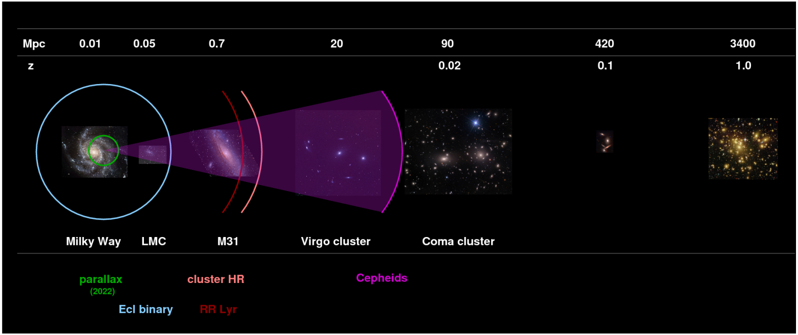
Dwarf Galaxies

Stream Detection

Dr. Nina Hernitschek
December 13, 2022

Recap Last Session

We saw that variable stars are important to calculate distances to old Milky Way components such as dwarf galaxies and globular clusters.



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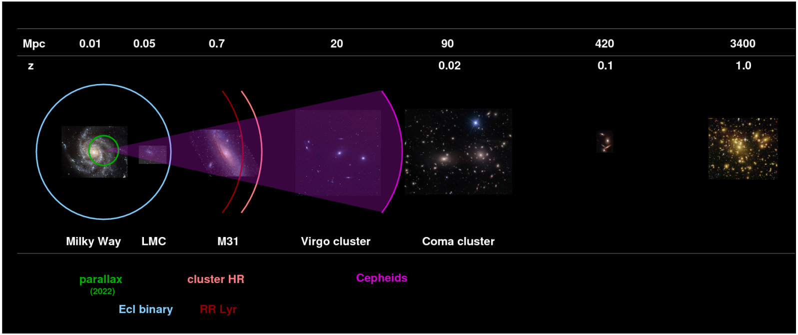
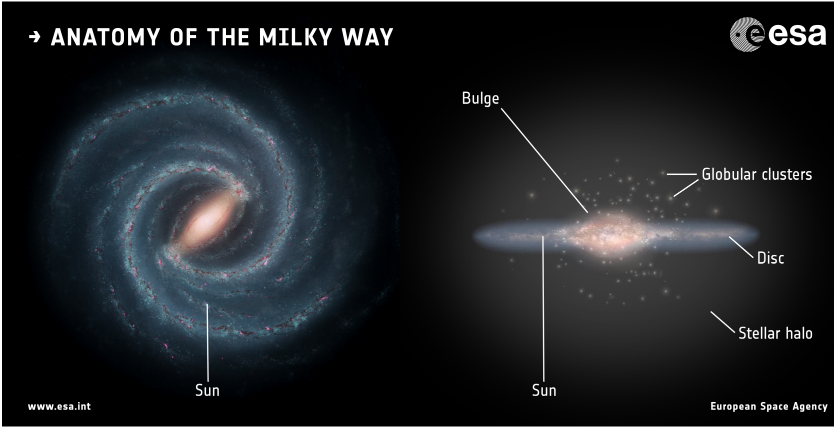


We can use variable stars to **trace old Milky Way substructure**.

Galactic Substructure

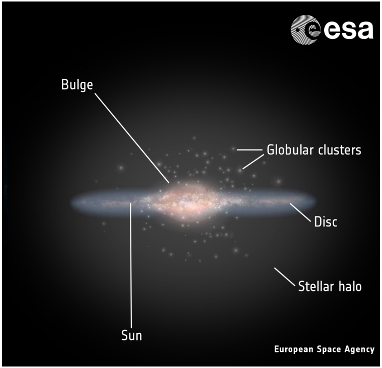


adapted from an illustration by European Space Agency

The Stellar Halo of the Milky Way

The Galactic Plane is surrounded by a stellar halo.

- extends to $\sim$140 kpc
- $L{\sim}10^9 L_\odot$, about 1% of the total luminosity of the Milky Way
- 0.2% of the thin disc at the Solar neighborhood
- very concentrated: half-light radius $\sim$3 kpc
- density profile of the halo stellar population: $n(r) \sim n_0(r/r_0)^{-3}$

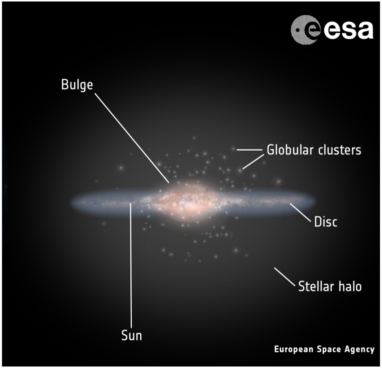


The Stellar Halo of the Milky Way

The Galactic Plane is surrounded by a stellar halo.

As stars are made from dense gas clouds, we would expect the central part of the Halo to be the denser ones: oldest (metal poorest). Instead, old stars are found in the halo globular clusters, its most extended component.

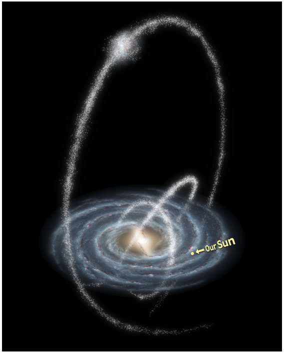
Why?



Our Milky Way, like other large galaxies, is a *cannibal*: frequent mergers with closest neighbor galaxies and its satellite galaxies

Stellar Streams

A **stellar stream** (also known as **tidal stream**) is an association of stars orbiting a galaxy that was once a globular cluster or dwarf galaxy that has now been torn apart and stretched out along its orbit by **tidal forces**.



credit: Spitzer, Caltech

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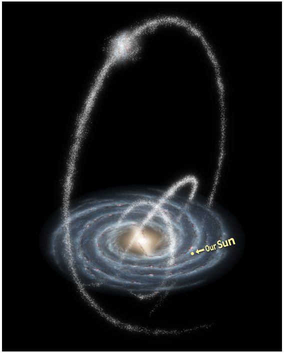

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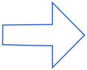
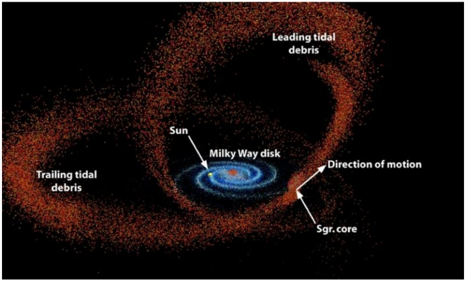


stellar streams are essential dynamical probes of the accretion history and the dark matter distribution of the Milky Way

Stellar Streams - Terminology

Stellar streams, also known as tidal streams, result from a **stream progenitor** - a globular cluster or a satellite dwarf galaxy - being disrupted by its host galaxy's **tidal forces**. Stars are drawn out from the progenitor into a tidal stream that then orbits the host galaxy; the progenitor itself may remain connected to the stream, orbit separately, or disrupt entirely. Stellar streams have **leading and trailing arms**, defined by the direction of motion.

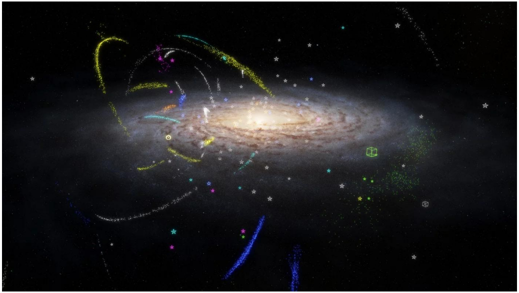


credit: David R. Law, UCLA

Galactic Archaeology

Stellar Streams (and other substructures in the halo) serve as probes of the Milky Way's merger history.

In recent years, large-scale surveys, e.g. Gaia, have dramatially increased the number of known stellar streams in the Milky Way, leading to field known as **Galactic archaeology**.

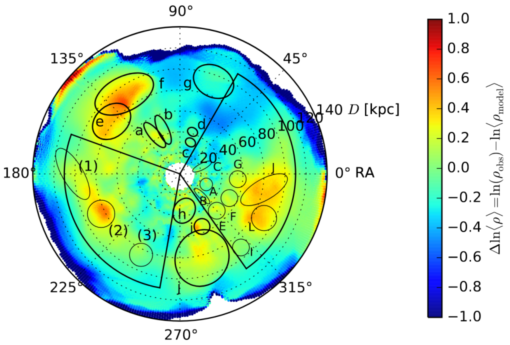


The Milky Way with stellar streams (colored dots), globular clusters (star symbols) and dwarf galaxies (small cubes). credit: S. Payne-Wardenaar / K. Malhan, MPIA

Galactic Archaeology

Stellar streams are great archaeological tools, e.g.:

- Constraining the Milky Way's gravitational potential, dark-matter distribution, lumpiness of the halo (e.g. Ibata et al 2002, Law & Majewski 2010, Bovy et al. 2015, Hernitschek et al. 2018)



Milky Way halo overdensities (credit: Hernitschek et al. 2018)

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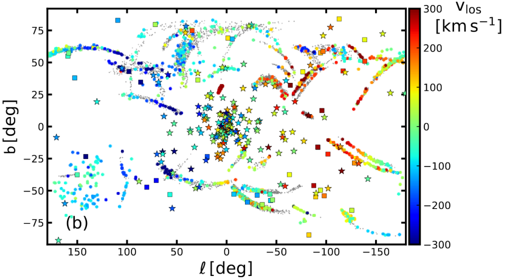
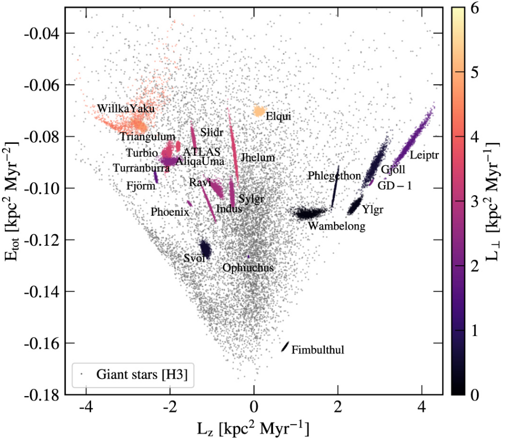
- Estimating fundamental parameters ($R_\odot$, $V_\odot$) of the MW Galaxy (Majewski et al. 2006, Kupper et al. 2015, Malhan & Ibata 2017)
- Merger history of our Galaxy (e.g. Malhan et al. 2022)



Galactic map showing measurements of 170 globular clusters (★), 41 stellar streams (○) and 46 satellite galaxies (□) (credit: Malhan et al. 2022)

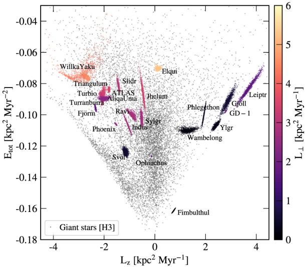
Stellar Streams in the Milky Way



The orbital energy vs. angular momentum of the stars in 23 of the Milky Way's stellar streams (colored and labeled data), as compared to field stars (black data) using Gaia data. From Bonaca et al. (2021).

Stellar Streams in the Milky Way

Motivation
Galactic Substructure
Stellar Streams
Stream Detection
Outlook



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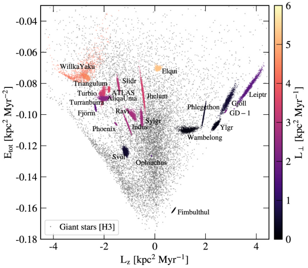

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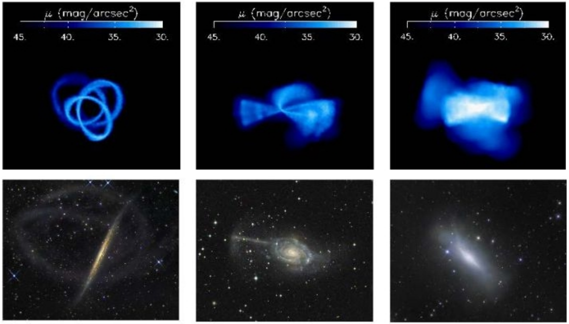
⇒ mapping out the big-picture distribution of dark matter in our galaxy and studying the small-scale structure of dark matter in the streams' host galaxies

Stellar Streams in other Galaxies

We have observed stellar streams in other galaxies (like NGC 5907):

Stellar Streams in other Galaxies

Numerical simulations predict what can be observed:



top row: predicted tidal stream morphologies tidal stream structures from Johnston et al. (2008), external views

bottom row: observational archetypes of tidal stream structure from by Martínez-Delgado et al. (2010): great circle stream in NGC 5907 (left); shell-like structure around NGC 4651 (center); "mixed" debris near NGC 5866 (right panel)

Evidence of Interactions

evidence of interactions: **tidal stripping, two-body relaxation and dynamical friction**

these interactions typically show in three ways:

- the stripping of stars from a satellite galaxy due to the tidal field of the primary
- the persistence of such tidal streams over long timescales, and
- the eventual consumption of the satellite galaxy by the primary due to dynamical friction.

Tidal Stripping

also called **tidal disruption**

We consider a satellite galaxy (such as a dwarf galaxy) or a globular cluster in a circular orbit around a host galaxy.

The tidal force of a massive body is defined as

$$\frac{\mathrm{d}F}{\mathrm{d}r} = -\frac{2GMu}{R^3} \qquad (1)$$

where u is a test mass at a distance R from a mass M.

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The tidal force experienced by the orbiting secondary mass as its orbits the primary is

$$F_T = -\frac{2GMu}{R^3} \times r \tag{3}$$

Tidal Stripping

The size of the orbiting secondary for which it will be stable against tidal stripping can be determined by setting $F_G = F_T$ and solving for r, i.e.

$$r = R\left(\frac{m}{2M}\right)^{1/3} = r_J \tag{4}$$

where r_J is called the Jacobi radius, tidal radius or the **Roche limit** where the gravitational force and the tidal force balance each other out.
Stars at $r > r_J$ will become unbound from the secondary, forming a tidal stream co-orbiting with the secondary but not longer bound to it.

caution: there are two definitions of the Roche limit: sometimes instead of the radius of the satellite, r, (like used here) it is solved for the distance between the centers of the bodies, R, when r is given.

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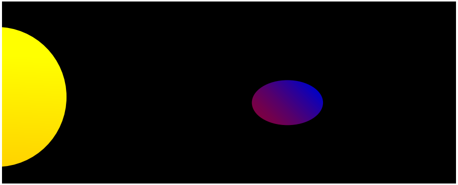

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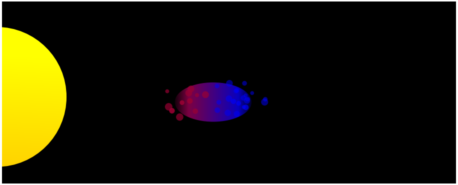

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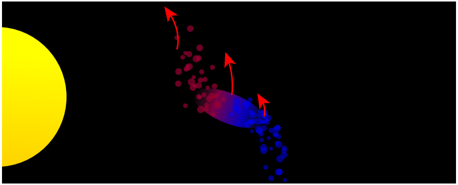

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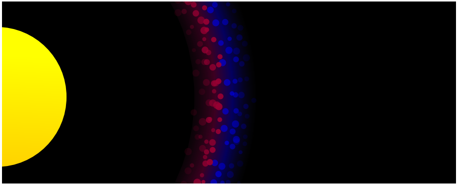

Tidal Stripping

We calculate the tidal stability of two satellite galaxies of the Milky Way: the LMC and Sagittarius dSph.

LMC

We take $m_{LMC} = 10^{10}\ M_\odot$, $R = 50\ \mathrm{kpc}$, $M_{MV}(< R) = 5 \times 10^{11} M_\odot$ with $V^2/R = M(< R)/R^2$. We then have:

$$r_{J,LMC} = 50\ \mathrm{kpc} \times \left(\frac{10^{10}}{2 \times 5 \times 10^{11}} \right) \approx 11\ \mathrm{kpc} \tag{9}$$

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Comparing this to the physical extent of the LMC which is about 4.5 kpc, we conclude that the LMC is stable against tidal stripping.

Credit: ESO/VMC Survey

Tidal Stripping

Sagittarius dSph
The mass of the Sag dSph is not well known. We take $L_{Sag} = 8 \times 10^7\ L_\odot$ and $M/L = 10$ which is reasonable for dwarf galaxies. We also take $R = 20\ kpc$ and $M(< R) = 2 \times 10^{10}\ M_\odot$. We get

$$r_{J,Sag} = 20\ \mathrm{kpc} \times \left(\frac{8 \times 10^8}{2 \times 2 \times 10^{11}} \right) \approx 2.5\ \mathrm{kpc} \tag{10}$$

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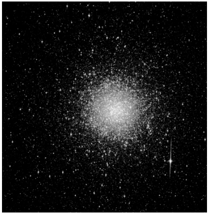
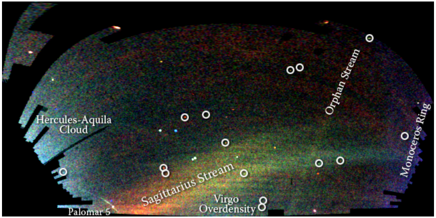
The long axis of Sag dSph extents 2.6 kpc. We conclude that this system is being actively stripped. Indeed it is the progentor of the Sagittarius stream, the Milky Way's largest stream.

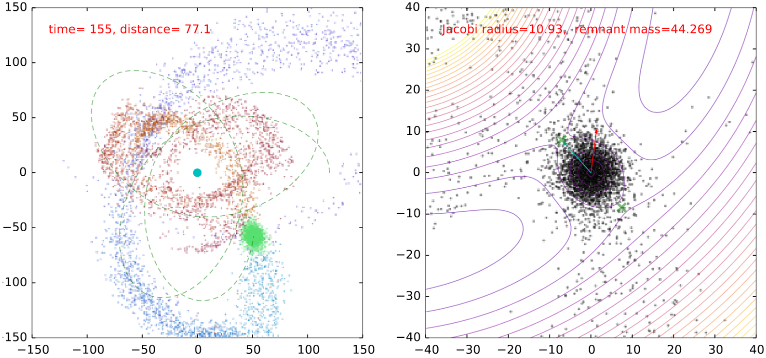




Credit: V. Belokurov and the Sloan Digital Sky Survey

Tidal Stripping

In the case of **eccentric orbits**, the satellite undergoes most stripping from *tidal shocks* during pericentre passages. A massive satellite further experiences **dynamical friction** in the host galaxy, which shrinks its orbit and accelerates tidal disruption even further.



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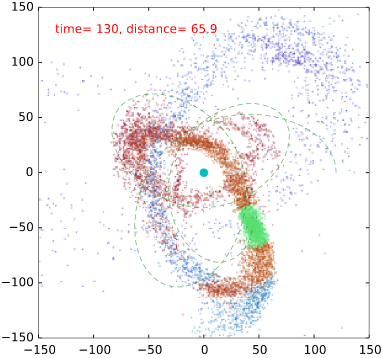

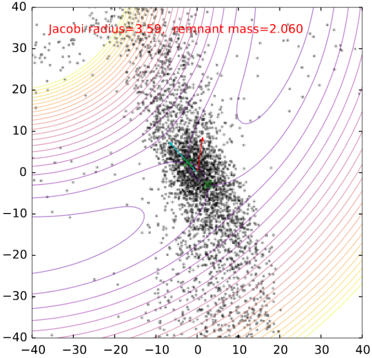

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Dynamical Friction

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As an object of mass M (the satellite) moves through a large collisionless system of particles $m \ll M$ (belonging to the primary), it experiences a drag force, called **dynamical friction**, transferring energy and momentum from the satellite to the field particles by the **integrated effect of numerous weak stellar encounters** between the satellite and primary.

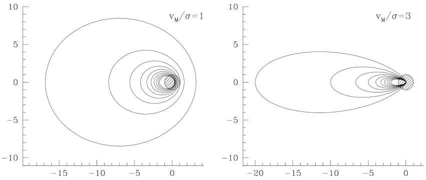

Figure: Object of mass M moves from left to right at speed v_M, through a homogeneous distribution of stars with 1D dispersion σ. Deflection of the stars by the mass enhances the stellar density downstream. The gravitational attraction of this wake on M leads to dynamical friction. Contour lines show equal stellar density in a plane containing the mass M and the velocity vector v_M.

Dynamical Friction

The **merging timescale from dynamical friction** is defined as the time for the satellite to reach zero velocity, i.e. (derivation not given here):

$$t_{merge} \sim \frac{v}{\mathrm{d}v/\mathrm{d}t} = \frac{v^3}{4\pi G^2 M \rho_*}$$

where M is the mass of the satellite galaxy and $\rho_* = nm$, the product of the number density of stars n.
One notes that $t_{merge} \sim 1/M$, i.e. more massive systems (e.g.: dwarf galaxies) are consumed faster than less massive systems (e.g.: GCs).
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example:
For a satellite galaxy with $v = 200\ \mathrm{km\,s^{-1}}$ and $M = 10^{10} M_\odot$ orbiting a galaxy at $R = 10\ \mathrm{kpc}$ and $M(< R) = 10^{11} M_\odot$ we get $t_{merge} \sim 3 \times 10^8\ \mathrm{yrs}$.
For Sgr dSph, one gets $t_{merge} \sim 10^{10}\ \mathrm{yrs}$. This indicates that it is reasonable to observe dwarf galaxies in close proximity to giants in the Local Group today: the merging time is of the order of the age of the Universe.

Two-Body Relaxation

How long might one expect the stellar features to persist?

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One can set the condition that a star will suffer a significant collision (leading to orbital mixing) when it encounters the potential of a star:

$$PE = KE \iff \frac{GM_*^2}{r} = \frac{m_* v^2}{2} \iff r < \frac{2Gm_*}{v^2}$$

Two-Body Relaxation

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Galactic Substructure

Stellar Streams

Stream Detection

Outlook

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With a mass of $1M_\odot$ and $v = 200\ \mathrm{km\,s^{-1}}$ (comparable to values for our Sun) one obtains $r = 2 \times 10^{-7}\ \mathrm{kpc}$.
The crossing time at a radius of 20 kpc can be approximated as $t_{cross} = \frac{6.2\times 10^{20} m}{2\times 10^5\ \mathrm{km\,s^{-1}}} = 3 \times 10^{15} s = 9 \times 10^7\ \mathrm{yrs.}$

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$\Rightarrow$ One would need to cross the Milky Way $\sim 3 \times 10^{10}$ times to encounter one star, which would take of the order 3×10^{18} years, i.e. longer than the age of the Universe.

Two-Body Relaxation

However, both giant and dwarf galaxies display coherent orbital motions. A significant level of relaxation must have occurred during their assembly.
One invokes the idea of **violent relaxation** in order to explain this: During the earliest epochs of galaxy assembly the potential in which the stars orbited was changing rapidly (violently) as galaxies built up their masses via vigorous merging with satellites **driven by dynamical friction**. The rapidly changing potential erased the original dynamical properties of the stars.

Detecting Stellar Streams

How to detect stellar streams?

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They aren't that obvious...

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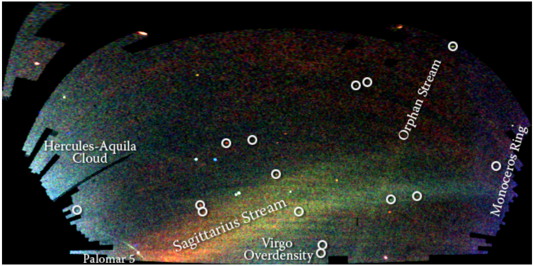
An **overview** of detection methods before we go into the details:

Detecting Stellar Streams

Resolved stellar structures (in the Local Group)

Stellar streams are **overdensities** - star counts will reveal them deep photometric surveys (SDSS, Gaia) allow for detection of tidal debris structure within the Milky Way

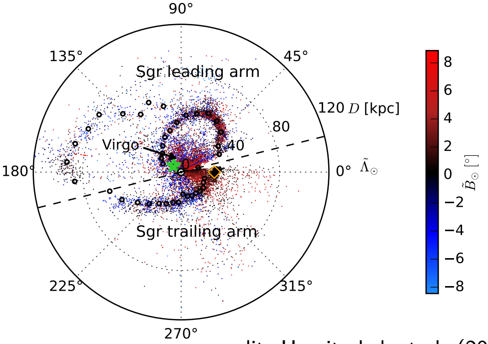
The famous *Field of Streams* image from SDSS (Belokurov et al. 2006) mapped substructure using main sequence turnoff (MSTO) starcounts fainter than $\sim$32 mag arcsec^{-2}:



Detecting Stellar Streams

Further stream details (low surface brightness features) detected by **kinematical selection** of stream members (i.e.: spectroscopic velocities). This allows features in the Galactic halo containing fewer than ~ 1 red giant branch (RGB) star per square degree to be identified.

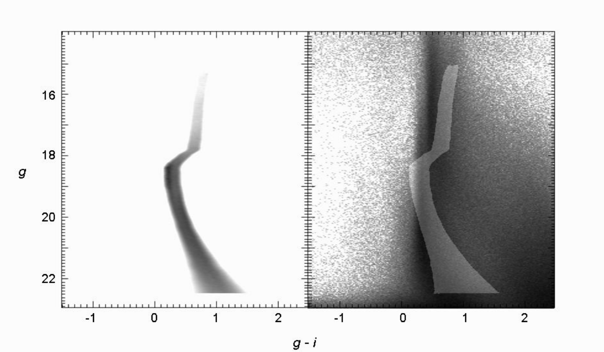
Stellar streams can be **traced by variable stars**, i.e. by selecting RR Lyrae stars.



credit: Hernitschek et al. (2017)

Matched Filter Analysis

a common modern tool to detect stellar streams is called **matched filter analysis**



left panel: Matched filter based on the SDSS CMD of stars in M13, luminosity function based on Ω Cen. The filter's peak response occurs on the blue side of the main-sequence turn-off, where there are relatively few foreground stars. The filter width is based on the SDSS photometric errors as a function of magnitude. right panel: The CMD of stars lying within 10° of the eastern half of the Cocytos stream, with the filter overlaid. credit: Grillmair et al. (2009), Figure 1

Matched Filter Analysis

how does a matched filter analysis actually work?

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In signal processing, a matched filter (Wiener 1949) is **obtained by correlating** a template with an unknown signal to detect the presence of the template in the unknown signal. This is equivalent to **convolving** the unknown signal with a conjugated time-reversed version of the template. The matched filter is the optimal linear filter for maximizing the signal-to-noise ratio (SNR) in the presence of additive stochastic noise:

$$(S/N)_{out} = s_0^2(t)/n_0^2(t)$$

where $s(t)$ is the input signal and $s_0(t)$ is the output signal.

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The solution for this filter can be found in the presence of noise, provided the **noise is well described**.

$\Rightarrow$ Design the filter such that the effect of noise is minimized while maximizing the signal.

in our case:

signal $\widehat{=}$ stream member stars
background $\widehat{=}$ field stars

Matched Filter Analysis

This approach has since become a **standard technique** in signal processing and is used in astronomy for finding low-level overdensities of a stellar population against the Galactic stellar background.

It is important that the **background is well specified** and the **expected signatures are well-defined** such as, in addition to stellar streams, also clusters of galaxies (Postman et al. 1996; Kawasaki et al. 1998; Kepner et al. 1999) and planets around other stars (Doyle et al. 2000).

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examples of streams found by matched filter:

Pal5 22d, NGC 5546, GD1, Orphan, anticenter of Monoceros (Grillmair et al. 2006)
Acheron, Cocytos, Lethe, and Styx streams (Grillmair et al. 2006)

further analysis was carried out by e.g. Ibata et al. (2007) and Rockosi et al. (2002)

Matched Filter Analysis

identifying **cluster, stream populations**:

Matched Filter Analysis

Motivation
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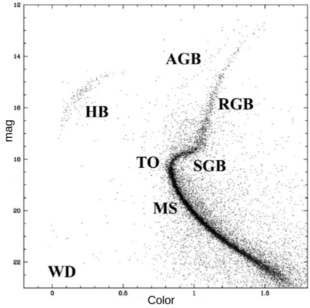
identifying **cluster, stream populations**:

A stellar population of **given age and metallicity** (e.g.: a globular cluster or stellar stream) is located in color-color space in a predictable way according to the astrophysical constraints of star formation and evolution. If this population is concentrated in space, then it is constrained in magnitude as well, resulting in the familiar globular cluster CMD.



The observational CMD of the globular cluster M12.

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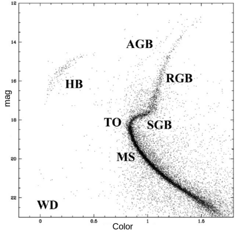

density of cluster stars on the CMD (observed, theory) $\Rightarrow$ two-dimensional **number density function** for cluster (or stream) stars, $n_{cl}(color, mag)$ which is normalized as $f_{cl}(color, mag)$

This is analogous to the probability density function from statistics: it describes the **relative probability** of finding a star drawn from the cluster or stream population at any location in color and magnitude.

Matched Filter Analysis

the **background** field star population:

Matched Filter Analysis

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Just as for the cluster stars, the field star background population is not randomly distributed on the color-magnitude plane.

The stellar background will vary:

Matched Filter Analysis

the **background** field star population:

Just as for the cluster stars, the field star background population is not randomly distributed on the color-magnitude plane.

The stellar background will vary:

- according to the constraints of stellar evolution, with the stars further spread in color and magnitude by the substantial range in age and distance within the major components of the Galaxy
- with the position in the galaxy

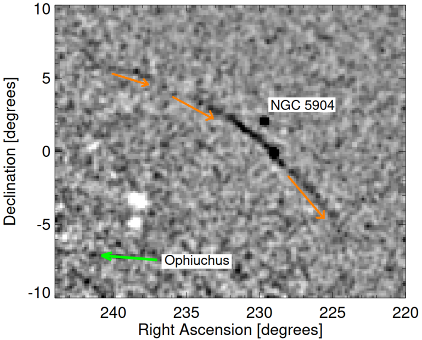
The **matched filter analysis** then assigns higher weights to stars in CMD regions dominated by the target stellar population.

Characterizing Stellar Streams

revealing the **orbial structure** of stellar streams: **kinematics**

example: Pal 5 stream.

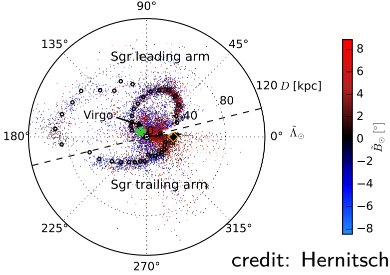
Discovered by Odenkirchen et al. (2001). This map was created by Bernard et al (2016).



Characterizing Stellar Streams

e.g.: **Sagittarius stream**:

- proposed by Lynden-Bell (1995) from analyzing the distribution of globular clusters
- discovered by Newberg et al. (2002) and Majewski et al. (2003) using data from the 2MASS and SDSS surveys
- two-branch structure was found by Belokurov (2006)
- stream was subsequently further characterized, e.g. by Hernitschek et al. (2017) tracing the complete extent of Sgr stream with RR Lyrae stars from Pan-STARRS1 3π



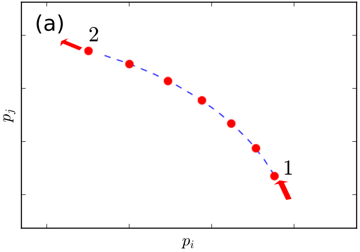
credit: Hernitschek et al. (2017)

STREAMFINDER (Malhan & Ibata (2018))

Maximize stream detection (and characterization) by:

- Use all the prior information about the stellar stream (knowledge of phase-space-color-magnitude distribution)
- Use all the information delivered by Gaia DR2

key idea: detect streams by looking at their orbits



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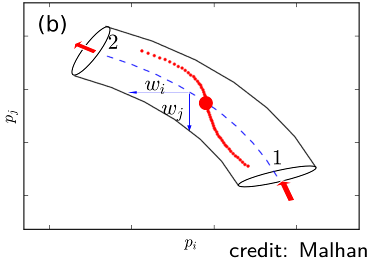
key idea: detect streams by looking at their orbits
assumption: stream members contained in a 6D hypertube and its 6D volume $\sim f(\sigma_w, \sigma_v, t_{orbit})$



credit: Malhan & Ibata (2018)

STREAMFINDER

Log-likelihood of a star being associated with a stellar stream

$$\mathscr{L}_k = L_{kinematics} + L_{LF} + L_{continuity}$$

data-orbit comparison given observed errors

luminosity function criteria

stream continuity critera

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- $L_{kinematics}$: data-orbit comparison given observed errors
- L_{LF}: luminosity function criteria
- $L_{continuity}$: stream continuity critera

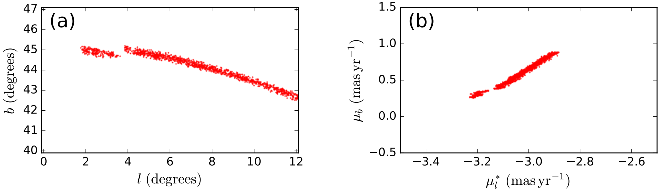
⇒ $\mathscr{L}_k$ acts as *weight* for every star to obtain stream density plot

STREAMFINDER

Testing algorithm with N-body simulated stream

- simulated a globular cluster stream with realistic galactic model (Dehnen & Binney 1998)
- retained only 50 stream objects, Σ_G =33 mag arcsec^{-2} (faint stream)
- retained only 4D phase-space information: l, b, μ_l, μ_b (with errors)
- v_{rad} and ω information was deleted
- convolved Gaia-like errors in proper motions
- assigned a SSP model to the stream of ([Fe/H], Age)= (-1.5, 10 Gyr)

"perfect" stream (no errors)



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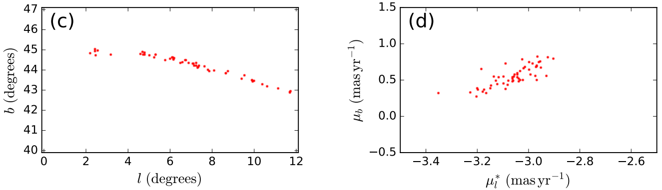
Gaia-like errors



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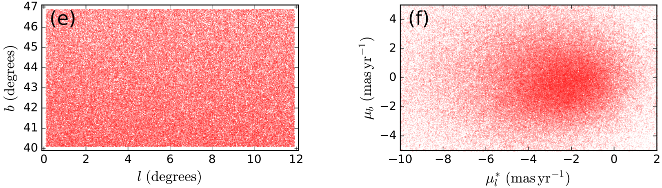
Mock field stars with the mock stream superposed, nstream/ndata $\sim$ 0.015%.



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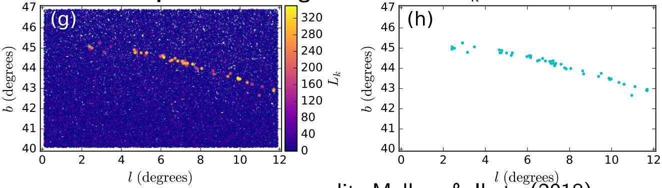
(g) relative likelihood $\mathscr{L}_k$, revealing the low contrast stream feature, while (h) represents the subsample with the highest values of $\mathscr{L}_k$



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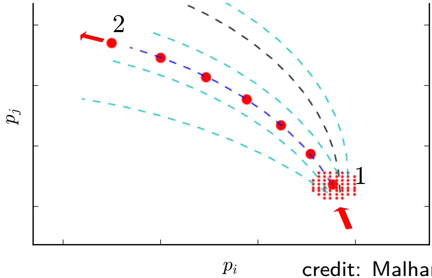
STREAMFINDER

Main advantage of the algorithm:

Orbit sampling: Completing the 6D phase-space $DF(x, v)$ of detected stellar streams. Due to measurement uncertainties and missing phase-space information of the stars, their current 6D phase-space position cannot be pinned down precisely, but likely orbits can be sampled.



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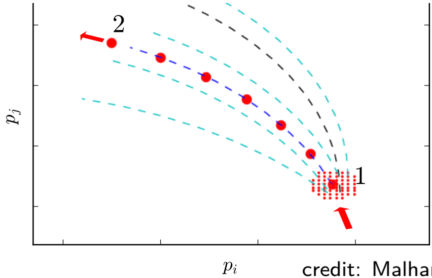


credit: Malhan & Ibata (2018)

infering orbital properties of stellar streams

STREAMFINDER - Results

MW Stellar Stream maps from Gaia DR2 using STREAMFINDER (Malhan, Ibata & Martin 2018)

Gaia DR2 released on 25 April 2018:

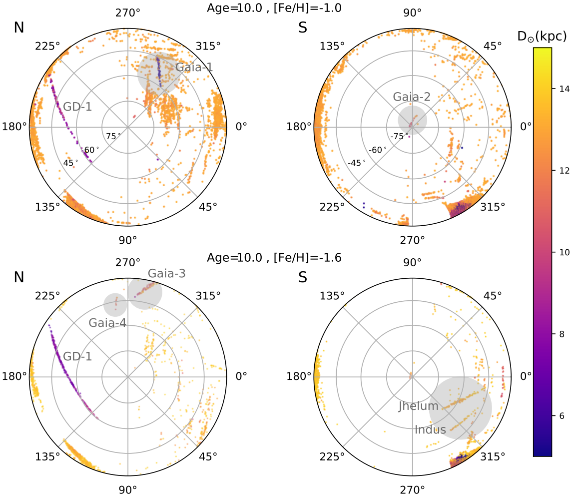
- 1.7 billion sources down to G$\sim$20.7.
- Positions $+$Proper motions$+$ parallaxes (not so good) $+$G,BP,RP for all sources

processed with STREAMFINDER:

- Gaia DR2 dataset $|b| > 30^\circ$
- GCs and DGs masked

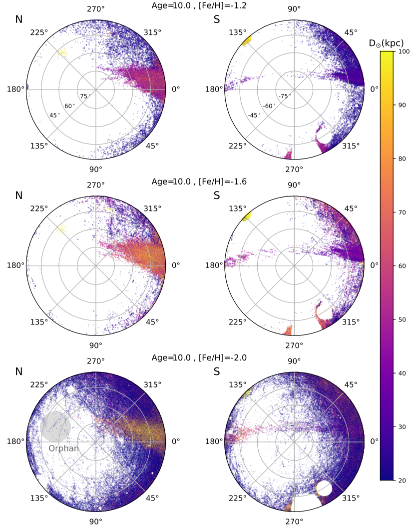
STREAMFINDER - Results

Inner halo. Distance =[5, 15] kpc. (Malhan et al. 2018b)



STREAMFINDER - Results

Outer halo. Distance =[20, 100] kpc. (Malhan et al. 2018b)



The Southern Stellar Stream Spectroscopic Survey (S^5)

~ 60 stellar streams known

They need **spectroscopic follow-up**: kinematics, metallicities

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The Southern Stellar Stream Spectroscopic Survey (S5) is the first systematic program pursuing a complete census of known streams in the Southern Sky

- >50 nights since 2018 on the AAT/AAOmega
- 80,000 targets across 20 stellar streams identified in Gaia and DES

first public data release in April 2021
data available via `s5collab.github.io`

⇨ largest homogeneously analyzed set of streams, full 6D kinematics and metallicities for 12 streams

The Southern Stellar Stream Spectroscopic Survey (S^5)

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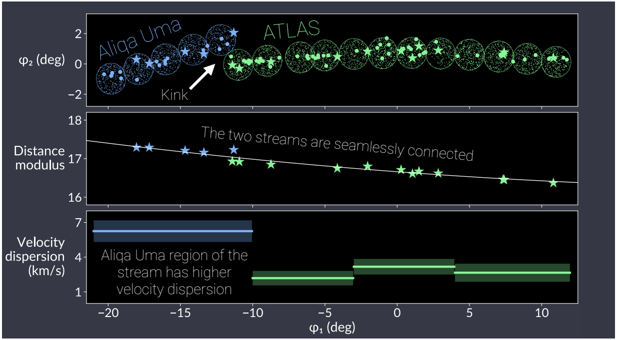
interesting findings from S^5:

S5-HVS1: a high-velocity star ejected from the Galactic centre

The Phoenix Stream: a stream created from a globular cluster in the *forbidden zone*

ATLAS-Aliqa Uma: one stream that was broken in two



credit: S^5 team

Detecting Progenitors of Stellar Streams

Globular clusters (GCs) and dwarf galaxies, the progenitors of stellar streams, reach luminosities ranging from 10^3 to $10^6 L_\odot$.

Globular clusters are stable, tightly bound clusters of $\sim 10^4 - 10^6$ of stars. The MW possesses some 150 GCs, M31 approximately 500. Giant elliptical galaxies may contain up to 13,000 GCs.

globular cluster M 10; credit: ESA/Hubble & NASA

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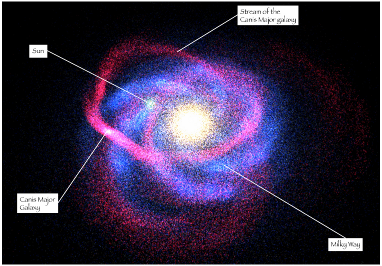
- kinematics do not indicate presence of dark matter
- stellar population is very uniform and old ($\sim$ the age of the Universe), metal poor (100th solar metallicity)
- blue, metal poor GCs are the oldest systems and they preferentially reside in the halo of the MW
- red, metal rich (i.e. 1/10th solar metallicity) GCs represent younger (by a couple of gigayears) populations and reside in the bulge of the MW

Detecting Progenitors of Stellar Streams

Local Group: brightest members are of sufficiently high surface brightness to have been catalogued by Messier ∼1781

dwarf galaxies Sculptor and Fornax: discovered by Harlow Shapley in 1937 and 1938 as faint **nebula** that can be **resolved** into individual stars

fainter dwarf galaxies: below the limit of even deep CCD exposures, e.g. $\mu_B = 27$ - 30; detection using resolved luminous red giant star counts (e.g. Sagittarius dSph, Ibata et al. 1994; Canis Major, Martin et al. 2003)



Canis Major Dwarf,

credit: R. Ibata

for **dynamics**: spectroscopy required to determine if stars making up a given overdensity form a dynamically coherent group

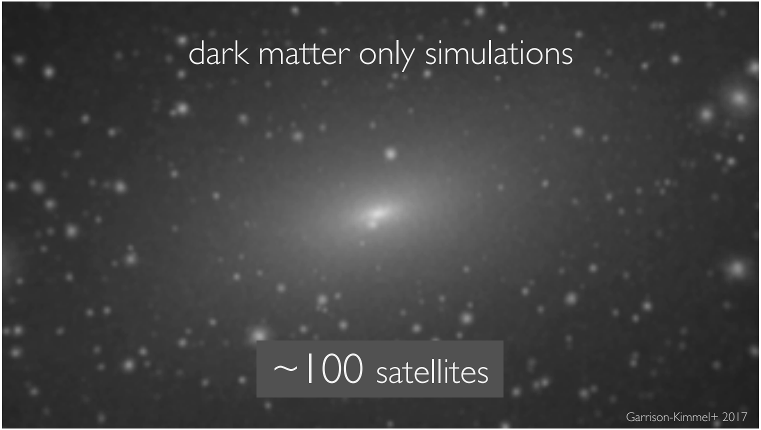
The "Missing Satellite(s)" Problem

The dwarf galaxy problem, also known as the **missing satellites problem**:

mismatch

observed dwarf galaxy numbers ⟺ numerical cosmological simulations

The “Missing Satellite(s)” Problem



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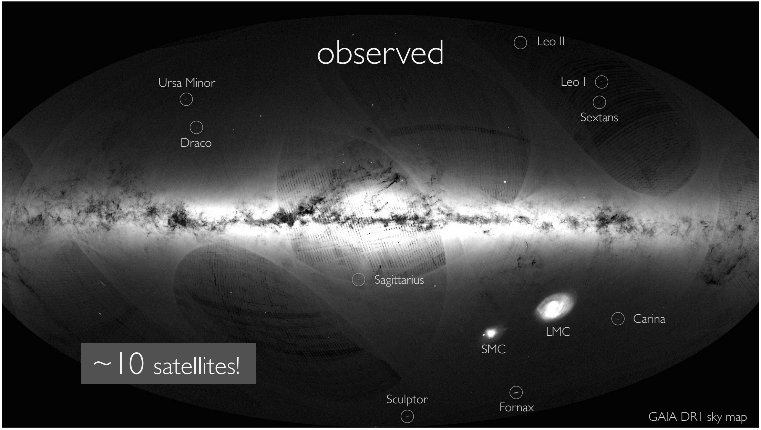

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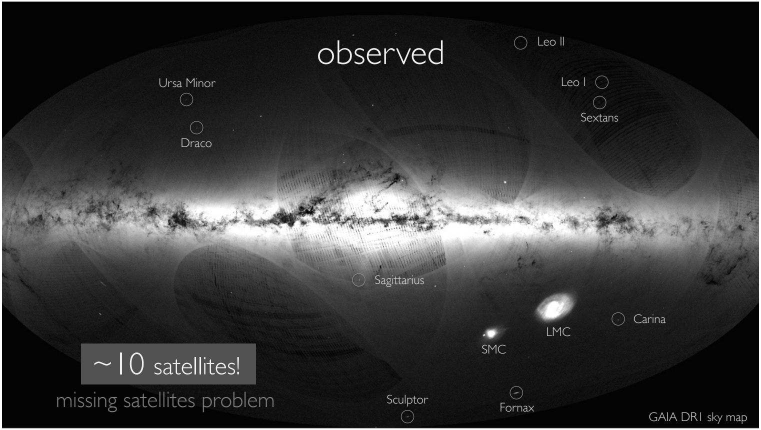

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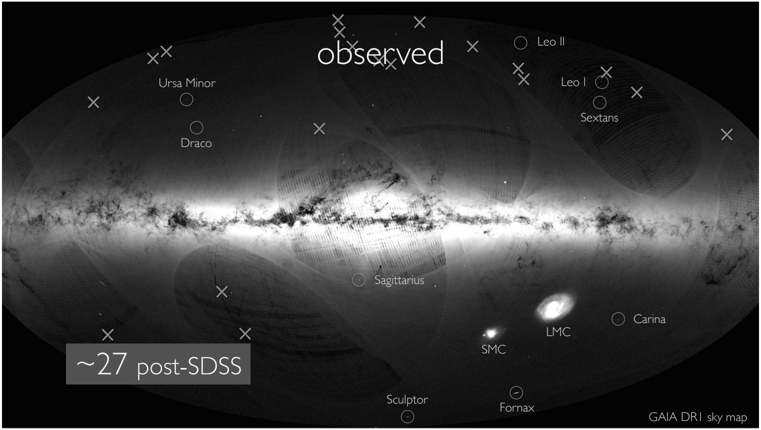

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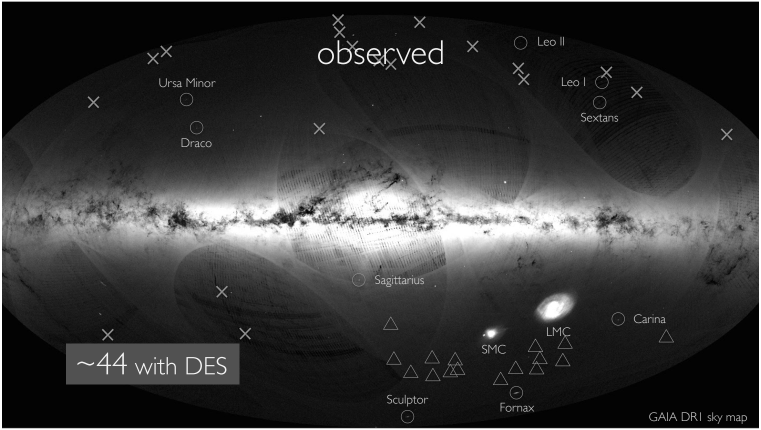

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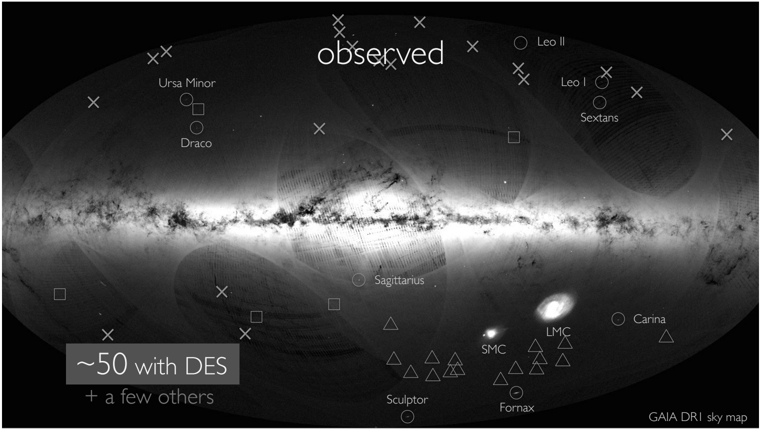


The “Missing Satellite(s)” Problem

simulations:

dark matter clusters hierarchically, in ever increasing numbers of concentrations with decreasing size

number of ‘normal-sized’ galaxies matches, number of dwarf galaxies ~ 1 magnitude higher than observed

Simulation: Myriad concentrations of dark matter are embedded within the galaxy’s halo. credit: Virgo Consortium.

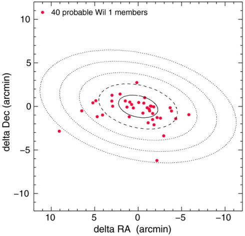
The "Missing Satellite(s)" Problem

The missing satellite problem has been **discussed** from two perspectives:

1. The cold dark matter hypothesis underpinning the computer simulations may be flawed at some level.
2. Observational census of the Local Group dwarf galaxy population may be incomplete.

ultrafaint dwarf galaxies: e.g. Segue 1 (Geha et al 2009) with a luminosity $L_V = 340L_\odot$ ($\sim$ of a single red giant), $M = 4.3 \times 10^5 M_\odot$.

Segue 1, credit: M. Geha



Willman 1, credit: Willman et al.

... beyond the Local Group

Current ground-based telescopes cannot resolve stellar tidal streams around most galaxies beyond the Local Group into individual stars.

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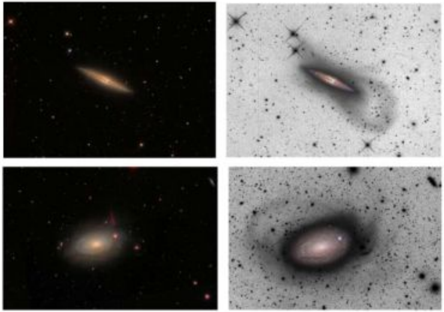
mapping such streams requires deep imaging that can map those streams at least as elongated, diffuse-light regions



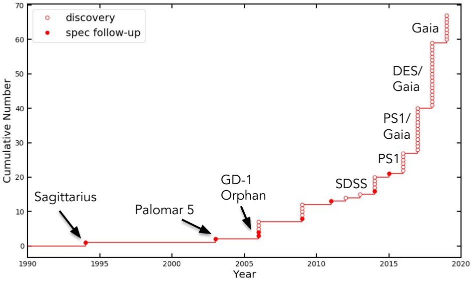
SDSS images of the nearby galaxies NGC 4013 (top) and M63 (bottom). SDSS (left) does not reveal tidal streams. Deep images (right) of these same galaxies show a low-latitude stellar stream around NGC 4013 (Martínez-Delgado et al. 2009) and a giant tidal stream around M63 (Chonis et al. 2011). Color-image insert for reference.

Outlook

Future telescopes like the Vera Rubin Observatory (LSST survey) and the Roman Space Telescope will be able to detect thousands of extragalactic stellar streams.

The tools built already will pave the way for exploring dark matter halos of all those galaxies!

Stream Discovery Timeline



Credit: Ting Li