Eugene Vasiliev

The second coming of the LMC?

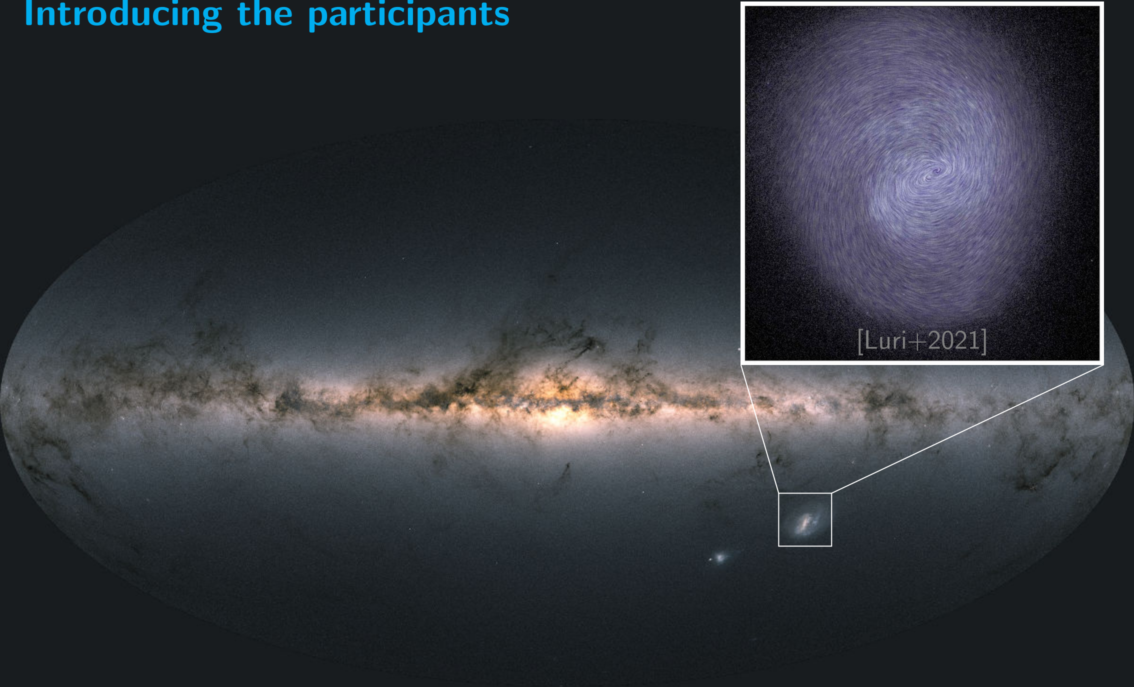
2304.09136
2306.04837

AIP seminar, 22 September 2023

Introducing the participants

credit: Gaia collaboration

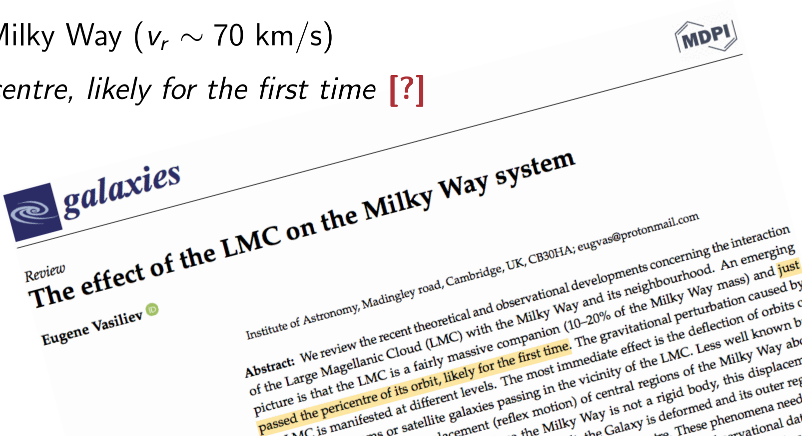
Introducing the participants



credit: Gaia collaboration

LMC factsheet

- stellar mass: $\sim 3 \times 10^9\ M_\odot$ [van der Marel+ 2002]
- total mass: $\sim (1-2) \times 10^{11}\ M_\odot$ [Erkal+ 2019; Shipp+ 2021; Koposov+ 2023; ...]
- current distance: ~ 50 kpc [Pietrzyński+ 2019]
- high tangential velocity ($\gtrsim 300$ km/s) [Kallivayalil+ 2006, 2014]
- receding from the Milky Way ($v_r \sim 70$ km/s)
- *just passed its pericentre, likely for the first time* [?]


galaxies
MDPI

Review

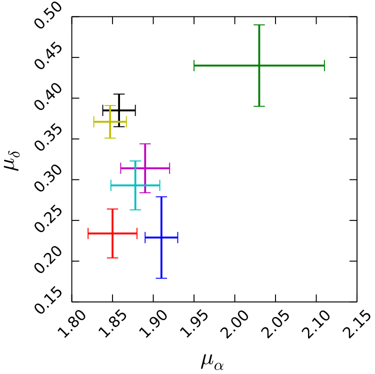
The effect of the LMC on the Milky Way system

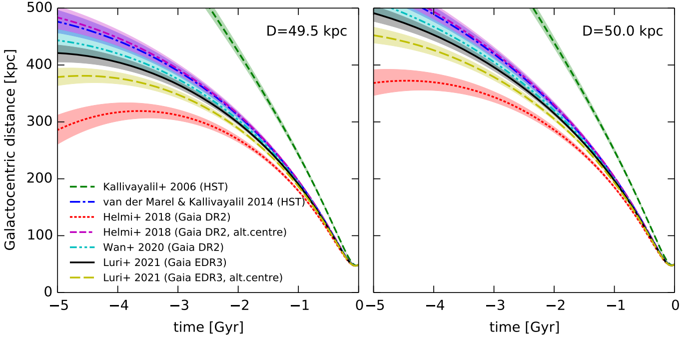
Eugene Vasiliev

Institute of Astronomy, Madingley road, Cambridge, UK, CB30HA; eugvas@protonmail.com

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 ... LMC is manifested at different levels. The most immediate effect is the deflection of orbits o... ...ms or satellite galaxies passing in the vicinity of the LMC. Less well known b... ...lacement (reflex motion) of central regions of the Milky Way ab... ...the Milky Way is not a rigid body, this displacem... ...the Galaxy is deformed and its outer reg... ...re. These phenomena need... ...rvational dat...

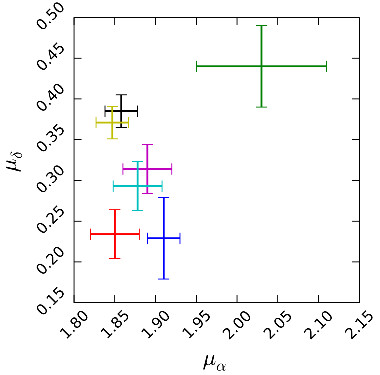
Sensitivity of the inferred LMC trajectory





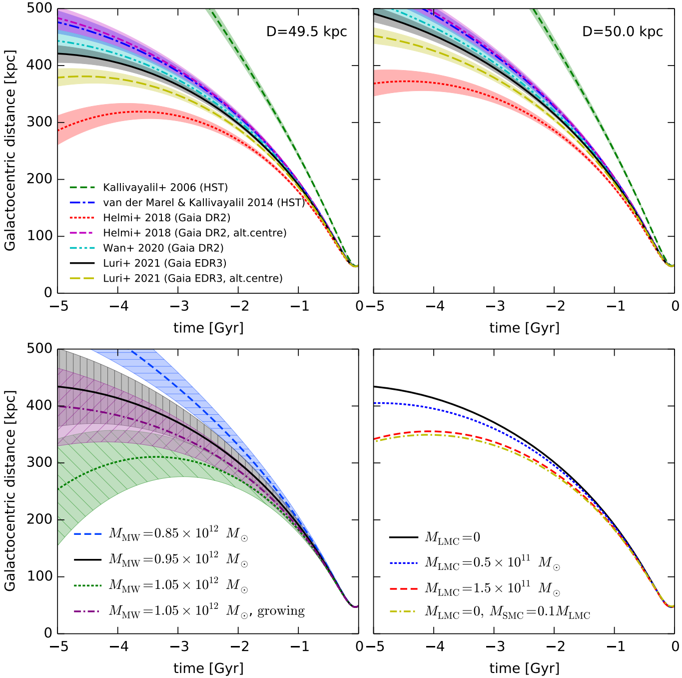
to the measured PM and distance

Sensitivity of the inferred LMC trajectory

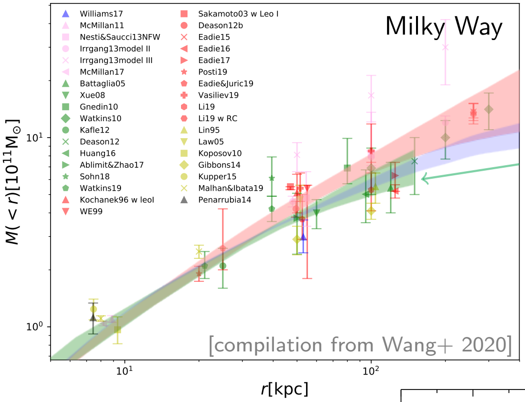


to the measured PM and distance

and to the assumed MW potential and LMC mass



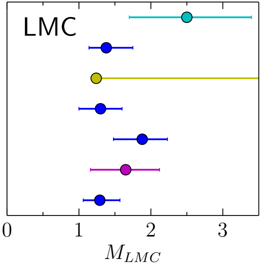
Masses of the Milky Way and the LMC



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

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

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

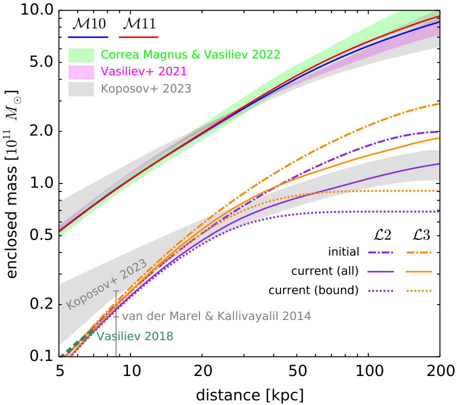


$2.50^{+0.90}_{-0.80}$	Penarrubia et al. (2016)
$1.38^{+0.37}_{-0.24}$	Erkal et al. (2019)
>1.24	Erkal & Belokurov (2020)
$1.30^{+0.30}_{-0.30}$	Vasiliev et al. (2021)
$1.88^{+0.35}_{-0.40}$	Shipp et al. (2021)
$1.65^{+0.47}_{-0.49}$	Correa Magnus & Vasiliev (2022)
$1.29^{+0.28}_{-0.23}$	Koposov et al. (2023)

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

Local Group — sat. census — streams — sat. kinem.

Initial models of both galaxies



	model	r_s	r_c [kpc]	r_{vir}	M_{vir} [$10^{11}\ M_\odot$]	M_{total}	N_{body} [10^6]
LMC halo	$\mathcal{L}2$	8.95	160.9	150	1.92	2.0	2
	$\mathcal{L}3$	11.7	220.6	169	2.76	3.0	
MW halo	$\mathcal{M}10$	15.0	500	260	10.0	11.8	7
	$\mathcal{M}11$	16.5	500	268	11.0	12.9	
MW stars	see equations below					0.62	1

$$\rho_{\text{halo}} \propto r^{-1} \left(1 + r/r_s\right)^{-2} \exp\left[-\left(r/r_c\right)^4\right]$$

$$\rho_{\text{bulge}} \propto \left(1 + r/0.2\,\text{kpc}\right)^{-1.8} \exp\left[-\left(r/1.8\,\text{kpc}\right)^2\right]$$

$$M_{\text{bulge}} = 1.2 \times 10^{10}\ M_\odot$$

$$\rho_{\text{disc}} \propto \exp\left[-R/3\,\text{kpc}\right] \cosh^{-2}\left[z/0.5\,\text{kpc}\right]$$

$$M_{\text{disc}} = 5 \times 10^{10}\ M_\odot$$

N-body simulations using GYRFALCON [Dehnen 2000], one full-res run (10^7 particles) = 40h

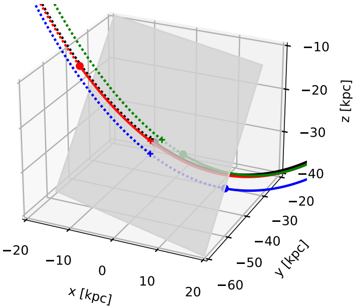
Fitting the present-day position/velocity of the LMC

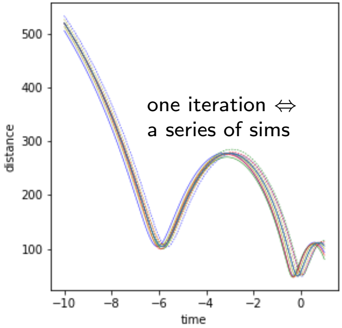
Need an accuracy better than 1 kpc and 1 km/s for a meaningful comparison of models!

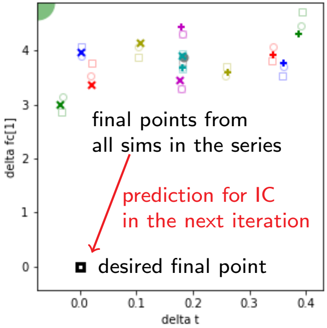
Three key technical developments:

- extract smooth trajectories of MW and LMC from *N*-body sims;
- nonlinear coordinate transformation to "straighten" a curvilinear trajectory;
- Newton iterative method with a Jacobian determined from an ensemble of nearby orbits.

Reach an acceptable solution in 5–8 iteration (using low-res sims at the initial stages);
a Jupyter notebook illustrating the method is included in the repository (zenodo/8015660).





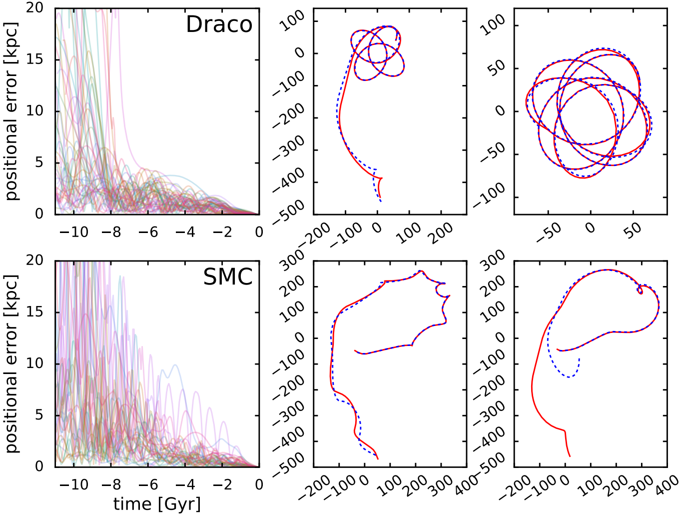


“Replaying” the simulation using a smooth evolving potential

Snapshots from the original N-body simulation $\Longrightarrow$ a series of `Multipole` or `BasisSet` potential expansions representing both galaxies moving on pre-recorded trajectories.

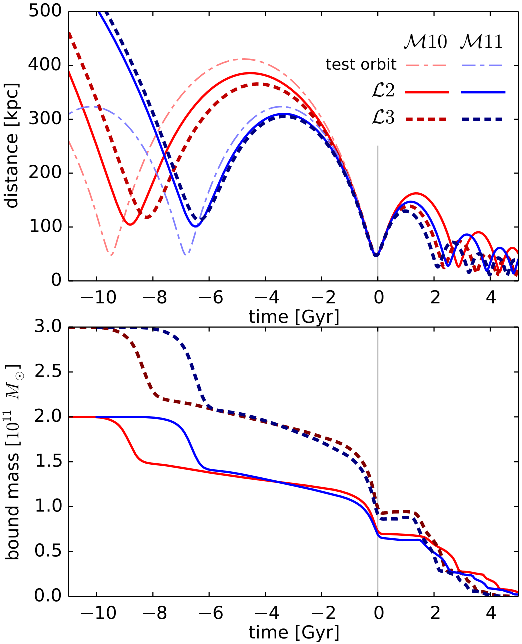
Can be used to reconstruct [approximately] the orbits of all particles in the simulation, as well as any other trajectory not present in the simulation.

[Lowing+ 2011; Sanders+ 2020]



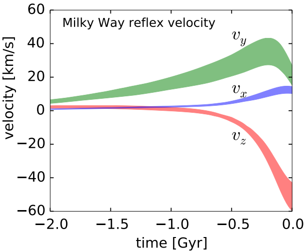
Past LMC orbits in the second-passage scenario

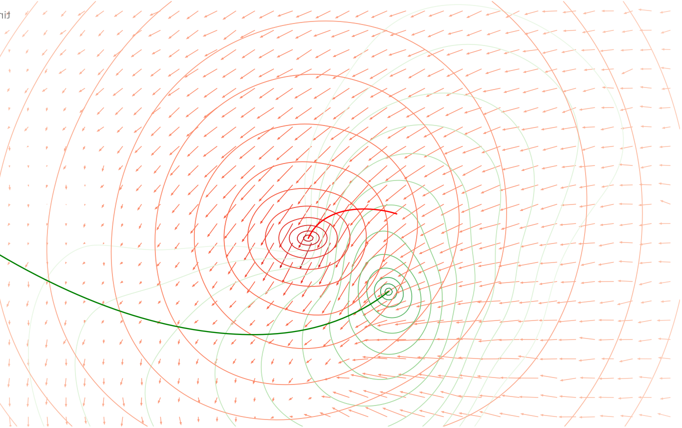
- previous orbital period: 6–10 Gyr ($\lesssim$ 10% difference in the MW mass $\Rightarrow$ $\gtrsim$ 30% difference in period!)
- previous pericentre distance: $\sim$ 100 kpc;
- more massive LMC $\Leftrightarrow$ shorter period: dynamical friction increases the period [Kallivayalil+2013, Gomez+ 2015], but the stronger gravitational pull from the LMC more than compensates this [e.g., Patel+ 2017, 2020];
- 1/3 of initial LMC mass is lost after the first pericentre passage; present-day bound mass is another 2× lower than 1 Gyr ago.



Global perturbation of MW halo

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

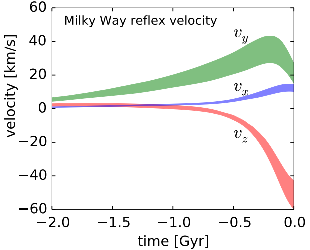


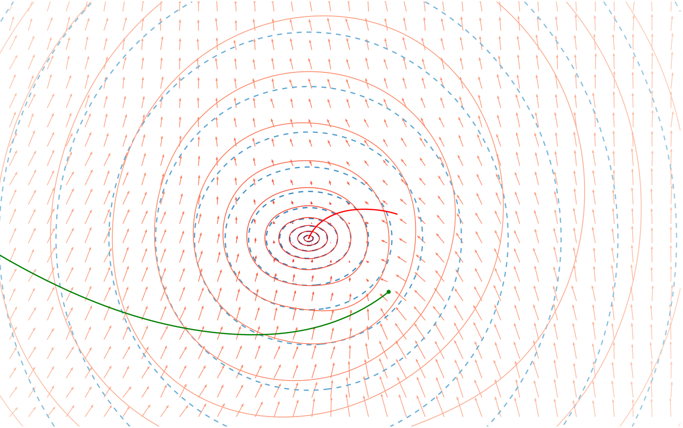


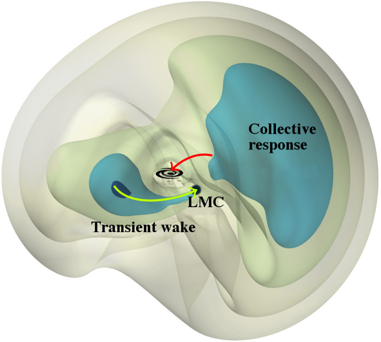
Global perturbation of MW halo

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".





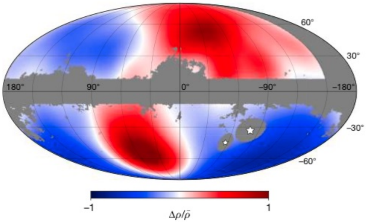


N-body sims [Garavito-Camargo+ 2021, see also Petersen & Peñarrubia 2020], perturbation theory [Rozier+ 2022]

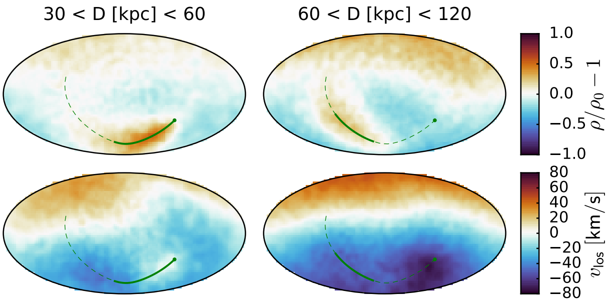
Global perturbation: predicted and observed signatures

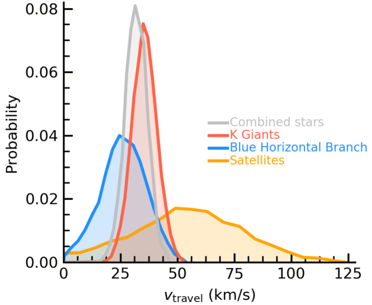
Since the MW is pulled "down" (in z) recently, perturbation is most visible in the north–south asymmetry of density and line-of-sight velocities at distances $\gtrsim 30$ kpc

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



density polarization [Conroy+ 2021]

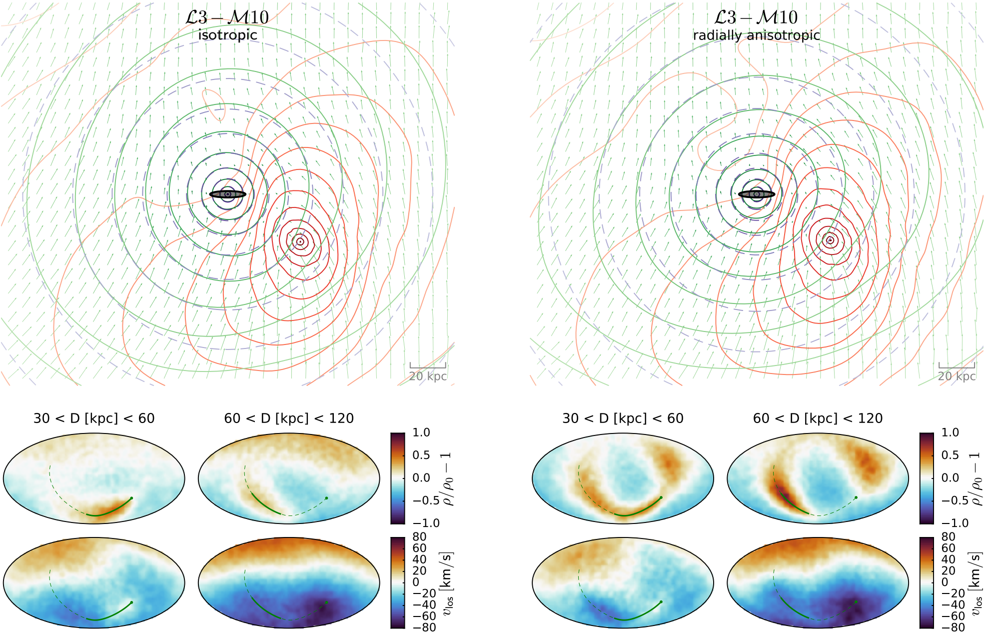




velocity offset [Petersen & Peñarrubia 2021, see also Erkal+ 2021]

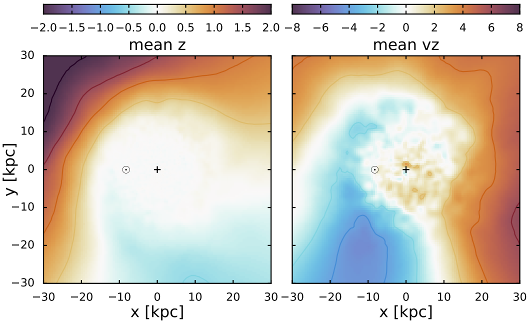
No difference between first- and second-passage scenarios!:(

Sensitivity of the MW halo deformation to velocity anisotropy



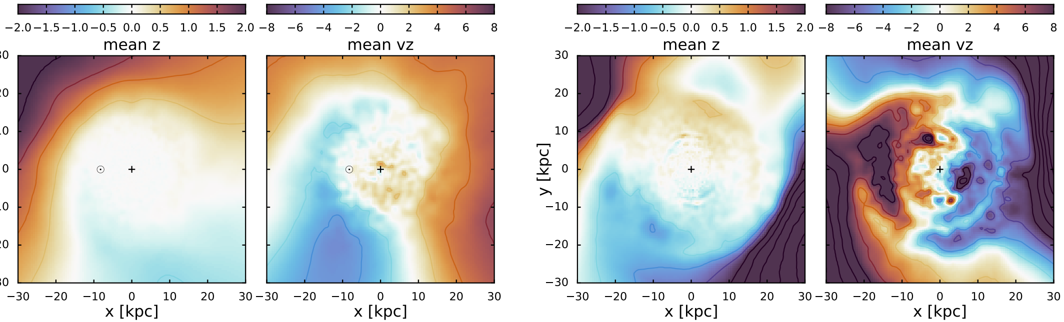
[see also Rozier+ 2022]

Perturbations in the MW disc



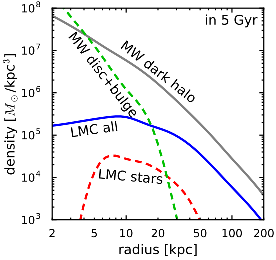
LMC induces a noticeable warp in the MW disc at distances $\gtrsim$ 15 kpc, qualitatively similar to the observed one (but smaller in amplitude; see also Laporte+2018a,b).

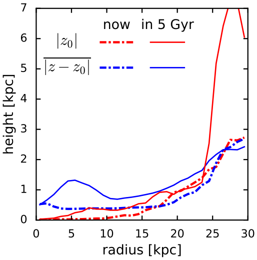
Perturbations in the MW disc

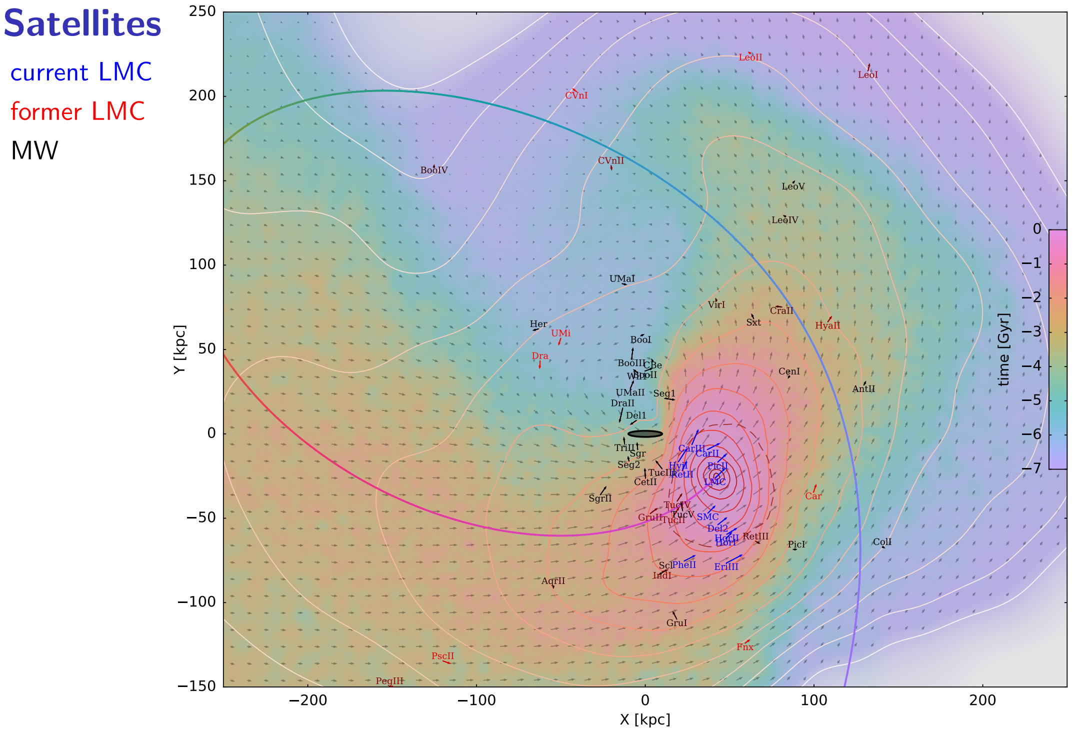


LMC induces a noticeable warp in the MW disc at distances $\gtrsim 15$ kpc, qualitatively similar to the observed one (but smaller in amplitude; see also Laporte+2018a,b).

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



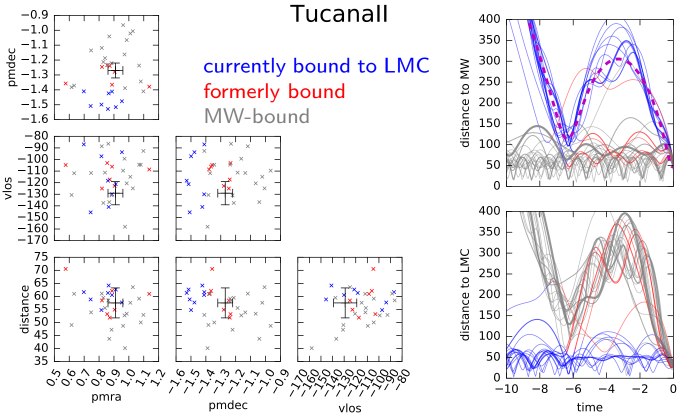




Satellites
current LMC
former LMC
MW
Y [kpc]
X [kpc]
time [Gyr]
250
200
150
100
50
0
−50
−100
−150
−200
−100
0
100
200
0
−1
−2
−3
−4
−5
−6
−7
LeoII
LeoI
CVnI
CVnII
BooIV
LeoV
LeoIV
UMaI
VirI
CraII
Sxt
HyaII
Her
UMi
BooI
Dra
BooIII
CBe
Wil1
BooII
CenI
AntII
UMaII
Seg1
DraII
Del1
TriII
Sgr
CarIII
CarII
Seg2
HyiI
PicII
TucIII
RetII
CetII
LMC
SgrII
Car
TucIV
GruII
TucV
TucII
SMC
Del2
HorII
RetIII
HorI
PicI
ColI
Scl
PheII
EriIII
IndI
AqrII
GruI
Fnx
PscII
PegIII

Classification of satellites using three different methods

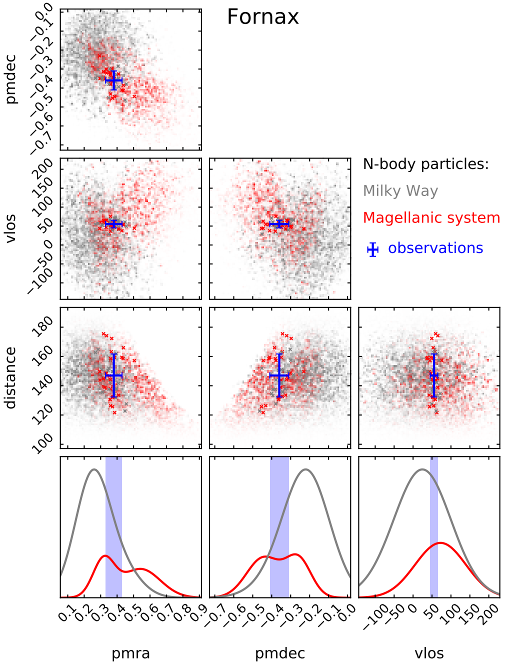
1. particles from the simulation:
   select particles from the present-day snapshot with probability proportional to the distance between the satellite and the particle in the space of observables (sky position, PM, $v_{\rm los}$, heliocentric distance), normalized by uncertainty in the satellite coordinates:
   $\mathcal{P}_i \propto \exp\big[-\frac{1}{2}(\mathbf{x}_{\rm sat} - \mathbf{x}_i)^T \; \mathsf{E}_{\rm sat}^{-1} \; (\mathbf{x}_{\rm sat} - \mathbf{x}_i)\big]$;
   then count the fraction of matching particles coming from the Magellanic system:
   $\mathcal{P}_{\rm sat,LMC} = \big[\sum_{i\in \rm LMC} \mathcal{P}_i\big] / \big[\sum_i \mathcal{P}_i\big]$.



Classification of satellites using three different methods

2. Gaussian mixture in velocity space (PM + v_{los}) from the simulation:

   build two GMMs from all MW and LMC particles within spatial region around the satellite, then evaluate $\mathcal{P}_{\mathrm{sat,MW}}$ and $\mathcal{P}_{\mathrm{sat,LMC}}$ from these smooth probability distributions.

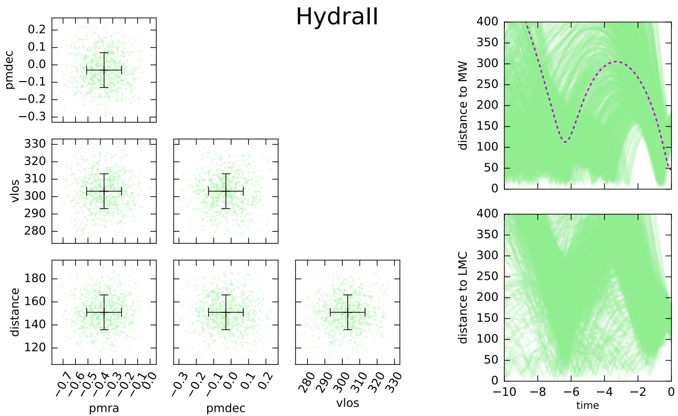


Classification of satellites using three different methods

3. orbit rewinding:

sample a large number of points from the observational uncertainties in the satellite coordinates;

integrate orbits backward in time in the pre-recorded smooth evolving potential extracted from the simulation to obtain the initial phase-space coordinates 10 Gyr ago;



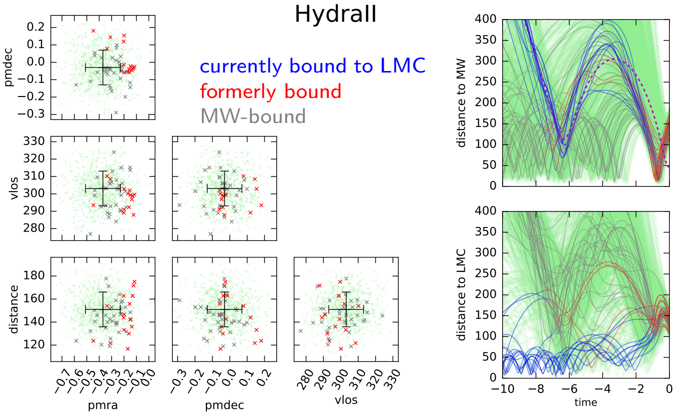
Classification of satellites using three different methods

3. orbit rewinding:

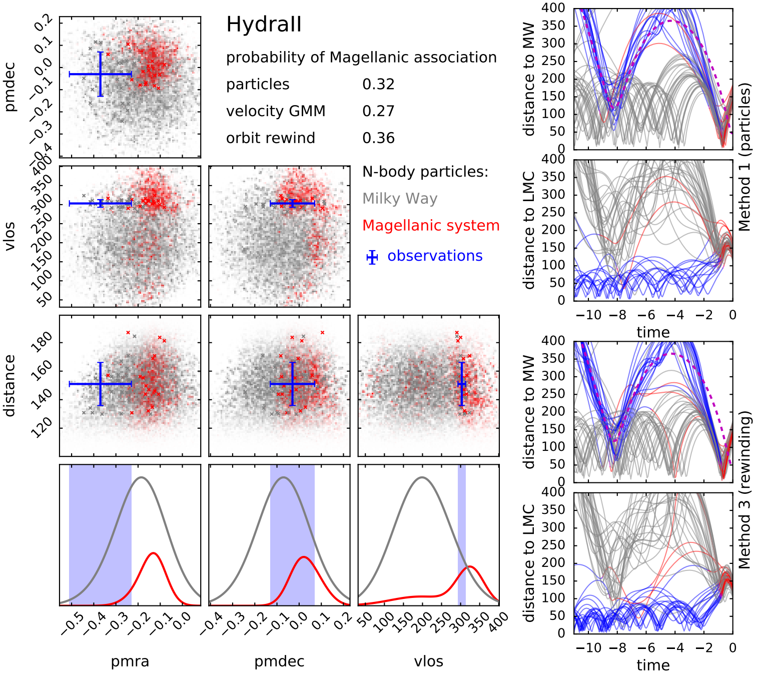
sample a large number of points from the observational uncertainties in the satellite coordinates;

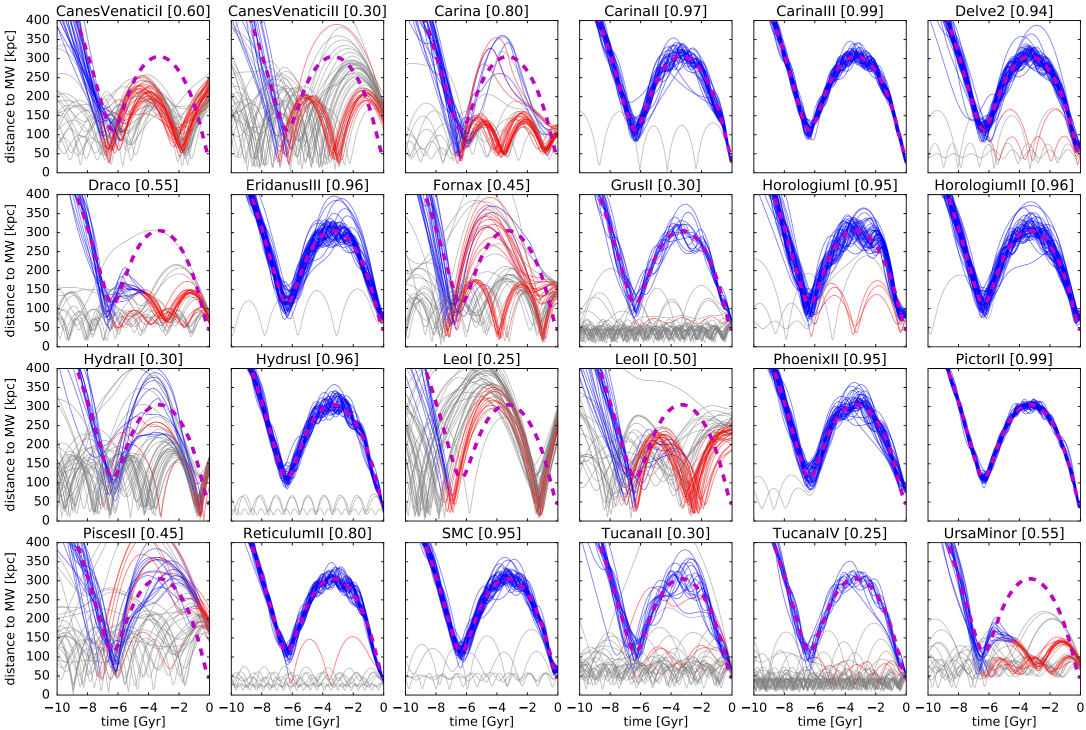
integrate orbits backward in time in the pre-recorded smooth evolving potential extracted from the simulation to obtain the initial phase-space coordinates 10 Gyr ago;

reweight the orbits according to the distribution functions of MW and LMC evaluated at these initial phase-space points, and count the fraction of LMC-associated orbits.



Classification of satellites using three different methods

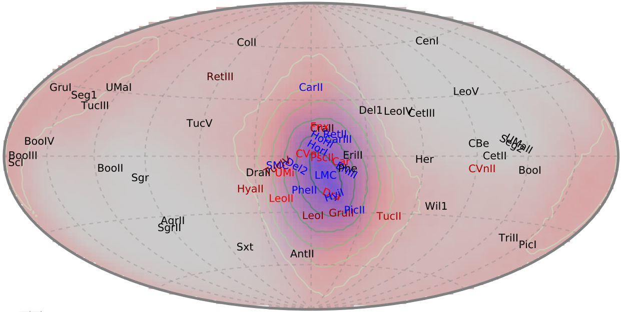


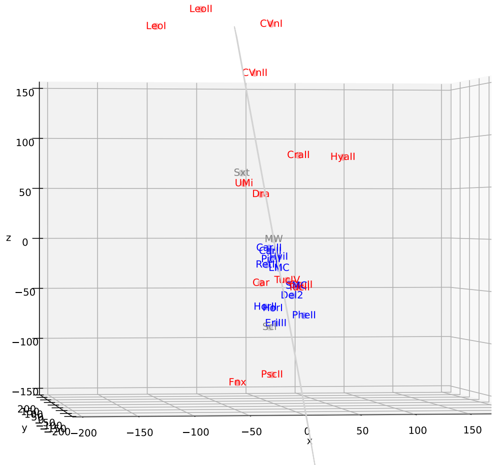


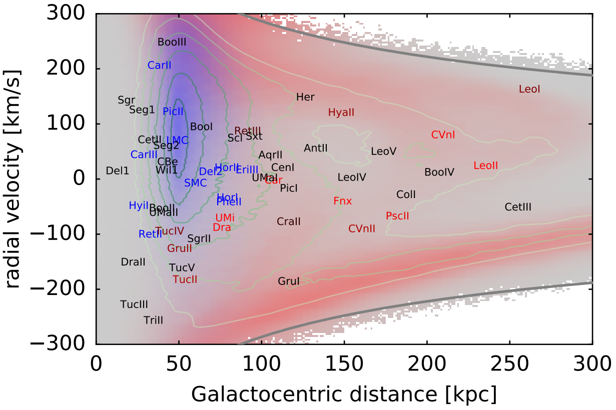
CanesVenaticiI [0.60]
CanesVenaticiII [0.30]
Carina [0.80]
CarinaII [0.97]
CarinaIII [0.99]
Delve2 [0.94]
Draco [0.55]
EridanusIII [0.96]
Fornax [0.45]
GrusII [0.30]
HorologiumI [0.95]
HorologiumII [0.96]
HydraII [0.30]
HydrusI [0.96]
LeoI [0.25]
LeoII [0.50]
PhoenixII [0.95]
PictorII [0.99]
PiscesII [0.45]
ReticulumII [0.80]
SMC [0.95]
TucanaII [0.30]
TucanaIV [0.25]
UrsaMinor [0.55]
distance to MW [kpc]
time [Gyr]
0
50
100
150
200
250
300
350
400
−10
−8
−6
−4
−2
0

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).

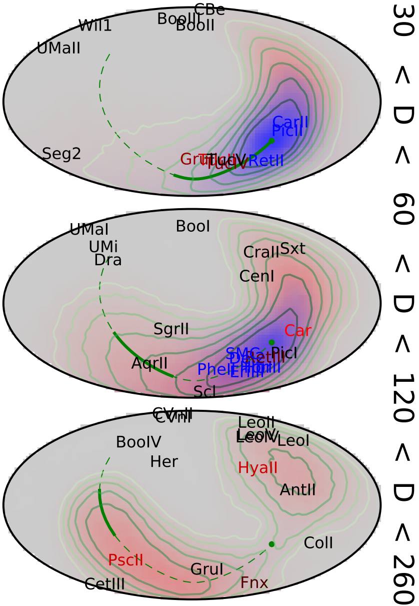




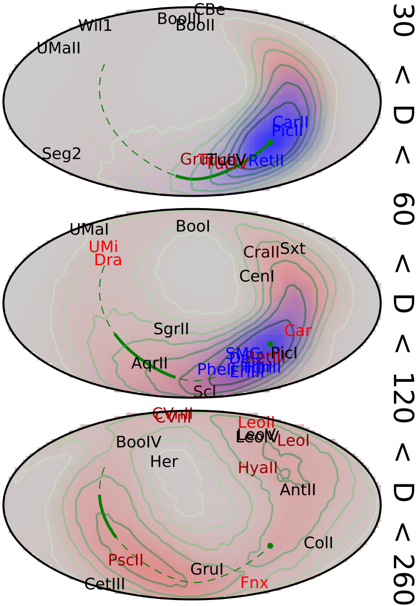


Satellites in the first- and second-passage scenarios

$\mathcal{L}2-\mathcal{M}10$, first passage



$\mathcal{L}3-\mathcal{M}10$, second passage



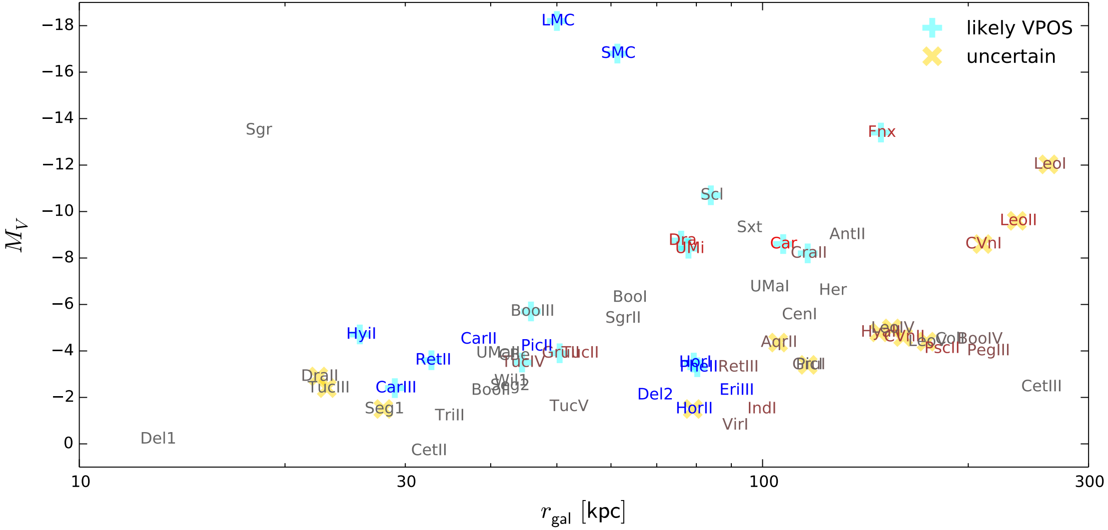
Difference:

CVen I
CVen II
Draco
Fornax
Leo I
Leo II
Ursa Minor

Satellites plane from the accretion of the Magellanic system?

This analysis suggests that many of the satellites belonging to VPOS *may* have been accreted during the previous passage of the LMC (in the second-passage scenario), but does not address the question how likely is this scenario itself.

[Taibi+ 2023 subm.]



Summary

- LMC is currently only marginally bound to the Milky Way $\Rightarrow$ past orbit is *very* sensitive to small changes in its observed velocity or the assumed Galactic potential.
- A second-passage scenario with a previous pericentre at ~ 100 kpc some 6–10 Gyr ago is *possible*, but not *mandated* (it mainly depends on the Milky Way mass).
- Perturbations in the Galactic halo or disc are produced very recently $\Rightarrow$ contain no information about previous passage.
- Many satellite galaxies (in particular, belonging to the satellite plane) have a considerable chance of being accreted from the Magellanic system.
- The simulations presented here should be viewed as a proof-of-concept, and need to be followed by a more cosmologically motivated setup (e.g., filamentary accretion?).