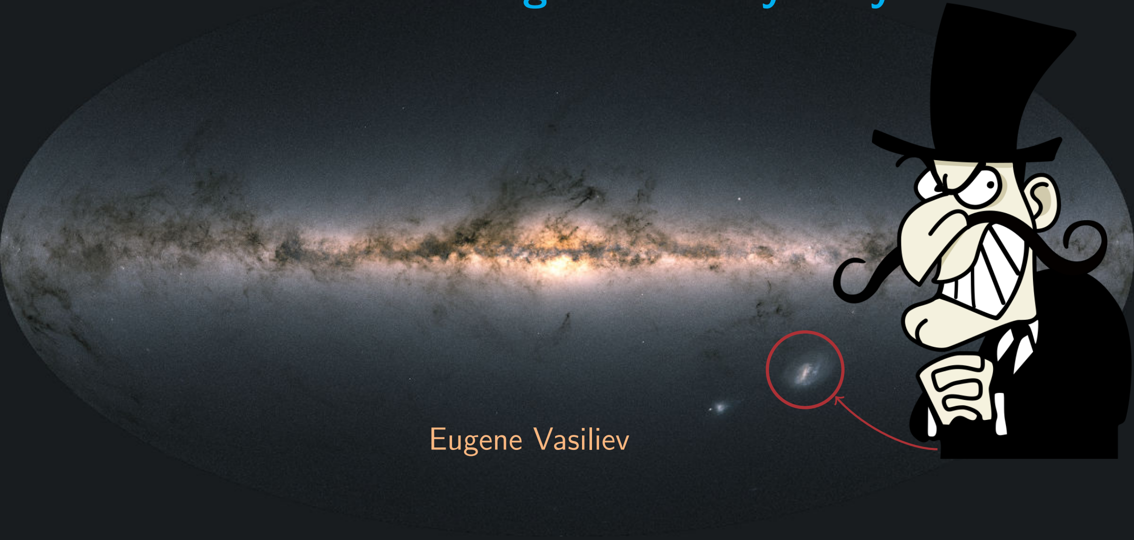
The unquiet neighbour: how the LMC bugs the Milky Way



Eugene Vasiliev

University of Barcelona, 10 April 2024

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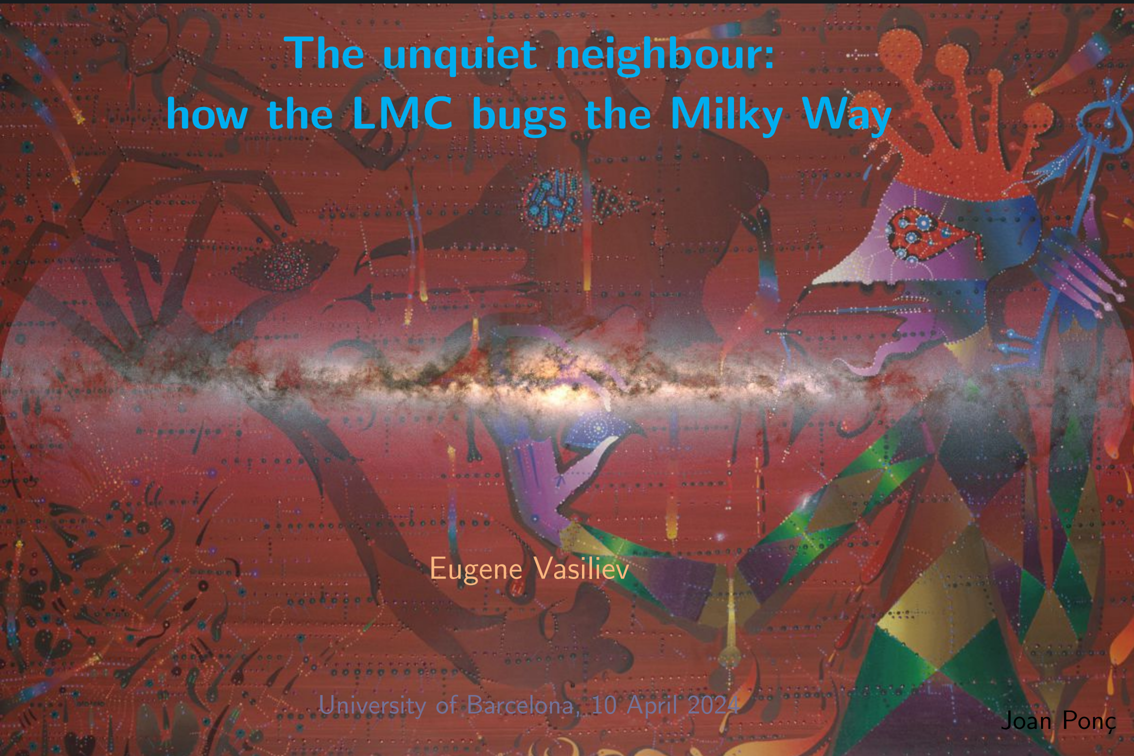

Joan Ponç

Eugene Vasiliev

University of Barcelona, 10 April 2024

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

just passed its (first?) pericentre

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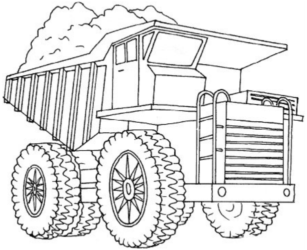
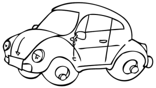
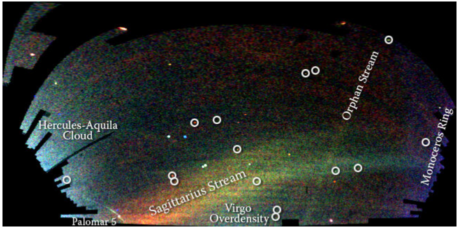




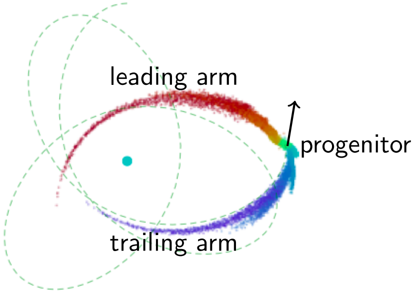
Consequences of the MW–LMC encounter

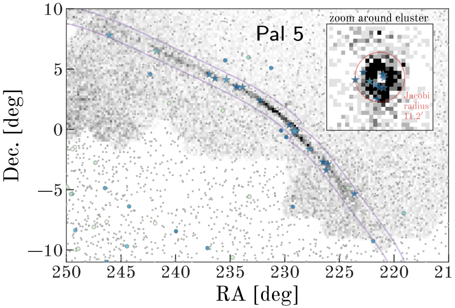
- LMC brings its own satellites, stars and clusters
- LMC deflects stars and streams passing close to its trajectory
- LMC creates a density wake in the MW halo
- LMC displaces the Milky Way
- LMC creates a dipole asymmetry in the outer MW halo
- LMC affects the velocities of other galaxies relative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

Stellar tidal streams in the Milky Way

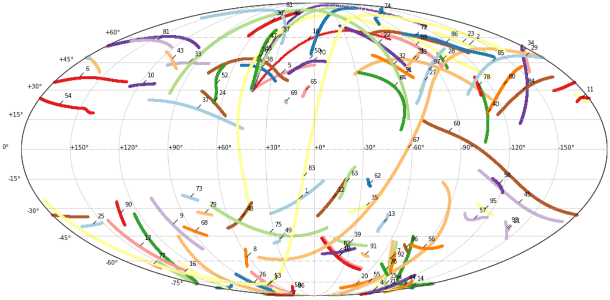


SDSS field of streams [Belokurov+ 2006]



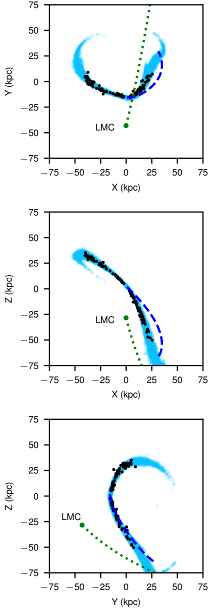


DECaLS+Gaia [Price-Whelan+ 2019]

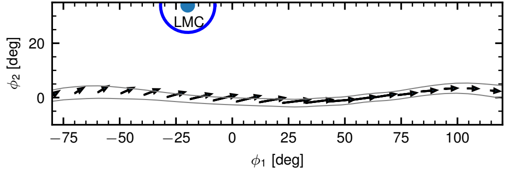


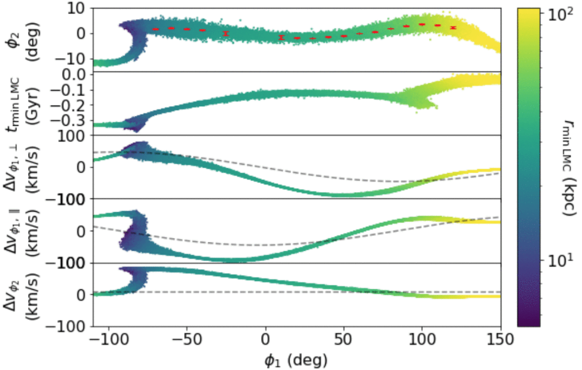
GalStreams database [Mateu 2023]

Local effects of the LMC: deflection of stellar streams



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.



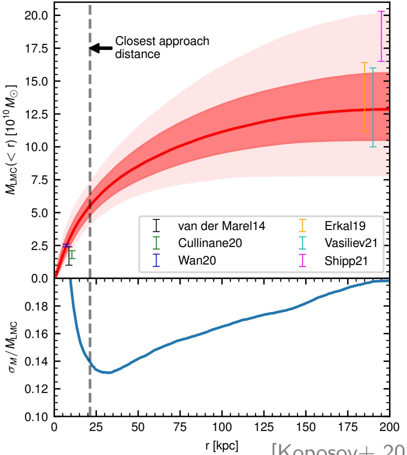


[Erkal+ 2019]

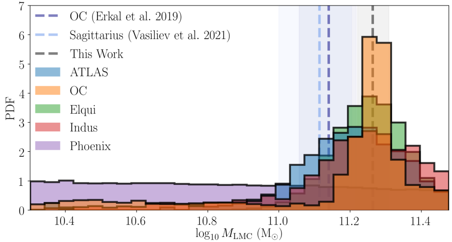
[Koposov+ 2023]

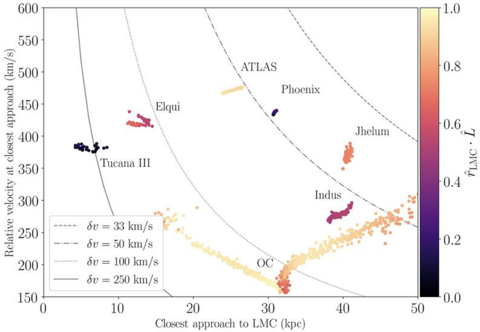
Local effects of the LMC: deflection of stellar streams

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]

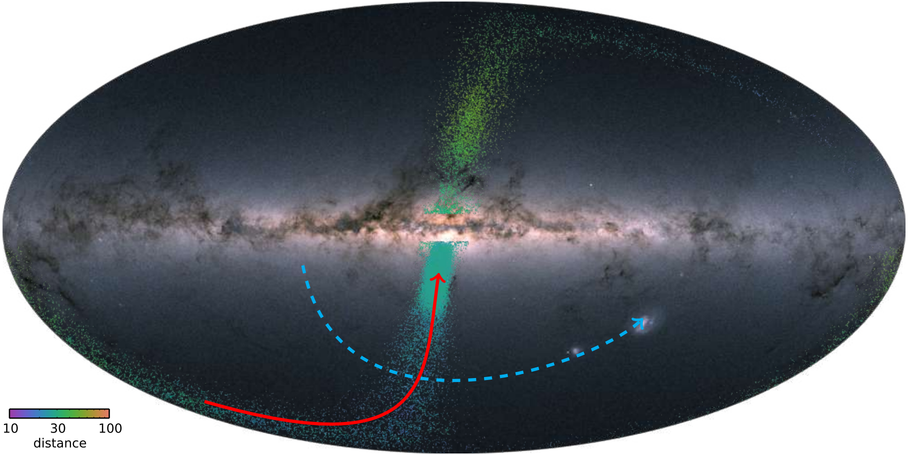




[Shipp+ 2021; see also Lilleengen+ 2022]

Effect of the LMC on the Sagittarius stream

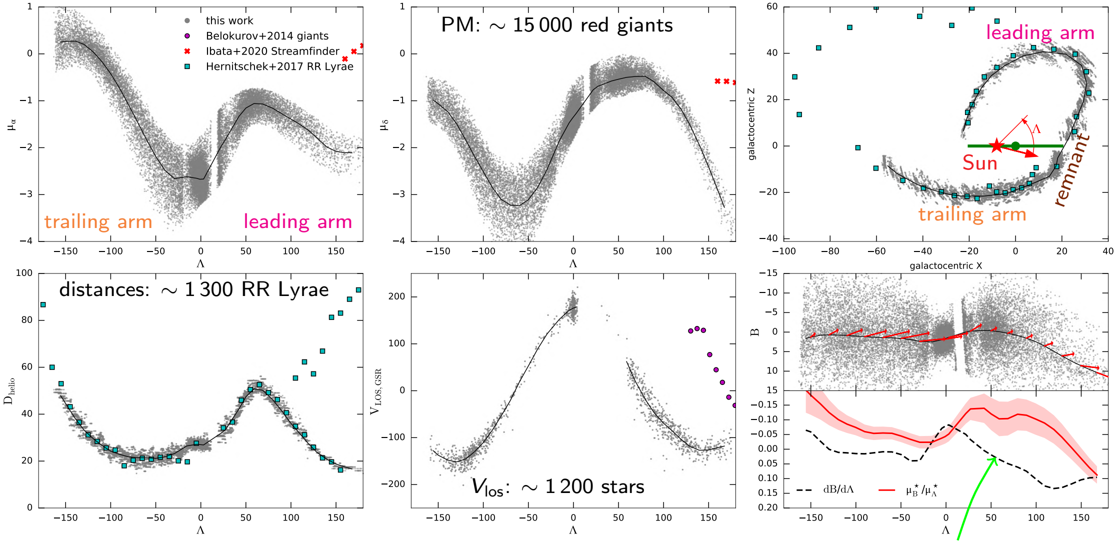
Sagittarius stream: by far the largest in the Milky Way, spans the entire sky.
First discovered in 2MASS [Majewski+ 2003]; studied extensively using SDSS [Belokurov+ 2006, Koposov+ 2012] and Gaia [Ibata+ 2020, Antoja+ 2020, Ramos+ 2020, 2022].
Progenitor: Sgr dSph (third-largest MW satellite after LMC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



Effect of the LMC on the Sagittarius stream

observations

Galactocentric side-on view

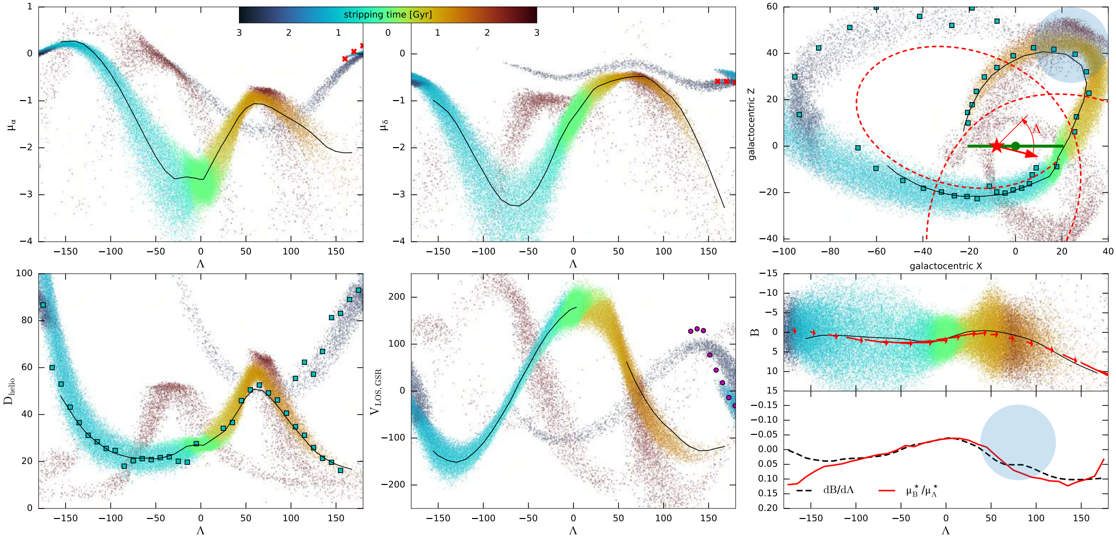


[Vasiliev+ 2021]

Misalignment between PM and stream track

Effect of the LMC on the Sagittarius stream

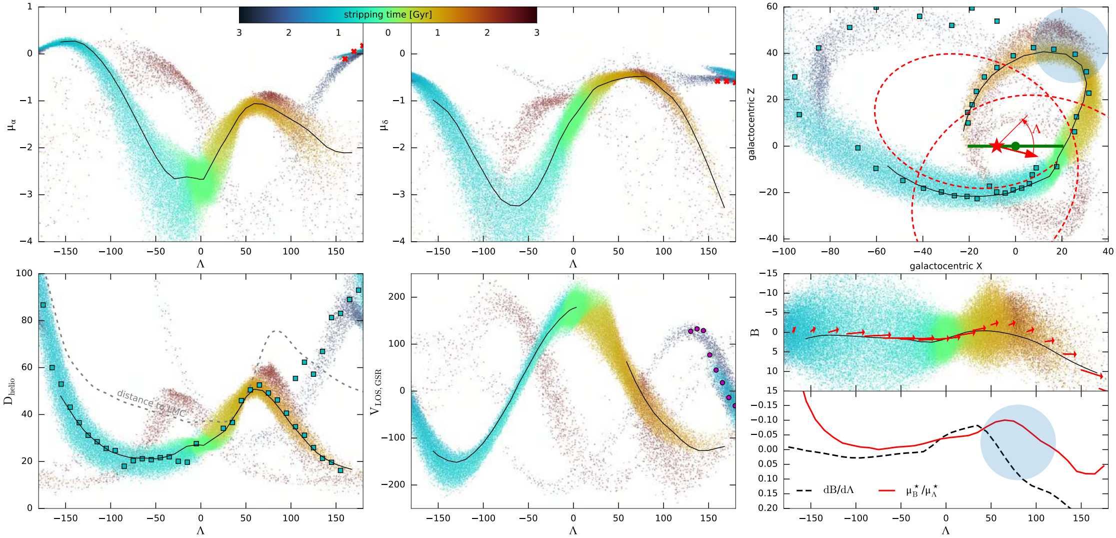
stream model in the best-fit (very flexible) MW potential



[Vasiliev+ 2021]

Effect of the LMC on the Sagittarius stream

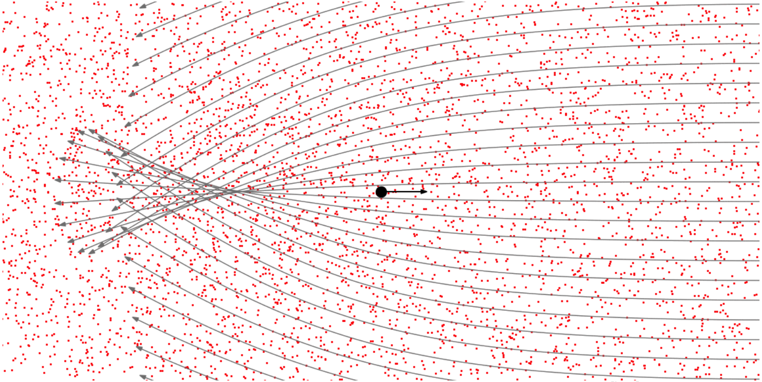
stream model including the perturbation from the LMC ($M_{\mathrm{LMC}} = 1.5 \times 10^{11}\, M_{\odot}$)



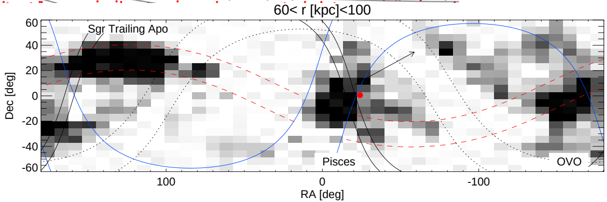
[Vasiliev+ 2021]

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]

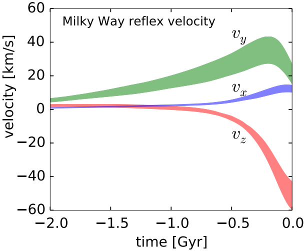


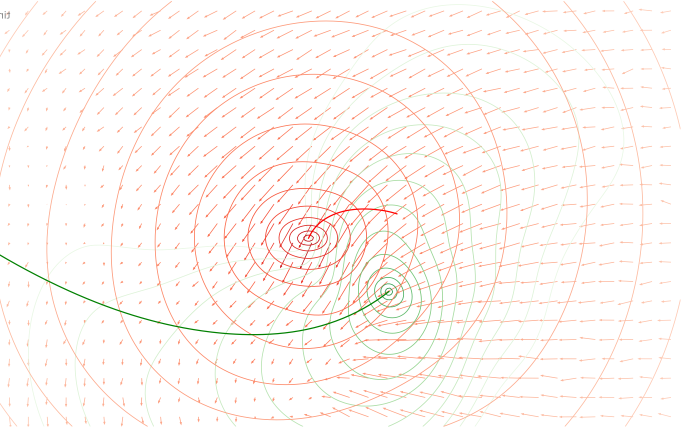
possibly detected as the Pisces overdensity [Belokurov+ 2019]



Global perturbation: mechanism

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





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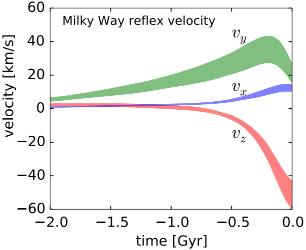
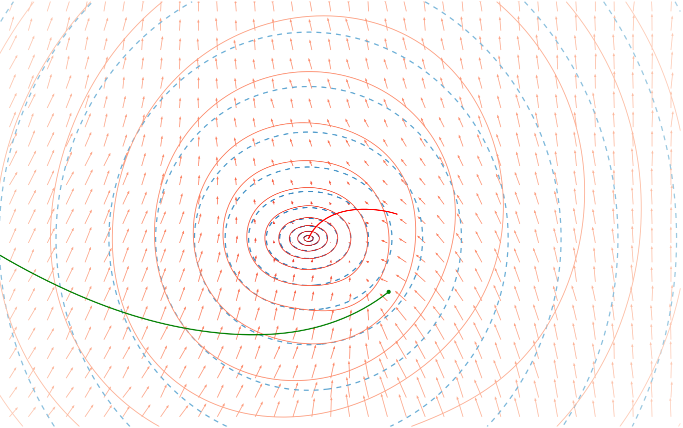
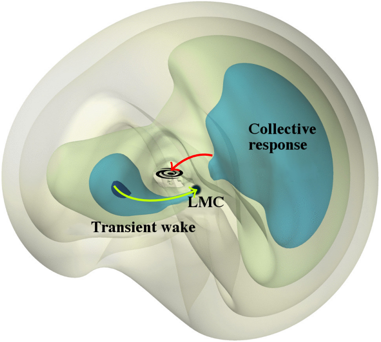
The Milky Way is pulled towards the LMC, but the displacement is not uniform in space.

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]

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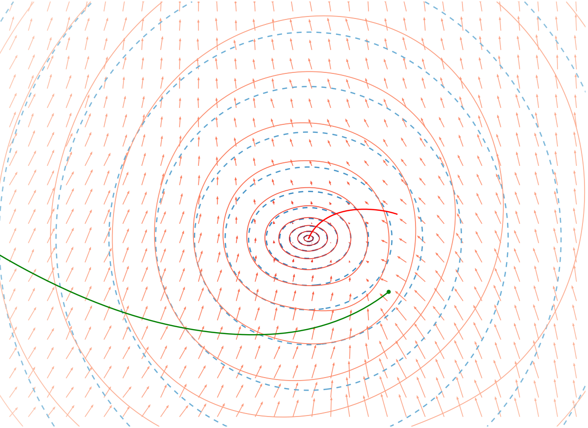
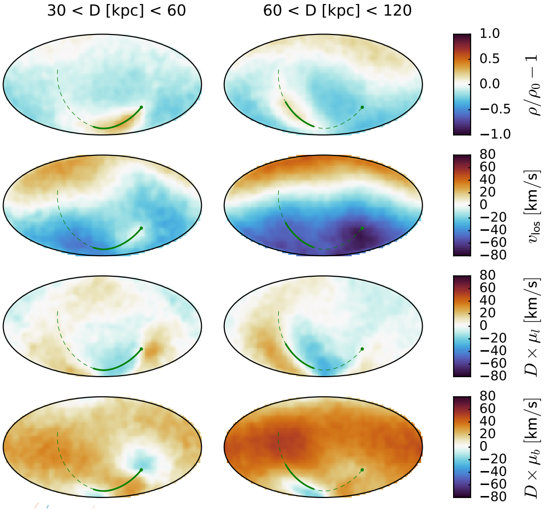
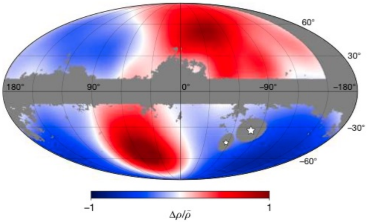


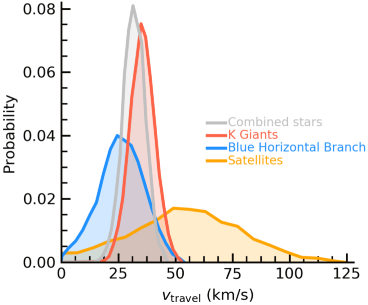


Global perturbation: predicted and observed signatures

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

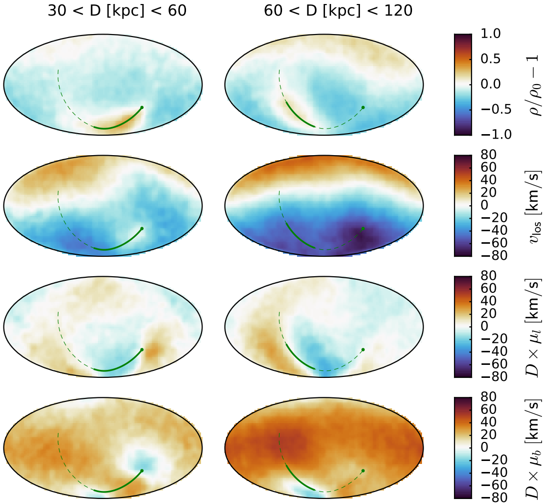


density polarization [Conroy+ 2021]

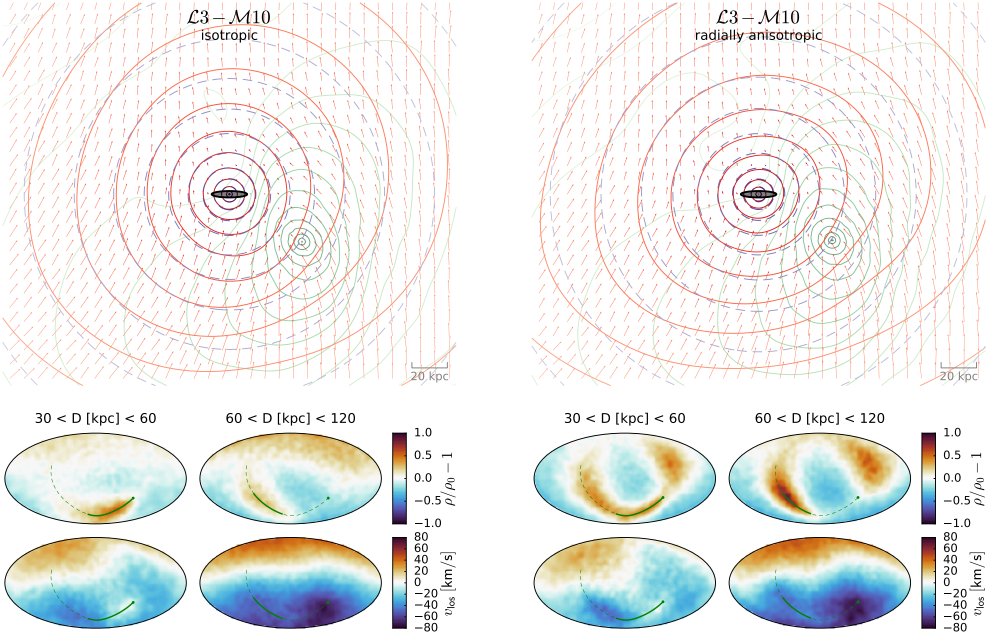


velocity offset

[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]

Measurement of the Milky Way potential

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

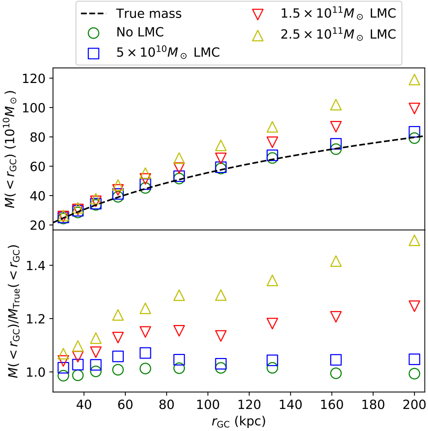
smoothly distributed populations:
assume dynamical equilibrium ⇒
density and velocity distributions
are linked through the potential

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].

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).

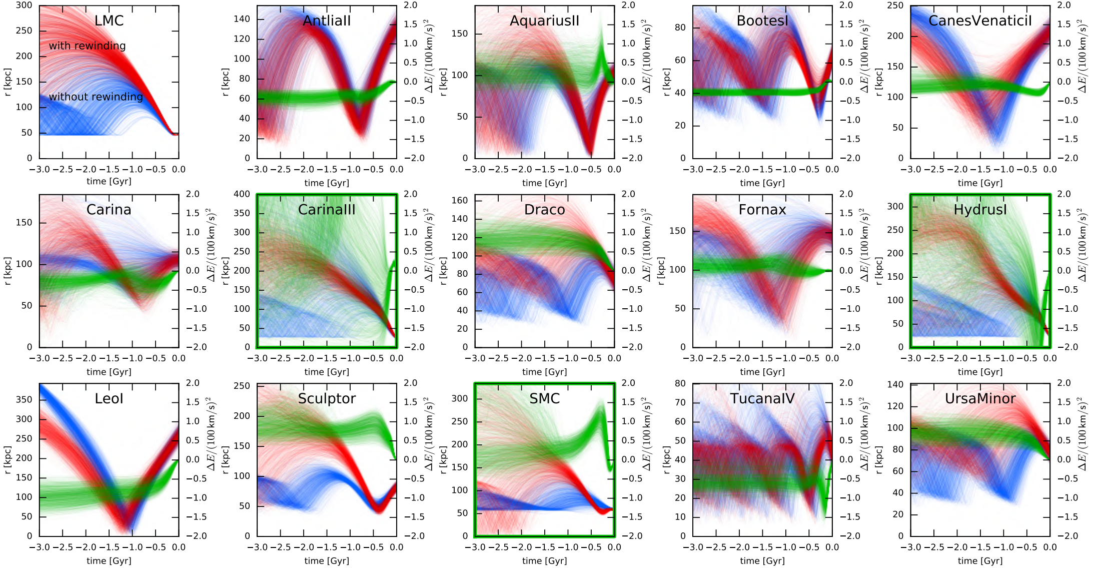
Vary the LMC mass, the parameters of the potential and the tracer DF
to maximize the likelihood of the *unperturbed* (rewound) dataset.

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].

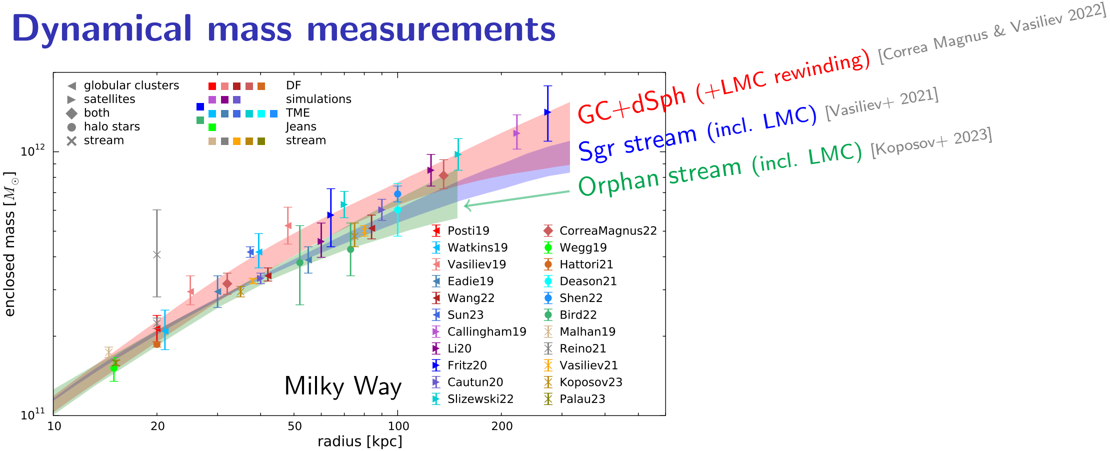
Changes in satellite orbits caused by the LMC

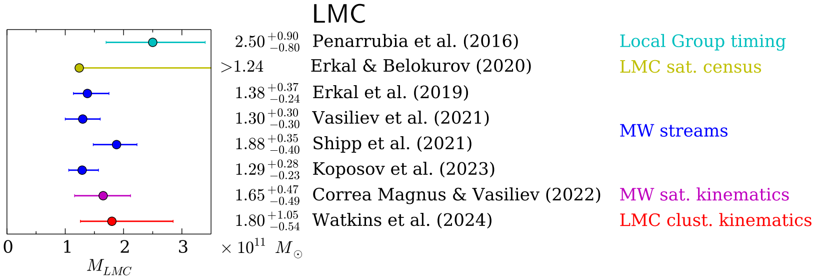
could be quite substantial!   shown are Galactocentric distances in the past 3 Gyr

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



Dynamical mass measurements





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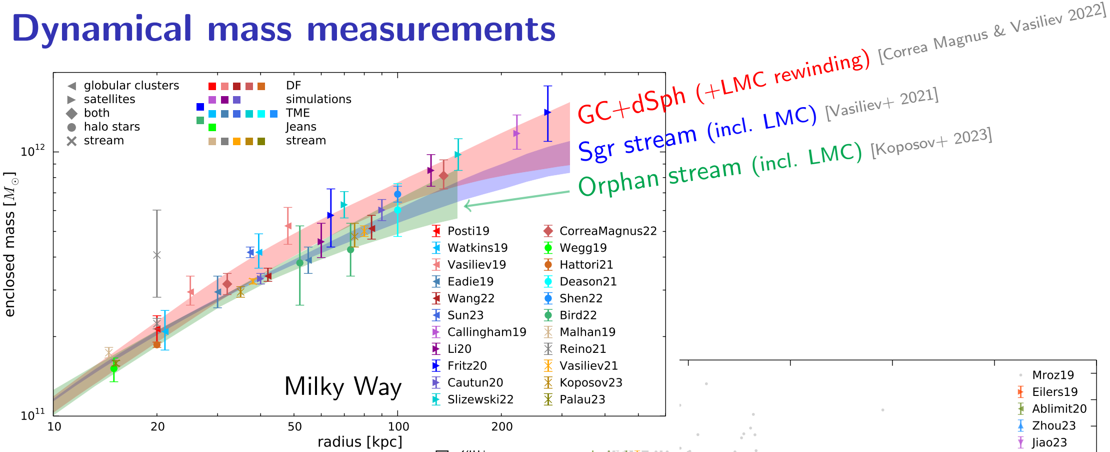
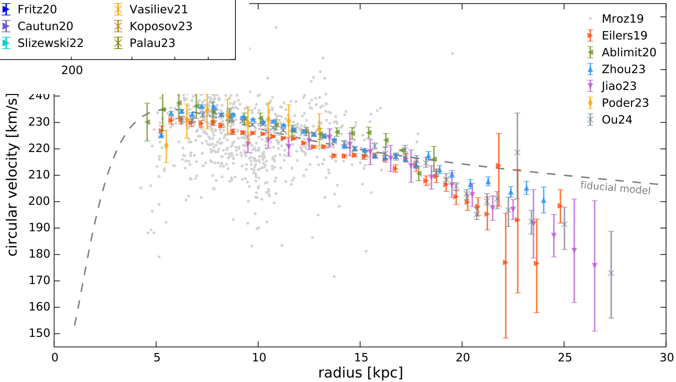
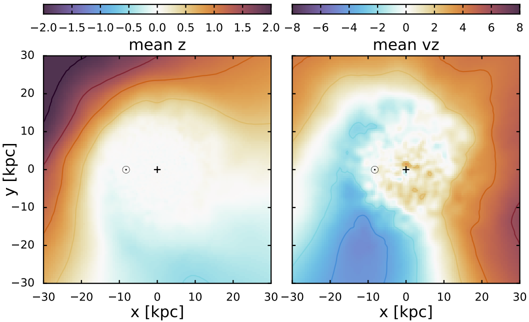




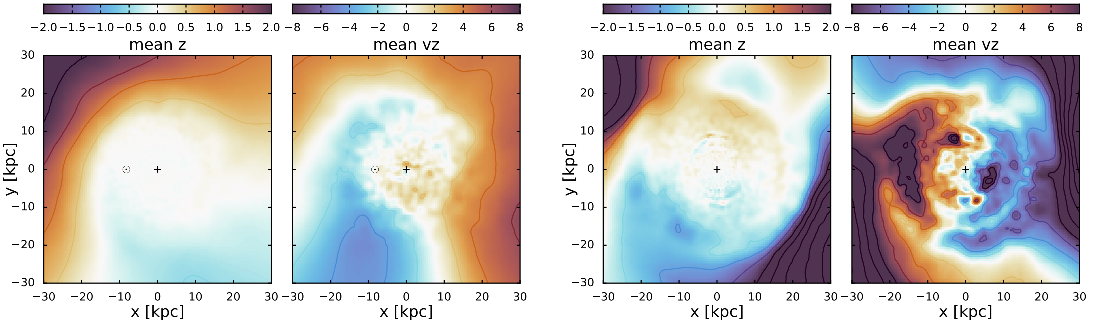
Circular-velocity curve inferred from Jeans modelling of disc stars sharply declines beyond 20 kpc, in contradiction with mass measurement further out. Is LMC the culprit here too?

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).

Perturbations in the MW disc



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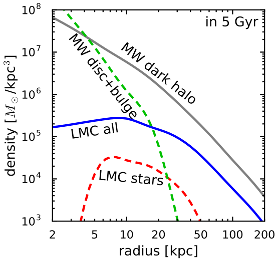
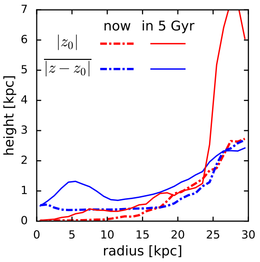
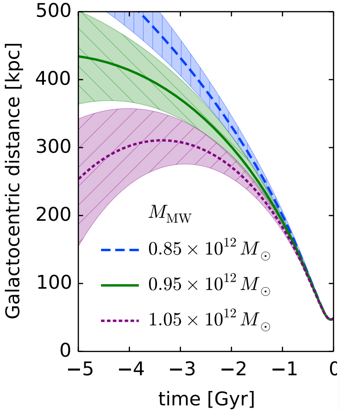
The warp will become much stronger in the future, the disc will be significantly heated, and the stellar halo will increase 4$\times$ in mass.

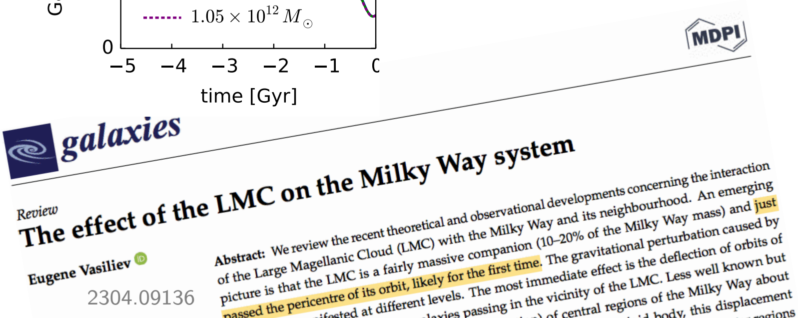




Past trajectory of the LMC

is very sensitive to the Milky Way mass!





galaxies

MDPI

Review

The effect of the LMC on the Milky Way system

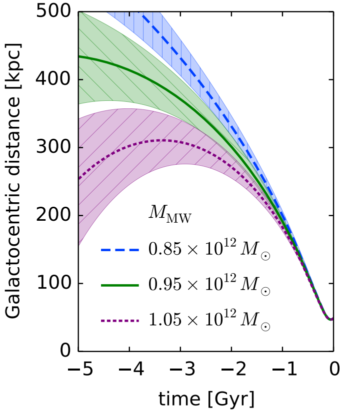
Eugene Vasiliev

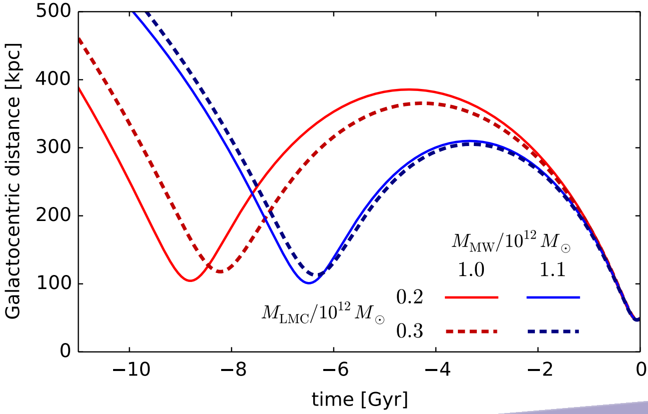
Abstract: We review the recent theoretical and observational developments concerning the interaction of the Large Magellanic Cloud (LMC) with the Milky Way and its neighbourhood. An emerging picture is that the LMC is a fairly massive companion (10–20% of the Milky Way mass) and just passed the pericentre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

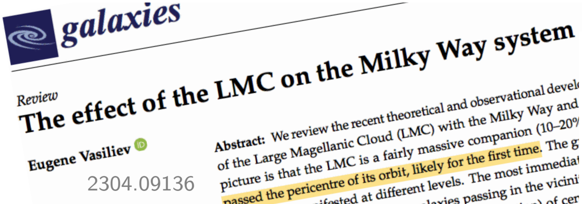
2304.09136

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

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

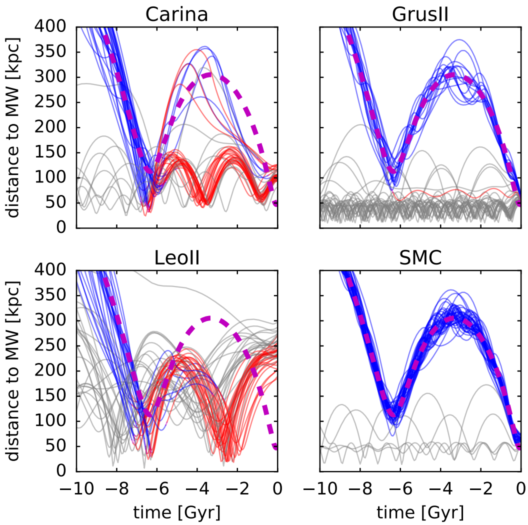
2306.04837

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
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

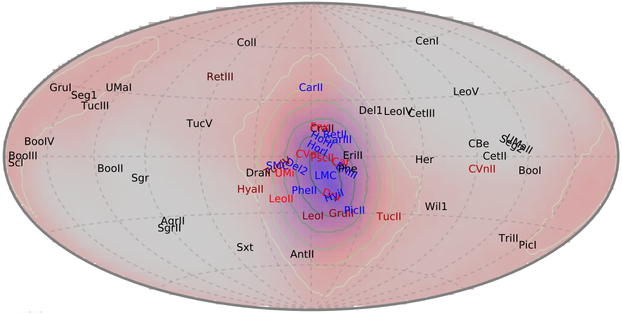
examples of possible past orbits

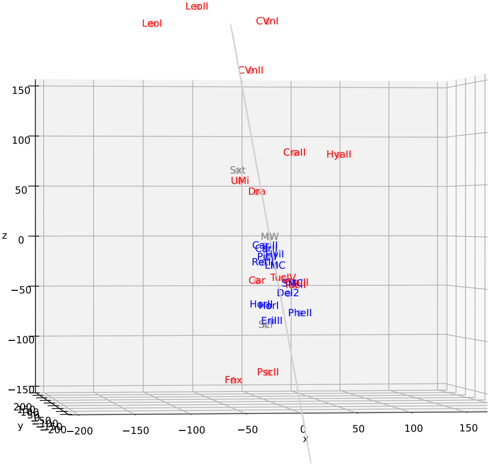


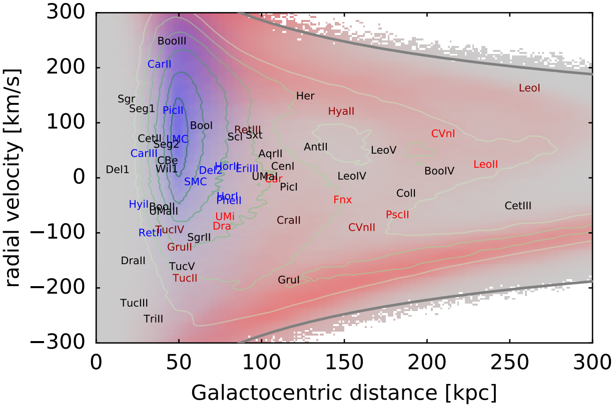
currently bound to LMC; formerly bound; MW-bound

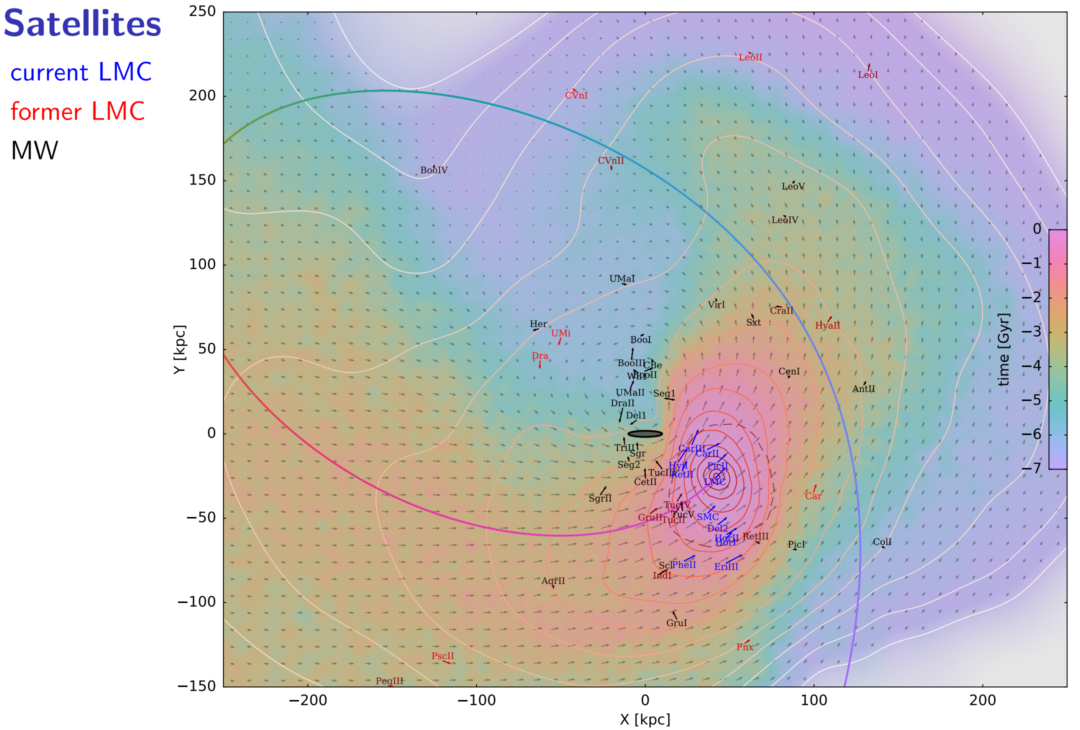
Satellites plane

Many satellite galaxies are located close to the LMC orbital plane and have similar orientations of angular momenta (a spatially and kinematically coherent structure).








Satellites
current LMC
former LMC
MW
Y [kpc]
X [kpc]
time [Gyr]
LeoII
LeoI
CVnI
CVnII
BooIV
LeoV
LeoIV
UMaI
VirI
CraII
Sxt
HyaII
Her
UMi
BooI
Dra
BooIII
CBe
WilI
UMaII
Seg1
DraII
Del1
CenI
AntII
TriII
Sgr
Seg2
CarIII
CarII
HyiI
PicII
RetII
TucIII
CetII
LMC
Car
SgrII
TucIV
TucV
GruII
TucII
SMC
Del2
HorII
HorI
RetIII
PicI
ColI
Scl
PheII
IndI
EriIII
AqrII
GruI
Fnx
PscII
PegIII

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

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