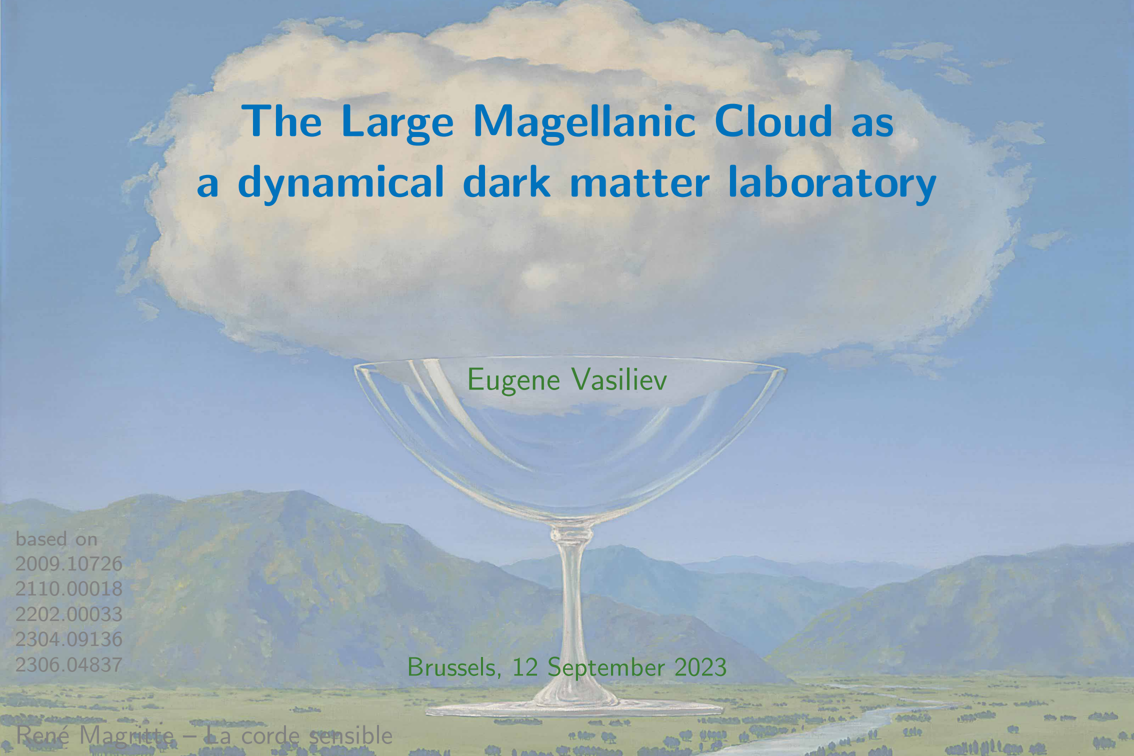
The Large Magellanic Cloud as a dynamical dark matter laboratory

Eugene Vasiliev

based on
2009.10726
2110.00018
2202.00033
2304.09136
2306.04837

Brussels, 12 September 2023

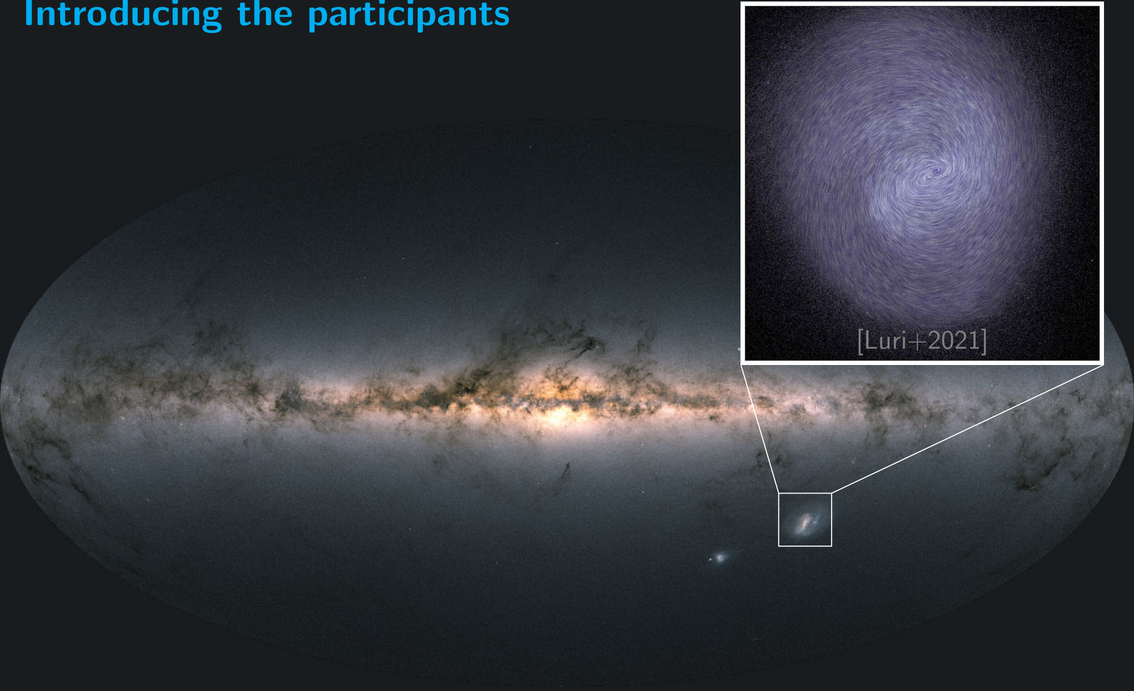


René Magritte – La corde sensible

Introducing the participants

credit: Gaia collaboration

Introducing the participants



credit: Gaia collaboration

Introducing the participants

	Milky Way	LMC
stellar mass	$\sim 6 \times 10^{10}\ M_\odot$	$\sim 3 \times 10^{9}\ M_\odot$
total mass	$\sim 10^{12}\ M_\odot$	$\sim (1-2) \times 10^{11}\ M_\odot$
peak v_{circ}	250 km/s	100 km/s
disc scale radius	3 kpc	1.5 kpc
distance to centre	8 kpc	50 kpc
morphological type	barred spiral	barred irregular?
# of satellites	~ 30	~ 10

just passed its (first?) pericentre

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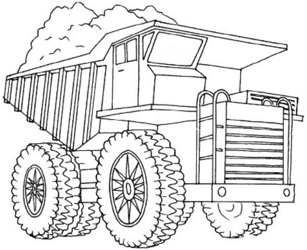
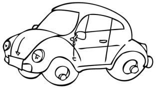
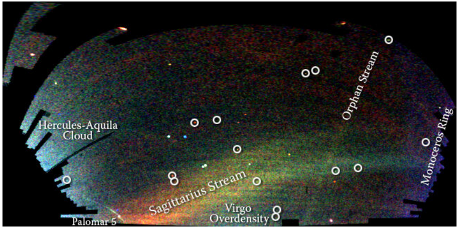




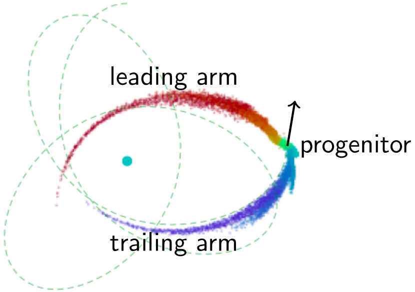
Consequences of the MW–LMC encounter

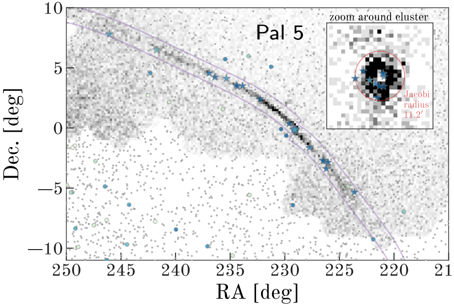
- LMC brings its own satellites, stars and clusters
- LMC deflects stars and streams passing close to its trajectory
- LMC creates a density wake in the MW halo
- LMC displaces the Milky Way
- LMC creates a dipole asymmetry in the outer MW halo
- LMC affects the velocities of other galaxies relative to MW

Stellar tidal streams in the Milky Way

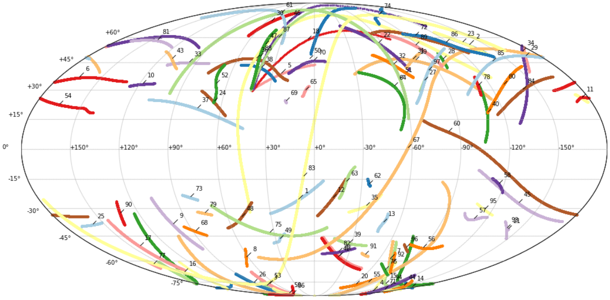


SDSS field of streams [Belokurov+ 2006]



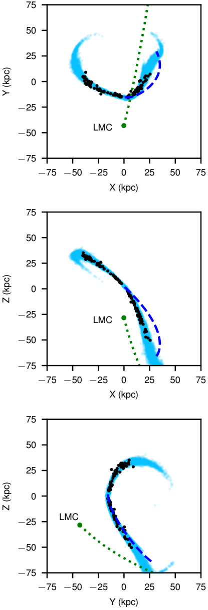


DECaLS+Gaia [Price-Whelan+ 2019]



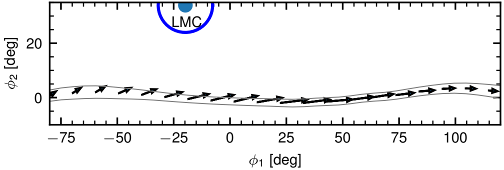
GalStreams database [Mateu 2023]

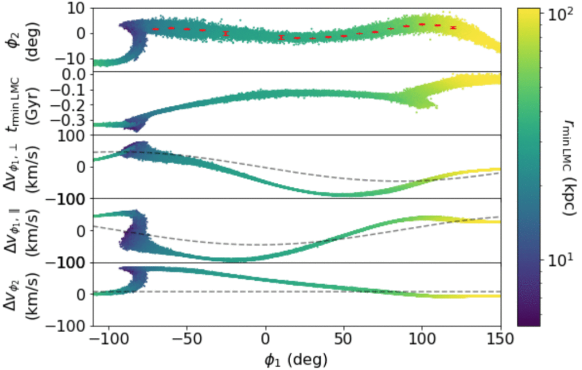
Local effects of the LMC: deflection of stellar streams



[Erkal+ 2019]

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.

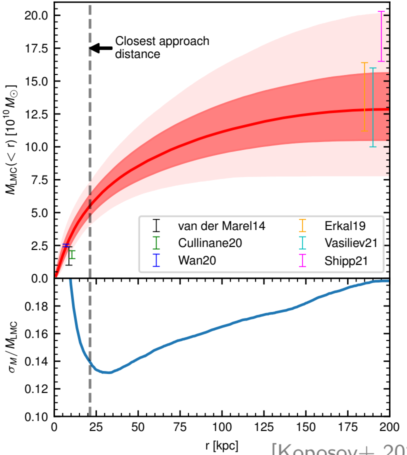




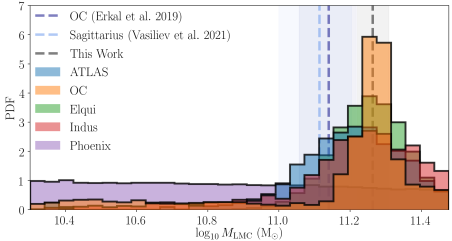
[Koposov+ 2023]

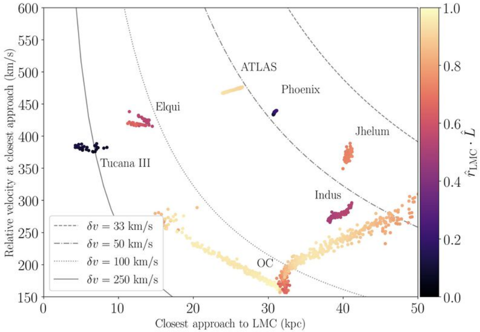
Local effects of the LMC: deflection of stellar streams

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.



[Koposov+ 2023]

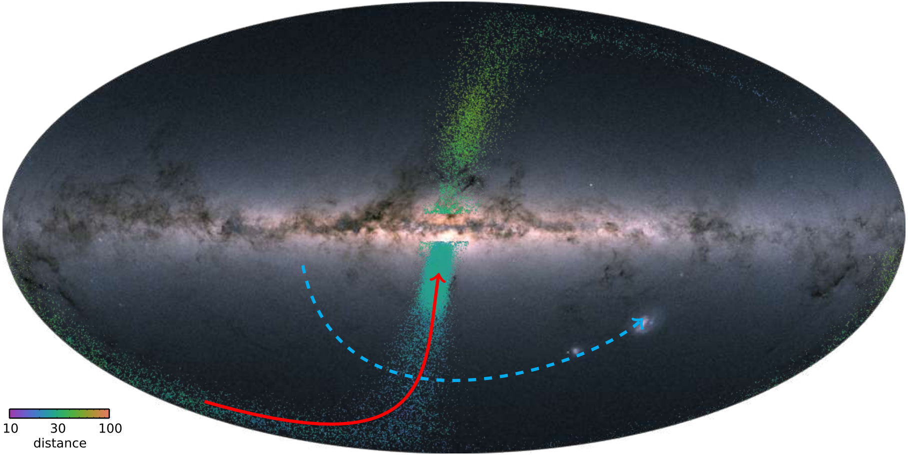




[Shipp+ 2021; see also Lilleengen+ 2022]

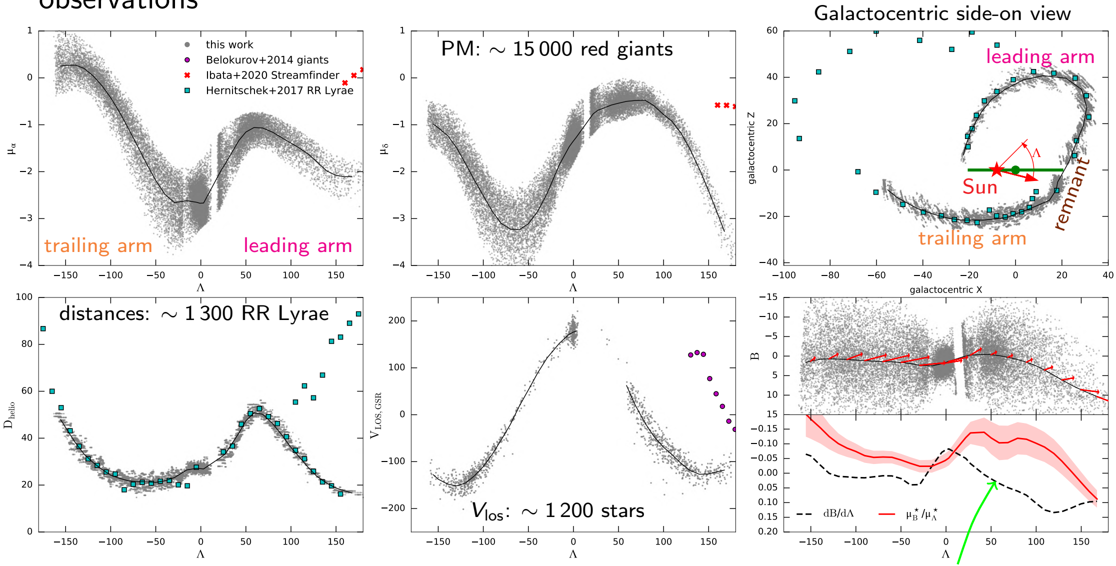
Effect of the LMC on the Sagittarius stream

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

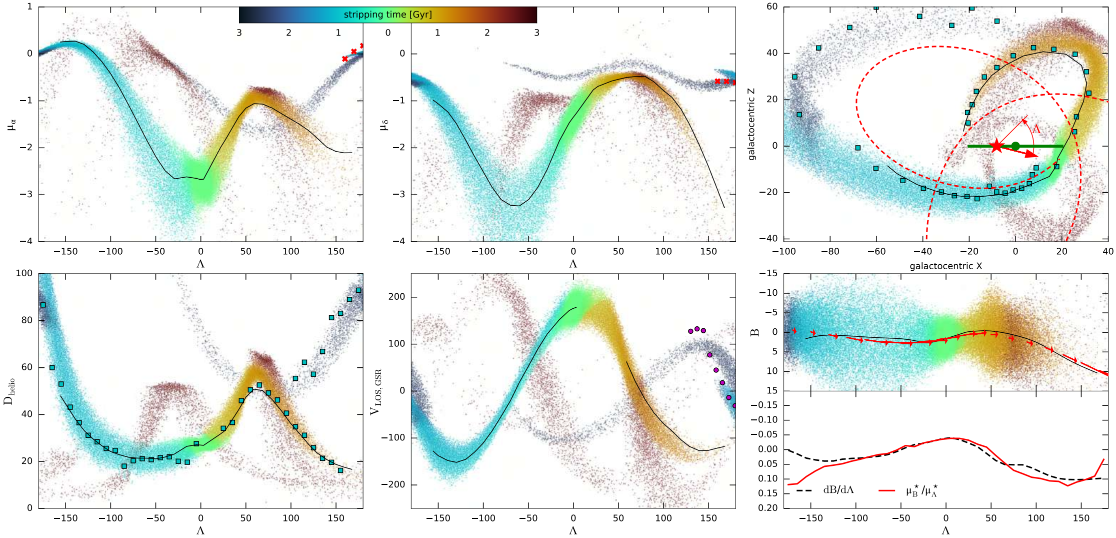


[Vasiliev+ 2021]

Misalignment between PM and stream track

Effect of the LMC on the Sagittarius stream

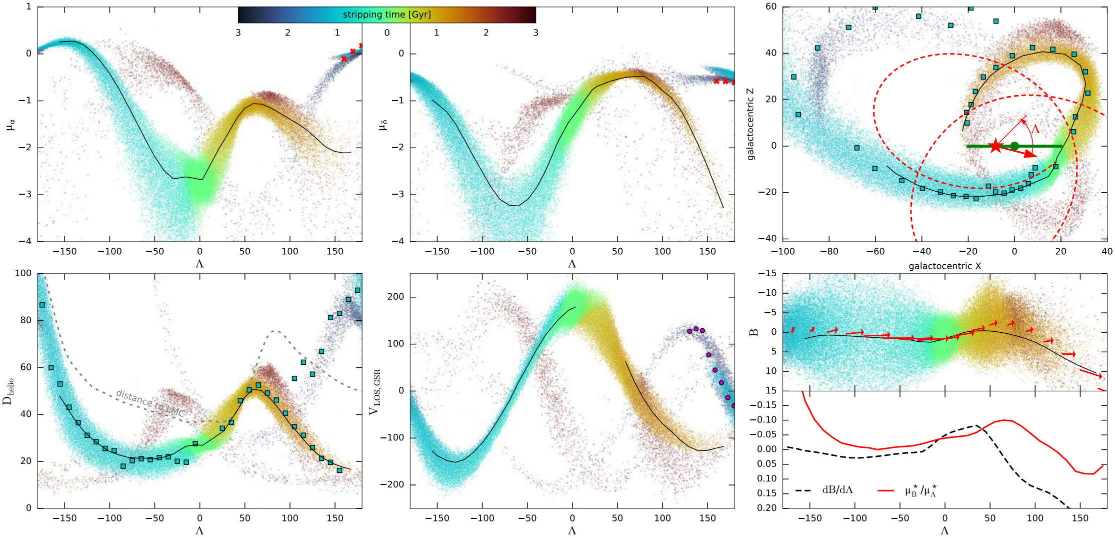
stream model in the best-fit (very flexible) MW potential



[Vasiliev+ 2021]

Effect of the LMC on the Sagittarius stream

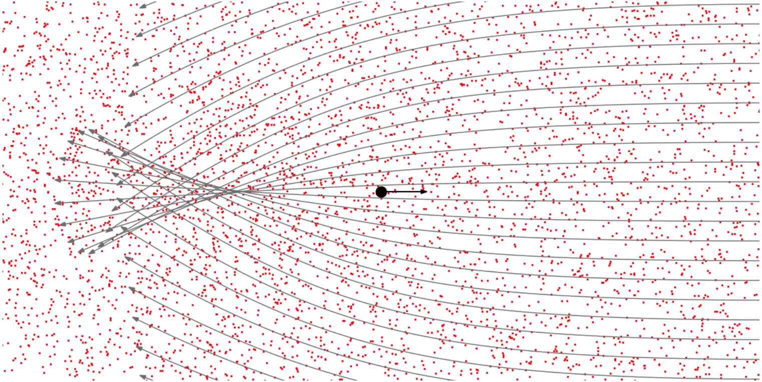
stream model including the perturbation from the LMC ($M_{\mathrm{LMC}} = 1.5 \times 10^{11}\, M_{\odot}$)



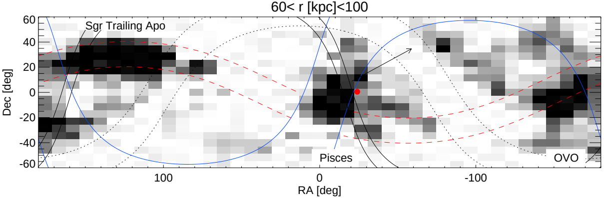
[Vasiliev+ 2021]

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]

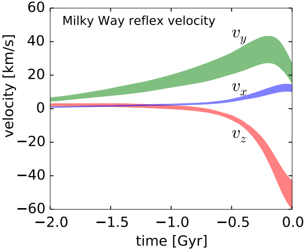


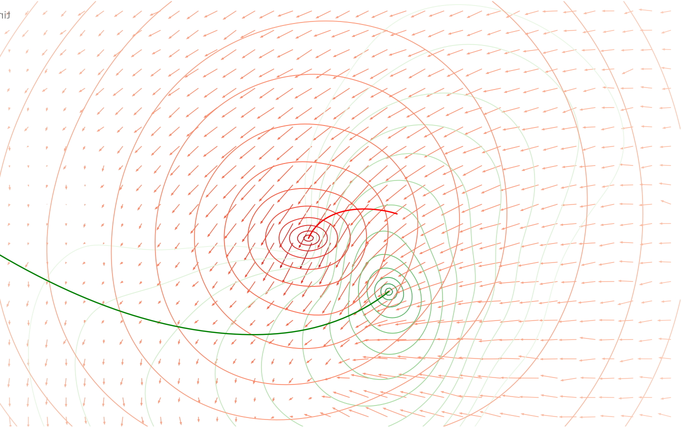
possibly detected as the Pisces overdensity [Belokurov+ 2019]



Global perturbation: mechanism

The Milky Way is pulled towards the LMC,
but the displacement is not uniform in space.





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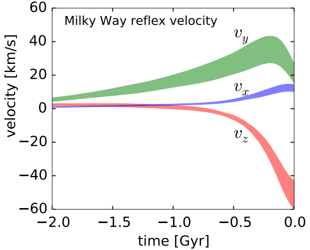
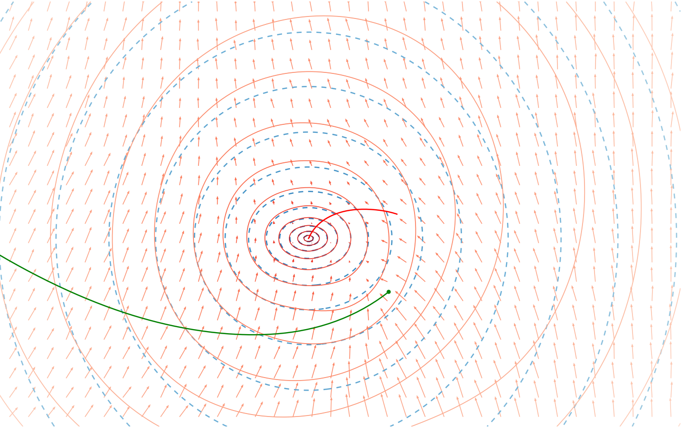
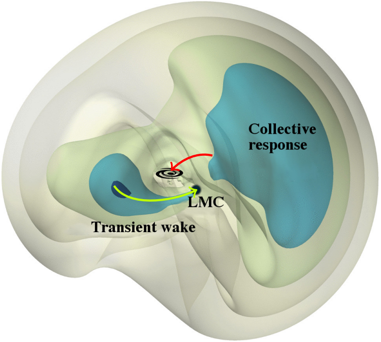
In the MW-centred reference frame, outer halo appears to move up and acquires a dipole “polarization pattern”.





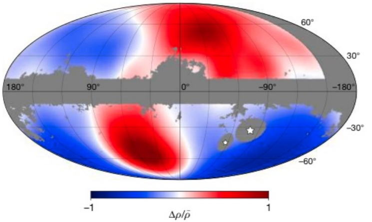


N-body sims [Garavito-Camargo+ 2021, see also Petersen & Peñarrubia 2020], perturbation theory [Rozier+ 2022]

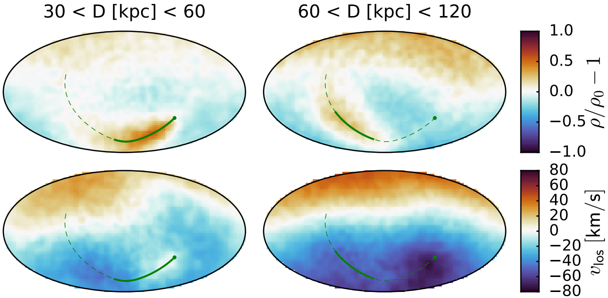
Global perturbation: predicted and observed signatures

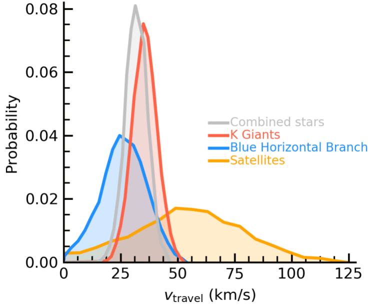
Since the MW is pulled "down" (in z) recently, perturbation is most visible in the north–south asymmetry of density and line-of-sight velocities at distances $\gtrsim 30$ kpc

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



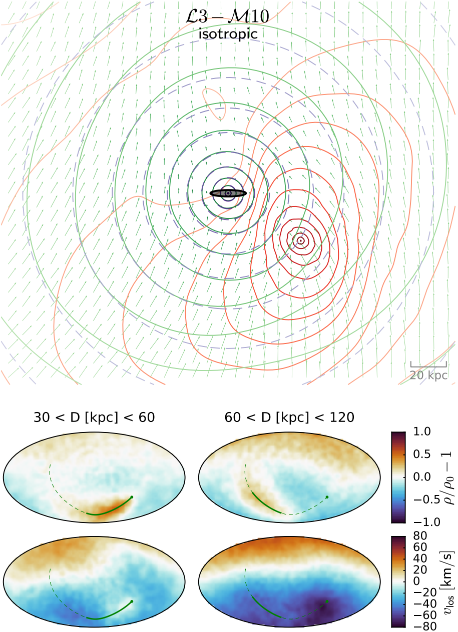
density polarization [Conroy+ 2021]

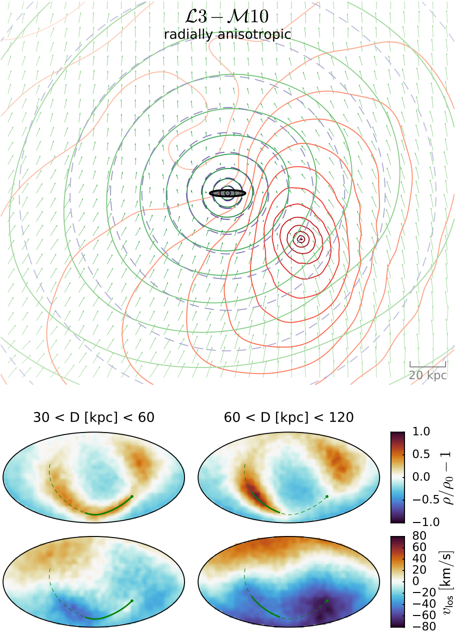




velocity offset [Petersen & Peñarrubia 2021, see also Erkal+ 2021]

Sensitivity of the MW halo deformation to velocity anisotropy



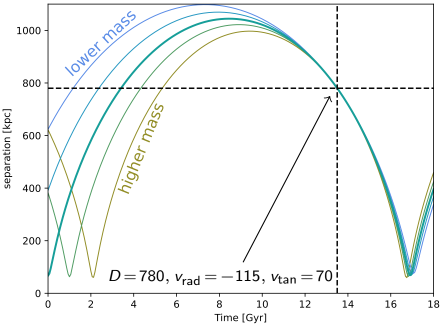


[Vasiliev 2023b; see also Rozier+ 2022]

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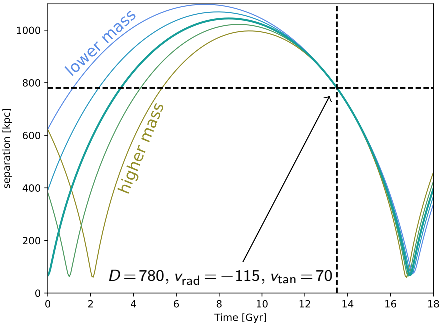
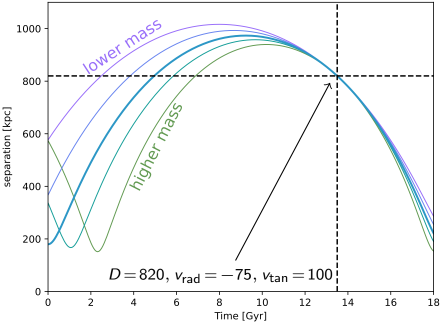
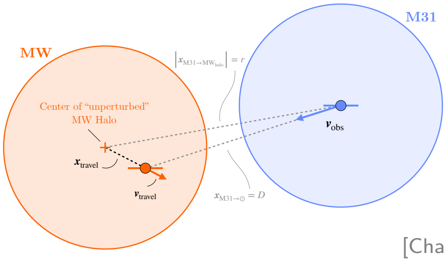
The recent LMC-induced change in the relative velocity of MW–M31 thus affects the inference about their past orbit and mass.

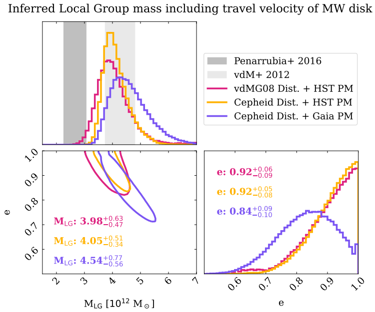




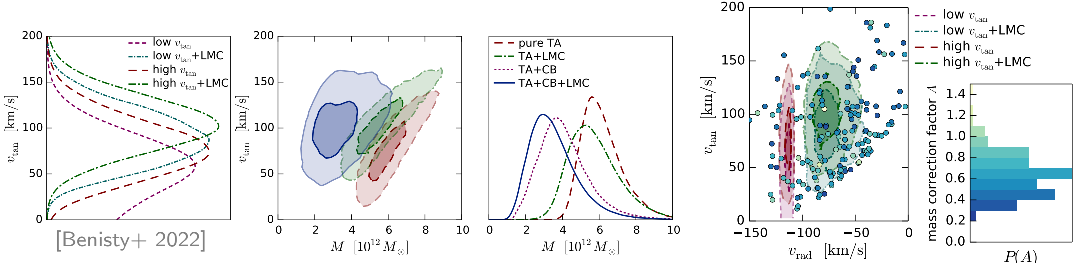
"Changes" in the orbit of Andromeda caused by the LMC

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



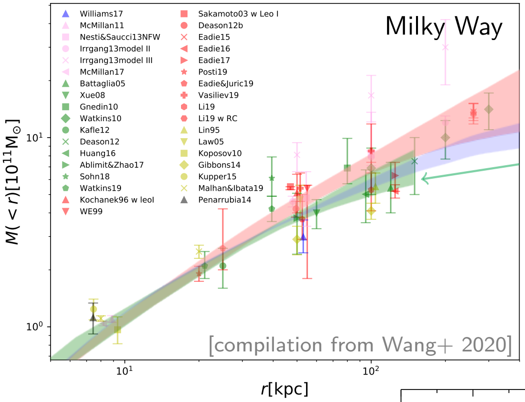


[Chamberlain+ 2022]



[Benisty+ 2022]

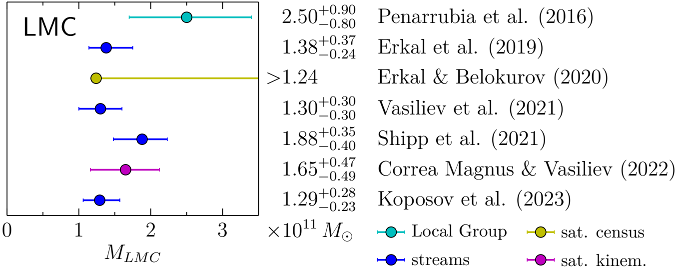
Dynamical mass measurements



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

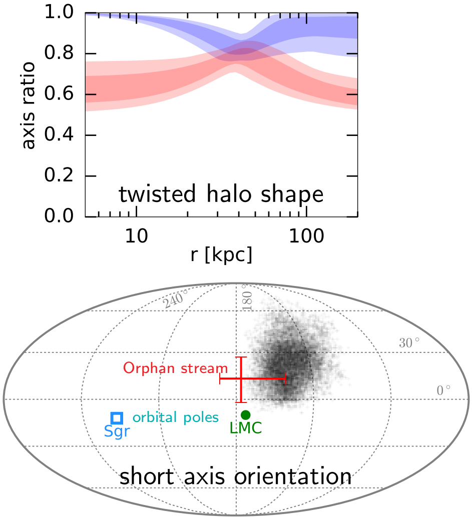
Sgr stream (incl. LMC) [Vasiliev+ 2021]

Orphan stream (incl. LMC) [Koposov+ 2023]

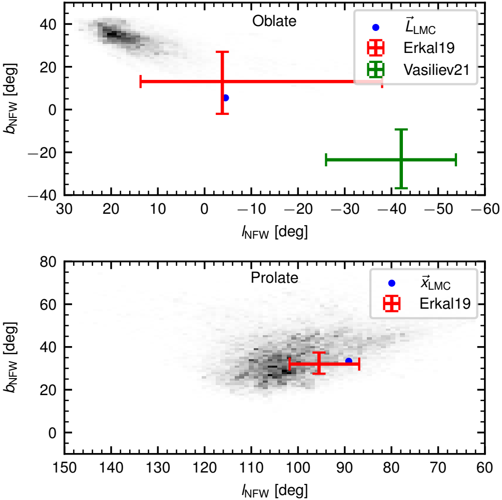


Constraints on the Milky Way halo shape from streams

ΛCDM haloes are expected to be triaxial in the outer parts, and oblate in the inner parts; alternative models (e.g. WDM) have different predictions for the shape. Stream modelling in the Milky Way so far has been inconclusive.



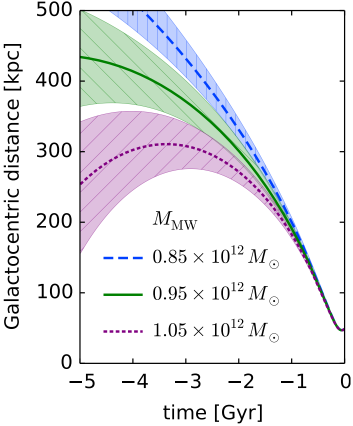
Sgr stream [Vasiliev+ 2021]



Orphan–Chenab stream [Koposov+ 2023]

Past trajectory of the LMC

is very sensitive to the Milky Way mass!



galaxies

Review

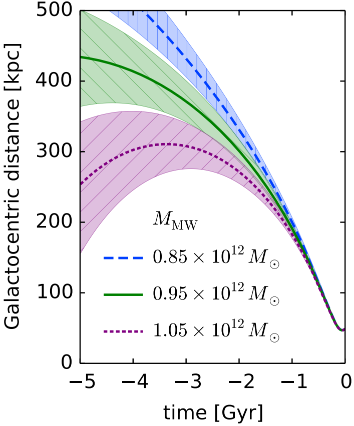
The Effect of the LMC on the Milky Way System

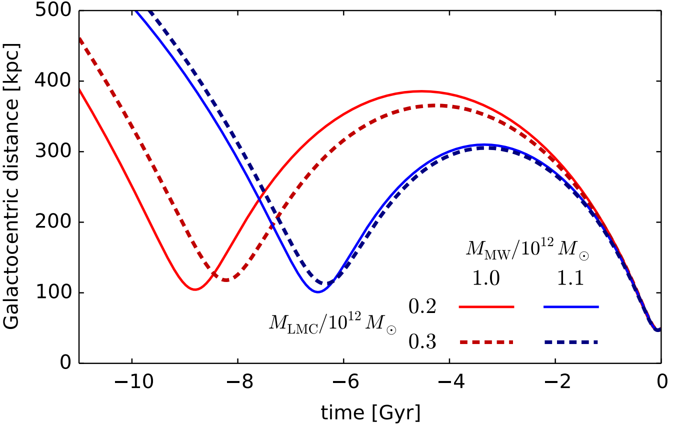
Eugene Vasiliev

2304.09136

Past trajectory of the LMC

is very sensitive to the Milky Way mass! a second pericentre passage is possible!





galaxies

Review

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MNRAS **000**, 000–000 (0000) Preprint 8 June 2023

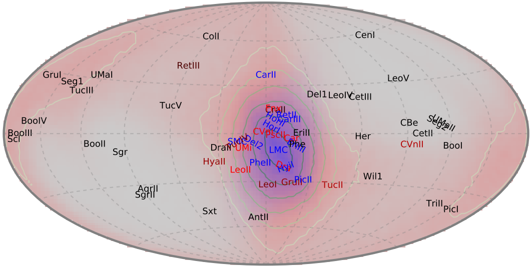
Dear Magellanic Clouds, welcome back!

Eugene Vasiliev[1★]

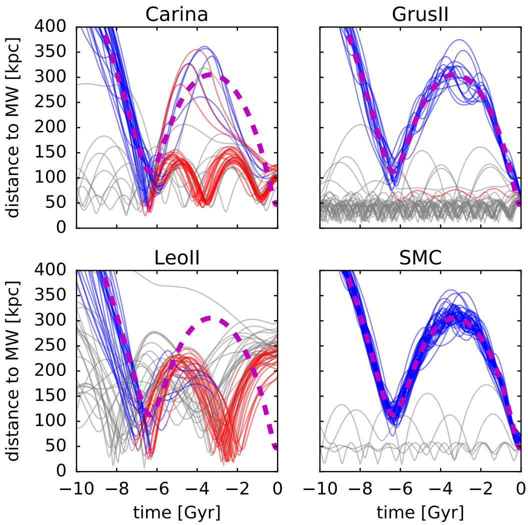
2306.04837

Second-passage scenario and the plane of satellites

Many Milky Way satellites have similar orbital planes [Kroupa+ 2005; Pawlowski+ 2012]: this could be explained if they were accreted with the Magellanic system and stripped off at the previous pericentre passage.



examples of possible past orbits



currently bound to LMC; formerly bound; MW-bound

Summary

- LMC causes a deformation of the Galactic halo, which is sensitive to the LMC mass and to the velocity anisotropy of the halo
- constraints on the Milky Way mass profile from modelling of stellar streams or satellites must take into account the LMC perturbation
- relative trajectories of Andromeda and Milky Way are affected by the LMC
- deflection of stellar streams probes the LMC mass profile
- a plane of satellites around the Milky Way may contain former satellites of the LMC if it is not on its first passage

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René Magritte – La victoire