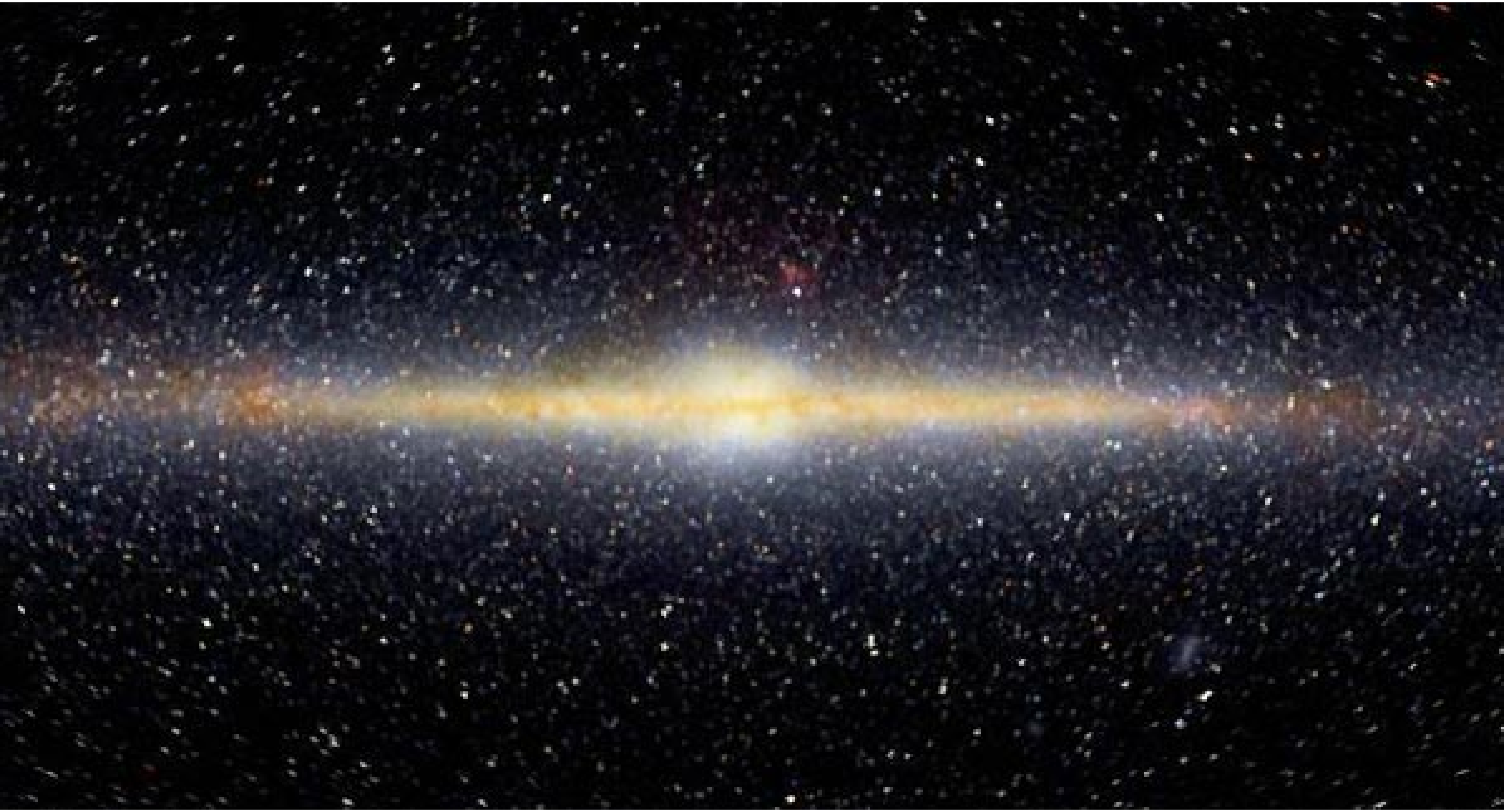
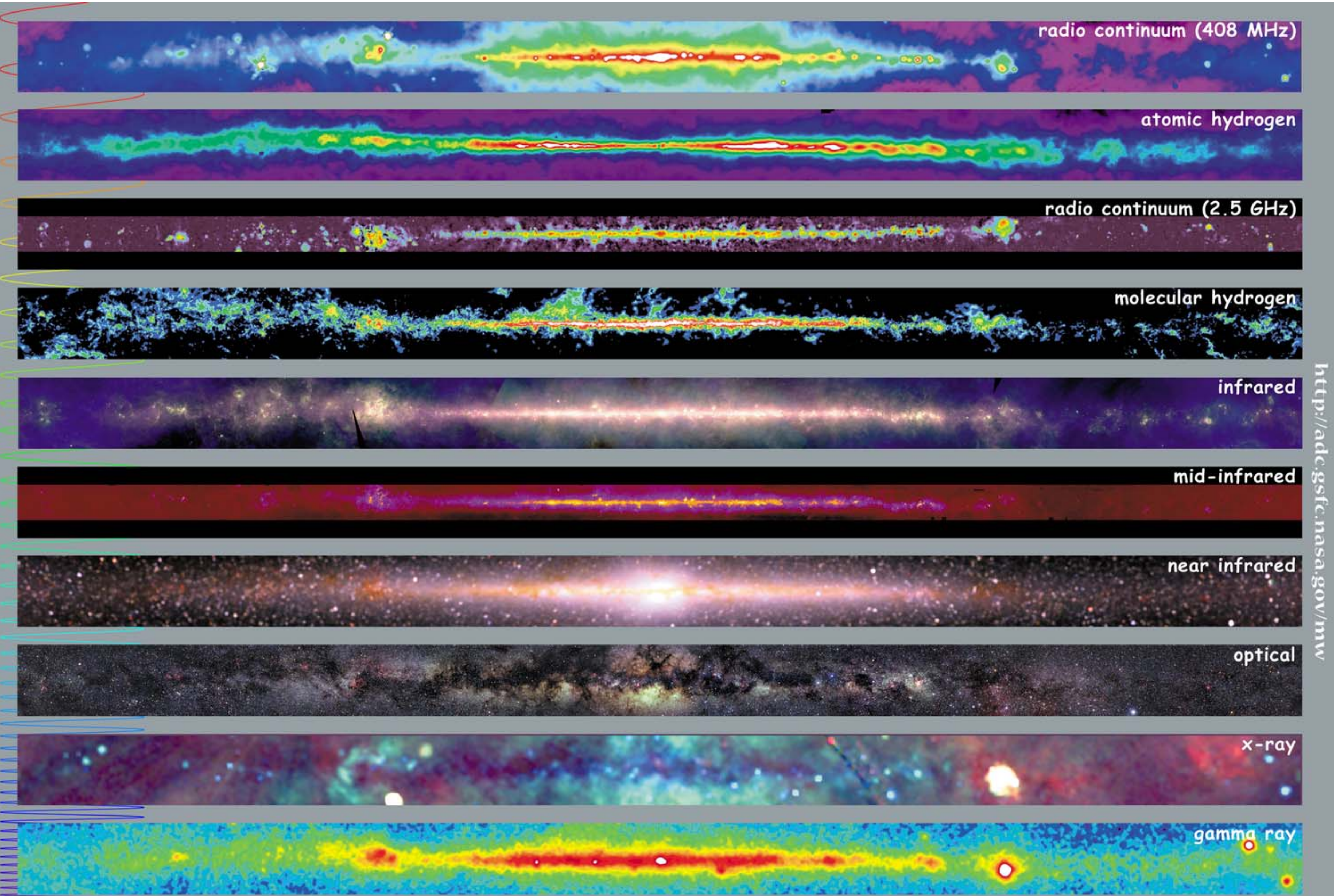
The structure of the Milky Way





Multiwavelength Milky Way

Spatial distribution of stars

- Derive the structure of its components
  - density distribution and characteristic scales

- Statistical approach: very large numbers of stars

- Couple structural info to age and chemical composition, kinematics

- Correlations between properties tells how Galaxy formed

Spatial distribution near the Sun

- What kinds of stars are present in the Solar neighborhood?

  Luminosity function

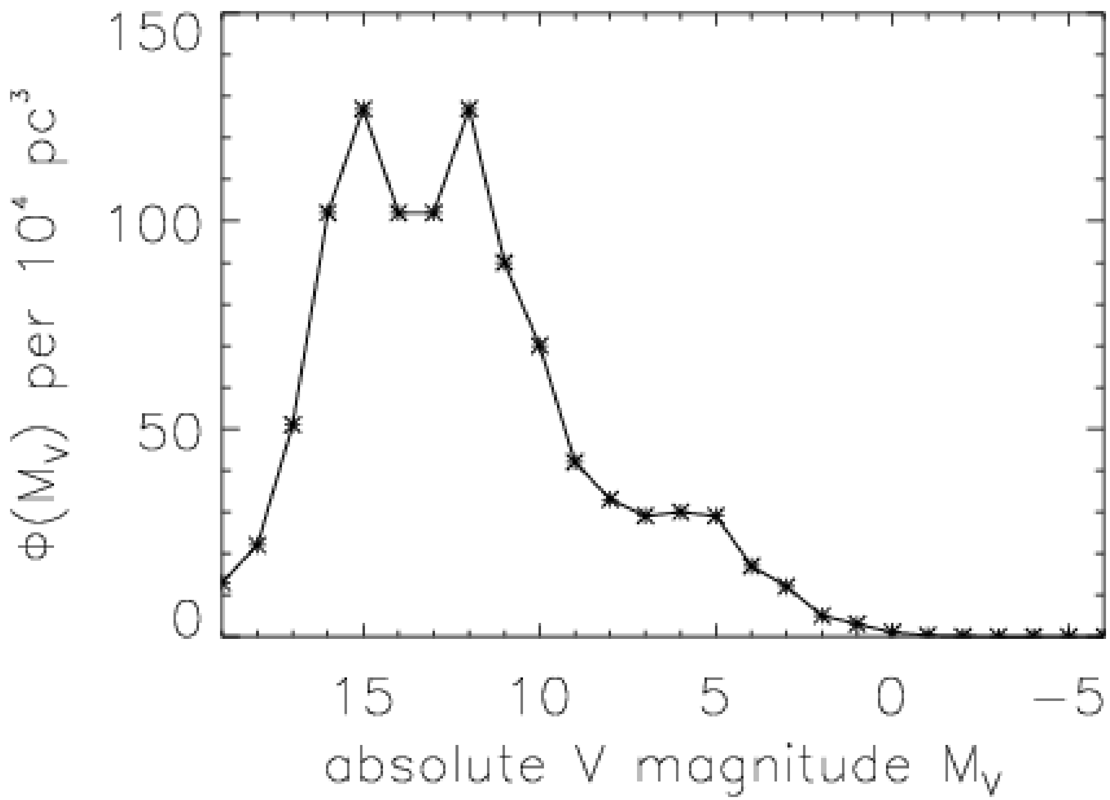
- What is their spatial distribution? How is this derived?

  In the plane: spiral arms

  Star counts perpendicular to the plane: thin and thick disk

- Are there correlations between spatial distribution, age, stellar type? Why?

The luminosity function near the Sun



Sparke and Gallagher Fig.2.3

Most stars are intrinsically faint (peak at $M_V \sim 14$)

This is correlated with the properties of the initial mass function

- All the light comes from the intrinsically most luminous stars

- Most of the mass in large numbers of low luminosity stars

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Table 3.16 The general luminosity function (per 10^4 pc^3)

M_V	$\Phi(M_V)$	$\delta L/L_\odot$	$\delta \mathcal{M}/\mathcal{M}_\odot$	M_V	$\Phi(M_V)$	$\delta L/L_\odot$	$\delta \mathcal{M}/\mathcal{M}_\odot$
−6	0.0001	2.6	0.005	7	29	4.0	21.3
−5	0.0006	5.1	0.020	8	33	1.8	21.8
−4	0.0029	9.4	0.060	9	42	0.90	24.2
−3	0.013	17.1	0.17	10	70	0.60	35.0
−2	0.05	28.2	0.05	11	90	0.30	36.0
−1	0.25	53.9	1.6	12	127	0.17	36.3
0	1	95.8	4.0	13	102	0.055	20.8
1	3	111	7.4	14	102	0.022	16.3
2	5	64	8.7	15	127	0.011	16.3
3	12	66	17.3	16	102	0.0035	10.5
4	17	36	19.4	17	51	0.0007	4.3
5	29	25	28.1	18	22	0.0001	1.6
6	30	10	24.7	19	13	0.0000	0.7
				Total	1008	532	356

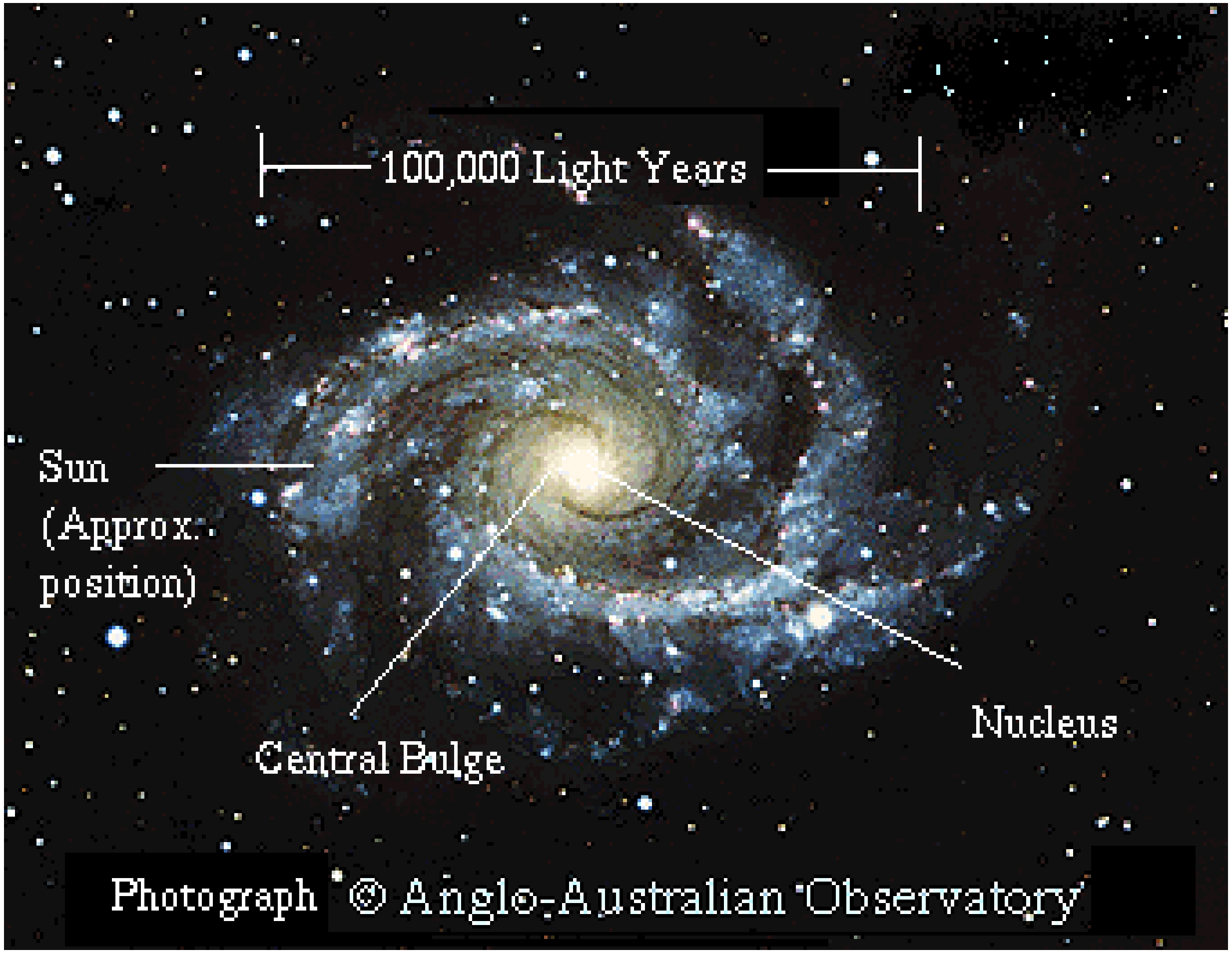
SOURCE: For $M_V \leq 0$ from data published in Allen (1973); for $M_V > 0$ from data published in Jahreiss & Wielen (1983) and Kroupa, Tout & Gilmore (1990)

- Luminosity density does not always trace the mass density (need dynamics)

- The average mass-to-light ratio near the Sun is $\langle M/L \rangle V = 0.67\ M_\odot/L_\odot$

  This is a lower limit (white dwarfs, neutron stars, etc, contribute mass but little light)

The distribution of stars in the plane



Most disk galaxies have spiral arms: also the Milky Way

Good Tracers of spiral arms:

- known to be associated with spiral arms in external galaxies
- young: not drifted away from their birthplace

- intrinsically luminous: seen at large distances

- intrinsic brightness known: to derive reddening and true spatial structure

•O-B associations, HII regions, Cepheids, young clusters...

The most recent studies suggest that the Milky Way has four spiral arms

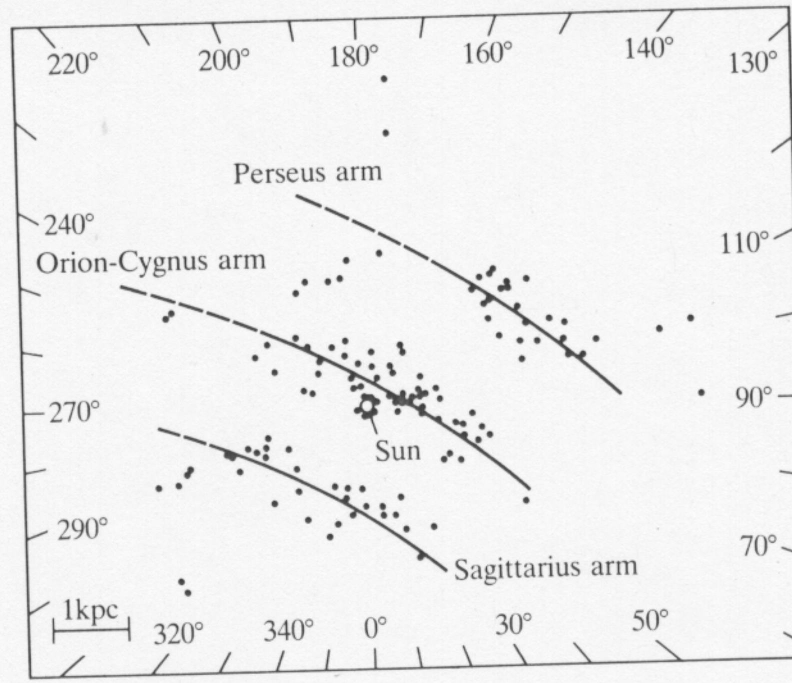


Figure 4-11. Spiral arms in the solar neighborhood as inferred from optical evidence. Individual points are at positions of young star clusters and H II regions. Three arms are clearly indicated, separated from one another by about 1.5 kpc: the outer Perseus arm, the local Orion-Cygnus arm, and the inner Sagittarius arm. The Sun is near the inner edge of the Orion-Cygnus arm. [From (**B5**, 205), by permission.]

Distribution perpendicular to the plane

- Dynamically interesting quantity
  - Determine the gravitational pull produced by the Galactic disk.
  - Measure the mass exerting that pull, and compare to the amount of light
  - Test for discrepancies (or "missing mass")

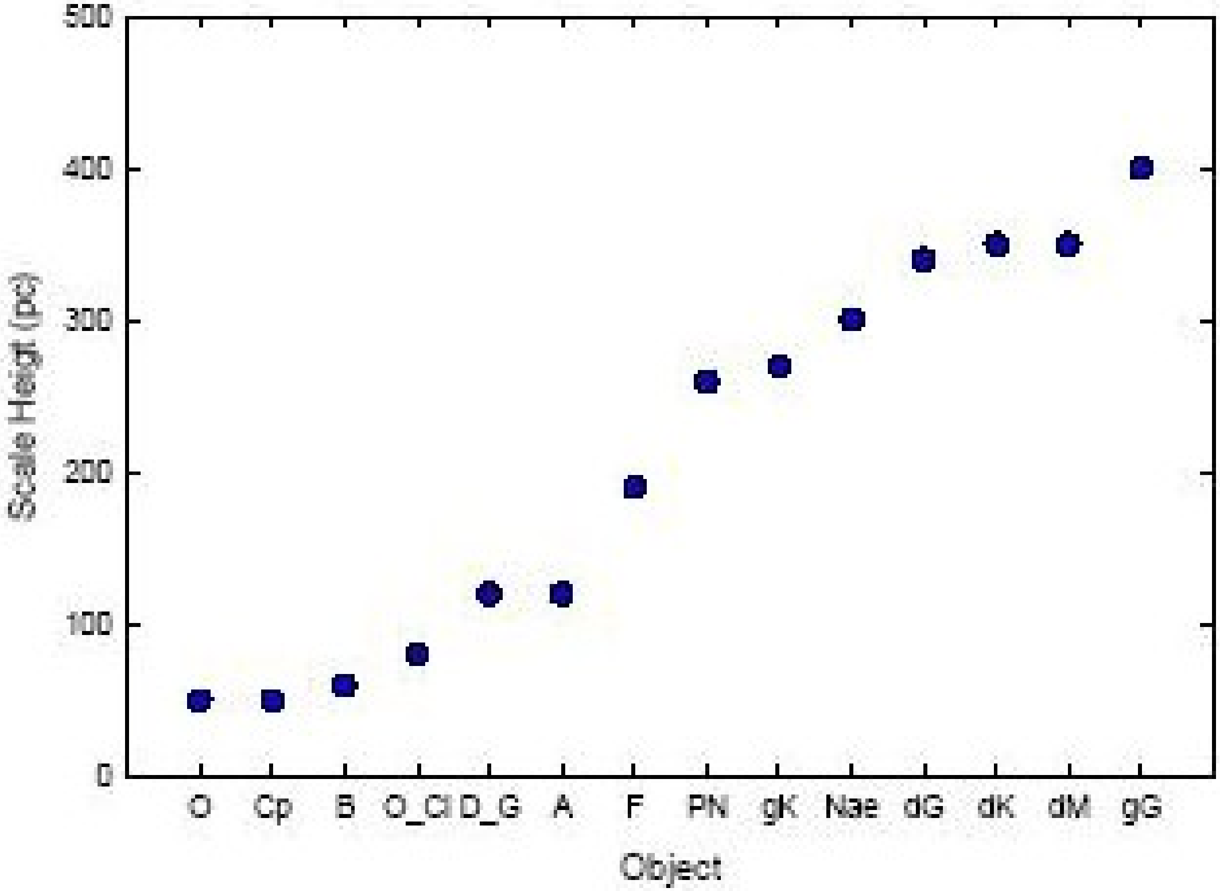
- Most noticeable feature in the distribution perpendicular to the plane is strong variation with spectral type

Star counts to estimate the density of stars as function of z

- Fields towards the Galactic pole
- Measure (V-I) for the stars
- Trigonometric parallaxes for subset to obtain M_V
- Relation between the M_V and (V-I): used to derive M_V for remaining stars (this is known as photometric parallax)

  Most stars are MS dwarfs and hence such a relation is not very surprising.

- Distance info allows to derive the density distribution as function of z



$$n(R,z,S) = n(0,0,S)\ \exp(-R/H_R(S))\ \exp(-z/H_z(S))$$

$H_R(S)$ is the scale-length of the disk

$H_z(S)$ is the scale-height

Strong dependence on spectral type

The thick disk

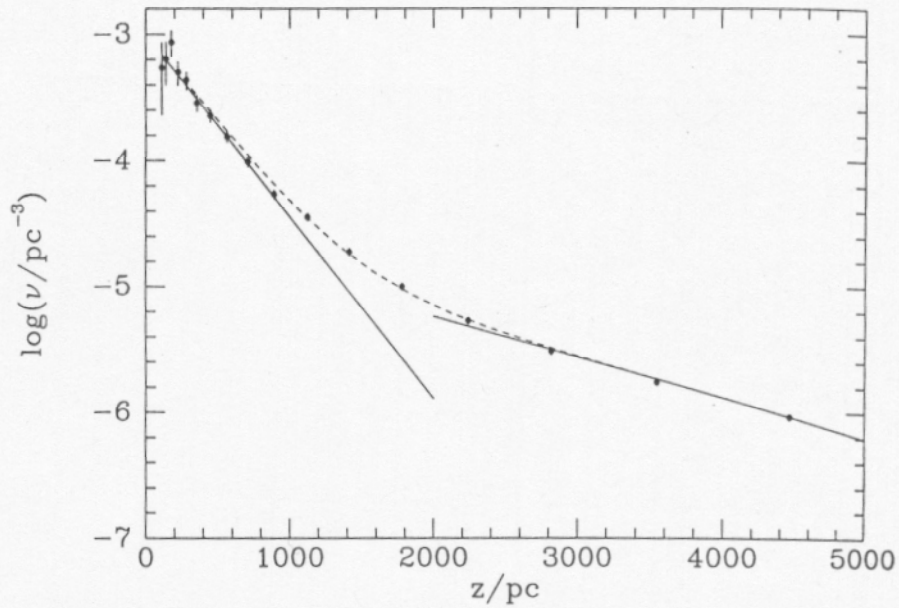


Figure 10.25 The space density as a function of distance z from the plane of MS stars with absolute magnitudes $4 \leq M_V \leq 5$. The full lines are exponentials with scale heights $z_0 = 300$ pc (at left) and $z_0 = 1350$ pc (at right). The dashed curve shows the sum of these two exponentials. [From data published in Gilmore & Reid (1983)]

The space density of stars cannot be fitted by a single exponential!

Good fit from superposition of two exponentials with different scale-heights: z_0 = 300 pc and z_0' = 1350 pc.

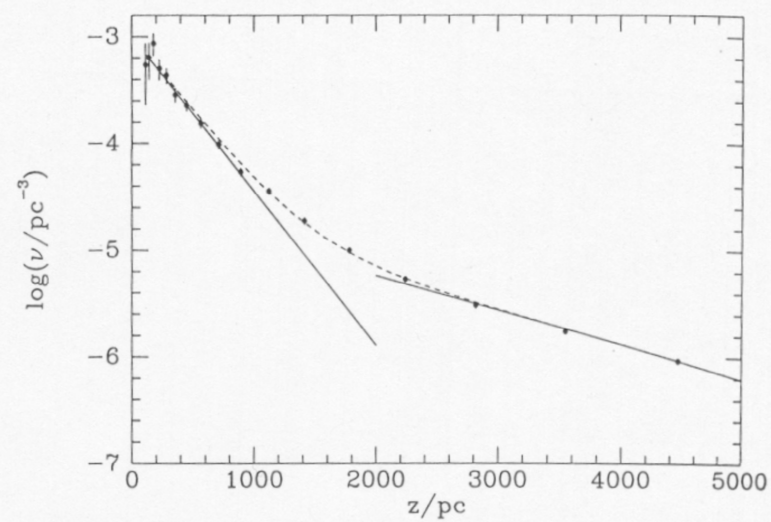
Two possible conclusions:

1. The functional form is not correct

2. There are two physically distinct components in our Galaxy: thin and thick disk.

To justify item 2.,it is necessary to prove that the two disks are made up of different kinds of stars (e.g. age, chemical abundance).

This seems to be the case…



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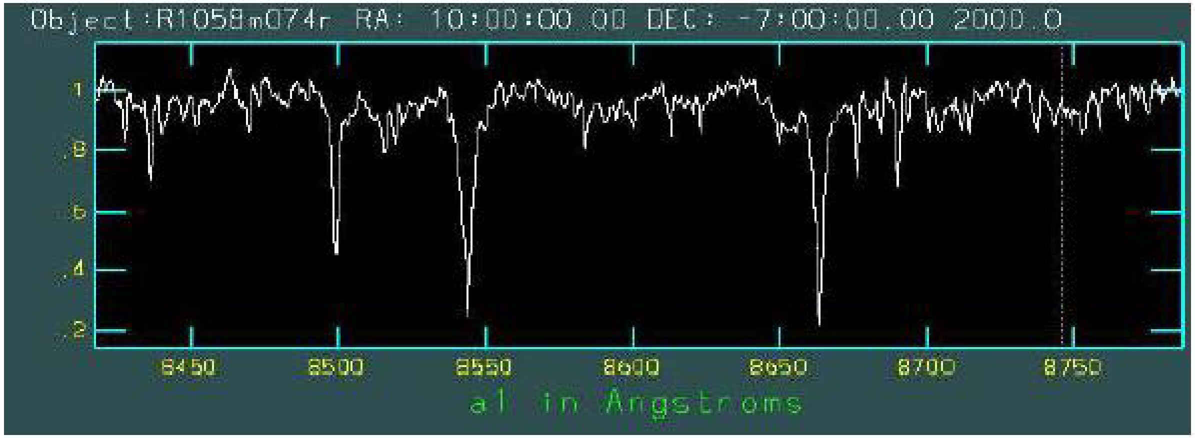
Chemical abundances and metallicity

- The amount of heavy elements or metals in stars relative to the amount in the Sun is the **chemical abundance**
- The "iron abundance" = **metallicity**
  [Fe/H] = $\log(n(Fe)/n(H))_{star} - \log(n(Fe)/n(H))_{Sun}$
- This defines the **solar metallicity** as [Fe/H] = 0.0.
  - A star with [Fe/H] = -1.0 has 10 times less iron than the Sun relative to Hydrogen
  - A star with twice the amount of iron of the Sun has [Fe/H] = 0.3.

Chemical abundances and metallicity

- The chemical abundances are measured from the spectra of stars



- The lines observed are produced in the atmospheres of the stars:
  - absorption by atoms of the radiation produced in the nucleus

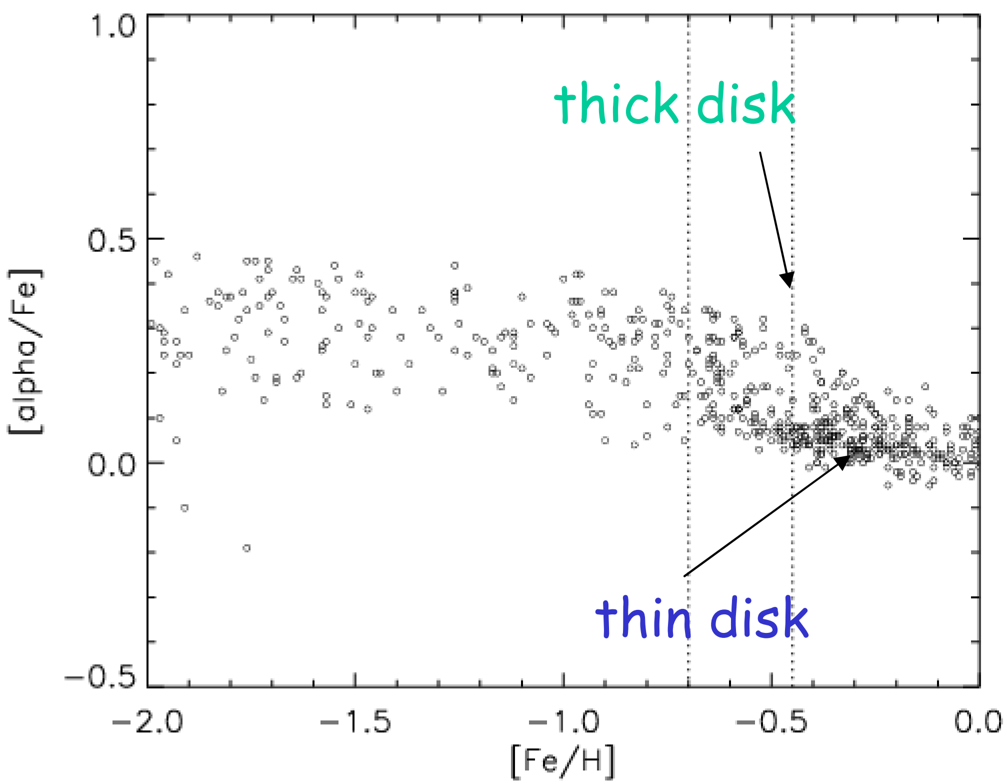
- The metallicity of a star does not change in time (generally)

- Chemical abundances reflect the initial values of the molecular clouds (ISM) in which stars formed

The **chemical patterns** of stars in the thick and thin disks are different:

α elements are produced in SNII (massive stars)
explosion on short timescales (~ 10 - 100 Myr)

iron is produced in SNIa (explosions of binary stars with a white dwarf)
timescales > 1 Gyr



The different trends show that the timescales of formation of the stars in both disks were different

This justifies the claim that they are physically distinct

Spatial distribution of stars in the spheroid: halo and bulge

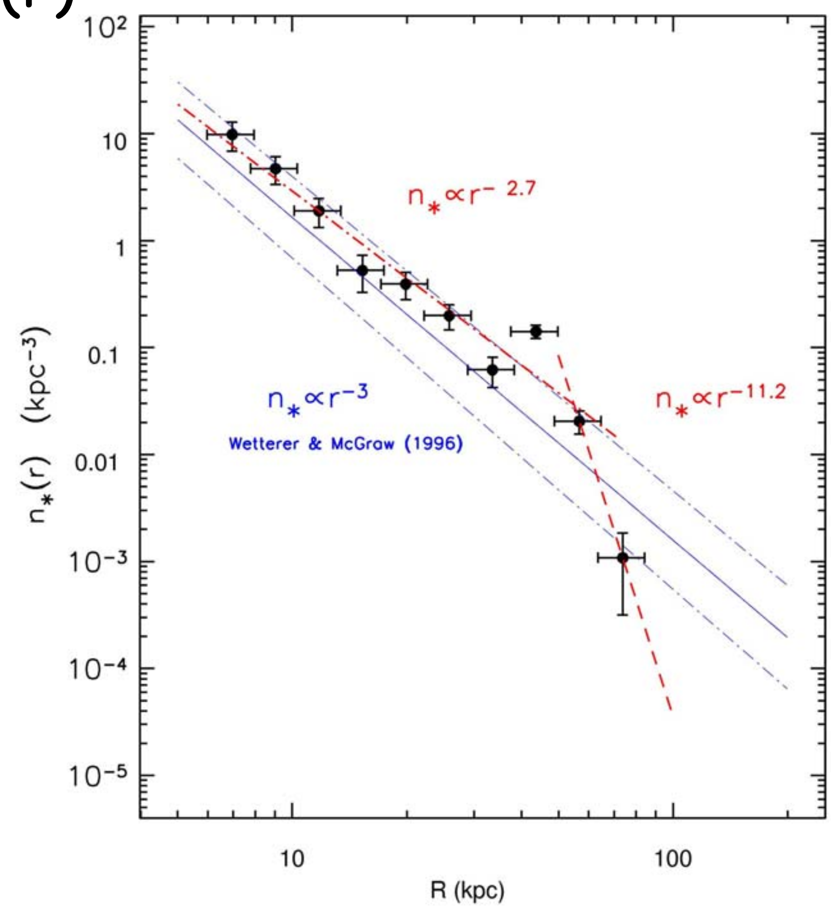
Metal-poor stars in the Galaxy located in a spheroidal halo

Star counts show that density D(r)

$$D(r) = D_0\,(r/r_0)^{-3.5}$$

i.e. very rapidly declining function of distance

The same distribution is seen for the (metal-poor) globular clusters



The stellar halo

- extends out to ~ 80 kpc from the Galactic centre

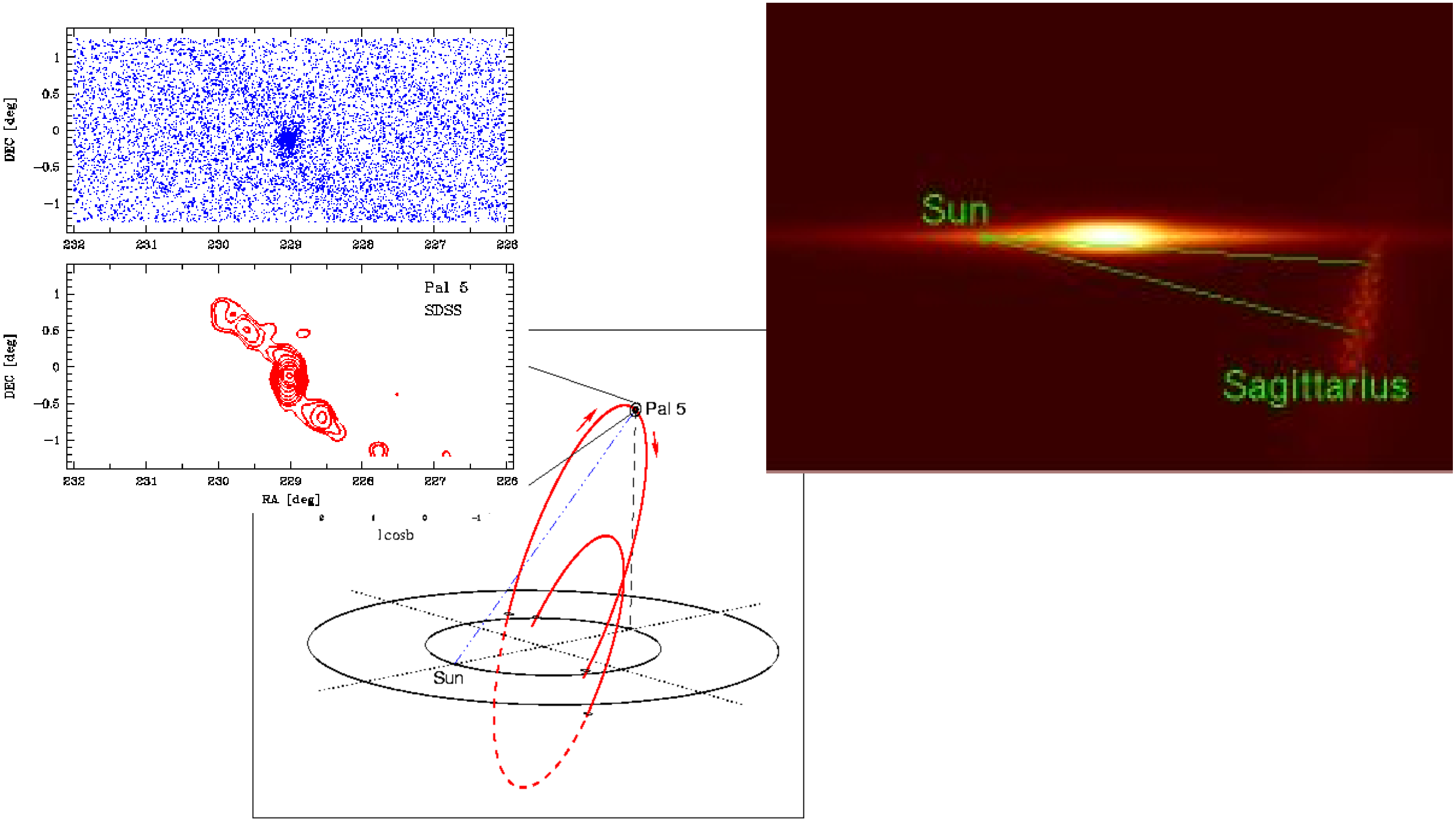
- total luminosity of ~ 10^9 Lsun (1% of total)

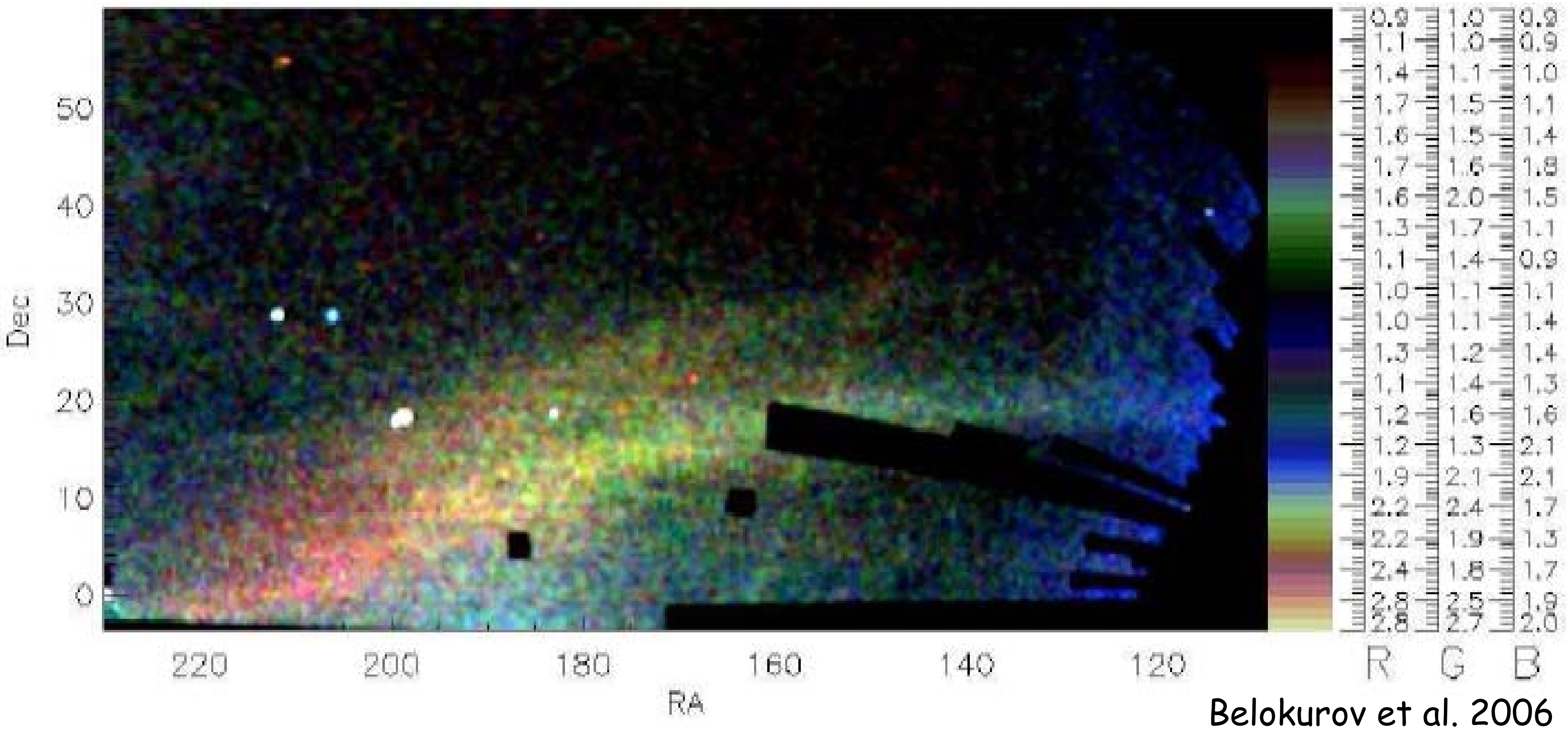
- very low density in the Solar Neighbourhood: 0.2% of the thin disk's central density

- very strongly concentrated: half light radius ~ 3 kpc

- Important clues on the formation of the Galaxy:
    - its stars are very metal-poor (pristine, link to early Universe)
    - very old (the halo globular clusters contain the oldest stars)

- Even today, we observe the stellar halo "in formation"
- dwarf galaxies and globular clusters are disrupted and add their stars to this component.





Belokurov et al. 2006

Sloan Digital Sky Survey (SDSS) view of ~ 1/3 northern sky

Stars with (g - r) < 0.3 dex (halo turn-off)

Lots of substructure: galaxy formation also happening today!

The bulge

- Heavily obscured by dust ~ 30 mag in V

- Dust is patchy, some windows of low reddening
- **Baade's window** within 500 pc of the galactic center

- Mostly old (ages > 9 Gyr)
- Range of metallicities (-1 < [Fe/H] < 0.5), average metallicity [Fe/H] = -0.2 dex.

- Complex formation history (e.g. evidence of recent star formation)

The bulge

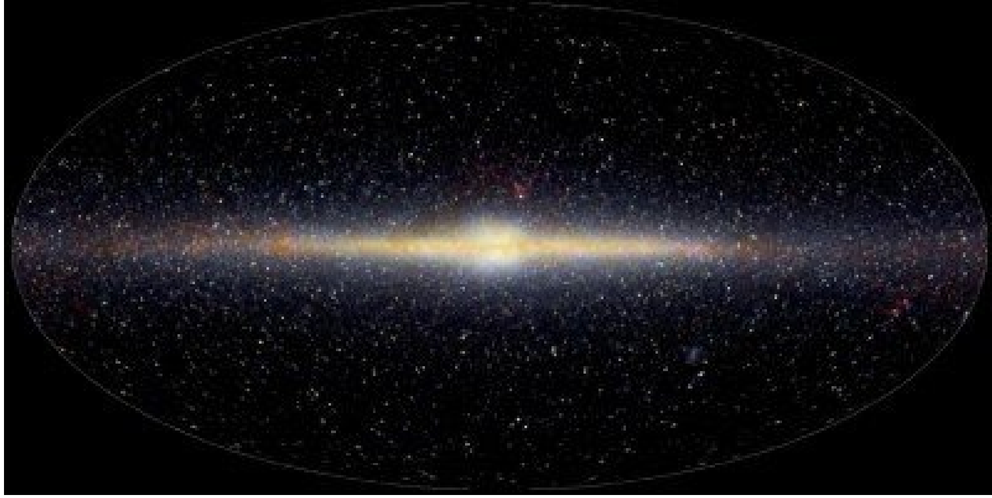
- Observations in the near infrared are particularly useful
  - stars dominate, while dust emits mostly in the mid & far infrared.

- Even though extinction is less important in the near IR, it still needs to be taken into account when modeling the data

The luminosity of the bulge in the near IR is $L_H \sim 3.3 * 10^{10} L_\odot$

It has approx. 1/6 - 1/3 the mass of Galactic disk

•Density distribution and structure derived from its surface brightness distribution ∑(l,b)



•The effect of dust in the measured ∑(l,b) is modeled and convolved with sets of models for the underlying stellar distribution to try and match the data best

•The model that provides the best fit may be considered a good approximation to the actual density distribution of the bulge.

Recent results show that bulge is not axisymmetric, but bar shaped

- First, the COBE infrared data showed that the bulge is bigger on one side.
- Secondly, if you look at the distances to stars on either side of the bulge, on average stars on one side of the bulge are closer than stars on the other.

The bar's major axis is ~20deg away from line defined by the Sun and the Galactic centre.

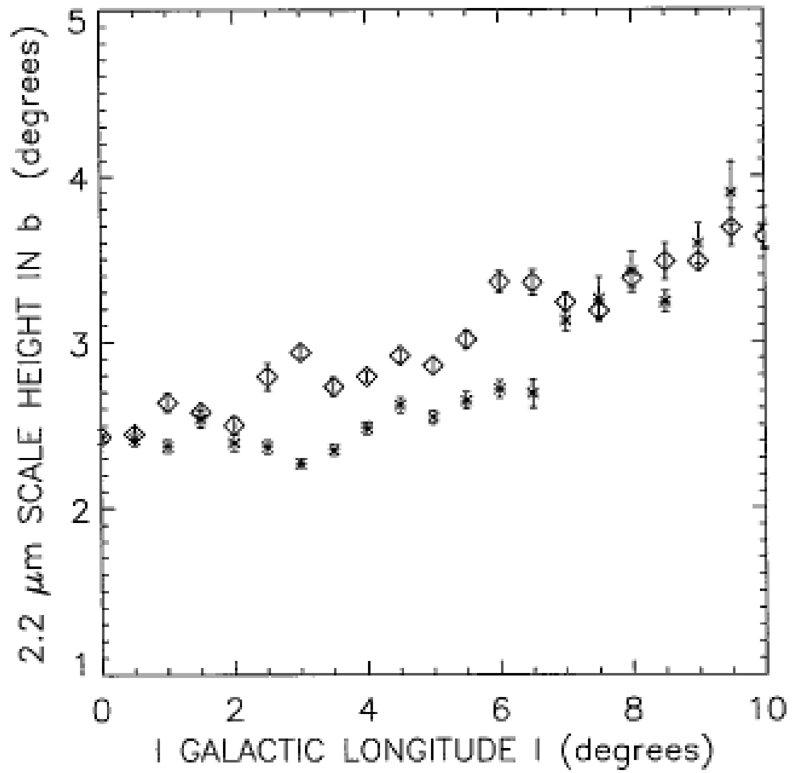


FIG. 2.—2.2 μm angular scale heights at fixed longitude. Scale heights for $l < 0°$ are represented by asterisks, whereas diamonds are for scale heights at positive Galactic longitudes. The error bars represent 1 σ errors on the computed scale height.

Population types and the Galaxy

- A stellar population is a group of stars with similar properties

- Traditionally:
  - Population I: young, metal rich stars in the disk of the Galaxy
  - Population II: old, metal weak stars in the spheroid.

- Fundamental difference is when/where/how they were formed

- Limitations:
  - strict distinction may eventually become obsolete
  - more population types have appeared (e.g. intermediate type II population, corresponding to the thick disk stars)

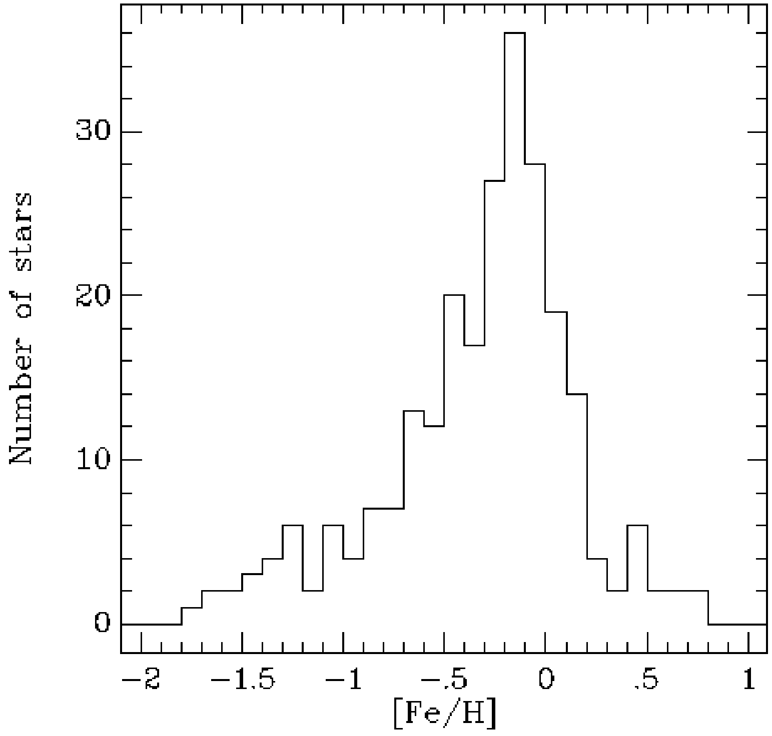
http://sci2.esa.int/interactive/media/applets/3_1_1.htm

Properties of the populations

Population I

- The Young Disk: O-B stars, young associations and clusters, as well as much of the gas layer, are concentrated towards the galactic plane, with a **scale height** of ~100 pc.

- The Old Disk: stars in the disk older than a few Gyr, (i.e. A-type stars or later). The iron abundance of old disk stars range from about [Fe/H] = -0.5 to [Fe/H] = 0.3.

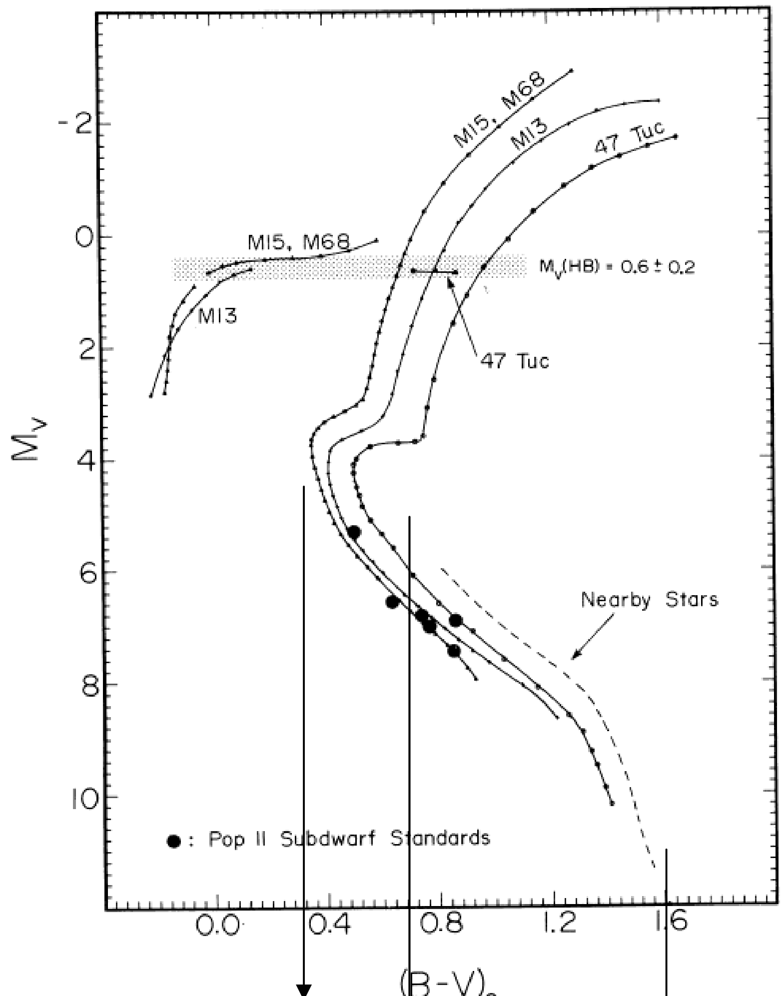


Metallicity distribution for K dwarfs near the Sun. Note the sharp peak at [Fe/H] ~ -0.2 dex (Kotoneva and Flynn, 1999).

Population II stars are old (12 - 15 Gyr), includes the **stellar halo** and the **bulge**. The stellar halo and bulge differ in their metallicities --- the halo is metal weak ([Fe/H] < -1) while the bulge is generally metal rich (with a metallicity distribution quite like that of the disk).

	Population I	Population II
Age	Young disk : < 1 Gyr Old disk : 1 - 10 Gyr	12 – 15 Gyr
Metallicity [Fe/H]	-0.5 < [Fe/H] < 0.3	Halo : [??, - 1.0] Bulge : [-0.5, +0.5]
Rotation, km/s	Young disk: 220 Old disk : 180 – 200	Halo : 0 Bulge : ~ 100
Velocity dispersion in (U,V,W) km/s	Young disk : (40, 30,10) Old disk : (80, 60, 20)	Halo : (150, 100,100) Bulge : ~ 130 km/s

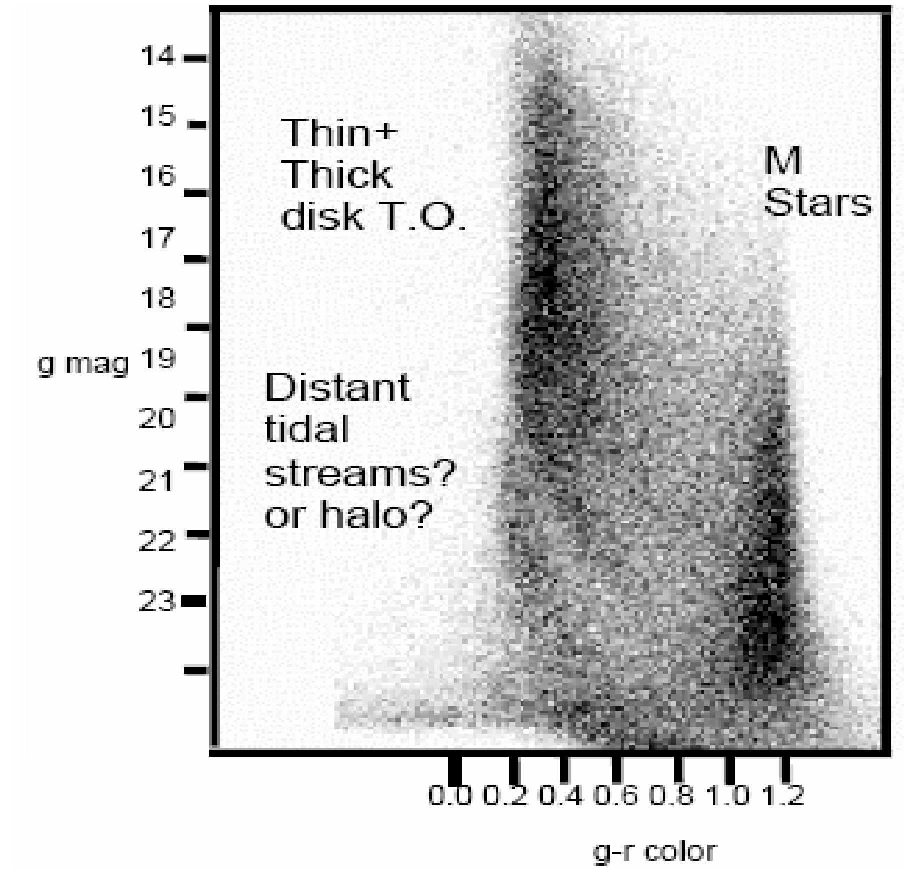
Photometric surveys show the Galaxy is a bit more complex



halo turn-off

thin disk turn-off

dwarfs



Rockosi 2006

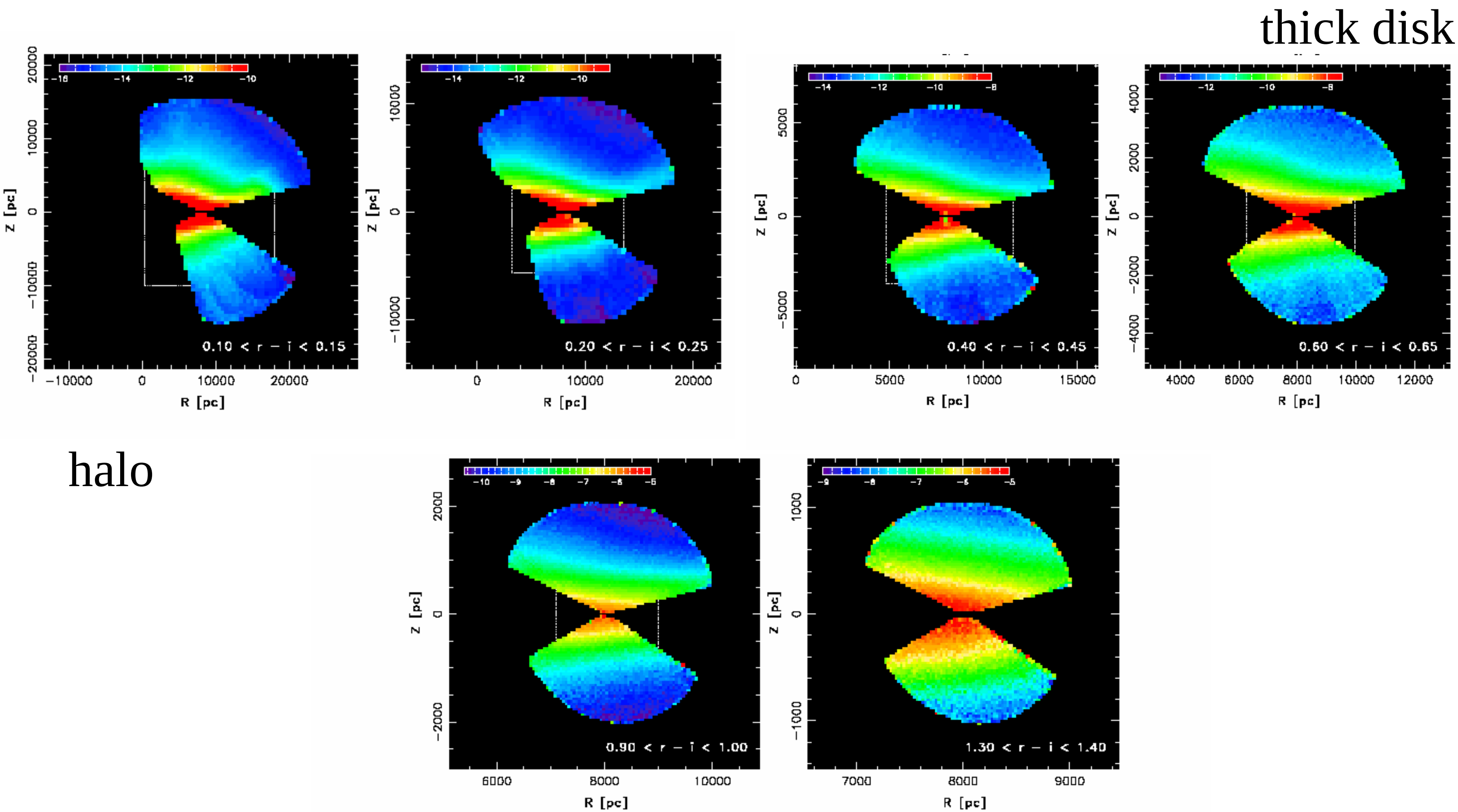


FIG. 6.— The stellar number density as a function of Galactic cylindrical coordinates R (distance from the axis of symmetry) and Z (distance from the plane), for different $r - i$ color bins, as marked in each panel. Each pixel value is the median for all polar angles. The density is shown on a logarithmic scale, and coded from blue to red (black pixels are regions without the data). Note that the distance scale greatly varies from the top left to the bottom right panel – the size of the the bottom right panel is roughly equal to the size of four pixels in the top left panel. Each white dotted rectangle denotes the bounding box of region containing the data on the following panel.

nearby thin disk

Comparison to models enables new determination of structure of the MW

Maps show great deal of complexity