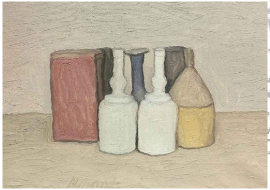
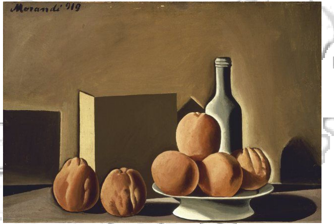





Eugene Vasiliev

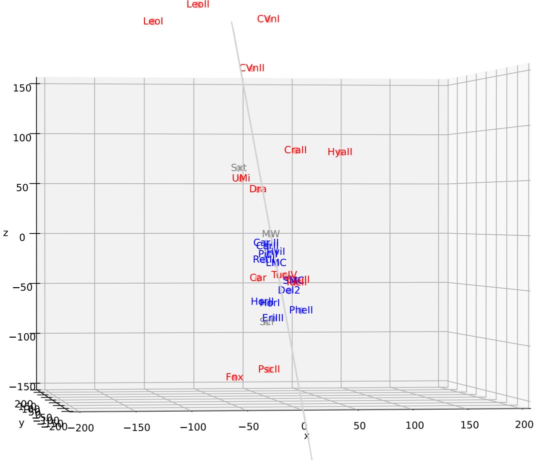
A Magellanic origin of the satellite plane?



The Milky Way Assembly Tale, Bologna, 29 May 2024

The 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) [Kroupa+ 2005; Pawlowski+ 2012].



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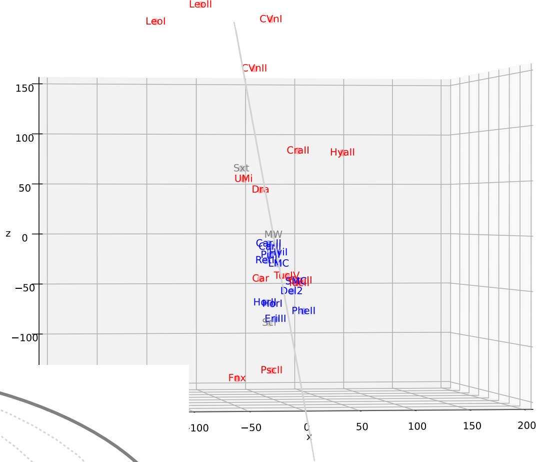

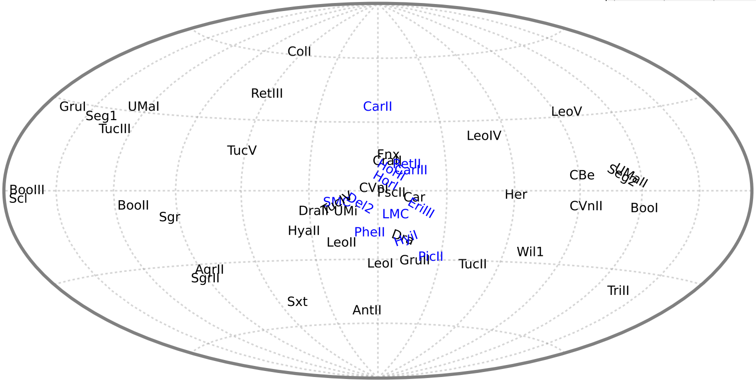

distribution of orbital poles using Gaia PM [Fritz+ 2018; Pawlowski & Kroupa 2020]

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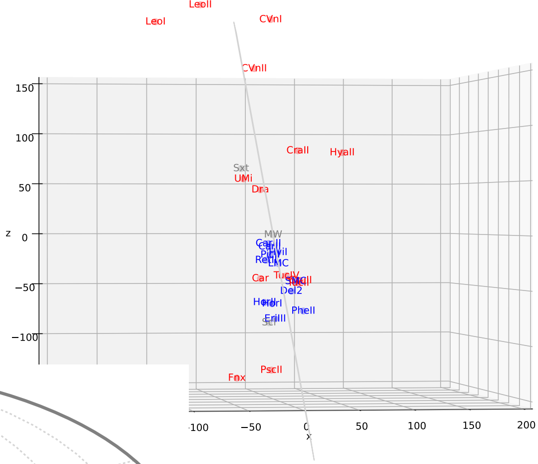

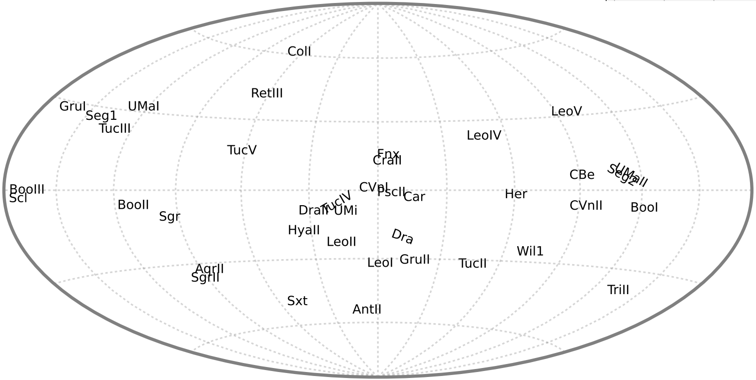

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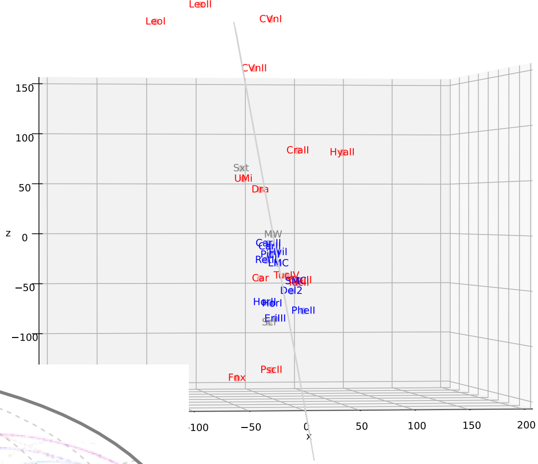

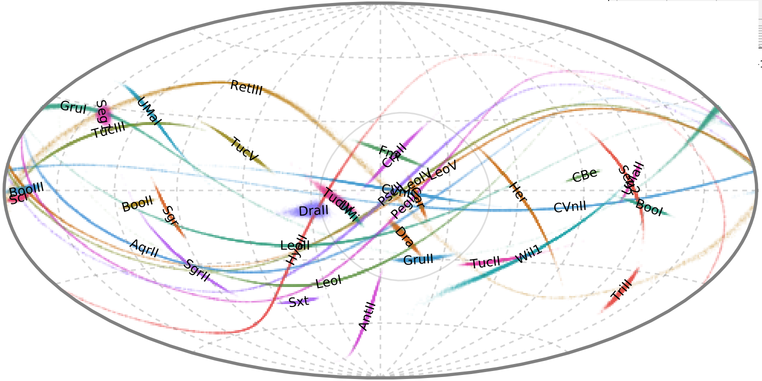

distribution of orbital poles using Gaia PM [Fritz+ 2018; Pawlowski & Kroupa 2020]

removing LMC satellites

adding PM uncertainties

Can LMC affect orbits of other dSph around the Milky Way?

The Astrophysical Journal, 923:140 (17pp), 2021 December 20
https://doi.org/10.3847/1538-4357/ac2c05

The Clustering of Orbital Poles Induced by the LMC: Hints for the Origin of Planes of Satellites

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Received 2021 June 17; revised 2021 September 16; accepted 2021 September 25; published 2021 December 16

Abstract

A significant fraction of Milky Way (MW) satellites exhibit phase-space properties consistent with a coherent orbital plane. Using tailored *N*-body simulations of a spherical MW halo that recently captured a massive ($1.8 \times 10^{11}\,M_\odot$) LMC-like satellite, we identify the physical mechanisms that may enhance the clustering of orbital poles of objects orbiting the MW. The LMC deviates the orbital poles of MW dark matter particles from the present-day random distribution. Instead, the orbital poles of particles beyond $R \approx 50$ kpc cluster near the present-day orbital pole of the LMC along a sinusoidal pattern across the sky. The density of orbital poles is enhanced near the LMC by a factor $\delta\rho_{max} = 30\%$ (50%) with respect to underdense regions and $\delta\rho_{iso} = 15\%$ (30%) relative to the isolated MW simulation (no LMC) between 50 and 150 kpc (150–300 kpc). The clustering appears after the LMC's pericenter (≈50 Myr ago, 49 kpc) and lasts for at least 1 Gyr. Clustering occurs because of three effects: (1) the LMC shifts the velocity and position of the central density of the MW's halo and disk; (2) the dark matter dynamical friction wake and collective response induced by the LMC change the kinematics of particles; (3) observations of particles selected within spatial planes suffer from a bias, such that measuring orbital poles in a great circle in the sky enhances the probability of their orbital poles being clustered. This scenario should be ubiquitous in hosts that recently captured a massive satellite (at least ≈1:10 mass ratio), causing the clustering of orbital poles of halo tracers.

The Astrophysical Journal, 932:70 (10pp), 2022 June 10
https://doi.org/10.3847/1538-4357/ac6ce0

On the Effect of the Large Magellanic Cloud on the Orbital Poles of Milky Way Satellite Galaxies

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Received 2021 November 4; revised 2022 April 22; accepted 2022 May 3; published 2022 June 16

Abstract

The reflex motion and distortion of the Milky Way (MW) halo caused by the infall of a massive Large Magellanic Cloud (LMC) has been demonstrated to result in an excess of orbital poles of dark matter halo particles toward the LMC orbital pole. This was suggested to help explain the observed preference of MW satellite galaxies to coorbit along the Vast Polar Structure (VPOS). We test this idea by correcting the positions and velocities of the MW satellites for the Galactocentric-distance-dependent shifts inferred from a LMC-infall simulation. While this should substantially reduce the observed clustering of orbital poles if it were mainly caused by the LMC, we instead find that the strong clustering remains preserved. We confirm the initial study's main result with our simulation of an MW-LMC-like interaction, and use it to identify two reasons why this scenario is unable to explain the VPOS: (1) the orbital pole density enhancement in our simulation is very mild (~10% within 50–250 kpc) compared to the observed enhancement (~220%–300%), and (2) it is very sensitive to the specific angular momenta (AM) of the simulation particles, with the higher-AM particles being affected the least. Particles in simulated dark matter halos tend to follow more radial orbits (lower AM), so their orbital poles are more easily affected by small offsets in position and velocity caused by a LMC infall than objects with more tangential velocity (higher AM), such as the observed dwarf galaxies surrounding the MW. The origin of the VPOS thus remains unexplained.

On the co-rotation of Milky Way satellites: LMC–mass satellites induce *apparent* motions in outer halo tracers

Nicolás Garavito-Camargo[1], Adrian M. Price-Whelan[1], Jenna Samuel[2,*], Emily C. Cunningham[3,1], Ekta Patel[4], Andrew Wetzel[5], Kathryn V. Johnston[3], Arpit Arora[6], Robyn E. Sanderson[6], Lehman Garrison[1], and Danny Horta[1]
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[6] Department of Physics & Astronomy, University of Pennsylvania, 209 S 33rd St, Philadelphia, PA 19104, USA

ABSTRACT

Understanding the physical mechanism behind the formation of a co-rotating thin plane of satellite galaxies, like the one observed around the Milky Way (MW), has been challenging. The perturbations induced by a massive satellite galaxy, like the Large Magellanic Cloud (LMC) provide valuable insight into this problem. The LMC induces an apparent co-rotating motion in the outer halo by displacing the ... of the halo with respect to the outer halo. Using the *Latte* suite of FIRE-2 cosmological ... firm that the *apparent* motion of the outer halo induced by ... poles of outer-halo tracers,

MNRAS 511, 2610–2630 (2022)
Advance Access publication 2021 December 30

Measuring the Milky Way mass distribution in the presence of the LMC

Lilia Correa Magnus[1★] and Eugene Vasiliev[2,3★]

However, if we 'undo' the LMC perturbation in the same way as for v_z, i.e. rewinding orbits in a time-dependent MW + LMC potential and then bringing them back to present time in a static MW potential, the resulting distribution of orbital poles does not significantly change (right-hand panel) and still remains rather non-uniform; thus the LMC perturbation cannot be the main cause of the orbital pole clustering (the same conclusion is independently reached by Pawlowski et al. 2021).

LMC and the Milky Way dynamics

- $M_{\rm LMC} \simeq (1-2)\times 10^{11}\,M_\odot$ [Erkal+ 2019; Shipp+ 2021; Koposov+ 2023; ...]
- deflection of stellar streams [Koposov+ 2019; Fardal+ 2019; Vasiliev+ 2021; Lilleengen+ 2022]
- dipole perturbation of the outer halo [Garavito-Camargo+ 2019, 2021; Cunningham+ 2020; Petersen & Peñarrubia 2020, 2021; Erkal+ 2021; Conroy+ 2021; Makarov+ 2023; Chandra+ 2023; ...]
- high tangential velocity ($\gtrsim 300$ km/s) [Kallivayalil+ 2006, 2014]
- just passed its pericentre, likely for the first time

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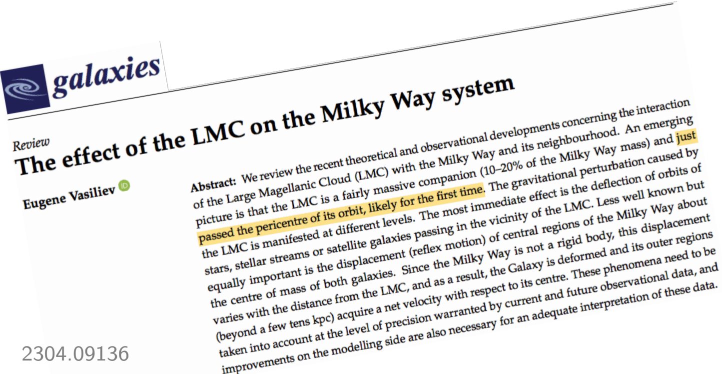
- just passed its pericentre, *likely for the first time* **[?]**



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 stars, stellar streams or satellite galaxies passing in the vicinity of the LMC. Less well known but equally important is the displacement (reflex motion) of central regions of the Milky Way about the centre of mass of both galaxies. Since the Milky Way is not a rigid body, this displacement varies with the distance from the LMC, and as a result, the Galaxy is deformed and its outer regions (beyond a few tens kpc) acquire a net velocity with respect to its centre. These phenomena need to be taken into account at the level of precision warranted by current and future observational data, and improvements on the modelling side are also necessary for an adequate interpretation of these data.

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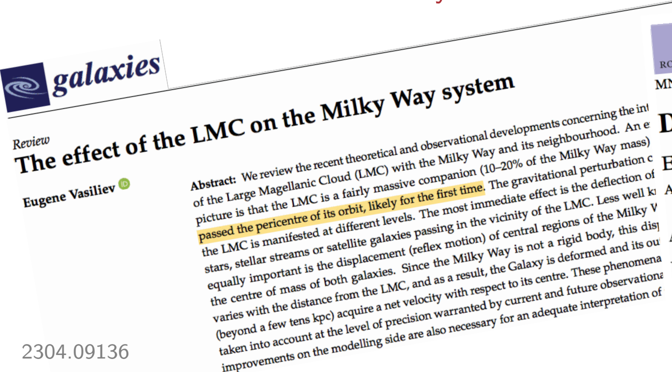
- just passed its pericentre, ~~*likely for the first time* [?]~~

  may be for the second time?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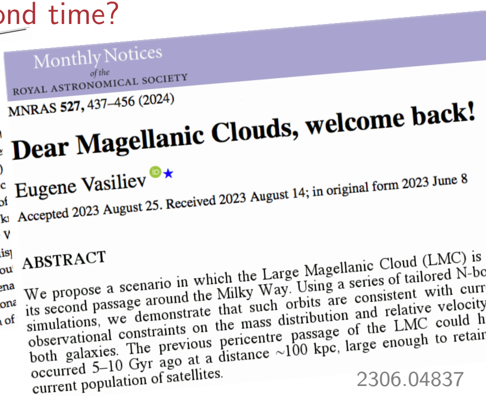
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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

ABSTRACT

We propose a scenario in which the Large Magellanic Cloud (LMC) is
its second passage around the Milky Way. Using a series of tailored N-bo
simulations, we demonstrate that such orbits are consistent with curr
observational constraints on the mass distribution and relative velocity
both galaxies. The previous pericentre passage of the LMC could h
occurred 5–10 Gyr ago at a distance ~100 kpc, large enough to retai
current population of satellites.

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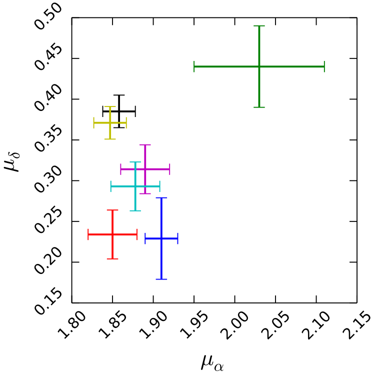
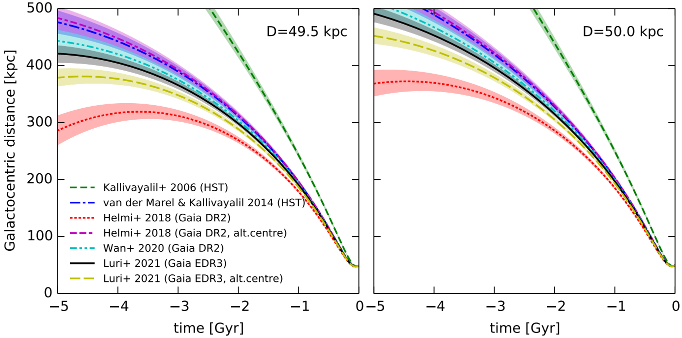
Sensitivity of the inferred LMC trajectory





to the measured PM and distance

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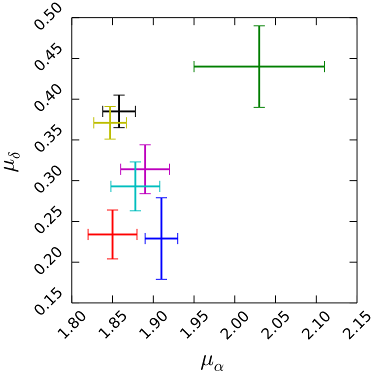
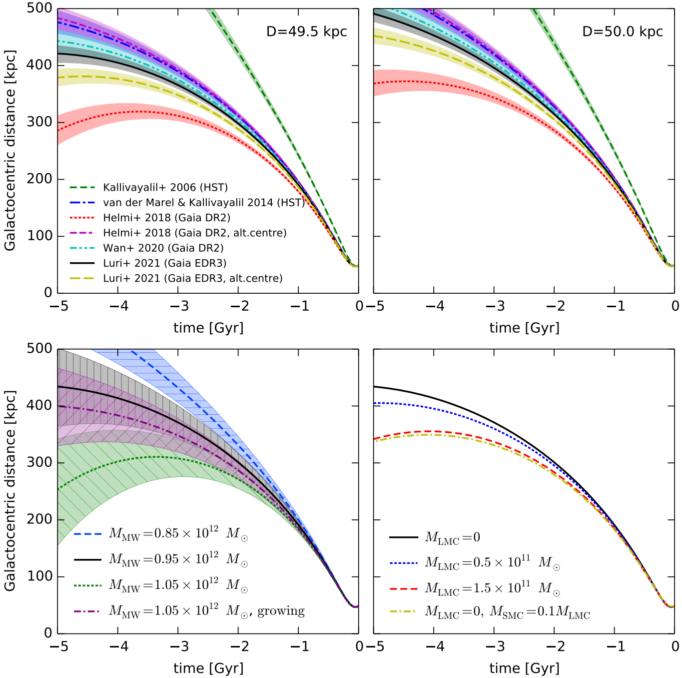


to the measured PM and distance

and to the assumed MW potential and LMC mass



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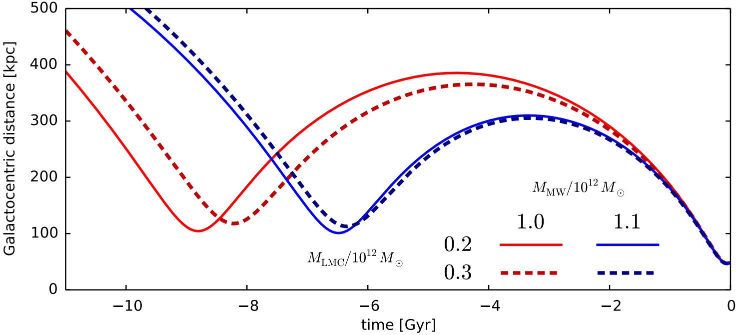

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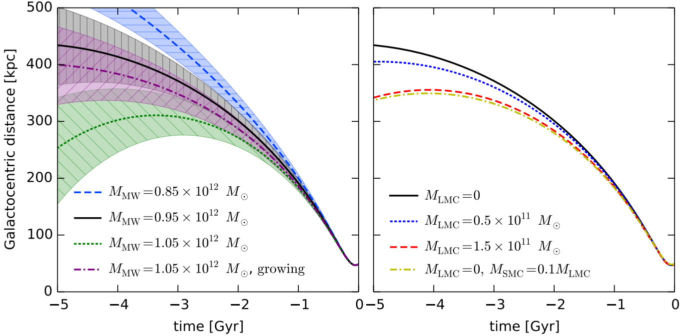
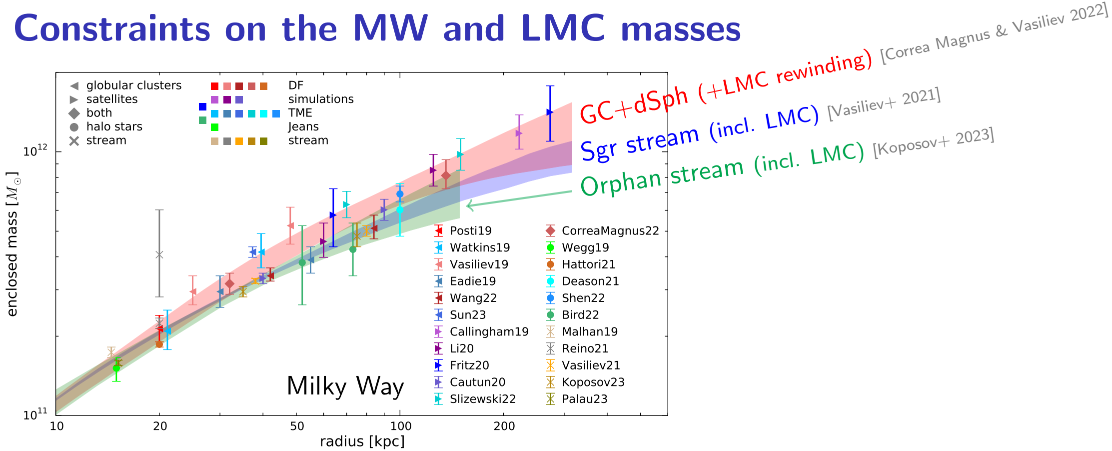
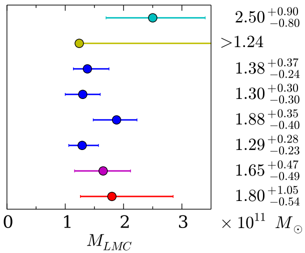


Constraints on the MW and LMC masses



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)	
$1.30^{+0.30}_{-0.30}$	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

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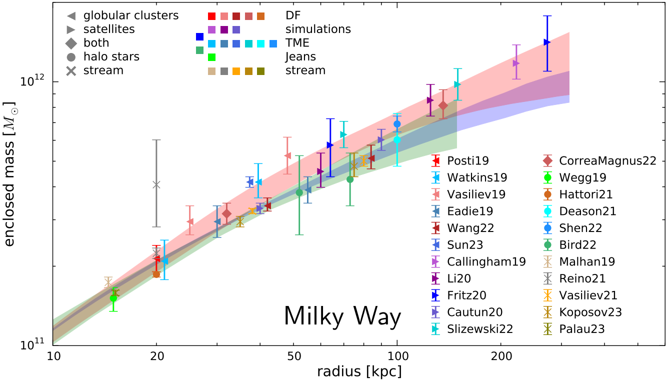
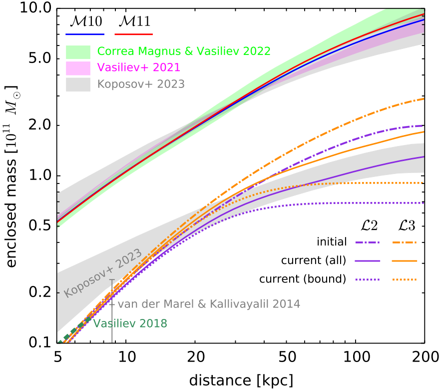
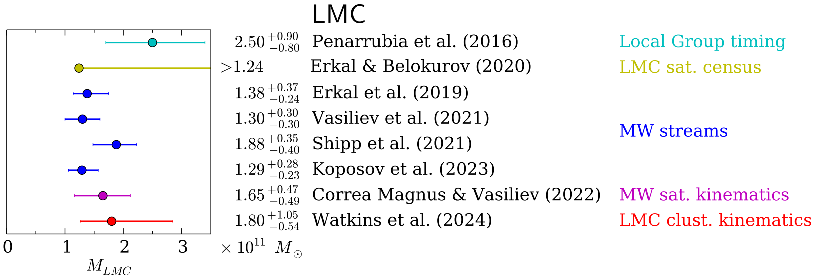






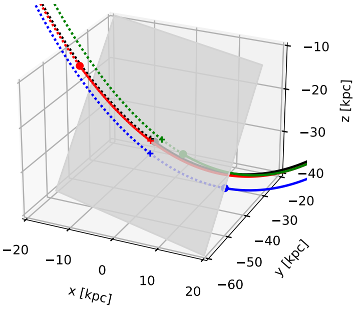
Fitting the present-day position/velocity of the LMC

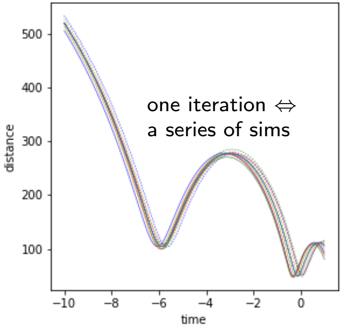
Need an accuracy better than 1 kpc and 1 km/s for a meaningful comparison of models!

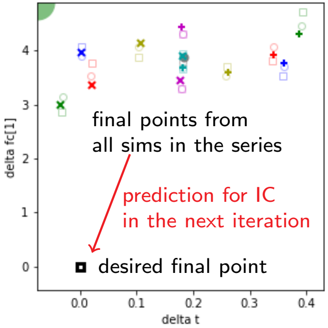
Three key technical developments:

- 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).

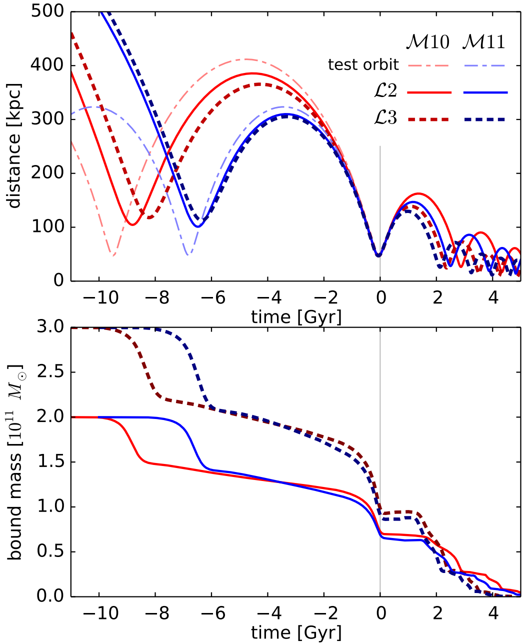






Past LMC orbits in the second-passage scenario

- 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.
- use `Multipole` potential expansions to represent the evolving potentials of both galaxies and "replay" any orbit [Lowing+ 2011; Sanders+ 2020; see also Garavito-Camargo+ in prep.]

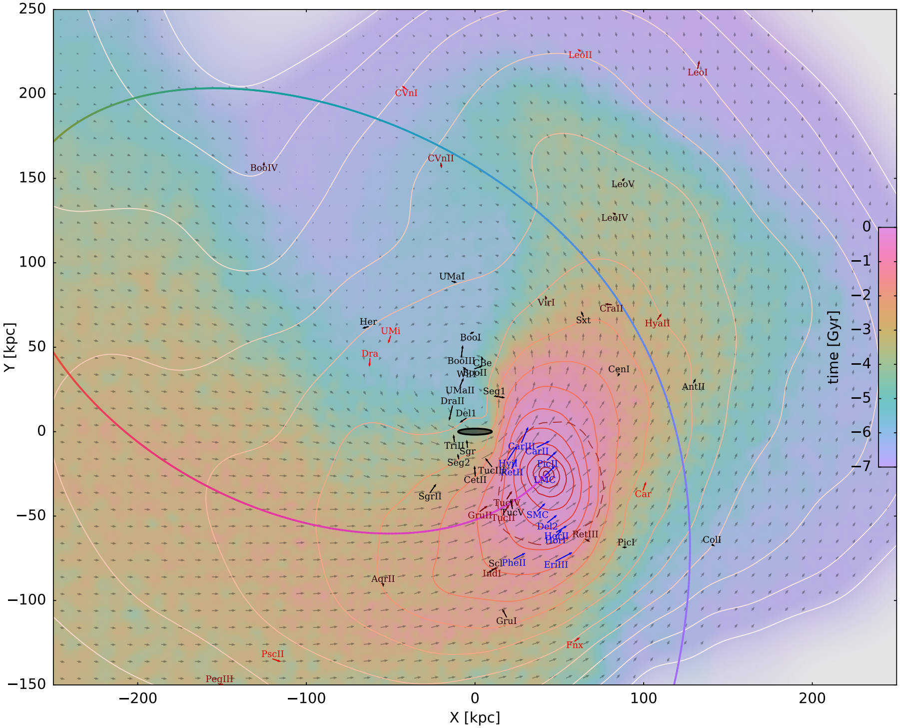


Satellites

current LMC

former LMC

MW



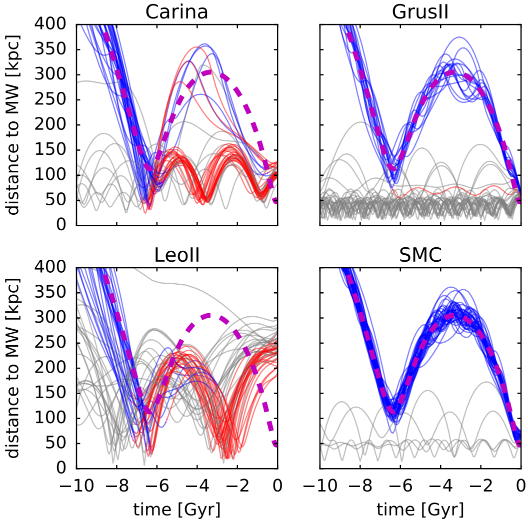
[movie]

Classification of satellite orbits

Determine the probability of Magellanic association and the stripping time for each of $\sim$ 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	

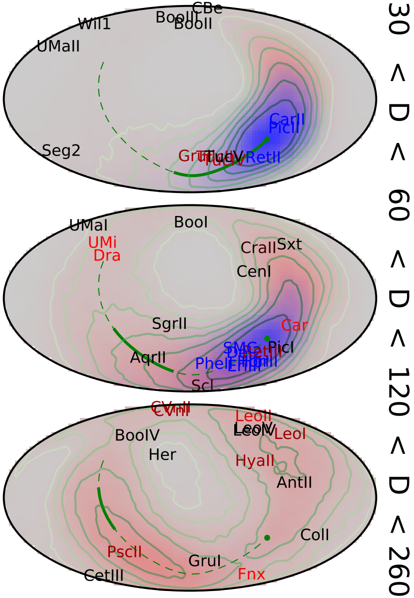
examples of possible past orbits

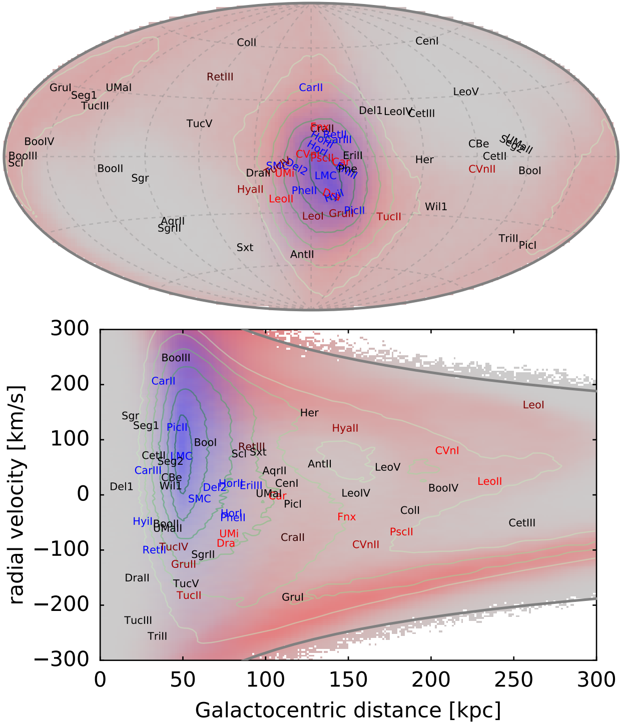


currently bound to LMC; formerly bound; MW-bound

Satellites plane

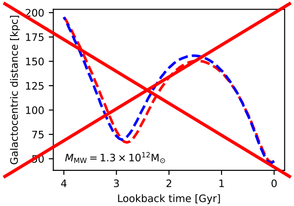
$\mathcal{L}3 - \mathcal{M}10$, second passage





Caveats

- isolated MW–LMC sims – no cosmological context (e.g. MW mass evolution): difficult to find precise MW–LMC analogues in cosmological sims...
- SMC is now heavily stripped, but it was much more massive in the past: this affects the inferred LMC orbit (making it more bound, i.e. strengthening the case for the second passage), but need to retain the SMC on the previous pericentre passage...
- Can LMC retain its gas reservoir during the previous passage?
- LMC trajectory in hydrodynamical sims may be quite different from pure N-body [e.g., Lucchini+ 2021].
- other observational consequences? halo perturbations are produced almost entirely in the last few hundred Myr, no difference between 1st and 2nd passage scenarios – unless the LMC period is shorter, e.g., 3–4 Gyr [Sheng+ 2024].



- any imprint on the LMC (& SMC) SFH? [e.g., Massana+ 2022; Ruiz-Lara+ in prep.]

Summary

- Past orbit of the LMC is *very* sensitive to the assumed Galactic potential;
- A second-passage scenario with a previous pericentre at $\sim$100 kpc some 6–10 Gyr ago is *possible*, but not *mandated*;
- In this case, many MW satellites have a considerable chance of being accreted from the Magellanic system.

Summary

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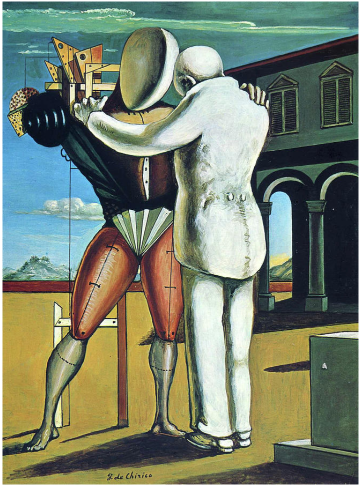
Welcome back my friends
to the show that never ends!
We're so glad you could attend,
come inside, come inside.

Emerson, Lake & Palmer



Giorgio de Chirico – The prodigal son