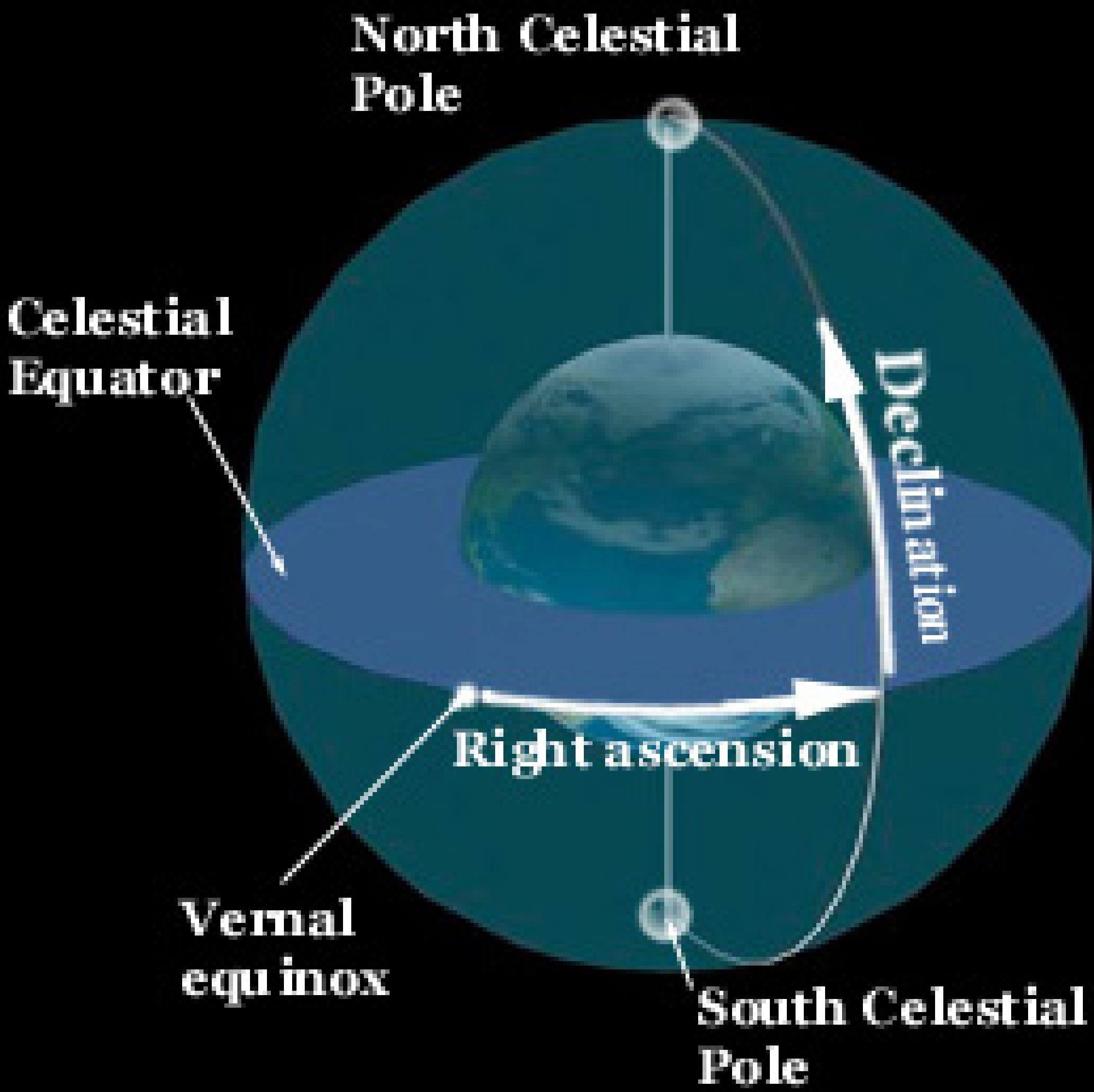
The Milky Way

- Coordinates
  - Equatorial, Galactic
  - Cylindrical coordinates within the galaxy
- Measuring distances
  - parallax
  - flux vs luminosity
  - photometric distance, reddening
  - spectroscopic distance
  - pulsating stars, period vs luminosity, metallicity
- Structure of the Milky Way
  - thin and thick disks, scale height
  - metallicity vs time, supernovae
- Dark matter in the Milky Way
- Nucleus and central black hole

Celestial Coordinates



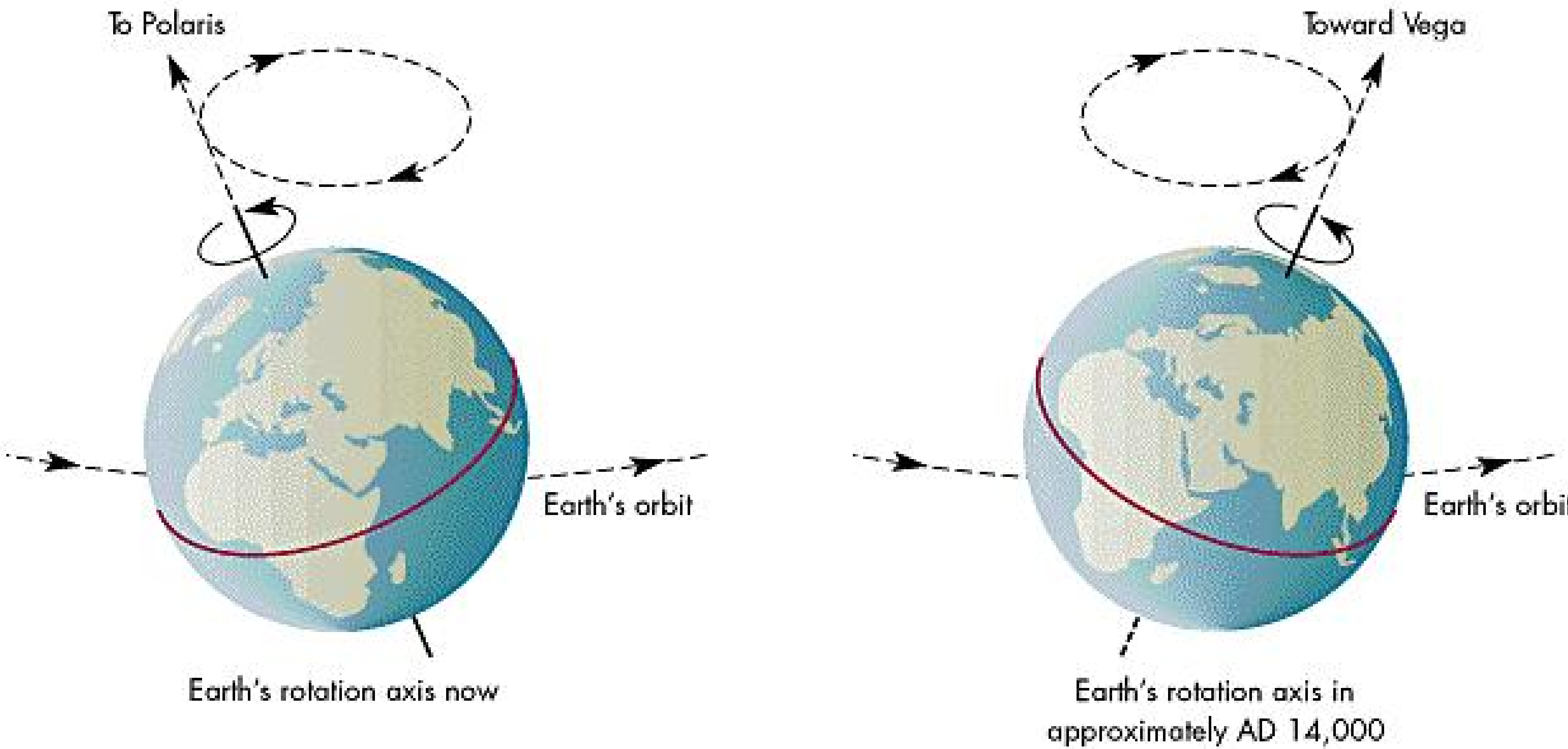
Coordinates are:

Declination = degrees North or South of the equator.

Right ascension = degrees East of the "Vernal equinox".

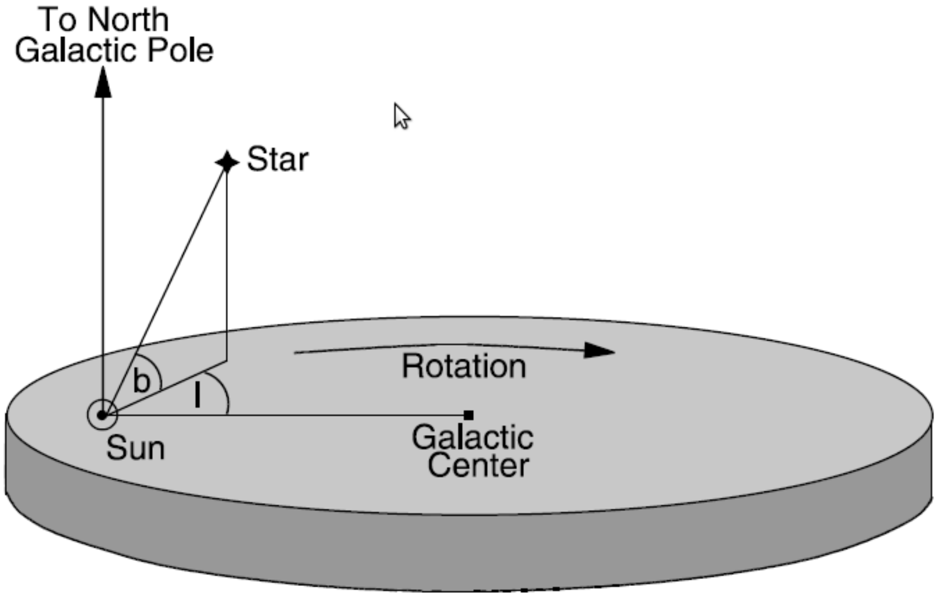
Vernal equinox is defined as the position of the Sun on the first day of spring. Note it is a point on the sky, not the earth.

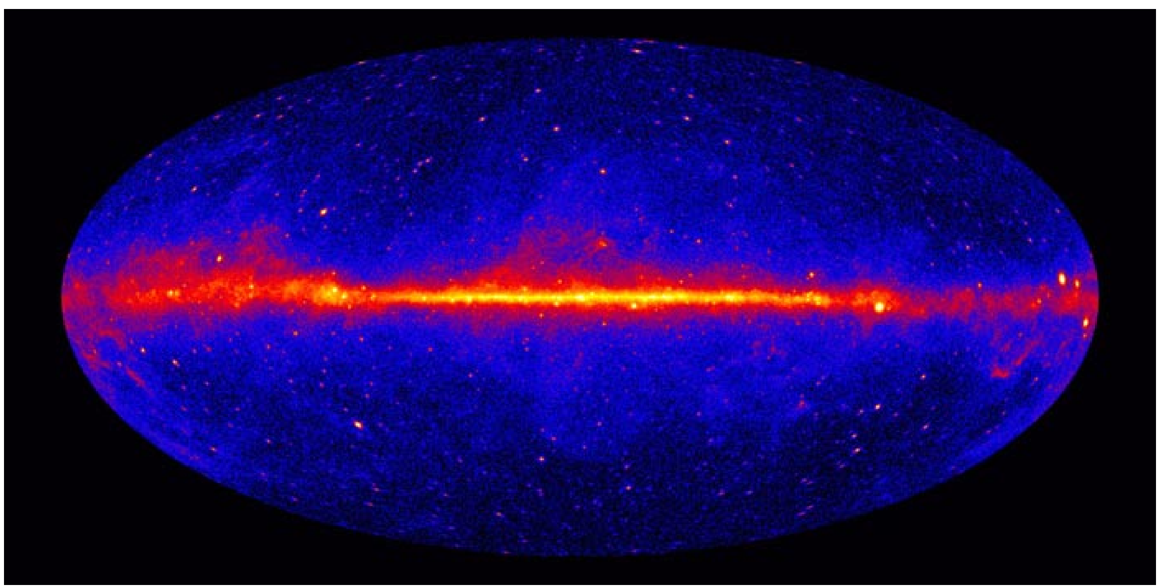
Precession of the Earth



Precession causes celestial coordinates to change slowly with time. When observing, one must have coordinates for the correct epoch. Recent coordinates specified as J2000, older ones as B1950.

Galactic coordinates





- Latitude (*b*) is angle above/below Galactic plane.
- Longitude (*l*) is angle in plane relative to center.
- Center of galaxy is at ($b = 0°$, $l = 0°$)
- Image shows Fermi gamma-ray map.
- For extragalactic studies one usually avoids the plane.

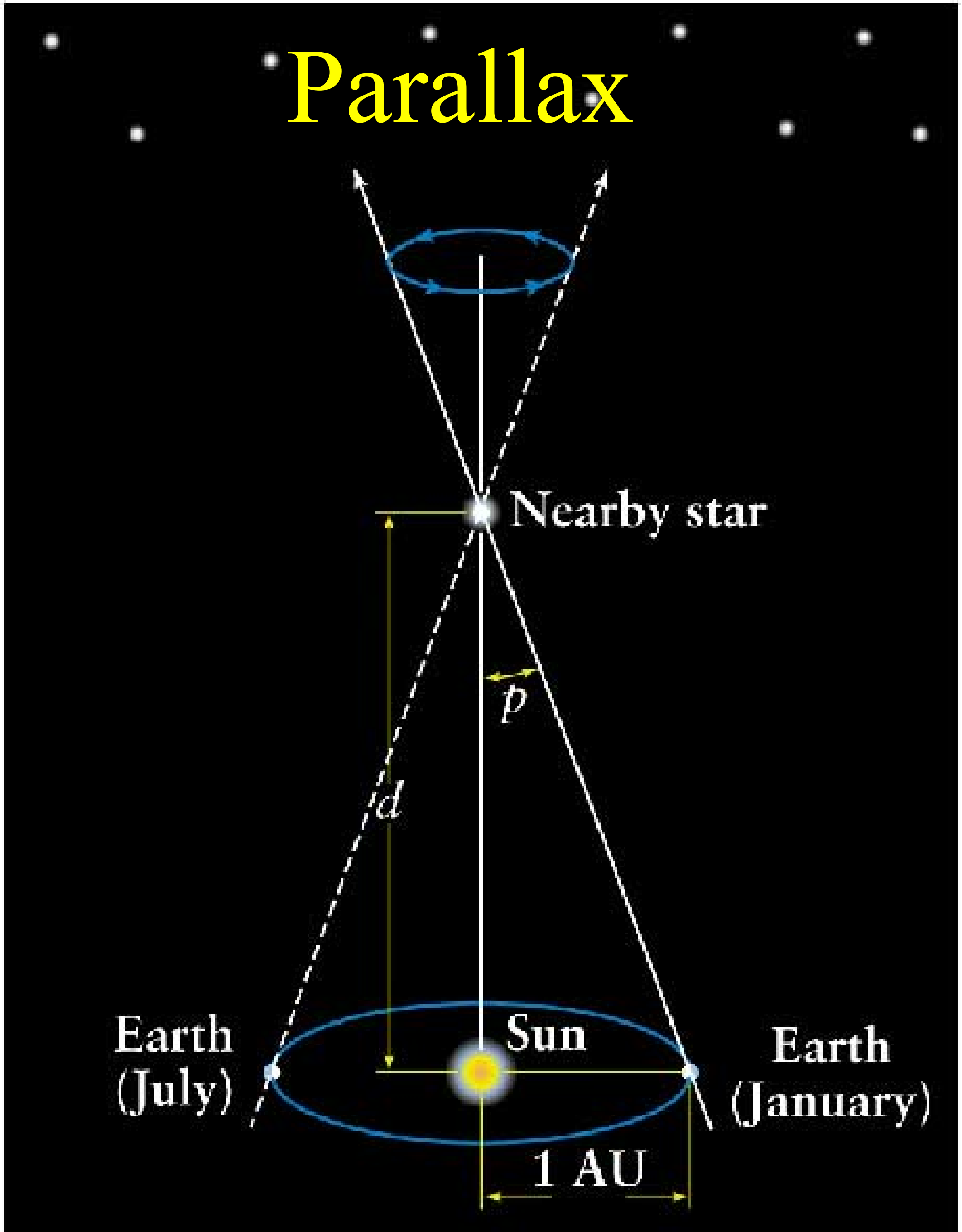
Cylindrical Galactic coordinates

- Cylindrical Galactic coordinates specific the location of an object within the Milky Way.
- R is distance within the plane from the center.
- z is distance above/below the plane
- θ is angular separation in the disk relative to the Sun.

- Then distance from the center is the square root of $R^2 + z^2$
- These coordinates are useful because the disk of the Milky Way is pretty flat.

Measuring distances

- Difficult to determine the distance to an object just by looking at it.
- Distance determination has been a major problem in astronomy since its inception
- Distance determination in extragalactic astronomy is actually easier than most branches of astronomy due to cosmological redshift



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Parallax

As Earth moves from one side of the Sun to the other, a nearby star will seem to change its position relative to the distant background stars.

$$d = 1 / p$$

d = distance to nearby star in parsecs

p = parallax angle of that star in arcseconds

1 parsec = 3.26 light years

$= 3.086\times10^{18}$ cm

Parallax

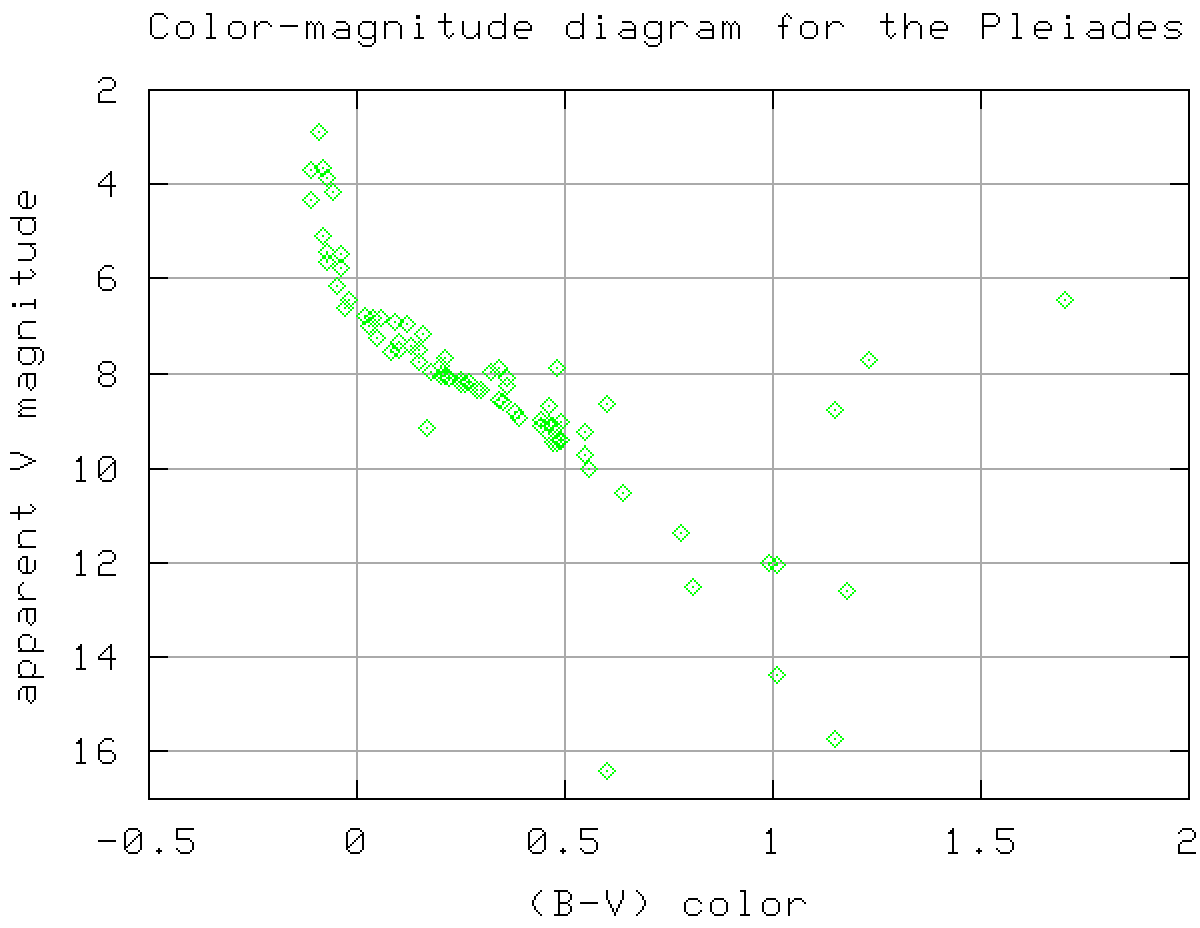
- Limit on how far one can reach with parallax measurements depends on how accurately one can measure positions on the sky.
- ESA's Hipparcos mission reached an accuracy of 0.001” or about 1 mas.
- In the radio, the VLBA can reach an accuracy ~0.05 mas.

- Hipparcos can reach to ~200 pc, VLBA to ~4000 pc.

Measuring distances

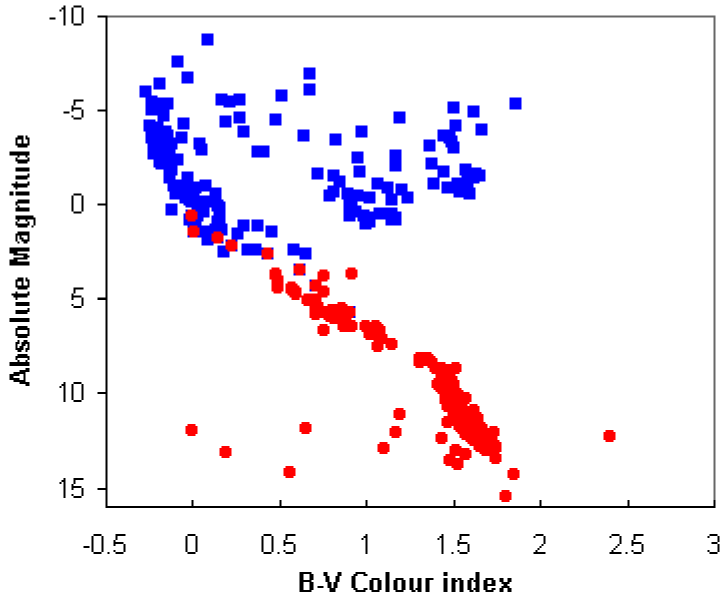
- One can measure a distance if an intrinsic property of an object is known, e.g. size, proper motion, or luminosity.
- Sizes have not been commonly used for distance measurements outside the solar system.
- Proper motion was historically important in measuring the distances to several nearby open clusters, has been superceded with parallax, particularly with Hipparcos. (Proper motion is component of motion on the plane of the sky as opposed to radial motion towards/away from observer.)
- Luminosity is the key to the most important distance measurement techniques that extend past the reach of parallax.
- Flux = Luminosity/Distance^2, so distance can be calculated from a measurement of flux if luminosity can be independently estimated.

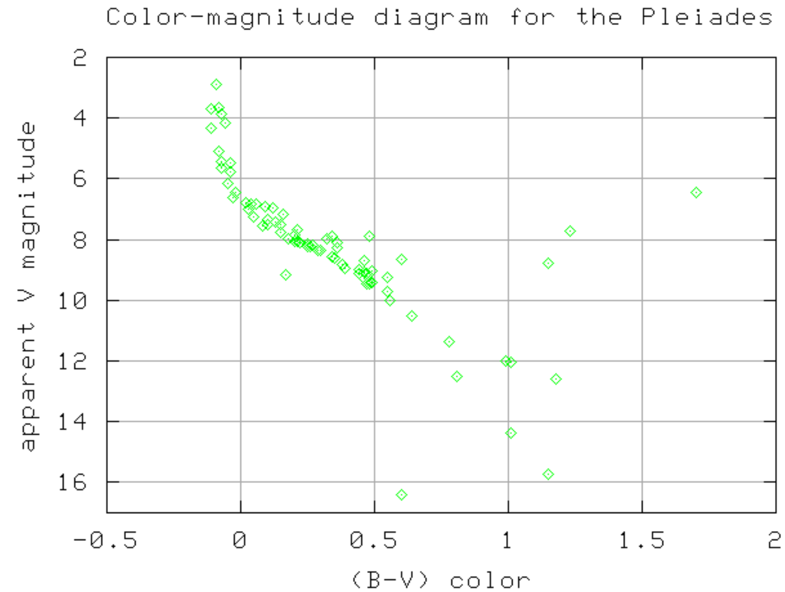
Distance to a star cluster



How can one determine the distance to a star cluster?

Distance to a star cluster





HR diagram from Hipparcos. Red circles are stars closer than 10 parsecs. Blue squares are stars with $M_V < 3$.

$$\text{B-V} = 0.5 \rightarrow m_V \sim 9 \pm 0.2$$

$$\text{B-V} = 0.5 \rightarrow M_V \sim 3 \pm 0.3$$

$$m - M = 6.0 \pm 0.4 = 5 \log(D/pc) - 5 \rightarrow D = 160 \pm 30 \text{ pc}$$

Extinction and Reddening

- Dust between us and the star cluster will scatter and absorb some of the light, decreasing the apparent magnitude.

- Optical depth τ is defined as $S_\upsilon = S_{\upsilon,0} \times e^{-\tau}$
  where S_υ is the observed flux and $S_{\upsilon,0}$ is the intrinsic flux

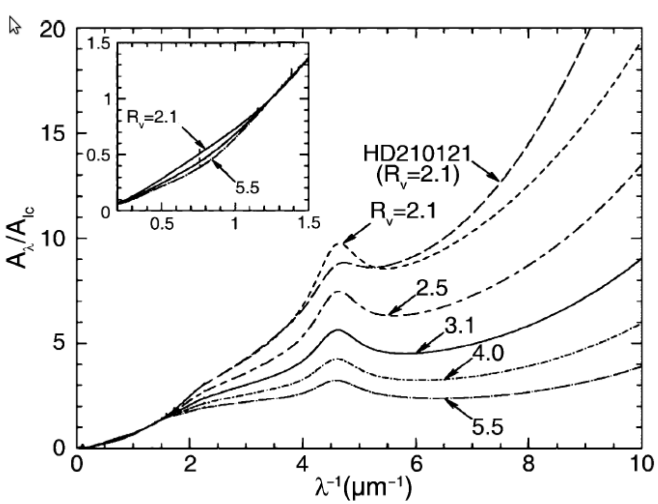
- Extinction coefficient $A_\upsilon = -2.5 \log(S_\upsilon / S_{\upsilon,0})$
- Color excess $E(B\text{-}V) = A_B - A_V = (B\text{-}V) - (B\text{-}V)_0$
- Visual extinction $A_V = R_V\, E(B\text{-}V)$ for nearby dust $R_V = 3.1$

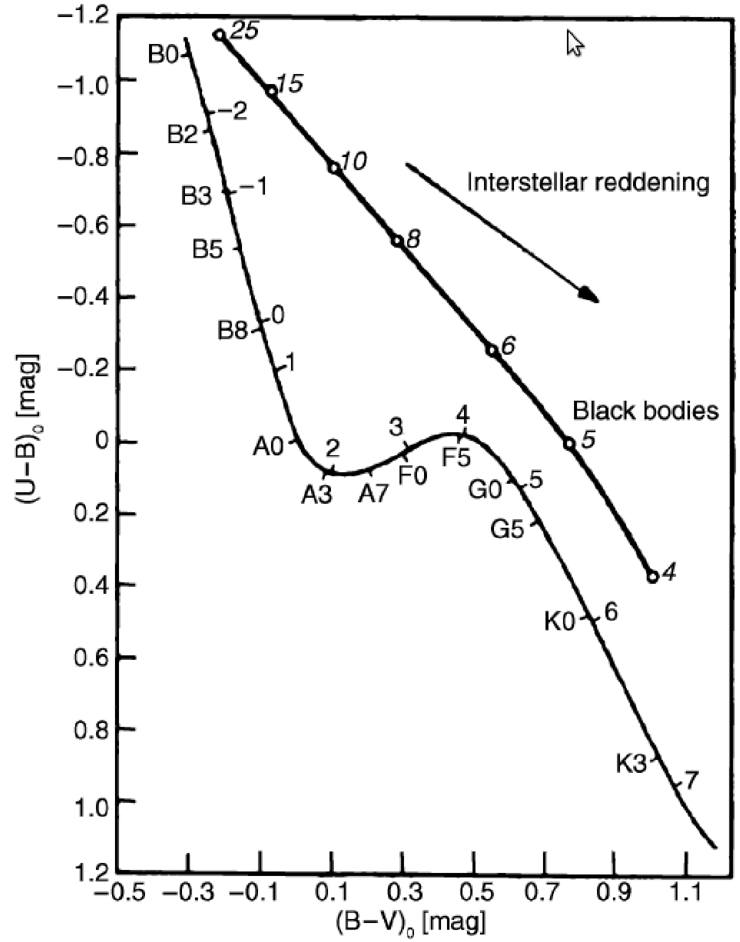
Extinction and Reddening

How to find color excess E(B-V)?

• For a given "reddening law" or value of R_V, the extinction at every wavelength is calculable.

• Plot stars on a color-color diagram. The main sequence will be shifted with a fixed relation between the two colors depending on the color excess.





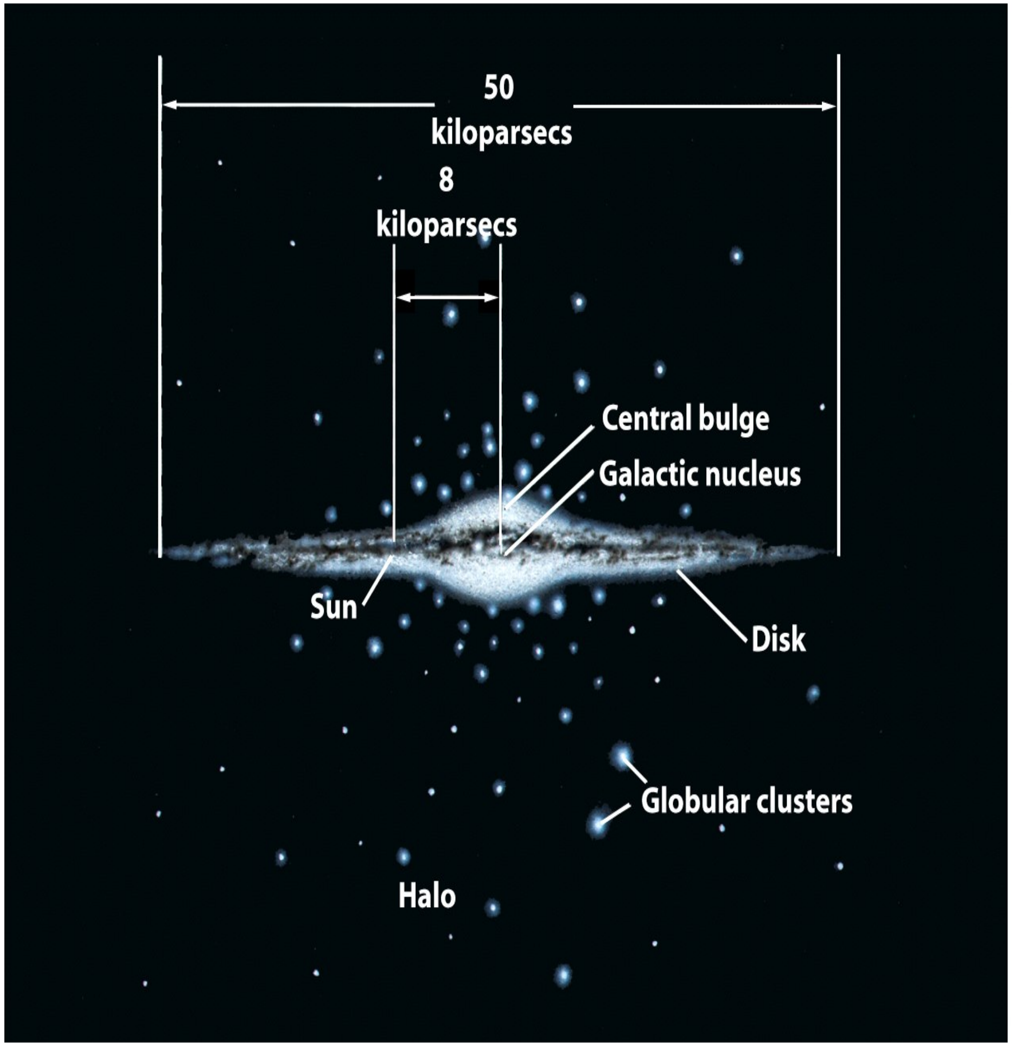
Extinction and Reddening

- For Pleiades, E(B-V) = 0.06
- Using $R_V = 3.1$, we find $A_V = R_V$ E(B-V) = 0.16
- $m_{V,0} = m_V - 0.2 = 8.8$
- $m_0 - M = 5.8 \pm 0.5 = 5 \log(D/pc) - 5 \rightarrow D = 140 \pm 30$ pc
- Actual distance is 120-140 pc.

Distance to a star

- Used color information to determine the intrinsic luminosity of a particular star (or set of stars) and then calculated the distance from the luminosity after correcting the measured flux for extinction.
- This can be applied to an individual star by its using its spectrum to determine the classification of the star.
- Most important application is to pulsating stars because there is a well-defined relation between pulsation period and luminosity for several classes of pulsating stars, notably for Cepheids.

Structure of the Milky Way



- Halo contains old stars, globular clusters, and dark matter
- Bulge contains old stars, maybe some young ones

- Disk has exponential profile $n \sim \exp(-|z|/h)$ where h is scale height, also $n \sim \exp(-R/h_R)$
- Disk has several components:
- Gas: h~130 pc (ISM)
- Thin: $h \sim 300$ pc, young stars
- Thick: $h \sim 1500$ pc, older stars

- Magnetic fields ~ few μG
- Cosmic rays, up to 10^{18} eV
- Star light
- Turbulence in ISM

Stellar populations and metallicity

- “Metal” is any element other than H or He
- “Metallicity” = Z is total mass fraction of all metals. For our Sun, $Z = 0.02$.
- “Metallicity index” = [X/H] is ratio of fraction of element X relative to H in star versus to the fraction of element X in the Sun on a log scale, e.g. [Fe/H] = +1 means a star as 10× as much iron as the Sun (per unit mass).

Stellar populations and metallicity

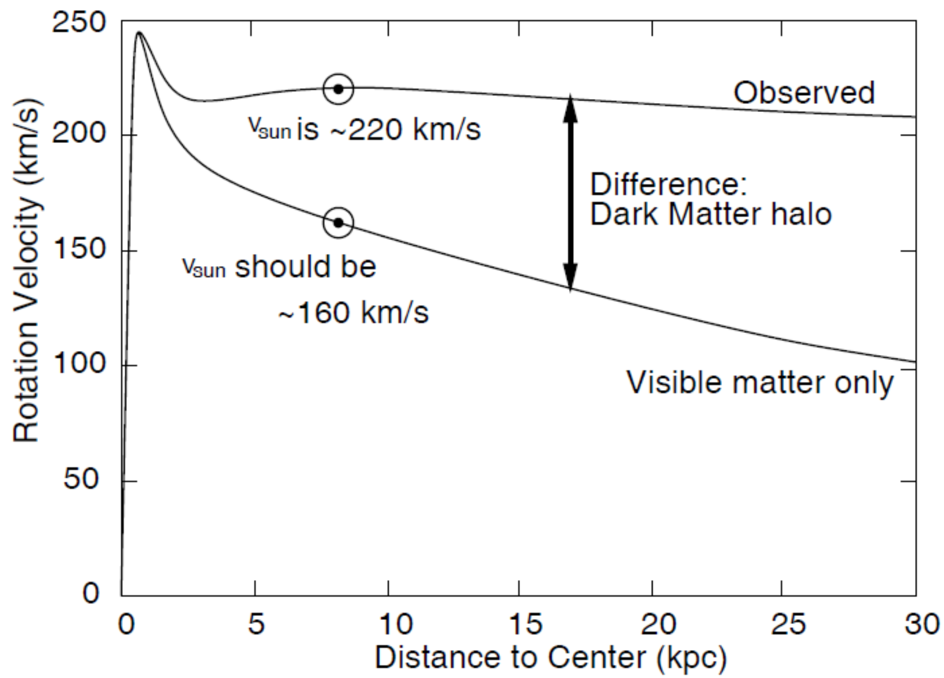
- Big Bang produced mainly H and He
- Metals are mainly produced by nuclear burning in and explosions of stars. Metals are then recycled into new stars.
- Thus, the first stars had very low metallicity and metallicity increases with each successive generation of stars.
- Population I stars have $Z \sim 0.02$ are in thin disk
- Population II stars have $Z \sim 0.001$ are in thick disk, bulge, and halo
-

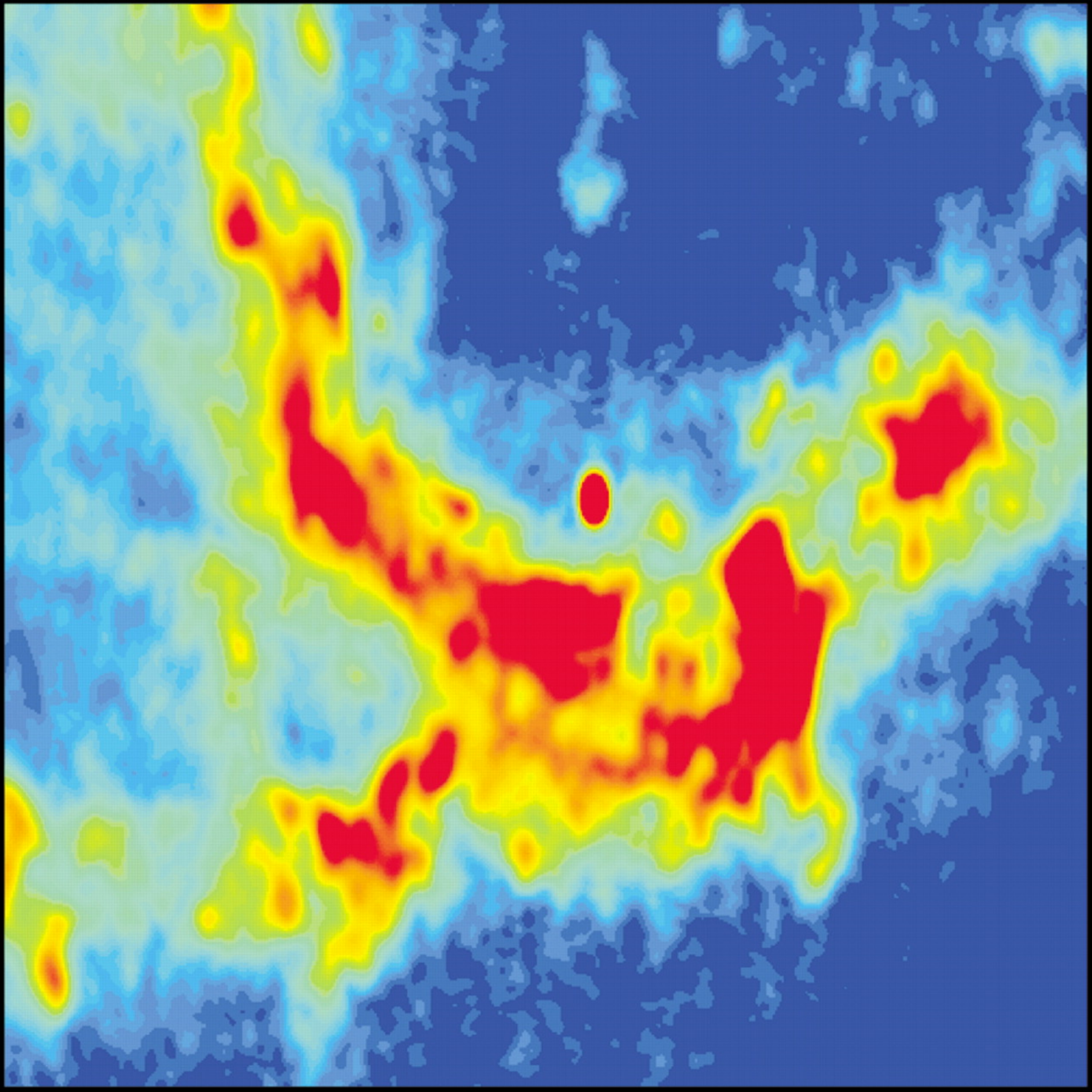
Mass to light ratio

- Given a population of stars, we can count up all the stars and determine the ratio of stellar mass to stellar light, M/L in terms of M and L for the Sun.
- Thin disk: $M/L \sim 3$
- Thick disk: $M/L \sim 15$
- Bulge: $M/L \sim 3$
- Since $L \sim M^3$, M/L increases for older populations with more low mass stars.

Kinematics of the Milky Way and dark matter

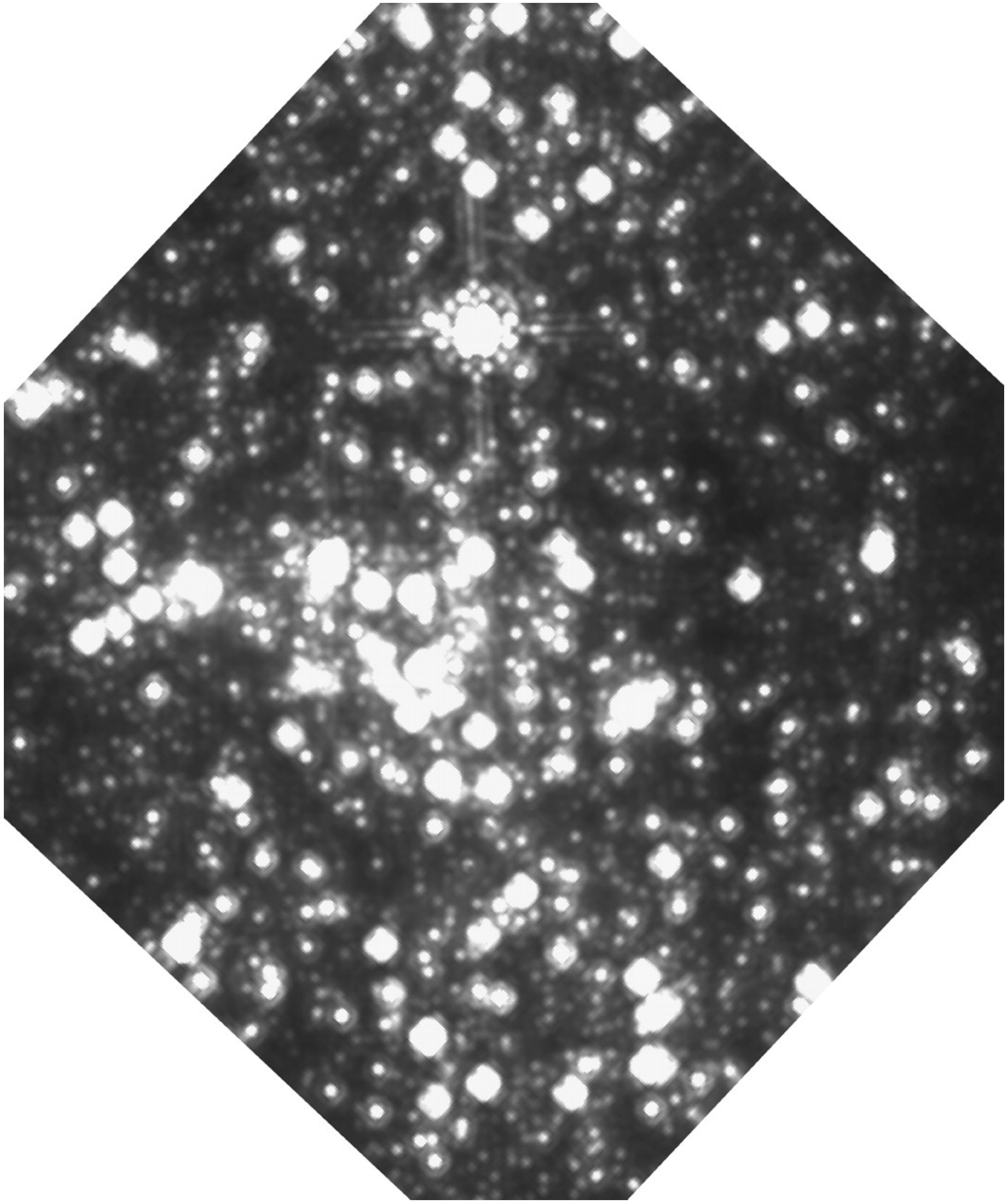
• Stars and gas in the outer parts of the Milky Way orbit faster than they should if only visible matter is present.
• Dark matter could be elementary particles or astrophysical, MACHOs = massive compact halo objects
• MACHOs should be gravitational lenses.
• Gravitational lensing searches limit MACHOs to < 20% of dark matter.





Radio image of central parsec

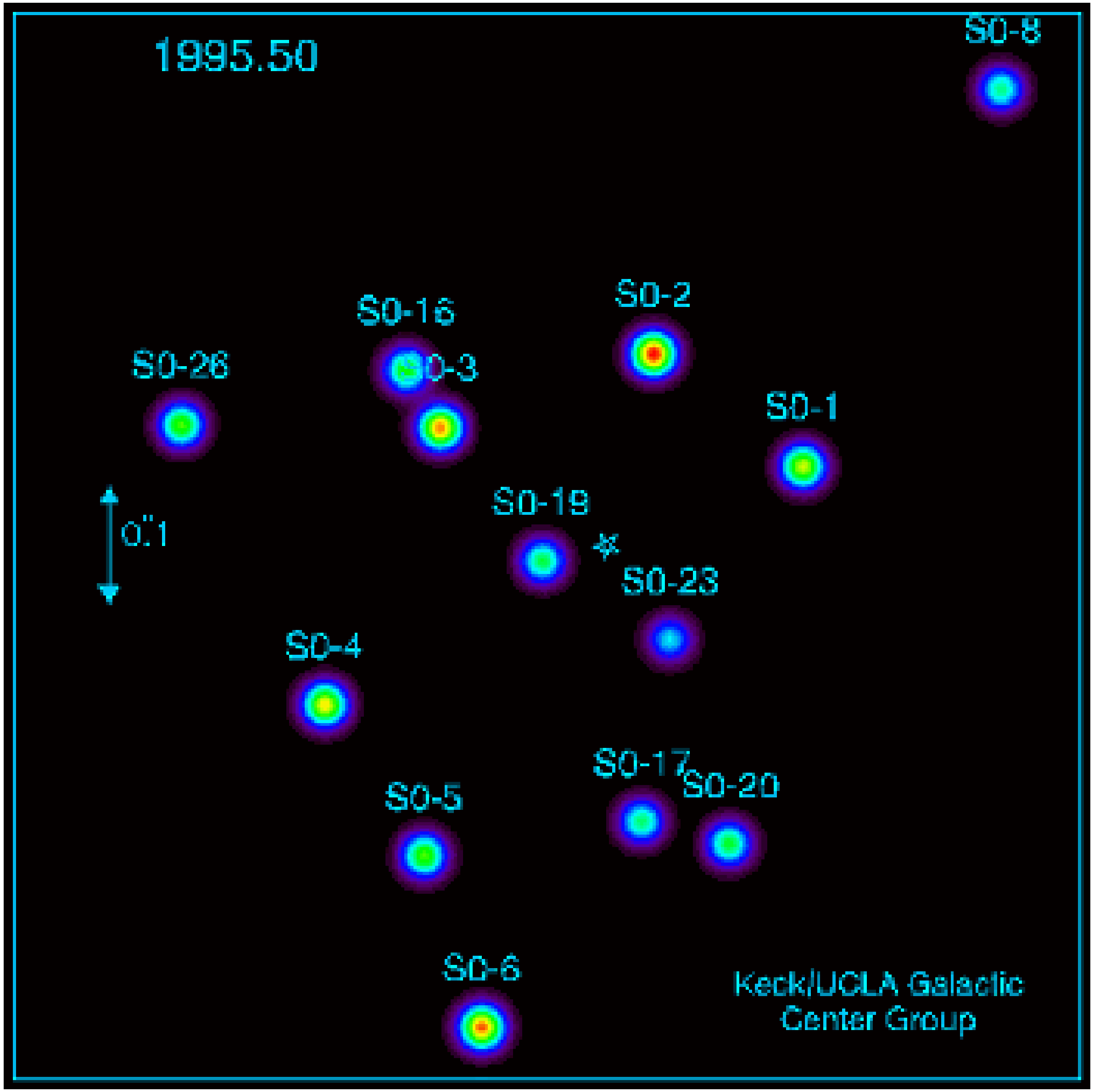
- Red ellipse is at the center
- Called Sgr A*



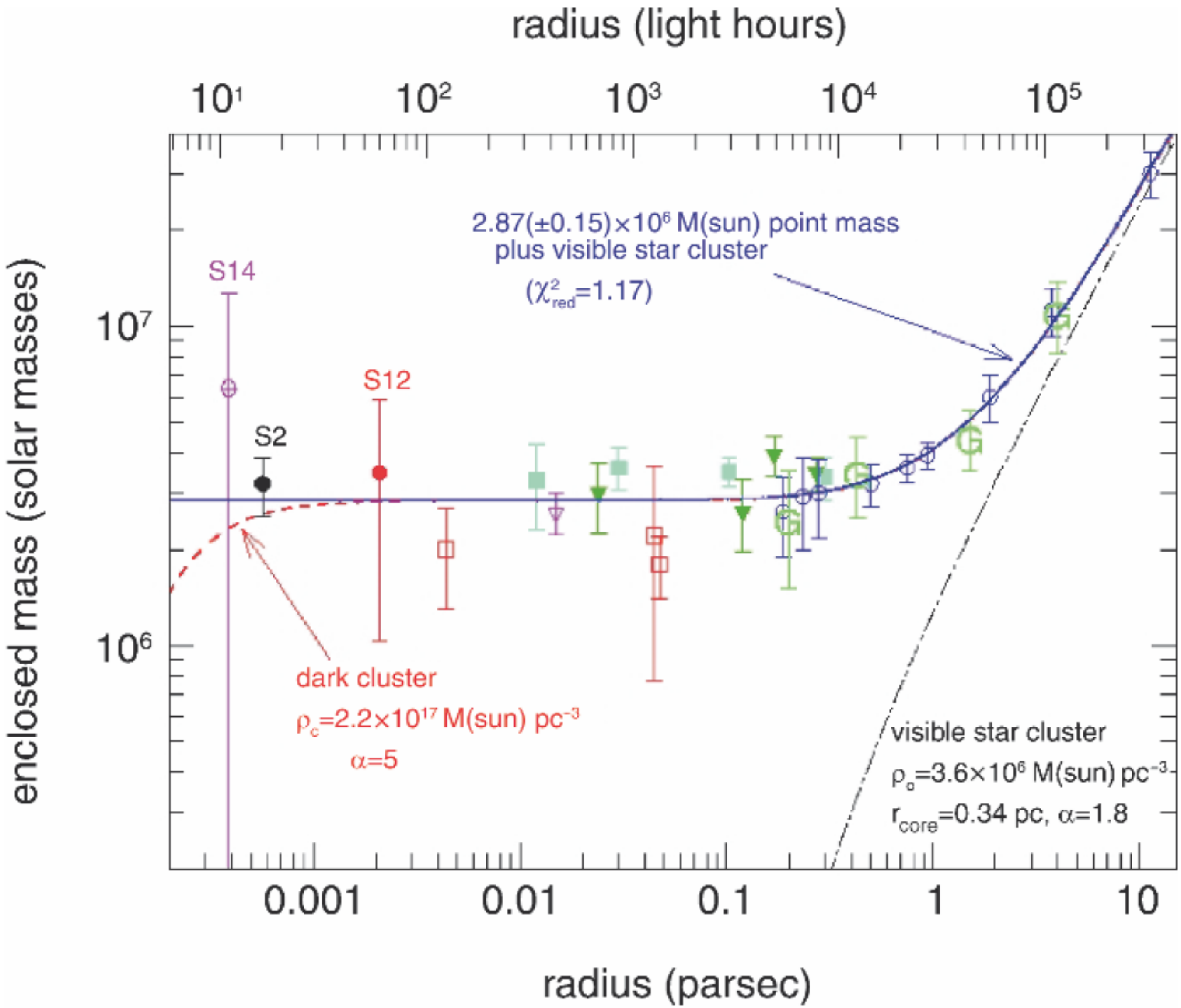
Infrared image of the central parsec

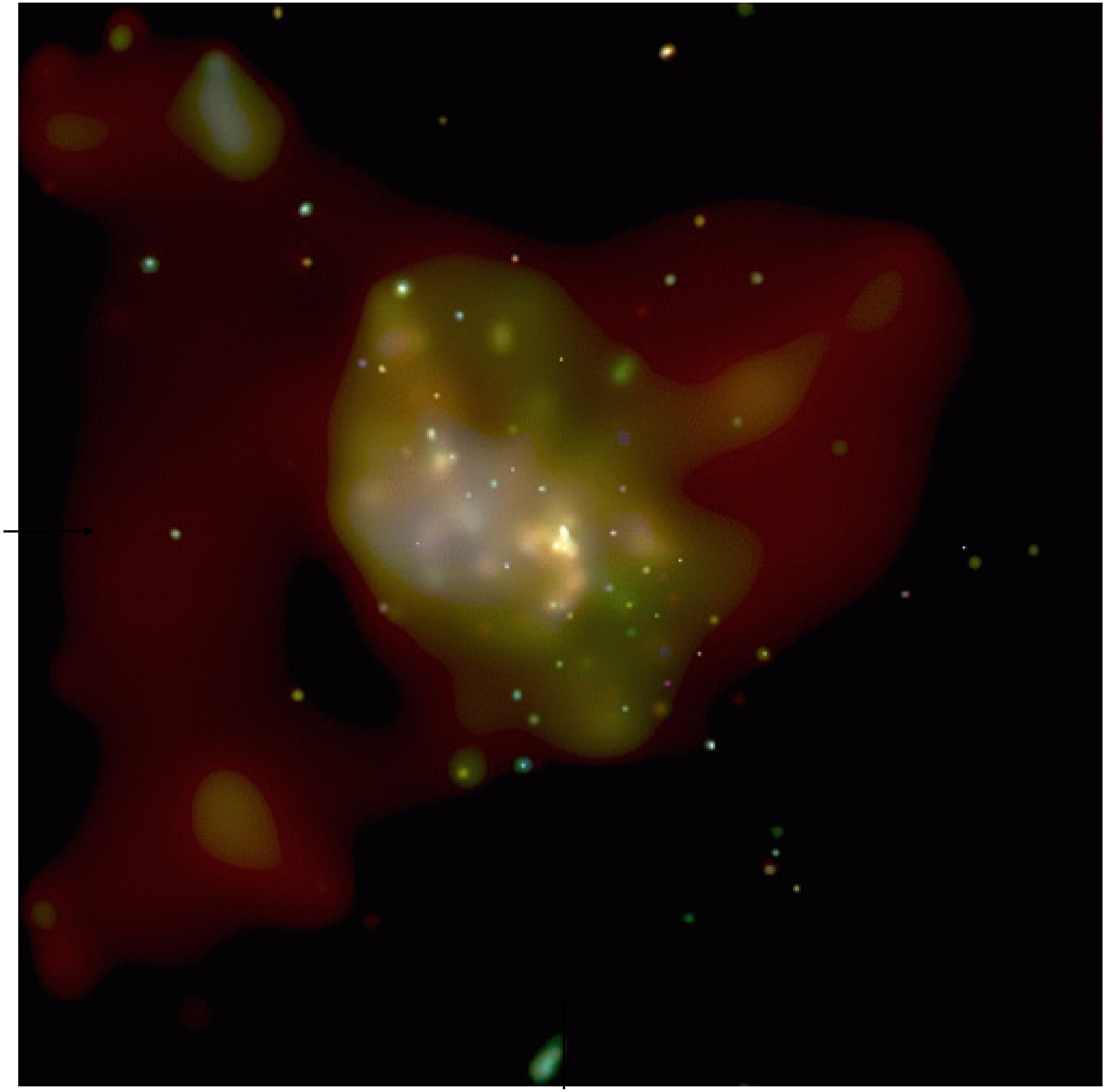
- Sgr A* does not appear.
- There are about 1,000,000 stars in the area covered by this image.
- Density ~ $r^{-1.8}$

Stellar Orbits in the Galactic Center



Enclosed mass versus radius





X-ray image, central 3 ly

Sgr A* is the bright object in the center of the image.

Makes flares in X-rays and NIR to radio.

For next class

- Read 3.1-3.4
- Work on HW #2 due Wednesday 8/29