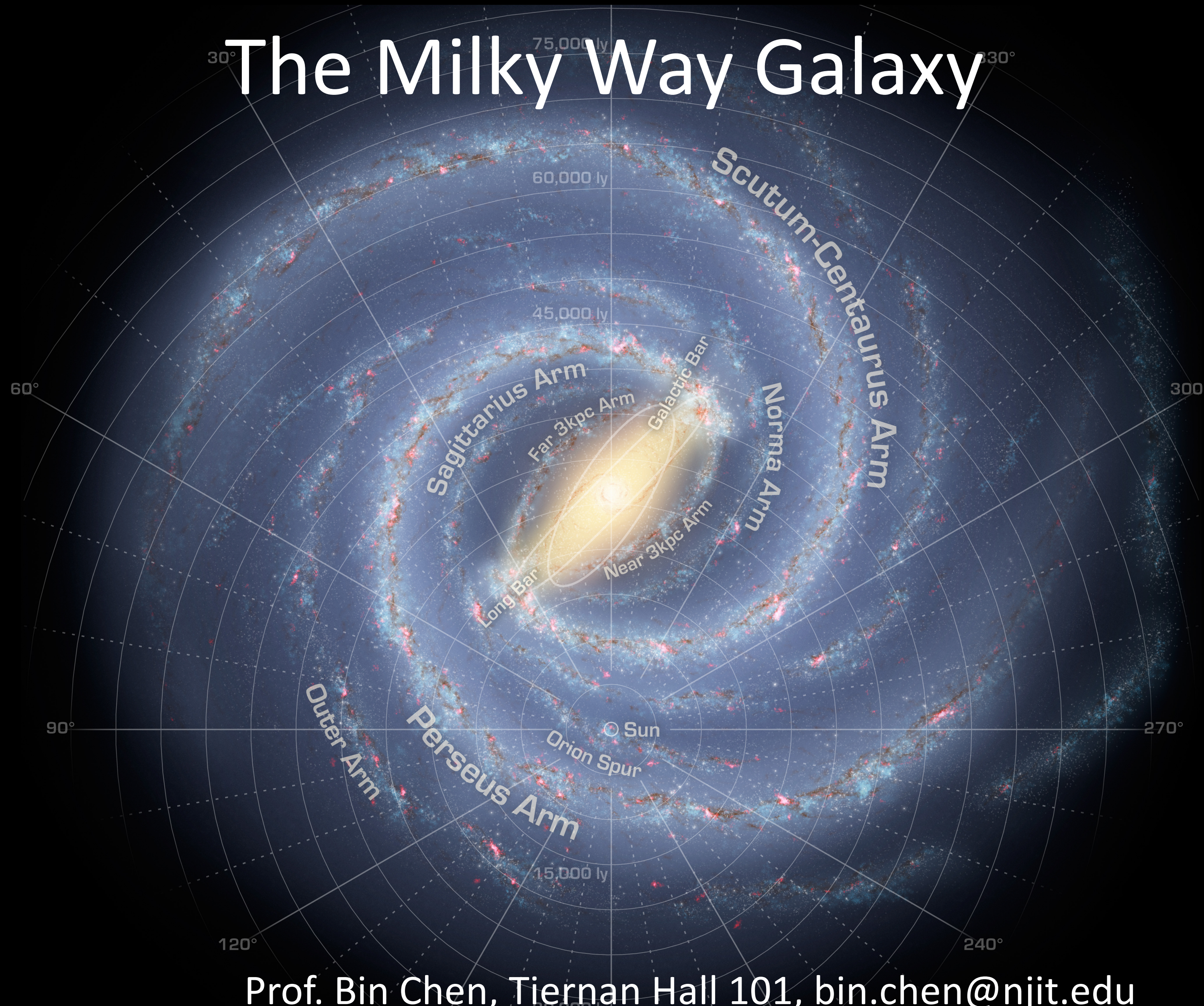
Phys 321: Lecture 9

The Milky Way Galaxy



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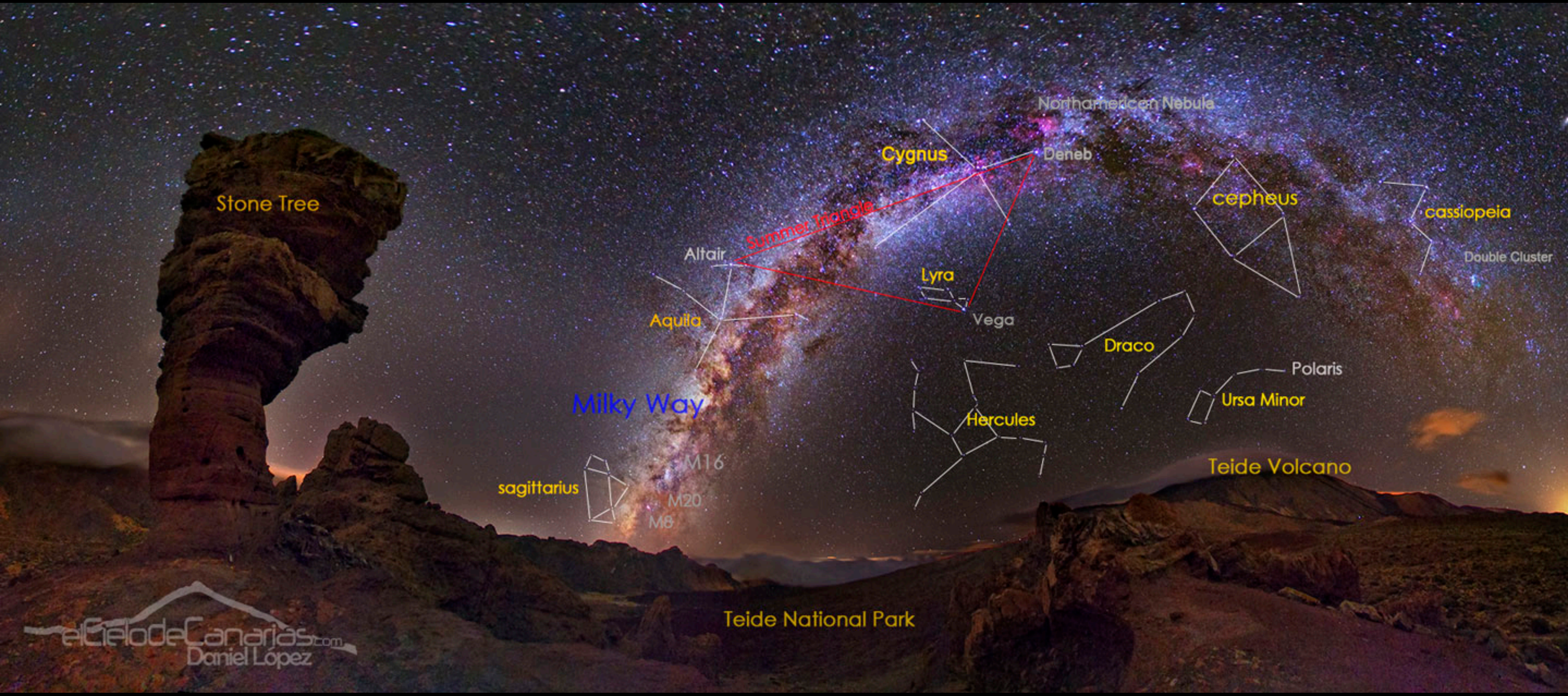
Outline

- Counting Stars
- The Morphology of the Galaxy
- The Kinematics of the Galaxy
- The Galactic Center

The Milky Way in the night Sky

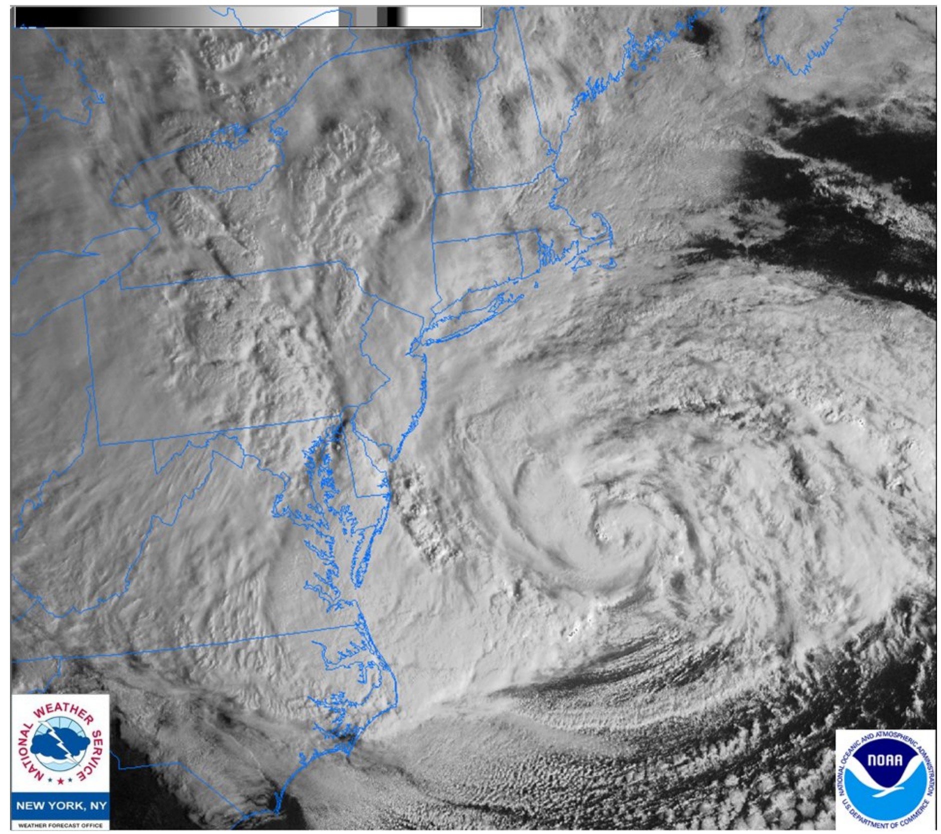
- It is very challenging to understand our own galaxy! Because … we are sitting right in it!



The “milky” fuzzy clouds are actually stars unresolved by our eyes, and the

It’s like … trying to figure out what the hurricane looks like by looking out your window in a (really) rainy day!

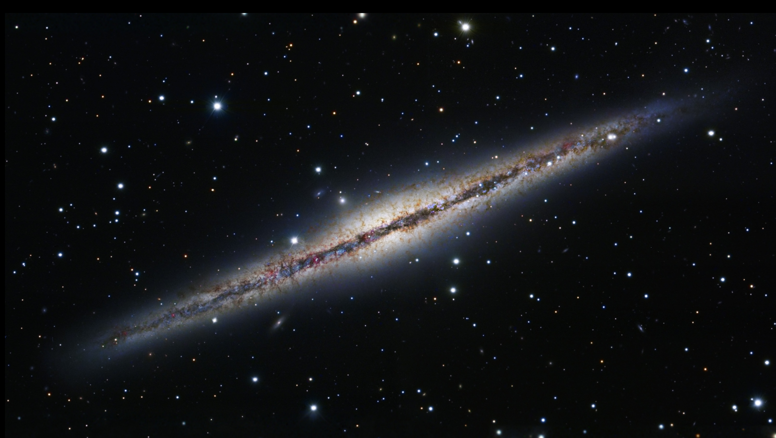
Hurricane Sandy



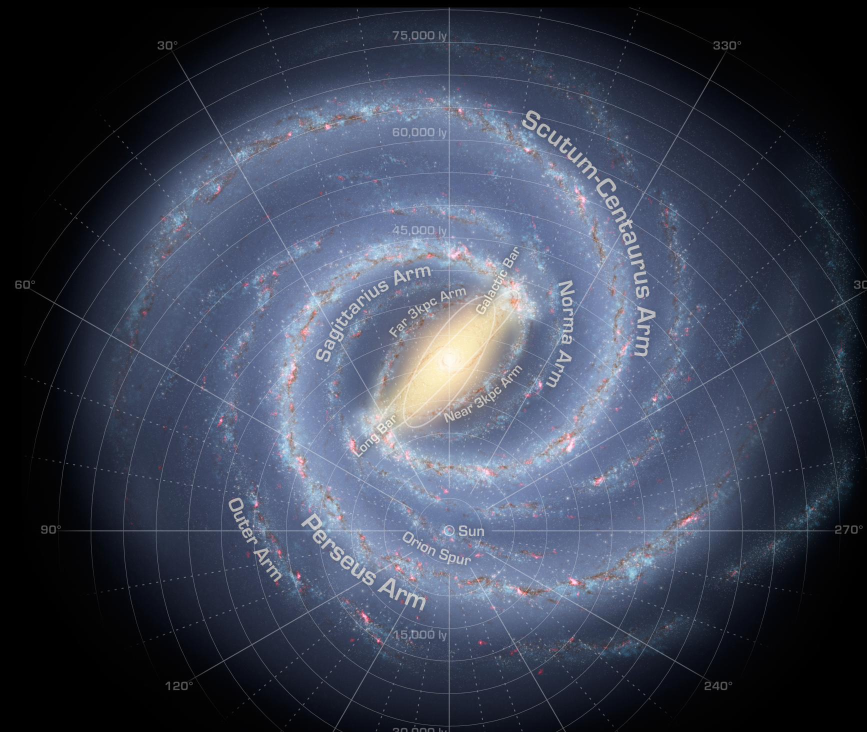
Hurricane Sandy satellite image

What Milky Way would look like?

The Andromeda Galaxy (M31)



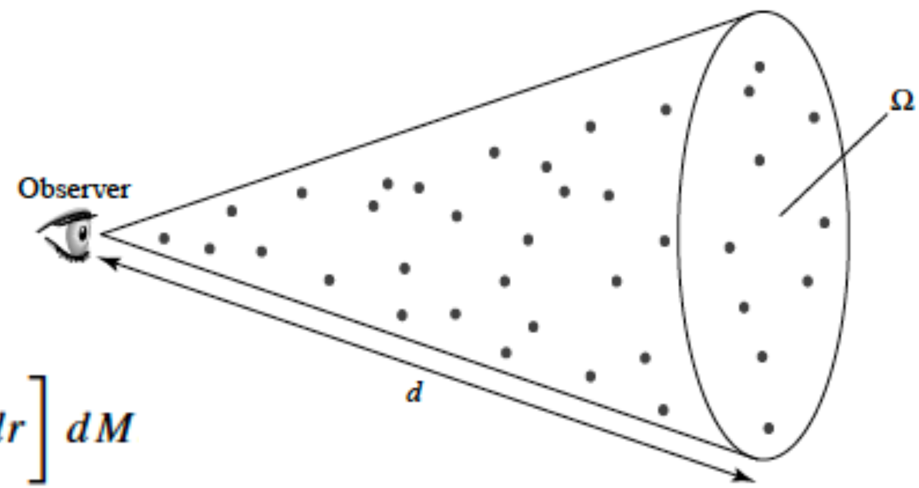
NGC 891



An artist's depiction of the Milky Way Galaxy

Counting Stars

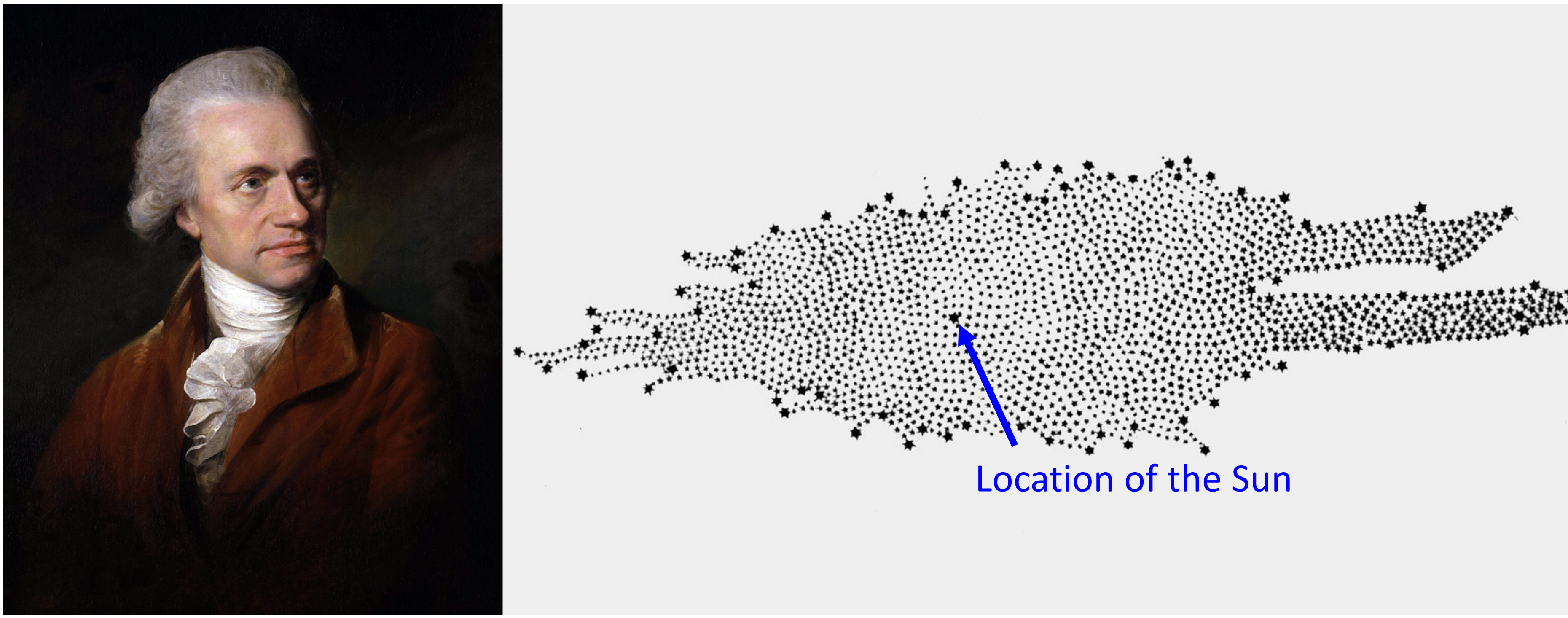
- Galaxies are made of stars
- So we can start from counting the stars
- What we really need is the (differential) number density in all directions and all distances $n_M(M, S, \Omega, r)dM$
- What we observe is $N_M(M, S, \Omega, d)$



They are related by

$$N_M(M, S, \Omega, d)\, dM = \left[\int_0^d n_M(M, S, \Omega, r)\, \Omega r^2\, dr\right] dM$$

First map of the Milky Way Galaxy



Sir William Herschel and his map of the Milky Way Galaxy (1780s)

The Kapteyn Universe

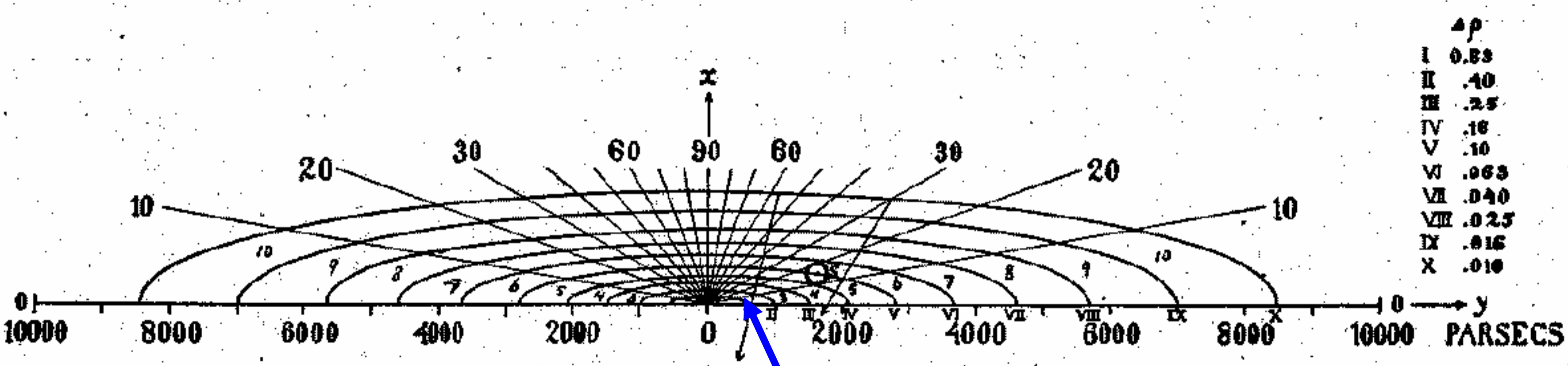


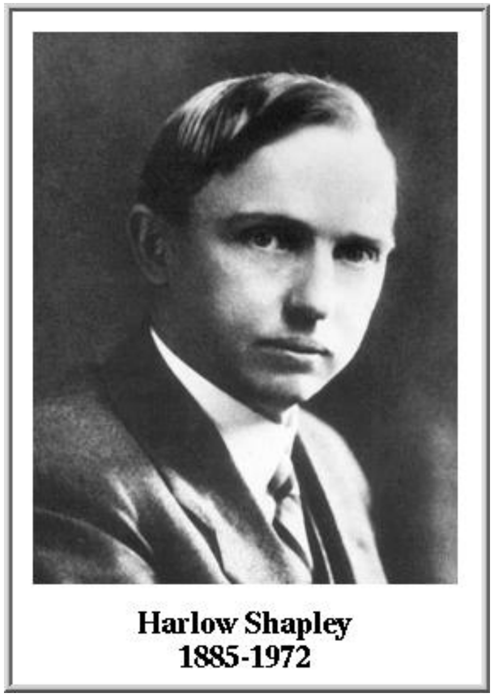
FIG. 1

Location of the Sun

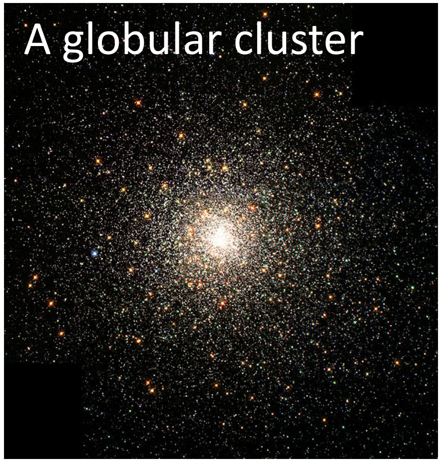
Kapteyn 1922, ApJ, 55, 302

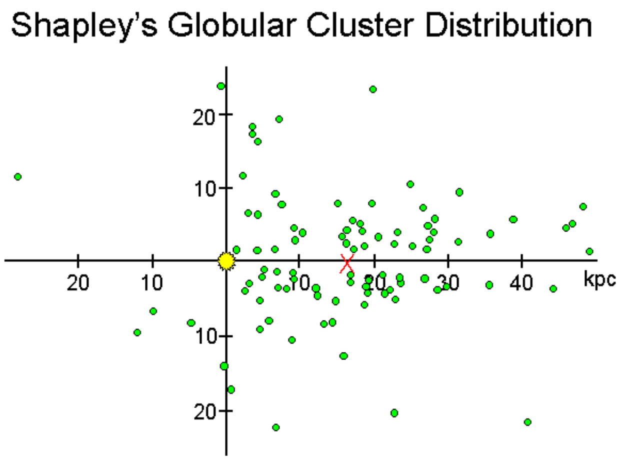
- All early models of the Milky Way Galaxy put the Sun at/near the center, just as ancient theorists put the Earth at the center of the Universe. Something is wrong…
- Why? Interstellar Extinction by molecular clouds and dust

Harlow Shapley's Galactic Model

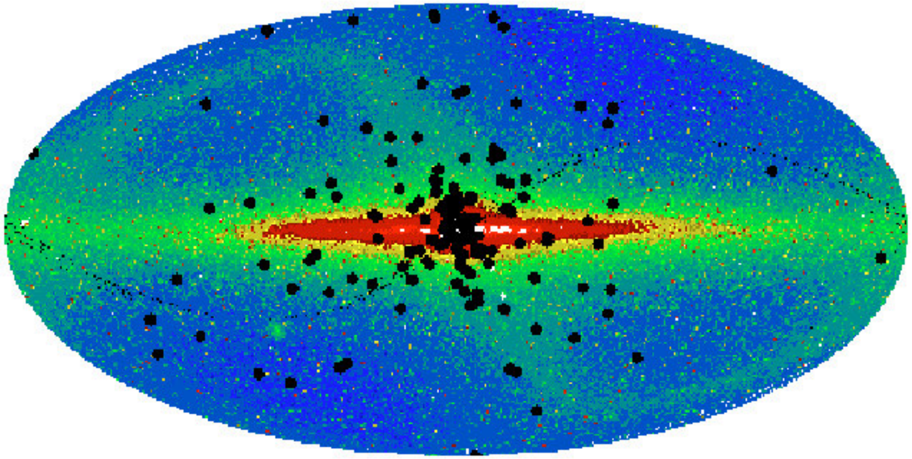


Harlow Shapley
1885-1972





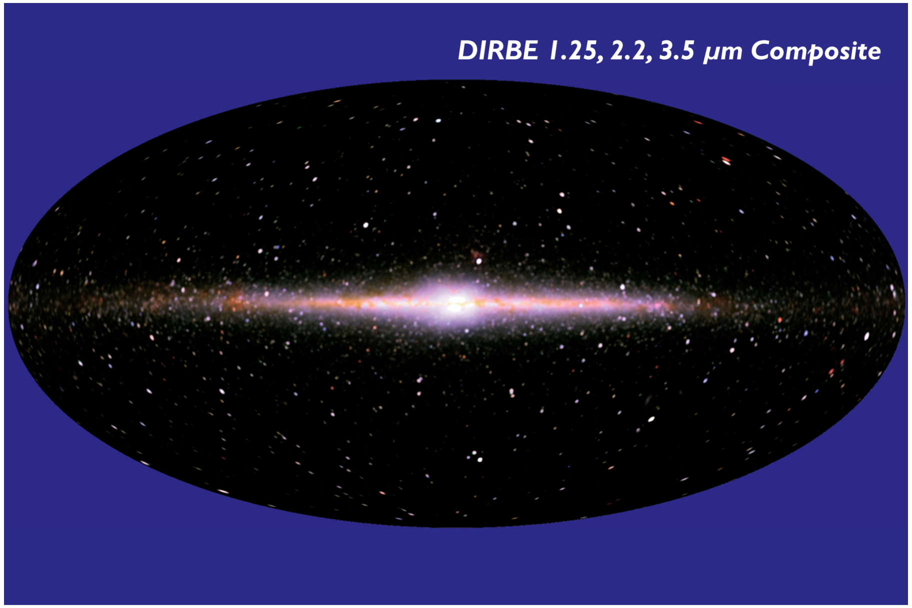
Globular clusters are brighter, and contain variable stars that can be used as standard candles to measure the distance. Shapley also avoided regions +- 10 deg of the Galactic plane, where the strongest extinction occurs



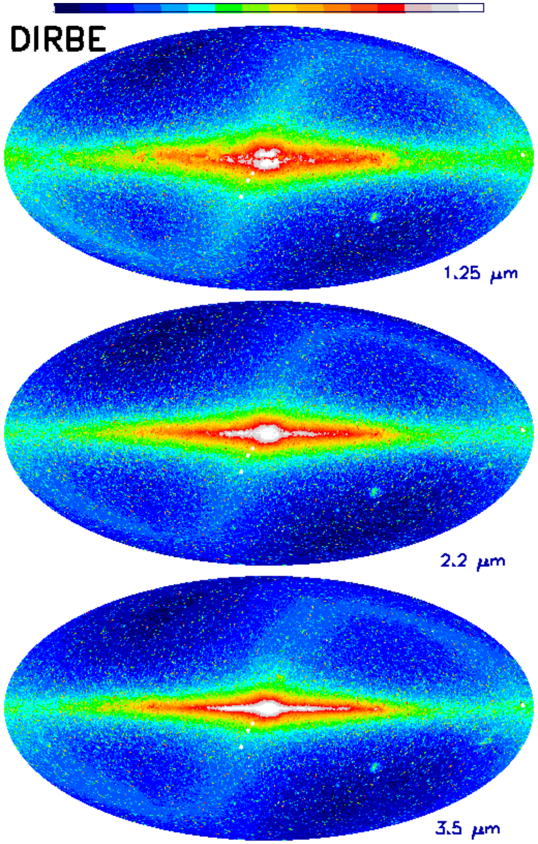
Modern version of globular clusters on an infrared all-sky image

Seeing the Milky Way in Infrared

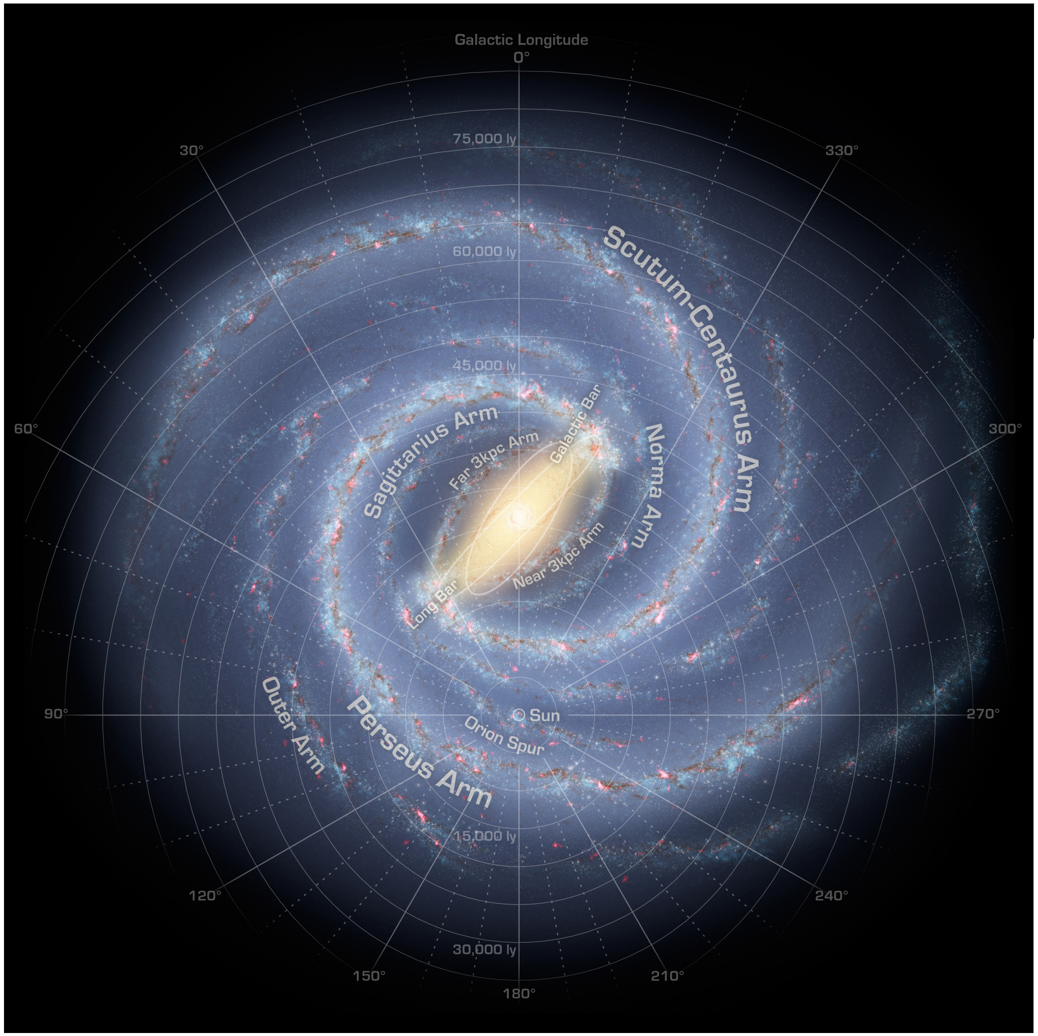
- Today we can observe the Milky Way Galaxy in infrared, the wavelength at which light can easily penetrate dust

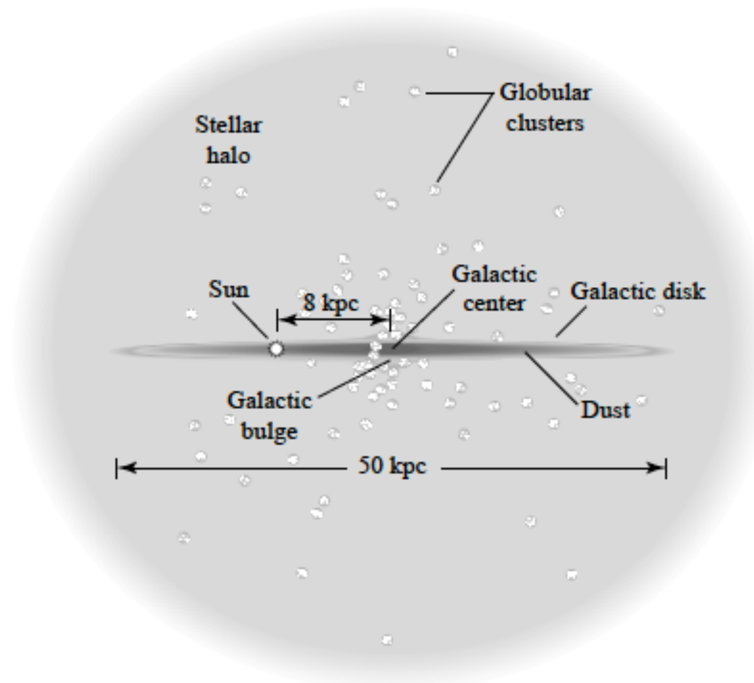


COBE all-sky map in infrared wavelengths



Morphology of the Galaxy





Morphology of the Galaxy

- Most of the stars of the galaxy reside in a disk. Also in the disk are gas clouds, dust, and very young stars. The stars tend to have high metallicity ($Z > 0.01$).
- There is a central bulge of stars near the center of the galaxy that is more spherical in shape. The stars here are older (and redder) than the disk population.
- Globular clusters are distributed in an approximately spherical halo above, below, and within the disk. A small number of high-velocity stars are also seen in this halo region. The stars here are very old, and typically have low metallicity ($Z < 0.001$)

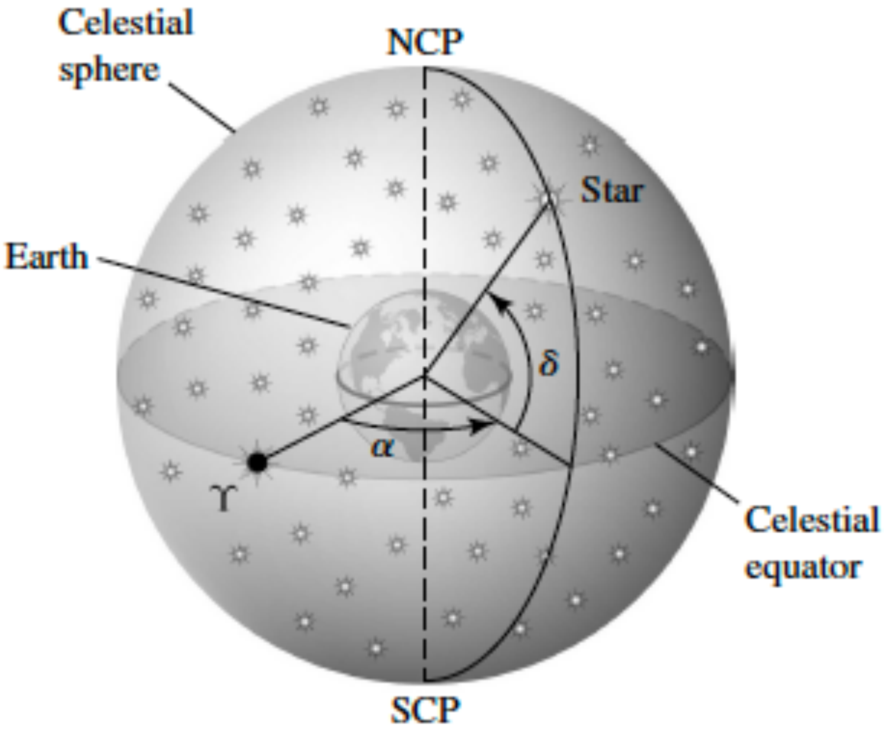
Kinematics of the Galaxy

- Now that we know how the Milky Way Galaxy looks like, we would like to know how things move: Kinematics
- Characterization of the kinematics of the galaxy resulted in great surprise to the astronomers, which are considered to be the primary evidence for the existence of dark matter

Galactic Coordinates

Recap: The Equatorial Coordinate System

Origin: Earth Center
α: Right Ascension (0 to 360 deg)
δ: Declination (-90 to 90 deg)

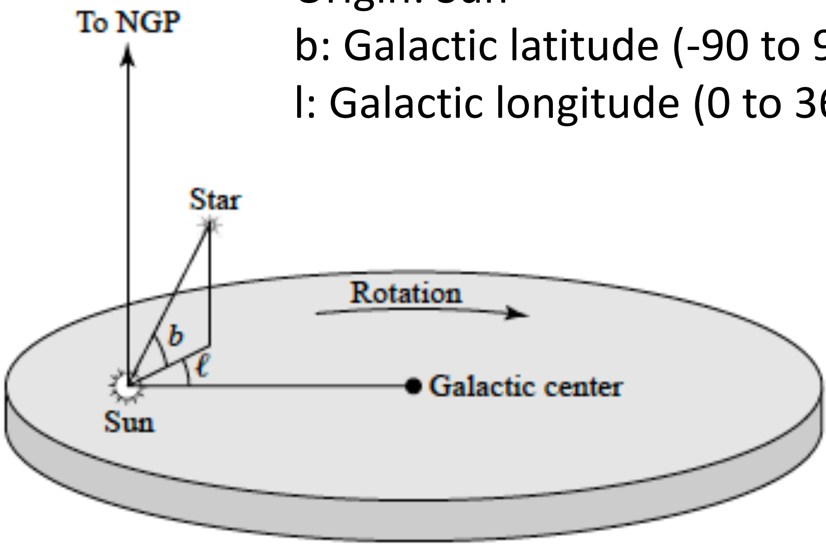


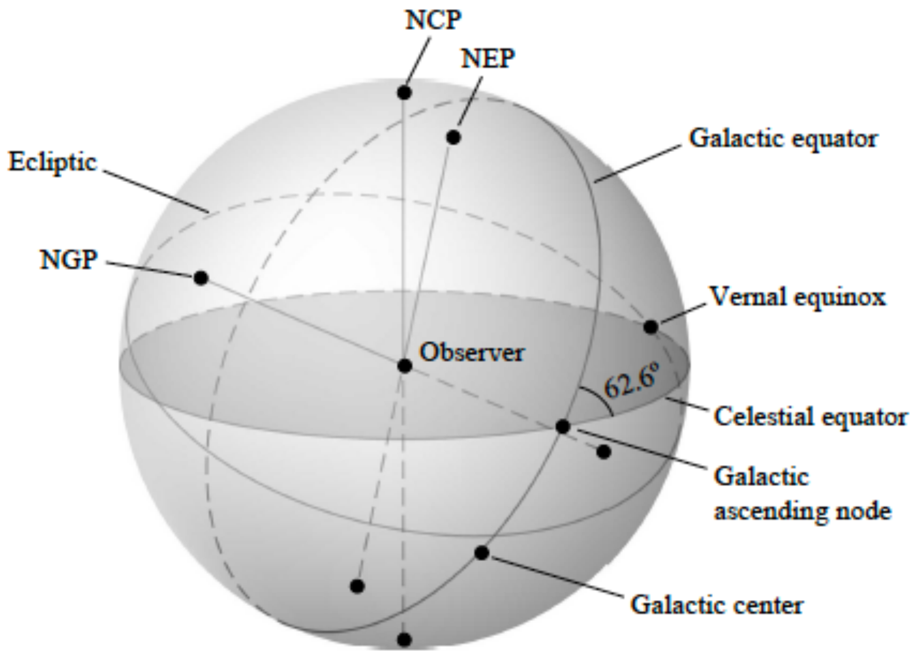
Galactic Coordinates

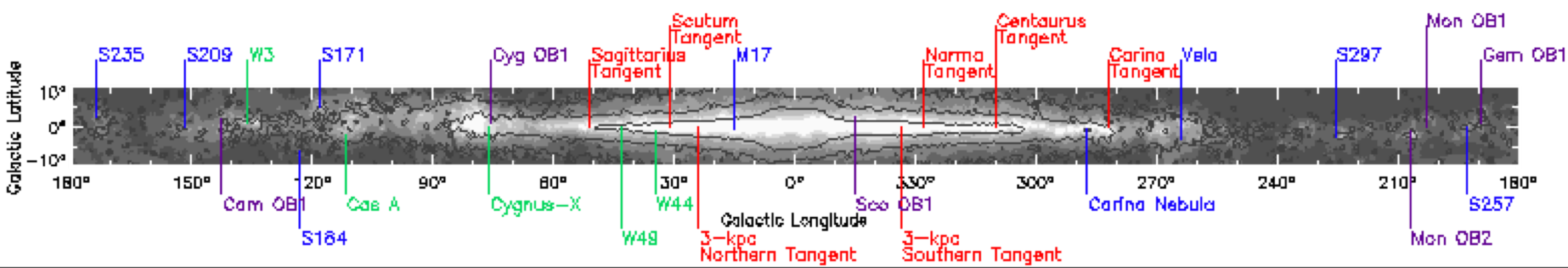
Origin: Sun

b: Galactic latitude (-90 to 90 deg)

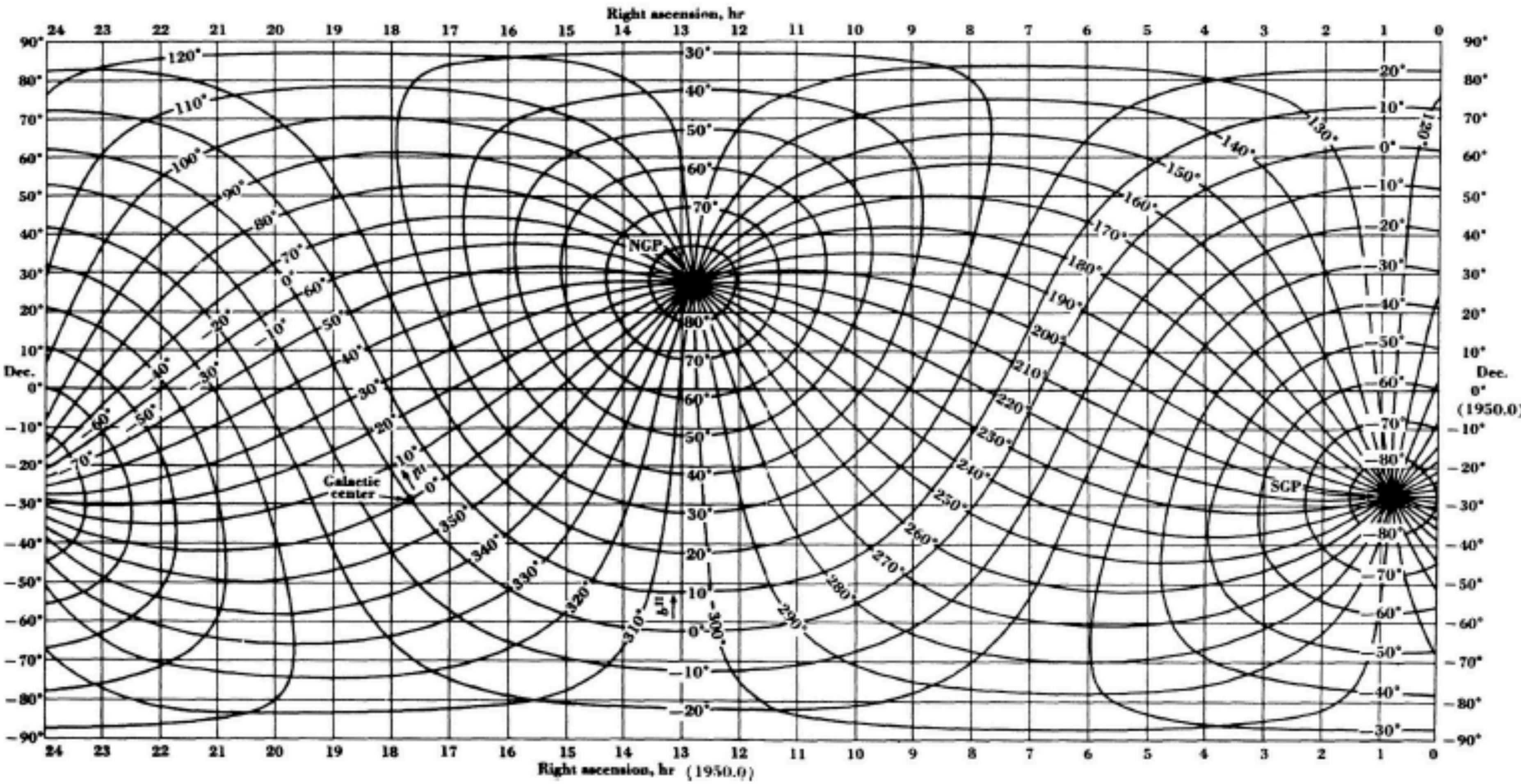
l: Galactic longitude (0 to 360 deg)







Map between Equatorial and Galactic Coordinate System

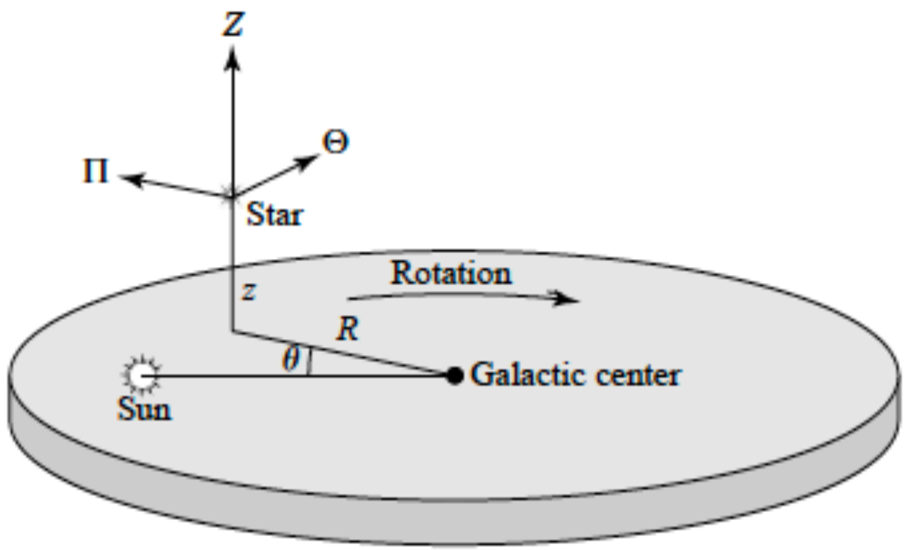


Characterizing stellar kinematics

Goal: Measuring stellar velocity w.r.t. the Galaxy

$$\Pi \equiv \frac{dR}{dt}, \qquad \Theta \equiv R\frac{d\theta}{dt}, \qquad Z \equiv \frac{dz}{dt}.$$

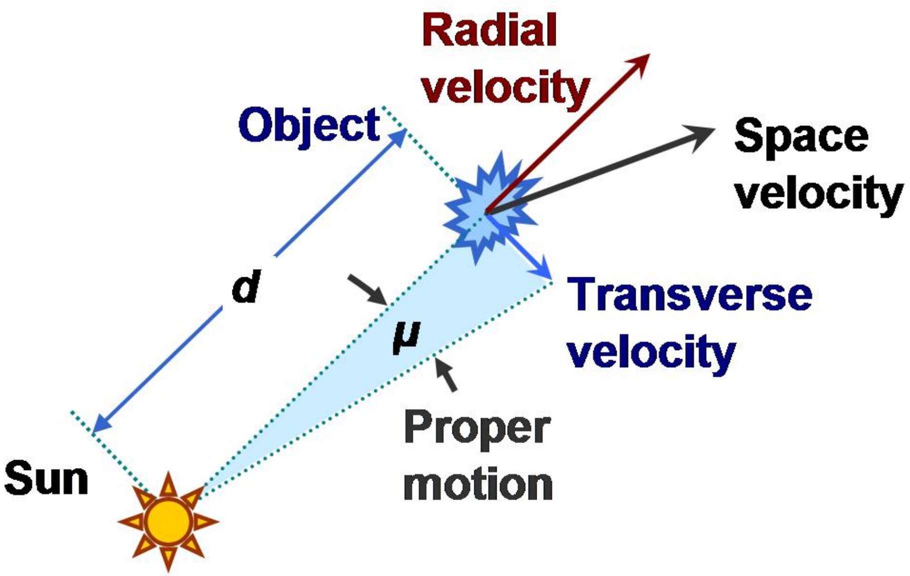
Radial Angular Vertical



The Cylindrical Coordinate System

Left-handed system

But all observations have been made from Earth (at least for now)!



Proper Motion μ

Radial Velocity v_r

$$\frac{\lambda_{\rm obs} - \lambda_{\rm rest}}{\lambda_{\rm rest}} = \frac{\Delta\lambda}{\lambda_{\rm rest}} = \frac{v_r}{c}$$

Observed changes of stellar position, in angular units, in the sky as a function of time, comparing to the background of more distant stars (usual unit: arcsec/yr)

$$\mu = v_t / d$$

Barnard’s star, μ~10.3”/yr (largest of all stars)

The **radial velocities (v_r) and transverse velocities** (**v_t** = proper motion times distance) of stars measured from an Earth-based observer are the relative velocities w.r.t. to our Earth. We know how the Earth revolves around the Sun pretty well, so they can be transformed to **relative velocities of stars w.r.t. the Sun**

But our Sun is just one of the many stars in the Galaxy, which

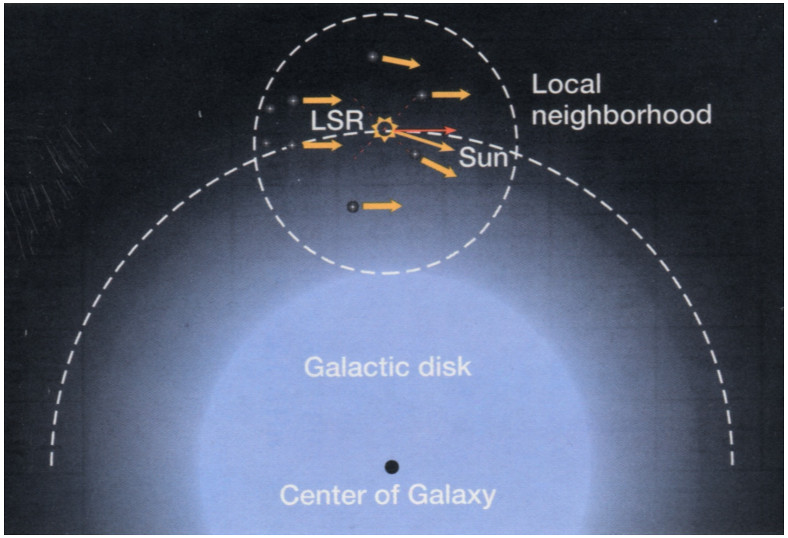
- Shares the ***general rotation*** of the Galaxy, and
- Has its own ***peculiar motion*** superimposed on this general rotation

Need to **subtract the Sun's motion** out in order to recover the true stellar kinematics w.r.t. the Galaxy. But how?

Local Standard of Rest (LSR)

A reference point in LSR is

- *Instantaneously* centered on the Sun, and
- Moving in a *perfectly circular orbit* along the solar circle about the Galactic center

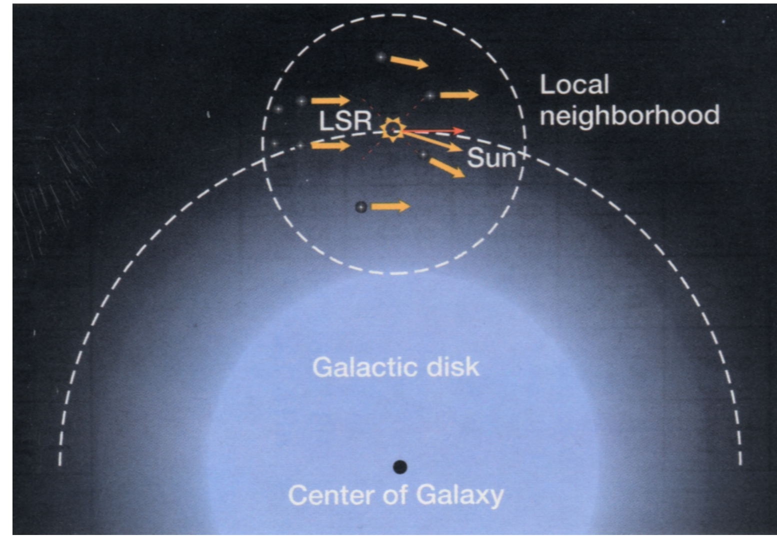


Velocity components of the LSR are

$$\Pi_{\mathrm{LSR}} \equiv 0, \qquad \Theta_{\mathrm{LSR}} \equiv \Theta_0, \qquad Z_{\mathrm{LSR}} \equiv 0,$$

Peculiar velocity relative to LSR

$$\mathbf{V} = (V_R, V_\theta, V_z) \equiv (u, v, w)$$



Where

$$u = \Pi - \Pi_{\text{LSR}} = \Pi,$$

$$v = \Theta - \Theta_{\text{LSR}} = \Theta - \Theta_0,$$

$$w = Z - Z_{\text{LSR}} = Z.$$

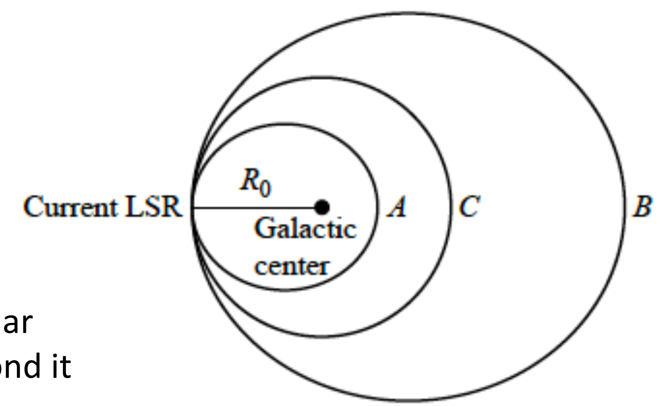
As the general motion of the stars in the solar neighborhood should coincide with the LSR, the average motion of all stars in the solar neighborhood should have

$$\langle u \rangle = \frac{1}{N} \sum_{i=1}^{N} u_i \simeq 0,$$

but $\langle v \rangle < 0.$

$$\langle w \rangle = \frac{1}{N} \sum_{i=1}^{N} w_i \simeq 0.$$

As more stars reside inside the solar Galactocentric distance than beyond it



Peculiar velocity of the Sun

Measured velocity of a star relative to the Sun (after decomposing to R, θ, z direction)

$$\Delta u \equiv u - u_\odot, \qquad \Delta v \equiv v - v_\odot, \qquad \Delta w \equiv w - w_\odot$$

Take the averaged values of neighborhood stars

$$\langle u \rangle = 0 \qquad u_\odot = -\langle \Delta u \rangle,$$

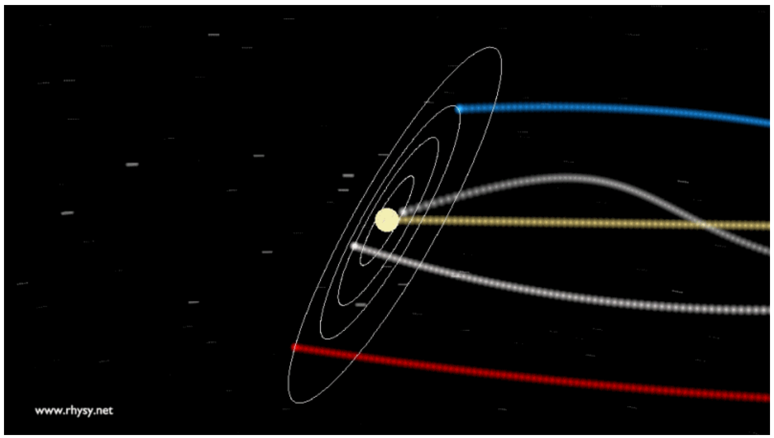
As $\langle v \rangle < 0 = C\sigma_u^2$ $\qquad v_\odot = \langle v \rangle - \langle \Delta v \rangle,$

$$\langle w \rangle = 0 \qquad w_\odot = -\langle \Delta w \rangle.$$

Stellar astronomers find

$$u_\odot = -10.0 \pm 0.4 \text{ km s}^{-1},$$
$$v_\odot = 5.2 \pm 0.6 \text{ km s}^{-1},$$
$$w_\odot = 7.2 \pm 0.4 \text{ km s}^{-1},$$

Peculiar velocity of the Sun



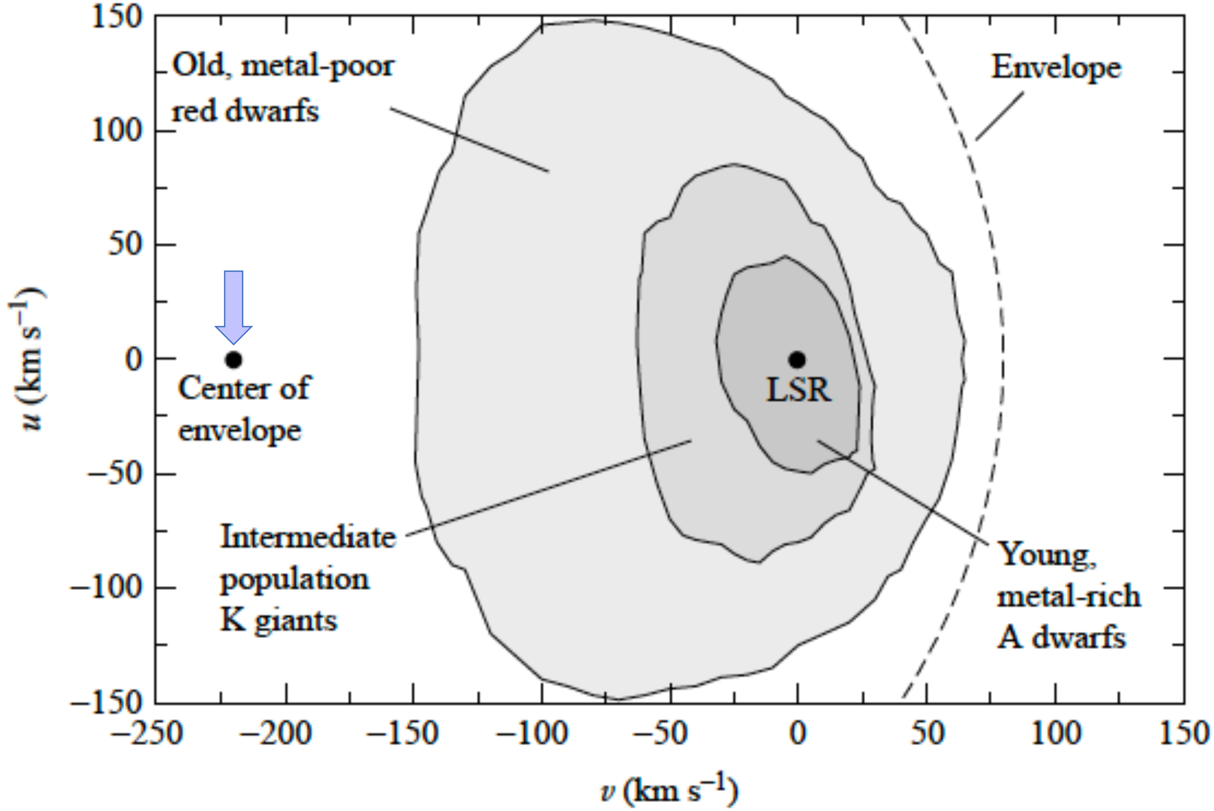
$$u_\odot = -10.0 \pm 0.4 \text{ km s}^{-1},$$
$$v_\odot = 5.2 \pm 0.6 \text{ km s}^{-1},$$
$$w_\odot = 7.2 \pm 0.4 \text{ km s}^{-1},$$

The Sun is flying at 13.4 km/s in the Galaxy (relative to other stars in its neighborhood)!

That is 30,000 miles per hour!

The point toward which the Sun is moving is called the **solar apex**; the point away from which the Sun is retreating is the **solar antapex** (see problem set #8)

Orbital speed of LSR



Orbital speed of LSR: $\Theta_0\,(R_0) = 220\ \mathrm{km\ s^{-1}}$ at R_0 = 8.5 kpc

Orbital speeds

- Orbital speed contains important information on the mass *interior* to the orbit

Kepler's 3rd law: P^2/R^3 = constant

Newton's law of gravity: $F = GMm/R^2$

Which gives $P^2 = (4\pi^2/GM)R^3$

For orbital motion, period is related to orbital velocity by

$$P = 2\pi R / V$$

So the orbital speed is

$$V = (GM/R)^{1/2} \sim R^{-1/2}.$$

If all the mass is within the orbit, orbit speed **decreases** with radius R

Orbit speeds

However, if we have a homogenous, spherical distribution of mass

The orbital speed **increases linearly** with radius R, or V/R = constant:
a **rigid-body rotation** with constant angular speed ω throughout the volume -> this is the case for the Milky Way Galaxy from close to the center to a few kpc

The way the mass is distributed within the galaxy is the key that determines how the orbital speed changes with R. In other words, we can use the measured **Galactic Rotation Curve**, V(R), to constrain **how the mass is distributed in the Galaxy**.

Galactic Rotation Curve

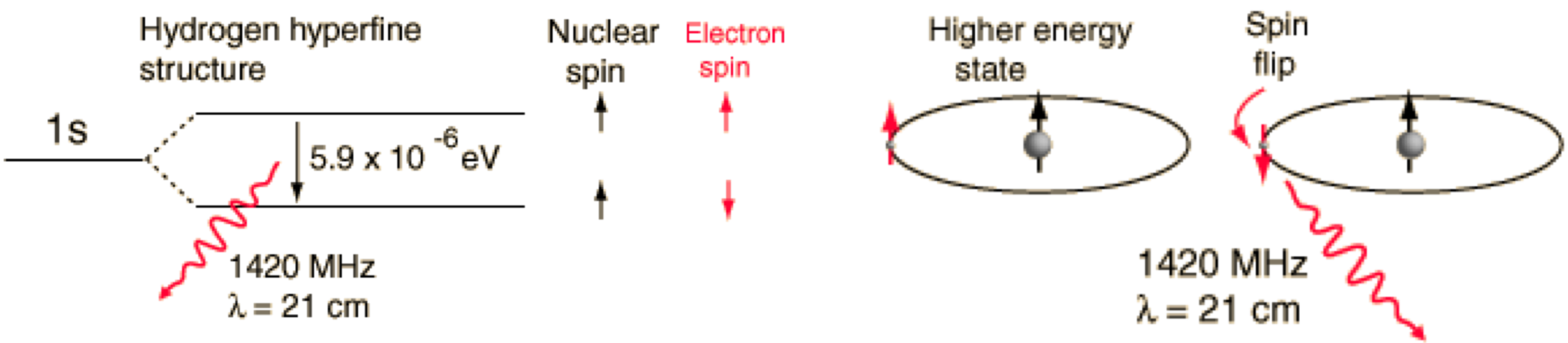
- We know rotation speed in the solar neighborhood by measuring radial velocity and proper motion of nearby stars

$$\Theta_0\,(R_0) = 220\ \mathrm{km\ s^{-1}}$$

- How about more distant stars in the disk through out the distribution of R?
- Difficult to do the same due to extinction!
- Hydrogen 21-cm line observation serves an excellent tool!

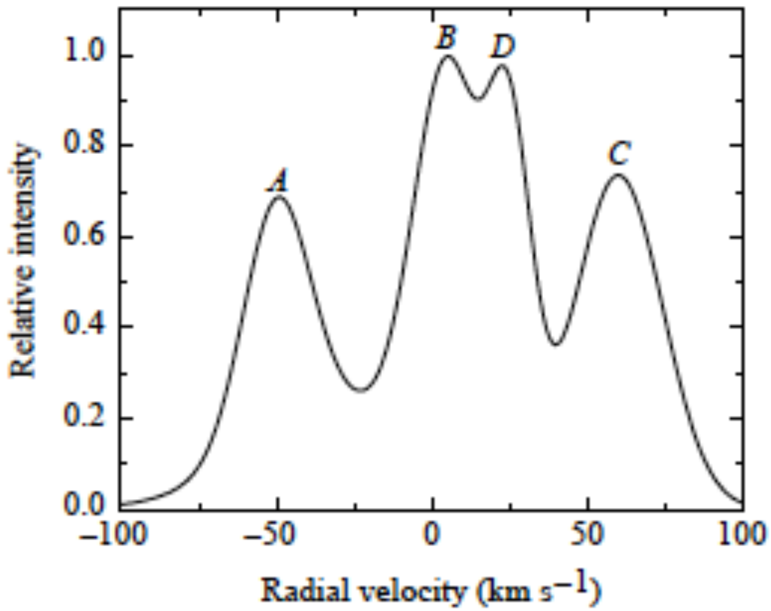
Hydrogen 21-cm line

- Comes from the transition between the two levels of the hydrogen 1s ground state, split by the interaction between the electron spin and nuclear spin

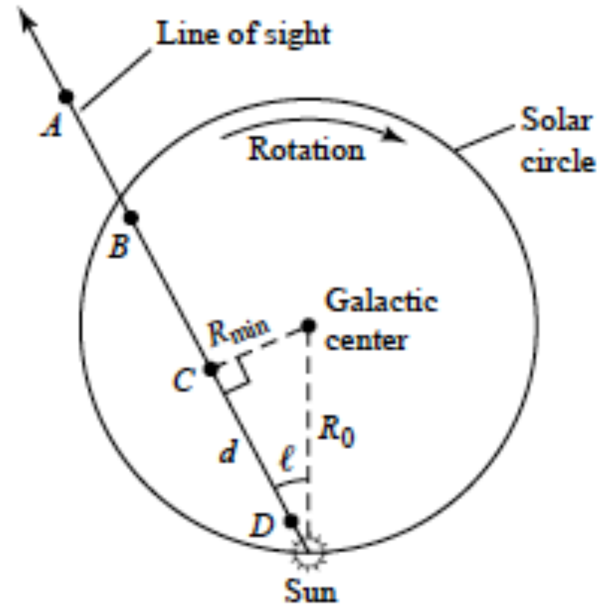


- Such emission from neutron hydrogen can easily penetrate the dust cloud, so there is very little **obscuration**

Measuring Galactic Rotation Curve



(a)



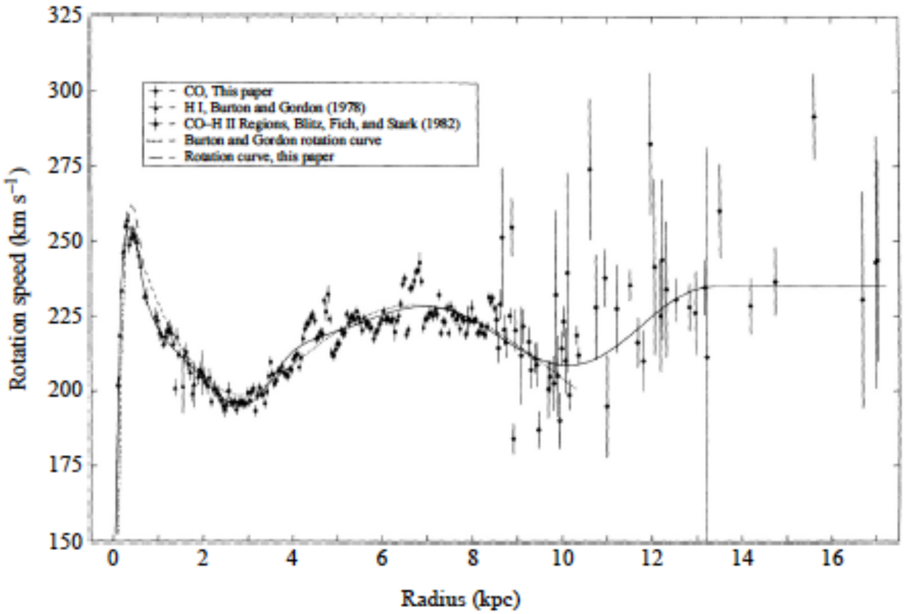
(b)

$$V(l)_{max} = V(R_{min}) = V(R_0 \sin(l))$$

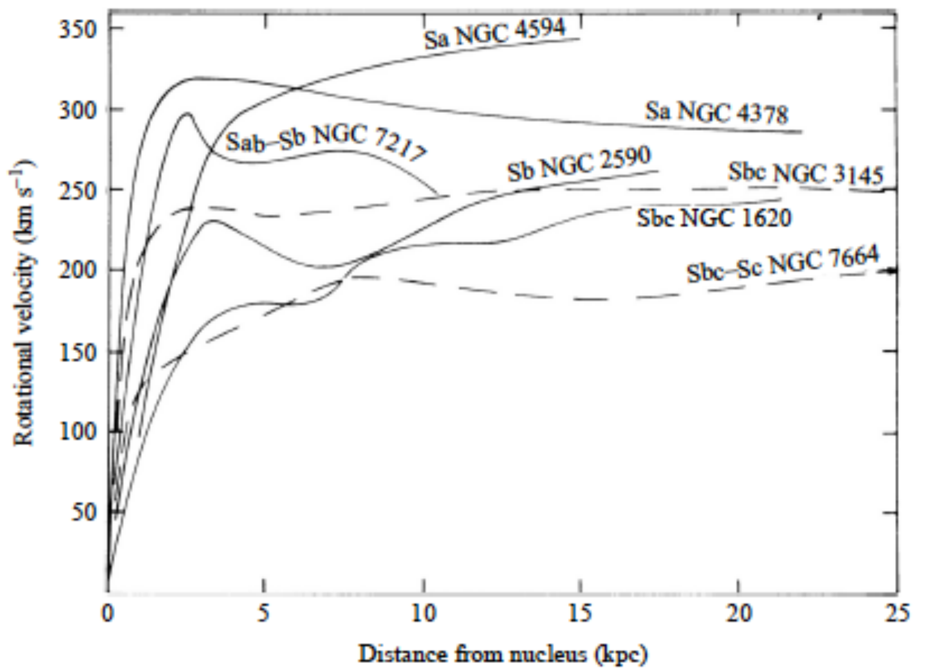
- Does not work near l = 90 or 270 deg
- Does not work for distances beyond R_0 = 8.5 kpc

Galactic Rotation Curves

The Milky Way Galaxy



Other galaxies



The rotation curves V(R) become **flat** beyond several kpc. What does this mean?

Flat Galactic Rotation Curves

Newton's law of gravity

$$\frac{mV^2}{r} = \frac{GM_r m}{r^2},$$

Centripetal Force

Gravitational Force

Solving for Mr: $M_r = \dfrac{V^2 r}{G}$

Take a derivative over r, noting that V is a constant: $\dfrac{dM_r}{dr} = \dfrac{V^2}{G}.$

Mass within a spherical shell from r to r + dr with density ρ: $\dfrac{dM_r}{dr} = 4\pi r^2 \rho,$

Combine the two equations above: $\rho(r) = \dfrac{V^2}{4\pi G r^2}.$

The r^{-2} density dependence drops much slowly than the luminous stellar halo, which varies as $r^{-3.5}$ -> The mass continues to grow with r even at great distance from the galactic center (why?) — Mass invisible to us, or **dark matter**!

Density Profile of Dark Matter Halo

The density profile on the previous slide diverges at r = 0

$$\rho(r) = \frac{V^2}{4\pi G r^2}.$$

A commonly used version that includes constant value near the center

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

Another universal profile proposed by Navarro, Frenk, and White in 1996 based on simulations of cold dark matter

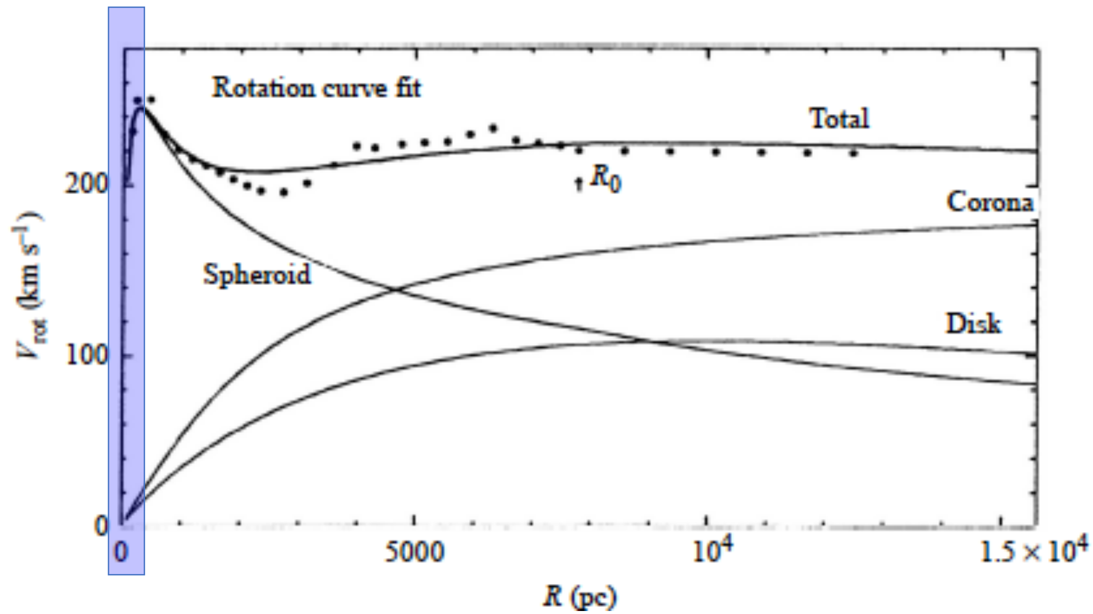
$$\boxed{\rho_{\mathrm{NFW}}(r) = \frac{\rho_0}{(r/a)(1 + r/a)^2}}$$

Dark Matter

- We know something massive exists through their gravitational influence
- But what are they?
  - Gas: No, should see absorption or emission lines of stars shining through it
  - Dust: No, dust causes extinction of starlight, and glows in infrared
  - MACHOs—Massive, compact halo objects? (e.g. small, faint stars such as black dwarfs [dead white dwarfs], brown dwarfs [failed stars], neutron stars, or black holes)?
  - WIMPs--Weakly interacting massive particles? (e.g. neutrinos, or some as-yet-undiscovered particle)?

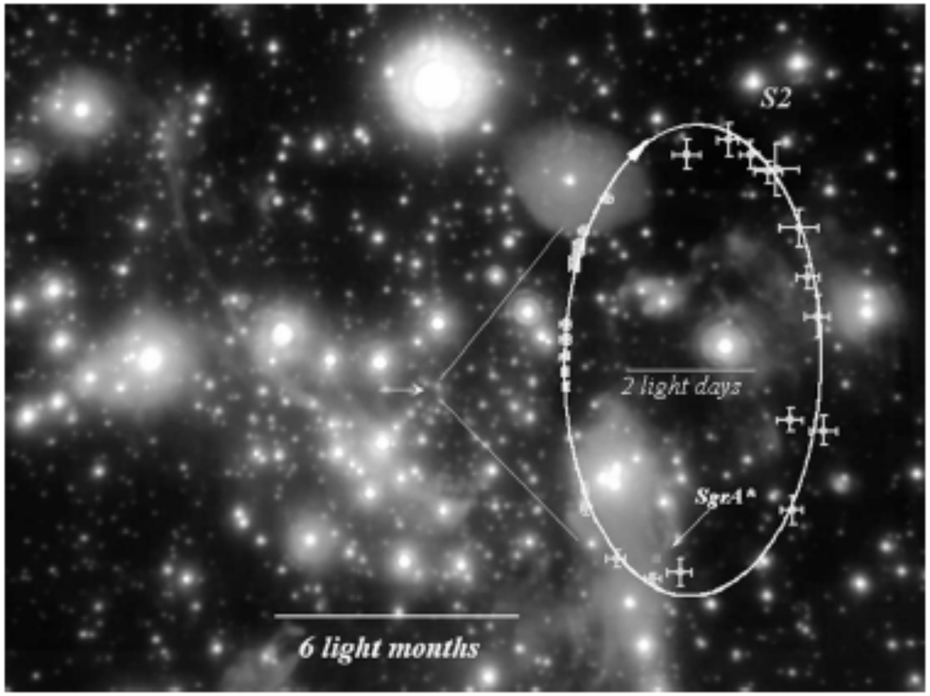
The Galactic Center

- At the inner region of the Galaxy, the rotation curve represents a **rigid body**, where $\omega = V/r \sim$ constant, or $V \sim r$
- At the central region of the Galaxy, the density is large, and there is enough close encounters to make the stellar distribution close to a nearly ***isothermal "stellar gas"***
- In a spherical symmetric case, it implies density $\rho \sim r^{-2}$, which is pretty close to the observed density variation $\rho \sim r^{-1.8}$

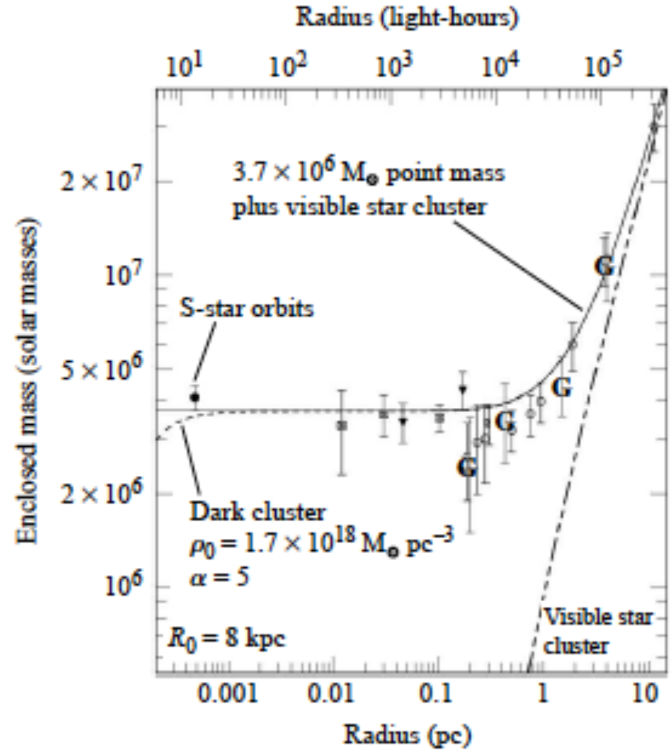


- However, at the very center (< 2 pc), the density dependence becomes much steeper than r^{-2} -> **Something massive is occupying a very small volume**!

Orbits of stars very close to the Galactic Center



Orbit of Star S2 about the Galactic Center



- Semi-axis of S2's orbit: ~933 AU, or 1.4×10^{14} m
- Orbital period 15.2 yr
- Using Kepler's 3rd law, the mass within its orbit (only a few times the semimajor axis of Pluto's orbit) amounts to 3.7×10^6 M_{sun}!

Supermassive black hole

- The luminous matter in the Galactic center region does not have sufficient mass to account for the rise of orbital velocity near the center
- Something compact, very massive, but not luminous
- Bright in radio, X-ray, and gamma ray -> from high energy particles and infalling materials
- A **supermassive black hole** (~4 million solar mass) is sitting at the center of our Galaxy!