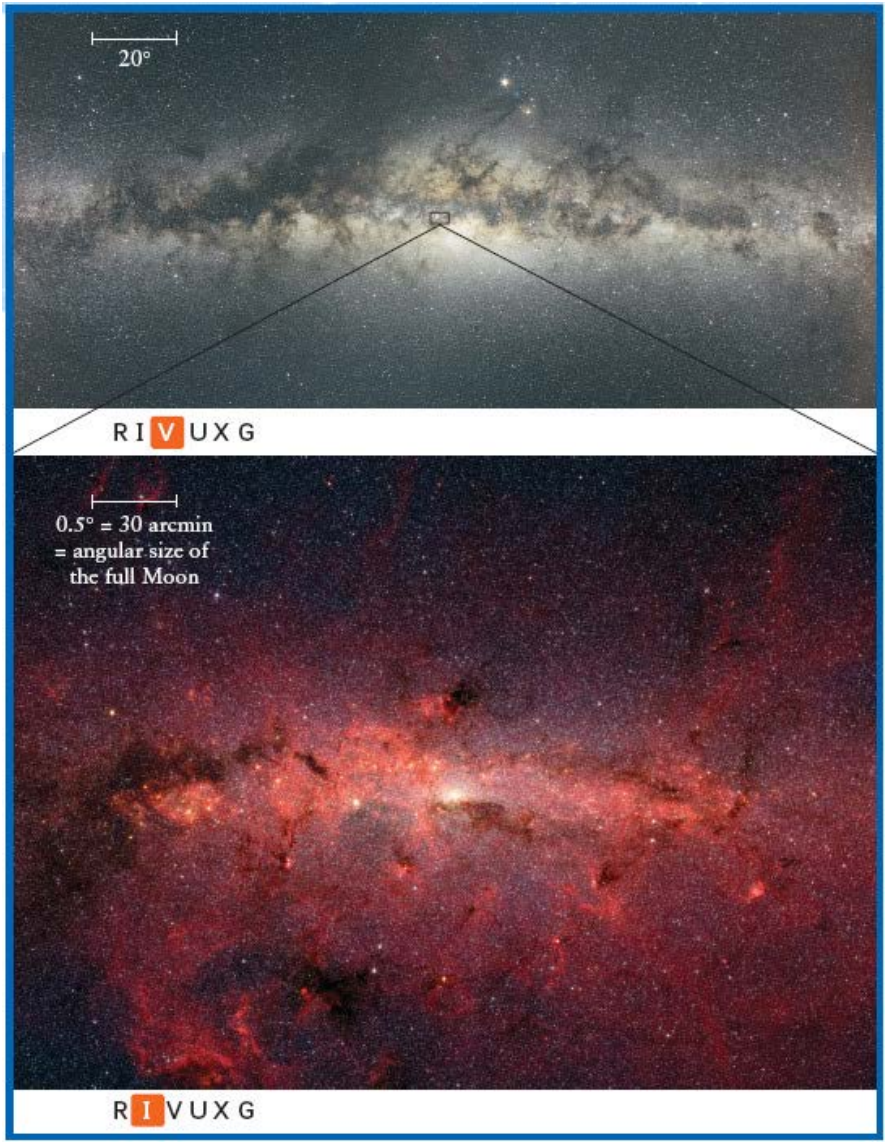
# The Milky Way Galaxy



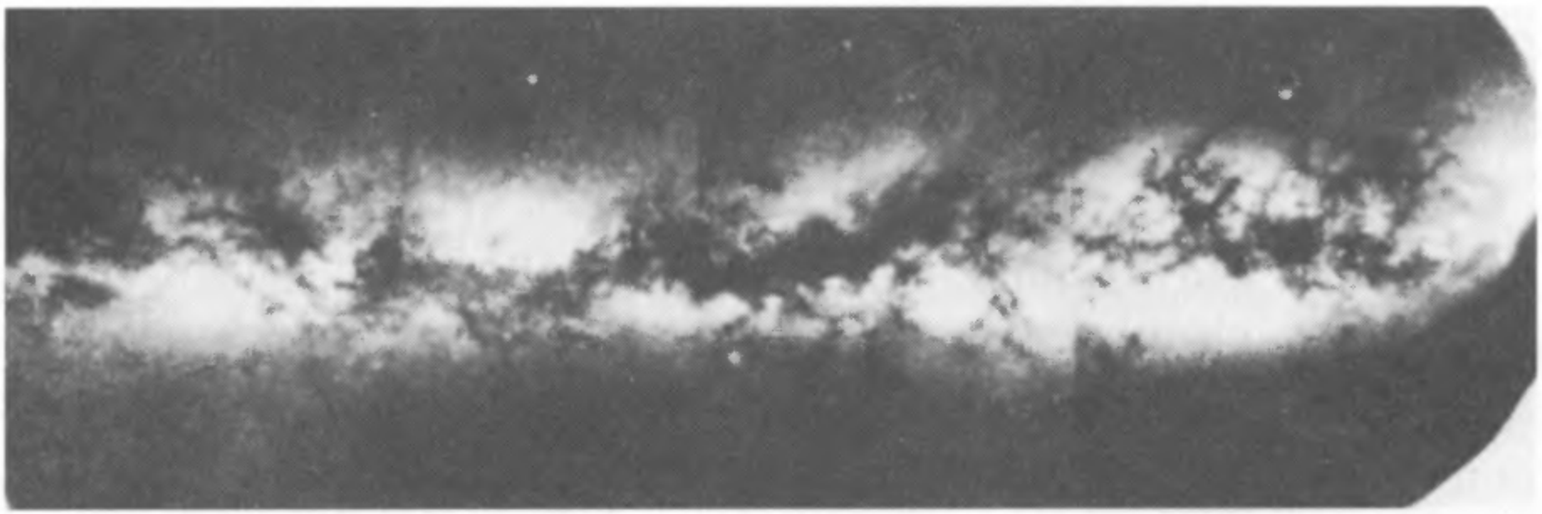
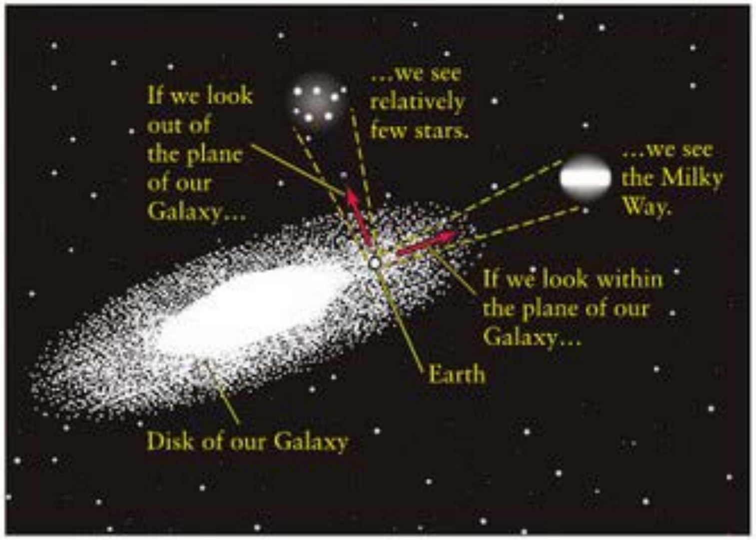
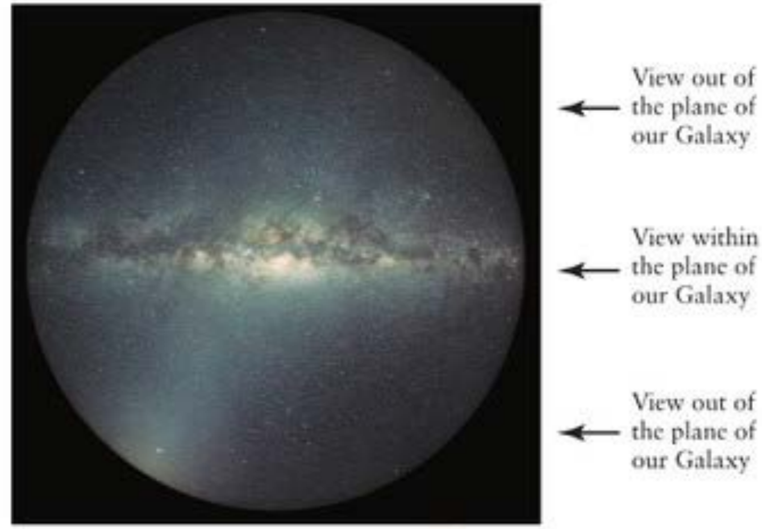


**FIGURE 24.1** A mosaic of the Milky Way showing the presence of dust lanes. (Courtesy of The Observatories of the Carnegie Institution of Washington.)

# Our Galaxy




(a)




(b) R I V U X G

**We are located in the disk of our galaxy** and this is why the disk appears as a band of stars across the sky.

Early attempts to locate our solar system produced erroneous results. The main **problem was that interstellar extinction** allows one to only see the nearby stars and **makes distant objects appear dimmer**.

The key to finding our location in the galaxy is locating bright objects out of the plane of the galaxy. Astronomers use **globular clusters** to locate the position of our solar system with respect to the Galaxy. We are ~ 26,000 ly from the Galaxy center.

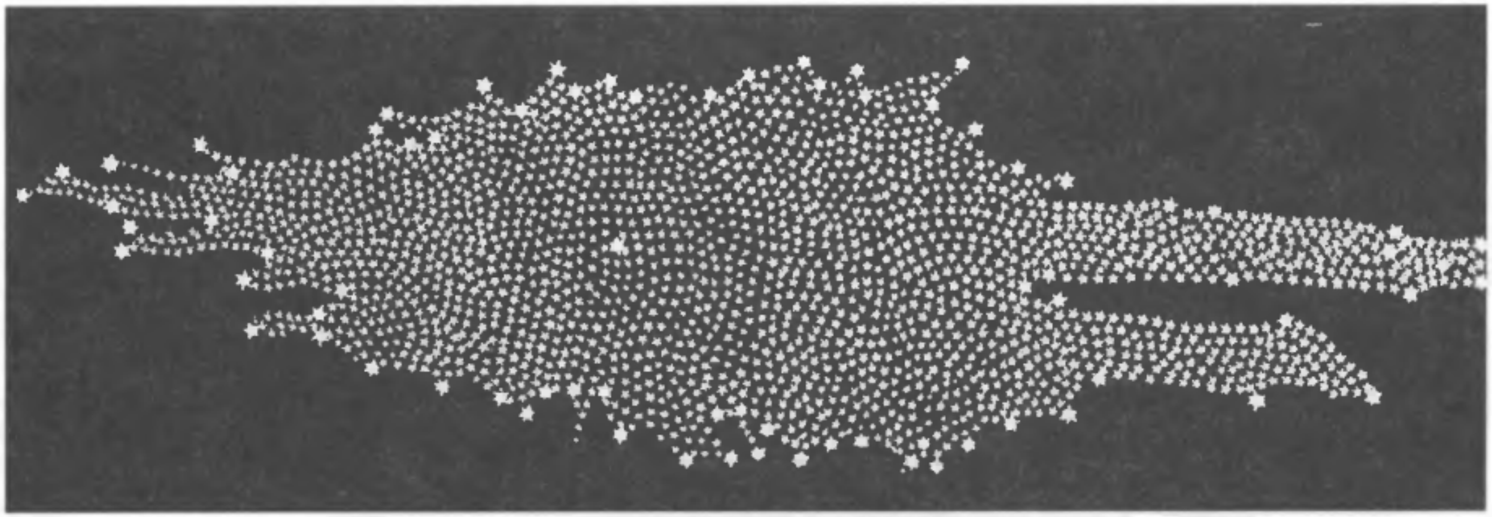


**FIGURE 24.2** William Herschel's map of the Milky Way Galaxy, based on a qualitative analysis of star counts. He believed that the Sun (indicated by a larger star) resided near the center of the stellar system. (Courtesy of Yerkes Observatory.)

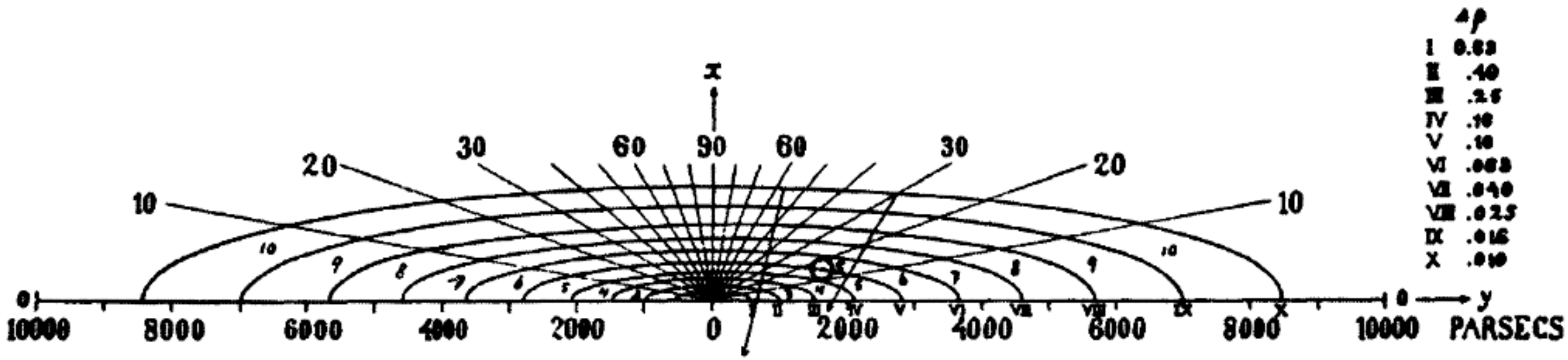
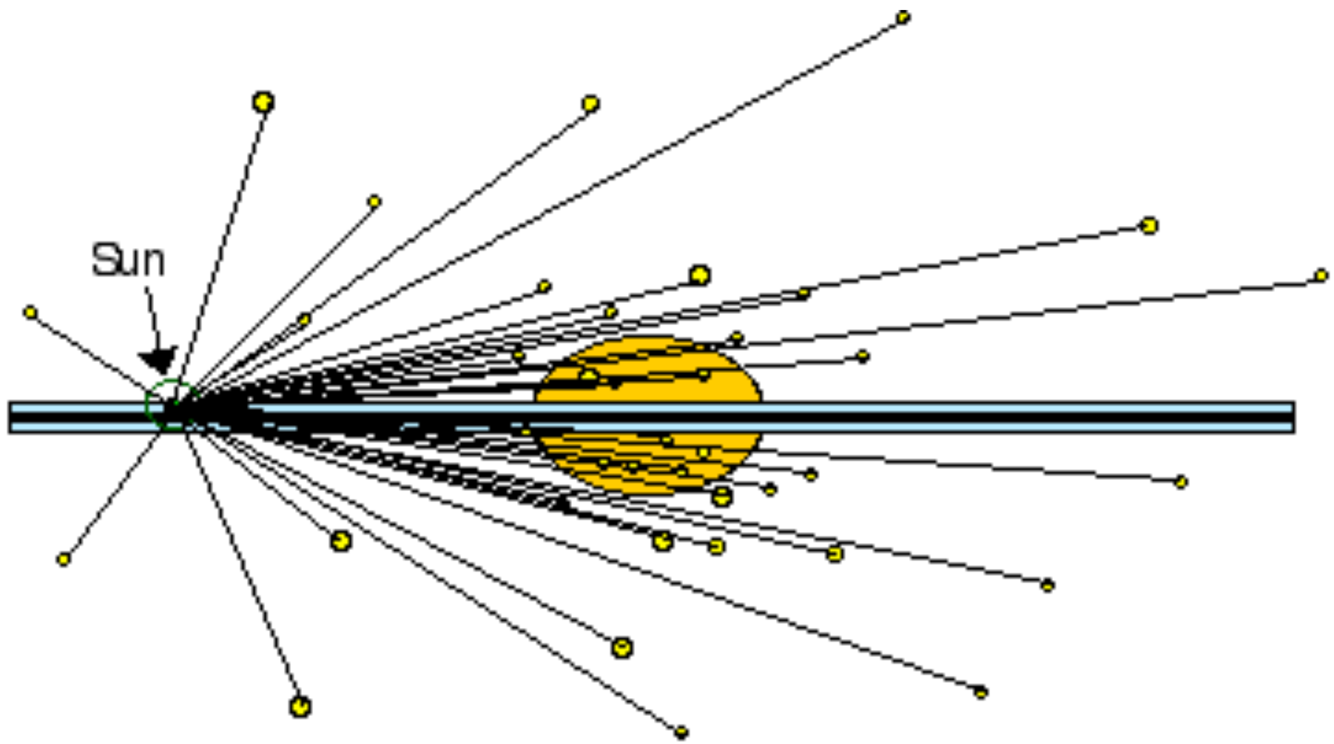



**FIGURE 24.3** The Kapteyn universe. Surfaces of constant stellar number density are indicated around the Galactic center. Note that the open circle does not represent the position of the Sun derived by Kapteyn. Rather, the open circle was used as an estimate from which Kapteyn began his analysis of the available data. (Figure from Kapteyn, *Ap. J.*, *55*, 302, 1922.)




Find the distance and direction to each globular cluster to find the direction to the center of the Galaxy and how far away the center is from us.

# Interstellar Extinction in Our Galaxy

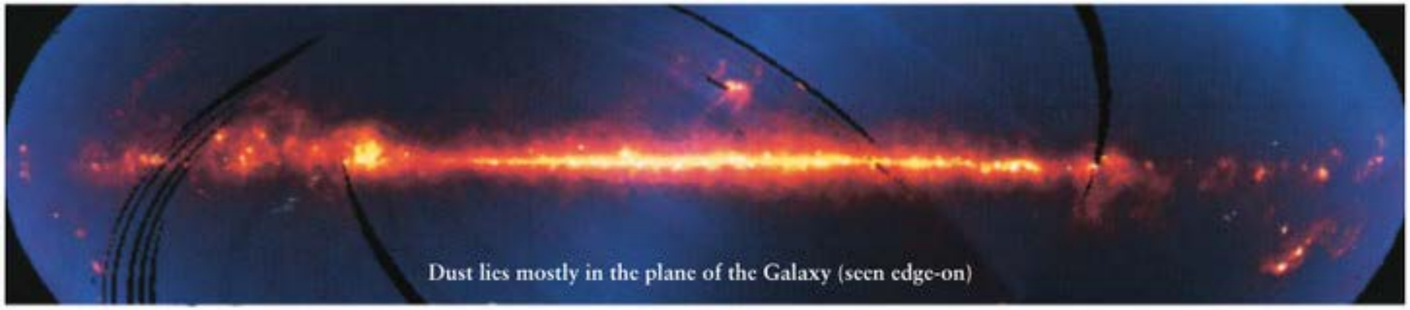
Interstellar extinction is roughly inversely proportional to wavelength. As a result we can see farther into the disk in radio and IR wavelengths than at visible wavelengths.

Starlight warms **dust grains** to temperatures of about 10K - 90K and thus they **emit predominately at far-infrared** wavelengths between 30 μm – 300 μm.

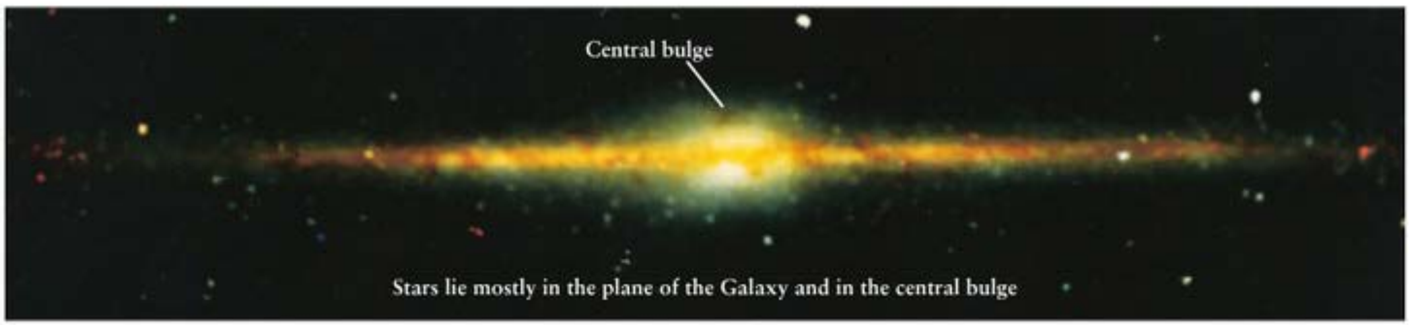
- **Far-infrared** light from our galaxy **traces cold interstellar dust.**

- **Near-infrared** light from our galaxy **traces mostly stars or hot dust**.

# Our Galaxy




(a) Infrared emission from dust at wavelengths of 25, 60, and 100 μm

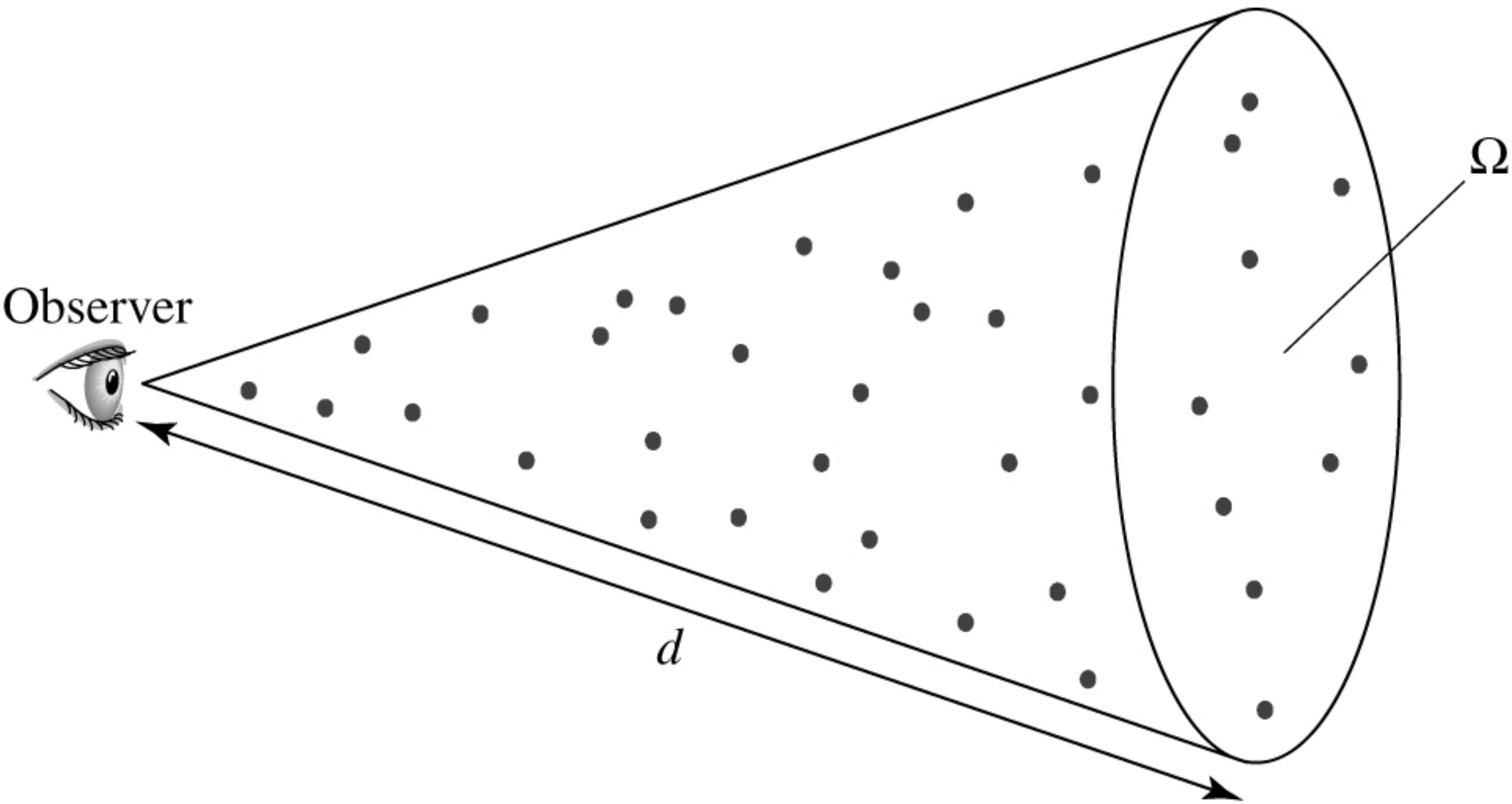



(b) Infrared emission from dust at wavelengths of 1.2, 2.2, and 3.4 μm

**(a)** **Far-infrared image of the Milky Way** taken with the IRAS spacecraft. **Interstellar dust**, which is mostly confined to the plane of the Galaxy, is the principal source of radiation in this wavelength range.

**(b)** **Near-infrared image of the Milky Way** taken with the COBE observatory. We can see farther through interstellar dust by observing in near-infrared wavelengths than at visible ones. Light in the near infrared range comes **mostly from stars** in the plane of the Galaxy and in the bulge at the Galaxy's center.

# Star Counting



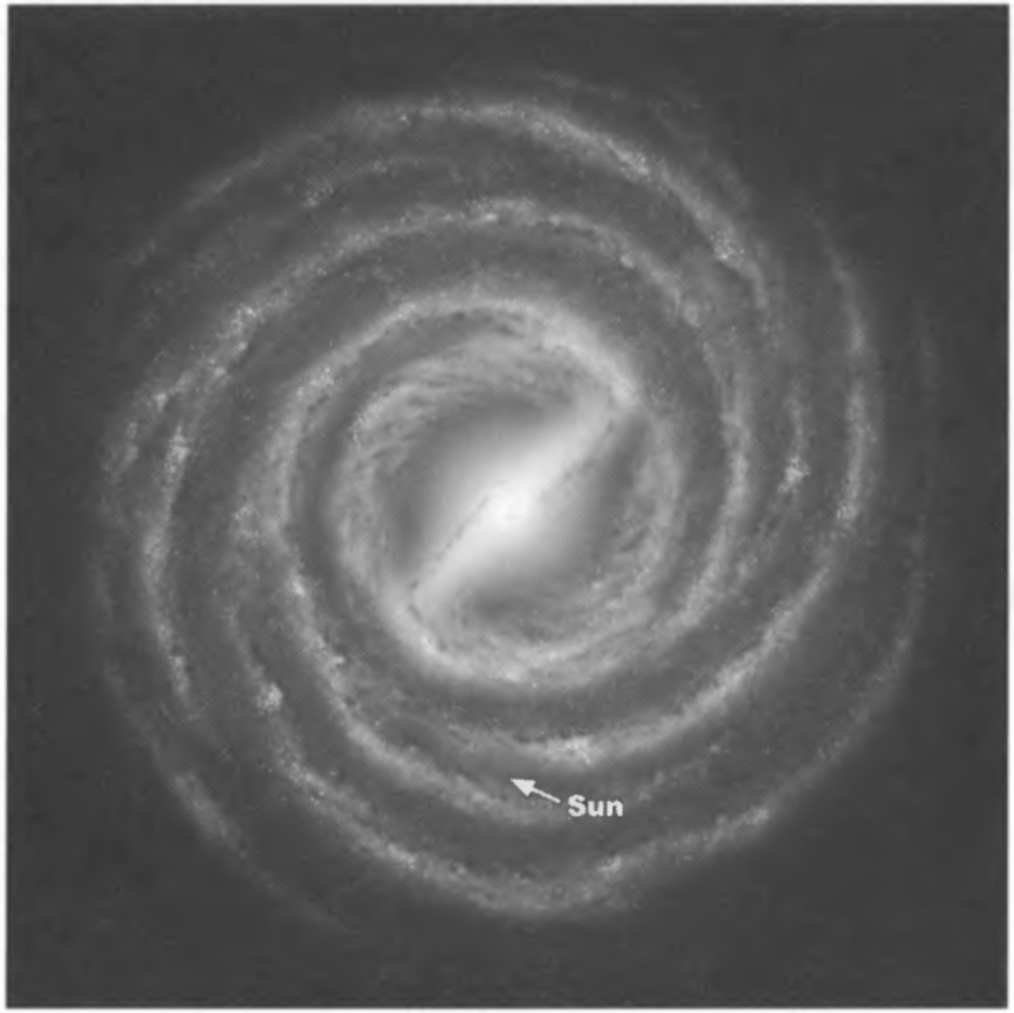



**FIGURE 24.5** An artist's depiction of the Milky Way Galaxy seen face-on. The shapes of the spiral arms and the length of the bar associated with the central bulge are based on currently available data. The position of the Sun is shown. [Courtesy of NASA/JPL-Caltech/R. Hurt (SSC).]

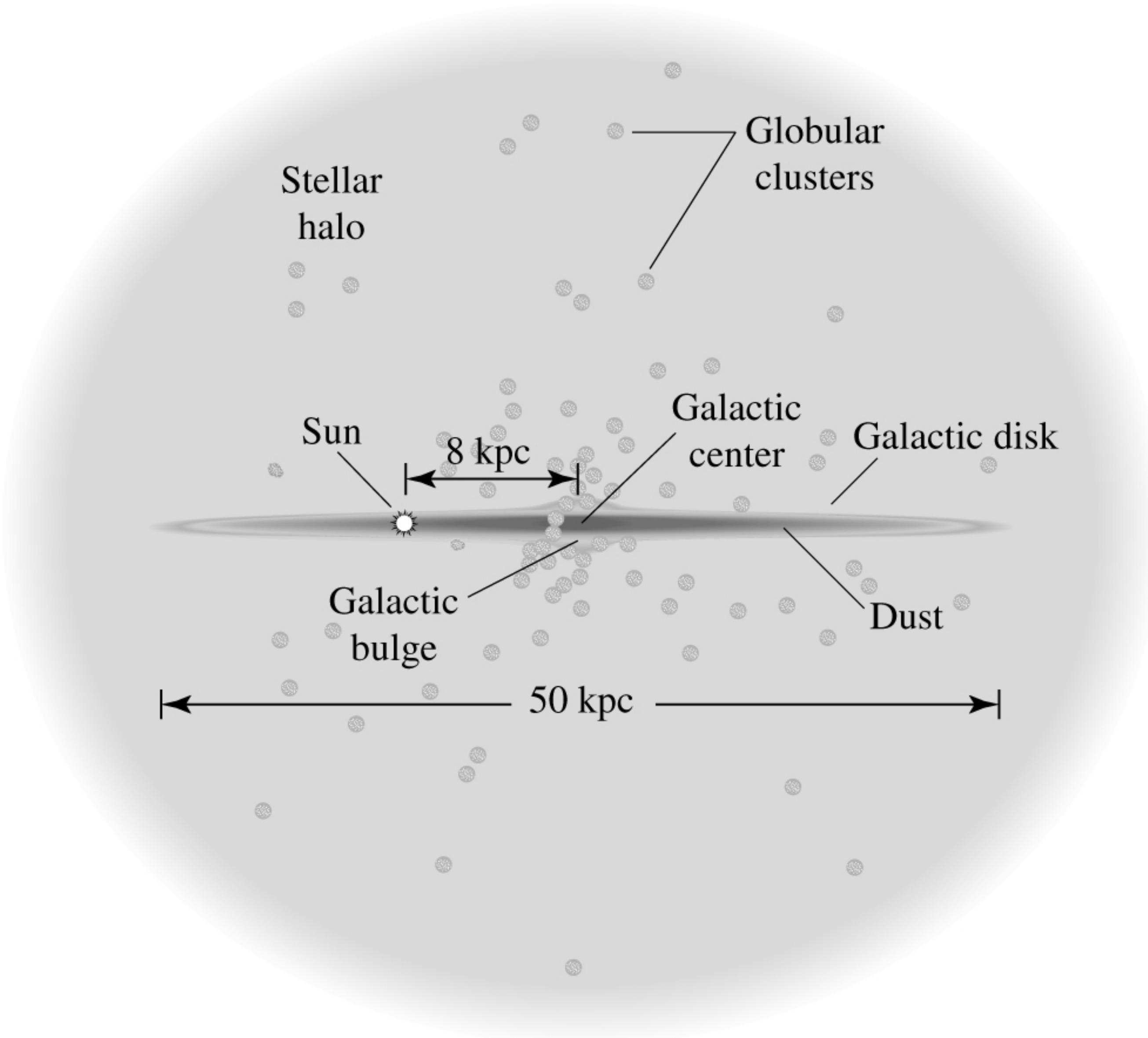

Globular
clusters
Stellar
halo
Sun
8 kpc
Galactic
center
Galactic disk
Galactic
bulge
Dust
50 kpc

**TABLE 24.1** Approximate Values for Various Parameters Associated with the Components of the Milky Way Galaxy. Definitions and details are discussed in the text.

| | **Disks** | | |
|---|---|---|---|
| | Neutral Gas | Thin Disk | Thick Disk |
| $M$ ($10^{10}$ M$_\odot$) | 0.5[a] | 6 | 0.2 to 0.4 |
| $L_B$ ($10^{10}$ L$_\odot$)[b] | — | 1.8 | 0.02 |
| $M/L_B$ (M$_\odot$/L$_\odot$) | — | 3 | — |
| Radius (kpc) | 25 | 25 | 25 |
| Form | $e^{-z/h_z}$ | $e^{-z/h_z}$ | $e^{-z/h_z}$ |
| Scale height (kpc) | $< 0.1$ | 0.35 | 1 |
| $\sigma_w$ (km s$^{-1}$) | 5 | 16 | 35 |
| [Fe/H] | $> +0.1$ | $-0.5$ to $+0.3$ | $-2.2$ to $-0.5$ |
| Age (Gyr) | $\lesssim 10$ | 8[c] | 10[d] |

| | **Spheroids** | | |
|---|---|---|---|
| | Central Bulge[e] | Stellar Halo | Dark-Matter Halo |
| $M$ ($10^{10}$ M$_\odot$) | 1 | 0.3 | $190^{+360}_{-170}$[f] |
| $L_B$ ($10^{10}$ L$_\odot$)[b] | 0.3 | 0.1 | 0 |
| $M/L_B$ (M$_\odot$/L$_\odot$) | 3 | $\sim 1$ | — |
| Radius (kpc) | 4 | $> 100$ | $> 230$ |
| Form | boxy with bar | $r^{-3.5}$ | $(r/a)^{-1}(1+r/a)^{-2}$ |
| Scale height (kpc) | 0.1 to 0.5[g] | 3 | 170 |
| $\sigma_w$ (km s$^{-1}$) | 55 to 130[h] | 95 | — |
| [Fe/H] | $-2$ to 0.5 | $< -5.4$ to $-0.5$ | — |
| Age (Gyr) | $< 0.2$ to 10 | 11 to 13 | $\sim 13.5$ |

[a] $M_{\rm dust}/M_{\rm gas} \simeq 0.007$.

[b] The total luminosity of the Galaxy is $L_{B,\rm tot} = 2.3 \pm 0.6 \times 10^{10}$ L$_\odot$, $L_{\rm bol,tot} = 3.6 \times 10^{10}$ L$_\odot$ ($\sim 30\%$ in IR).

[c] Some open clusters associated with the thin disk may exceed 10 Gyr.

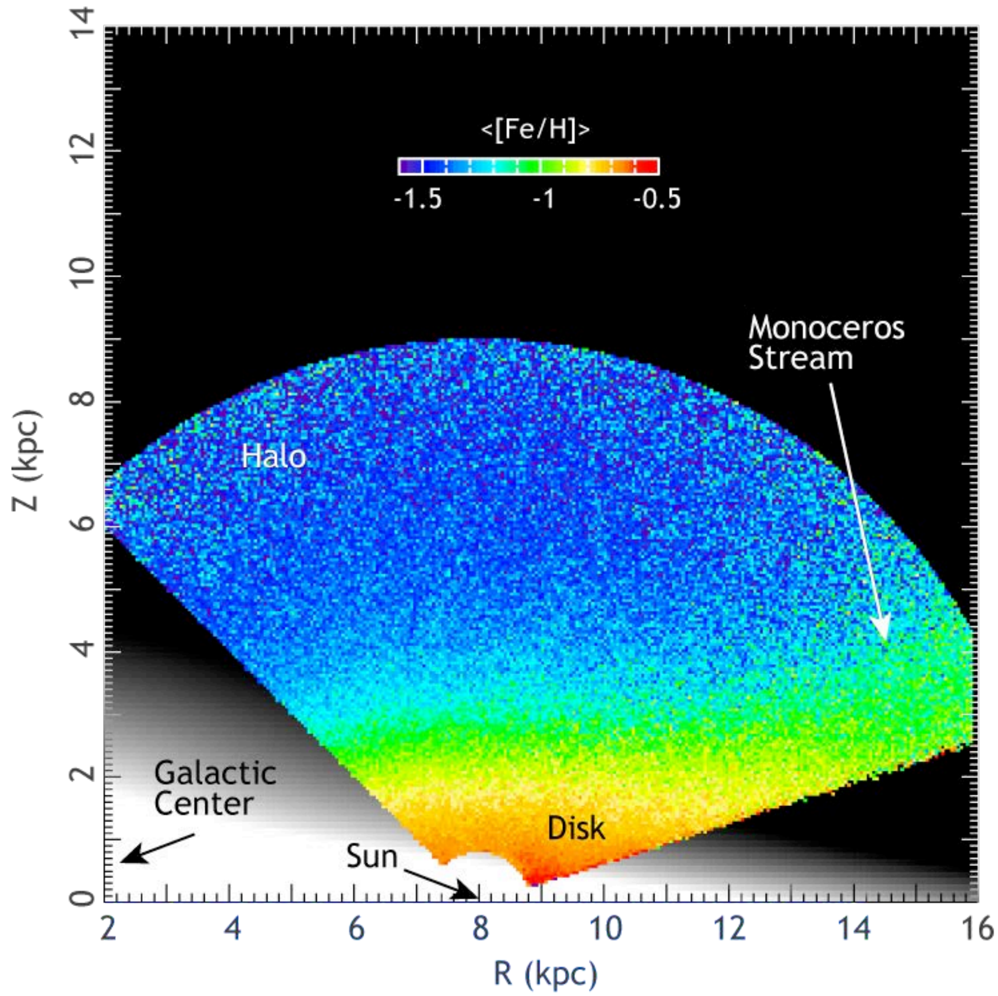
[d] Major star formation in the thick disk may have occurred 7–8 Gyr ago.

[e] The mass of the black hole in Sgr A* is $M_{\rm bh} = 3.7 \pm 0.2 \times 10^6$ M$_\odot$.

[f] $M = 5.4^{+0.2}_{-3.6} \times 10^{11}$ M$_\odot$ within 50 kpc of the center.

[g] Bulge scale heights depend on age of stars: 100 pc for young stars, 500 pc for old stars.

[h] Dispersions increase from 55 km s$^{-1}$ at 5 pc to 130 km s$^{-1}$ at 200 pc.




A detailed map of the chemical composition of Milky Way stars. Such maps allow astronomers to decipher how our galaxy, the Milky Way, formed and how it evolved over the 13 billion years since its formation (Zeljko Ivezic + SDSS team).

# Mass-to-Light Ratio

- An object's mass-to-light ratio (M/L) is its total mass in solar mass units divided by its visible luminosity in units of solar luminosity.

$$\left(\frac{M}{L}\right)_{Milky\,Way} = \frac{9\times10^{10}M_{\odot}}{15\times10^{9}L_{\odot}} = 6\,\frac{M_{\odot}}{L_{\odot}}$$

Most of the mass in our galaxy is dimmer per unit mass than the Sun

A galaxy with a large M/L ratio may imply the presence of a significant amount of dark matter

Mass-to-Light ratio of the thin disk based on the information in Table 24.1

**TABLE 24.1** Approximate Values for Various Parameters Associated with the Components of the Milky Way Galaxy. Definitions and details are discussed in the text.

| | Disks | | |
|---|---|---|---|
| | Neutral Gas | Thin Disk | Thick Disk |
| $M$ ($10^{10}$ $M_\odot$) | 0.5[a] | 6 | 0.2 to 0.4 |
| $L_B$ ($10^{10}$ $L_\odot$)[b] | — | 1.8 | 0.02 |
| $M/L_B$ ($M_\odot/L_\odot$) | — | 3 | — |
| Radius (kpc) | 25 | 25 | 25 |
| Form | $e^{-z/h_z}$ | $e^{-z/h_z}$ | $e^{-z/h_z}$ |
| Scale height (kpc) | $< 0.1$ | 0.35 | 1 |
| $\sigma_w$ (km s$^{-1}$) | 5 | 16 | 35 |
| [Fe/H] | $> +0.1$ | $-0.5$ to $+0.3$ | $-2.2$ to $-0.5$ |
| Age (Gyr) | $\lesssim 10$ | 8[c] | 10[d] |

$$\left(\frac{M}{L}\right)_{thin\ disk} = \frac{M_* + M_{gas}}{L_B} = \frac{6\times10^{10} M_\odot + 0.5\times10^{10} M_\odot}{1.8\times10^{10} L_\odot} = 3.6 \frac{M_\odot}{L_\odot}$$

# Luminosity-Mass Relation For Main Sequence Stars

$$L \propto M^{\alpha}$$

Where

$\alpha \sim 4$ for $M > 0.5M_{\odot}$

$\alpha \sim 2.3$ for $M < 0.5M_{\odot}$

$$\frac{L}{L_{\odot}} = \left(\frac{M}{M_{\odot}}\right)^{\alpha}$$

Estimate the mass of a thin disk star using the above L-M relation

and $$\left(\frac{M}{L}\right)_{thin\,disk} = 3.6\,\frac{M_{\odot}}{L_{\odot}}$$

## Luminosity-Mass Relation For Main Sequence Stars

$$L \propto M^{\alpha}$$

Where

$\alpha \sim 4$ for $M > 0.5M_{\odot}$

$\alpha \sim 2.3$ for $M < 0.5M_{\odot}$

$$\frac{L}{L_{\odot}} = \left(\frac{M}{M_{\odot}}\right)^{\alpha}$$

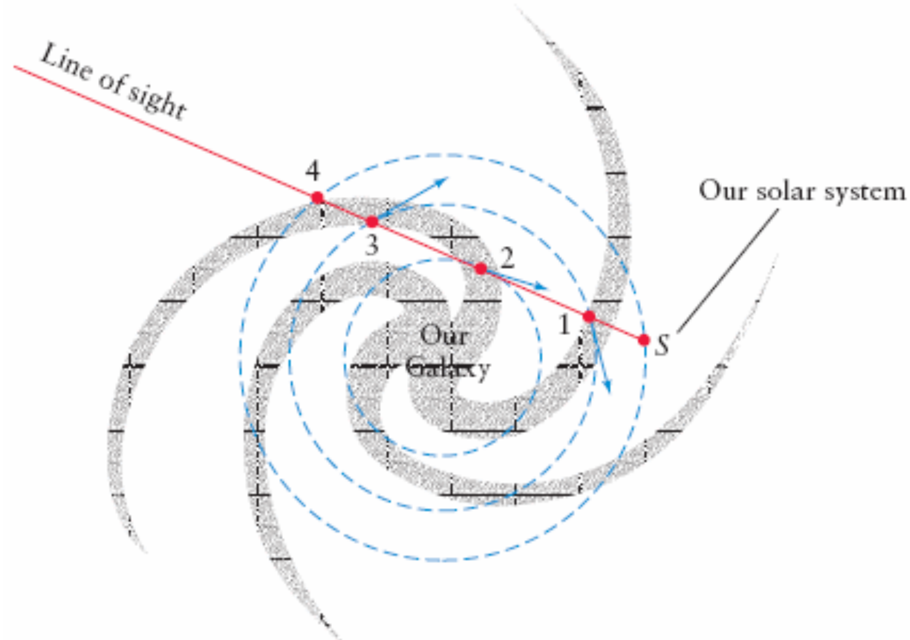
Estimate the mass of a thin disk star:

$$\left(\frac{M}{L}\right)_{thin\ disk} = 3.6\frac{M_{\odot}}{L_{\odot}} \rightarrow \left(\frac{M}{M_{\odot}}\right) = 3.6\frac{L}{L_{\odot}} \rightarrow \left(\frac{M}{M_{\odot}}\right) = 3.6\left(\frac{M}{M_{\odot}}\right)^{\alpha}$$

$$\rightarrow \left(\frac{M}{M_{\odot}}\right)^{1-\alpha} = 3.6 \rightarrow \left(\frac{M}{M_{\odot}}\right) = 3.6^{\frac{1}{1-\alpha}} \rightarrow \left(\frac{M}{M_{\odot}}\right) \sim 0.7$$

# Mapping our Galaxy in Radio Wavelengths

The spirals of our galaxy were mapped out using Doppler shift measurements of the 21 cm emission originating from neutral H in the spiral arms.

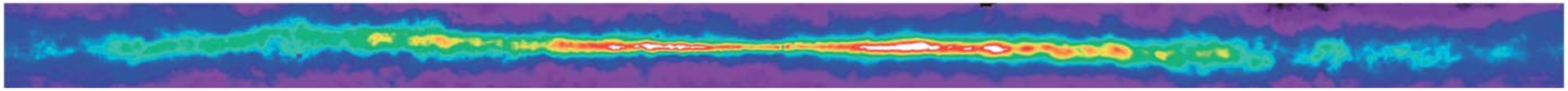



- Hydrogen clouds 1 and 3 are approaching us: They have a moderate blueshift.
- Hydrogen cloud 2 is approaching us at a faster speed: It has a larger blueshift.
- Hydrogen cloud 4 is neither approaching nor receding: It has no redshift or blueshift.

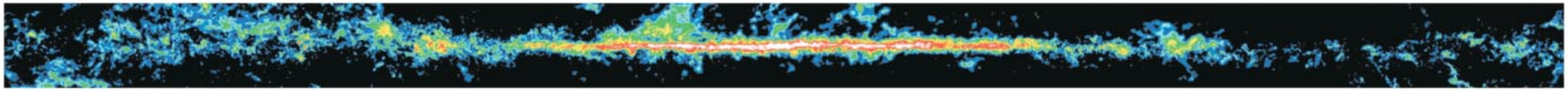
**FIGURE 24.9** NGC 891, seen edge-on, clearly shows a thin dust band in the plane of the disk. The Milky Way Galaxy probably appears much like NGC 891 when viewed from a distant vantage point. (From Sandage and Bedke, *The Carnegie Atlas of Galaxies*, The Carnegie Institution of Washington, Washington, D.C., 1994.)

# Methods of Mapping Gas and Dust in our Galaxy

1. Mapping the effects of extinction caused by gas and dust
2. Mapping the **atomic HI** using the 21 cm line emitted by atomic hydrogen
3. Mapping out CO ( **molecular $H_2$** tracer) in radio



**Radio (21 cm) (atomic hydrogen)**



Radio (CO)

# Methods of Mapping Gas and Dust in our Galaxy

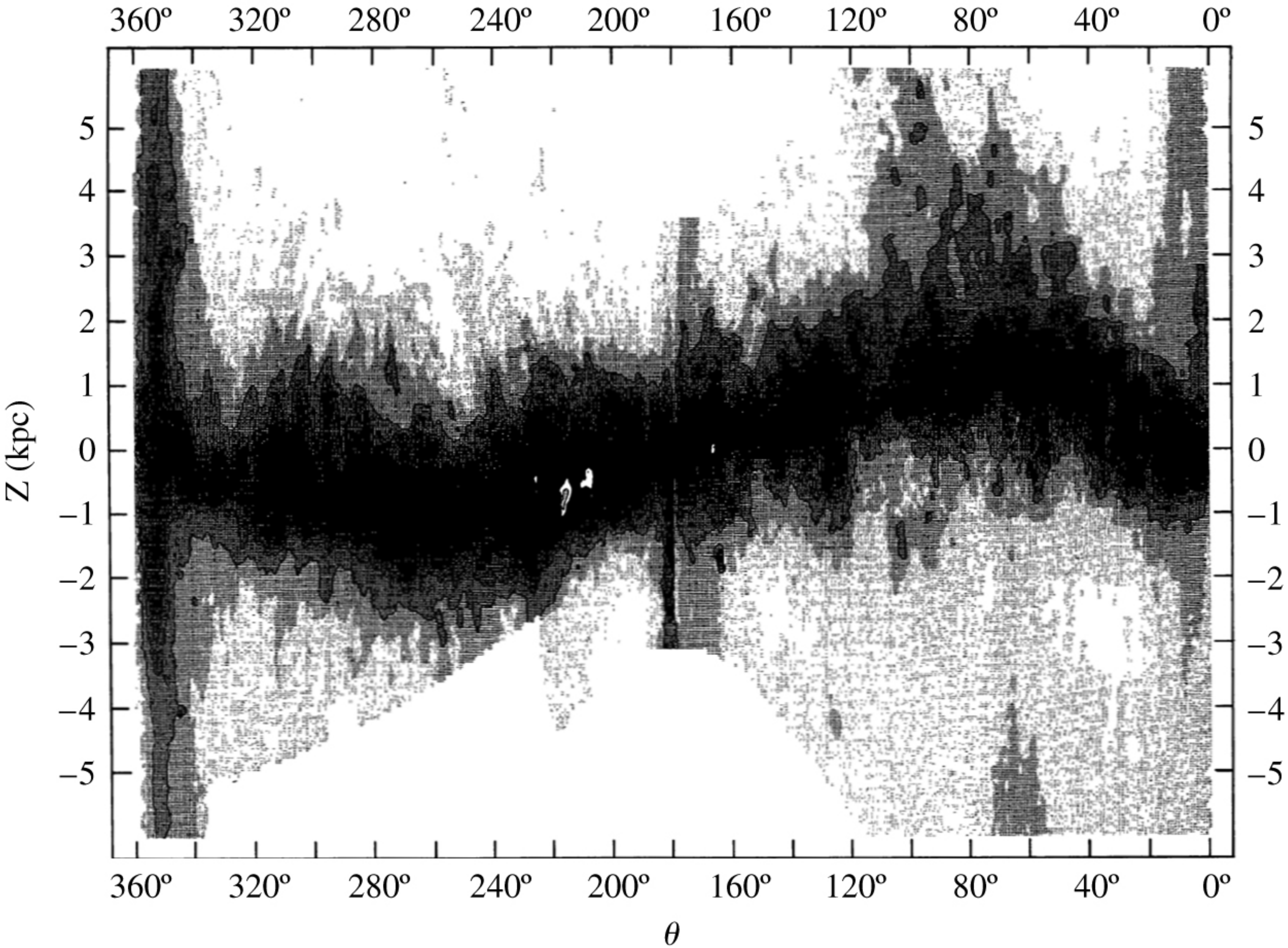
Most of the **molecular $H_2$** and dust are relatively near the Galactic Center (up to 8 kpc).

**Atomic HI** can be found all the way to the edge of the disk (R ~ 25 kpc)

The **scale height of the atomic HI** in the disk beyond ~ 12kpc increases dramatically reaching a value of about 900 pc.

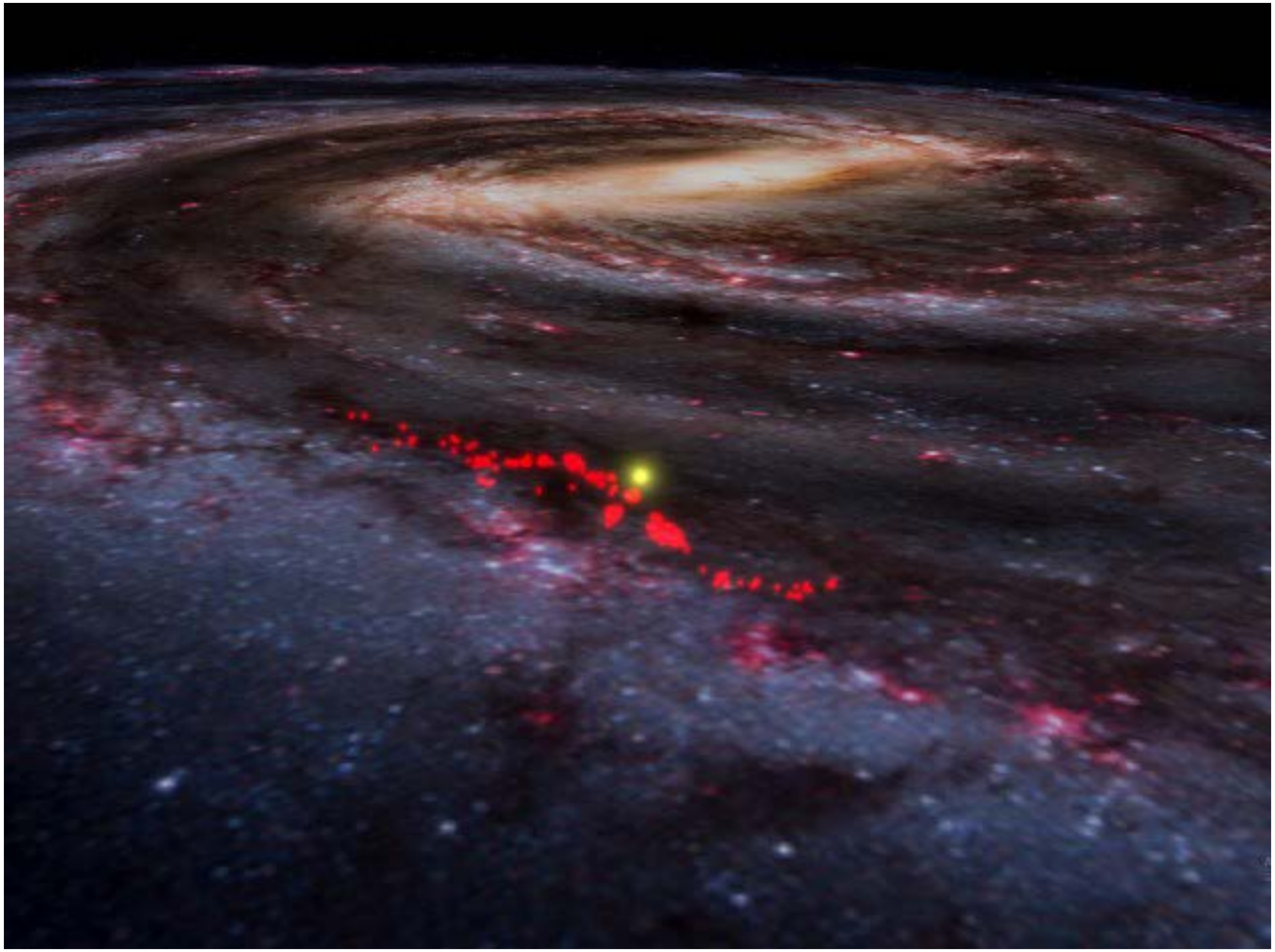
The distribution of atomic HI at large distances from the center exhibits a **warp.**

The distribution of Atomic HI at large distance exhibits a warp.

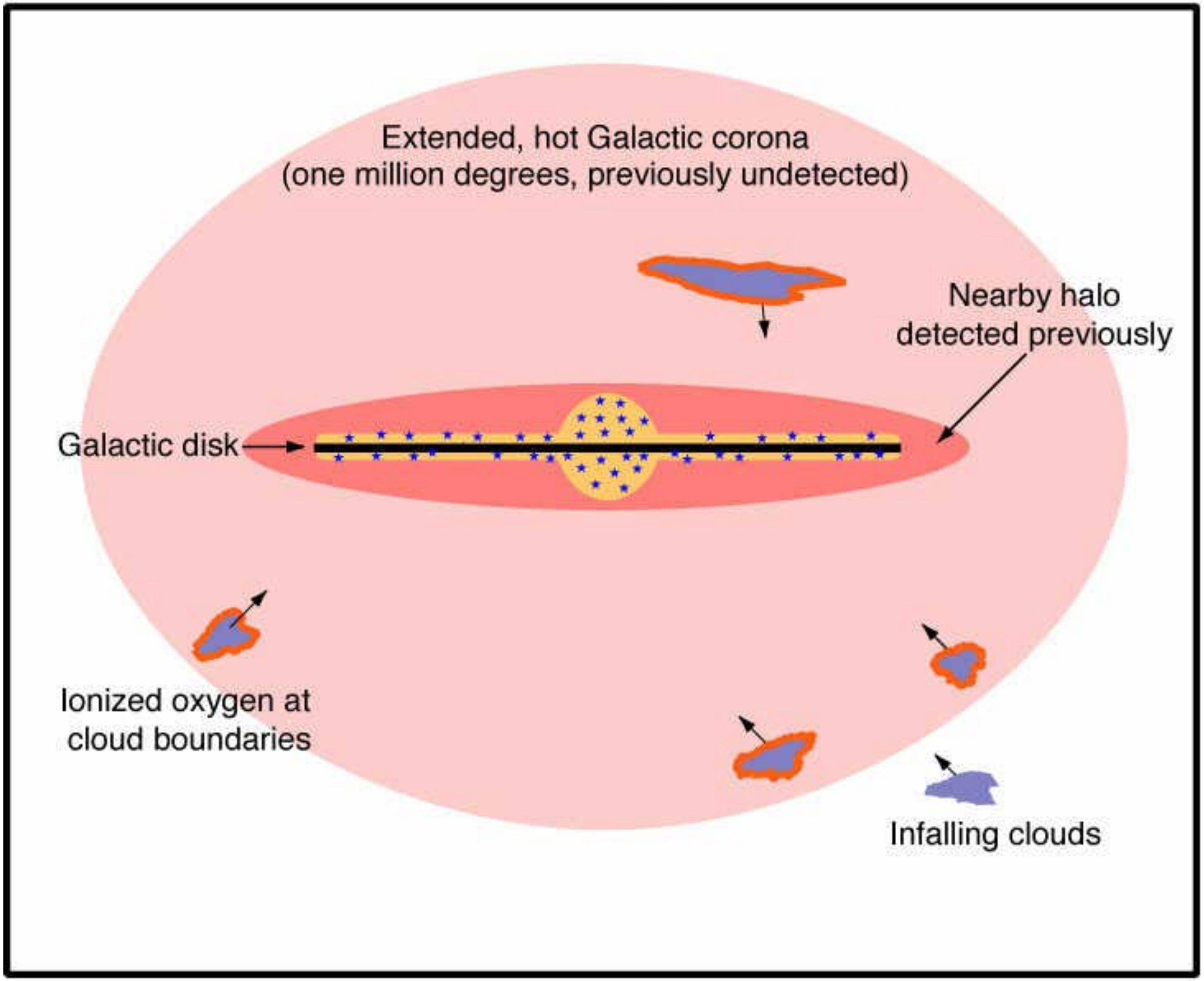



HI distribution map at a Galactic radius of 13.6 kpc

# An Interstellar Ribbon of Clouds in the Sun's Backyard

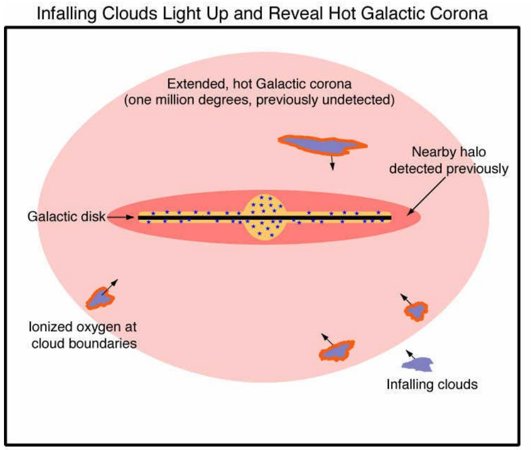


# Infalling Clouds Light Up and Reveal Hot Galactic Corona




This illustration shows clouds falling onto our galaxy, the Milky Way. These clouds "light up" in ionized oxygen when they encounter the hot, extended corona of gas that surrounds the Milky Way.

# Properties of Hot Galactic Coronal Gas



This illustration shows clouds falling onto our galaxy, the Milky Way. These clouds "light up" in ionized oxygen when they encounter the hot, extended corona of gas that surrounds the Milky Way.

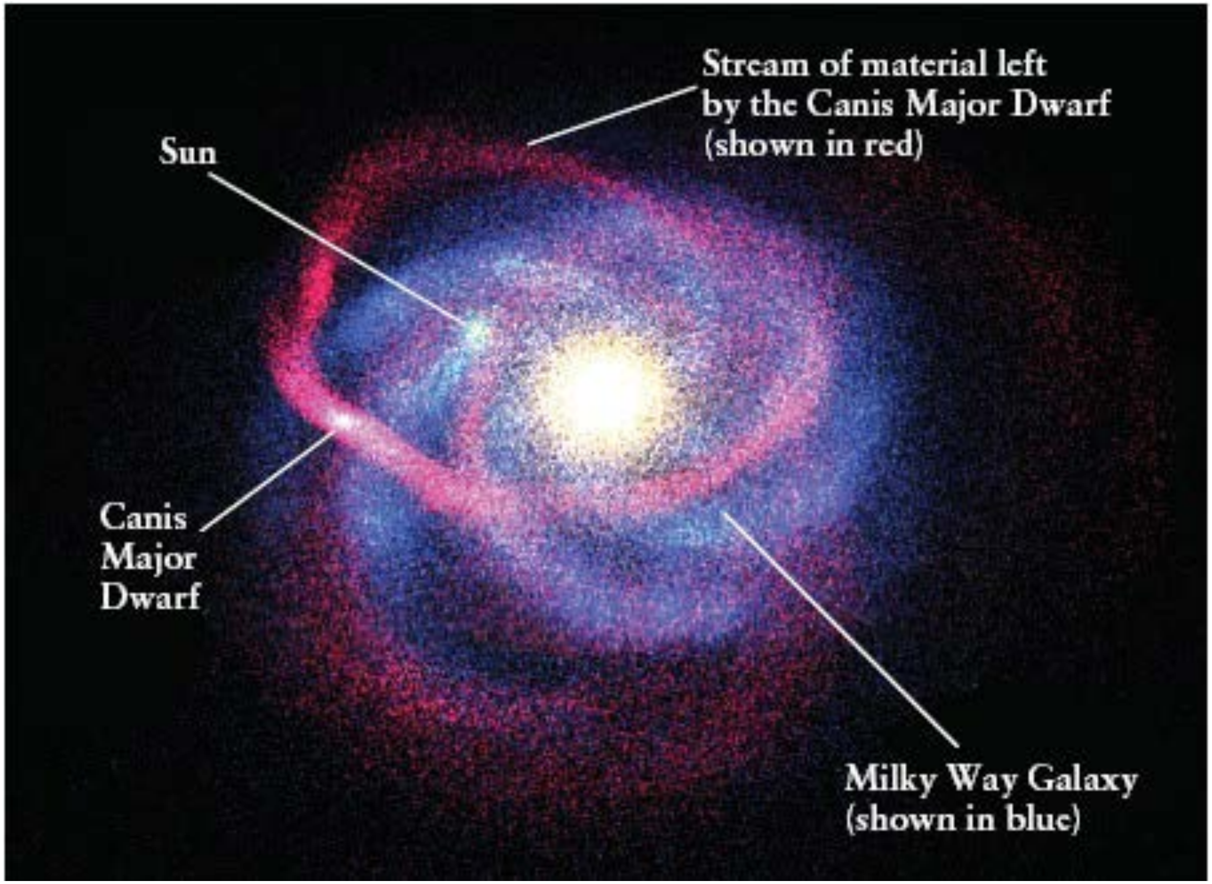
T ~ $10^6$ K
R ~ 70 kpc
Scale Height ~ 3 kpc
Density $n_H \sim 10^2 - 10^3$ m$^{-3}$

Detection made via OVI absorption lines in the spectra of distance extragalactic objects.

## Estimate Mass of Hot Coronal Gas

$M_C = n_H m_H V = n_H m_H 2z\pi R^2 =$
$=(10^2\ m^{-3})(1.67\times 10^{-27} kg)(6\times10^3\times3.086\times10^{16}\text{m})\pi(70\times10^3\times3.086\times10^{16}\text{m})^2=$
$M_C = 2.3\times10^8 M_\odot$

# Tidal Forces on Canis Major from Milky Way




Material from Canis Major Dwarf is being pulled away from it by tidal forces from our Galaxy.

# Galactic Bulge

A near spherical distribution of stars and gas is found around the center of the Galaxy.

$$M_{Bulge} \sim 10^{10} M_{\odot}$$
$$L_{Bulge} \sim 3 \times 10^{9} L_{\odot}$$

The surface brightness of the bulge I(r) measured in $L_{\odot}$pc$^{-2}$

$\log_{10}\left[\frac{I(r)}{I_e}\right] = -3.3307\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right]$ or it can be written as:

$$I(r) = I_e e^{-7669\left[\left(\frac{r}{r_e}\right)^{1/4} - 1\right]}$$

De Vaucouleurs Profile

# Galactic Bulge

Properties of Galactic Bulge

Three distinct age groups of stars

- Young stars ($t < 200$ Myr)
- Intermediate age 200 Myr $< t <$ 7 Gyr
- Old $t >$ 7 Gyr

- $M_{Bulge} \sim 10^{10} M_{\odot}$
- Radius ~ 4 kpc

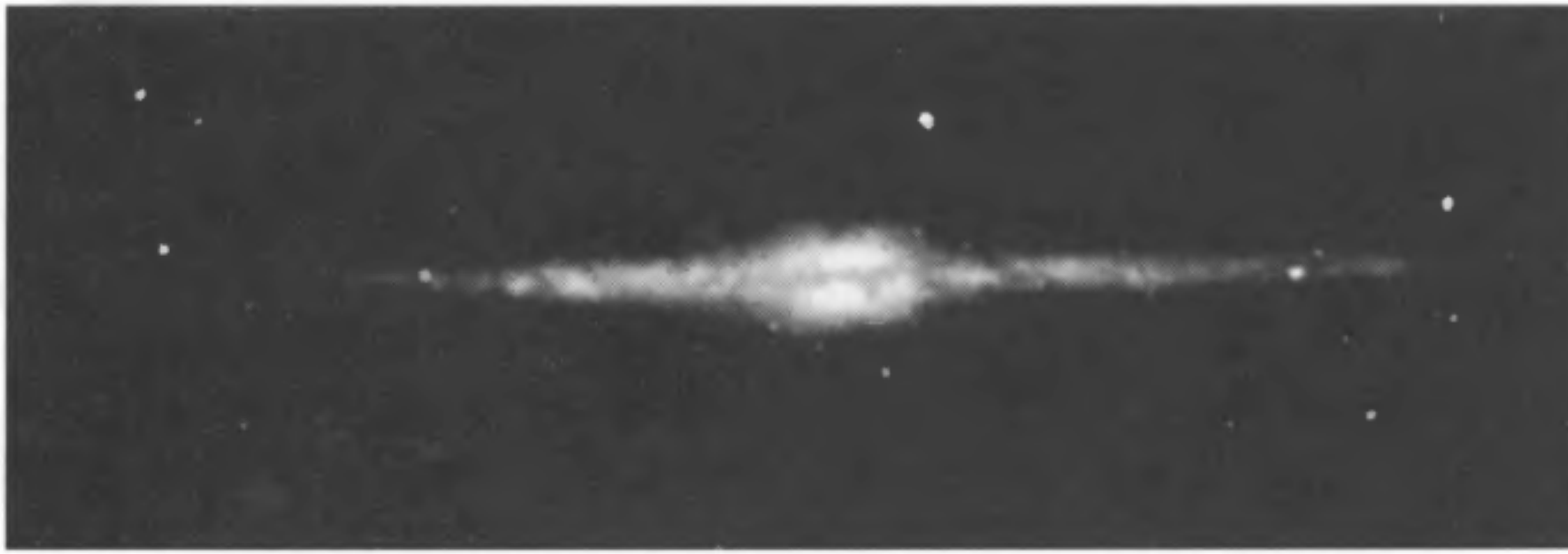


**FIGURE 24.11** An infrared view of the Galaxy, as seen by COBE. The image was produced from observations at 1.2 $\mu$m, 2.2 $\mu$m, and 3.4 $\mu$m, and extends 96° either side of the Galactic center. (Courtesy of the COBE Science Working Group and NASA's Goddard Space Flight Center.)

# Stellar Halo

The stellar halo contains field stars (high velocity stars) and 2 distinct populations of globular clusters

**1: Metal Poor Globular clusters**
[Fe/H] < -0.8
Spherical distribution around galactic center with a radius of 50 kpc. Most stars in these metal poor GCs are very old
$t_{age} \sim 13$ Gyr

**2: Less Metal Poor Globular clusters**
[Fe/H] > -0.8
These GCs are concentrated near the galactic center and
$t_{age} \sim 11$ Gyr

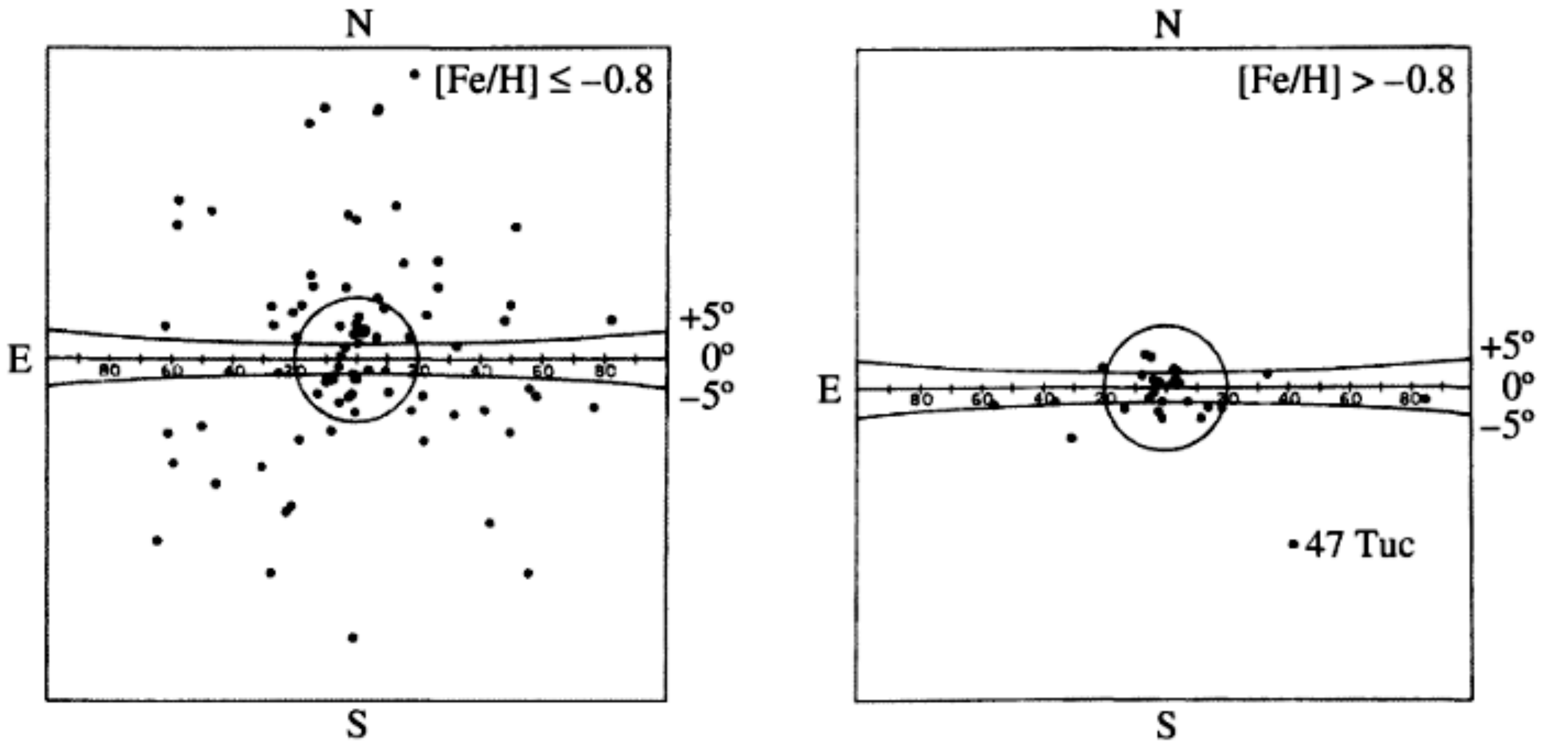



**FIGURE 24.12** Metal-poor globular clusters form a nearly spherical distribution about the Galactic center, while more metal-rich clusters are found preferentially near the plane of the Galaxy, possibly associated with the thick disk. (Figure adapted from Zinn, *Ap. J.*, *293*, 424, 1985.)

# Distribution of Metal Poor Globular Cluster and Field Stars in Halo

$n_{halo}(\mathrm{r}) = n_0 \left(\frac{r}{a}\right)^{-3.5}$

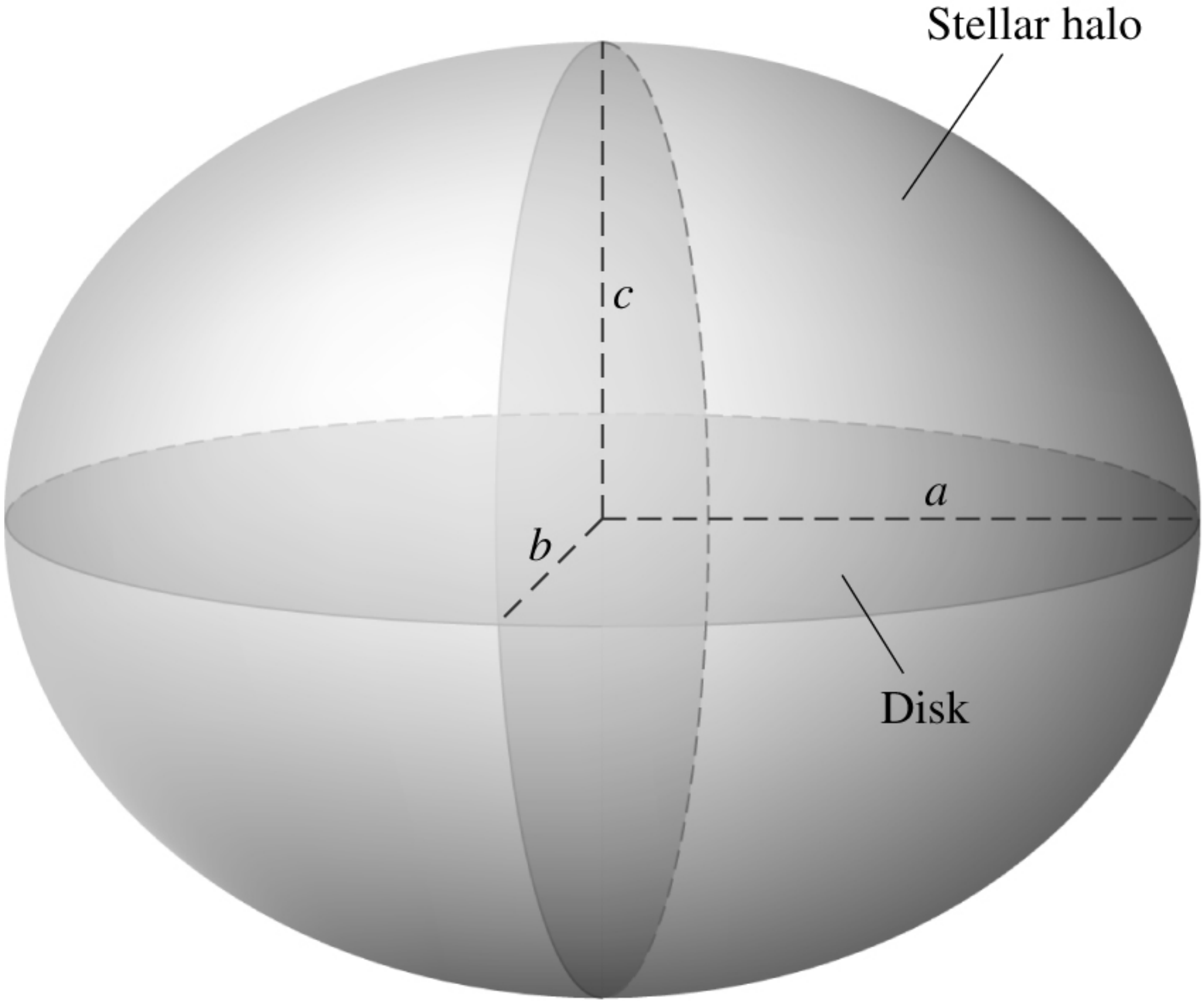
$n_0$=$4\times10^{-5}\ pc^{-3}$

$a$ ~ 3kpc

Total mass of halo stars ~ $10^9 M_\odot$

99% field stars

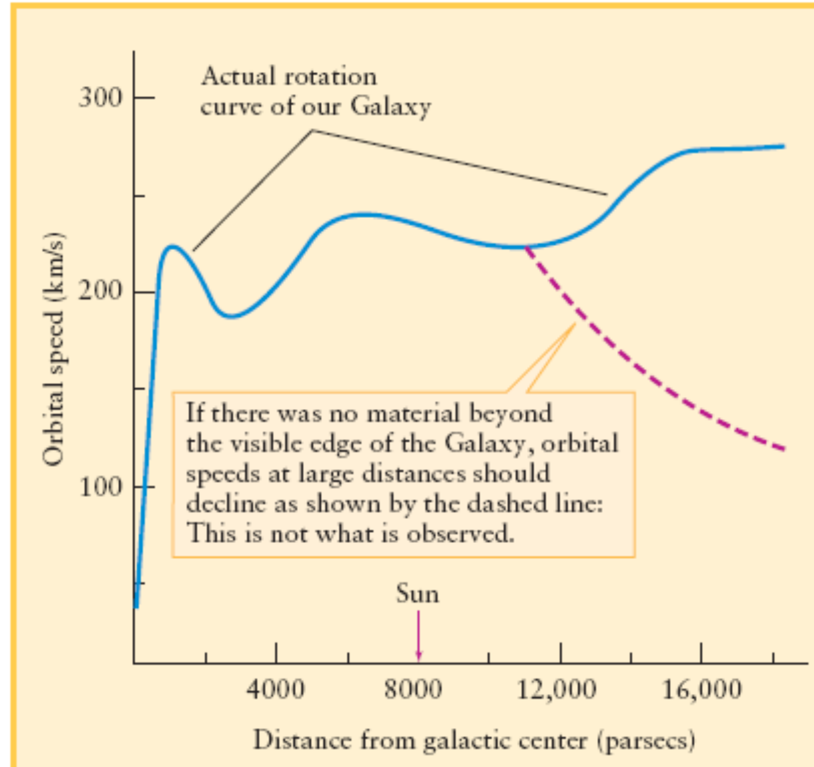
1% GC stars




$$0.8 < \frac{c}{a} < 0.9$$

# Rotation Curve of our Galaxy

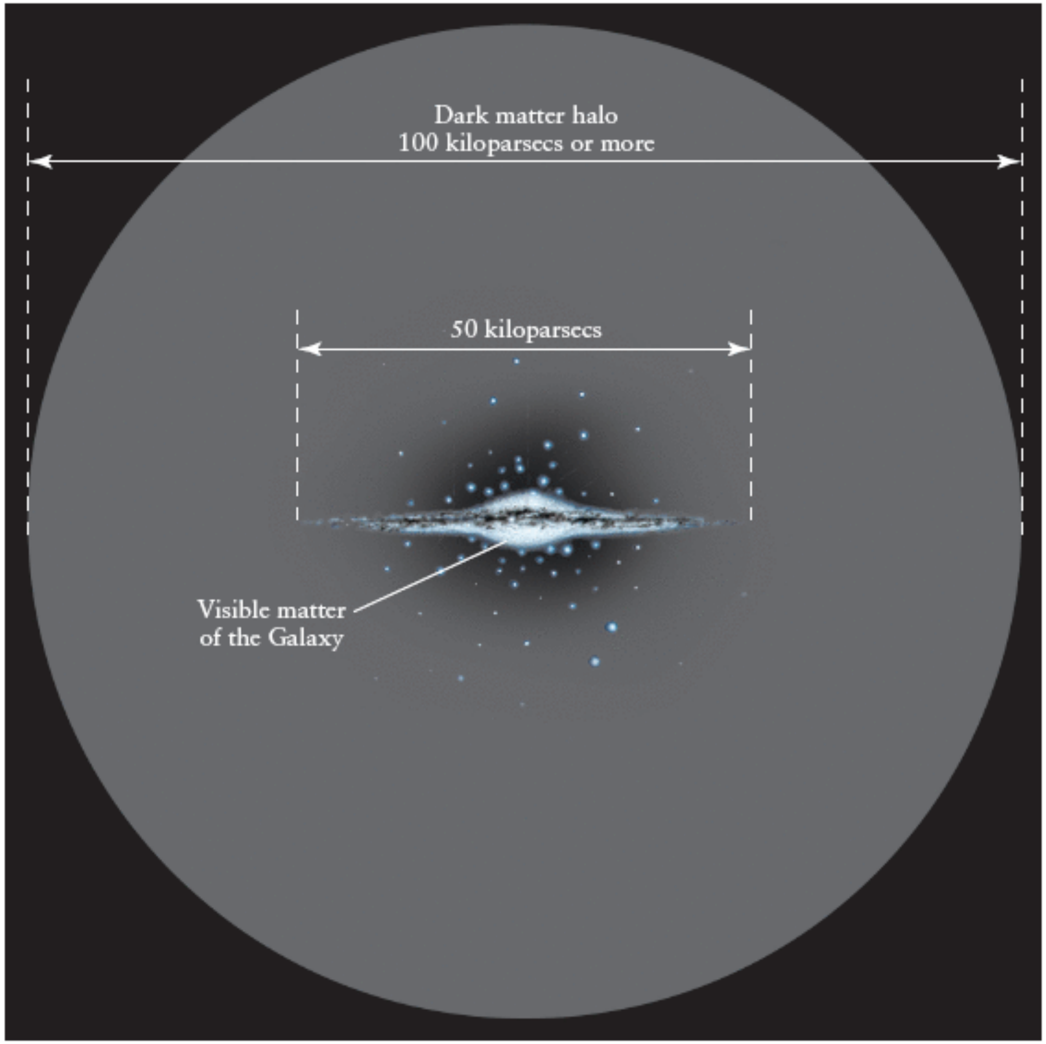
On the right is a plot of the **rotational speed** of stars in the galaxy as a function of radius. The orbital velocities were inferred from Doppler measurements and from the absolute measurement of the Sun's velocity around the center.




One expects, based on Kepler's third law, that objects outside most of the mass to have orbital velocities that decline with distance.

The fact that the rotation curve does not decline beyond the visible edge of the galaxy implies the presence of **dark matter.**

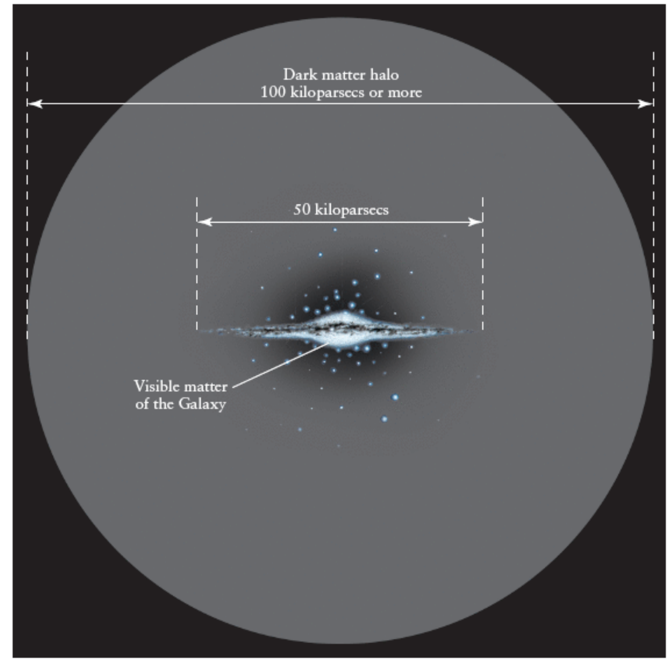
# Flat rotation curve implies dark matter in our Galaxy



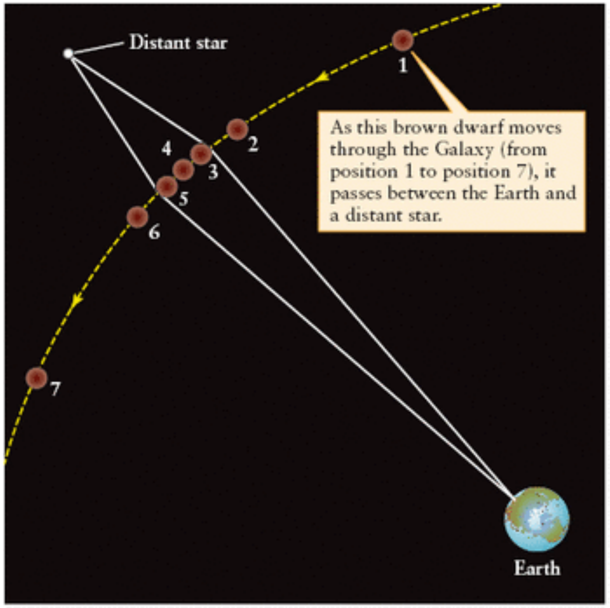
# Flat rotation curve implies dark matter in our Galaxy

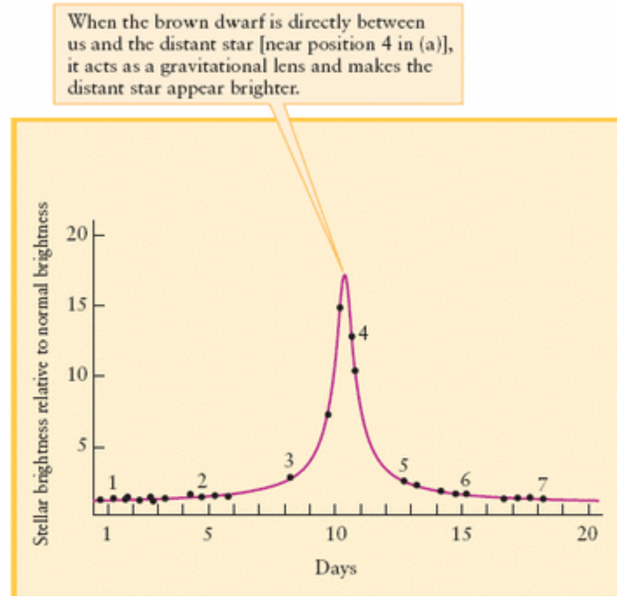
Navarro-Frank-White (NFW) Dark Matter Density Profile

$$\rho(r) = \frac{\rho_0}{\left(\frac{r}{a}\right)\left(1+\frac{r}{a}\right)^2}$$



# Dark Matter in our Galaxy




One speculation for dark matter was that it is composed of dim objects with masses less than 1 $M_\odot$. These objects which would include **brown dwarfs** (object not massive enough to sustain H fusion), **white dwarfs, and black holes** are called **massive compact halo objects (MACHOs)**.

When a MACHO passes between a background star and us it will magnify the light from the star. The degree of magnification and the length of the event provide constraints on the mass of the MACHO object. Astronomers estimate that MACHO’s can only account for about half of the dark matter halo.

# Dark Matter in our Galaxy

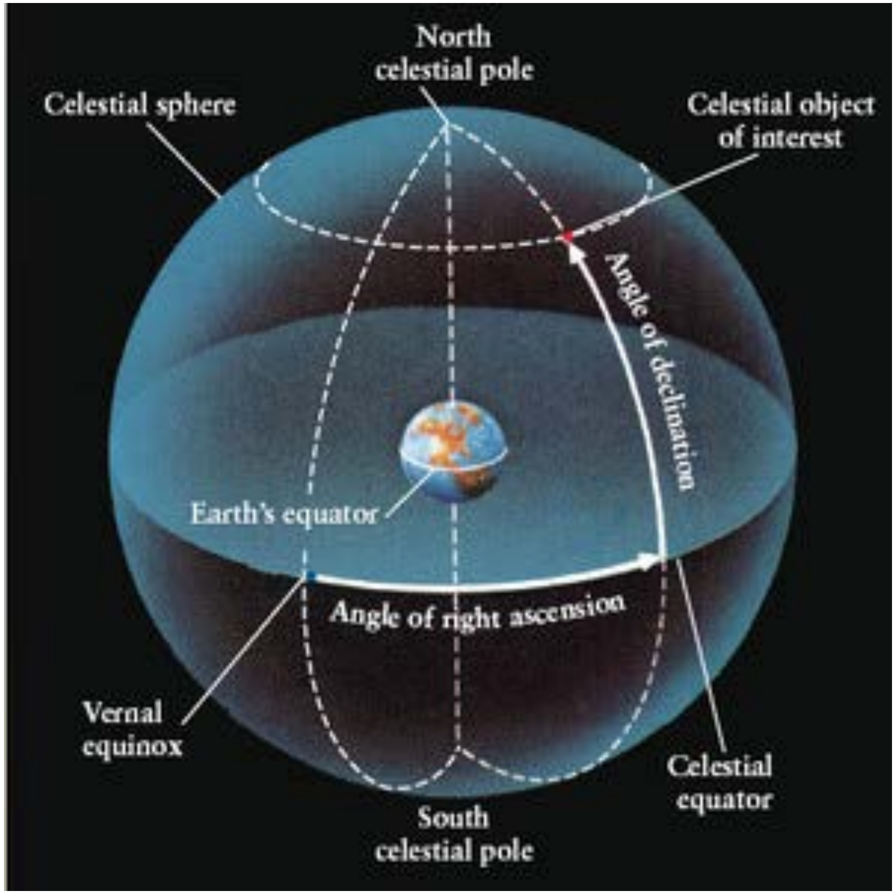
Various dark matter candidates recently proposed are made of more exotic forms of matter. One suggestion is that dark matter is made up of **weakly interacting massive particles** (**WIMPs**).

**WIMPs** do not interact with electromagnetism (photons) and they don’t interact with the strong nuclear force but they do **interact with the weak force and gravity**.

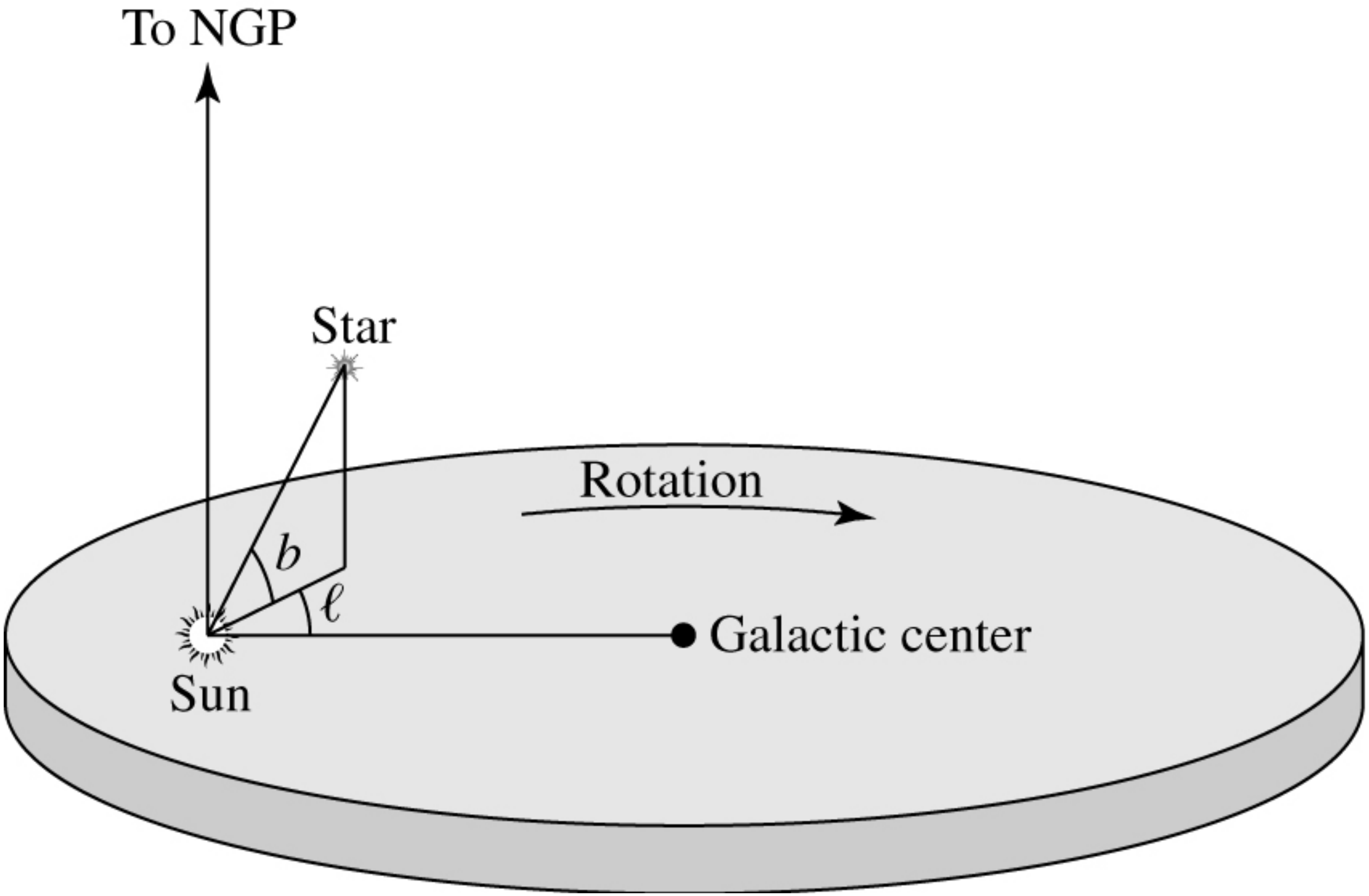
**WIMPs** are predicted by some particle theories and **are expected to have masses between 10 to 10,000 times that of a proton**.

# Equatorial (Celestial) Coordinate System

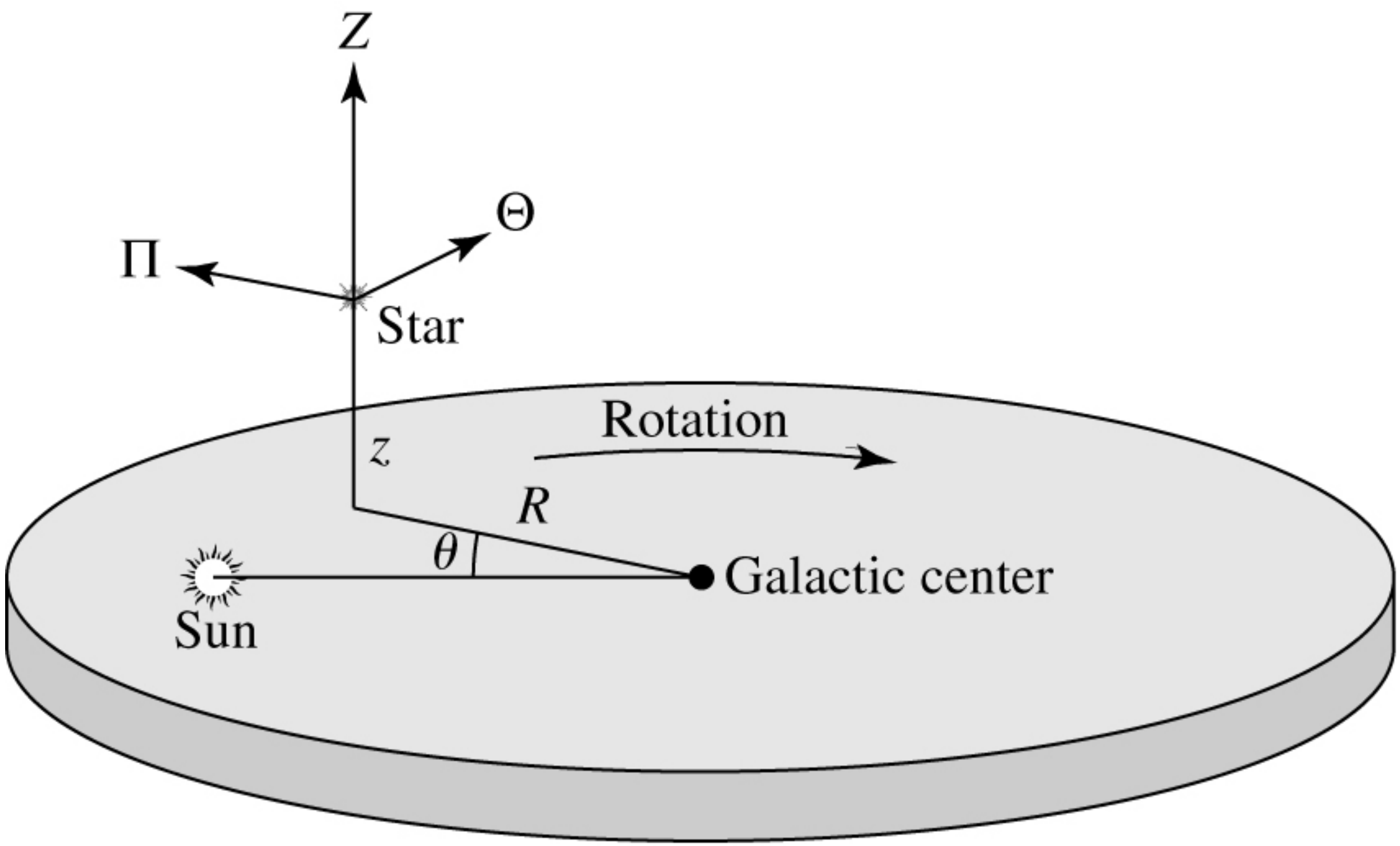
- Right Ascension (RA) is the angle from the Vernal Equinox (increasing from West to East) measured in hours, minutes, and seconds of arc.
- Declination (Dec) is the angle in degrees north or south of the celestial equator.



# Galactic Coordinate System



# Galactocentric Coordinate System



# Velocity of a star with respect to the LSR

$\vec{v} = (v_R, v_\Theta, v_Z) = (u, v, w)$ (peculiar velocity of star with respect to LSR)

Where the velocity components of star with respect to the LSR are:

$u = \Pi_{star} - \Pi_{LSR} = \Pi_{star}$
$v = \Theta_{star} - \Theta_{LSR}$
$w = Z_{star} - Z_{LSR} = Z_{star}$

Where $\Pi_{star}, \Theta_{star}, Z_{star}$ are the velocity components of the star relative to the Galactic center
and $\Pi_{LSR}, \Theta_{LSR}, Z_{LSR}$ are the velocity components of the LSR relative to the Galactic center

The average velocity components of stars in the solar neighborhood are:
$\langle u \rangle \approx 0$, $\langle w \rangle \approx 0$, $\langle v \rangle \neq 0$

The average tangential velocity of stars with respect to the Local Standard of Rest in the solar neighborhood is not zero: $\langle v \rangle \neq 0$

Because…
$\Theta_A < \Theta_{LSR}$, star A is at apogalacticon when in the solar neighborhood
$\Theta_B > \Theta_{LSR}$, star B is at perigalacticon when in the solar neighborhood
where $\Theta$ is the tangential velocity of a star with respect to the Galactic center. Since there are more stars within the LSR we expect:
$\langle \Theta - \Theta_{LSR} \rangle = \langle v \rangle < 0$

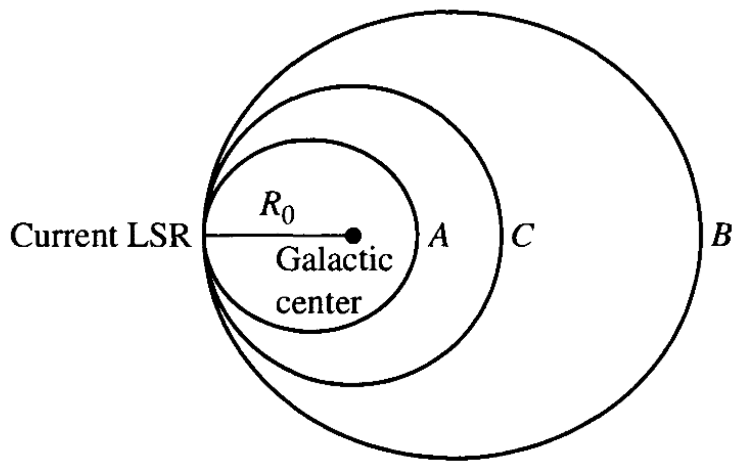



**FIGURE 24.20** The orbits of three hypothetical stars intersecting at the LSR. *A* and *B* represent stars in elliptical orbits with semimajor axes $a_A < R_0$ and $a_B > R_0$, respectively. *C* represents a star following the perfectly circular path of the LSR.

# Velocity of the sun with respect to the LSR

The velocity components of the sun with respect to the LSR are:

$u_{\odot}$, $v_{\odot}$, $w_{\odot}$

We usually measure the velocity components of a star with respect to the Sun:

$\Delta u = u - u_{\odot}$

$\Delta v = v - v_{\odot}$

$\Delta w = w - w_{\odot}$

*u, v, w are the velocity components of a star with respect to the LSR*

Where

$u_{\odot}$ = -10 +/- 0.4 km/s

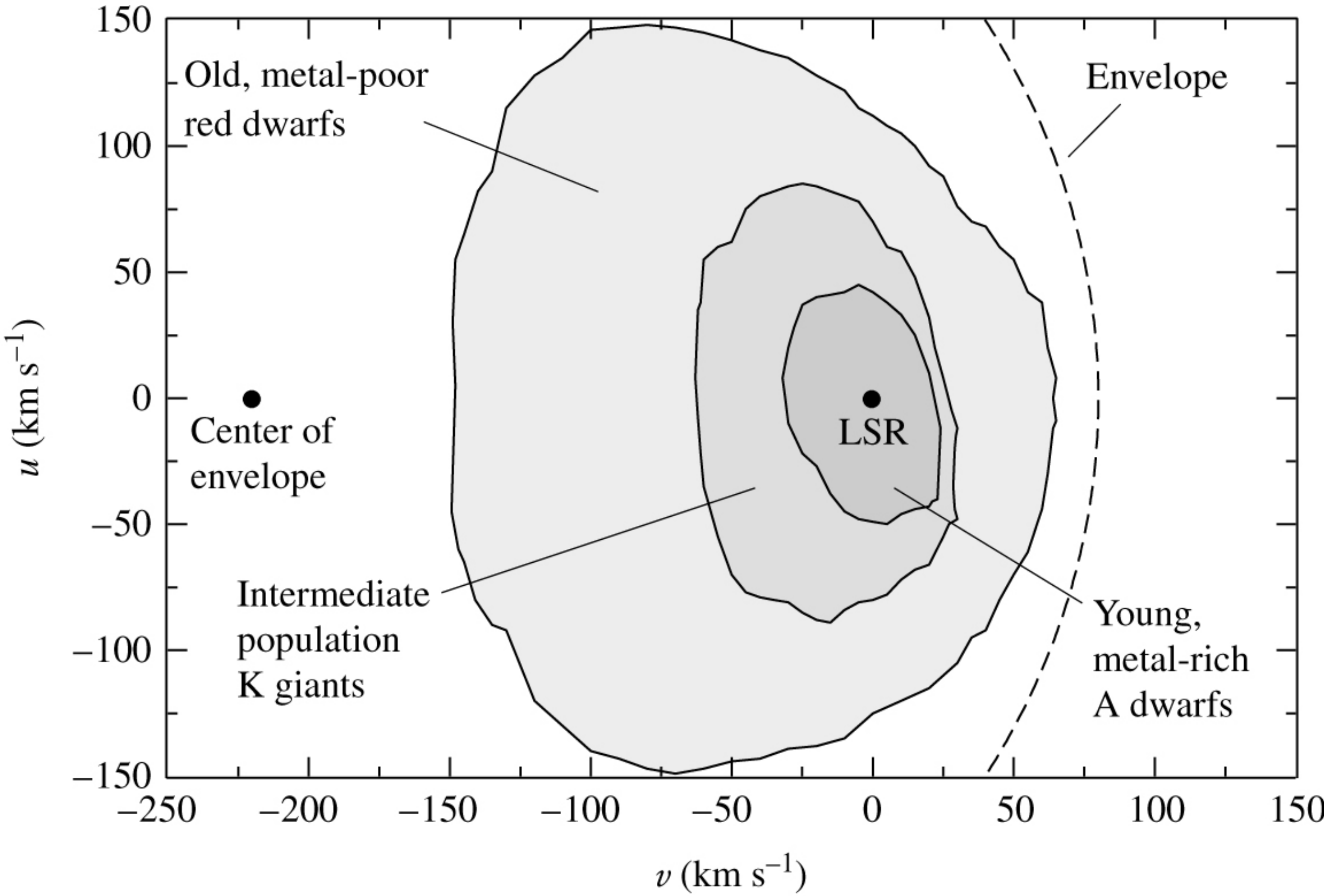
$v_{\odot}$ = 5.2 +/- 0.6 km/s

$w_{\odot}$ = 7.2 +/- 0.4 km/s

*** From measured velocities of stars with respect to the sun ($\Delta u, \Delta v, \Delta w$) and the known velocities of the sun with respect to the LSR, ($u_{\odot}, v_{\odot}, w_{\odot}$) we can infer the velocities of stars with respect to the LSR ($u, v, w$).

# Velocity Ellipsoids of Stars in Our Galaxy

Radial velocity of star with respect to LSR




Tangential velocity of star with respect to LSR

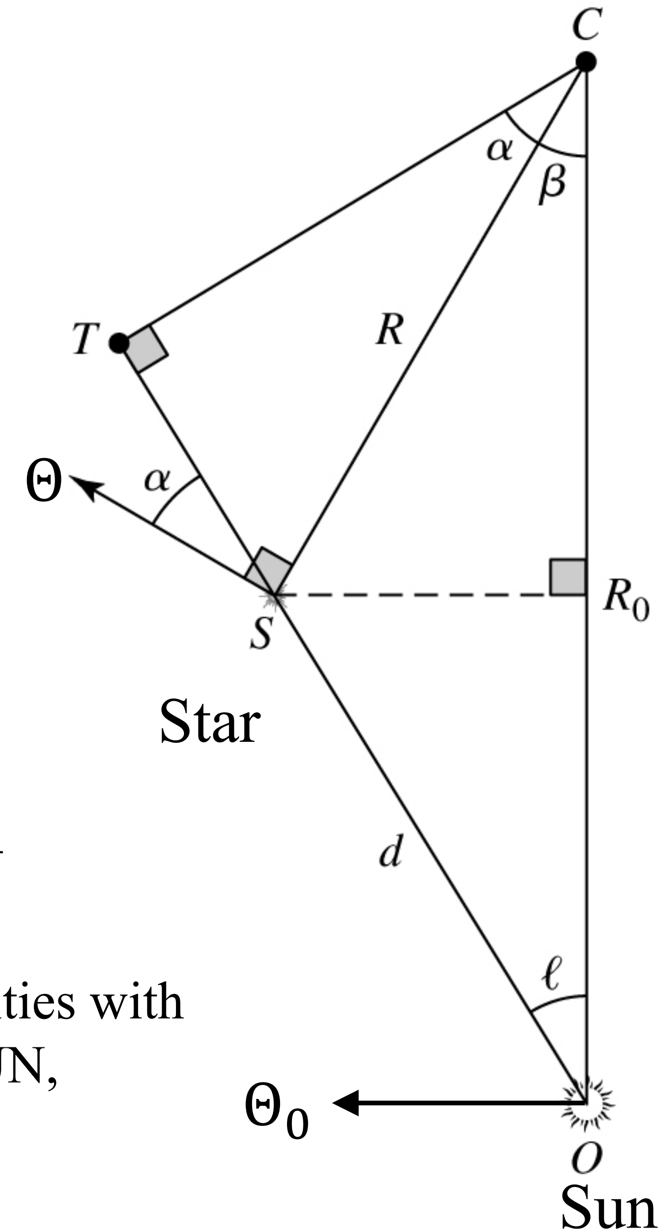
# Differential Galactic Rotation and Oort's Constants

$$v_r = \Theta\cos(\alpha) - \Theta_0\sin(l) = Ad\sin(2l)$$
$$v_t = \Theta\sin(\alpha) - \Theta_0\cos(l) = Ad\cos(2l) + Bd$$

## Oort's Constants

$$A = -\frac{1}{2}\left[\frac{d\Theta}{dR}\Big|_{R=R_0} - \frac{\Theta_0}{R_0}\right]$$
$$\cong 14.8 \pm 0.8 km^{-1}s^{-1}kpc^{-1}$$

$$B = -\frac{1}{2}\left[\frac{d\Theta}{dR}\Big|_{R=R_0} + \frac{\Theta_0}{R_0}\right]$$
$$\cong -12.4 \pm 0.6 km^{-1}s^{-1}kpc^{-1}$$




Where Θ and $\Theta_0$ are the tangential linear velocities with respect to the Galactic center of the star and SUN, respectively.

# Differential Galactic Rotation and Oort's Constants

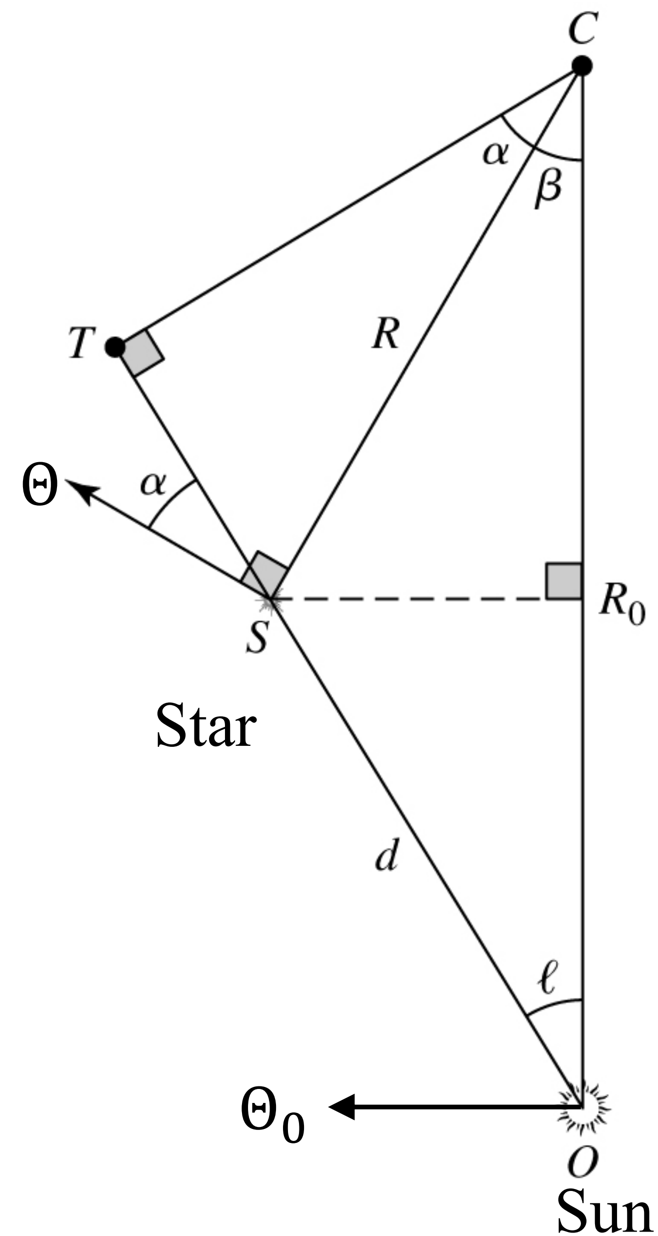
$$\Omega_0 = \Omega(R_0) = A - B$$

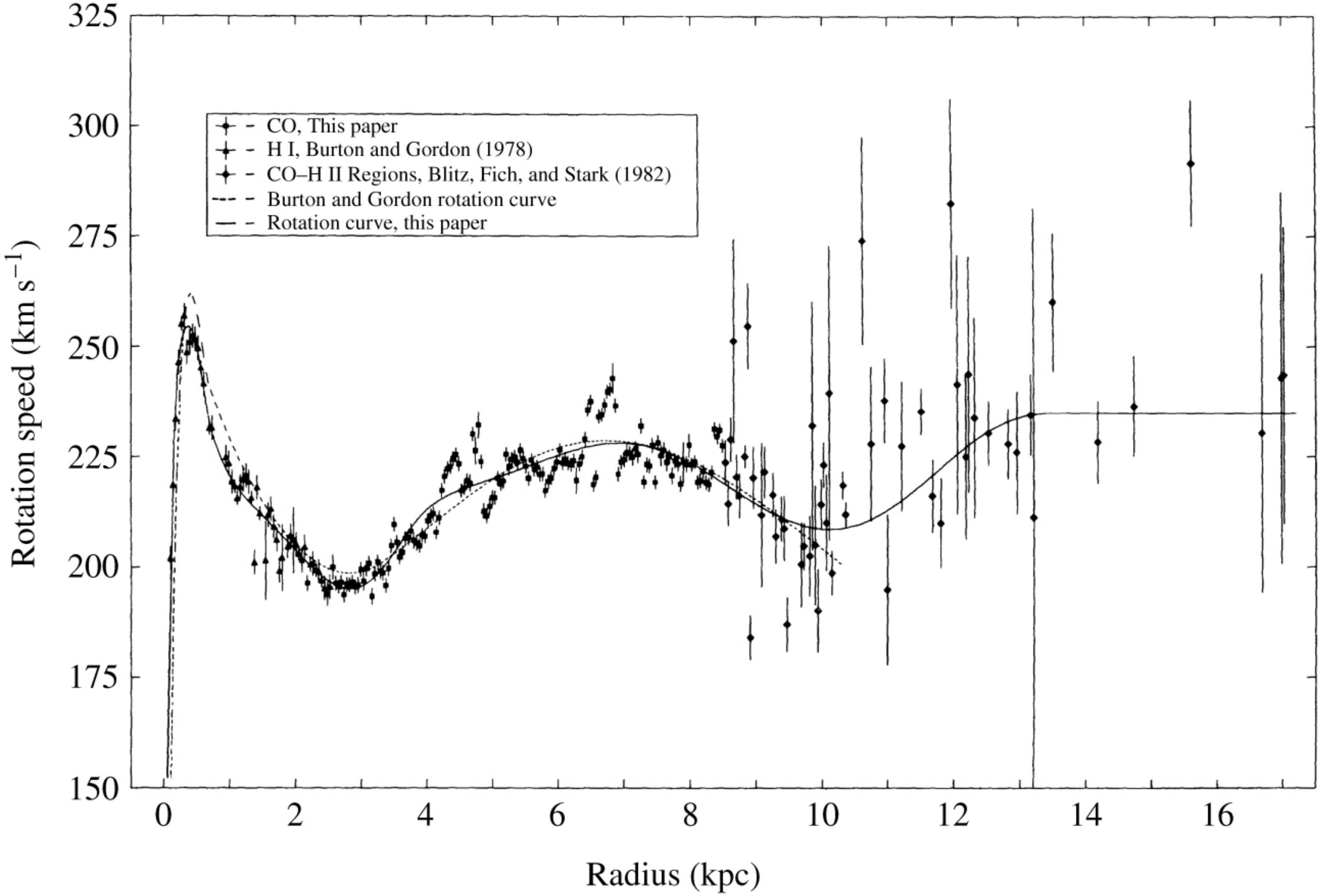
$$\frac{d\Theta}{dR}\Big|_{R=R_0} = -(A+B)$$

$$v_{r,max} \cong 2AR_0(1 - \sin l)$$

$$\frac{-B}{A-B} = \frac{\sigma_v^2}{\sigma_u^2}$$

Where $v_{r,max}$ is the maximum radial velocity, $\sigma_v^2$ and $\sigma_u^2$ are the transverse and radial velocity dispersions




CO, This paper
H I, Burton and Gordon (1978)
CO–H II Regions, Blitz, Fich, and Stark (1982)
Burton and Gordon rotation curve
Rotation curve, this paper
Rotation speed (km s$^{-1}$)
Radius (kpc)
325
300
275
250
225
200
175
150
0
2
4
6
8
10
12
14
16

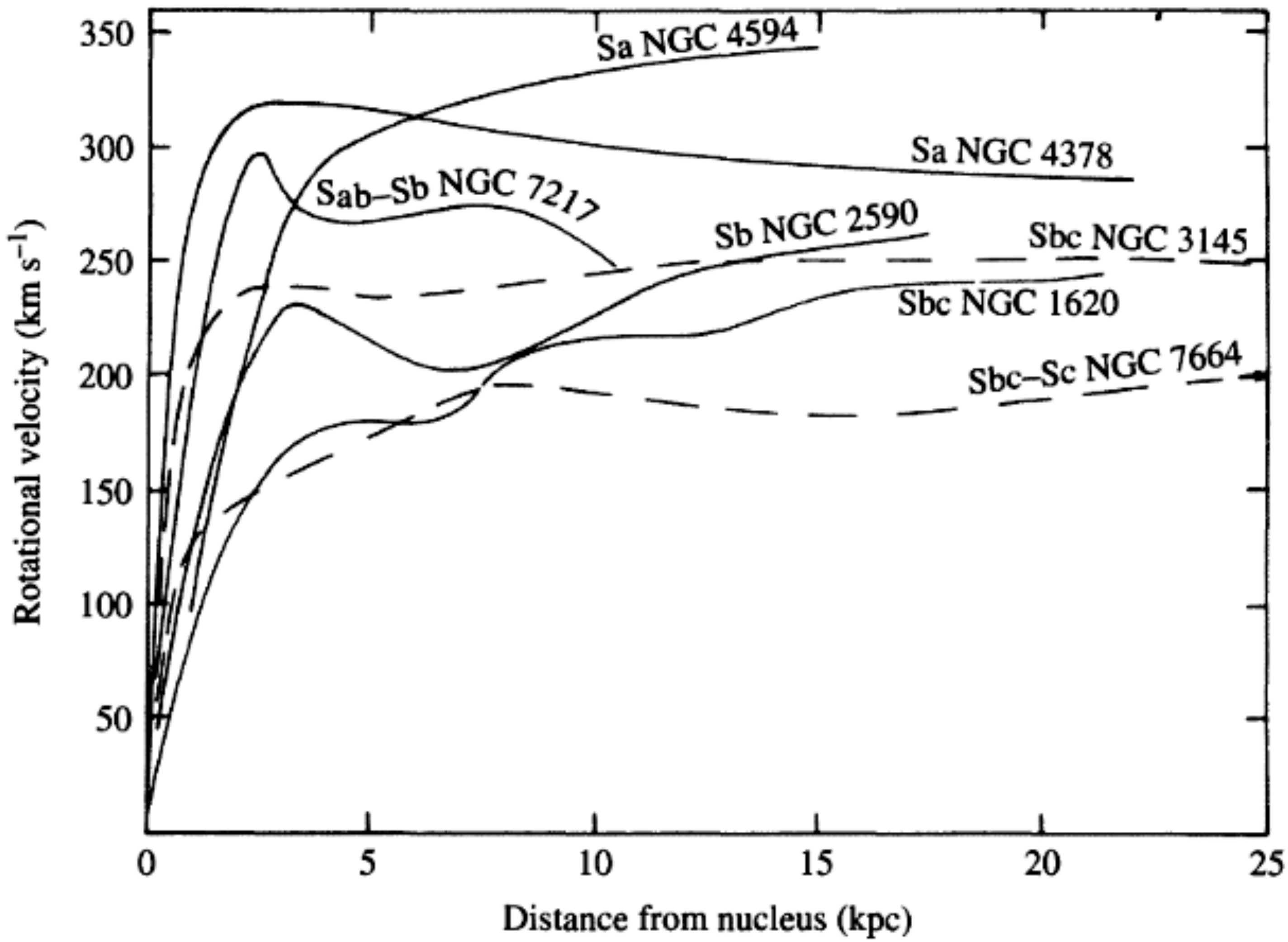



**FIGURE 24.27** A series of rotation curves for spiral galaxies. (Figure adapted from Rubin, Ford, and Thonnard, *Ap. J. Lett.*, *225*, L107, 1978.)

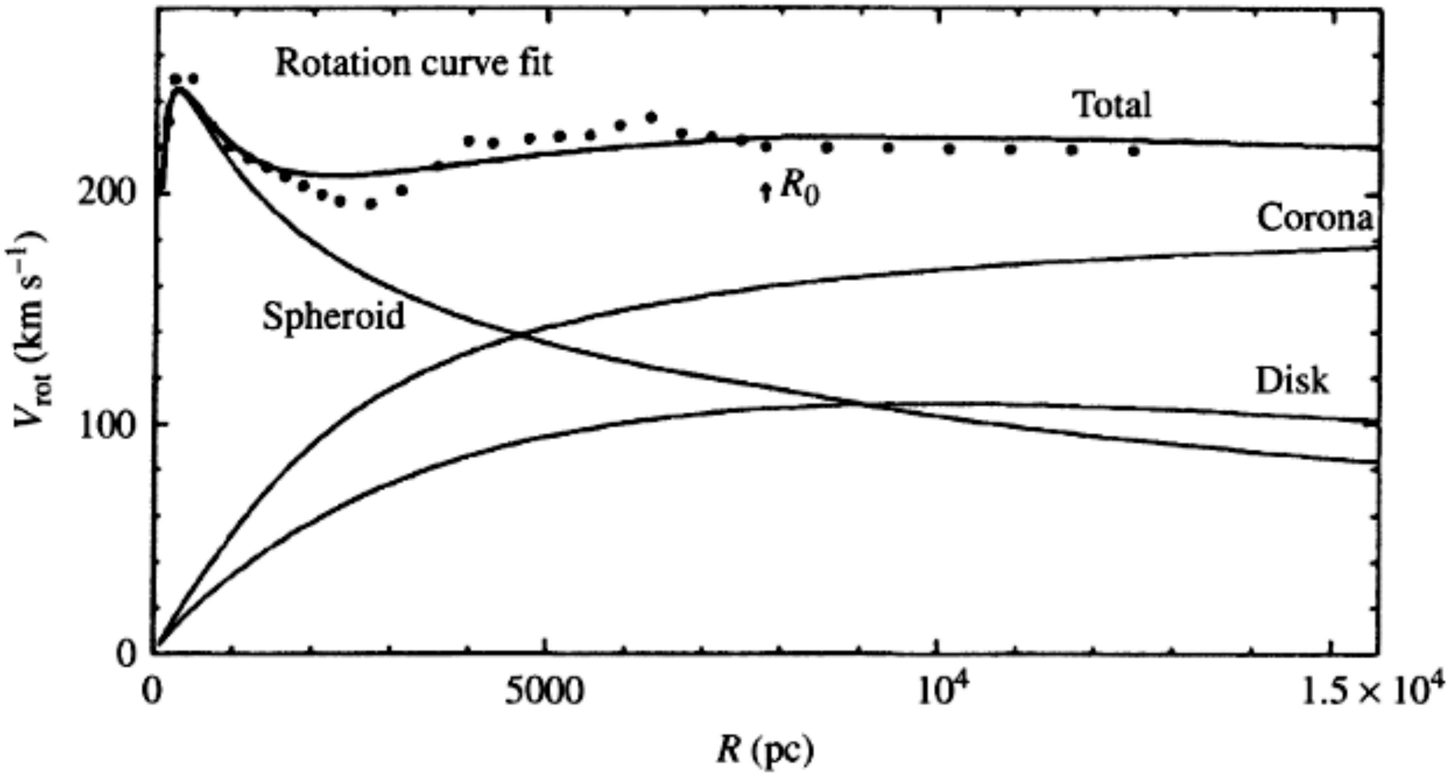



**FIGURE 24.28** One model of the rotation curve of the Galaxy. The mass distribution of each Galactic component contributes to the overall velocity structure of the disk. The dots represent observational data. Note that the "spheroid" represents the bulge and stellar halo combined and the "corona" represents the dark matter halo. (Figure adapted from Gilmore, King, and van der Kruit, *The Milky Way as a Galaxy*, University Science Books, Mill Valley, CA, 1990.)

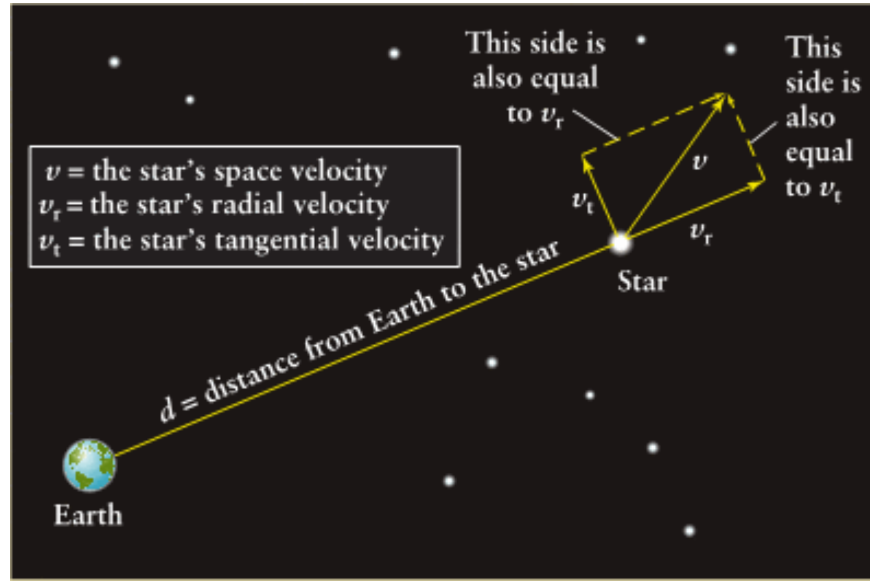
# Stellar Motions

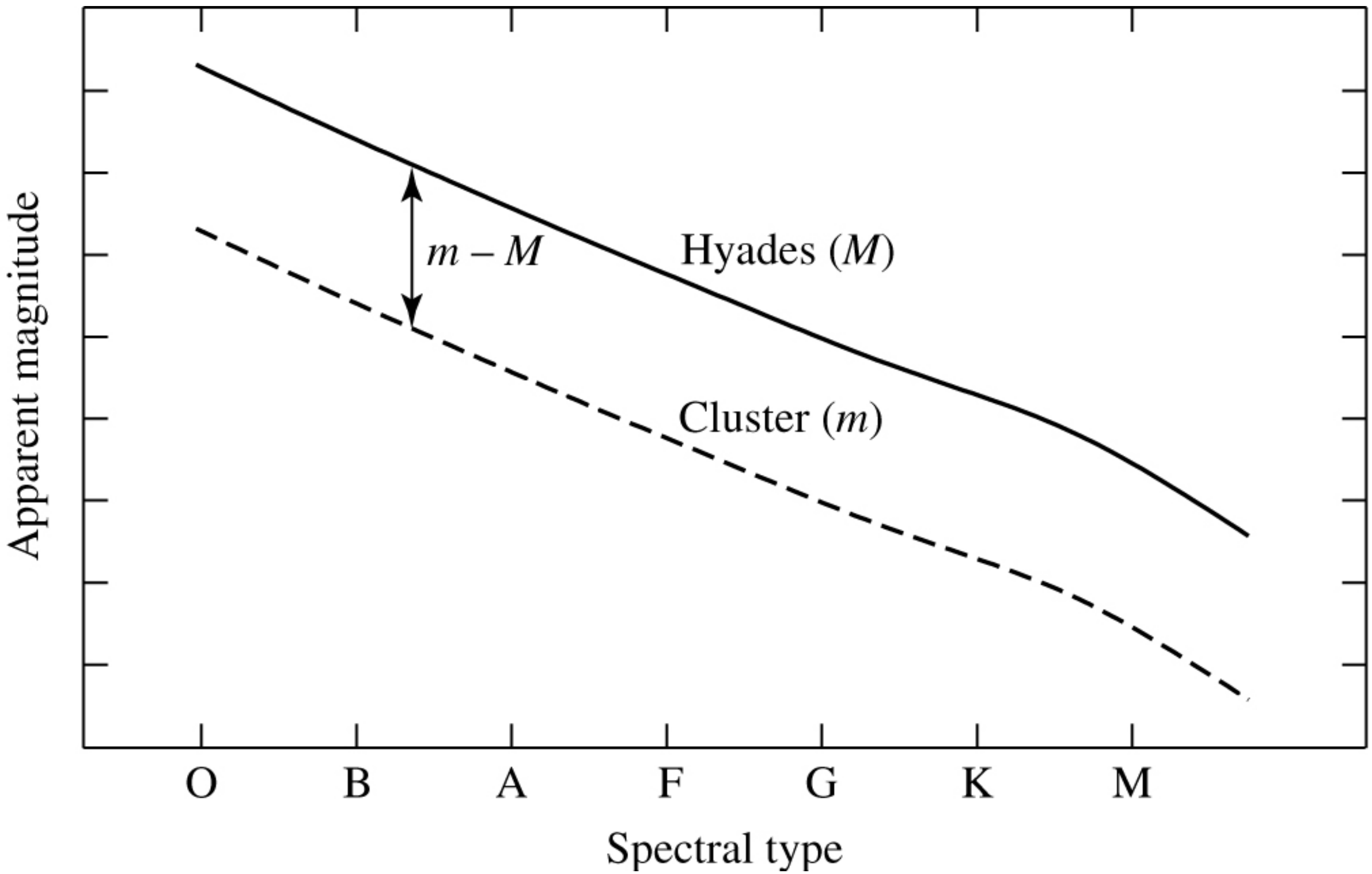
$v = \sqrt{v_t^2 + v_r^2}$
$v_r$ = radial velocity
$v_t$ = tangential velocity

$v_r$ is determined from Doppler Shift
$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{v_r}{c}$

$v_t$ is determined from measurements of the proper motion $\mu$.
$v_t = 4.74 \mu d$

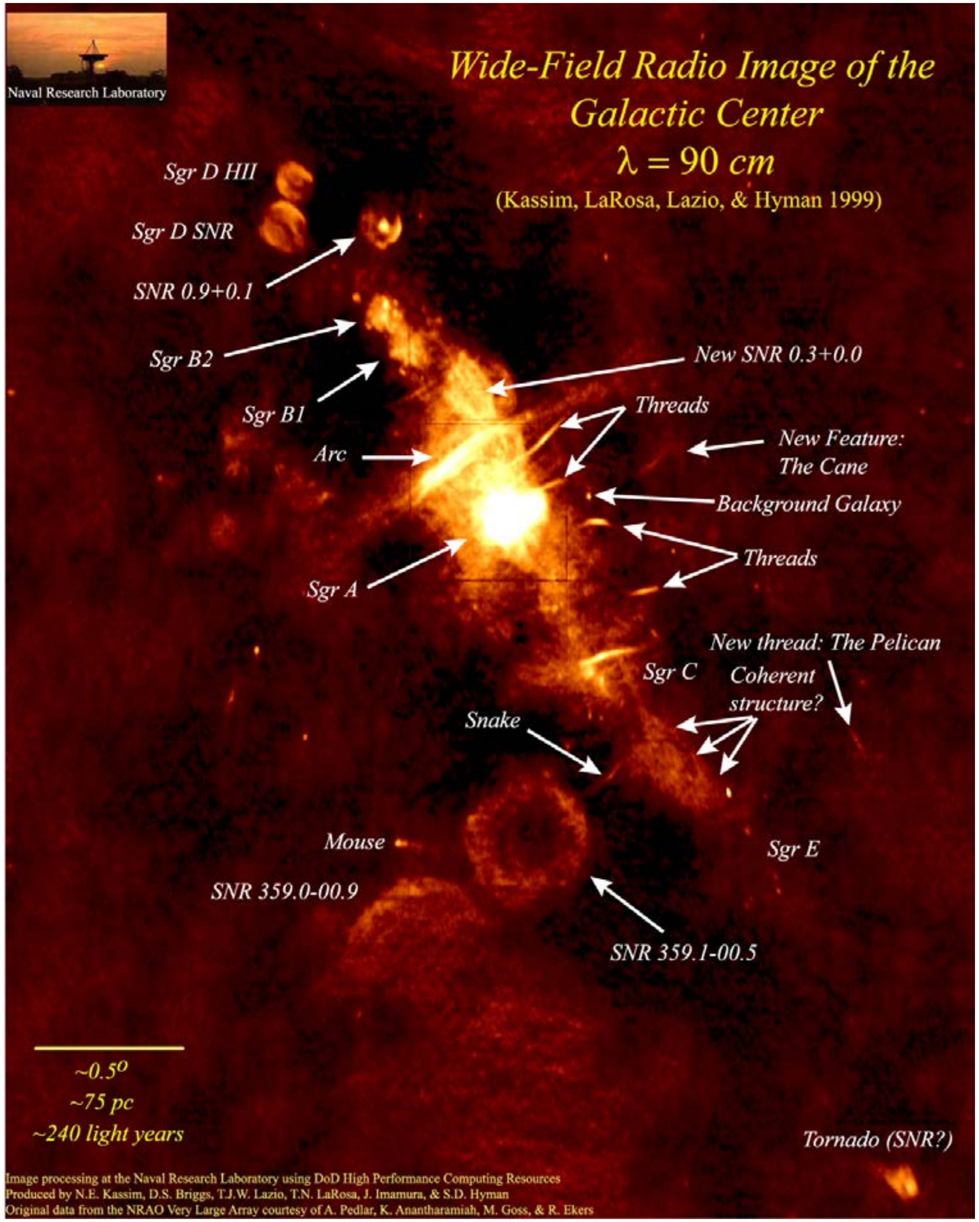
where:
$v_t$ is in units of km/s
$\mu$ *(arcsec/year)* is the angular distance in arcsecs that the star moves in the sky in a year
d is the distance to the star in parsec





Apparent magnitude
m – M
Hyades (M)
Cluster (m)
O
B
A
F
G
K
M
Spectral type

# Galactic Center



# Mass Distribution Towards Galactic Center

Assume the tangential velocity is $\Theta(r) = v = \text{constant}$

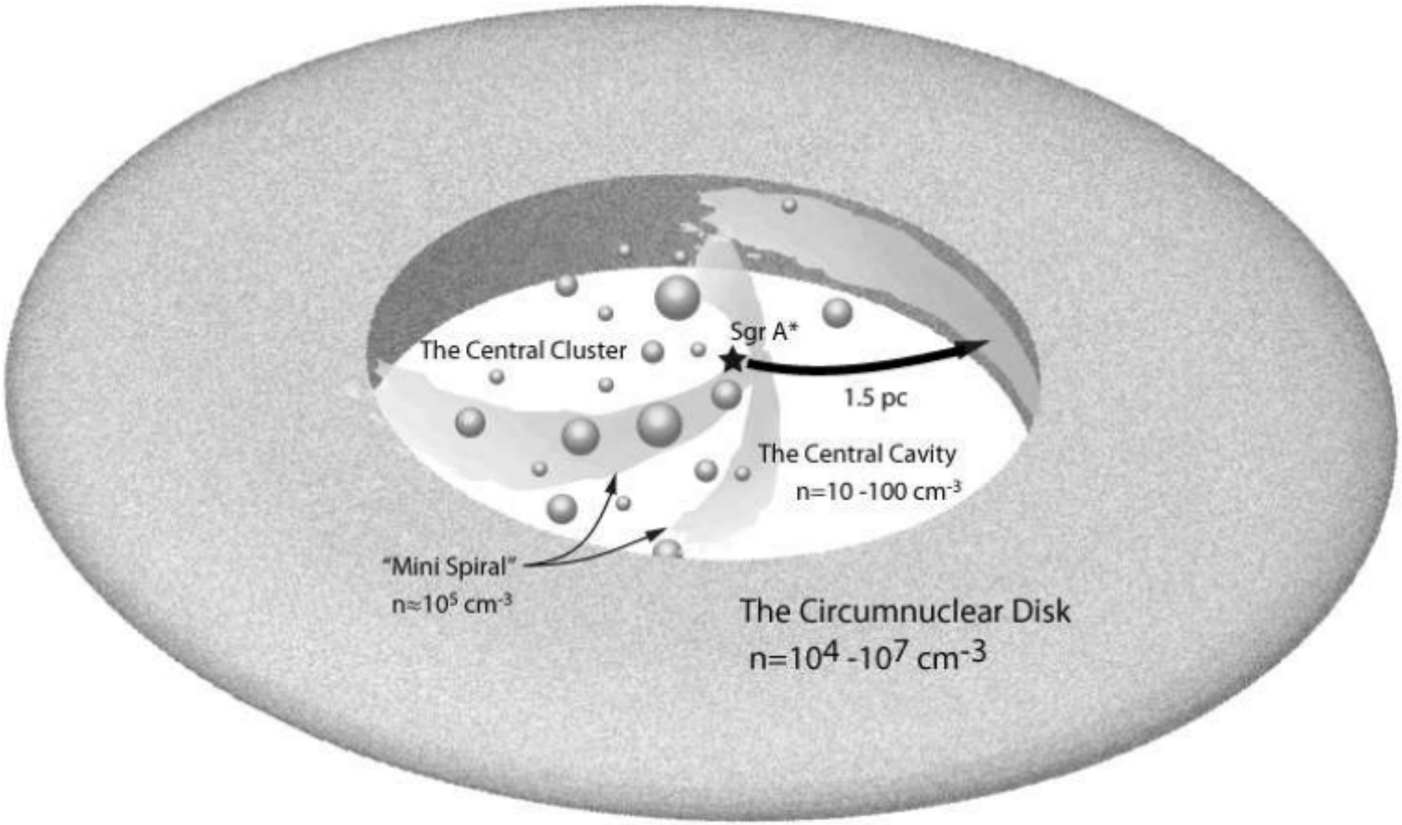
$$\frac{m\Theta^2}{r} = \frac{GmM(r)}{r^2} \Longrightarrow M(r) = \frac{rv^2}{G} \quad (1)$$

$$\frac{dM(r)}{dr} = \frac{v^2}{G} \quad (2)$$

$$dM(r) = \rho(r)4\pi r^2 dr \quad (3)$$

$$(2) \wedge (3) \Longrightarrow \rho(r)4\pi r^2 = \frac{v^2}{G} \Longrightarrow \rho(r) = \frac{v^2}{4\pi G r^2}$$

# Galactic Center

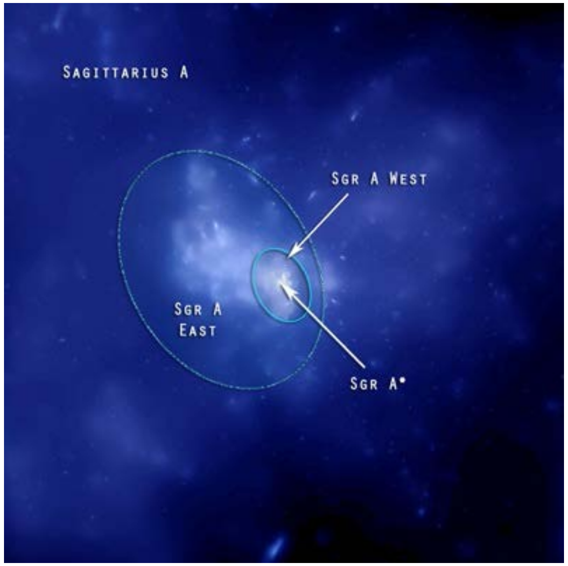



Schematic view of the central few parsecs of the galaxy (central molecular zone), showing the central black hole, Sgr A*, stars in the central star cluster, and the circumnuclear disk which contains dense molecular clouds.
The ring is inclined some 20degrees with respect to the Galactic plane and rotates at about 110 km/s. The ring has very sharp boundaries implying a recent violent event like a supernova may have recently occurred.

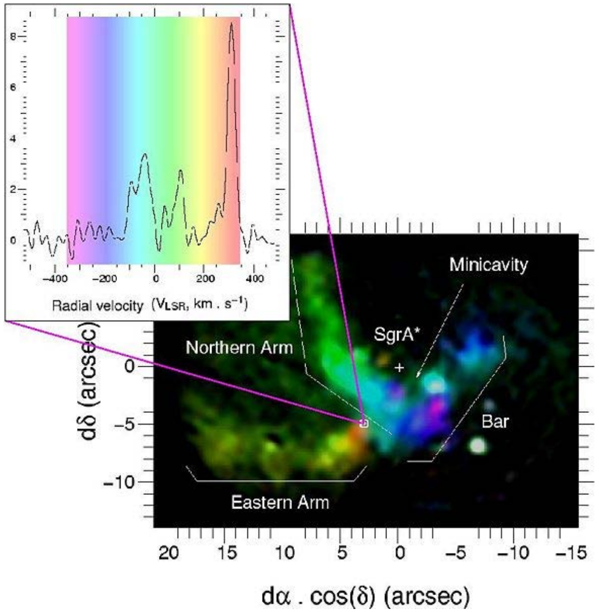
# Galactic Center

**Sgr A East** is 25 light-years in width and has the attributes of a **supernova remnant** from an explosive event that occurred between 35,000 and 100,000 BCE.

**Sgr A West** has the appearance of a three-arm spiral, from the point of view of the Earth. The apparent spiral is made of several dust and gas clouds, which orbit and fall onto Sagittarius A* at velocities as high as 1,000 km/s. The surface layer of these clouds is ionized. The source of ionisation is the population of massive stars (more than one hundred OB stars have been identified so far) that also occupy the central parsec.




The central parsec around Sagittarius A* contains thousands of stars. Although most of them are old red main-sequence stars, the Galactic Center is also rich in massive stars. Astronomers have found a population of more than a 100 very young (O, B and Wolf–Rayet) stars close to the Galactic Center. They seem to have all been formed in a single star formation event a few million years ago.



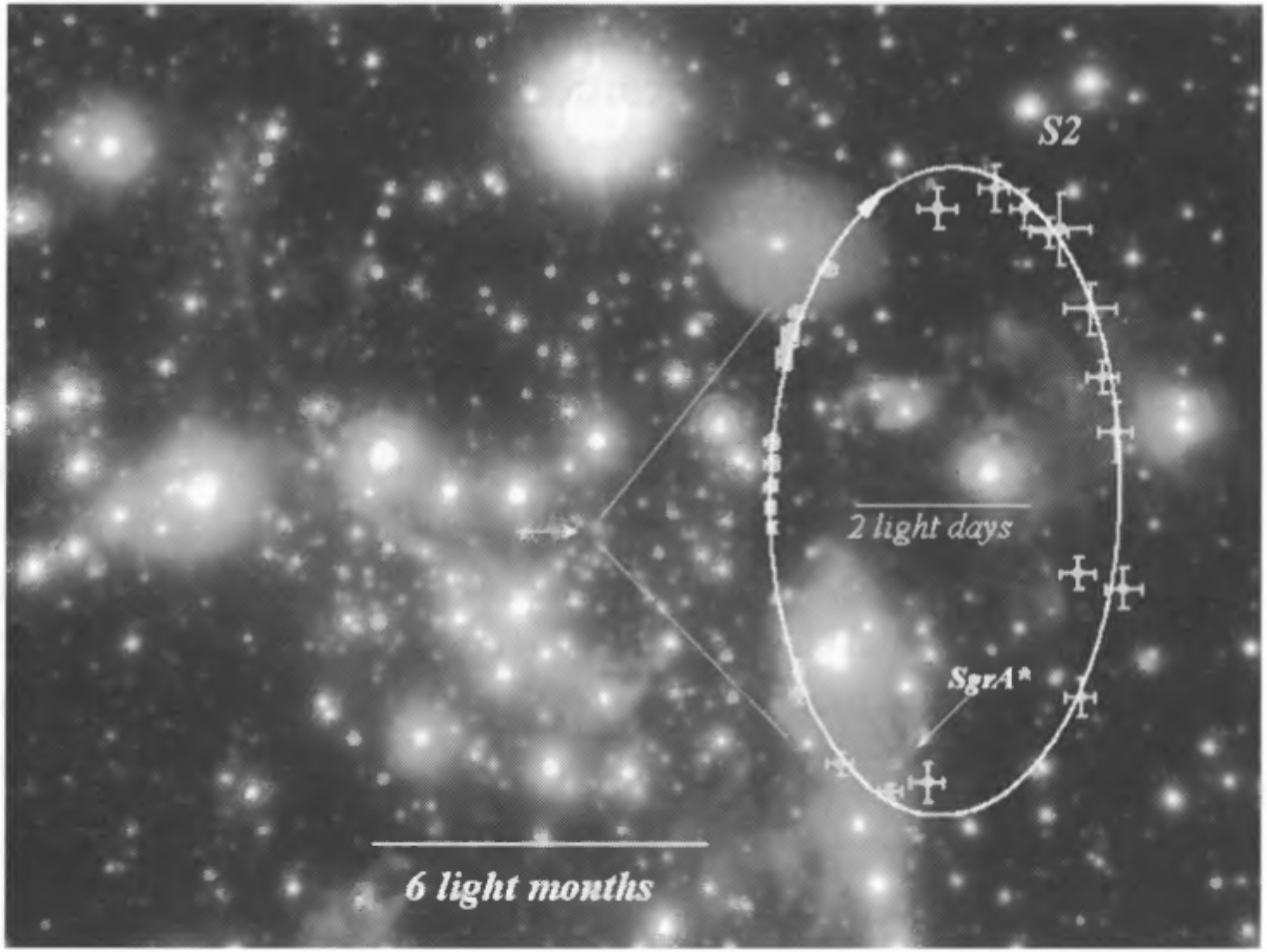
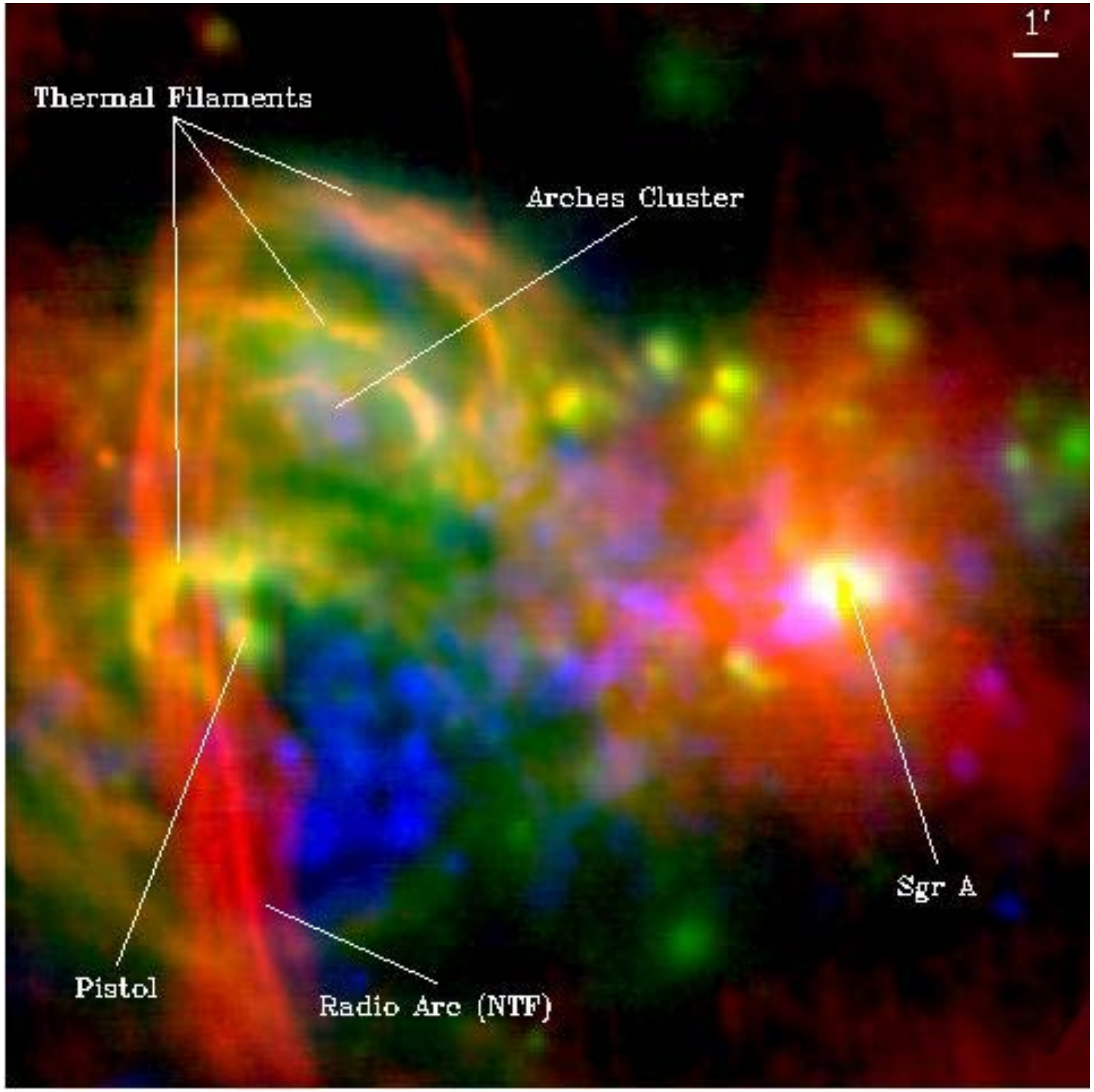



**FIGURE 24.32** The orbit of S2 about the center of the Milky Way Galaxy. The center is designated as Sgr A*. (Courtesy of Reinhard Genzel and Rainer Schödel.)




A multiwavelength close-up of the recent massive star-forming region near the Galactic center. The color image, plotted also in standard Galactic coordinates, is a composite of 20-cm radio continuum (red); 25-µm mid-infrared (green); and 6.4-keV line emission (blue).

# Black Holes in Hibernation

To penetrate the dust and gas near the center of our galaxy astronomers typically observe this region in the infrared.

Infrared images show that the **density of stars** increases dramatically near the nucleus of a galaxy.

In our galaxy the density of stars near the sun is ~ 0.006 stars per cubic light-year

Near the center of our galaxy the density is $\sim 10^6$ stars per cubic light-year

# Black Holes in Hibernation

To improve the spatial resolution of the IR observations of the galactic center astronomers employed adaptive optics.

With adaptive optics the distorted and flickering image of a star is compared to every few milliseconds to the point-like appearance it would have with the absence of turbulence.
The telescopes mirrors are slightly deformed in real time to compensate.

Reinhard Genzel and Andrea Ghez mapped the orbits of stars close to the galactic center and showed that it must contain a supermassive black hole with a mass of about $4 \times 10^6\ M_\odot$.

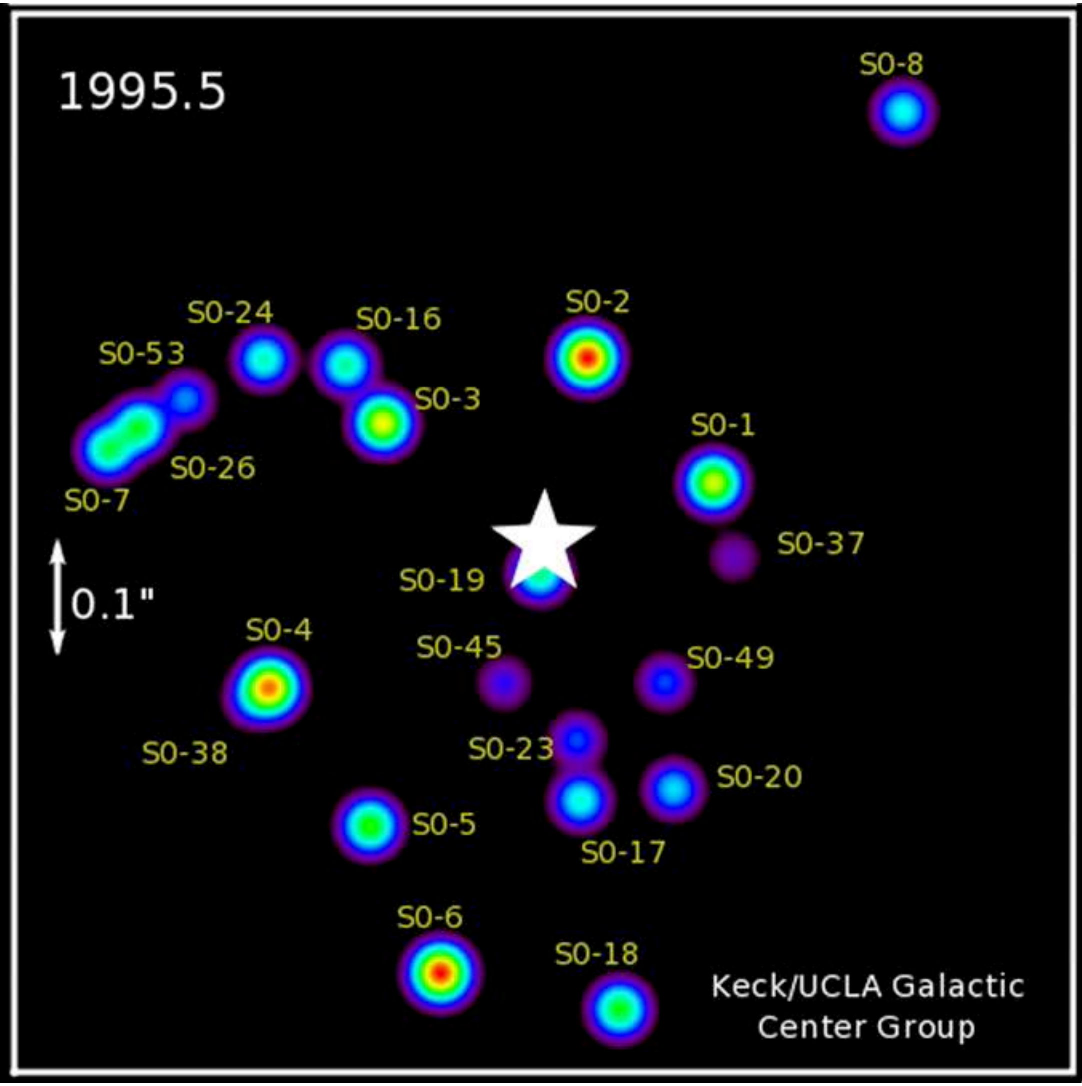
# Mass of SgrA*

Star S2
Period = 15.2 years
Orbital eccentricity of e = c/a = 0.87
Perigalacticon distance = $r_p = 1.8 \times 10^3$ m

The semi-major axis is $a = \frac{r_p}{1-e} = \frac{1.8\times10^3 m}{1-0.87} = 1.385\times10^{14} m$

Kepler's 3rd Law

$$P^2 = \frac{4\pi^2}{G(M_{BH} + M_{S2})} a^3 \Longrightarrow M_{BH} \sim 4\times10^6 M_{\odot}$$




Observations over more than a decade have enabled the Ghez and Genzel groups to trace the orbits of individual stars around Sgr A*, providing incontrovertible evidence for a SMBH. Distance to Sgr A*~ 26,000 ly, $M_{BH} \sim 4.2 \times 10^6 M_{\odot}$.

# Black Holes with Low Accretion Rates

Low accretion rates in black holes are found in environments that are gas poor.

The luminosity of an AGN due to accretion is:

$L_{accretion} = \frac{GM\dot{M}}{R} = \eta \dot{M} c^2$, where $\dot{M} = \frac{dM}{dt}$ is the accretion rate

For a black hole η~0.06-0.42

SgrA* appears to have a luminosity much lower than what is expected for its accretion rate.

# Fueling a Black Hole by Tidal Disruption

Tidal disruption of stars is thought to be a mechanism of fueling black holes. For this mechanism to work the star needs to be disrupted but not swallowed completely by the black hole.

A star of mass density $\rho_*$ approaching a massive body of mass density $\rho_{BH}$ and radius $R_s$ must reach at least a distance of the Roche limit for it to be tidally disturbed. The Roche limit is given by:

$$r_R = 2.4\left(\frac{\rho_{BH}}{\rho_*}\right)^{1/3} R_S$$

For a star approaching a black hole to be disrupted but not swallowed by the hole its Roche limit must be larger than the Schwarzschild radius, $r_R > R_s$. This then places an upper limit on the mass of the Black Hole for fueling by tidal disruption of:

$$M < 5\times10^8 \rho_*^{-1/2} M_\odot$$

$\rho_*$ is the density of the star in gr/cm$^3$.

# Fueling a Black Hole by Tidal Disruption

$$r_R = 2.4\left(\frac{\rho_{BH}}{\rho_*}\right)^{1/3} R_s$$

$$r_R > R_s = \frac{2\mathrm{GM_{BH}}}{\mathrm{c}^2} \Rightarrow \mathrm{M_{BH}} < \frac{r_R\mathrm{c}^2}{2\mathrm{G}} = \frac{2.4\left(\frac{\rho_{BH}}{\rho_*}\right)^{1/3} R_s\mathrm{c}^2}{2\mathrm{G}} \Rightarrow$$

$$\mathrm{M_{BH}} < \frac{2.4\left(\frac{M_{\mathrm{BH}}}{\frac{4}{3}\pi R_S^3}\right)^{1/3} R_s\mathrm{c}^2}{2G\rho_*^{1/3}} = \frac{2.4\left(\frac{M_{\mathrm{BH}}}{\frac{4}{3}\pi}\right)^{1/3} \mathrm{c}^2}{2G\rho_*^{1/3}} \Rightarrow \mathrm{M_{BH}^{2/3}} < \frac{2.4\left(\frac{4}{3\pi}\right)^{1/3} \mathrm{c}^2}{2G\rho_*^{1/3}}$$

$$\mathrm{M_{BH}} < \left[\frac{2.4\left(\frac{4}{3\pi}\right)^{1/3} \mathrm{c}^2}{2G\rho_*^{1/3}}\right]^{3/2} = \mathrm{C}\rho_*^{-1/2}, \text{where } \mathrm{C} = 5 \times 10^8\ \mathrm{M_{solar}}$$

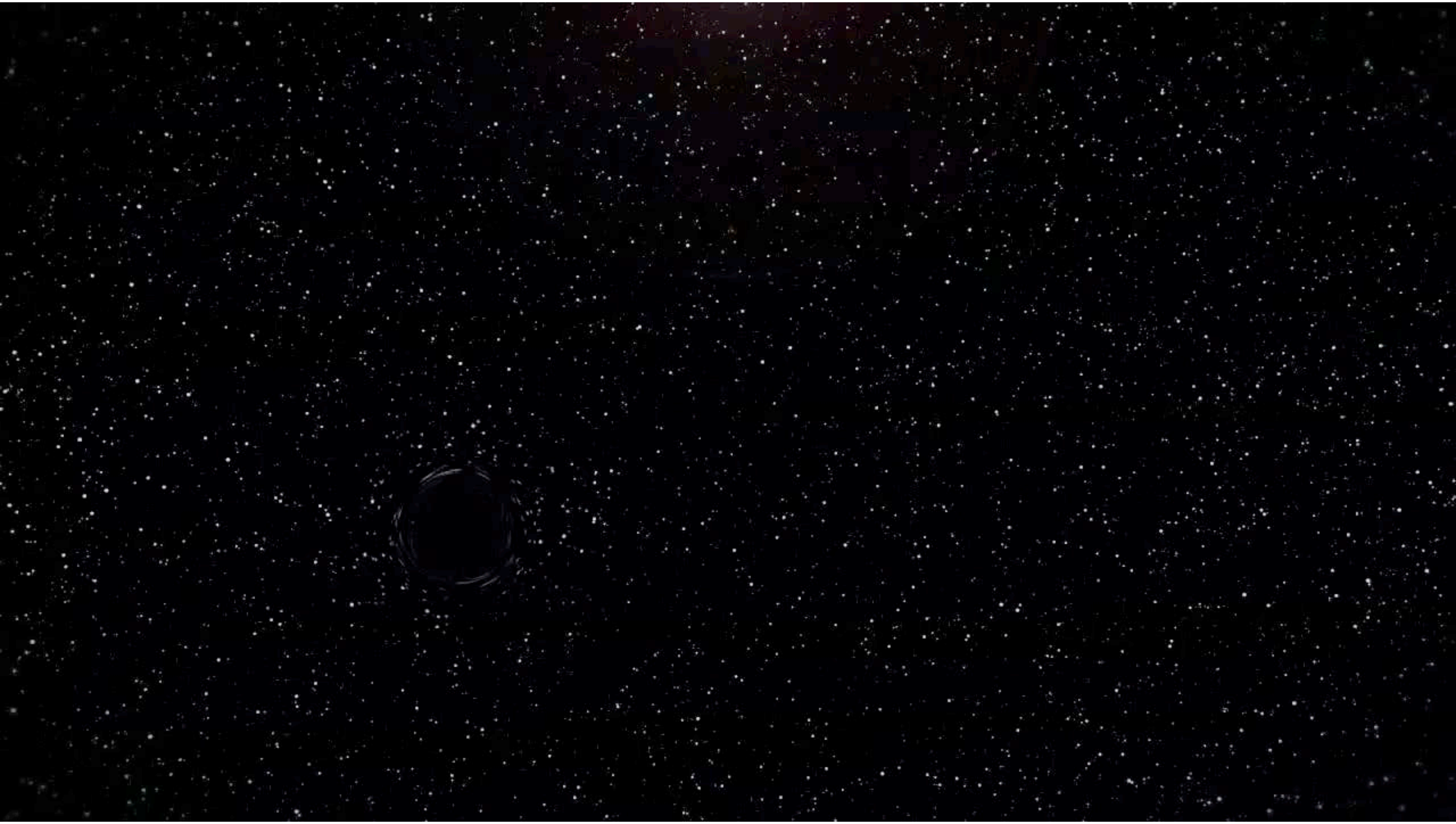
# Fueling a Black Hole by Tidal Disruption

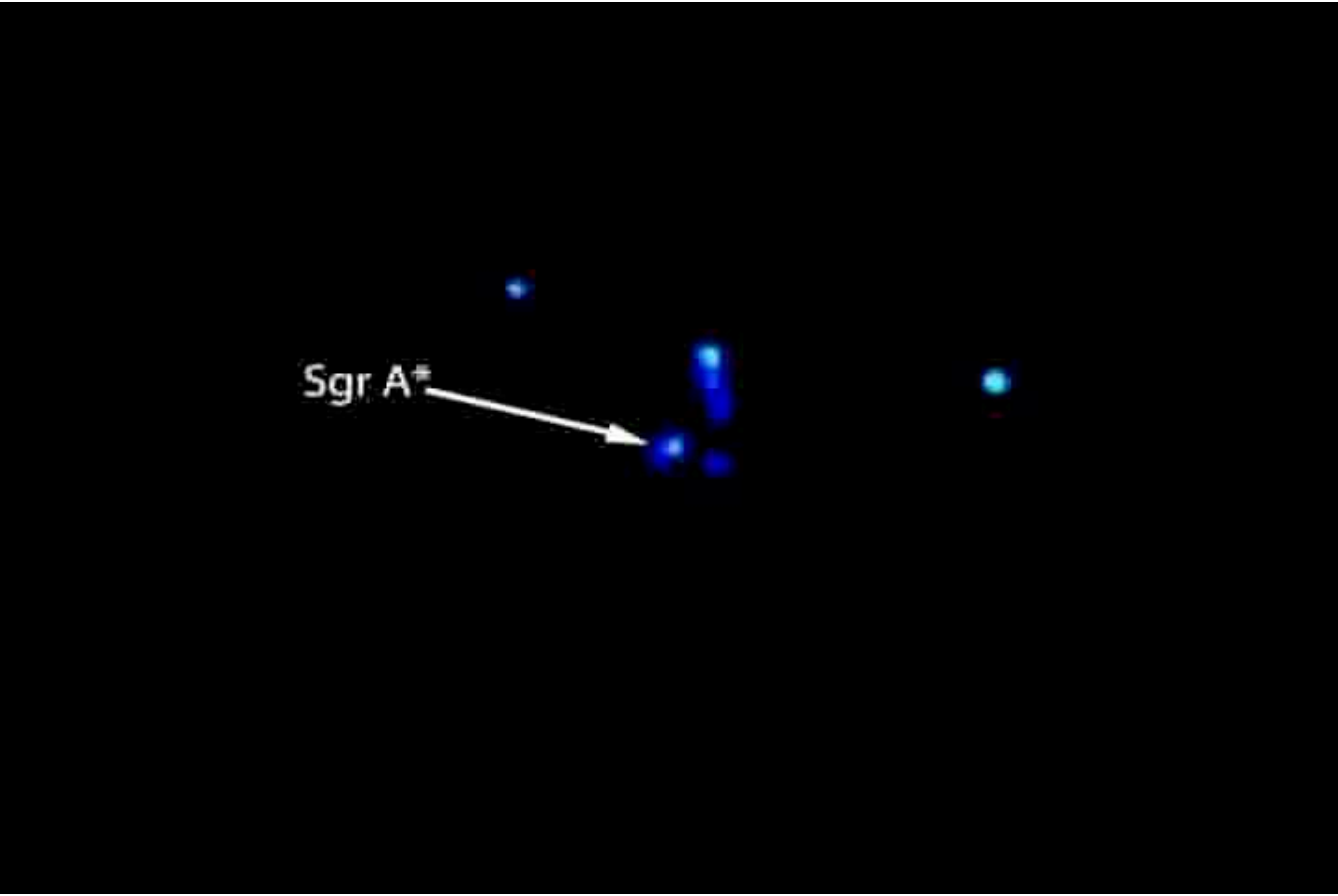
What are the **chances of a tidal disruption happening in Sgr A* ?** Astronomers estimate that these events happen only about **once every 10,000 years**, so the chances are low.

Sagitarius A*

If our Galactic Center's black hole were to tear a star apart, the resulting X-ray source would easily outshine every other X-ray source in the sky besides the Sun, frying the instruments aboard the X-ray satellites *Chandra* and *XMM*!

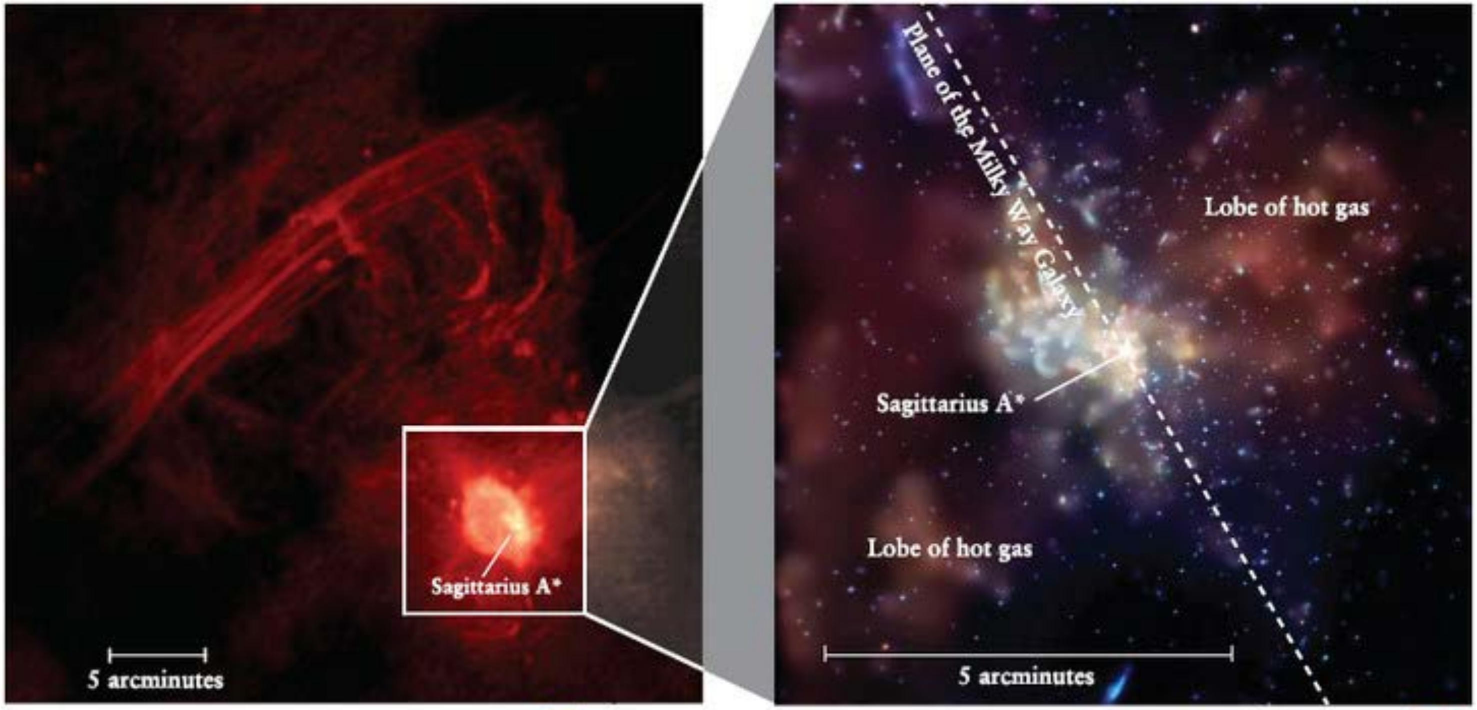
The center of the Milky Way would become a hundred billion times brighter in X-rays than it is now.




Sgr A*

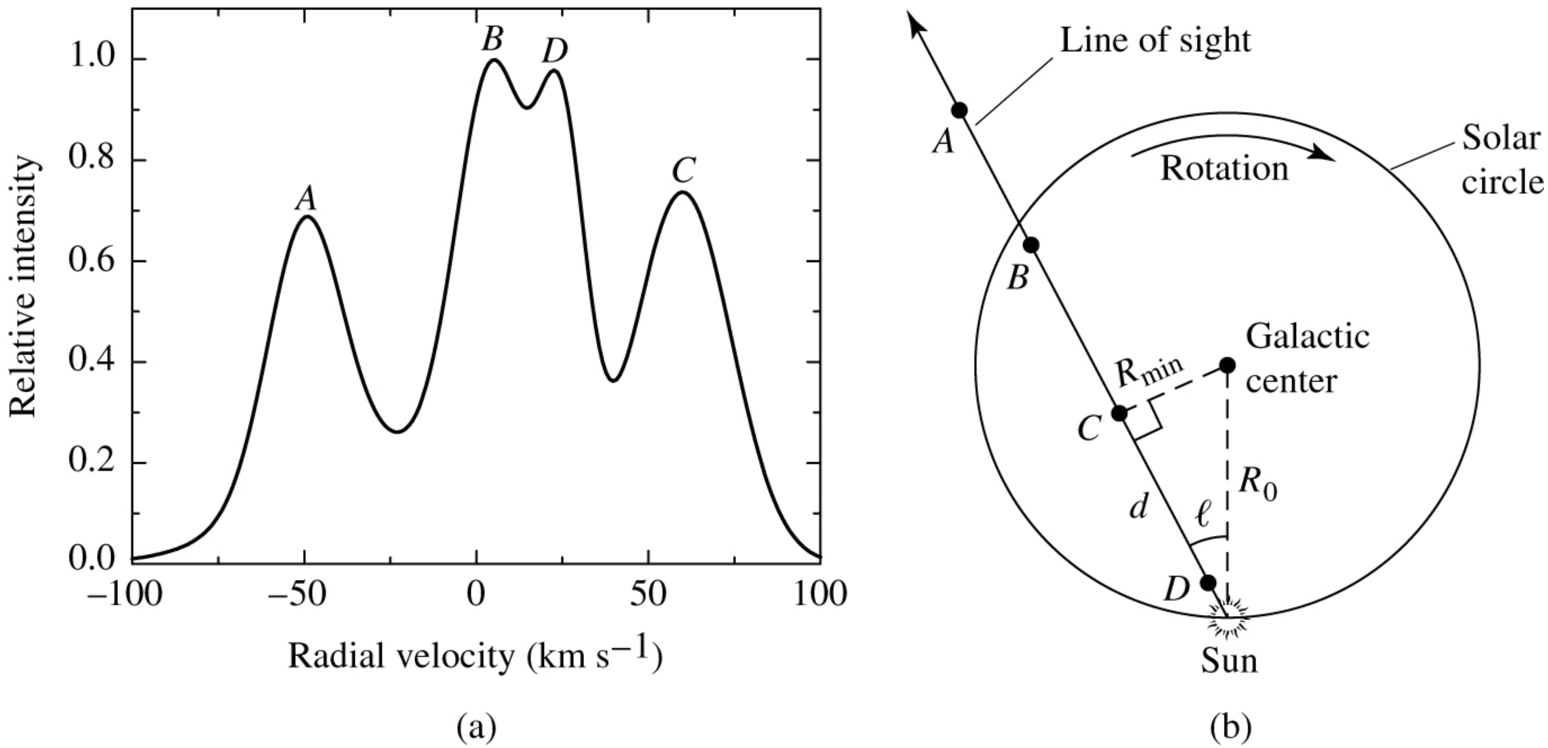

Asteroid Heading toward Black Hole

# Galactic Center: Sagittarius A*




(a) A radio view of the galactic center R I V U X G (b) An X-ray view of the galactic center R I V U X G

X-ray observations of Sgr A* revealed **X-ray flares on timescales of 10 min** which indicates that the emission region must be smaller than the distance travelled by light in 10 min. The **X-ray emission** from Sgr A* **is very feeble** indicating that the fuel supply is very limited. The immediate vicinity of Sgr A* contains lobes of hot, ionized X-ray gas. It is thought that many **explosions** may have taken place here that perhaps **cleared away most of the gas** leaving only a small amount to fall into the black hole.


1.0
0.8
0.6
0.4
0.2
0.0
Relative intensity
–100
–50
0
50
100
Radial velocity (km s−1)
A
B
D
C
(a)
Line of sight
A
B
C
D
Rotation
Solar circle
Galactic center
R_min
R_0
d
ℓ
Sun
(b)

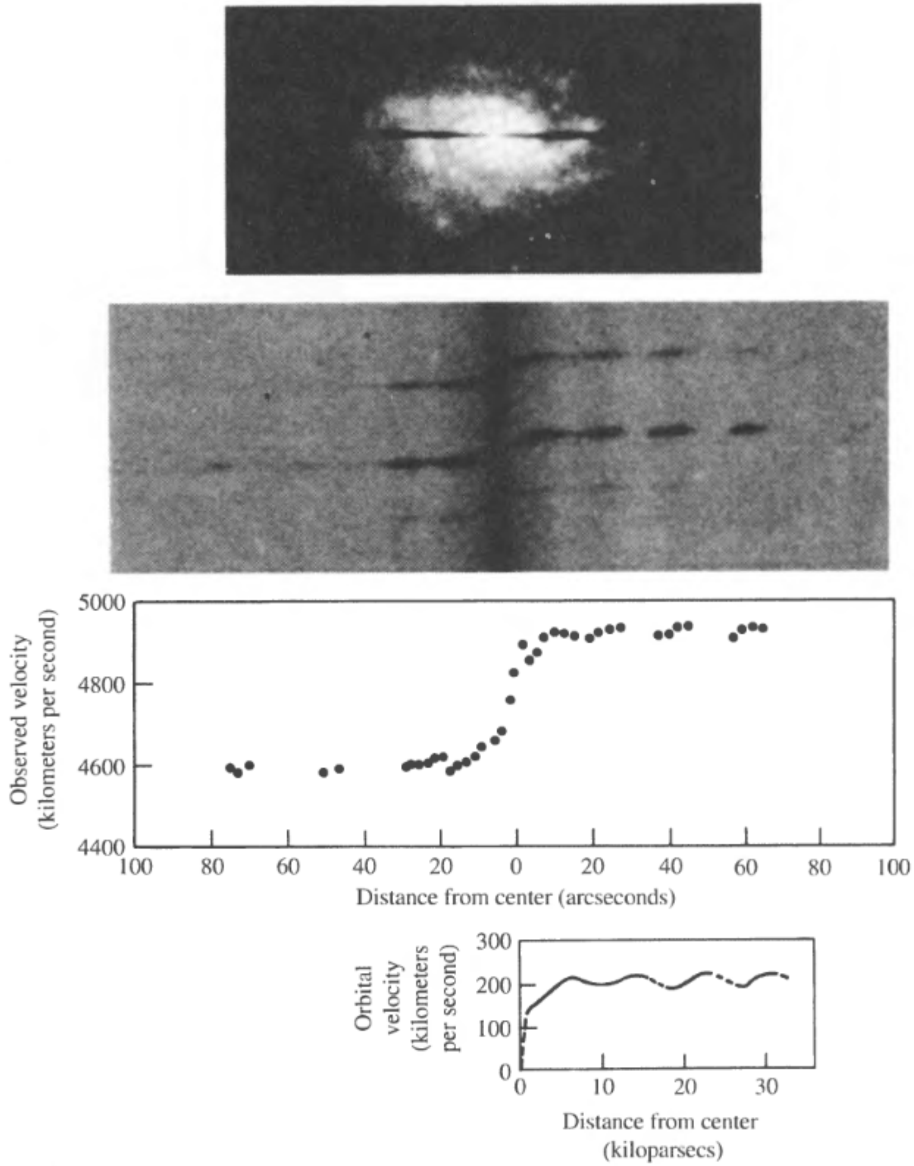



**FIGURE 24.26** The rotation curve of NGC 2998 was measured using a slit spectrograph. The H$\alpha$ wavelength region is shown. Note that overall, the entire galaxy is receding from us at a speed of 4800 km s$^{-1}$. (Adapted from a figure courtesy of Vera Rubin, 1983.)