Tango for three:

Sagittarius, LMC, and the Milky Way

Eugene Vasiliev

Institute of Astronomy, Cambridge

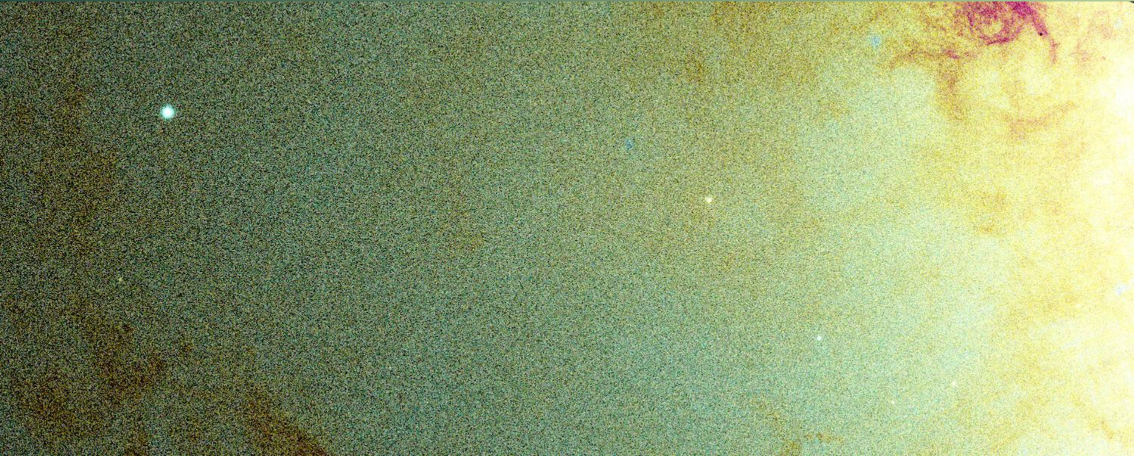
based on
Vasiliev & Belokurov, arXiv:2006.02929 – Sgr remnant
Vasiliev, Belokurov & Erkal, arXiv:2009.10726 – Sgr stream

UMich seminar, 3 November 2020

Three dancers

Sagittarius

- distance: ~ 27 kpc
- mass: few $\times 10^8\ M_\odot$



Sagittarius

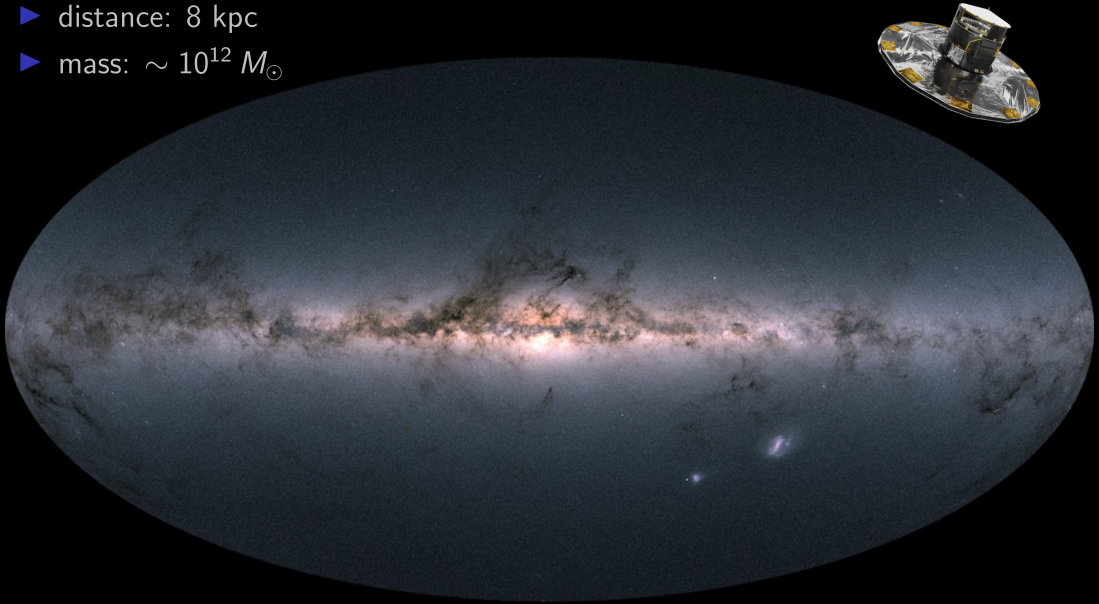
- distance: ~ 27 kpc
- mass: few $\times\ 10^8\ M_\odot$

Large Magellanic Cloud

- distance: ~ 50 kpc
- mass: $\gtrsim 10^{11}\ M_\odot$

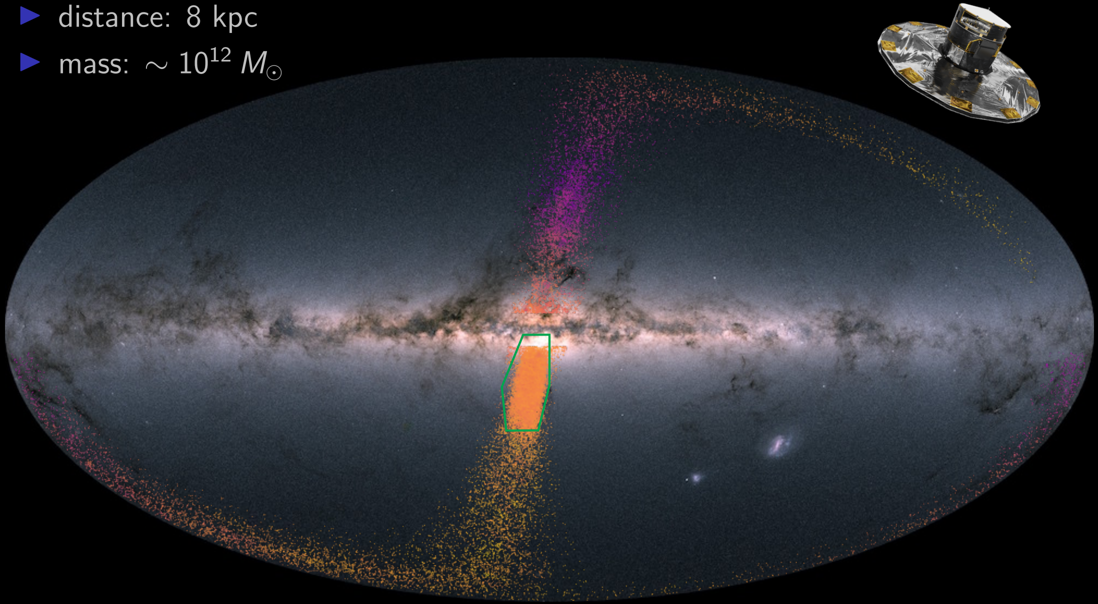
Milky Way

- distance: 8 kpc
- mass: $\sim 10^{12}\,M_\odot$



Milky Way

- distance: 8 kpc
- mass: $\sim 10^{12}\ M_\odot$



How it all started: the discovery of Sagittarius dSph

LETTERS TO NATURE

VOL 370 · 21 JULY 1994

A dwarf satellite galaxy in Sagittarius

R. A. Ibata*, G. Gilmore* & M. J. Irwin†

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WE have detected a large, extended group of comoving stars in the direction of the Galactic Centre, which we interpret as belonging to a dwarf galaxy that is closer to our own Galaxy than any other yet known. Located in the constellation of Sagittarius, and on the far side of the Galactic Centre, it has not previously been seen because of the large number of foreground stars (in the Milky Way) in that direction. Following convention, we propose to call it the Sagittarius dwarf galaxy. Its properties are similar to those of the eight other dwarf spheroidal companions to the Milky Way, and it is comparable in size and luminosity to the largest of them—the Fornax system. The Sagittarius dwarf is elongated towards the plane of the Milky Way, suggesting that it is undergoing some tidal disruption before being absorbed by the Milky Way.

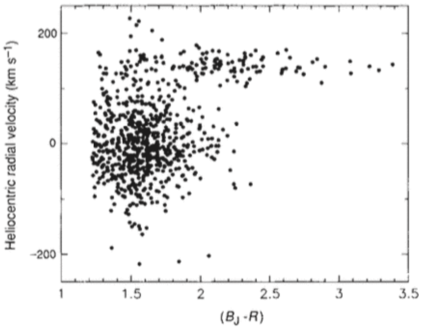

FIG. 1 The heliocentric radial velocity–colour distribution for three selected regions at Galactic coordinates $l=5°$, $b=-12°$, $-15°$ and $-20°$. The population with mean velocity of 0 km s^{-1} and dispersion 70 km s^{-1} is the expected Galactic bulge. There is a clear excess of stars at a common velocity of $\sim$140 km s^{-1} extending to (B_J-R) colours >3. This feature does not appear in any of the other regions for which spectroscopy has been obtained. The excess of stars is most prominent at $l=5°$, $b=-15°$ but is also unambiguously present in the other two regions.

How it all started: the discovery of Sagittarius dSph

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A dwarf satellite galaxy in Sagittarius

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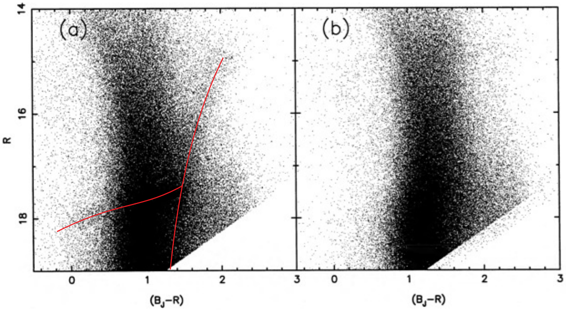
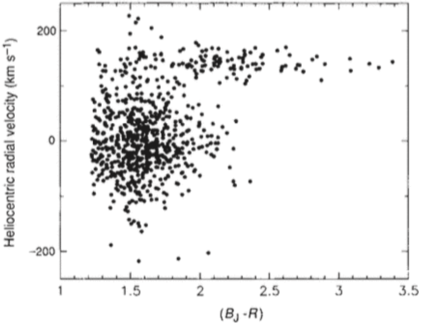
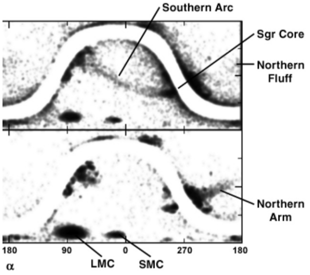


Sgr field

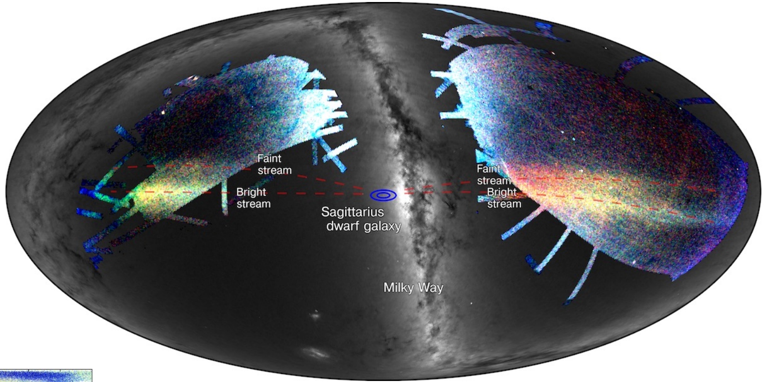
control field



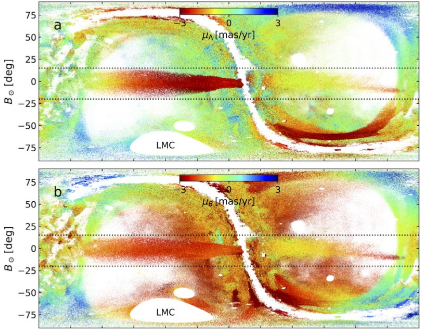
How it continued

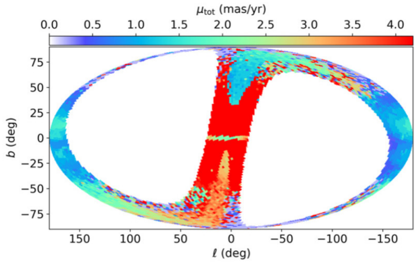


[Majewski+ 2003] – 2MASS



[Belokurov+ 2006; Koposov+ 2012] – SDSS

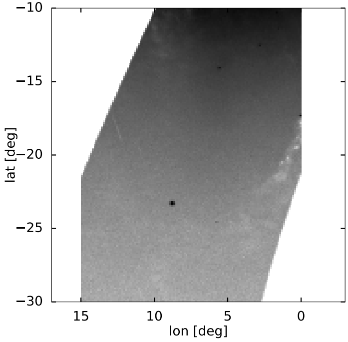




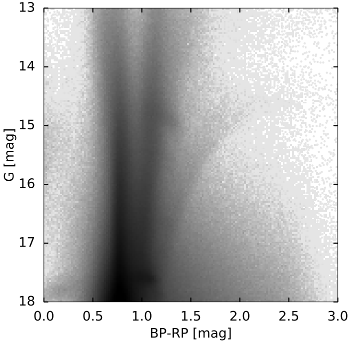
[Ibata+ 2020] ← Gaia DR2 → [Antoja+ 2020; Ramos+ 2020]

Separating the grains from the chaff

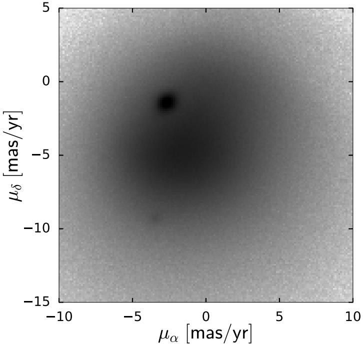
All $\sim 10^7$ stars in the input sample ($13 < G_0 < 18$)



spatial distribution



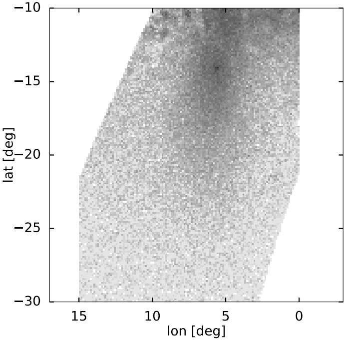
colour–magnitude diagram



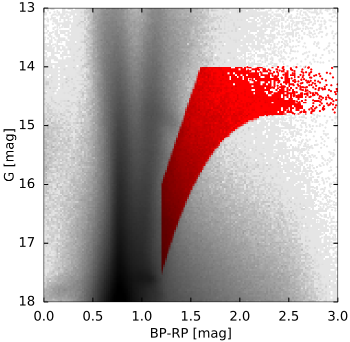
proper motion space

Separating the grains from the chaff

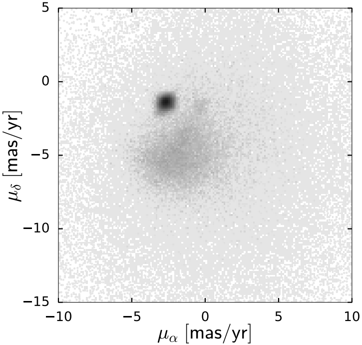
Selection by CMD



spatial distribution



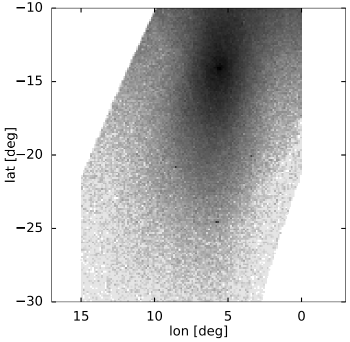
colour–magnitude diagram



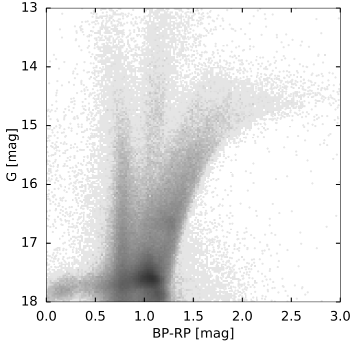
proper motion space

Separating the grains from the chaff

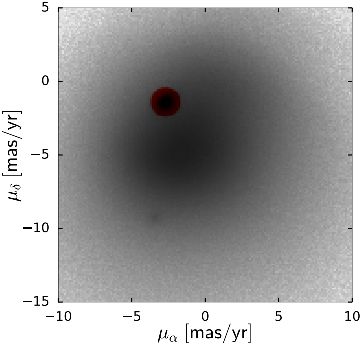
Selection by PM



spatial distribution



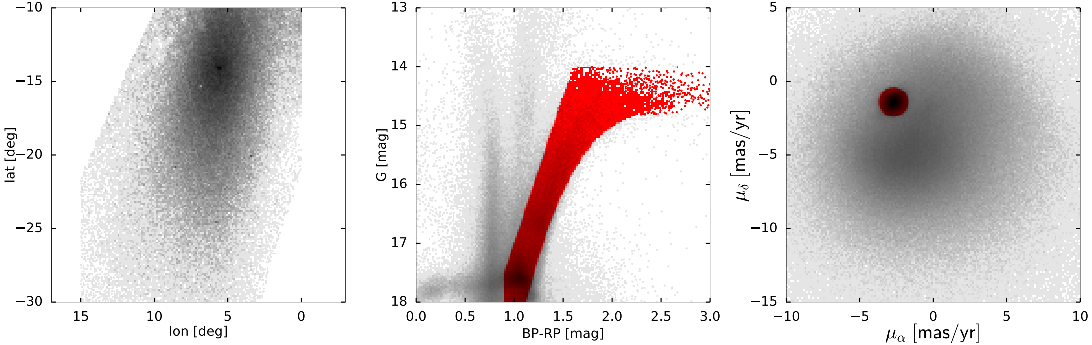
colour–magnitude diagram



proper motion space

Separating the grains from the chaff

Selection by CMD and PM



spatial distribution | colour–magnitude diagram | proper motion space

Separating the grains from the chaff – the fancy way

Mixture modelling approach:

$$\text{maximize} \quad \ln \mathscr{L} \equiv \sum_{i=1}^{N_{\text{stars}}} \ln \left[\eta\, f_{\text{memb}}(\mathbf{x}_i \mid \boldsymbol{\theta}_{\text{memb}}) + (1-\eta)\, f_{\text{field}}(\mathbf{x}_i \mid \boldsymbol{\theta}_{\text{field}}) \right],$$

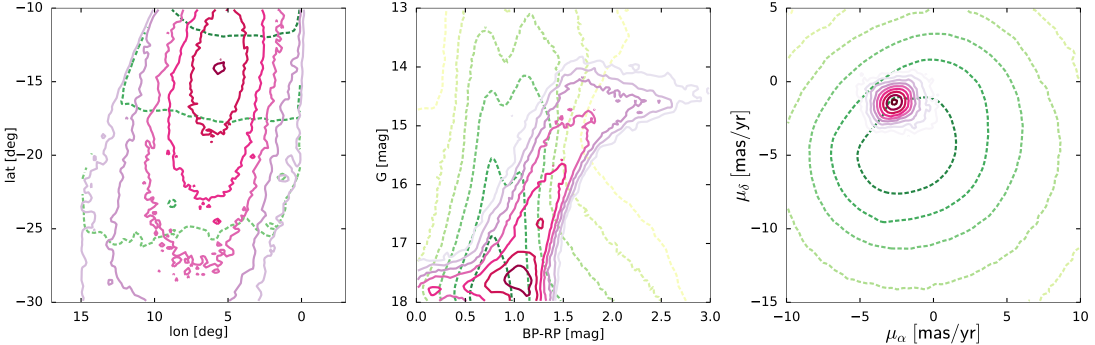
measurements

parameters of distributions

fraction of members

membership probability of i-th star:

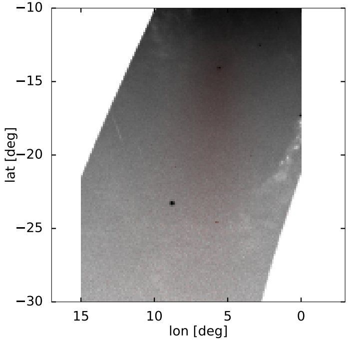
$$p_i = \frac{\eta\, f_{\text{memb}}(\mathbf{x}_i)}{\eta\, f_{\text{memb}}(\mathbf{x}_i) + (1-\eta)\, f_{\text{field}}(\mathbf{x}_i)}$$



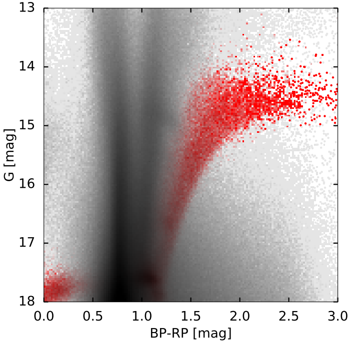
spatial distribution | colour–magnitude diagram | proper motion space

Separating the grains from the chaff – the fancy way

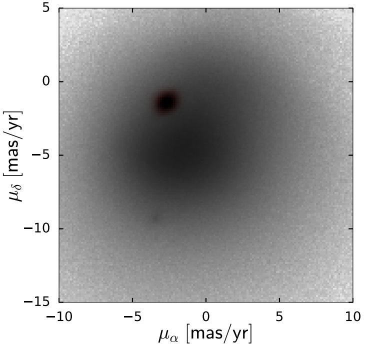
saturation: membership probability; brightness: density



spatial distribution



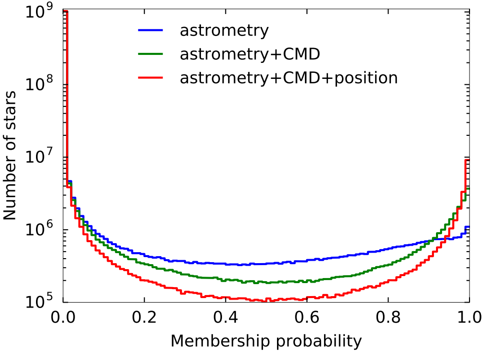
colour–magnitude diagram



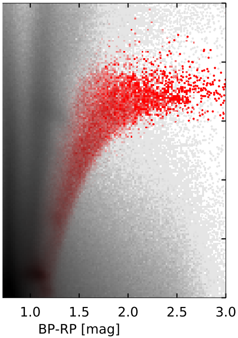
proper motion space

Separating the grains from the chaff – the fancy way

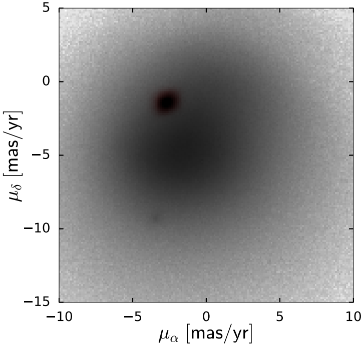
The combination of all selection criteria produces a very sharp distinction between Sgr members and field stars



spatial distribution



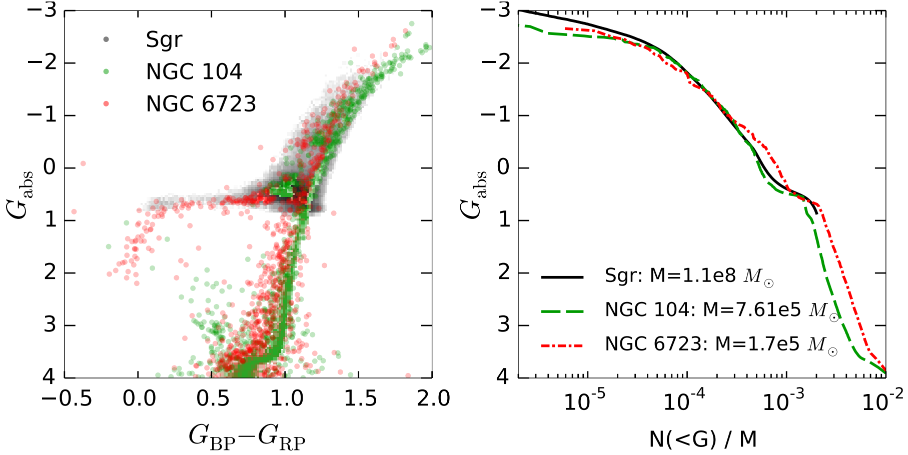
colour–magnitude diagram



proper motion space

The Sagittarius galaxy remnant: photometry and total mass

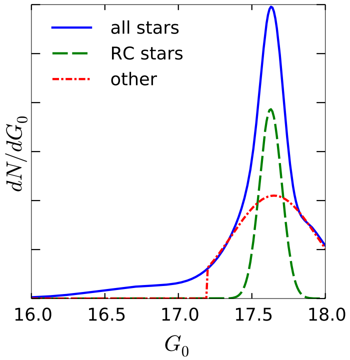
comparison of magnitude distribution of Sgr members with that of globular clusters of similar metallicity ($z \simeq -0.7 .. -1$)
$\Longrightarrow$ determine the total mass of stars in Sgr $M_\star \simeq 10^8\, M_\odot$.

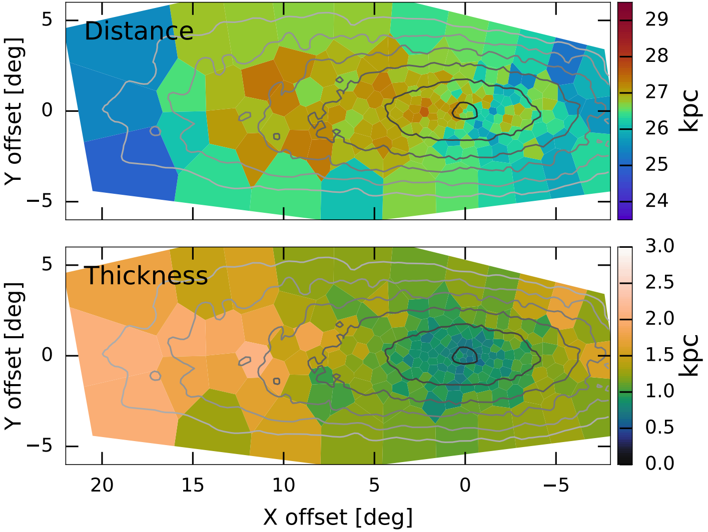


dynamical masses of clusters from Baumgardt+ 2019

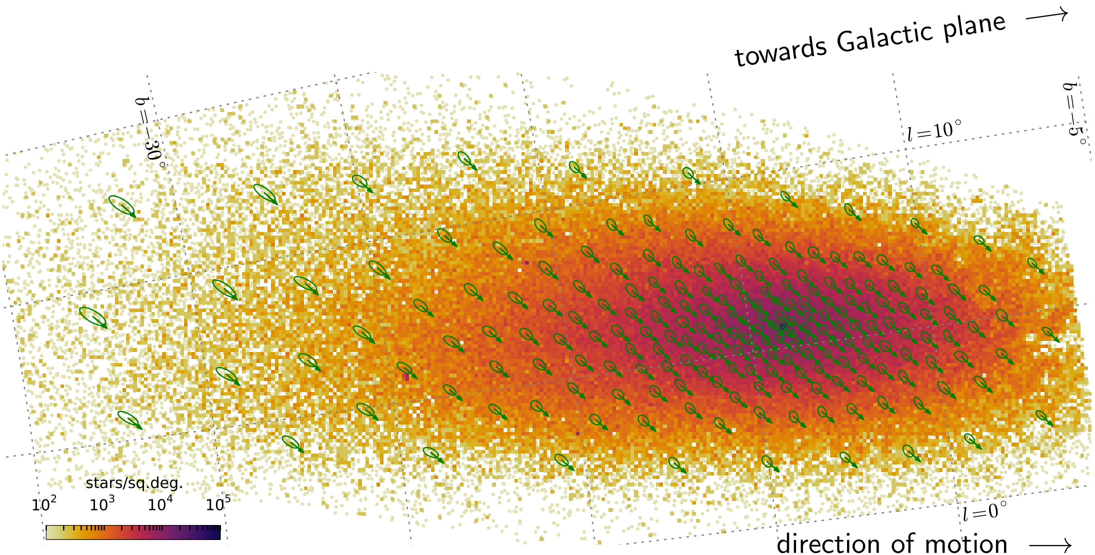
The Sagittarius galaxy remnant: photometry and distance

magnitude distribution
of red clump stars





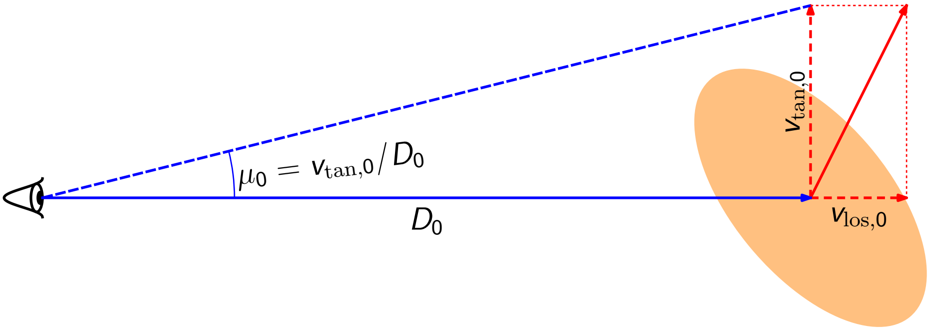
The Sagittarius galaxy remnant: kinematics



Putting things into perspective

$$\mu_0 = v_{\tan,0}/D_0$$

$v_{\mathrm{los},0}$

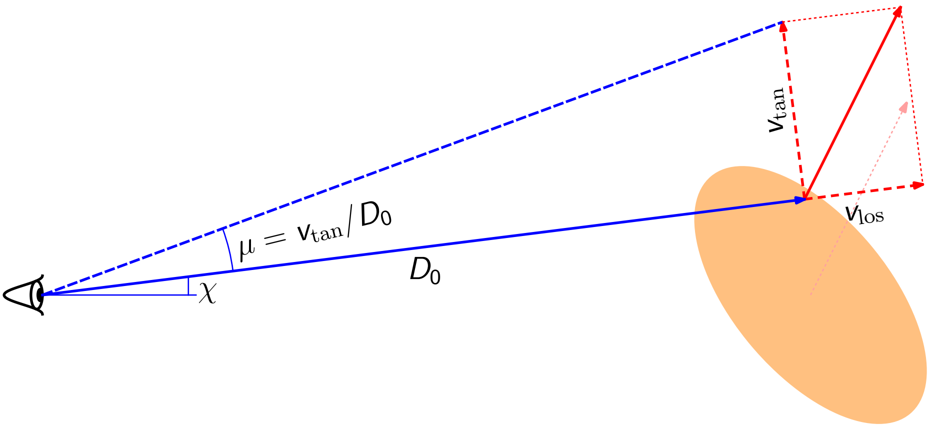


Putting things into perspective

$$\mu \approx \mu_0 - v_{\rm los,0}/D_0\,\chi$$

$$v_{\rm los} \approx v_{\rm los,0} + \mu_0\,D_0\,\chi$$

perspective corrections



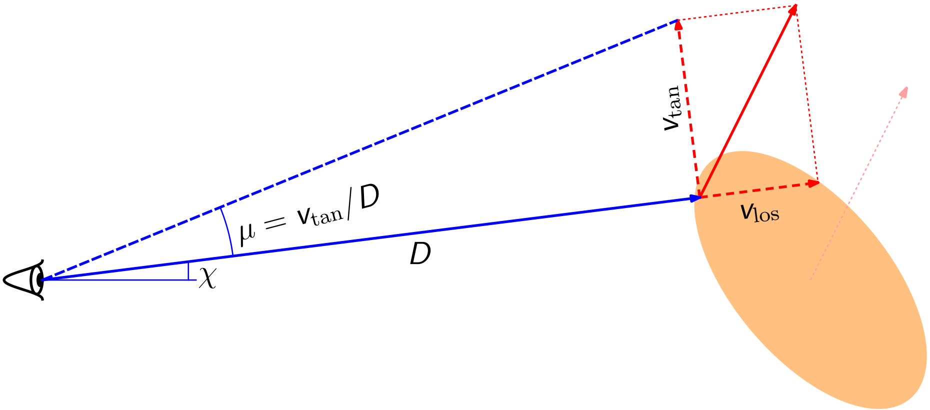
Putting things into perspective

$$\mu \approx \mu_0 - v_{\rm los,0}/D_0\,\chi - \mu_0\,(D/D_0 - 1)$$

$$v_{\rm los} \approx v_{\rm los,0} + \mu_0\,D_0\,\chi$$

perspective corrections

distance correction



Putting things into perspective

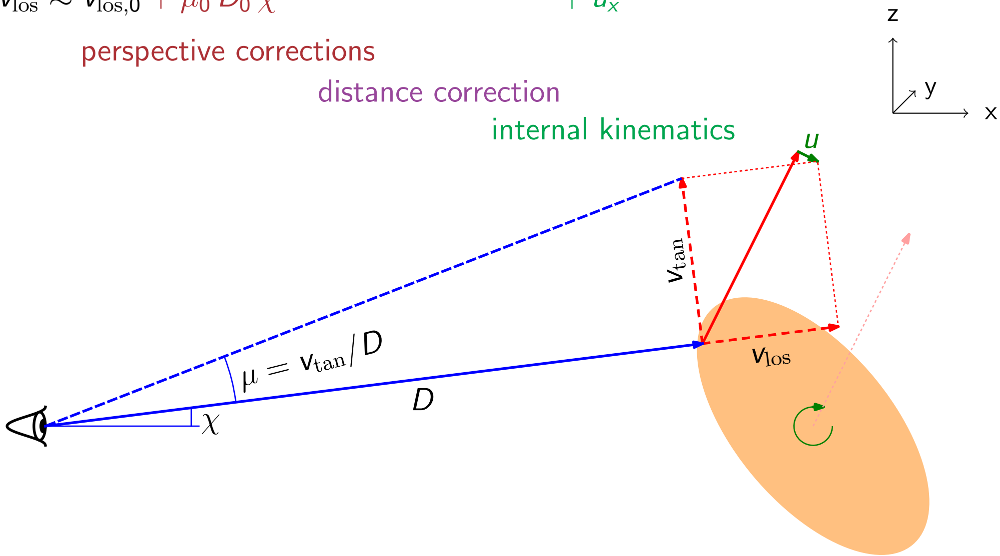
$$\mu \approx \mu_0 - v_{\rm los,0}/D_0\,\chi - \mu_0\,(D/D_0 - 1) + u_z/D$$

$$v_{\rm los} \approx v_{\rm los,0} + \mu_0\,D_0\,\chi + u_x$$

perspective corrections

distance correction

internal kinematics



Putting things into perspective

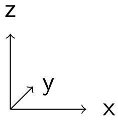
$$\mu \approx \mu_0 - v_{\mathrm{los},0}/D_0\,\chi - \mu_0\,(D/D_0 - 1) + u_z/D$$

$$v_{\mathrm{los}} \approx v_{\mathrm{los},0} + \mu_0\,D_0\,\chi + u_x$$

perspective corrections

distance correction

internal kinematics



Perspective corrections can be compensated since we know $v_{\mathrm{los},0}$ and D_0, however, D is not known to sufficient accuracy to be corrected for.
But it affects only one component of the proper motion parallel to μ_0:

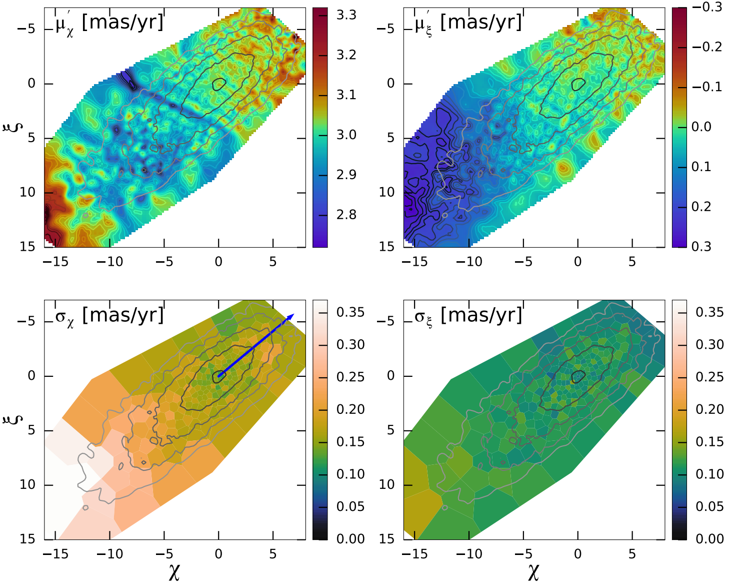
$$\chi \parallel \mu_0 : \quad \mu'_\chi \equiv \mu_\chi + v_{\mathrm{los},0}/D_0\,\chi \approx \mu_0 + u_z/D - \mu_0\,(D/D_0 - 1)\,\chi$$

$$\sigma_\chi \approx \sqrt{\sigma^2 + (\mu_0^2\,h)^2}\,/\,D_0$$

$$\xi \perp \mu_0 : \quad \mu'_\xi \equiv \mu_\xi + v_{\mathrm{los},0}/D_0\,\xi \approx u_y/D$$

$$\sigma_\xi \approx \sigma\,/\,D_0$$

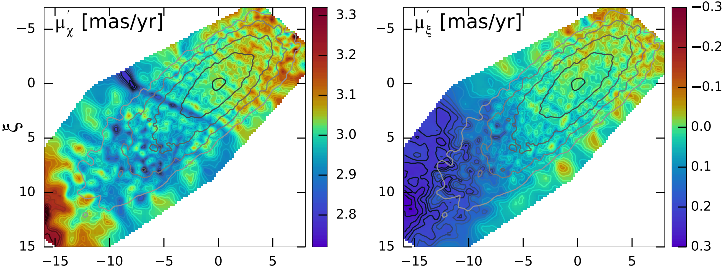
The Sagittarius galaxy remnant: kinematics



towards Galactic plane →

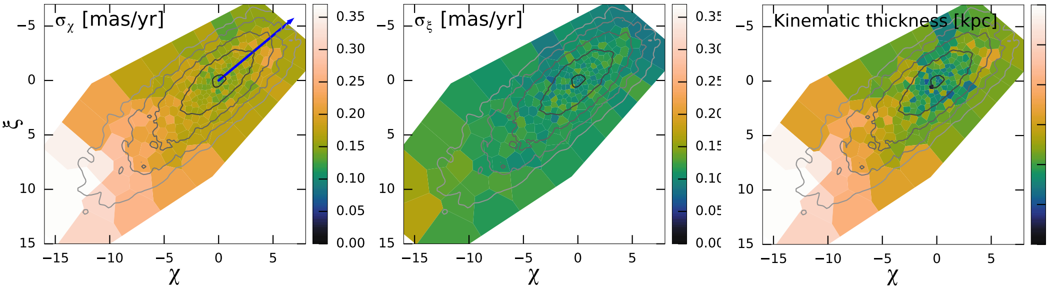
direction of apparent motion →

The Sagittarius galaxy remnant: kinematics

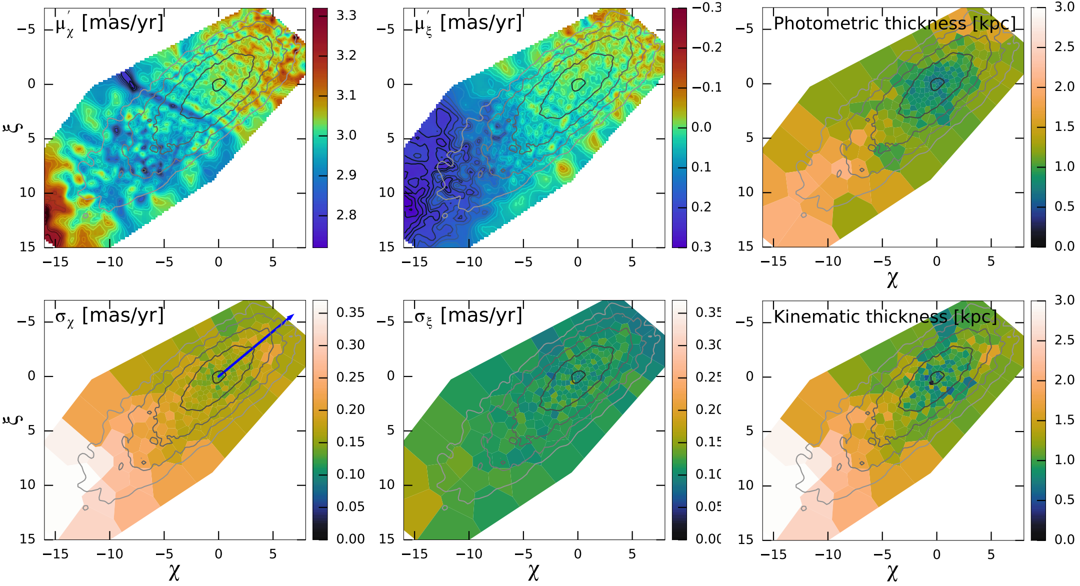


kinematic thickness:

$$h_{\text{kin}} = D_0 \sqrt{\sigma_\chi^2 - \sigma_\xi^2} / \mu_{\chi,0}$$

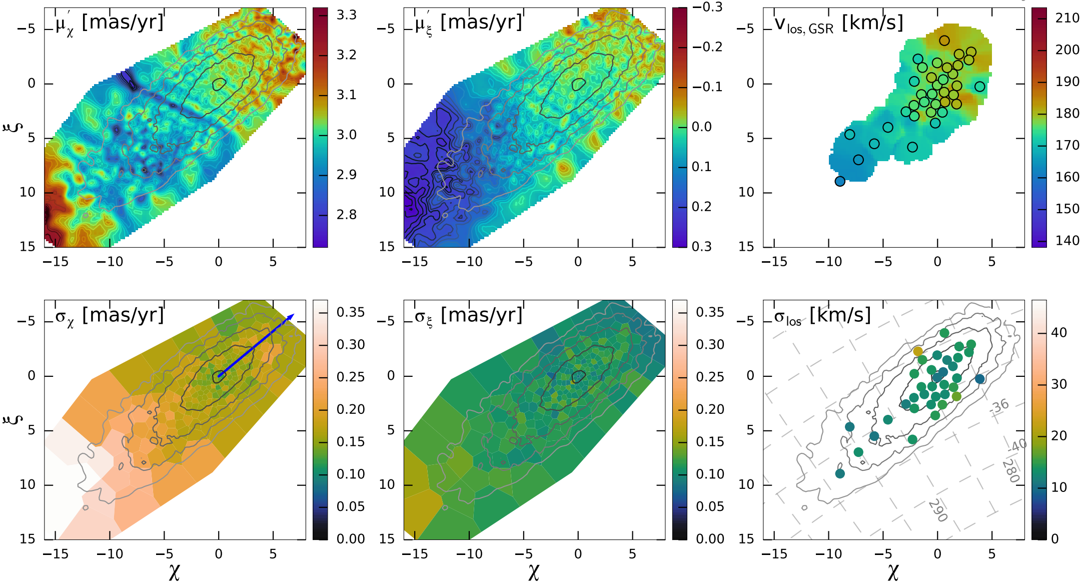


The Sagittarius galaxy remnant: kinematics



The Sagittarius galaxy remnant: kinematics

line-of-sight velocities for ∼ 3300 stars:
compilation of Gaia RVS, APOGEE,
Peñarrubia+ 2011, Frinchaboy+ 2012



N-body models of a disrupting satellite

Goals:

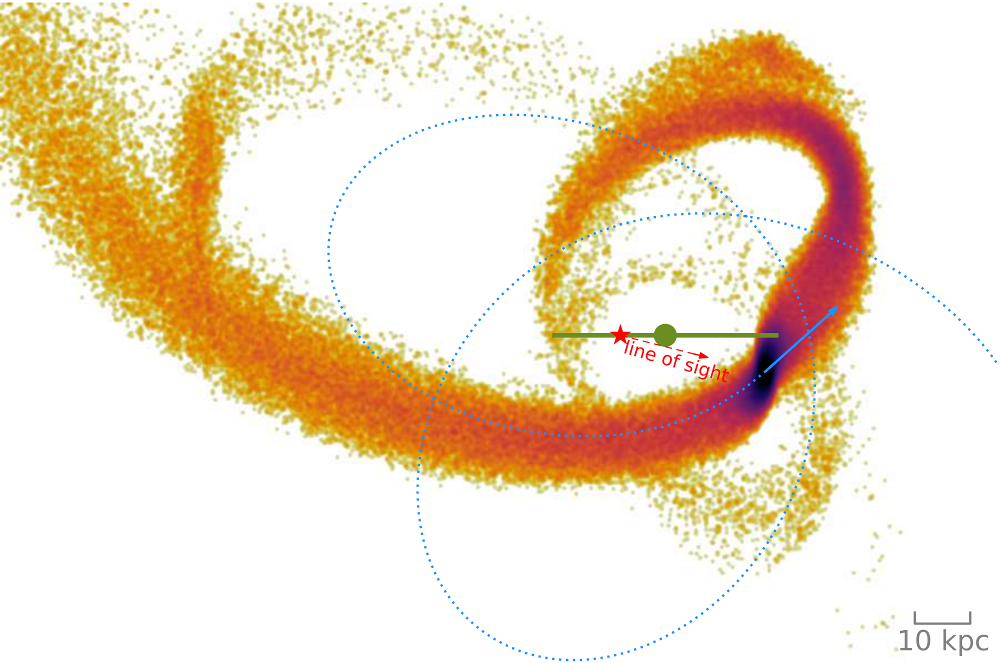
- provide an interpretation of the observed kinematics
- estimate the present-day total mass of the Sgr remnant
- explore possible evolutionary histories and progenitor properties

Method:

- construct various initial equilibrium models (stars + dark halo): spherical, flattened, rotating, different density profiles, ...
- evolve the satellite in the static external potential of the Milky Way
- iteratively adjust initial conditions to match its present-day position/velocity
- compare the simulated and observed kinematic maps

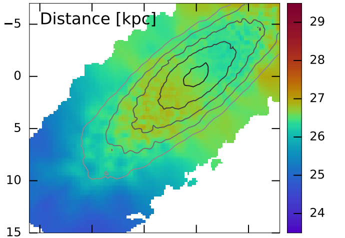
repeat dozens of times

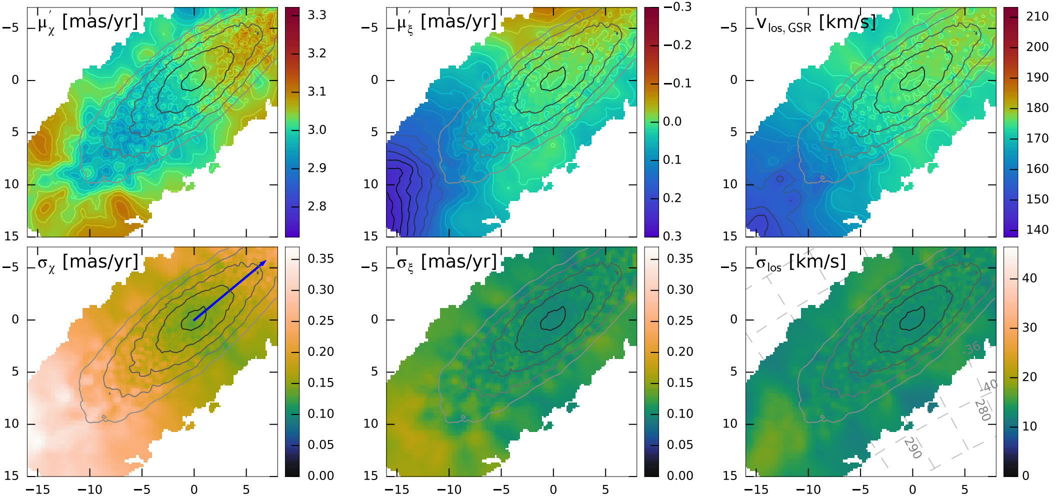
Galactic side-on view



An example of a successful model

- velocity and PM dispersions ⇒ total mass and thickness
- elongation and distance gradient ⇒ 3d orientation
- distinct dip in μ'_χ correlated with distance





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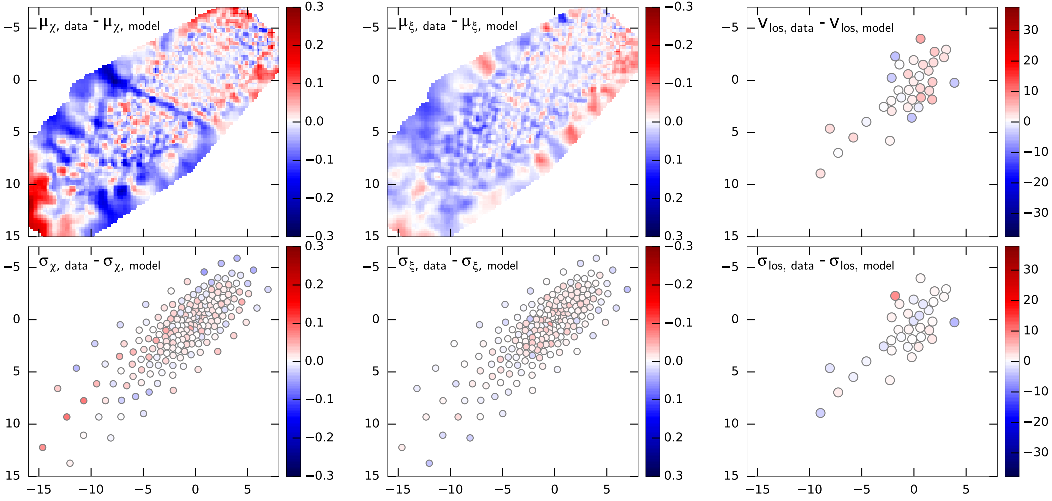
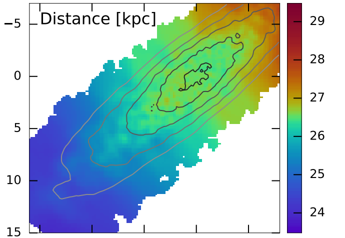
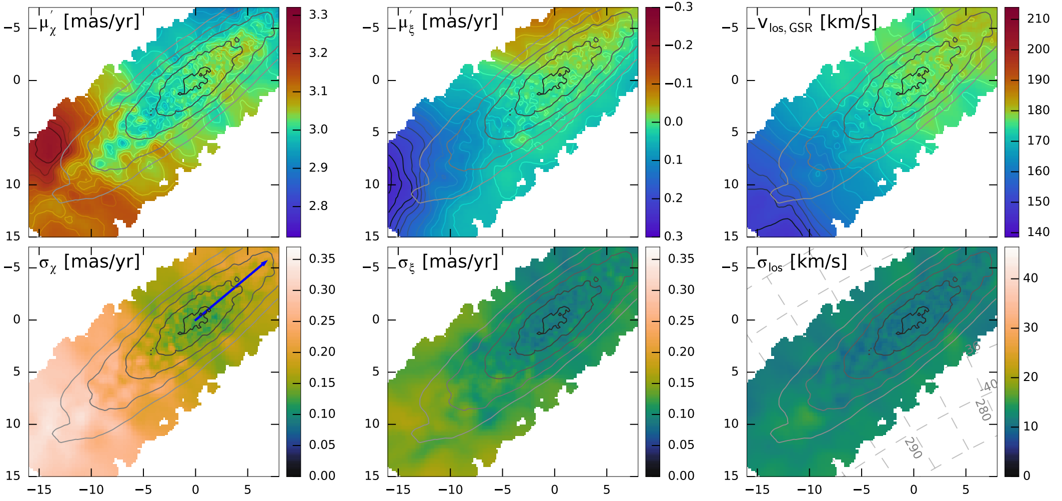


Strongly tidally disturbed model

- too stretched along the orbit
- monotonic distance decrease towards the trailing arm
- serious misfit in μ'_χ





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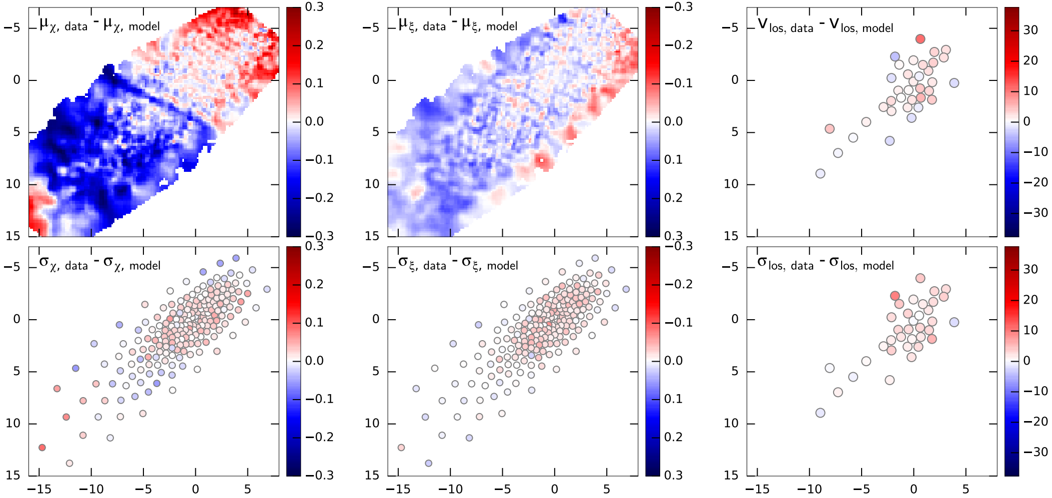
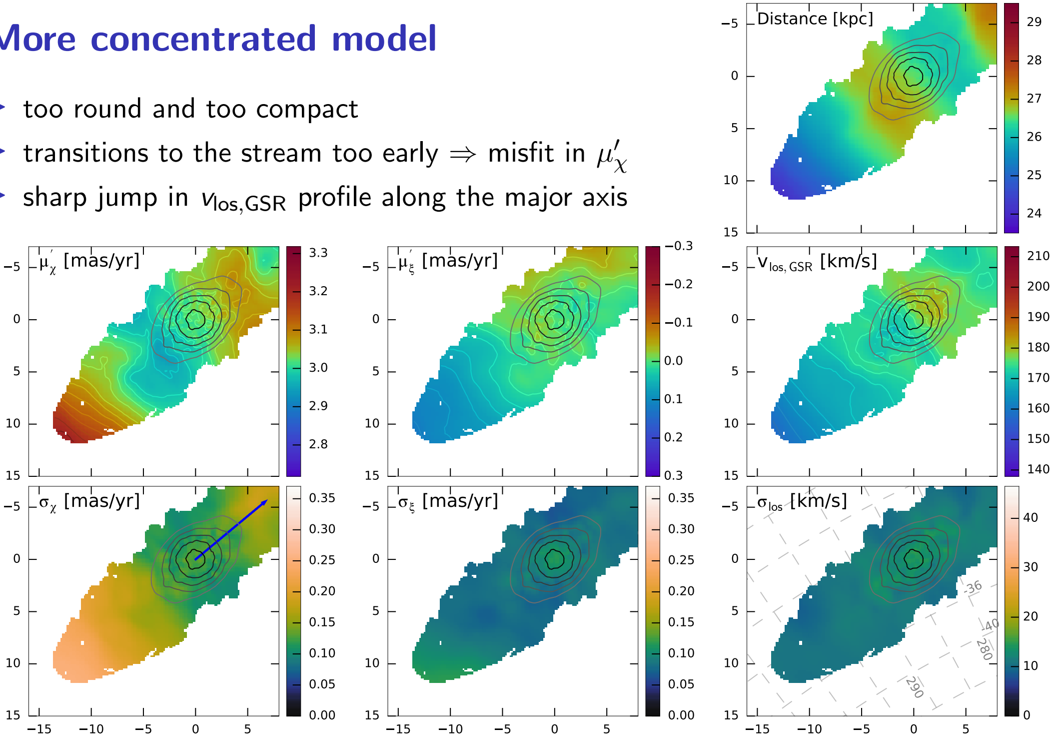


More concentrated model

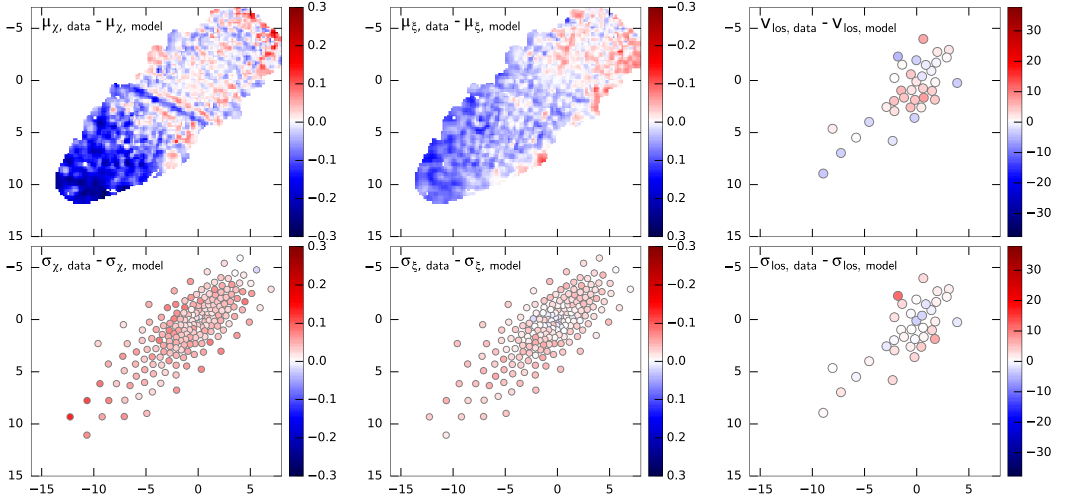
- too round and too compact
- transitions to the stream too early $\Rightarrow$ misfit in μ'_χ
- sharp jump in $v_{\mathrm{los,GSR}}$ profile along the major axis



More concentrated model

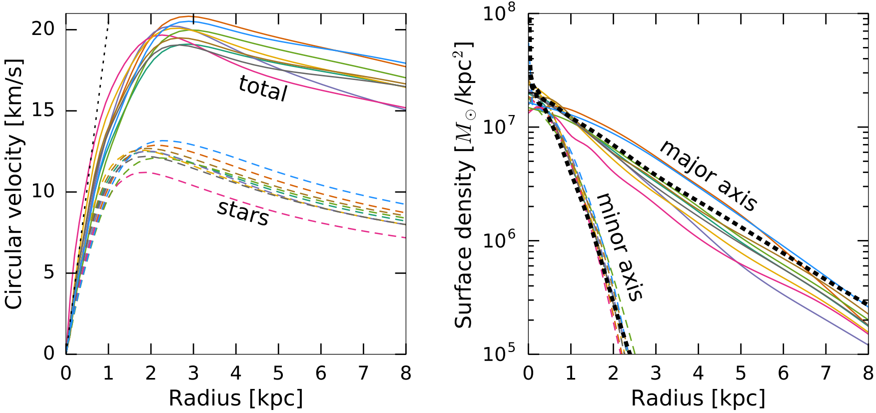
Law & Majewski 2010 – the most widely used model for the Sgr stream

- too round and too compact
- transitions to the stream too early ⇒ misfit in μ'_χ
- sharp jump in $v_{\mathrm{los,GSR}}$ profile along the major axis



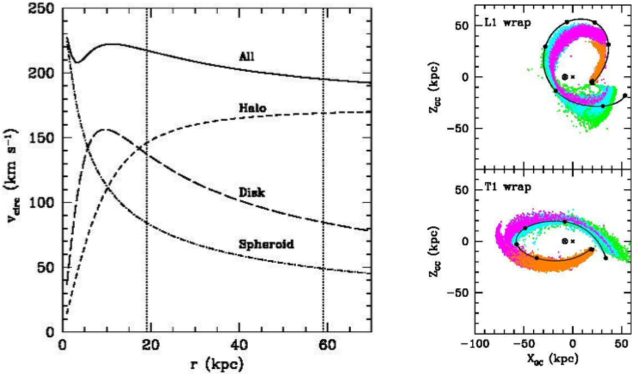
Common features of all successful models of the remnant

- stellar mass $\sim 10^8\,M_\odot$, total mass $(3-5)\times 10^8\,M_\odot$ within 5 kpc, peak circular velocity ~ 20 km/s
- stellar profile more spatially concentrated than total mass profile
- prolate cigar-shaped remnant extending up to ~ 5 kpc and tilted at $\sim 45^\circ$ to the orbit – essential for reproducing the kinematics, particularly the μ'_χ field

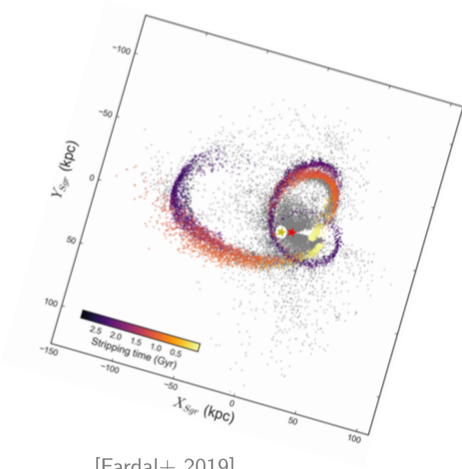


Part 2: Sgr stream as the probe of the Milky Way potential

Fit the stream position on the sky, line-of-sight velocity [and proper motion] by varying the Milky Way potential (mass distribution and shape).
[e.g., Helmi 2004; Johnston+ 2005; Law+ 2005; Law&Majewski 2010; Gibbons+ 2014; Dierickx&Loeb 2017; Fardal+ 2019; etc.]

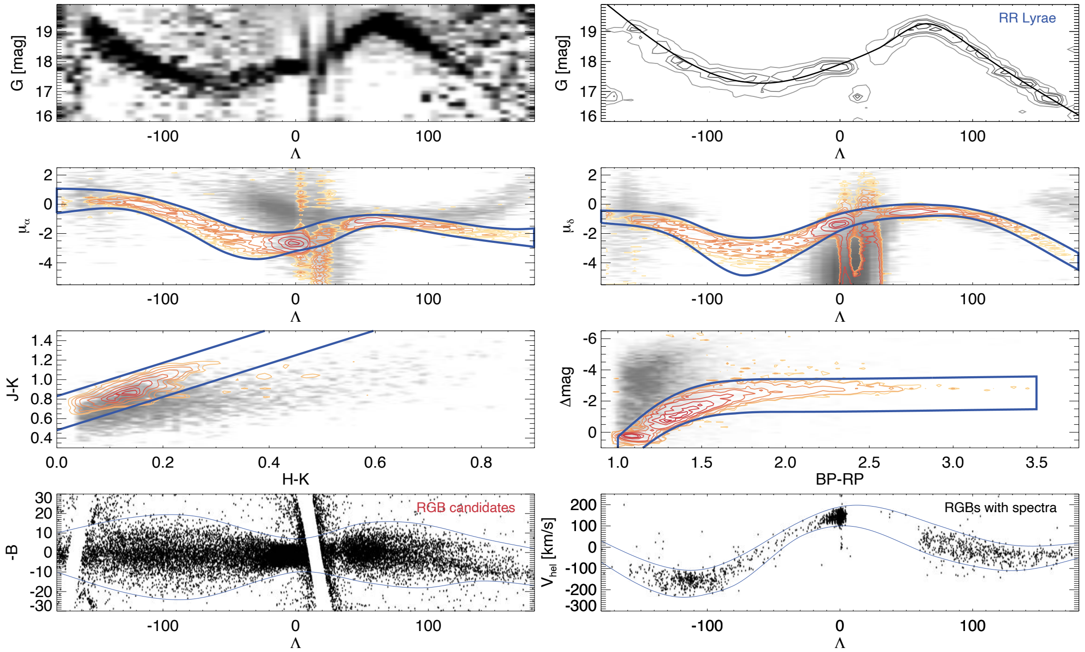


[Law & Majewski 2010]



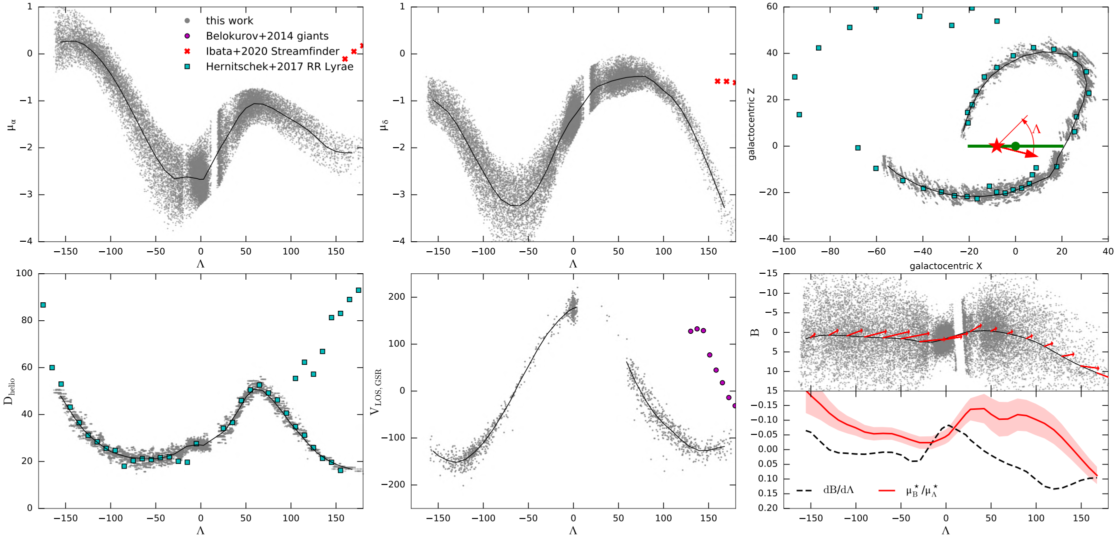
[Fardal+ 2019]

Selection of stream candidate members



Sgr stream in full glory

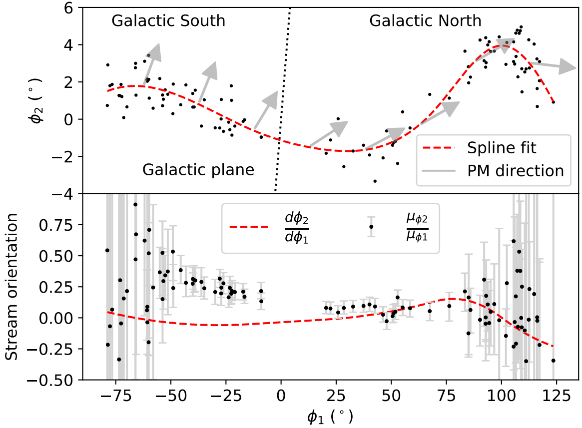
observations

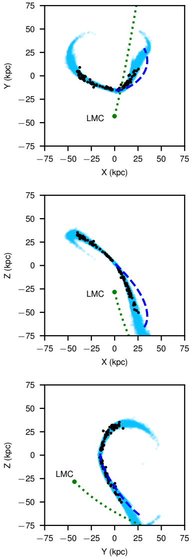


Orphan stream deflection by the Large Magellanic Cloud

Long ($\gtrsim 200^\circ$) and thin stream with no known progenitor

- Sky-plane velocity is misaligned with the stream track
- Stream can be fitted only when taking LMC into account
- Implied LMC mass $\gtrsim 10^{11}\,M_\odot$ (also supported by other arguments)



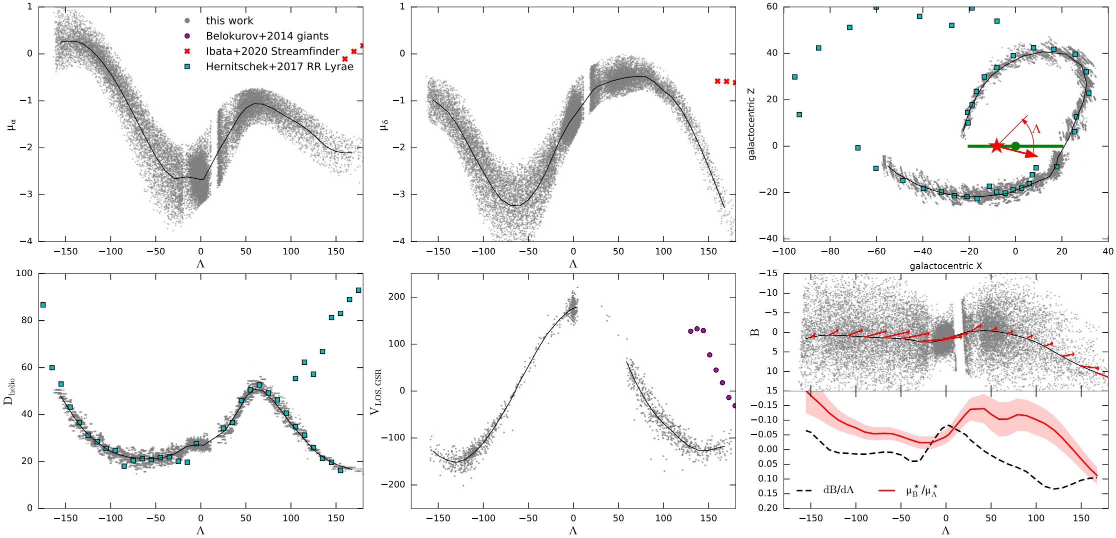


[movie]

[Erkal+ 2019]

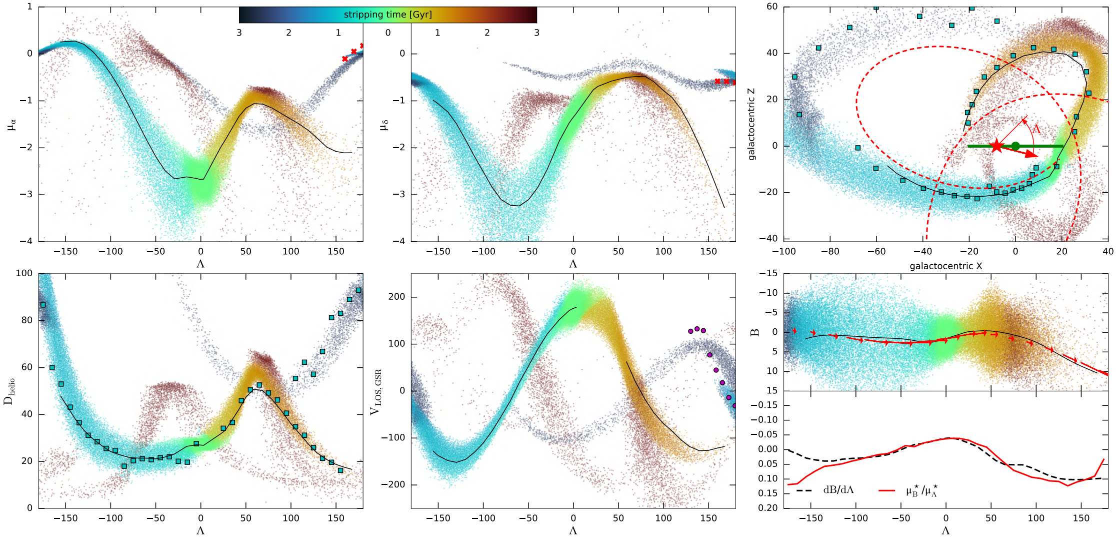
Sgr stream in full glory

observations



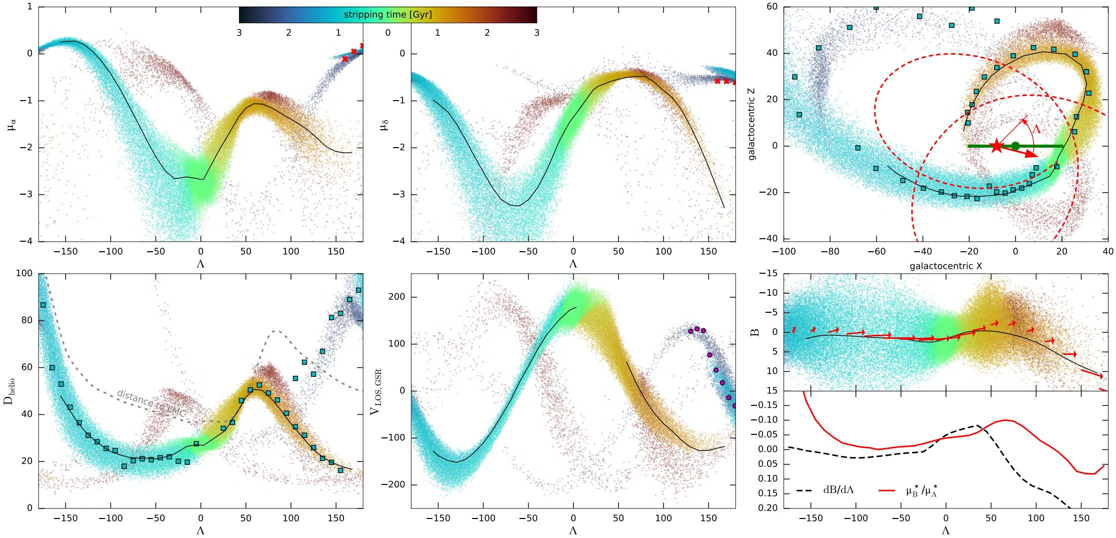
Sgr stream in full glory

model without LMC



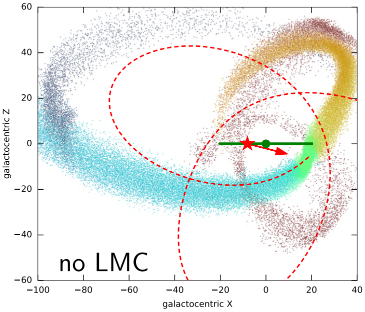
Sgr stream in full glory

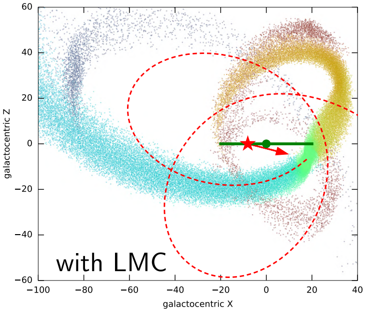
model with LMC

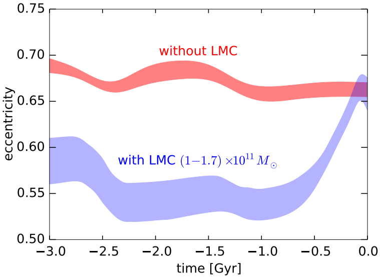


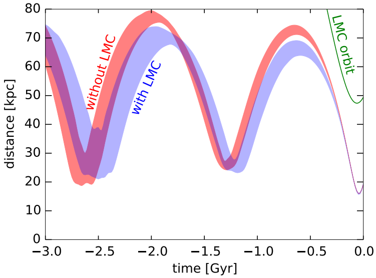
Sgr orbit

- period ~ 1.2 Gyr
- pericenter ~ 15 – 25 kpc
- apocenter ~ 60 – 70 kpc
- orbit has been less eccentric until recently in the case with the LMC

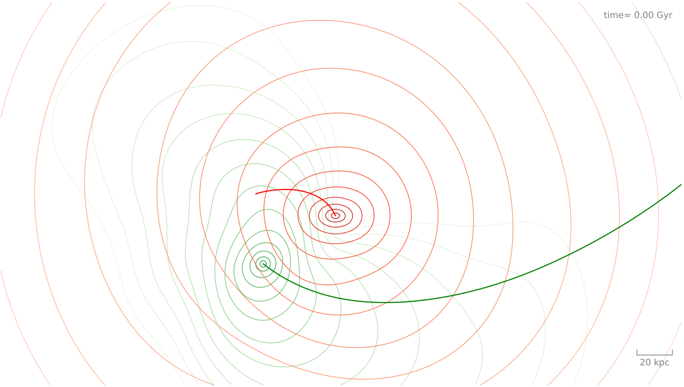


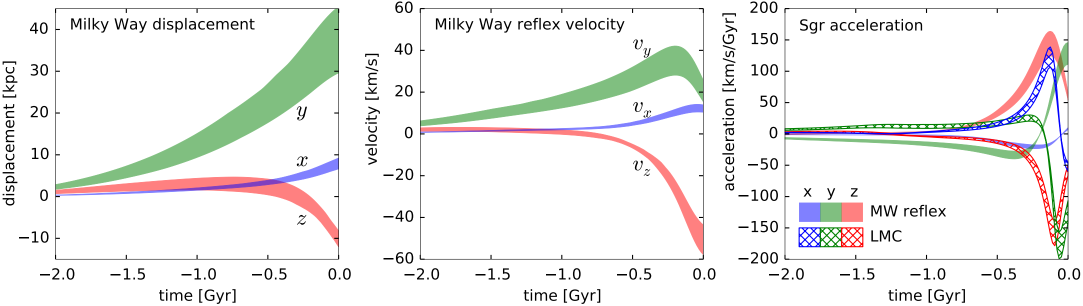




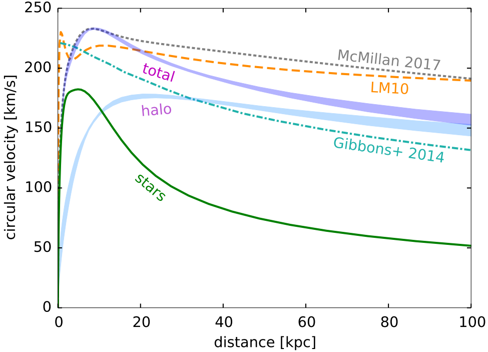


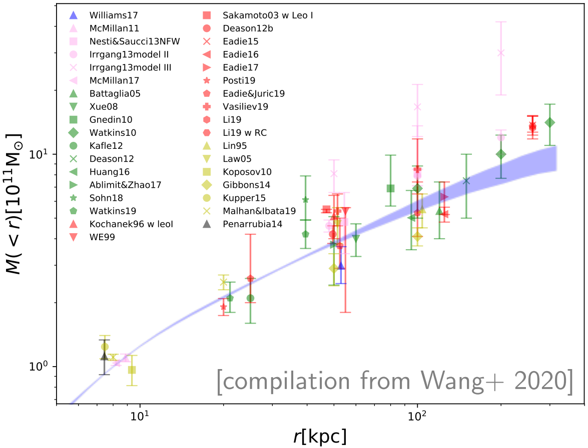
Non-inertial frame

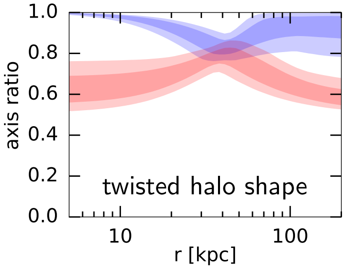




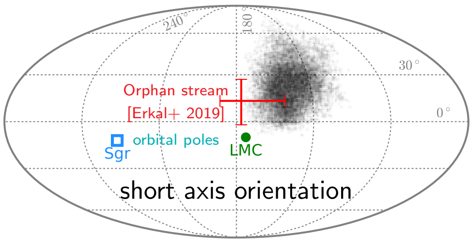
Milky Way potential





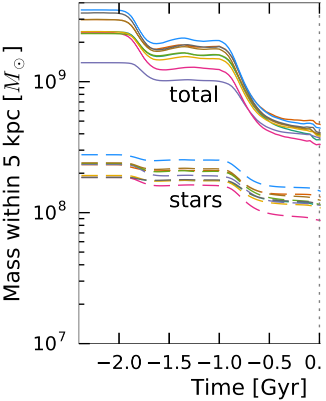


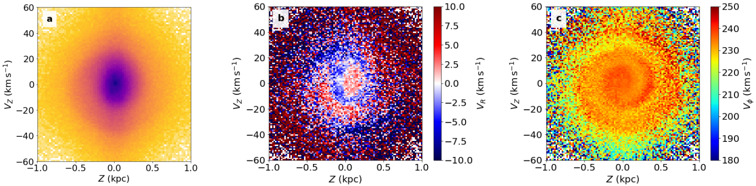
[movie]



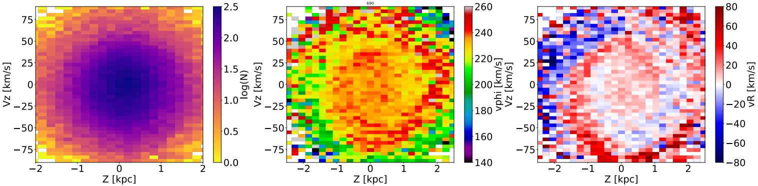
Impact on the Milky Way disc dynamics

Sgr remnant mass evolution





Gaia phase-space spiral [Antoja+2018]

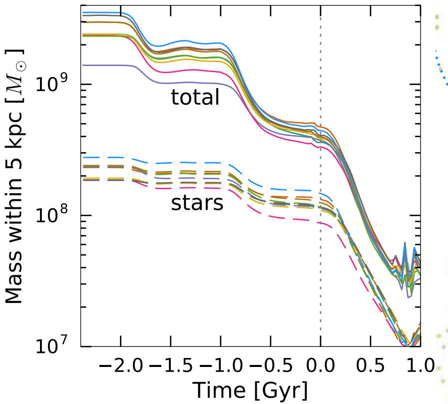


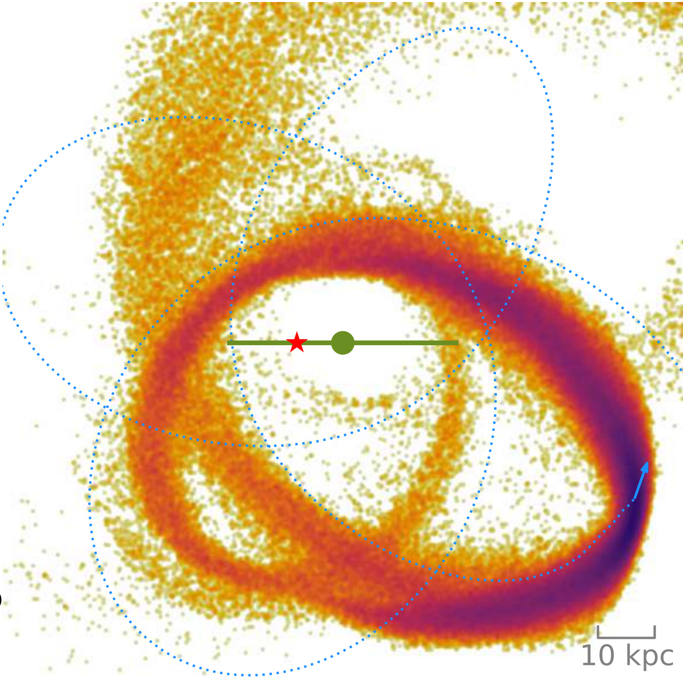
Standard scenario: perturbation from a $(2-10)\times10^{10}\ M_\odot$ satellite (implying Sgr) crossing the disk a few hundred Myr ago [Laporte+ 2018, 2019; Darling & Widrow 2018; Binney & Schönrich 2018; Bland-Hawthorn+ 2018; Li & Shen 2019]

Alternative scenario: bar buckling [Khoperskov+ 2019]

Future fate

Sgr is completely disrupted over the next orbit (~ 1 Gyr)





Summary

- Gaia DR2 made possible a detailed study of our closest satellite
- Velocity misalignment in the stream requires a time-dependent potential
- Interaction with a massive LMC is needed to explain the stream properties
- Present-day stellar mass is $\sim 10^8\, M_\odot$, total mass is a factor of few higher
- Sgr remnant was a bound system until the most recent pericentre passage...
- ...but is no more