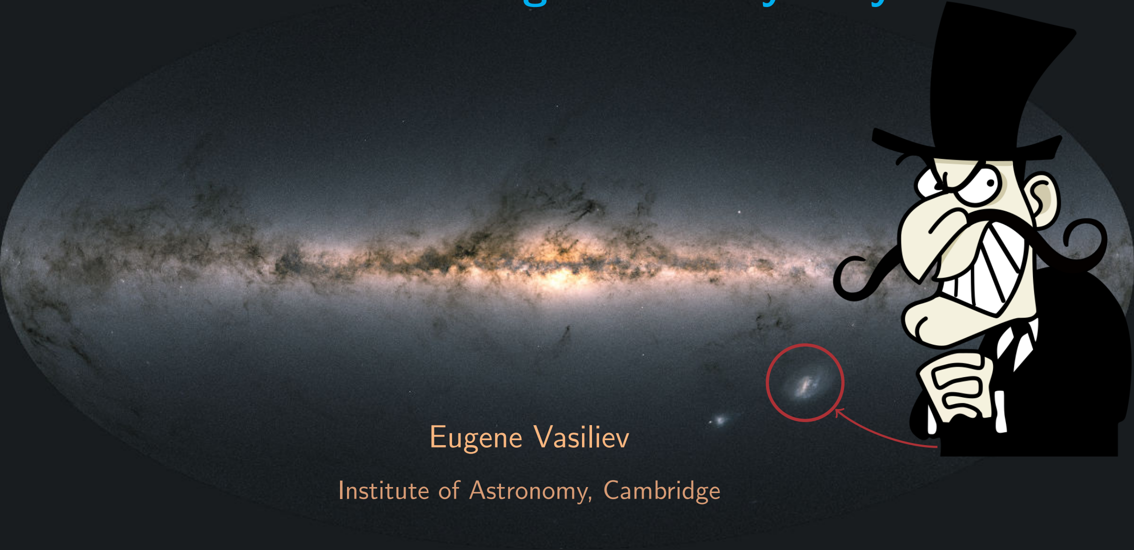
The unquiet neighbour: how the LMC bugs the Milky Way

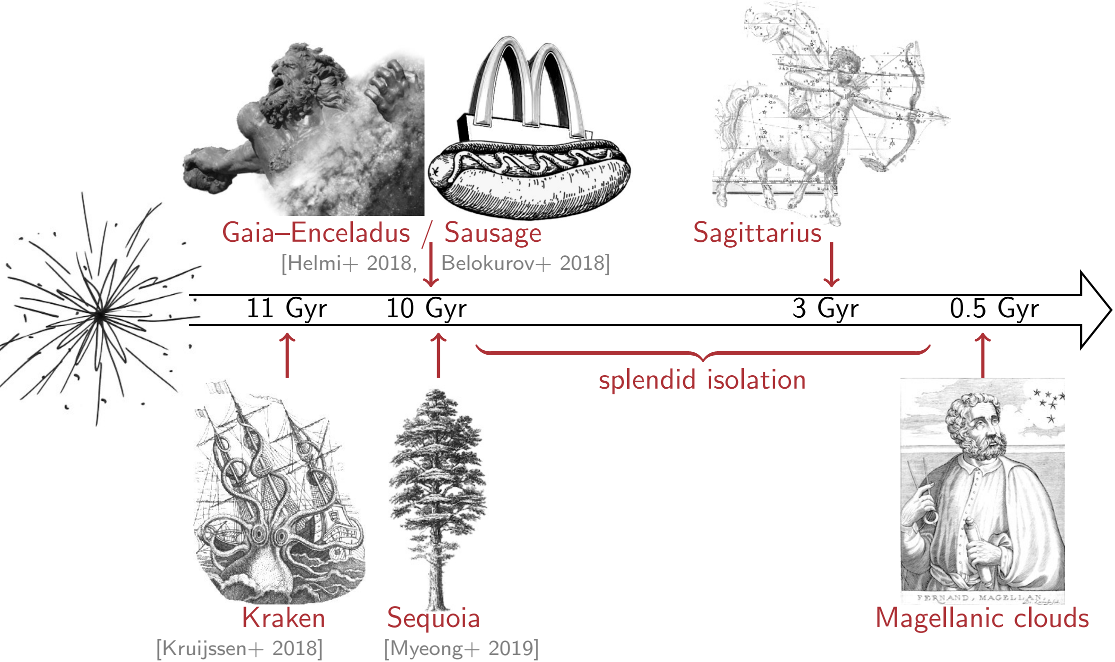


Eugene Vasiliev

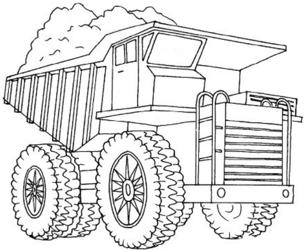
Institute of Astronomy, Cambridge

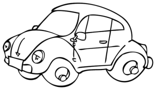
$\Gamma\alpha\tilde{\imath}\alpha$ – Beyond the Milky Way workshop, Athens, 27–29 September 2022

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

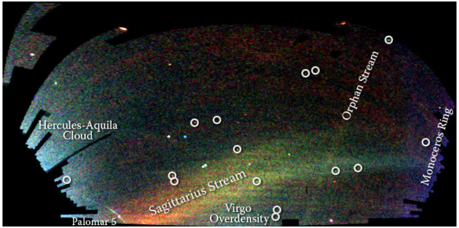
1. LMC deflects stars and streams passing close to its trajectory

2. LMC creates a density wake in the MW halo

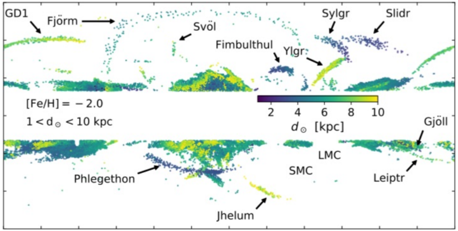
3. LMC displaces the Milky Way

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

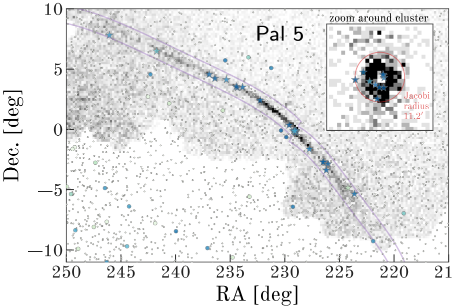
Digression: stellar streams



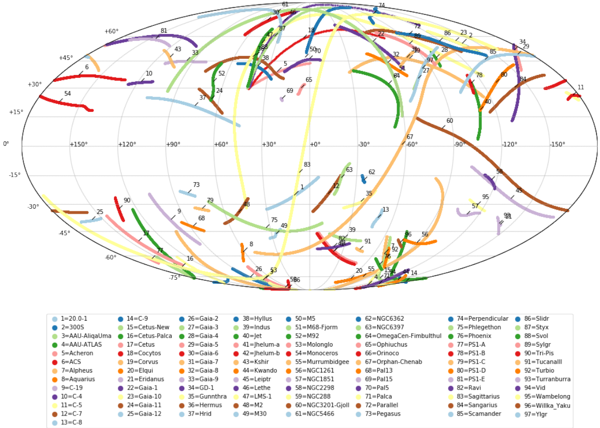
SDSS field of streams [Belokurov+ 2006]



Gaia-STREAMFINDER [Ibata+ 2019]



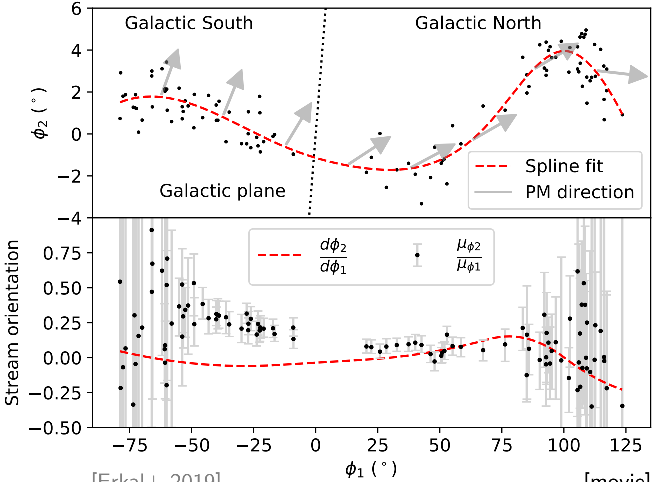
DECaLS+Gaia [Price-Whelan+ 2019]



GalStreams database [Mateu 2022]

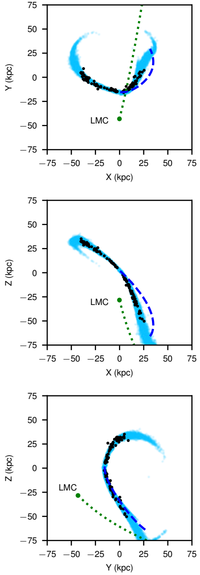
Local effects of the LMC: deflection of stellar streams

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.



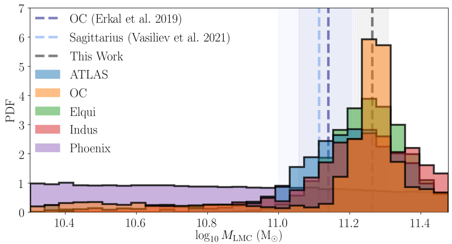
[Erkal+ 2019]

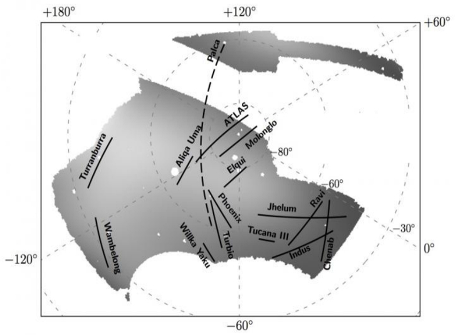
[movie]



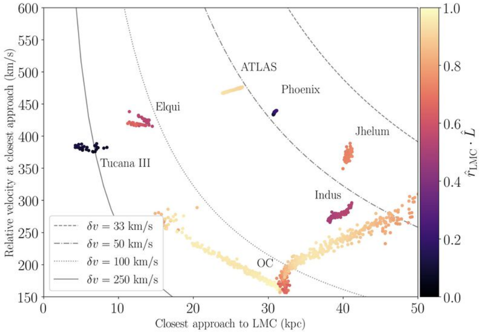
Local effects of the LMC: deflection of stellar streams

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].





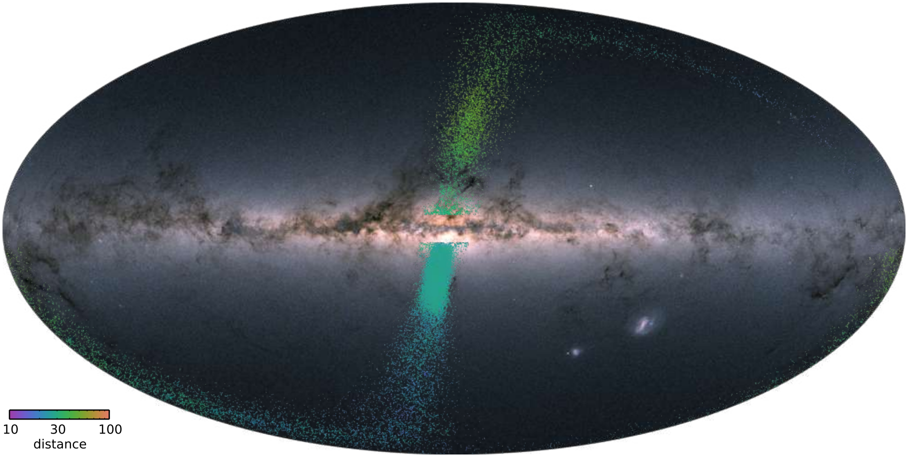
streams discovered in the DES survey [Shipp+ 2019]



[Shipp+ 2021]

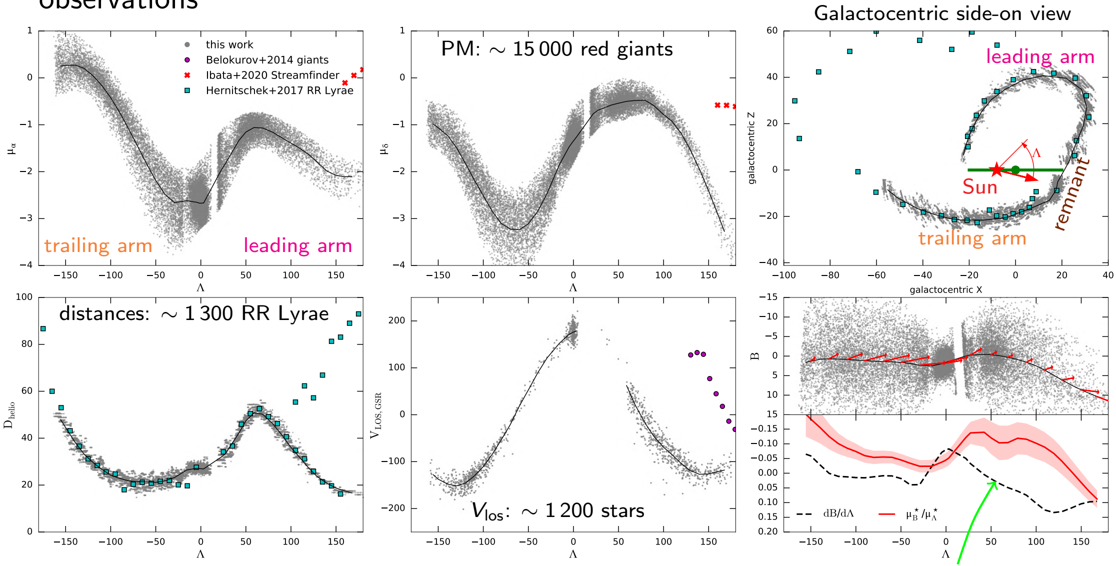
Effect of the LMC on the Sagittarius stream

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

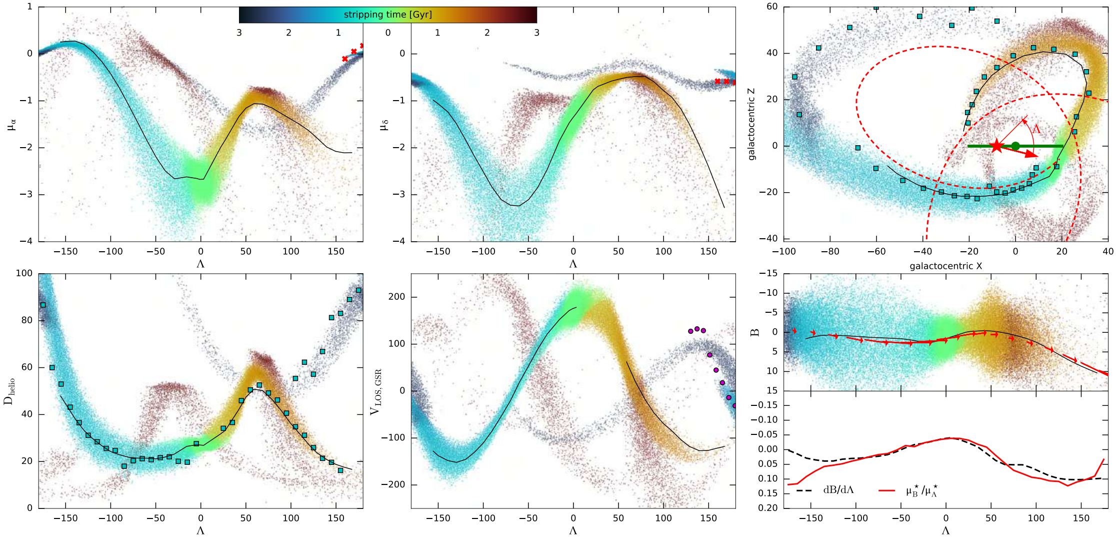


[Vasiliev+ 2021]

Misalignment between PM and stream track

Effect of the LMC on the Sagittarius stream

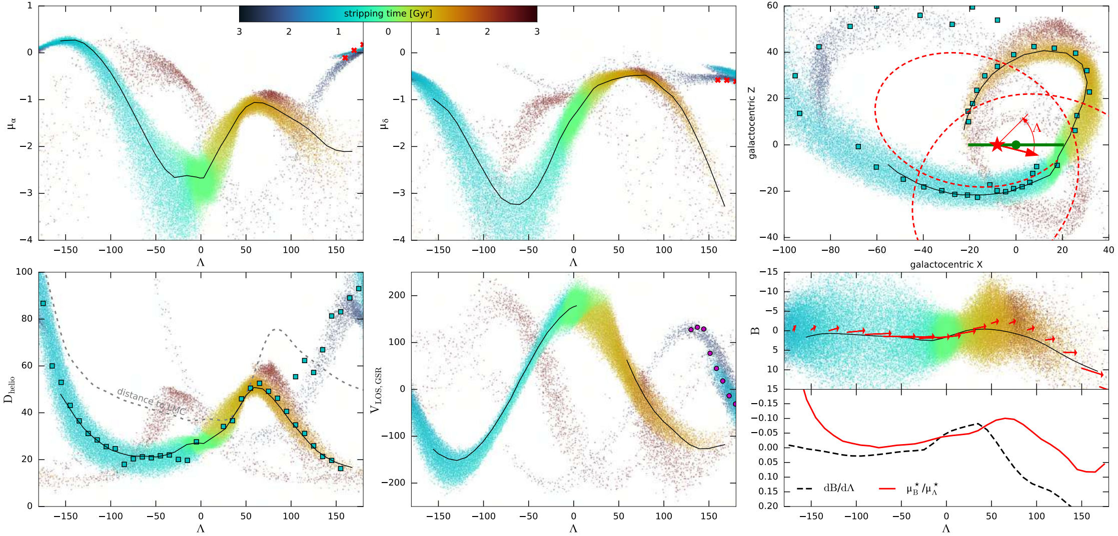
stream model in the best-fit (very flexible) MW potential



[Vasiliev+ 2021]

Effect of the LMC on the Sagittarius stream

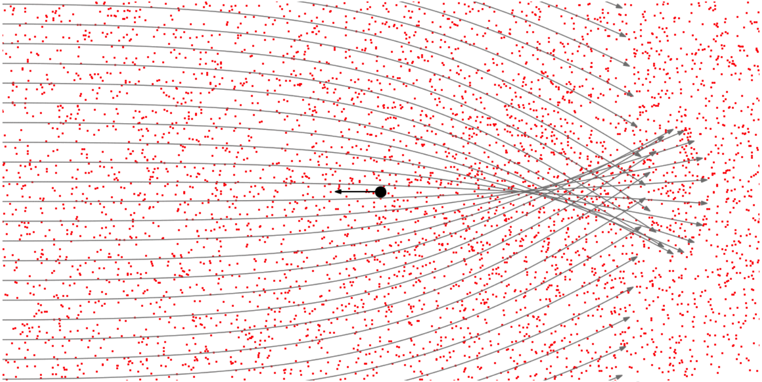
stream model including the perturbation from the LMC ($M_{\mathrm{LMC}} = 1.5 \times 10^{11}\, M_{\odot}$)



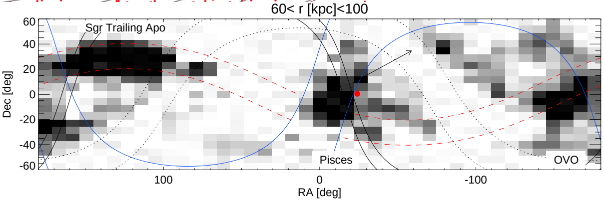
[Vasiliev+ 2021]

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]

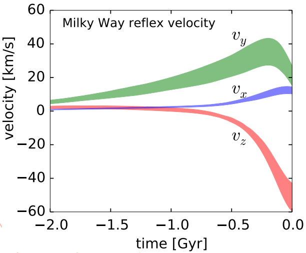


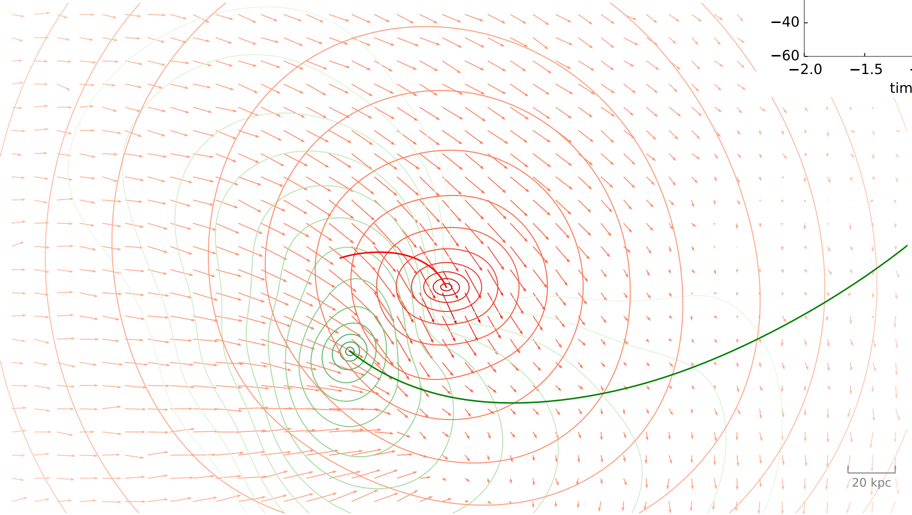
possibly detected as the Pisces overdensity [Belokurov+ 2019]



Global perturbation

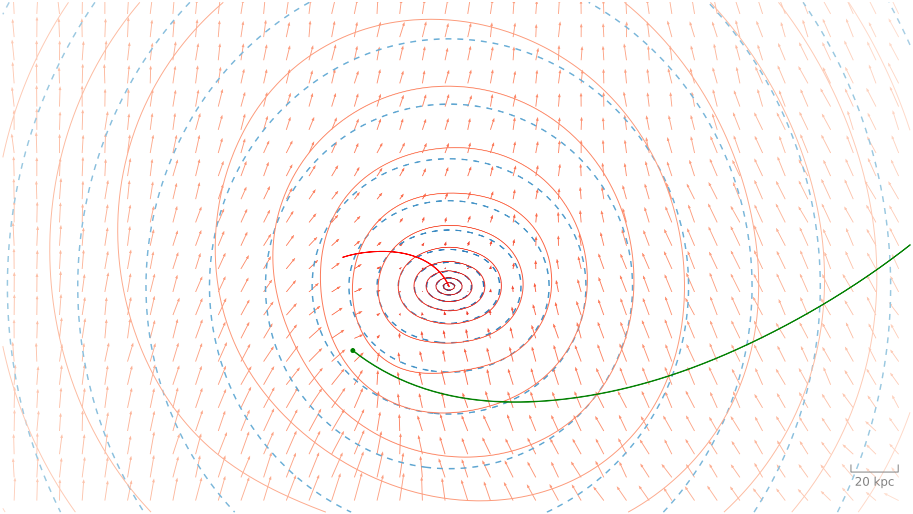
The Milky Way is pulled towards the LMC, acquiring a reflex velocity of few tens km/s in the centre-of-mass frame; however, it does not move as a rigid body – the displacement and velocity varies in space.





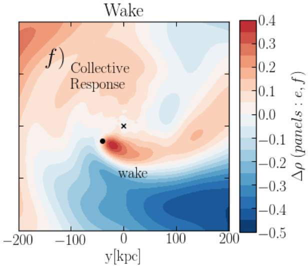
Global perturbation

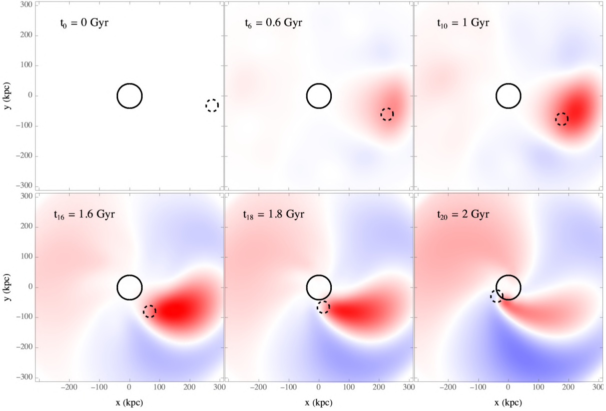
In the *non-inertial* reference frame centered on the inner part of the Galaxy, outer halo appears to move up and acquires a dipole “polarization pattern”.



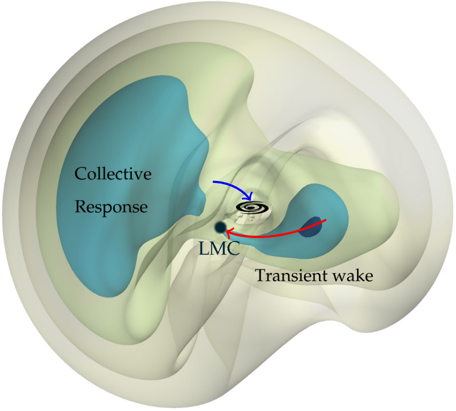
Global perturbation

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





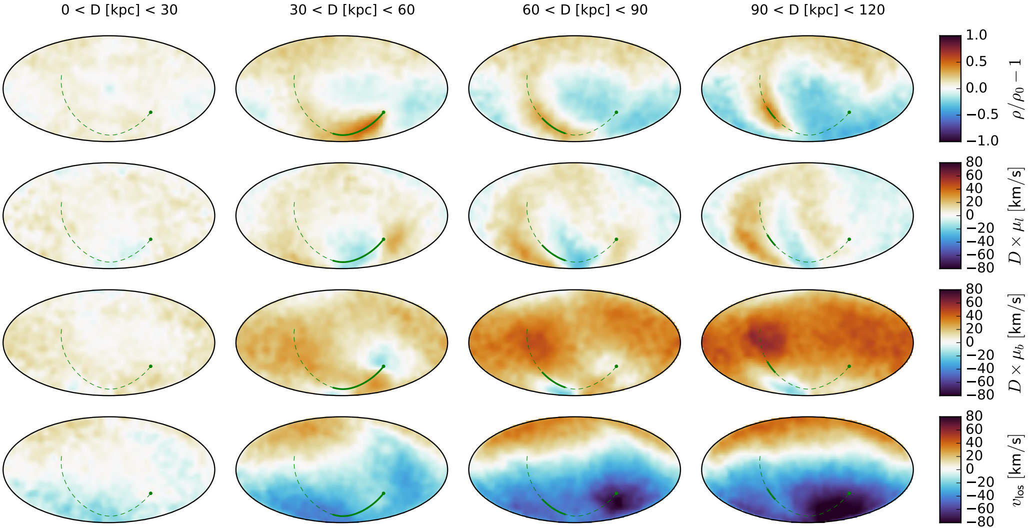
perturbation theory [Rozier+ 2022]



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]

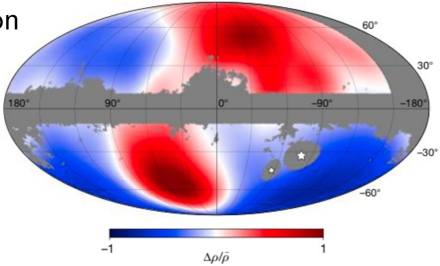
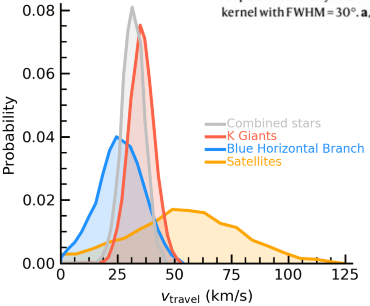
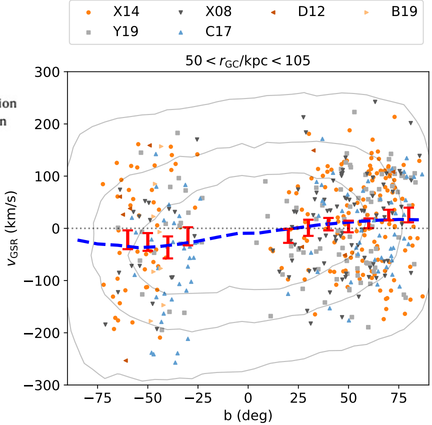


Fig. 1 | Distribution of stars in the Galactic halo. All-sky Mollweide projection maps of the density of stars at 60 kpc < R_{gal} < 100 kpc, smoothed by a Gaussian kernel with FWHM = 30°. **a**, Data based on K giant stars.



[Petersen & Peñarrubia 2021]

Velocity offset



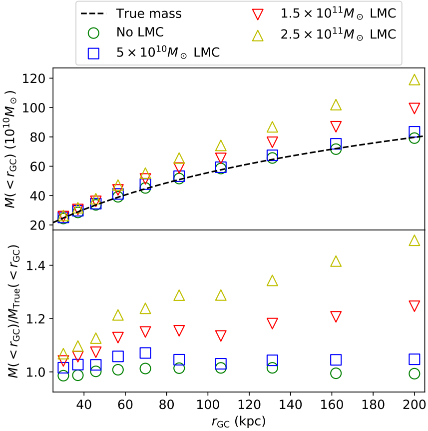
[Erkal+ 2021]

Measurement of the Milky Way potential

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

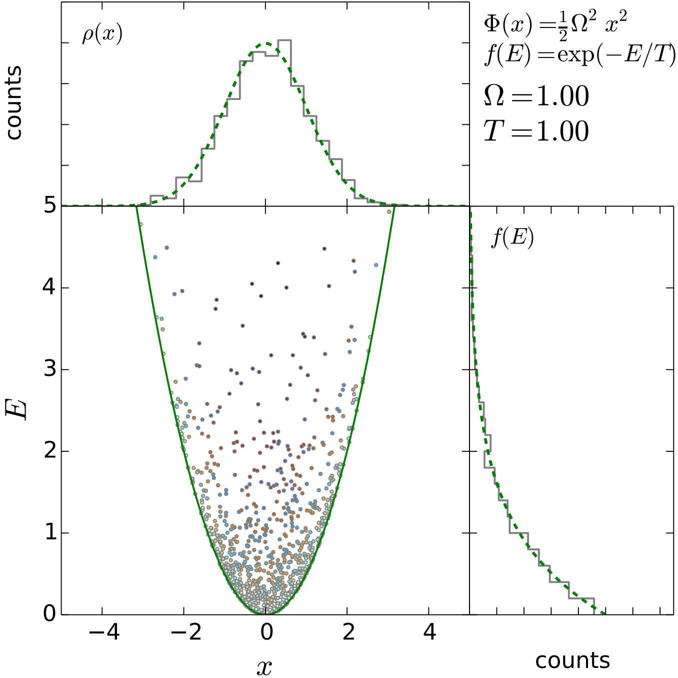
smoothly distributed populations:
assume dynamical equilibrium ⇒
density and velocity distributions
are linked through the potential

- 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].

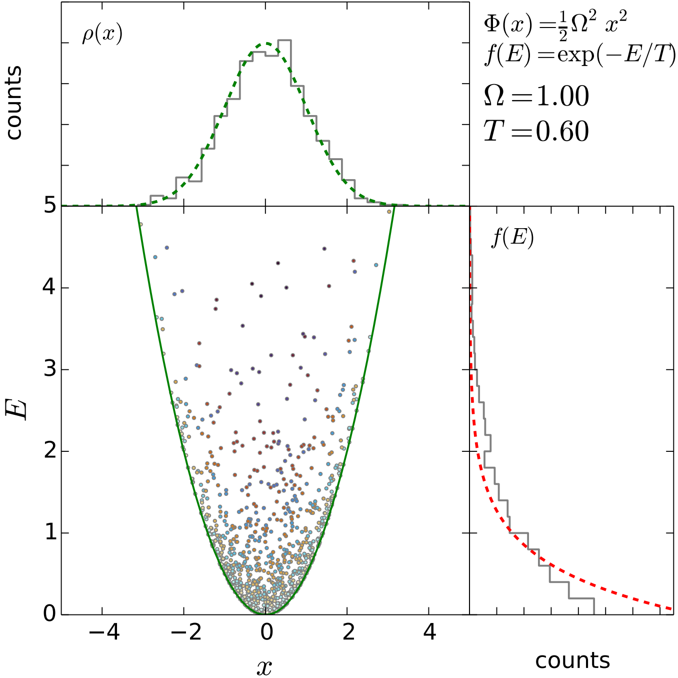
Dynamical modelling with discrete tracers



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

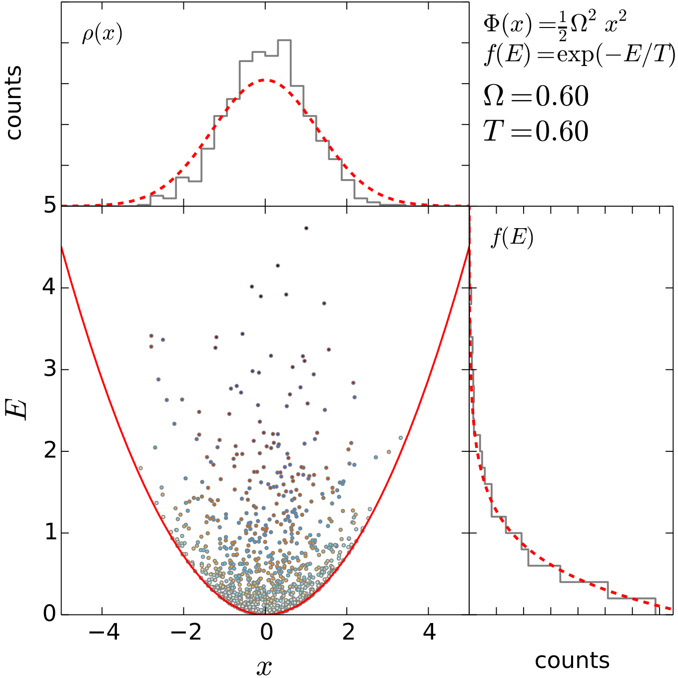
We have measured positions and velocities for $N \gg 1$ particles and want to infer the parameters of the potential (Ω) and the DF (T) that best describe the observed sample.

Dynamical modelling with discrete tracers



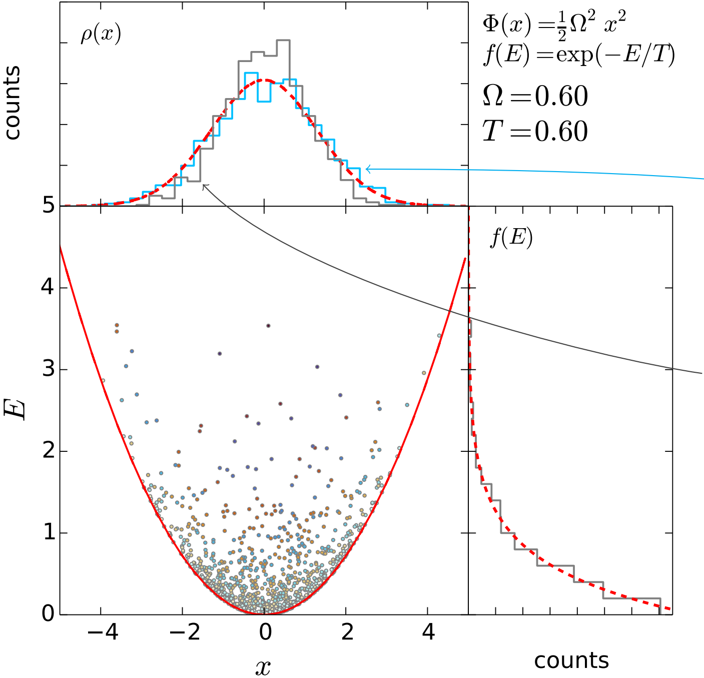
If we assume a wrong temperature T in the true potential, obviously the predicted $f(E)$ will differ from the actual distribution.

Dynamical modelling with discrete tracers



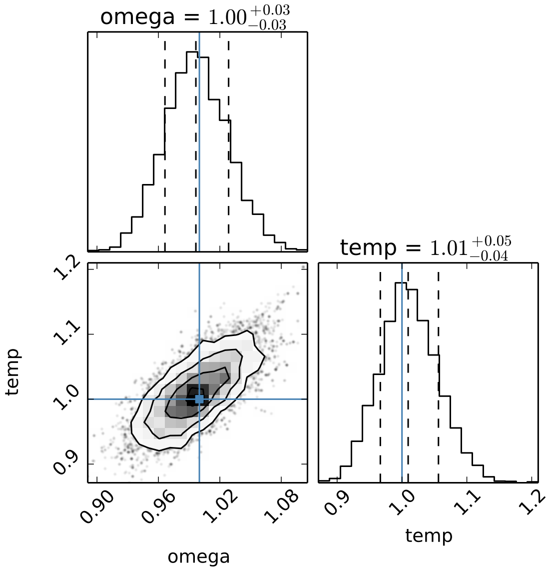
But what if we assume wrong values for both Ω and T? $f(E)$ now agrees with the observed (but incorrectly computed) energy distribution of particles, but their predicted spatial distribution should be wider: there are too many particles near $x = 0$ and too few near turnaround points ($v = 0$).

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]

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:

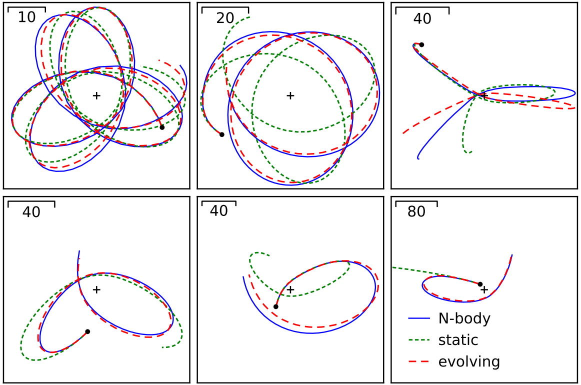
1. Reconstruct the past trajectories of both the MW and the LMC;
2. Rewind the orbits of tracers (halo stars, globular clusters, MW satellites ...)
in the evolving MW+LMC potential back in time
until the LMC is far enough not to cause trouble ($\sim 2-3$ Gyr).

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

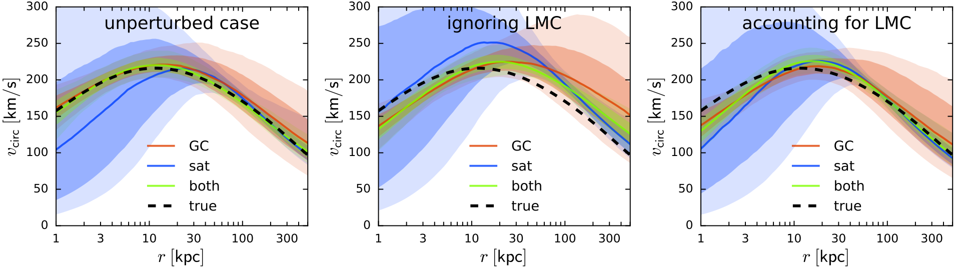


1. past orbits of satellites are well reconstructed in the approximate time-dependent MW+LMC potential;
2. MW potential is well recovered by the DF fitting approach

circular velocity ⇔ enclosed mass

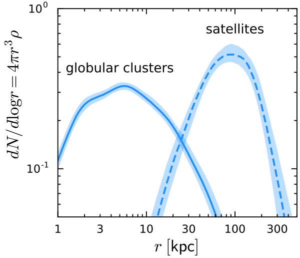
$$v_{\rm circ}(r) \equiv \sqrt{r\,\frac{\partial\Phi}{\partial r}} \approx \sqrt{\frac{G\,M(<r)}{r}}$$

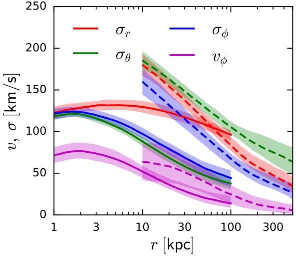
potential reconstruction



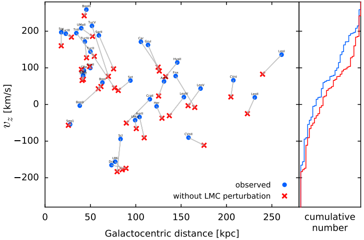
Results

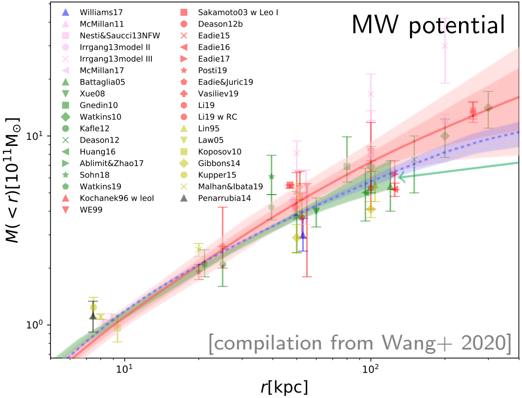
tracer populations





velocity perturbation

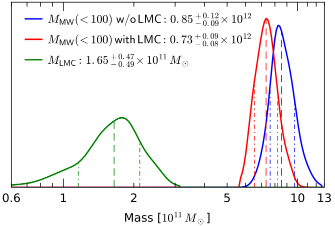




GC+dSph (+LMC rewinding) [Correa Magnus & Vasiliev 2022]

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

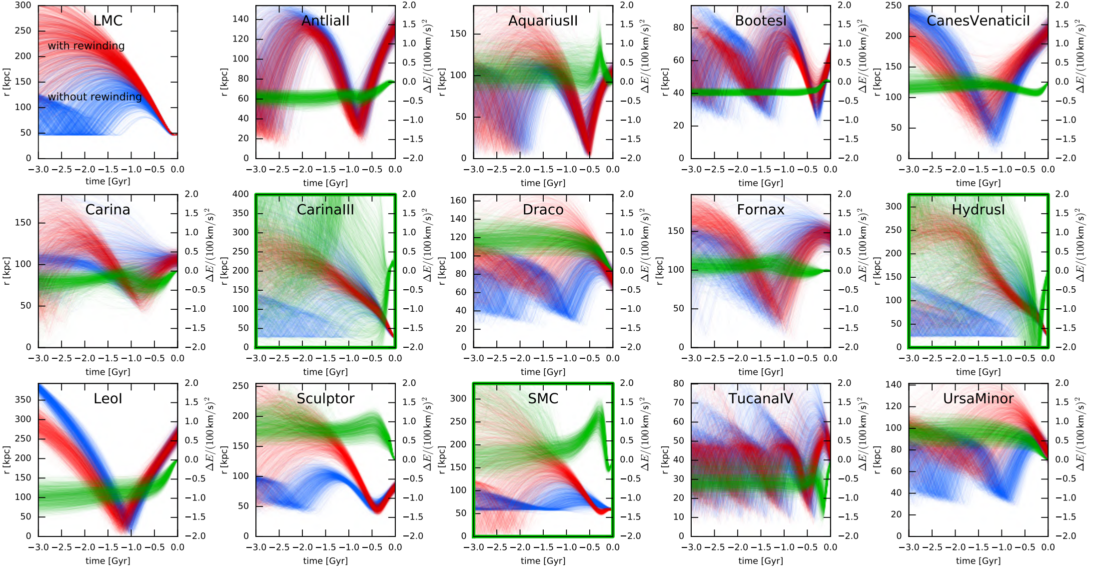
Orphan stream (incl. LMC) [Koposov+ in prep.]



Changes in satellite orbits caused by the LMC

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

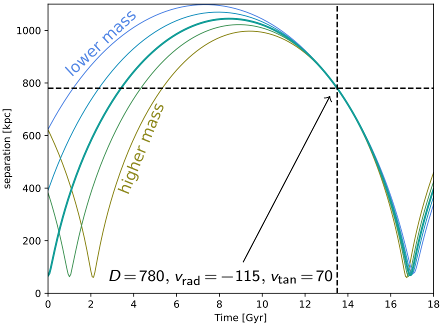
blue: without LMC;   red: with LMC;   green: energy evolution with LMC;   green frame: LMC satellites



"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 Local Group (MW+Andromeda) mass via the "timing argument" [e.g. Peñarrubia+ 2016].

The two galaxies are assumed to fly apart from [nearly] the same point in the early Universe, then turn around and are now approaching each other. The combined mass of MW+M31 is constrained by their present-day relative velocity.



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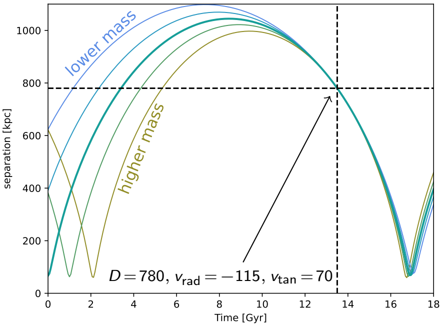
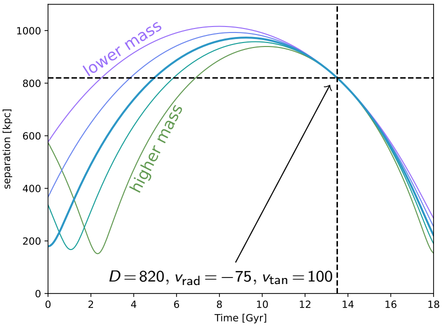
The two galaxies are assumed to fly apart from [nearly] the same point in the early Universe, then turn around and are now approaching each other. The combined mass of MW+M31 is constrained by their present-day relative velocity.

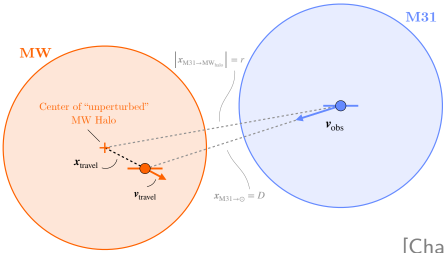
The recent LMC-induced change in the relative velocity of MW–M31 thus affects the inference about their past orbit and mass.

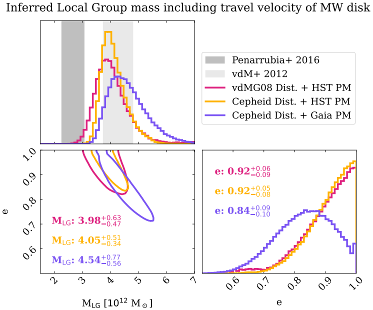




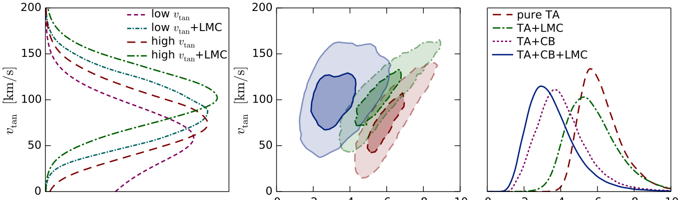
"Changes" in the orbit of Andromeda caused by the LMC

The corrected velocity implies a less eccentric orbit of M31 and a lower Local Group mass.

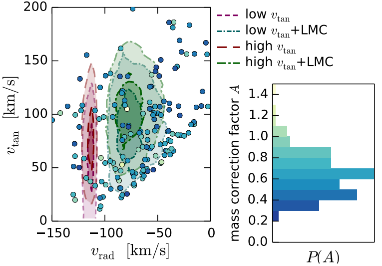




[Chamberlain+ 2022]



[Benisty+ 2022]



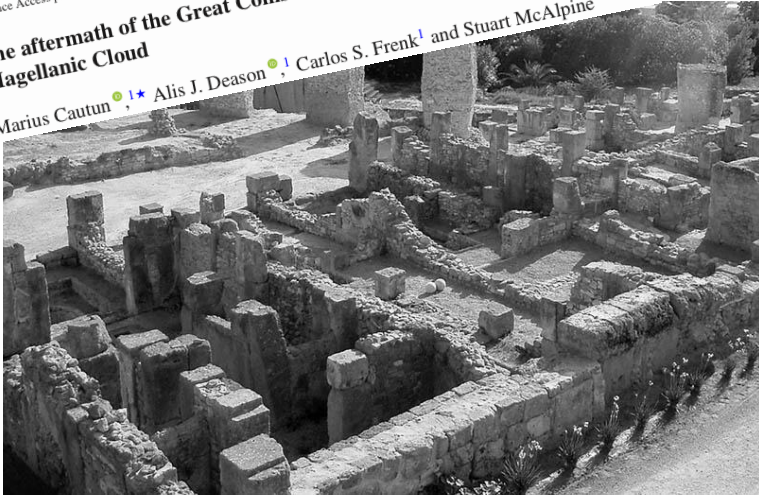
Future fate

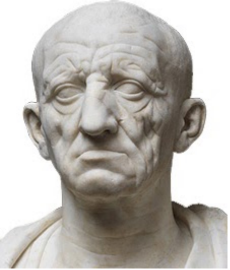

doi:10.1093/mnras/sty3

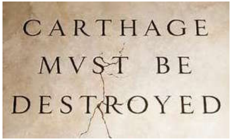
MNRAS **483**, 2185–2196 (2019)
Advance Access publication 2018 November 13

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]