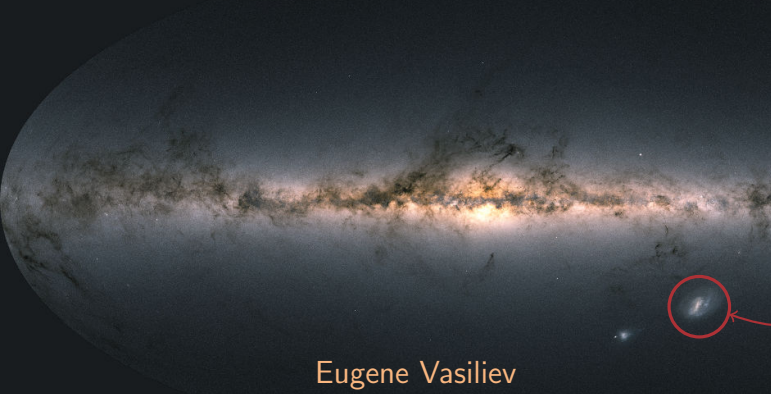


# The unquiet neighbour: how the LMC bugs the Milky Way




Eugene Vasiliev



## Introducing the participants

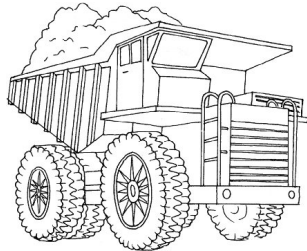
	Milky Way	LMC
stellar mass	$\sim 6 \times 10^{10} M_{\odot}$	$\sim 3 \times 10^9 M_{\odot}$
total mass	$\sim 10^{12} M_{\odot}$	$\sim (1 - 2) \times 10^{11} M_{\odot}$
peak $v_{\text{circ}}$	250 km/s	100 km/s
disc scale radius	3 kpc	1.5 kpc
distance to centre	8 kpc	50 kpc
morphological type	barred spiral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

just passed its (first?) pericentre



# Introducing the participants

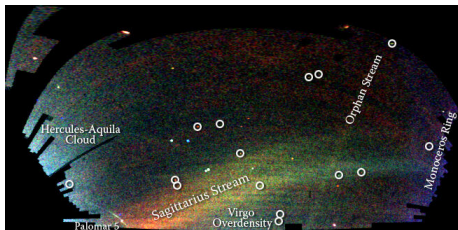
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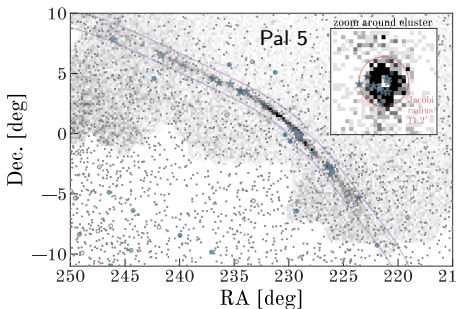
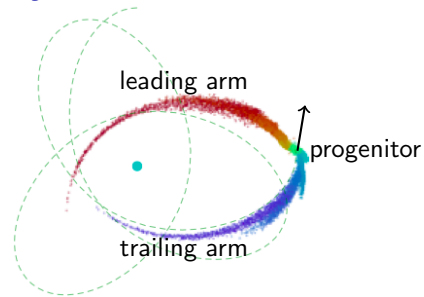
## Consequences of the MW–LMC encounter

- ▶ 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

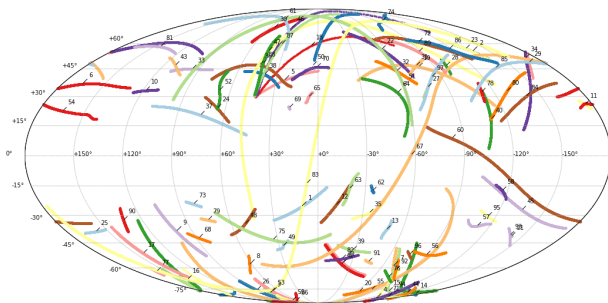
# Stellar tidal streams in the Milky Way



SDSS field of streams [Belokurov+ 2006]



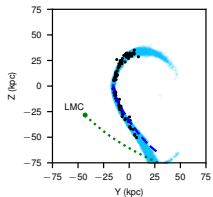
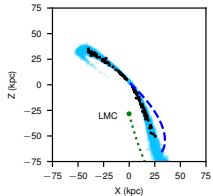
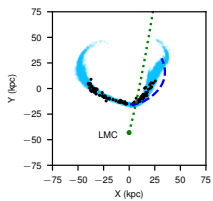
DECaLS+Gaia [Price-Whelan+ 2019]



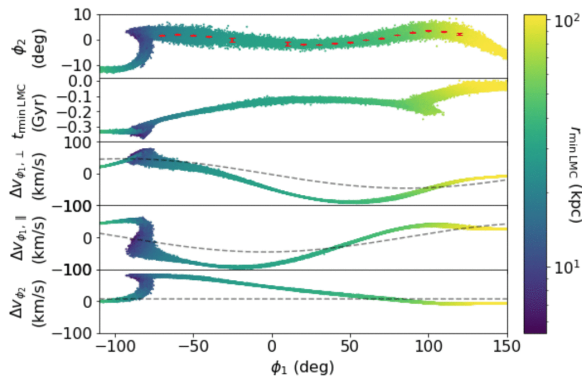
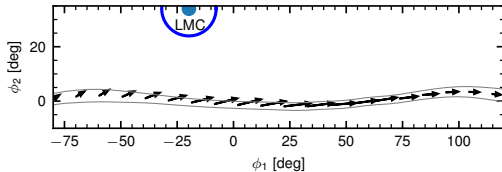
GalStreams database [Mateu 2023]

# Local effects of the LMC: deflection of stellar streams

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.



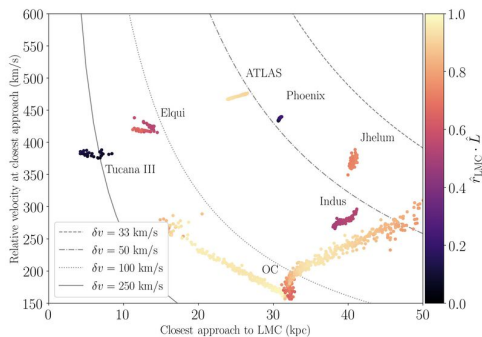
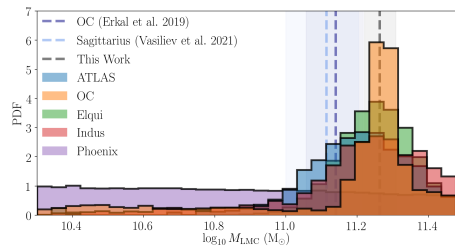
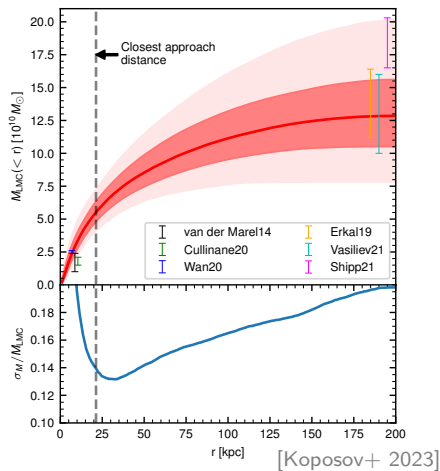
[Erkal+ 2019]



[Koposov+ 2023]

# Local effects of the LMC: deflection of stellar streams

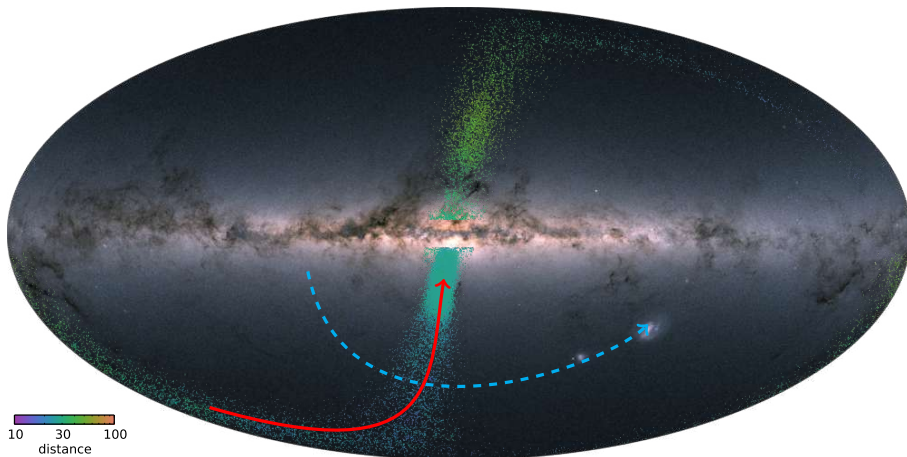
LMC passes close to several other streams in the Southern hemisphere;  
by analyzing the perturbations of individual streams, one may probe the total mass and even the radial mass distribution of the LMC.



[Shipp+ 2021; see also Lilleengen+ 2022]

## Effect of the LMC on the Sagittarius stream

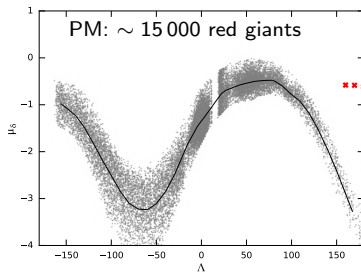
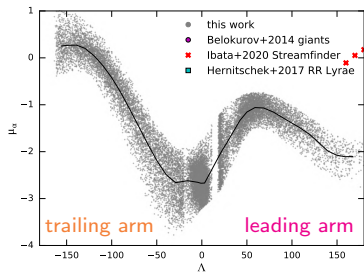
Sagittarius stream: by far the largest in the Milky Way, spans the entire sky.  
First discovered in 2MASS [Majewski+ 2003]; studied extensively using SDSS [Belokurov+ 2006, Koposov+ 2012] and Gaia [Ibata+ 2020, Antoja+ 2020, Ramos+ 2020, 2022].  
Progenitor: Sgr dSph (third-largest MW satellite after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



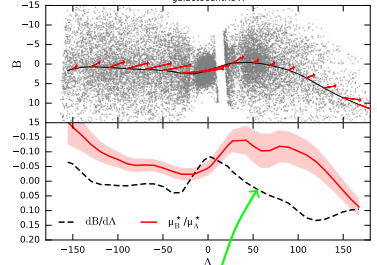
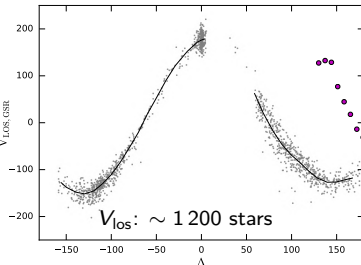
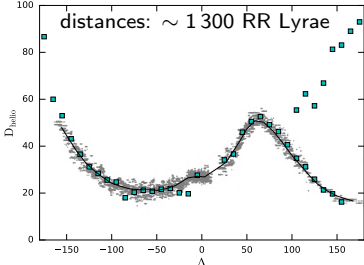
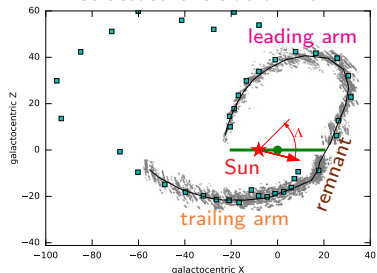


# Effect of the LMC on the Sagittarius stream

observations



Galactocentric side-on view

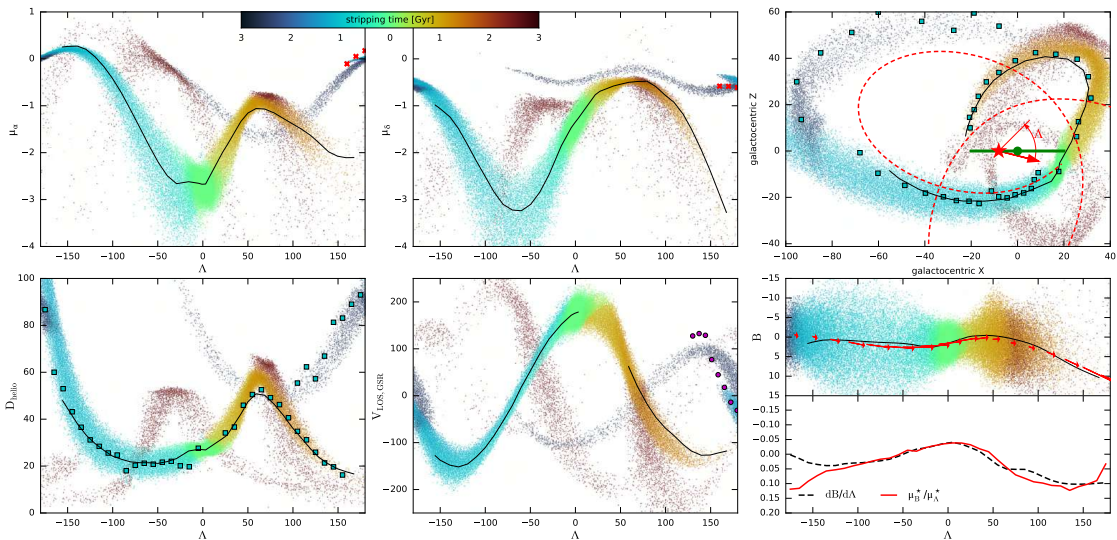


[Vasiliev+ 2021]

Misalignment between PM and stream track

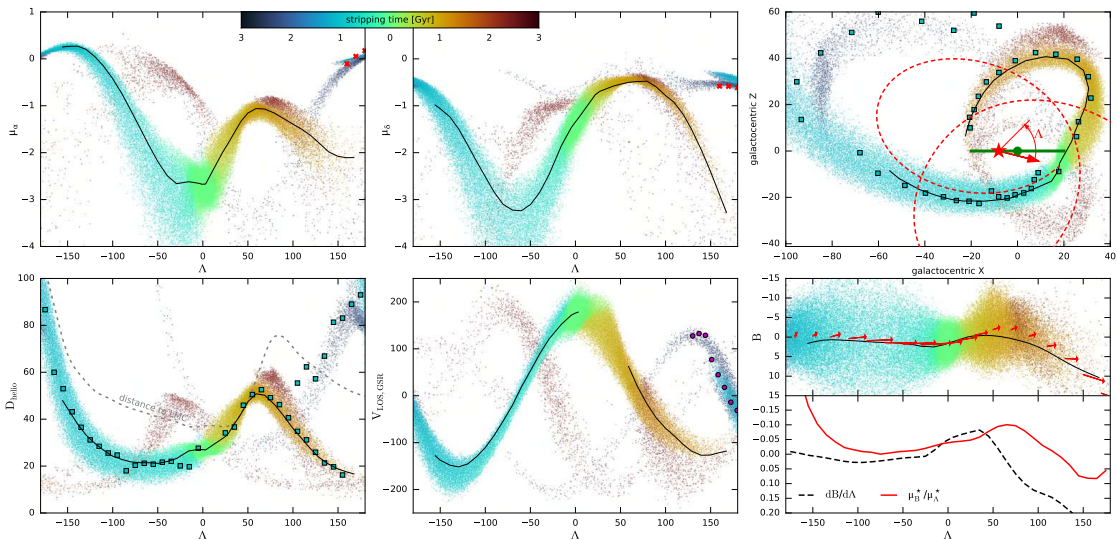
# Effect of the LMC on the Sagittarius stream

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



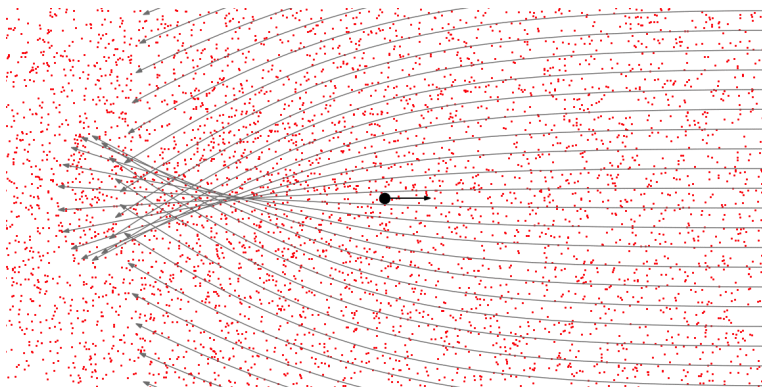
# Effect of the LMC on the Sagittarius stream

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

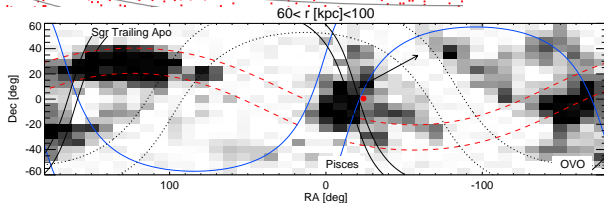


# Density wake and dynamical friction

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

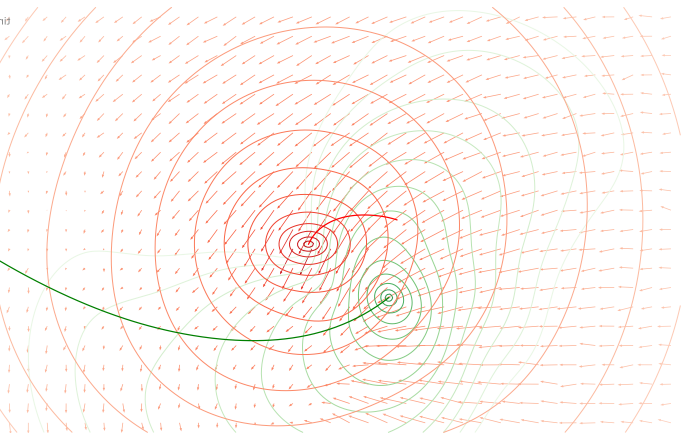
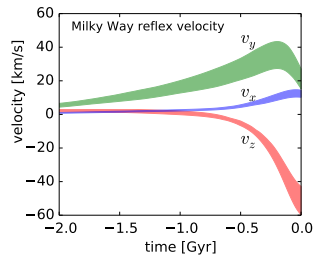


possibly detected as the Pisces overdensity [Belokurov+ 2019]



## Global perturbation: mechanism

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

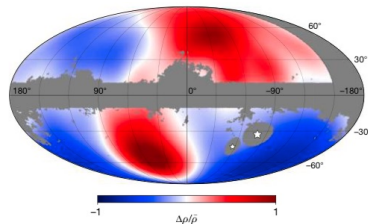




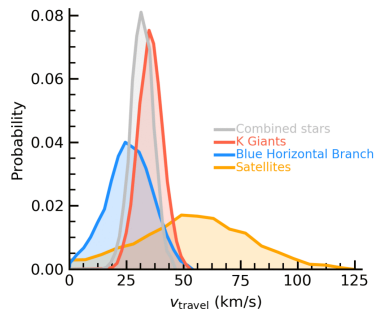
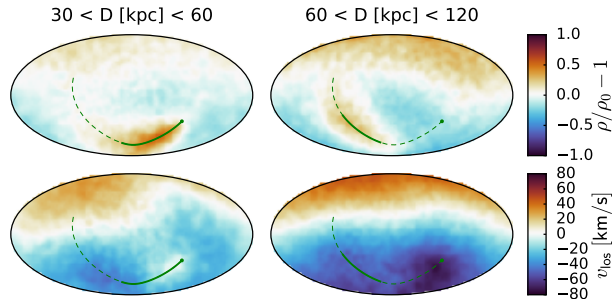
# Global perturbation: predicted and observed signatures

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]

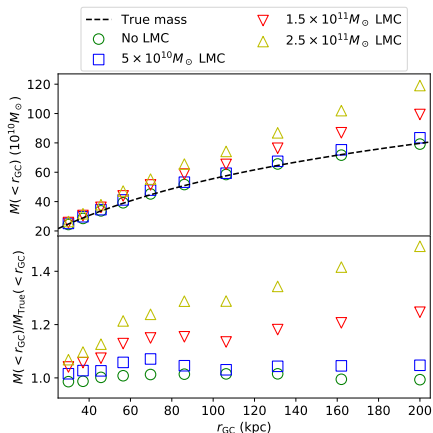


velocity offset [Petersen & Peñarrubia 2021, see also Erkal+ 2021]

# 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].



## 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:

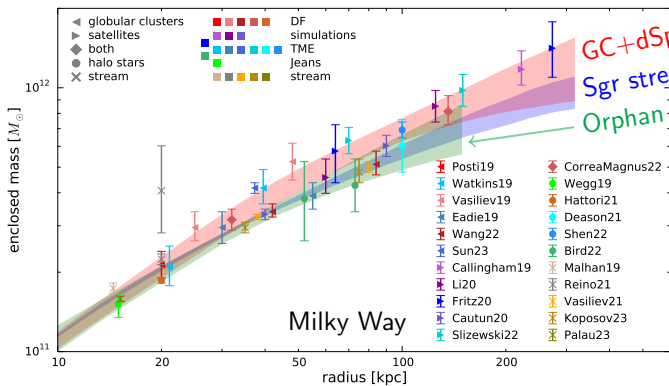
1. Reconstruct the past trajectories of both the MW and the LMC;
2. Rewind the orbits of tracers (halo stars, globular clusters, MW satellites ...) in the evolving MW+LMC potential back in time until the LMC is far enough not to cause trouble ( $\sim 2 - 3$  Gyr).

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+ 2022].

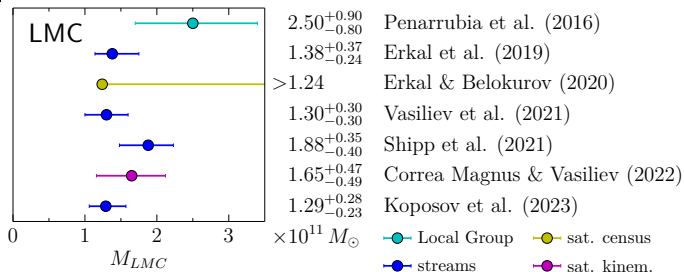
# Dynamical mass measurements



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

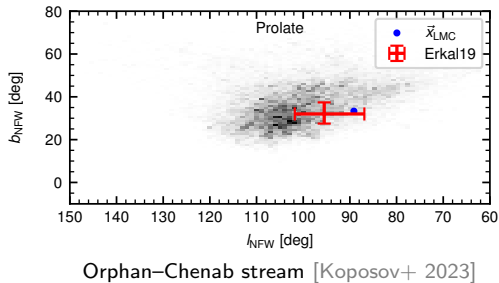
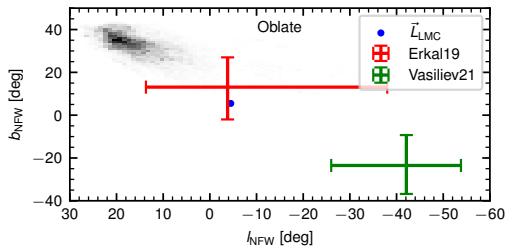
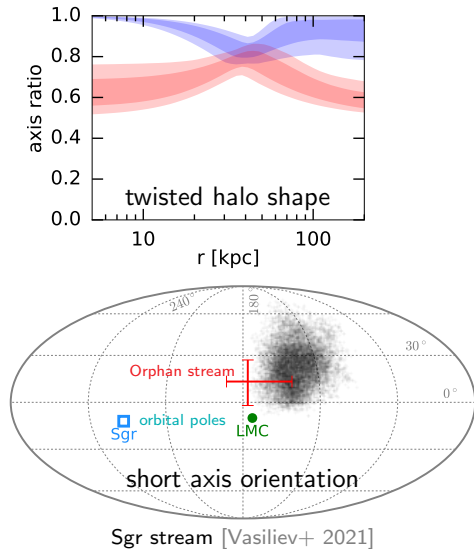
Sgr stream (incl. LMC) [Vasiliev+ 2021]

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



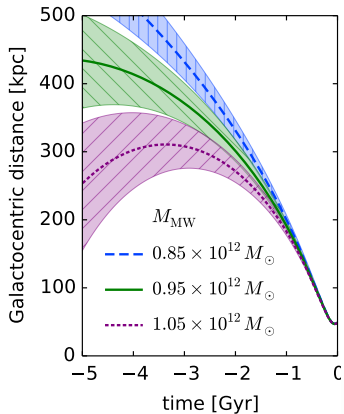
# Constraints on the Milky Way halo shape from streams

$\Lambda$ CDM 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.



# Past trajectory of the LMC

is very sensitive to the Milky Way mass!



Review

## The effect of the LMC on the Milky Way system

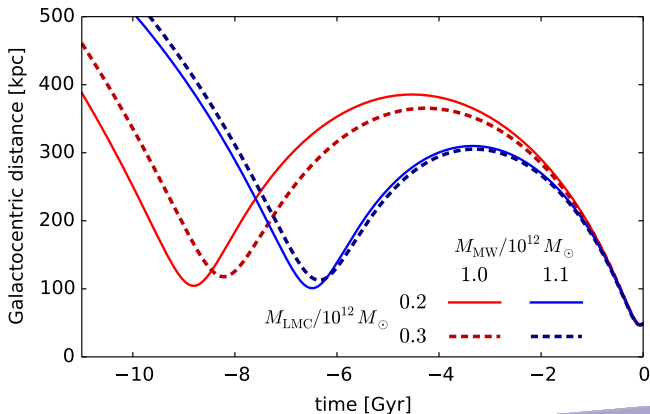
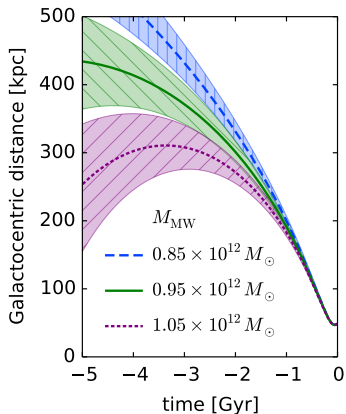
Eugene Vasiliev

2304.09136

**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 galaxies passing in the vicinity of the LMC. Less well known but **manifested at different levels.** The most immediate effect is the deflection of orbits of central regions of the Milky Way about the central body, this displacement

# Past trajectory of the LMC

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



Review

## The effect of the LMC on the Milky Way system

Eugene Vasiliev

2304.09136

**Abstract:** We review the recent theoretical and observational developments of the Large Magellanic Cloud (LMC) with the Milky Way and picture is that the LMC is a fairly massive companion (10–20% of the Milky Way mass) that has passed the pericentre of its orbit, likely for the first time. The most immediate consequence is that the LMC is currently passing in the vicinity of the Galactic Centre, likely at different levels. The most immediate consequence is that the LMC is currently passing in the vicinity of the Galactic Centre, likely at different levels.

Monthly Notices  
of the  
ROYAL ASTRONOMICAL SOCIETY  
MNRAS 527, 437–456 (2024)

## Dear Magellanic Clouds, welcome back!

Eugene Vasiliev

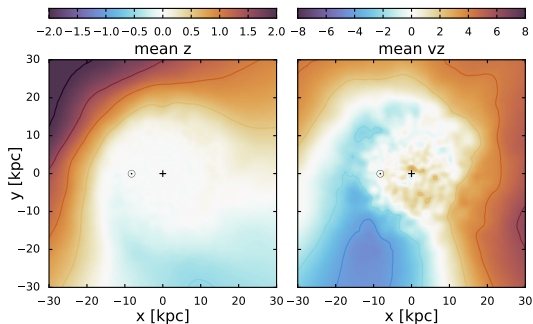
Accepted 2023 August 25. Received 2023 August 14; in original form 2023 June 8

2306.04837





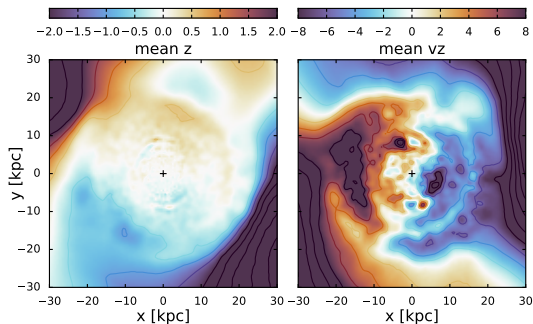
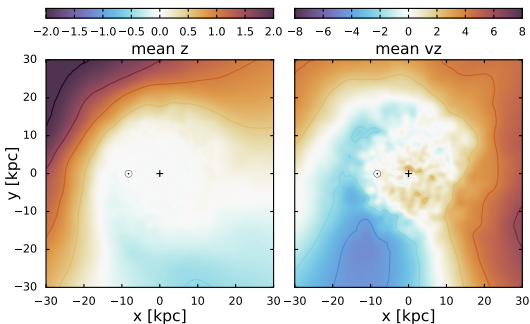
# Perturbations in the MW disc



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).

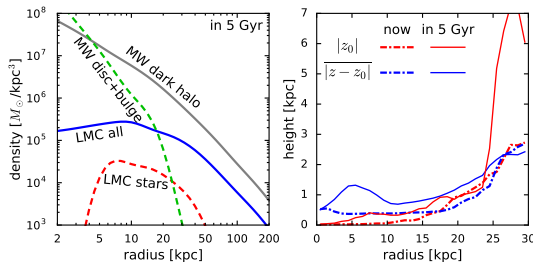


# Perturbations in the MW disc



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).

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.

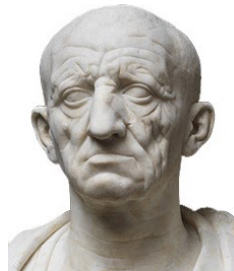


# Future fate

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<sup>1,★</sup>, Alis J. Deason<sup>1</sup>, Carlos S. Frenk<sup>1</sup> and Stuart McAlpine<sup>1,2</sup>  
<sup>1</sup>Department of Physics, Institute of Computational Cosmology, Durham University, South Road, Durham DH1 3LE, UK



CARTHAGE  
MVST BE  
DESTROYED

[Cato –149]

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

[Cautun+ 2019]