THE STRUCTURE OF OUR GALAXY

Lezione I- Fisica delle Galassie

Binney & Merrifield (1998) Cap.1

Sparkle & Gallagher (2007), Cap. 2

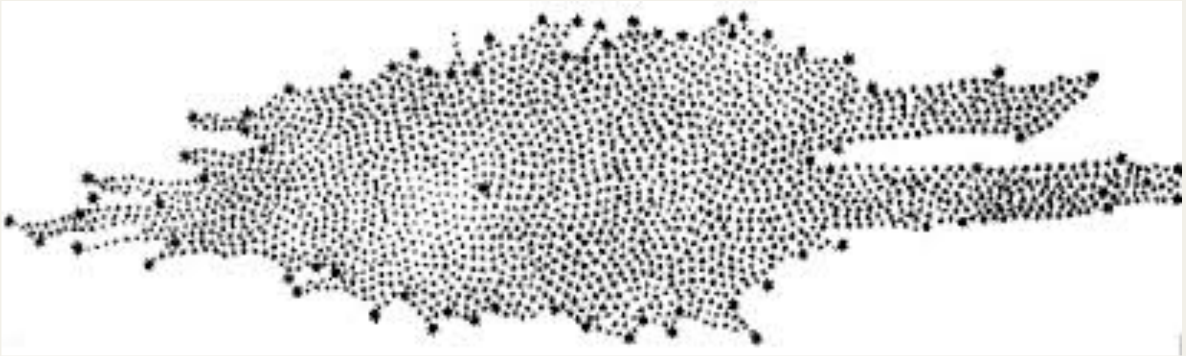
Laura Magrini

Naming system

- La Galassia (the Galaxy)
- Via Lattea (Milky Way) (MW)
- The components of the MW: the Plane, the Bulge, the Halo, etc.

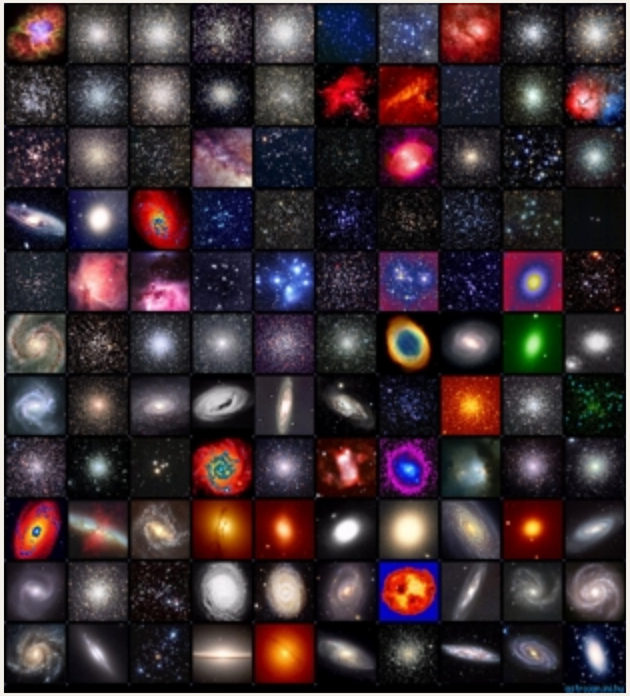
Historic Overview

- The term *Galaxy* derives from the Greek world *milk*
- The Romans called *Via Lactea* the bright stripe seen in the sky
- In 1610 the observations of Galileo demonstrated that it was composed by faint stars
- Kant in "*General Natural History and Theory of the Heavens*" (1755) pointed out that the structure of the MW was shaped by rotation and gravity, as in the Solar System
- The observations of William Herschel in the XVIII sec. produced the first map of the MW



William Herschel (1785)

Historic Overview



Catalogue of Messier

- The observations of Charles Messier produced the *Catalogue* of the 109 brightest nebulae in the Norther sky [from that Catalogue the naming system M, as M31 for Andromeda].

- The next catalogues of Dreyer (1888) *New General Catalogue* [NGC] and *Index Catalogue* [IC] and the studies of Huggins allowed to distinguish among stellar and nebular objects

The new telescope of Lord Rosse (1845) allowed more accurate images, and to observe, for the first time, 'spiral nebulae'

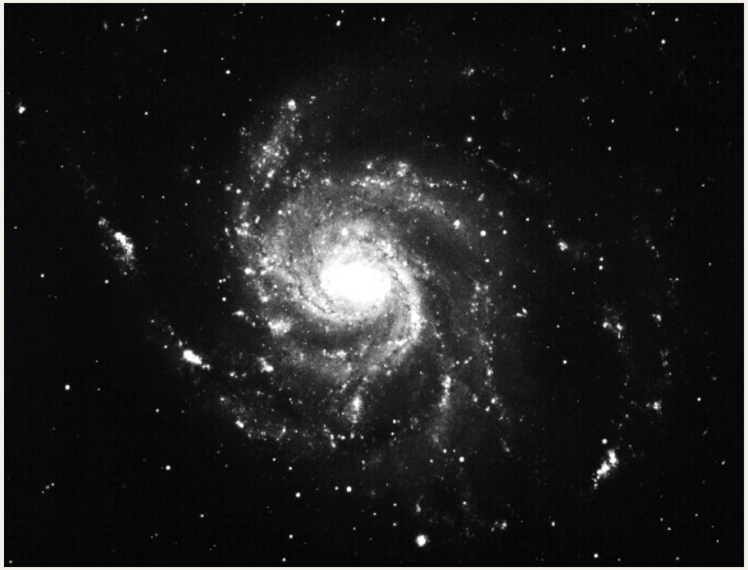
M51 observed by Lord Rosse with his 72-inch telescope

Island Universe

- Connection between resolved objects in the MW and their distribution in a Plane→ with "spiral nebulae" with resolved components (stars, nebulae, etc,)

Fig. 447.

M101 observed by Lord Rosse, with his 72-inch telescope



M101 observed with a small modern telescope

M101 is the first object identified as 'spiral nebula'

Large, spiral, faintish; several arms and knots. 14' diameter at least.

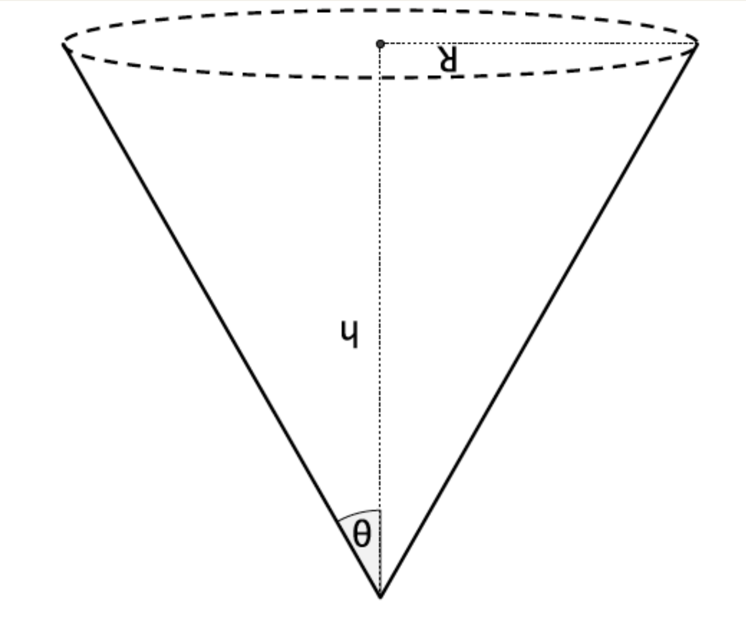
Photometric models of the MW

Star gauging: technique adopted by W. Herschel to determine the shape of the MW

- It consists in measuring the number of stars in different direction of the sky, under the following **assumptions:**

1. **Stars are distributed more or less uniformly** with the MW system and they are not found beyond the boundaries

2. The telescope is capable of **resolving all stars** in the cone visible from the telescope, with aperture 2 ϑ and height h (edge of the MW in that direction)



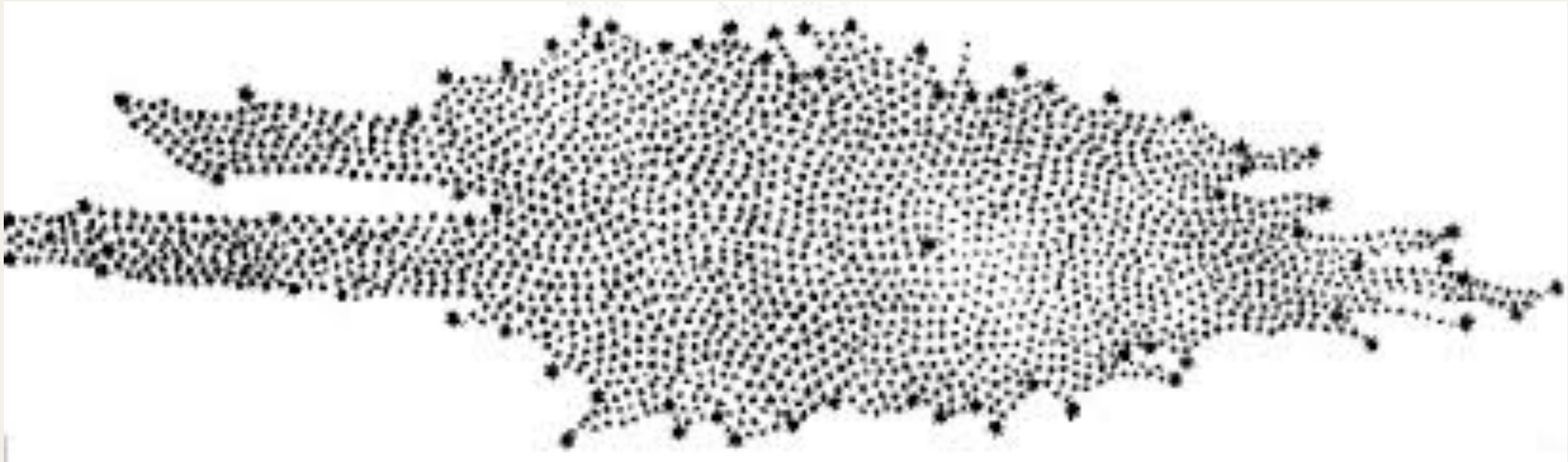
$$V = 1/3\, \pi\, h^3 \tan^2 \vartheta$$

Under assumption 1., V is proportional to the number of stars N:

$$\mathbf{h = \sqrt[3]{(3\, N / \pi\ \tan^2 \vartheta)}}$$

h is expressed in 'stellar units', the average distance between neighbouring stars

Photometric models of the MW



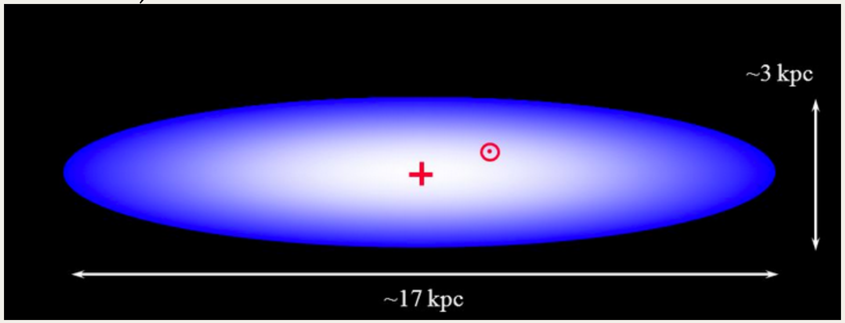
- The cross-section of the MW is roughly elliptical in shape
- It is much more extended along the Galactic plane
- A great cleft is observed in the direction the constellation Aquila → dust lines
- The Sun is located around the centre of the distribution

The models of **Kapteyn** and of Shapley

- Jacobus Kapteyn (1851-1922) → studied parallaxes and proper motions of stars, derived their distances, made a complete 3D map of stars in space

- **Kapteyn Universe:** the Sun is located close to the centre of an approximatively oblate spheroidal distribution of stars, which extends about five times in the plane, with the density of stars dropping towards the outskirts

- Problems:
  - Interstellar medium was not considered → incorrect distance scale
  - First attempt to consider the **reddening** due to Rayleight scatter (more efficient fro blue light than for red light) → **the effect of Rayleight scatter is negligible**
  - Interstellar dust produces absorption (not scatter), which has a different effect on distance scale (studied for the first time by Robert Trumpler (1930) with his analysis of the size-distance relationship in open clusters)



The models of Kapteyn and of **Shapley**

- Harlow Shapley (1885-1972) → studied the distribution of globular clusters located around the Plane, measured their distance with variable stars
- **Shapley Universe**

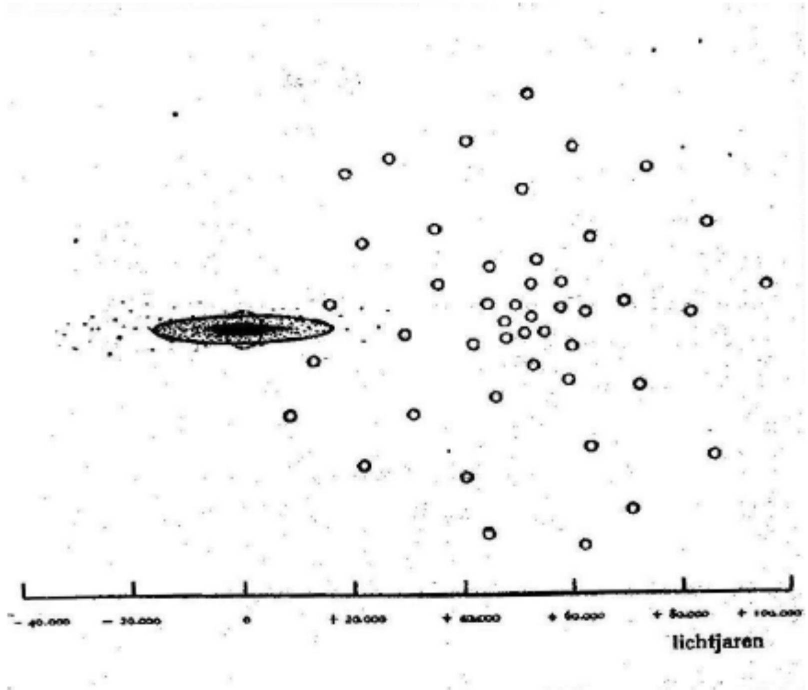


Fig. 1 Oort's illustration of the discrepancy of the Kapteyn Universe and Shapley's system of globular clusters. It appeared in de Sitter;s book 'Kosmos'.

- The **distribution of globular clusters is not uniform**, but there are concentrated towards Sagittarius**→ the gravitational centre of the MW**
- The distance scale of Shapley Universe is very huge
- Interstellar absorption is not considered

The Great Debate (1920)

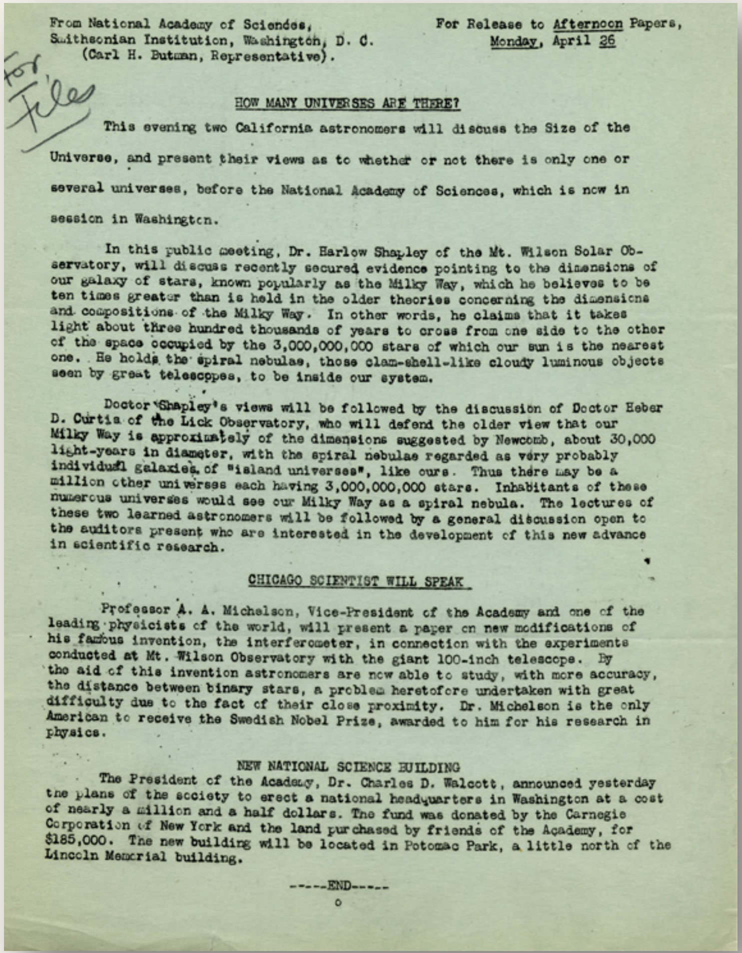
Herbert Curtis vs Harlow Shapley

Are 'spiral nebulae' other Island Universe? Or are they part of the Milky Way?

With the discovery of Cepheid variable stars in M31, Hubble thanks to the relationship between their luminosity and their period could measure their distance

→ M31 was at a distance of about 300 kpc, thus it could not be inside the MW

The Milky Way is only one galaxy amongst others!



From National Academy of Sciences,
Smithsonian Institution, Washington, D. C.
(Carl H. Butman, Representative).

For Release to Afternoon Papers,
Monday, April 26

For Files

HOW MANY UNIVERSES ARE THERE?

This evening two California astronomers will discuss the Size of the Universe, and present their views as to whether or not there is only one or several universes, before the National Academy of Sciences, which is now in session in Washington.

In this public meeting, Dr. Harlow Shapley of the Mt. Wilson Solar Observatory, will discuss recently secured evidence pointing to the dimensions of our galaxy of stars, known popularly as the Milky Way, which he believes to be ten times greater than is held in the older theories concerning the dimensions and compositions of the Milky Way. In other words, he claims that it takes light about three hundred thousands of years to cross from one side to the other of the space occupied by the 3,000,000,000 stars of which our sun is the nearest one. He holds the spiral nebulae, those clam-shell-like cloudy luminous objects seen by great telescopes, to be inside our system.

Doctor Shapley's views will be followed by the discussion of Doctor Heber D. Curtis of the Lick Observatory, who will defend the older view that our Milky Way is approximately of the dimensions suggested by Newcomb, about 30,000 light-years in diameter, with the spiral nebulae regarded as very probably individual galaxies of "island universes", like ours. Thus there may be a million other universes each having 3,000,000,000 stars. Inhabitants of these numerous universes would see our Milky Way as a spiral nebula. The lectures of these two learned astronomers will be followed by a general discussion open to the auditors present who are interested in the development of this new advance in scientific research.

CHICAGO SCIENTIST WILL SPEAK

Professor A. A. Michelson, Vice-President of the Academy and one of the leading physicists of the world, will present a paper on new modifications of his famous invention, the interferometer, in connection with the experiments conducted at Mt. Wilson Observatory with the giant 100-inch telescope. By the aid of this invention astronomers are now able to study, with more accuracy, the distance between binary stars, a problem heretofore undertaken with great difficulty due to the fact of their close proximity. Dr. Michelson is the only American to receive the Swedish Nobel Prize, awarded to him for his research in physics.

NEW NATIONAL SCIENCE BUILDING

The President of the Academy, Dr. Charles D. Walcott, announced yesterday the plans of the society to erect a national headquarters in Washington at a cost of nearly a million and a half dollars. The fund was donated by the Carnegie Corporation of New York and the land purchased by friends of the Academy, for $185,000. The new building will be located in Potomac Park, a little north of the Lincoln Memorial building.

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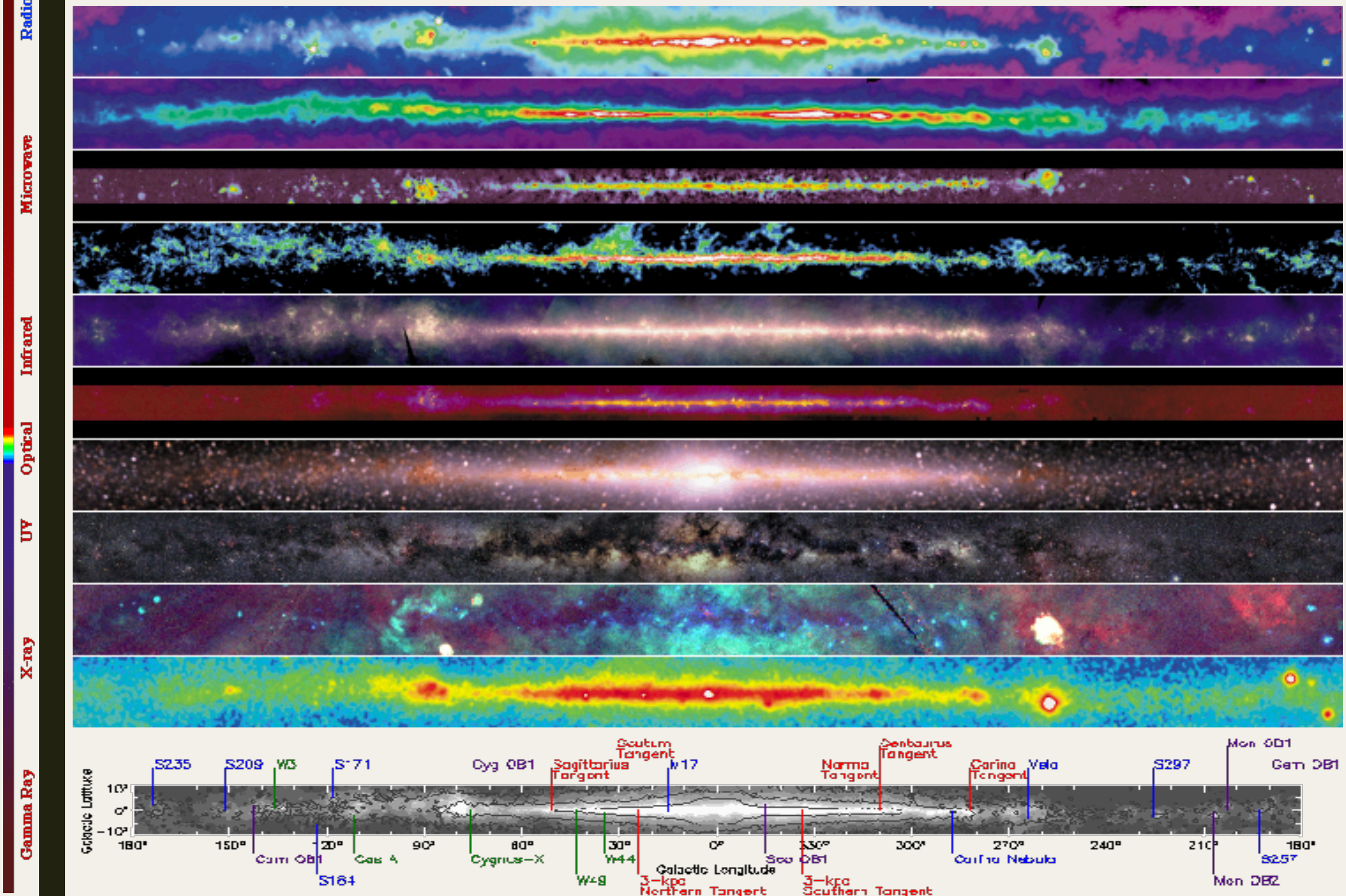
A Galaxy from inside

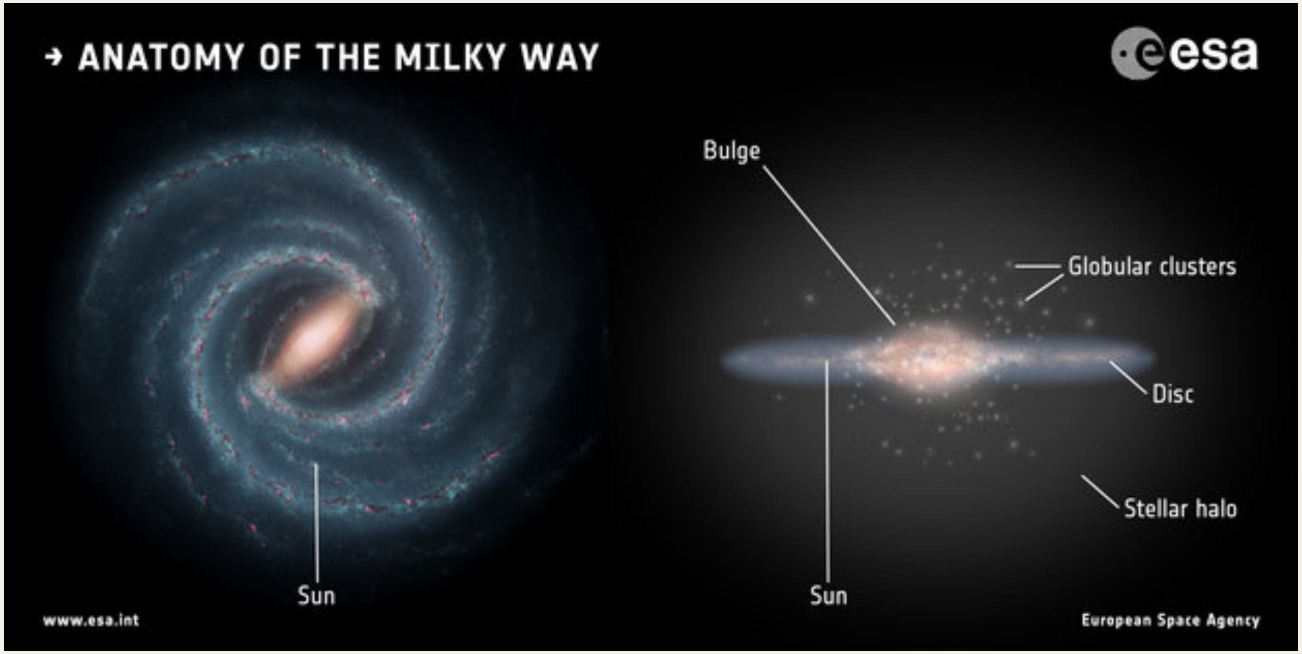


https://asd.gsfc.nasa.gov/archive/mwmw/mmw_images.html

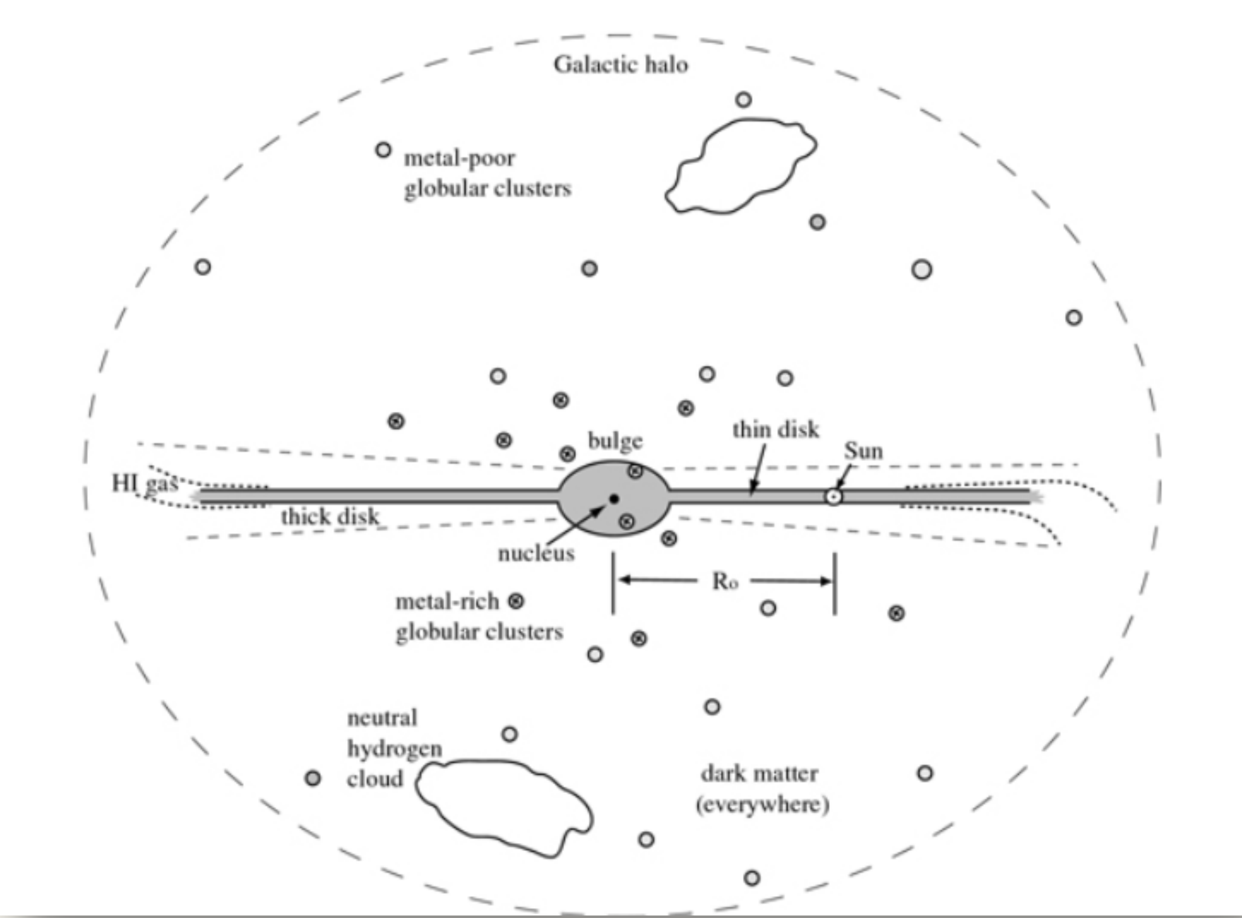
The aim is of these lectures:

→ to understand the structure of the Galactic components

→ their relationships with mechanisms of galaxy formation

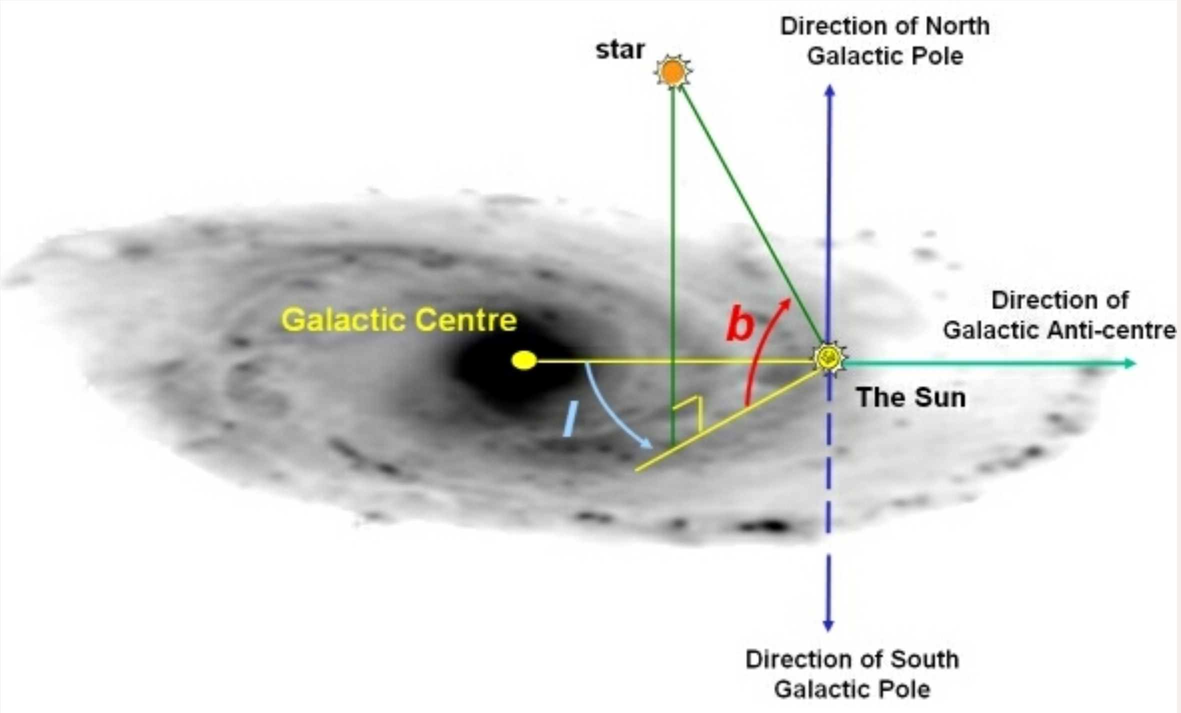


The Milky Way galaxy: an overview



A schematic side view of the Milky Way
(from Galaxies in the Universe) – Sparke & Gallagher

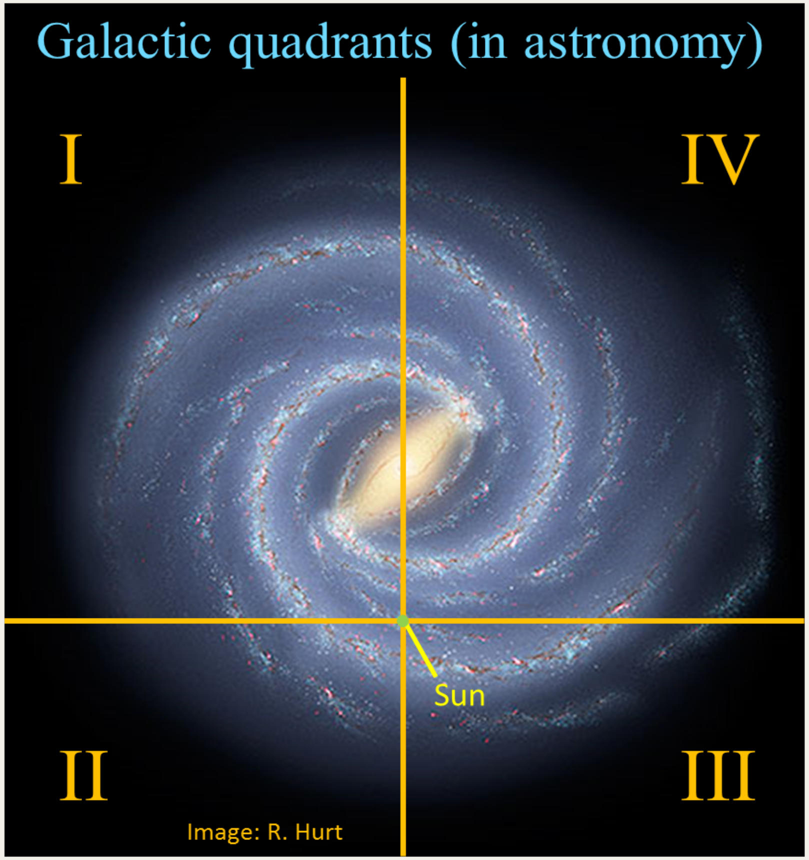
The Galactic Coordinate system

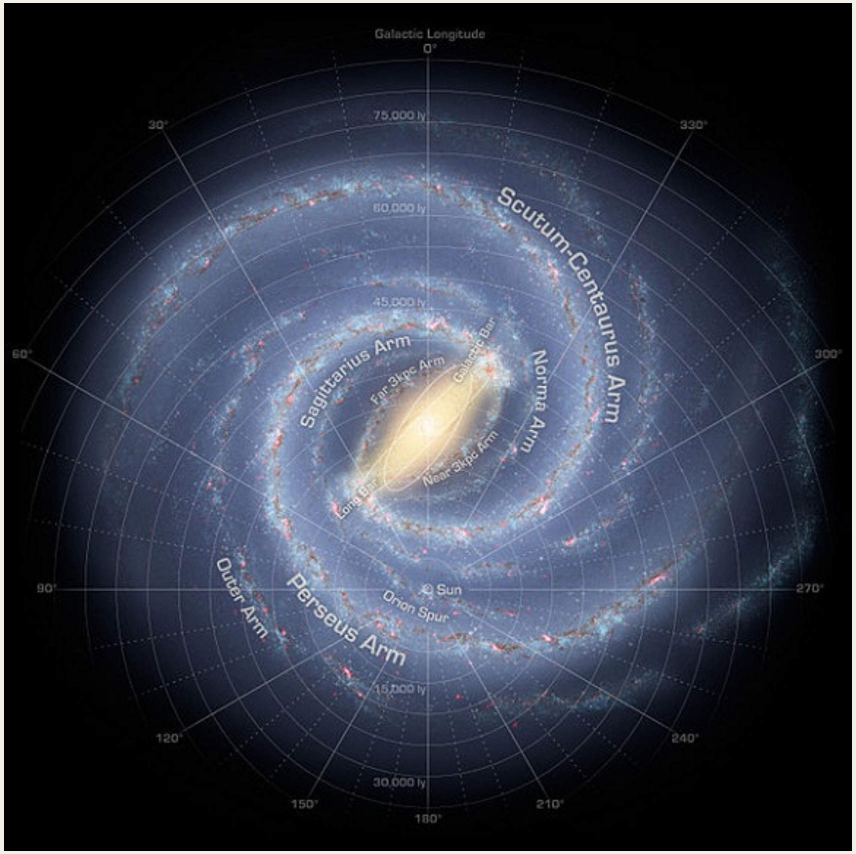


System of coordinates with a physical direct connection with the structure of the MW:

- The galactic longitude *l* of an object is the angular distance from the Galactic Centre, which is at $l = 0^0$. It increases counter-clockwise as viewed looking down from the North Galactic Pole (NGP) from 0° to 360°.
- The Galactic latitude b is the angle of the star from the Galactic plane towards NGP (from -90° to +90° (below and above the Galactic plane respectively)

Finding your way in the Milky Way





How determine the shape and structure of Milky Way from an internal point of view?

- Stellar density
- Distances
- Radial velocities and proper motions
- Chemical composition
- Ages
- …

For as many stars as possible belonging to the different components

(Here we mainly focus on the stellar component)

The components of the MW:

1. The Disc

The stellar Disc(s):

- about **15 kpc in radius**, with the Sun located at 8 kpc from the Galactic Centre
- **Thin Disc**: 95% of the stars in the Disk, with a typical height of **300-400 pc**
- **Thick Disc**: 5% of the stars, with a height of about **1kpc**

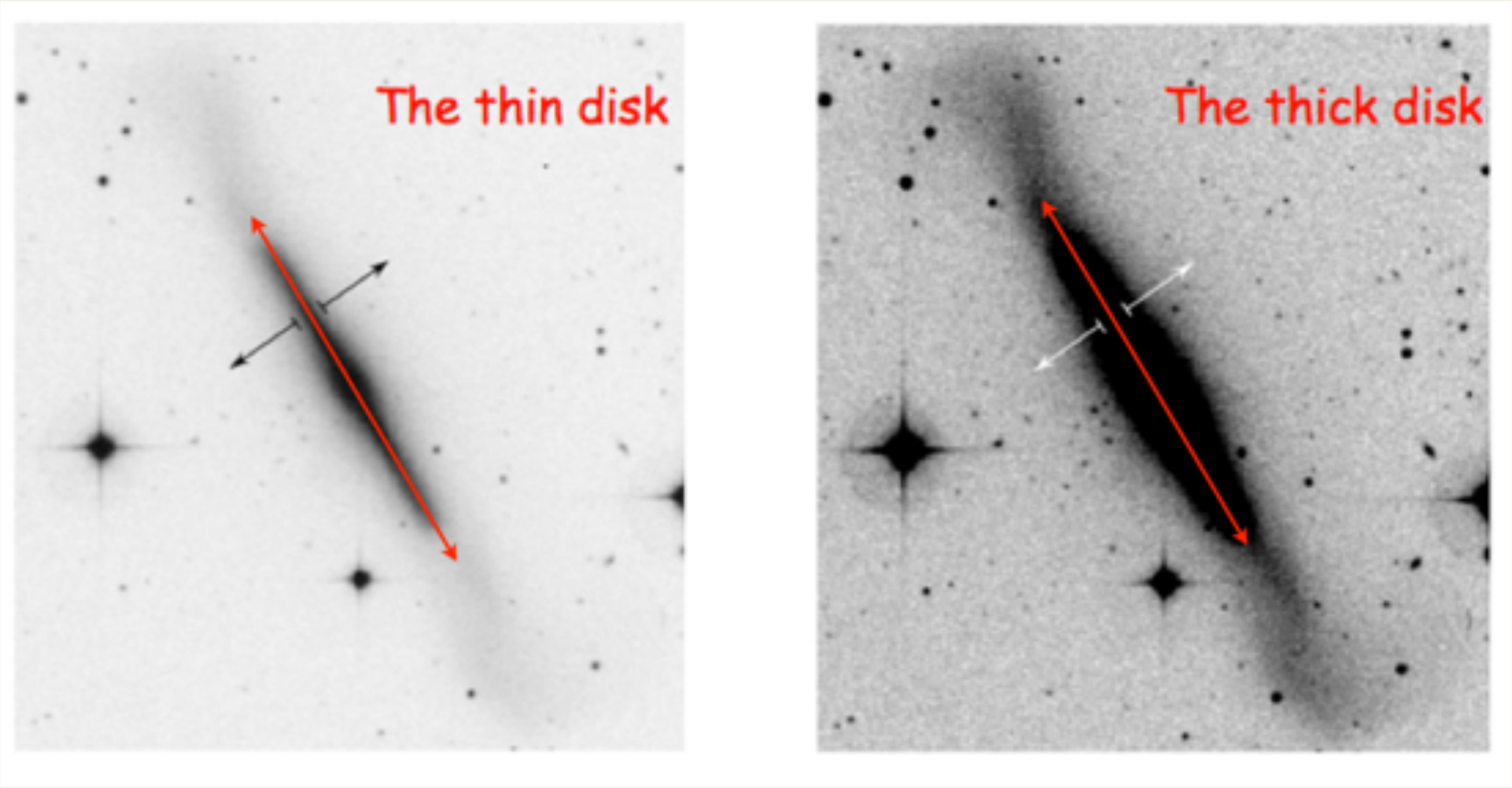
The gaseous disc:

- The gas and dust lie in a very thin layers of about 100 pc

Stars in the disc orbit around the Galactic center at about 200 km s^{-1}, so the Sun takes roughly 250 Myr to complete its orbit. They follow nearly circular orbits.

The luminosity of the Disc $L=(15–20) \times 10^9 L_{\odot}$, and the mass in stars is around $60 \times 10^9 M_{\odot}$

Thin and thick discs: common features of galaxies



NGC 4762 - a disk galaxy with a bright thick disk (Tsikoudi 1980). Deeper exposure reveals a thicker disk component, as extended as the thin one. Red line has the same length in both panels.

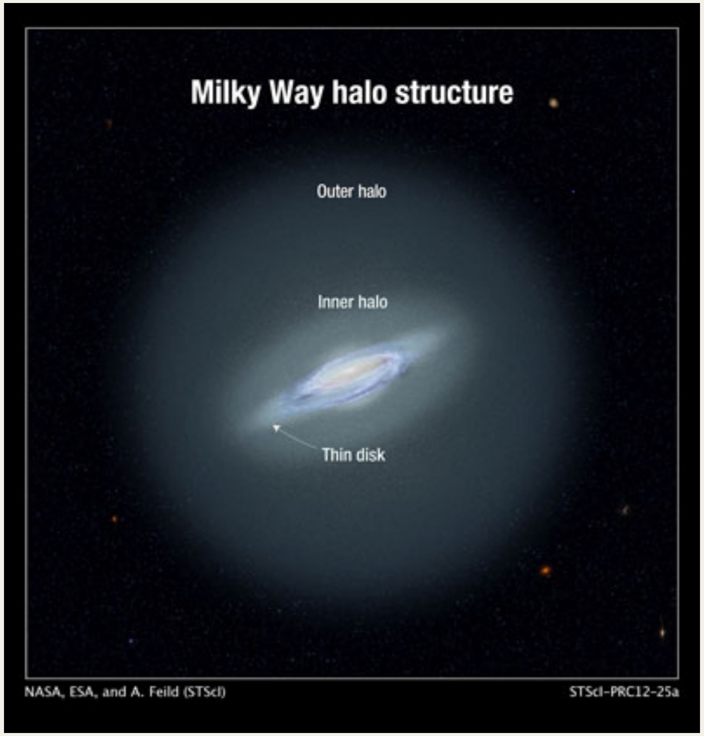
The components of the MW:

2. The Halo

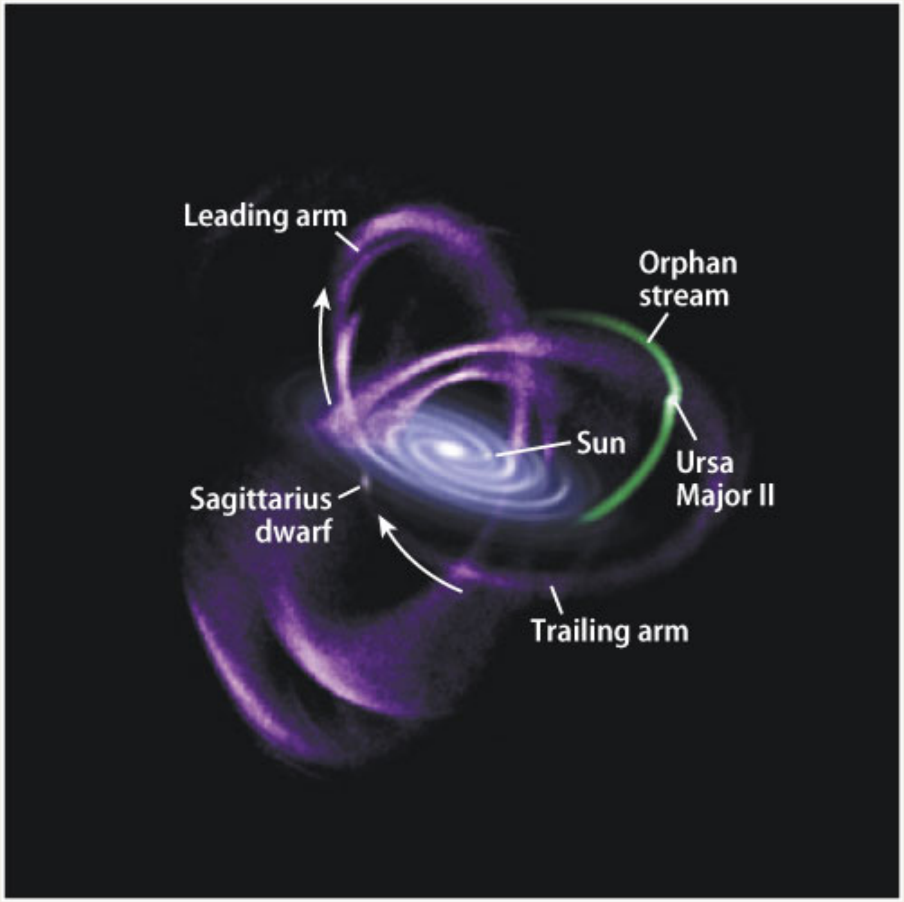
- Stars in the Galactic Halo are only a few percent of the Galaxy mass, about 1 x $10^9 M_\odot$

- Composed by old and metal poor stars

- Stars and globular clusters of the metal-poor halo do not have any organized rotation around the center of the Galaxy.



Stellar halo: remnants of the past merger history



The distribution of stars in the Milky Way's halo is not smooth, but shows evidence for stellar streams.

The components of the MW:

3. The Bulge

- The central Bulge: few kpc in radius

- At its center there is a dense nucleus of stars (central star cluster) and a black hole with mass $M_{BH} \approx 4 \times 10^6 M_\odot$

- Bulge stars have larger random velocities, but follow a general rotation.

- The luminosity of the Bulge $L = 5 \times 10^9 L_\odot$, and the mass in stars is around $20 \times 10^9 M_\odot$

The vertical stellar densities in the Galactic Disc(s): characterising the Galactic components

The stellar density of stars of a particular type S, **n(R, z, S),** in the Disc can be approximated with with a double exponential:

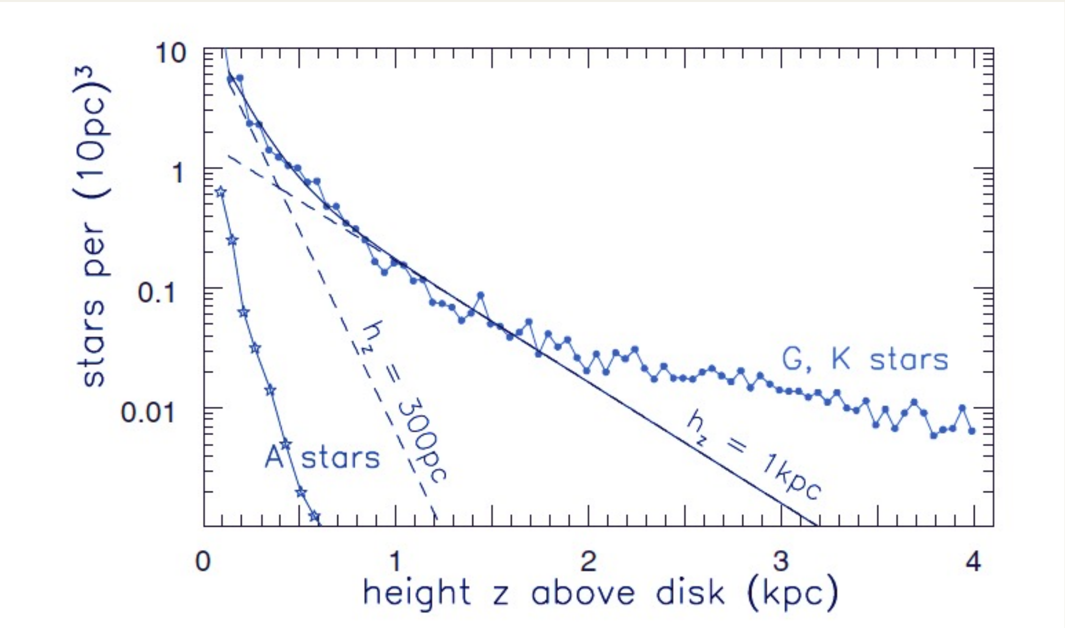
$$n(R, z, S) = n(0, 0, S) \exp[-R/h_R(S)] \exp[-|z|/h_z(S)]$$

where h_R is called the scale length of the disk and h_z is the scale height.

Near the mid-plane, $h_z \approx$ 300–350 pc for K dwarfs, while for more massive and shorter-lived stars, such as the A dwarfs, it is smaller, h_z <200 pc.

The stellar density in the Galactic Disc(s):

At z > 2 kpc G, K stars belong to the Halo



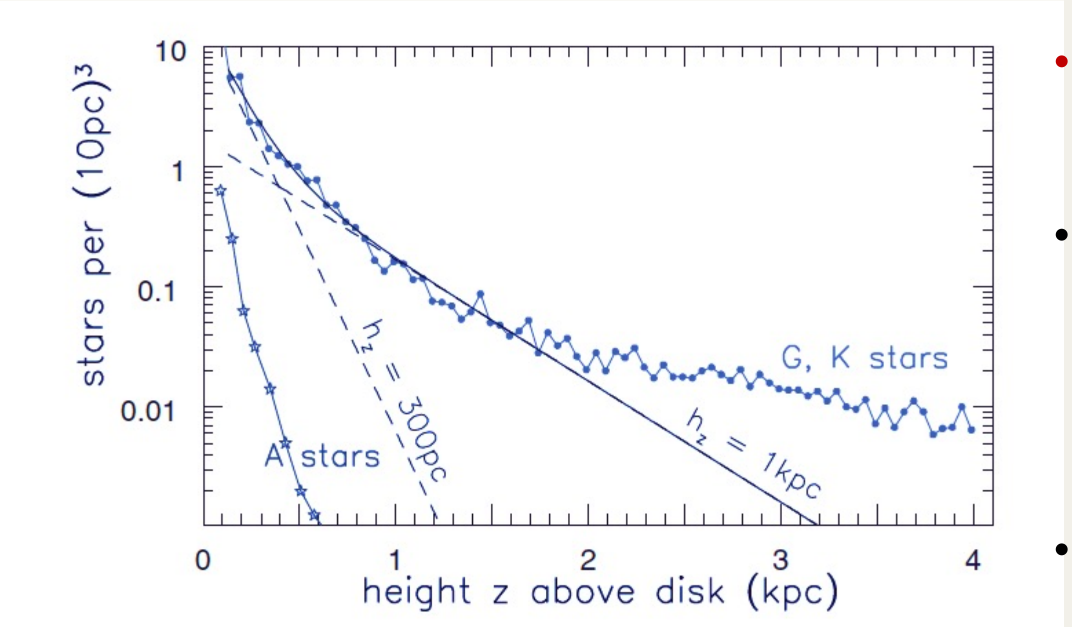
Vertical density:

- On the South Pole direction (outside the Plane)
- **Density of G,K stars (old, low mass)**
- **Density of A type stars (young, massive)**
- Sloping dashed lines show n(z) ∝ exp(−z/300 pc) (**thin disk**) and n(z) ∝ exp(−z/1 kpc) (**thick disk**)

Young stars are very close to the Plane, with heights smaller than the typical height of the thin disc

- At z < 2 kpc G, K stars belong to the Thin and to Thick Discs
- At z > 2 kpc, they have constant density

The stellar density in the Galactic Disc(s):



A single exponential law cannot fit the vertical distribution of stars:

- **Evidence of the presence of several distributions of stars**
- Height scales:
  - Thin disc ~ 300 pc
  - Thick disc > 1000 pc
  - Halo > 2000 pc
- Characterized by different type of stars:
  - Young/massive in the thin disc
  - Old/low mass in the thick disc and halo

Scales h_z of the Galactic components

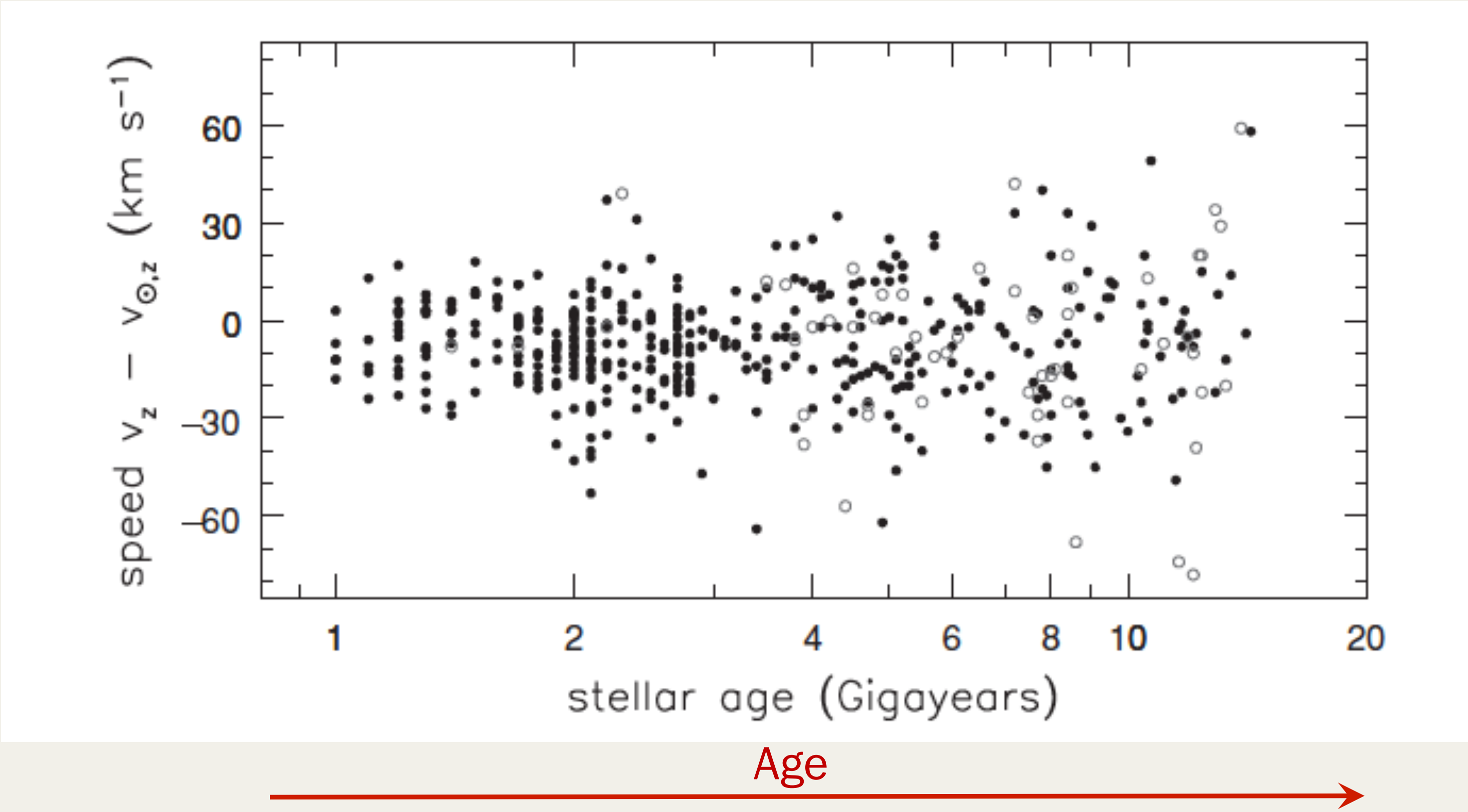
Galactic component	*h_z or shape*
HI gas near the Sun	130 pc
Local CO, H_2 gas	65 pc
Thin disk: $Z > Z_\odot/4$	(Figure 2.9)
$\tau < 3$ Gyr	≈ 280 pc
$3 < \tau < 6$ Gyr	≈ 300 pc
$6 < \tau < 10$ Gyr	≈ 350 pc
$\tau > 10$ Gyr	
Thick disk	0.75–1 kpc
$\tau > 7$ Gyr, $Z < Z_\odot/4$	(Figure 2.9)
$0.2 \lesssim Z/Z_\odot \lesssim 0.6$	
Halo stars near Sun	$b/a \approx 0.5$–0.8
$Z \lesssim Z_\odot/50$	
Halo at $R \sim 25$ kpc	Round

Age

Increasing h_z with age of the population:

- At the beginning the Disc is very thin (gaseous disc), then stellar orbits are perturbed
- Orbits are disturbed by the gravitational force of giant molecular clouds ($10^7 M_\odot$) and by clumps of stars and gas in the spiral arms
- This increases both their in-and-out motion in radius and their vertical speed

Vertical velocity component:



Increasing v_z with age of the population:

- The velocity perpendicular to the Galactic Plane increases with the age of the star
- Older stars tend to move faster; the average velocity is negative

Characteristics of the Thick disc:

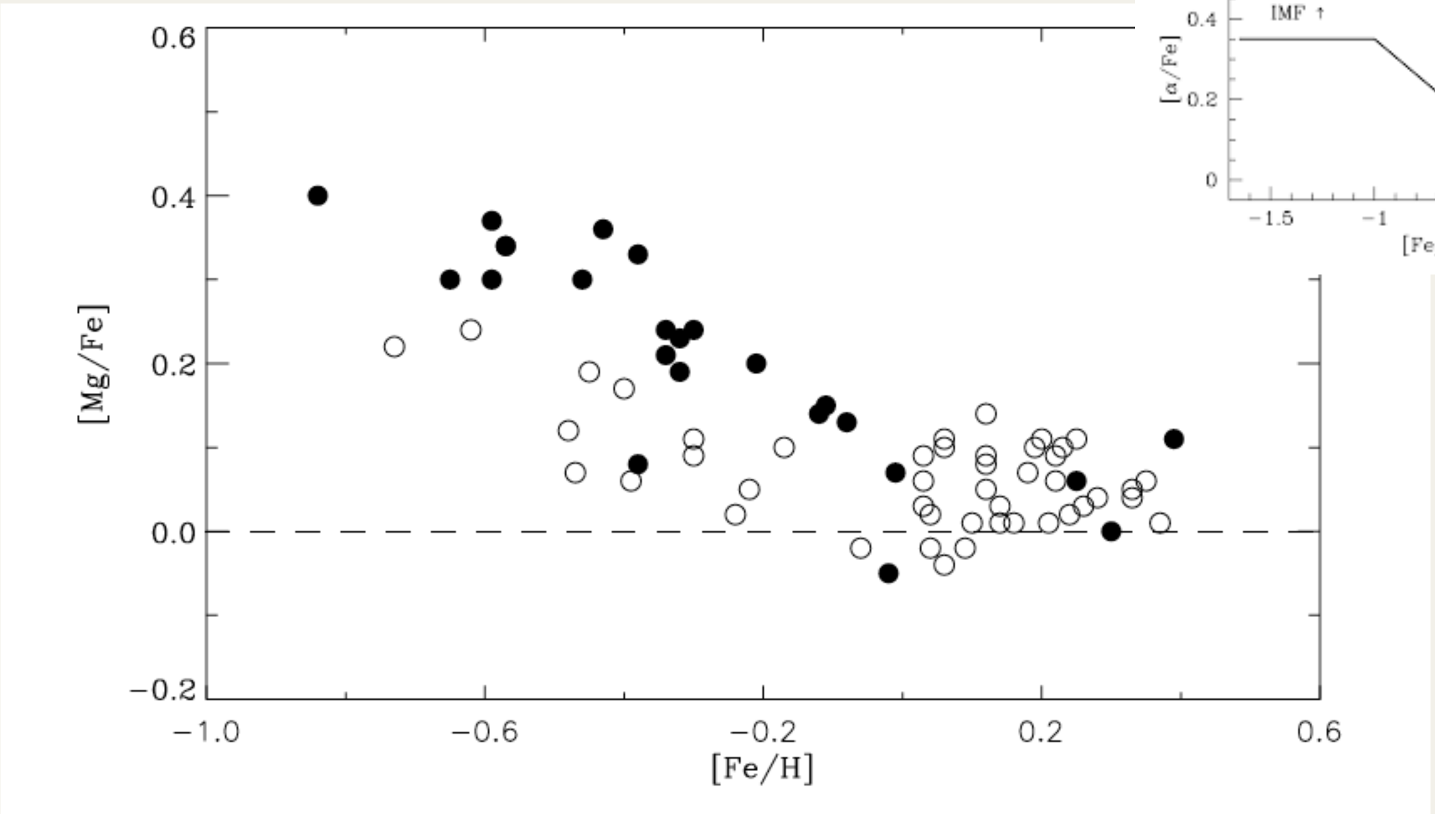
Evidence of the presence of a Galactic thick disc was first presented by Gilmore & Reid (1983), from the different vertical density of old and young stellar populations.

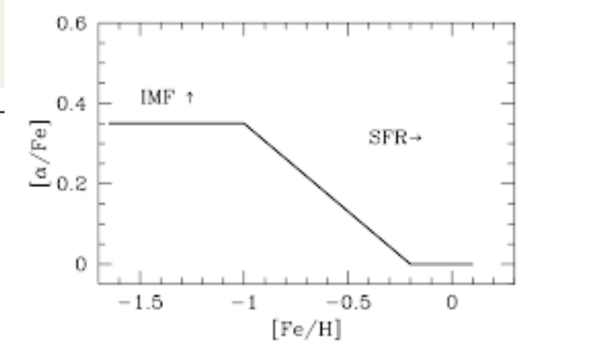
Subsequent observational studies have established that the thick disc stellar population:

- is a kinematically hotter population
- rotates more slowly than the Thin Disc
- is mainly an old stellar population
- has different chemical properties, with higher [α/Fe] ratios at a given metallicity

(See Bensby et al. 2003, 2005, 2007b; Reddy et al. 2006; Fuhrmann 2008).

Characteristics of the Thick disc:





Chemical dichotomy of the Discs

The stellar Halo of the Milky Way

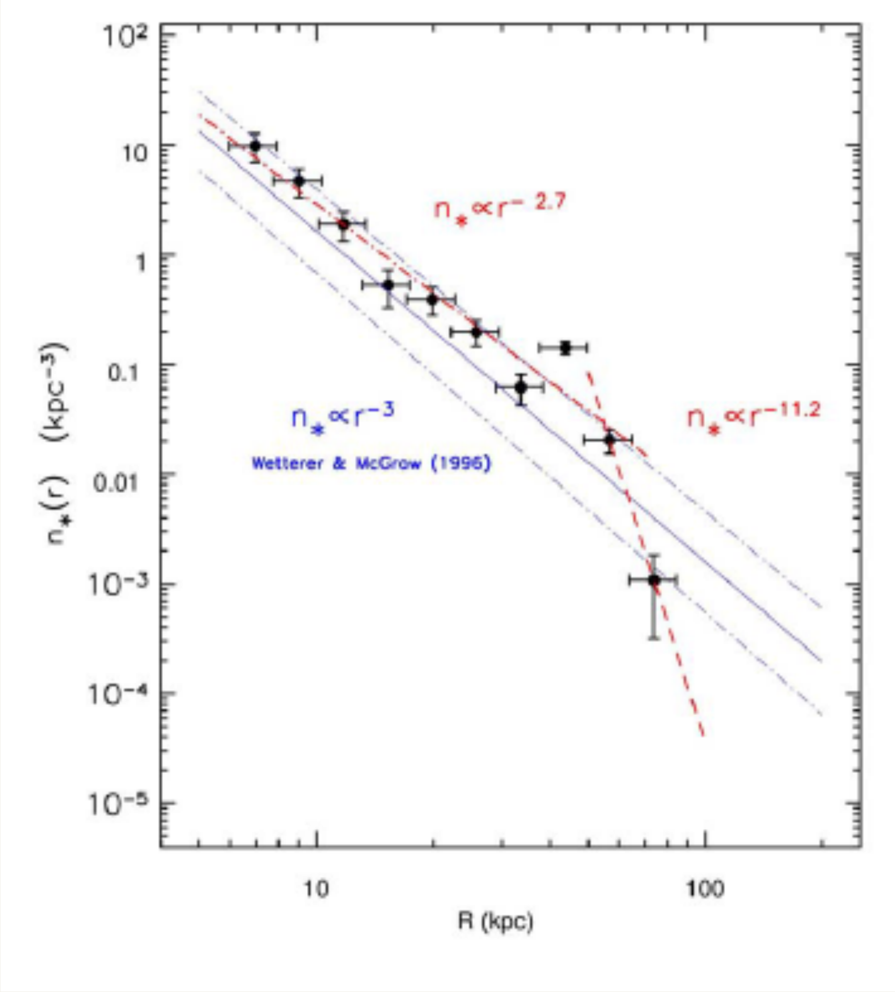
The Galactic Plane is surrounded by a tenuous stellar “halo”.

The density profile of the halo stellar population:

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

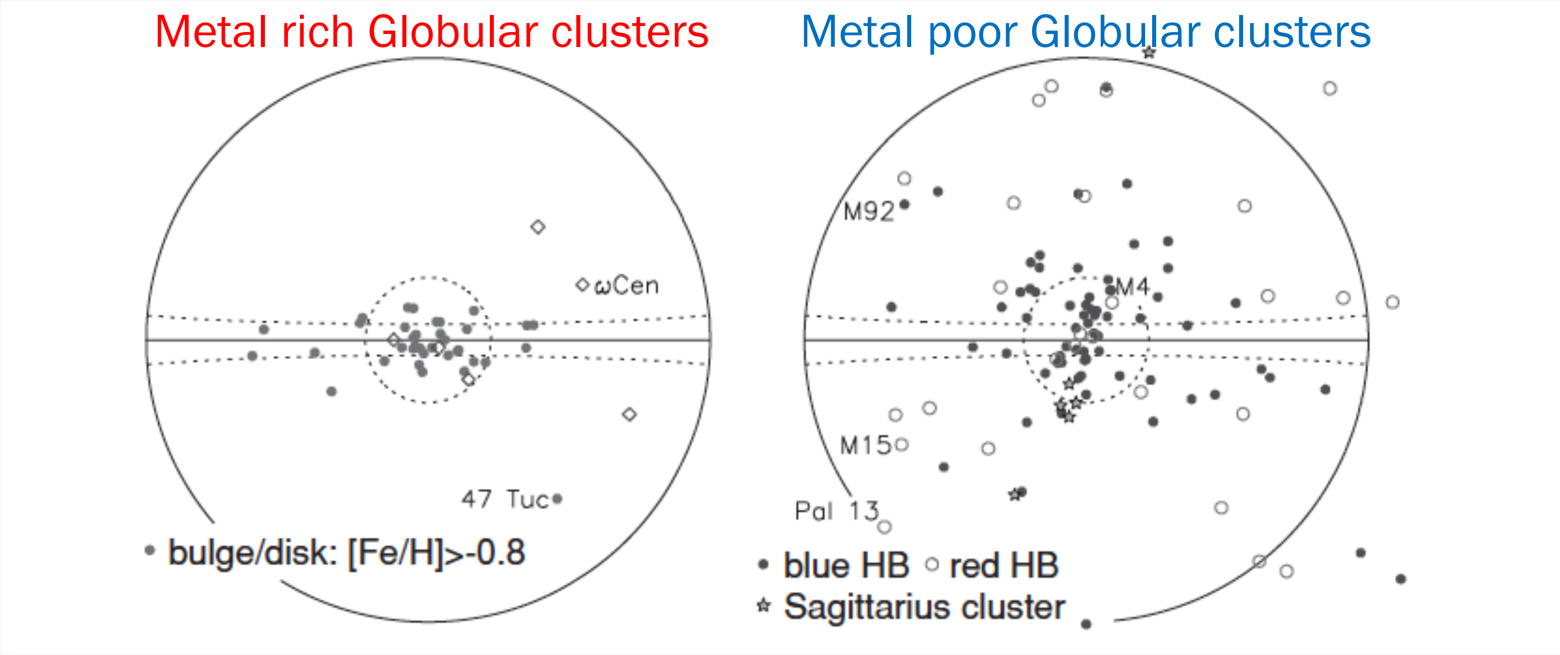
Properties of the Galactic stellar halo:

- 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 disc at the Solar neighborhood
- very concentrated: half-light radius ~3 kpc



Adapted From Lecture 7, PoG, E. Tolstoy

The stellar Halo of the Milky Way



Stars are made from dense gas clouds, the central part of the Halo should be the denser ones: oldest (metal poorest) [stars should be in its dense center].

Instead, they are in the halo globular clusters, its most extended component.

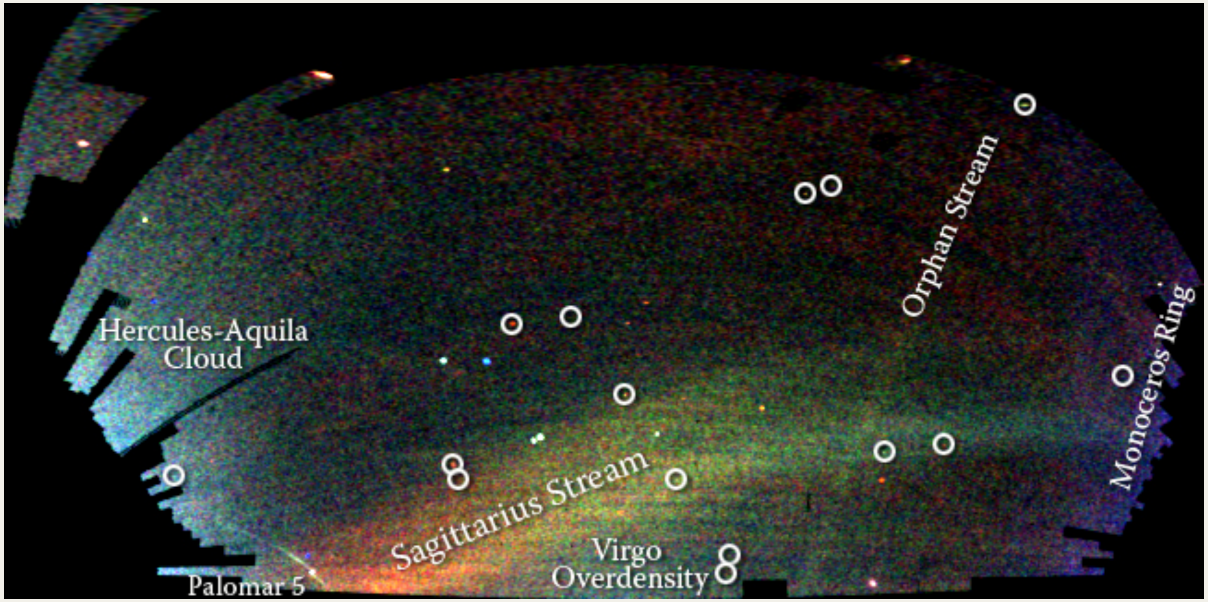
Why?

Our Milky Way, like other large galaxies, is a cannibal: it has eaten its closest neighbors and satellites

Adapted From Lecture 7, PoG, E. Tolstoy

The stellar Halo of the Milky Way

Stellar streams in the halo:



A map of stars in the outer regions of the Milky Way Galaxy, derived from the SDSS images of the northern sky.

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.

Adapted From Lecture 7, PoG, E. Tolstoy

The stellar Halo of the Milky Way

Stars in the Halo trace the merger history of the Galaxy:

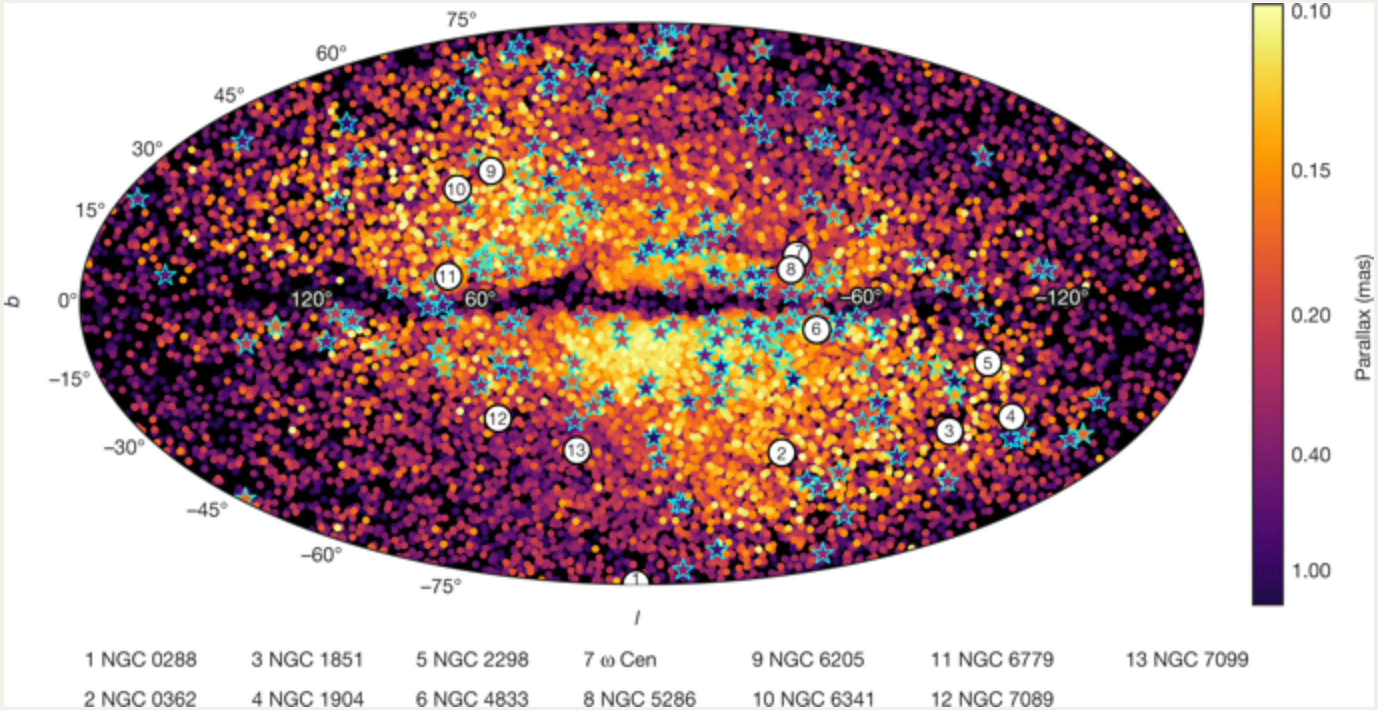
The discovery of Gaia-Enceladus (GE):

“We conclude that the halo near the Sun is strongly dominated by a single structure of accreted origin and leaves little room for an in situ contribution. This is however not necessarily representative of the whole stellar halo, as debris from other accreted large objects (for example, with different chemical abundance patterns) might dominate elsewhere in the Galaxy. ”

Helmi et al. 2018, *Nature* volume 563, pages 85–88 (2018)

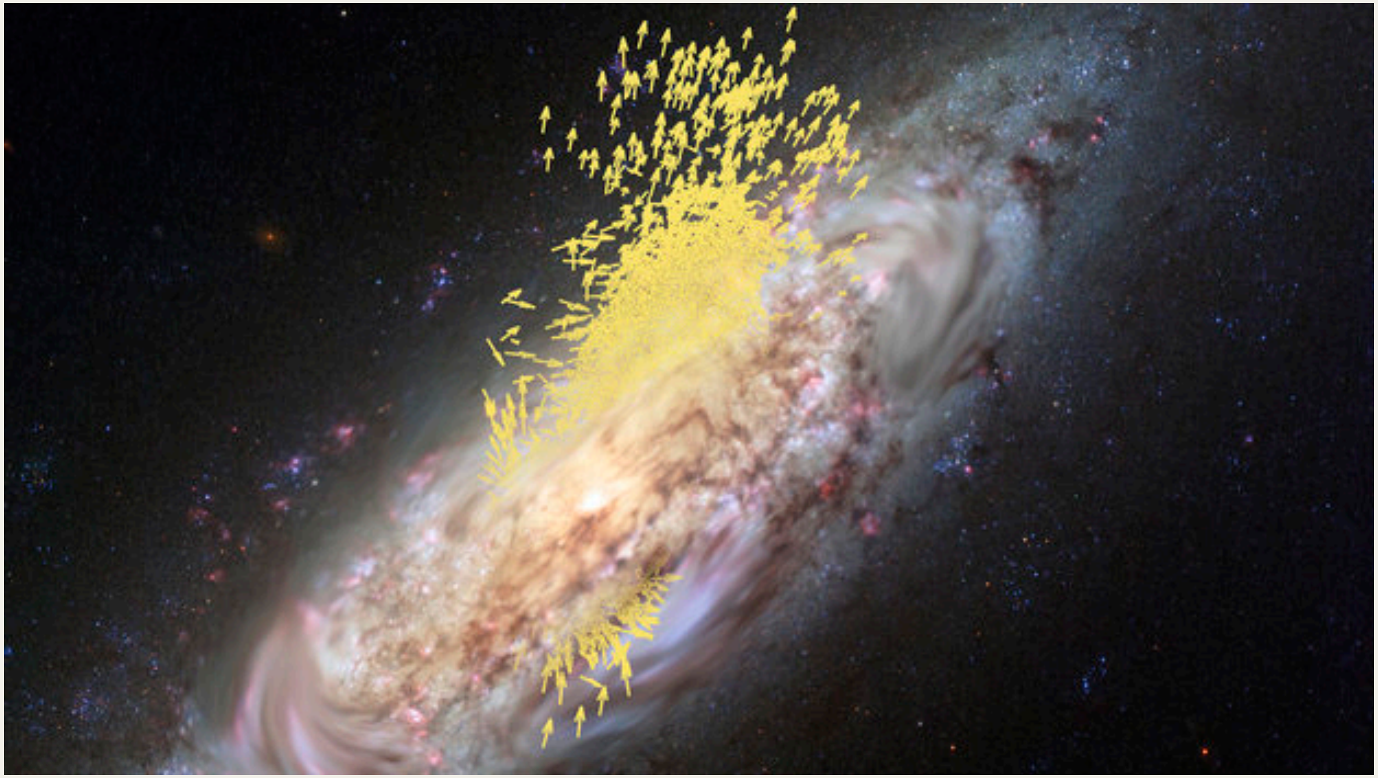
The stellar Halo of the Milky Way

Sky distribution of candidate Gaia–Enceladus (GE) members from a Gaia subsample of stars with full phase-space information.

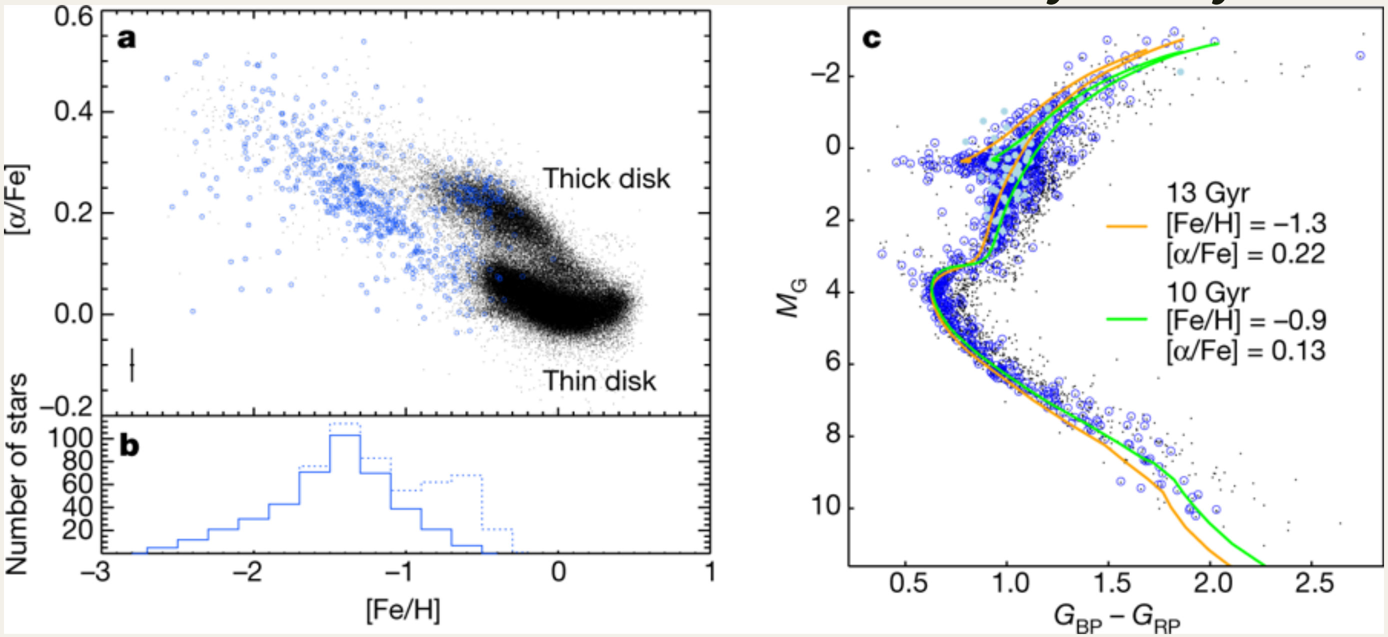


The stellar Halo of the Milky Way

Radial velocities of Gaia-Enceladus stars



The stellar Halo of the Milky Way



- Retrograde stars
- Separate sequence in the [a/Fe] vs [Fe/H] plane
- Blue sequence in the Colour-Magnitude diagram compatible with an age range of 10–13 Gyr
- A chemical evolution model with SFR=0.3 $M_\odot$ yr^{-1} and lifetime of 2 Gyr can explain the [a/Fe] vs [Fe/H] distribution and give:

$$M_*^{GE} = 0.3\ M_\odot\ yr^{-1} \times 2\ 10^9\ yr = 6\ 10^8\ M_\odot$$

The stellar Halo of the Milky Way

We can estimate the mass ratio of this merger at the time that it took place:

$$M^{GE}{}_{h}/M^{MW}{}_{h}=(f^{MW}/f^{GE})\times(M^{GE}{}_{*}/M^{MW}{}_{*})$$

f is the luminous-to-total mass ratio (virial to stellar)

M_h the halo mass

M_* stellar mass

At the present time, $f^{MW,0} \approx 0.04$ and $f^{GE,0} \approx 0.01$.

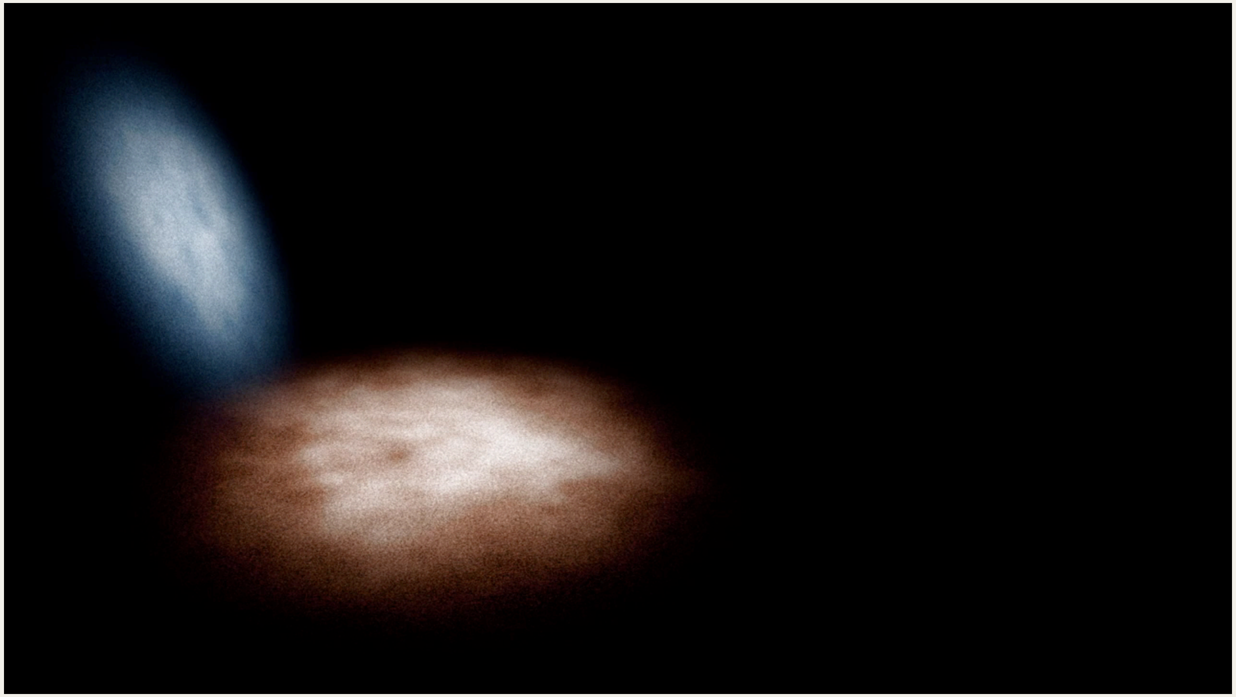
There is no redshift evolution of f between $z = 2$ and $z = 0$ for LMC and the MW

$$f^{MW}/f^{GE} = f^{MW,0}/f^{GE,0} \approx 4.$$

Therefore, by taking $M^{MW} = 10^{10} M_{\odot}$ (mass of the thick disk), **we obtain a mass ratio of about 0.24 for the merger.**

This implies that the merging of Gaia–Enceladus must have led to considerable heating and to the formation of a thick (or thicker) disk.

Model for the MW-GE merger

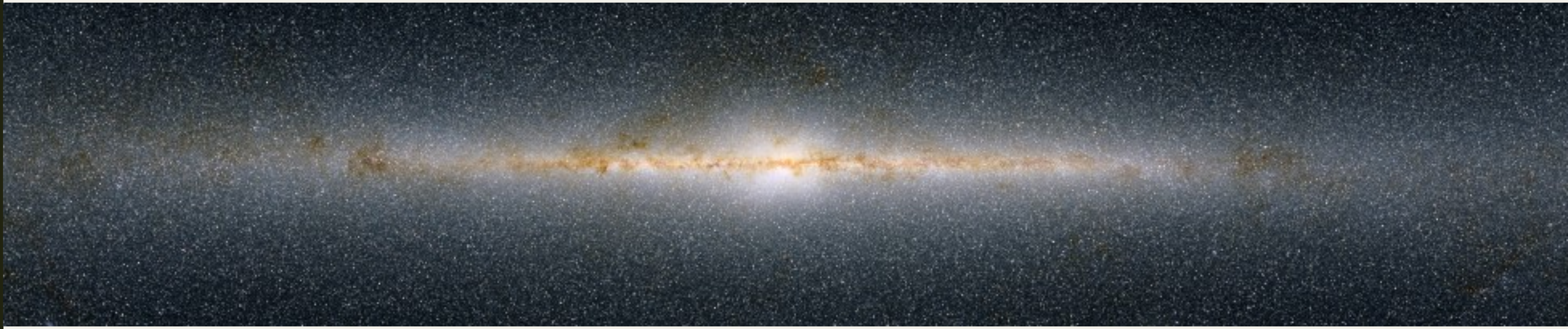


The properties of the Bulge of the Milky Way

The bulge appears peanut-shaped, larger on one side than the other, with a central bar, extending 3–4 kpc from the center (MW is probably an Sbc or Sc galaxy)

The bulge is not an overdensity of the central halo:

- The bulge stars are several Gyr old, but not metal-poor like the halo.
- The bulge is more flattened than the inner halo, and the bulge stars have a rotation speed of about 100 km s^{-1} and larger random motions.

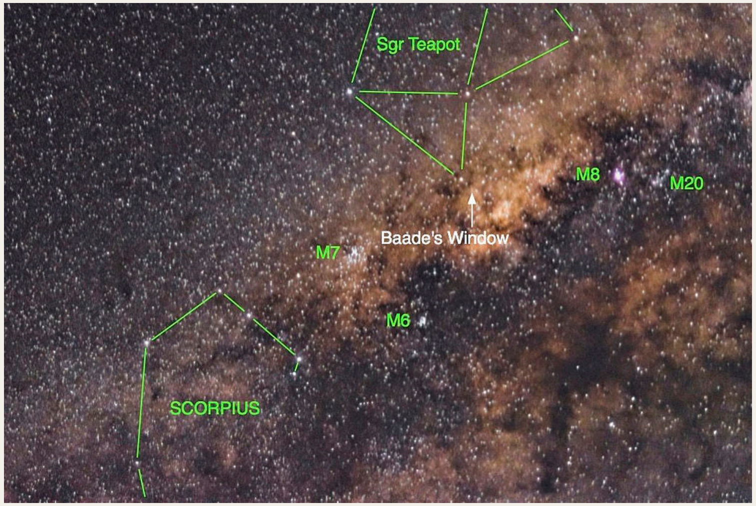


The properties of the Bulge of the Milky Way

The best way to map the Milky Way's central bulge is to **use infrared light**, which travels more freely than visible light through the dusty disk.

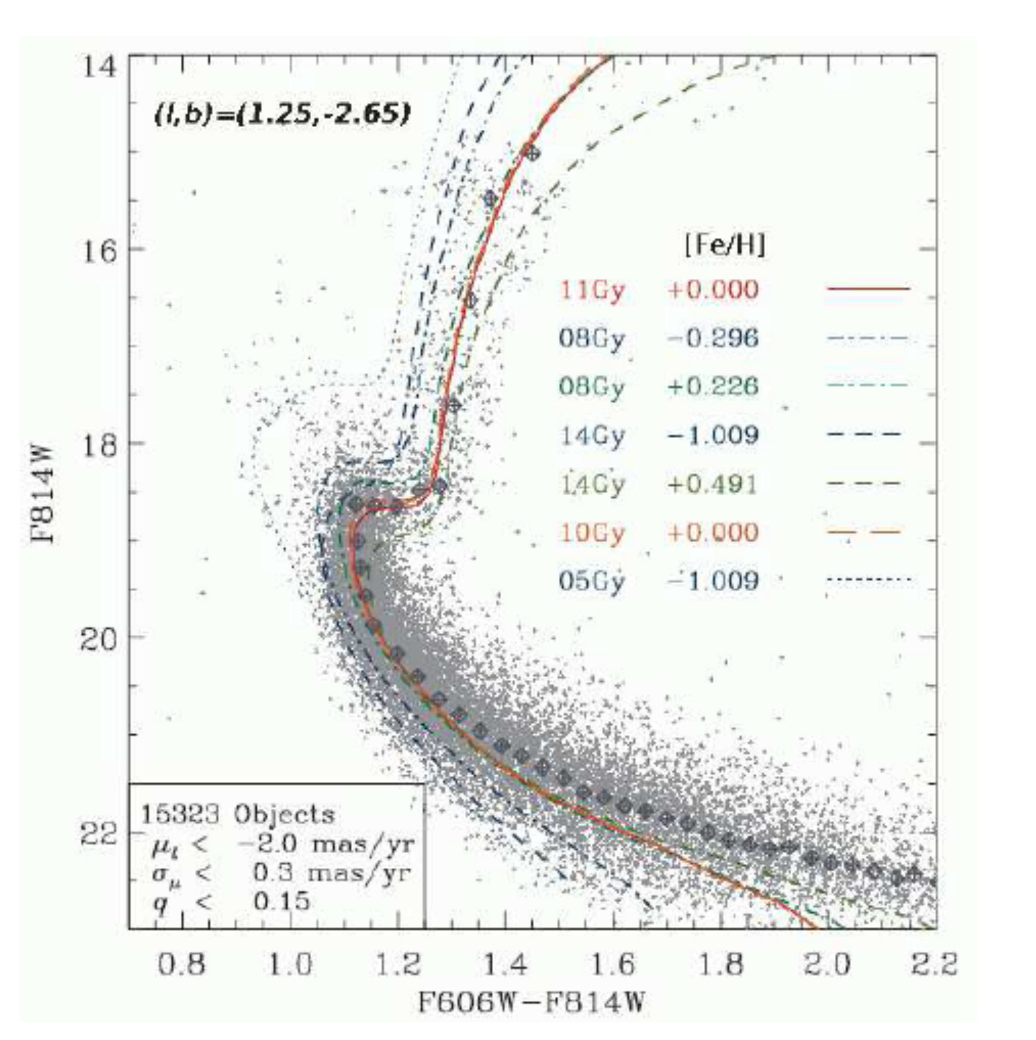
(Spitzer image of the central pert of the MW)

In the past, most of the Bulge observations were limited to the Baade's Window at (l,b)=(1º,–3.9º), with lower extinction 1.3<AV<2.8, which is low enough to observe stars in the optical.



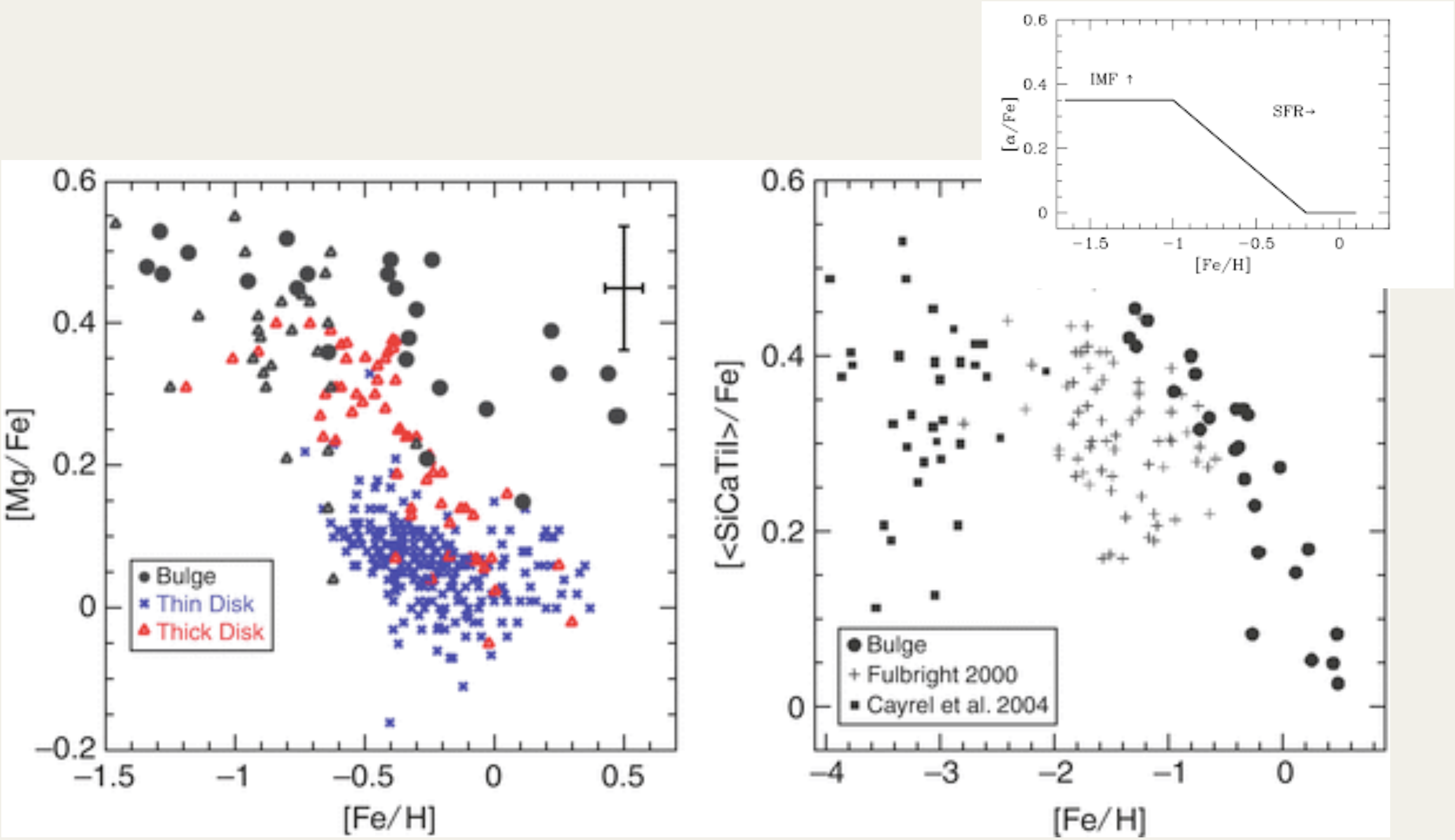
The properties of the Bulge of the Milky Way

- Its stellar population is old (10– 12 Gyr) and it has a metallicity distribution compatible with a **fast star formation.**
- The abundance ratio of alpha elements over iron also supports a **short** star formation timescale
- The presence of a radial metallicity gradient favors a formation scenario via dissipational collapse

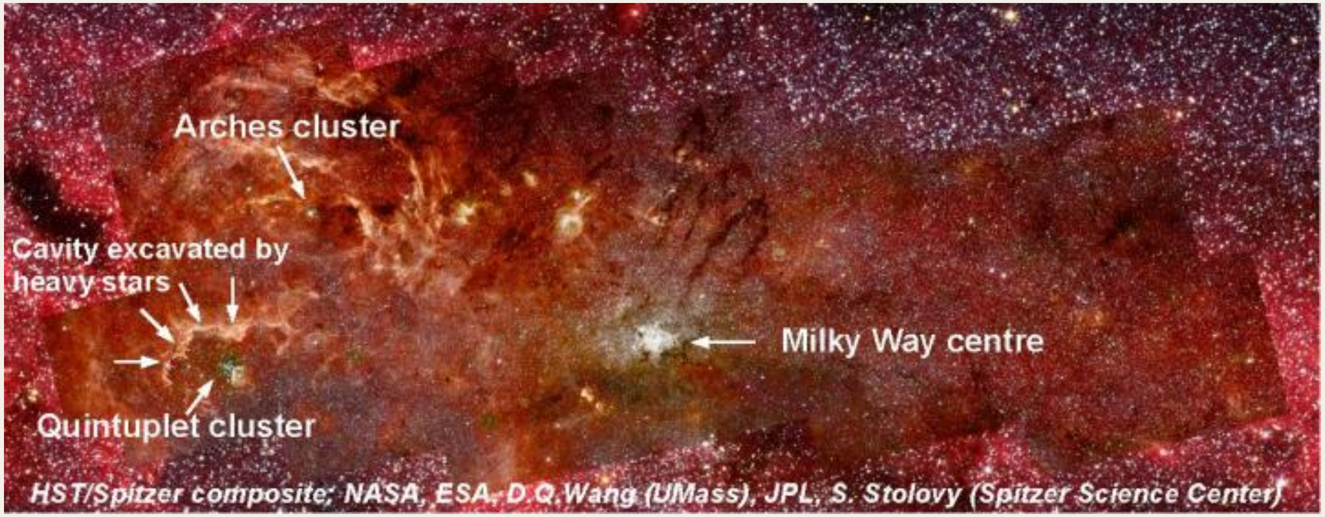


See, e.g. Zoccali et al. 2009

The properties of the Bulge of the Milky Way

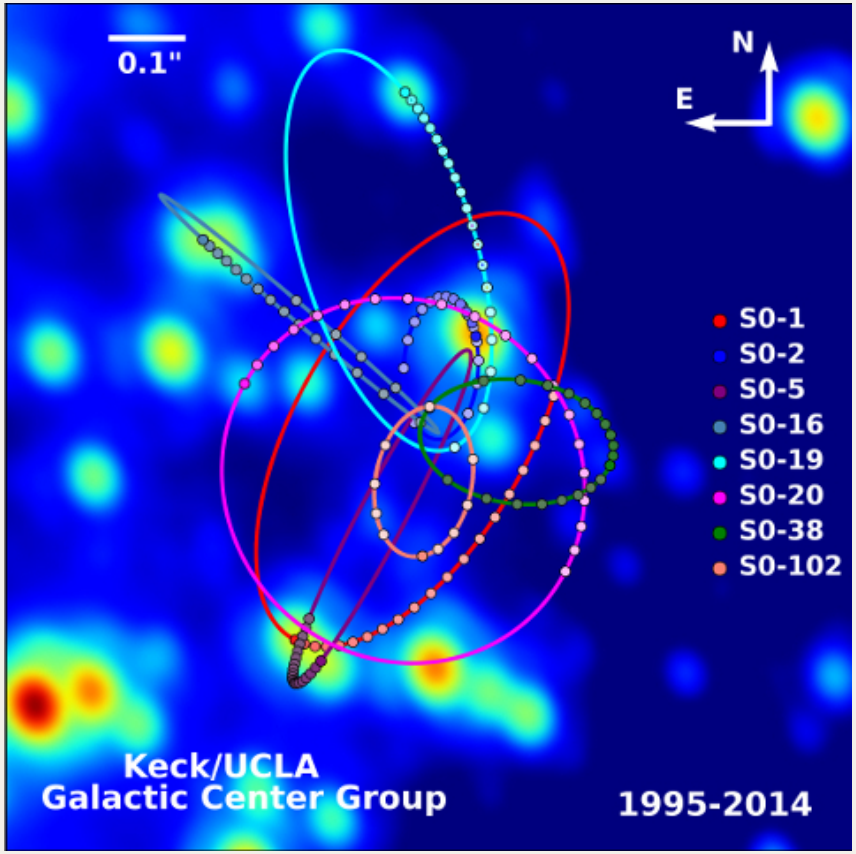


The properties of the stellar nucleus of the Milky Way



- At 30–50 pc from the center, the Quintuplet and Arches clusters are each more luminous than $10^6\ L_\odot$, containing several very massive stars.
- At the heart of the Galaxy is a torus of hot dense molecular clouds, about 2 pc in radius with $10^6 M_\odot$ of gas. It surrounds the Milky Way's stellar nucleus, a massive star cluster of $3\ 10^7 M_\odot$ of stars within a central cusp of 0.2 pc, with an age of 2-7 Myr

The properties of the stellar nucleus of the Milky Way

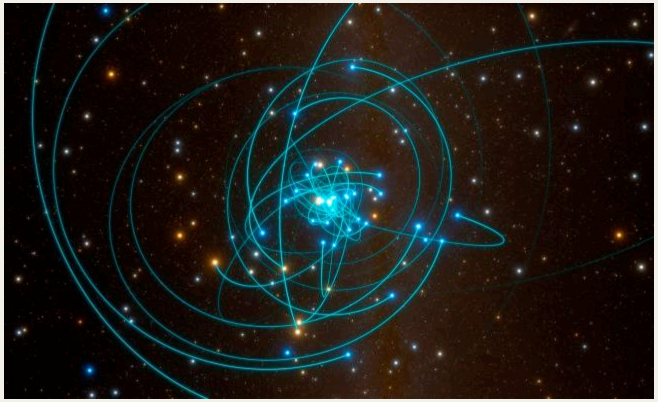


The innermost young stars are less than 0.05 pc from the central radio source.

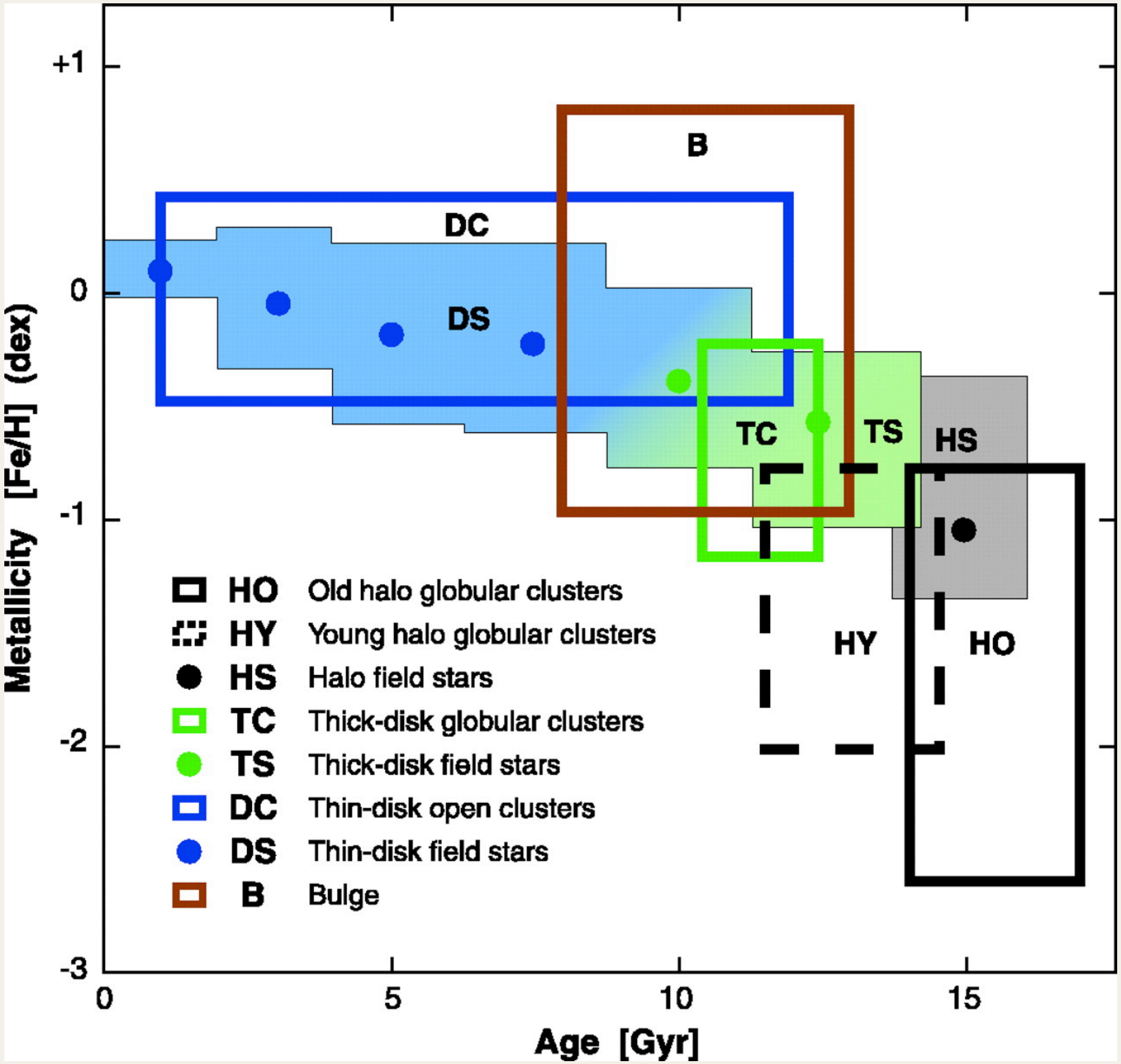
These stars follow Keplerian motions, which can be used to measure the mass of the central compact object.

This is almost certainly a **black hole with a mass of 4 10^6 $M_\odot$**

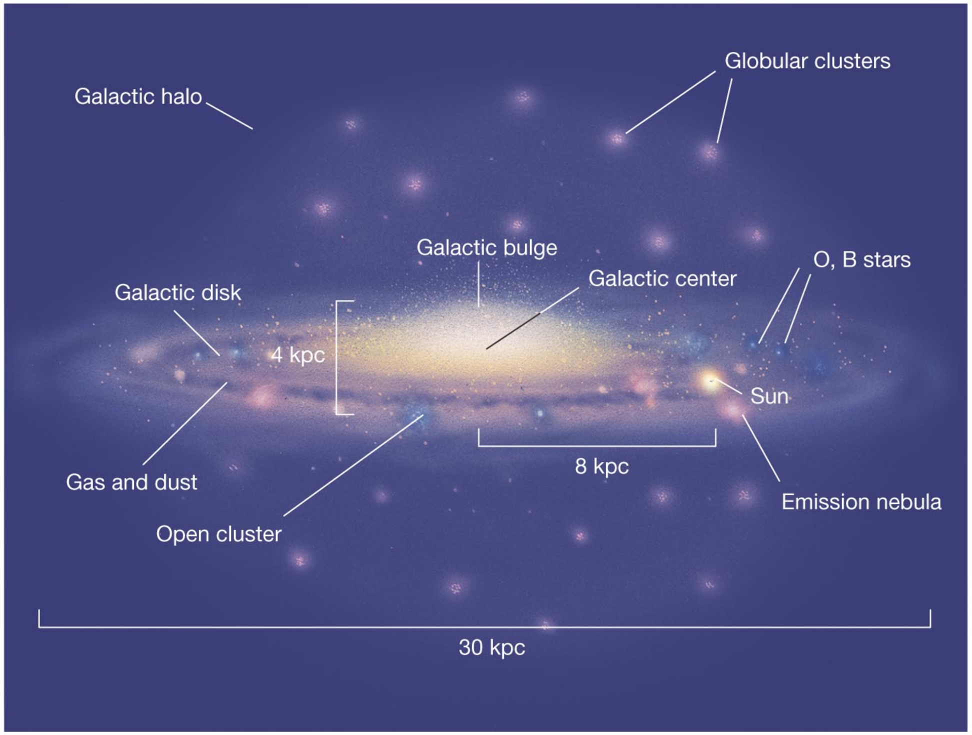
The properties of the central black hole of the Milky Way



The formation sequence in the MW components



The Galaxy and the 'Near field cosmology'



The Galaxy has built up through a process of accretion and merging over billions of years which is still continuing.

The stellar surveys (both astrometric, photometric and spectroscopic) are deriving three-dimensional space motions and elemental abundances for millions of stars throughout the Galaxy and its neighborhoods. **The new observations will reveal signatures of the formation and evolution of the Local Group: the so-called 'near field cosmology.'**