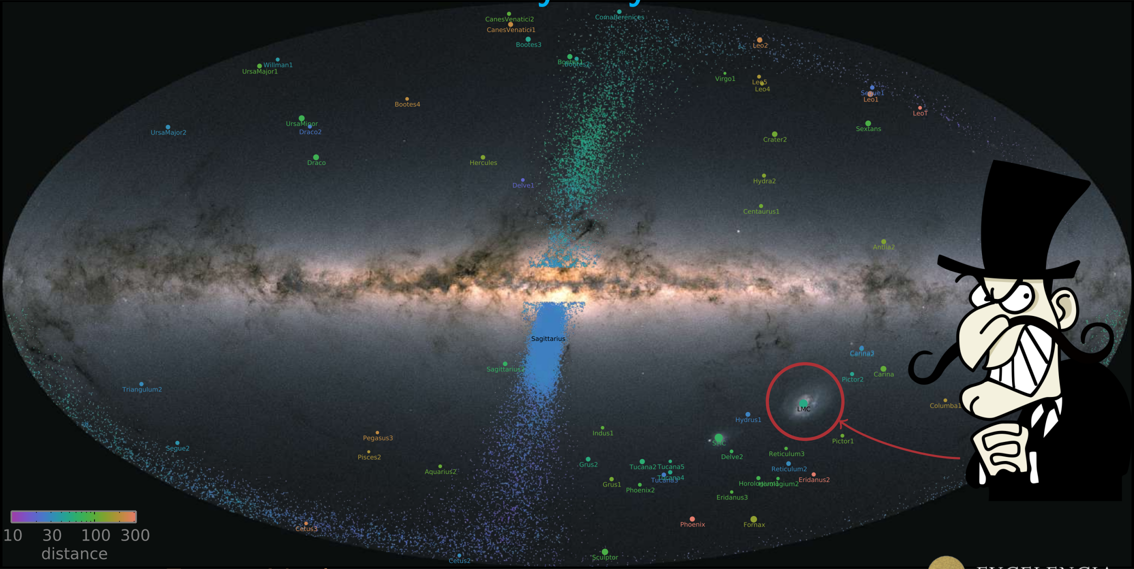
Tango for three and ballet for thirty:
the interaction of the Milky Way with its satellites

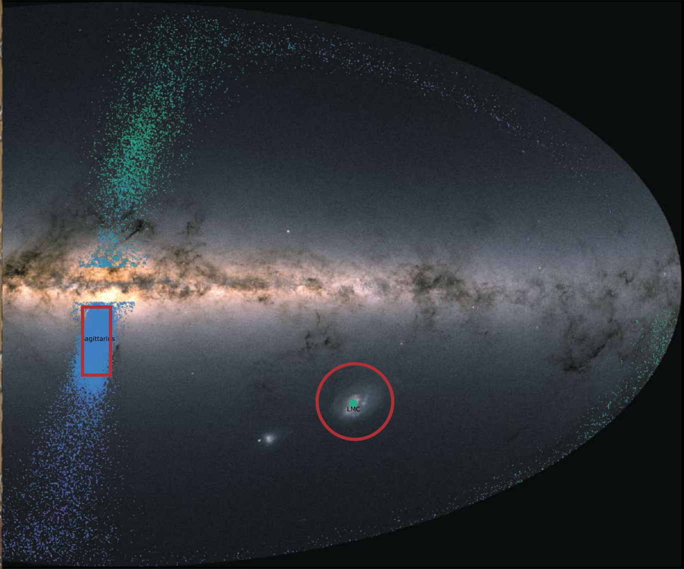


Eugene Vasiliev
Institute of Astronomy, Cambridge

Instituto de Astrofísica de Canarias, 12 May 2022

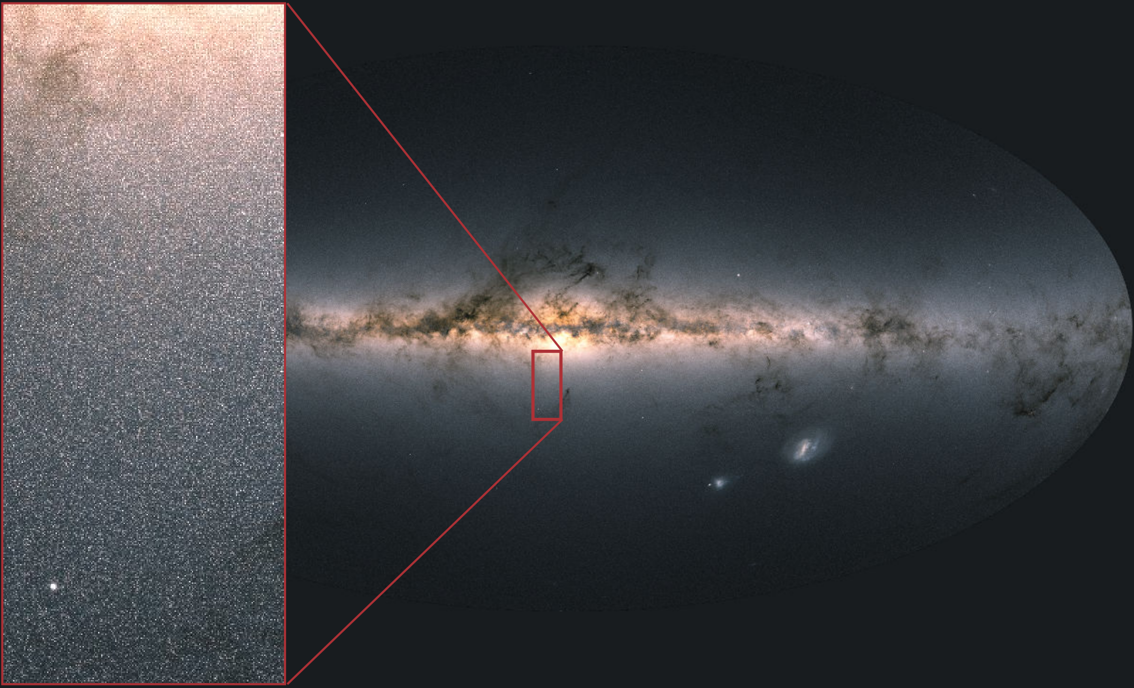
EXCELENCIA SEVERO OCHOA

Tango for three: Sagittarius, LMC, and the Milky Way

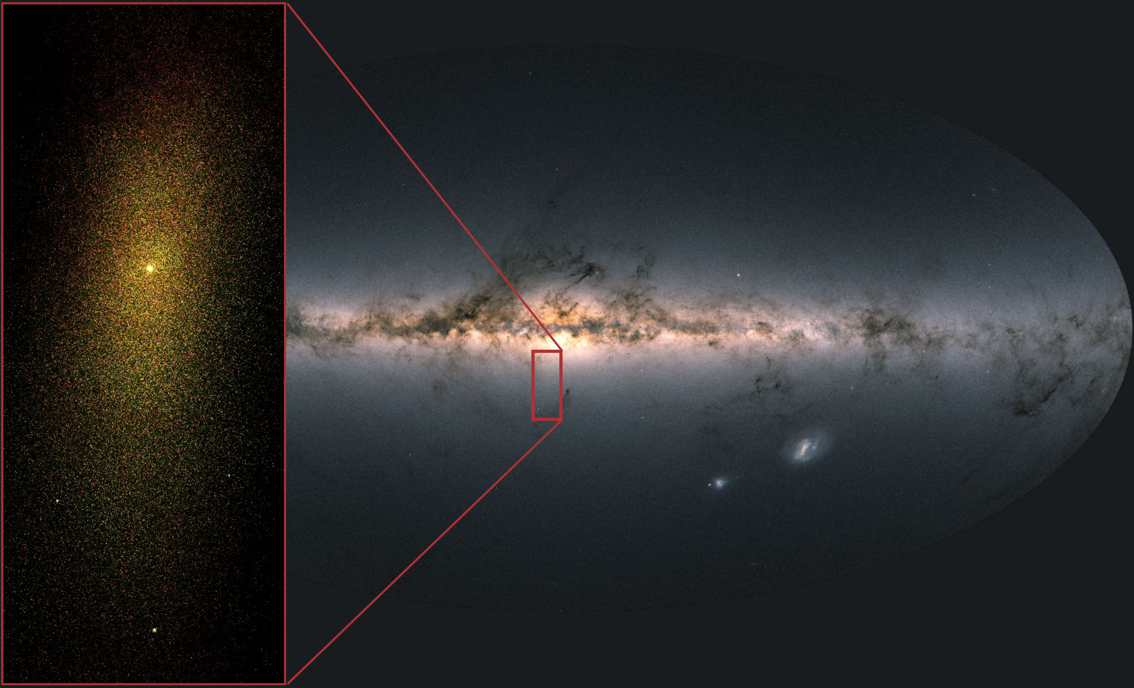


based on
Vasiliev & Belokurov, MNRAS, 497, 4162 (2020) – Sgr remnant
Vasiliev, Belokurov & Erkal, MNRAS, 501, 2279 (2021) – Sgr stream

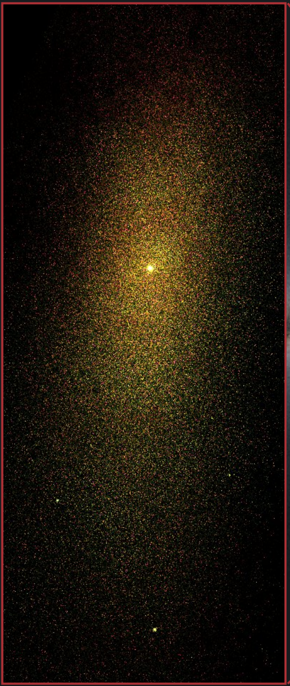
Sagittarius dSph



Sagittarius dSph



Sagittarius dSph



- discovered accidentally when studying kinematics of Galactic bulge [Ibata+ 1994]
- distance: ~ 27 kpc ($3\times$ the distance to the Galactic centre)
- mass: few $\times\ 10^8\ M_\odot$

- Sgr stream spanning the entire sky, first discovered in 2MASS [Majewski+ 2003] and studied extensively using SDSS [Belokurov+ 2006, Koposov+ 2012] and Gaia [Ibata+ 2020, Antoja+ 2020, Ramos+ 2020, 2022]

Sagittarius dSph: membership determination

Mixture modelling approach:

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

measurements ($\mathbf{x}_i$)

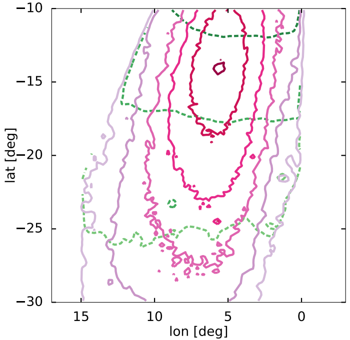
parameters of distributions ($\boldsymbol{\theta}_{\rm memb}$, $\boldsymbol{\theta}_{\rm field}$)

fraction of members (η)

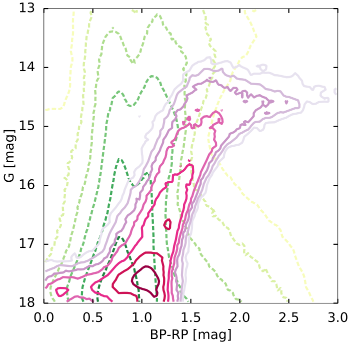
membership probability of i-th star:

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

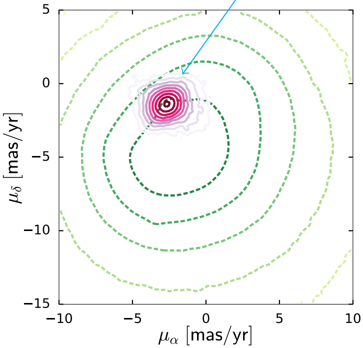
$\overline{\boldsymbol{\mu}}(\mathbf{x}),\ \sigma_\mu(\mathbf{x})$



spatial distribution



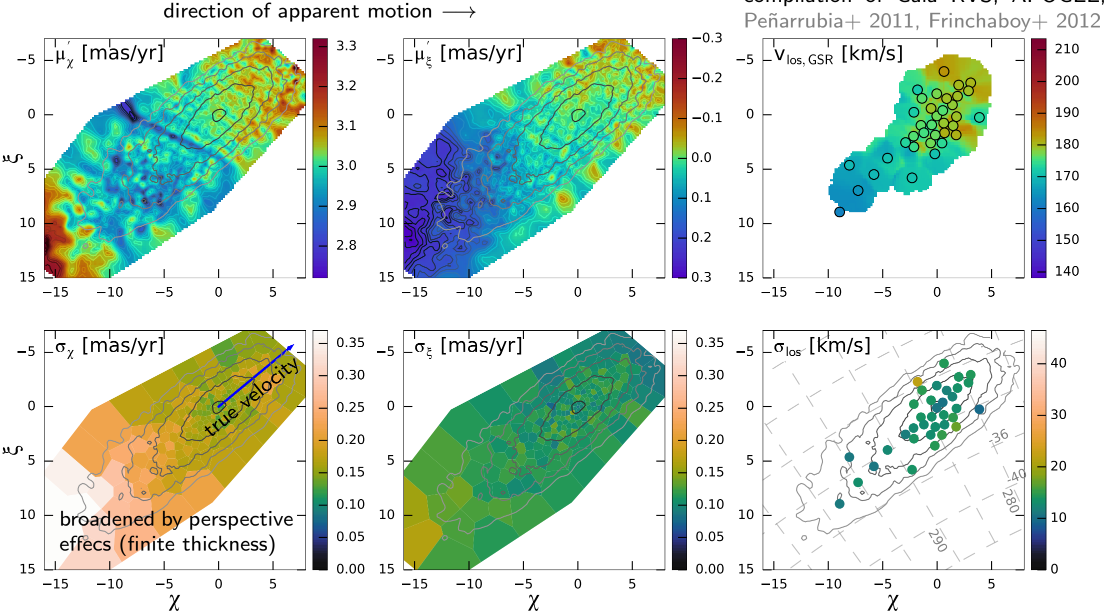
colour–magnitude diagram



proper motion space

Sagittarius dSph: 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:

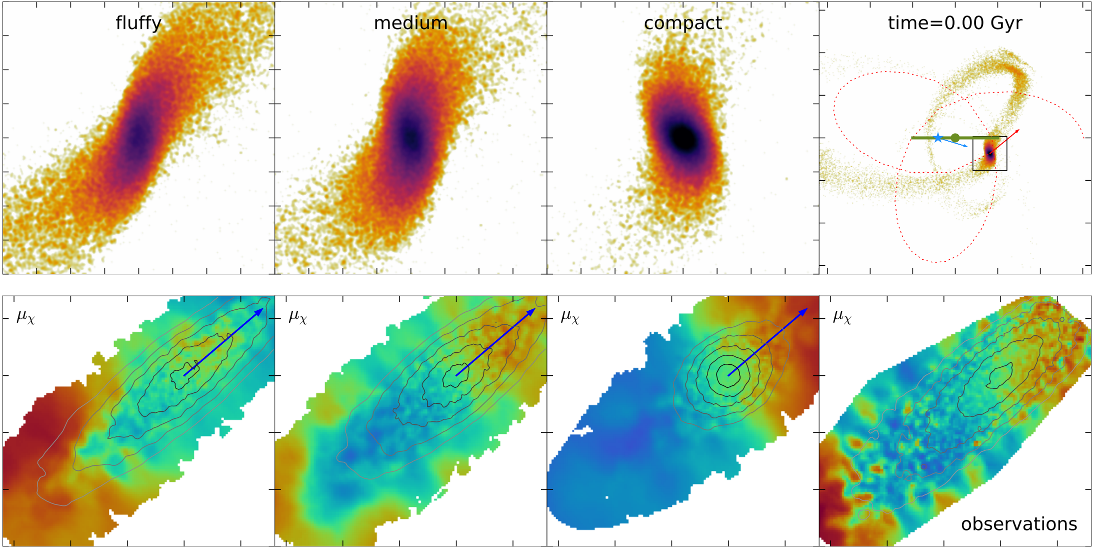
- provide an interpretation of the observed kinematics
- estimate the present-day total mass of the Sgr remnant
- explore possible evolutionary histories and progenitor properties

Method:

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

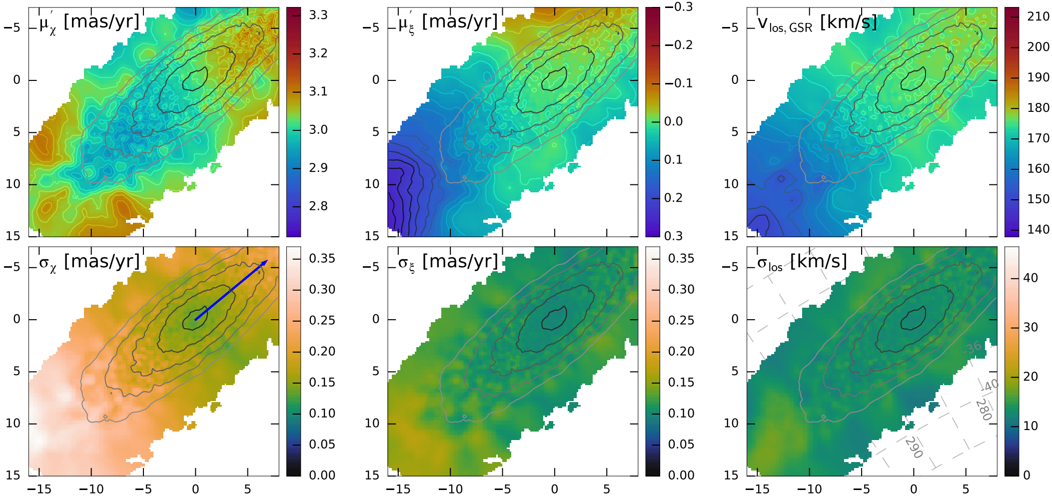
repeat dozens of times

Constraints on the remnant geometry from kinematics



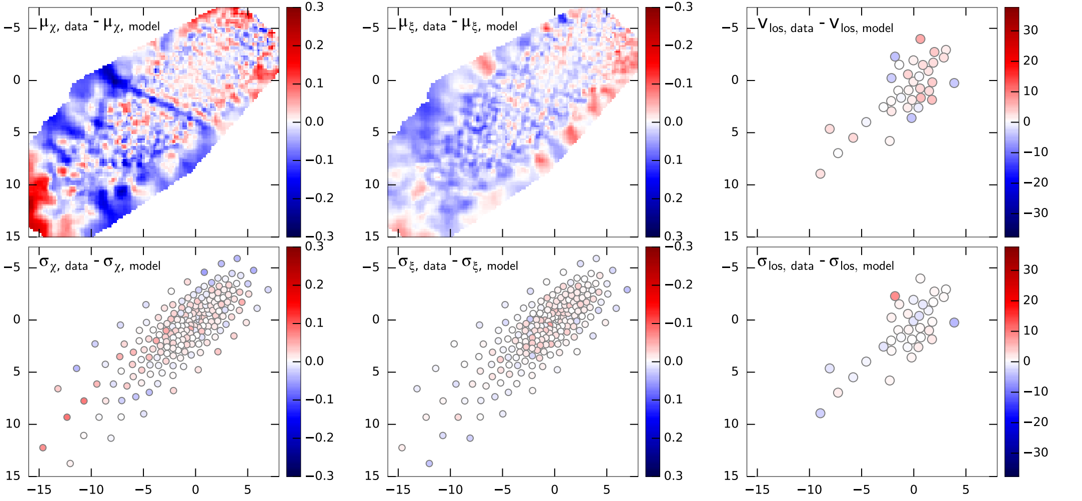
An example of a successful model

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



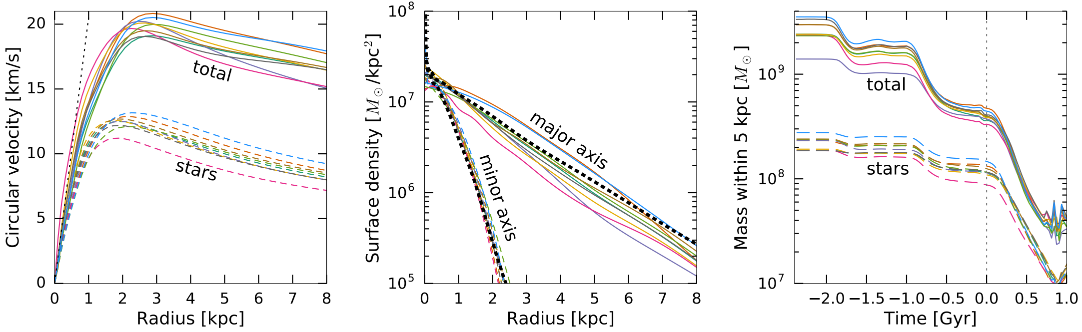
An example of a successful model

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



Common features of all successful models of the Sgr remnant

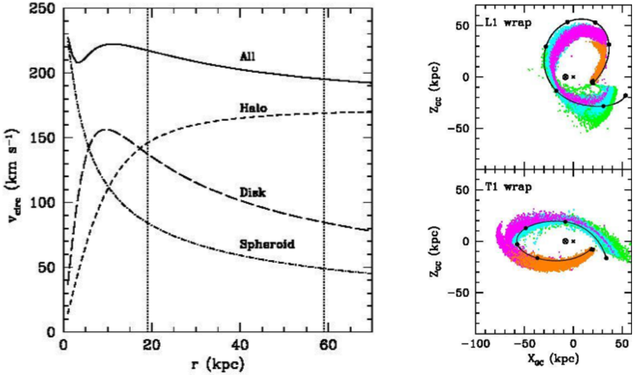
- stellar mass $\sim 10^8\,M_\odot$ (from photometry), total mass $(3-5)\times 10^8\,M_\odot$ within 5 kpc (from PM and v_los dispersions), peak circular velocity ~ 20 km/s
- stellar profile more spatially concentrated than total mass profile
- prolate cigar-shaped remnant extending up to ~ 5 kpc and tilted at $\sim 45^\circ$ to the orbit (from μ'_χ) – constrains the degree of tidal perturbation (i.e. fluffiness)
- mass reduced by a factor of a few since the last pericentre passage ~ 1 Gyr ago
- Sgr remnant will be fully disrupted during the next orbital period



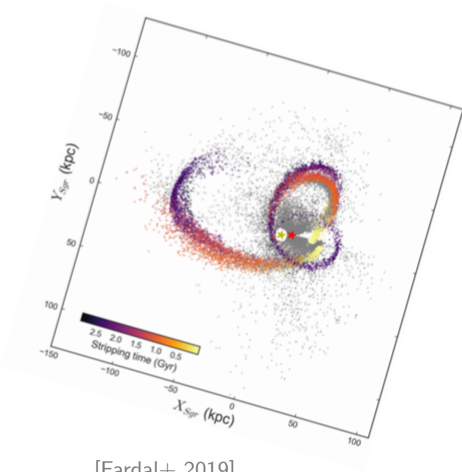
Sgr stream as the probe of the Milky Way potential

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.]



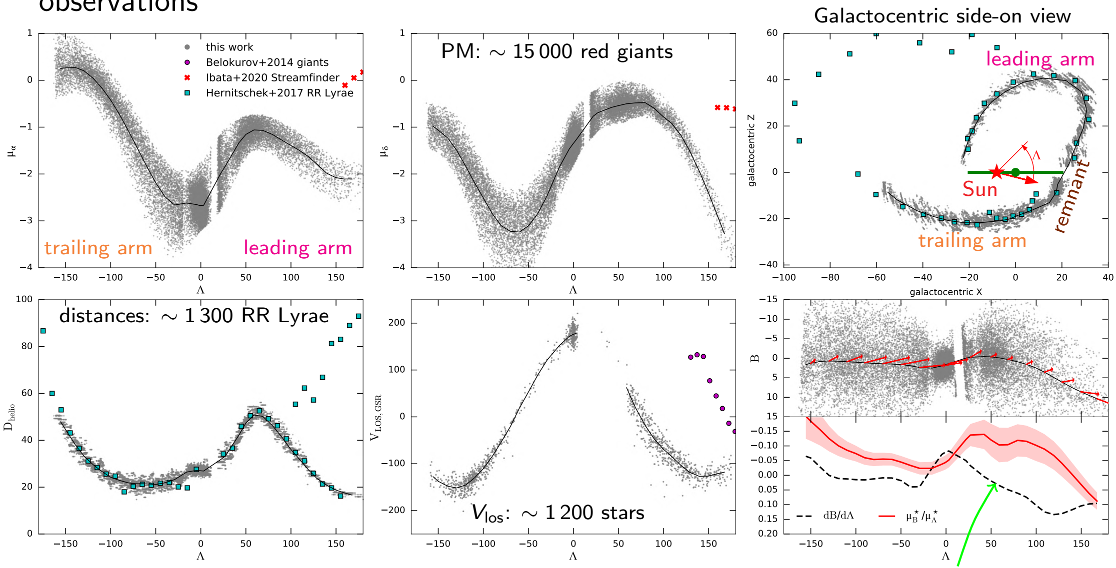
[Law & Majewski 2010]



[Fardal+ 2019]

Sgr stream in 6 dimensions

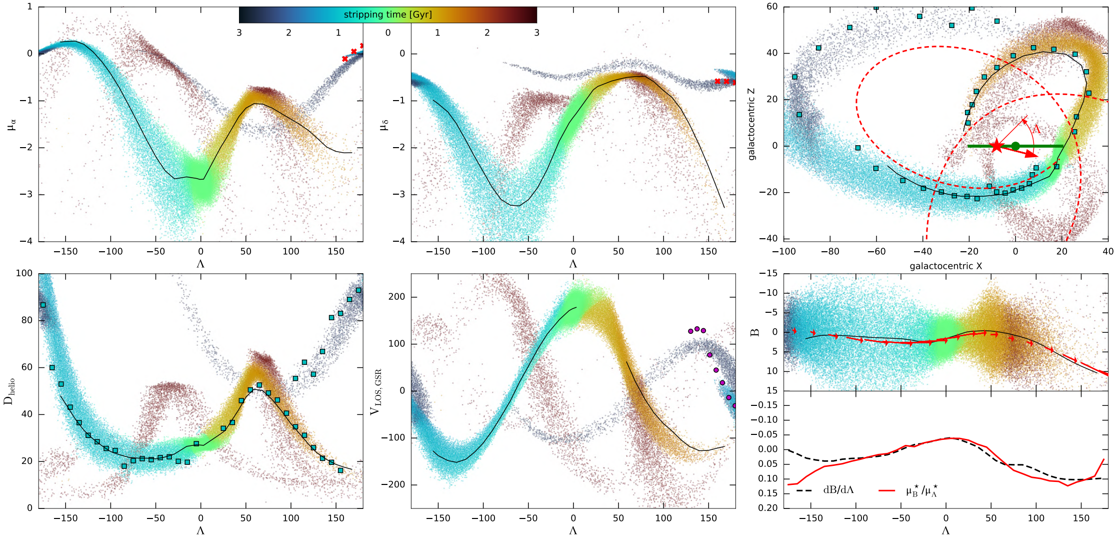
observations



Misalignment between PM and stream track

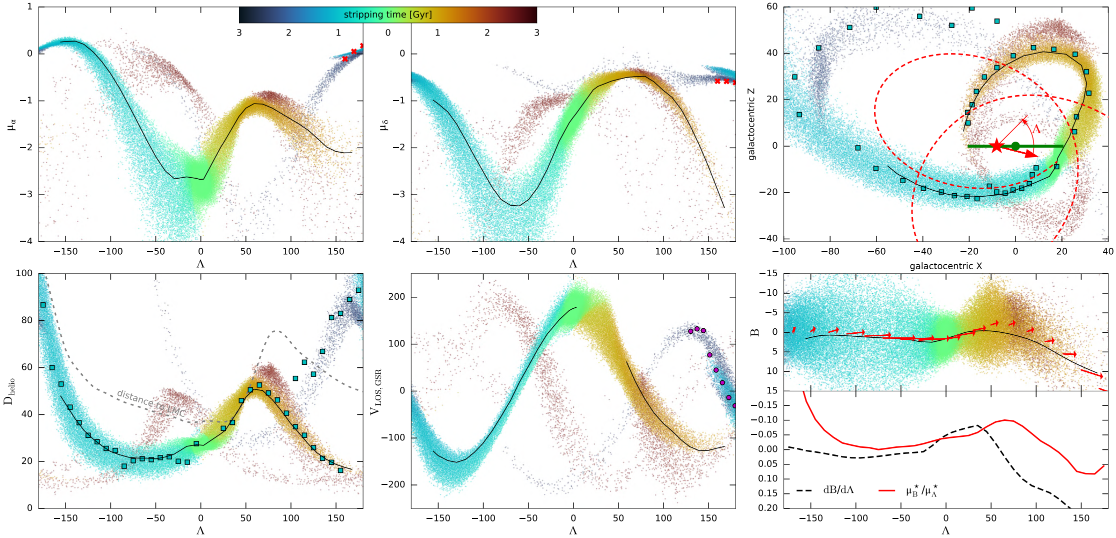
Sgr stream in 6 dimensions

stream model in the best-fit (very flexible) MW potential



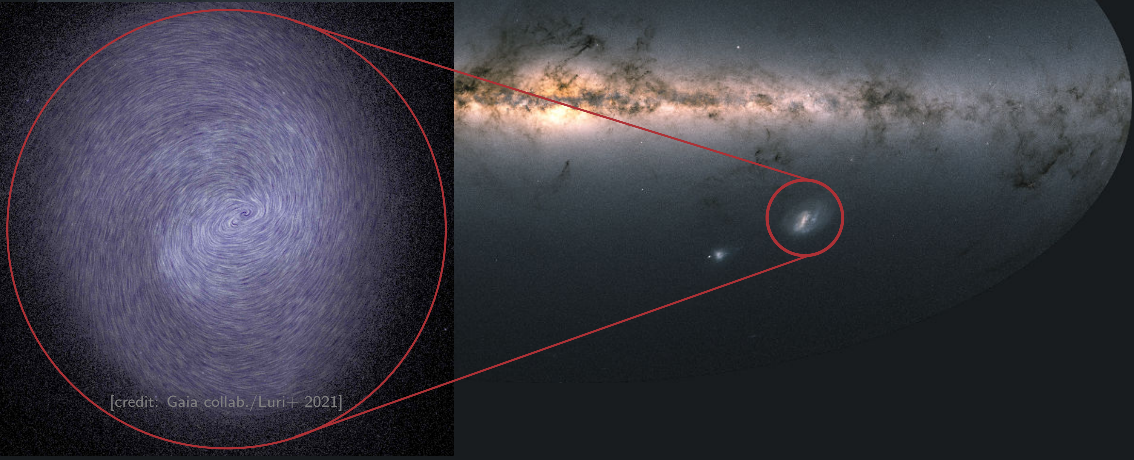
Sgr stream in 6 dimensions

stream model including the perturbation from the LMC ($M_{LMC} = 1.5 \times 10^{11}\, M_\odot$)

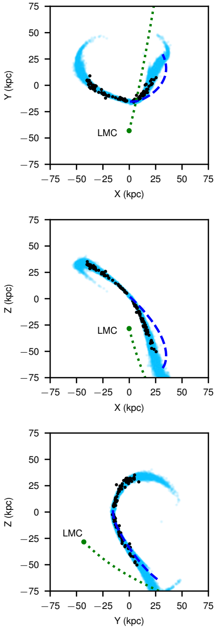


Large Magellanic Cloud

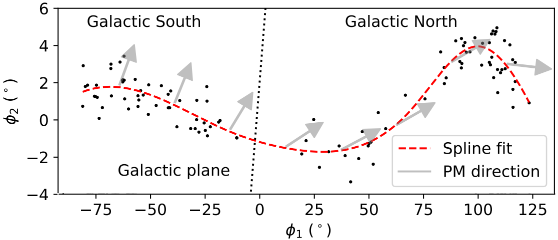
- the largest satellite of the Milky Way (mass $\sim (1-2) \times 10^{11}\, M_{\odot}$)
- distance: ~ 50 kpc
- just passed its pericentre, likely for the first time
- brings an entourage of its own satellites
- wreaks havoc in the outer Milky Way halo!



Local effects of the LMC: deflection of stellar streams

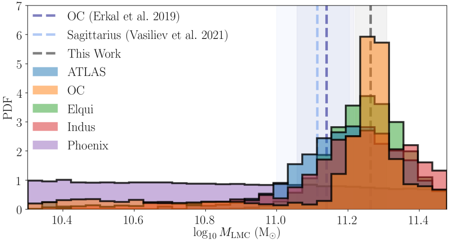


Orphan–Chenab stream: no remnant, spans $> 200^\circ$ on the sky. Proper motion is misaligned with the stream track in the southern part of the stream due to a close encounter with the LMC.



[Erkal+ 2019]

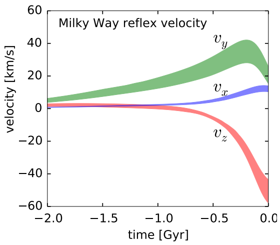
Many streams in the Southern hemisphere show signatures of deflection by the LMC, which can be used to measure the LMC mass – it turns out to be $(1-2)\times 10^{11}\ M_\odot$, compared to $\sim 10^{12}\ M_\odot$ for the Milky Way itself!

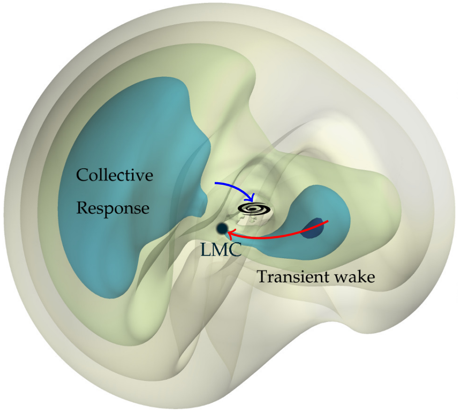


[Shipp+ 2021]

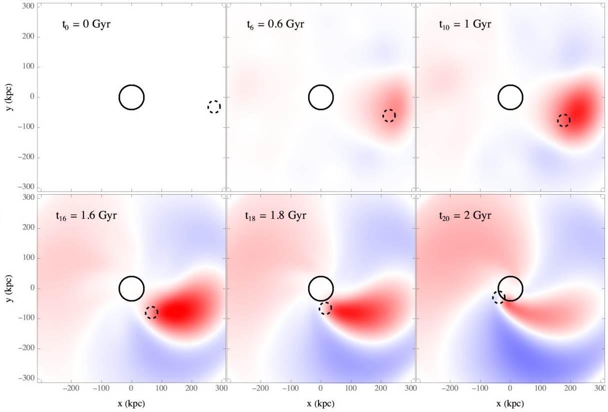
Global perturbation: mechanism

- central part of the Milky Way is pulled towards the LMC;
- outer halo is too slow to catch up;
- this creates a dipole "polarization cloud" (collective response) in addition to the "local wake" from dynamical friction.





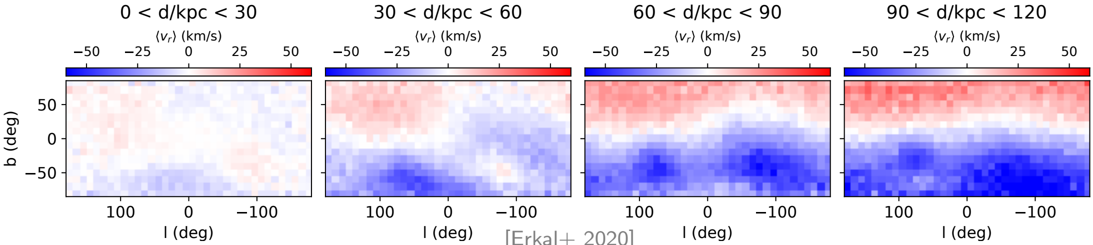
N-body sims [Garavito-Camargo+ 2020]



perturbation theory [Rozier+ 2022]

Global perturbation: signatures

Since the MW is pulled "down" (in z) recently, most of the kinematic signal is in the north–south asymmetry of line-of-sight velocities in the outer halo ($\gtrsim 50$ kpc).



[Erkal+ 2020]

⇑
prediction

⇐ observations ⇒

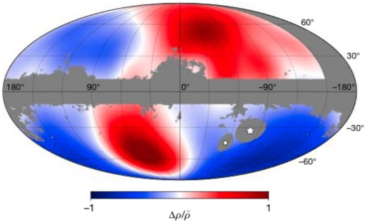
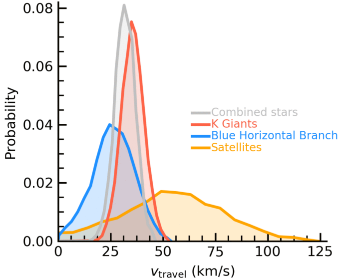


Fig. 1 | Distribution of stars in the Galactic halo. All-sky Mollweide projection maps of the density of stars at 60 kpc < R_{gal} < 100 kpc, smoothed by a Gaussian kernel with FWHM = 30°. **a**, Data based on K giant stars.

density polarization [Conroy+ 2021]



velocity offset [Petersen & Peñarrubia 2021]

Measurement of the Milky Way potential

stellar streams:
stars [nearly] follow a single orbit $\Rightarrow$
constrain the potential by orbit fitting

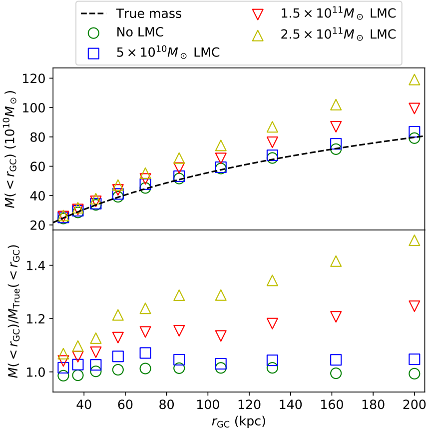
smoothly distributed populations:
assume dynamical equilibrium $\Rightarrow$
density and velocity distributions
are linked through the potential

Jeans eqns

distribution functions

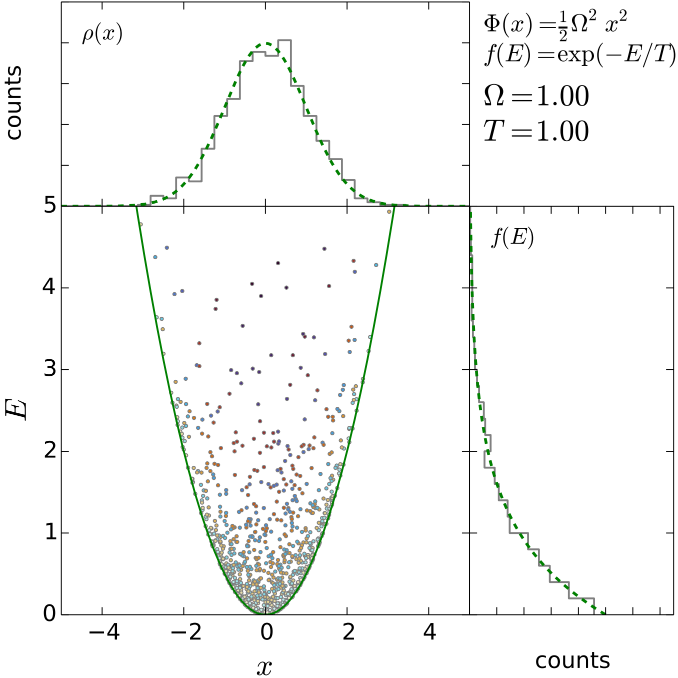
made-to-measure

orbit-superposition



Perturbations in the kinematics of outer halo stars and other tracers (globular clusters, satellite galaxies) violate the equilibrium assumption and cause an upward bias in Milky Way mass estimates [Erkal+ 2020].

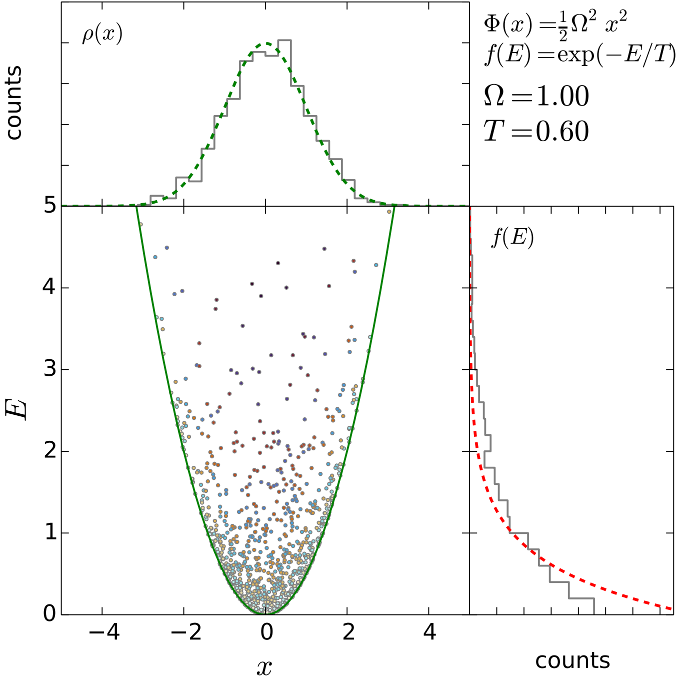
Dynamical modelling with discrete tracers



Example: particles moving in a 1d simple harmonic oscillator potential with a Maxwell–Boltzmann distribution function.

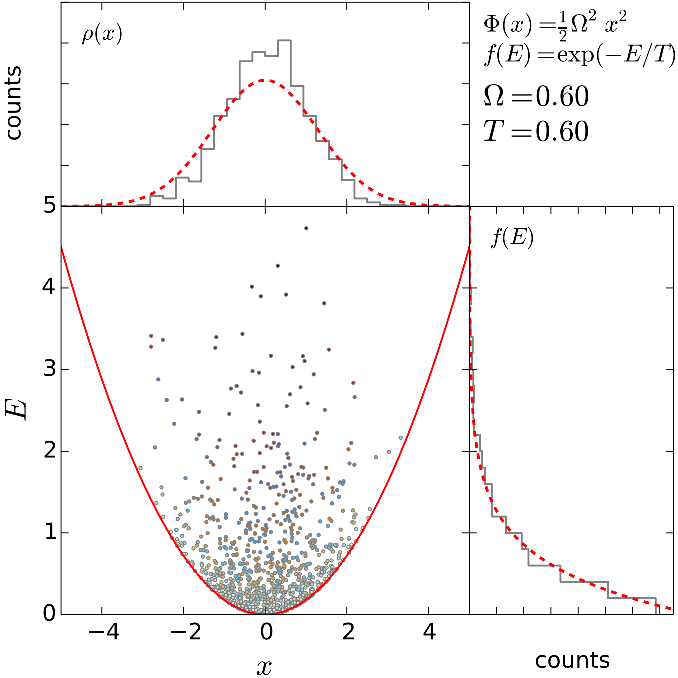
We have measured positions and velocities for $N \gg 1$ particles and want to infer the parameters of the potential (Ω) and the DF (T) that best describe the observed sample.

Dynamical modelling with discrete tracers



If we assume a wrong temperature T in the true potential, obviously the predicted $f(E)$ will differ from the actual distribution.

Dynamical modelling with discrete tracers



$\Phi(x) = \frac{1}{2}\Omega^2\, x^2$

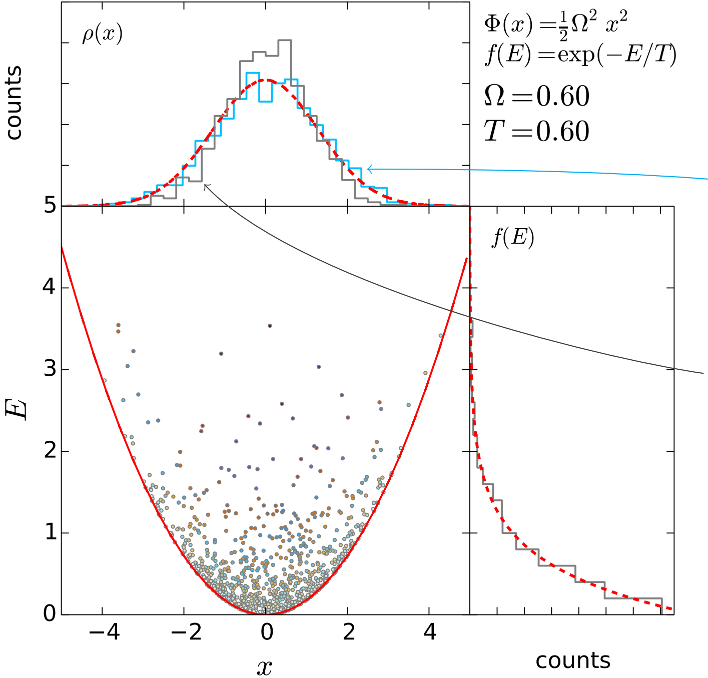
$f(E) = \exp(-E/T)$

$\Omega = 0.60$

$T = 0.60$

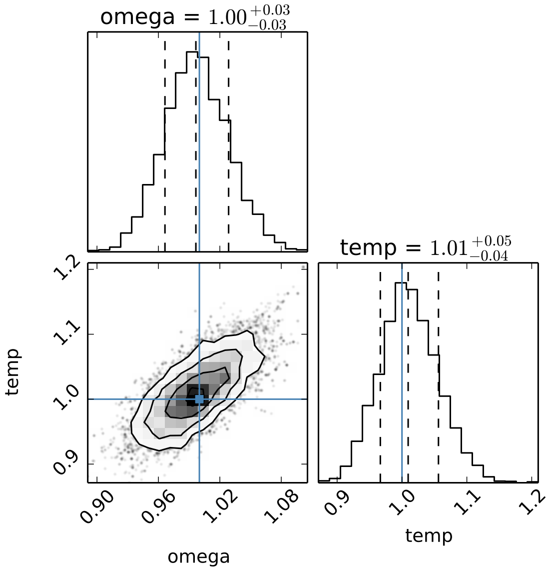
But what if we assume wrong values for both Ω and T? $f(E)$ now agrees with the observed (but incorrectly computed) energy distribution of particles, but their predicted spatial distribution should be wider: there are too many particles near $x = 0$ and too few near turnaround points ($v = 0$).

Dynamical modelling with discrete tracers



The phase-mixed population of particles predicted by the model with wrong parameters will differ from the observed distribution.

Dynamical modelling with discrete tracers



Thus we should be able to infer *both* the potential and the DF from the observed distribution of points in phase space *under the assumption of equilibrium (phase-mixedness)*.

Compensating the LMC perturbation

[Correa Magnus & Vasiliev 2022] – grew out of a summer internship project

Assumption: the MW was in a tranquil equilibrium
before the unceremonious arrival of the LMC.

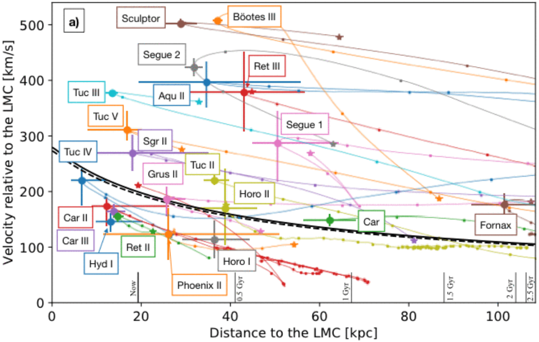
To reconstruct the original unperturbed state for *any* choice
of Galactic potential and LMC mass:

1. Reconstruct the past trajectories of both the MW and the LMC;
2. Rewind the orbits of tracers (halo stars, globular clusters, MW satellites ...)
in the evolving MW+LMC potential back in time
until the LMC is far enough not to cause trouble ($\sim 2-3$ Gyr).

Vary the LMC mass, the parameters of the potential and the tracer DF
to maximize the likelihood of the *unperturbed* (rewound) dataset.

Use two tracer populations: $\sim$150 globular clusters and 36 satellite galaxies
with 6d phase-space coordinates (*Gaia* EDR3 and other recent measurements)
[Baumgardt & Vasiliev 2021; Vasiliev & Baumgardt 2021; Battaglia+ 2021].

Ballet for the satellites

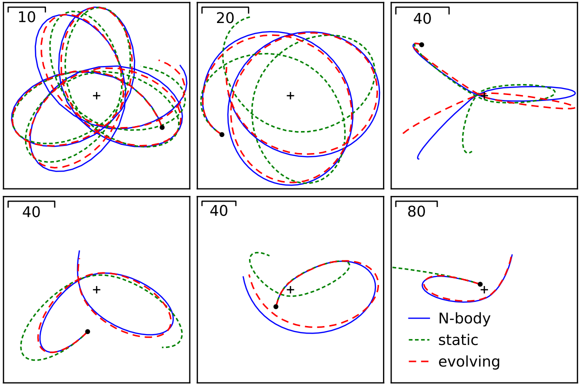


encounters of dSph with the LMC

[Battaglia+ 2021]

Tests of the method

orbit rewinding

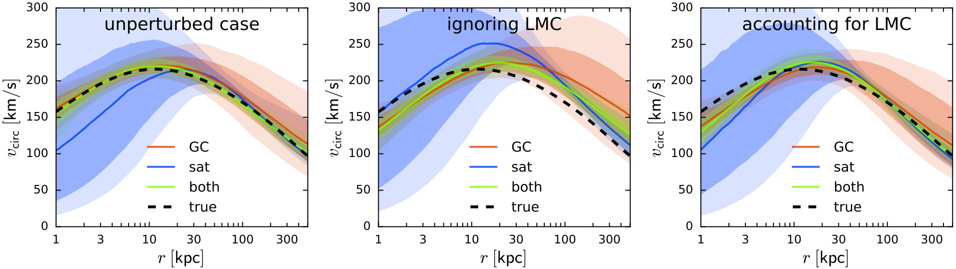


1. past orbits of satellites are well reconstructed in the approximate time-dependent MW+LMC potential;
2. MW potential is well recovered by the DF fitting approach

circular velocity ⇔ enclosed mass

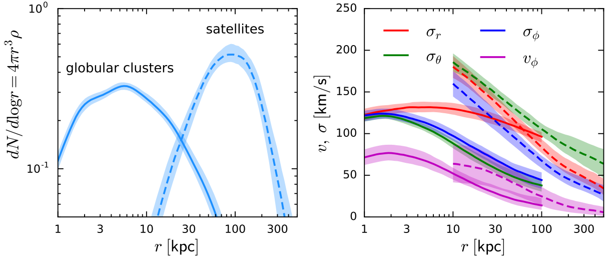
$$v_{\rm circ}(r) \equiv \sqrt{r\,\frac{\partial\Phi}{\partial r}} \approx \sqrt{\frac{G\,M(<r)}{r}}$$

potential reconstruction

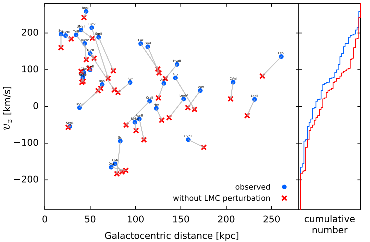


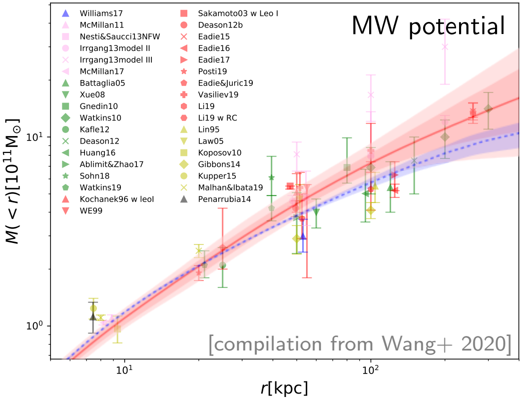
Results

tracer populations



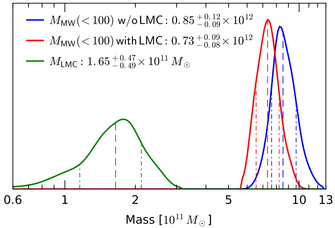
velocity perturbation





GC+dSph (+LMC rewinding)

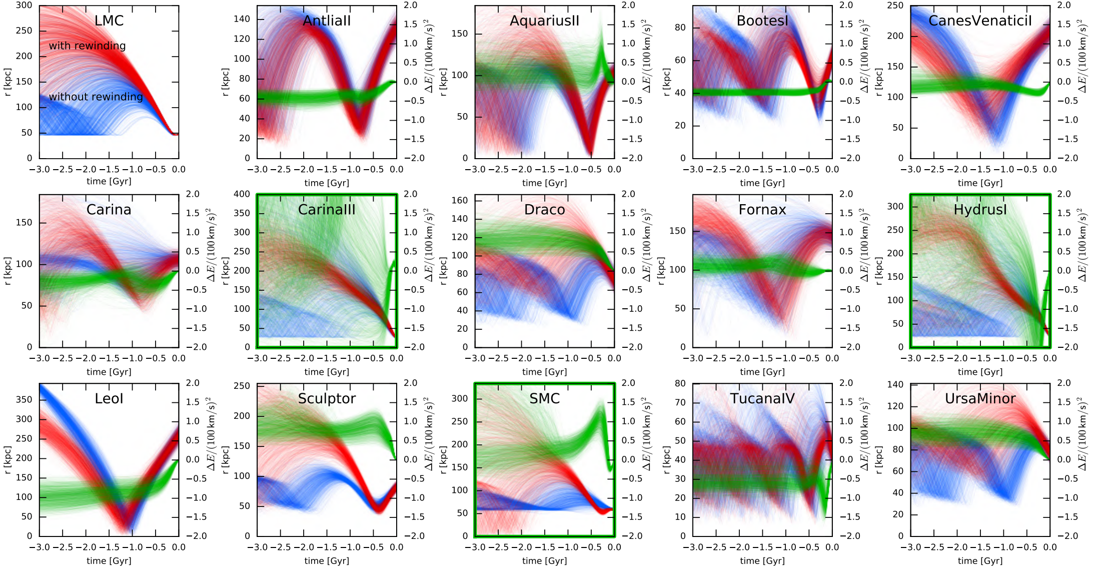
Sgr stream (incl. LMC)



Changes in satellite orbits caused by the LMC

could be quite substantial! shown are Galactocentric distances in the past 3 Gyr

blue: without LMC; red: with LMC; green: energy evolution with LMC; green frame: LMC satellites



Summary

- The ongoing interaction between the Milky Way and the LMC creates a substantial perturbation in the outer halo kinematics
- LMC needs to be taken into account when modelling the Sagittarius stream
- and affects the orbits of many other satellite galaxies

Summary

- The ongoing interaction between the Milky Way and the LMC creates a substantial perturbation in the outer halo kinematics
- LMC needs to be taken into account when modelling the Sagittarius stream
- and affects the orbits of many other satellite galaxies
- Future astronomers won't have to deal with all this mess, as the LMC will be eventually disrupted by the Milky Way!