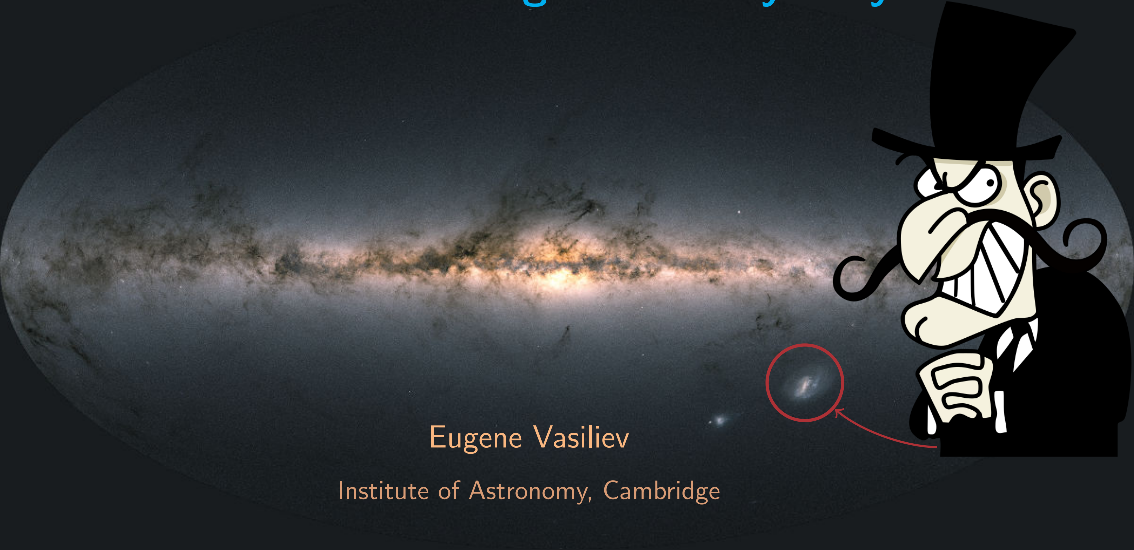
The unquiet neighbour: how the LMC bugs the Milky Way

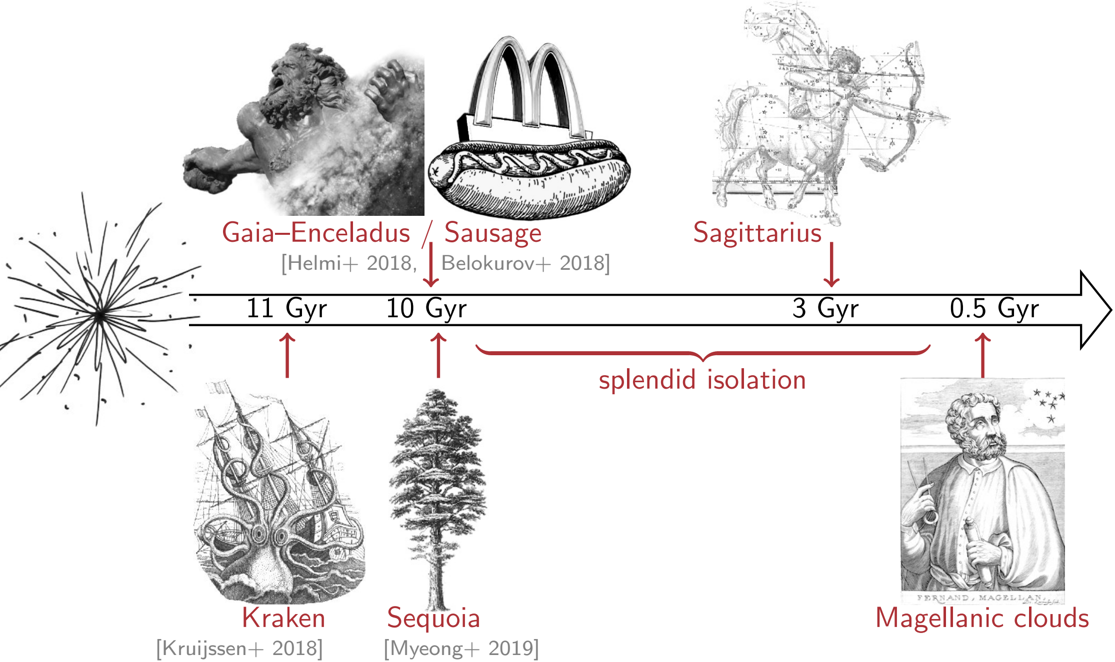


Eugene Vasiliev

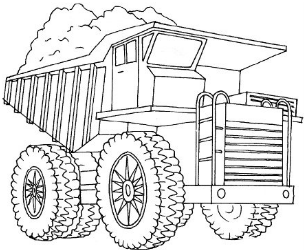
Institute of Astronomy, Cambridge

$\Gamma\alpha\tilde{\iota}\alpha$ – Beyond the Milky Way workshop, Athens, 27–29 September 2022

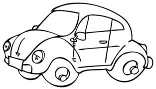
A brief history of the Milky Way



Rendez-vous with the LMC



MW mass: $\sim 10^{12}\,M_\odot$;



LMC mass: $(1-2)\times 10^{11}\,M_\odot$

Dire consequences of the MW–LMC encounter:

0. LMC brings its own satellites, stars and clusters

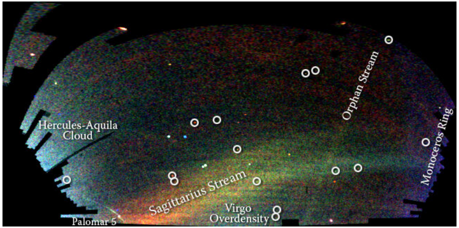
1. LMC deflects stars and streams passing close to its trajectory

2. LMC creates a density wake in the MW halo

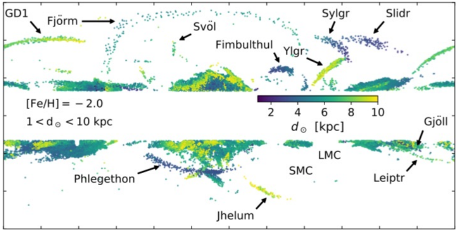
3. LMC displaces the Milky Way

4. LMC creates a dipole asymmetry in the outer MW halo

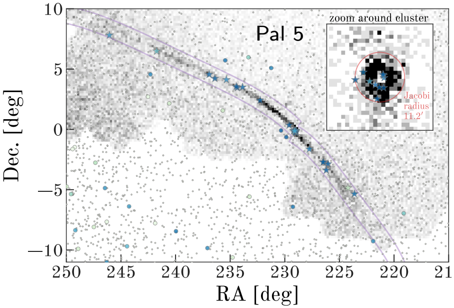
Digression: stellar streams



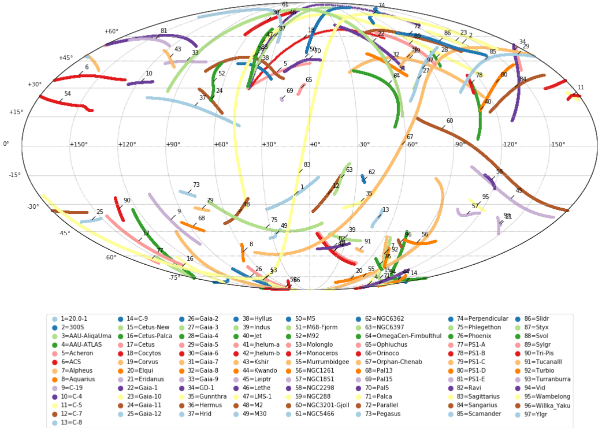
SDSS field of streams [Belokurov+ 2006]



Gaia-STREAMFINDER [Ibata+ 2019]



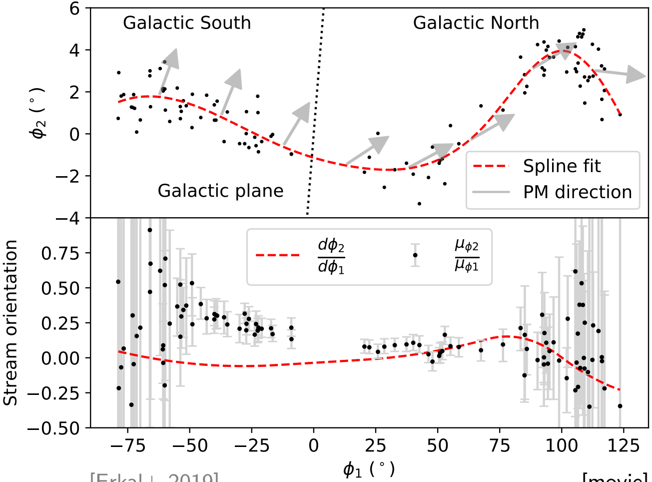
DECaLS+Gaia [Price-Whelan+ 2019]



GalStreams database [Mateu 2022]

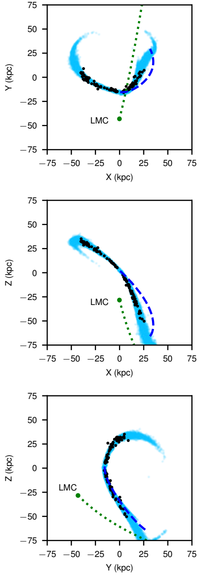
Local effects of the LMC: deflection of stellar streams

Orphan–Chenab stream: no remnant, spans $> 200^\circ$ on the sky.
Sky-plane velocity (reflex-corrected PM) is misaligned with the stream track; stream can be fitted only when taking LMC into account.



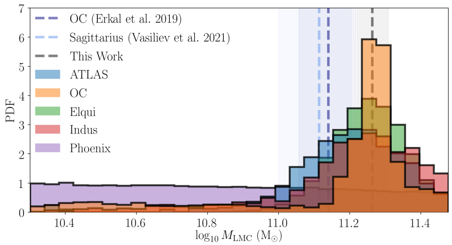
[Erkal+ 2019]

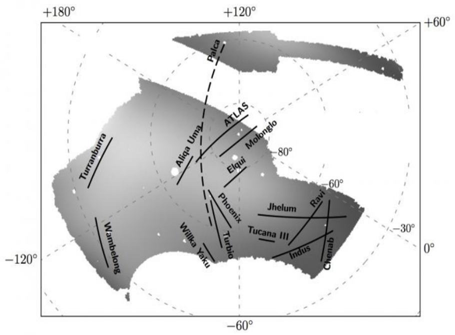
[movie]



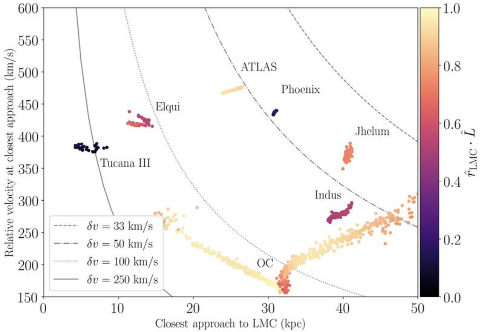
Local effects of the LMC: deflection of stellar streams

LMC passes close to several other streams in the Southern hemisphere;
by analyzing the perturbations of individual streams, one may probe the total mass and even the radial mass distribution of the LMC [Shipp+ 2021; Lilleengen+ 2022].





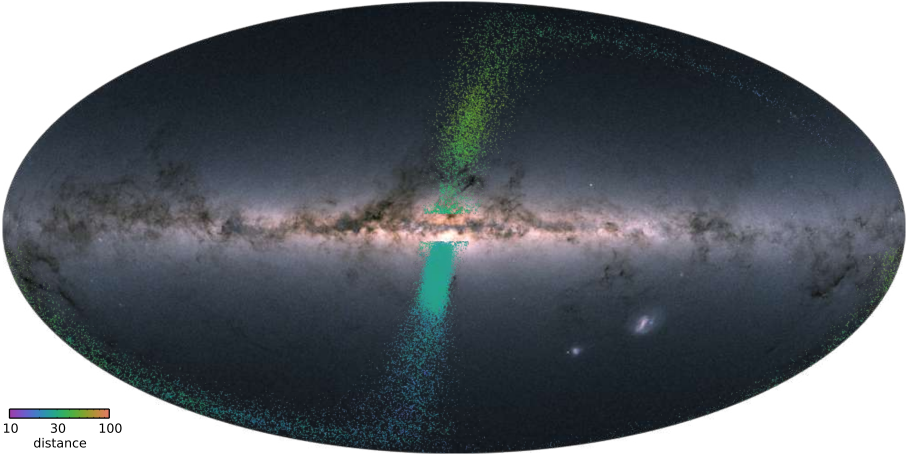
streams discovered in the DES survey [Shipp+ 2019]



[Shipp+ 2021]

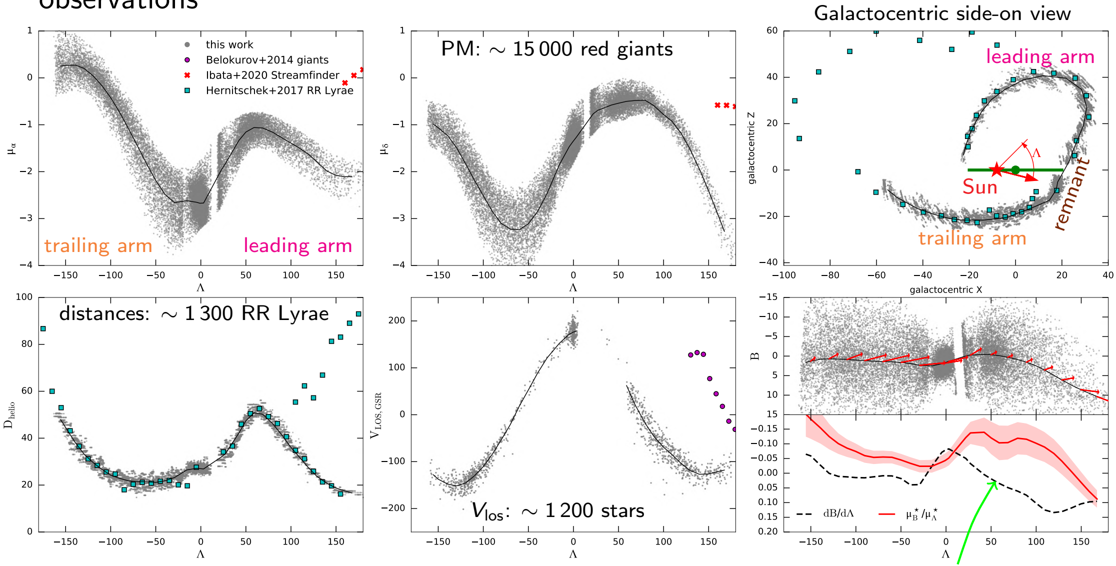
Effect of the LMC on the Sagittarius stream

Sagittarius stream: by far the largest in the Milky Way, spans the entire sky.
First discovered in 2MASS [Majewski+ 2003]; studied extensively using SDSS [Belokurov+ 2006, Koposov+ 2012] and Gaia [Ibata+ 2020, Antoja+ 2020, Ramos+ 2020, 2022].
Progenitor: Sgr dSph (third-largest MW satellite after LMC and SMC; $M_\star \simeq 10^8\,M_\odot$).



Effect of the LMC on the Sagittarius stream

observations

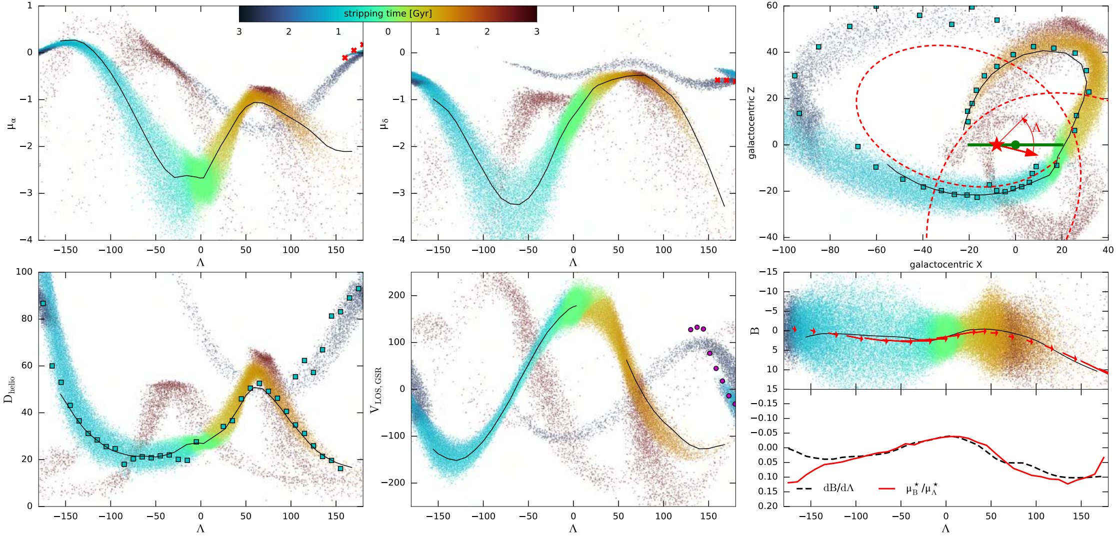


[Vasiliev+ 2021]

Misalignment between PM and stream track

Effect of the LMC on the Sagittarius stream

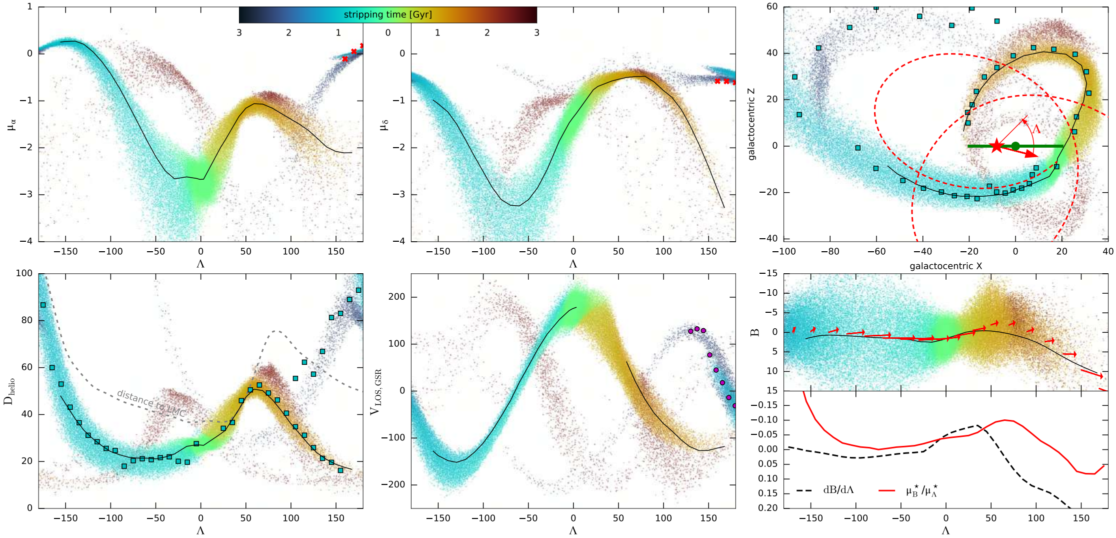
stream model in the best-fit (very flexible) MW potential



[Vasiliev+ 2021]

Effect of the LMC on the Sagittarius stream

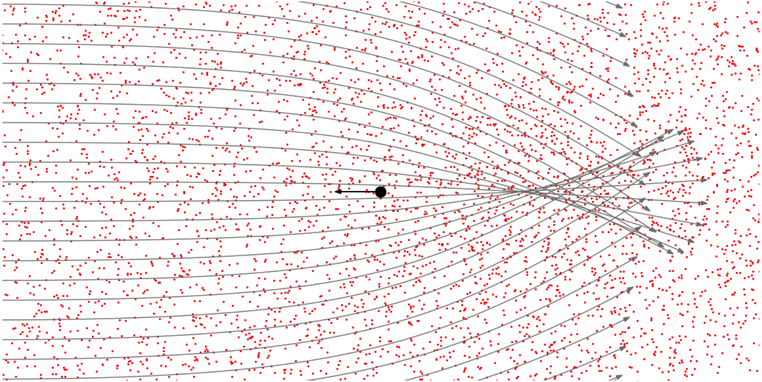
stream model including the perturbation from the LMC ($M_{\rm LMC} = 1.5 \times 10^{11}\, M_\odot$)



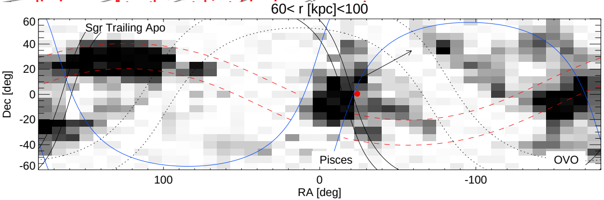
[Vasiliev+ 2021]

Local effects of the LMC: density wake and dynamical friction

deflection of incoming stars by the moving massive object creates
an overdensity behind it, which in turn causes its deceleration [Chandrasekhar 1943]

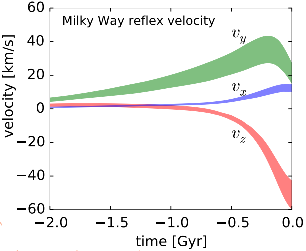


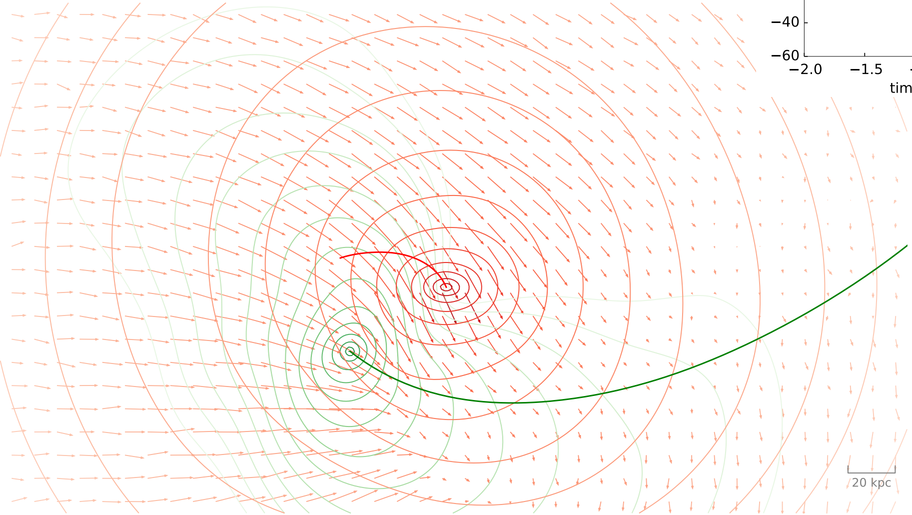
possibly detected as the Pisces overdensity [Belokurov+ 2019]



Global perturbation

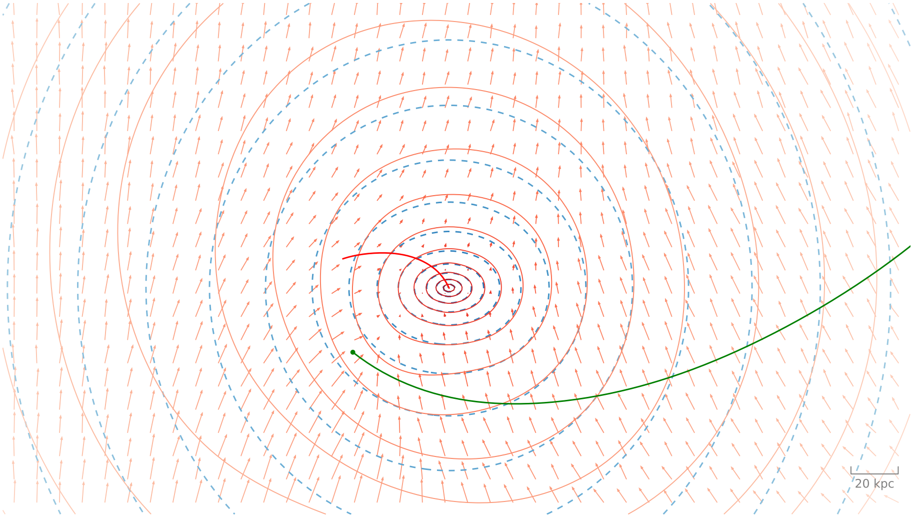
The Milky Way is pulled towards the LMC, acquiring a reflex velocity of few tens km/s in the centre-of-mass frame; however, it does not move as a rigid body – the displacement and velocity varies in space.





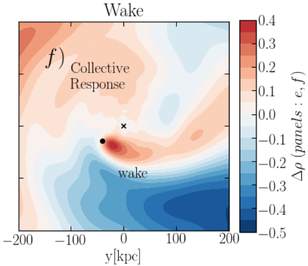
Global perturbation

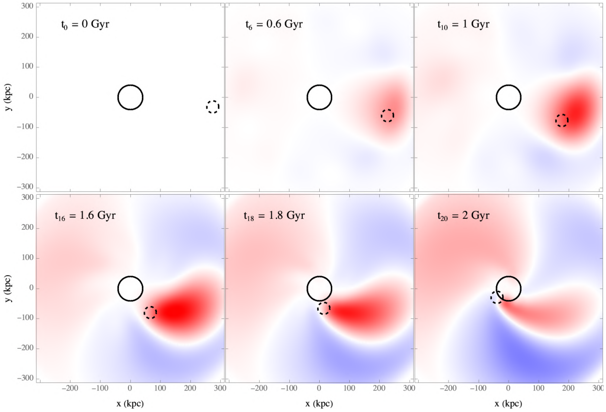
In the *non-inertial* reference frame centered on the inner part of the Galaxy, outer halo appears to move up and acquires a dipole "polarization pattern".



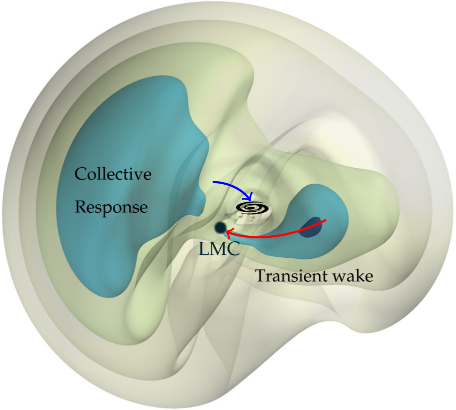
Global perturbation

The classical Chandrasekhar dynamical friction picture only describes the local wake, but not the global deformation, and is unsuitable for high mass ratio mergers ($\gtrsim 1:10$).





perturbation theory [Rozier+ 2022]

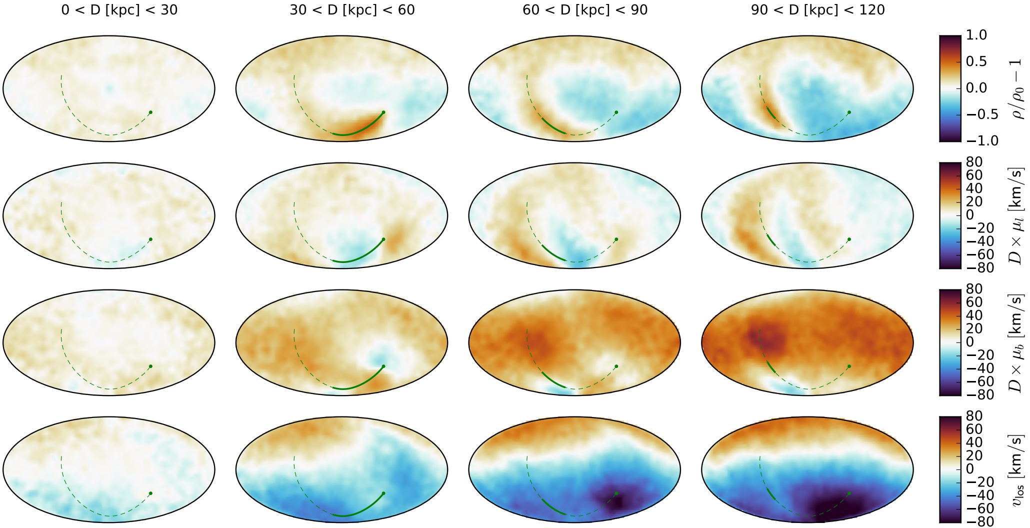


N-body sims [Garavito-Camargo+ 2021]

Global perturbation – predicted 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 at distances $\gtrsim$ 30 kpc

[Erkal+ 2020; Cunningham+ 2020; Petersen & Peñarrubia 2020].



Global perturbation – observed signatures

Density polarization
[Conroy+ 2021]

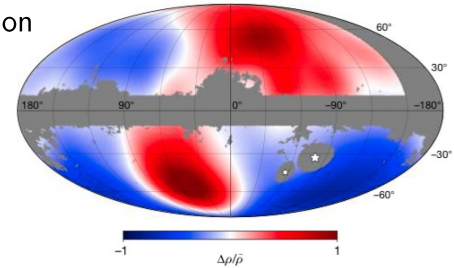
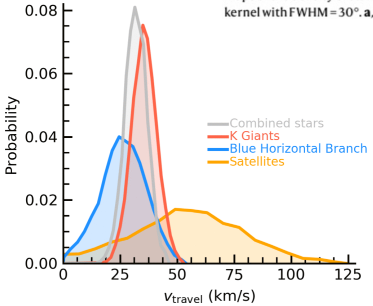
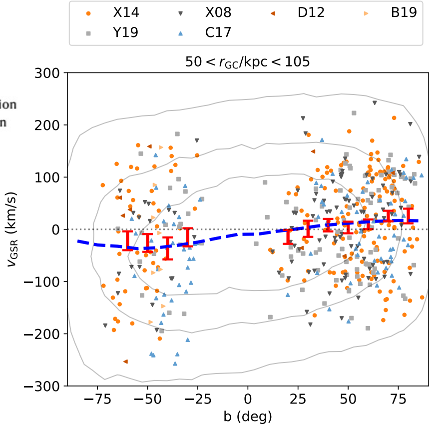


Fig. 1 | Distribution of stars in the Galactic halo. All-sky Mollweide projection maps of the density of stars at 60 kpc < R_{gal} < 100 kpc, smoothed by a Gaussian kernel with FWHM = 30°. **a**, Data based on K giant stars.



[Petersen & Peñarrubia 2021]

Velocity offset



[Erkal+ 2021]

Measurement of the Milky Way potential

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

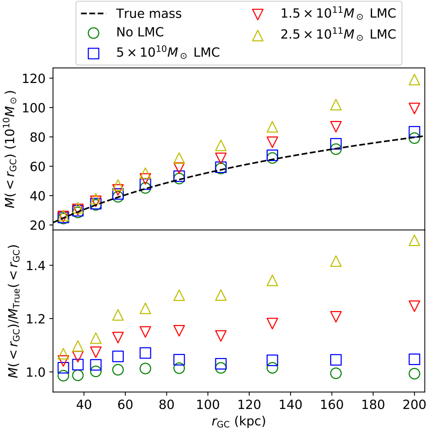
smoothly distributed populations:
assume dynamical equilibrium ⇒
density and velocity distributions
are linked through the potential

Jeans eqns

distribution functions

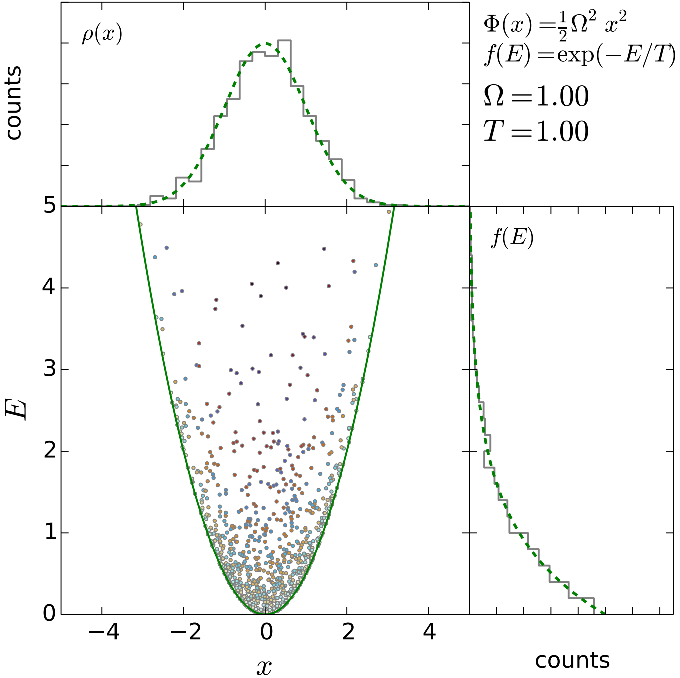
made-to-measure

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].

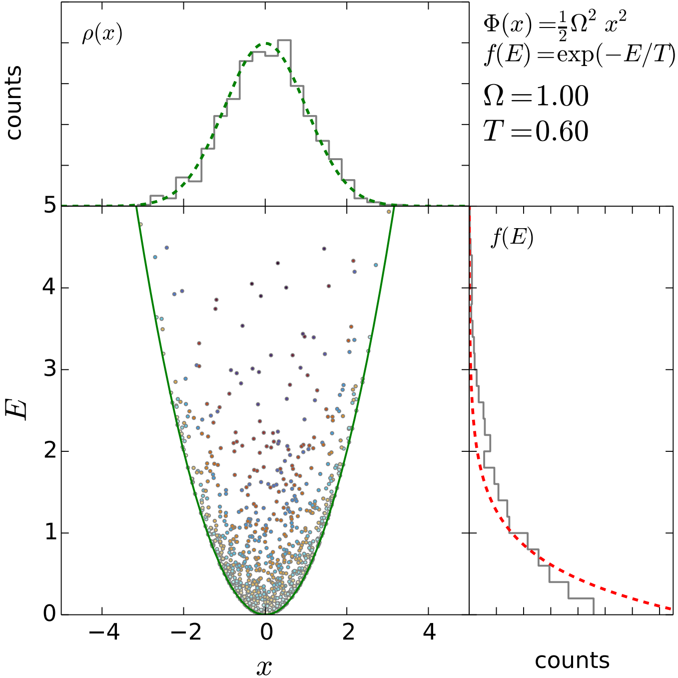
Dynamical modelling with discrete tracers



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

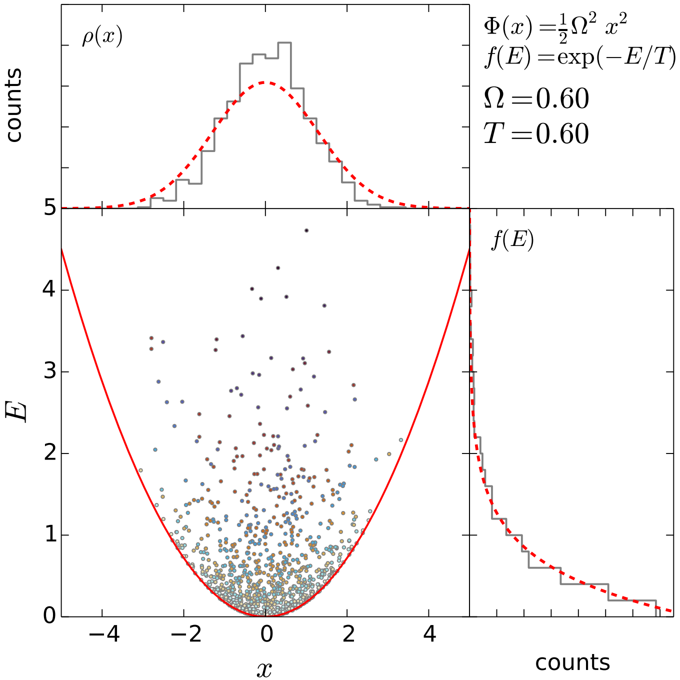
We have measured positions and velocities for $N \gg 1$ particles and want to infer the parameters of the potential (Ω) and the DF (T) that best describe the observed sample.

Dynamical modelling with discrete tracers



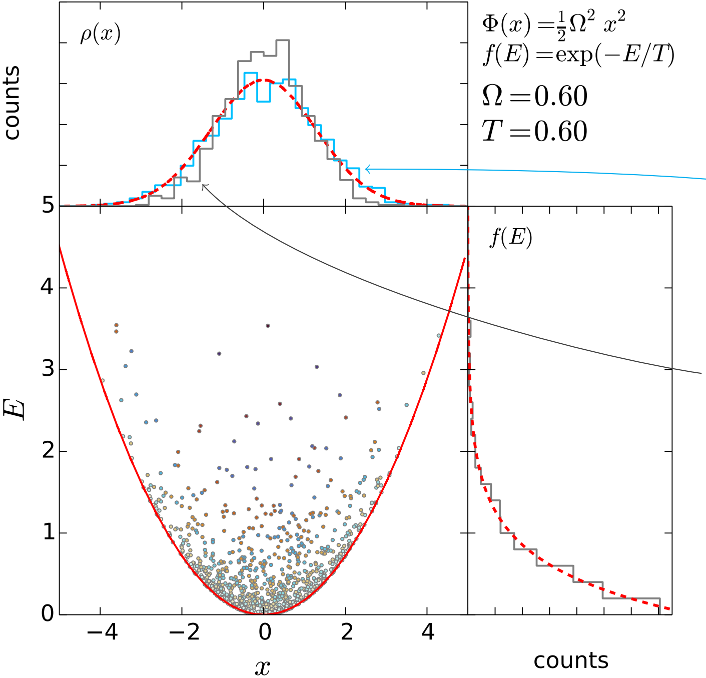
If we assume a wrong temperature T in the true potential, obviously the predicted $f(E)$ will differ from the actual distribution.

Dynamical modelling with discrete tracers



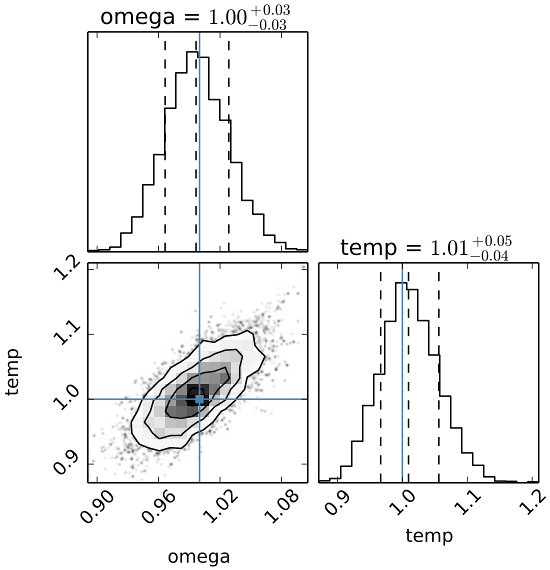
But what if we assume wrong values for both Ω and T? $f(E)$ now agrees with the observed (but incorrectly computed) energy distribution of particles, but their predicted spatial distribution should be wider: there are too many particles near $x = 0$ and too few near turnaround points ($v = 0$).

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)*.

Dynamical modelling in a dynamical context?

Dynamical *equilibrium* models are inadequate for the MW–LMC system, we need dynamical *evolution* models?

Cyclades, c.3000 BCE

Attica, c.530 BCE

Myron (Athens), c.450 BCE

Dynamical modelling in a dynamical context?

Dynamical *equilibrium* models are inadequate for the MW–LMC system, we need dynamical *evolution* models?

Or perhaps we can draw inspiration from the antiquity while still being modern?

Cyclades, c.3000 BCE

Attica, c.530 BCE

Myron (Athens), c.450 BCE

Modigliani, 1910

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:

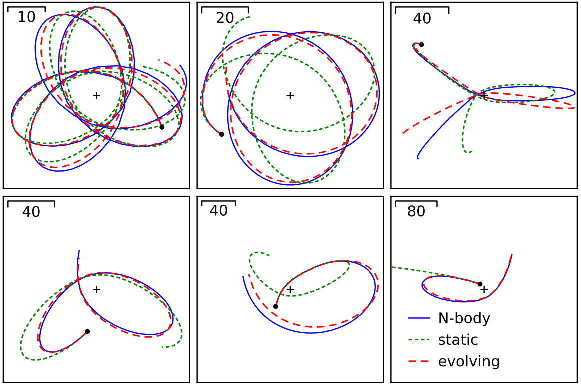
1. Reconstruct the past trajectories of both the MW and the LMC;
2. Rewind the orbits of tracers (halo stars, globular clusters, MW satellites . . .)
in the evolving MW+LMC potential back in time
until the LMC is far enough not to cause trouble ($\sim 2 - 3$ Gyr).

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].

Tests of the method

orbit rewinding

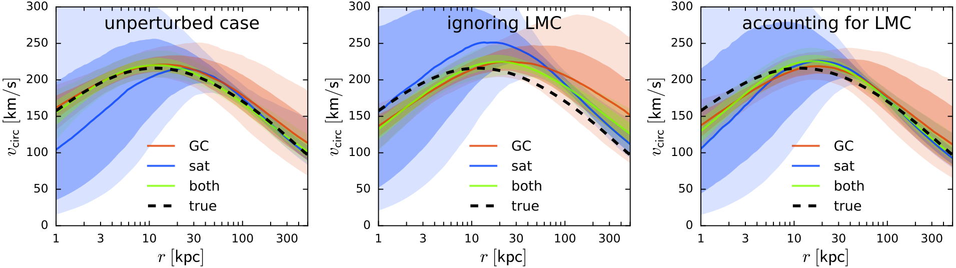


1. past orbits of satellites are well reconstructed in the approximate time-dependent MW+LMC potential;
2. MW potential is well recovered by the DF fitting approach

circular velocity ⇔ enclosed mass

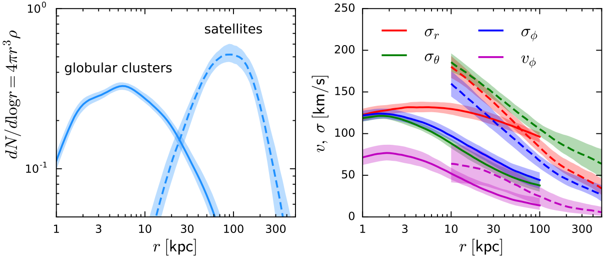
$$v_{\rm circ}(r) \equiv \sqrt{r\,\frac{\partial\Phi}{\partial r}} \approx \sqrt{\frac{G\,M(<r)}{r}}$$

potential reconstruction

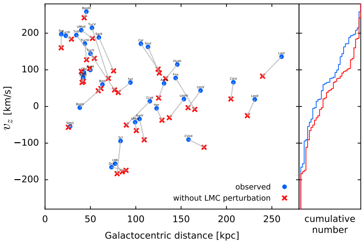


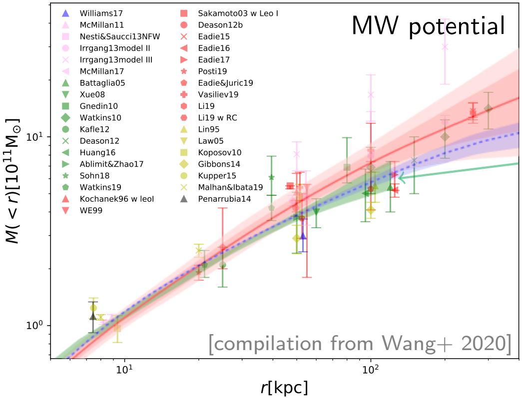
Results

tracer populations



velocity perturbation

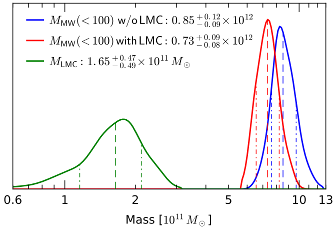




GC+dSph (+LMC rewinding) [Correa Magnus & Vasiliev 2022]

Sgr stream (incl. LMC) [Vasiliev+ 2021]

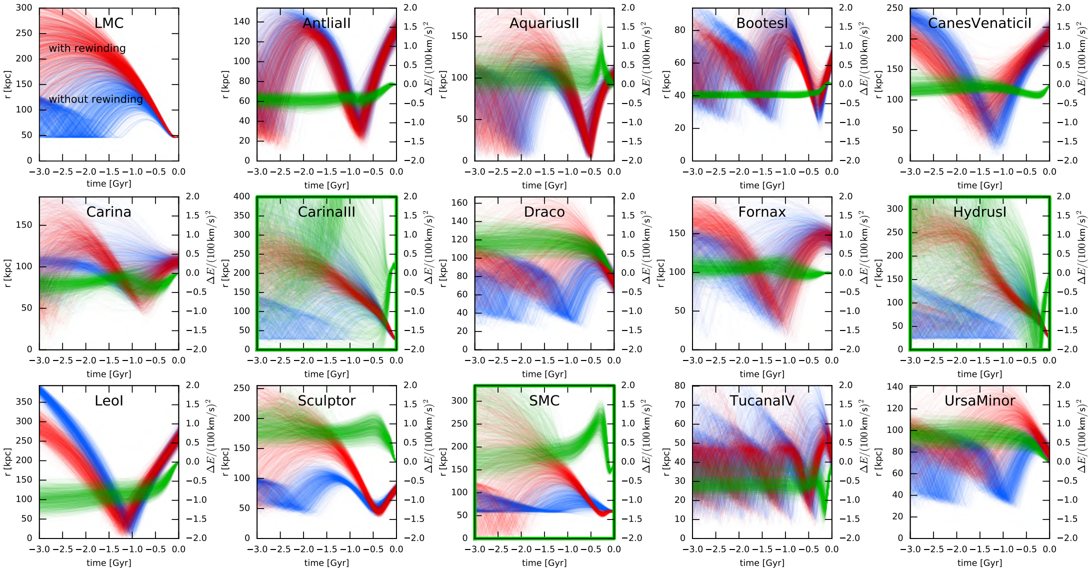
Orphan stream (incl. LMC) [Koposov+ in prep.]



Changes in satellite orbits caused by the LMC

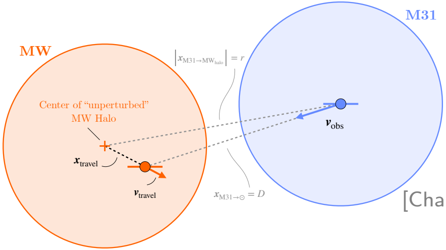
could be quite substantial!   shown are Galactocentric distances in the past 3 Gyr

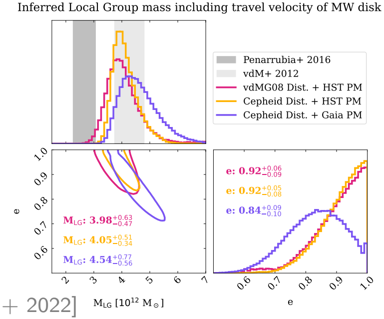
blue: without LMC;   red: with LMC;   green: energy evolution with LMC;   green frame: LMC satellites



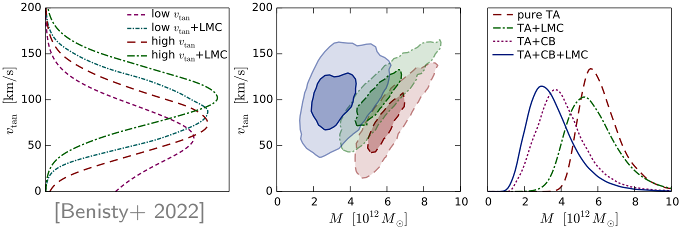
"Changes" in the orbit of Andromeda caused by the LMC

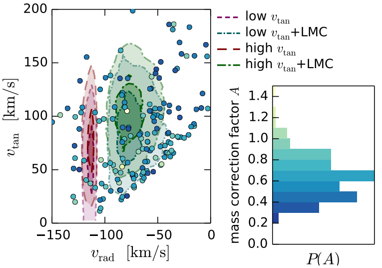
In fact, the reflex velocity of a few tens km/s imparted on the Milky Way by the LMC has implications even for the estimate of the MW+M31 mass via the "timing argument" [e.g. Peñarrubia+ 2016].
The corrected velocity implies a less eccentric orbit of M31 and a lower Local Group mass.





[Chamberlain+ 2022]

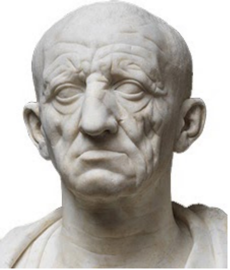


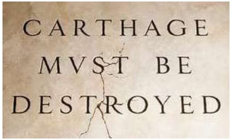


[Benisty+ 2022]

Future fate


doi:10.1093/mnras/sty3
MNRAS 483, 2185–2196 (2019)
Advance Access publication 2018 November 13
The aftermath of the Great Collision between our Galaxy and the Large Magellanic Cloud
Marius Cautun[1★], Alis J. Deason[1], Carlos S. Frenk[1] and Stuart McAlpine[1,2]





[Cato −149]

"This catastrophic and long-overdue event will restore the MW to normality"

[Cautun+ 2019]