Streams, Substructures, and the Early History of the Milky Way

Author: Amina Helmi

Presented by - Geeta Rangwal

This review explains the early history of the Milky Way understood so far and presented discoveries of Gaia DR2 in combination of the spectroscopic datasets from APOGEE, GALAH, RAVE and LAMOST. All these data sets are joining the pieces of the puzzle reported in the literature and putting out the complete picture of the Galaxy history.

Milky Way and its traditional components

Visible components are: thin disk, thick disc, bulge/bar and stellar halo. Stars in these components are spatially and kinematically different and also have different ages and chemical distribution.

1. The thin disk is the site of star formation and stars move on fairly circular orbits.
2. The thick disk is thicker, more diffuse, and hotter than the thin disk. Stars are older than thin disk.
3. Bar/bulge is the most centrally concentrated component, but current understanding is limited.
4. The stellar halo is the most extended component, but at the same time, it is rather centrally concentrated. The stellar halo contains very metal-poor and old stars.
5. There is also warm ionized gas in a halo or circumgalactic medium and cold gas mostly in the disk.
6. If our understanding of gravity is correct, the Galaxy is embedded in a dark matter halo, where most of the mass of the system is located.

Galactic archeology

Research on the formation and history of the Milky Way and its stellar populations. The idea is to use the properties of long-lived stars to reconstruct the Galaxy's history. Low-mass stars live longer hence some will have formed at very early times and survived until the present day.

Three ways:

1. **Chemical Abundances:** Low mass stars will have retained in their atmospheres a fossil record of the environment in which they were born because the chemical composition of a star's atmosphere, particularly if it has not yet evolved off the main sequence, reflects the chemical composition of the molecular cloud from which it formed. This means access to the physical conditions present at the time of formation of the star. For very old stars, the conditions might have been very different than today therefore provide a window into the early Universe. Stars with similar chemical abundance patterns likely have a common origin. This common DNA would then allow the identification of stars with similar histories (chemical tagging).
2. **Age determination:** Knowing the ages of stars would permit us to date the sequence of events that led to the formation of the different components of the Galaxy. However, obtaining precise ages for very old stars is very difficult. The combination of ages and chemical abundances of stars is very powerful and can be used to establish a timeline.
3. **Motion:** Stars also retain memory of their origin in the way they move. For example, as a galaxy gets torn apart by the tidal forces of a larger system like the Milky Way, the stripped stars continue to follow similar trajectories as their progenitor system. This implies that if the Milky Way halo is the result of the mergers of many different objects, their stars should define streams that crisscross the whole Galaxy.

Chemical abundances

Stars with different metallicities have different chemical abundance patterns. Because different elements are produced in different environments and on a range of timescales.

1. α elements (O, Mg, Si, Ca, S, and Ti) are released in large amounts during the explosion of a massive star as a supernova (type II) that occurs after a few million years of the star's birth.
2. Iron-peak elements are produced in type Ia SNe, which are the result of a thermonuclear explosion of a white dwarf in a binary system. Because both stars in the binary are of lower mass, these SN explosions take place typically on a longer timescale than for type II SNe, of the order of 0.1 to a few Gyr.
3. In terms of the chemical evolution of a (closed) system, we thus expect that [α/Fe] will eventually decrease as time goes by as the ISM of the system becomes polluted by type Ia SNe. When a significant number of such explosions has occurred, the initial nearly constant [α/Fe] trend with [Fe/H] bends over, and this leads to the appearance of a knee, after which [α/Fe] can only decrease further.
4. Heavier elements beyond the iron peak are created by neutron capture processes, through the so-called slow (s) and rapid (r) processes.

Age determination

- It is comparatively difficult.
- Traditionally done by isochrone fitting.
- Recently, Bayesian inference tools have been employed to derive ages for large numbers of stars by using multicolor photometry, astrometric data and chemical abundance.
- A new way of estimating the age of stars using asteroseismology is also devised which uses time series photometry.

The photometric variations are due to internal oscillations, and their frequencies depend on the star's mass, radius, and effective temperature. Because the frequencies relate in different ways to each of these parameters, the mass of a star can, in principle, be derived with knowledge of the basic frequencies as well as of its temperature from, for example, broad-band photometry. The star's mass can then be used to determine its age using stellar evolution models.

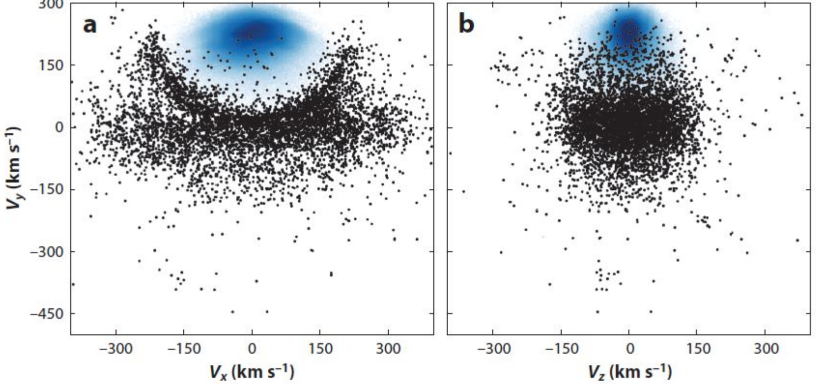
Kinematic properties of stars: Dynamics as tool

- A regular orbit may be characterized by the integrals of motion (IoM), such as energy and angular momentum.
- Since a small galaxy may be seen as an ensemble of stars with similar positions and velocities, hence IoM are also similar.
- If these are conserved through time then the tidally stripped stars will follow very similar orbits to their progenitor and result in the formation of a stream. A stream may thus be seen as a portion of an orbit populated by stars.
- Streams are long and narrow if they originated from a small system or formed recently.
- Massive object results in a broader population of orbits and hence in broader streams (sometimes hard to distinguish spatially).

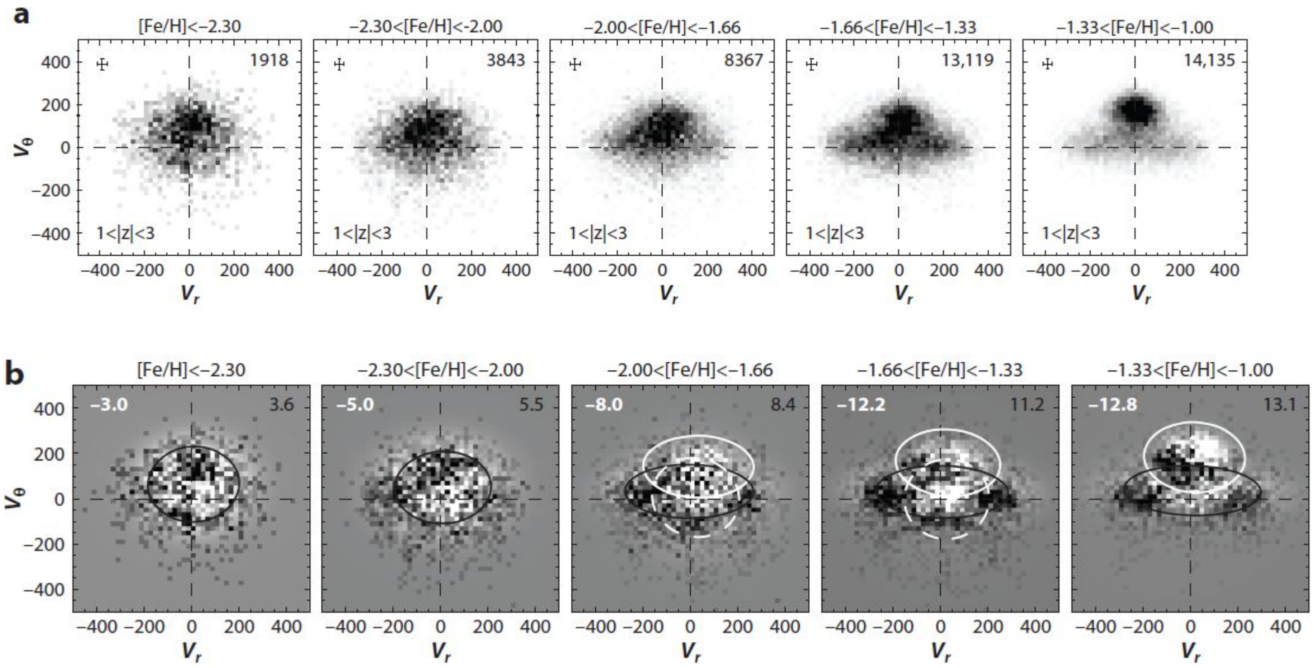
The Galactic halo

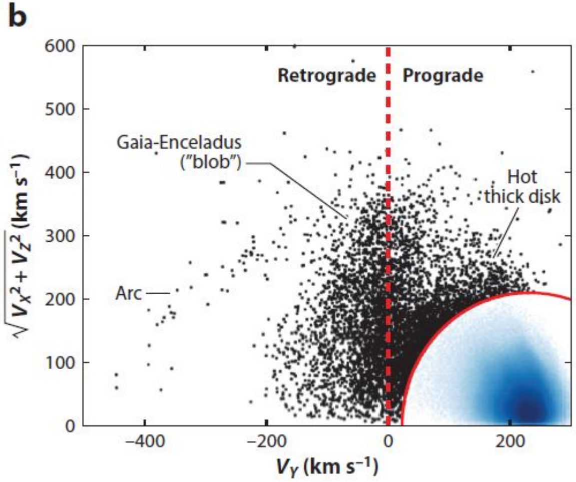
- Mergers play a key role in the hierarchical cosmological paradigm, that is how the galaxies build up their dynamical mass (hence understanding mergers is the way to understand this)..
- The stellar halo is interesting not only from the point of view of the merger history, but also it contains some of the oldest stars and the most metal-poor ones and gives us a window into the physical conditions present in the early universe and early phases of the assembly of the Milky Way, hence its relevance in a cosmological context.
- Several wide-field photometric surveys (SDSS, Pan-STARRS and more recently DES) have revealed large over-densities on the sky and many narrow streams. These are direct testimony of accretion events that have built up the outer halo
- Gaia DR2 is, driving a true revolution in our understanding of the inner Galactic halo. Recently there is a discovery that a large fraction of the halo near the Sun appears to be constituted by the debris from a single object, named Gaia-Enceladus.
- The other very important contributor in the vicinity of the Sun to stars on halo-like orbits is the (tail of the) Milky Way thick disk. These (proto–)thick disk stars were likely dynamically heated during the merger with Gaia-Enceladus.

Gaia-Enceladus

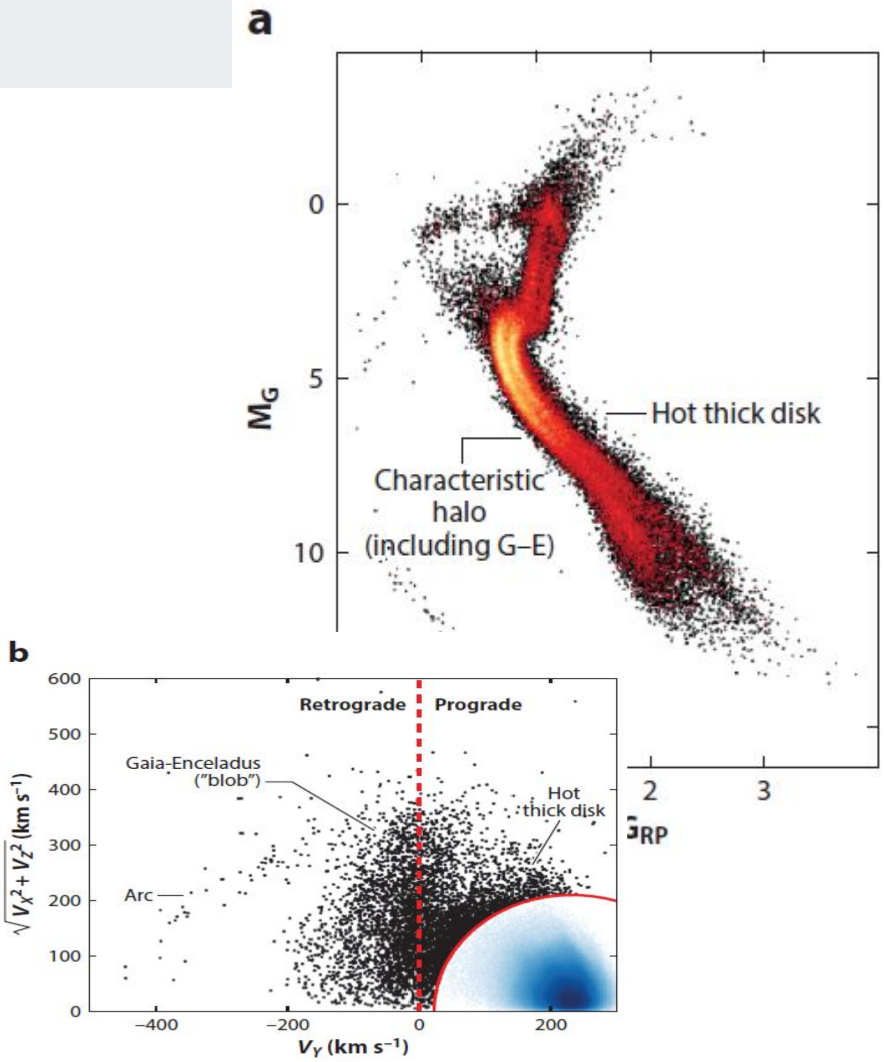


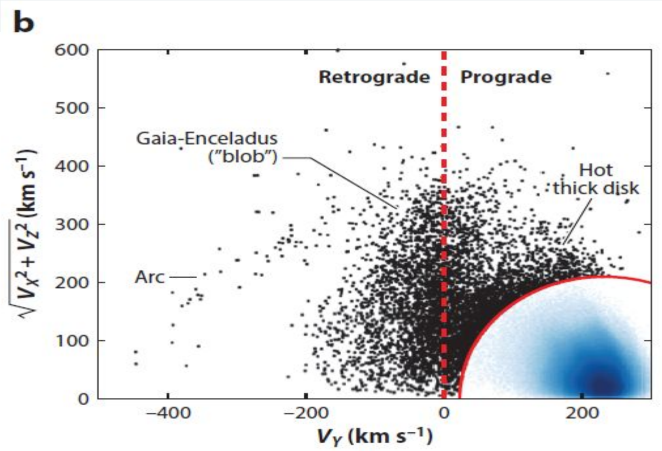
Stars with metallicities typical of the thick disk but with halo-like kinematics

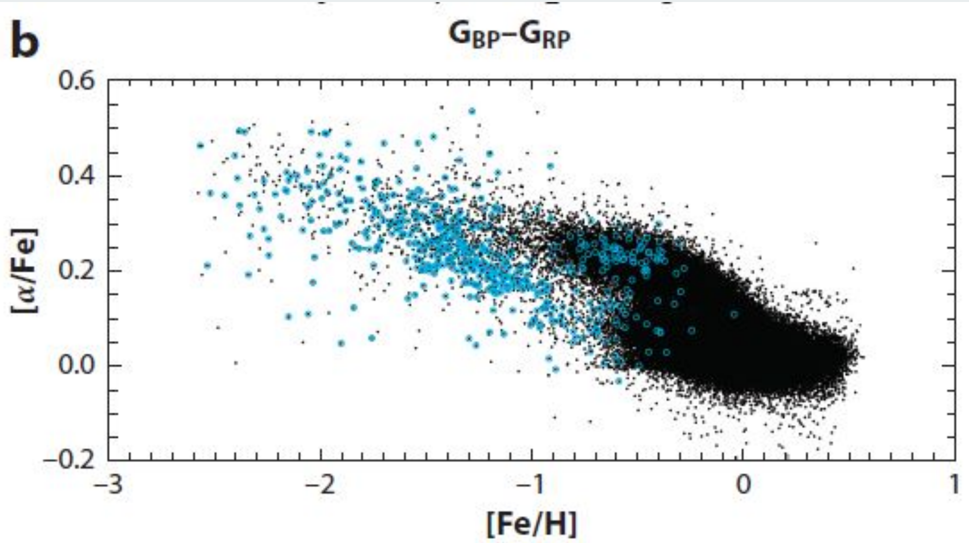




- The color-(absolute) magnitude diagram of stars with halo-like kinematics (tangential velocities > 200 km/s).
- Two sequences hence presence of distinct stellar populations (different ages and metallicities) and are evocative of a dual halo.
- Where the older and more metal-poor sequence corresponded to low α-abundance stars on retrograde orbits. Koppelman et al. (2018) demonstrated that this sequence was dominated by the large kinematic structure (blob).







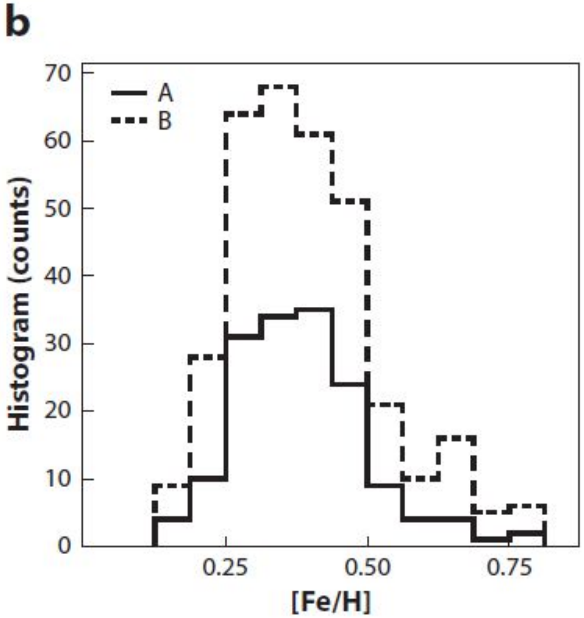
- Helmi et al. (2018) showed that these stars define a well-populated extended chemical sequence (stars in blue) of at least 1 dex in [Fe/H] that runs below that of the thick disk in [α/Fe] versus [Fe/H], because the stars have lower [α/Fe] at the [Fe/H] where there is overlap with thick disk (which, by and large, must have formed in-situ), this immediately implies that the stars formed in a different system than the thick disk, as [α/Fe] will generally decrease as [Fe/H] increases. This means that these stars must have been accreted (called Gaia-Enceladus).

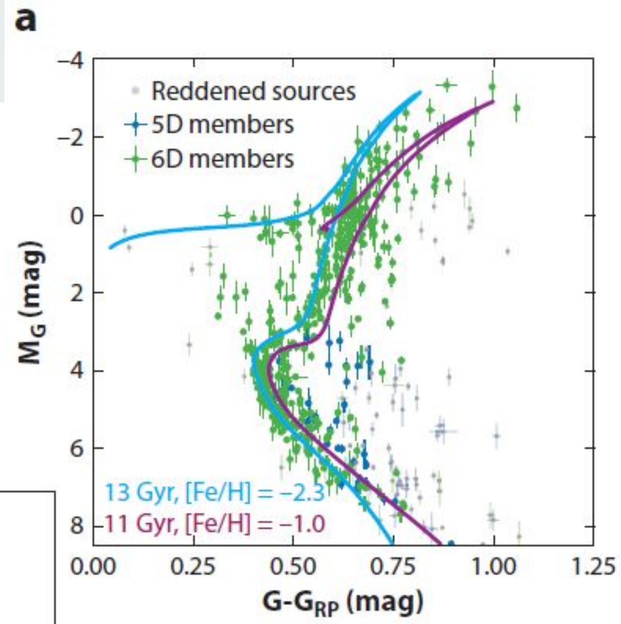
- These are the most metal-rich stars and likely formed in Gaia-Enceladus before it was fully disrupted, this also dates the time of the merger and, at the same time, demonstrates that a disk was already in place in the Milky Way at this time, roughly 10 Gyr ago.

- In summary, the halo near the Sun (if not in a hot thick disk) is dominated by debris from Gaia-Enceladus, a very massive object that was accreted 10 Gyr ago. As such, it most likely represents the last significant merger that the Milky Way experienced.
- Probably after this was completed, the current Milky Way thin disk started a more quiescent growth phase, and this would be consistent with the ages of its oldest stars.
- Other large mergers the Milky Way has experienced since then include that with the Sagittarius dwarf, but because of the late time of infall (~8 Gyr ago) and mass ratio of 1–5% (M ~ 5 × 108M), this has resulted in a less dramatic impact.
- Even the ongoing merger with the Large Magellanic Cloud is less important (with a mass ratio of probably ~10%).
- Although in both cases we do see their effect on the disk of our Galaxy, in the form of phase-space spirals and waves (vertical and radial oscillations).

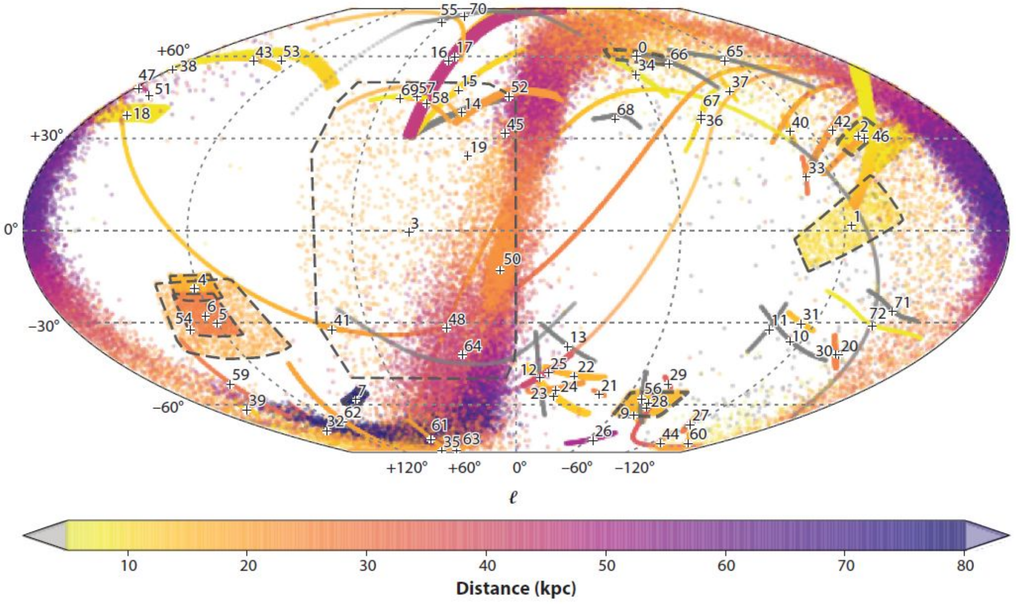
Dual halo and sub structures

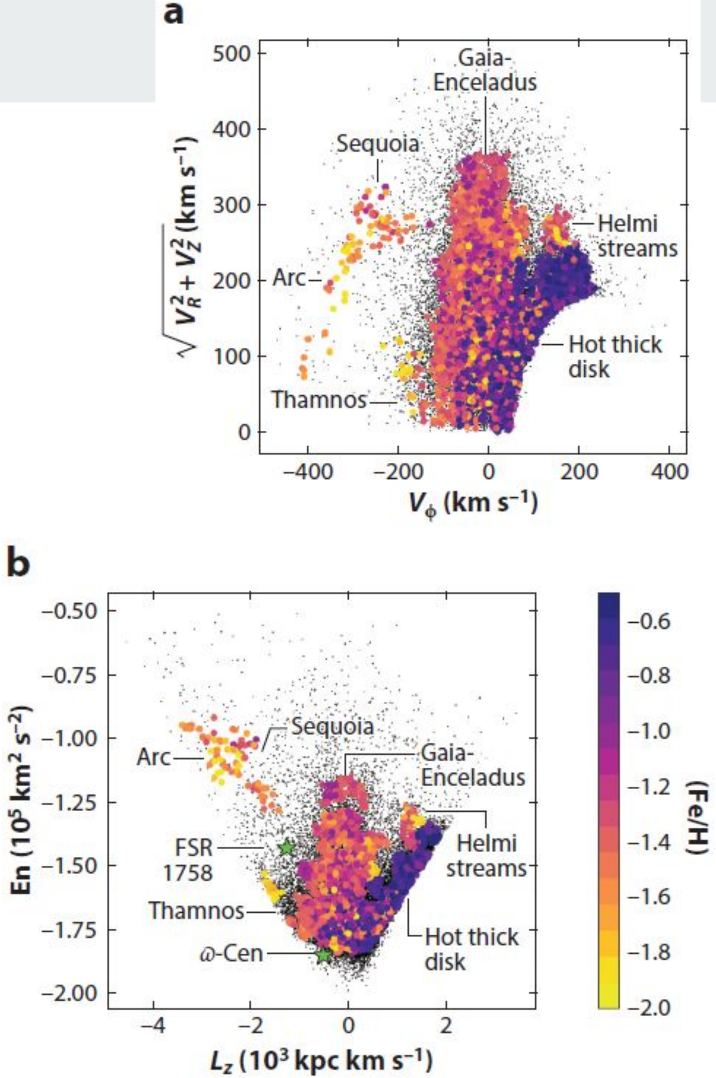
- There are so many studies with evidences which propose presence of dual halo.
- 20 kpc around solar neighbourhood regarded as inner halo.
- Gaia DR2 found several substructure inside it. Helmi streams.





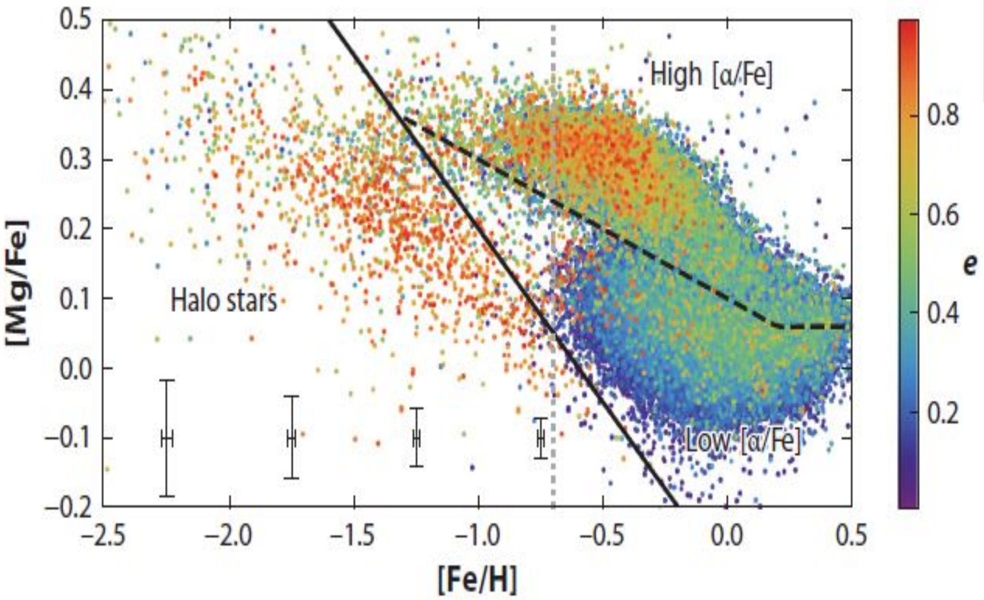
Other substructures and streams





The early/thick disc

- Stars in the thick disk had different kinematics (lower rotational speeds (by about 30–50 km/s) than the thin disk.
- The thick disk is more metal poor than the thin disk and is composed of older stars.
- Thick disk stars organize themselves in a segregated sequence from that of the thin disk stars in the solar neighborhood in [α/Fe] versus [Fe/H].
- The sequences are truly separate, and hence that the two components really are physically distinct, as they are made up of stars that do not overlap in their properties.
- Stars in the thin and thick disks follow very tight and well defined tracks in [α/Fe] and [Fe/H] with age, with a break occurring at ~8–9 Gyr, which marks the oldest stars present in the thin disk. These distributions display a small scatter, a result that, although based on a local sample, can be extended beyond the solar vicinity since the orbits of the stars probe a relatively large radial range (from 2–10 kpc from the Galactic center). This small scatter (which implies no radial gradient) can be explained if the majority of thick disk stars formed rather quickly in a massive gaseous disk, possibly supported by turbulence.



- The thick disk metallicity near the Sun peaks at [Fe/H]~−0.5 and extends on the metal-rich side up to solar metallicity. It also has a very significant tail, which is often referred to as the metal weak thick disk. The stars associated with this tail are clearly visible as the data points with high [Mg/Fe], [Fe/H] −1, and low eccentricity in Figure. This metal-weak thick disk could potentially be related to the very first disk or the oldest disk that was ever formed in the proto–MilkyWay.

Formation pathways

1. The traditional and oldest is that it formed via a minor merger onto a pre existing disk, which leads to dynamical heating and the formation of a hotter but still rotation-supported component.
2. The accretion scenario is based on cosmological simulations, which showed that if satellites are preferentially accreted from specific directions, this can lead to their debris being deposited in a planar configuration. On this preferred plane, gas would later cool down and form the thin disk.
3. The gas-rich scenario is inspired by cosmological hydrodynamical simulations that show that disks were highly turbulent and hotter in the past, partly because they were more gas rich and partly because of the ongoing merger activity that prevented full settling. This is also what observations of high-redshift disks appear to suggest.
4. A final scenario is that of migration of stars from the inner (thin) disk, they have migrated with time to the outer regions of the disk. Because of inside-out formation and metallicity gradients, these stars would be older and have different chemical composition.

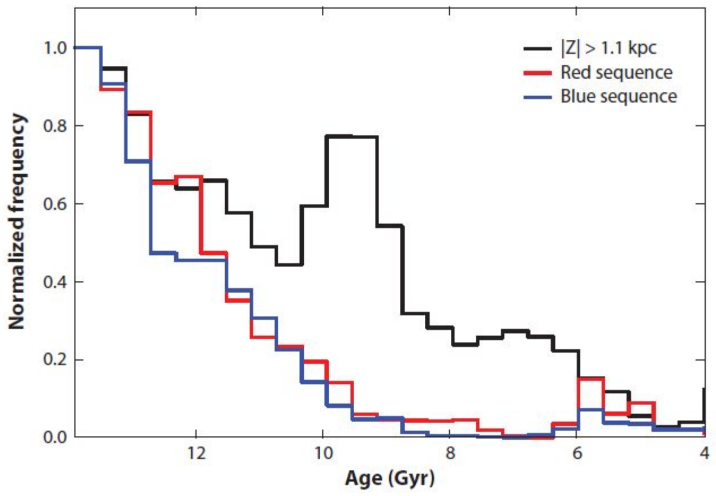
What observation say?

Different mechanism show different eccentricity distribution:

1. Radial migration only slightly changes the low eccentricities of the stars.
2. Dry large minor merger would leave behind a distribution of stars with intermediate eccentricity (the heated disk)
3. High-eccentricity bump formed mostly by accreted stars.

RAVE and SDSS data showed that the most likely path was through gas-rich mergers, i.e., turbulent disks in which stars were forming during mergers (which is confirmed by Gaia DR2).

- ➔ Majority of the thick disk stars likely formed during/after the merger with Gaia-Enceladus and not before. During the merger, the stars already present were dynamically heated, and star formation was triggered (possibly in a starburst), leading to the formation of the bulk of the stars in the thick disk.
- ➔ Some fraction did form before, as in the dry merger scenario (the predicted bump at high eccentricity associated with the accreted stars is not seen in the thick disk).
- ➔ These stars make up a large fraction of the Galactic halo (interesting connection between the thick disk and halo had not been fully made until recently).
- ➔ It is probable that radial migration has played some role in the evolution of the thick disk, and that some fraction of the stars in the thick disk have an (inner) thin disk origin.



Thick disc stars, Gaia-Enceladus, Hot thick disc

Next steps

- Simulations
- Statistical analysis
- Surveys

Thank you