^9
Disk Gas	$\sim 10 \times 10^9$
Bulge	20×10^9
Halo Stars	1×10^9
Nucleus	0.01×10^9
MACHOS	????
Dark Matter	????

From orbital motion of the Sun

- Mass closer than Sun is about 90 billion $M_\odot$ Expect as we go outwards, this mass will remain about the same
- This results in rotation curves that fall off at large r



Populations of Stars

- This is not on the test
  - I am simply informing you in case you need to talk to astronomers
- I am not including it because it is not in the book

Astronomers describe stars as belonging to various “Populations”

- *Population I* stars high metallicity
  - The Sun
  - Thin disk stars
  - Thick disk stars are sometimes called “intermediary”

- *Population II stars* are stars with low metallicity
  - Halo stars

- *Population III stars* are hypothetical stars with no metals
  - Believed that the first stars in the universe were like this
  - None seen today
  - One of the primary goals of James Webb Space Telescope