Milky Way I

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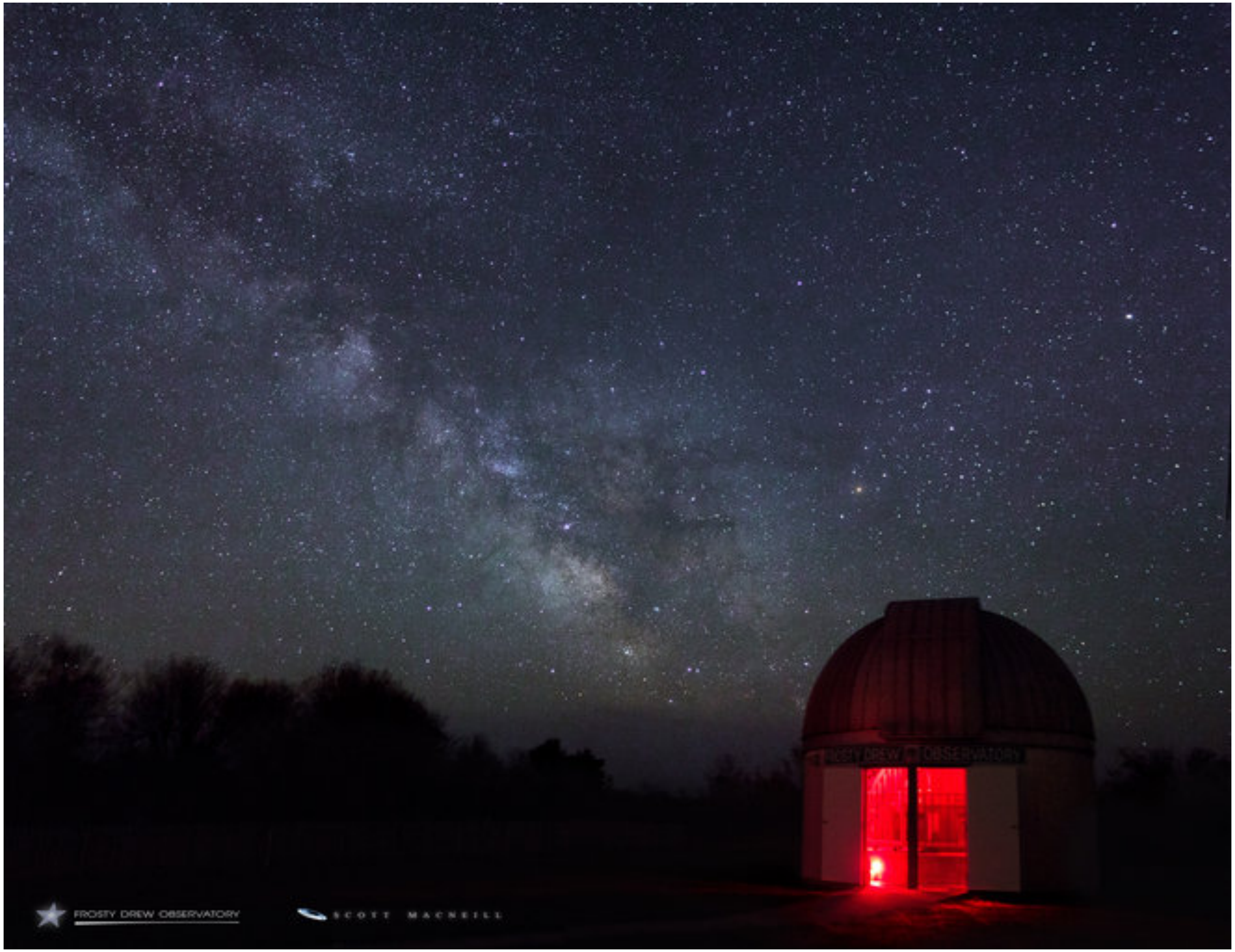
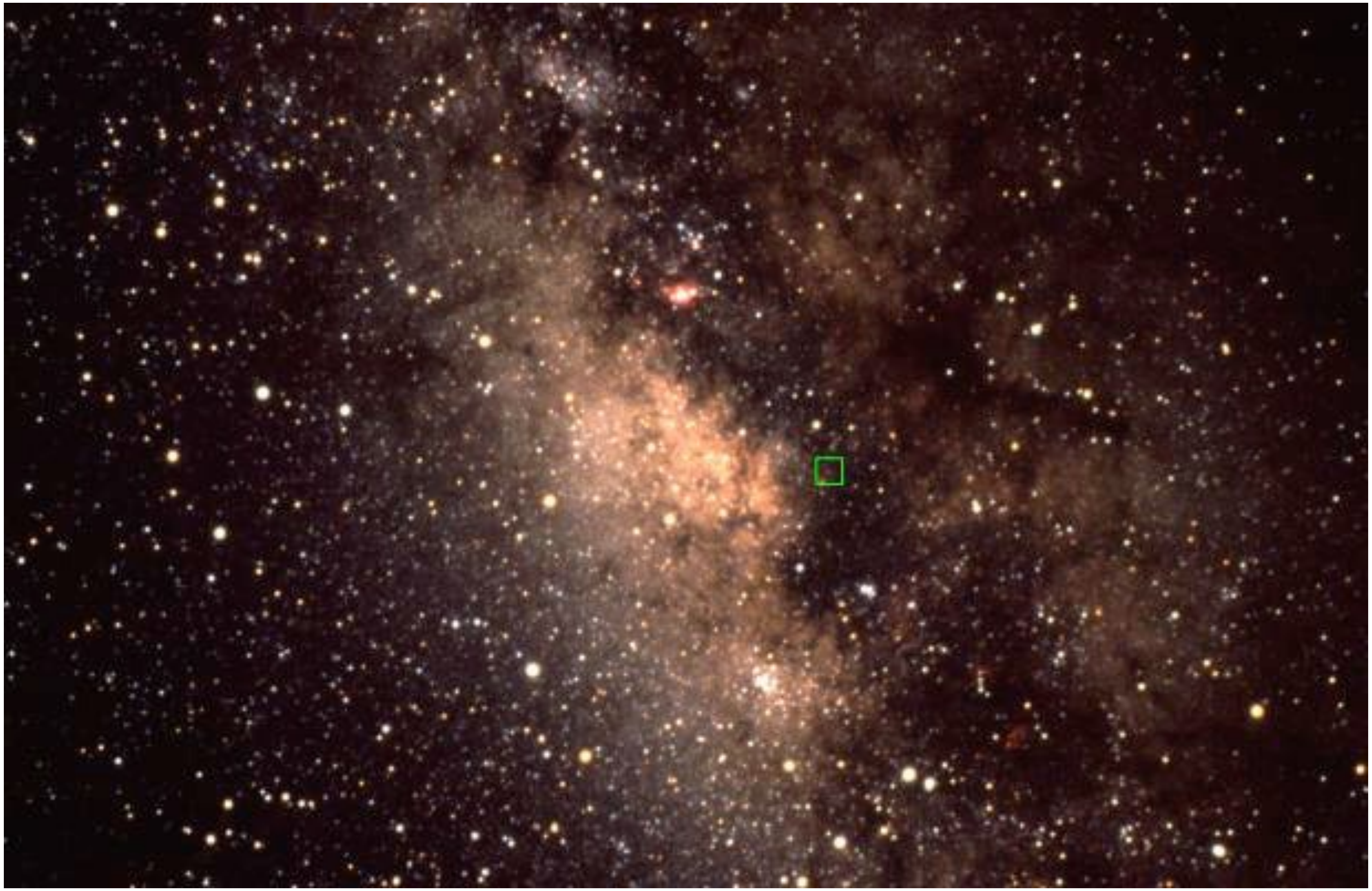
Physics of Galaxies 2019-2020 Q4
Rijksuniversiteit Groningen

The internal view

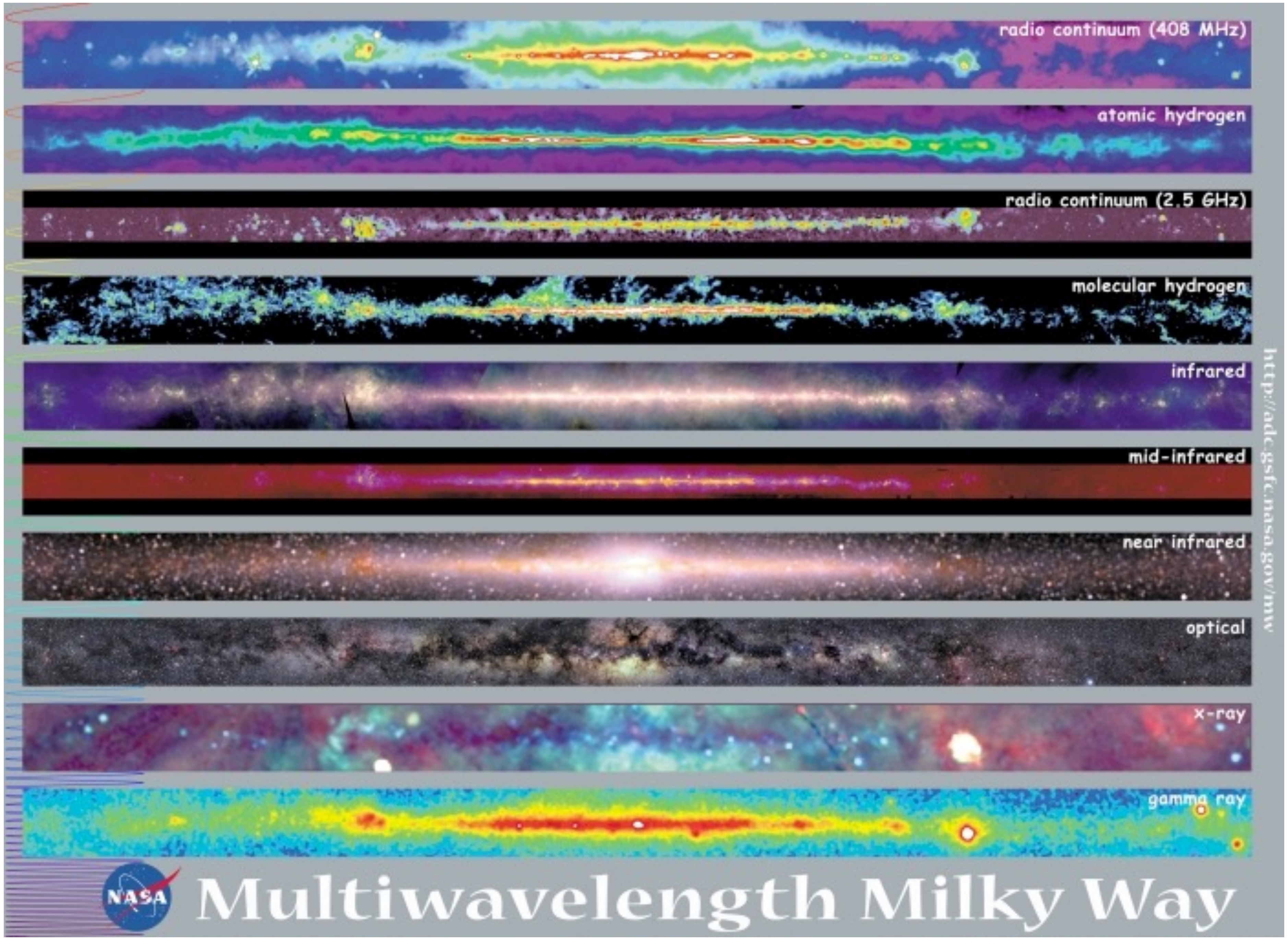


An optical view of the Milky Way



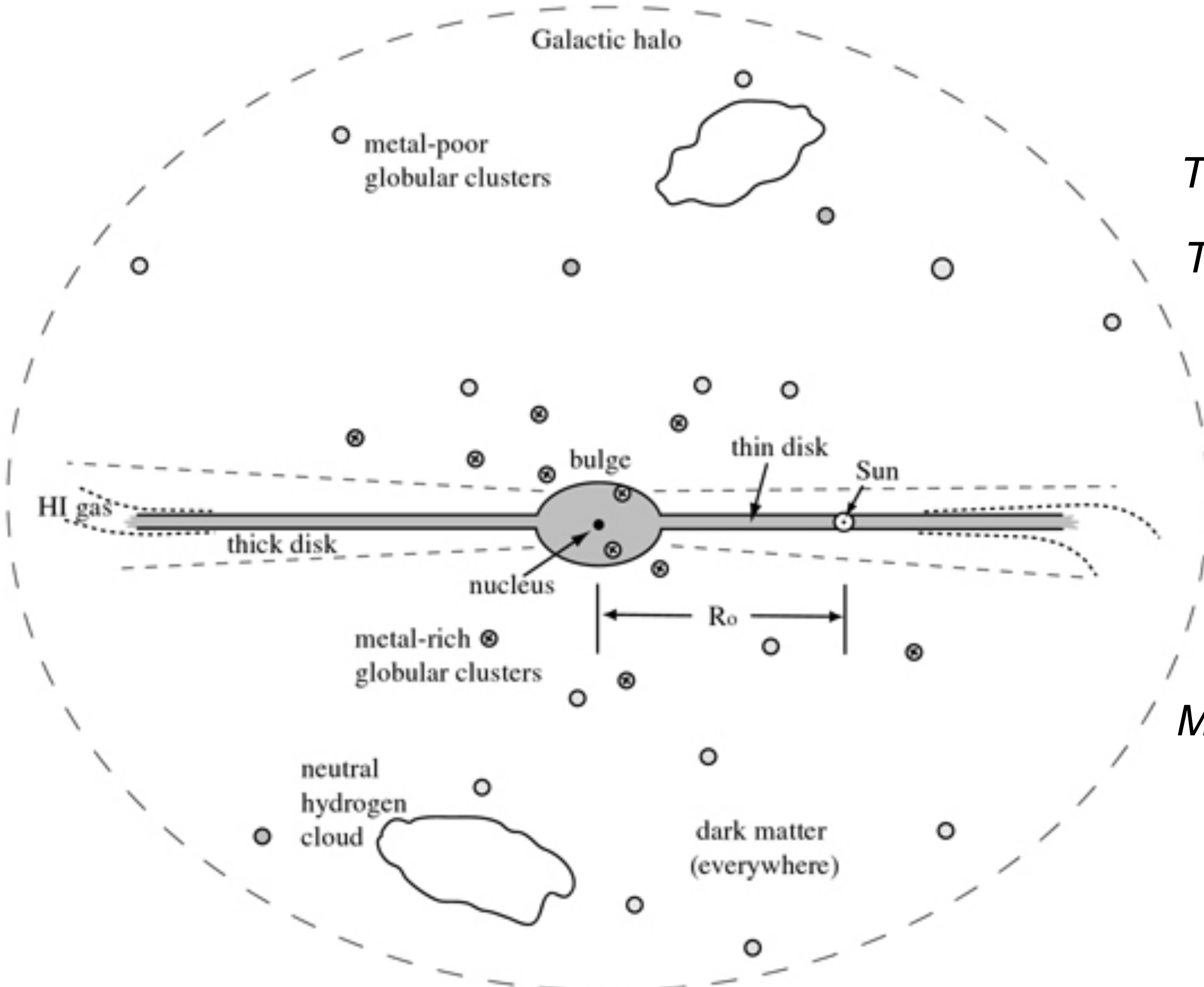
Picture credit: D. Talent @ Cerro Tololo

The Multi-wavelength view



Picture credit: https://mwmw.gsfc.nasa.gov/mmw_images.html

The components of the MW



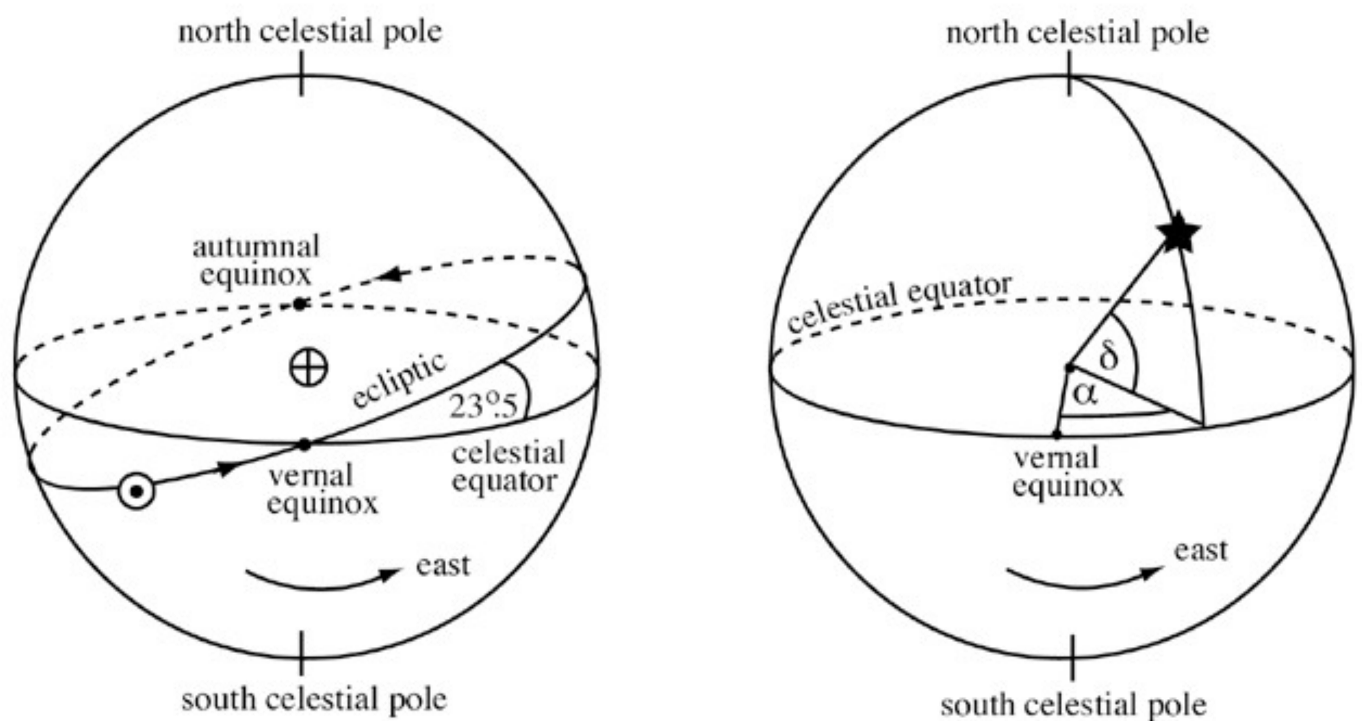
Thin disk ~ 400 pc

Thick disk ~ 1 kpc

MW diam ~ 30 kpc

Figure 1.8, Sparke & Gallagher (2nd edition)

The Celestial Sphere



<u>We use equatorial coordinates to determine the positions of stars in the sky.</u>

A stars declination (like latitude on the Earth) is the angle between its position and the celestial equator.

Figure 1.9, Sparke & Gallagher (2nd edition)

Galactic coordinates

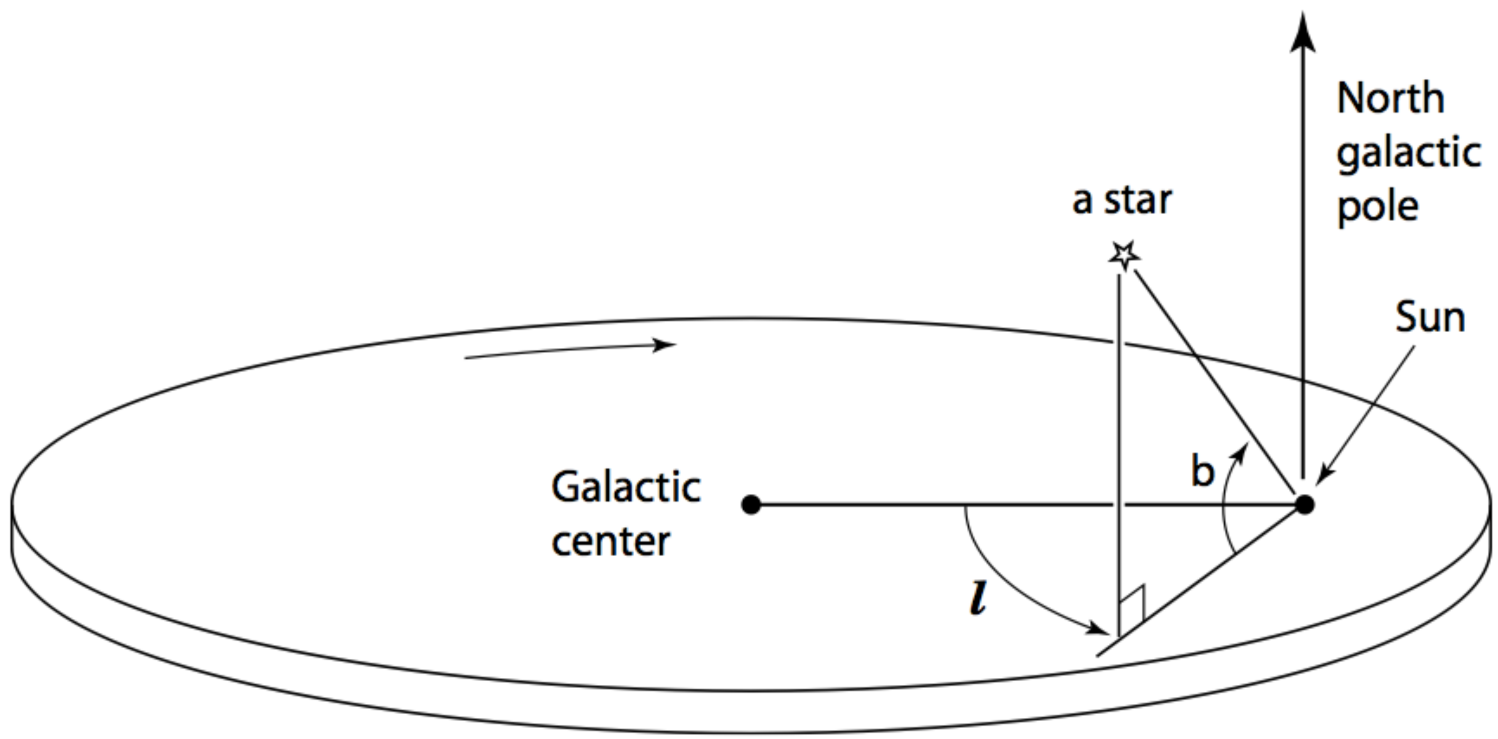
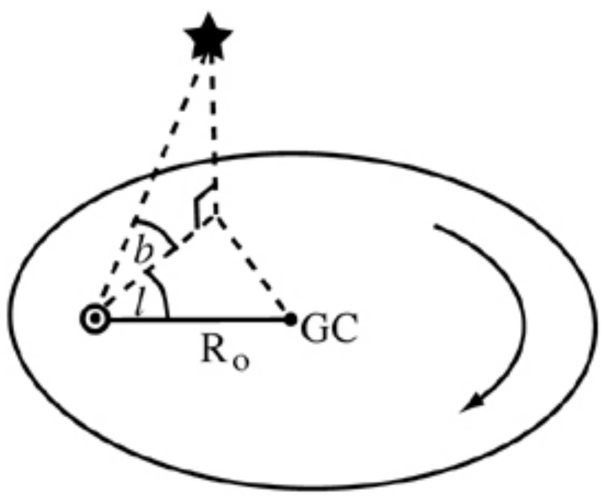


Figure 1.3 A schematic picture of the Sun's location in the Galaxy, illustrating the Galactic coordinate system. An arrow points in the direction of Galactic rotation, which is clockwise as viewed from the north Galactic pole.

Binney & Tremaine, Galactic Dynamics (2nd edition)

Galactic coordinates II



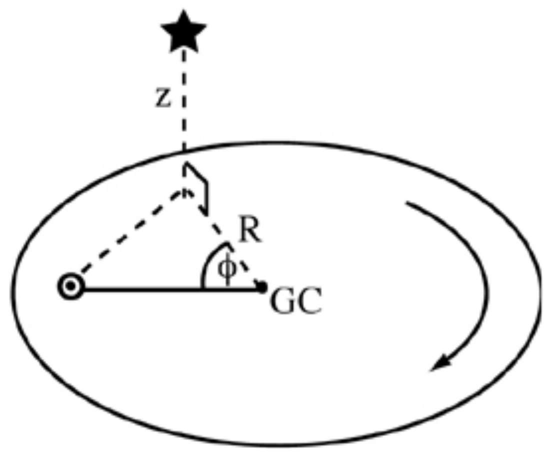
<u>We use Galacto-centric coordinates to measure positions in the Milky Way</u>

Galactic longitude l is measured in the plane of the disc from the Sun-GC line, towards the direction of the Sun's rotation.

The Galactic latitude b is the angle of the star from the Galactic plane towards "North Galactic Pole" (NGP)

Figure 1.10, Sparke & Gallagher (2nd edition)

The MW in cylindrical coordinates



To specify the positions of stars in three-dimensional space, we use Galactic cylindrical coordinates (R,ϕ,z)

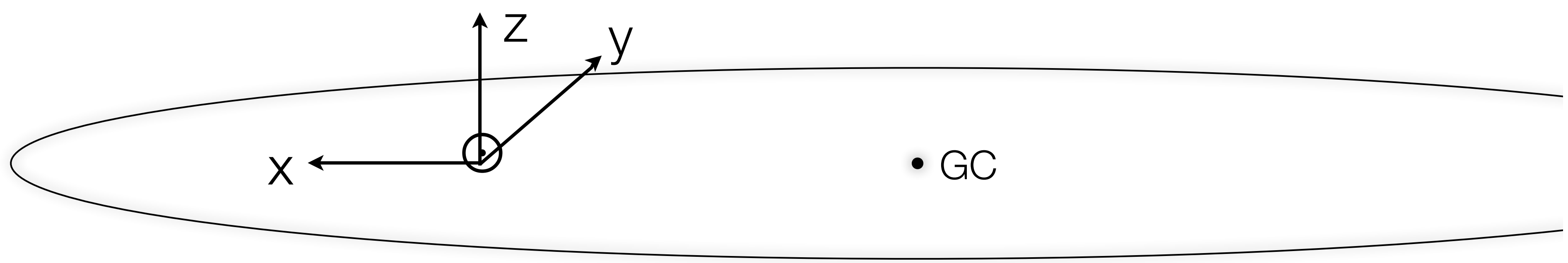
The radius, R, is the distance from the Galactic Centre in the disc-plane of the Galaxy

The azimuthal angle ϕ is angle from the Sun-Galactic Centre line.

The height above the midplane, z, is positive towards North Galactic Pole

Figure 1.10, Sparke & Gallagher (2nd edition)

The MW in Cartesian coordinates



<u>For motions near the Sun, we use Cartesian x, y, z coordinates</u>

x: radially outwards (away from Galactic Centre)

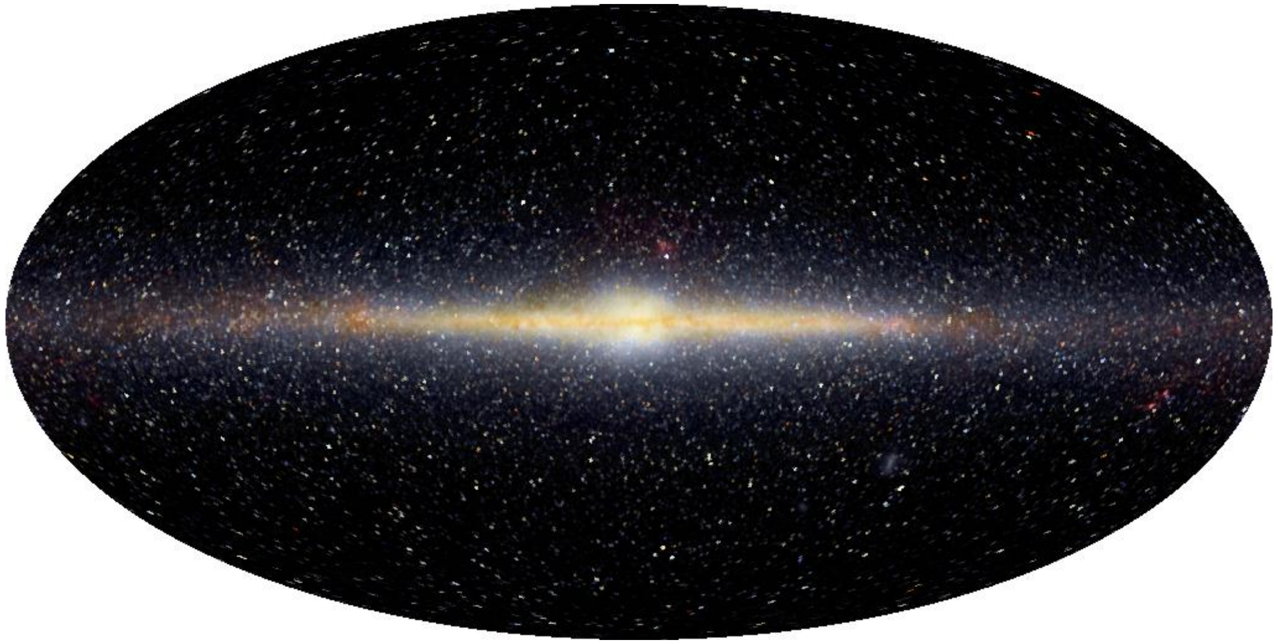
y: in direction of Sun's rotation around Milky Way

z: out of Galactic plane, positive towards North Galactic Pole

The MW's shape and structure

It has more than one component, and so we need to determine the density distribution and characteristic scales of each component. This means we need to observe the properties of a large number of stars in each component.

We can then ask - how do these components relate to each other and the formation of Milky Way? This requires the coupling of density info with ages, compositions, etc.



The Milky Way as seen by COBE in the infrared

Stellar density in the MW

For disc galaxies, we can approximate the stellar density in the disc as double exponential:

$$n(R, z, S) = n(0, 0, S)\exp[-R/h_R(S)]\exp[-|z|/h_Z(S)]$$

where h_R is the scale length of the disk – the length over which the density falls by a factor of e – and h_z is the scale height of the disk – again, the height over which the density falls by e for some population S

mid-plane: $h_z \sim$ 300-350pc for K-dwarfs

for more massive shorter lived A-dwarfs, h_z < 200pc

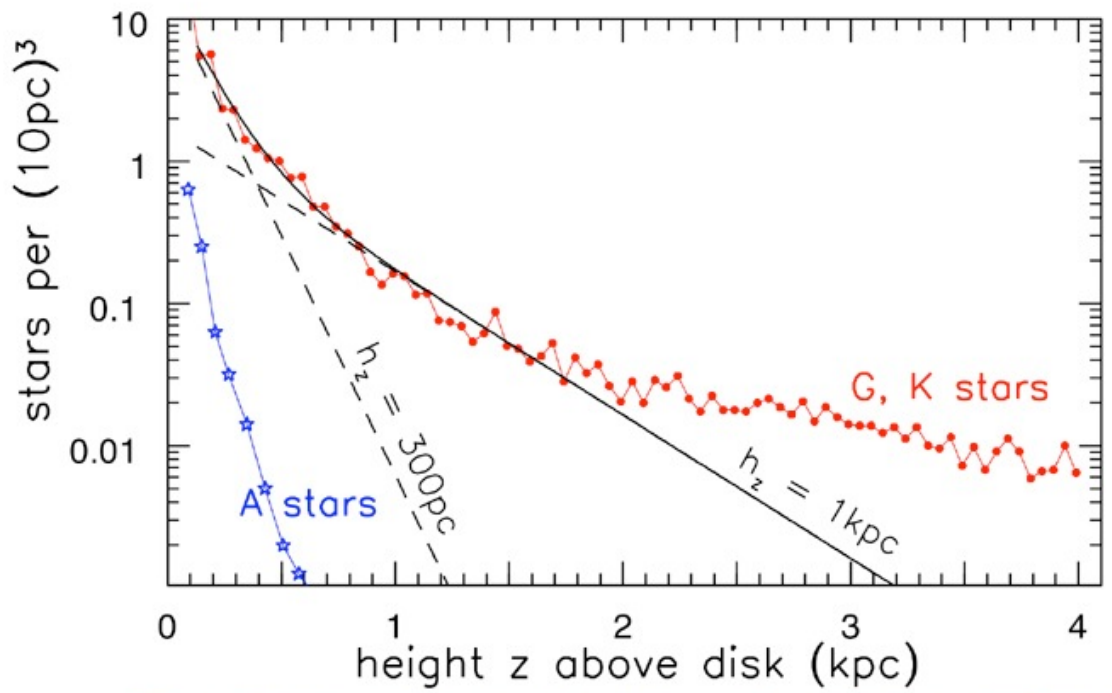


Figure 2.8, Sparke & Gallagher (2nd edition)

The MW's disccs

thin disc; thick disc

thick disc ~10% of total near the Sun

thick disc ~30% of stellar density in thin disc

thick disc contains no O, B or A stars, it is not still forming stars - this also means a higher M/L

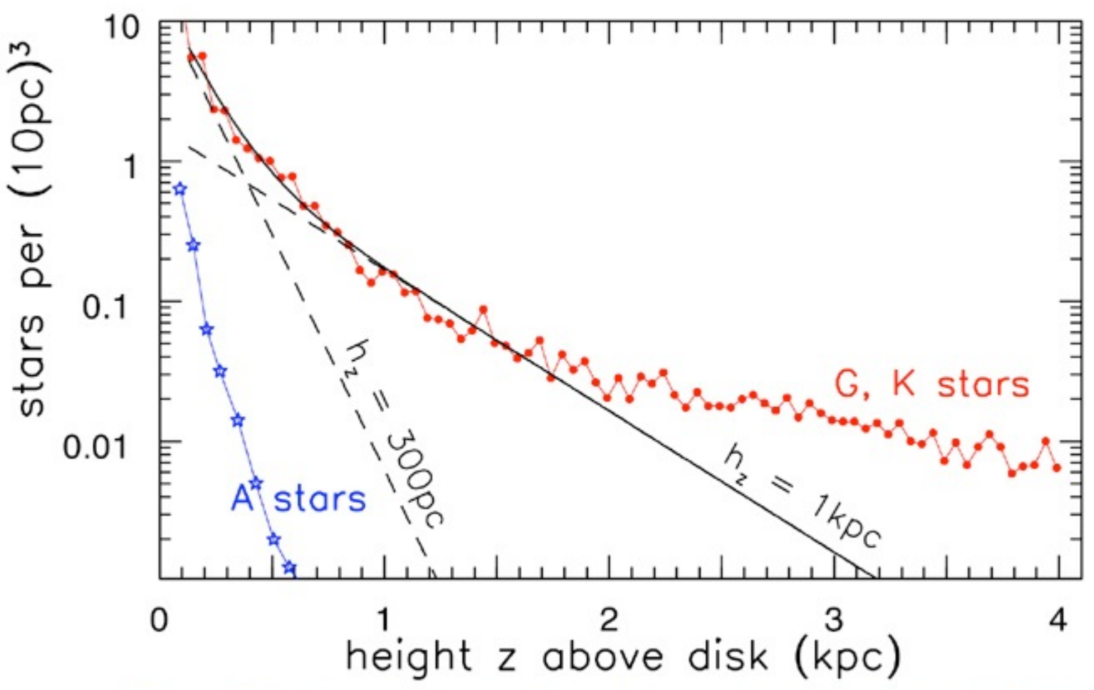


Figure 2.8, Sparke & Gallagher (2nd edition)

Age versus scale height

There is an effect relating stellar age to scale height.

This is caused by giant molecular clouds scattering stars as they pass by, increasing the scale height, and this effect increases with time.

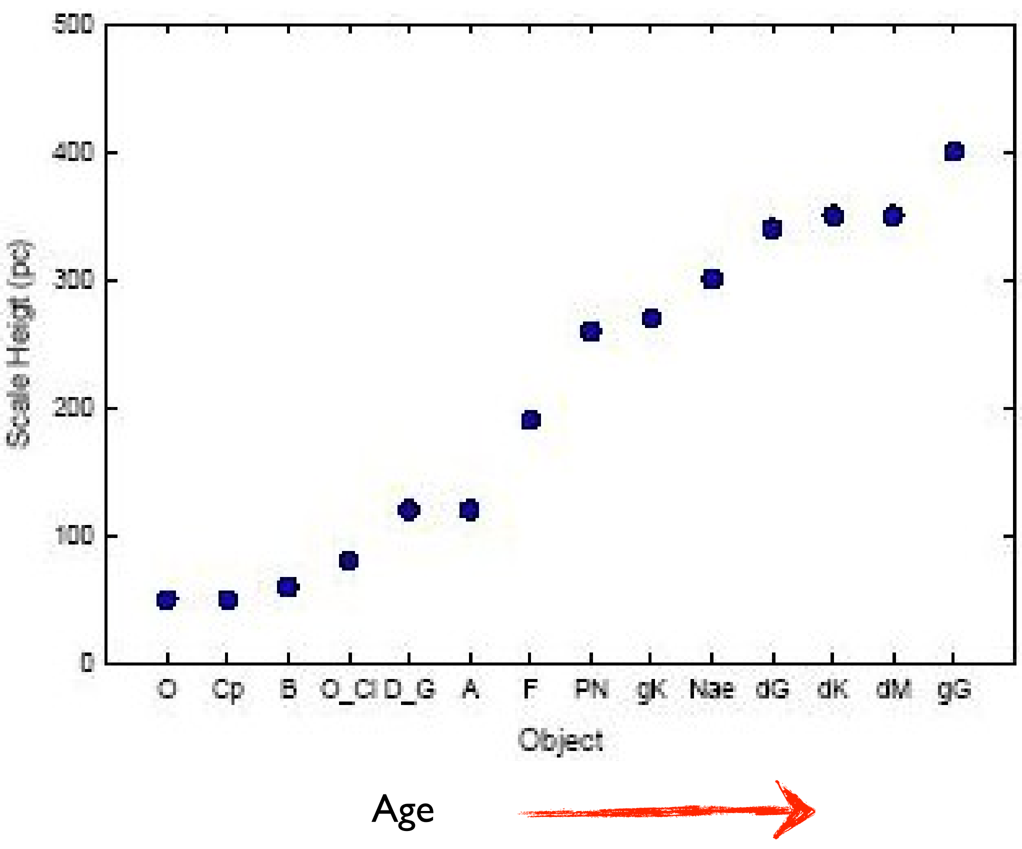
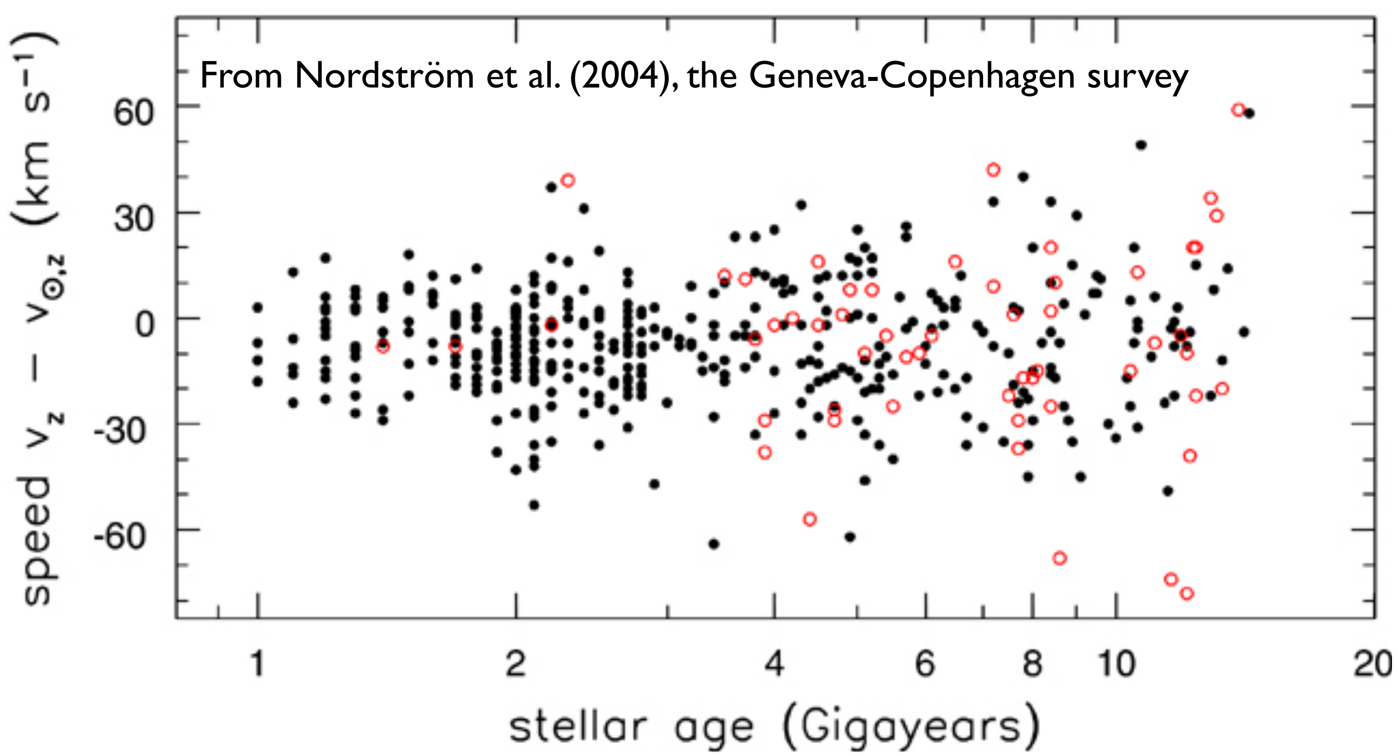


Figure 2.10, Sparke & Gallagher (2nd edition)

Stellar velocity distributions vs. age

This is caused by giant molecular clouds scattering stars as they pass by, increasing the scale height, and this effect increases with time.

Open circles show stars with less than a quarter of the Sun's iron abundance



The distribution of the motions of (F and G) stars in the z direction, shows that older stars have a larger vertical velocity dispersion:

$$\sigma_z^2 \equiv \langle v_z^2 - \langle v_z \rangle^2 \rangle$$

the Sun moves upwards at ~ 7 km/s

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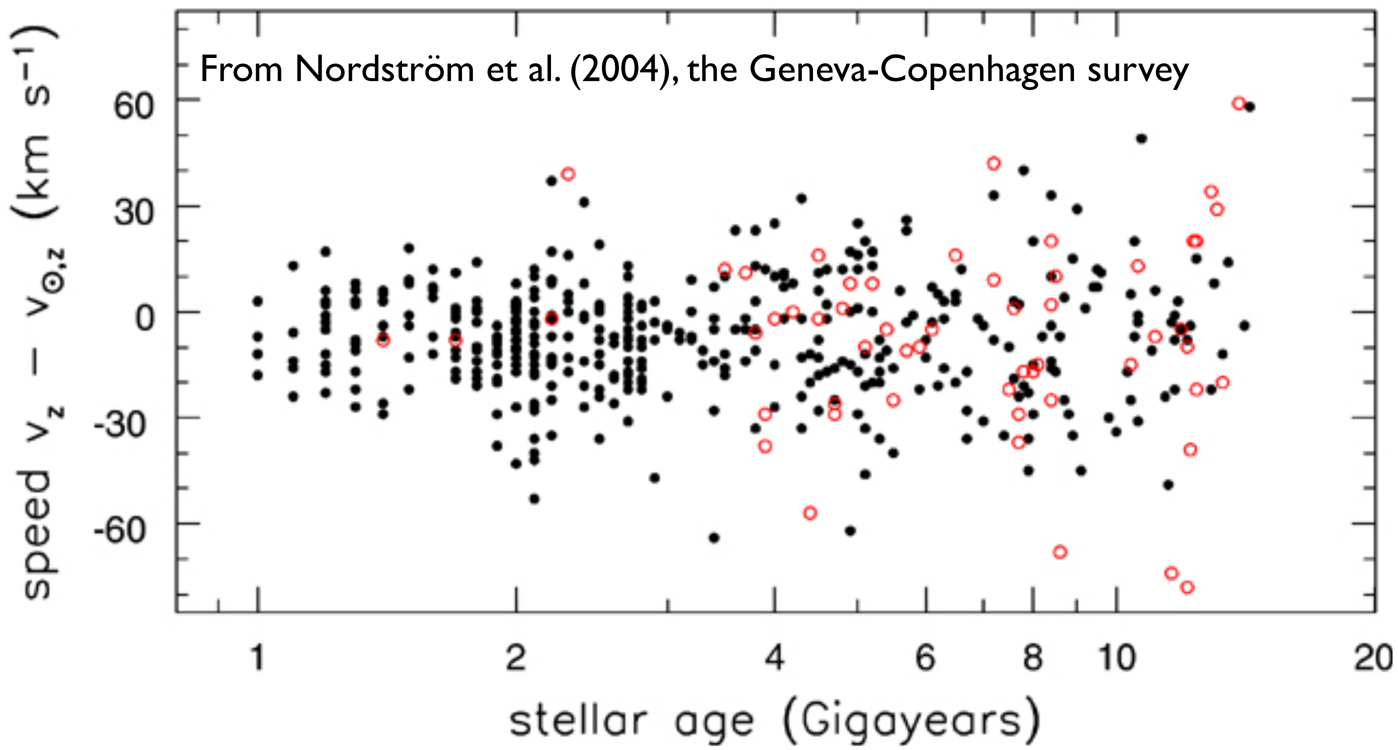

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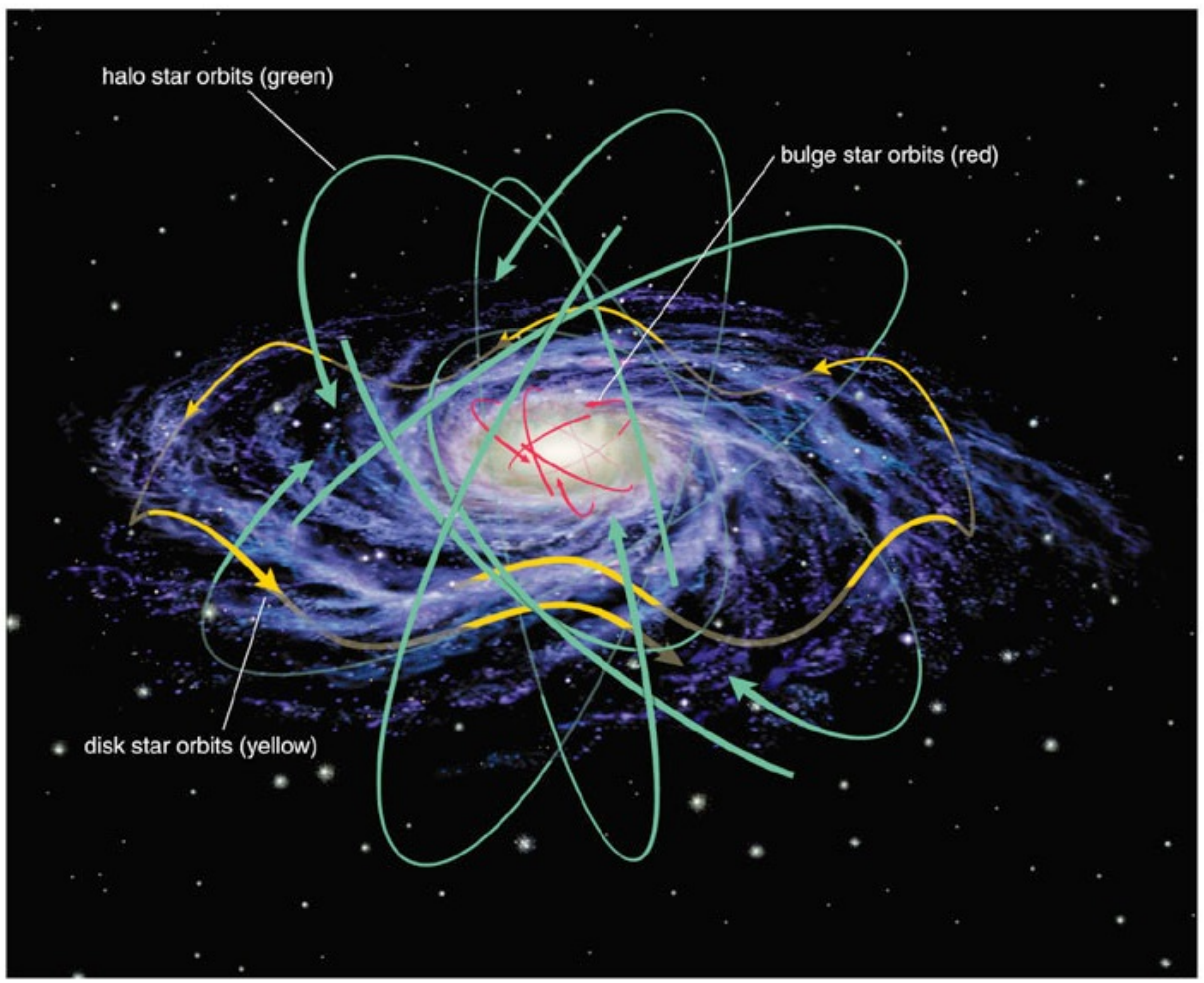
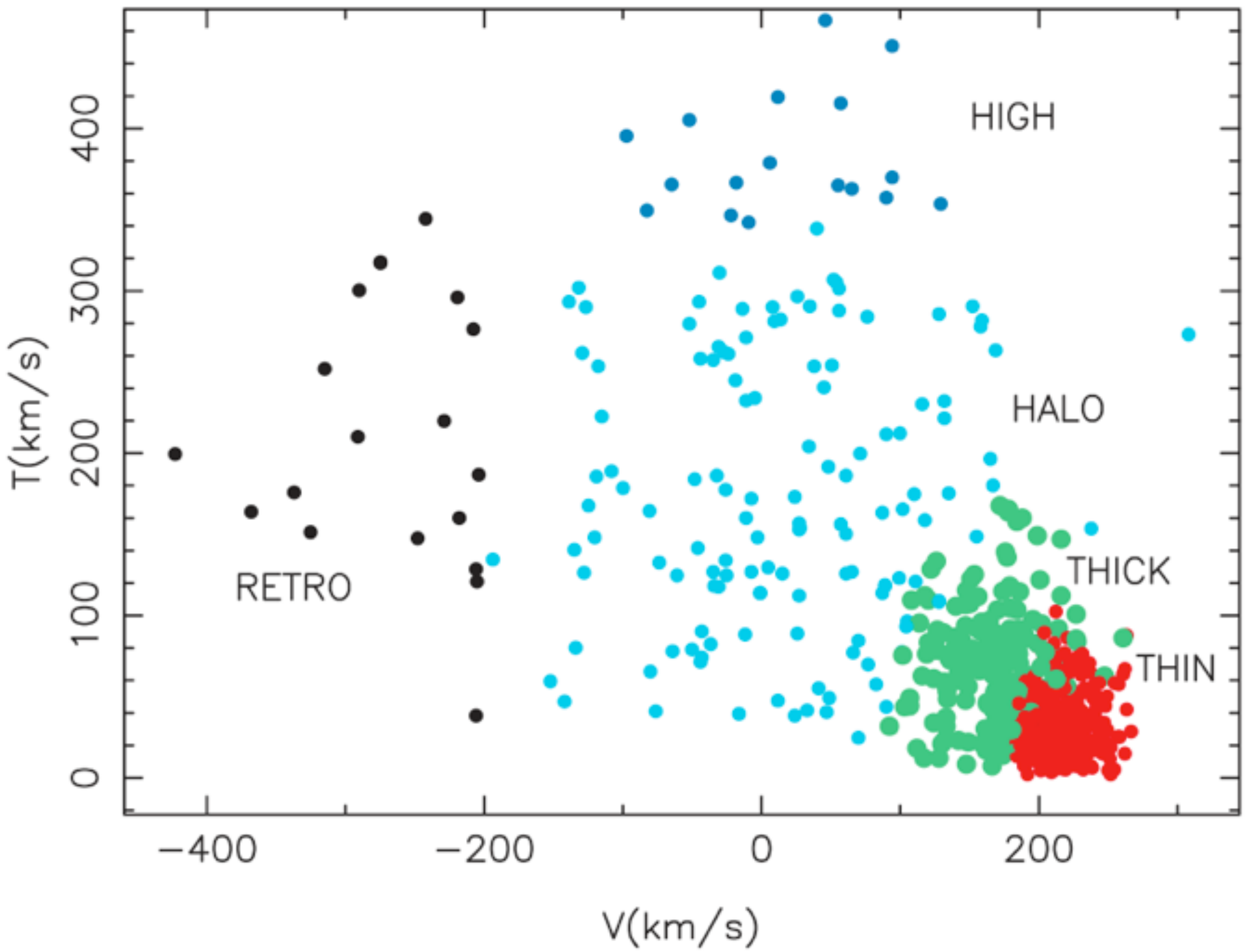
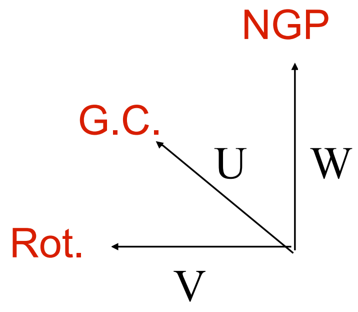
Stellar orbits in the MW



- Stars in the disc all orbit the Galactic centre:
  - in the same direction
  - in the same plane (like planets do)
  - they "wobble" up and down
    - this is due to gravitational pull from the disk
    - this gives the disk its thickness

Analysis of MW components

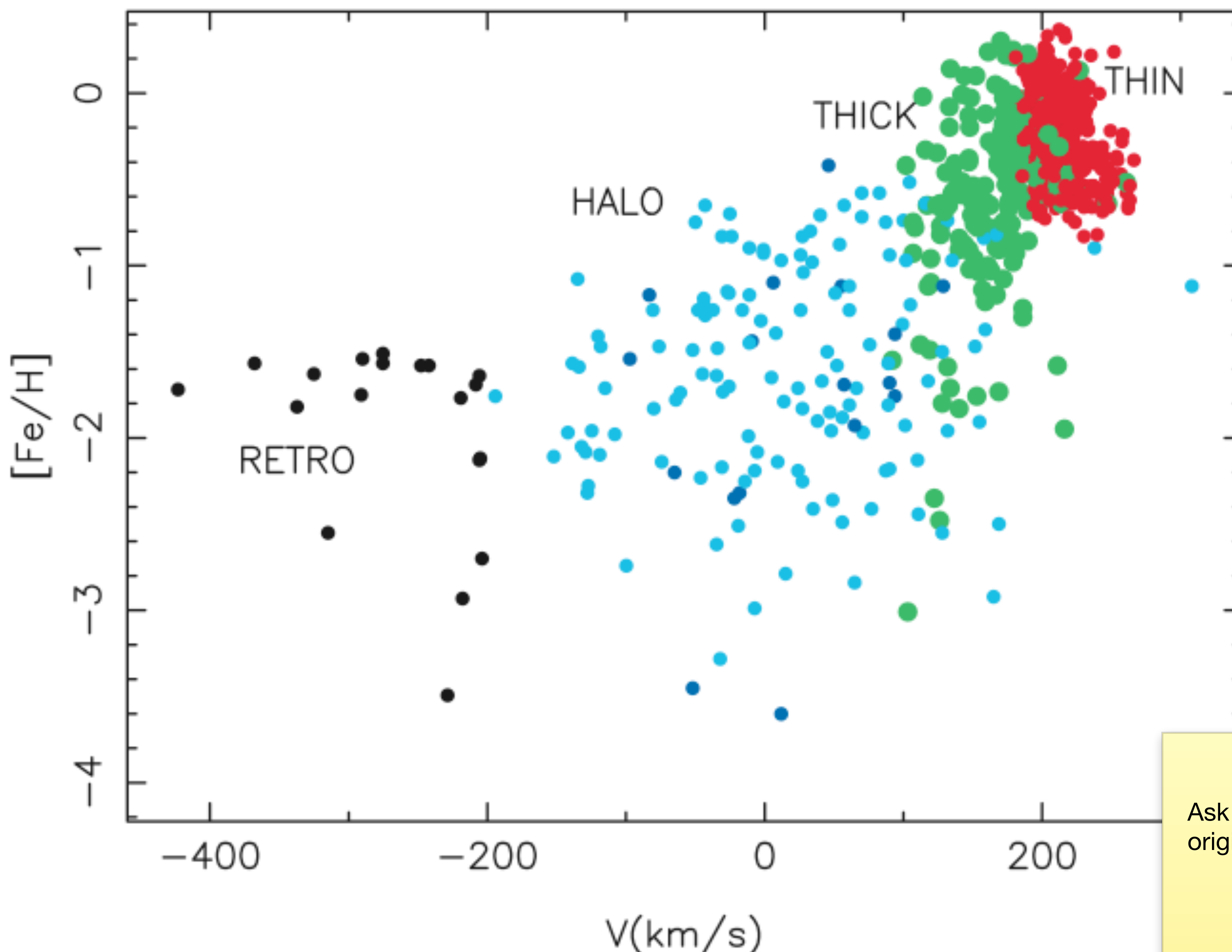




$T=(U^2+W^2)^{1/2}$

Venn et al. 2004

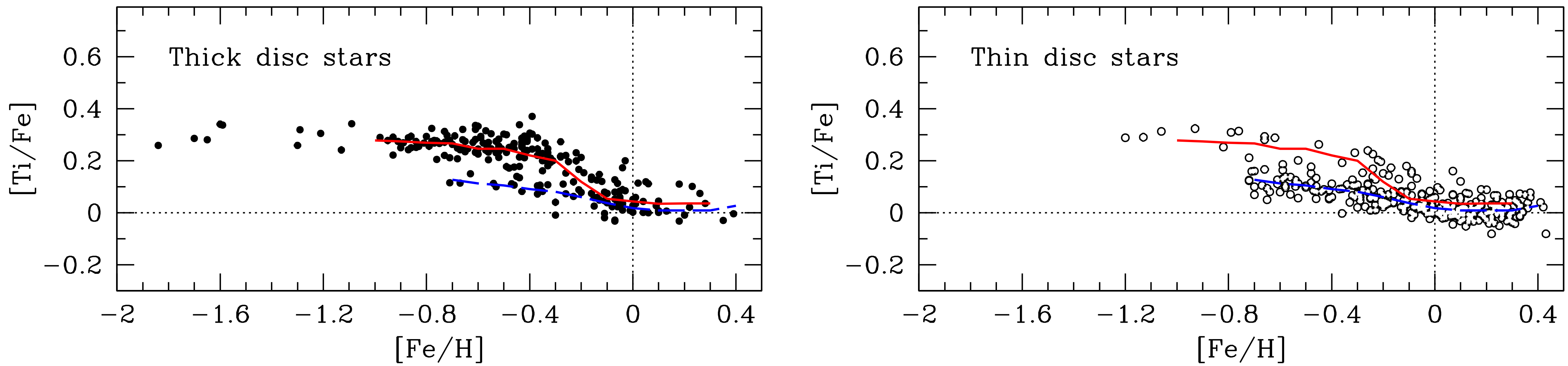
Properties of different components



Ask class: what do you think about the origin of the retrograde component?

Venn et al. 2004

The MW discs (stars)



The thick disc stars have distinctly different chemical properties from thin disc stars.

Thin disc stars make up ~90% of the stars near the Sun.

Integrated over the z direction, the thick disk has ~1/3 the surface density of the thin disc

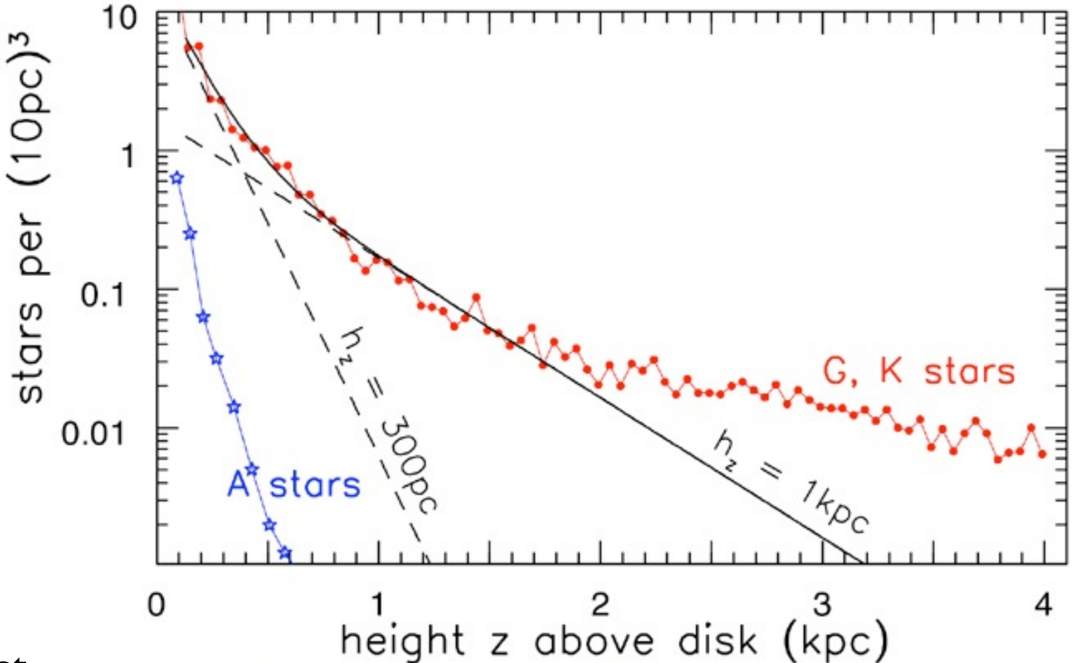
- One idea is that there was originally a thin disc that was puffed up by a collision with a small satellite galaxy; this became the thick disc, while remaining gas settled into a new thin disc

- Another possibility is that radial migration of stars from the inner disc, combined with scattering off of giant molecular clouds, may cause an apparent thick disc that is really just the central thin disc extending outwards

The MW discs (stars II)

The Milky Way disc(s)

The vertical distribution of stars in the Milky cannot be fit by single exponential curve. There is only a good fit with two exponentials: z_0=300 pc (close to plane) and z_0=1350 pc (farther from plane)



Two possibilities:

- Functional form (exponential) is incorrect
- There are two physically distinct components of the disk of the Galaxy: a thin and a thick disk

For the second possibility to be correct, need to conclusively demonstrate that they have different and distinct properties!

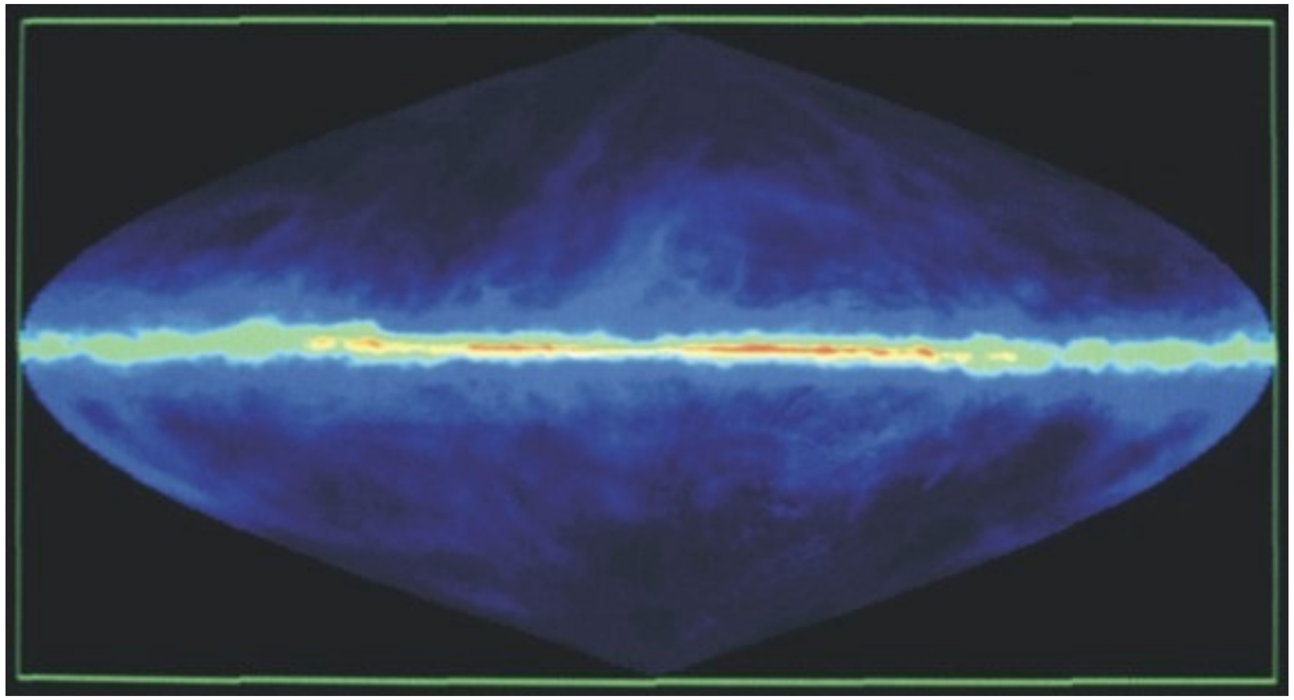
Figure 2.8, Sparke & Gallagher (2nd edition)

The MW discs (gas)

The Milky Way gas disc(s)

for neutral HI gas, h_z < 150pc

for molecular gas, h_z < 60-70pc



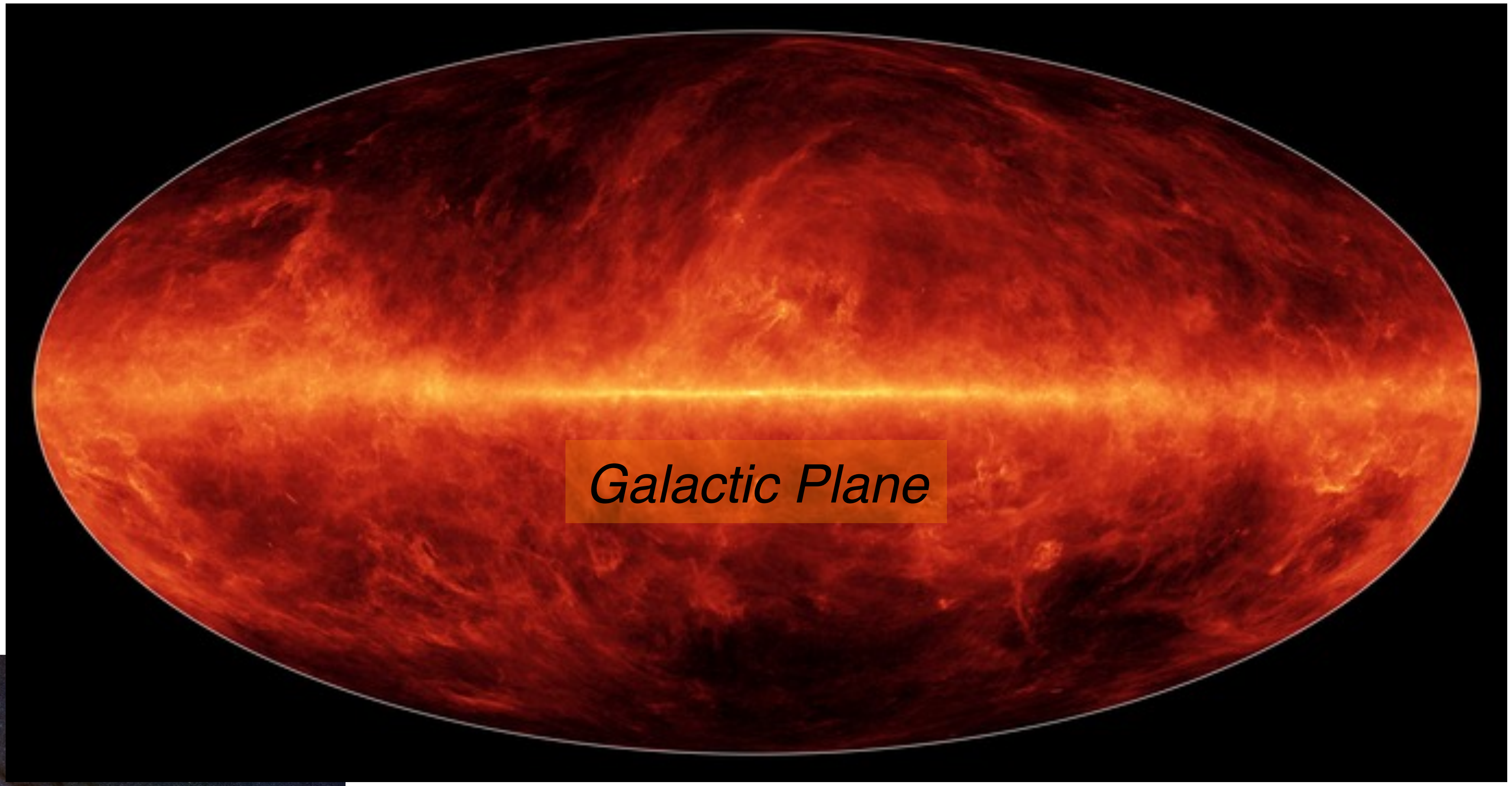
HI gas (mixed with dust) in the disc is even thinner than young stellar distribution near the Sun h_z < 150pc. For cold molecular clouds this even less, h_z < 60-70pc.

Assuming the M/L~2, it can be shown that the total luminosity of the disc is $L_d \sim 1.5\times10^{10}\ L_\odot$ corresponding to $M_d \sim 3\times10^{10}\ M_\odot$

If stars are produced with the standard IMF then to build the disc over 10Gyr the Milky Way must produce 3-5 $M_\odot$ of new stars every year.

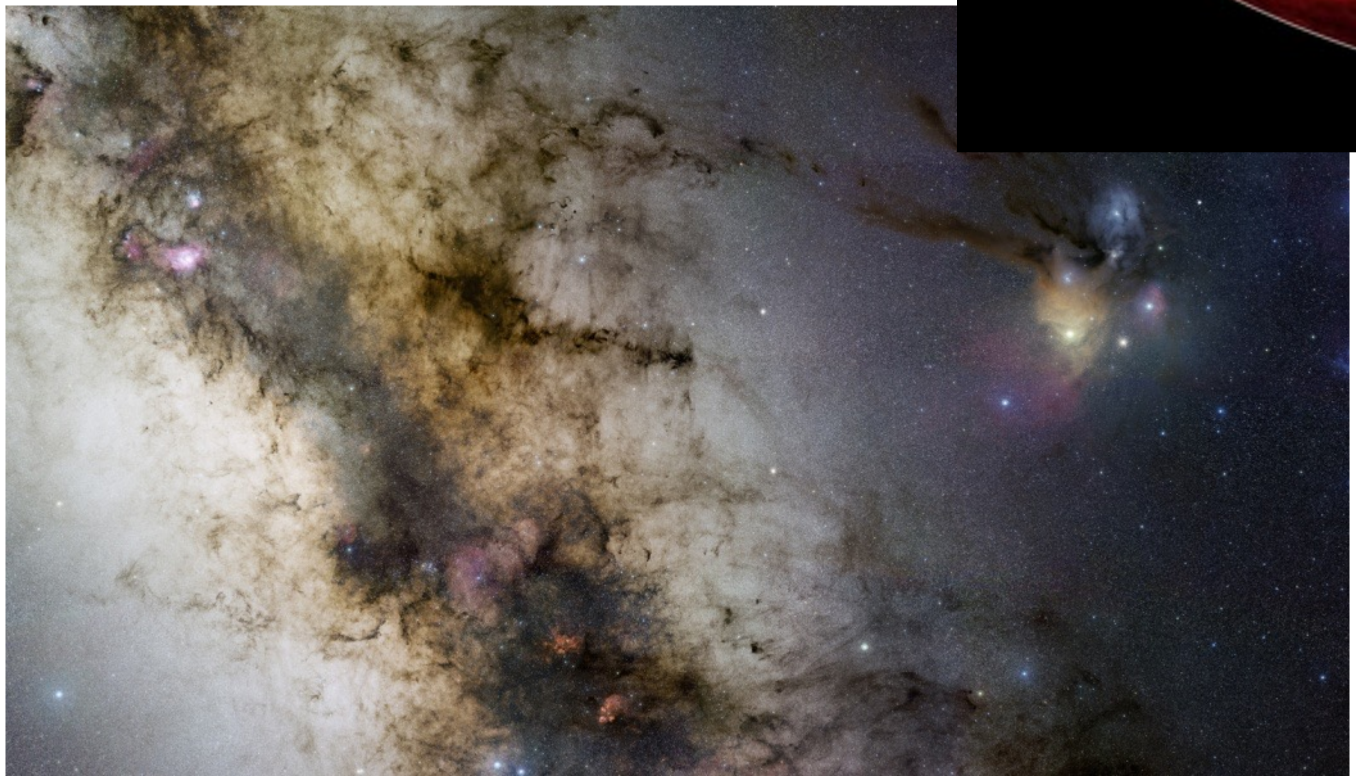
Dust in the MW

Planck's all sky map



Picture credit: NASA/ESA

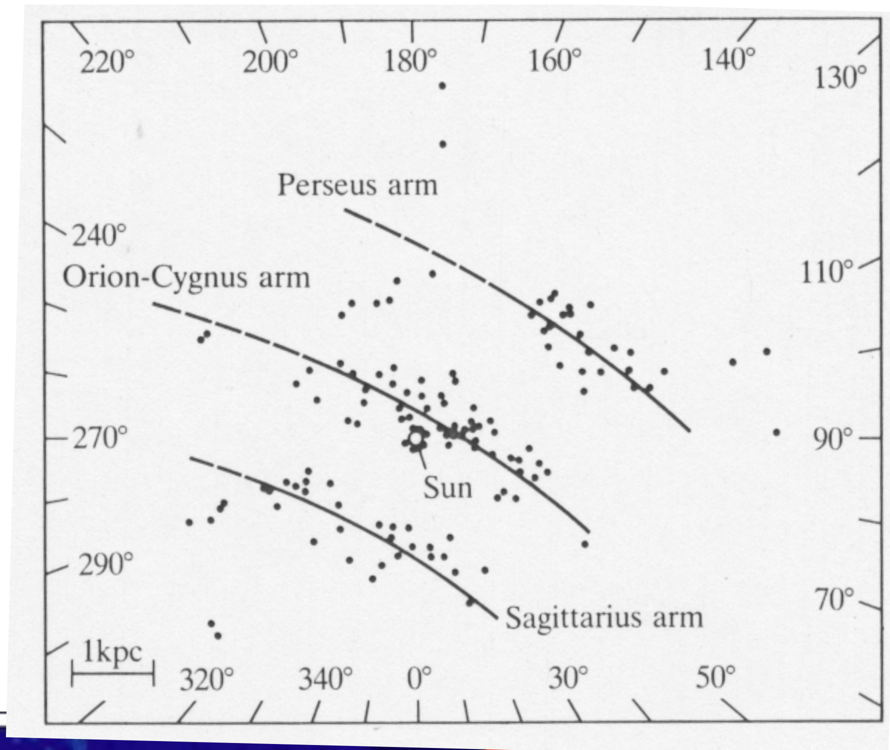
Galactic Centre

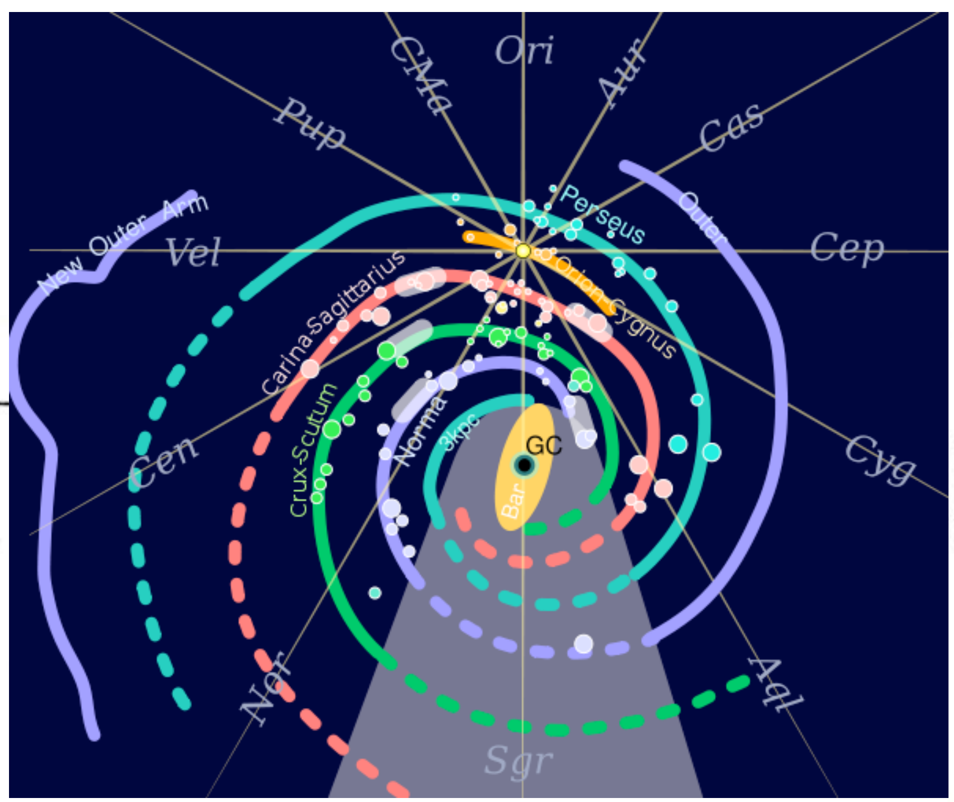


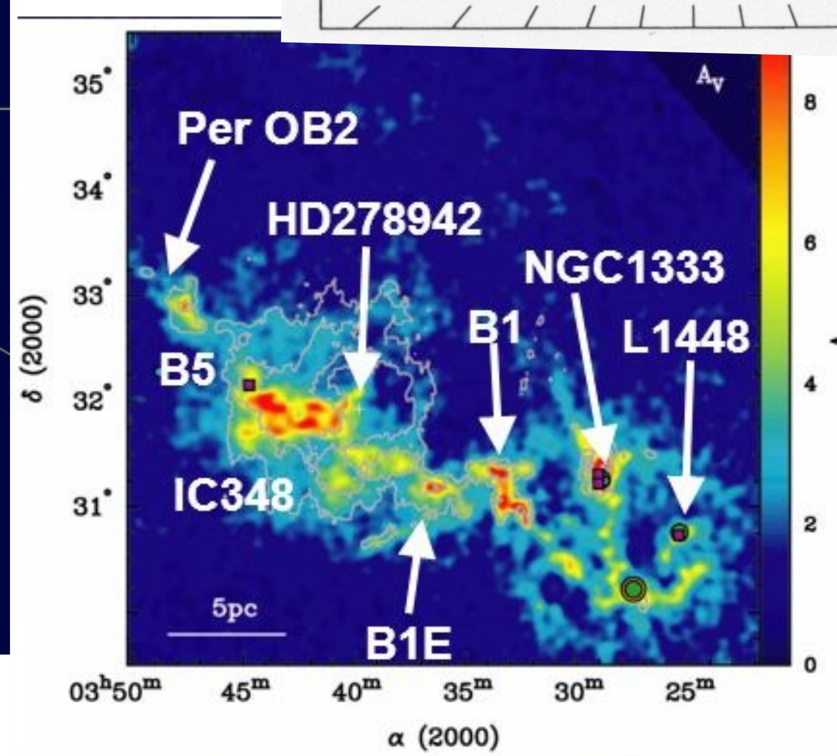
Picture credit: S. Guisard

Structure of the Galactic Plane

The locations of young stellar OB associations and clusters and the HII regions that surround hot, massive young stars trace three (or four) spiral arms in the disc.

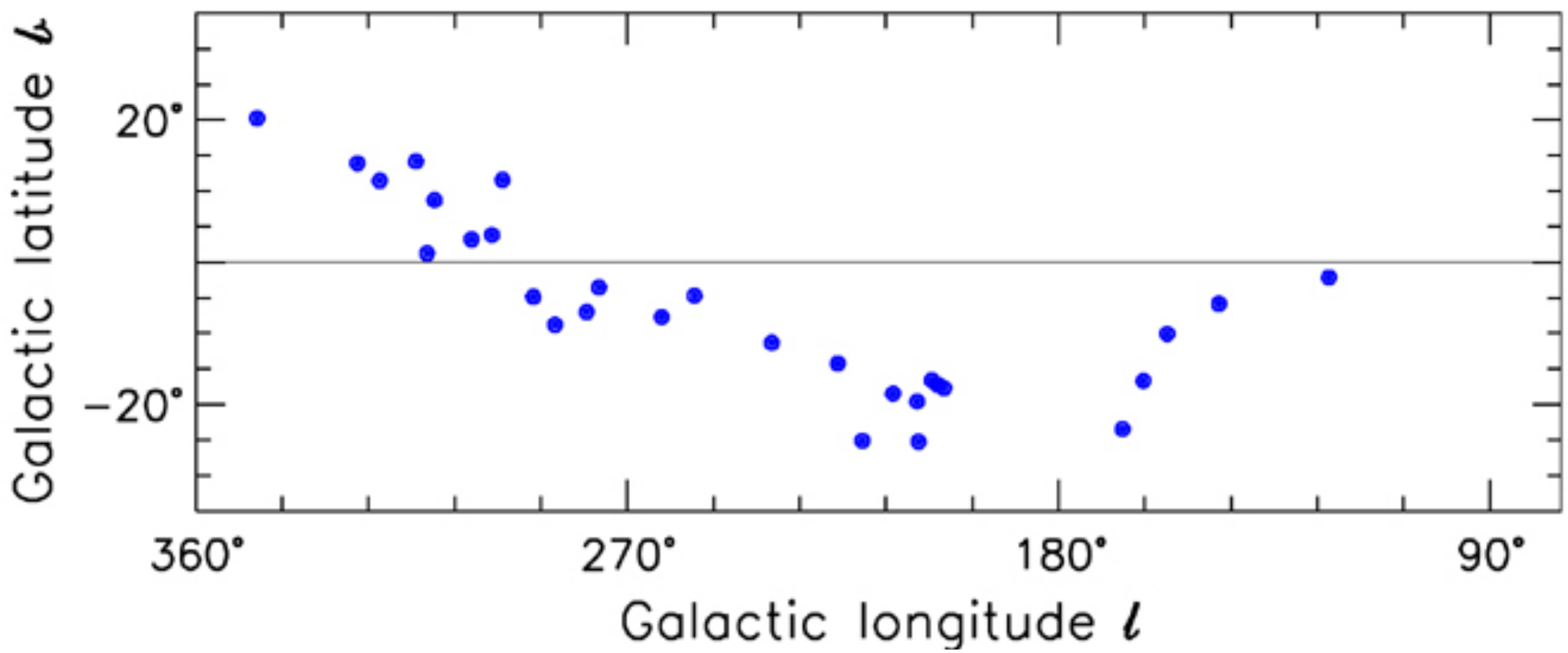






Young stars on the MW discs

within 500pc



The youngest stars (<30 Myr) – and the associations and clusters in which they form are found in a (partial) ring called "Gould's Belt" that is tilted by ~20° from the Galactic plane, with stars closer to the centre lying further off the plane

Figure 2.10, Sparke & Gallagher (2nd edition)

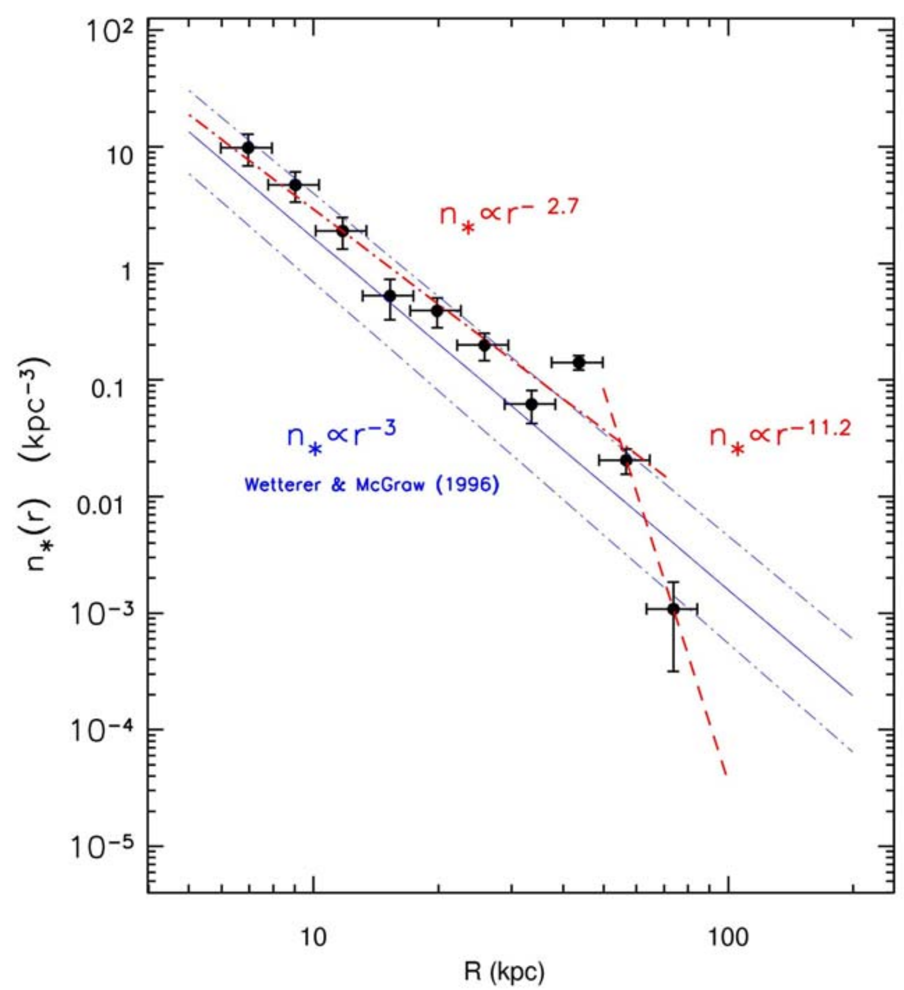
Stars in the MW halo

The Galactic stellar halo

Looking even farther out from the plane of the Galaxy, it appears that there is a sort of "truncation" of the disk into a much more tenuous stellar "halo"

The density profile of these stars is

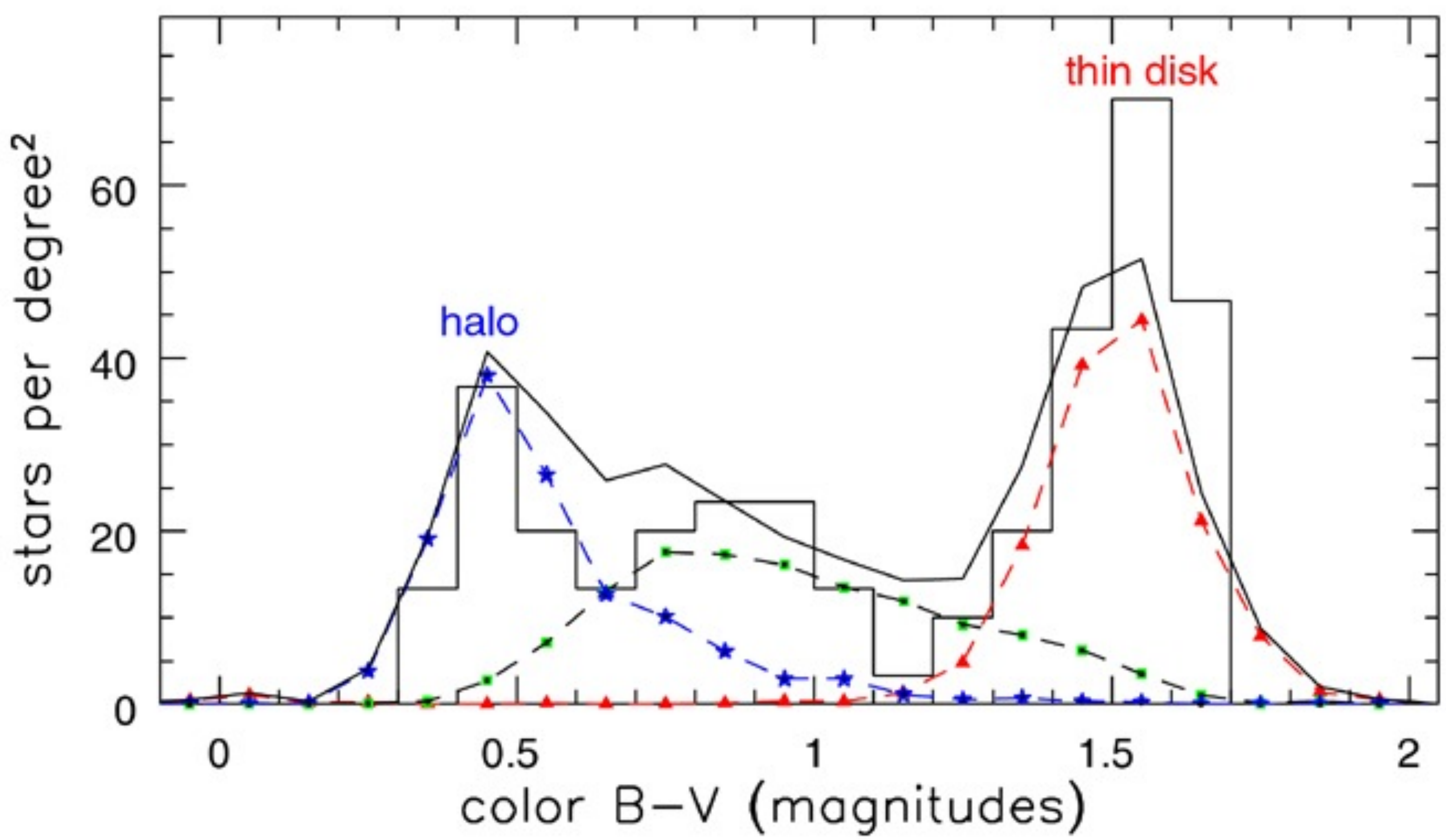
$$n(r) \approx n_0 (r/r_0)^{-3}$$



Properties of the Galactic stellar halo:

- extends to (at least) 80 kpc
- $L \sim 10^9\ L_\odot$ – about 1% of the total luminosity of the MW
- 0.2% of the thin disk's central density in the Solar neighborhood
- very concentrated: half-light radius ~3 kpc

Mapping the MW halo



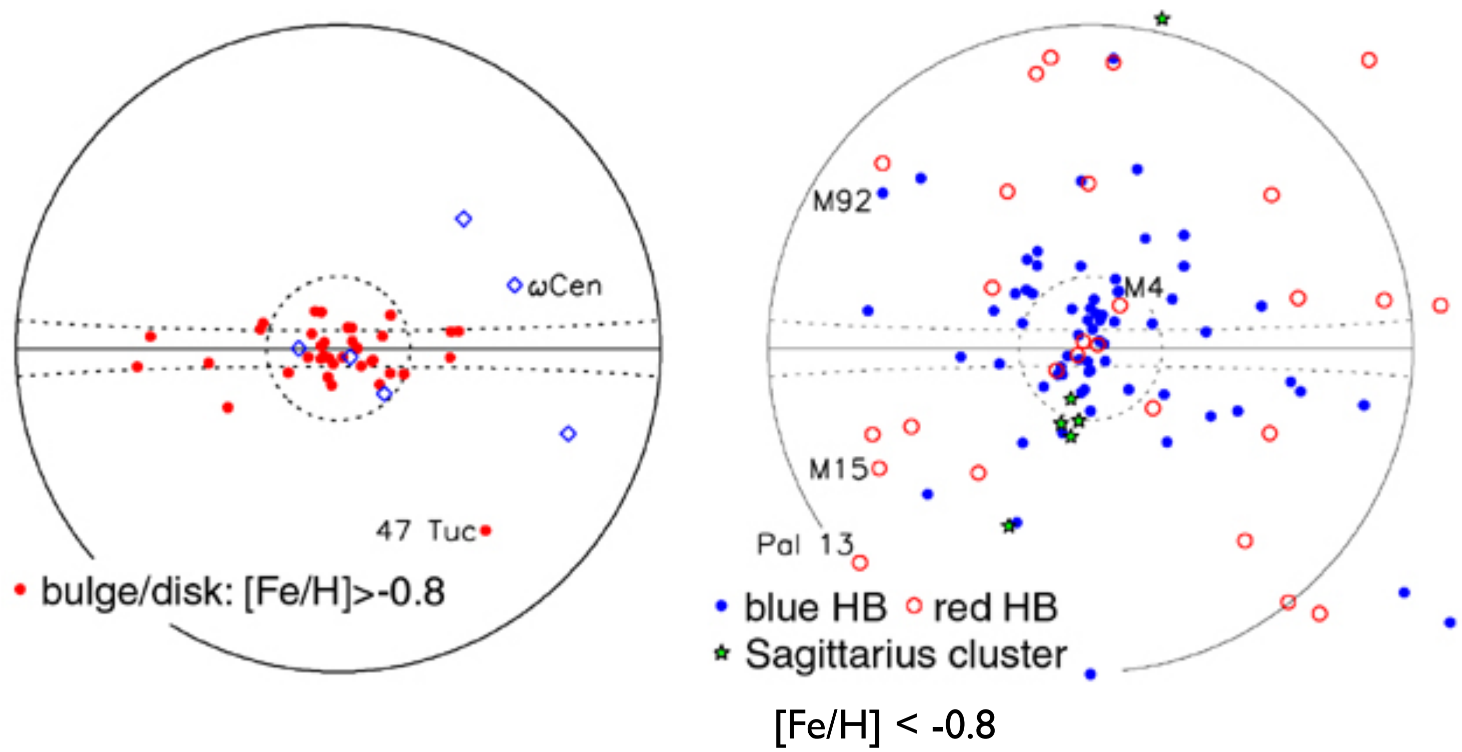
Numbers of stars at each $B - V$ color with apparent V magnitude $19 < m_V < 20$, per square degree at the north Galactic pole. The solid line shows the prediction of a model where 0.15% of stars near Sun belong to metal-poor halo: thin-disk stars (triangles) are red, halo stars (stars) are blue, and thick-disk stars (green squares) have intermediate colors – N. Reid.

Looking in a range of directions shows a slightly flattened but basically round stellar halo

Figure 2.16, Sparke & Gallagher (2nd edition)

The MW stellar halo

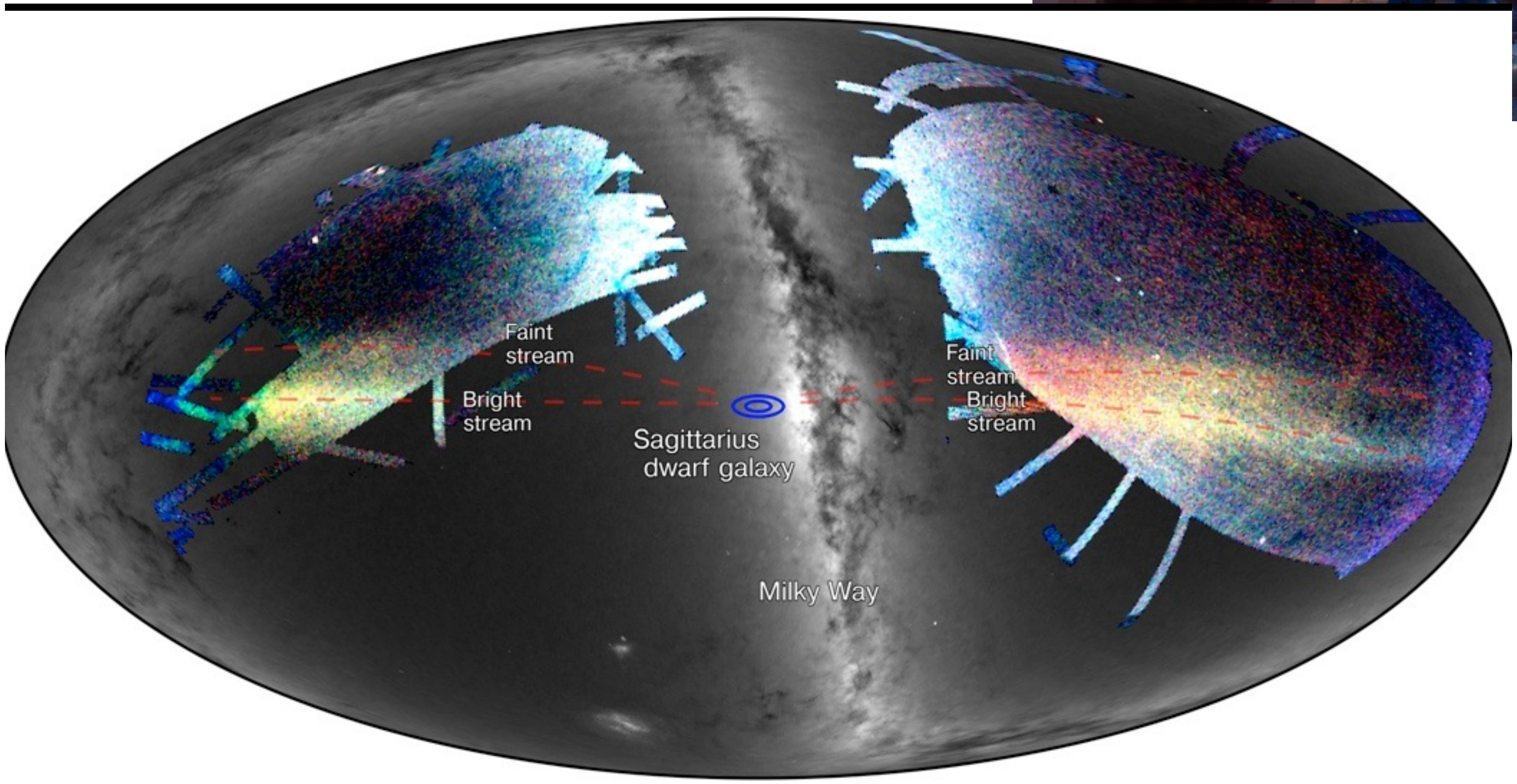
The stellar halo is very important for understanding the formation of the Milky Way, as the stars are generally very old and metal-poor. The stellar halo preserves the early formation history of the Galaxy, and we can see similar processes at work today.



Interestingly, the metal-poor globular clusters trace the halo distribution!

Figure 2.15, Sparke & Gallagher (2nd edition)

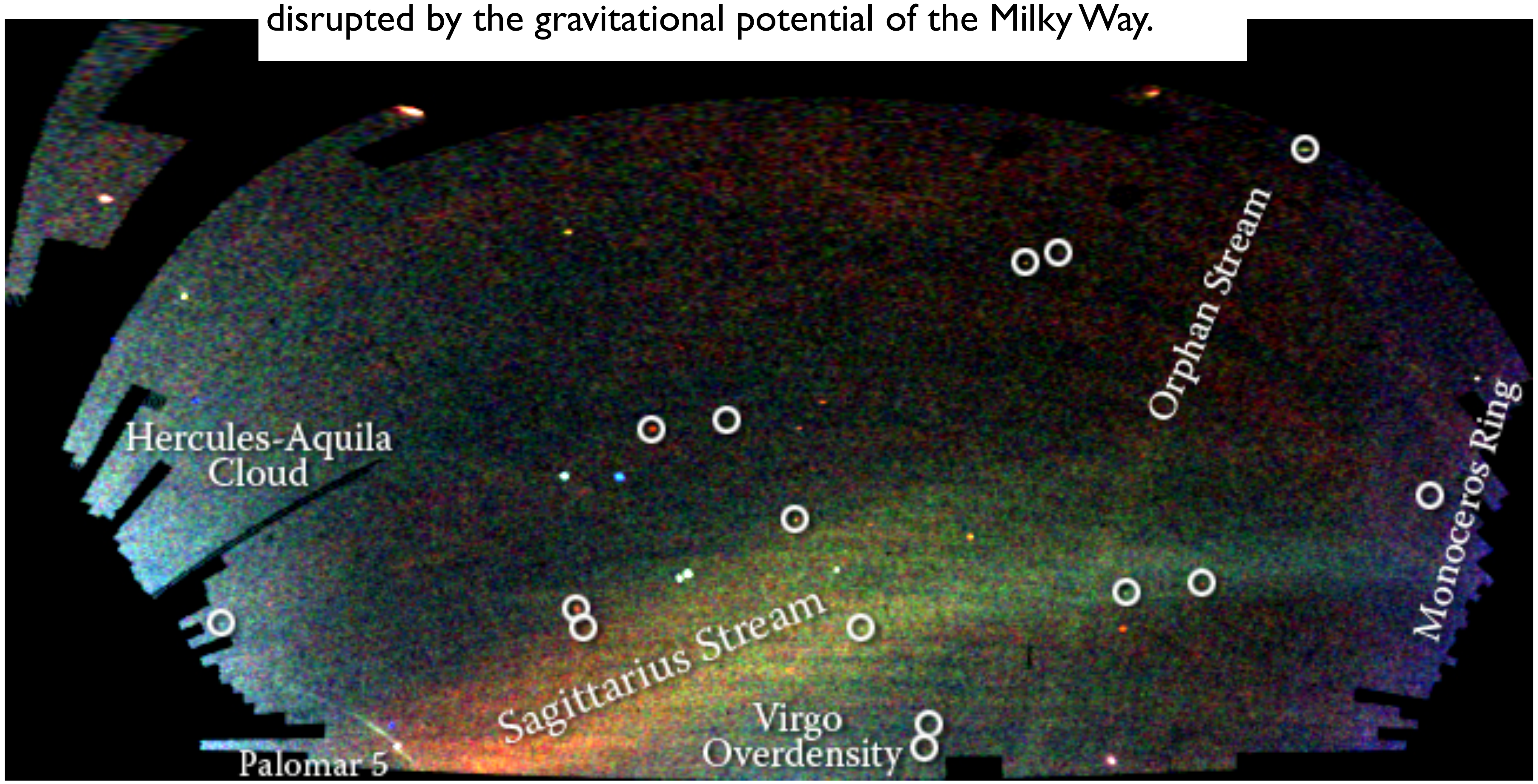
The ‘field of streams’



Credit: S. Koposov and the SDSS-III collaboration

The ‘field of streams’

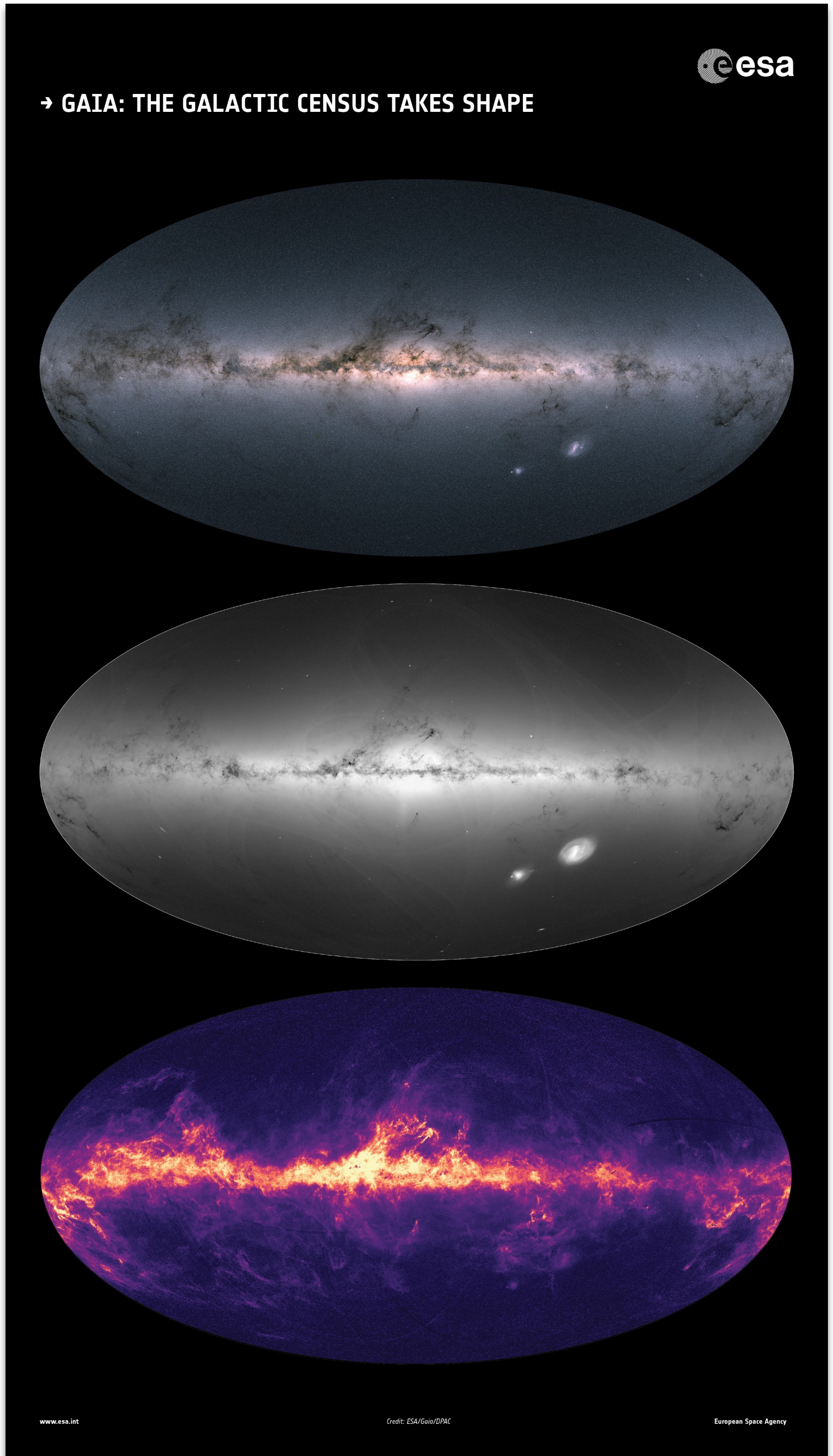
These are the remnants of objects (satellites, GCs) being disrupted by the gravitational potential of the Milky Way.



Belokurov et al. 2006

A map of stars in the outer regions of the Milky Way Galaxy, derived from the SDSS images of the northern sky, shown in a Mercator-like projection. The color indicates the distance of the stars, while the intensity indicates the density of stars on the sky. Structures visible in this map include streams of stars torn from the Sagittarius dwarf galaxy, a smaller 'orphan' stream crossing the Sagittarius streams, the 'Monoceros Ring' that encircles the Milky Way disk, trails of stars being stripped from the globular cluster Palomar 5, and excesses of stars found towards the constellations Virgo and Hercules. Circles enclose new Milky Way companions discovered by the SDSS; two of these are faint globular star clusters, while the others are faint dwarf galaxies.
Credit: V. Belokurov and the Sloan Digital Sky Survey.

New Gaia maps of the MW



1.7 billion stars in the 2nd data release (2018)

stellar total brightness

stellar number density

interstellar dust