# Astronomy 537

Lecture 2: The Milky Way Galaxy I

**Why do we classify galaxies?**

The classification can be shown to correlate with:

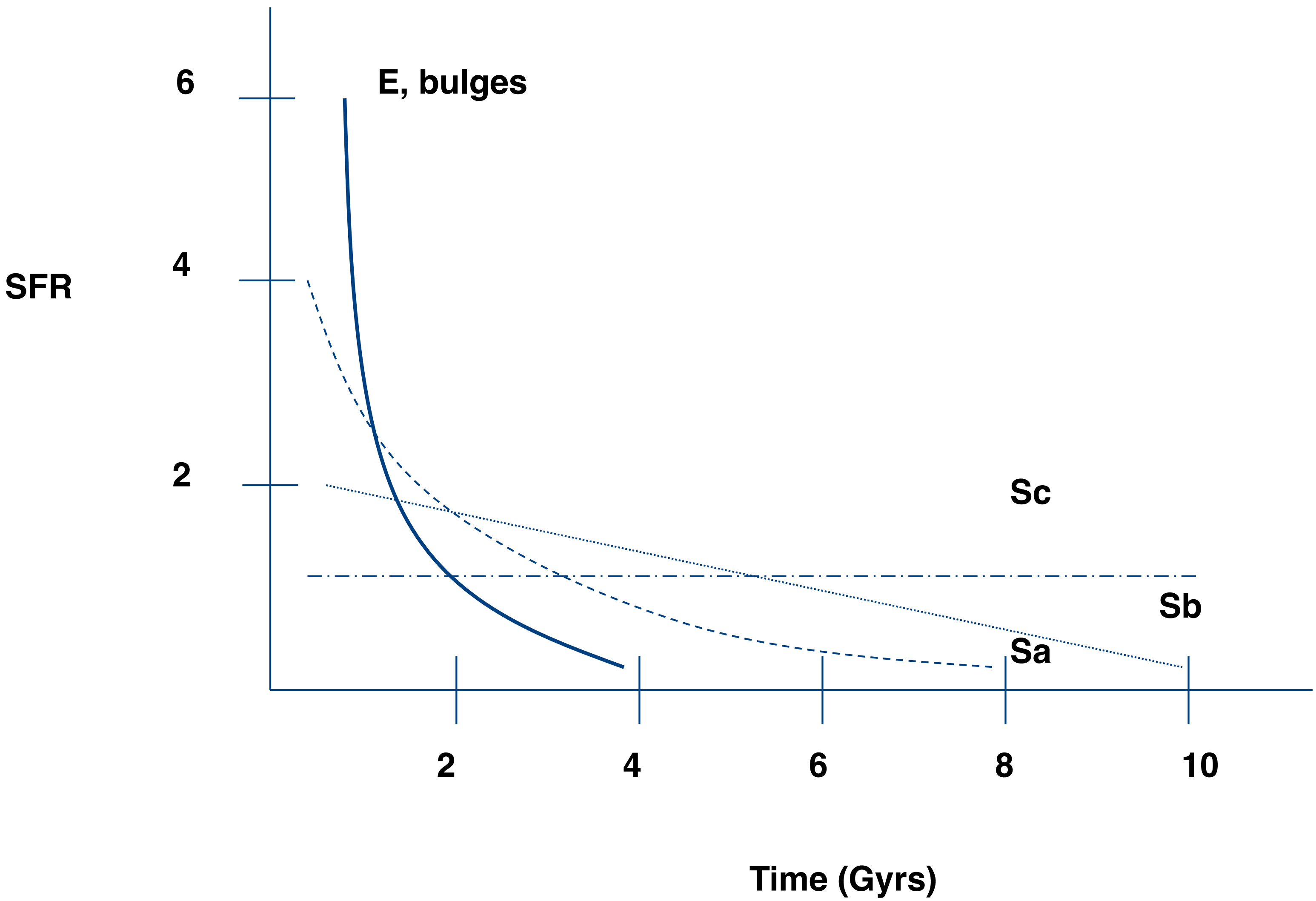
- Bulge/disk luminosity ratio
- Mass concentration
- Bulge – Black Hole Mass correlation
- Relative HI content (M(HI)/L(B))
- Stellar population
- Nuclear properties
- Chemical abundances in the ISM
- Star formation history, and integrated stellar spectrum

Provides clues to formation and evolution of galaxies.

## Overview of galaxy properties

| | E | S0 | Sa | Sb | Sc | Sd | Irr |
|---|---|---|---|---|---|---|---|
| | | | | | | | |
| Color | Red | → | → | → | → | → | Blue |
| Stellar pop | Old | Old/interm | | Old + interm + young | | Intermediate young | |
| SFR | None | Low | → | Higher | → | → | High |
| HI | None/Low | Low | → | Modest | → | High | Highest |
| Dust | None/Low | Higher | | High | — | High | Lower (less metals) |
| Dyn | Bulge/halo dominated | | Disk dom (rot) | — | — | Disk dom | |

Schematic star formation histories:



**Key concepts:**

Morphology

Stellar number density – the Log N – log S relation

First look at MW structure and gas distribution

**Teaching Exercise:**

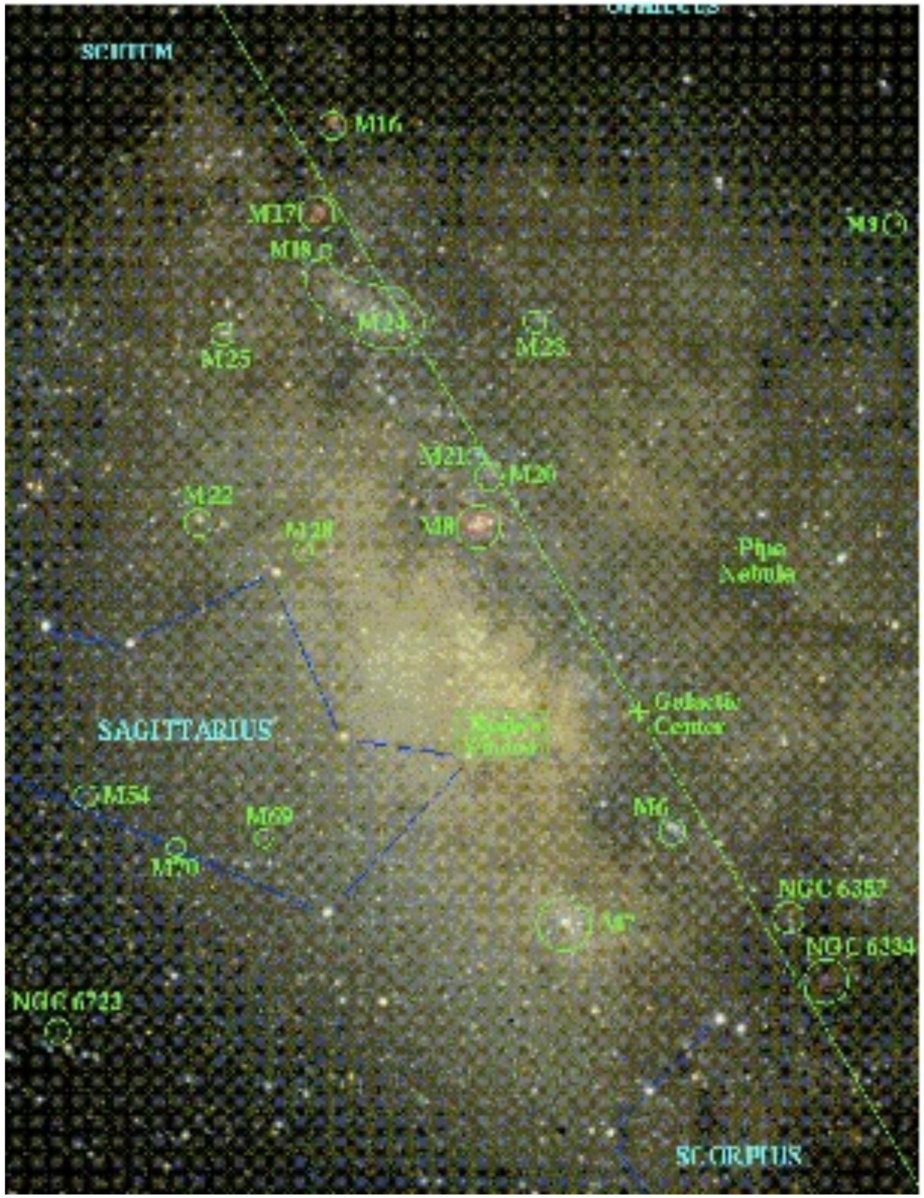
See also
https://leo.phys.unm.edu/~gbtaylor/astr537/topic_instructions.pdf

- Decide on a topic by Feb 11. Provide a hard-copy in class (so I can mark it up)
- Draft slides by Apr 15. 6/page, provide hard copy in class (so I can mark it up)
- Aim for 25 minutes + Q&A

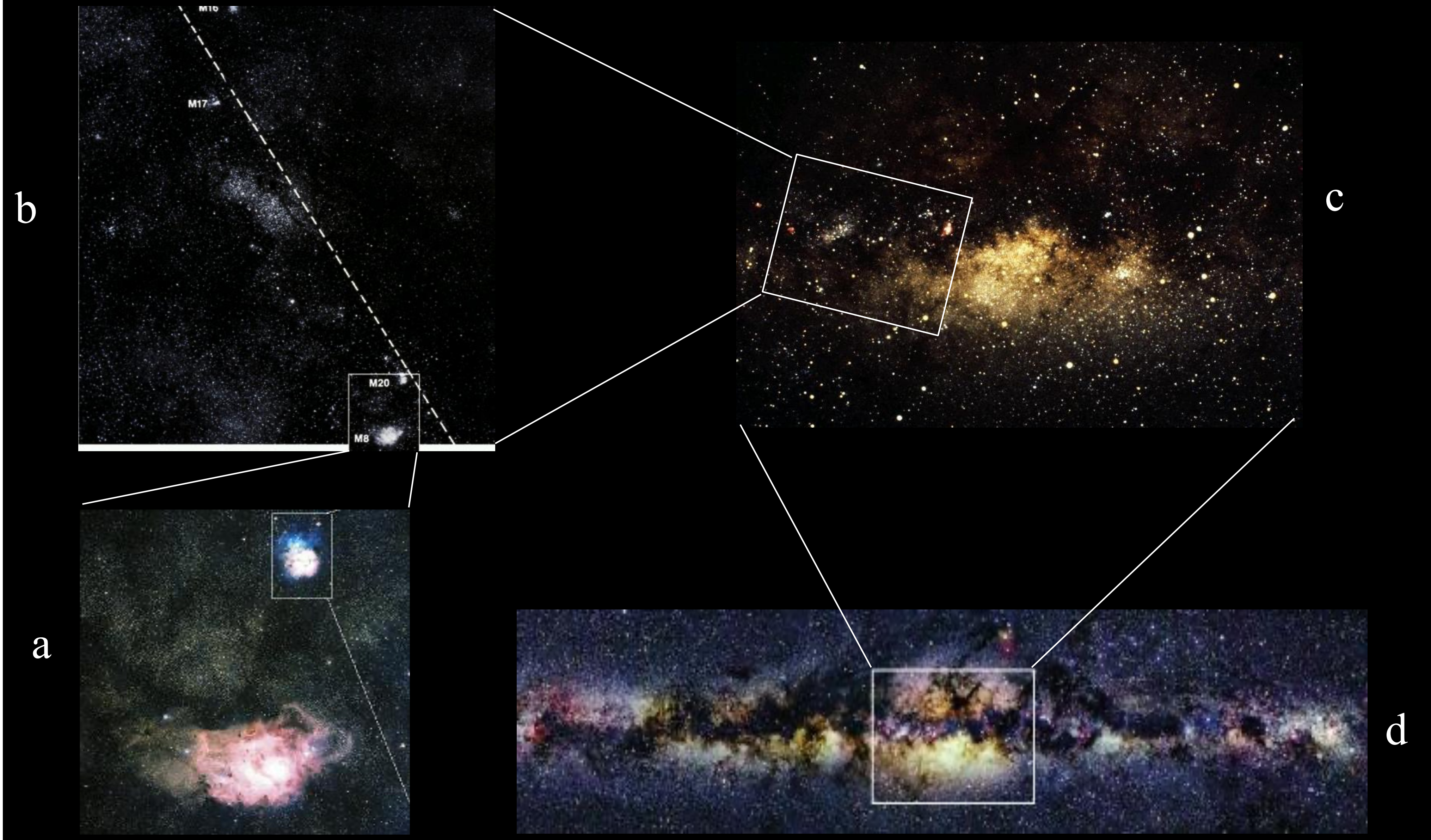
Sample topics:

- Advances in instrumentation to measure galaxies at any wavelength
- galactic magnetic fields in starburst galaxies or Ellipticals
- warps in galaxies
- Globular clusters
- Black holes and their accretion disks
- Supernovae and role as cosmic accelerators
- JWST's Little Red Dots

## Structure of the Milky Way is hard to determine from where we are sitting

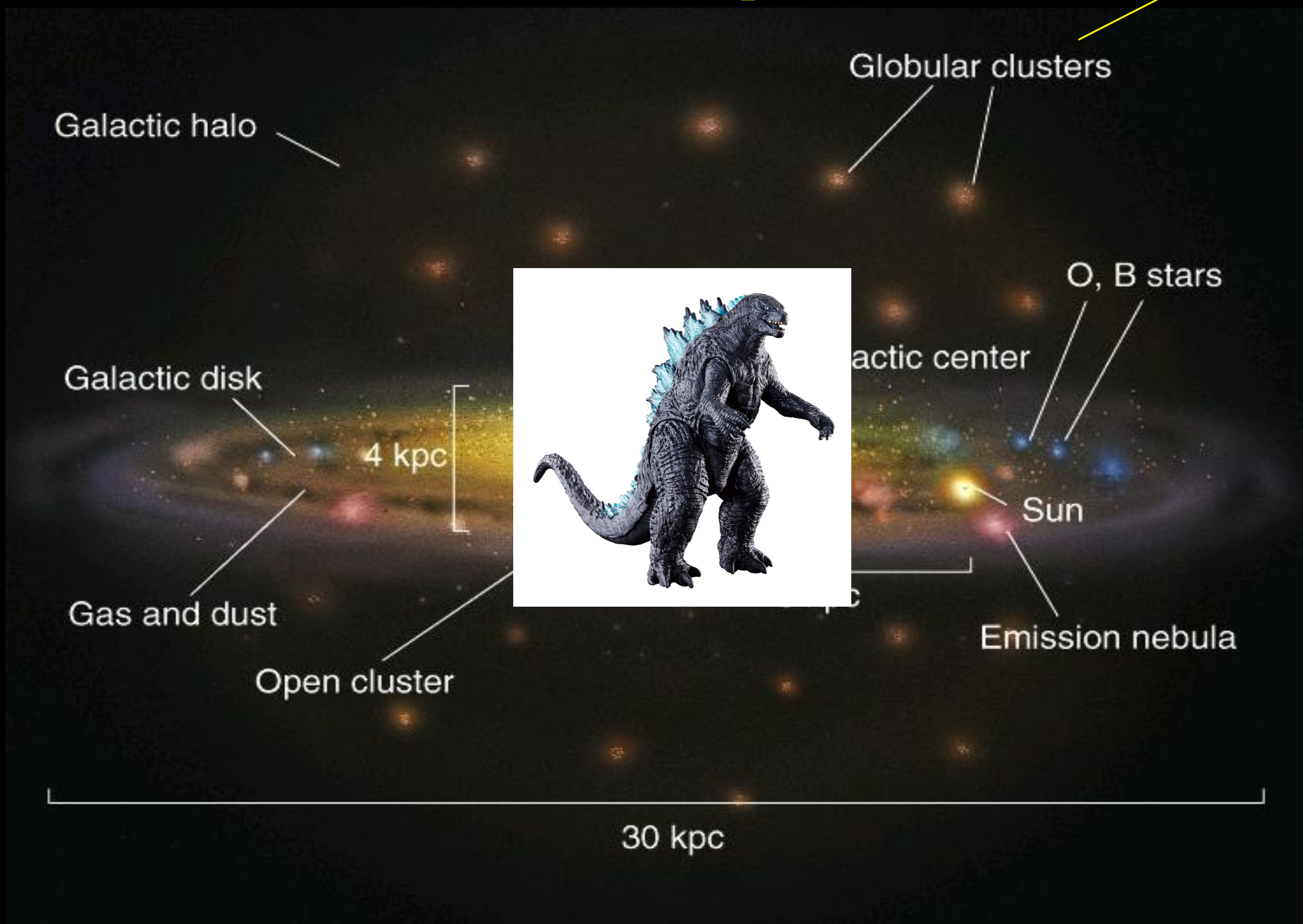


# The Milky Way Galaxy



# Take a Giant Step Outside the Milky Way

## Artist's Conception




Example (not to scale)

# Structure of the Milky Way is hard to determine from where we are sitting

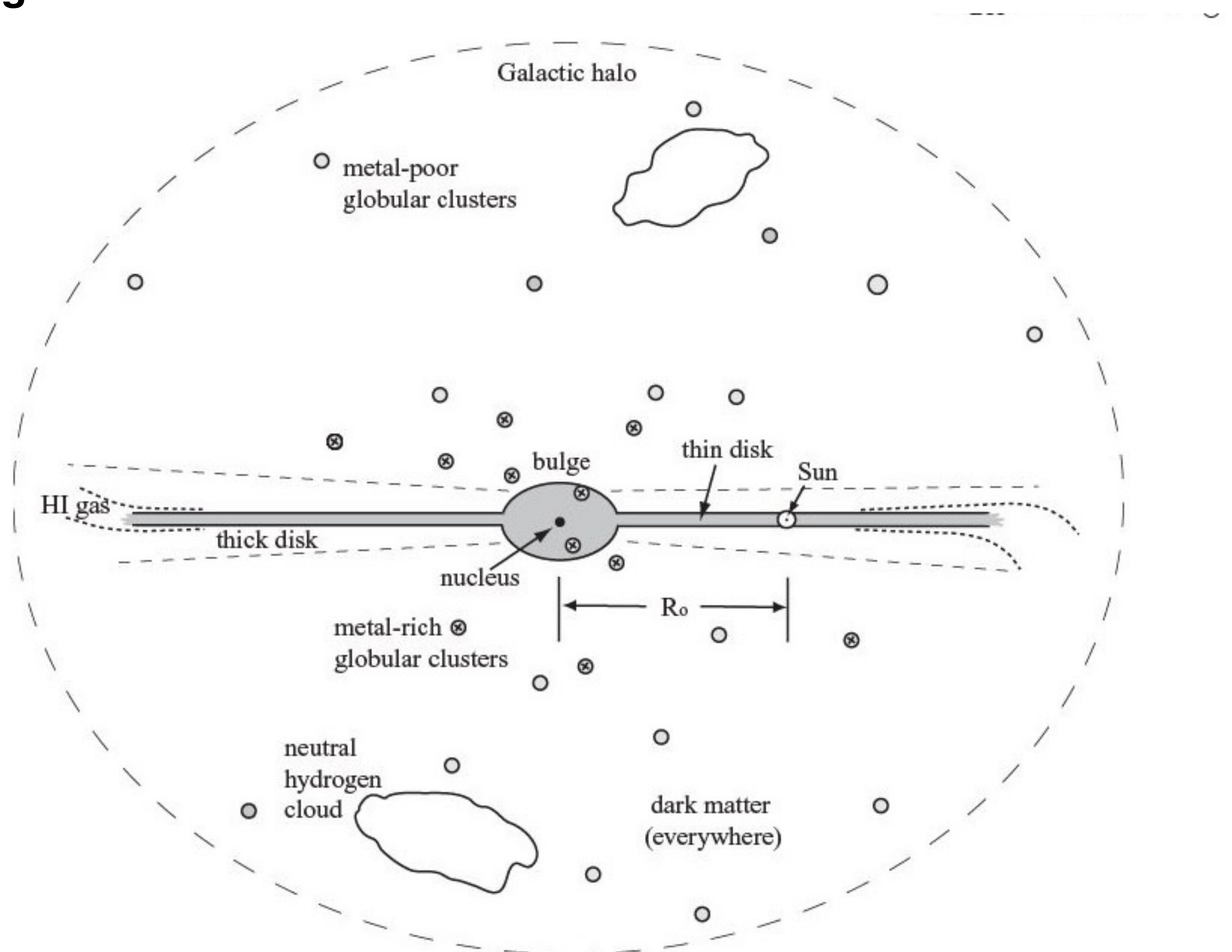
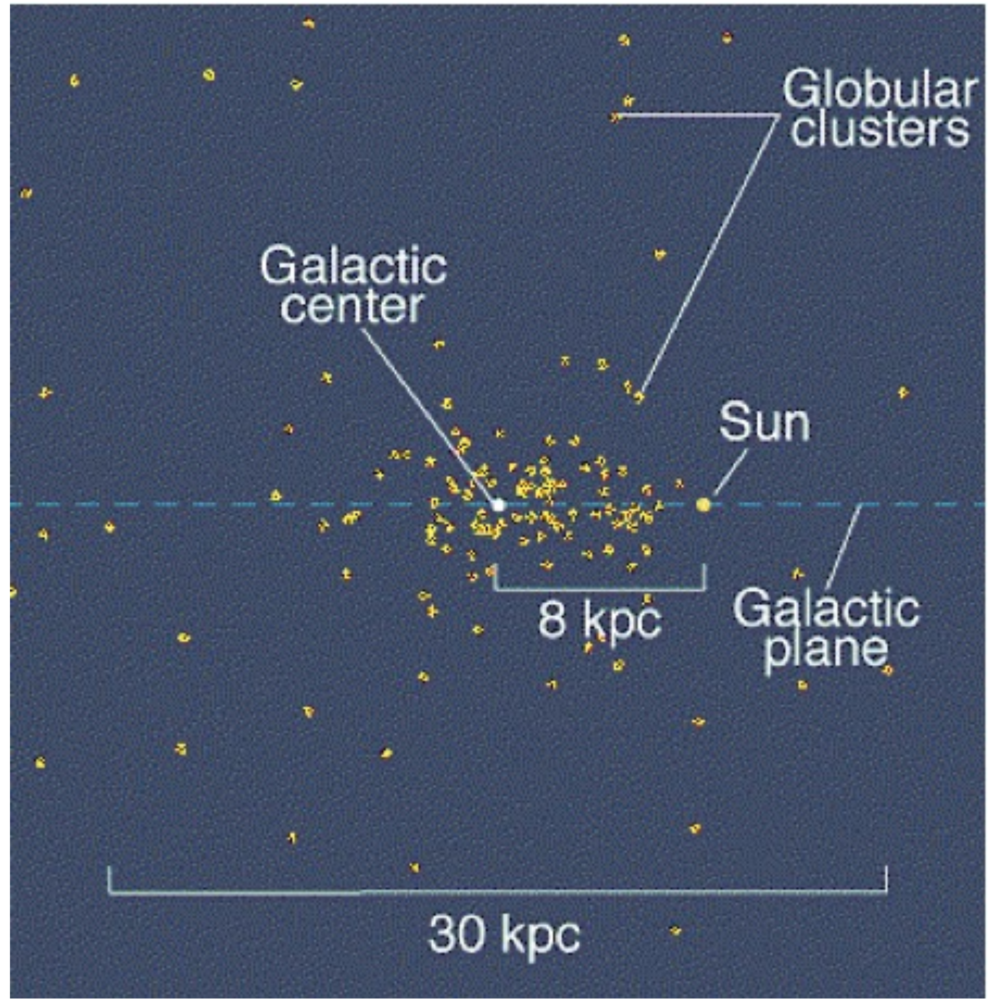



**Fig. 1.8.** A schematic side view of the Milky Way.

## Morphology and size of the Milky Way

- Shapley (~1915) measured distances to globular clusters from RR Lyraes, and estimated
  - –Diameter of Milky Way to ~ 100 kpc.
  - –Sun-to-center distance $R_0$ ≈15 kpc. This was about two times too large, due to a poor luminosity calculation. Modern value $R_0 \approx$ 8 kpc.



Shapley reasoned globular clusters were so massive that they would trace the Galactic gravitational potential: with spherical distribution centered on MW.

- Star counts (Kapteyn 1922, still used today for stars, galaxies, FRBs, etc.): For stars of some fixed $L$ or $M_V$, count them in random directions.
  - Distribution of stars with different apparent brightness gives distribution in space.

Simple example: Class of stars with luminosity *L*. For star at a distance $r_0$:

$$f_0 = \frac{L}{4\pi r_0^2}$$

Stars at $r<r_0$ will have $f>f_0$ and vice versa.

Suppose density, *n(L),* independent of *r*. Number of stars of luminosity *L* with $f>f_0$ is:

$$N_L(f > f_0) = n(L)\frac{4\pi r_0^3}{3} = \frac{n(L)L^{3/2}}{3(4\pi)^{1/2}} f_0^{-3/2}$$

One can measure $N_L$ for various choices of $f_0$ and look at the distribution.

Worksheet: What can we learn about the distribution of stars by looking at how $N_L$ varies with $f_0$ ?

Case (a): Uniform distribution, *n(L)* = constant, gives

$$N_L(f > f_0) \propto f_0^{-3/2}$$

Case (b): If $n(L) \propto r$, the number *N* in a volume is

$$n\frac{4\pi r_0^3}{3} \propto r_0^4$$

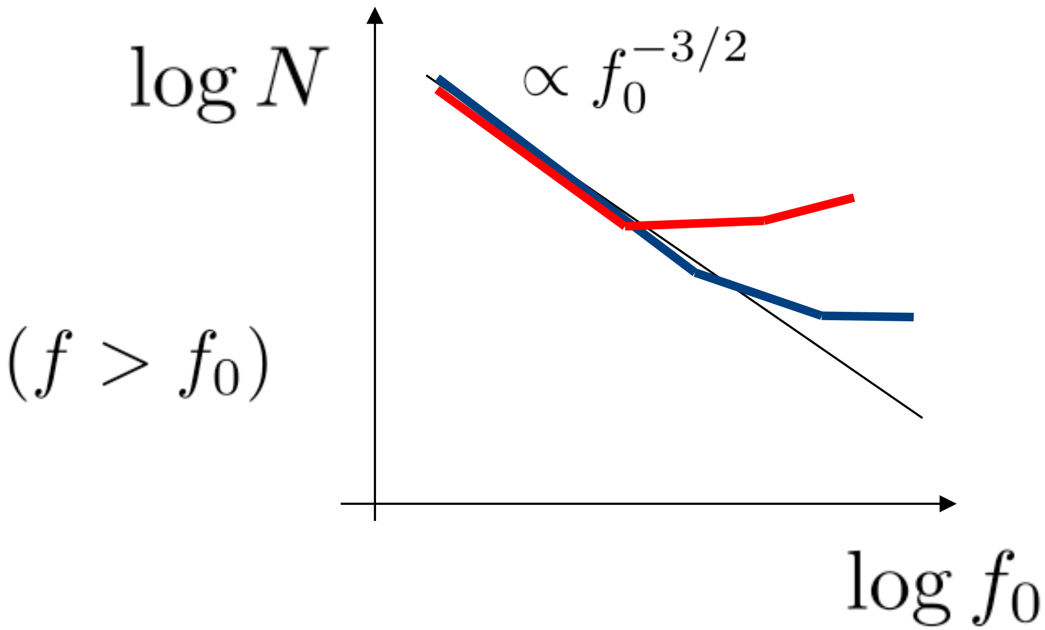
Since $r_0^4 \propto f_0^{-2}$ , we get $N_L \,\alpha\, f_o^{-2}$

Case (c): If $n(L) \propto 1/r$ so $N_L \,\alpha\, f_o^{-1}$

When n(L) diverges - Olber's paradox

- If power = -3/2, *n(L)* is constant and light from shell at distance r or r+dr is constant so the sum of light from shells diverges
- If power < -3/2, *n(L)* increases with *r and there is even more light*

Actual star counts are less than predicted by a uniform distribution.




Star counts in the direction of the disk, and perpendicular to it (blue and red lines respectively).

What does that tell us about the density of stars in these directions?

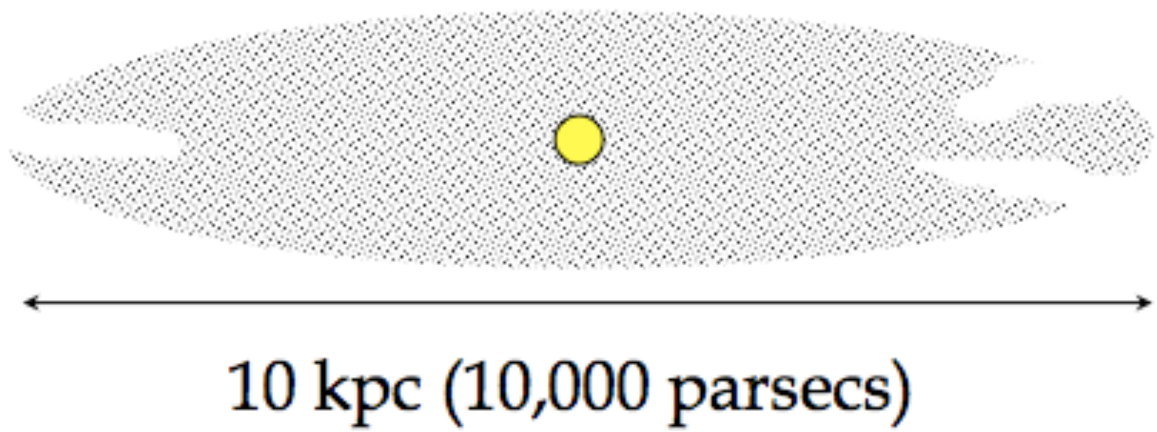
This is generally referred to as the log N log S relation and the S^-1.5 is called the Euclidean case

**The Kapteyn Universe**

The conclusions are that the stellar density is NOT uniform:

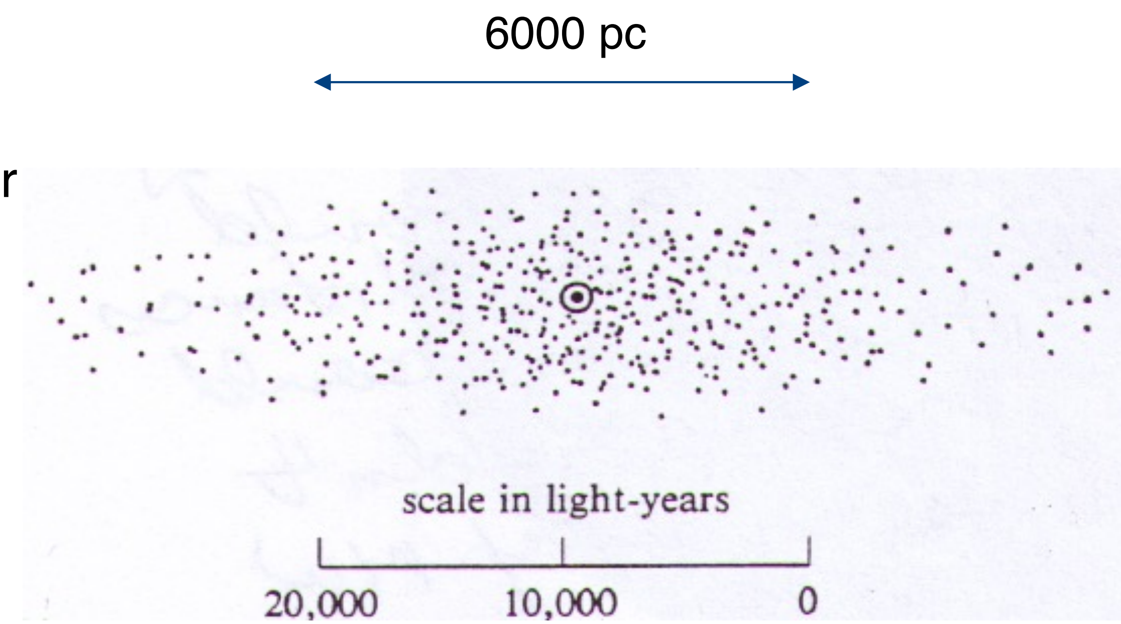
It decreases as a function of distance from the Solar system.

It decreases more slowly in the plane of the Milky Way, and faster perpendicular to it.



Kapteyn used star counts to find more details about the Milky Way shape:

- ~ 8 kpc across
- ~ 2 kpc thick
- ~ 650 pc distance Sun-to-Center



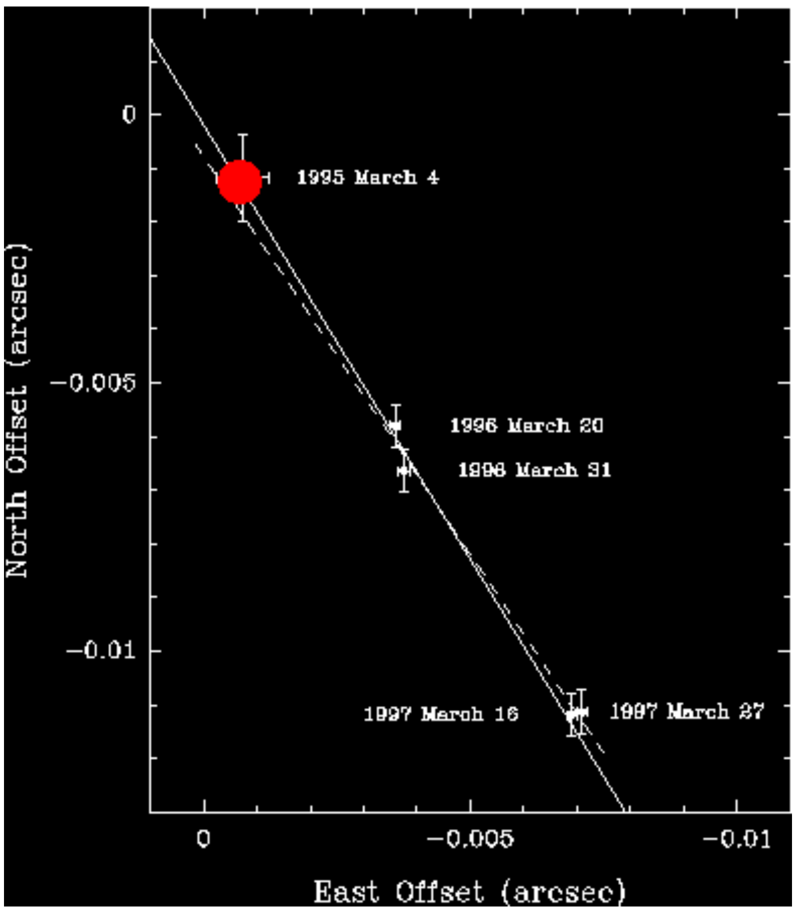

Compare modern values: ~30-50 kpc across, and $R_0$~8kpc.

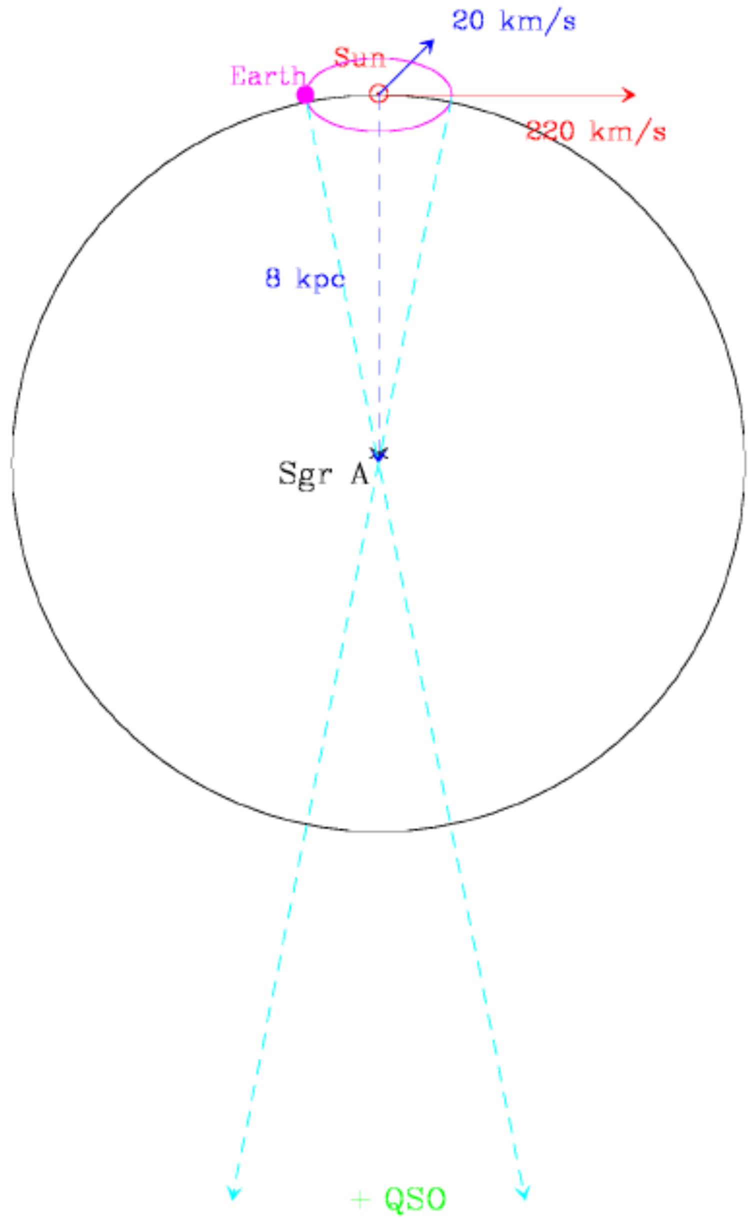
Q: Why so far off?

A: Didn't know about dust. Extinction mimics density falling with r.
What is a direct way to measure $R_0$?

# Precise Distance to Galactic Center

Distance = 8 kpc



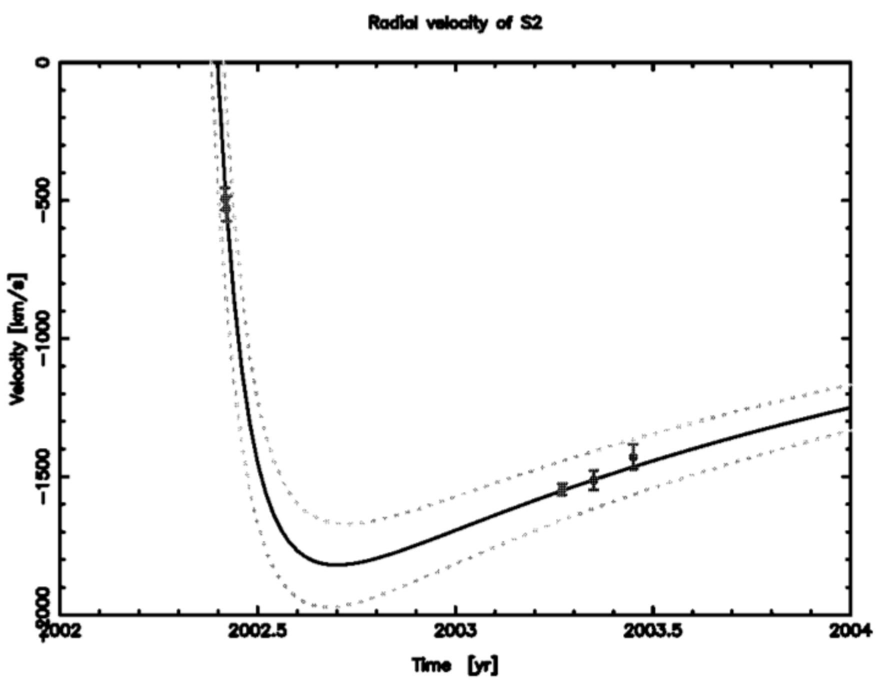



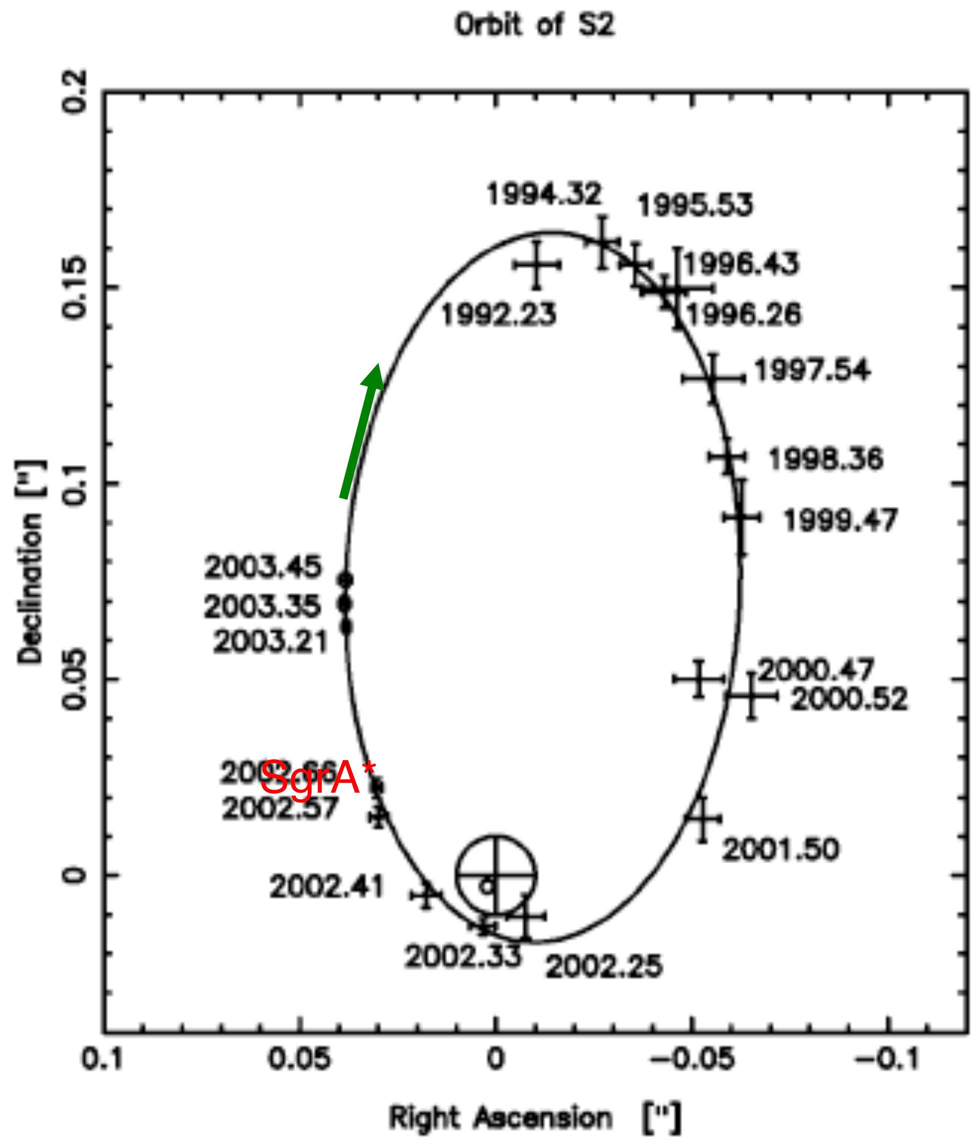

Orbital motion 6.37 mas/yr

# Precise Distance to Galactic Center

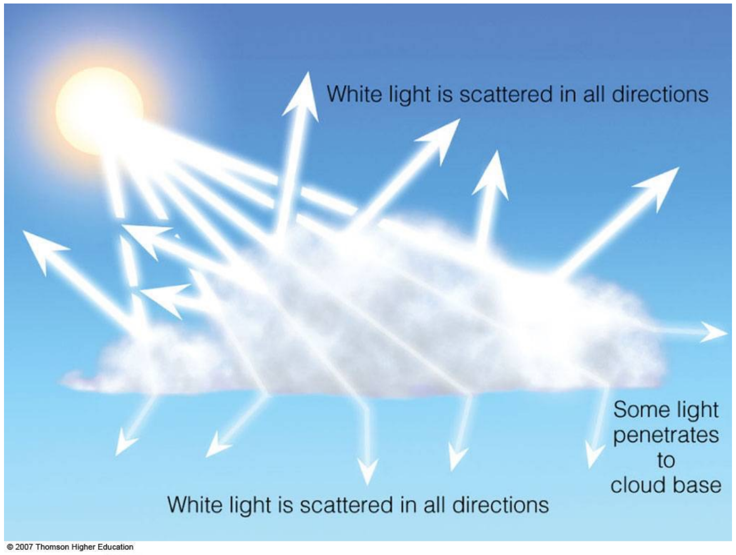
Distance = 7.94 +/- 0.42 kpc

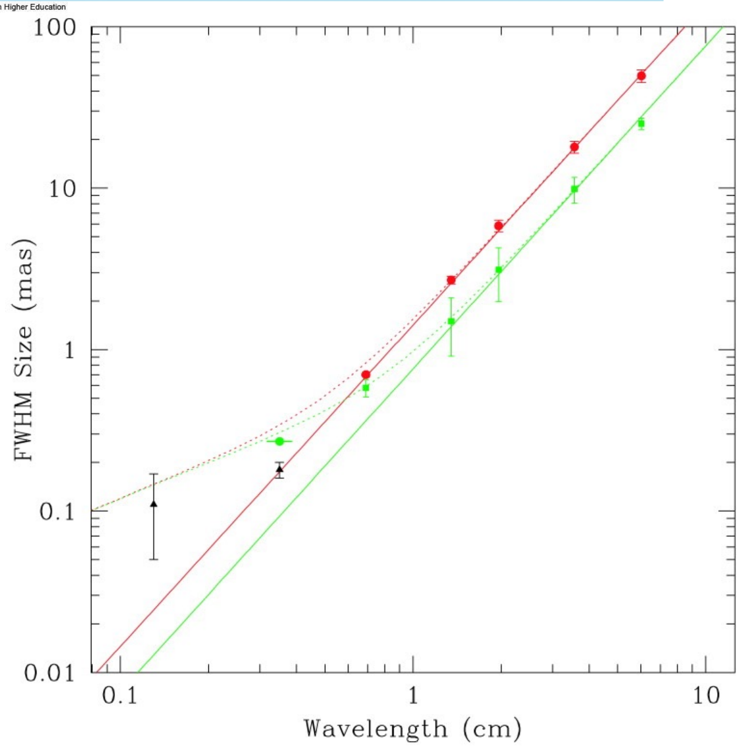
Eisenhauer et al. 2003

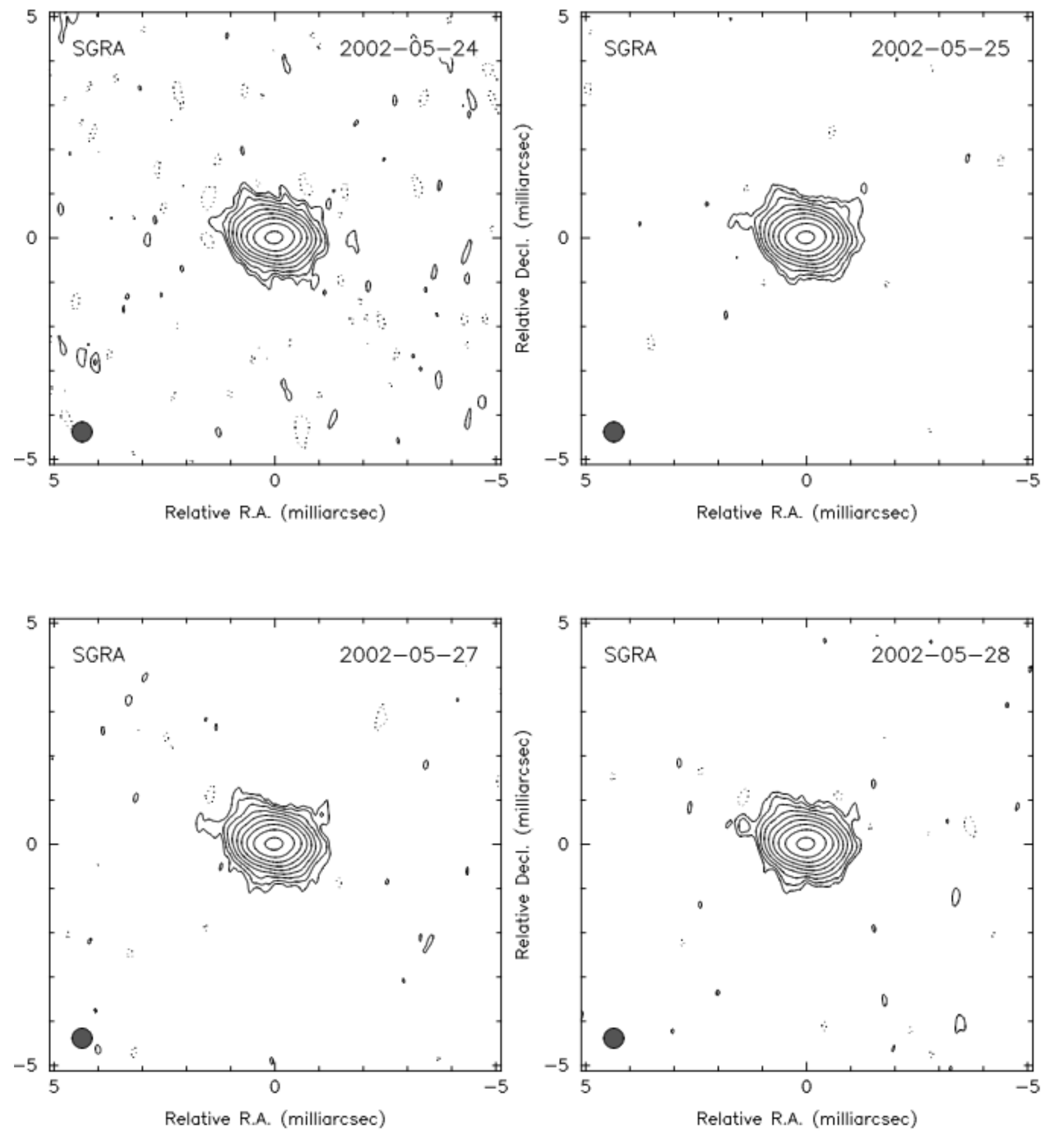


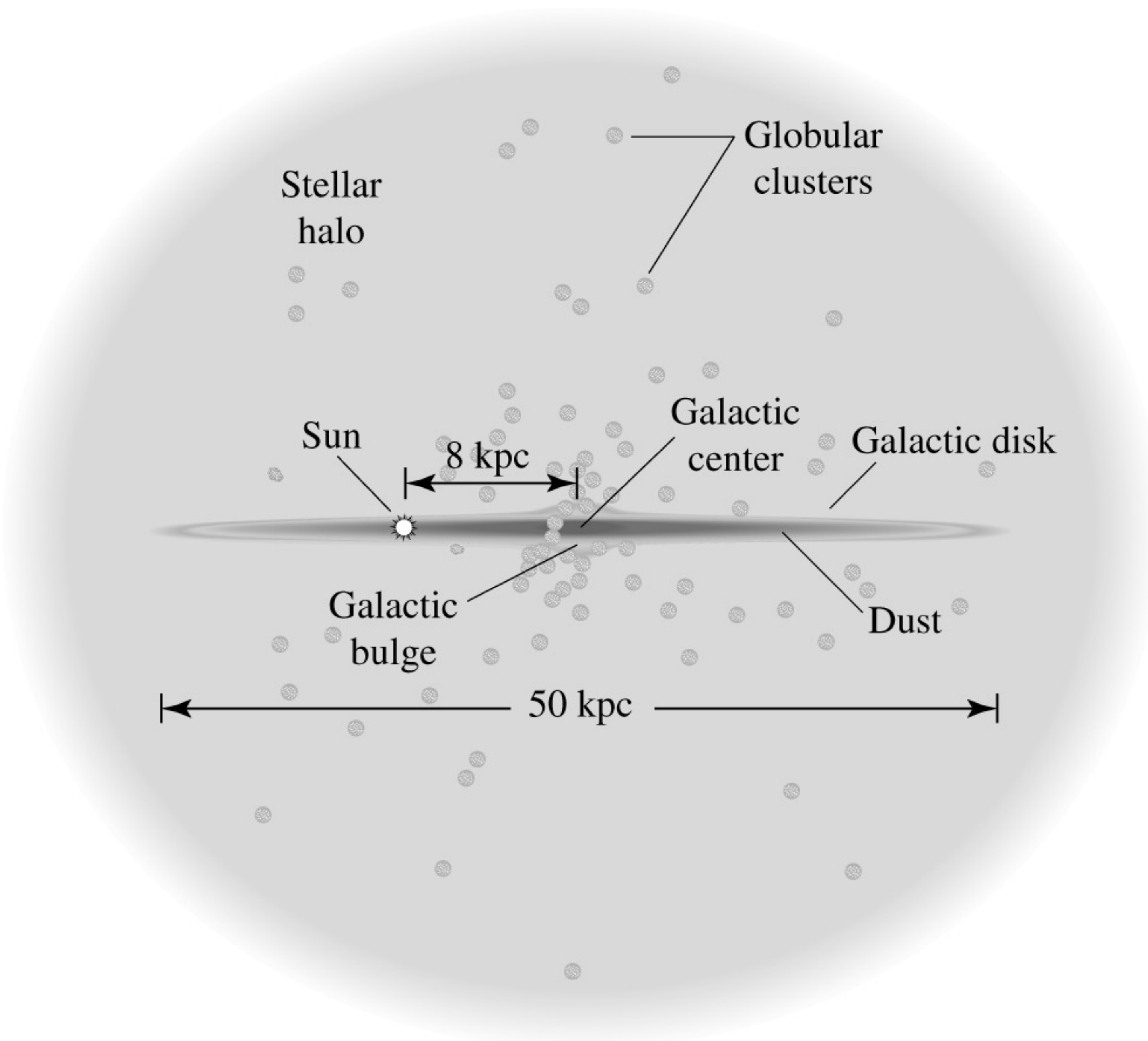
# High Resolution Imaging of the Galactic Center




milliarcsec


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

**Modern view of the Milky Way:**

- Thick disk
- Thin disk
- Central bulge
- Central bar
- Molecular ring outside bar
- Halo
- Gas and Dark Matter

We also know something about the age. Iron abundance in stellar atmosphere gives us *metallicity.*

$$\left[\frac{Fe}{H}\right] \equiv \log\left(\frac{N_{Fe}}{N_H}\right) - \log\left(\frac{N_{Fe}}{N_H}\right)_{\odot}$$

From cluster MS turnoff points, older cluster => lower metallicity.

Use calibration from clusters for field stars.

Some Milky Way parameter values (Table 24.1 in C&O)

| | 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) | $\lesssim 10$ | $8^c$ | $10^d$ |

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

[b] The total luminosity of the Galaxy is $L_{B,tot} = 2.3 \pm 0.6 \times 10^{10}$ $L_\odot$, $L_{bol,tot} = 3.6 \times 10^{10}$ $L_\odot$ (~ 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.

- Disks are also exponential in *r*
- $\sigma_W$ related to the thickness

| 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 | $\sim 13.5$ |

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

[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.

Metallicity of bulge:

- bursts of star formation?
- accretion of satellites?
- gas inflow?

**Stellar populations**

Pop I: small velocity dispersion, heavy metal absorption lines, confined to thin plane, young.

Pop II: large velocity dispersion, located further from plane.

Pop I mostly in the disk, less in bulge, not in halo.
Pop II can be found in all three places.

Visible mass of Galactic halo small compared to disk and bulge. Some arguments to believe that mass of halo is comparable to the rest, leading to a hypothetical Pop III stars (dim, low-metal stars).

**Disk component**

Stellar number density in the disk:

$$n(Z,R) = n_0 \left( e^{-Z/Z_{thin}} + 0.085 e^{-Z/Z_{thick}} \right) e^{-R/h_R}$$

where

$Z$: height above the plane

$R$: distance from the Galactic Center

$n_0$: 0.02 stars/pc$^3$ (4.5 ≤ $M_V$ ≤ 9.5, G to M stars only)

$Z_{thin}$: ~ 350 pc

$Z_{thick}$: ~ 1 kpc

$h_r$: ≥ 2.25 kpc

Radial properties hard because of dust.

Disk *mass-to-light ratio* gives an estimate of average stellar mass:

Total mass of disk $6 \times 10^{10}\ M_\odot$

Total luminosity of disk (stars) in B-band: $1.8 \times 10^{10}\ L_\odot$

Thus,

$$\frac{M}{L_B} \approx 3 \frac{M_\odot}{L_\odot}$$

Recall that $L \propto M^{\alpha}$, with $\alpha \sim$ 3-4, and find a typical stellar mass ~0.7 $M_\odot$

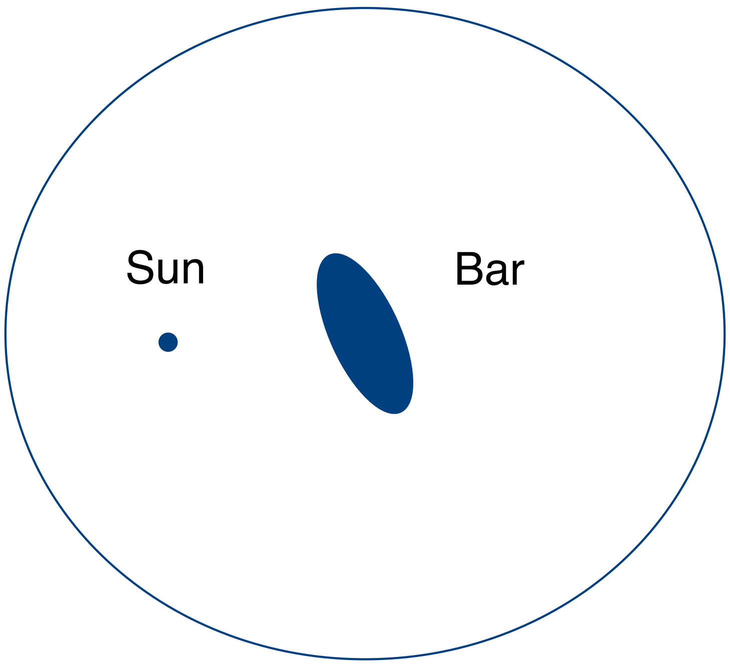
Thus, a higher *M/L* means *lower* stellar masses.

**Spheroidal components**

Central bulge:

~ 2 kpc in diameter, vertical scale height ~0.4 kpc.

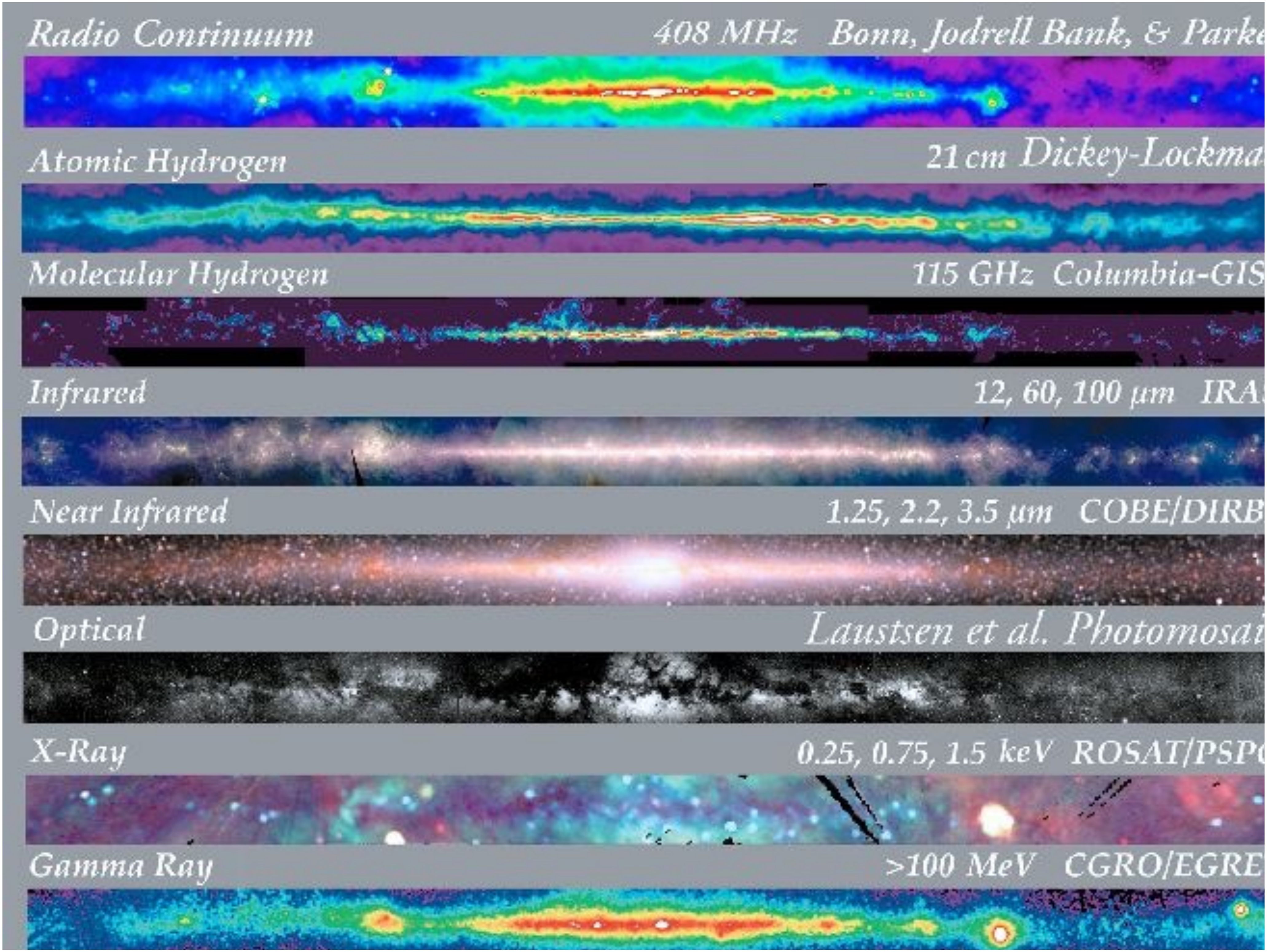
Consists of spheroidal component and bar




Top view of the Milky Way.

Range of metallicity => wide range of stellar ages.

Galactic bulge, as observed by COBE (1.2 to 3.4 micrometers).

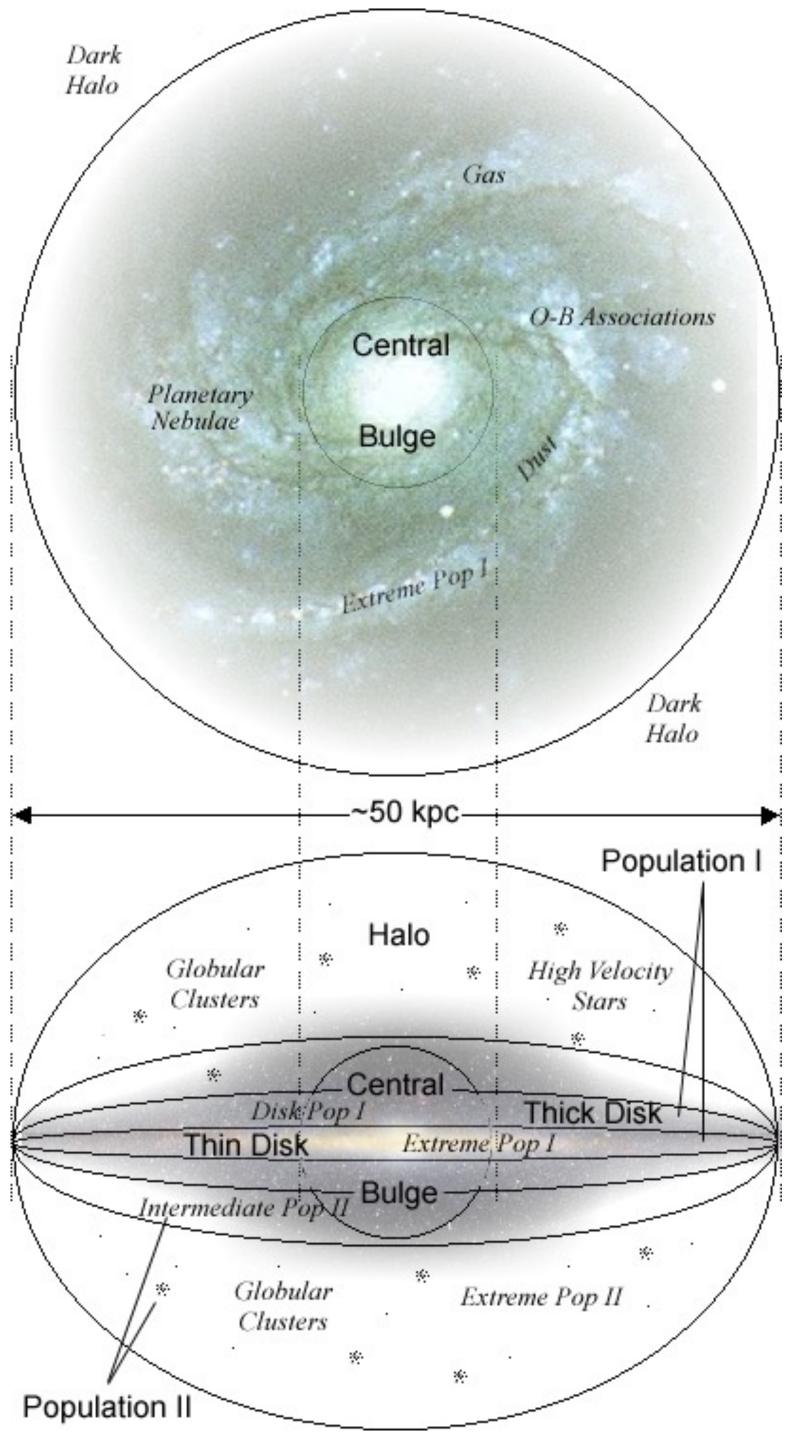

Radio Continuum
408 MHz Bonn, Jodrell Bank, & Parke
Atomic Hydrogen
21 cm Dickey-Lockma
Molecular Hydrogen
115 GHz Columbia-GIS
Infrared
12, 60, 100 μm IRA
Near Infrared
1.25, 2.2, 3.5 μm COBE/DIRB
Optical
Laustsen et al. Photomosai
X-Ray
0.25, 0.75, 1.5 keV ROSAT/PSP
Gamma Ray
>100 MeV CGRO/EGRE

Halo:

Composed of globular clusters and *field stars.* Roughly spherical.

Globular clusters ~ 200 or so (?). Oldest stars in the Milky Way. Two populations:

1. Older, very spherical distribution in halo.
2. Somewhat younger, flattened distribution (like a thick disk).


Dark Halo
Gas
O-B Associations
Central
Planetary Nebulae
Bulge
Dust
Extreme Pop I
Dark Halo
~50 kpc
Population I
Halo
Globular Clusters
High Velocity Stars
Central
Disk Pop I
Thick Disk
Thin Disk
Extreme Pop I
Bulge
Intermediate Pop II
Globular Clusters
Extreme Pop II
Population II

**Milky Way ISM distributions**

- HI: density roughly constant with *R*, located outside a central hole of 3 kpc radius. Total extent ~ 50 kpc diameter.

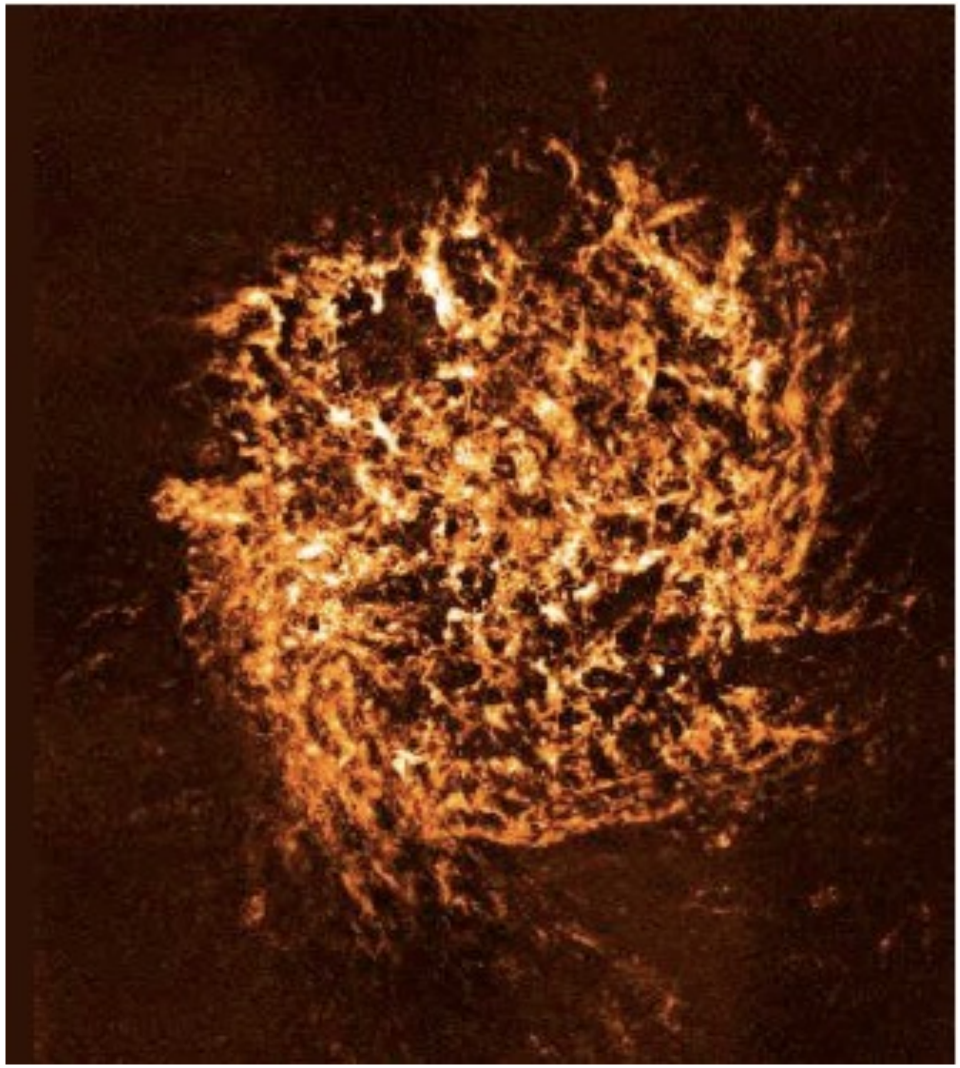
  Vertically $n = n_0 e^{-Z/160\mathrm{pc}}$ $n_0 \approx 1\mathrm{cm}^{-3}$

- $H_2$: CO indicates a *molecular ring* centered at *R*=5 kpc. Vertically, there is a population of GMCs ~100 pc.

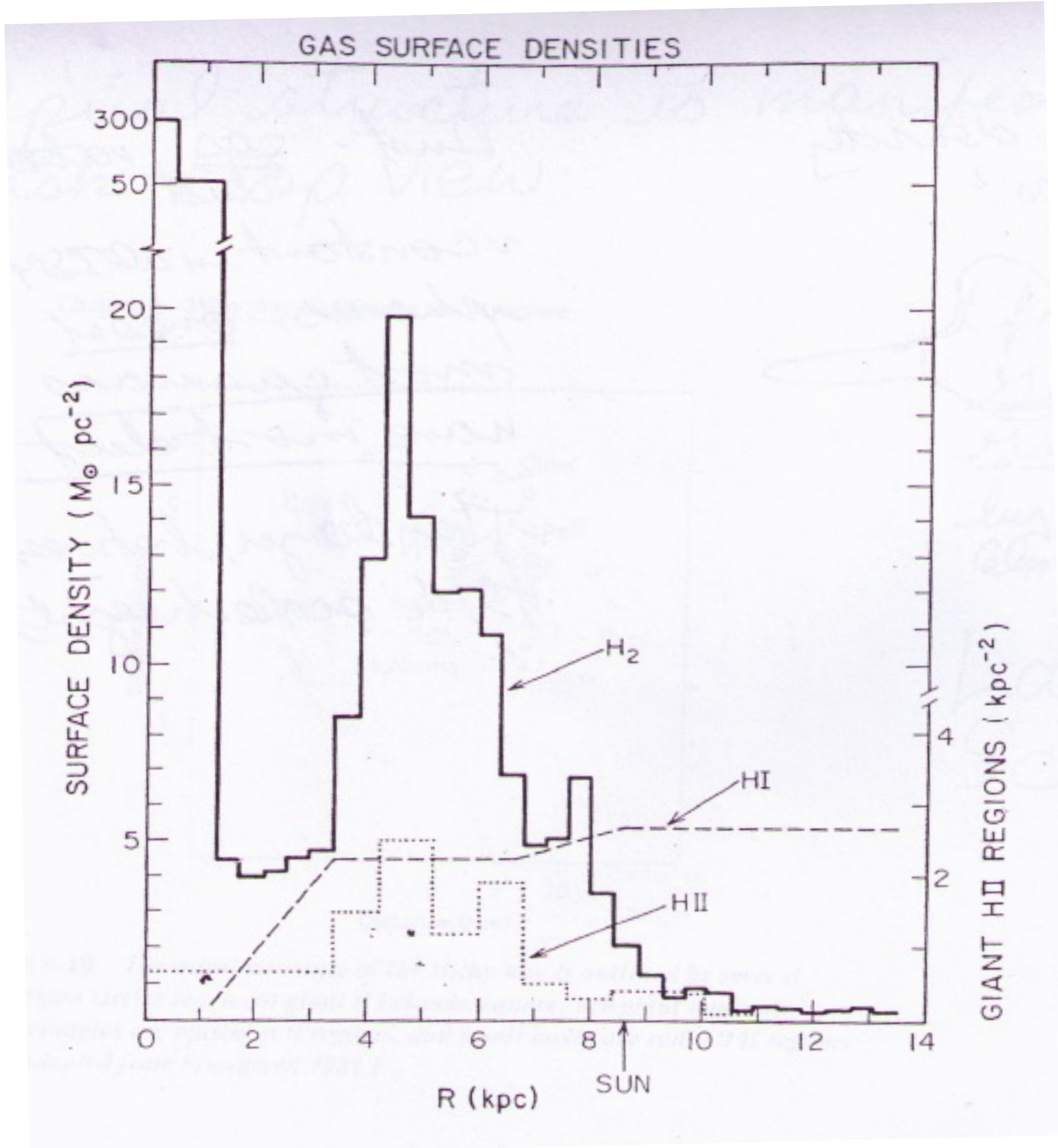
- HII regions: radial distribution like $H_2$, similar scale height.

- Overall: mass in HI ~ mass in $H_2$ ~ $2\mathrm{x}10^9 M_\odot$

  HII, WIM, HIM, dust much less, ~ a few % of total mass.



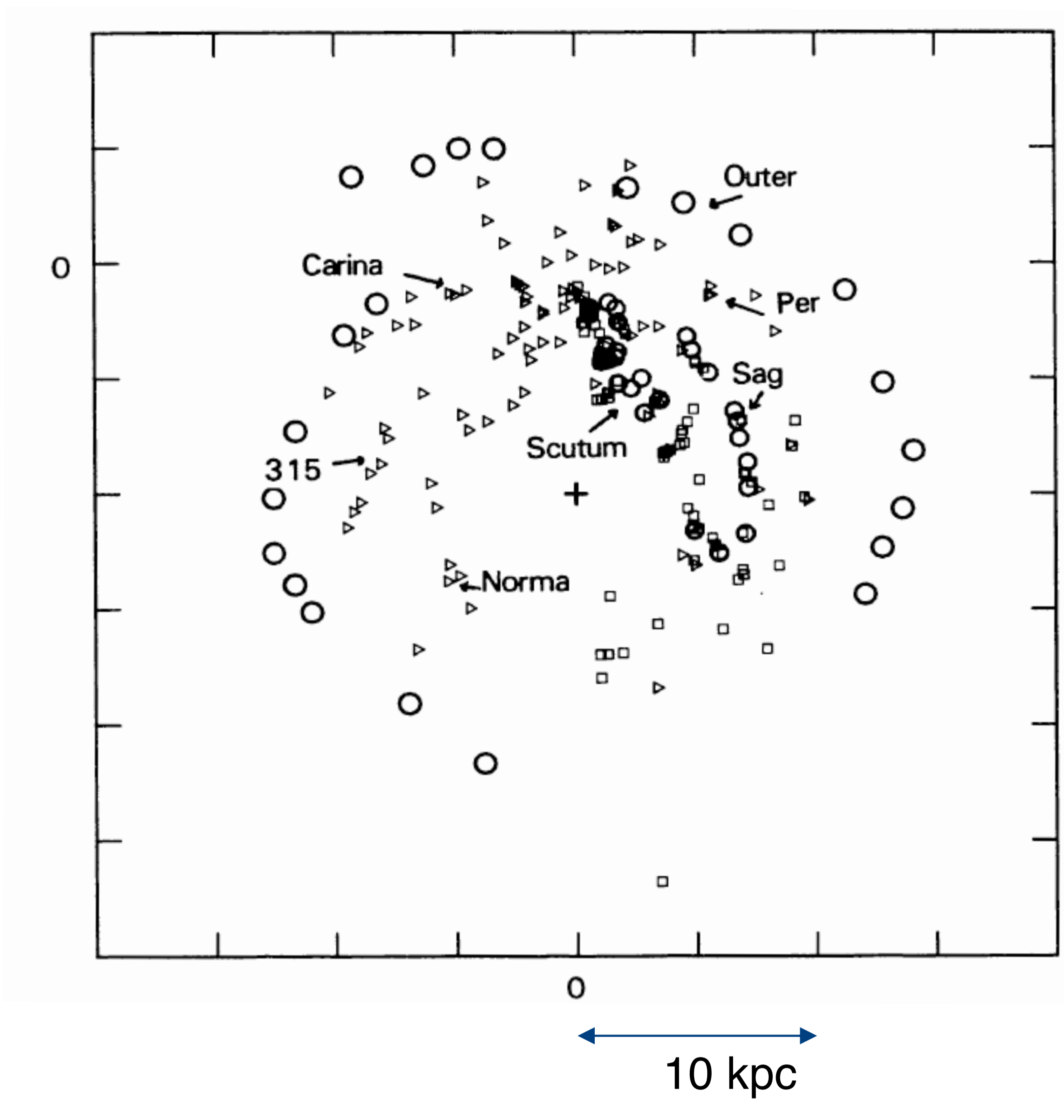
HI observations of the LMC: (Kim et al). HI shells and super shells.




Scoville & Sanders

**Spiral structure**

Clear in HI, GMC, HII regions, OB stars, and young clusters.  The exact shape is hard to infer from within the Galaxy.




*Large scale*

Open circles: giant HI clouds

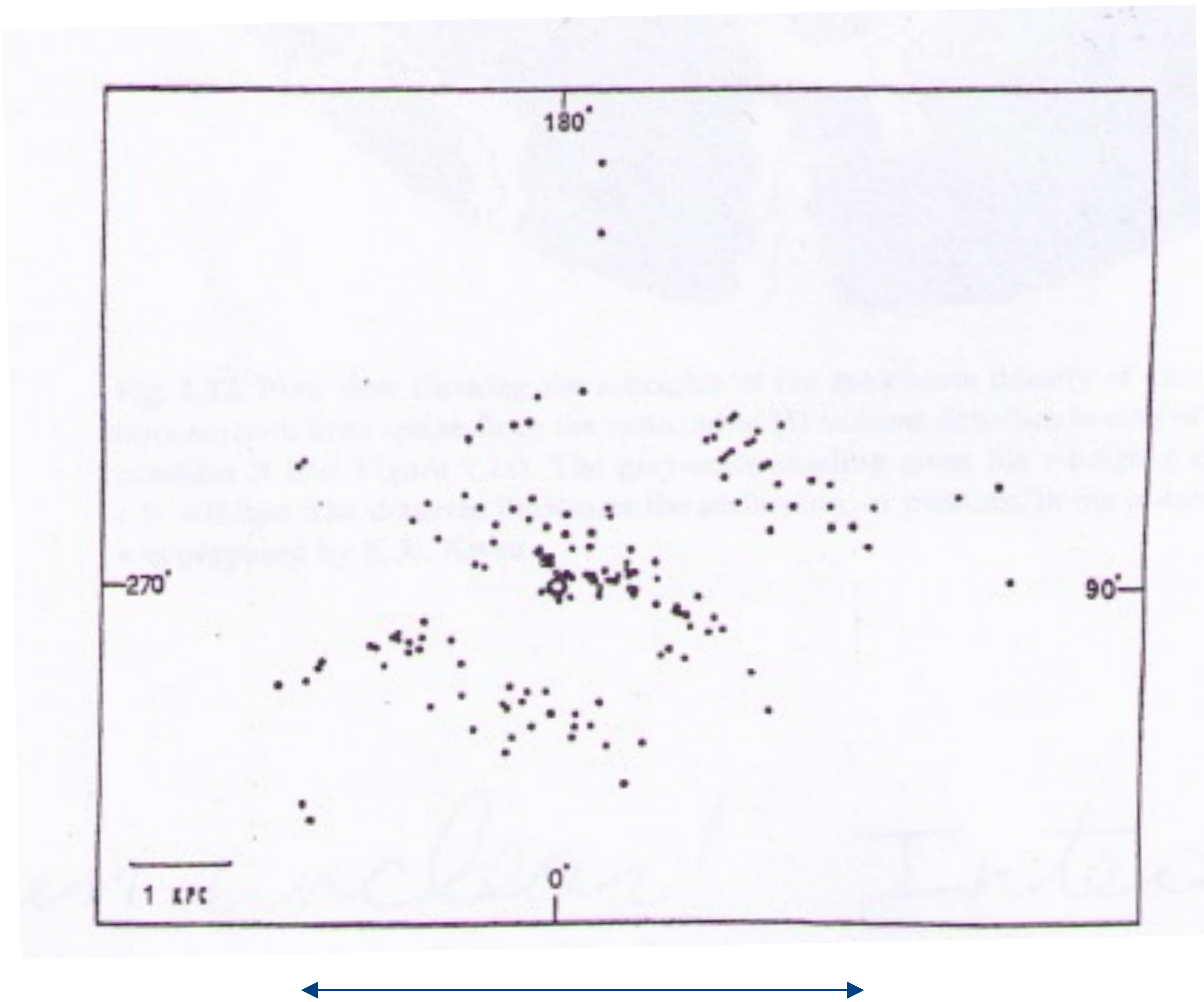
Squares: GMCs

Triangles: optical HII regions

Small boxes: radio HII regions

Elmegreen 1985

Smaller scale:



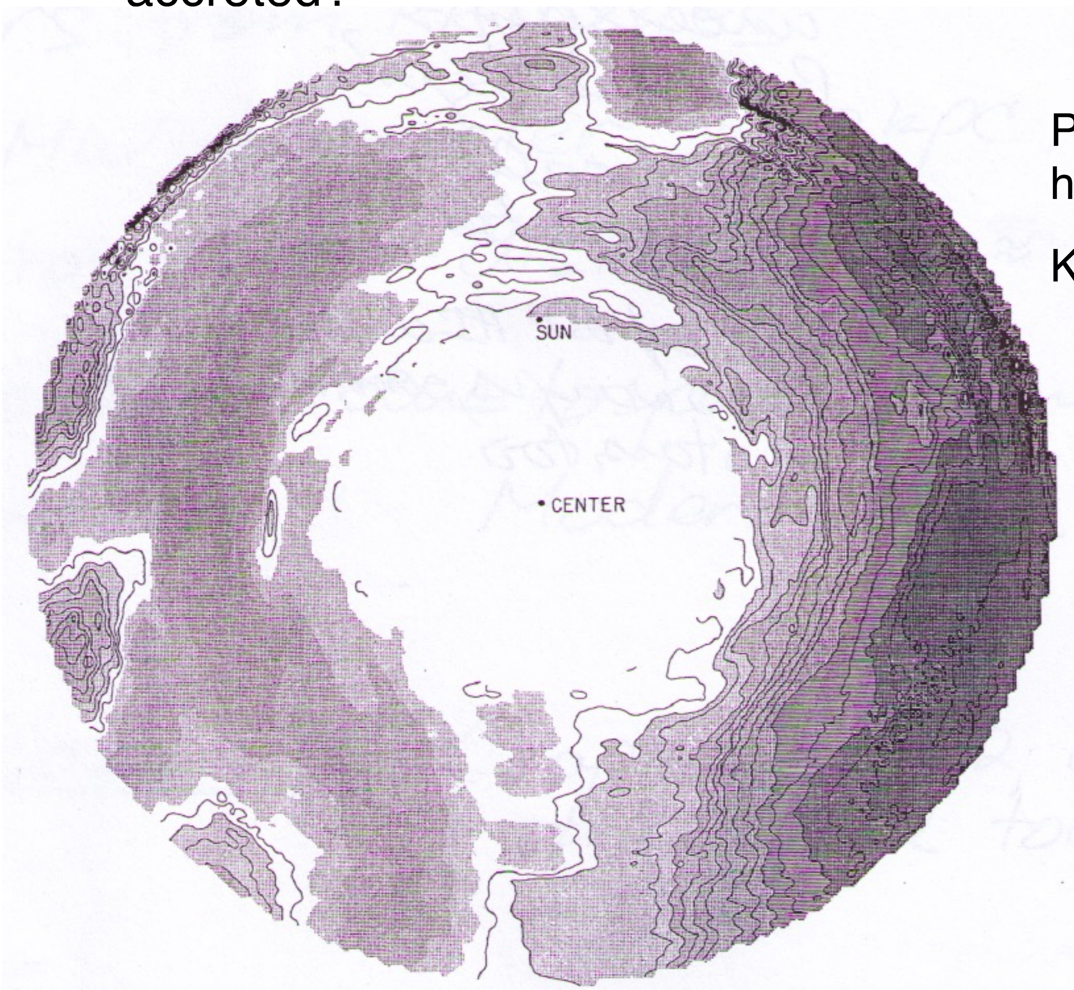

4 kpc

Distribution of young Galactic clusters and HII regions.

Sun in center, near Orion-Cygnus Arm.

HI layer is 'warped' at radii beyond $R \sim 15$ kpc.

The origin of this warp is unclear: interactions? But isolated galaxies also exhibits warps. Bending modes? Halo changing shape as new material accreted?




Plan view showing z-heights of HI.

Kwee et al.

UGC 3697

**Coronal gas**

Observed in highly ionized lines, e.g. far-UV OIV (absorption).