Dynamics of Milky Way globular clusters and satellite galaxies in the Gaia era

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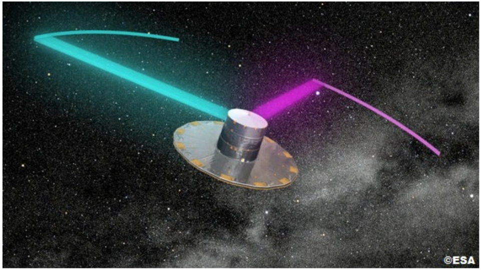
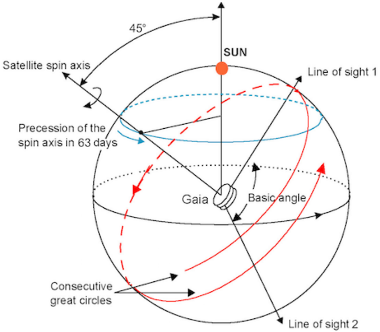
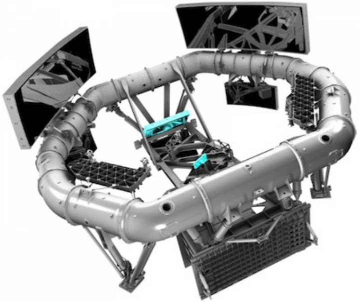
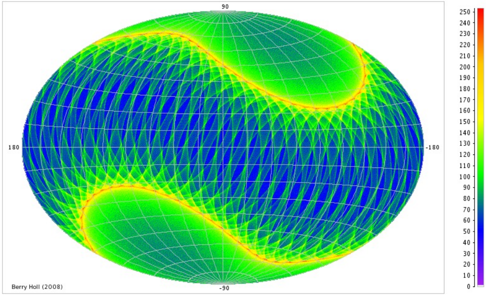
Gaia mission: the Milky Way in motion









Gaia mission timeline

Dec 2013	launch
Sep 2016	DR1: G-band photometry for $> 10^9$ sources, astrometry for 2×10^6 bright stars previously observed by *Hipparcos* (1990s)
Apr 2018	DR2: G, G_{BP}, G_{RP} photometry for 1.4×10^9 sources, astrometry (parallaxes & proper motions) for 1.3×10^9 stars, line-of-sight velocity for 7×10^6 bright stars
Jun 2019	end of nominal 5-year mission; extended for a few years
Dec 2020	Early DR3: improved photometry and astrometry for 1.5×10^9 sources
1h 2022	DR3: astrometry/photometry remains the same, line-of-sight velocity for $\sim 3 \times 10^7$ stars, mean BP, RP and RVS spectra, astrometric solutions for non-single stars, lightcurves for variable sources
∼2024	end of extended mission (limited by onboard fuel supply)
2024 ?	DR4: full analysis of the nominal 5-year mission data; improved astrometry, photometry, spectroscopy; individual epoch data
?	DR5: full analysis of the extended mission, final catalogue.

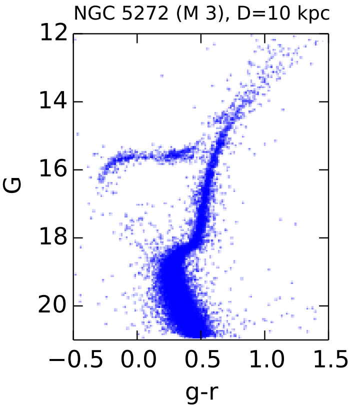
Gaia astrometric precision

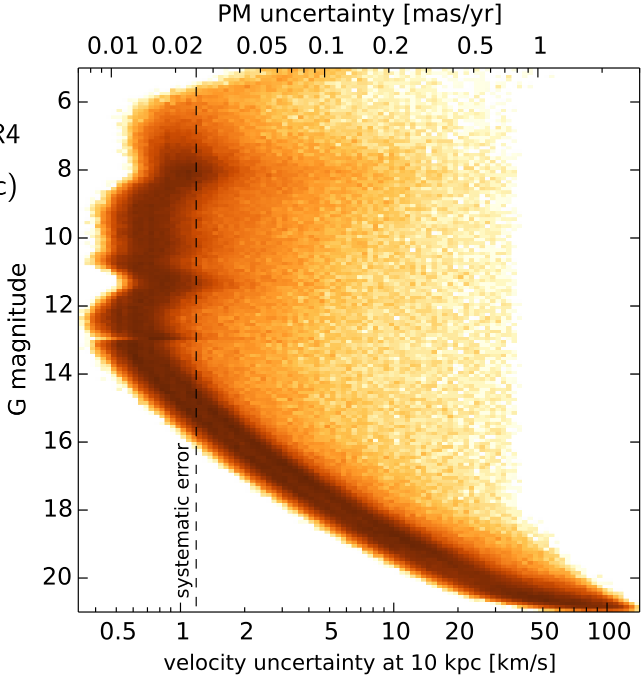
$\epsilon_\mu \gtrsim 0.01$ mas/yr in EDR3

$\epsilon_\mu \propto T^{-3/2}$:
expect $2.5\times$ improvement in DR4

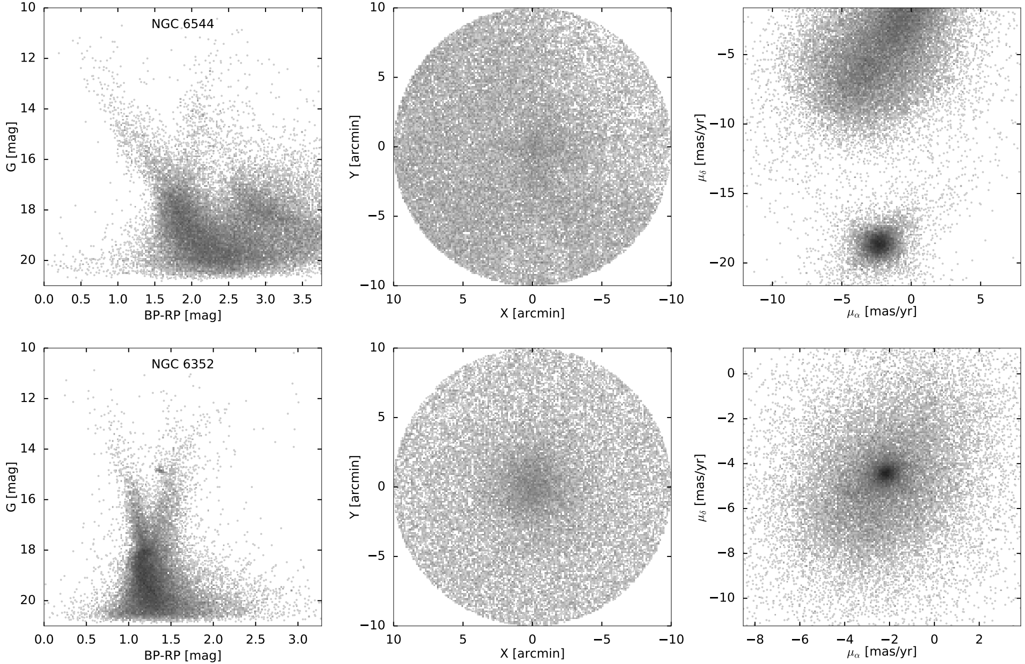
$1\,\mathrm{mas/yr} = 4.7\,\mathrm{km/s} \times (D/1\,\mathrm{kpc})$

$\sigma \sim 2 - 10$ km/s in clusters





Determination of cluster membership



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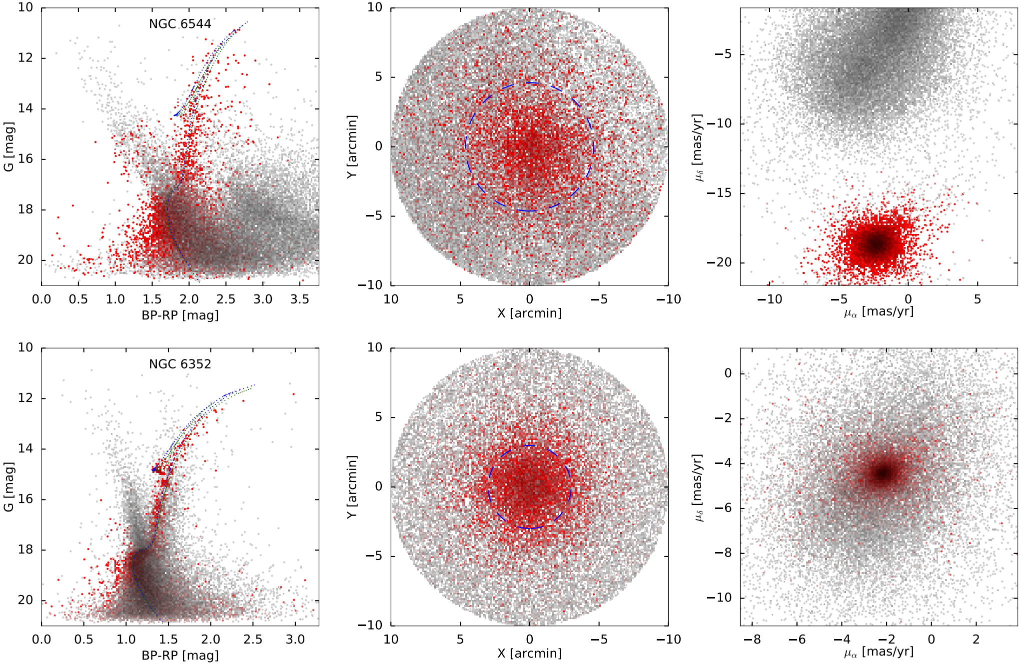
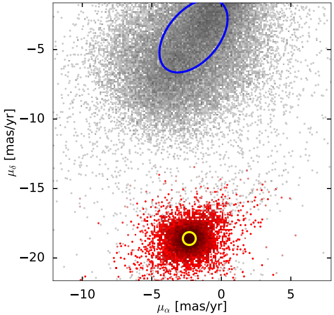


Determination of cluster membership and parameters

A hard cutoff in PM space is not always possible and is conceptually unsatisfactory.

A more mathematically well-grounded alternative: mixture modelling [Gaussian or more general].

Write down the distribution functions for both cluster and field populations, and vary their parameters $\boldsymbol{\theta}$ to maximize the likelihood of the observed data data:



true DF convolved with errors

measurements: $\varpi, \boldsymbol{\mu}, R$

measurement uncertainties

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

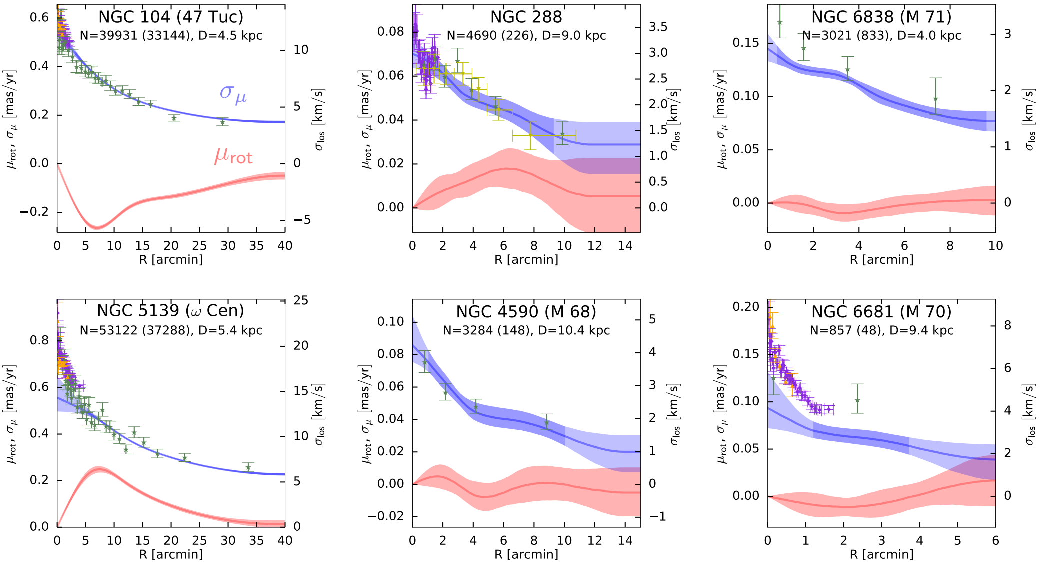
fraction of members

parameters of distributions

Results: cluster properties $\overline{\varpi},\ \overline{\boldsymbol{\mu}},\ \sigma_\mu(R),\ \mu_\mathrm{rot}(R),\ \eta,\ \dots$

and membership probability of each star: $p_i = \dfrac{\eta\, f_\mathrm{memb}(\mathbf{x}_i)}{\eta\, f_\mathrm{memb}(\mathbf{x}_i) + (1-\eta)\, f_\mathrm{field}(\mathbf{x}_i)}$.

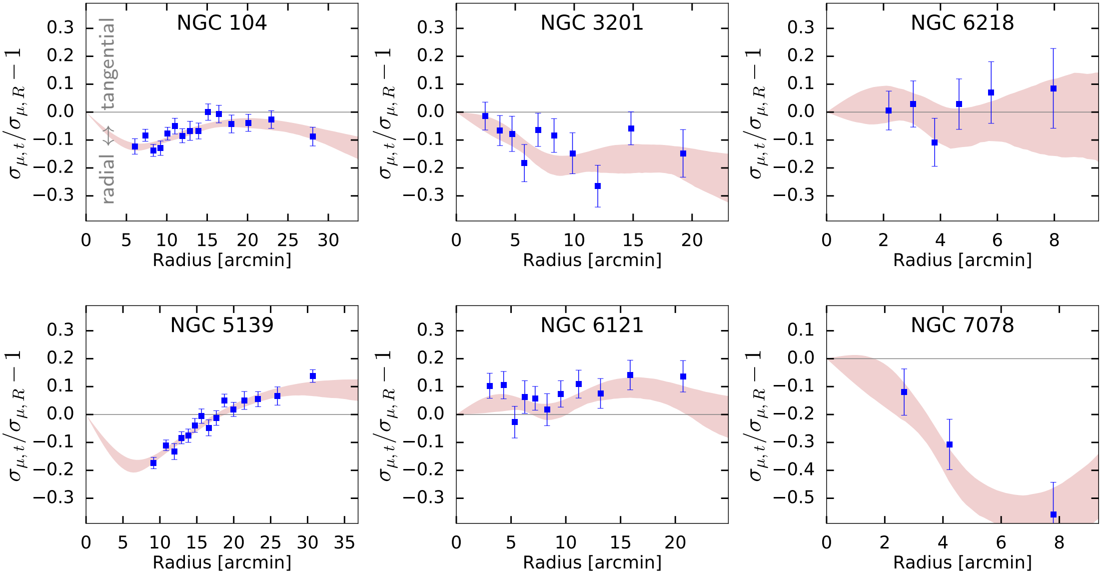
Internal kinematics of star clusters: rotation, dispersion



Good agreement with HST σ_μ [Watkins+ 2015, Cohen+ 2021] and $\sigma_{\rm LOS}$ from literature

[Vasiliev & Baumgardt 2021; see also Bianchini+ 2018, Baumgardt+ 2019, Vasiliev 2019, Sollima+ 2019]

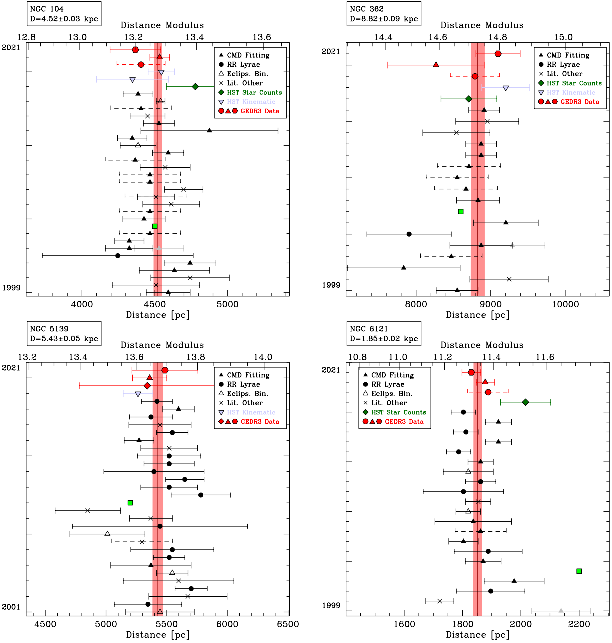
PM anisotropy profiles

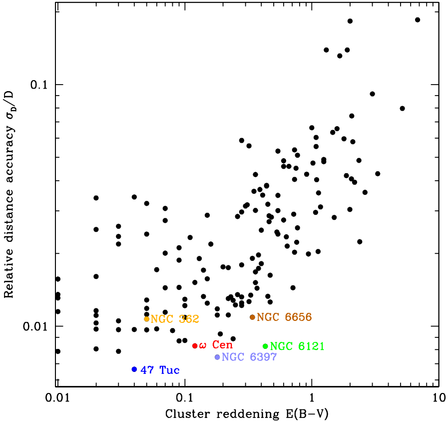


variety of profiles, mostly weakly radial or isotropic

[Vasiliev & Baumgardt 2021; see also Jindal+ 2019, Bianchini+ 2019]

Distances to globular clusters



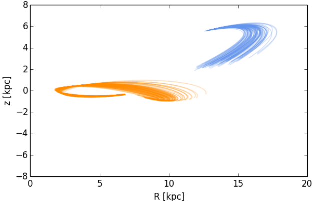


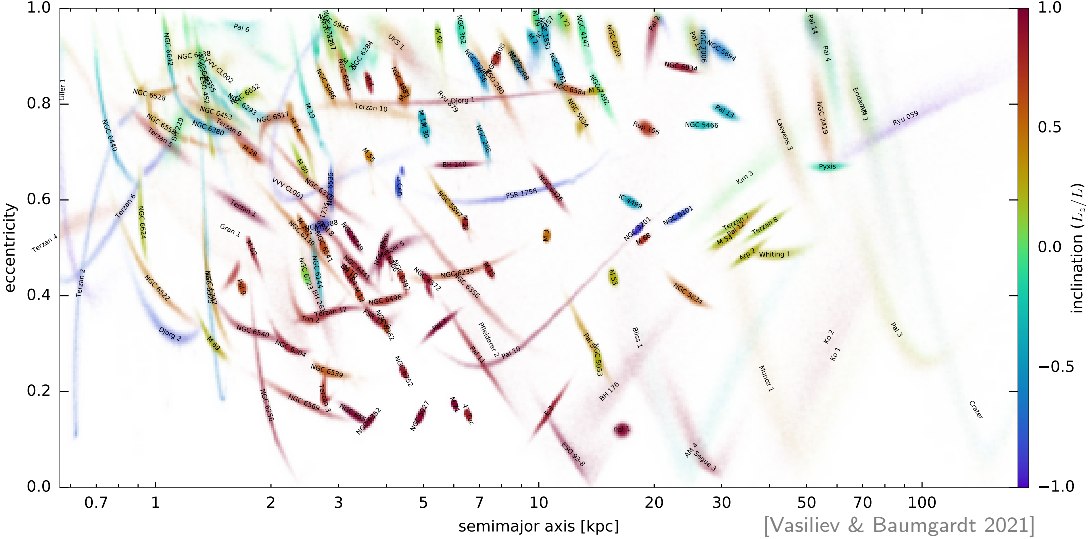
compilation of ∼ 1300 literature measurements (CMD, RR Lyrae, eclipsing binaries) + HST/Gaia dynamical fits & parallaxes [Baumgardt & Vasiliev 2021]

https://people.smp.uq.edu.au/HolgerBaumgardt/globular/

Orbits of globular clusters

each cluster is shown by a cloud representing its measurement uncertainties (primarily in distance)

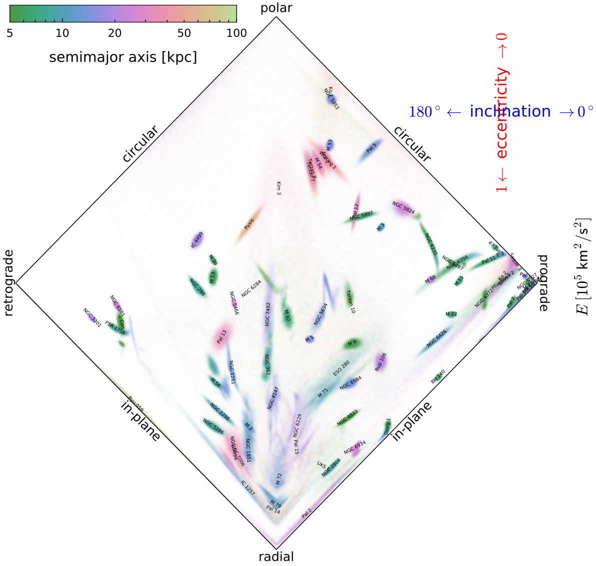


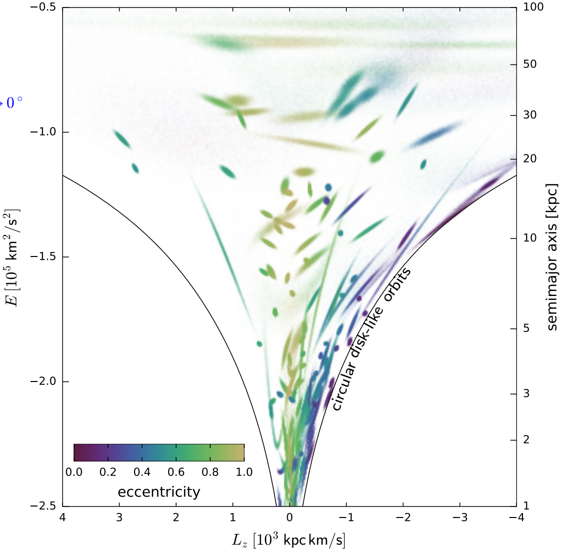


[Vasiliev & Baumgardt 2021]

Clusters in the space of integrals of motion

(energy, angular momentum, actions. . .)





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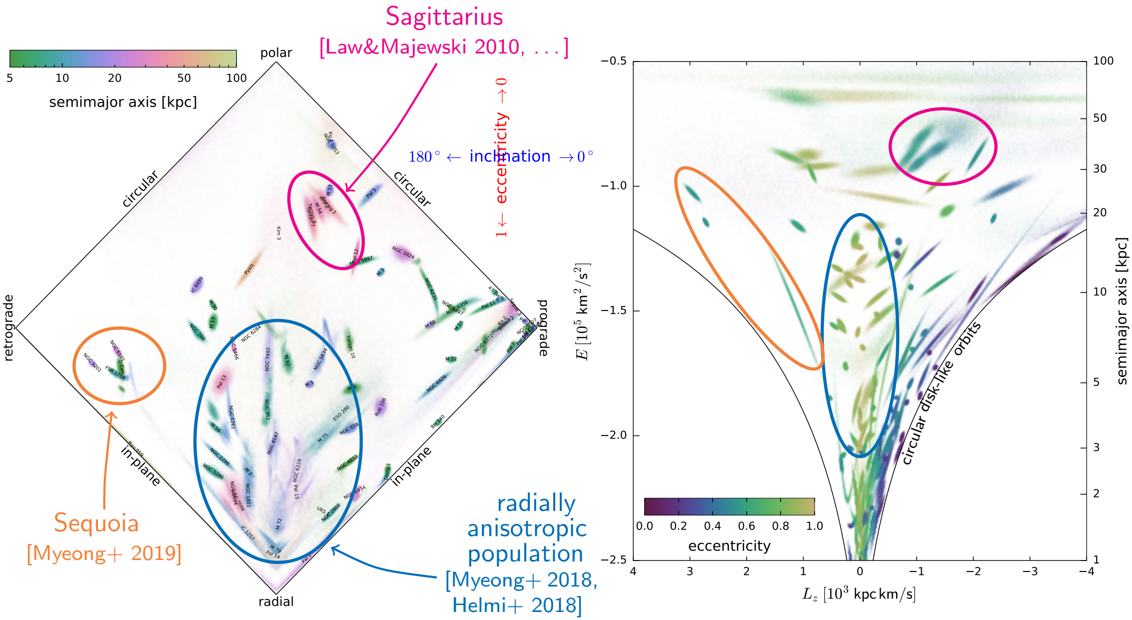
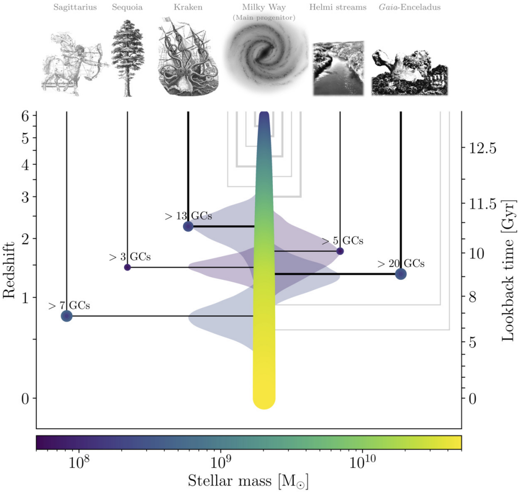
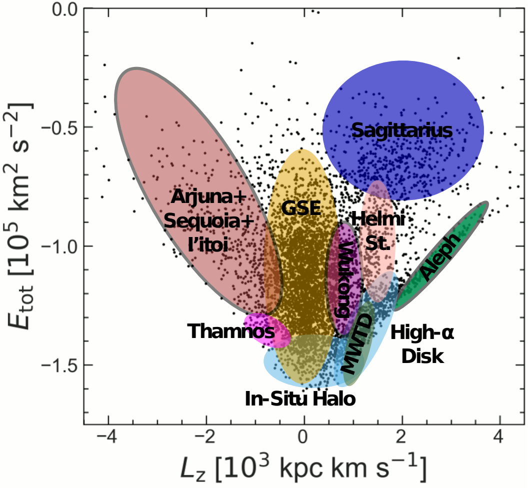


Galactic archeology with clusters, streams and halo stars

Reconstruction of the accretion history and progenitor properties



[Kruijssen+ 2020]

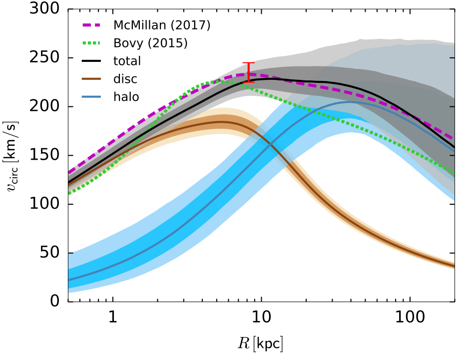


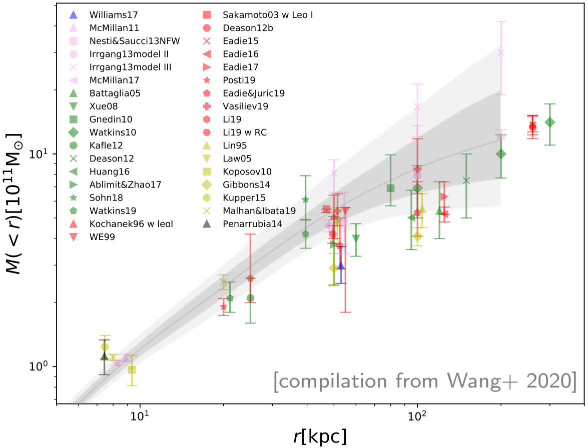
[Naidu+ 2020]

see also Massari+ 2019, Koppelman+ 2019, Forbes 2020, Yuan+ 2020, Malhan+ 2021, . . .

Constraints on the Milky Way potential from globular clusters

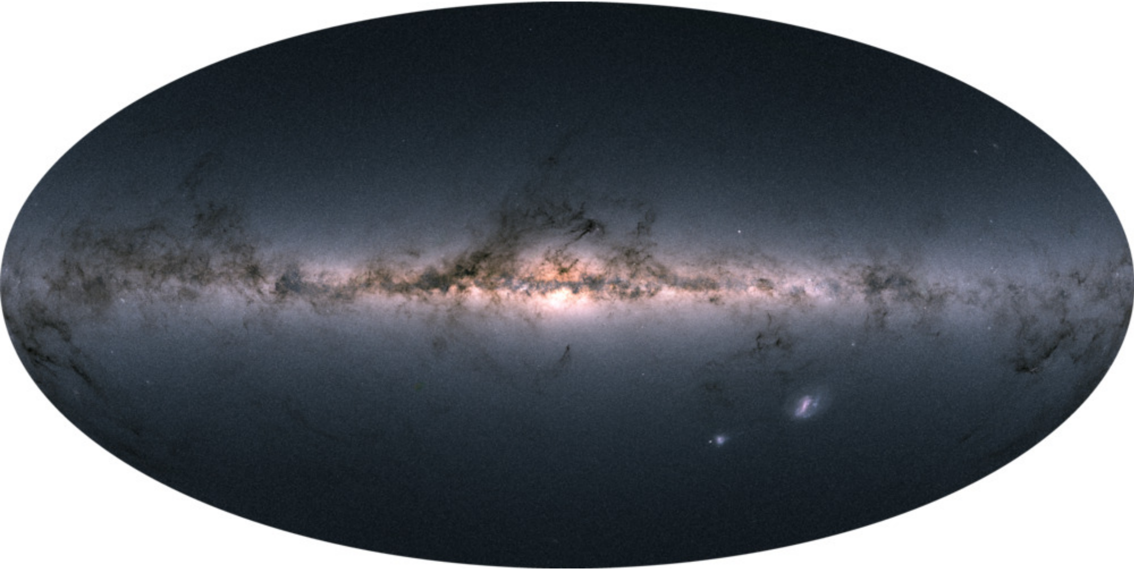
Method:
simultaneously fitting the potential
and the tracer distribution function,
maximizing the likelihood of
the observed sample of tracers





[Vasiliev 2019; see also Sohn+ 2018, Watkins+ 2019, Posti&Helmi 2019, Eadie&Juric 2019]

Structure and kinematics of Milky Way satellites



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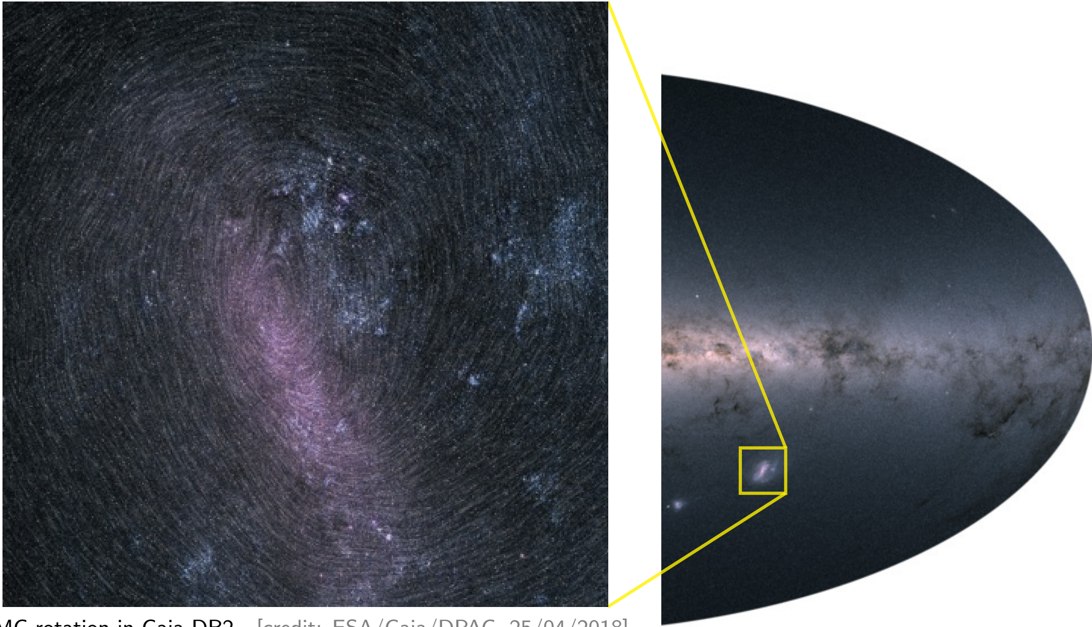
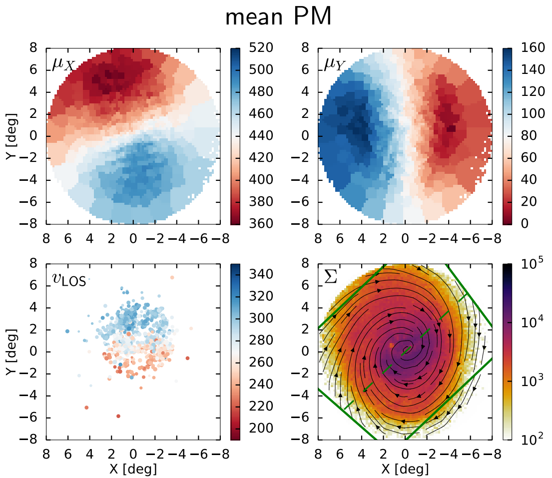
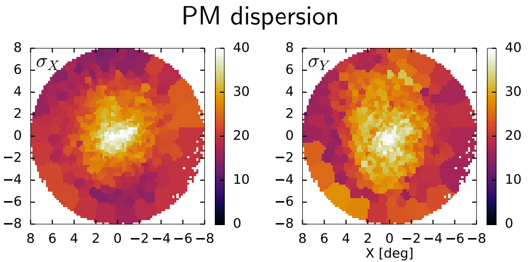
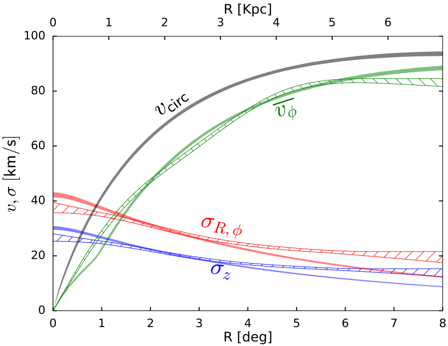


LMC rotation in Gaia DR2 [credit: ESA/Gaia/DPAC, 25/04/2018]

Structure and kinematics of the LMC



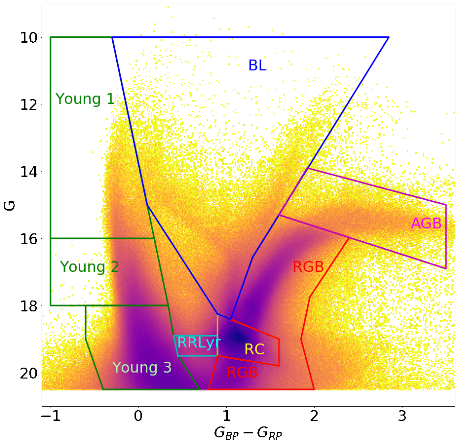


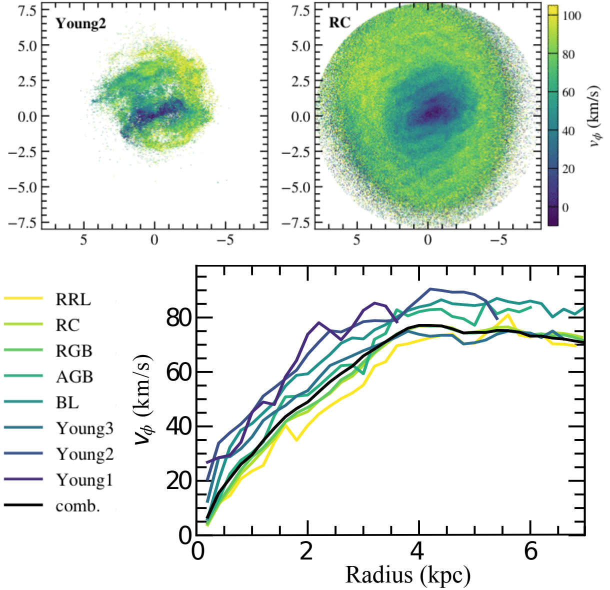


Jeans modelling of the LMC using Gaia DR2

[Vasiliev 2018]

Structure, kinematics and stellar populations of the LMC



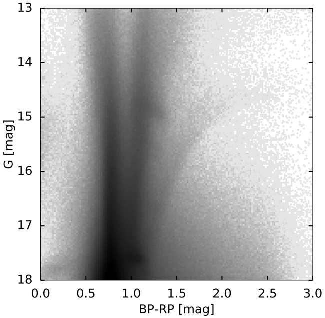


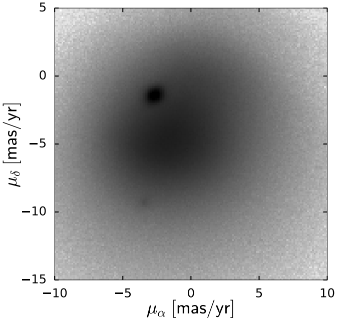
LMC in Gaia EDR3

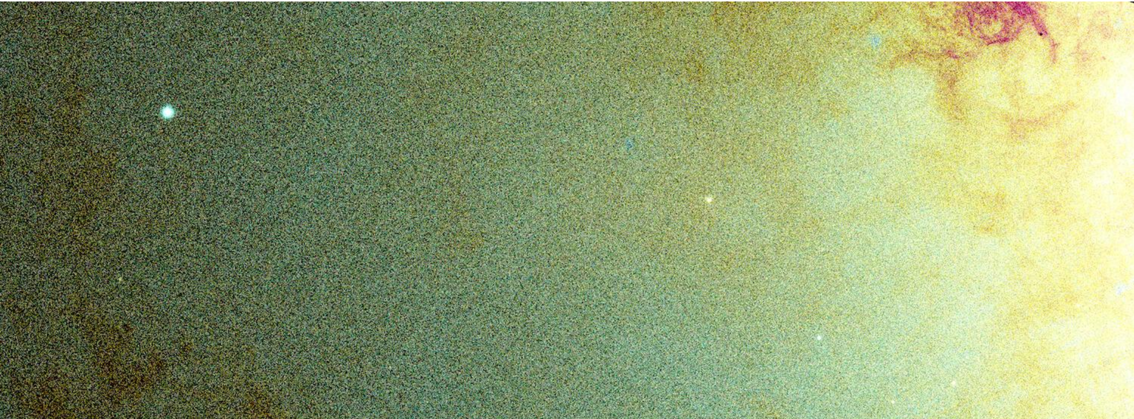
[Gaia Collaboration (Luri et al.) 2021]

Sagittarius dSph

our closest satellite ($D = 27$ kpc), but discovered only in 1994 [Ibata et al.]







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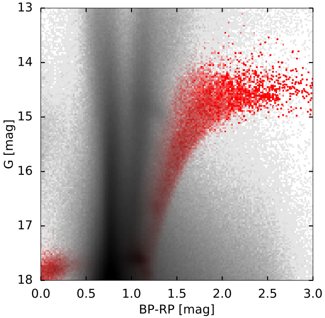
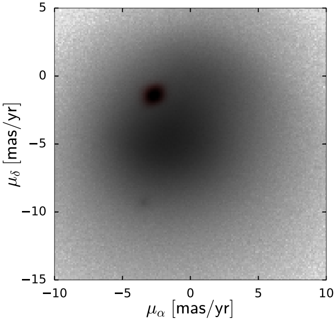
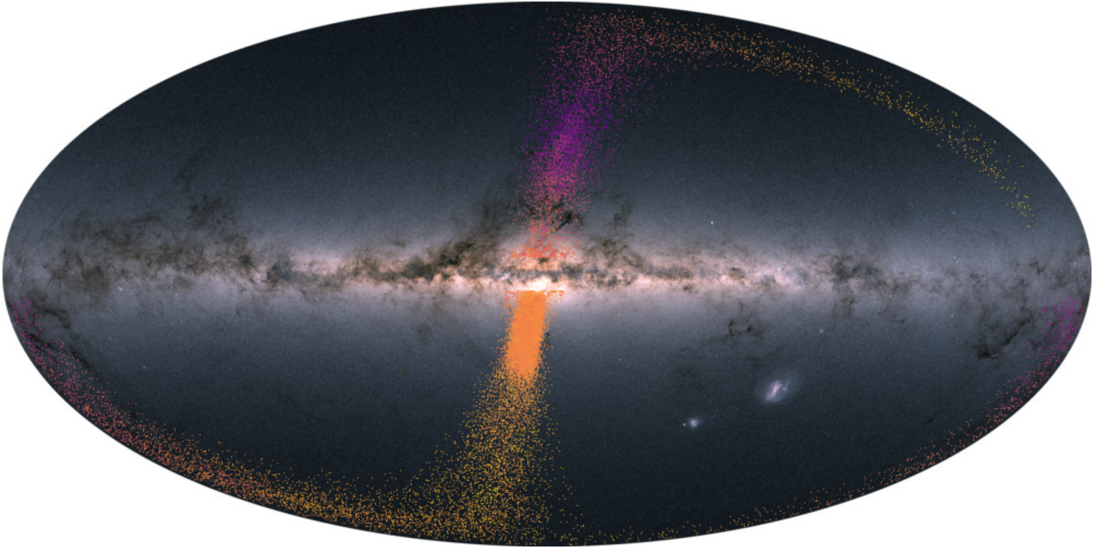




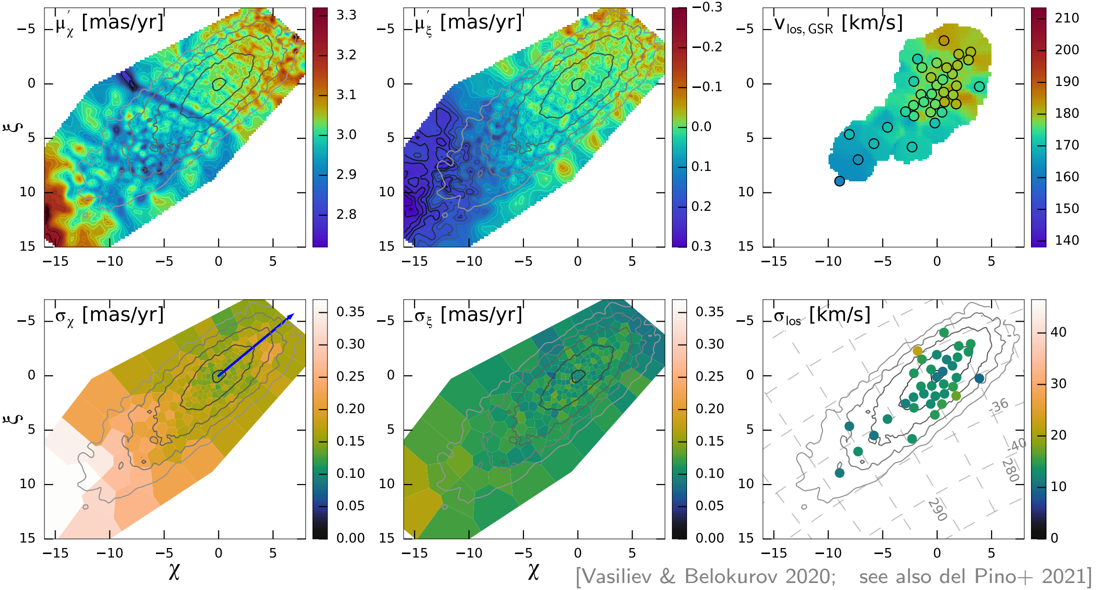
Sagittarius dSph and its tidal stream

Stream first detected in the 2MASS survey [Majewski+ 2003];
explored in greater detail in SDSS [Belokurov+ 2006, Koposov+ 2012],
and most recently in Gaia DR2 [Antoja+ 2020; Ramos+ 2020; Ibata+ 2020; Vasiliev+ 2021]



Kinematics of the Sagittarius dSph remnant

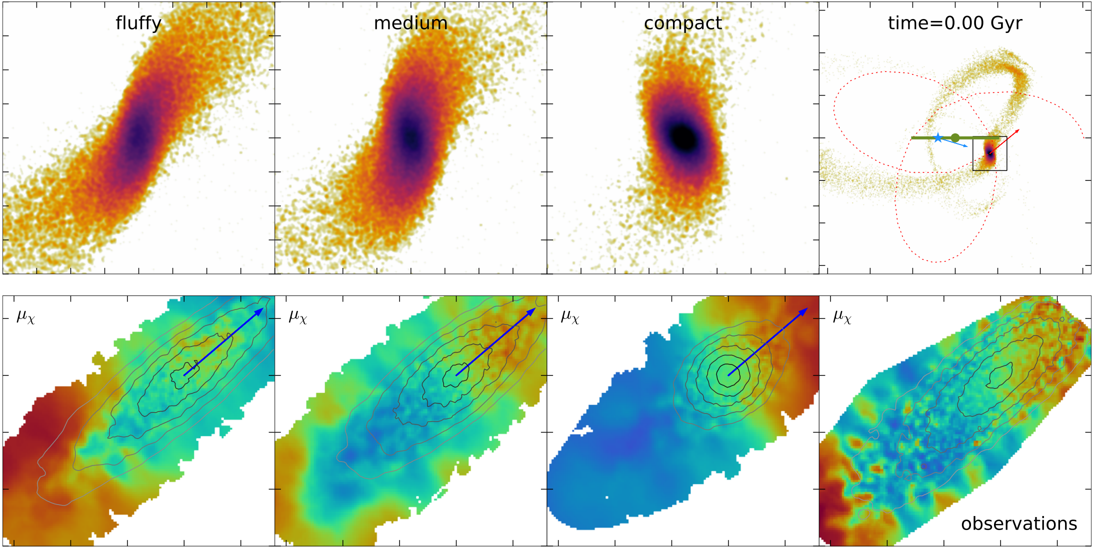
Maps of mean PM and its dispersion for ∼ 250 000 Gaia DR2 stars;
line-of-sight velocities for ∼ 3300 stars from Peñarrubia+ 2011, Frinchaboy+ 2012 and APOGEE



[Vasiliev & Belokurov 2020; see also del Pino+ 2021]

Constraints on the remnant geometry from kinematics

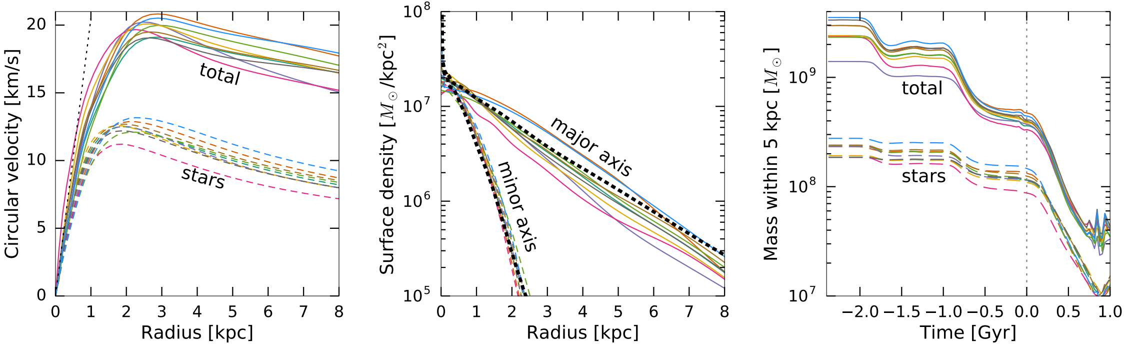
N-body simulations of a disrupting satellite with different initial structural properties



[Vasiliev & Belokurov 2020]

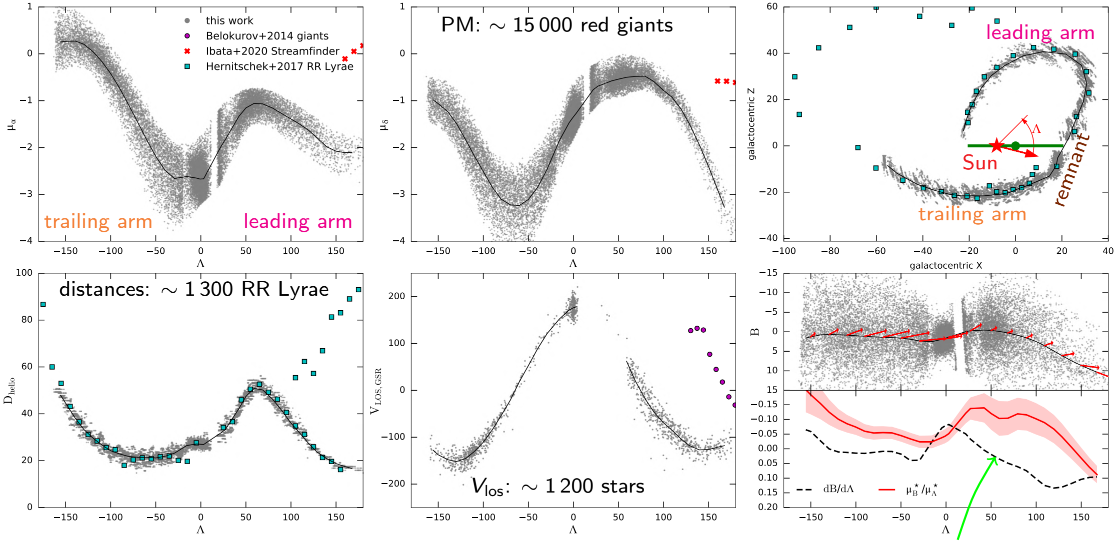
Structure, history and future fate of the Sagittarius galaxy

- 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 tilted at $\sim 45^\circ$ to the orbit;
- rapidly losing stars and on the brink of destruction.



Sagittarius stream in six dimensions

observations

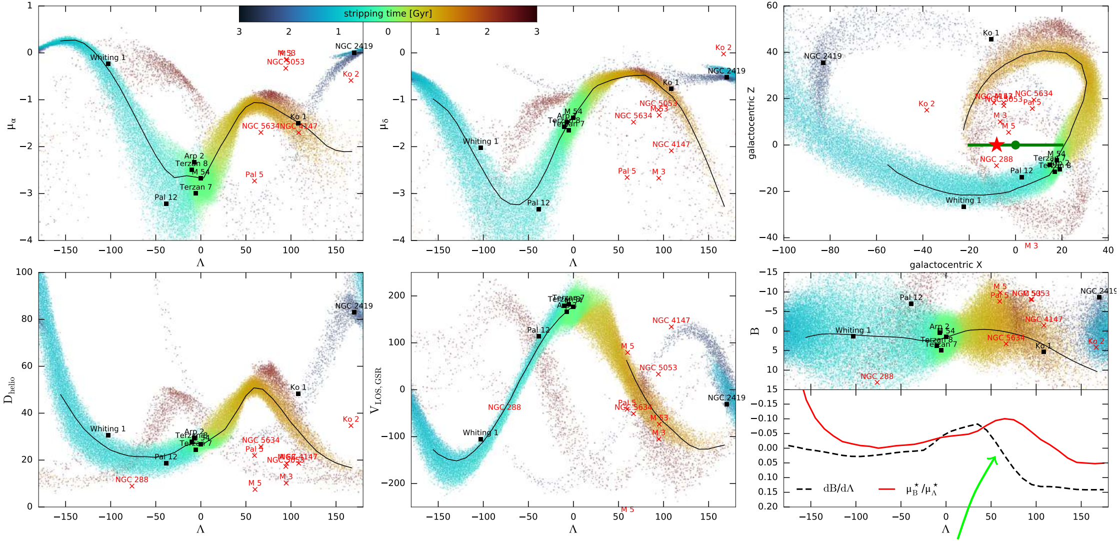


[Vasiliev+ 2021]

Misalignment between PM and stream track

Sagittarius stream in six dimensions

N-body fit of the Sgr stream in a flexible Milky Way potential and taking into account the effect of the LMC flyby



[Vasiliev+ 2021]

Misalignment between PM and stream track

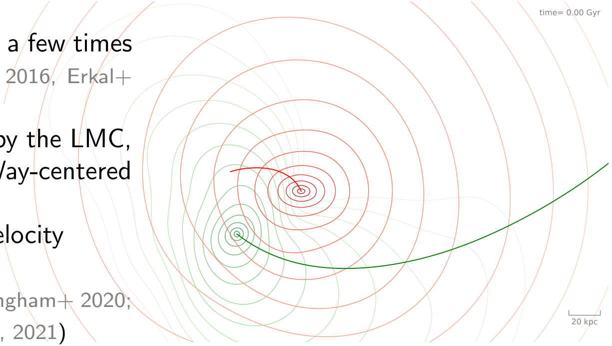
Gravitational influence of the LMC

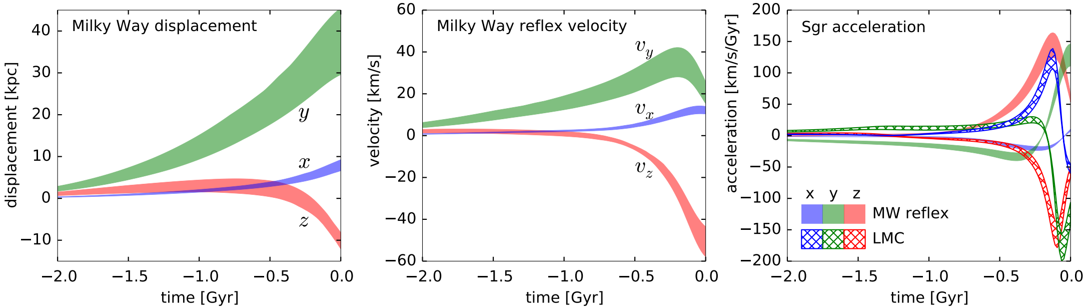
The LMC mass is $(1-2)\times 10^{11}\,M_\odot$, only a few times smaller than the Milky Way [Peñarrubia+ 2016, Erkal+ 2019, Shipp+ 2021].

The Galaxy is accelerated and deformed by the LMC, introducing fictitious forces in the Milky Way-centered non-inertial reference frame;

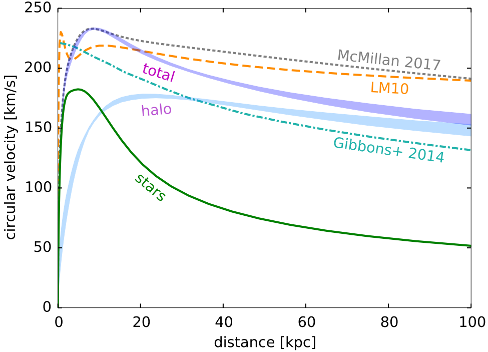
MW halo stars at $r \gtrsim 50$ kpc have net velocity perturbations of a few tens km/s

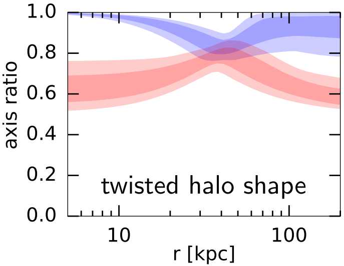
(see also Garavito-Camargo+ 2019, 2020; Cunningham+ 2020; Petersen & Peñarrubia 2020, 2021; Erkal+ 2020, 2021)

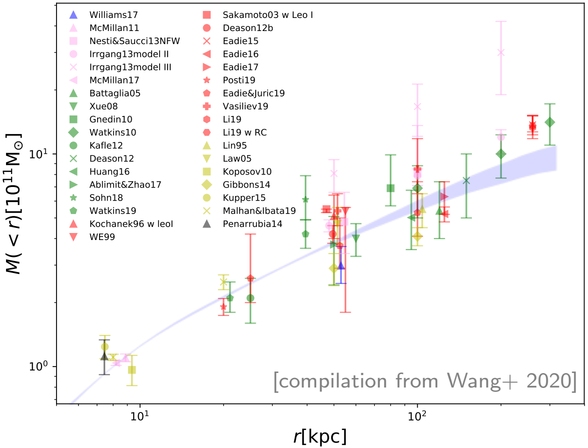




Constraints on the Milky Way potential from Sgr stream







Mass within 100 kpc is $\sim 30\%$ lower than inferred from globular cluster fits (which ignored the LMC)

Summary: Gaia – the ongoing revolution

- Gaia reaches out to the edge of the Milky Way galaxy,
- allows to study the internal motions in star clusters within ~ 10 kpc, and in the largest satellites (LMC, SMC, Sgr),
- finds streams and other building blocks of our Galaxy;
- and the LMC appears to play a major role in the Milky Way dynamics