Eugene Vasiliev

Dynamics of the LMC–Milky Way system

"Night sky" by Alma Nungarrayi Granites (NT, Australia)

see arXiv:2009.04973 for a history of MC naming

CCA, New York, 27 February 2024

THE ASTRONOMICAL KNOWLEDGE OF THE MAORI, GENUINE AND EMPIRICAL

by ELSDON BEST

Wellington, 1922

Kokirikiri	Larger Magellan Cloud
Manako-tea	One of the Magellan Clouds
Manako-uri	One of the Magellan Clouds
Nga Pataritari-hau	The Magellan Clouds
Nga Patari-kai-hau	The Magellan Clouds
Patari-rangi	Larger Magellan Cloud
Patari-kaihau	Smaller Magellan Cloud
Nga Patari-hau	The Magellan Clouds
Pioriori	Upper Magellan Cloud
Purangi	The Magellan Clouds
Rangi-matanuku	Larger Magellan Cloud
Tikatakata	Smaller Magellan Cloud
Tioreore	Larger Magellan Cloud
Tiripua	One of the Magellan Clouds
Tiritiripua	One of the Magellan Clouds
Tuputuputu	One of the Magellan Clouds
Whakaruru-hau	The Magellan Clouds
Kokouri	One of the Magellan Clouds
Kokotea	One of the Magellan Clouds

THE MAGELLAN CLOUDS. – Here we encounter a truly generous list of names before which our own sinks into insignificance. It is not clear why they should rejoice in so many names. The natives look to them for wind-signs. As one put it, "Those persons, *Tioreore* and *Tikatakata*, ward off winds. When wind rises, one of them goes to obstruct it; thus their permanent task is to protect their people."

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 $v_{\rm circ}$	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

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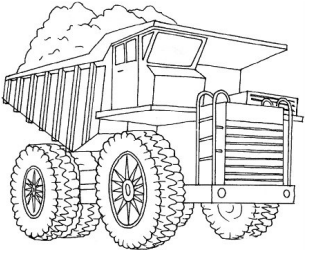
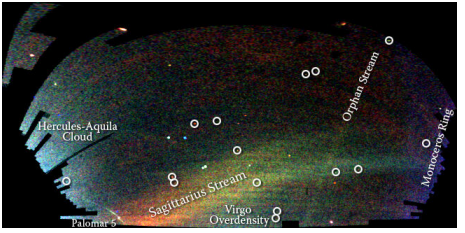
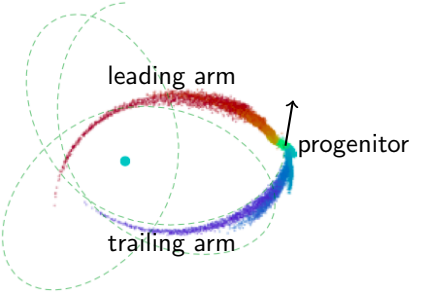
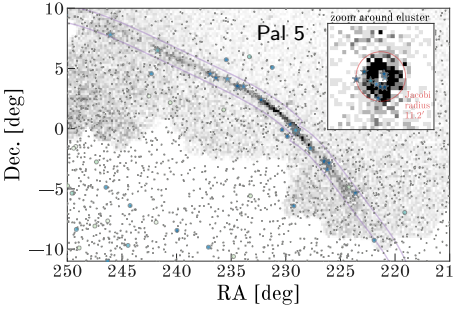


Stellar tidal streams in the Milky Way

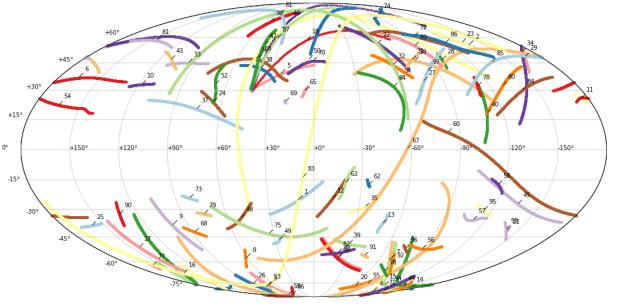


SDSS field of streams [Belokurov+ 2006]



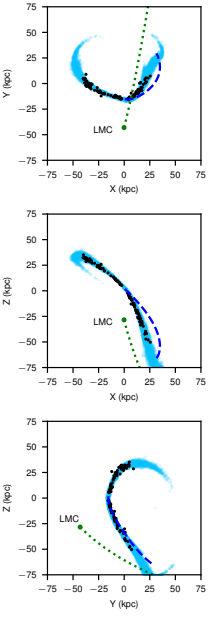


DECaLS+Gaia [Price-Whelan+ 2019]

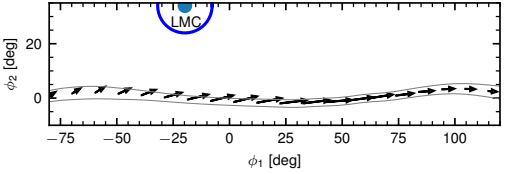


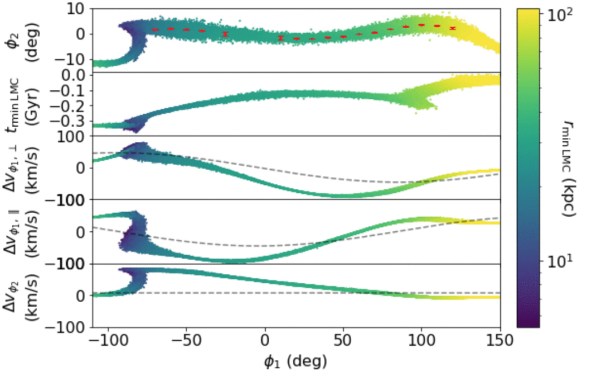
GalStreams database [Mateu 2023]

Local effects of the LMC: deflection of stellar streams



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.





movie [Erkal+ 2019]

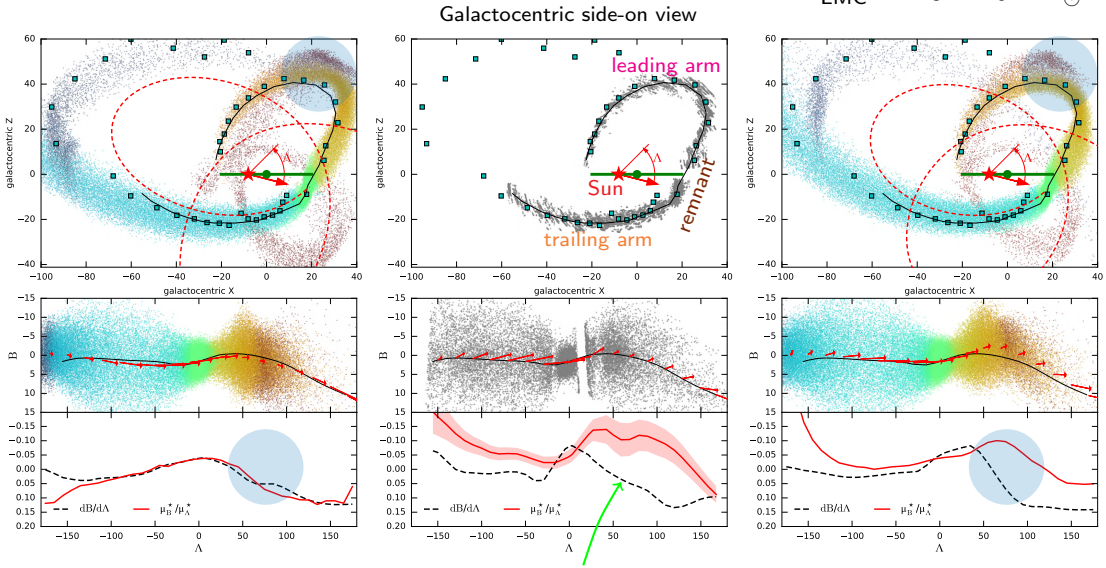
[Koposov+ 2023]

Effect of the LMC on the Sagittarius stream

model without LMC

observations

model with $M_{\rm LMC} = 1.5 \times 10^{11}\, M_\odot$

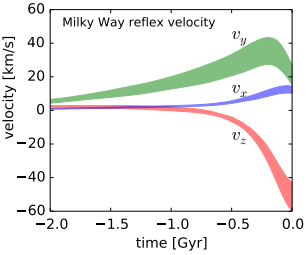


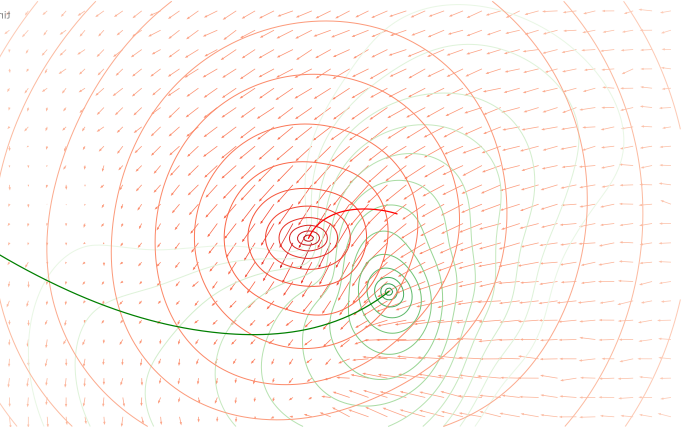
Misalignment between PM and stream track

[Vasiliev+ 2021]

Global perturbation: mechanism

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





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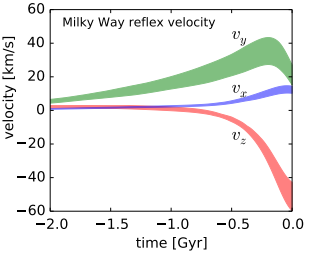
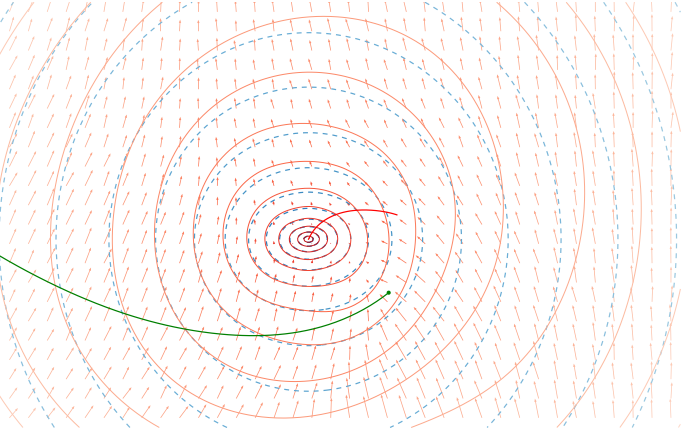
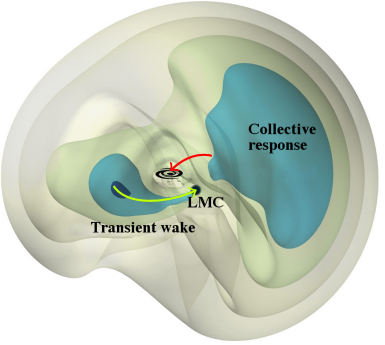
In the MW-centred reference frame, outer halo appears to move up (dipole perturbation).







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

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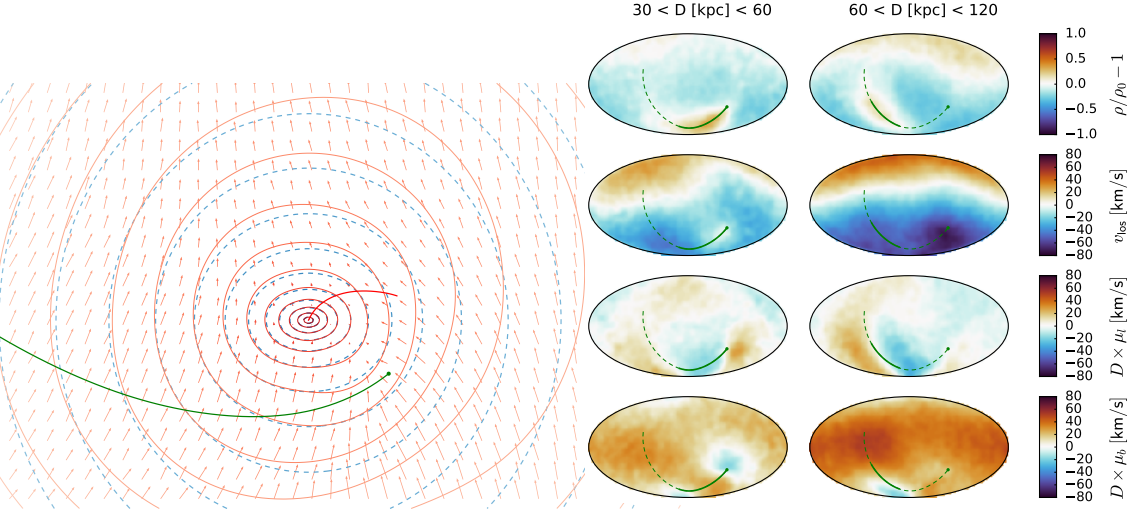
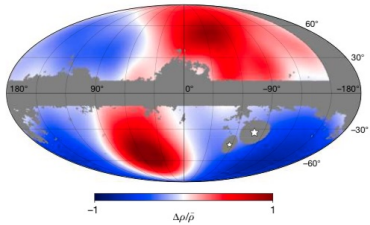
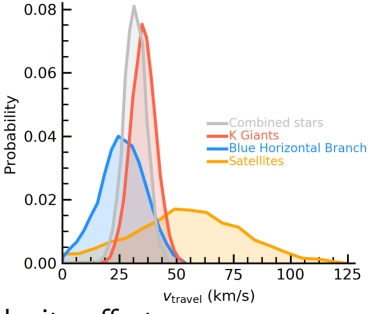


Global perturbation: predicted and observed signatures

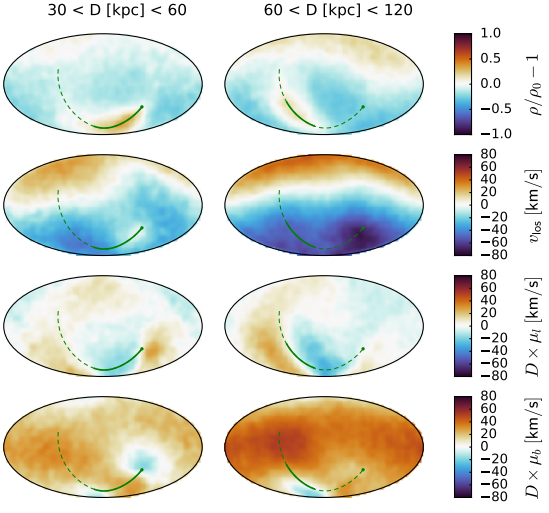


density polarization [Conroy+ 2021]

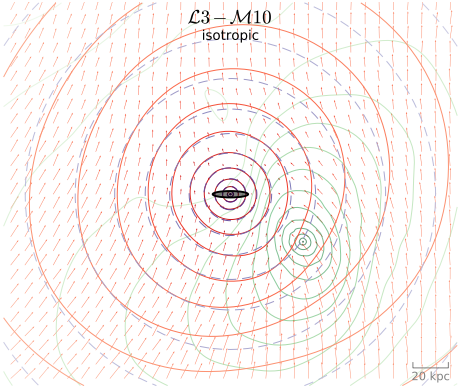


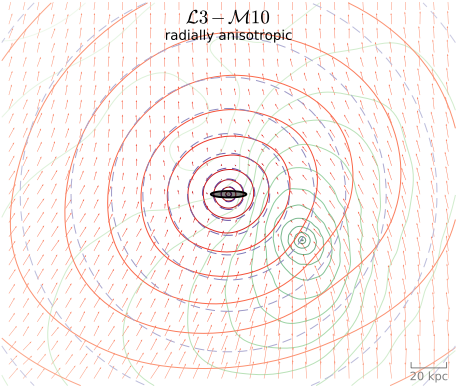
velocity offset

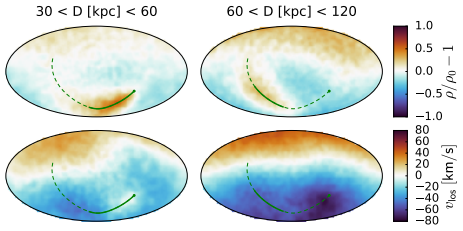
[Petersen & Peñarrubia 2021, see also Erkal+ 2021]

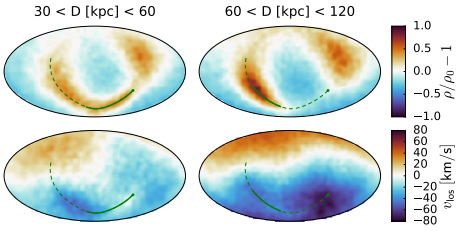


Sensitivity of the MW halo deformation to velocity anisotropy



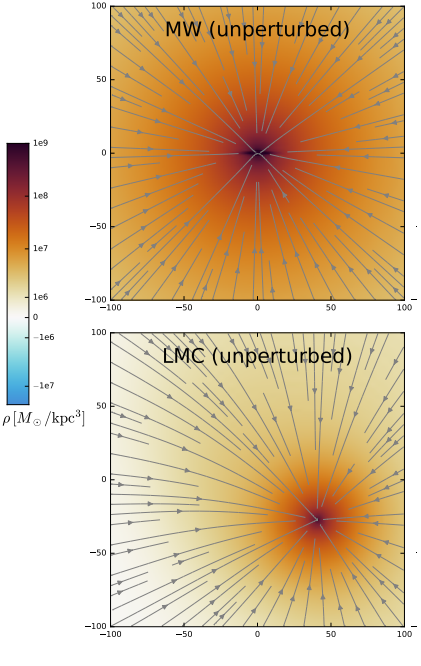






[Vasiliev 2024 – *N*-body sims; originally found by Rozier+ 2022 using linear response theory]

Dissecting the force field



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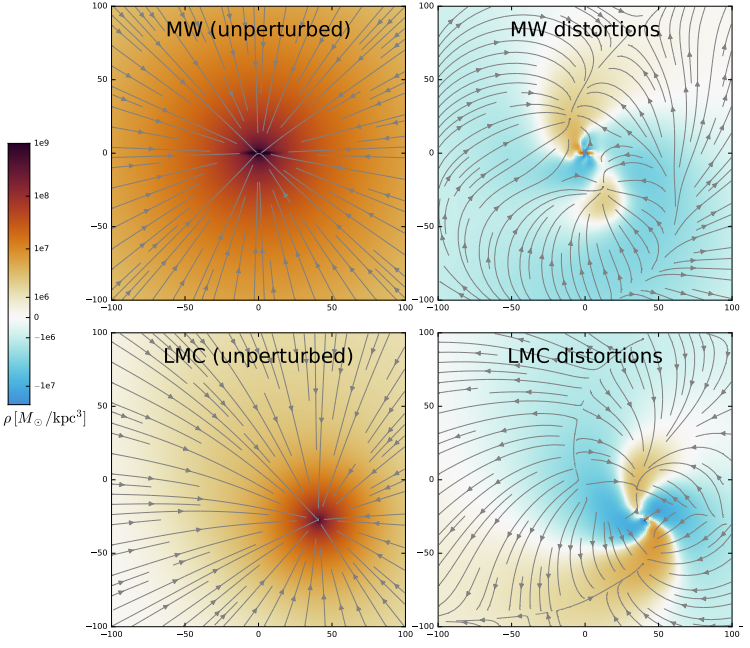

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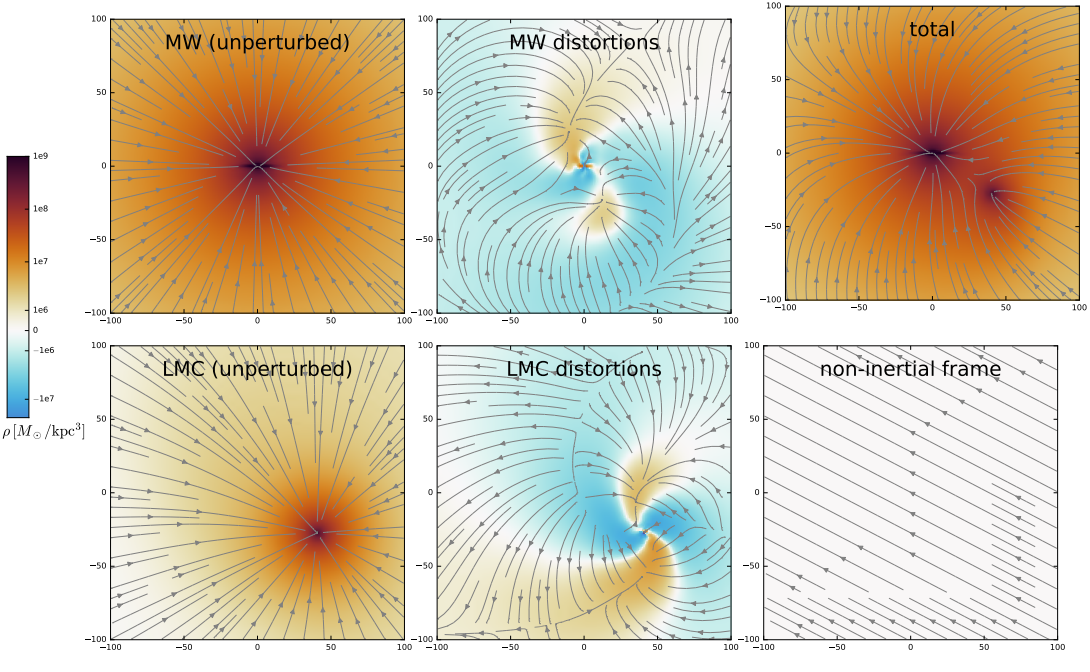
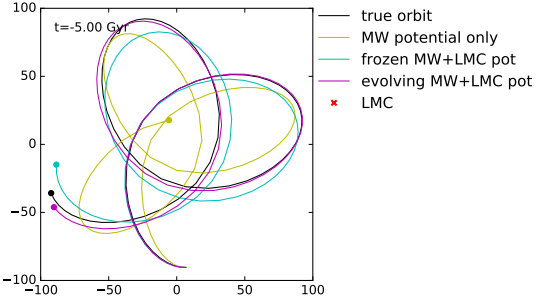
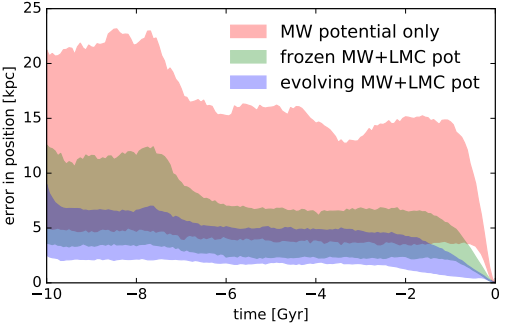


Accuracy of orbit reconstruction in the evolving potential





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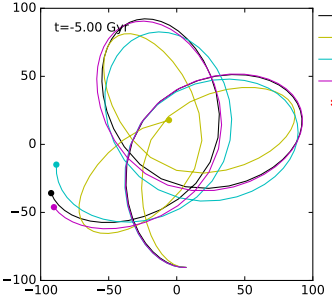
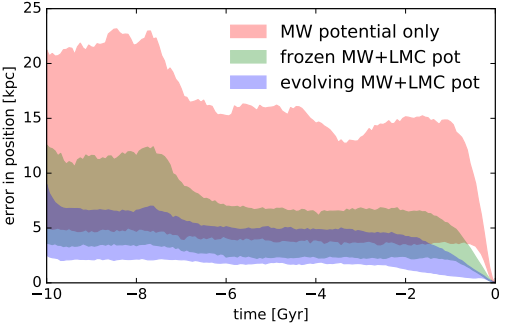
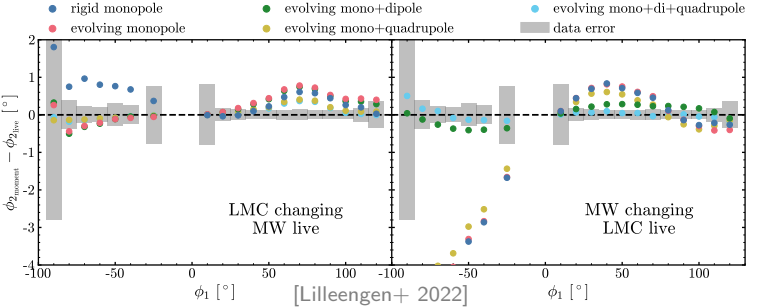


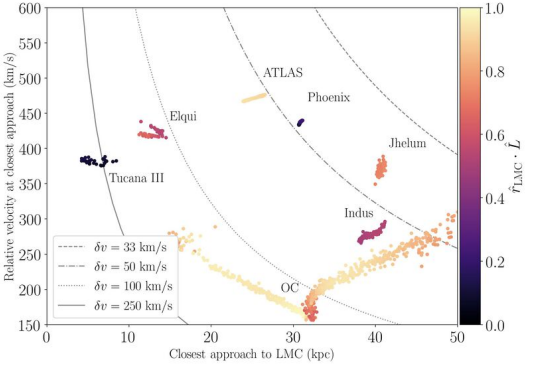


sensitivity of Orphan–Chenab stream track to deformations

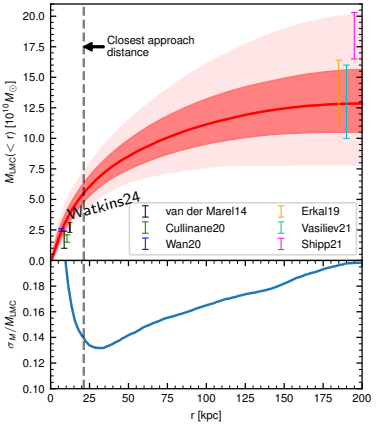


[Lilleengen+ 2022]

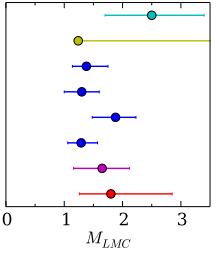
Dynamical mass measurements: LMC



[Shipp+ 2021; see also Lilleengen+ 2022]

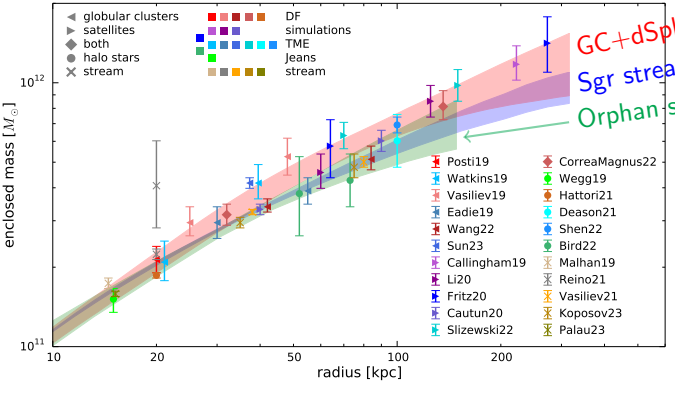


[Koposov+ 2023]



$2.50^{+0.90}_{-0.80}$	Penarrubia et al. (2016)	Local Group timing
>1.24	Erkal & Belokurov (2020)	LMC sat. census
$1.38^{+0.37}_{-0.24}$	Erkal et al. (2019)	
$1.30^{+0.30}_{-0.30}$	Vasiliev et al. (2021)	MW streams
$1.88^{+0.35}_{-0.40}$	Shipp et al. (2021)	
$1.29^{+0.28}_{-0.23}$	Koposov et al. (2023)	
$1.65^{+0.47}_{-0.49}$	Correa Magnus & Vasiliev (2022)	MW sat. kinematics
$1.80^{+1.05}_{-0.54}$	Watkins et al. (2024)	LMC clust. kinematics

Dynamical mass measurements: Milky Way



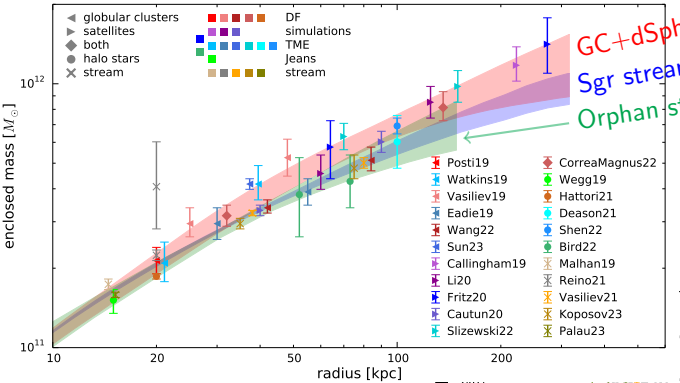
GC+dSph (+LMC rewinding) [Correa Magnus & Vasiliev 2022]

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

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

NB: neglecting the LMC biases the MW mass up by 10–20% [Erkal+ 2020]

Dynamical mass measurements: Milky Way



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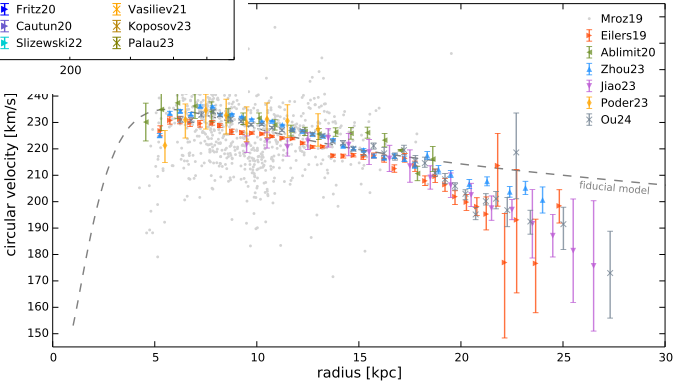
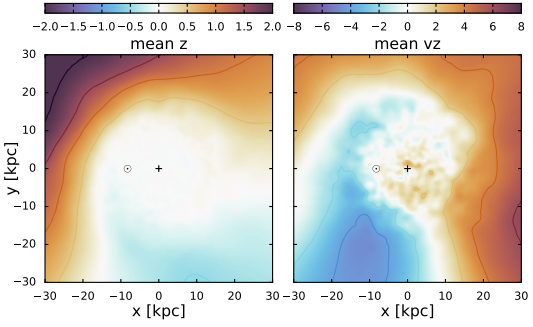
Circular-velocity curve inferred from Jeans modelling of disc stars sharply declines beyond 20 kpc, in contradiction with mass measurement further out. Is LMC the culprit here too?



Perturbations in the MW disc



LMC induces a noticeable warp in the MW disc at distances $\gtrsim$ 15 kpc, qualitatively similar to the observed one (but smaller in amplitude; see also Laporte+2018a,b).

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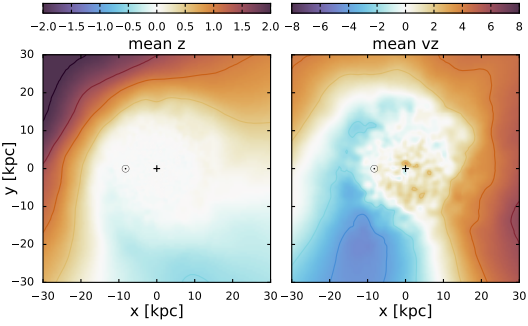

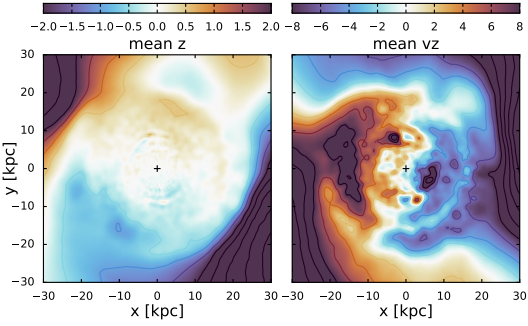

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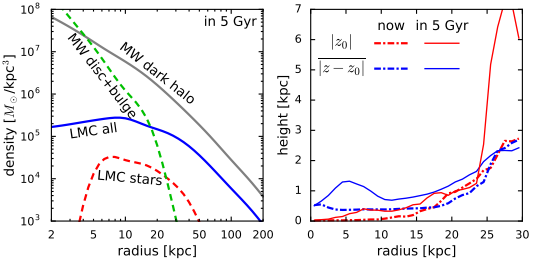
The warp will become much stronger in the future, the disc will be significantly heated, and the stellar halo will increase 4$\times$ in mass.

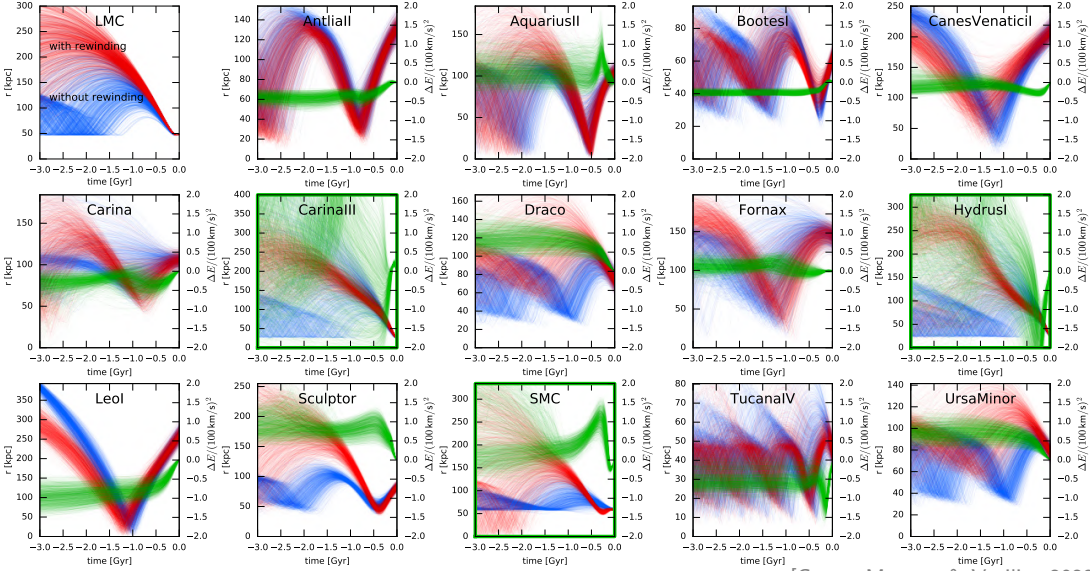


[Vasiliev 2024]

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

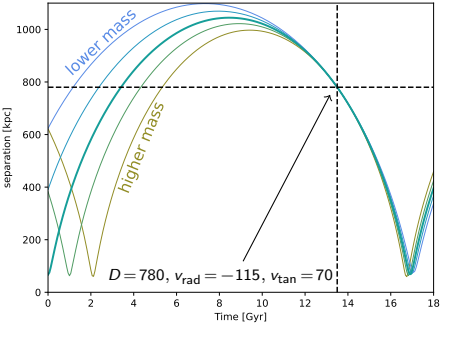


[Correa Magnus & Vasiliev 2022]

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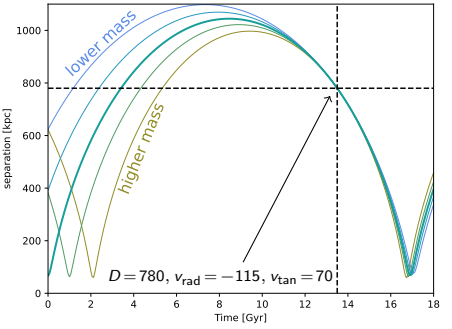
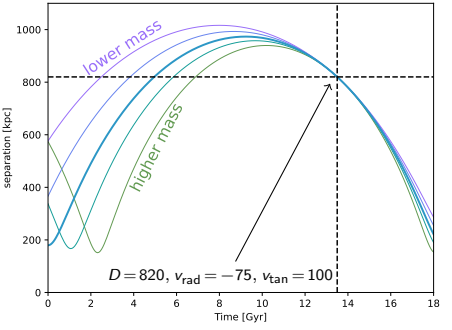
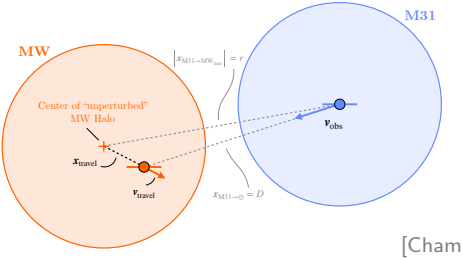
The recent LMC-induced change in the relative velocity of MW–M31 thus affects the inference about their past orbit and mass.

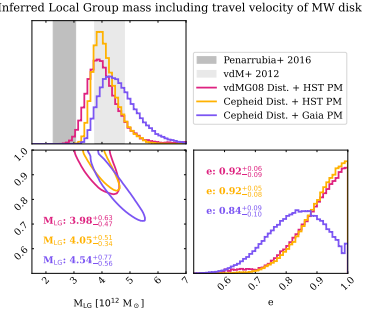




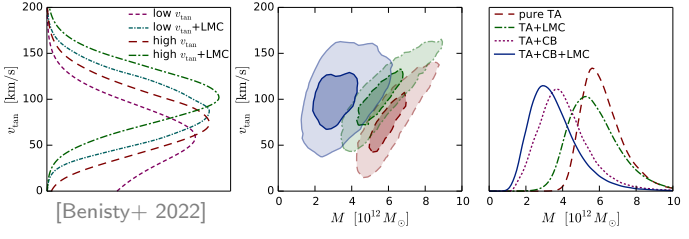
"Changes" in the orbit of Andromeda caused by the LMC

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

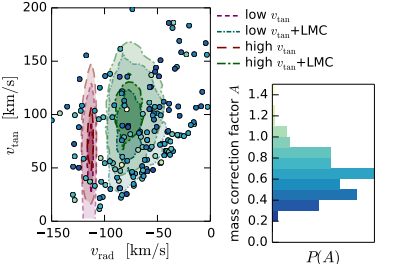




[Chamberlain+ 2022]

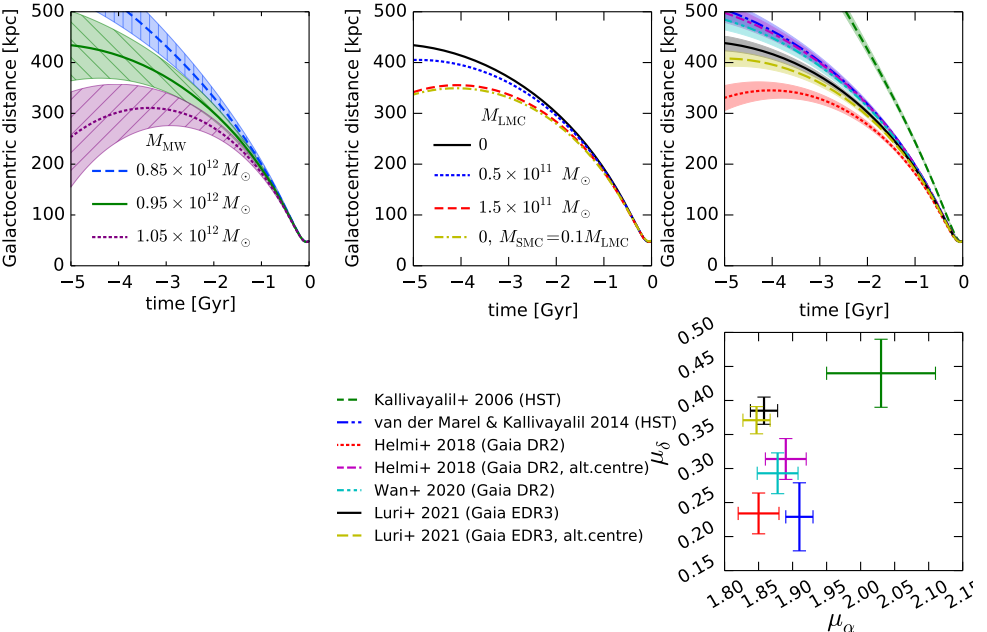


[Benisty+ 2022]



Past trajectory of the LMC

is very sensitive to the Milky Way mass, LMC mass, and its current pos/vel!



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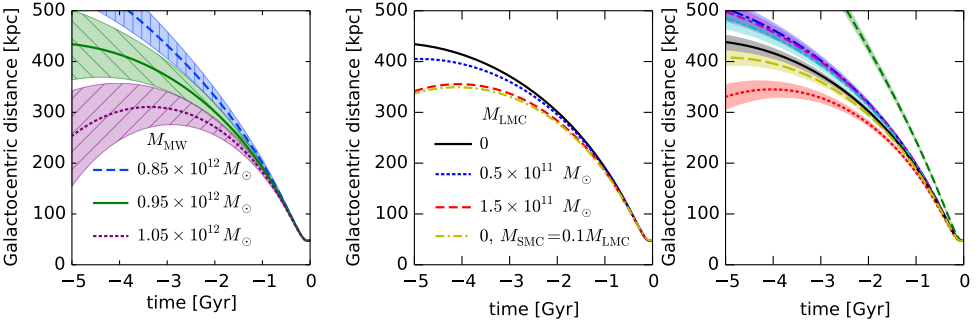

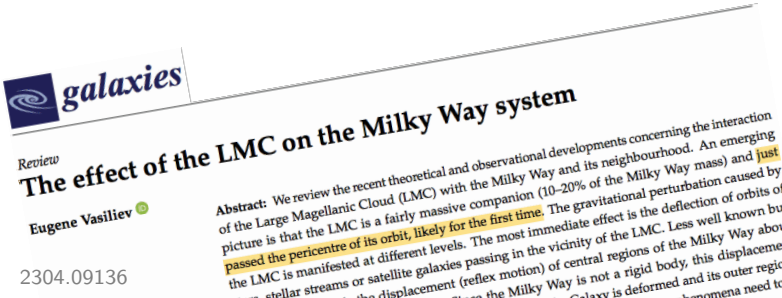

galaxies

Review

The effect of the LMC on the Milky Way system

Eugene Vasiliev

Abstract: We review the recent theoretical and observational developments concerning the interaction of the Large Magellanic Cloud (LMC) with the Milky Way and its neighbourhood. An emerging picture is that the LMC is a fairly massive companion (10–20% of the Milky Way mass) and just passed the pericentre of its orbit, likely for the first time. The gravitational perturbation caused by the LMC is manifested at different levels. The most immediate effect is the deflection of orbits of stellar streams or satellite galaxies passing in the vicinity of the LMC. Less well known but the displacement (reflex motion) of central regions of the Milky Way about the Milky Way is not a rigid body, this displacement Galaxy is deformed and its outer regions

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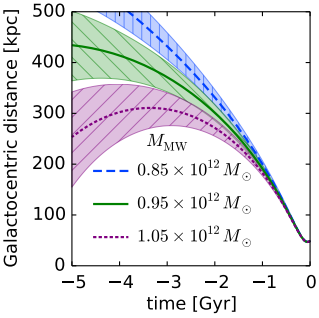
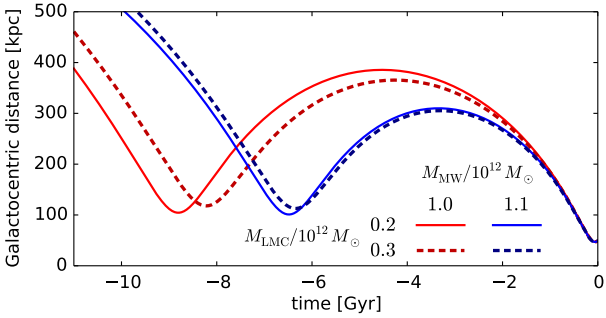
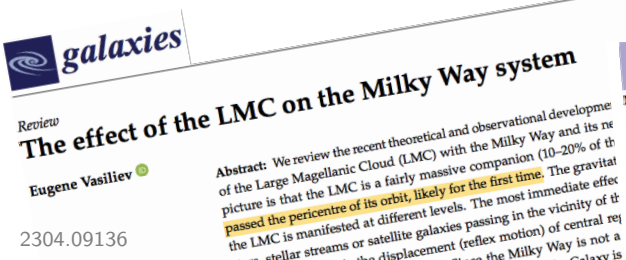
Past trajectory of the LMC

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







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Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **527,** 437–456 (2024)

Dear Magellanic Clouds, welcome back!

Eugene Vasiliev ★

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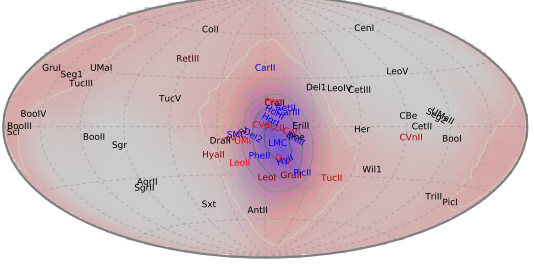
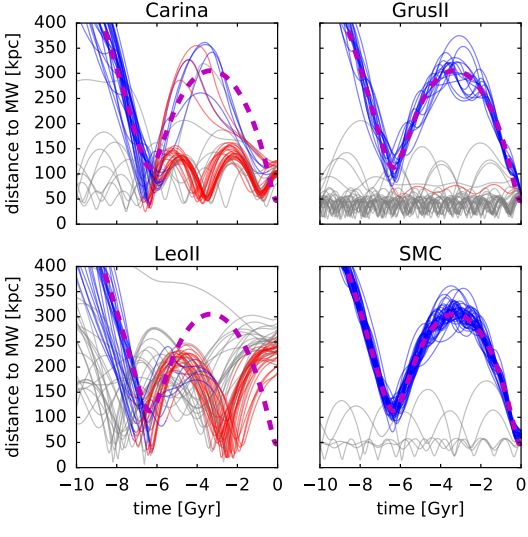
2306.04837

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

Satellites

current LMC

former LMC

MW