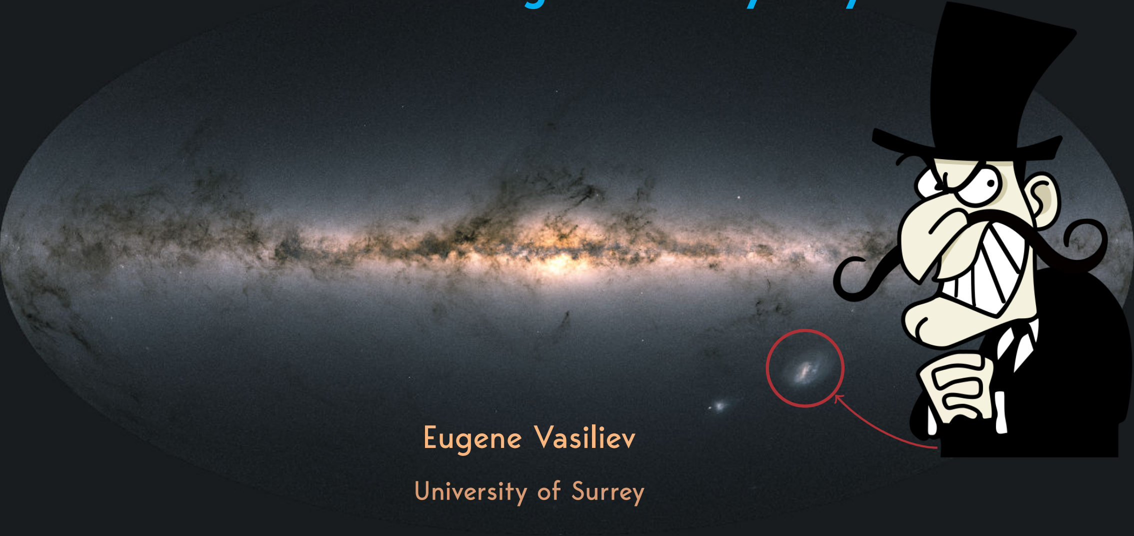
The unquiet neighbour: how the LMC bugs the Milky Way

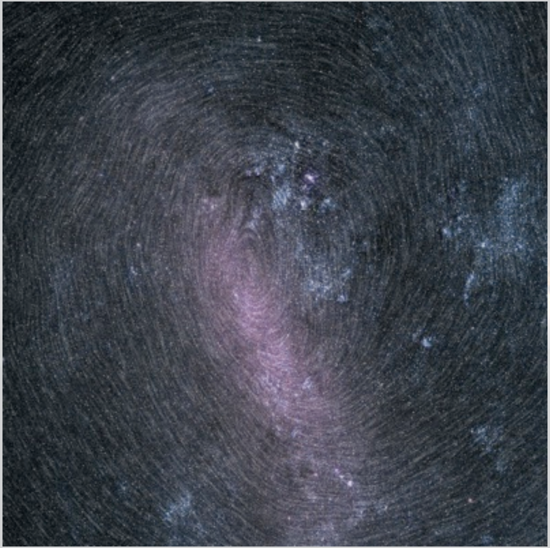


Eugene Vasiliev

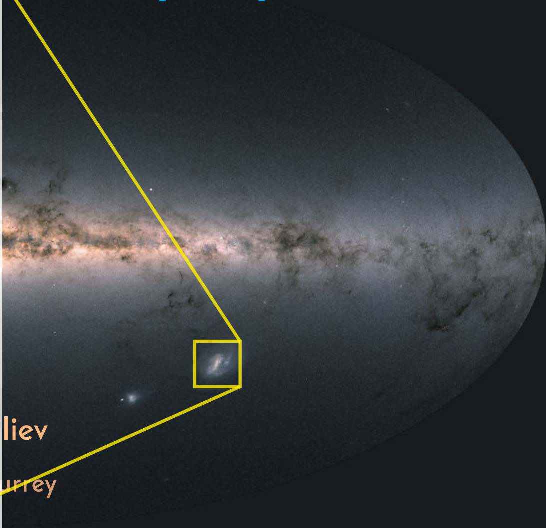
University of Surrey

Leibniz Institute for Astrophysics, Potsdam, 5 September 2024

The unquiet neighbour: the Milky Way



LMC rotation in Gaia DR2 [credit: ESA/Gaia/DPAC, 25/04/2018]

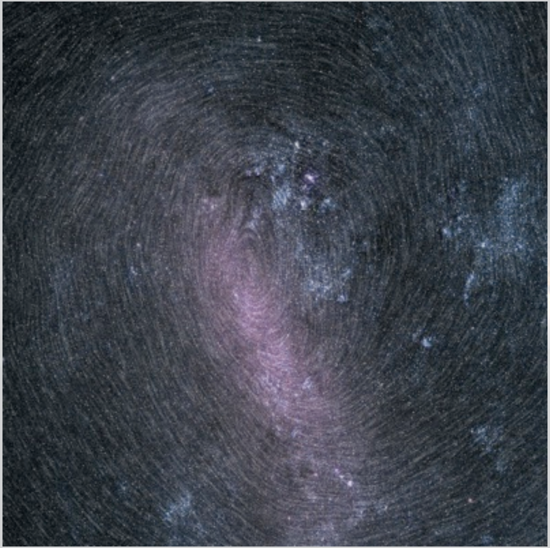


siliev

Surrey

Leibniz Institute for Astrophysics, Potsdam, 5 September 2024

The unquiet neighbour:



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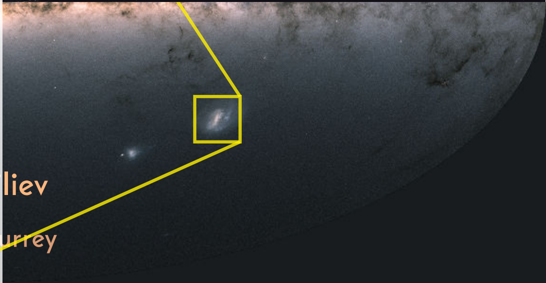
Caspar David Friedrich – Wanderer über dem Nebelmeer

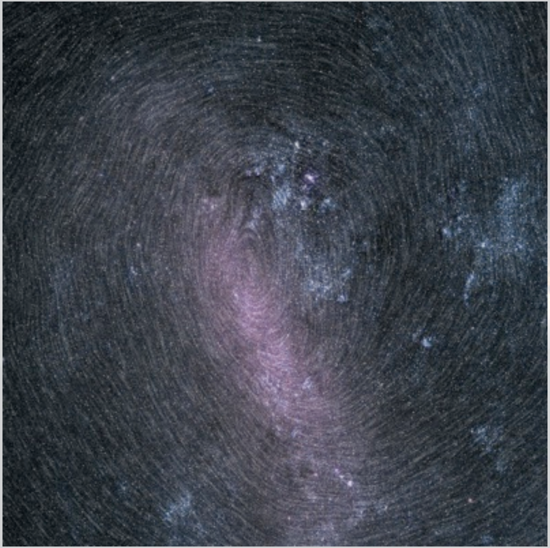


siliev

Surrey

Leibniz Institute for Astrophysics, Potsdam, 5 September 2024

The unquiet neighbour:



LMC rotation in Gaia DR2 [credit: ESA/Gaia/DPAC, 25/04/2018]

Caspar David Friedrich – Wanderer über dem Nebelmeer

Caspar David Friedrich – Eismeer

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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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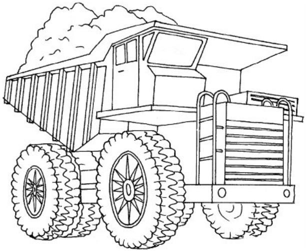
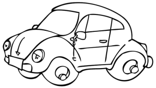
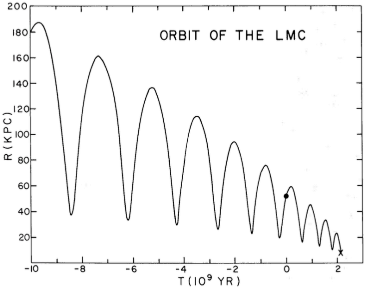


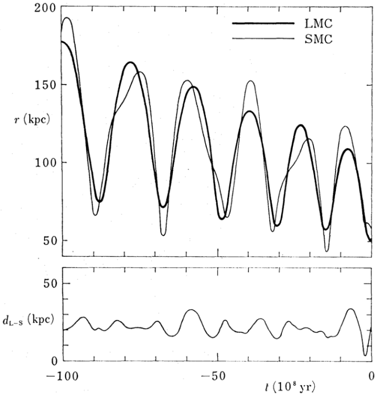


The Magellanic system

[Tremaine 1976]



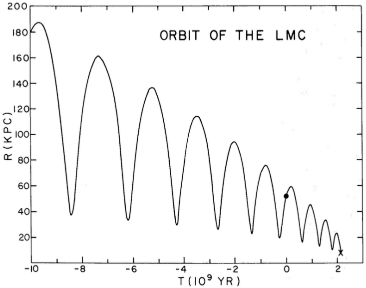
[Murai & Sugimoto 1980]



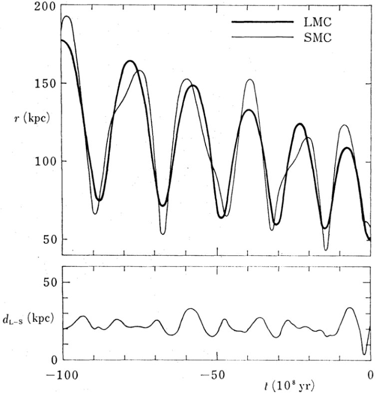
Early studies assumed a short-period orbit

The Magellanic system

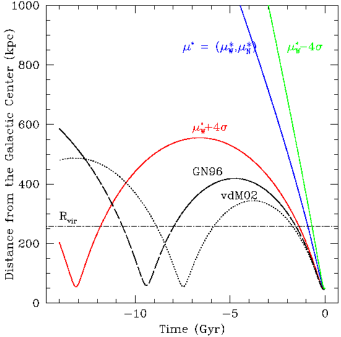
[Tremaine 1976]



[Murai & Sugimoto 1980]



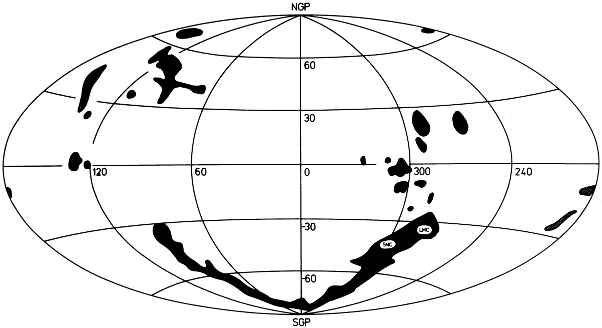
[Besla+ 2007]



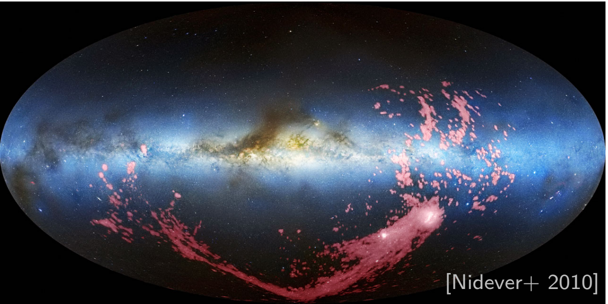
Early studies assumed a short-period orbit

With new PM from HST [Kallivayalil+ 2006], LMC seems to be on its first passage

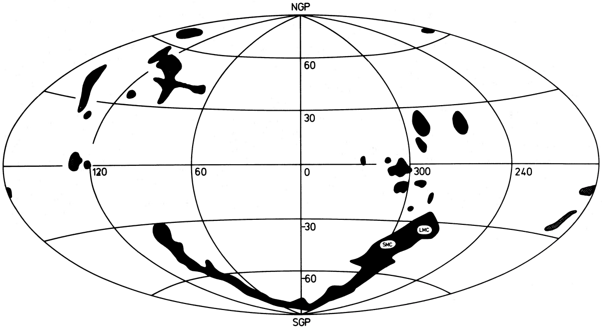
The Magellanic system



Magellanic gas stream [Mathewson+ 1974]

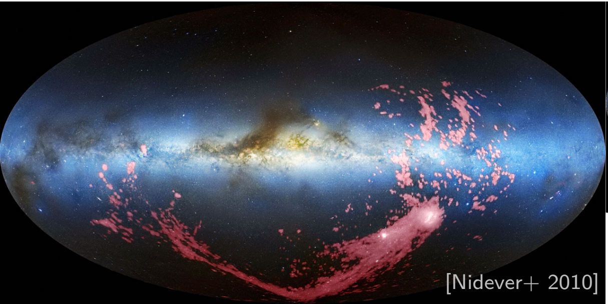


The Magellanic system

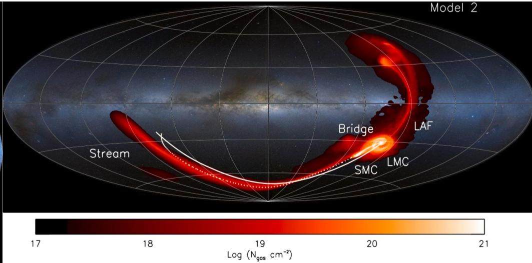


Magellanic gas stream [Mathewson+ 1974]

likely produced by the encounter between LMC and SMC, which are subsequently accreted into the Milky Way



[Nidever+ 2010]

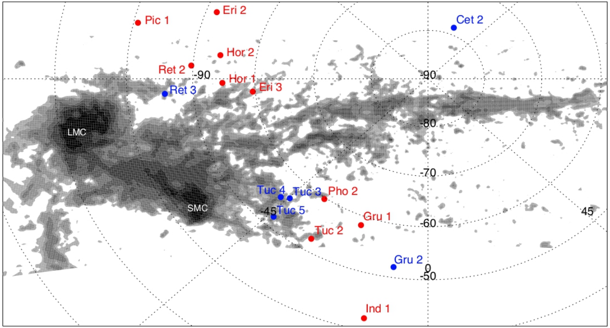


[Besla+ 2012]

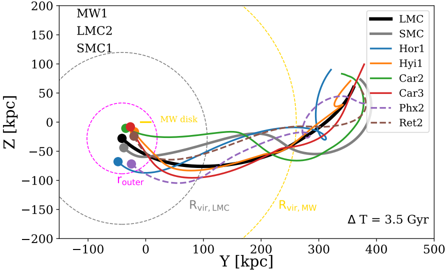
The Magellanic system

Apart from SMC, there are ~ 10 ultrafaint galaxies that are also LMC satellites. This implies that the LMC is sufficiently massive ($\gtrsim 10^{11}\, M_\odot$, Erkal & Belokurov 2020).

SMC is heavily tidally stripped and is currently 1–2 orders of magnitude less massive than LMC.

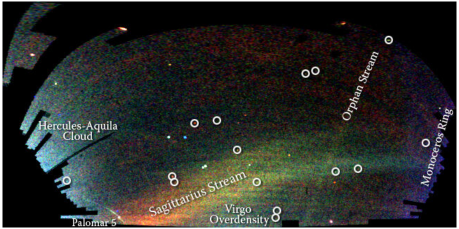


D'Onghia & Fox 2016, adapted from Koposov+ 2015 using DES

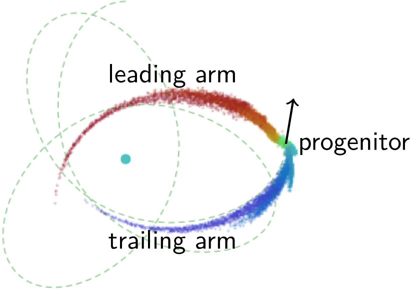


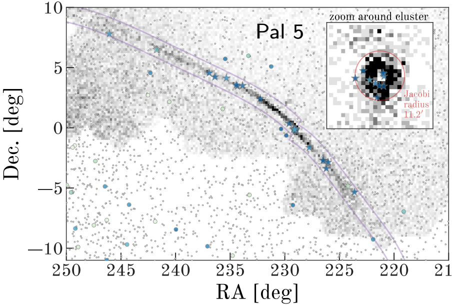
Patel+ 2020, using Gaia DR2 PM

Stellar tidal streams in the Milky Way

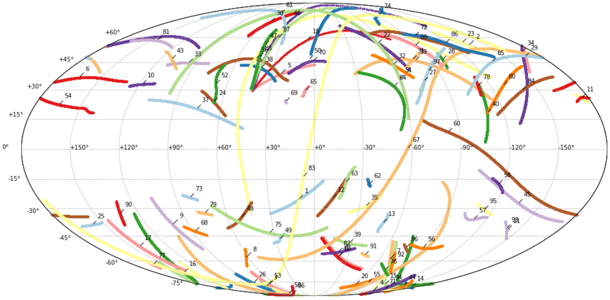


SDSS field of streams [Belokurov+ 2006]



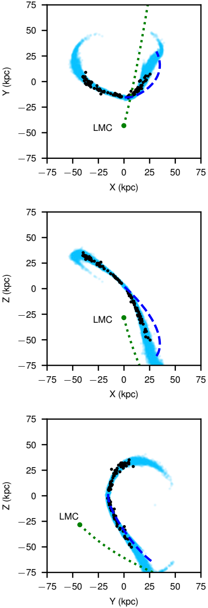


DECaLS+Gaia [Price-Whelan+ 2019]

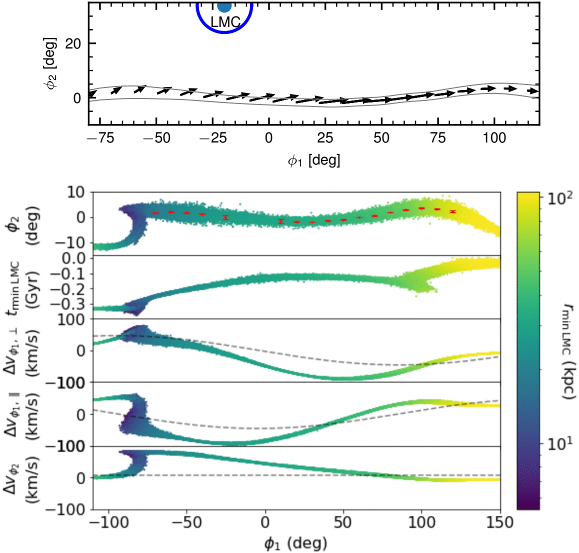


GalStreams database [Mateu 2023]

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.

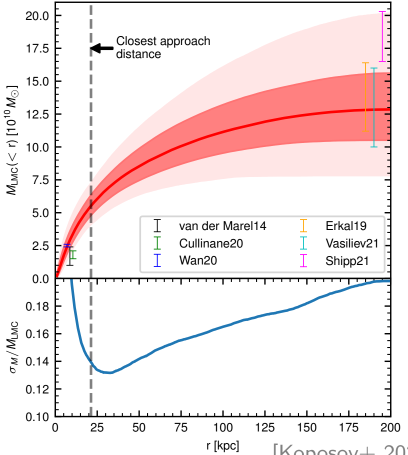


[Erkal+ 2019]

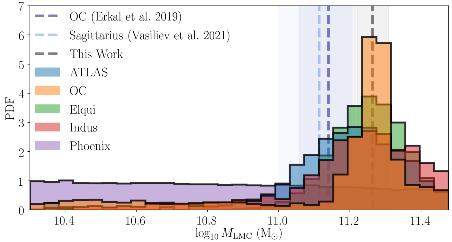
[Koposov+ 2023]

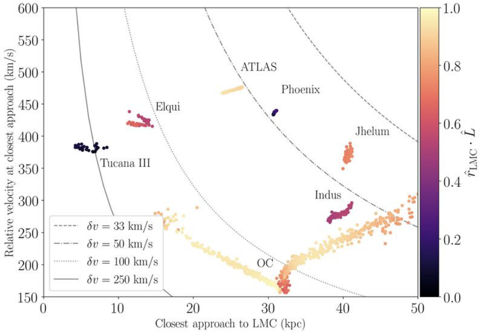
Local effects of the LMC: deflection of stellar streams

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.



[Koposov+ 2023]

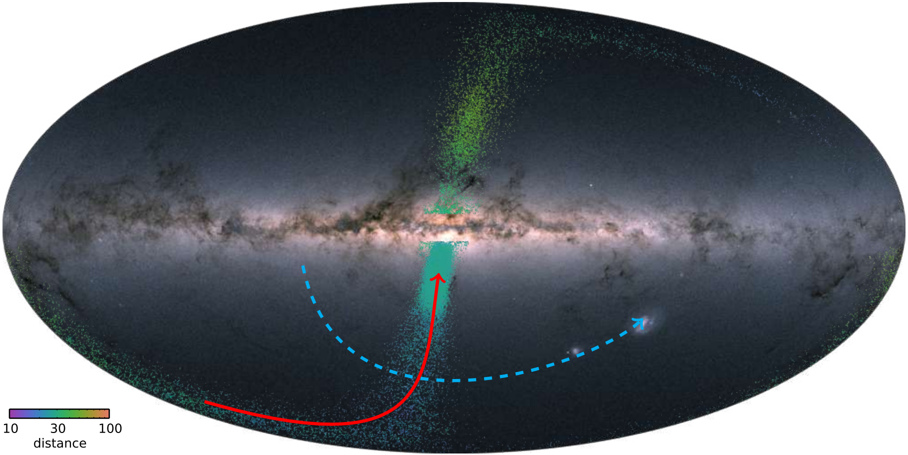




[Shipp+ 2021; see also Lilleengen+ 2022]

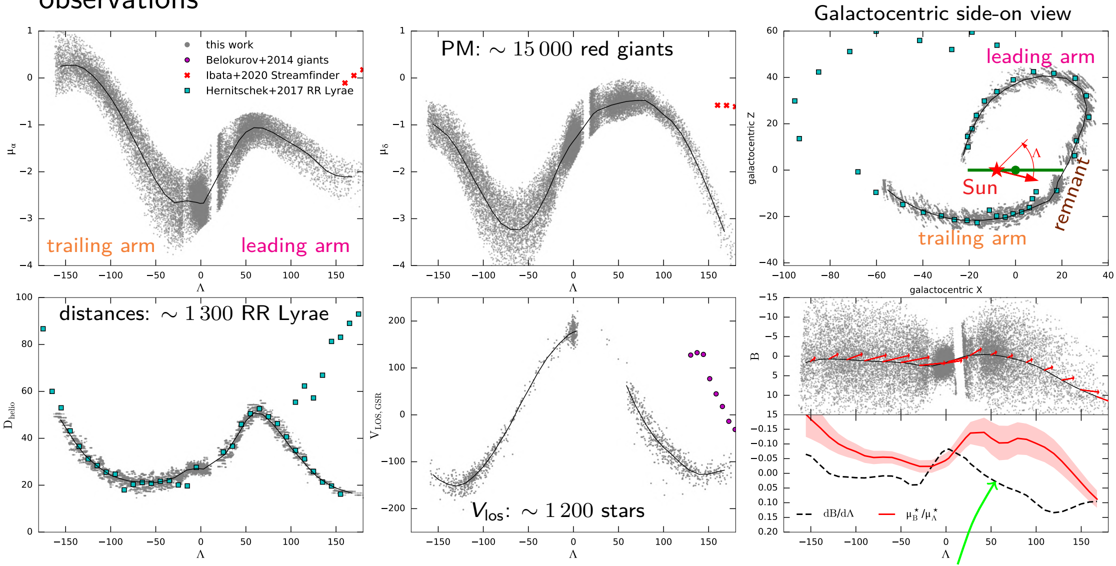
Effect of the LMC on the Sagittarius stream

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

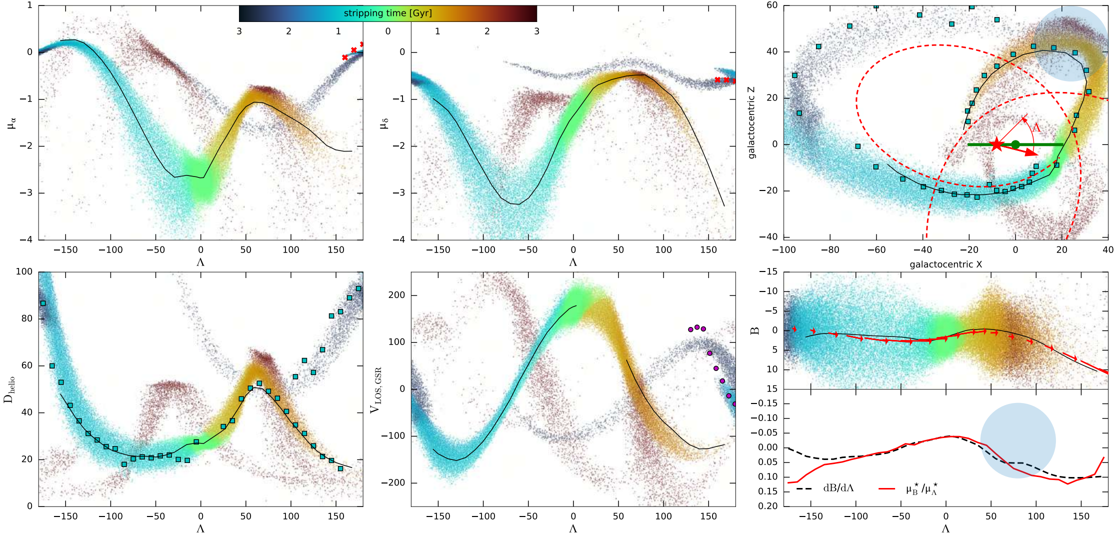


Misalignment between PM and stream track

[Vasiliev+ 2021]

Effect of the LMC on the Sagittarius stream

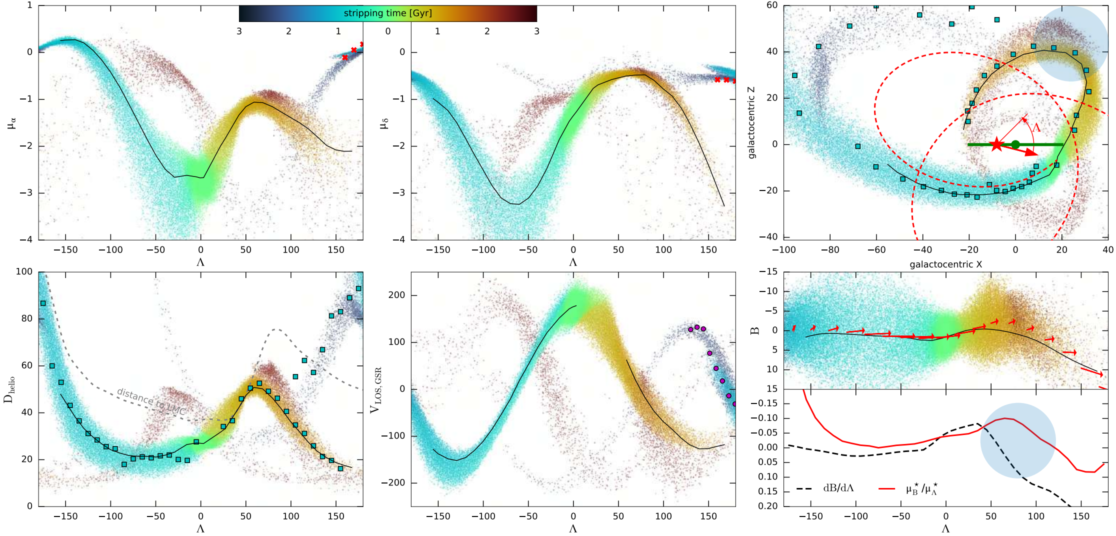
stream model in the best-fit (very flexible) MW potential



[Vasiliev+ 2021]

Effect of the LMC on the Sagittarius stream

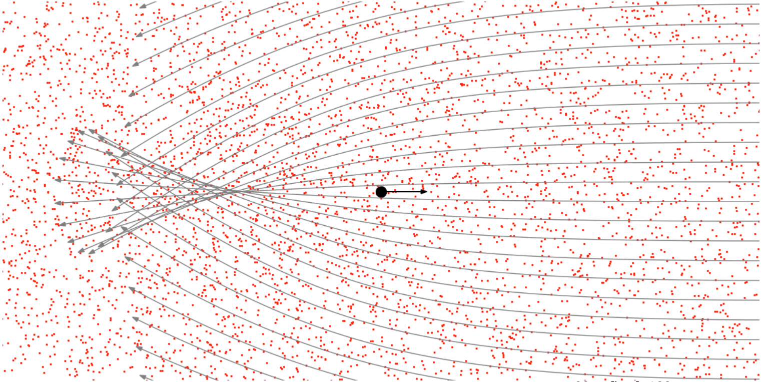
stream model including the perturbation from the LMC ($M_{\rm LMC} = 1.5 \times 10^{11}\, M_\odot$)



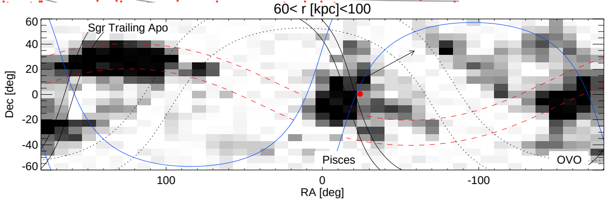
[Vasiliev+ 2021]

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]

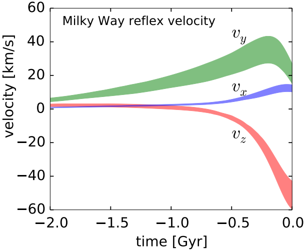


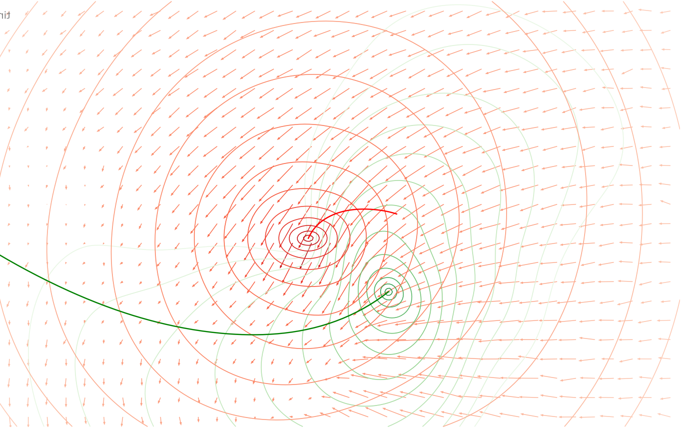
possibly detected as the Pisces overdensity [Belokurov+ 2019]



Global perturbation: mechanism

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

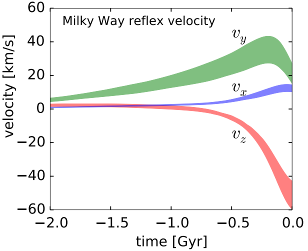


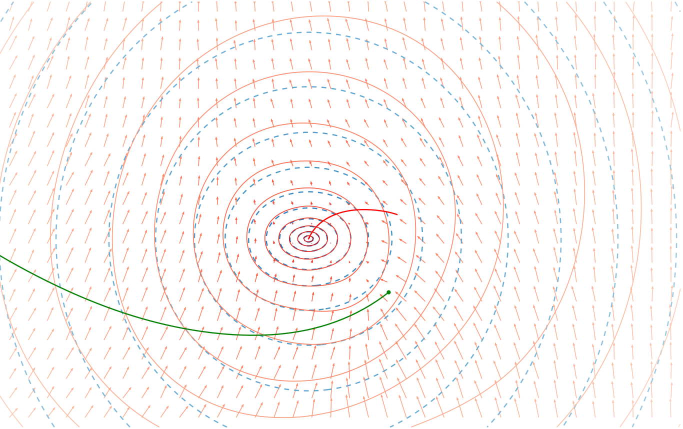


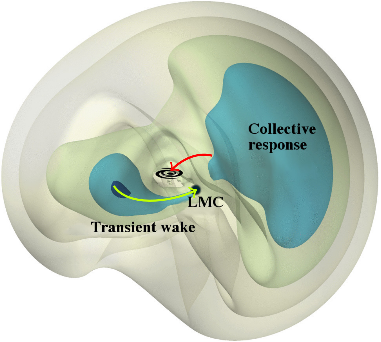
Global perturbation: mechanism

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

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], linear response theory [Rozier+ 2022]

Global perturbation: mechanism

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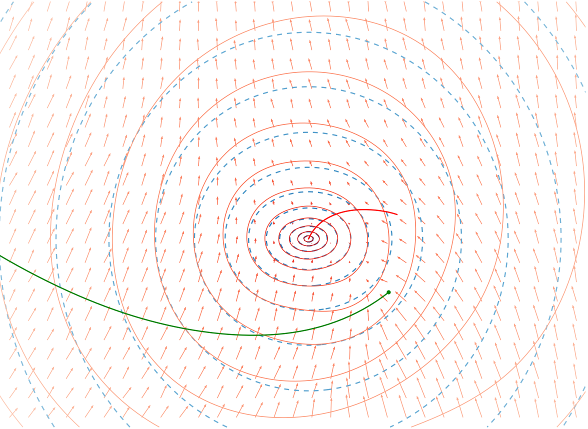
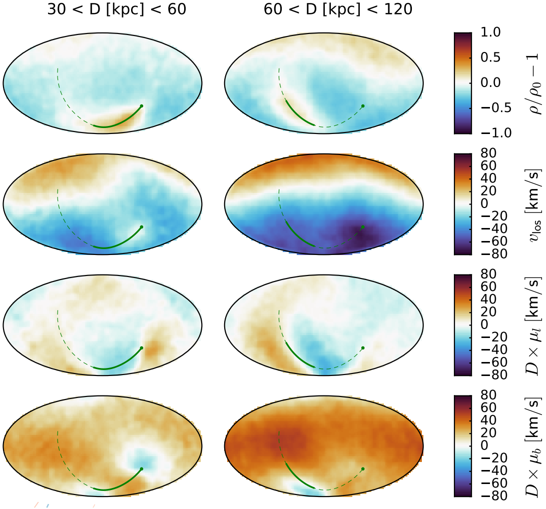
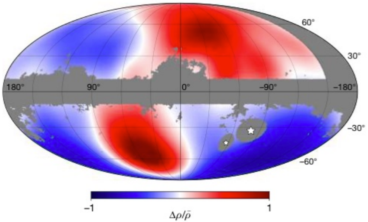


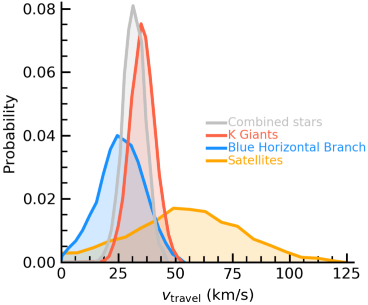


Global perturbation: predicted and observed signatures



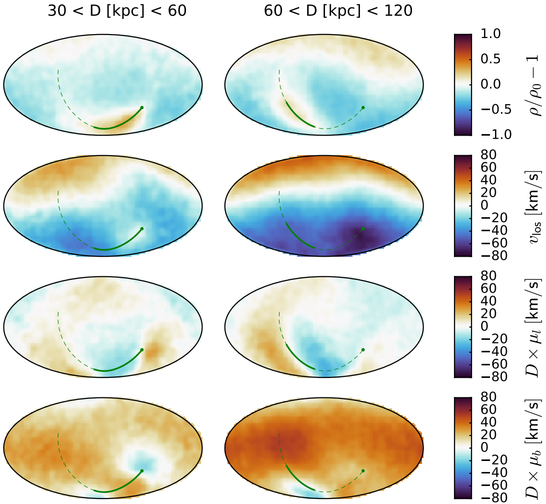
density polarization [Conroy+ 2021]

[alternative views: Chandra+ 2023, Amarante+ 2024]



velocity offset [Petersen & Peñarrubia 2021, see also Erkal+ 2021, Yaaqib+ 2024; Chandra+ 2024]

perturbation is most visible in the north–south asymmetry of density and line-of-sight velocities at distances $\gtrsim 30$ kpc



Measurement of the Milky Way potential

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

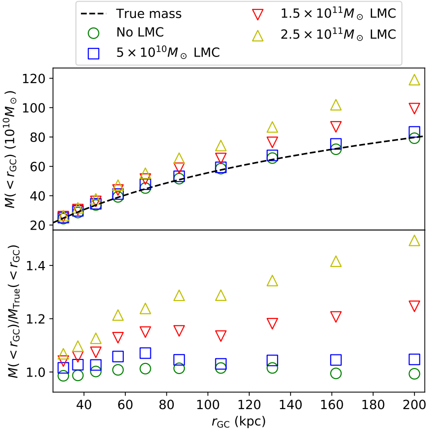
smoothly distributed populations:
assume dynamical equilibrium $\Rightarrow$
density and velocity distributions
are linked through the potential

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).

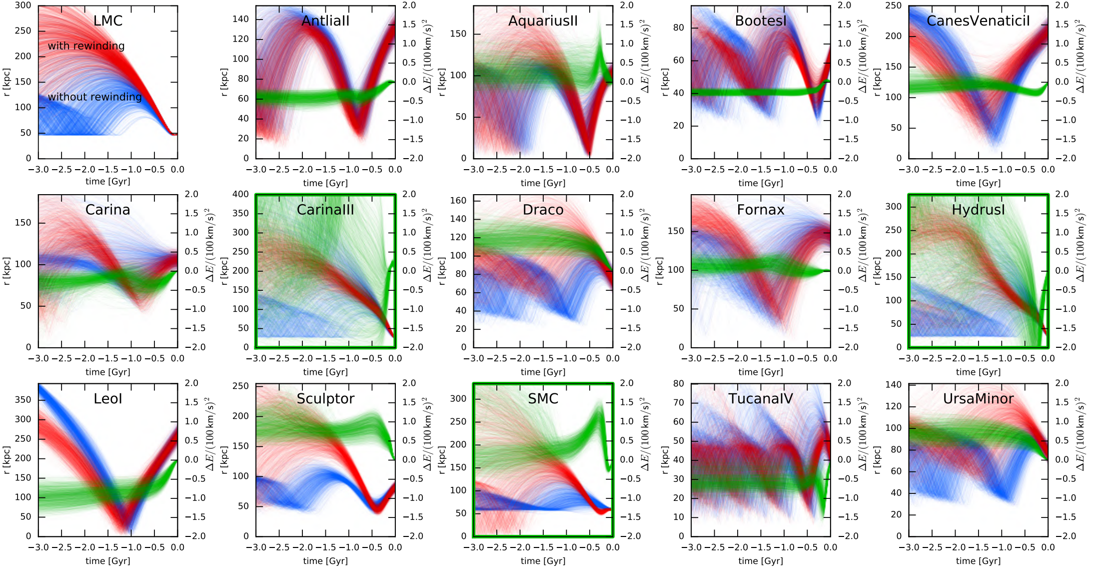
Vary the LMC mass, the parameters of the potential and the tracer DF
to maximize the likelihood of the *unperturbed* (rewound) dataset.

Use two tracer populations: ~ 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].

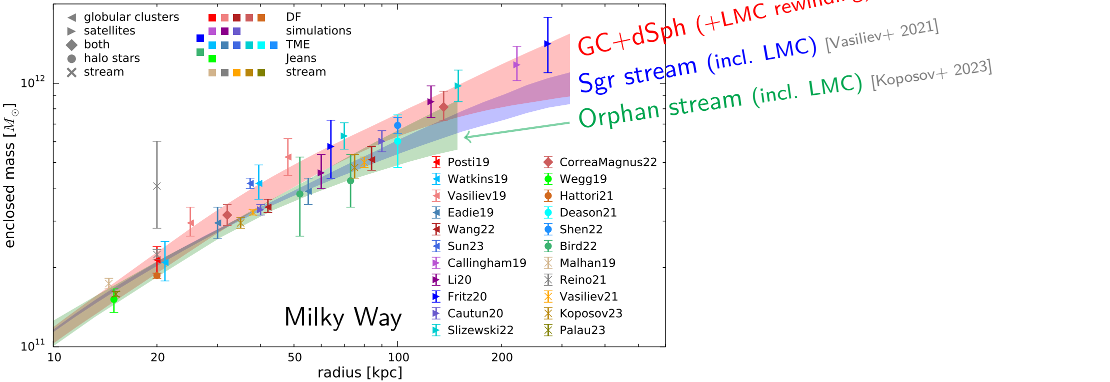
Changes in satellite orbits caused by the LMC

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

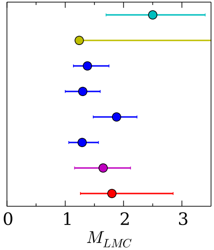
blue: without LMC;   red: with LMC;   green: energy evolution with LMC;   green frame: LMC satellites



Dynamical mass measurements



LMC



$2.50^{+0.90}_{-0.80}$	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)	MW streams
$1.30^{+0.30}_{-0.30}$	Vasiliev et al. (2021)	MW streams
$1.88^{+0.35}_{-0.40}$	Shipp et al. (2021)	MW streams
$1.29^{+0.28}_{-0.23}$	Koposov et al. (2023)	MW streams
$1.65^{+0.47}_{-0.49}$	Correa Magnus & Vasiliev (2022)	MW sat. kinematics
$1.80^{+1.05}_{-0.54}$	Watkins et al. (2024)	LMC clust. kinematics

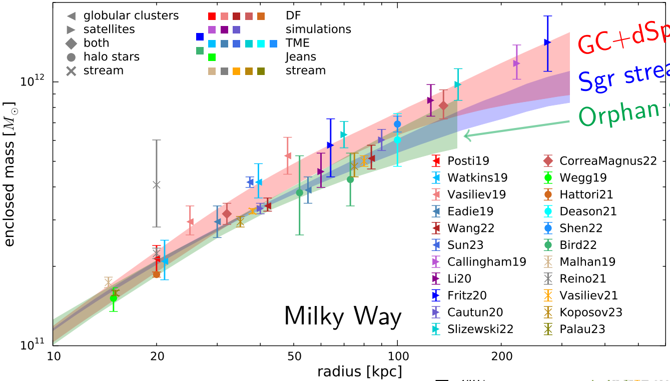
$\times 10^{11}\ M_\odot$

Dynamical mass measurements

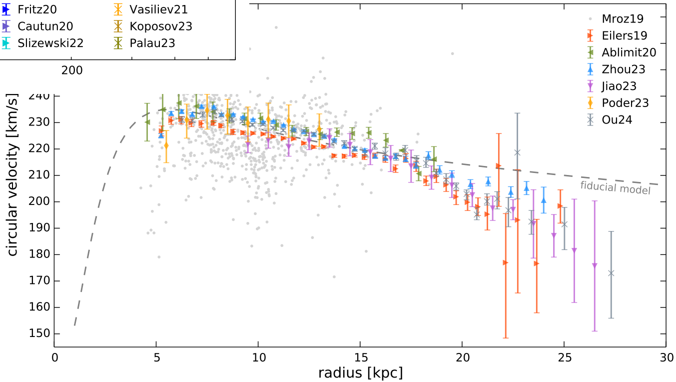
GC+dSph (+LMC rewinding) [Correa Magnus & Vasiliev 2022]

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

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

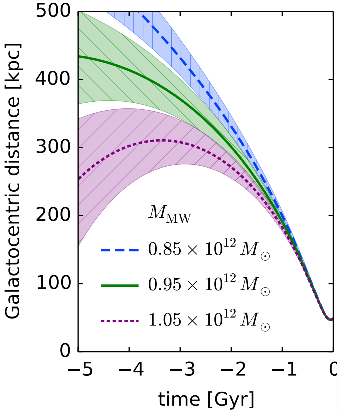


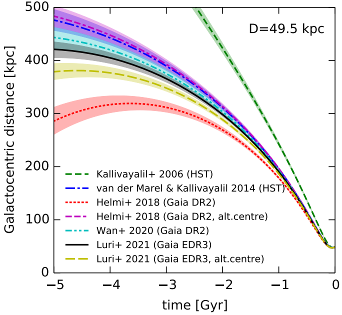
Circular-velocity curve inferred from Jeans modelling of disc stars sharply declines beyond 20 kpc, in contradiction with mass measurement further out. Is LMC the culprit here too? see Koop+ 2024 for discussion...

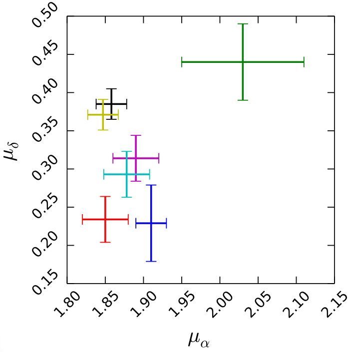


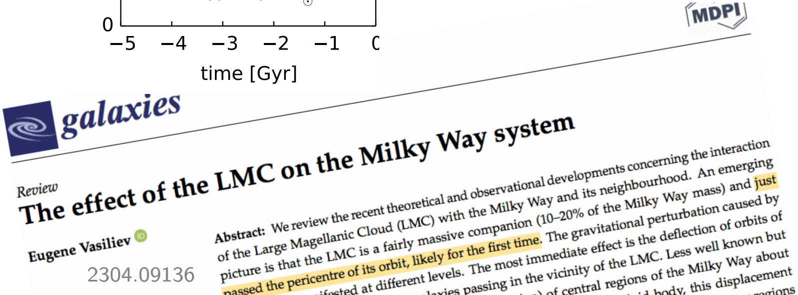
Past trajectory of the LMC

is very sensitive to the Milky Way mass and to the assumed PM!








galaxies

Review

The effect of the LMC on the Milky Way system

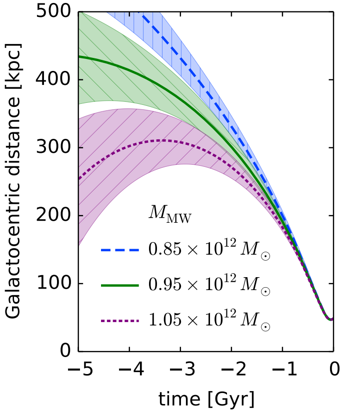
Eugene Vasiliev

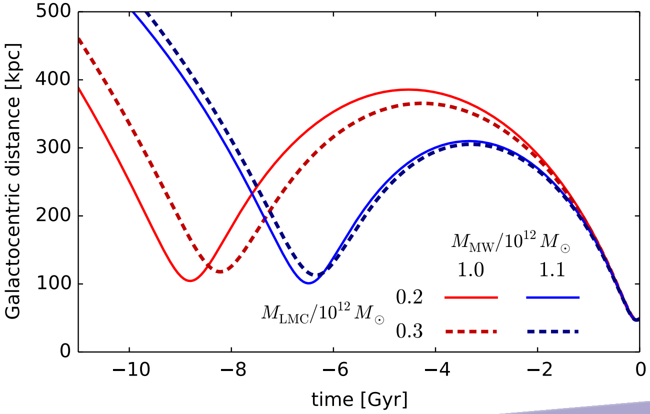
2304.09136

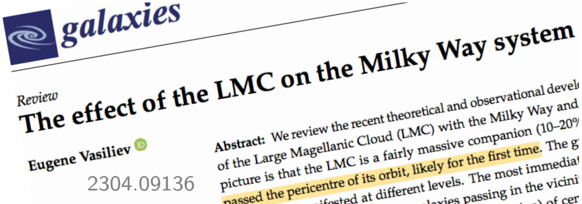
Abstract: We review the recent theoretical and observational developments concerning the interaction of the Large Magellanic Cloud (LMC) with the Milky Way and its neighbourhood. An emerging picture is that the LMC is a fairly massive companion (10–20% of the Milky Way mass) and just passed the pericentre of its orbit, likely for the first time. The gravitational perturbation caused by ... manifested at different levels. The most immediate effect is the deflection of orbits of ... galaxies passing in the vicinity of the LMC. Less well known but ... of central regions of the Milky Way about ... rigid body, this displacement ... regions

Past trajectory of the LMC

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



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MNRAS **527**, 437–456 (2024)

Dear Magellanic Clouds, welcome back!

Eugene Vasiliev

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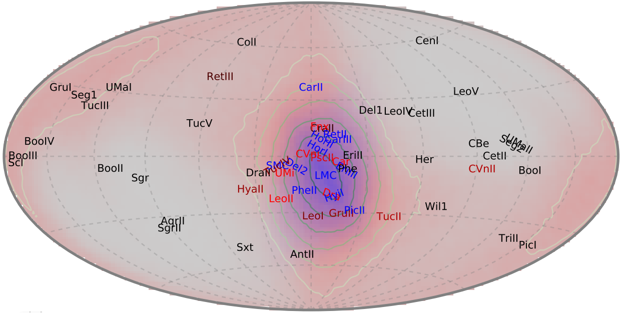
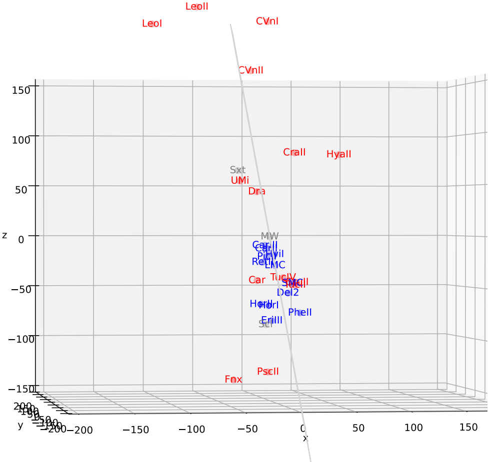
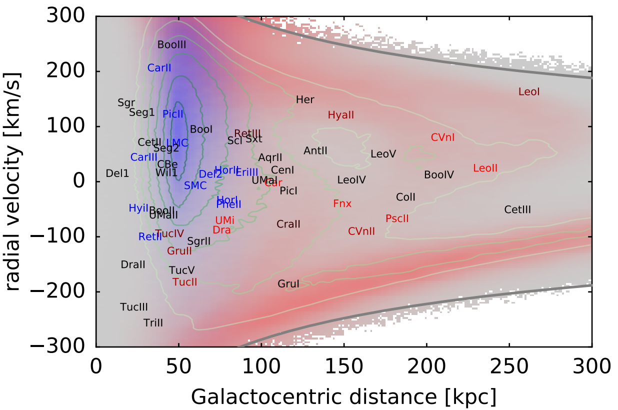
2306.04837

Satellite plane

Many satellite galaxies are located close to the LMC orbital plane and have similar orientations of angular momenta (spatially and kinematically coherent structure) [Kroupa+ 2005; Pawlowski+ 2012].





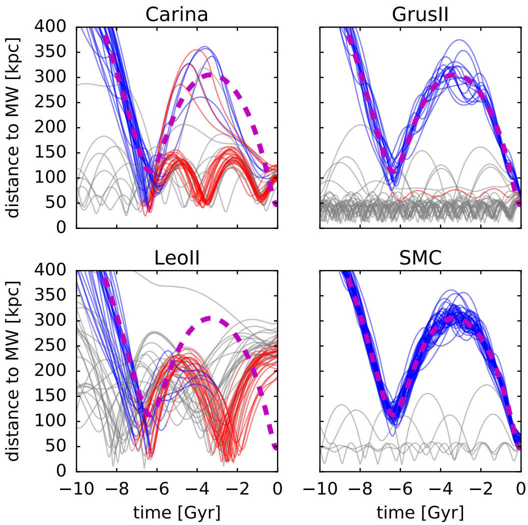


Classification of satellite orbits

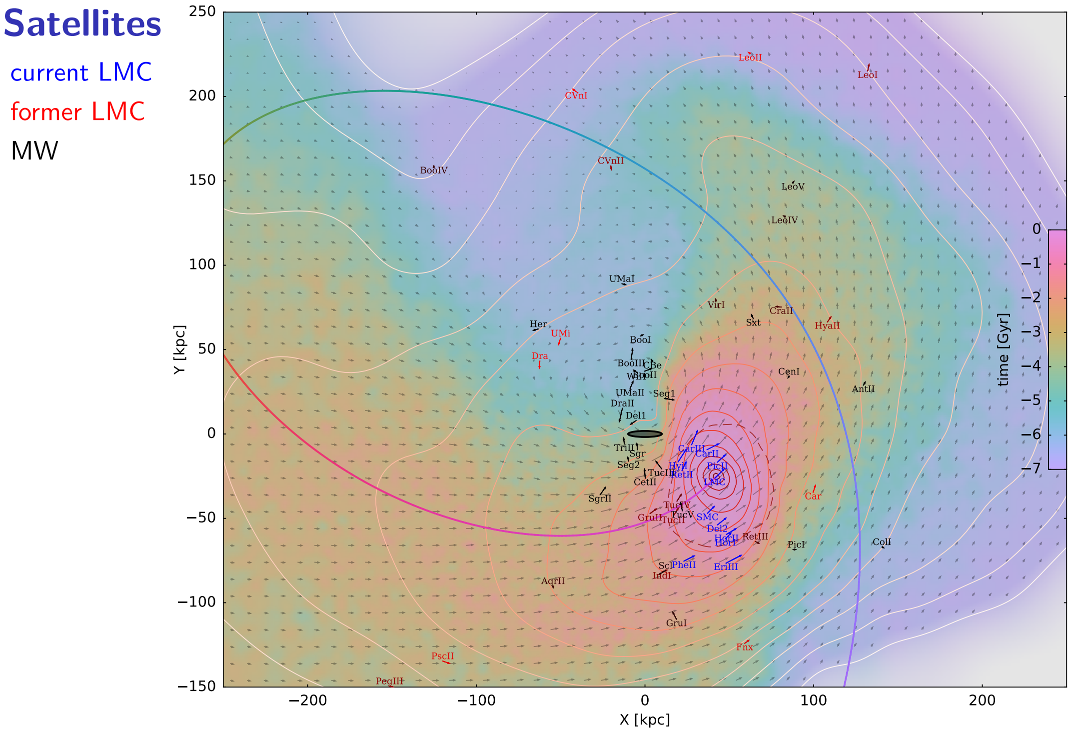
Determine the probability of Magellanic association and the stripping time for each of ~ 60 Milky Way satellites:

Name	M_V	D	probability
Canes Venatici I	-8.6	210	
Canes Venatici II	-4.6	160	
Carina	-8.6	106	
Carina II	-4.5	37	
Carina III	-2.4	28	
Crater II	-8.2	117	
Delve 2	-2.1	71	
Draco	-8.7	76	
Eridanus III	-2.3	91	
Fornax	-13.4	147	
Grus II	-3.9	55	
Horologium I	-3.5	79	
Horologium II	-1.5	78	
Hydra II	-4.8	151	
Hydrus I	-4.7	28	
Indus I	-1.5	105	
Leo I	-12.0	258	
Leo II	-9.6	233	
Phoenix II	-3.3	83	
Pictor II	-4.2	46	
Pisces II	-4.1	183	
Reticulum II	-3.6	31	
Reticulum III	-3.3	92	
SMC	-16.8	63	
Tucana II	-3.9	58	
Tucana IV	-3.5	47	
Ursa Minor	-8.4	76	
Virgo I	-0.8	91	

examples of possible past orbits



currently bound to LMC; formerly bound; MW-bound



Satellites
current LMC
former LMC
MW
Y [kpc]
X [kpc]
time [Gyr]
LeoII
LeoI
CVnI
BooIV
CVnII
LeoV
LeoIV
UMaI
VirI
CraII
Sxt
HyaII
Her
UMi
BooI
Dra
CenI
AntII
Seg1
DraII
Del1
TriII
Sgr
Seg2
CetII
SgrII
Car
SMC
RetIII
PicI
ColI
Del2
SclPheII
EriIII
IndI
AqrII
GruI
Fnx
PscII
PegIII
LMC

Summary

- LMC is the biggest troublemaker in the dynamics of the outer Milky Way
- Its past orbit is very sensitive to the current position/velocity and the Galactic potential
- A second-passage scenario is *possible*, but not *mandated*; however, in this case...

Summary

- LMC is the biggest troublemaker in the dynamics of the outer Milky Way
- Its past orbit is very sensitive to the current position/velocity and the Galactic potential
- A second-passage scenario is *possible*, but not *mandated*; however, in this case...
- Several satellite galaxies could have been accreted from the Magellanic system