The Stars Beyond (on the Galactic Stellar Halo)

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Our Universe, when viewed on the largest scales, is a vast network of galaxies. Galaxies—not stars—map out the broad structure of the cosmos. From this grand perspective it's easy to start thinking of galaxies as minor points of interest, pit stops along a majestic cosmic highway. But like cities that dot roadways here on Earth, galaxies have rich identities, born of histories that are complex and varied.

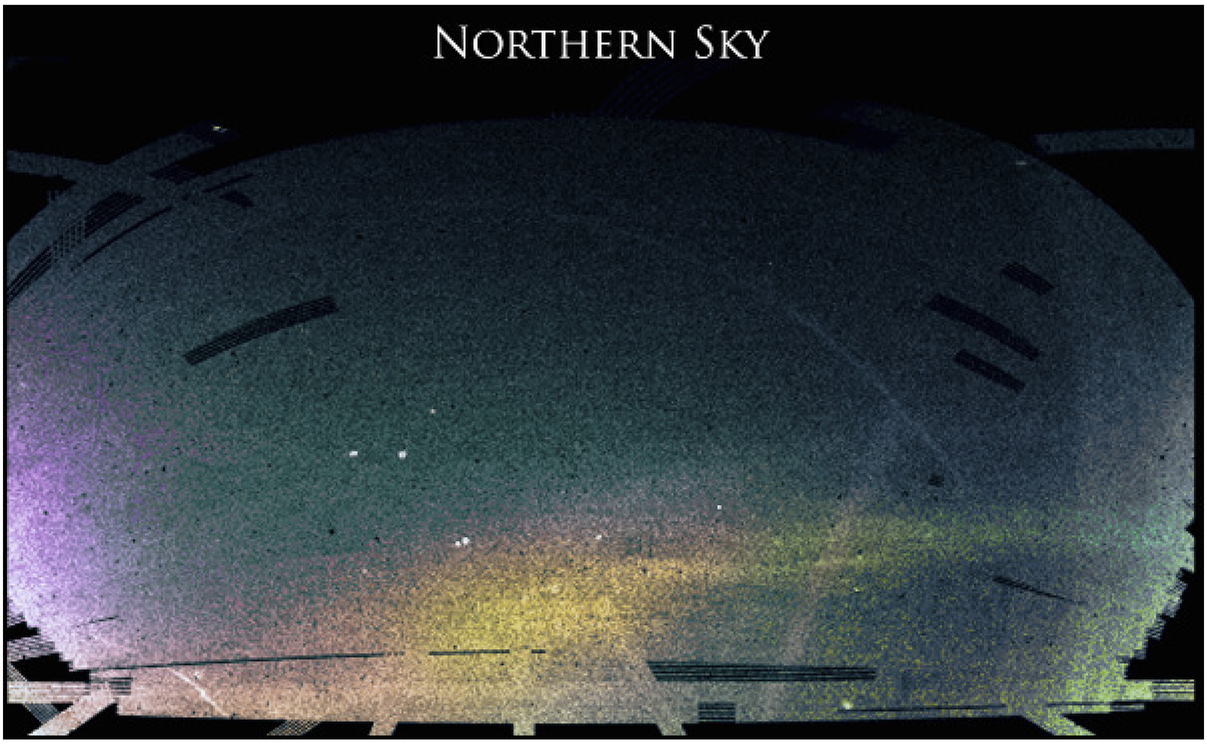
Each galaxy has a story. Some are small but growing rapidly. Others look bland but betray a complex, vibrant past. What's more, most large galaxies—again like some cities—appear to be built upon the ruins of smaller, more ancient ones. Our home galaxy, the Milky Way, is not unlike Rome in this respect. Ancient stellar remains show up viscerally in the the faint, extended outer reaches of galaxies—regions of light so diffuse that they've been difficult to study until recently.

An SDSS image of elliptical galaxy NGC474 (center) and spiral galaxy NGC470 (right).

The same pair of galaxies imaged to very low surface brightness with the MegaCam camera on CFHT. A complex and extended stellar halo consisting of stars of various ages (colors) is apparent. Image credit: Duc/Cuillandre/CFHT/Cole.

Over the last fifteen years we've come to understand that most big galaxies are embedded within extended complexes of diffuse light called *stellar halos.* These envelopes stretch hundreds of thousands of light years in diameter, multiple times the widths of galaxy disks you usually see in pictures. The outer parts of stellar halos appear to be built from the shredded remains of older star-cities long since destroyed. It took astronomers almost a century to piece this together. The stars of interest spread out to such low surface brightness that they are transparent in most astronomical images. You can get a sense of the difficulty by looking at the two pictures shown above. The upper panel shows a pair of galaxies as you'd normally see them in a telescopic image. The bottom panel shows the same pair taken from a survey specifically designed to reveal low surface brightness features. Clearly there is much more going on here than you might otherwise know. The shells and streams all around the central galaxy (called NGC474) correspond closely to what we expect to happen when small galaxies are ripped apart by the strong gravitational pull of a larger one.

Unfortunately, NGC474 is not typical. It has one of the brightest stellar halos known, and even still it took a tremendous effort to image it so clearly. Most galaxies (like the Milky Way) have halos that are even harder to detect.



A sky-projection star map of the outer stellar halo of the Milky Way (Bonaca et al. 2012) constructed using data from the Sloan Digital Sky Survey. The image looks up out of the Galactic disk. Complex structures (streams and clumps) are apparent throughout.

For the Milky Way and other similar galaxies, stellar halos can only be mapped effectively by carefully cataloging the locations of individual stars. This is hard work, but it's an approach that has become possible in the era of modern digital sky surveys. We now know that outer regions of the Milky Way are extremely complex— filled with streams and lumps left over from ancient, shredded star systems. Given the technology required to construct these maps, you may find it surprising that we've actually known about the Milky Way's extended stellar halo for a very long time, some 90 years. The initial picture was admittedly incomplete, but qualitatively correct. Astronomers in the early 20th century couldn't detect those distant stars directly, but they inferred their existence all the same. The story of how they did so is a triumph of reason and the scientific method, and reaches back to a time when stars (not galaxies) were thought to map out the Universe.

Jan Oort (c. 1935, age 35) Passport photo by H. Jonker, Leiden.

In the Fall of 1922, a relatively unknown Dutch Ph.D. student named Jan Oort published a paper on some peculiarities he noticed with the fastest stars then known. It was his first publication, but one that would spark a revolution in our understanding of the Milky Way, and by extension the Universe itself. It's important to remember that Oort regarded himself (at the time) as a cosmologist. For many (though not all) astronomers in 1922, the Milky Way *was* the Universe. Star maps at the time suggested that the Sun was near the middle of the cosmos, one that was tiny by today's standards. Oort was aiming to make sense of the sidereal Universe itself by understanding how the individual entities moving through it —such as stars— behaved.

Though he didn't know it then, Oort was coming of age during the most transformative decade in the history of astronomy. He would take part in a tidal wave of change that that rivaled the Copernican revolution in scope, but that happened over a much shorter time. Within a few years the existence of "island universes"—galaxies beyond the confines of the Milky Way—would become established fact. But in 1922 Oort did not know any of this. Instead he was focused on a specific problem: how to make sense of these weird, speedy stars?

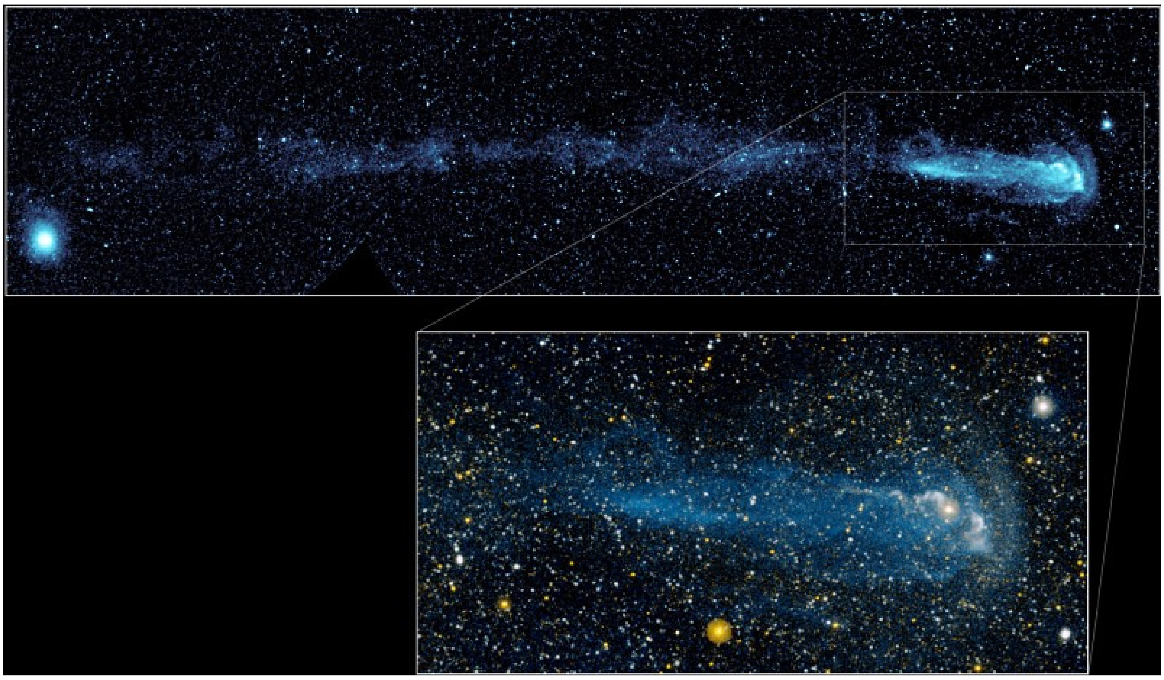
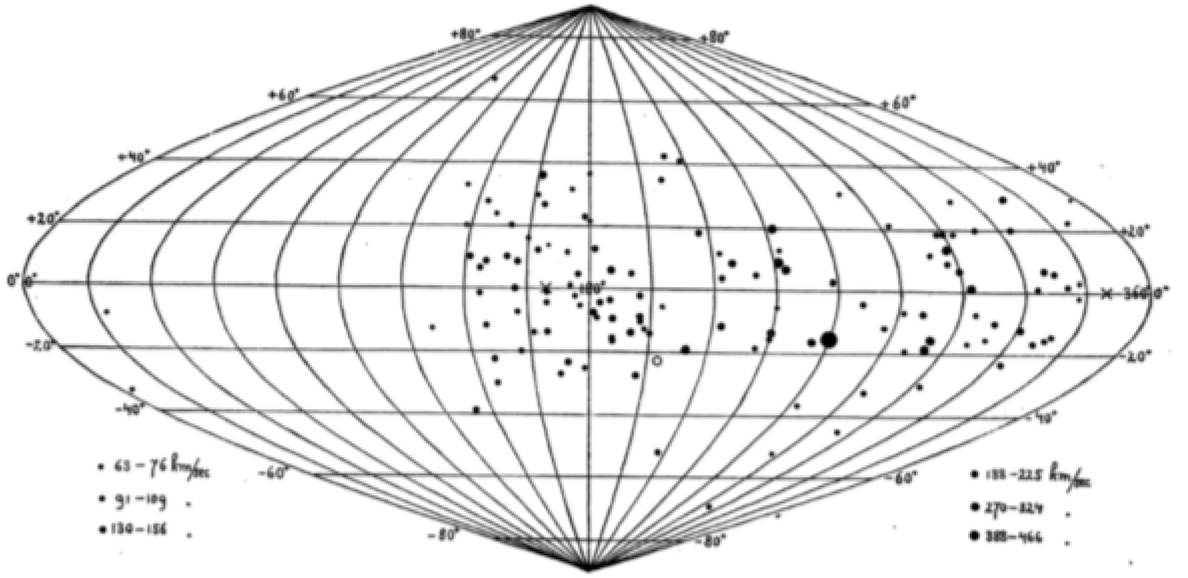


Image credit: the ultra-high velocity star Mira, shown in ultraviolet light by NASA's GALEX spacecraft, via http://www.galex.caltech.edu/media/glx2007-04r_img03.html.

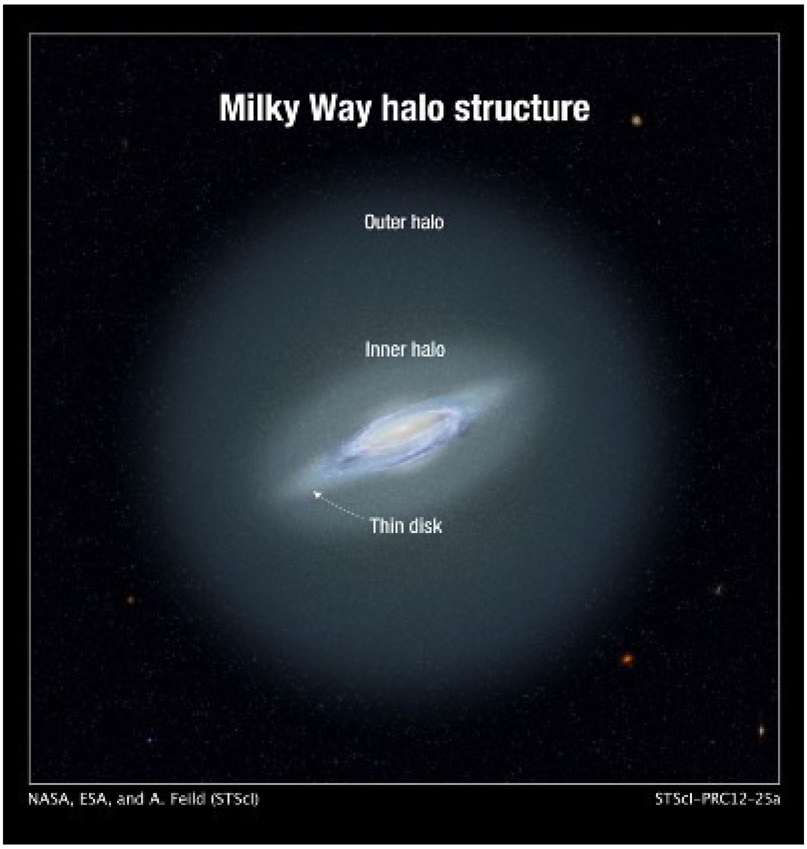
By the early 1920's it was pretty well established that most stars around us are moving randomly with respect to the Sun. Astronomers knew that some stars were moving faster than others, and if they counted up the frequency of velocities, they even seemed to follow a Gaussian distribution—the distribution one naturally expects for a complicated physical system. What struck Oort as particularly odd was that the fastest stars were *much* more common than they should have been. The tail of the distribution stuck out like an string on an old sweater. Many people would have seen an irregularity like this and dismissed it as a distraction. But often times in science, a small oddity followed up with care can lead to transformative discoveries. Oort was wise to pull that string.



All-sky plot of the direction of motion of the fastest stars from Oort’s Ph.D. thesis (1926). The crucial point is that they are all moving towards a single hemisphere, traveling in roughly the same direction. Why are there no points in the left region of the plot? This would later be recognized as a a clear signature that the Milky Way disk is rotating within a vast “halo” of fast-moving stars. The fastest stars appear to be moving at us in the opposite direction of our rotation around the Galactic center, like wind in the face of a runner as she sprints around a track.

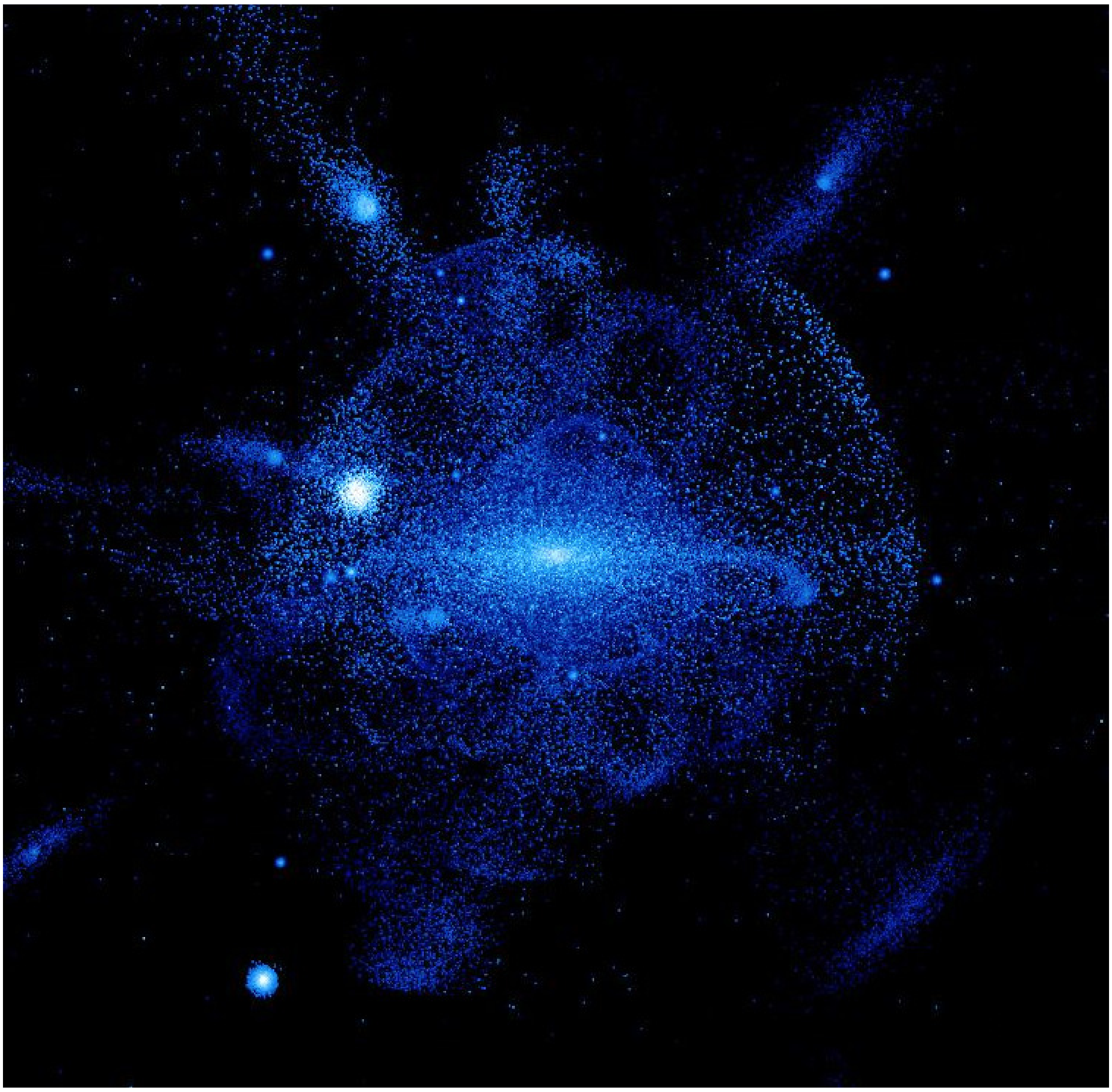
When Oort examined the high-velocity stars more carefully, he saw something striking: they were all moving in roughly *the same direction* with respect to the Sun. Specifically, he noticed that when he looked only at the fastest stars, they were all traveling towards a single hemisphere in the sky. It was almost like those speedy stars were flowing past the Sun in a sort of Galactic wind. It would take Oort several years and the help of a theorist named Bertil Lindblad to interpret this signal correctly: the Sun and other similar stars in the Milky Way disk are orbiting together about the Galactic Center at very high *coherent* speed together. The fastest stars we measure are *not* rotating like this, so they appear to us as a wind against the Sun’s motion, like stationary air rushing in the face of a runner as she speeds around a circular track. Oort and Lindblad had discovered something astounding: the Milky Way rotates. By about 1927 there was pretty good evidence that our island universe was in fact spinning and that the center of rotation was quite far from the Sun.

The Oort-Lindblad discovery of Galactic rotation stands among the most important in the history of the field. But Oort made a *second* insight *as a graduate student* that could be regarded as even more surprising: he deduced the existence of the stellar halo. In that same 1922 paper he realized that the fast stars he was studying were likely “foreigners” that came from “immense distances” well beyond the vicinity of the Sun. This was a major realization. He figured out that these fast-moving stars betrayed a much larger physical scale to the Galaxy, a volume well beyond the confines of the Milky Way disk. Two years later, in 1924, Oort showed that the velocities of the fastest stars mirrored those that had been observed for globular clusters, the same globular clusters that Harlow Shapley had been using to argue that the Milky Way was big and centered far from the Sun.



Classical depiction of the Milky Way stellar halo: a smooth, semi-spherical distribution of extended stars and globular clusters, surrounding a thin disk and central bulge. Image credit: NASA, ESA, A. Field (STScI).

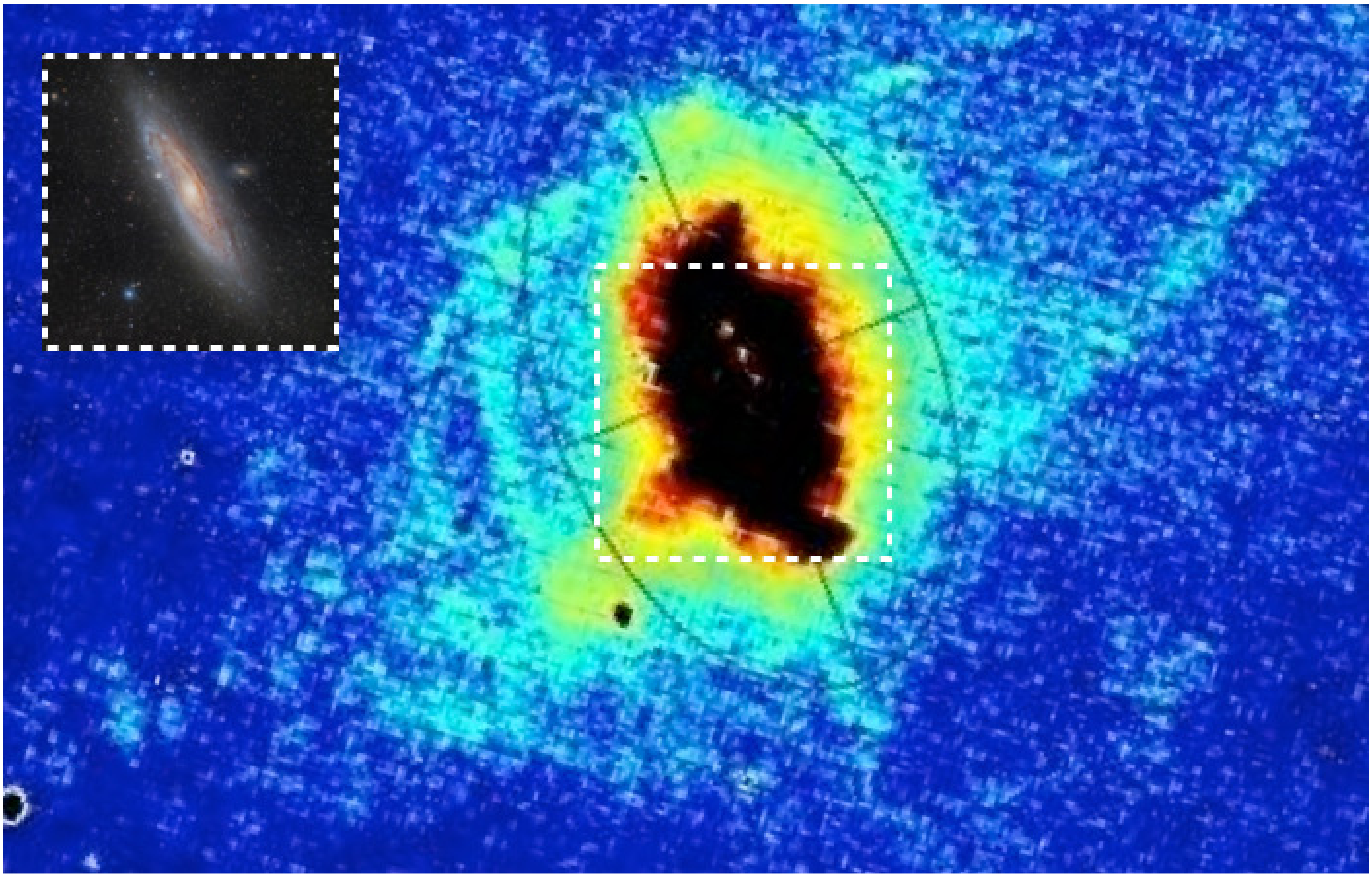
Over the rest of the 20th century, Galactic astronomers began studying these fast halo stars with ever greater precision, though most studies were limited to stars fairly close to the Sun. The picture of the Milky Way that began to develop is much like the one shown on the left. Our Sun, about half-way out in the disk, orbits around in something like a circle. The stars in the stellar halo, on the other hand, are on fast, plunging orbits that are randomly oriented. This allows halo stars to spend some time in the inner galaxy (near the Sun where we can see them easily) but a lot of time far out, well beyond the Solar circle. Though the bulk of the initial data was restricted to stars that are *currently* near the Sun, their dynamical properties allowed astronomers to deduce that they had orbits that would typically take them much farther away. Based on the data in hand, astronomers developed self-consistent toy model for the stellar halo that looked like the one shown above: a smooth, almost spherical distribution of stars that extends well beyond the Galactic disk. It’s common to see pictures like this in introductory astronomy textbooks today. *The trouble is that this picture is almost certainly wrong.* The map of the outer Milky Way we saw earlier was riddled with structure.



A more realistic depiction of the Milky Way's stellar halo (probably): a complex web of stellar streams and clumps. Image credit: Bullock & Johnston (2005).

A more realistic expectation for the halo of the Milky Way is shown above. This is taken from a simulation that Kathryn Johnston and I published in 2005. What we have done is modeled the cosmologically-motivated merger history of a galaxy like the Milky Way. We were able to make predictions for the frequency and shapes of faint stellar features around galaxies under the crucial assumption that our basic cosmological theory about dark matter is correct. This theory, known as cold dark matter, does a great job at explaining the large scale universe, but has faced difficulties on smaller scales (predicting the detailed properties of galaxies)— suggesting that perhaps the theory needs to be refined in some way.

Importantly, cold dark matter is a hierarchical theory. It predicts that small objects form first, merging to form bigger things over time. The small mergers that make faint stellar halo features must occur fairly often in this theory. The fact that predictions like this seemed to have held up over the years in the face of increasingly larger data sets is one of *my* main reasons for thinking that this theory may be truly accurate even on the length scales of galaxies.



The stellar halo of the spiral galaxy M31 (shown to scale in the inset) as mapped out by the PAndAS collaboration. Streams and loops of stars built by past merger events are apparent. Image credit: Irwin/McConnachie/Martin.

Arguably the most complete picture we have of any stellar halo is the one around the Milky Way's sister galaxy, Andromeda (M31). Our view of the Milky Way is incomplete because we are buried inside of it. Andromeda, on the other hand, is far enough away to see it all at once, but also close enough that we can map out the locations of individual stars. A team of scientists lead by Alan McConnachie has produced a portrait of Andromeda's stellar halo that is nothing short of astounding. Andromeda too is surrounded by a complex web stellar streams, plumes, and clumps—the residue of ancient star systems, long since destroyed.

There is a burgeoning field in astronomy that goes by the name *galactic archeology*. The goal is to study old galactic stars, the ruins of galaxies long since toppled, with the hope of uncovering secrets about some of the very first galaxies to form in the Universe. This type of "near-field" cosmology (a term coined by Freeman & Bland-Hawthorn) is complementary to "deep-field" research, which aims to study the first galaxies by effectively looking back in time to study them directly. In many ways studies of our own Galaxy have come full circle. Just as the young Jan Oort did in 1922, we aim to inform our cosmology by mapping the stars.