The Geometry of Sagittarius Stream from PS1 3π RR Lyrae

Nina Hernitschek, Caltech

collaborators:
Hans-Walter Rix, Branimir Sesar, Judith Cohen

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Pan-STARRS 1 as a Time Domain Survey

most ambitious panoptic multi-epoch multi-band survey to date:

- solar system objects
- transients
- proper motions (& parallaxes)
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RR Lyrae:

- periodically varying on 1/4 day timescales
- high-precision 3D mapping of the (old) Milky Way [Hernitschek+2016], [Sesar+2017b]

Pan-STARRS 1 as a Time Domain Survey

PS1 3π in one sentence:
An optical/near-IR survey of 3/4 the sky in non-simultaneous *grizy* to $r \sim 21.8$ based on ~ 70 visits over a 5.5-year period.

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map galactic halo to $\sim$120 kpc

DEC $> -30^\circ$

5σ single-visit depth of 22.0, 21.8, 21.5, 20.9, 19.7 mag

coadded depth of $r \sim 23.2$ mag

sky coverage of $\sim$31,000 deg^2 (3/4 sky)

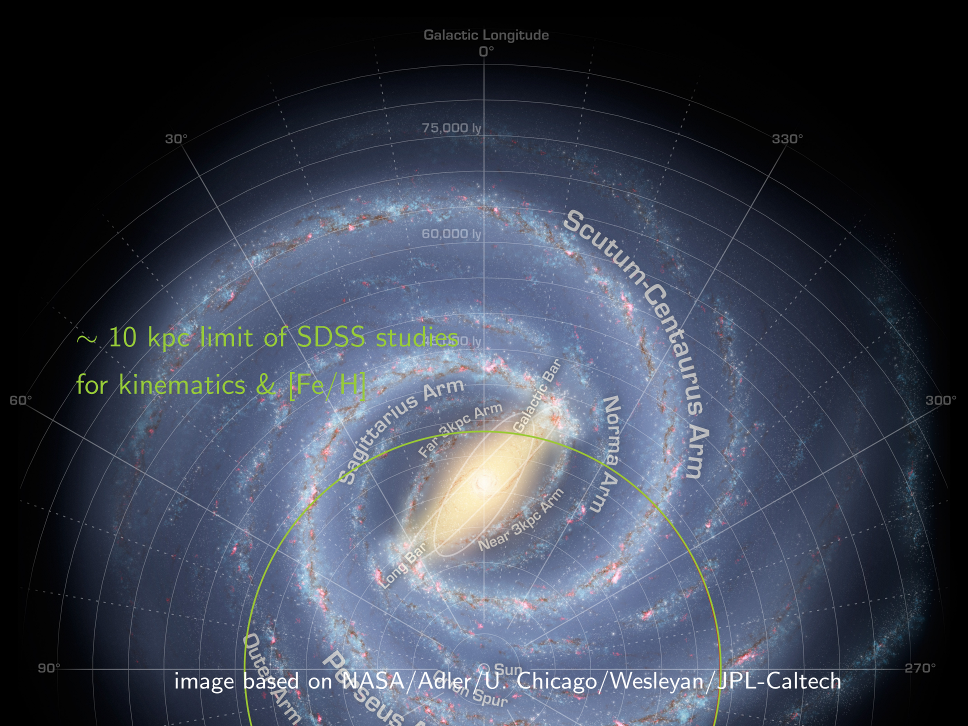

image based on NASA/Adler/U. Chicago/Wesleyan/JPL-Caltech

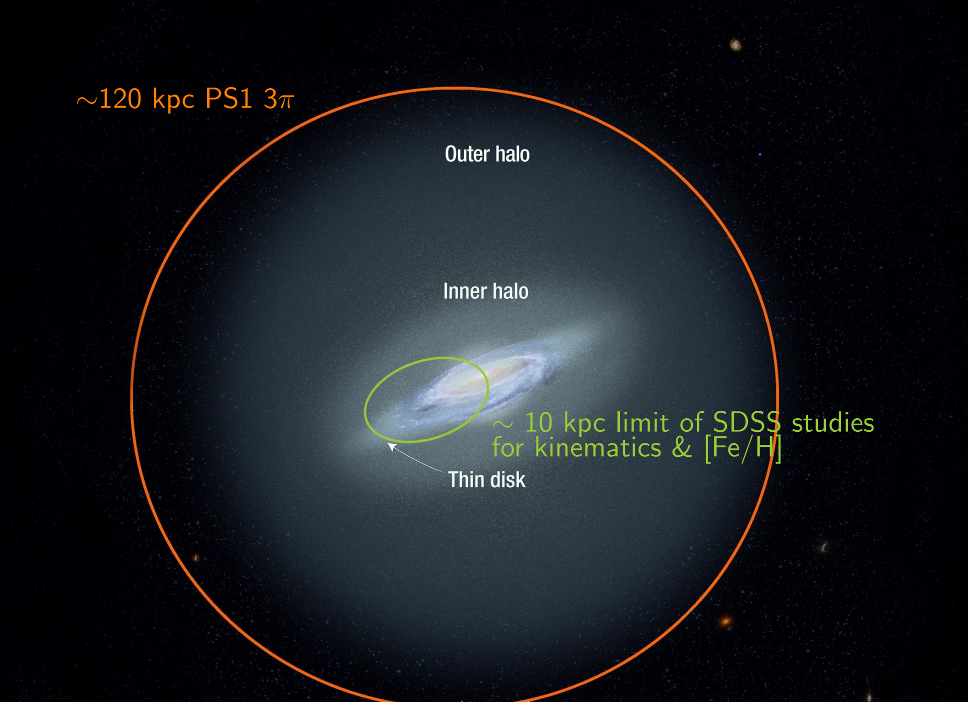

image based on NASA, ESA, and A. Feild (STScI)

RR Lyrae from PS1 3π

RR Lyrae variables are

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- periodical pulsators

$\Rightarrow$ easy to find and important tracers for old halo substructure

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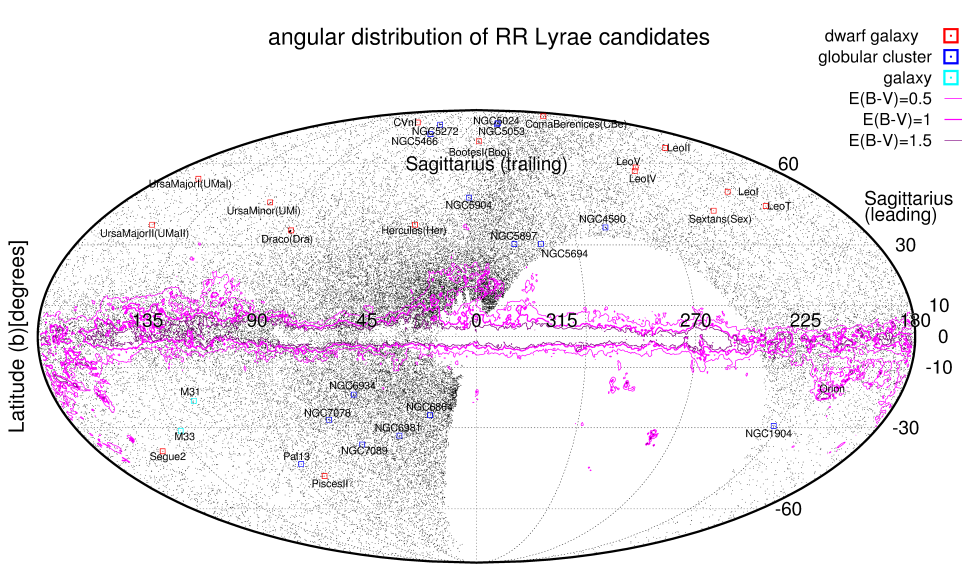
select RRab stars

using variability characterization & machine-learning source classification [Hernitschek+2016, Sesar+2017b]

$\Rightarrow$pure (90 %) and complete (80% at 80 kpc) sample of 44,403 RRab stars, distance estimates up to $\sim$130 kpc, precise to 3%

Map of PS1 3π RRab stars



Stellar Streams

sets of stars on similar orbits $\rightarrow$ constraining the dynamical mass within their orbit $\rightarrow$ probe of the Galactic mass profile and shape including DM halo & accretion history

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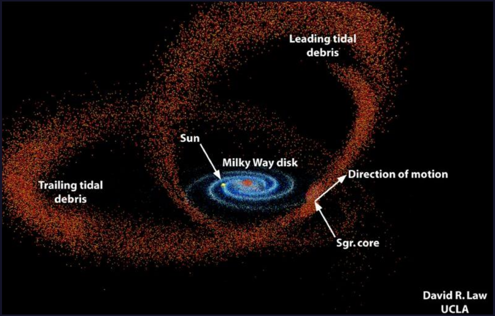
There are many streams, why the Sagittarius stream?

$\Rightarrow$ has a larger distance compared to others like GD-1 [Koposov+2010, Bovy+2016] and Ophiuchus [Sesar+2016]

Sagittarius Stream

dominant tidal stellar stream of the Galactic stellar halo, discovered by [Ibata+1994]



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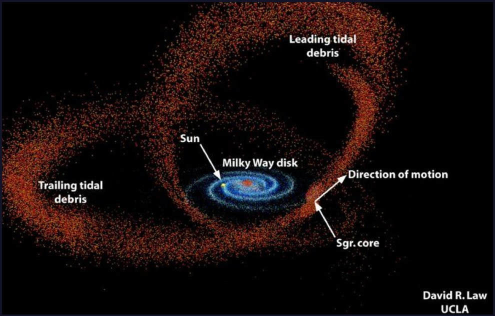
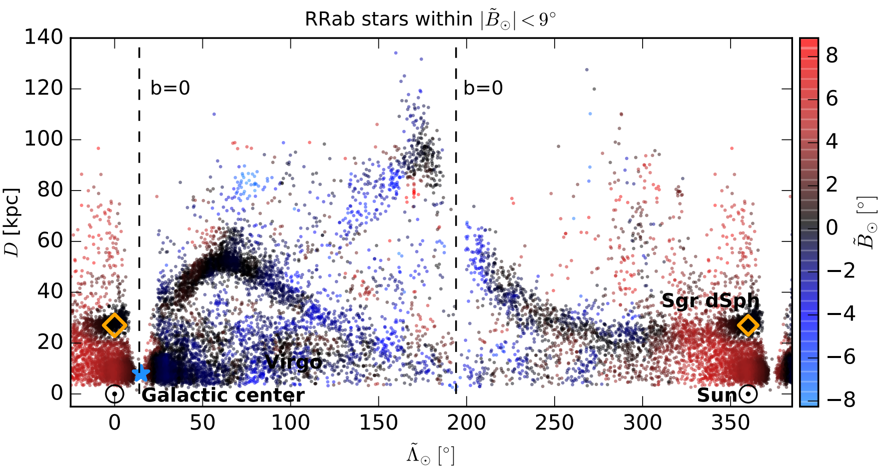


shows **two pronounced tidal tails** extending each $\sim 180^\circ$ and reaching Galactocentric distances from 20 to more than 100 kpc: referred to as **leading and trailing arm** [Majewski+2003]

Sagittarius Stream

PS1 3π RRab sample: enables us to **trace the complete** angular extent of the Sgr stream as well as to look even to its **outskirts**



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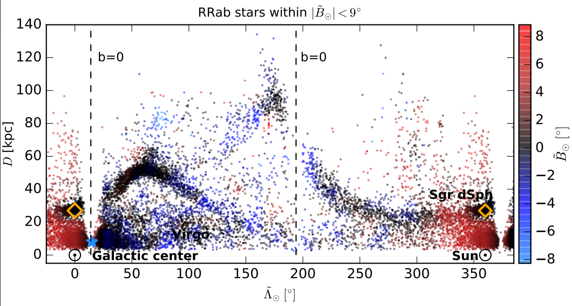

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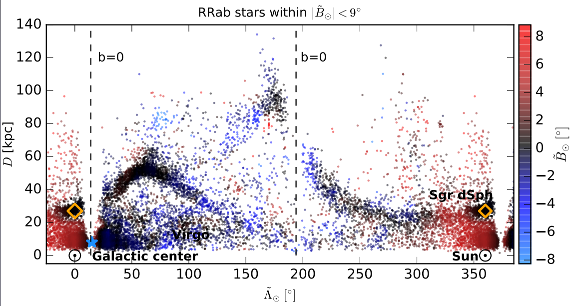

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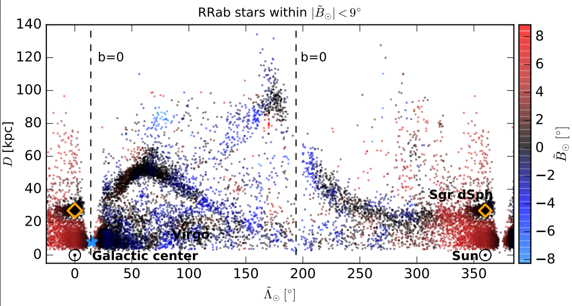

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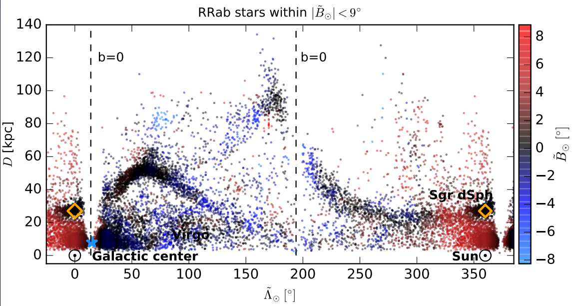

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- substructure at the apocenters of both the leading and trailing arm: two "clumps" (at $D \sim 60$ and 80 kpc) beyond the leading arm's apocenter, and a "spur" of the trailing arm reaching up to 130 kpc, predicted by dynamical models e.g. [Gibbons2014], [Diericks2017]

A Model for the Sagittarius Stream

quantitative description of the Sgr stream: mean distance and (line-of-sight and true) depth vs. $\tilde{\Lambda}_{\odot}$

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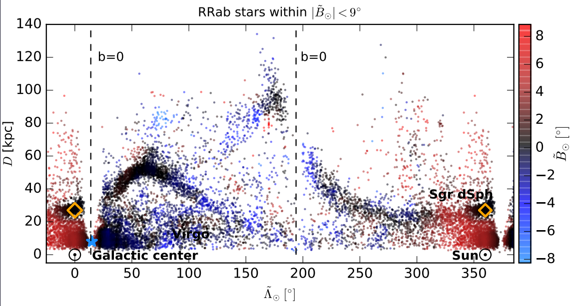

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distance distribution $p_{\mathrm{RRL}}(D)$ towards any $\tilde{\Lambda}_\odot$ is modeled as the superposition of a **stream** and a **halo** component

Gaussian, characterized by D_{sgr} and the l.o.s. depth, σ_{sgr}

power-law

$$\rho_{\mathrm{halo}}(X, Y, Z) = \rho_{\odot\mathrm{RRL}} \left(\frac{R_\odot}{r}\right)^n$$

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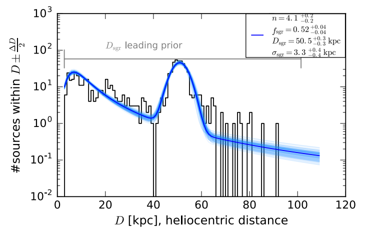

fit likelihood approach for each 10° $\tilde{\Lambda}_{\odot}$ slice, maximize with MCMC

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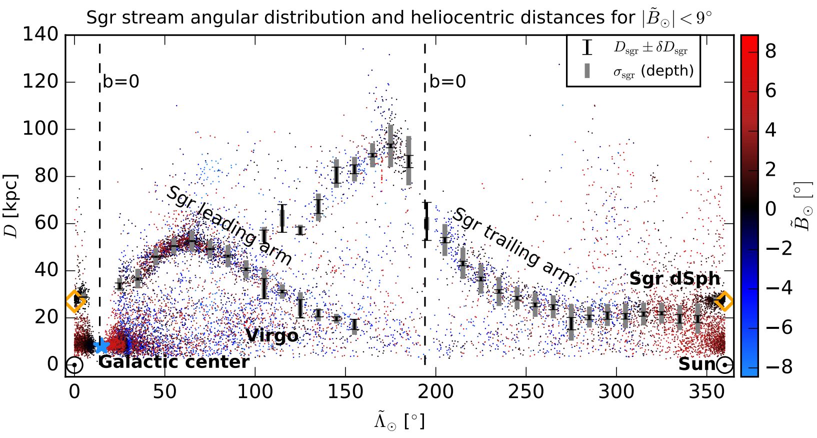
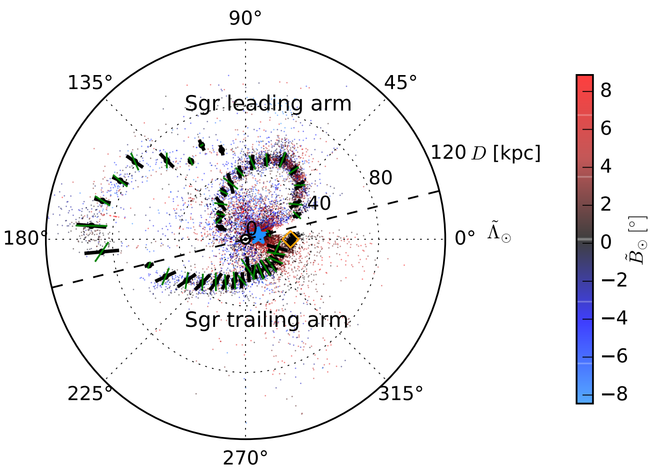


The Depth of the Sagittarius Stream

actual depth of the stream: we know the angle between the normal on the stream, and the line of sight $\Rightarrow$ **deproject**



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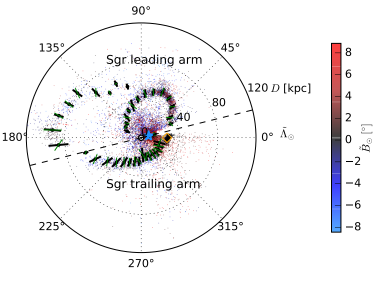
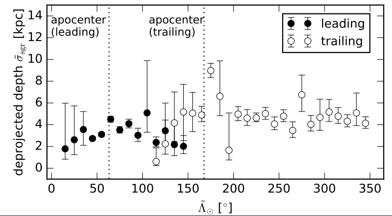
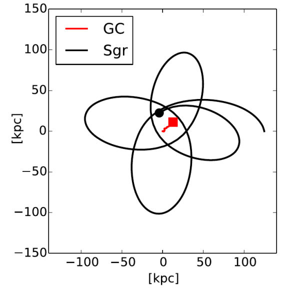


⇒ larger depth at the apocenters is a **combination of projection & true broadening** due to velocity decrease near the apocenters



The Orbital Precession of the Sgr Stream

Sources orbiting in a potential show a **precession**: do not follow an identical orbit each time, but actually trace out a shape made up of rotated orbits



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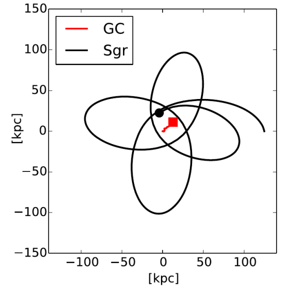

the precession depends primarily on the **shape of the potential**

$\Rightarrow$ radial mass distribution including Dark Matter

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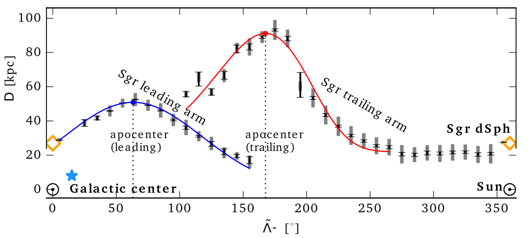

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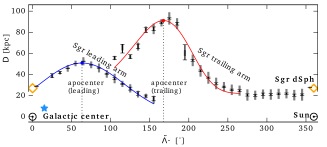

heliocentric orbit precession: $\omega_{\odot} = \tilde{\Lambda}^{T}_{\odot} - \tilde{\Lambda}^{L}_{\odot} = 104^{\circ}.4 \pm 1^{\circ}.3$

actual Galactocentric orbital precession: $\omega_{\mathrm{GC}} = 96^{\circ}.8 \pm 1^{\circ}.3$

$\Rightarrow$ comparable to [Belokurov+2014]: smaller value than for logarithmic haloes (120°)

$\Rightarrow$ strong indicator for a steeper profile of the MW's DM halo

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The **weight** of each star is the probability that the star is associated with the Sgr stream.

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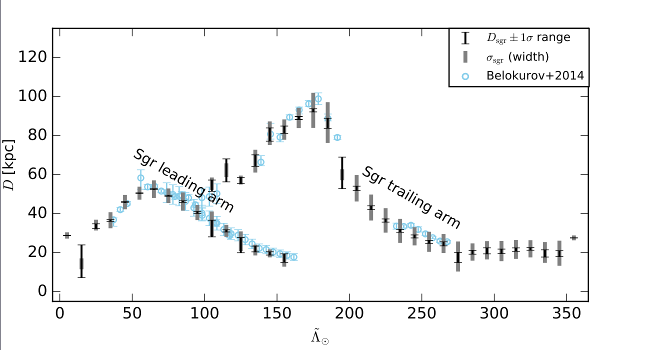
$\Rightarrow$ evidence for the leading arm staying in or close to the plane defined by $\tilde{B}_\odot = 0^\circ$, whereas the trailing arm is found within within -5° to 5° around the plane

$\Rightarrow$ we find a separation of $\sim 10^\circ$, as derived by [Johnston+2005]

Summary

We **quantified the geometry** of the Sagittarius stream: extent & depth as given by RRab stars out to > 120 kpc

best model before: [Belokurov+2014] using BHB, SGB & RGB stars



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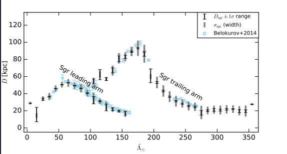

new: complete 360°**, single type of tracer, precise distances, mapping and deprojecting depth**

find striking features from [Dierickx+2017] simulation

B. Sesar et al., The > 100 kpc Distant Spur of the Sagittarius Stream and the Outer Virgo Overdensity, as seen in PS1 RR Lyrae stars, 2017, ApJL, 844, 1, L4

N. Hernitschek et al., The Geometry of Sagittarius Stream from Pan-STARRS1 3π RR Lyrae, 2017, ApJ submitted