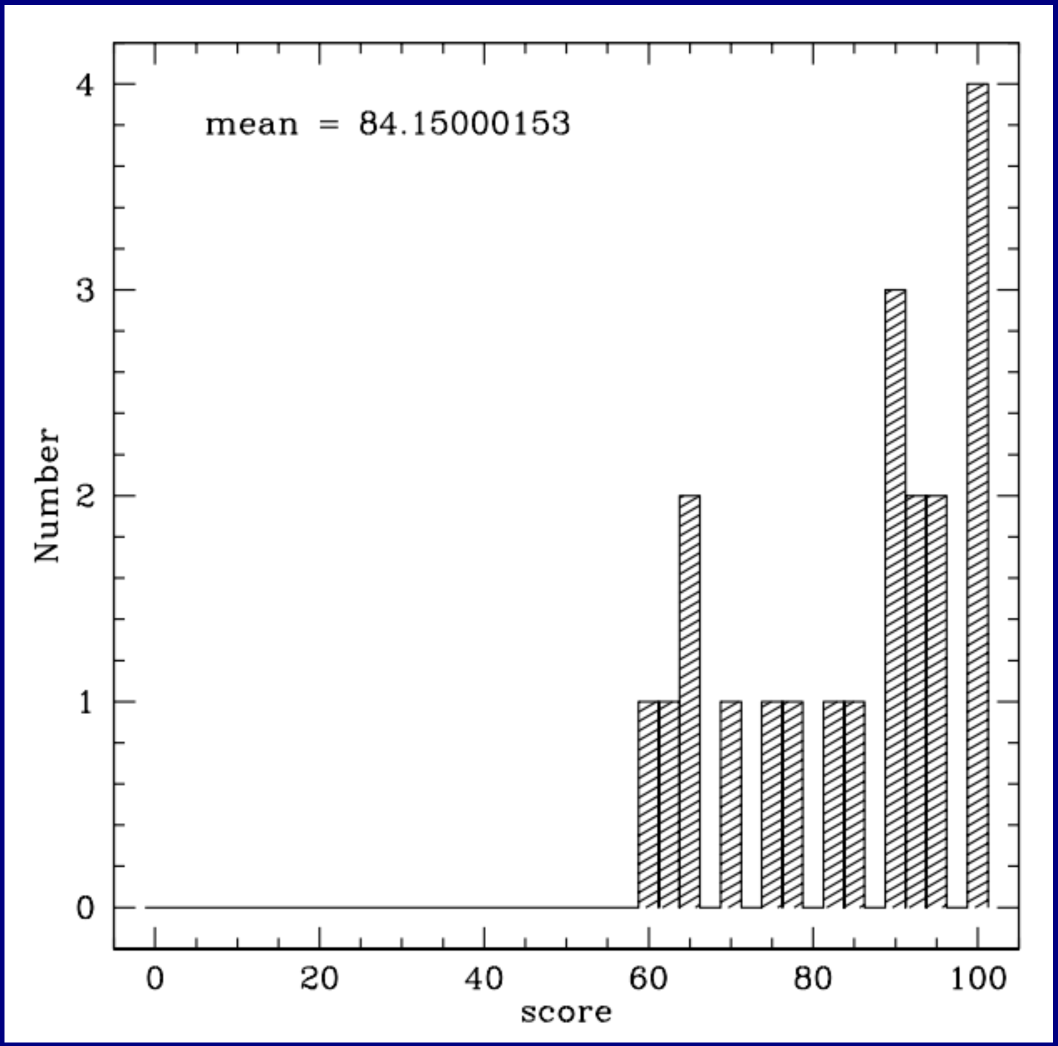
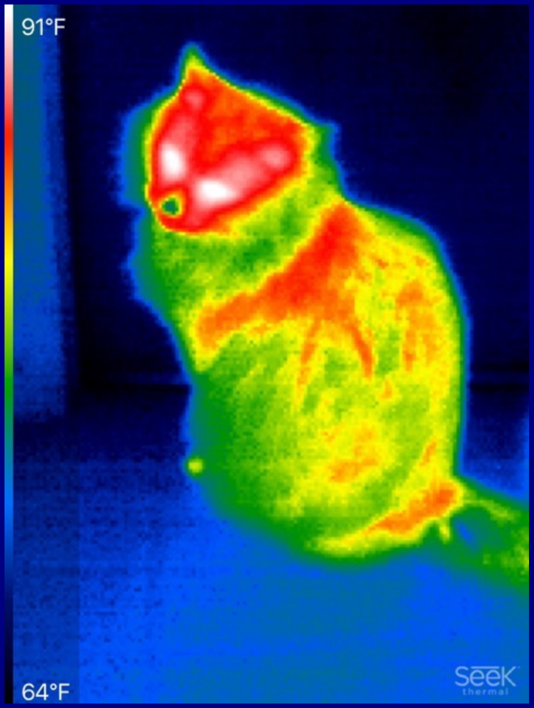
# Announcements

Test average was 84




90 – 100: A
80 – 89: B
70 – 79: C
60 – 69: D
< 59 : F



# Aurora Borealis in New Mexico

# Aurora Borealis in New Mexico

# Comet Tsuchinshan-ATLAS

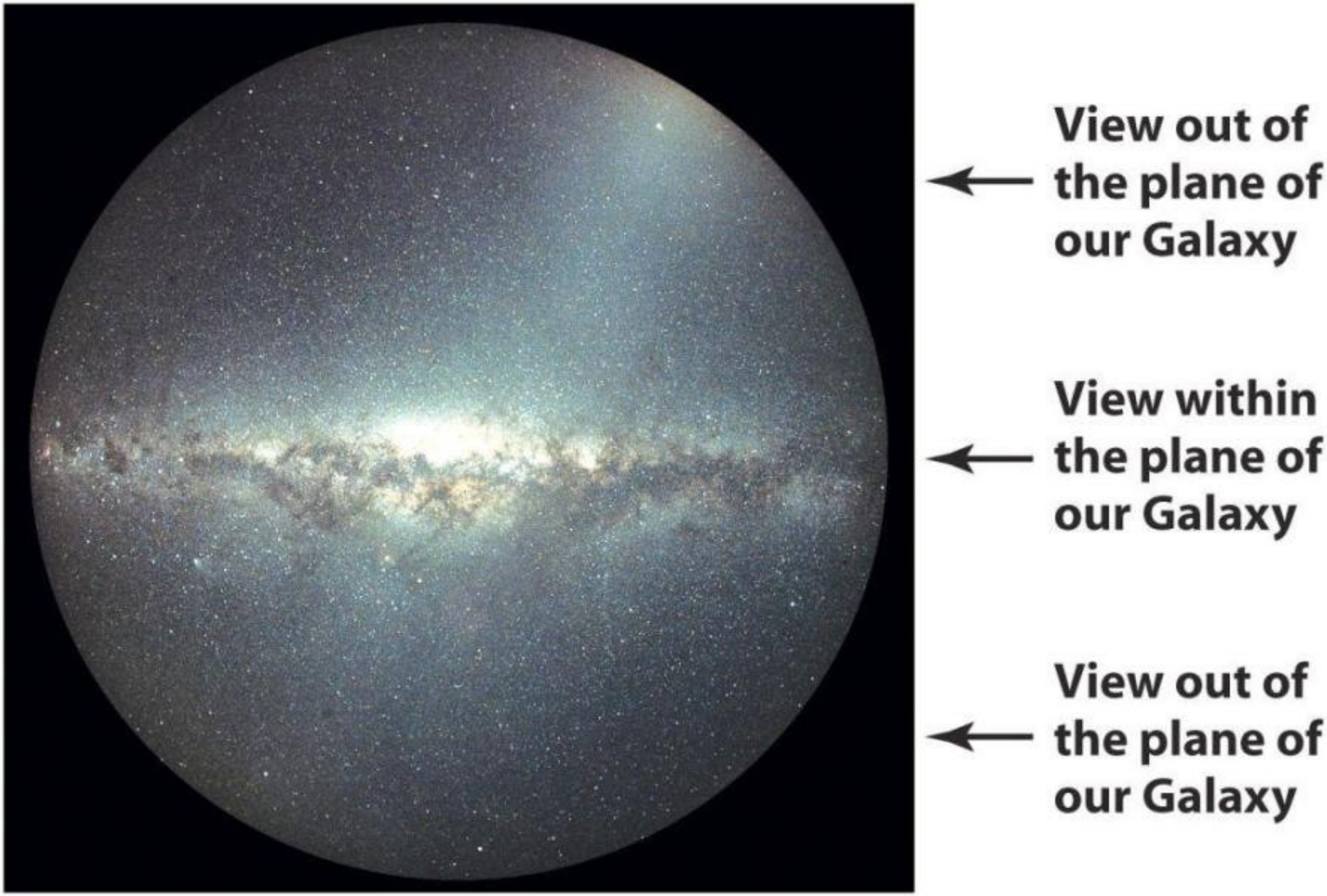
# Announcements

- Drawing for University Appointments – TODAY
- Topic Selection – by end of day Oct 17 or will be assigned
- HW#6 Due on Thursday, Oct 17

# The Milky Way

# The Milky Way Galaxy

- A galaxy: huge collection of stars and interstellar matter (gas & dust).
- Held together by gravity.
- Much bigger than any star cluster we have discussed.
- Our galaxy:  *the Galaxy*, or *the Milky Way, ~$10^{11}$ stars*


View out of the plane of our Galaxy
View within the plane of our Galaxy
View out of the plane of our Galaxy

# The Starry Messenger (1610)

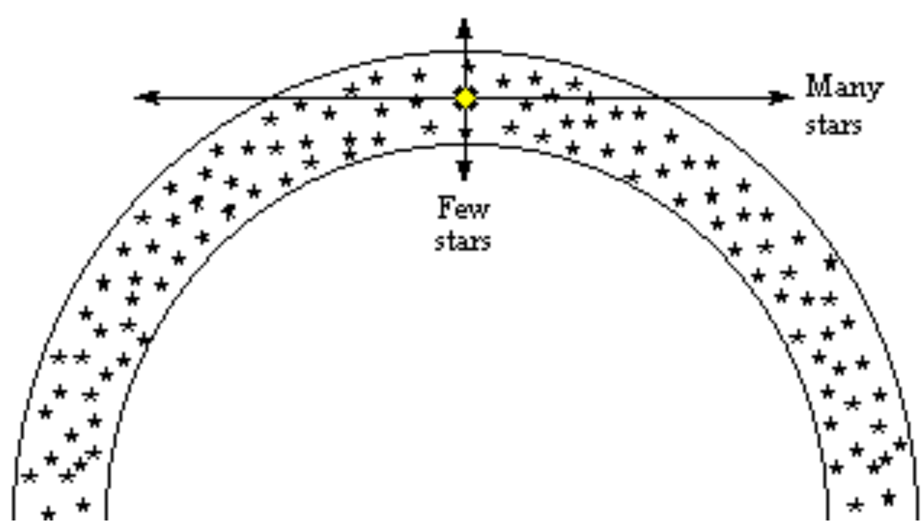
- Galileo observed the Milky Way stars with his telescope:

  *"For the Galaxy is nothing else than a congeries of innumerable stars distributed in clusters."*

  At this point, no one knew the size and shape.

- Thereafter: Wright (1750), more theological motivation (few observations). Stars positioned in a thin shell.

Wright's Milky Way (1750)

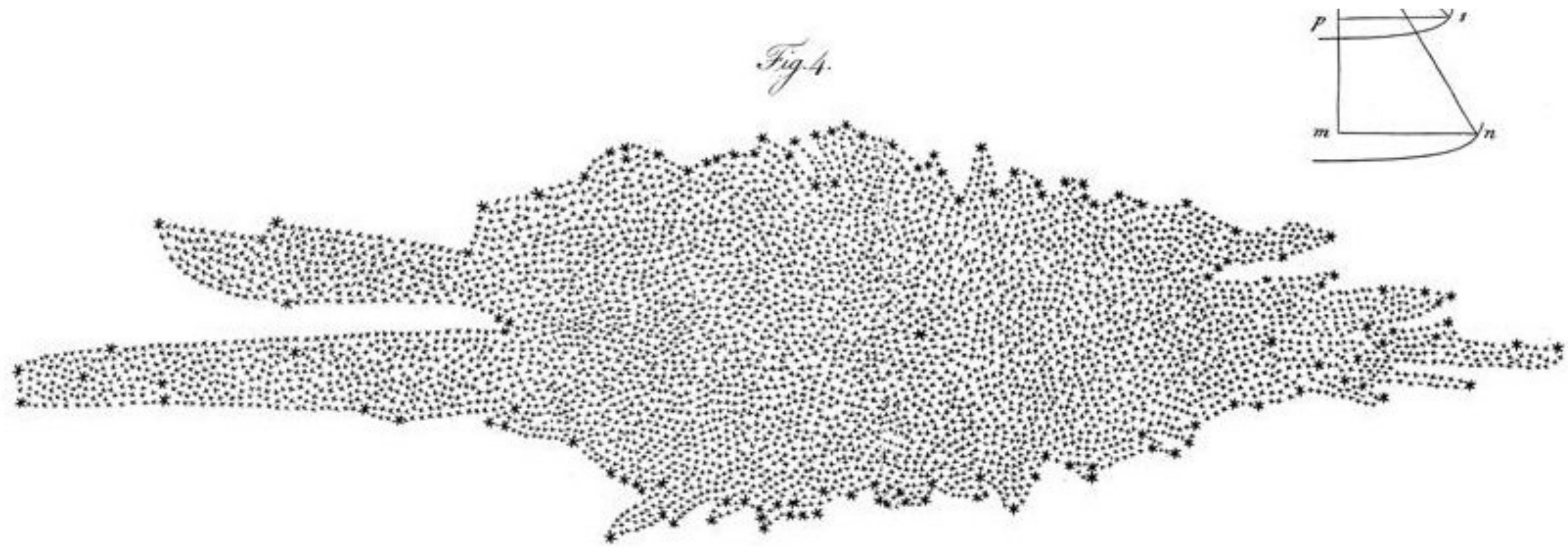


# The Island Universe

- Immanuel Kant (1755) came up with another interpretation:
  - A lens shaped distribution of stars rotating around its center.
  - The Sun has no special place.
  - Other nebulae are rotating systems like ours.

- Not based on any new observations

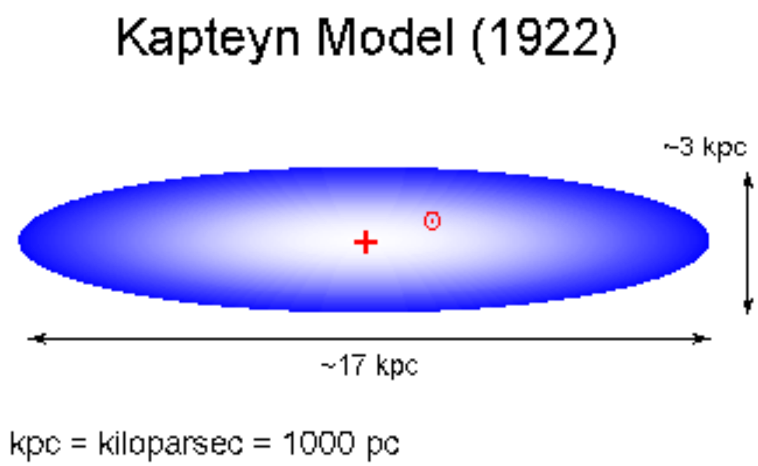
# Herschel: new observations

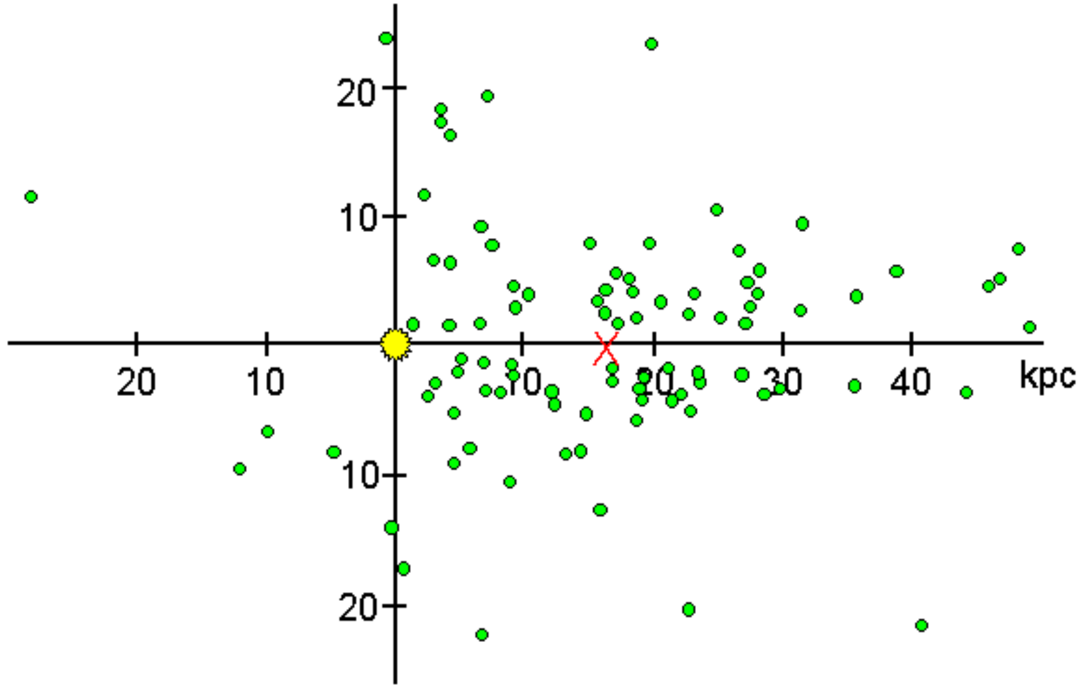



- Caroline & William Herschel (1785) counted stars along 683 lines-of-sights
- Assumptions: all stars same luminosity (gives distance) and that they could see to the edge

# Kapteyn: photographic counts

- Early 1900s: estimated distances statistically based on parallaxes and proper motions of nearby stars
- But: neglected interstellar absorption
- => MW is a ~15 kpc flattened disk, ~3 kpc thick with Sun slightly off-center



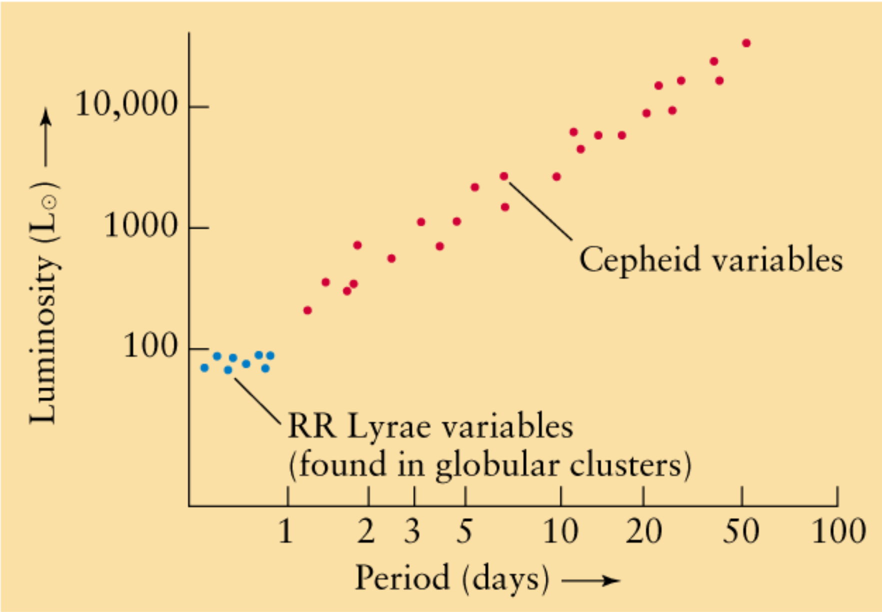


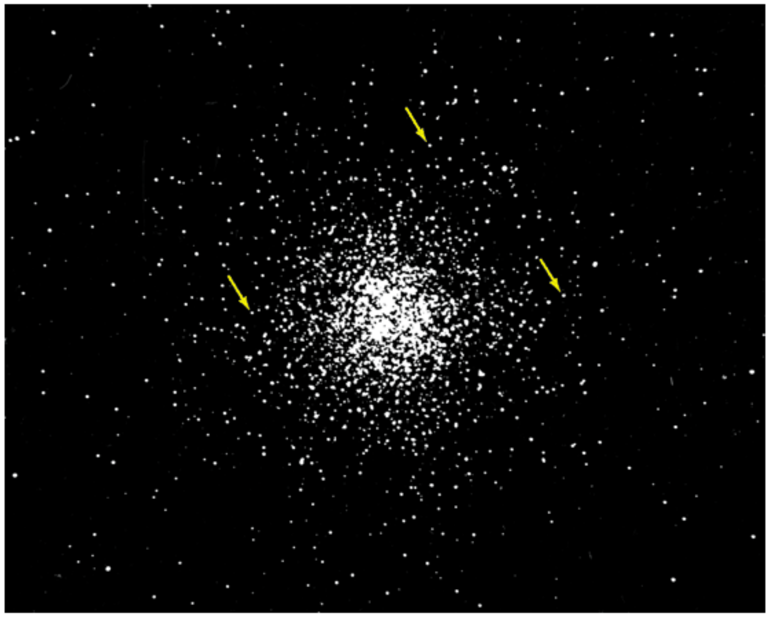

- Shapley (1915-21) used globular clusters:
  - Uniformly distributed above & below the MW.
  - Concentrated toward Sagittarius.

- Mapped distribution of globular cluster using RR Lyrae stars to get distances.

- Did not correct for absorption.

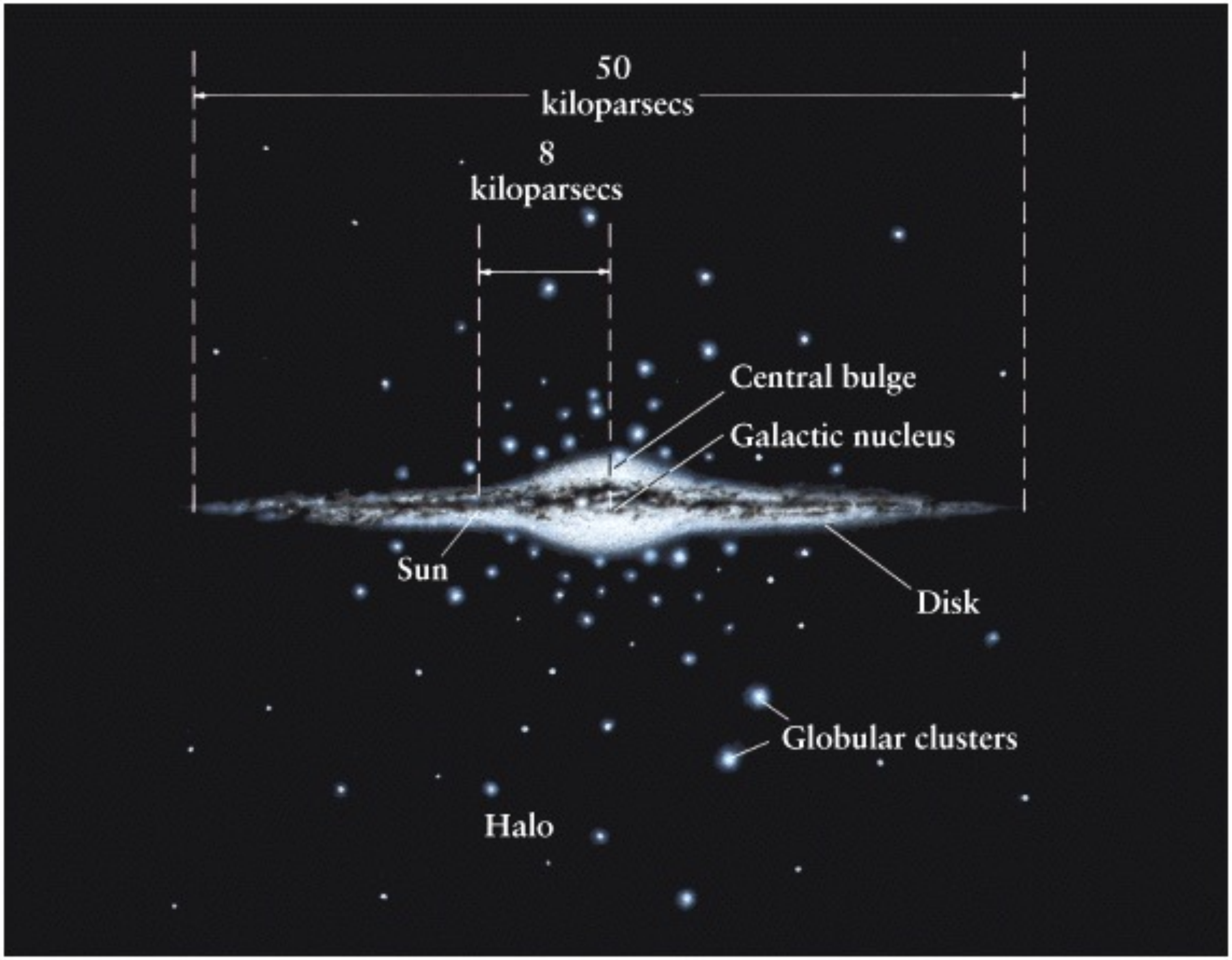
- Shapley used the known absolute magnitudes of RR Lyrae variables in globular clusters to determine the size of the MW.
- RR Lyrae variables:
  - Smaller than Cepheids => vary faster.
  - Formed from low mass stars, thus older than Cepheids.



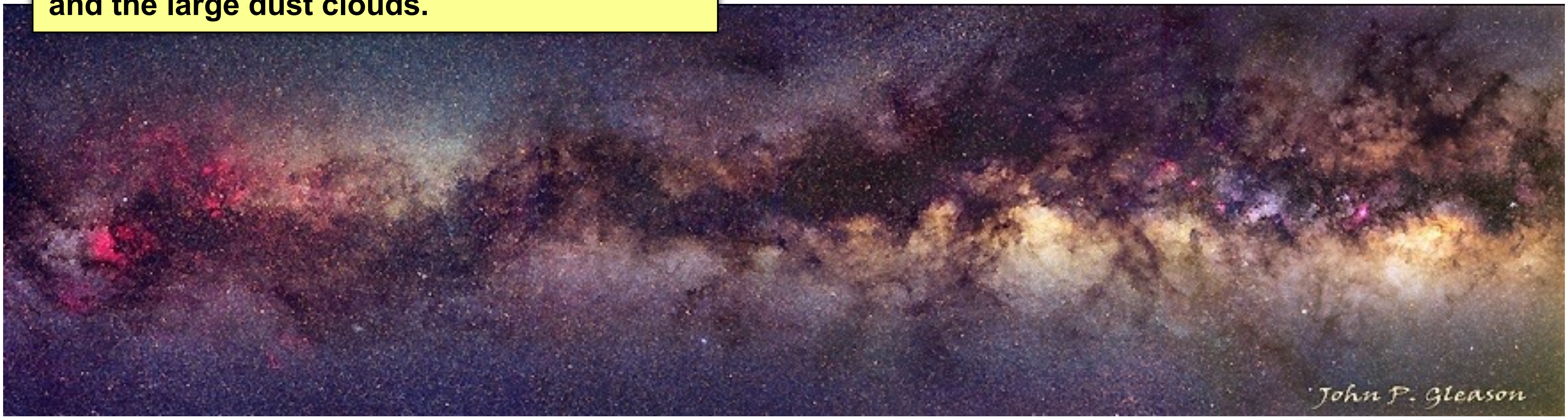



- These, and earlier ideas of size and shape were *overestimates*: no correction for absorption of light by interstellar dust.

Modern “Artist’s conception” of the Milky Way (edge-on view)
Overall structure: disk, central bulge, halo.



A photo mosaic of the Milky Way seen in visible light.  Note the vast number of stars and the large dust clouds.




2MASS: near-IR (cool stars) showing the plane and the central bulge where most stars are located.

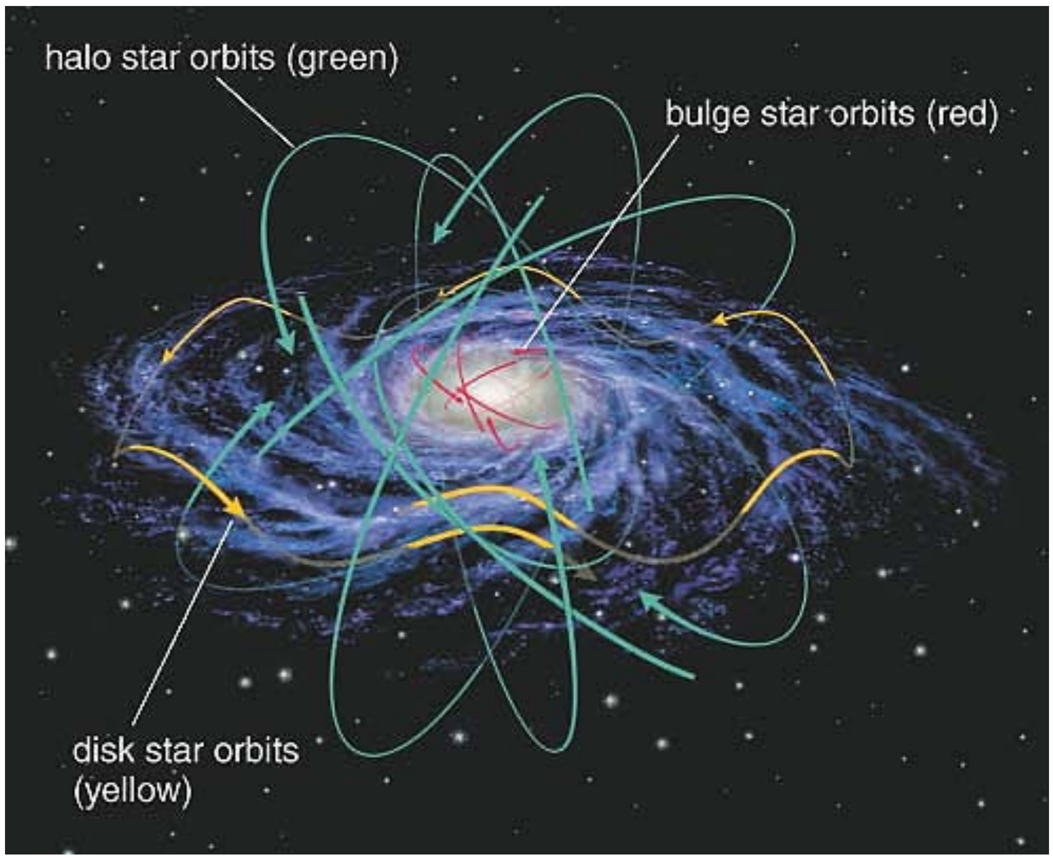
# Clues to the formation of the MW

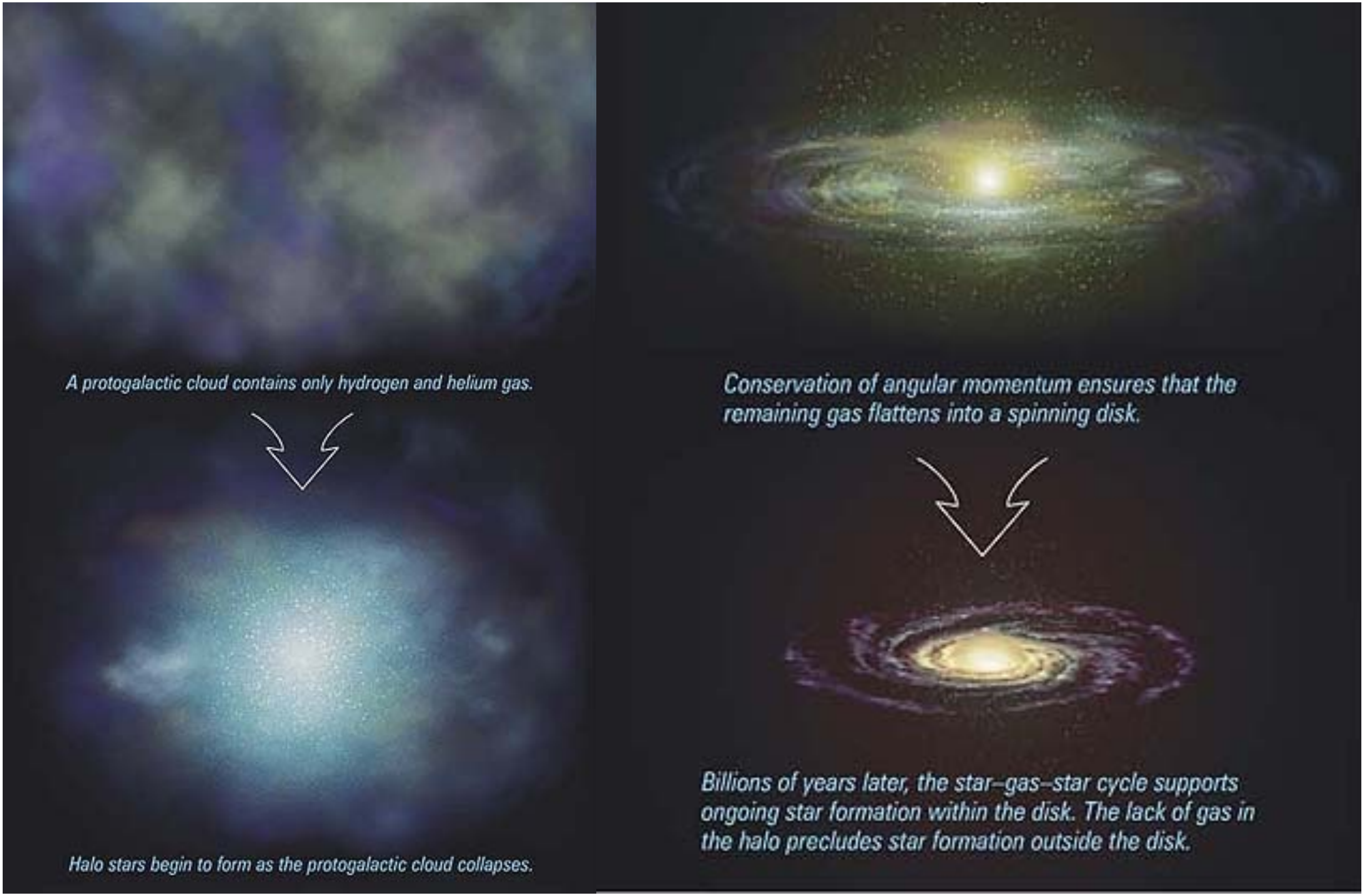
Different populations of stars lie in different components of the Galaxy:

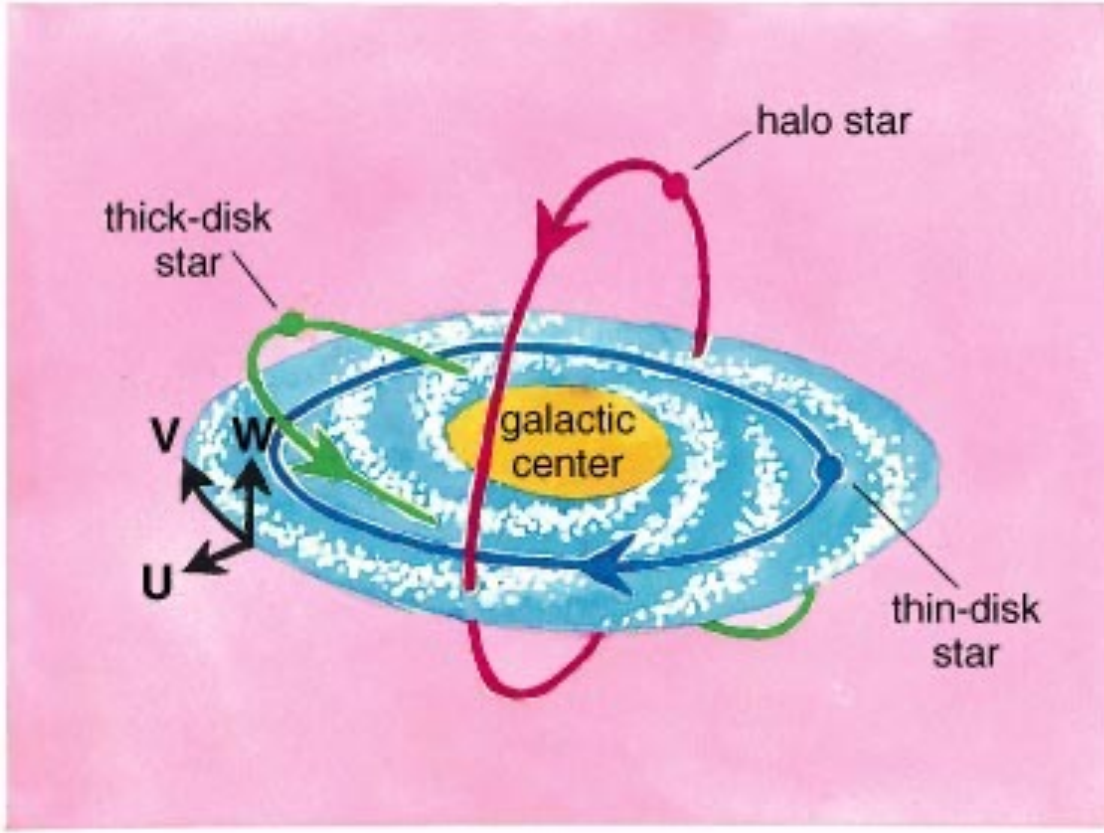
- Pop I: in the disk
  - young stars, circular orbits, high metallicity.
- Pop II: in the halo
  - old stars, highly elliptical orbits, low metallicity.
- Bulge has mixture.

# Differences in stellar orbits

- Stars belonging to different physical parts of the Milky Way display different orbital behavior.
- Our model for the formation of the Milky Way must be able to explain this.



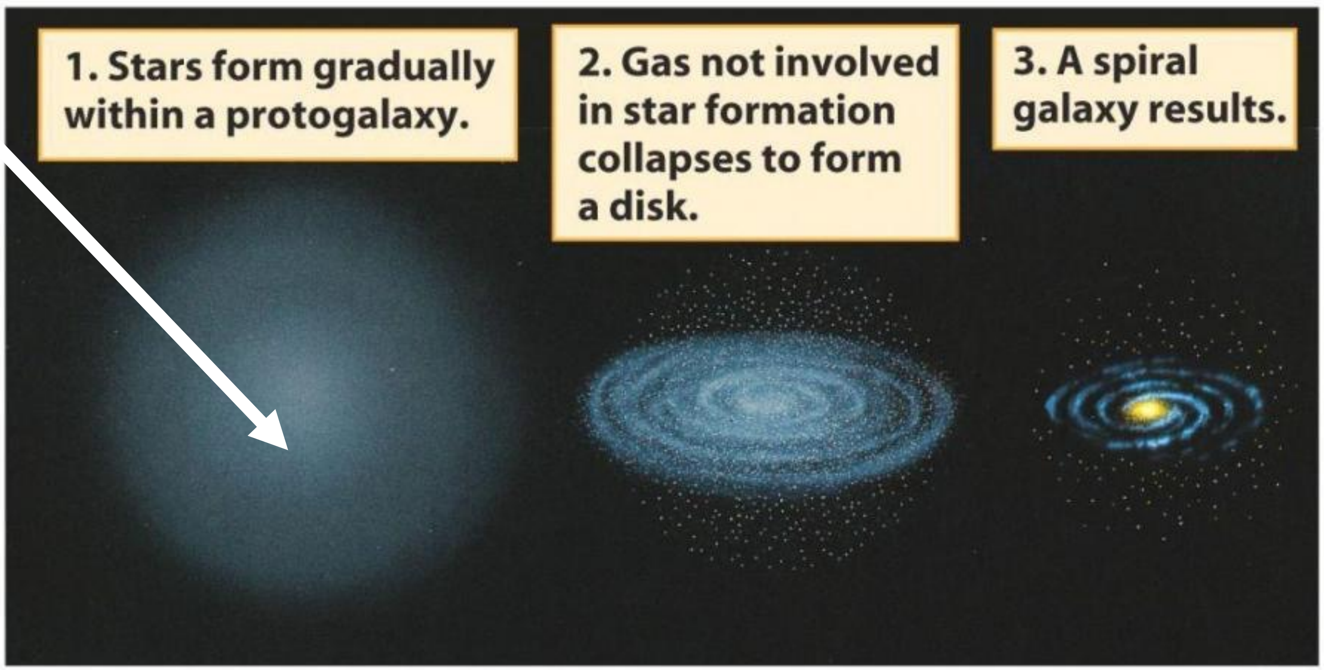

A protogalactic cloud contains only hydrogen and helium gas.
Halo stars begin to form as the protogalactic cloud collapses.
Conservation of angular momentum ensures that the remaining gas flattens into a spinning disk.
Billions of years later, the star–gas–star cycle supports ongoing star formation within the disk. The lack of gas in the halo precludes star formation outside the disk.




This explains why the orbits of the stars in different parts of the Galaxy are so different.

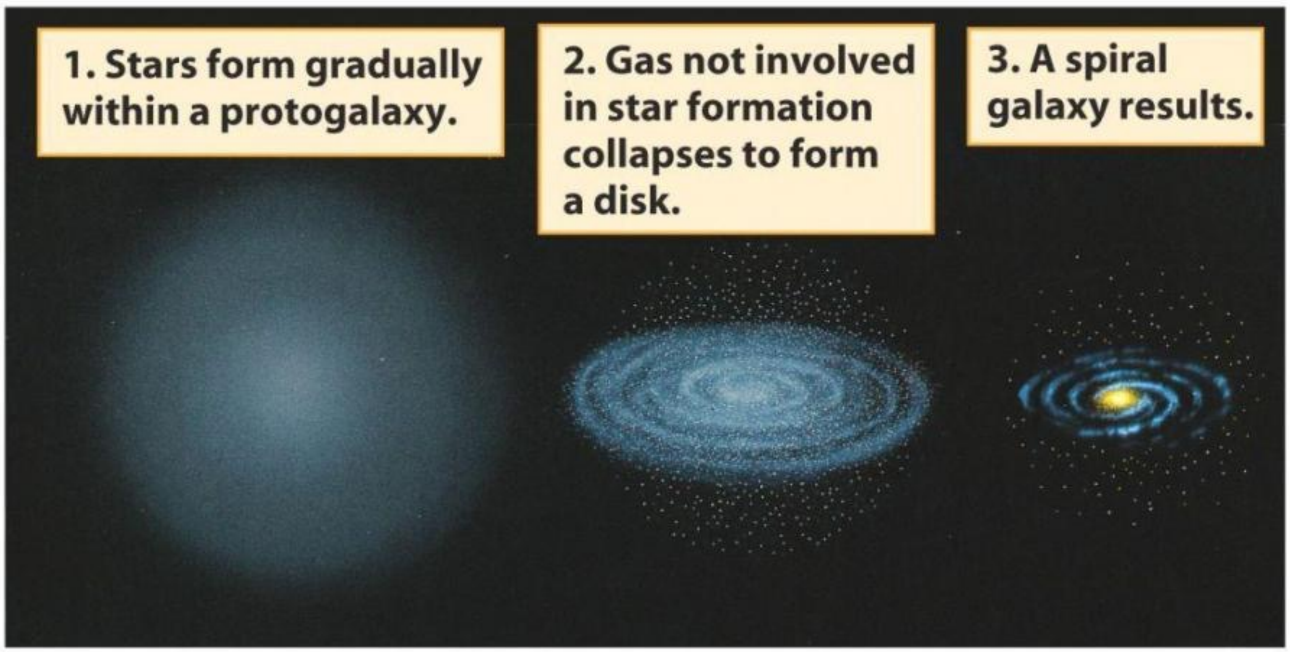
- Original cloud(s) with slow rotation have early period of star formation $\Rightarrow$ Pop II.

- Nearly spherical distribution with highly elliptical orbits. Low metals, due to "clean" gas.




Formation of a spiral galaxy

- With time, remaining gas dissipates into a rotating disk.
- Stars that form in the disk are younger (Pop I) and have coplanar orbits with primarily circular motions.
- High metals, due to enriched gas from previous star formation.

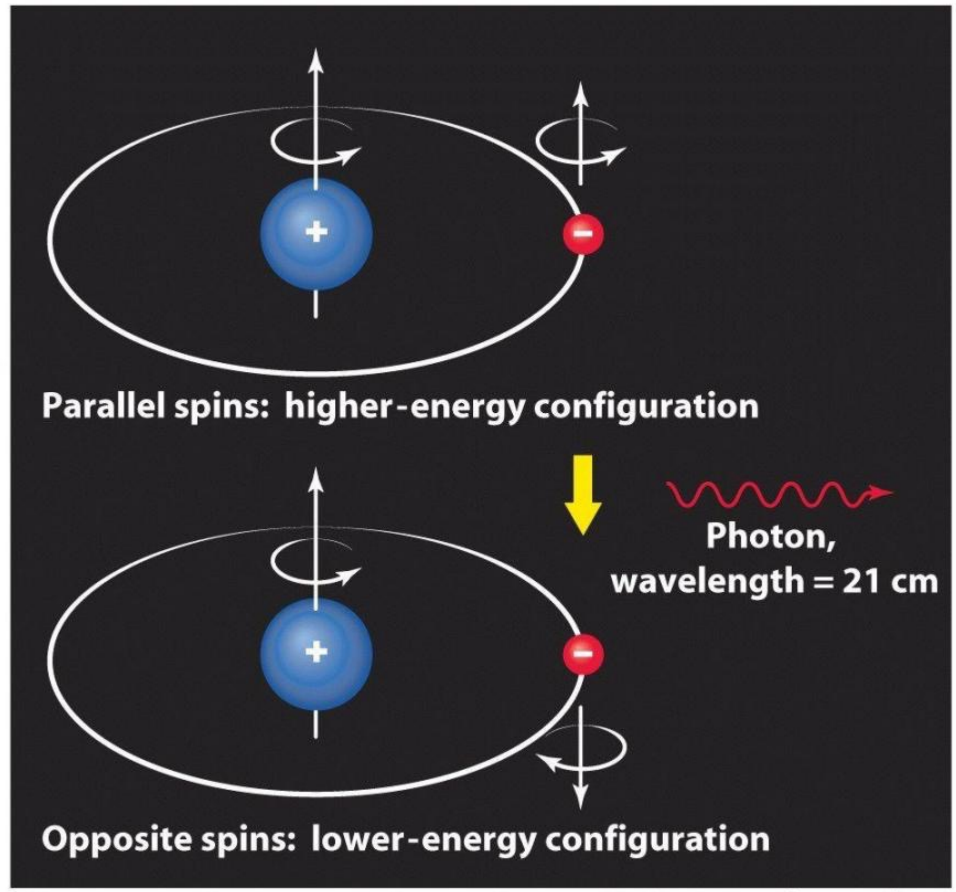



Formation of a spiral galaxy

# Detailed shape of the Galaxy

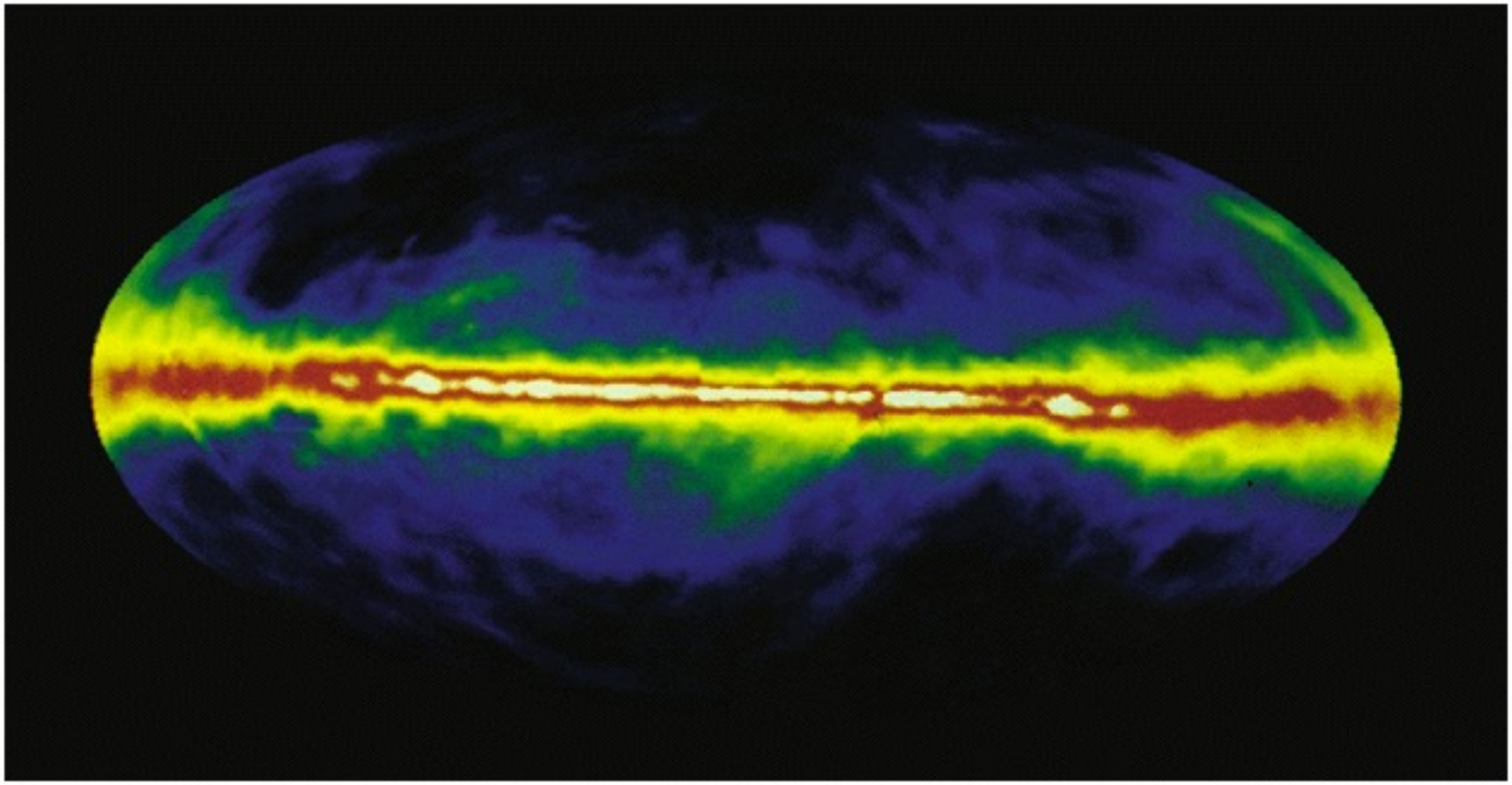
- Recall: flip of the electron spin in cold neutral hydrogen gas produces radiation with very low energy ($\lambda$=21cm)

- This can be traced all across the Galaxy



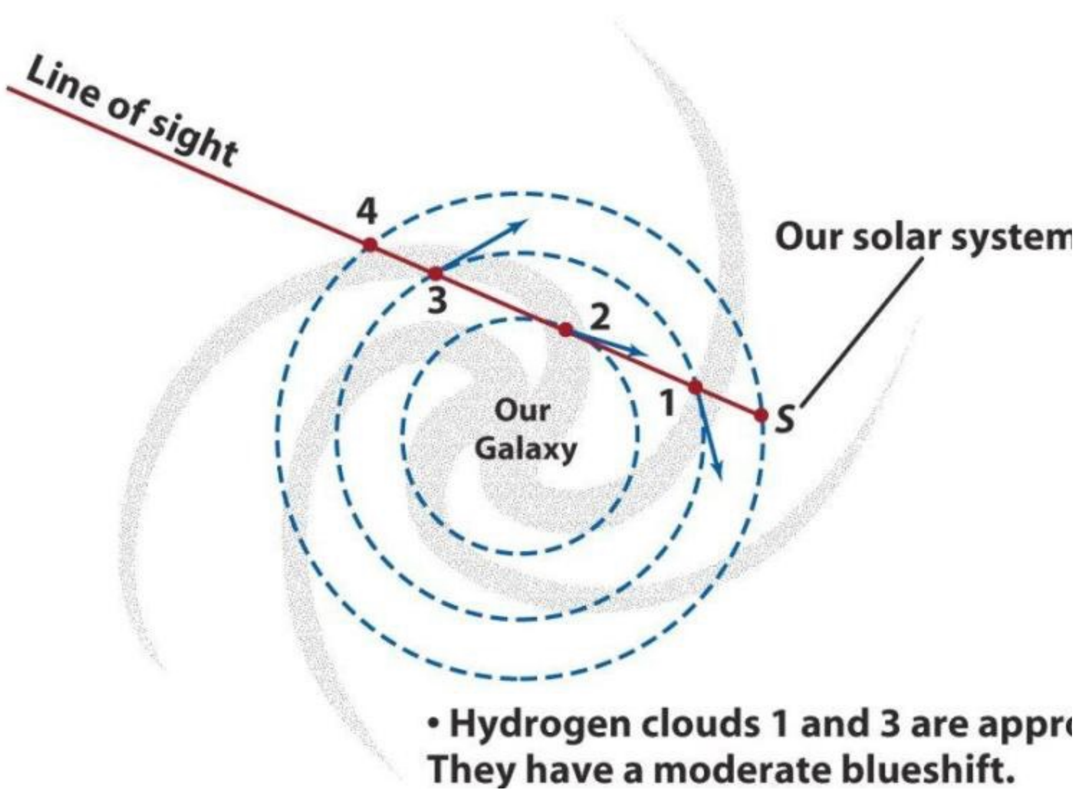

The magnetic energy of a proton and electron depends on their relative spin orientation

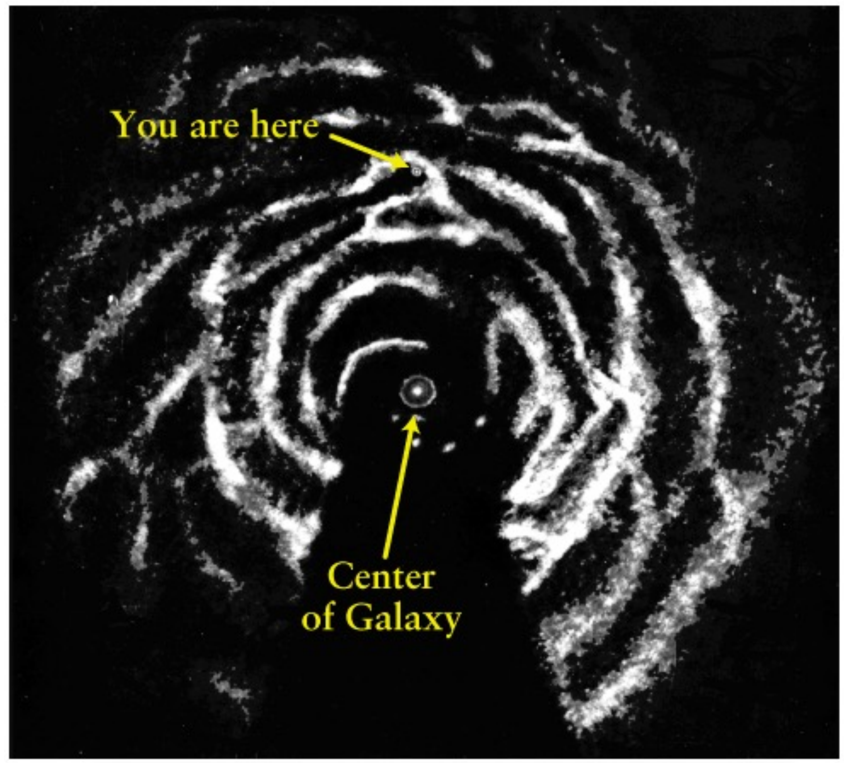
False-color image of sky at 21-cm



Thin disk of gas and dust, ~100pc thick embedded within the stellar disk (~1kpc thick).

- Distribution of stars can be determined from Doppler shifts of stellar absorption lines.
- Ionized gas via emission lines from HII regions.
- Atomic gas via the 21cm line - can trace nearly the entire disk beyond where stars thin out.



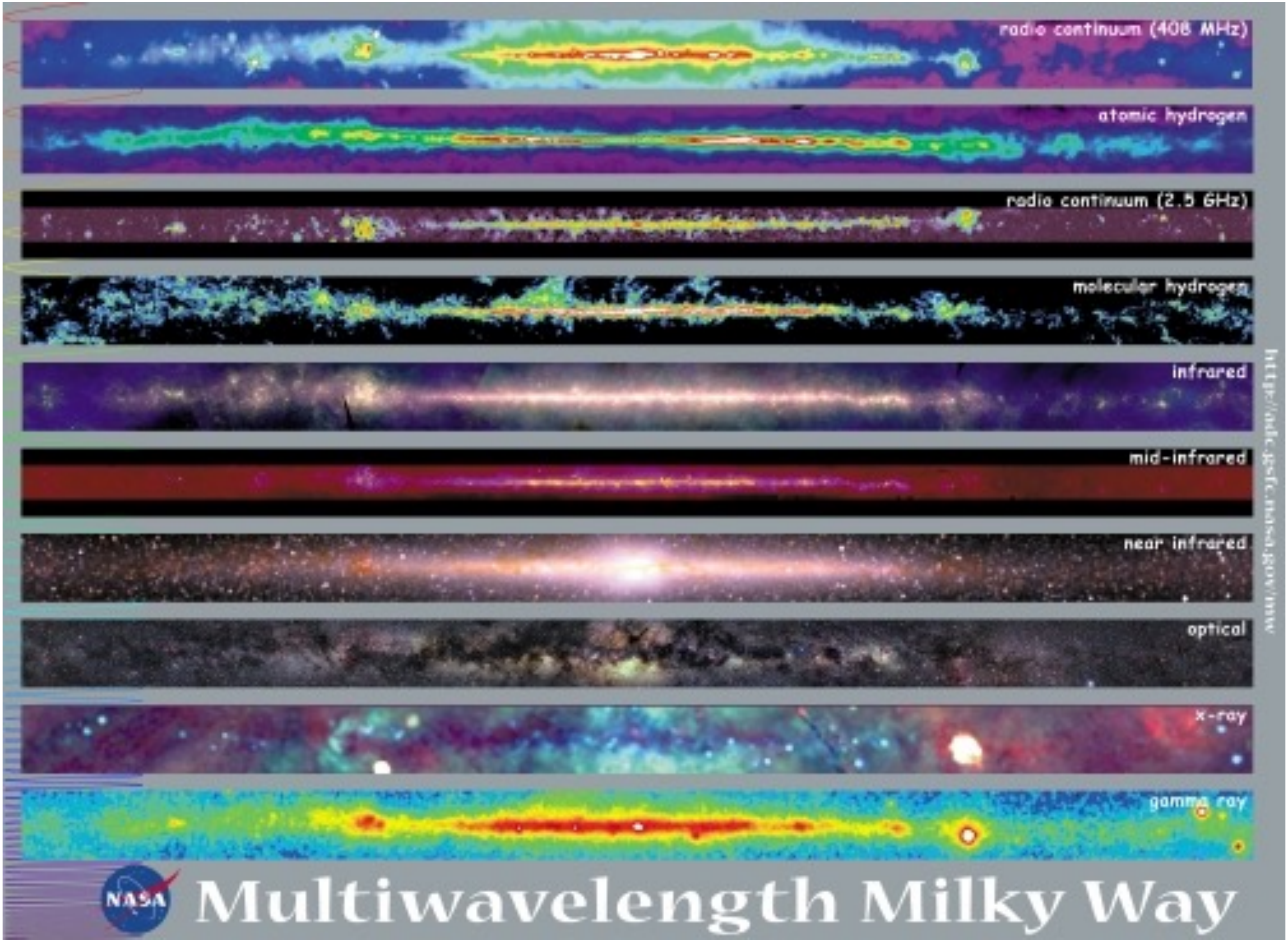



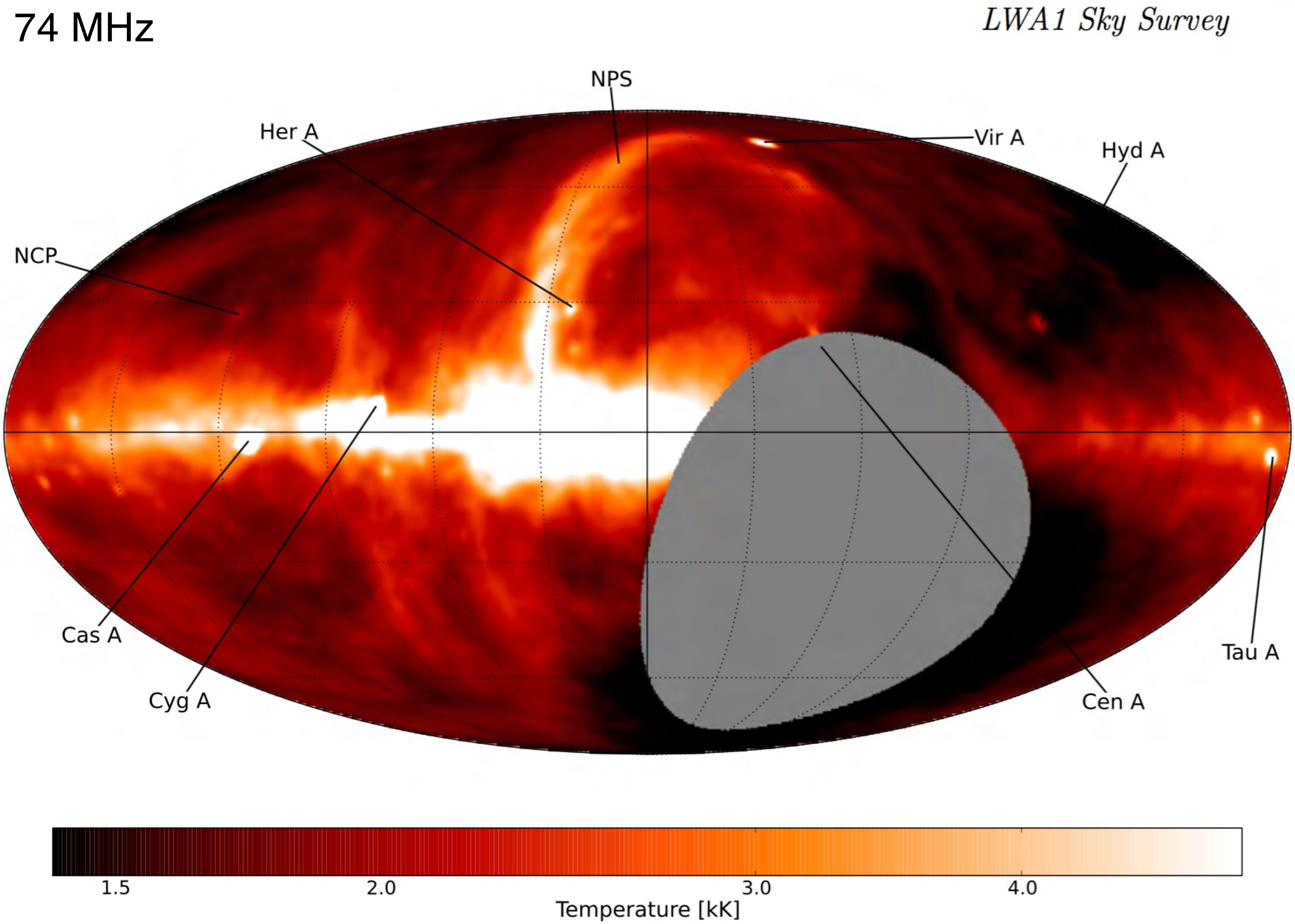

**Atomic gas in *spiral arms* (not uniformly distributed).**

- The disk dominates the shape of the Galaxy – visible at many wavelengths.

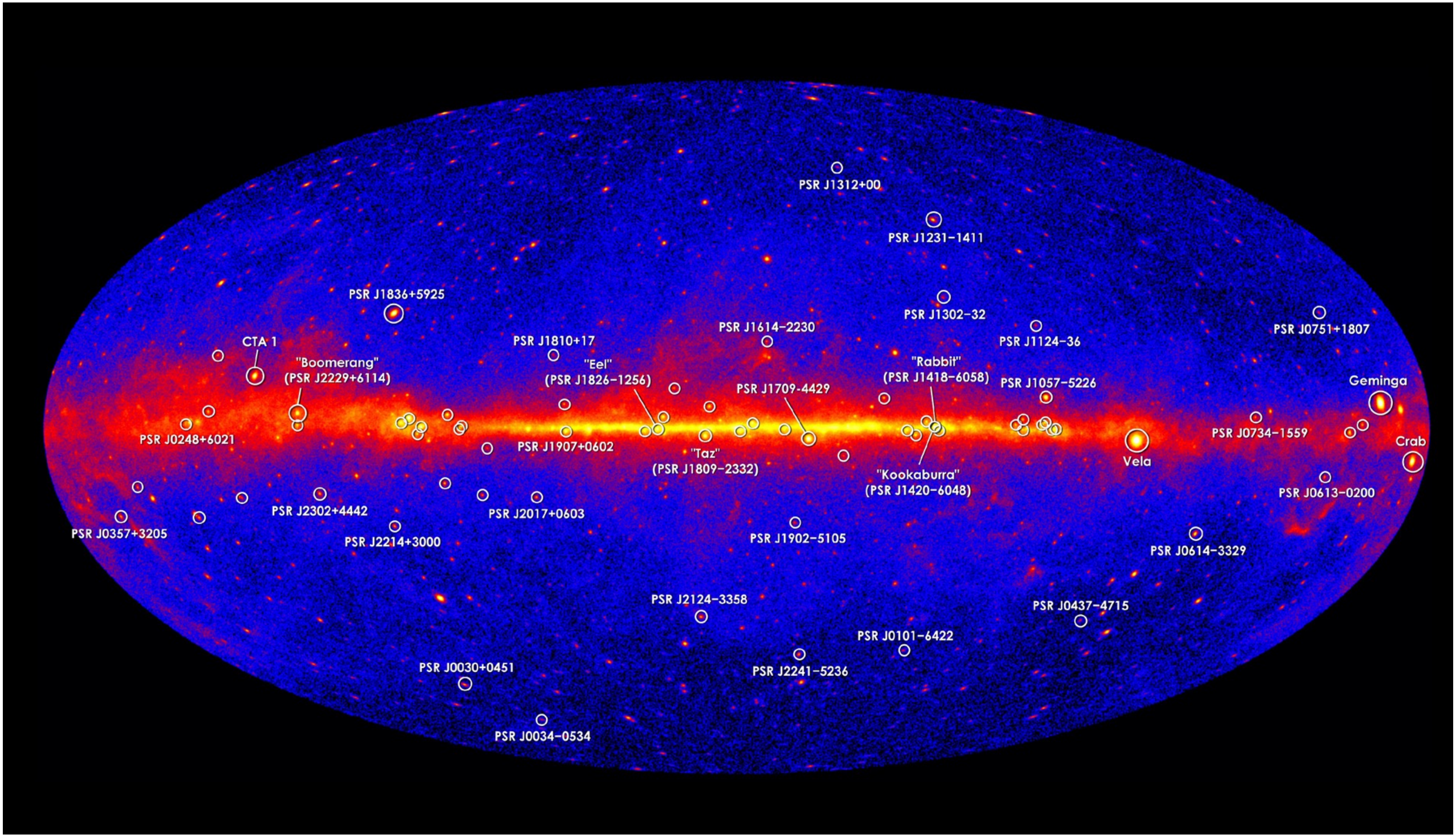
- There is also a noticeable bulge around the nucleus (center).

**NGC 4501 – an analog to the Milky Way.**


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

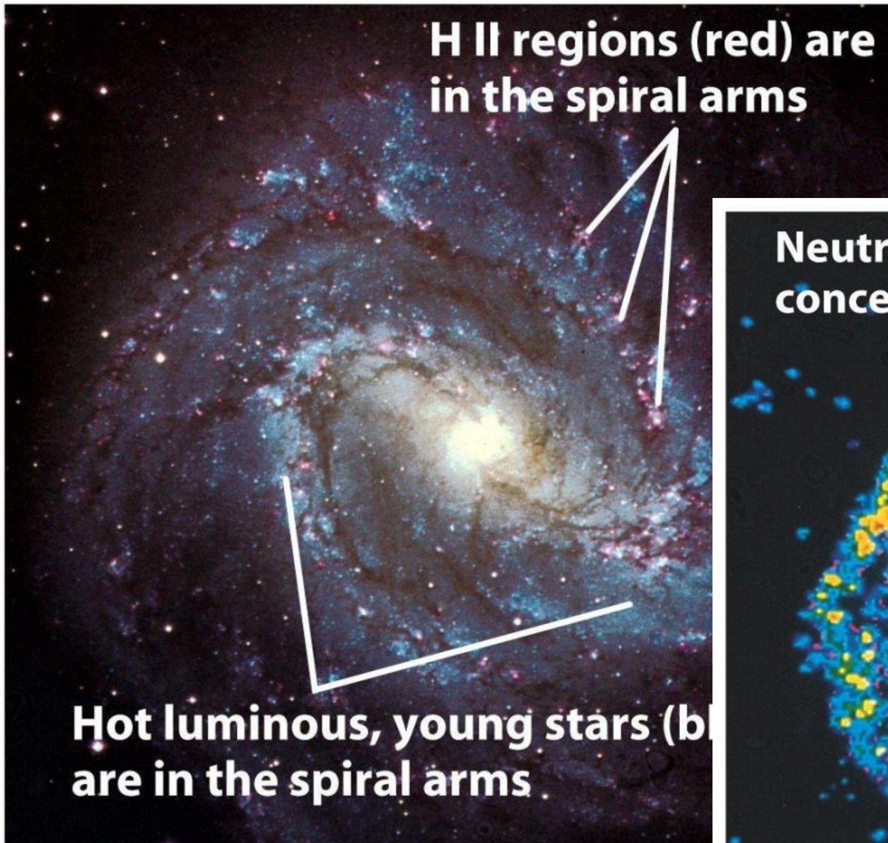

74 MHz
LWA1 Sky Survey
NPS
Her A
Vir A
Hyd A
NCP
Cas A
Cyg A
Cen A
Tau A
1.5
2.0
3.0
4.0
Temperature [kK]

# Fermi gamma-ray observations

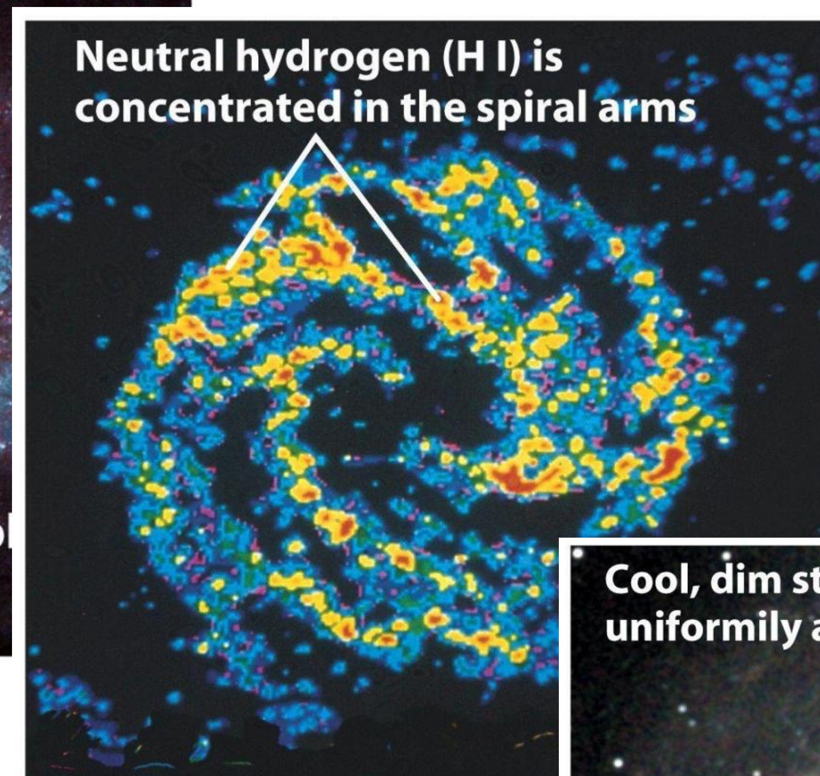


DIRBE 1.25, 2.2, 3.5 μm Composite

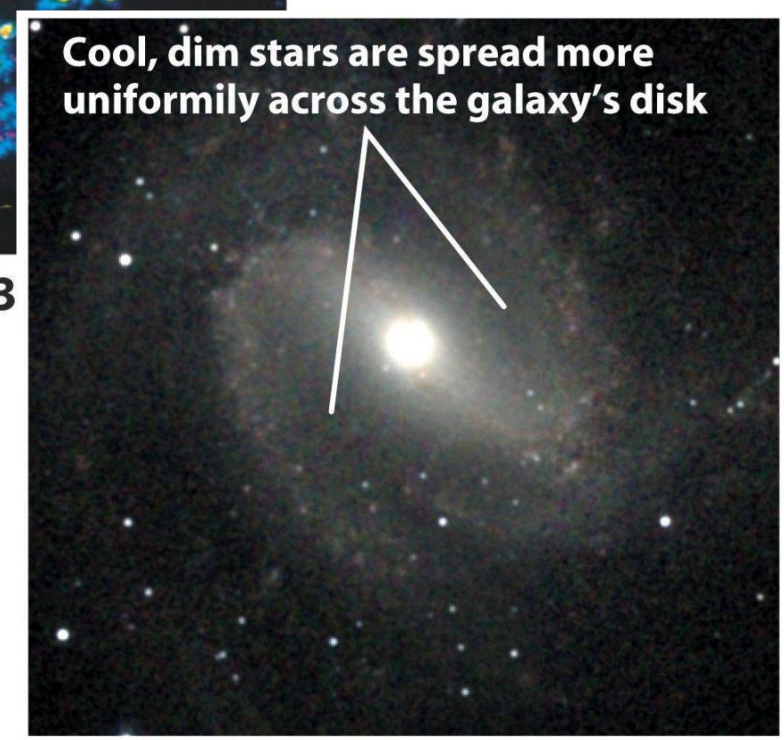
Face-on view of Milky Way would look something like this:
See “spiral arms”.



Visible-light view of M83

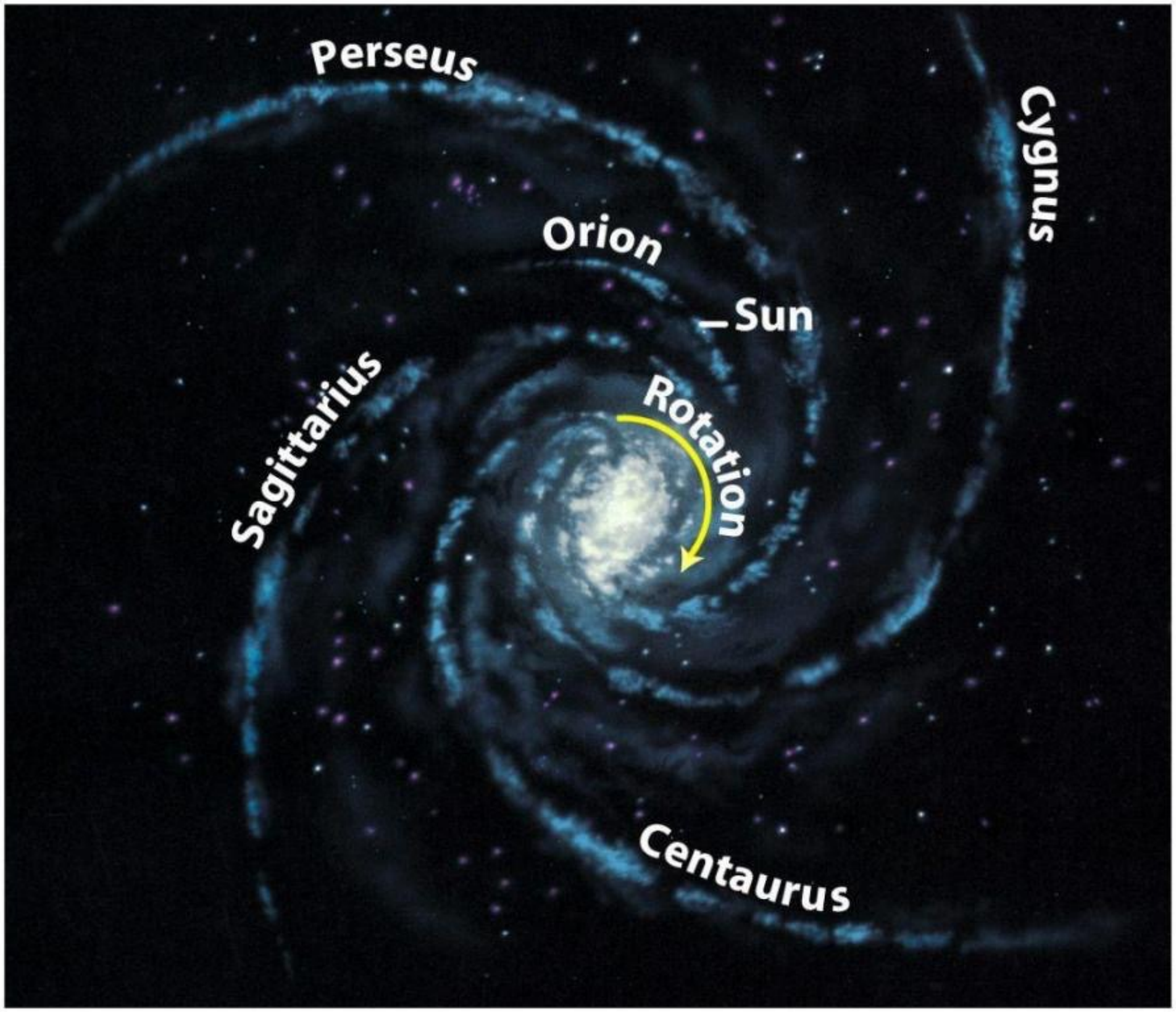


21-cm radio view of M83



Near-infrared view of M83

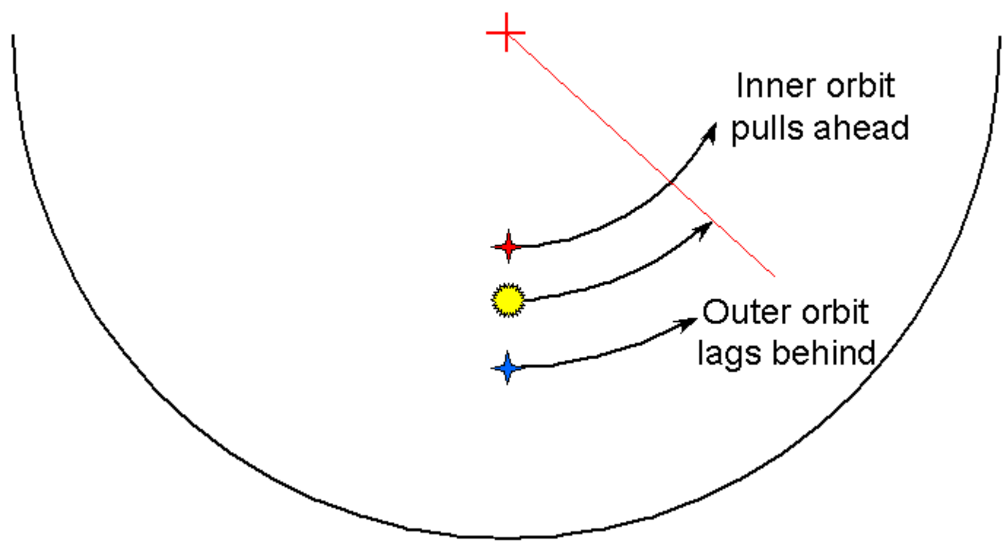
- Spiral arm tracers include HII regions, O&B stars, and giant molecular clouds.




**Question: What do these objects have in common?**

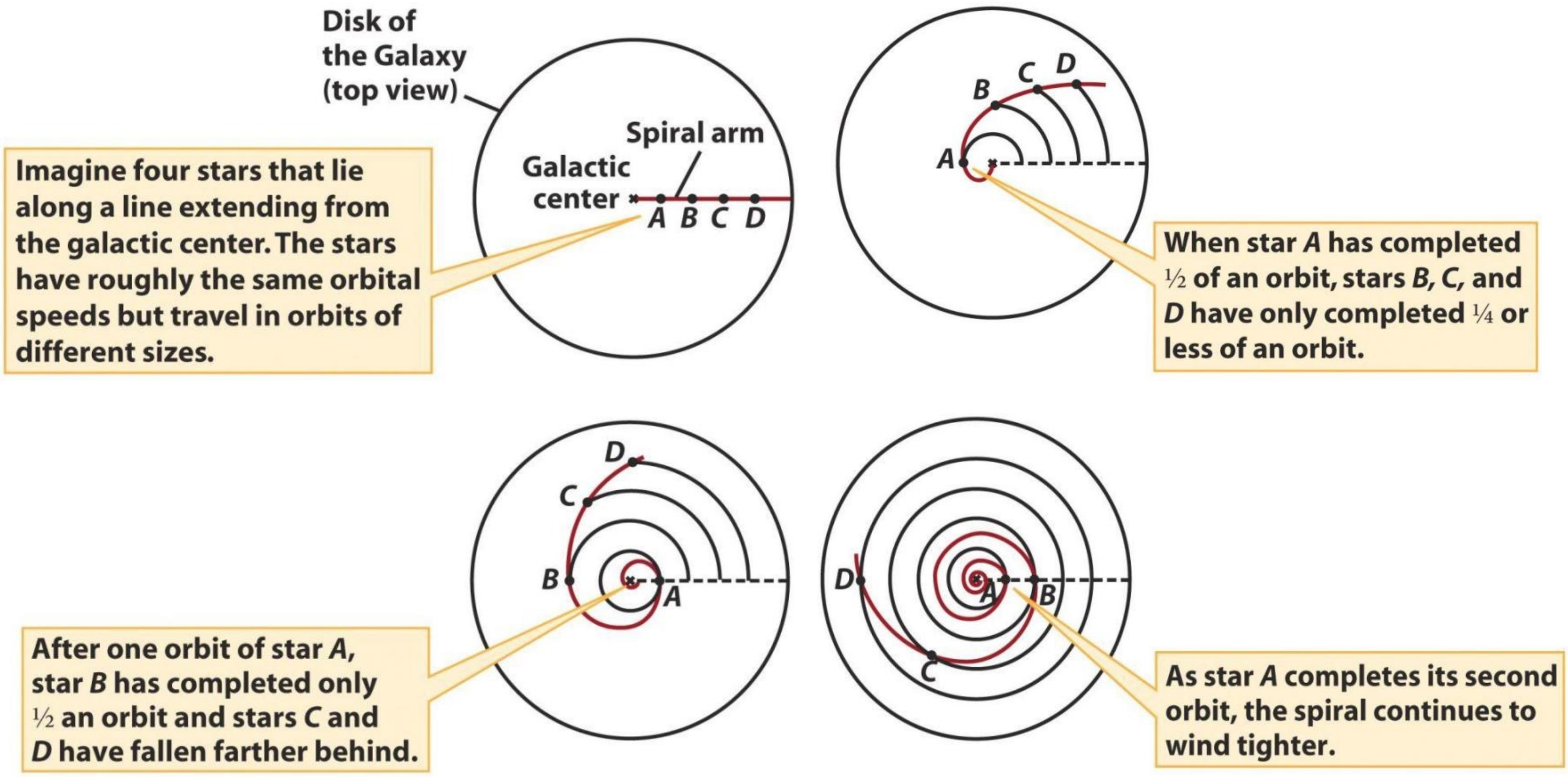
# Spiral arms

- Rotation of the Galaxy is *differential*: all stars rotate with about the same circular speed.



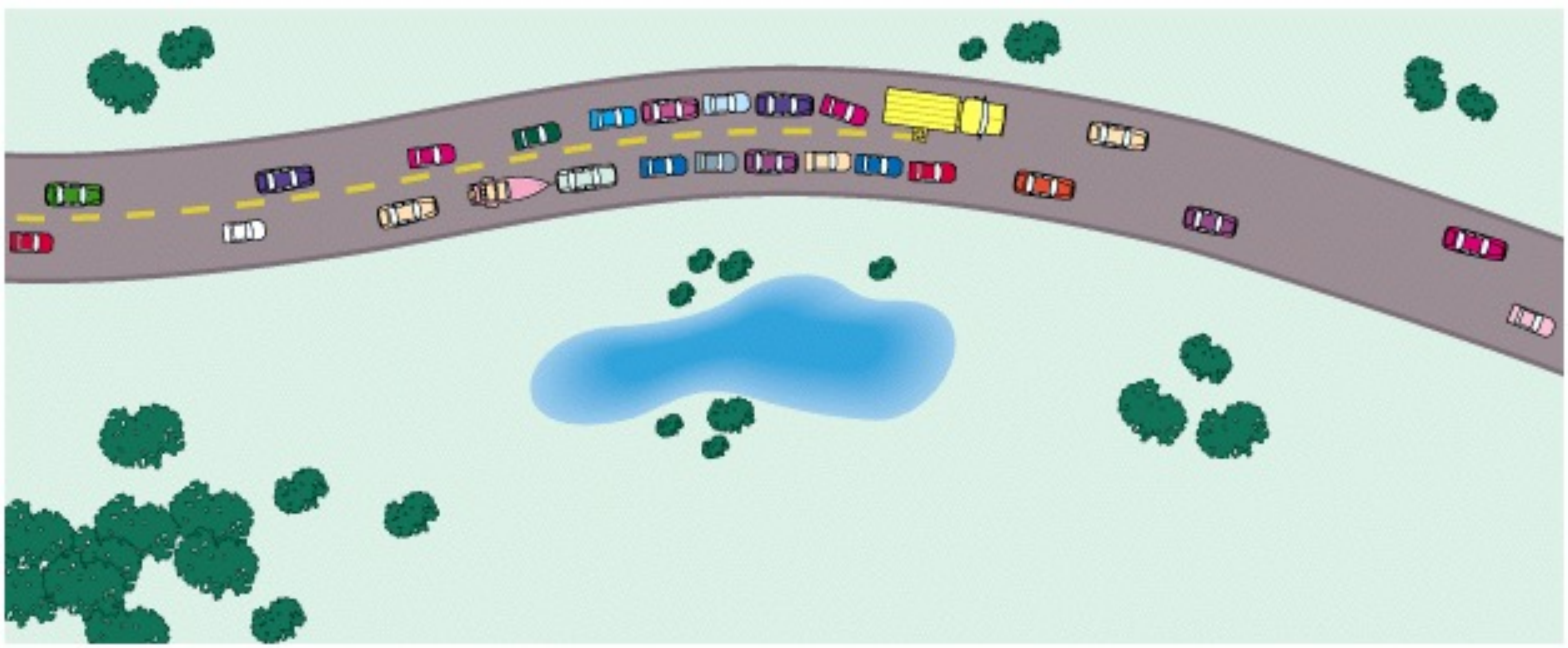

- Cf *solid body rotation*: object one piece, all parts rotate with same angular velocity (outer parts must then have higher circular speeds than inner parts).

Can the differential rotation cause spiral arms?  No -  the arms would “wind up” with time.

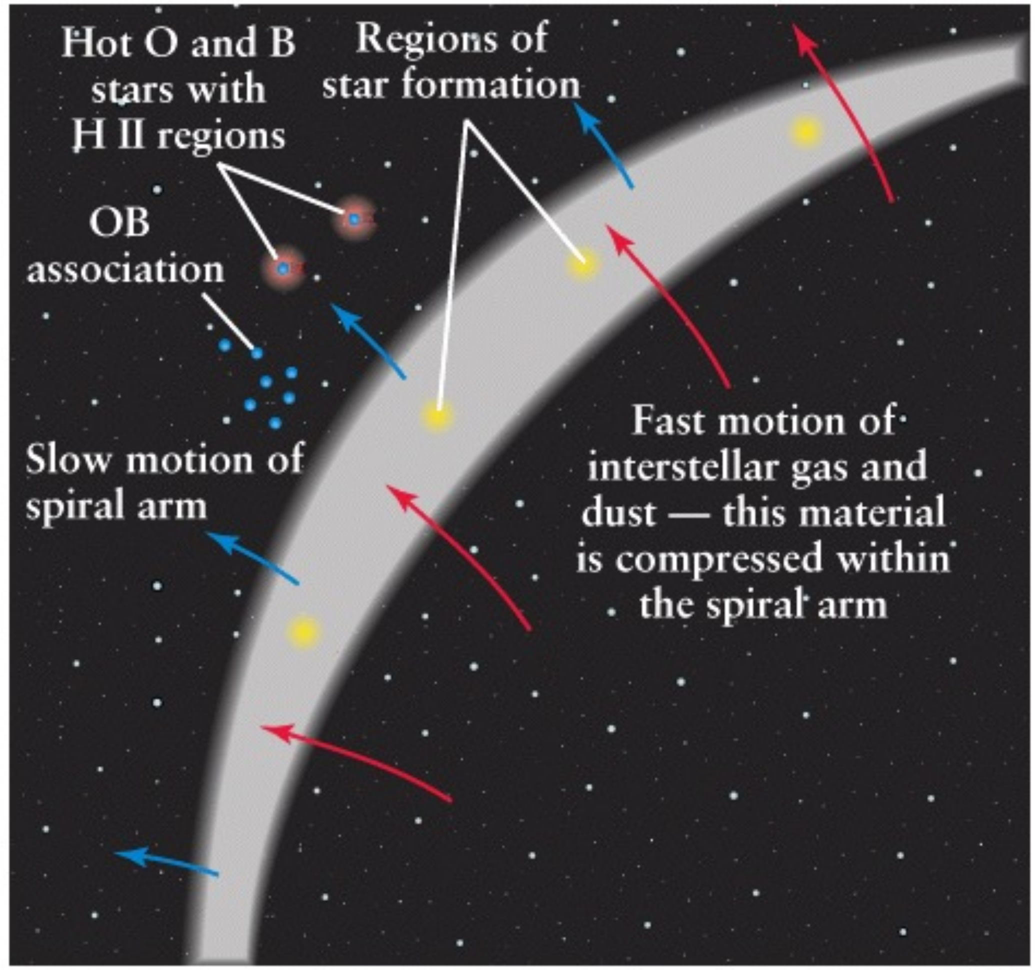


# Spiral arms are density waves

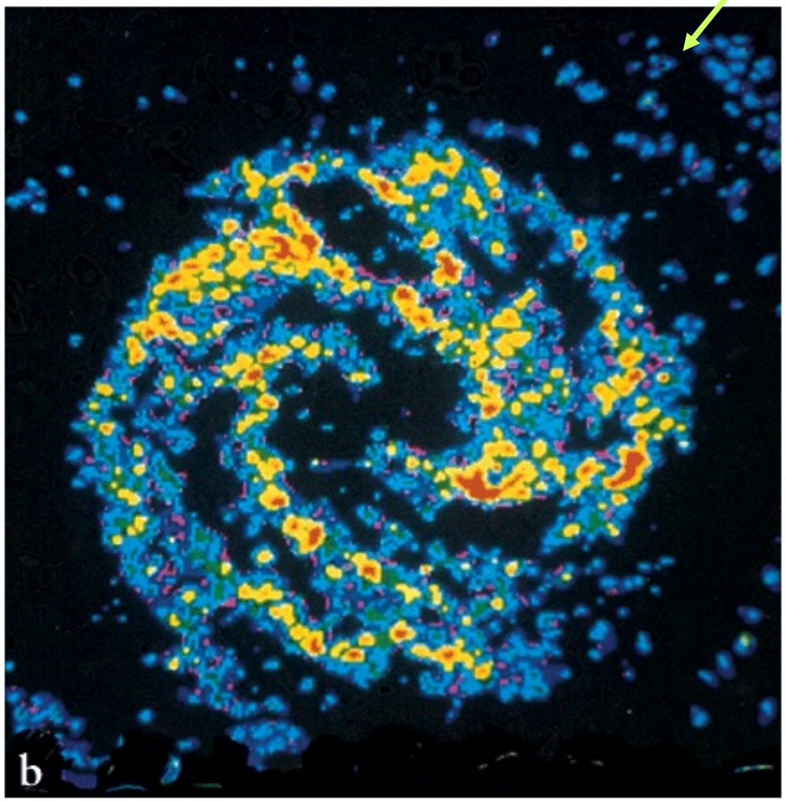
- Regions of relatively high density of material moving around the Galaxy.
- An orbital "traffic jam".



- Idea: spiral arms are waves of high density sweeping around the Galaxy.
- Gravitational field of spiral pattern compresses interstellar clouds, triggering star formation. Makes these regions look brighter.
- O&B stars ionize leftover gas, then die before moving far away from the waves.
- Waves move at slower speed than rotation of material in the Galaxy.



Recall: M83 shows arms clearly in visible light and HI, but NOT as much in near-IR. Near-IR traces more of the old stellar population.

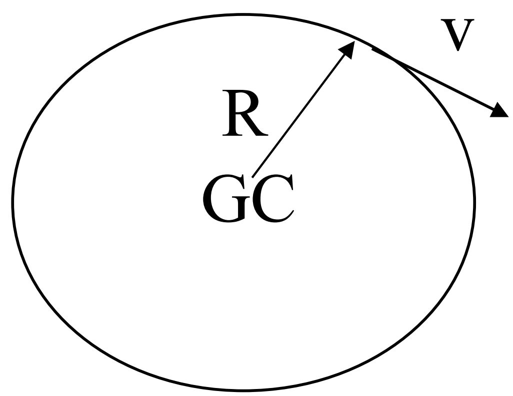



# WS11: Estimating the mass of the Galaxy

- We know the rotational speed of the Sun; $V_{ROT}$ = 220 km/s.
- The distance from the Galactic center; R=8 kpc.
- Use Newton's laws to deduce the mass within 8 kpc.

# Estimating the mass of the Galaxy

- We know the rotational speed of the Sun; $V_{ROT}$ = 220 km/s.
- The distance from the Galactic center; R=8 kpc.
- Use Newton's laws to deduce mass.



For object moving at speed *V* in a circular orbit of radius *R* the acceleration is:

$$\frac{V^2}{R}$$

From Newton's second law, *F=ma*, along with law of gravitation,

$$\frac{GMm}{R^2} = m\frac{V^2}{R}$$

where *m* is mass of the Sun, and *M* is the mass of the Galaxy within the solar orbit. Thus

$$M = \frac{V^2 R}{G}$$

Putting in numbers, we get the mass of Galaxy.

$$M \geq 9 \times 10^{10}\, M_\odot \qquad \text{(Why "}\geq\text{" ?)}$$

Is there significant mass beyond 8 kpc?

We can tell from the "rotation curve", which is a plot of speed of rotation as a function of distance from the Galactic center.

Rearranging:

$$M = \frac{V^2 R}{G} \quad \Rightarrow \quad V = \sqrt{\frac{GM}{R}}$$

If the mass of the Galaxy were concentrated in or near the center, then we would see circular velocities of stars and gas falling with radius:

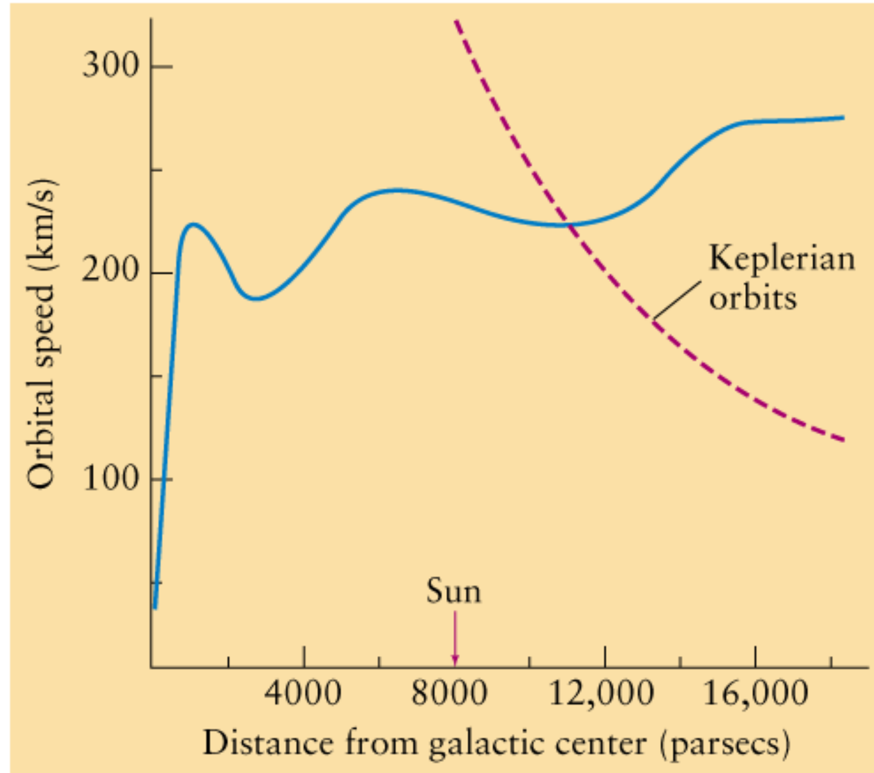
$$V \propto \sqrt{\frac{1}{R}}$$

We recognize this as *Keplerian motion* – it' s what we see with the planets.

We expect stars and gas farther from the Galactic center to orbit at a slower speed.

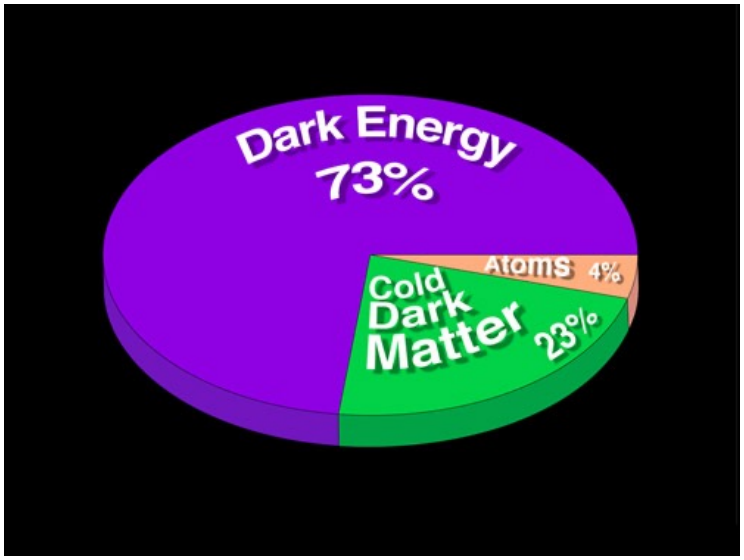
# The Milky Way rotation curve

- Not Keplerian! Outer objects move faster than we expect.
- The total mass of the Galaxy is about $1.5 \times 10^{12}\ M_{\odot}$ (based on globular cluster orbits)
- There is much more gravitational pull (more mass) than we see in "normal" material.
- Only about 10% is normal stuff, e.g., stars, gas, dust.
- There must be *dark matter*.  We are not seeing all the matter that exists!  We can weigh it but not see it.



# What is dark matter?

Composition of the Universe

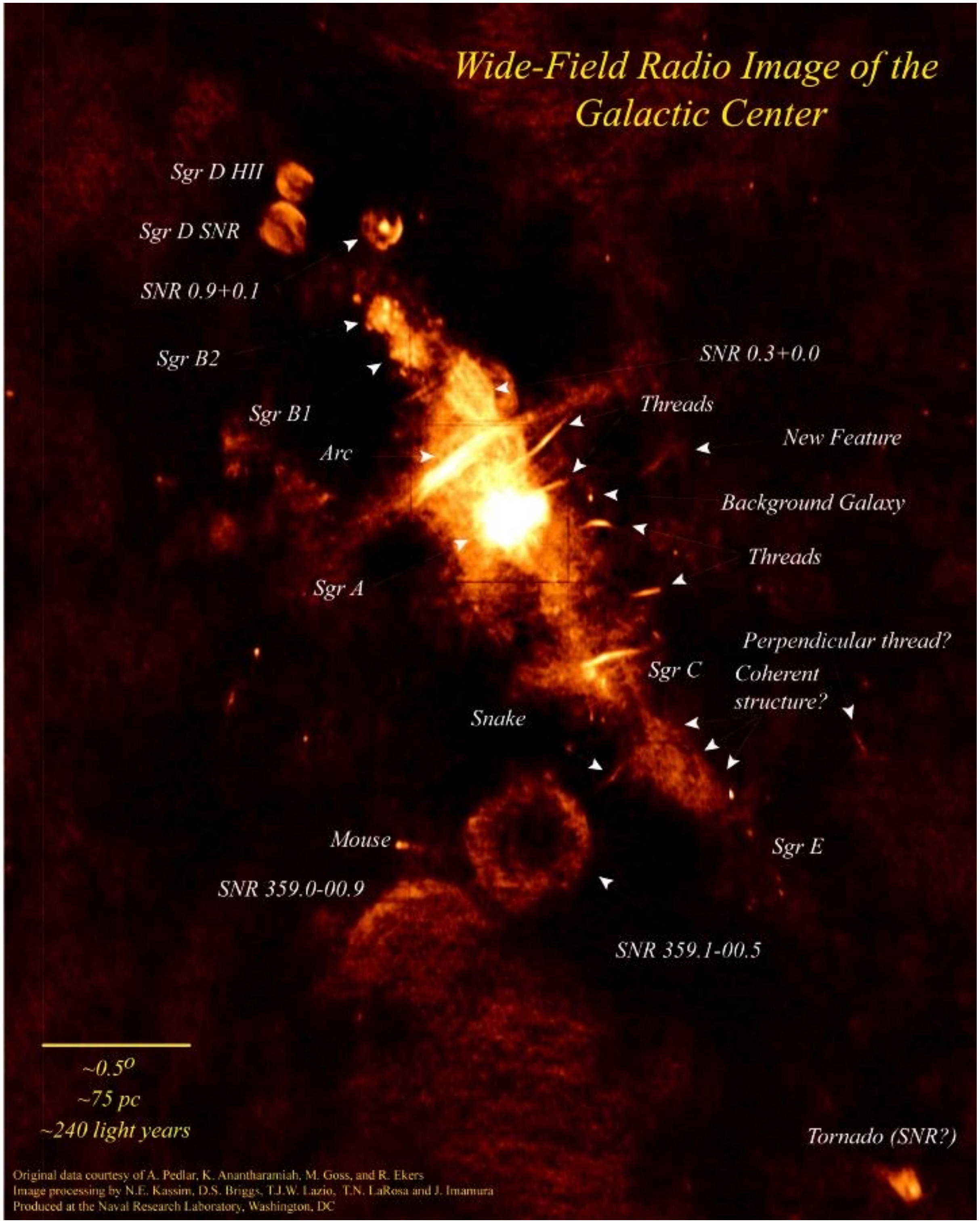



- Some is dim objects (brown dwarfs, white dwarfs, black holes), but not all.

- Some is likely exotic, perhaps neutrinos with mass, and perhaps new types of subatomic particles.

- True nature is not yet known

**The general region of the Galactic center – many SNRs and other moving clouds of gas.**



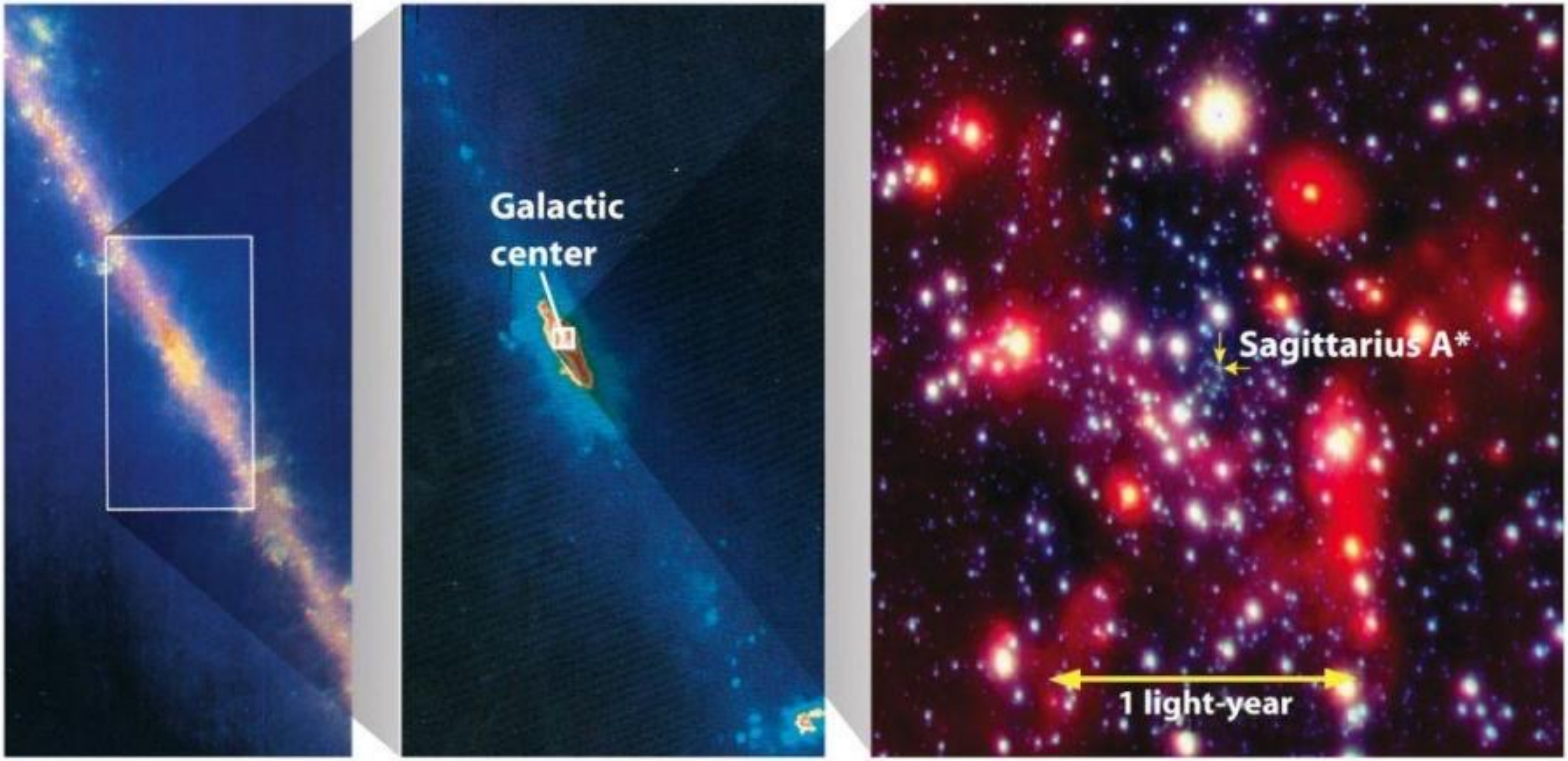
# The Galactic Center

- Strong evidence for a supermassive black hole: high rotation speeds of stars within 1AU of the center.

- The best current mass estimates are that the central "beast" has about 4 million solar masses within the size of the solar system.

$\Rightarrow$ Black hole

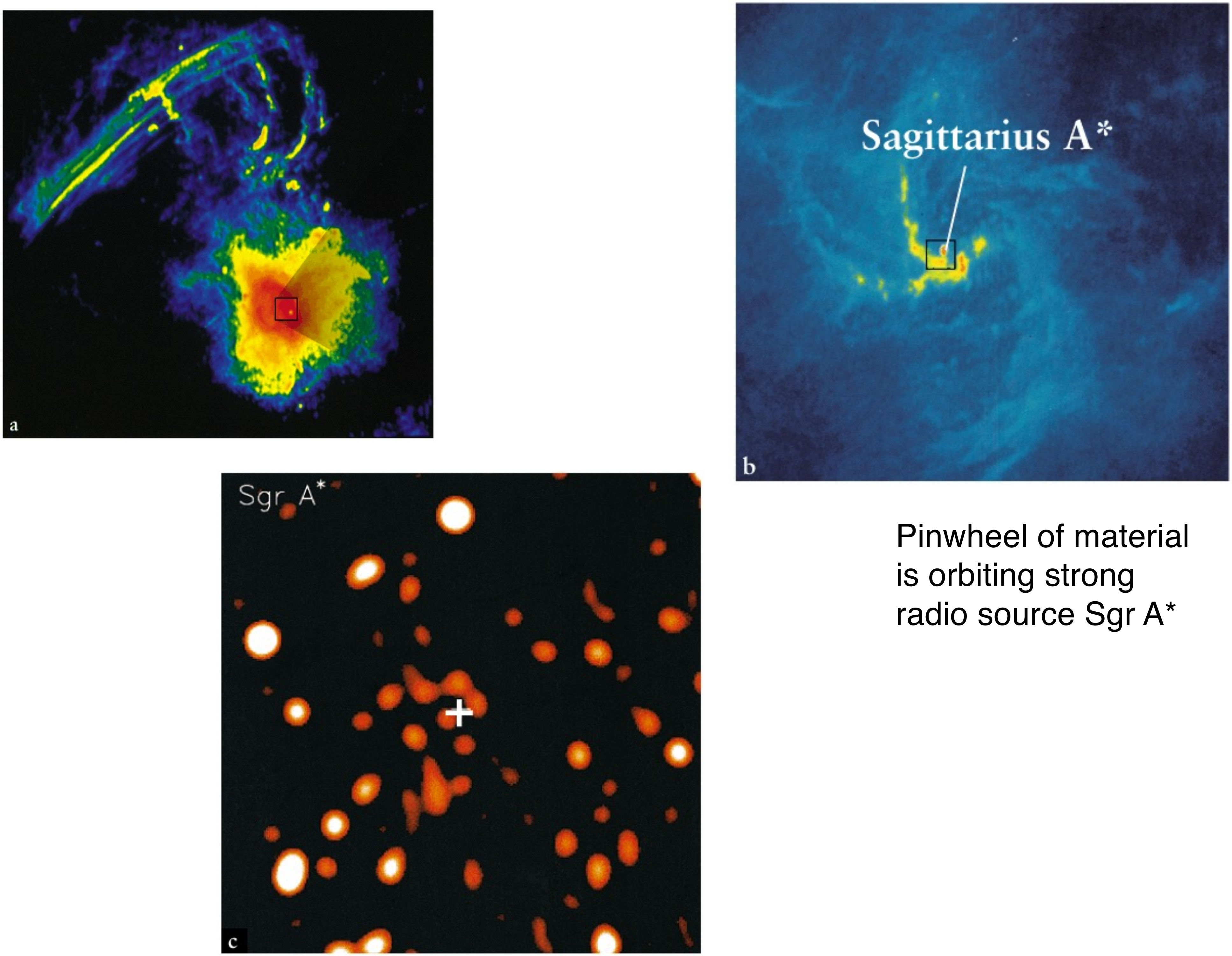
# IR views




**(a)** A wide-angle (50°) infrared view

**(b)** A close-up view shows a more luminous region at the galactic center

**(c)** An extreme close-up view centered on Sagittarius A*, a radio source at the very center of the Milky Way Galaxy, shows hundreds of stars within 1 ly (0.3 pc)

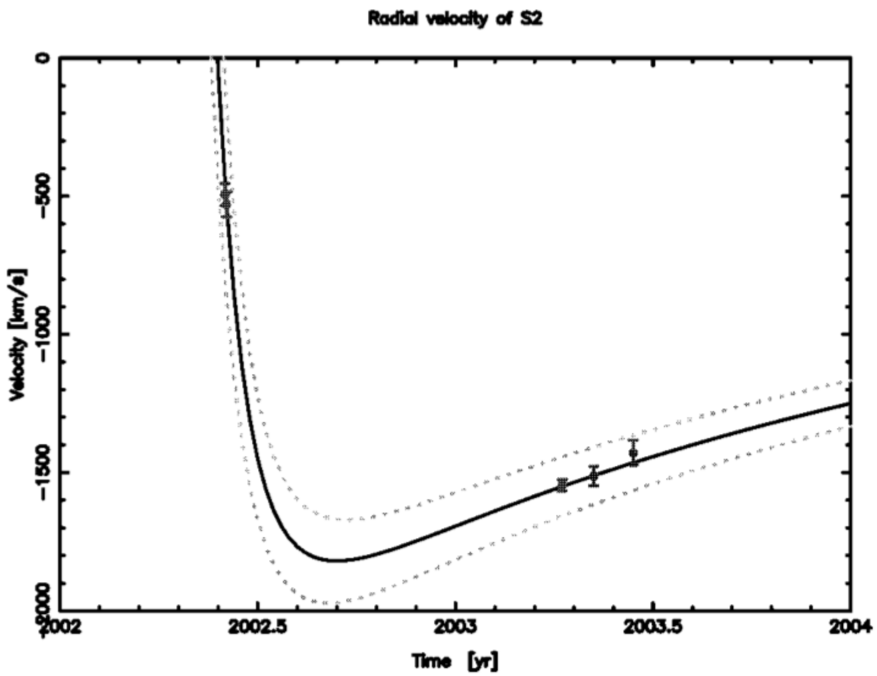


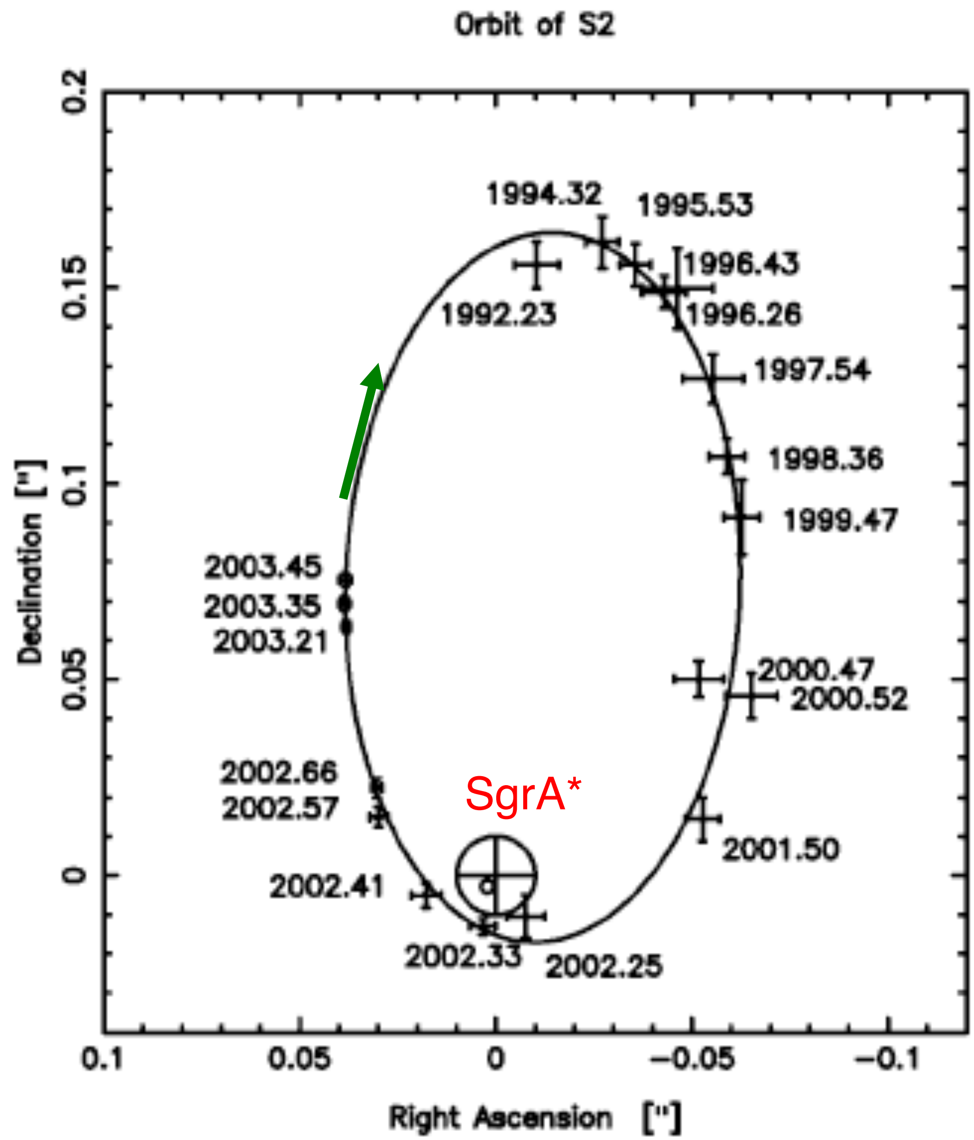

Pinwheel of material is orbiting strong radio source Sgr A*

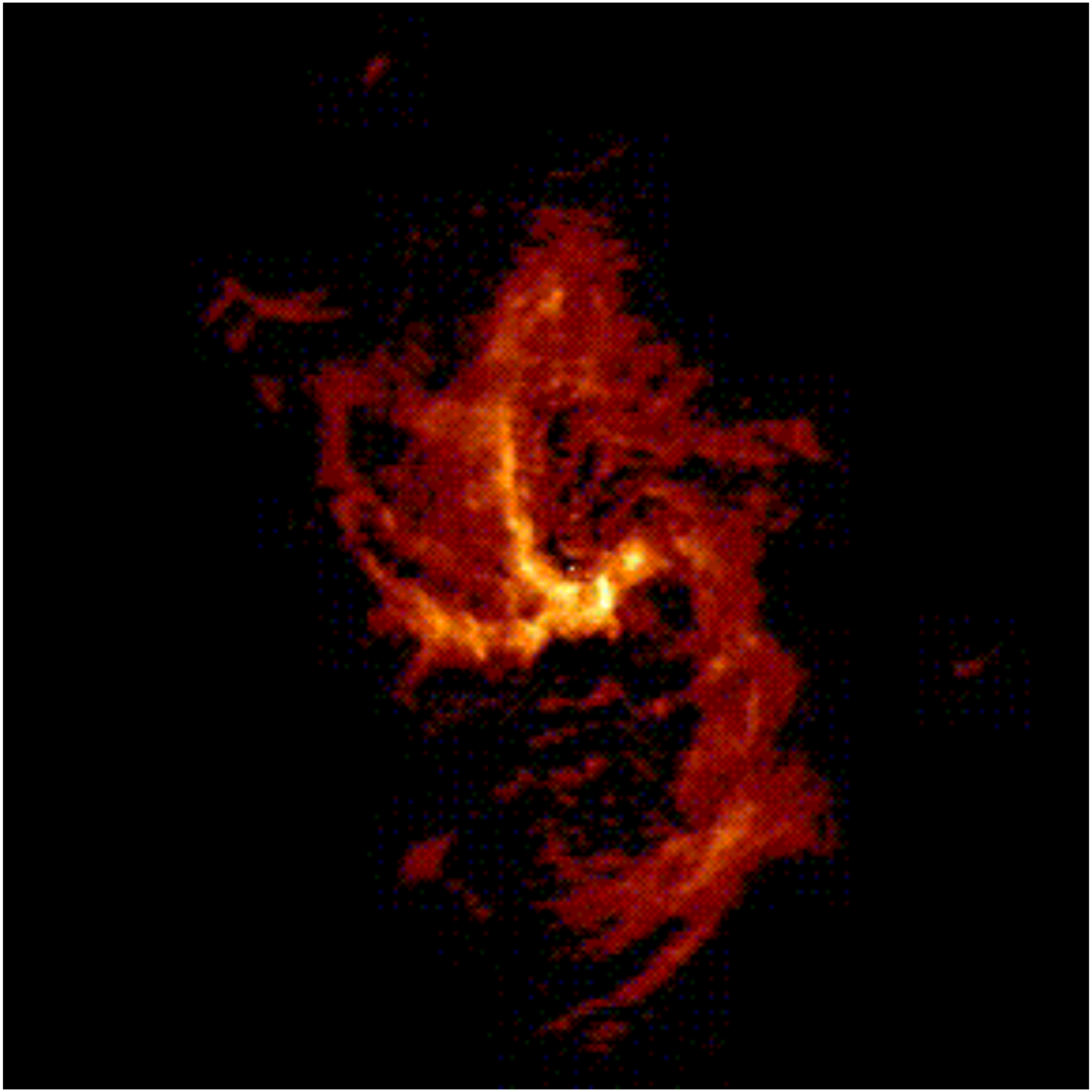
# Precise Distance to Galactic Center

Distance = 7.94 +/- 0.42 kpc

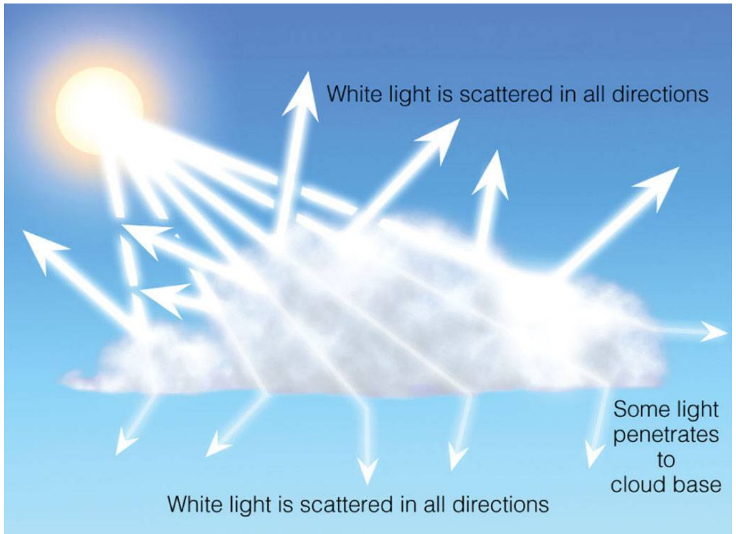
Eisenhauer et al. 2003



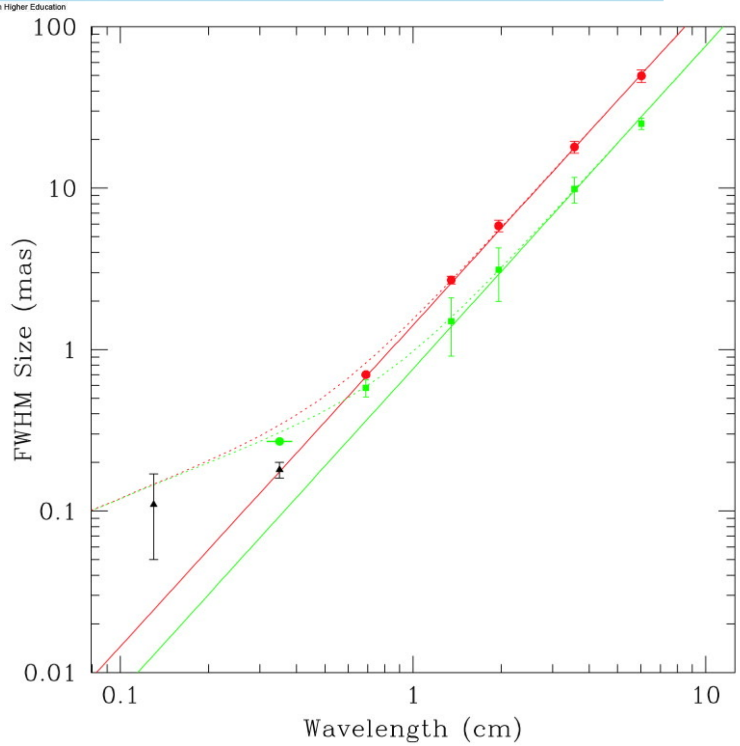



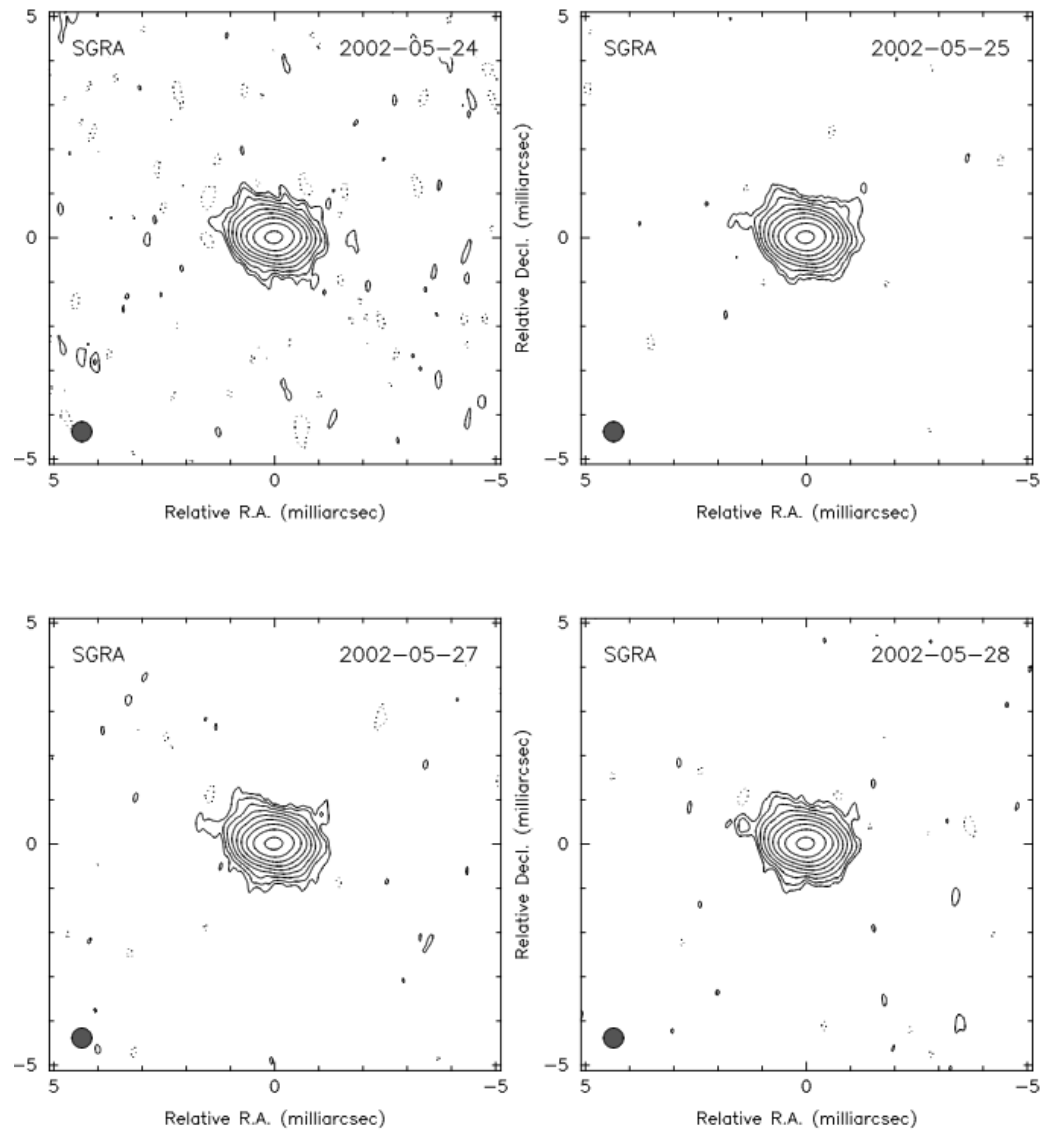


# High Resolution Imaging of the Galactic Center






milliarcsec