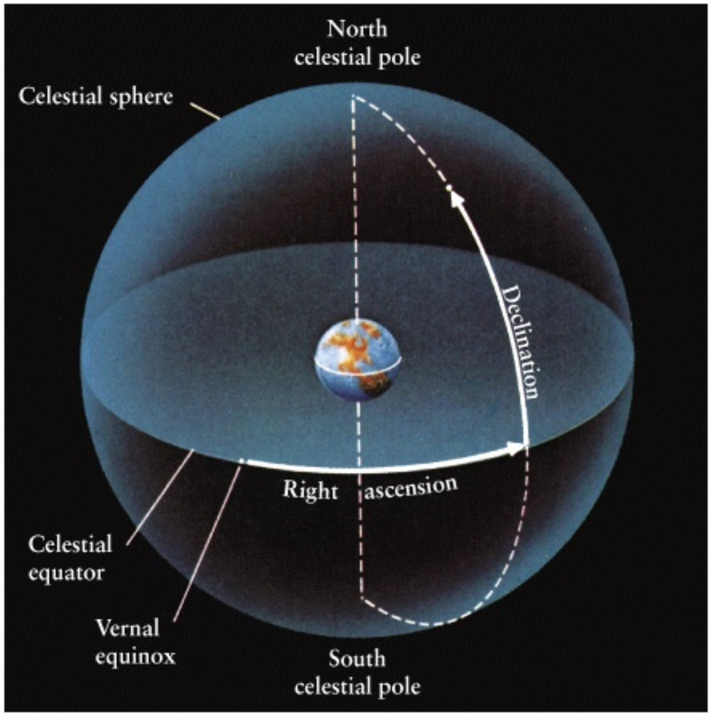
Astronomy 303
Mapping the Milky Way

1. Coordinate systems
2. Parallax, proper motion and space motions
3. The solar neighbourhood
4. Stars in the Galaxy
5. Galactic rotation




Galactic vs. equatorial coords

- "equatorial" ("celestial") coordinates



right ascension
α RA
[h m s]

declination
δ dec
[° ′ ″]

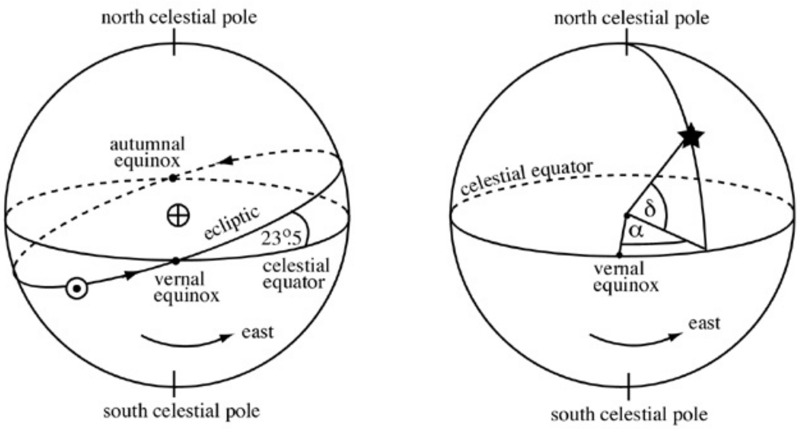
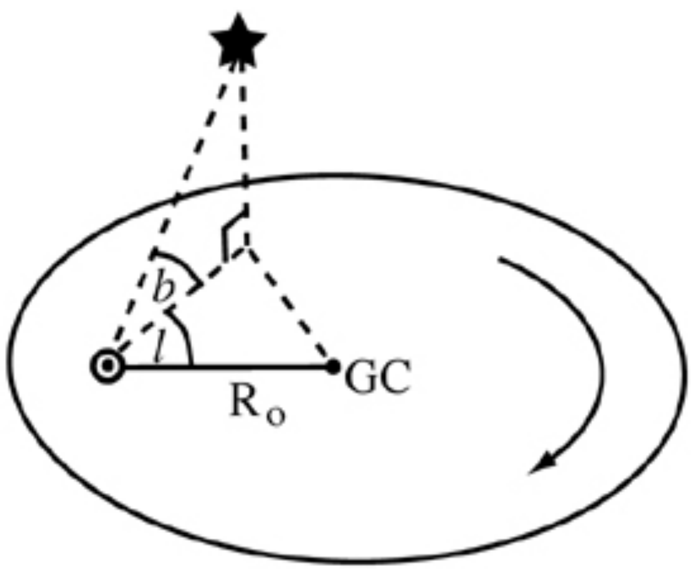


Fig 1.9 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

- NCP, SCP, celestial equator

Galactic Coordinates

- Galactic coordinates
  - b,l [° ' "]
  - measured relative to Milky Way (equatorial plane)
  - Galactic centre defines zero longitude ℓ = 0°



- Cylindrical coordinates
  - (R,ϕ,z)
  - measured from the Milky Way's centre

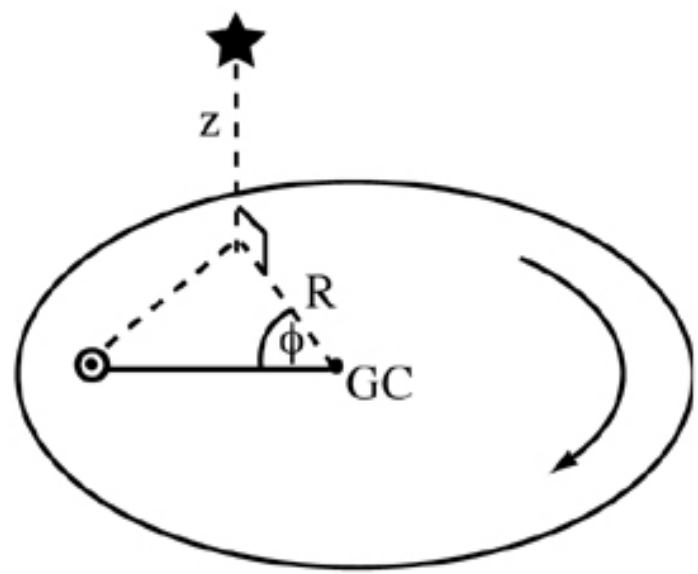
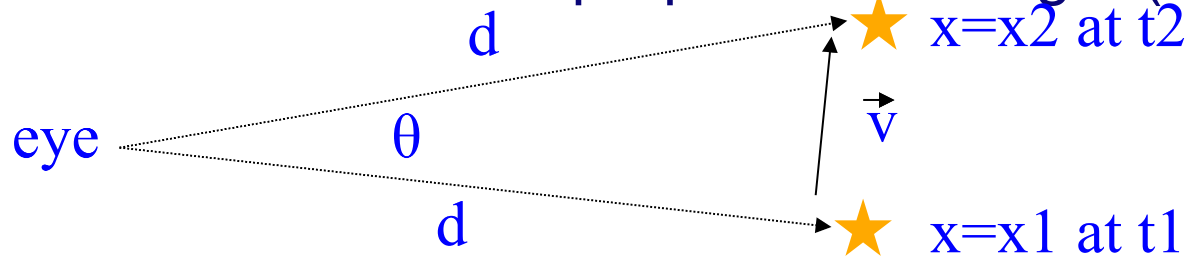


Fig 1.10 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Proper Motion

- μ [arcsec/yr]
- due to motion of sun and stars in Milky Way
- largest – Barnard's star - 10.2 arcsec/yr
- only sensitive to motion perp. to line of sight (V_T)



$$\Delta\theta = \Delta x/d \quad [\text{rad}]$$

$$\Delta\theta/\Delta t = (1/d)\, \Delta x/\Delta t$$

$$\mu = V_T/d \quad (\mu \text{ in rad/s, } v \text{ in m/s, } d \text{ in m!})$$

Better: $$\mu\,[''/\text{yr}] = \frac{V_T\,[\text{km/s}]}{4.74\ \ d\,[\text{pc}]}$$ (derive "4.74"!)

e.g. Barnard's star μ= 10"/yr, d=10pc - v_T=???

Proper motion, radial velocity, space velocity

Radial velocity v_r - measured directly from the Doppler effect

$$\Delta\lambda/\lambda_o = v_r/c \quad \text{(non-relativistic)}$$

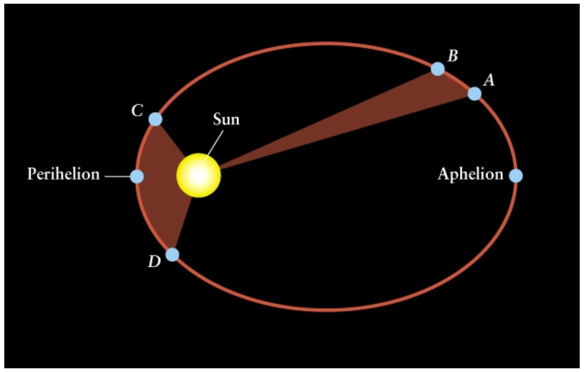
- *e.g. spectral line Hα (656.3nm at rest) observed at 656.5nm. What is the corresponding radial velocity?*

Space velocity $v = (v_r^2 + v_T^2)^{½}$

Doppler effect

μ, d

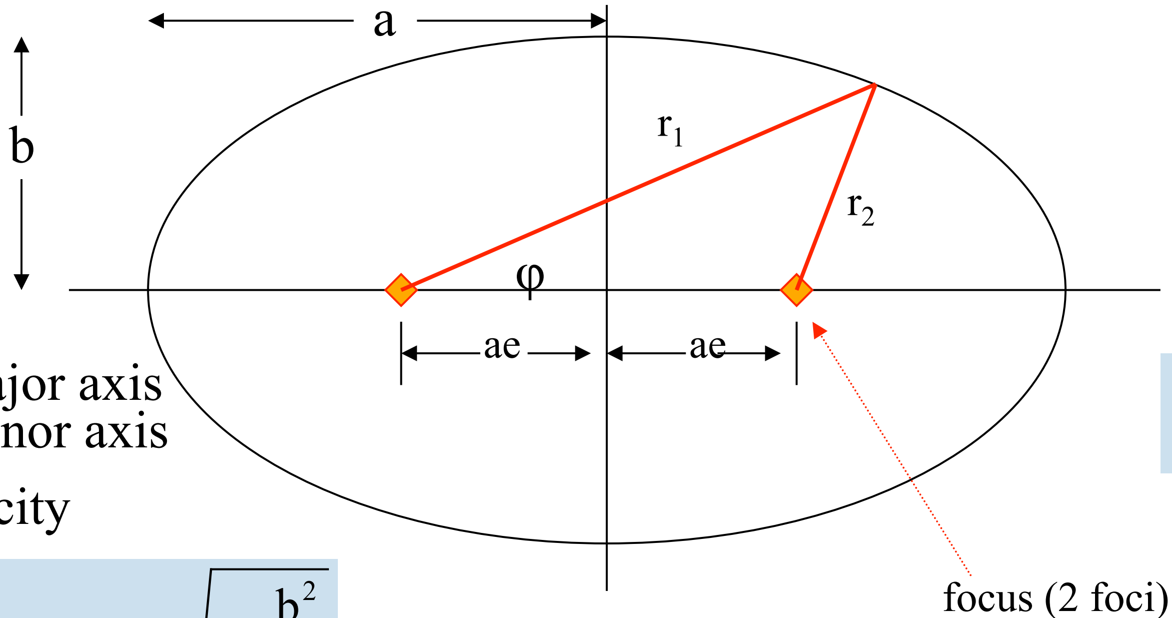
Gravity & Kepler's Laws



From Tycho Brahe's observations …

I. Planets move in elliptical orbits with the sun at one focus.
II. Radius vector between the sun and a planet sweeps out equal areas in equal time.
III. P^2 prop. to a^3 for orbit (P=period, a=semimajor axis)

Ellipses and conic sections



a=semi-major axis
b=semi-minor axis

e=eccentricity

$$\frac{b}{a} = \sqrt{1-e^2} \quad \text{or} \quad e = \sqrt{1-\frac{b^2}{a^2}}$$

$$r_1 + r_2 = 2a$$

Ellipse in x-y: $$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

$$r = \frac{a\,(1-e^2)}{1 + e\cos\phi}$$

r=distance **from focus**
φ=angle from x-axis in r direction

- Kepler's 3rd Law: centripetal force =gravitational force

$$\frac{mv^2}{r} = \frac{GMm}{r^2}, \quad v = 2\pi r / P$$

$$\therefore \frac{4\pi^2 r^2}{r\,P^2} = \frac{GM}{r^2}$$

$$\therefore \; P^2 = \left(\frac{4\pi^2}{GM}\right) r^3 \quad or \quad P^2 \propto a^3$$

for circular orbits

P in yr, a in AU, M in solar masses:

$$\mathrm{M} = \mathrm{m}_1 + \mathrm{m}_2 \cong \mathrm{M}_{\mathrm{sun}} \text{ for solar system}$$

$$P^2 = a^3 / M$$

Energy Considerations

- Total energy of orbit:

$$E_{tot} = -\frac{GMm}{2a}$$

Why is energy conserved?

- Energy in orbit

$$E_{tot} = -\frac{GMm}{2a} = \frac{mv^2}{2} - \frac{GMm}{r} \quad \text{at any point in orbit}$$

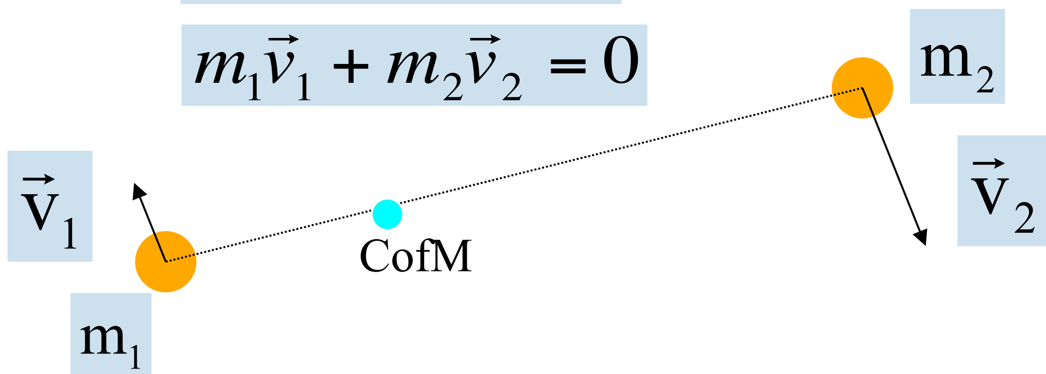
$$\text{A little algebra gives:} \qquad v^2 = GM\left(\frac{2}{r} - \frac{1}{a}\right)$$

Centre of Mass

- In rest-frame of centre of mass of two bodies, conservation of momentum says:

$$m_1\vec{r}_1 + m_2\vec{r}_2 = 0$$

$$m_1\vec{v}_1 + m_2\vec{v}_2 = 0$$



- $\vec{v}_1$ and $\vec{v}_2$ are antiparallel. Therefore objects 1 and 2 trace orbits about the centre of mass which have the same shape but opposite direction.

- Scaling of m,v,r for each object:

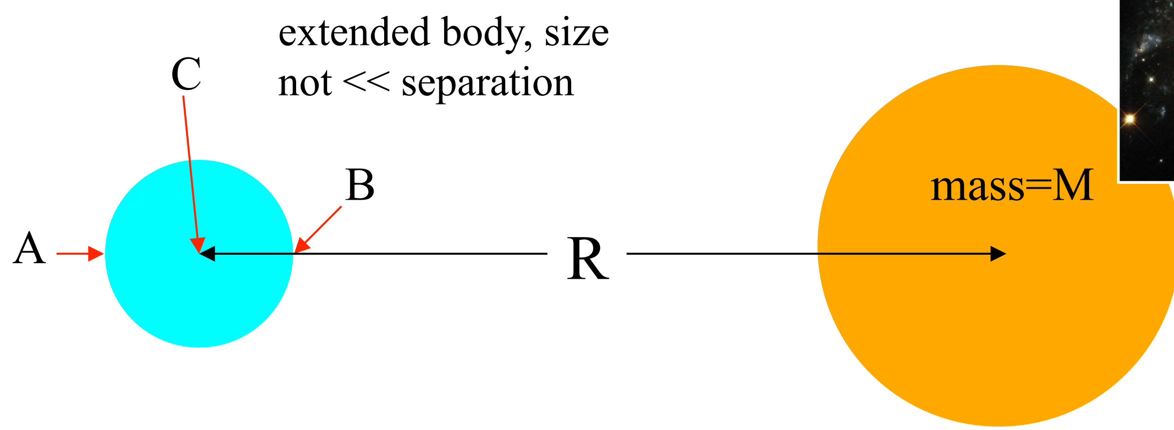
$$m_1|v_1| = m_2|v_2| \quad \rightarrow \quad \frac{\mathrm{v}_1}{v_2} = \frac{m_2}{m_1}$$

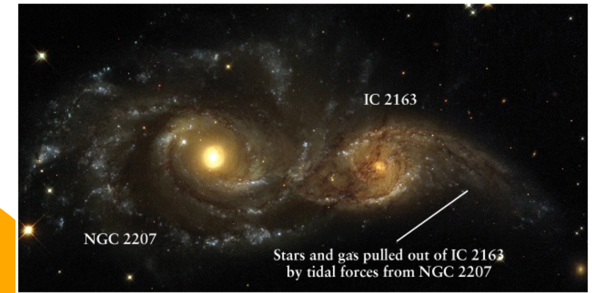
Angular velocity same for each object

$$\omega_1 = \omega_2 \quad \rightarrow \quad \frac{\mathrm{v}_1}{\mathrm{r}_1} = \frac{\mathrm{v}_2}{\mathrm{r}_2} \quad \rightarrow \quad \frac{\mathrm{v}_1}{\mathrm{v}_2} = \frac{\mathrm{r}_1}{\mathrm{r}_2}$$

- $$\text{Combining} \ldots \quad \frac{\mathrm{m}_2}{\mathrm{m}_1} = \frac{\mathrm{r}_1}{\mathrm{r}_2}$$

Tidal Forces



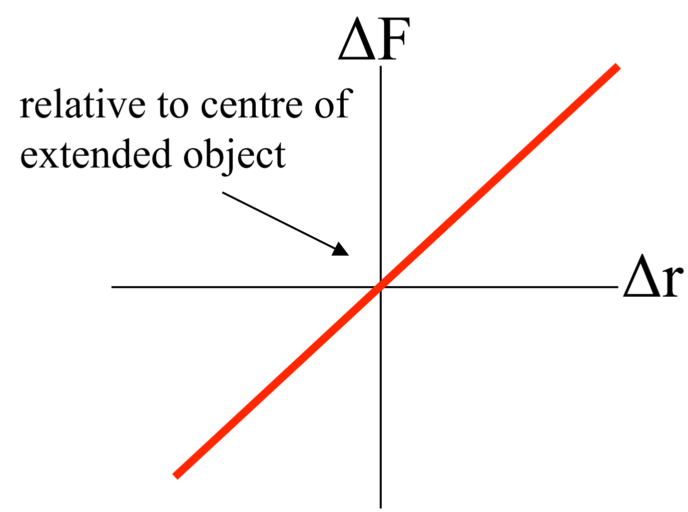


- Test particle m_t at A, B, and C: what is force of gravity due to M?
  Ans: $|F_A| < |F_C| < |F_B|$ because $F = -GMm_t / r^2$

$$\frac{dF}{dR} = \frac{d}{dR}\left(-\frac{GMm_t}{R^2}\right) = +\frac{2GMm_t}{R^3}$$

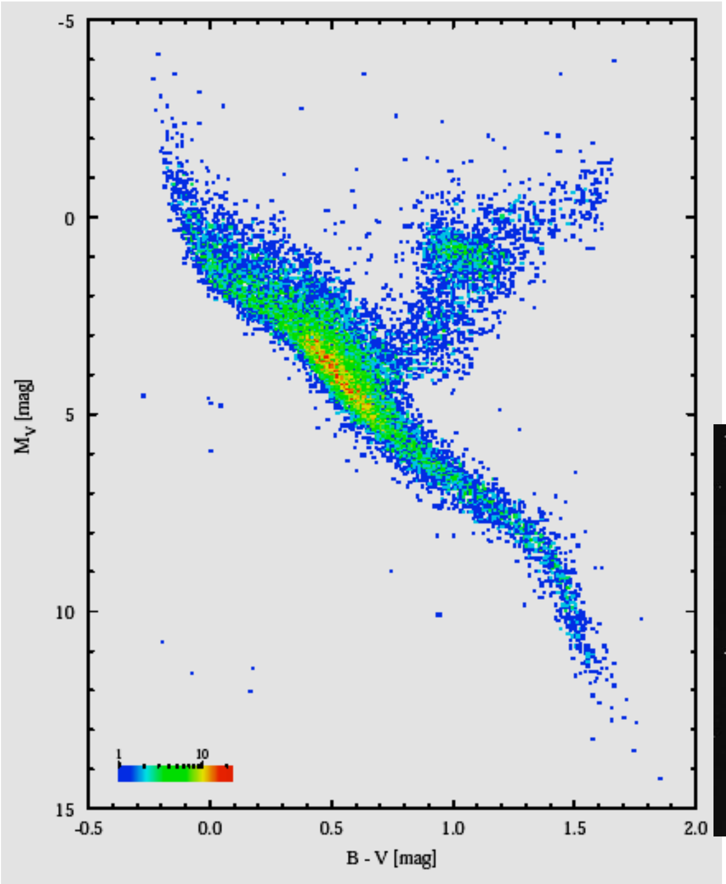
$$\therefore \quad \boxed{dF = \frac{2GMm_t}{R^3}\, dR}$$

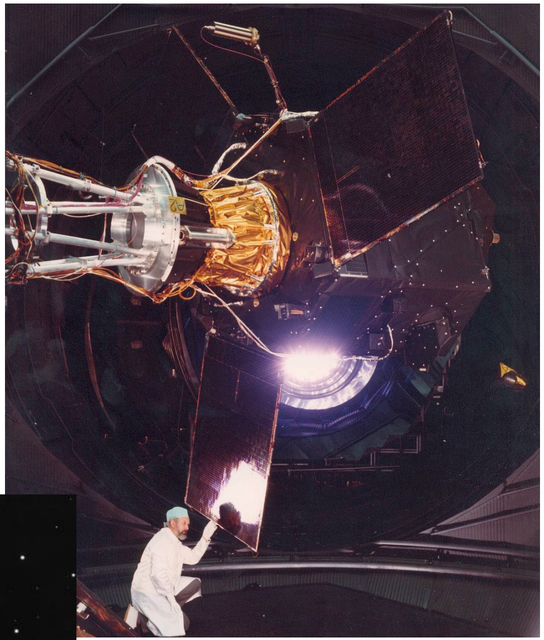
separation of centres

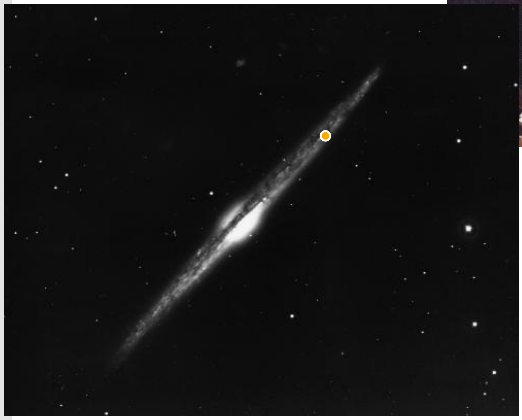


The solar neighbourhood

- Distances to stars
  - The Hipparcos mission
    - >100,000 stars within ~100pc from the Sun
  - HR diagram of nearby stars

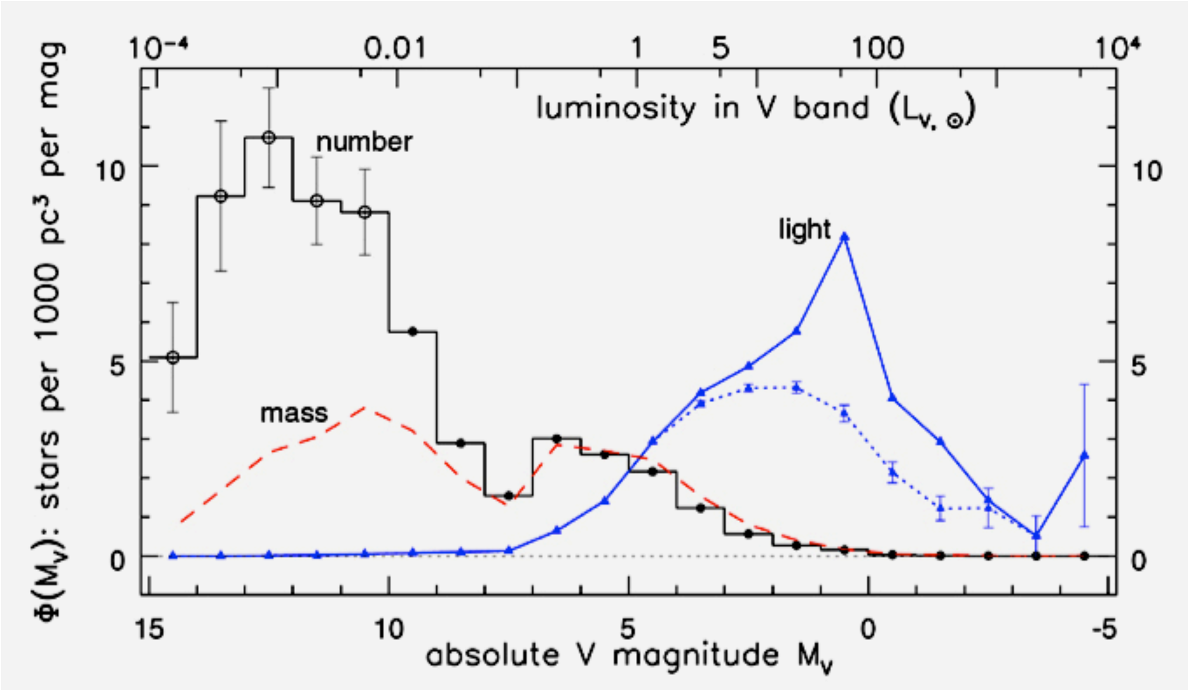






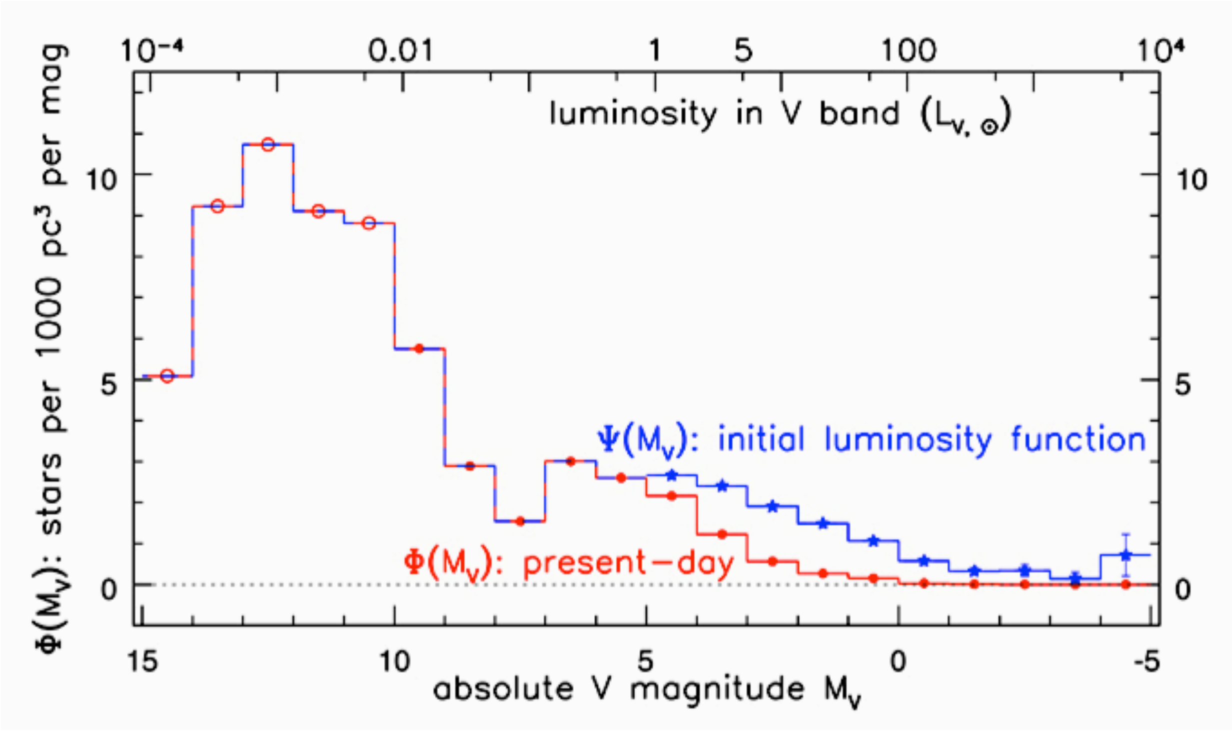
The solar neighbourhood

- Luminosity function
  - Hipparcos measured distances for all stars brighter than m_V~8.
  - A star like the Sun (M_V=4.83) would not be included if their distance modulus is greater than 8-4.83=3.17 (d~43 pc)
  - This sets the volume surveyed for Sun-like stars,
    - $V_{max}=(4/3)\pi d^3$
  - The luminosity function $\phi(M_V)$ can then be computed from that



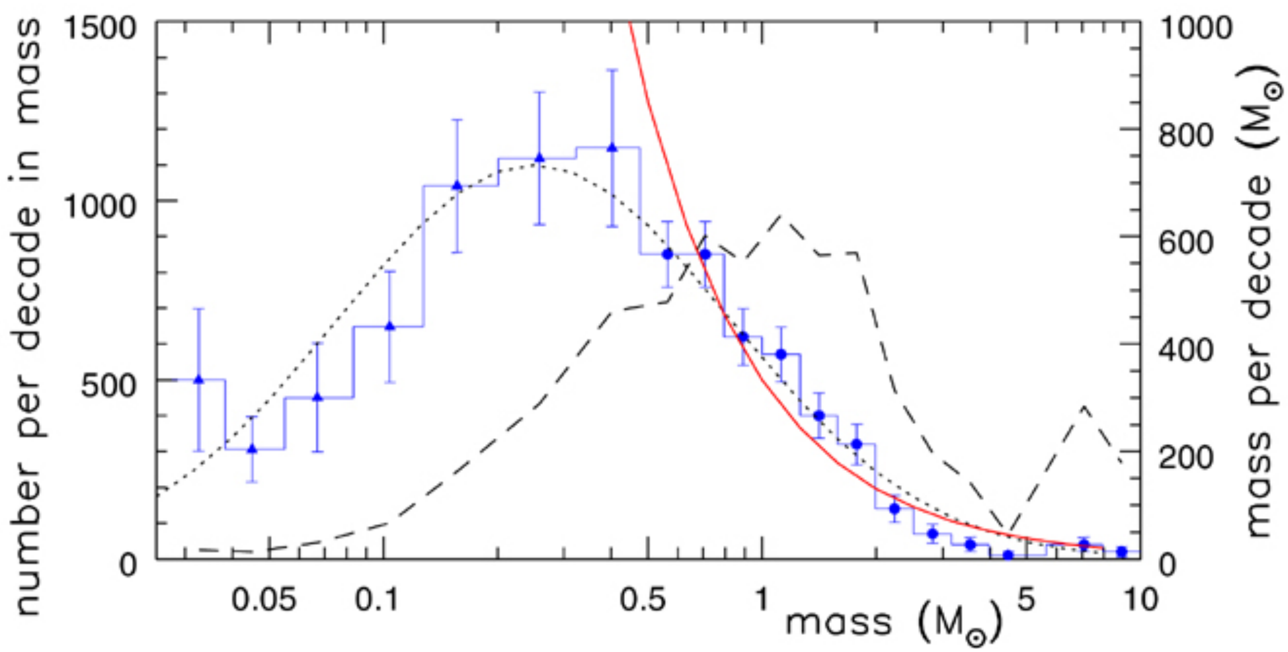
The solar neighbourhood

- The Initial Luminosity function
  - Using stellar evolution models one may estimate the number of stars as a function of the magnitude they had when they were in the main sequence
    - Need an estimate for the “age of the Galaxy” (how would you do that?)
  - The “initial luminosity function” differs from the observed luminosity function only at the bright end



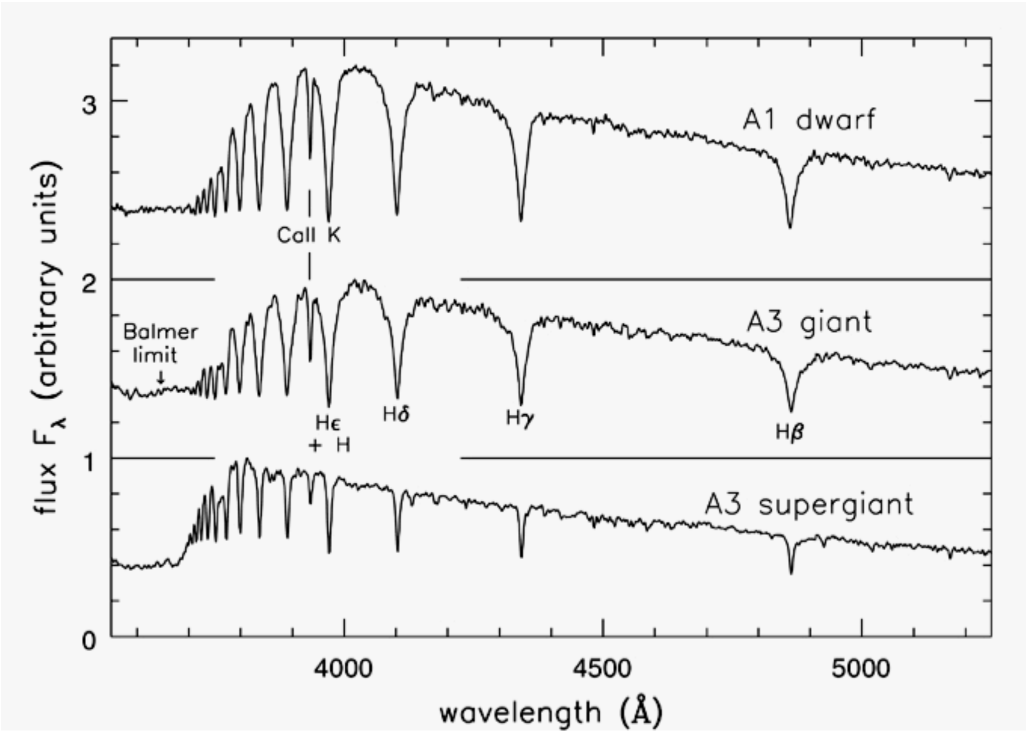
The solar neighbourhood

- The Initial Mass Function (IMF)
  - Since we know the mass-luminosity relation along the main sequence, we can turn the initial luminosity function in an estimate of the IMF
    - $\xi(M)dM=\xi_0\ (M/M_0)^{-2.35}\ dM$ (Salpeter IMF)
  - The Salpeter IMF is a good approximation for stars with mass exceeding about 0.5 M_{sun}.
  - The IMF is surprisingly similar in very different environments!



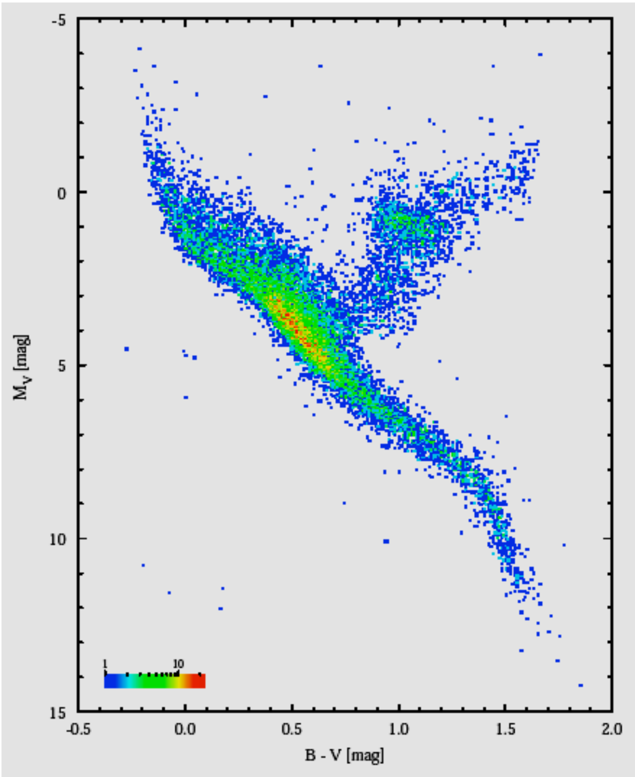
Beyond the solar neighbourhood

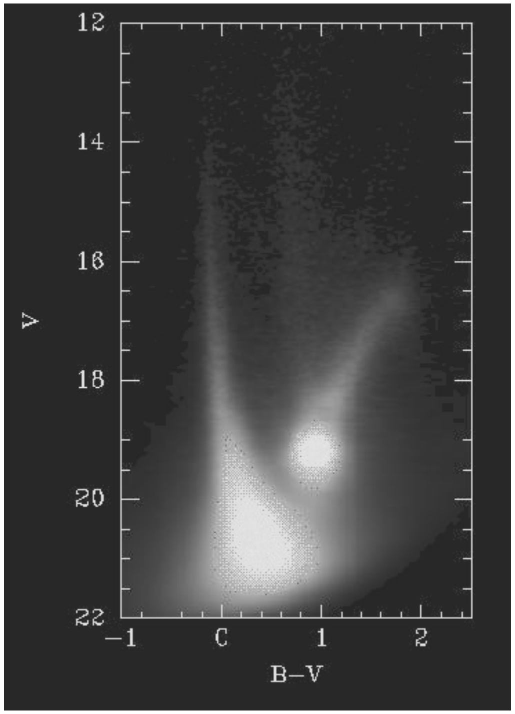
- Spectroscopic Parallax
  - If a star can be ascertained to be in the main sequence, then it is possible to use its effective temperature to estimate its intrinsic luminosity and hence its distance
    - The surface gravity of a star shapes the absorption lines
    - Measurements are hard to do for a large number of stars



Beyond the solar neighbourhood

- Photometric Parallax
  - If spectra are not available, then one can resort to studying some stars whose colors imply that they are likely MS stars
    - Late G and early K dwarfs
    - Avoid the red clump and the red giant branch
    - A simple color measurement (B-V) allows distance estimates





LMC "Hess" diagram

The structure of the disk

- The exponential nature of galactic disks
  - Surface photometry of other disk galaxies (seen face-on) show that the distribution of stars is nearly exponential
    - It is usually assumed to hold also for the disk of the Milky Way
    - An exponential is a useful approximation, but recall that it is just an approximation!

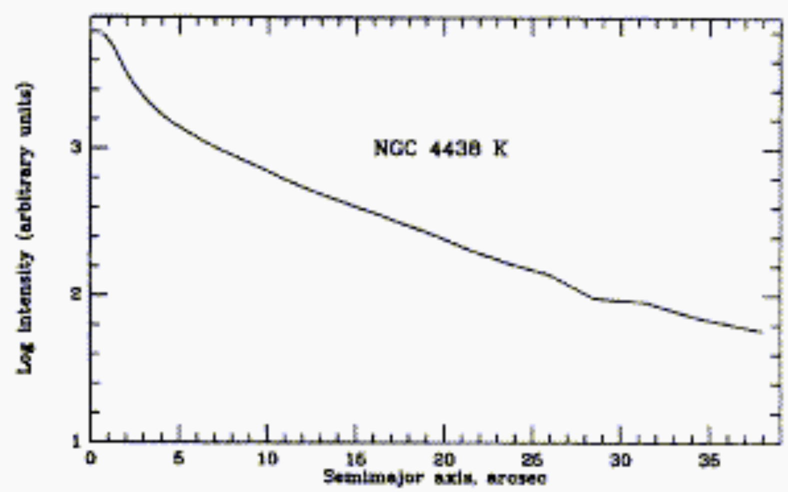
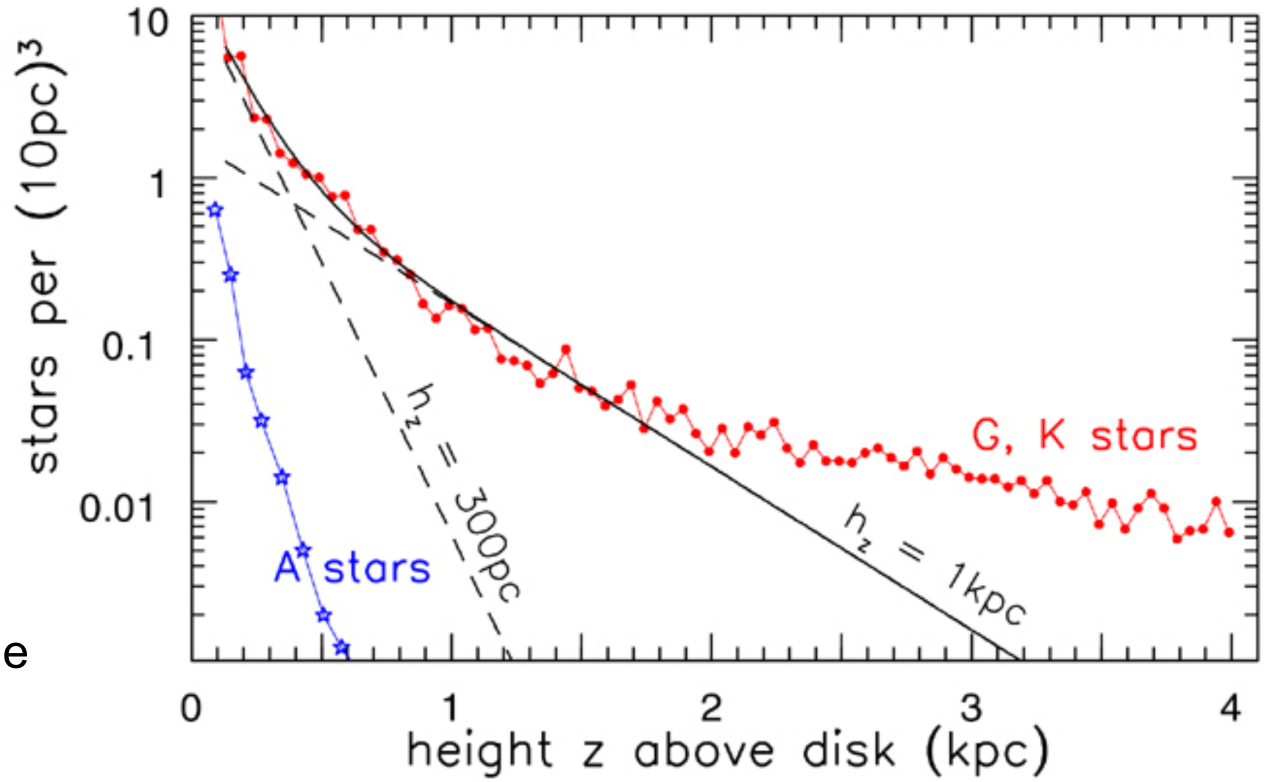


FIG. 6. Radial intensity profile of NGC 4438 at 2.2 μ, as a function of semimajor axis of ellipses fit to the isophotes. Distinct bulge, lens, and disk components may be seen; this sort of profile is often associated with normal S0 galaxies.

The vertical structure of the disk

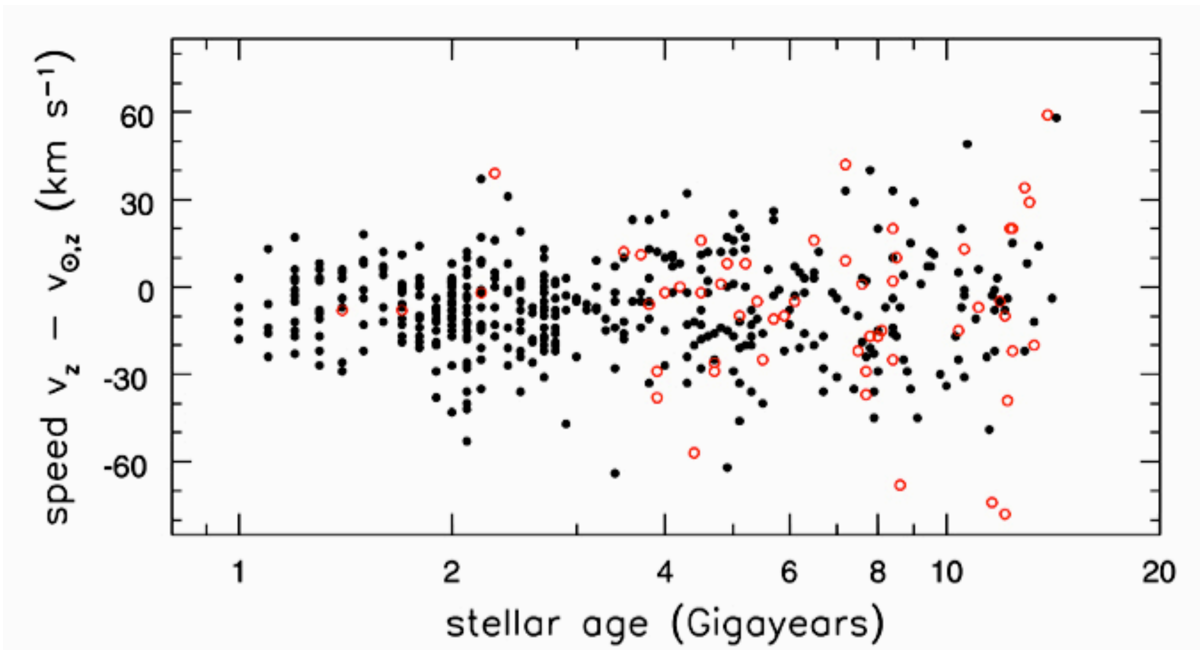
- The vertical nature of galactic disks
  - From photometric parallaxes one can derive the vertical density profile of the disk
  - It seems to be approximately exponential for young stars
  - Long-lived stars deviate from a simple exponential (usually described as a *thin* disk + a *thick* disk)



Looking toward
the Galactic pole

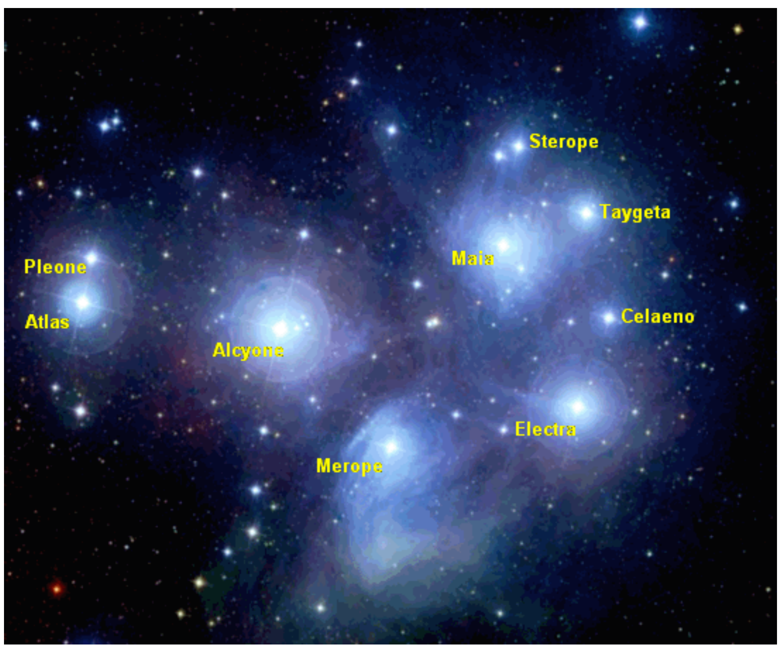
The vertical structure of the disk

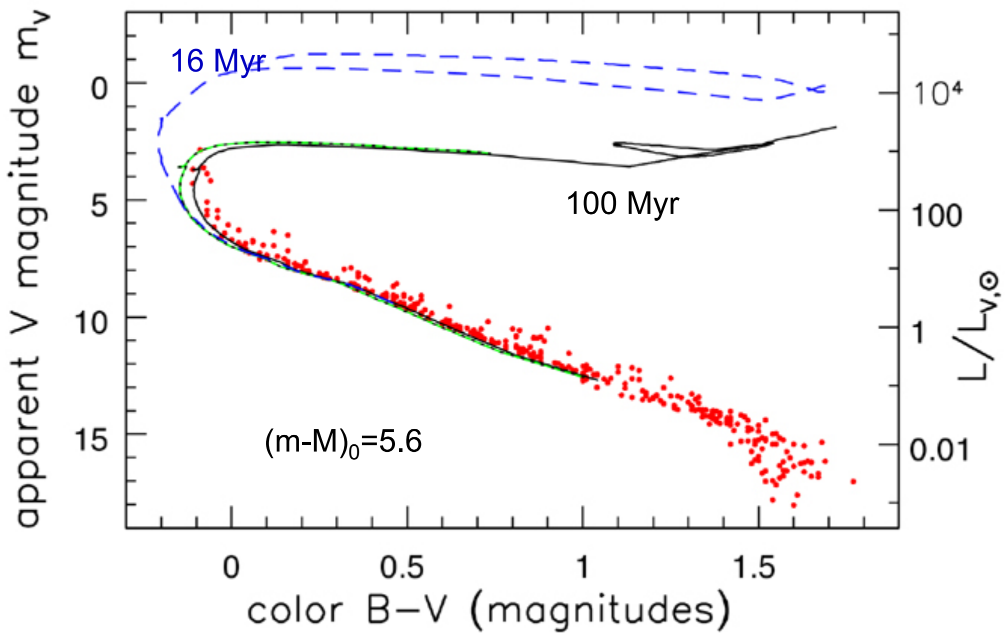
- The density profile of galactic disks
  - $n(R,z)=n_0\, e^{-(R/hr)}\, e^{-(z/hz)}$
  - h_r is the disk scale length; h_z the disk scale height
  - Long-lived stars deviate from a simple exponential (usually described as a *thin* disk + a *thick* disk)
  - Confirmed by the velocity dispersion of stars as a function of age
  - Origin of the thick disk?



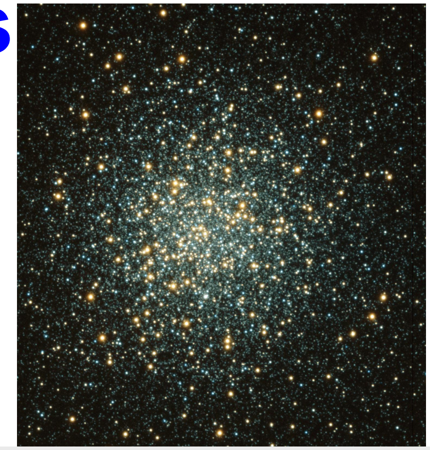
Distances to star clusters

- Main Sequence or Isochrone fitting
  - All stars are at the same distance and they formed at roughly the same time in the past
  - The Pleiades is an example of a young “open” cluster
  - Isochrones are lines in the HR diagram showing where stars of the same age (but different mass) would lie some time after their formation
  - Corrected by dust, this gives a *distance* and *age* for the cluster

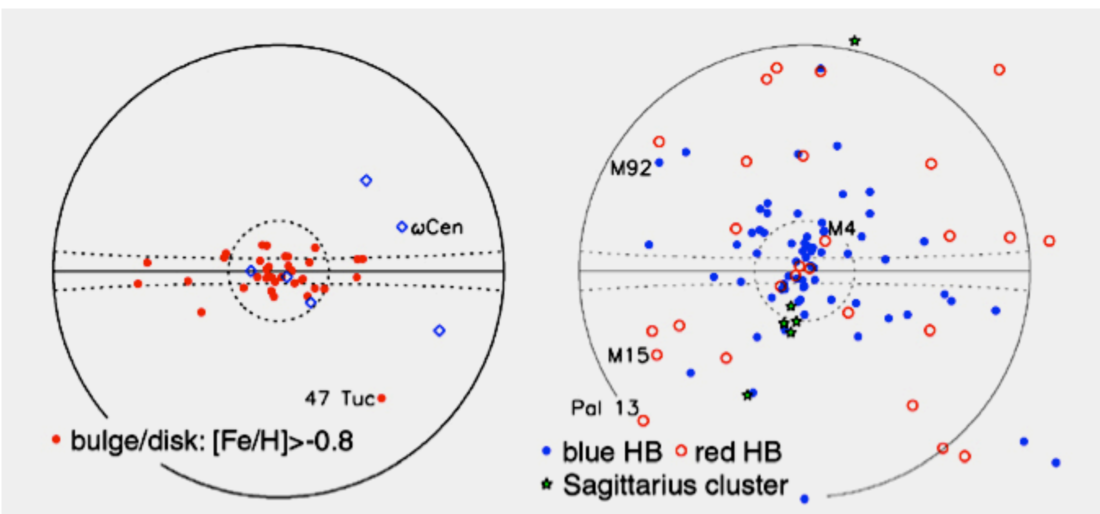


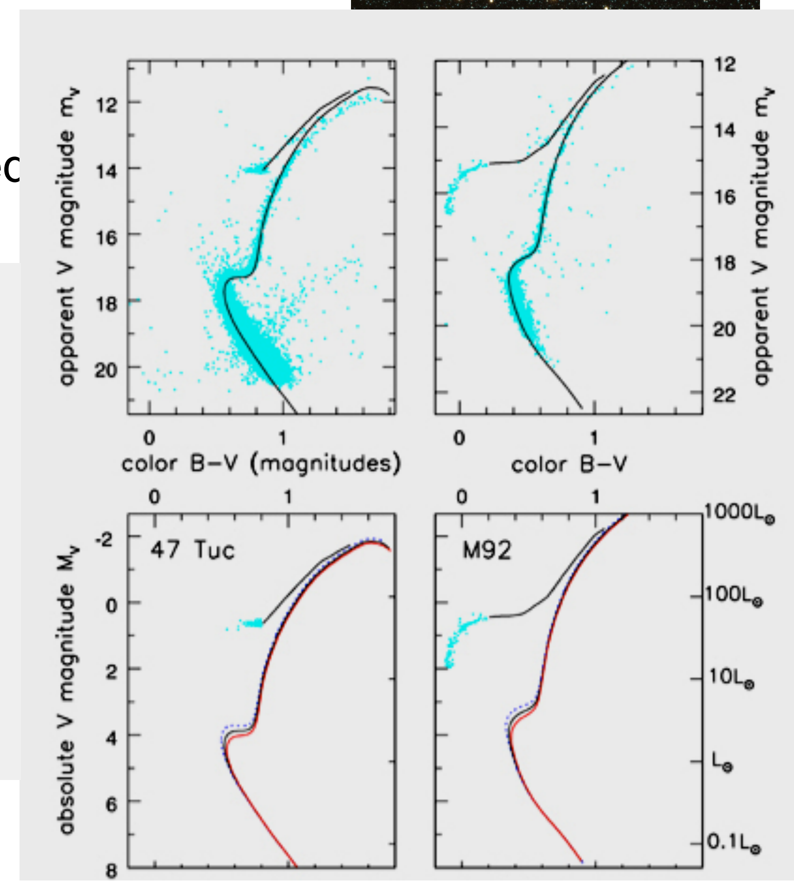


Distances to Globular Clusters



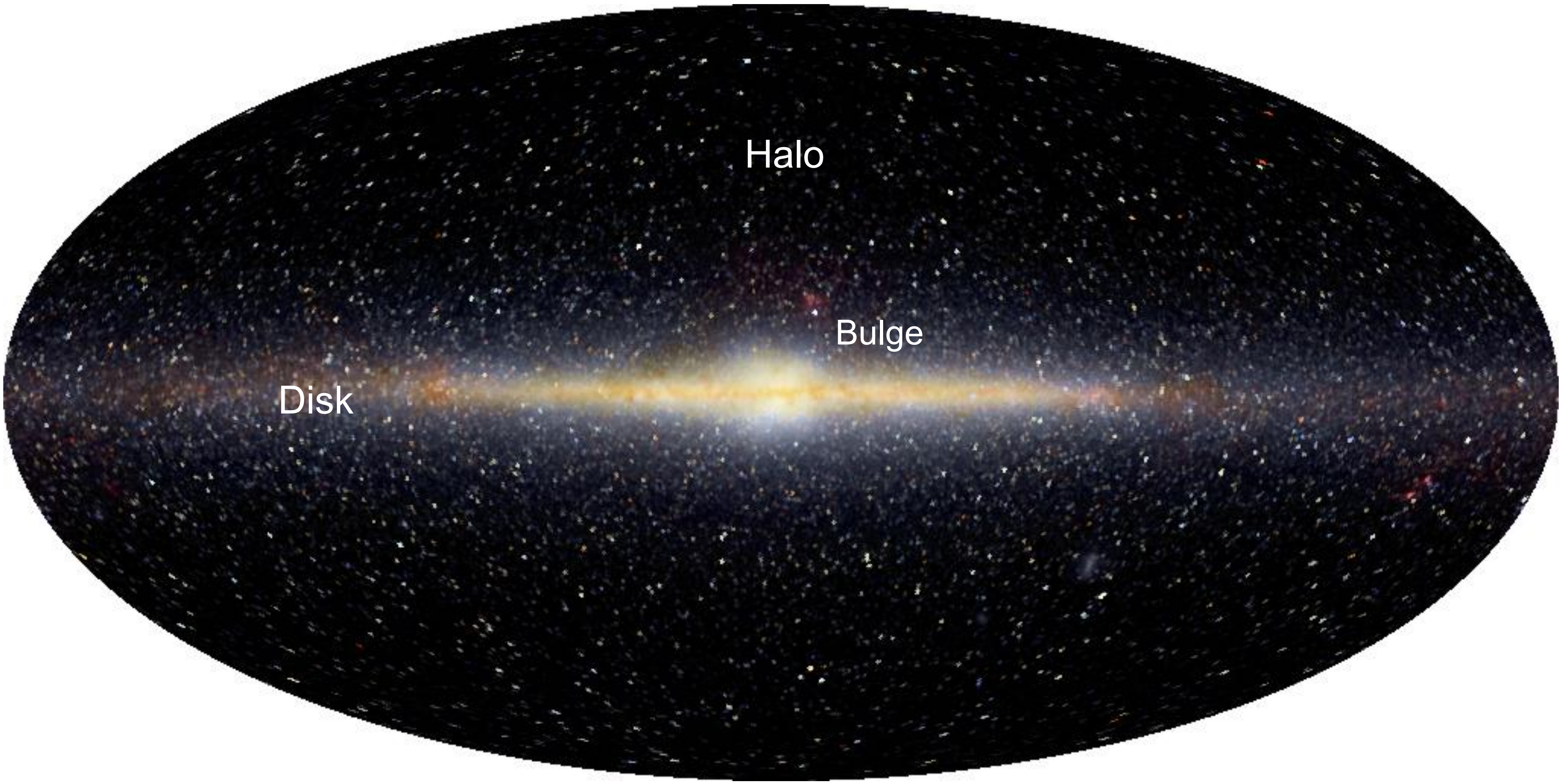
- Globular Clusters
  - More compact than open clusters
  - Older and more metal “poor”
  - Distances from pulsating stars “RR Lyrae” or from isochrone fitting
  - Are distributed following roughly a spheroid centered at the Galactic center—many are outside the disk on plunging orbits
  - The more metal “rich” clusters are distributed like the thick disk

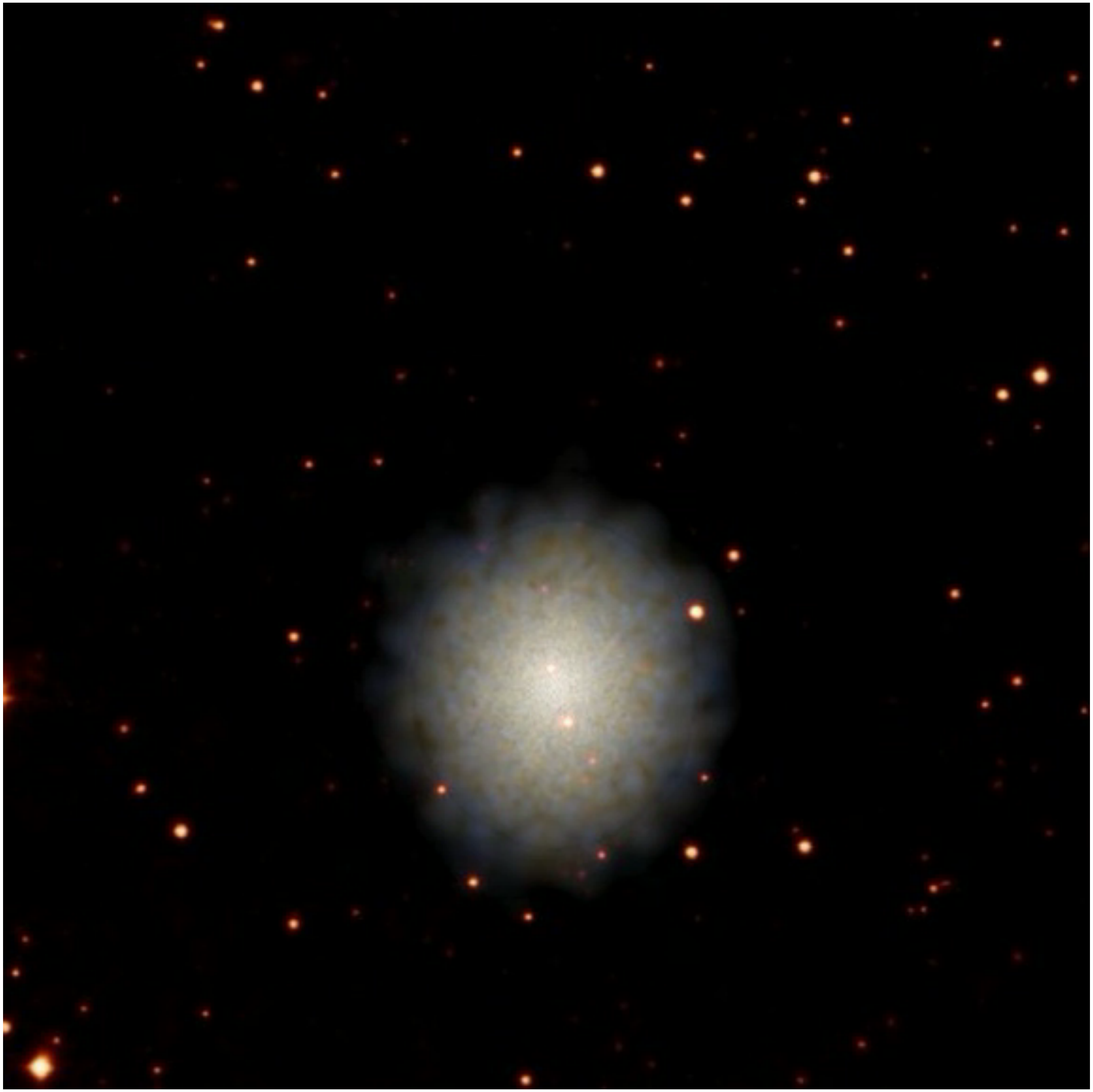




The Stellar "Halo"

- Similar to Globular Clusters
  - Originate in the accretion and disruption of other galaxies?



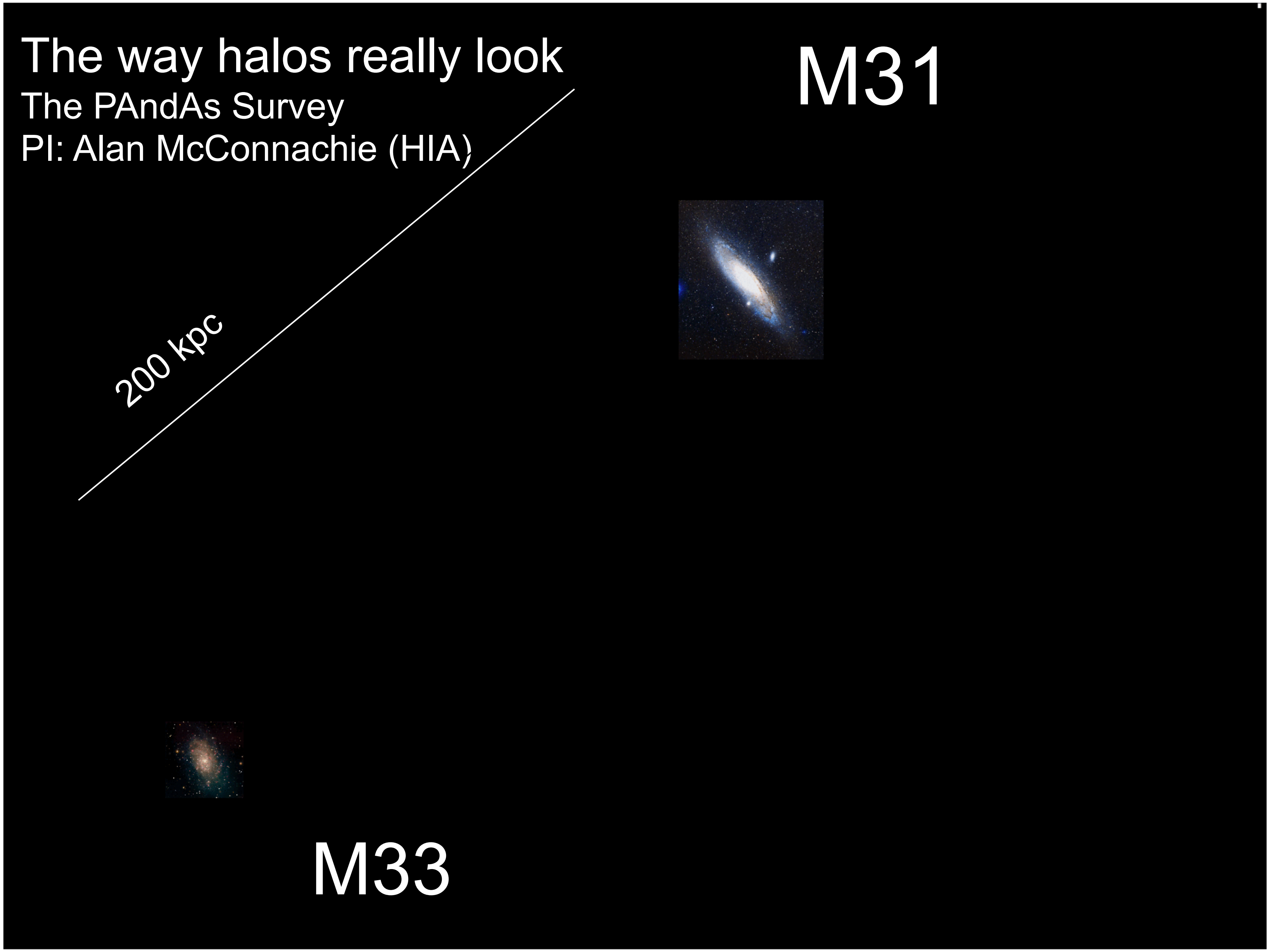


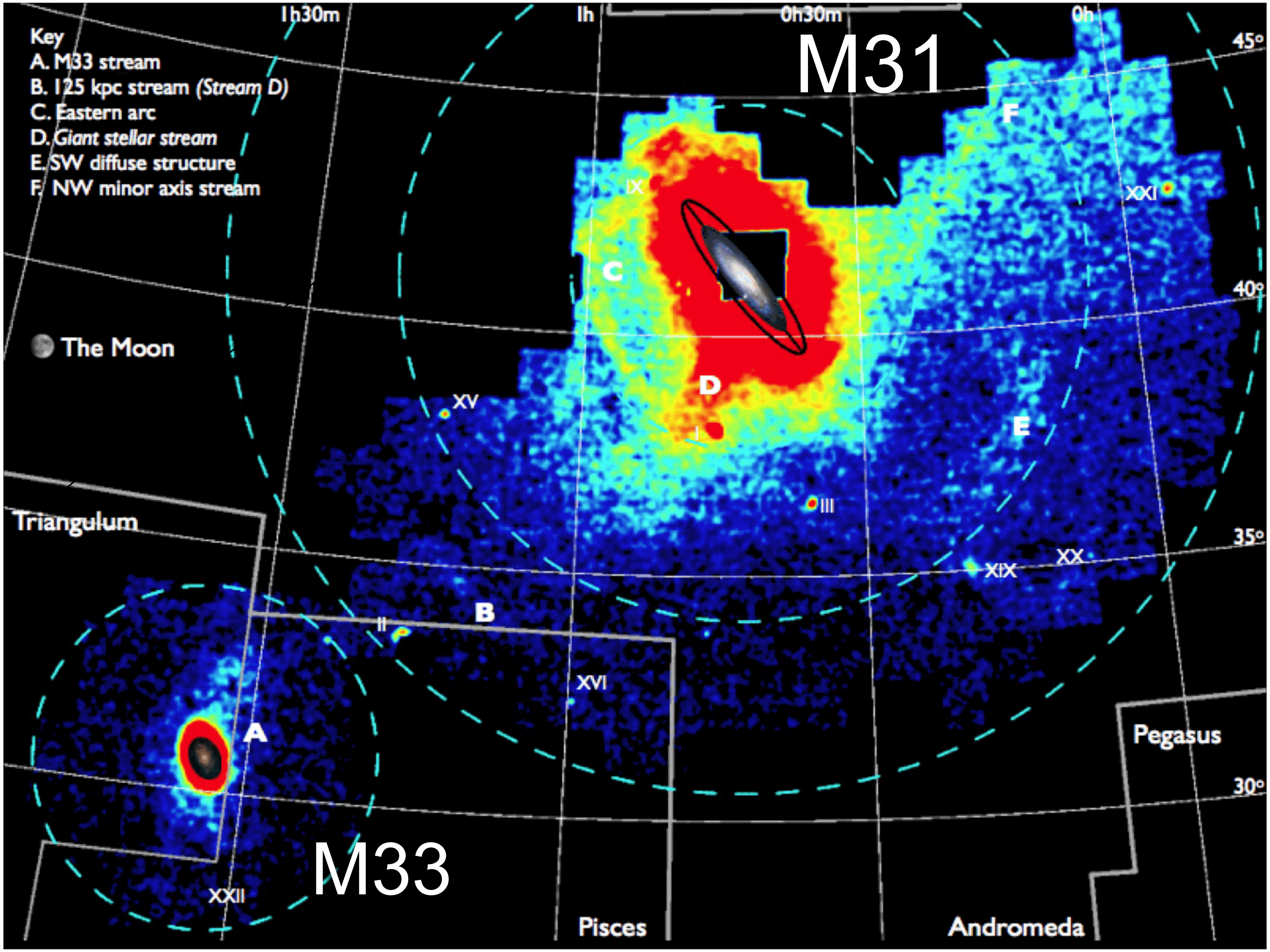
The Sagittarius Dwarf

- Galactic "Cannibalism" caught in the act
  - Several globular clusters are associated with the "tails" of the Sagittarius dwarf

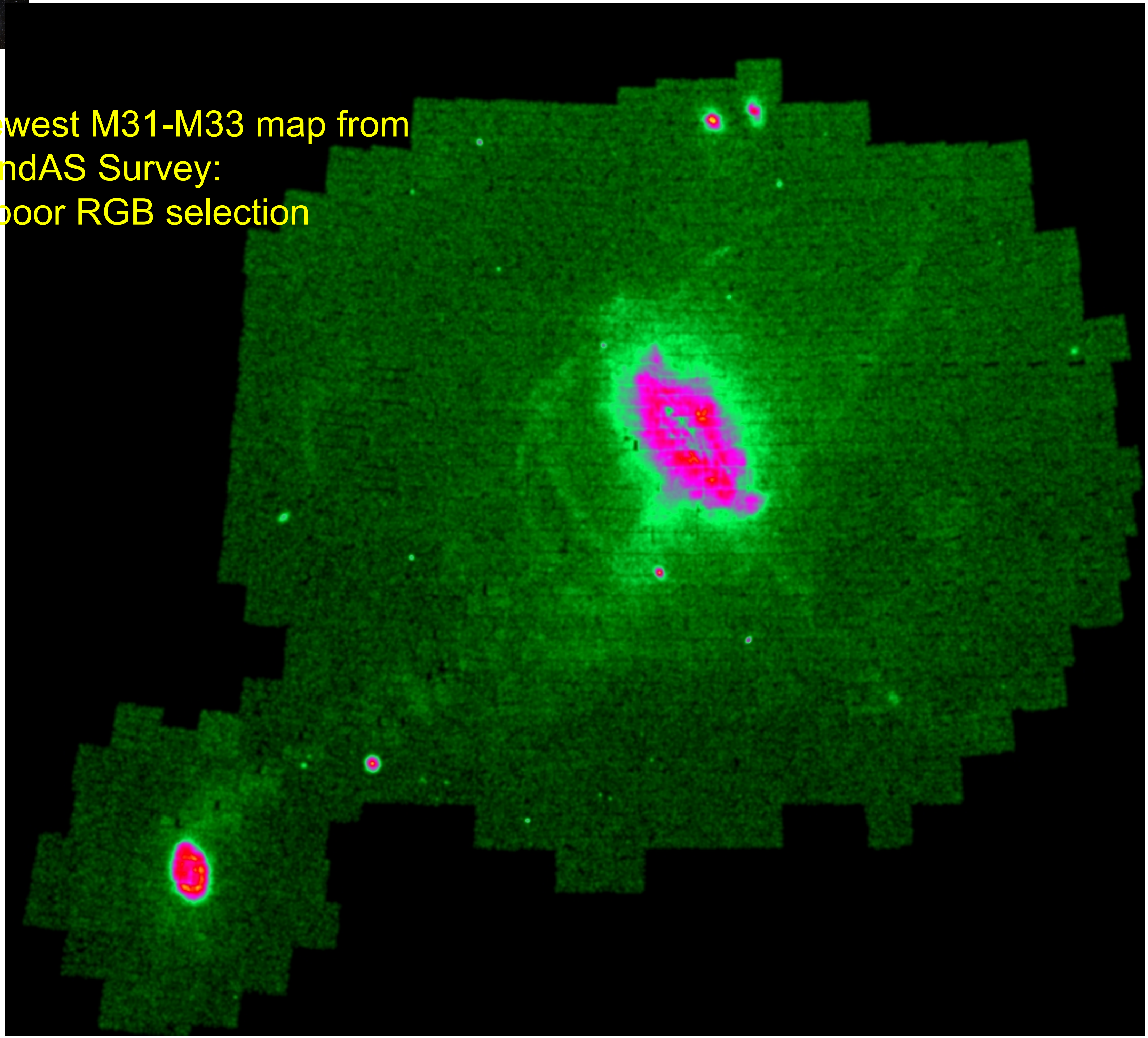
Tidal features in NGC5907

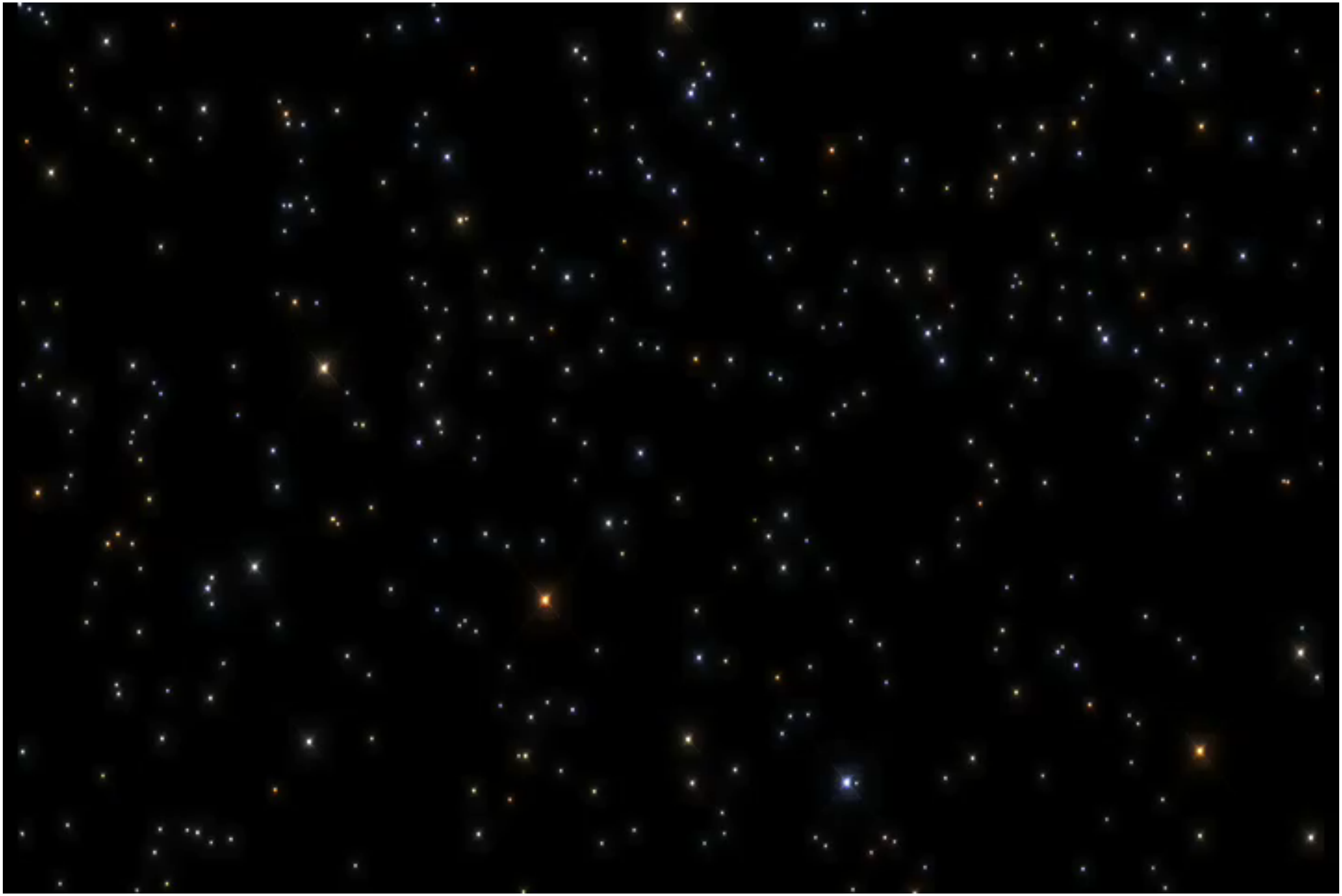
Martínez-Delgado et al 2008


The way halos really look
The PAndAs Survey
PI: Alan McConnachie (HIA)
M31
200 kpc
M33


M31
M33
Key
A. M33 stream
B. 125 kpc stream (Stream D)
C. Eastern arc
D. Giant stellar stream
E. SW diffuse structure
F. NW minor axis stream
The Moon
Triangulum
Pisces
Andromeda
Pegasus
1h30m
1h
0h30m
0h
45°
40°
35°
30°
A
B
C
D
E
F
I
II
III
IX
XV
XVI
XIX
XX
XXI
XXII

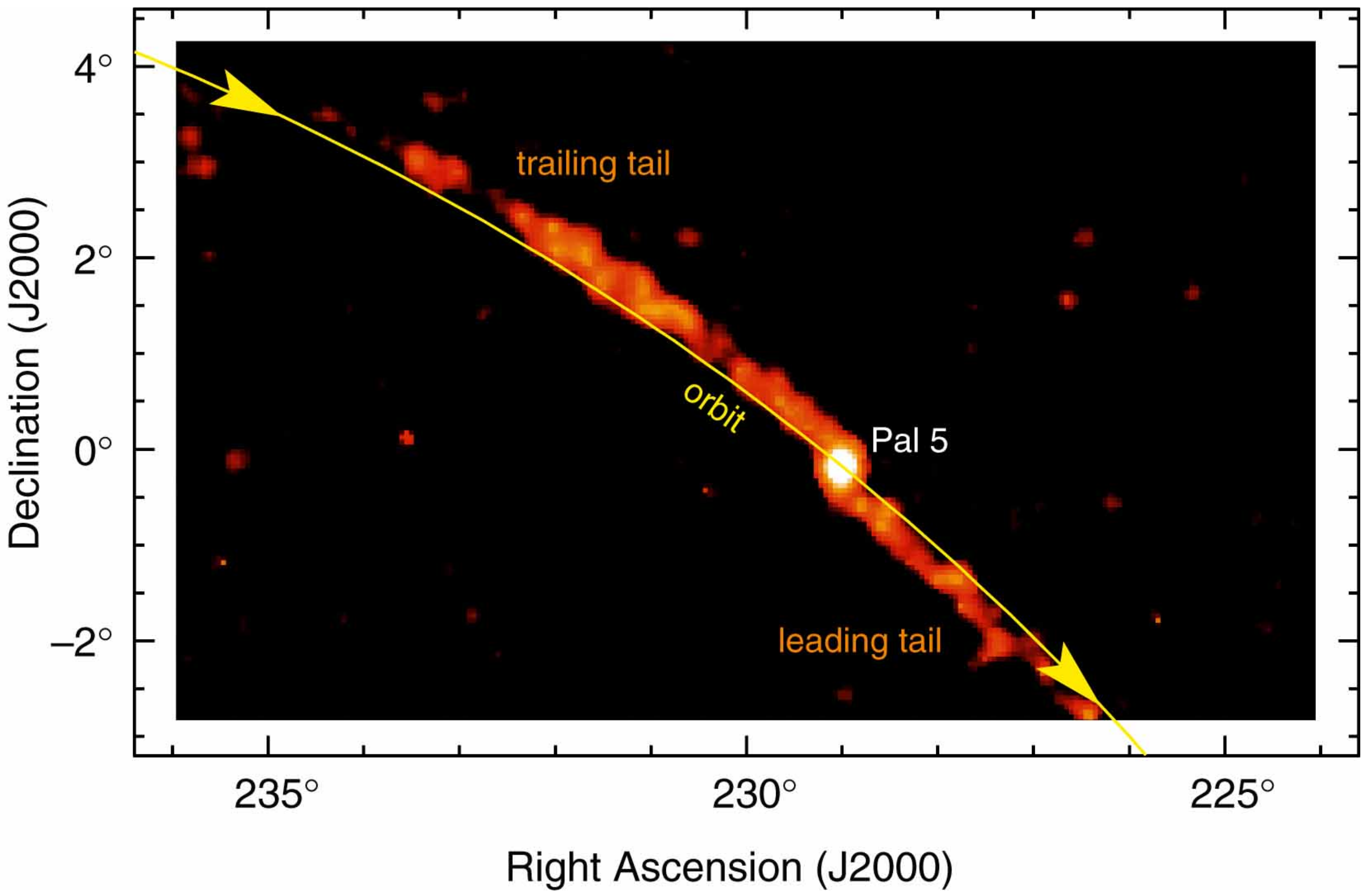
The newest M31-M33 map from
the PAndAS Survey:
metal-poor RGB selection





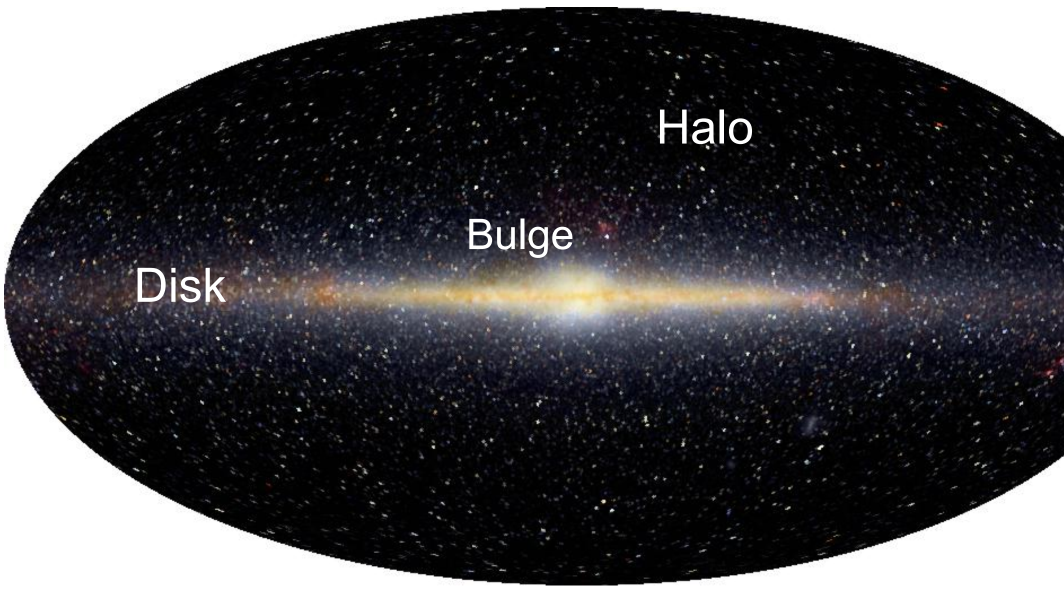
Palomar 5

- Even Globular Clusters can be destroyed by tides

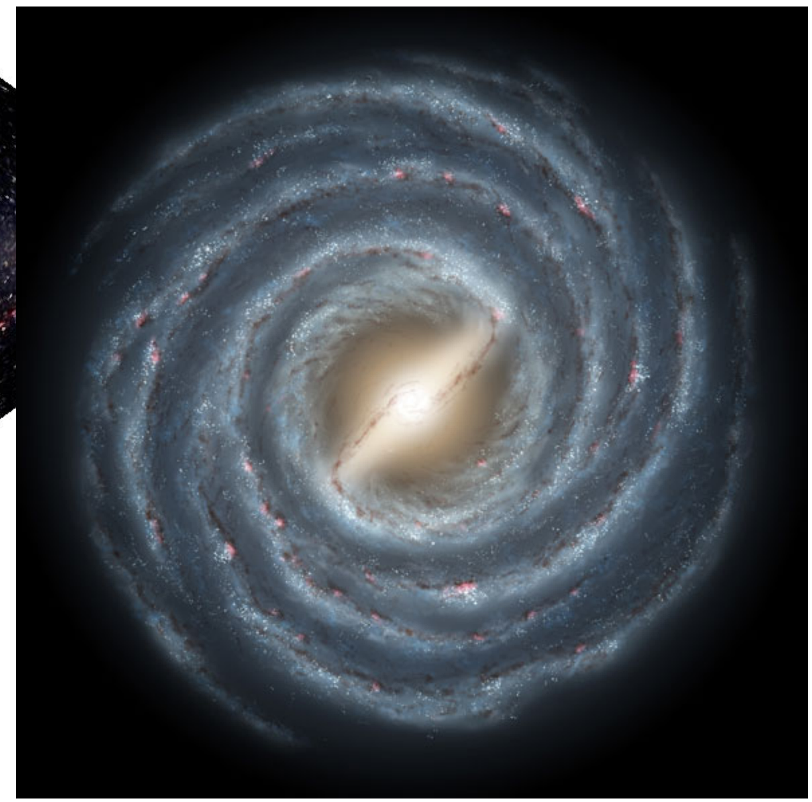


The Bulge

- A bar seen almost end-on?

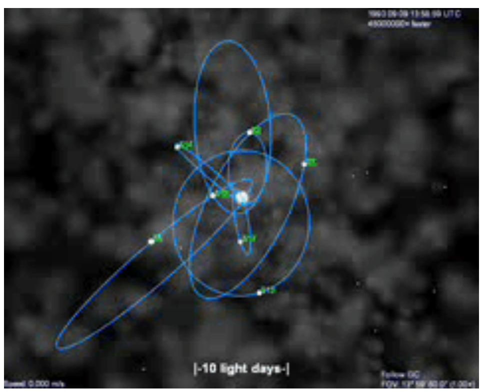


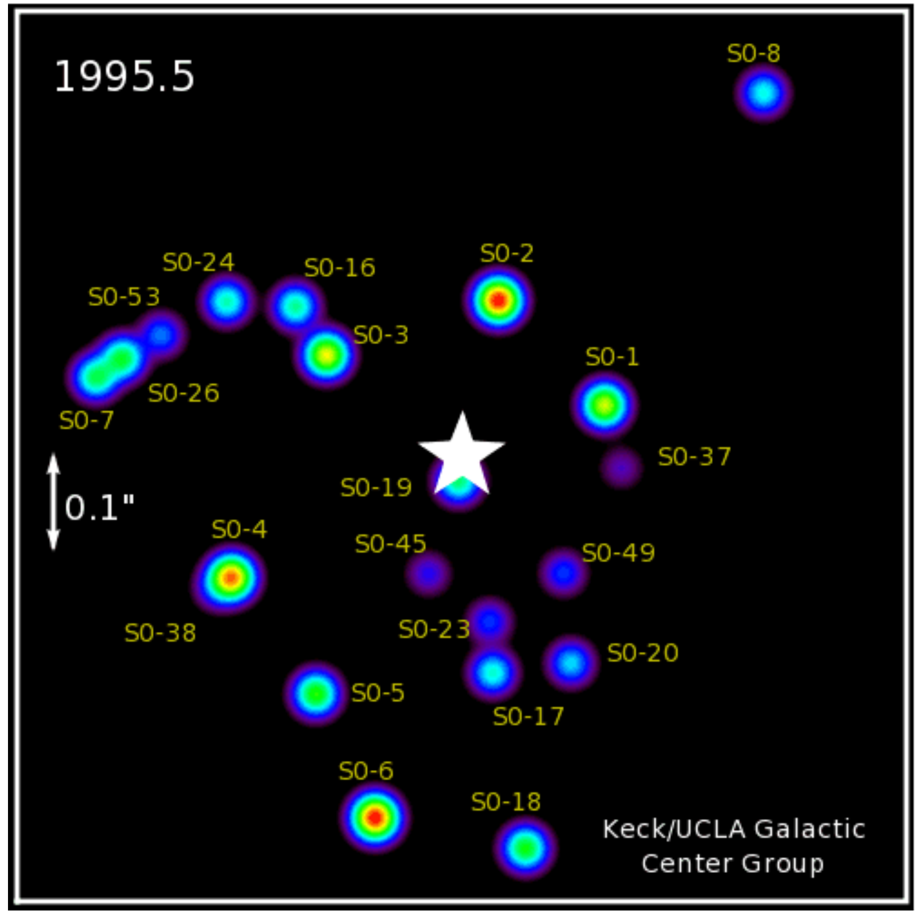
Infrared picture



The Galactic Center

- Need infrared observations to be able to penetrate the dust
  - Done using laser-guided adaptive optics both at the Keck telescopes in Mauna Kea and at the ESO VLT telescopes in Cerro Paranal, Chile.
  - Unmistakable evidence for a 4×10^6 Msun concentration of mass at the Galactic Center—a black hole?





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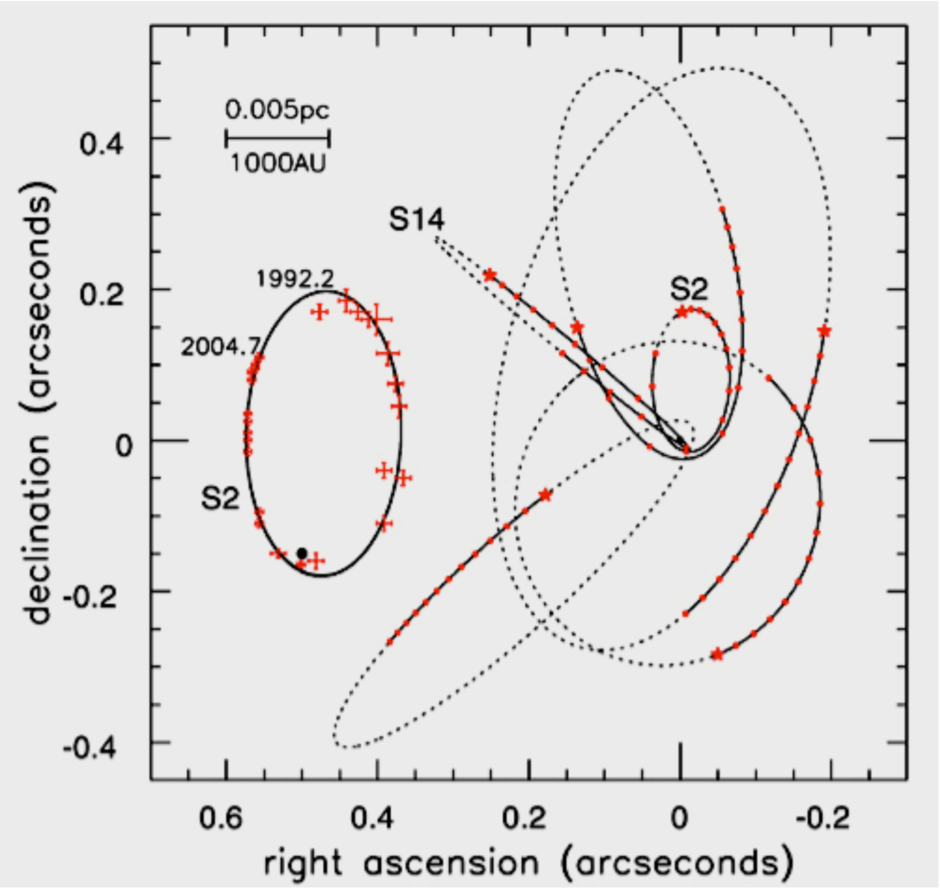
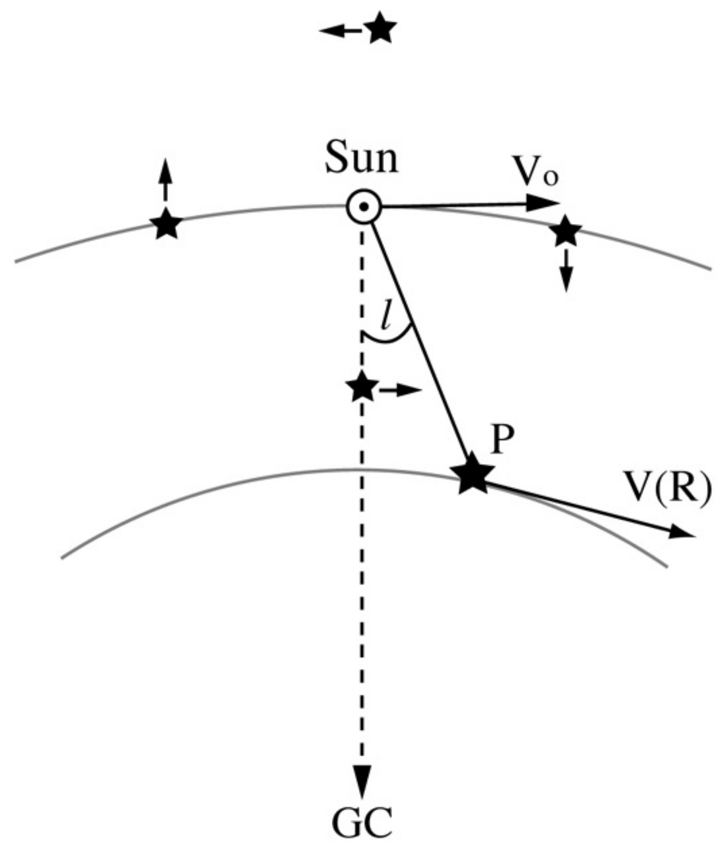


Galactic Rotation

- Much of the luminous component of the Milky Way is in a disk
  - This implies that *circular orbits* are common
  - The pattern of proper motions across the sky suggests *differential rotation*: the angular velocity (ω=V/R) decreases with increasing Galactocentric distance R
  - "Local Standard of Rest" (LSR)
  - Asymmetric drift
  - IAU values
    - $V_{rot}(R_0)$=220 km/s
    - R_0=8.5 kpc



Galactic Rotation

- Asymmetric drift
  - Relative to the Sun, the *mean velocity* in the direction of galactic rotation of different samples of stars depends on their *velocity dispersion*
- "Local Standard of Rest" (LSR)

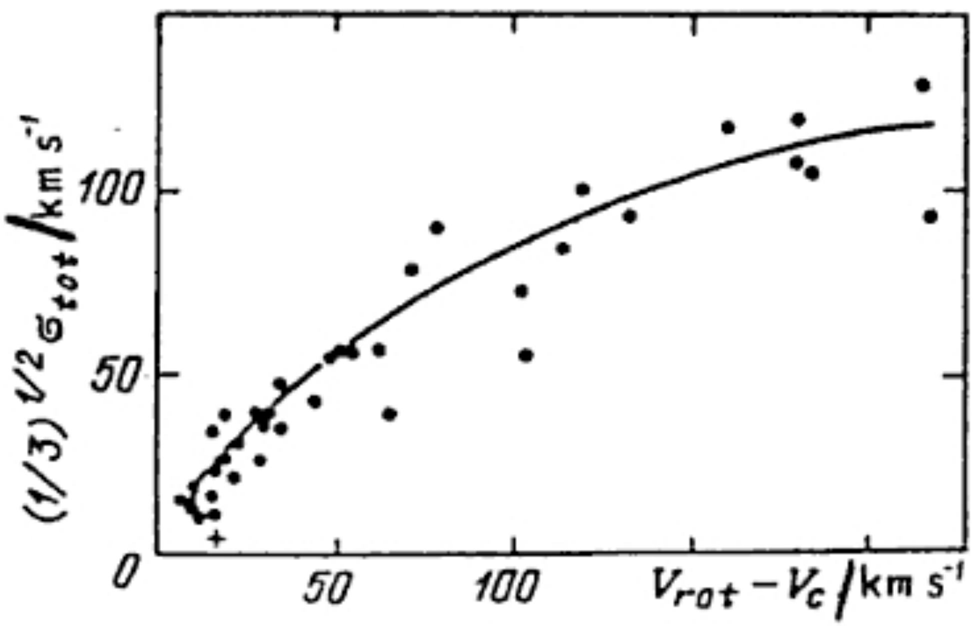


Figure 4.9 The asymmetric drift: the relationship between the centroid rotation velocity V_C and the stellar velocity dispersion σ_{tot} (Einasto, 1973)

Galactic Rotation Curve

- For stars on circular orbits, we have that their *radial velocities*, measured relative to the Sun will be:

  V_r=Vcos(α) – V_0 sin(*l*)

  Using R_0*sin(l)=R*cos(α) (i.e., length GC-T), we have that
  $V_r=R_0$ *sin(l)*(V/R- V_0/R_0)

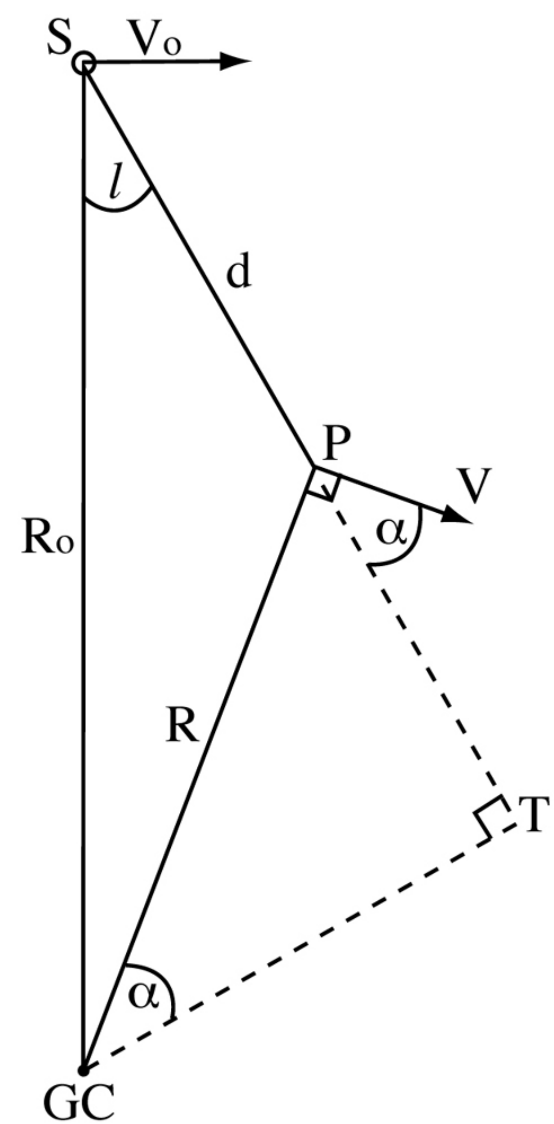
  And, for d<<R, we can use R-R_0=d*cos(l) to write

  V_r~R_0*sin(l)*dω/dR (R-R_0) ~
  ~ d*sin(2l)*[-R/2*dω/dR]$_0$, or

  V_r=d**A**sin(2l)

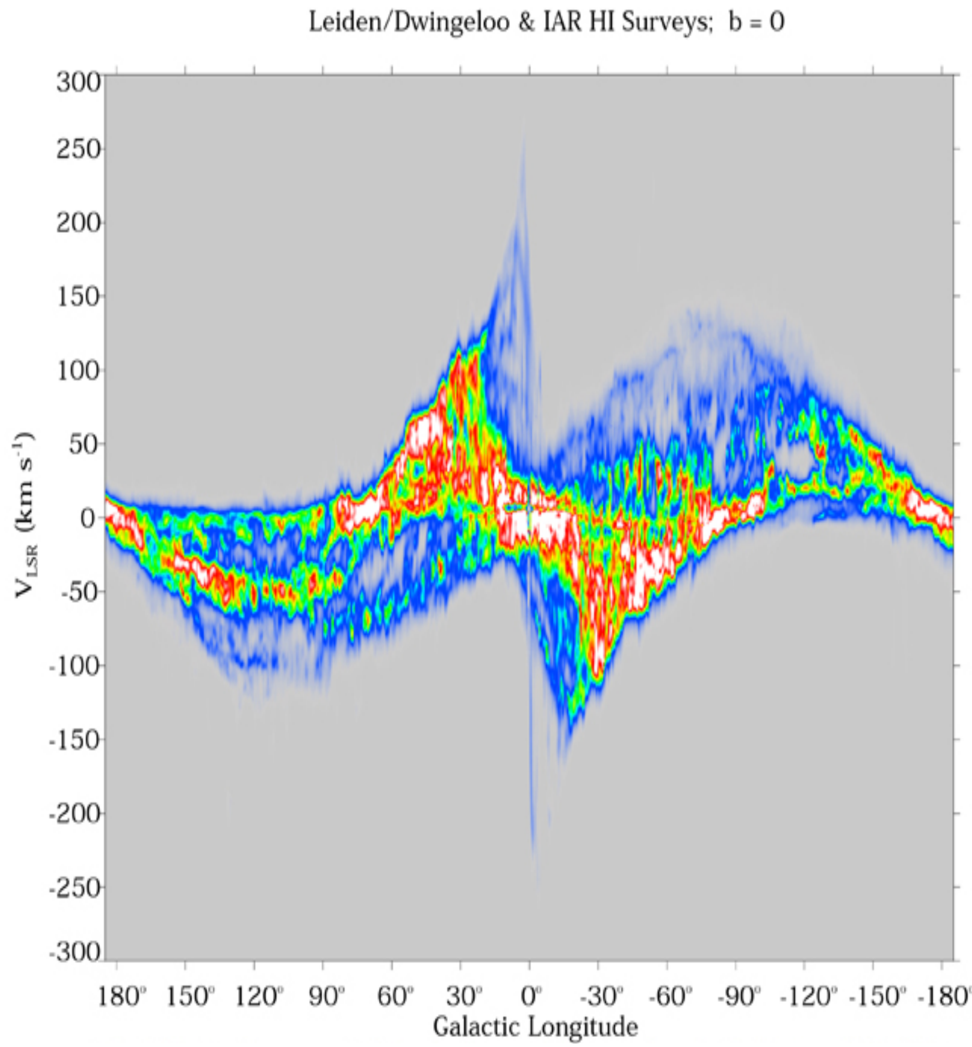
  Where *A*=14.8 km/s/kpc is one of "Oort's constants"

  - *A* measures how much the rotation curve deviates locally from ω=constant



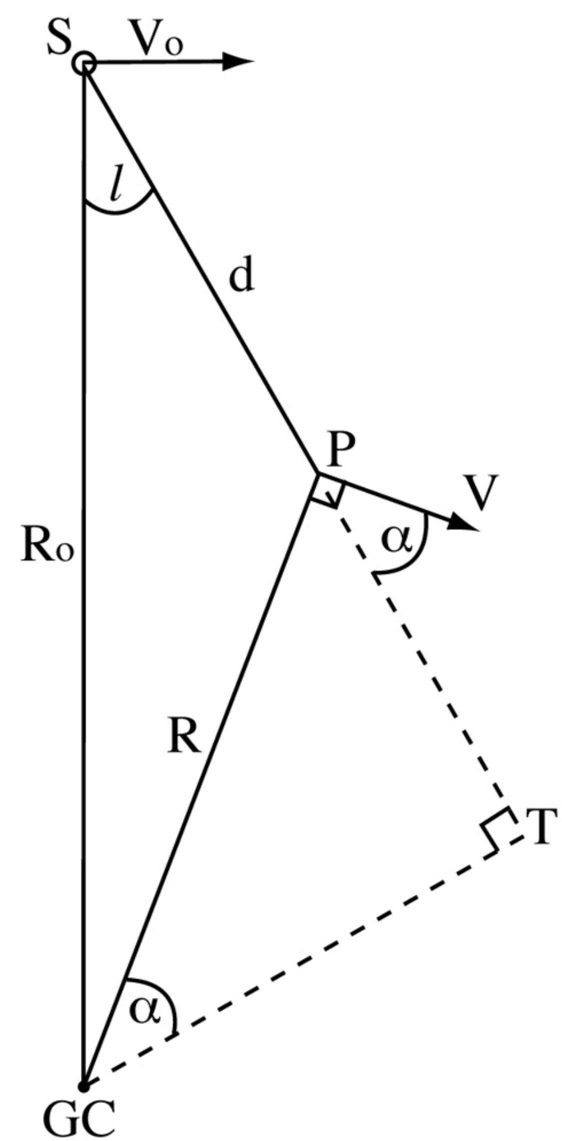
Galactic Rotation Curve

- $V_r = d*A*\sin(2l)$
- Note that the radial velocities of neutral hydrogen (HI) appear to follow the pattern with longitude implied by Oort's interpretation
- Notation (HI, HII)
- How is HI measured?



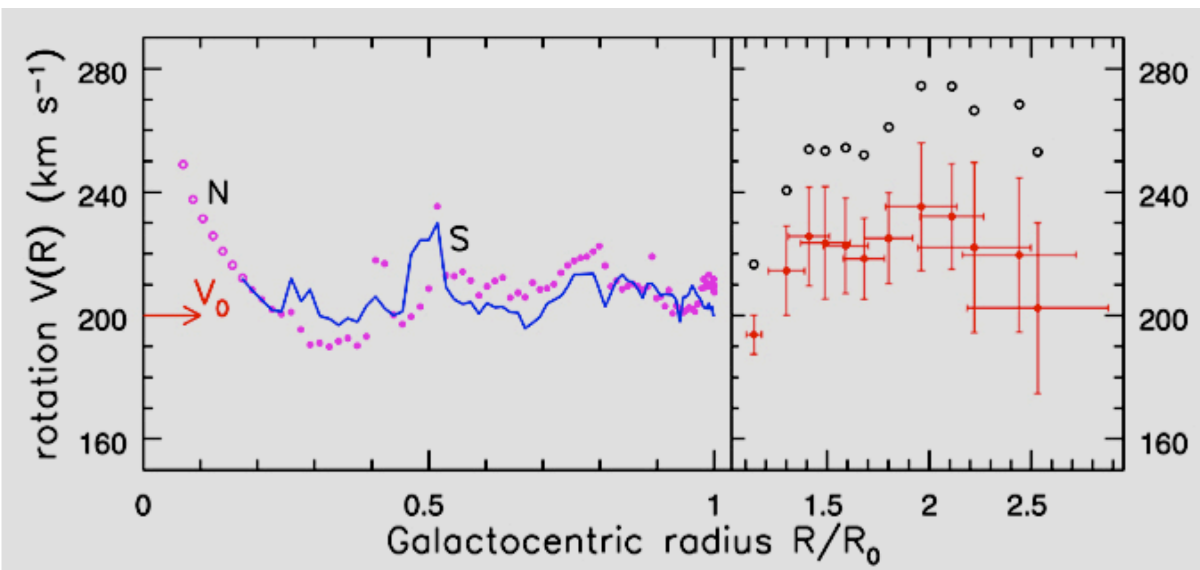
Galactic Rotation Curve

- Proper motions also follow a similar pattern, and one can show that
- $V_t = V*\sin(\alpha) - V_0*\cos(l)$ or, using $R_0*\cos(l) = d + R*\sin(\alpha)$
- $V_t = R_0*\cos(l)*(V/R - V_0/R_0) - V*d/R$
- Or, for d<<R
- $V_t = d*\cos(2l)[-R/2*d\omega/dR]_0 -$
  $-(d/2)*[1/R*d(\omega*R^2)/dR]_0$
- Which may be written as
  $V_t = d*(A*\cos(2l) + B)$
- Where B=-12.4 km/s/kpc is another of Oort's constants
- B measures how much the *specific angular momentum* of circular orbits changes locally as a function of R



The Rotation Curve of the Milky Way

- The Tangent Point method allows us to measure the rotation curve of the *inner* galaxy.
  - This uses the maximum radial velocity measured on the disk at a particular longitude (l).
  - From the figure, we see that $V_{circ}(R) = V_{r,max} + V_0 * \sin(l)$
- Measuring the outer galaxy is harder!



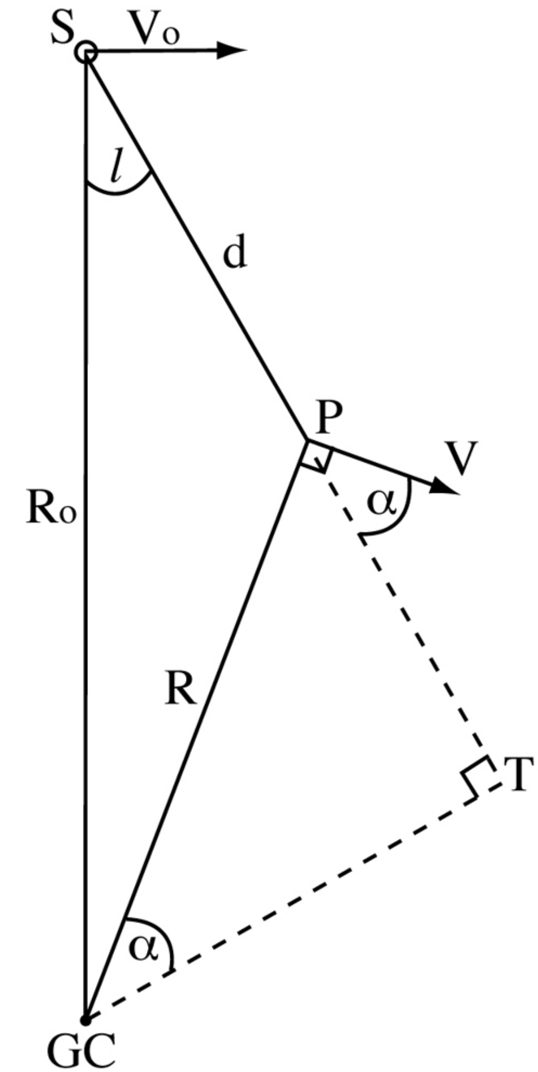
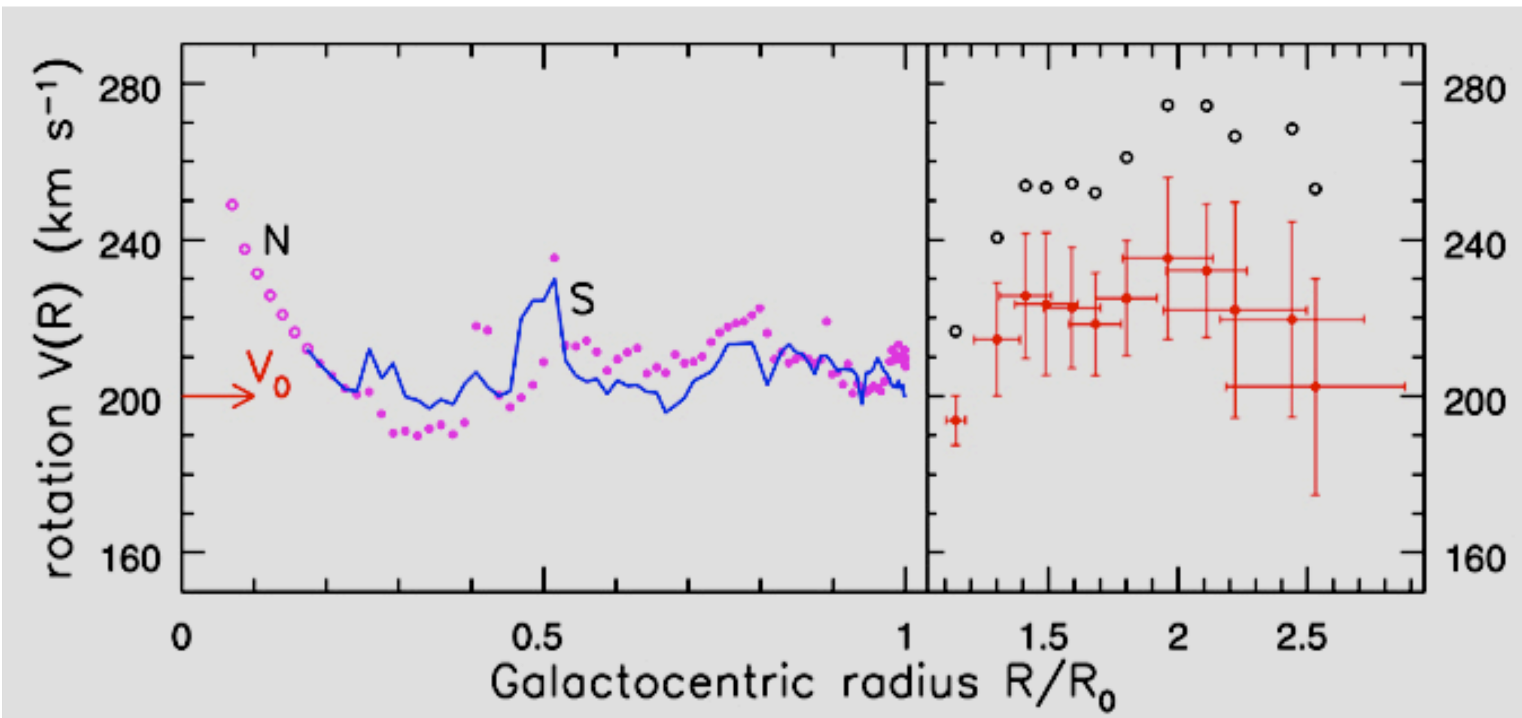


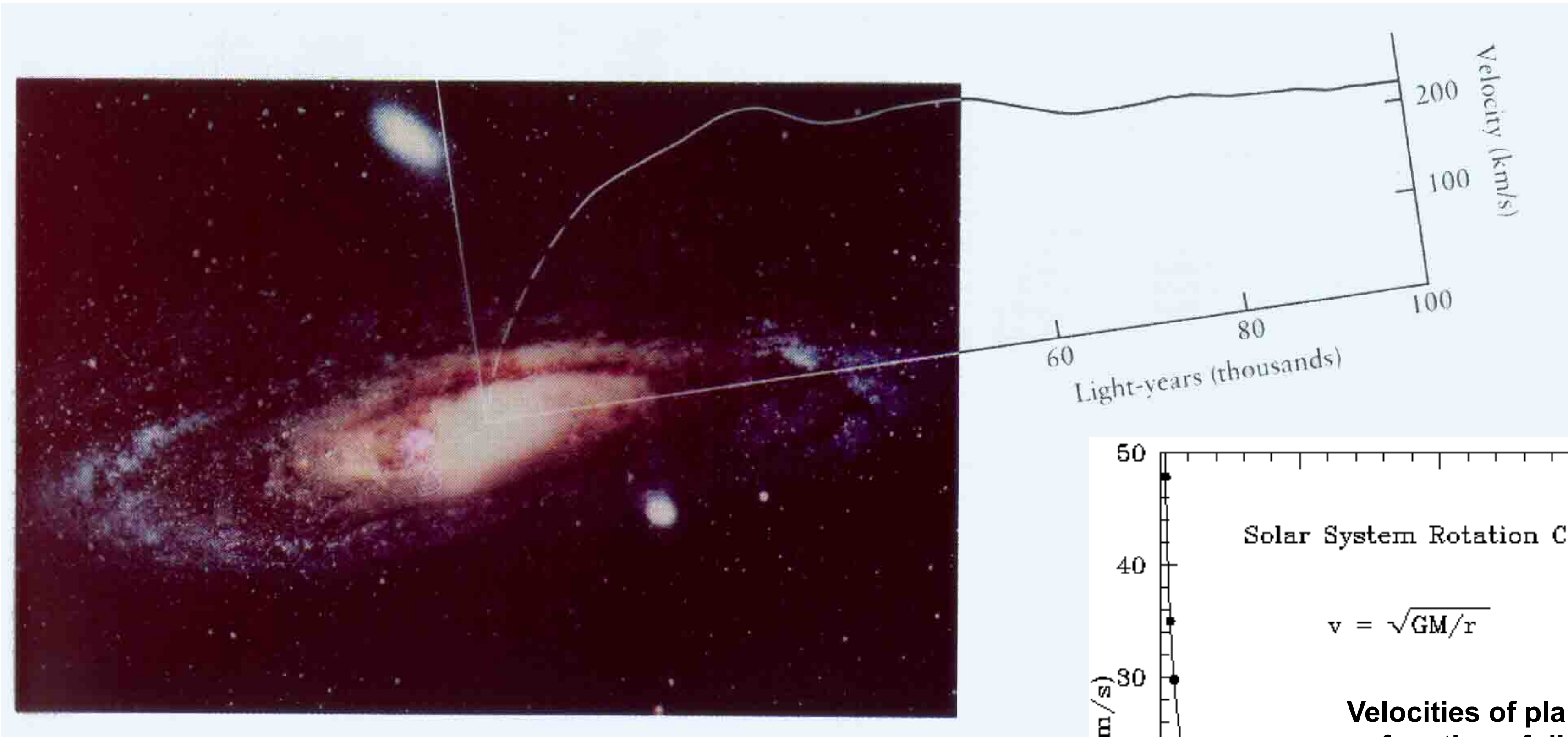
Fig 2.19 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

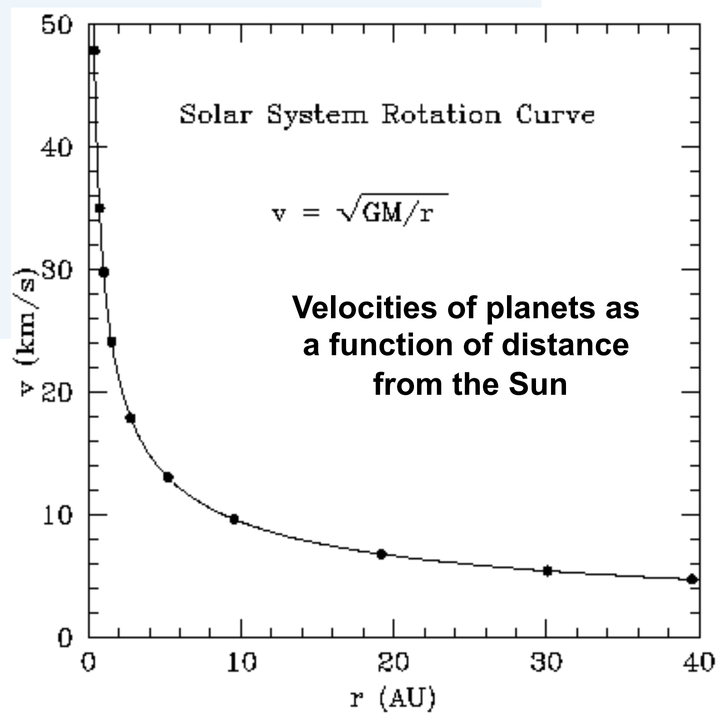
Dark Matter in the Milky Way

- The measured rotation curve shows that the rotation speeds remain more or less constant with radius.
  - The enclosed mass within R scales like $V_{circ}^2 * R$, which means that the total mass of the Milky Way increases linearly with distance
  - We need dark matter to hold the Galaxy together!



Dark Matter: the dominant mass form in the Universe





Stars in galaxies rotate too fast to be held in place by the gravitational pull of visible mass