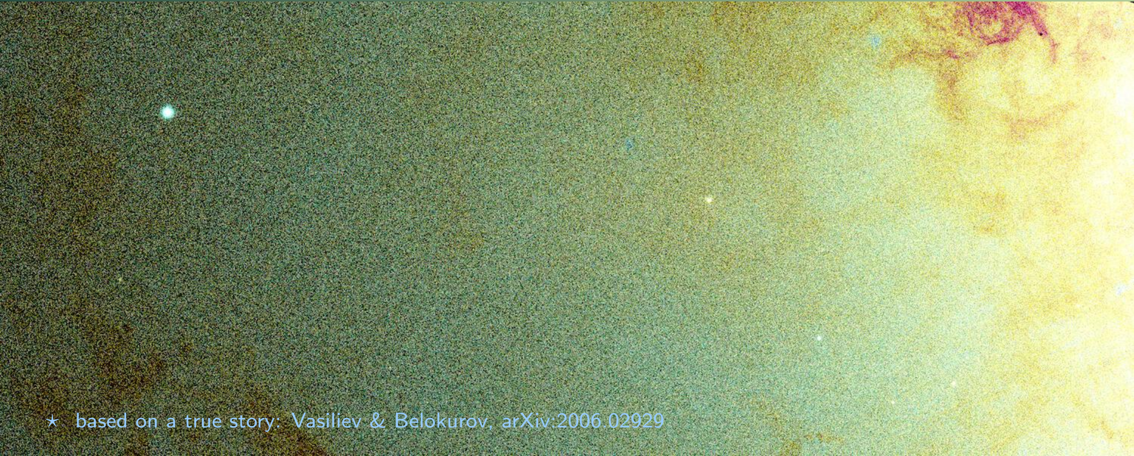
The demise of Sagittarius*

Eugene Vasiliev

IoA galaxy evolution seminar, 5 June 2020



* based on a true story: Vasiliev & Belokurov, arXiv:2006.02929

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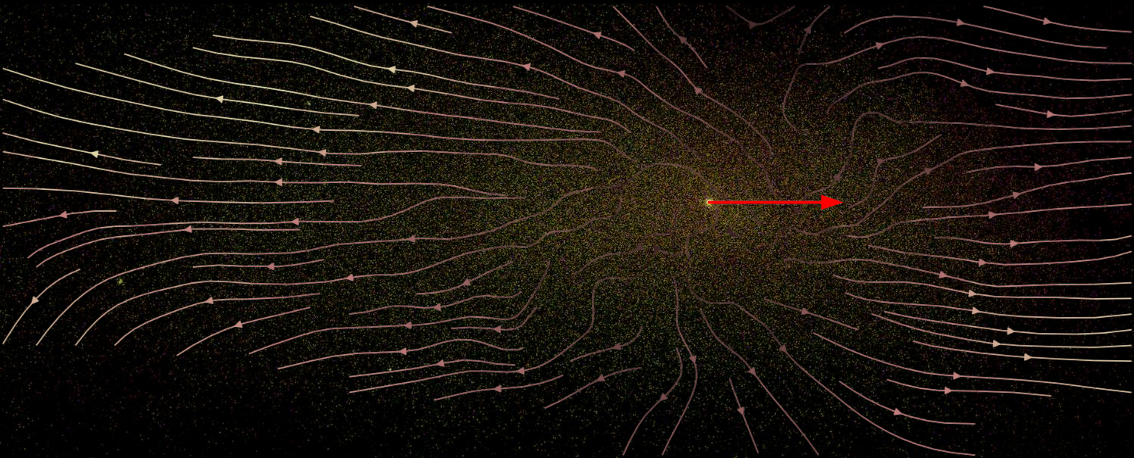

The demise of Sagittarius

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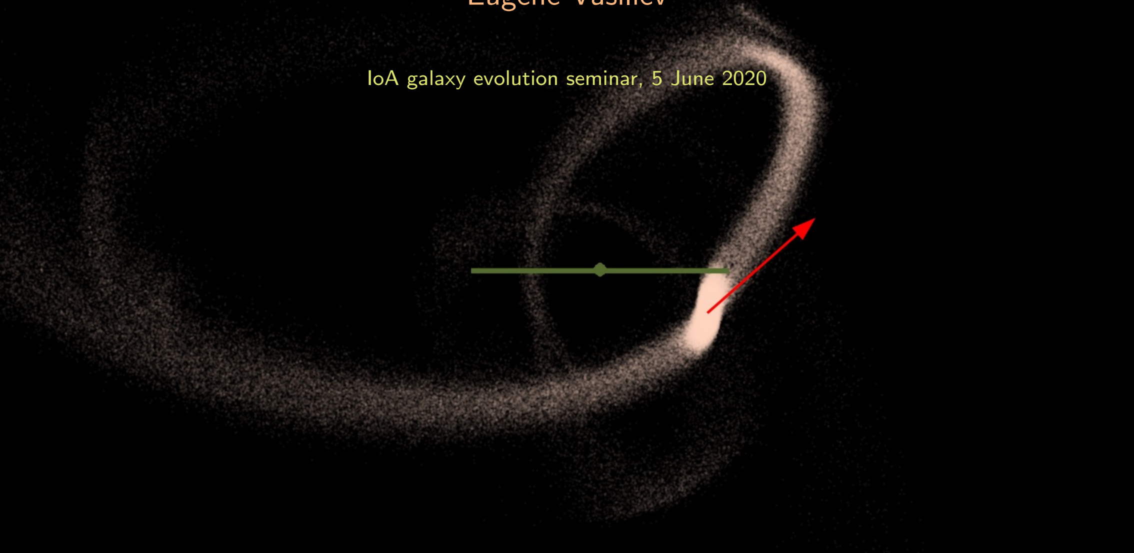

The prehistoric times (1990s)

LETTERS TO NATURE

VOL 370 · 21 JULY 1994

A dwarf satellite galaxy in Sagittarius

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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

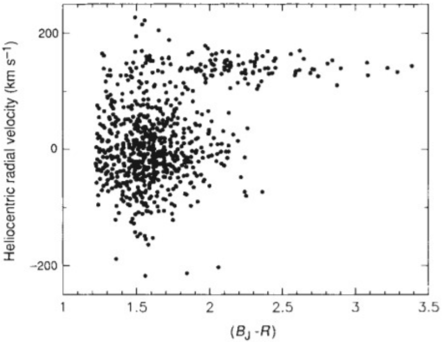

FIG. 1 The heliocentric radial velocity–colour distribution for

The prehistoric times (1990s)

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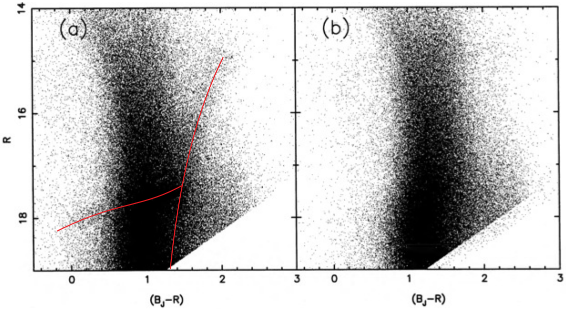
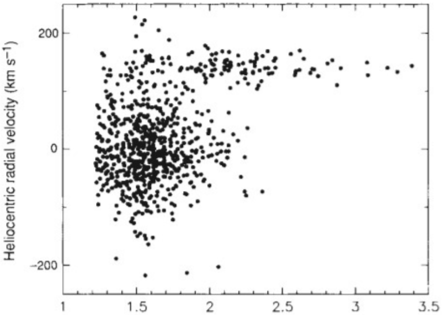
A dwarf satellite galaxy in Sagittarius

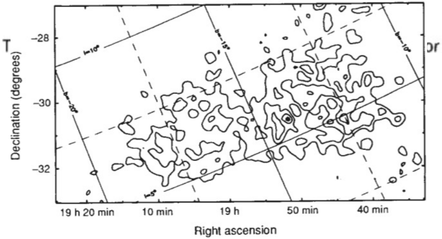


Sgr field

control field

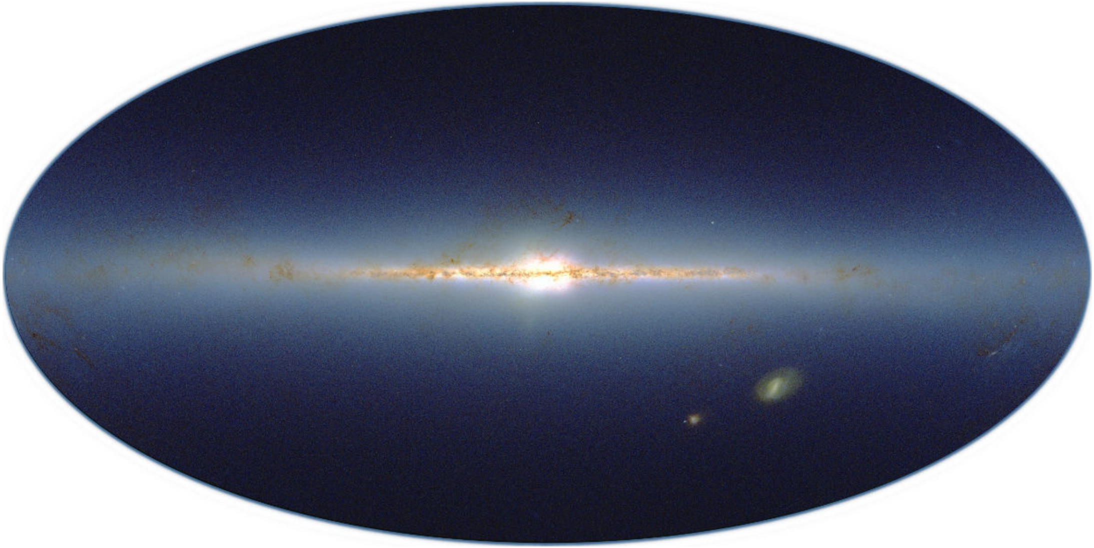
FIG. 1 T





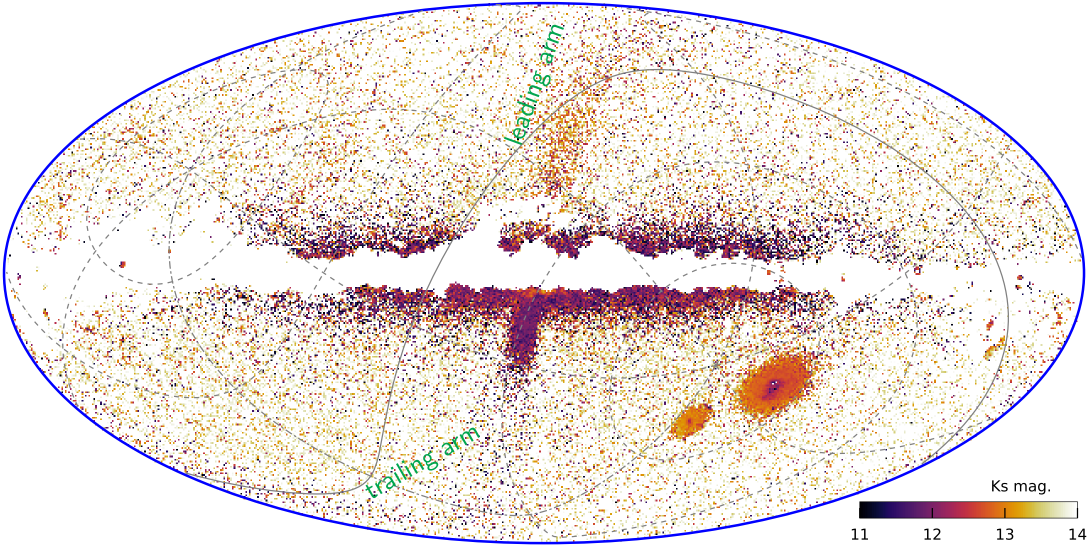
or

The ancient era: 2MASS (early 2000s)



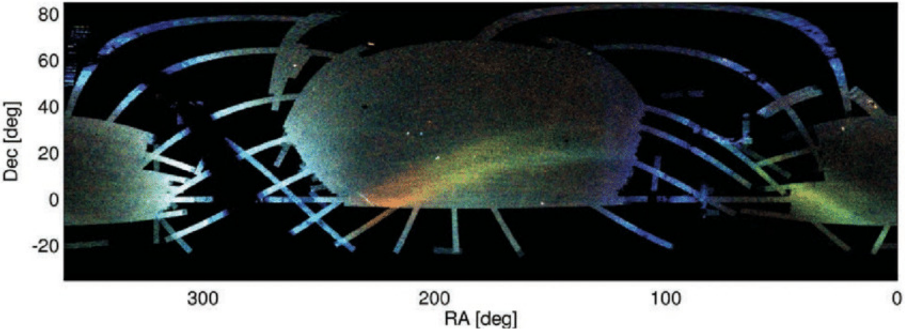
The ancient era: 2MASS (early 2000s)

colour selection corresponding to M giants reveals the Sgr stream [Majewski+ 2003]



The medieval era: SDSS (late 2000s)

field of streams with a bifurcation in the Sgr stream [Belokurov+ 2006]



The medieval era: SDSS (late 2000s)

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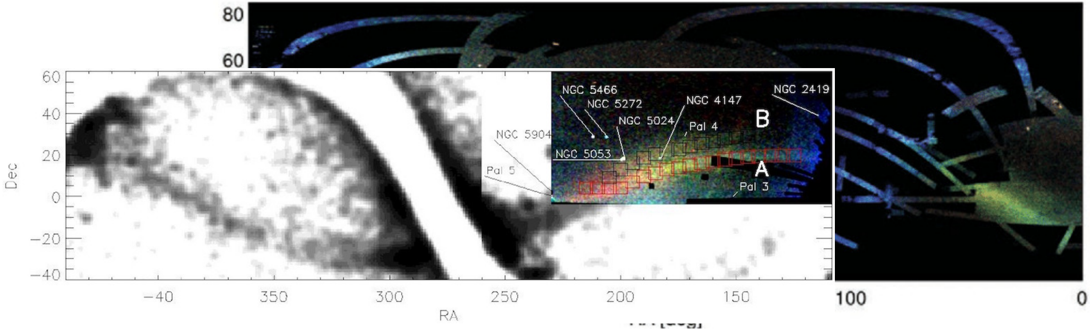
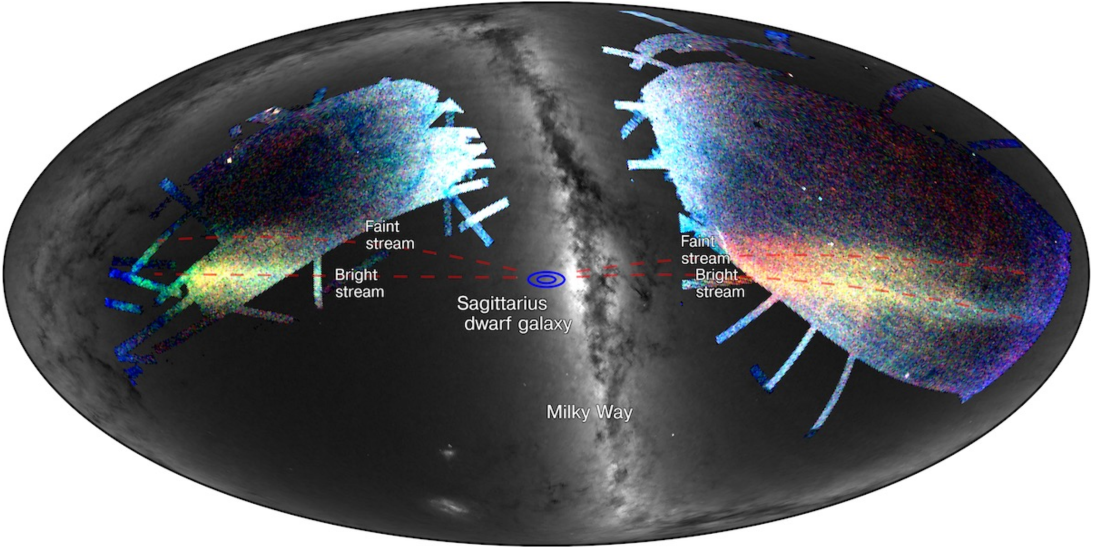


The medieval era: SDSS (late 2000s)

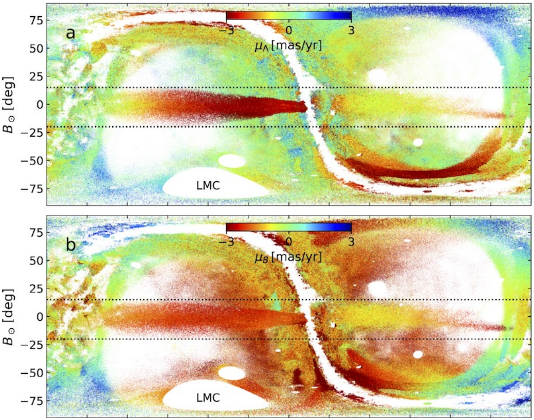
another bifurcation in the trailing arm of the Sgr stream [Koposov+ 2012]

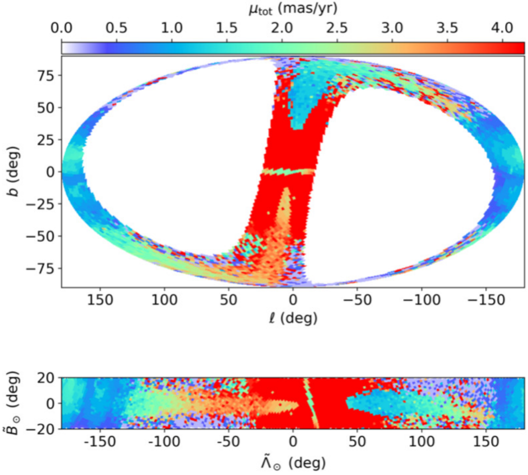


The Gaia era (2018–)

only a few recent studies tried to refine the selection of stars in the Sgr stream

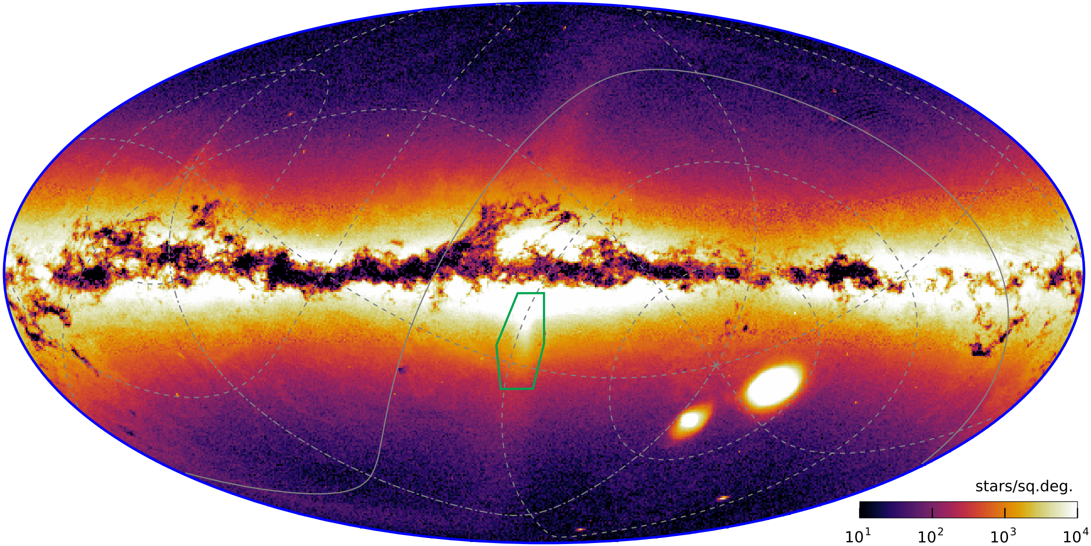
[Ibata+ 2020] [Antoja+ 2020; Ramos+ 2020]





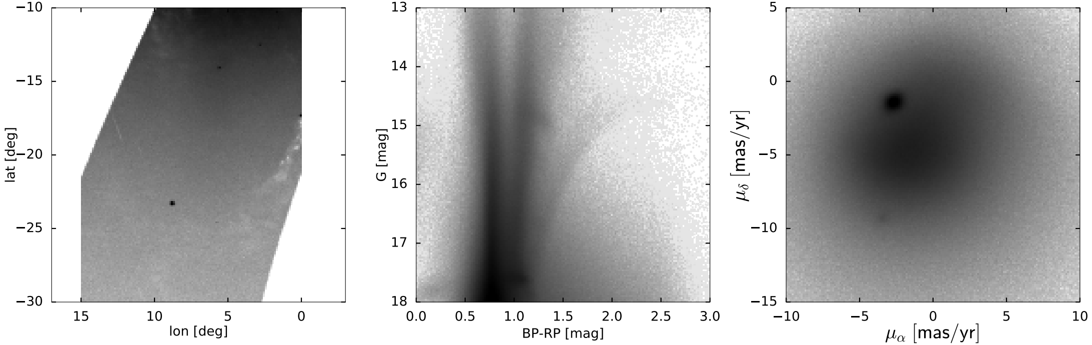
The Gaia era (2018–)

the present study focuses on the Sgr galaxy itself



Separating the grains from the chaff

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



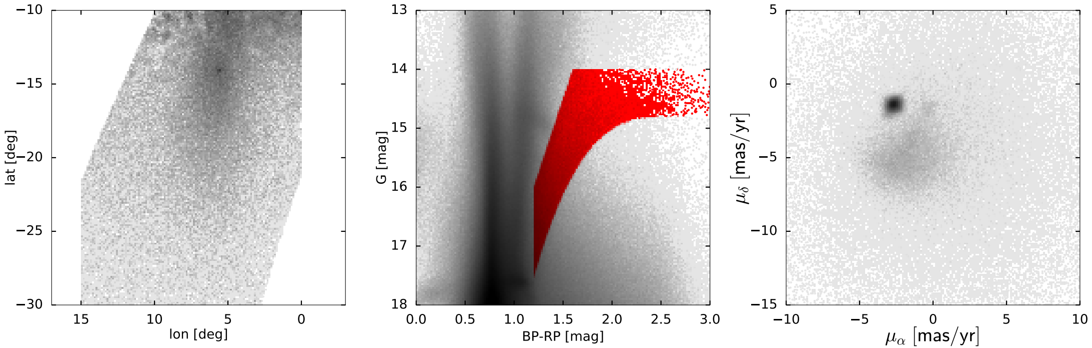
spatial distribution

colour–magnitude diagram

proper motion space

Separating the grains from the chaff

Selection by CMD



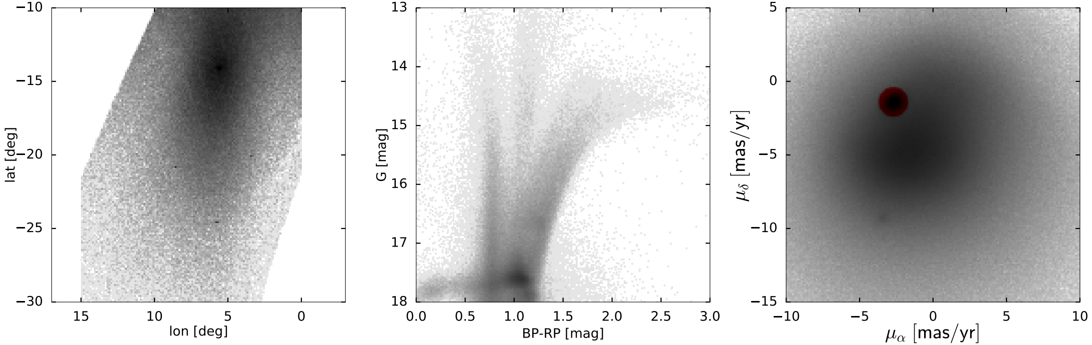
spatial distribution

colour–magnitude diagram

proper motion space

Separating the grains from the chaff

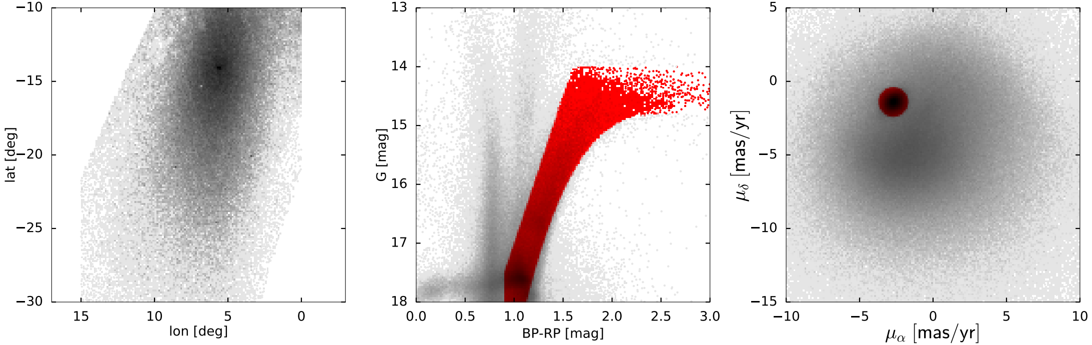
Selection by PM



spatial distribution   colour–magnitude diagram   proper motion space

Separating the grains from the chaff

Selection by CMD and PM



spatial distribution

colour–magnitude diagram

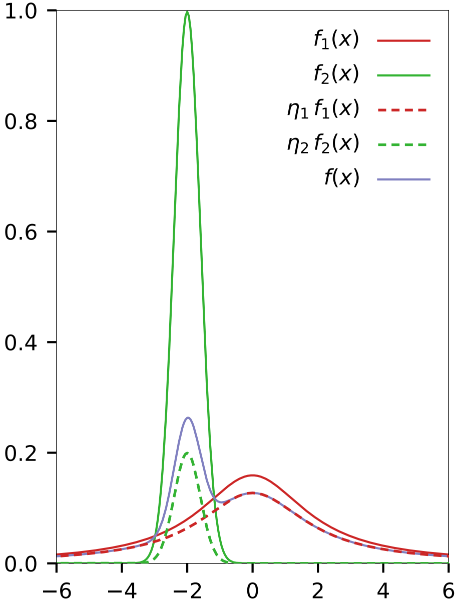
proper motion space

Membership determination from mixture modelling

$\mathbf{x}$ – all observable properties of a star (location α, δ; parallax ϖ, PM μ_α, μ_δ; photometry G, $BP - RP$)

Each star belongs to one of C populations described by probability distributions $f_c(\mathbf{x} \mid \boldsymbol{\theta})$ with some (unknown) parameters $\boldsymbol{\theta}$, normalized to unity: $\int f_c(\mathbf{x})\, d\mathbf{x} = 1$.

The mixture DF is a weighted sum of component DFs:
$f(\mathbf{x} \mid \boldsymbol{\theta}) = \sum_{c=1}^{C} \eta_c\, f_c(\mathbf{x} \mid \boldsymbol{\theta})$,
where η_c is the fraction of stars in c-th component, and $\sum_{c=1}^{C} \eta_c = 1$.



Membership determination from mixture modelling

We have a dataset of N stars with measured parameters $\mathbf{x}_i$, $i = 1..N$;
i-th star belongs to the component with index a_i.

The log-likelihood of the observed dataset, given the model parameters $(\boldsymbol{\theta}, \boldsymbol{\eta})$, is

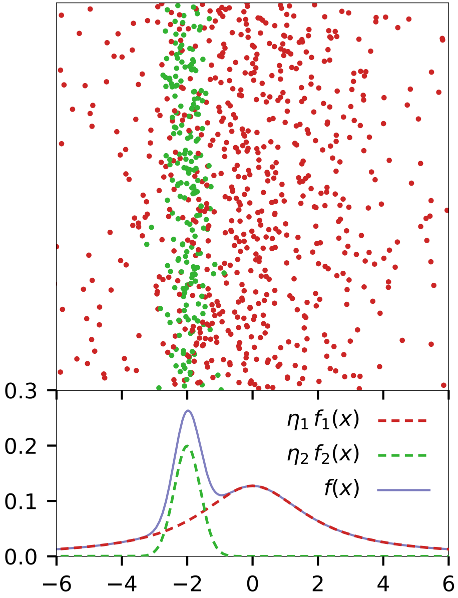
$\ln \mathcal{L} = \sum_{i=1}^{N} \ln \mathcal{L}_i$, where

$$\mathcal{L}_i \equiv f_{a_i}(\mathbf{x}_i \mid \boldsymbol{\theta}) = \sum_{c=1}^{C} \delta_{c\,a_i}\, f_c(\mathbf{x}_i \mid \boldsymbol{\theta}).$$

However, since we do not know the indices a_i, we use the mixture DF:

$$\mathcal{L}_i \equiv f(\mathbf{x}_i \mid \boldsymbol{\theta}) = \sum_{c=1}^{C} \eta_c\, f_c(\mathbf{x}_i \mid \boldsymbol{\theta}).$$

As usual, the model parameters may be inferred by maximizing $\ln \mathcal{L}$ (optionally with some priors).

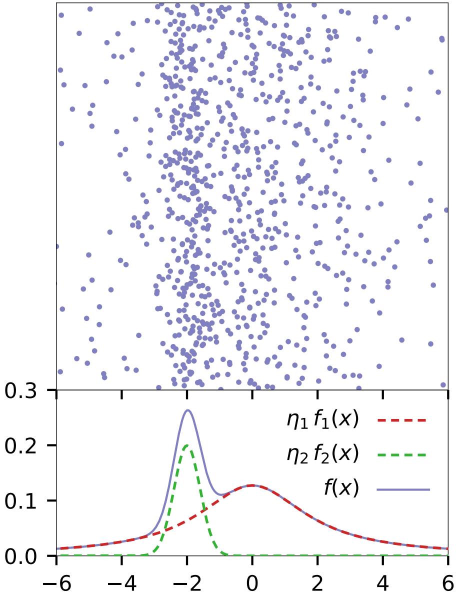


Membership determination from mixture modelling

Assume first that we know the parameters for all DFs $\boldsymbol{\theta}$ and their fractions η_c, but do not know which star belongs to which component.

η_c are prior membership probabilities (identical for all stars), while the posterior probabilities for i-th star with measured properties $\mathbf{x}_i$ are

$$p_i^{(c)} = \frac{\eta_c\, f_c(\mathbf{x}_i \mid \boldsymbol{\theta})}{\sum_{k=1}^{C} \eta_k\, f_k(\mathbf{x}_i \mid \boldsymbol{\theta})} \;.$$



Membership determination from mixture modelling

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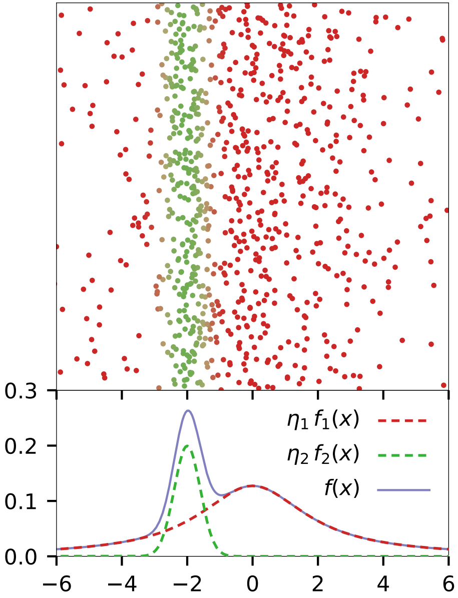
η_c are prior membership probabilities (identical for all stars), while the posterior probabilities for i-th star with measured properties $\mathbf{x}_i$ are

$$p_i^{(c)} = \frac{\eta_c\, f_c(\mathbf{x}_i \mid \boldsymbol{\theta})}{\sum_{k=1}^{C} \eta_k\, f_k(\mathbf{x}_i \mid \boldsymbol{\theta})} \;.$$

At the same time, $\eta_c = \dfrac{1}{N}\displaystyle\sum_{i=1}^{N} p_i^{(c)}$,

so the fractions can be computed alongside membership probabilities.



Membership determination from mixture modelling

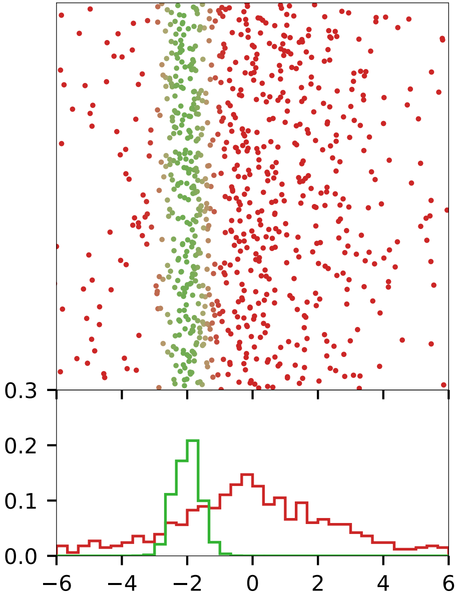
Now that we know (probabilistically) the membership of each point $p_i^{(c)}$, we may update the parameters of the DFs $\boldsymbol{\theta}$:

$$\boldsymbol{\theta}^{(new)} = \arg\max_{\boldsymbol{\theta}} \big(\ln \mathcal{L} \big) = \arg\max_{\boldsymbol{\theta}} \Big(\sum_{i=1}^{N} \sum_{c=1}^{C} p_i^{(c)} \ln f_c(\mathbf{x}_i \mid \boldsymbol{\theta}) \Big).$$

Fit the parameters $\boldsymbol{\theta}$ of each DF f_c to the measured values $\mathbf{x}_i$, weighted by probabilities $p_i^{(c)}$.

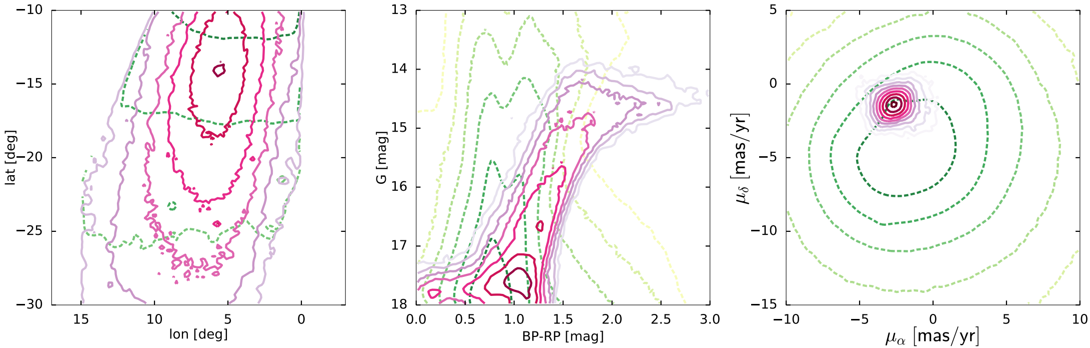
$f_c(\mathbf{x})$ may have any suitable functional form:
– a Gaussian ($\boldsymbol{\theta}$ are the mean and dispersion);
– a histogram ($\boldsymbol{\theta}$ are the bin heights);
– …

Repeat these steps until convergence: this is the expectation/maximization algorithm.



Separating the grains from the chaff – the fancy way

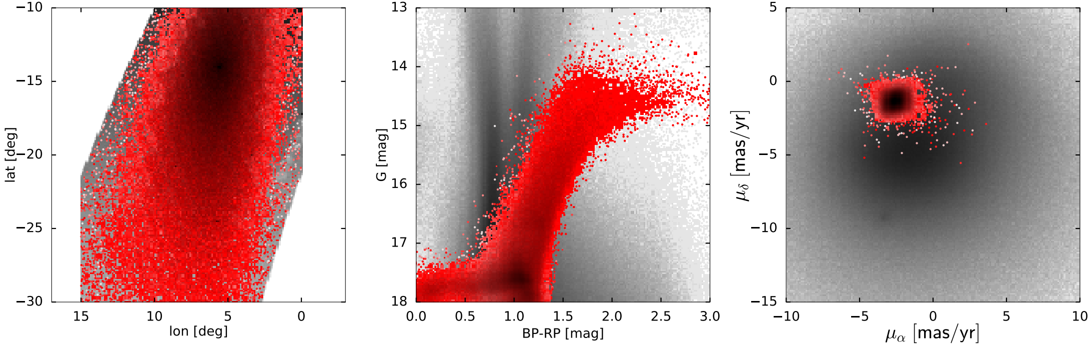
red: Sgr members; green: Milky Way foreground



spatial distribution | colour–magnitude diagram | proper motion space

Separating the grains from the chaff – the fancy way

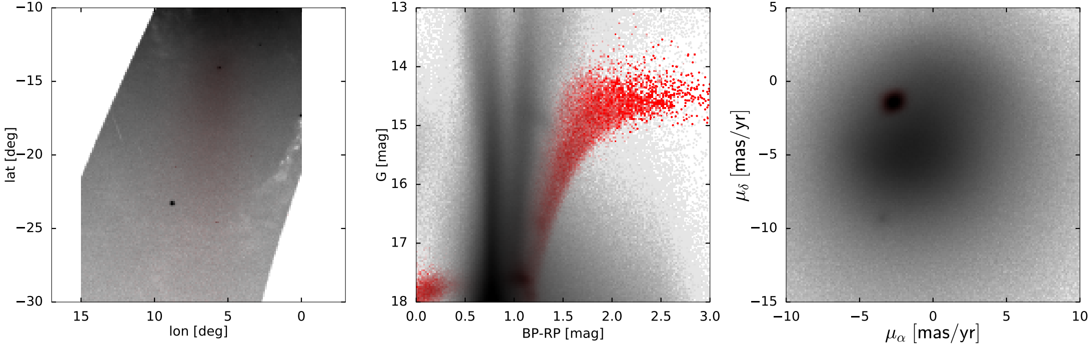
red: Sgr members; gray: Milky Way foreground



spatial distribution | colour–magnitude diagram | proper motion space

Separating the grains from the chaff – the fancy way

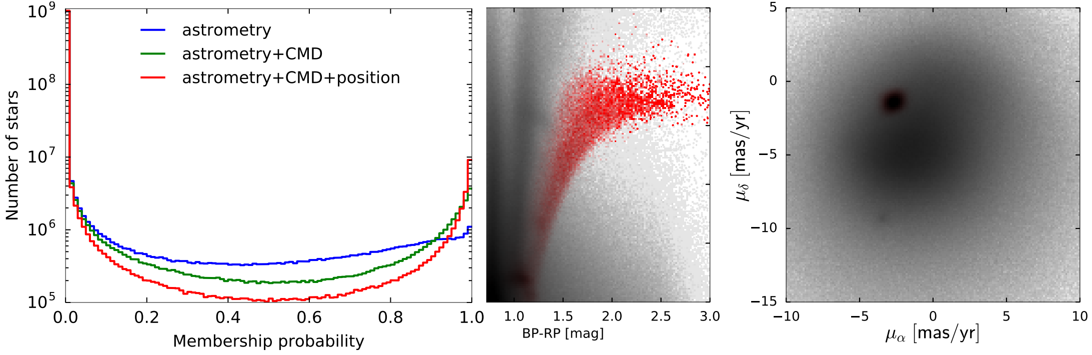
saturation: membership probability; brightness: density



spatial distribution | colour–magnitude diagram | proper motion space

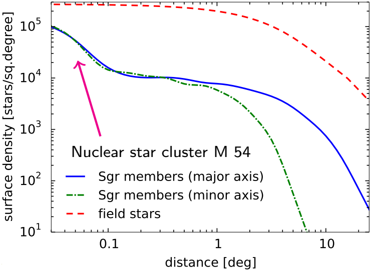
Separating the grains from the chaff – the fancy way

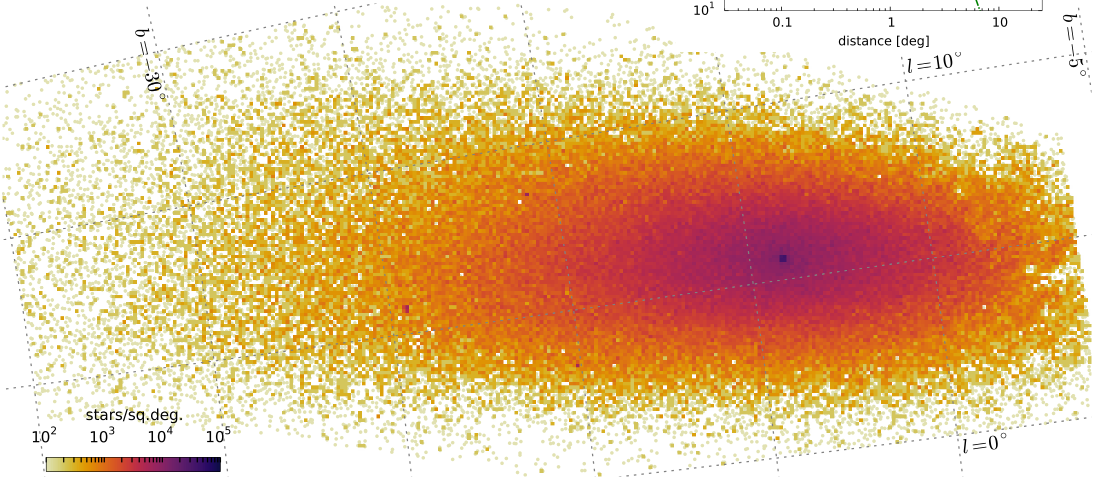
The combination of all selection criteria produces a very sharp distinction between Sgr members and field stars



spatial distribution | colour–magnitude diagram | proper motion space

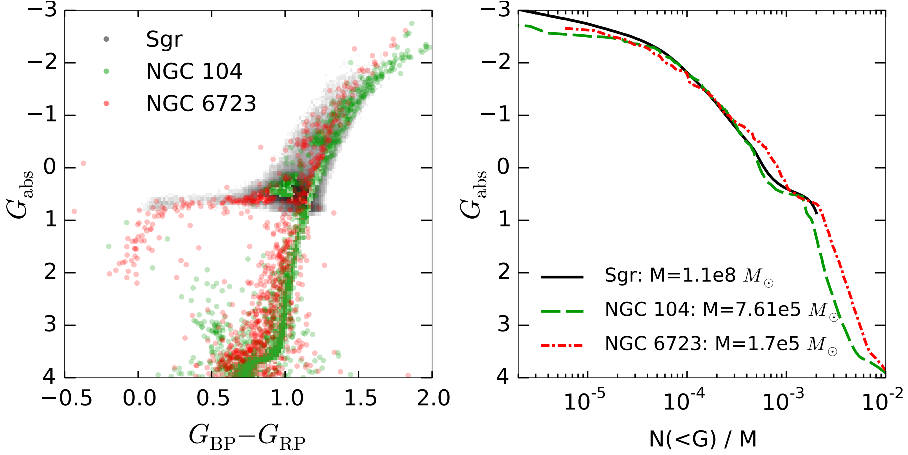
The Sagittarius galaxy remnant





The Sagittarius galaxy remnant: photometry and total mass

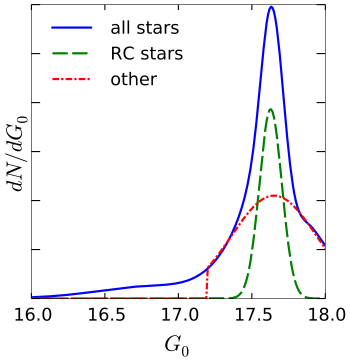
comparison of magnitude distribution of Sgr members with
that of globular clusters of similar metallicity ($z \simeq -0.7 .. -1$)
$\Longrightarrow$ determine the total mass of stars in Sgr $M_\star \simeq 10^8\, M_\odot$.

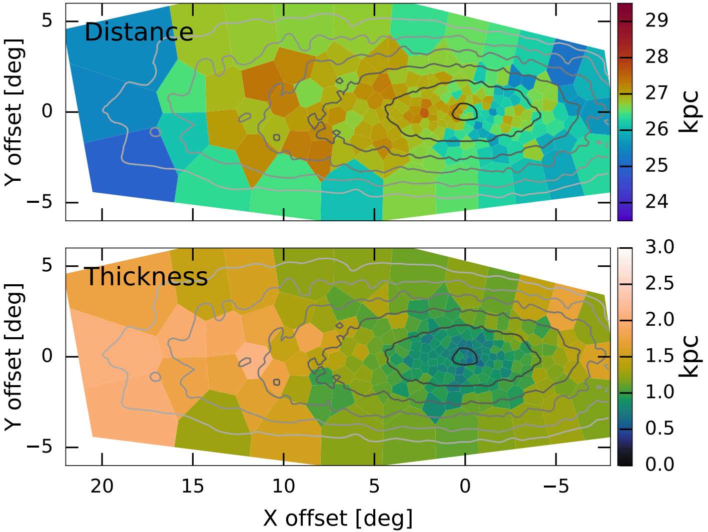


dynamical masses of clusters from Baumgardt+ 2019

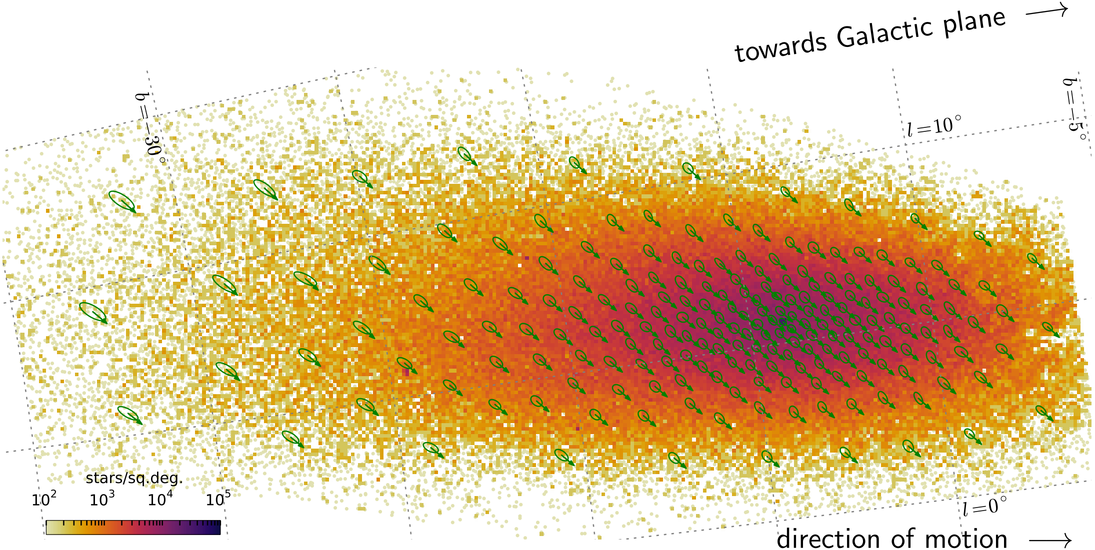
The Sagittarius galaxy remnant: photometry and distance

magnitude distribution
of red clump stars





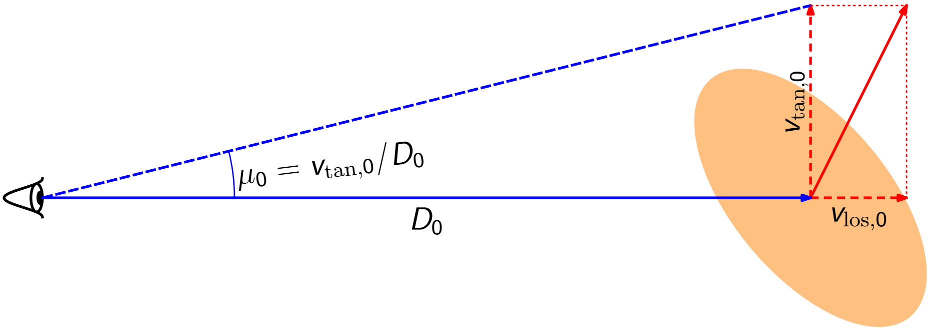
The Sagittarius galaxy remnant: kinematics



Putting things into perspective

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

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

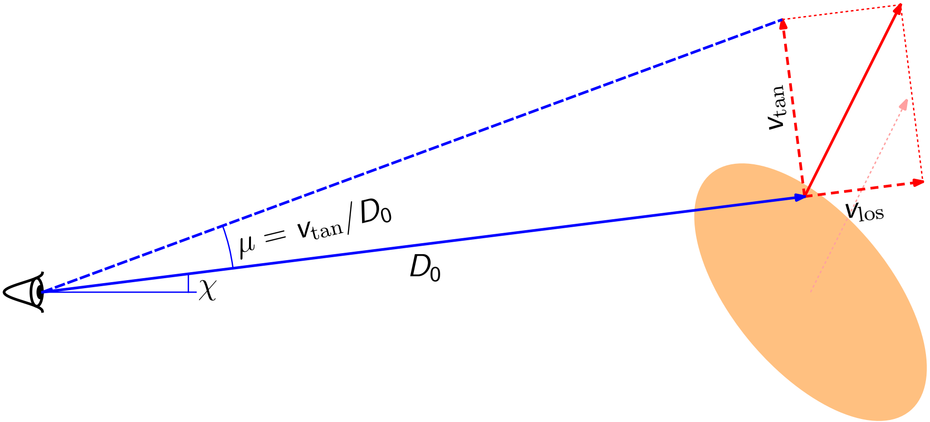


Putting things into perspective

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

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

perspective corrections



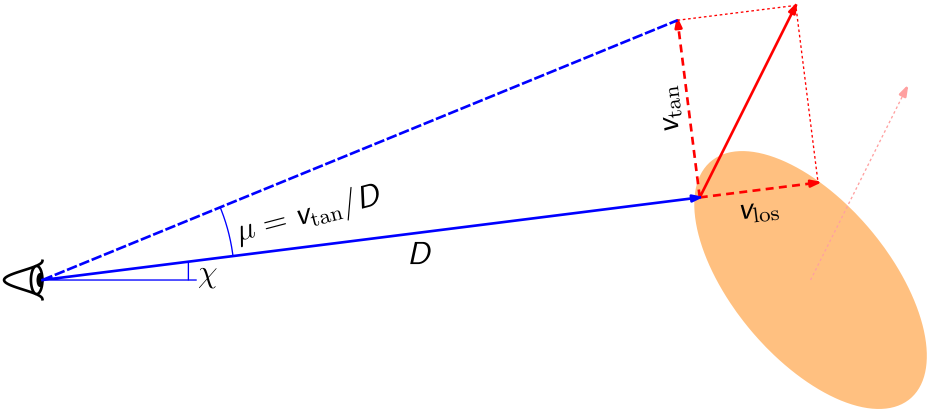
Putting things into perspective

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

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

perspective corrections

distance correction



Putting things into perspective

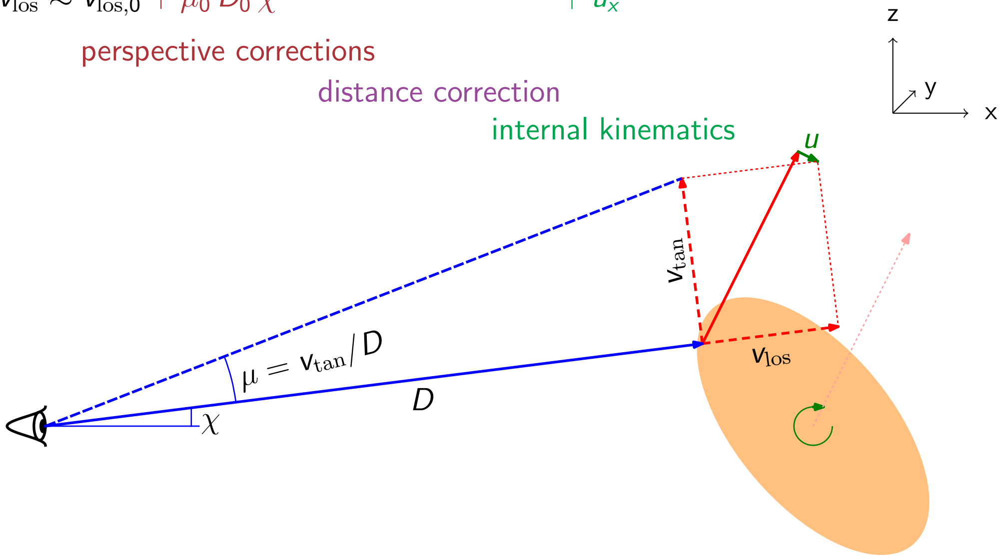
$$\mu \approx \mu_0 - v_{\mathrm{los},0}/D_0\,\chi - \mu_0\,(D/D_0 - 1) + u_z/D$$

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

perspective corrections

distance correction

internal kinematics



Putting things into perspective

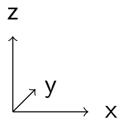
$$\mu \approx \mu_0 - v_{\mathrm{los},0}/D_0\,\chi - \mu_0\,(D/D_0 - 1) + u_z/D$$

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

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:

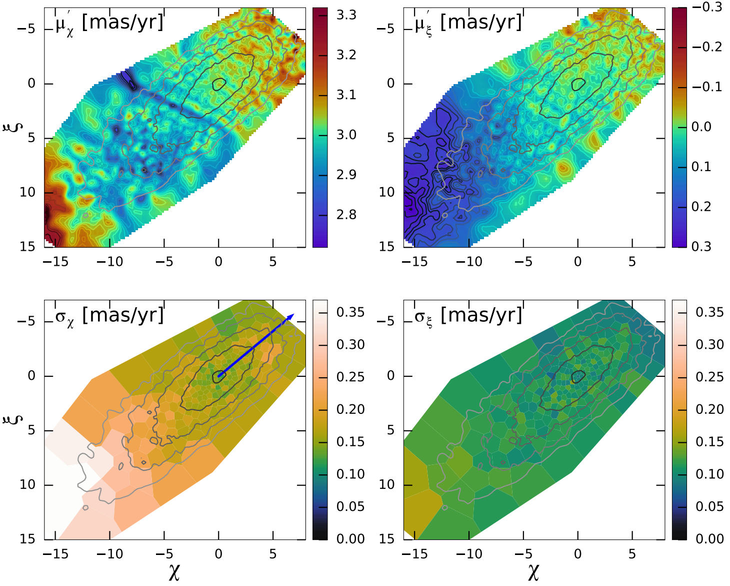
$$\chi \parallel \mu_0 : \quad \mu'_\chi \equiv \mu_\chi + v_{\mathrm{los},0}/D_0\,\chi \approx \mu_0 + u_z/D - \mu_0\,(D/D_0 - 1)\,\chi$$

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

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

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

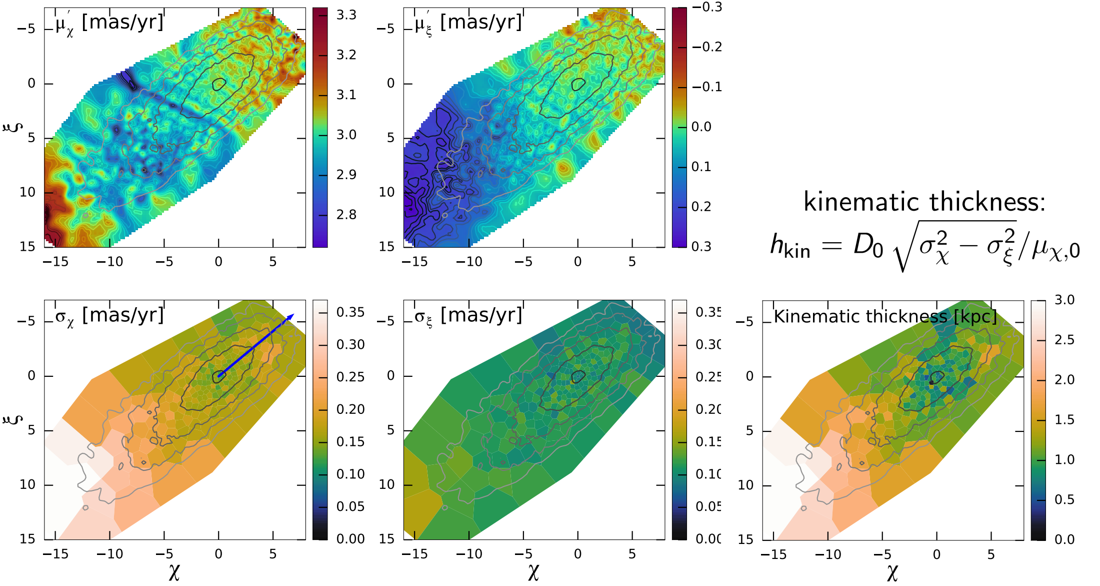
The Sagittarius galaxy remnant: kinematics



towards Galactic plane →

direction of apparent motion →

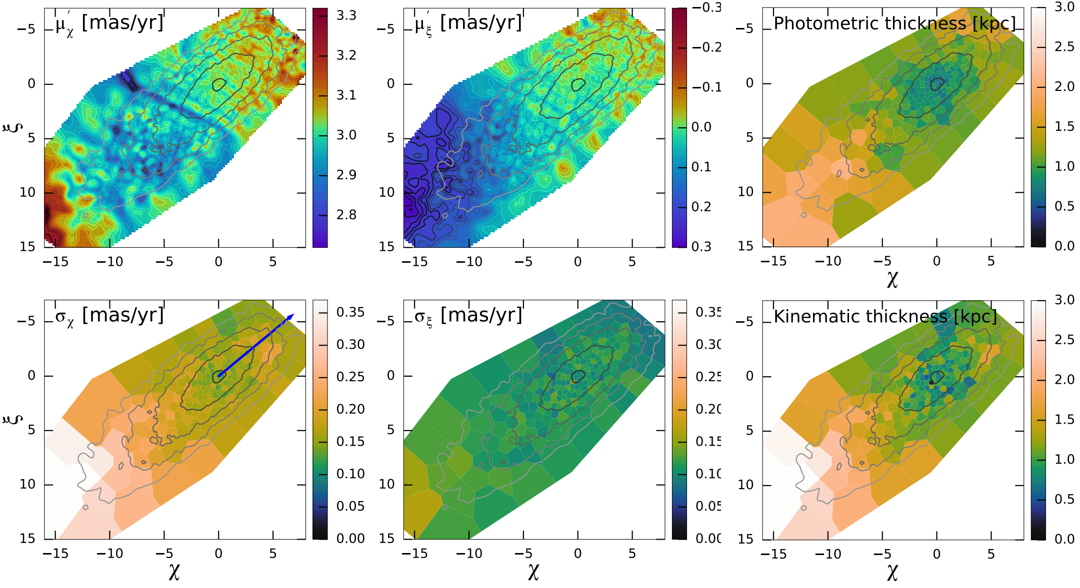
The Sagittarius galaxy remnant: kinematics



kinematic thickness:

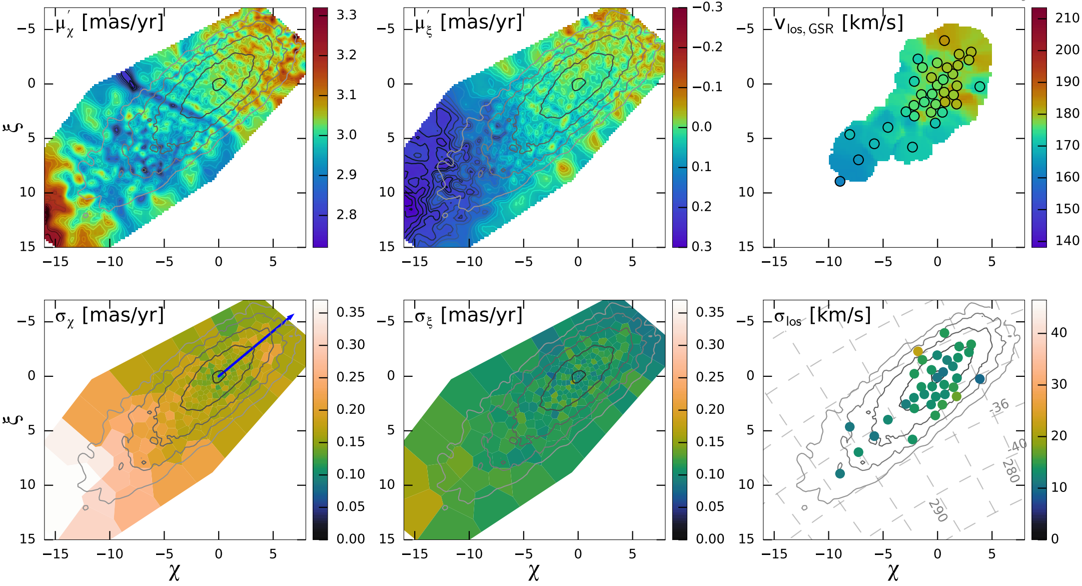
$$h_{\rm kin} = D_0\,\sqrt{\sigma_\chi^2 - \sigma_\xi^2}/\mu_{\chi,0}$$

The Sagittarius galaxy remnant: kinematics



The Sagittarius galaxy remnant: kinematics

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



N-body models of a disrupting satellite

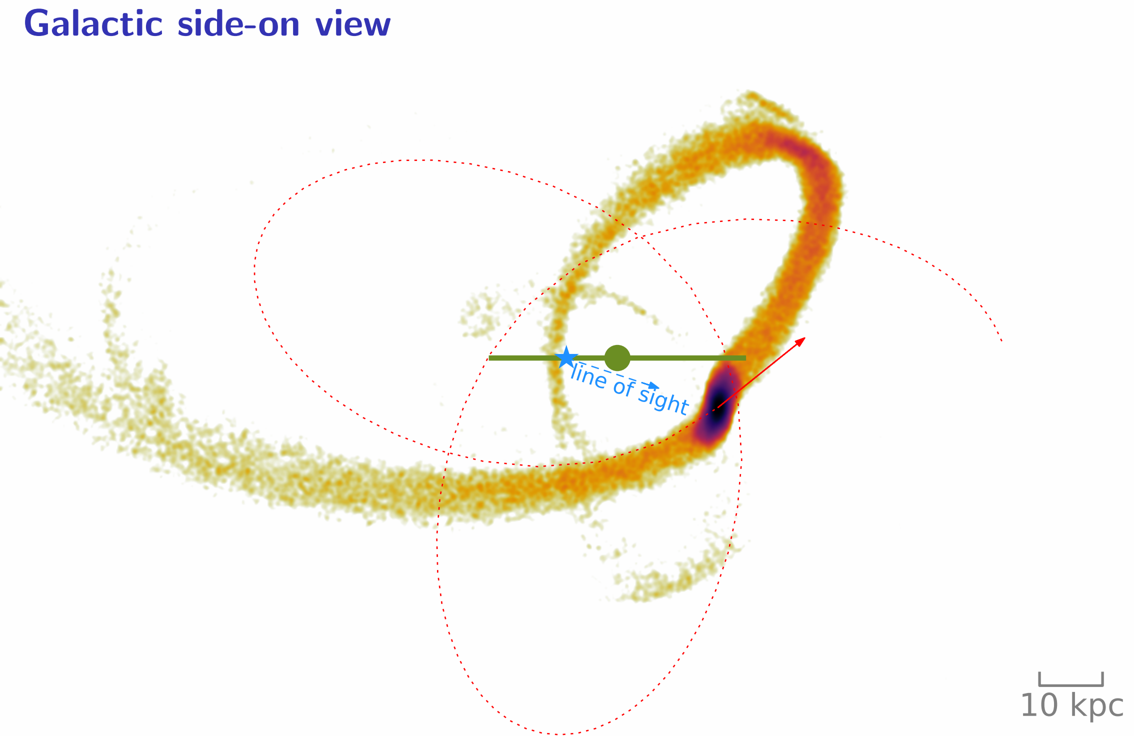
Goals:

- 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:

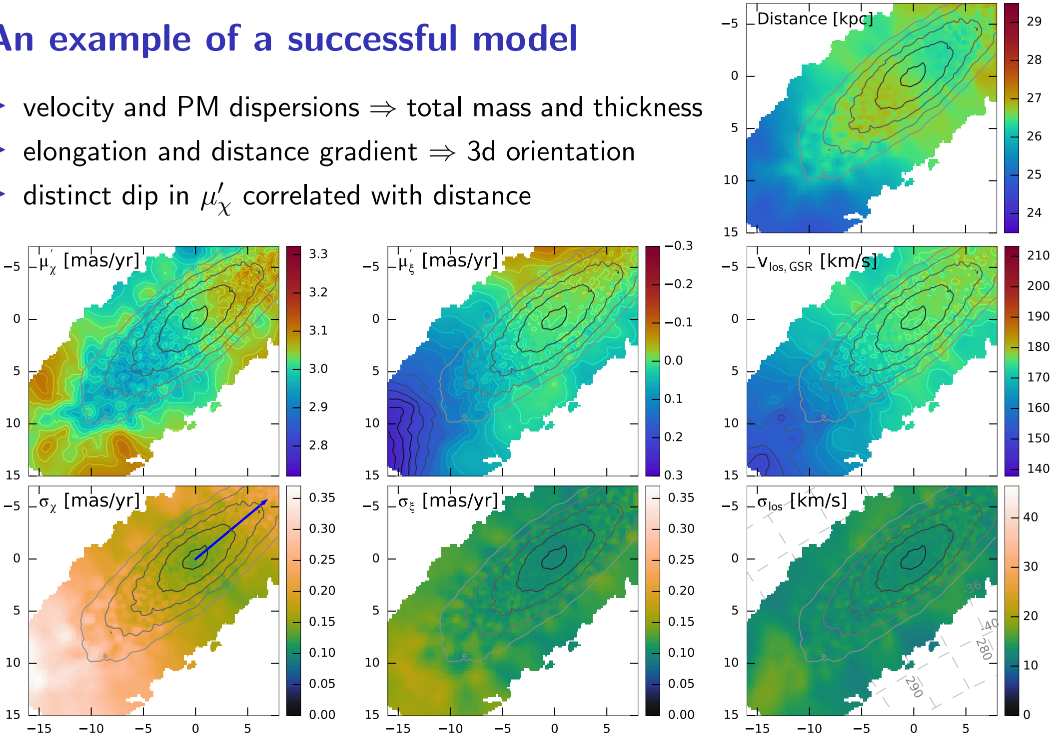
- construct various initial equilibrium models (stars + dark halo):
  spherical, flattened, rotating, different density profiles, ...
- evolve the satellite in the static external potential of the Milky Way
- iteratively adjust initial conditions to match its present-day position/velocity
- compare the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

repeat dozens of times


Galactic side-on view
line of sight
10 kpc

An example of a successful model

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



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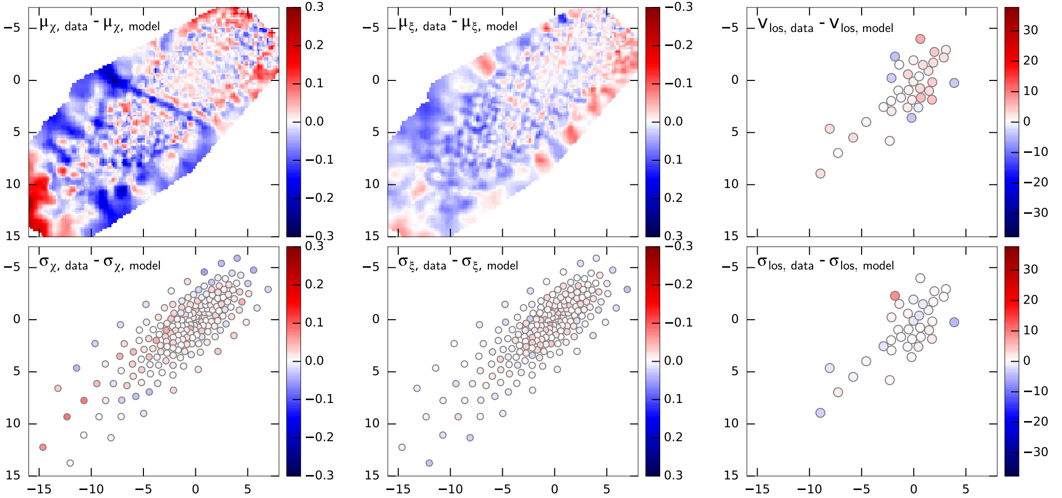
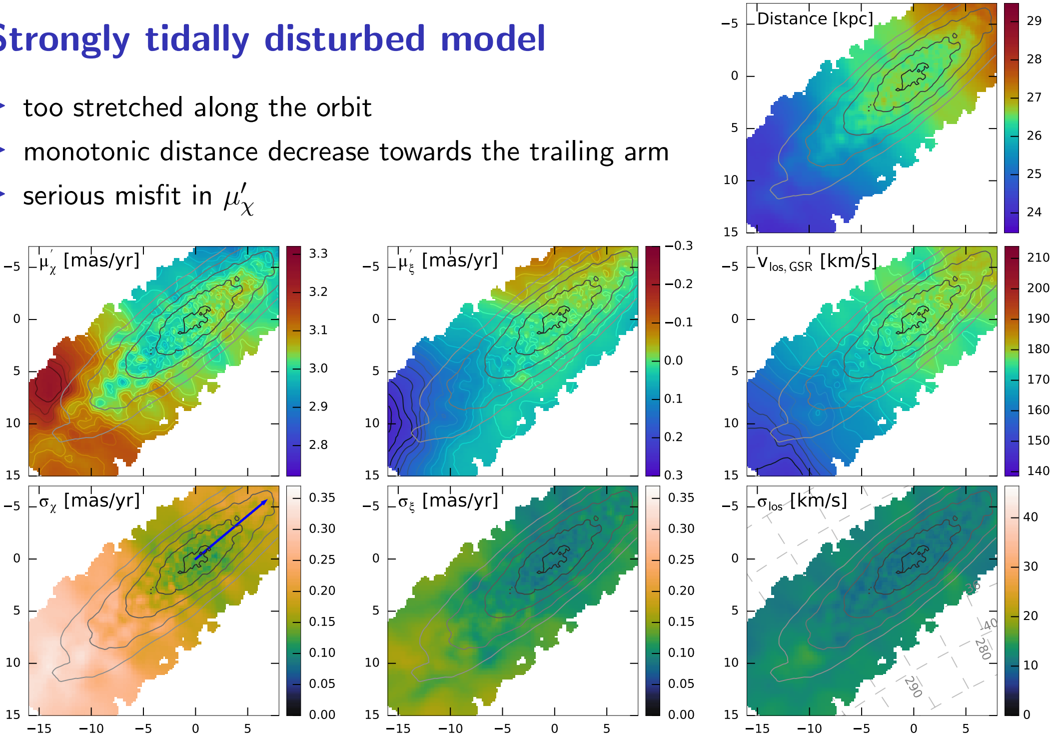


Strongly tidally disturbed model

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



Strongly tidally disturbed model

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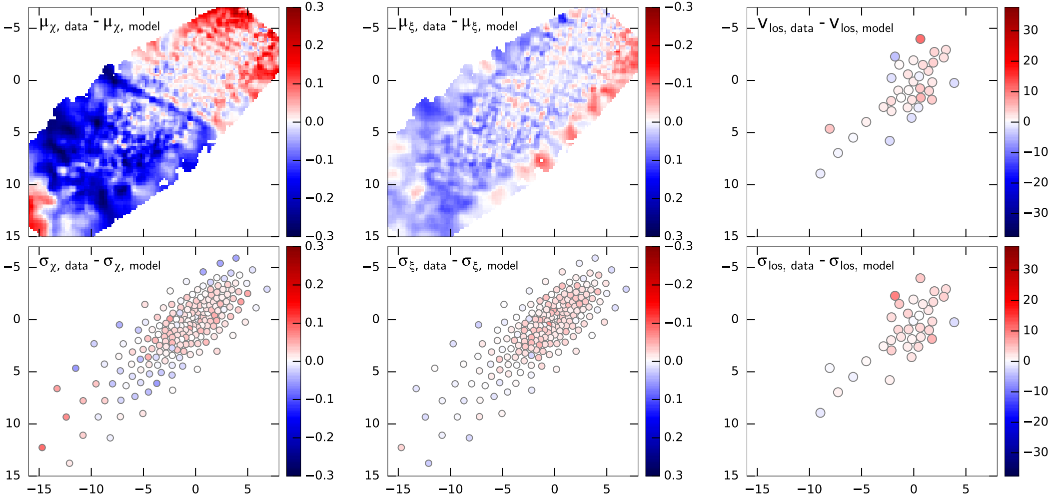
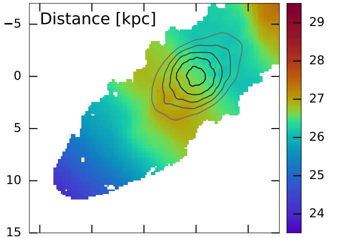
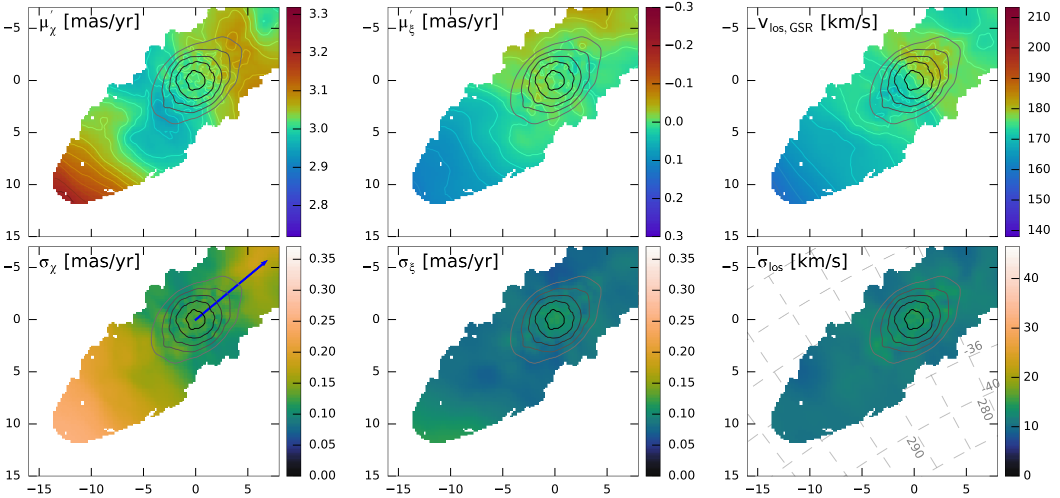


More concentrated model

- 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 successful model for the Sgr stream

- too round and too compact
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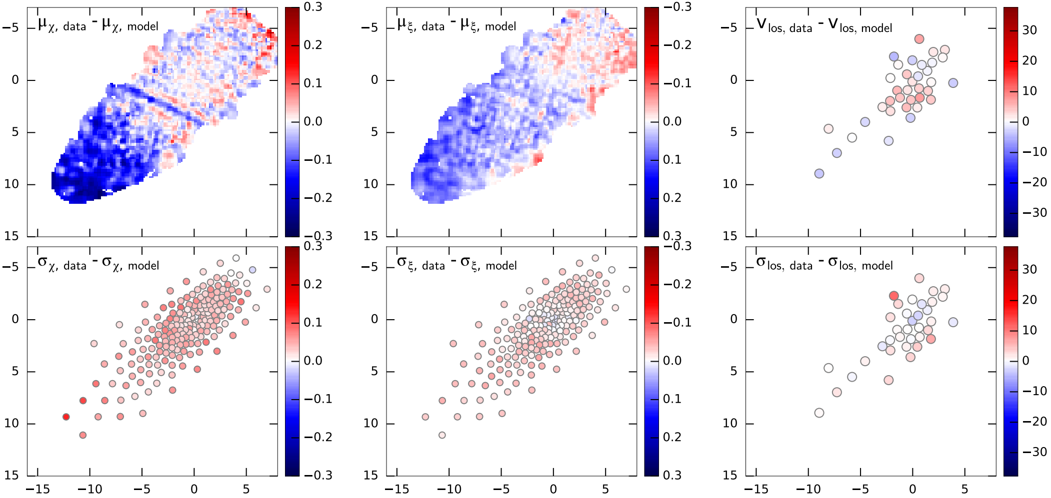
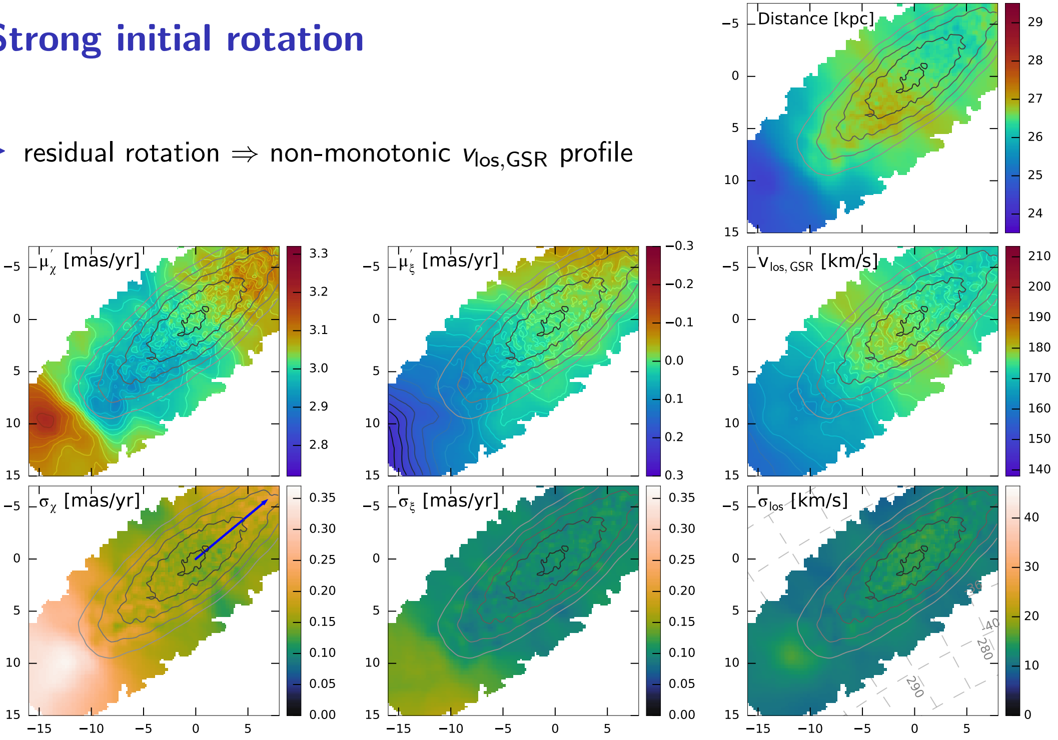


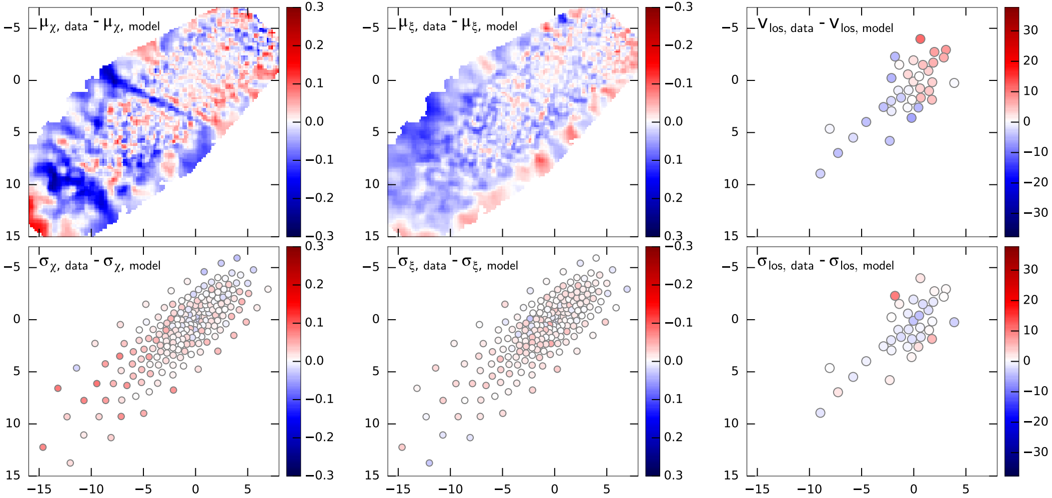
Strong initial rotation

- residual rotation $\Rightarrow$ non-monotonic $v_{\text{los,GSR}}$ profile



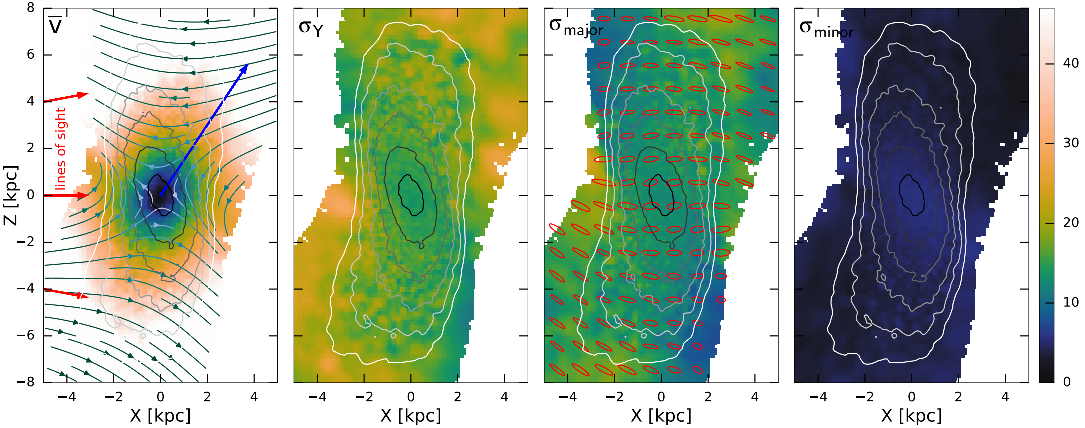
Strong initial rotation Łokas+ 2010 scenario of a tidally induced bar

- residual rotation $\Rightarrow$ non-monotonic $v_{\mathrm{los,GSR}}$ profile



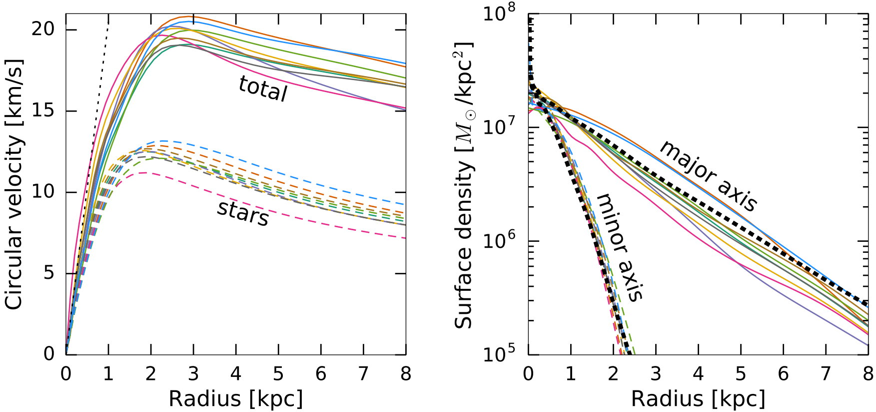
Internal structure and kinematics of the Sgr remnant

- characteristic S-shape and $\sim 45^\circ$ tilt w.r.t. the orbit extending up to ~ 5 kpc
- X-shaped streamlines of relative velocity (shear and moderate rotation)
- very anisotropic velocity dispersion tensor $\perp$ to the photometric major axis



Common features of all successful models

- 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
- central density $\lesssim 2.5\times 10^7\, M_\odot/\mathrm{kpc}^3$ (below the tidal limit)



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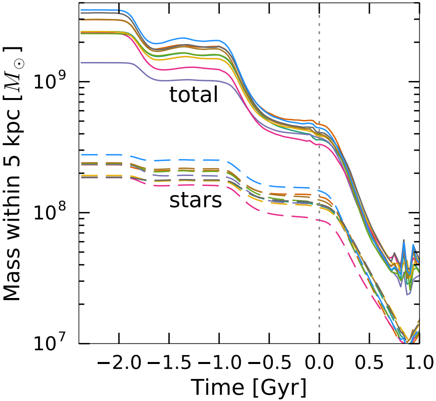
- stellar profile more spatially concentrated than total mass profile
- central density $\lesssim 2.5 \times 10^7\, M_\odot/\mathrm{kpc}^3$ (below the tidal limit)
- prolate cigar-shaped remnant extending up to ~ 5 kpc and tilted at $\sim 45^\circ$ to the orbit – essential for reproducing the kinematics, particularly the μ'_χ field
- current state of the remnant – neither too compact nor too fluffy

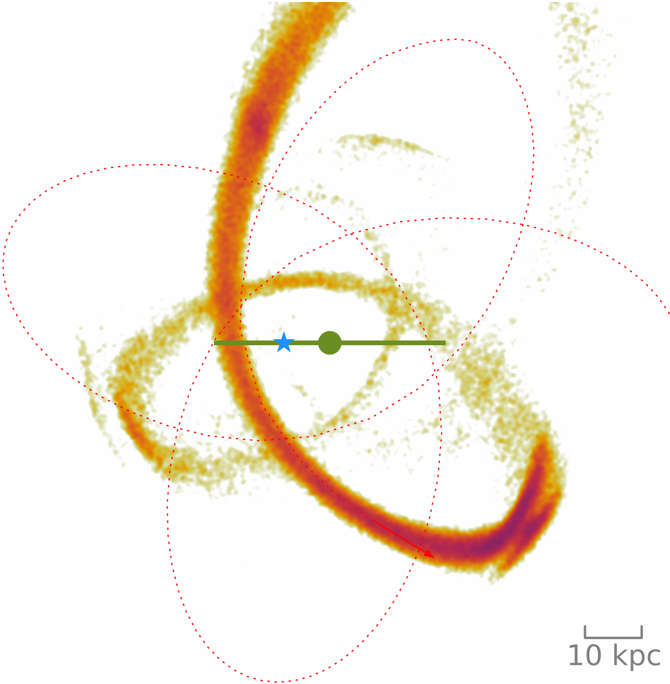
Limitations

- Sgr stream not fitted by the N-body model (intentionally)
- assumed a particular choice for the Milky Way potential and kept it fixed
- simulation not started from ab initio cosmologically motivated models

Looking into the future

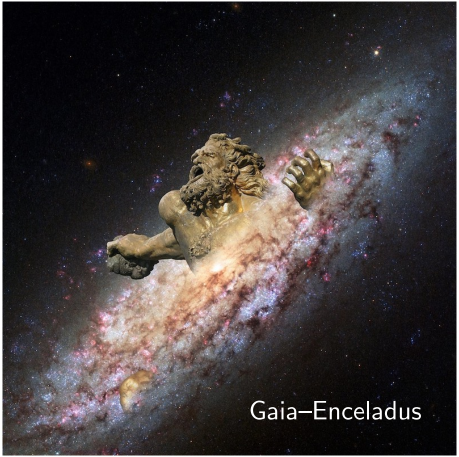
Sgr is completely disrupted over the next orbit (~ 1 Gyr)





Looking into the past

Not the first time that a satellite is devoured by the Milky Way!



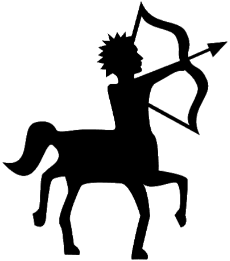
[Helmi+ 2018]

Looking into the past

Not the first time that a satellite
is devoured by the Milky Way!

[Belokurov+ 2018; Helmi+ 2018]

Looking into the past



Time:	~ 10 Gyr ago	now
Stellar mass:	$\sim 10^9\, M_\odot$ [Mackereth+ 2019; Deason+ 2019]	$\sim 2 \times 10^8\, M_\odot$ [Niederste-Ostholt+ 2012]
# of globular clusters:	~ 20 [Myeong+ 2018,2019]	≥ 6 [Law & Majewski 2010; Bellazzini+ 2020]
Legacy:	metal-rich half of the MW halo	stream; perturbations in the MW disc [Antoja+ 2018]

Summary

- Gaia DR2 made possible a detailed study of our closest satellite
- Present-day structure and kinematics of the remnant is tightly constrained
- 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