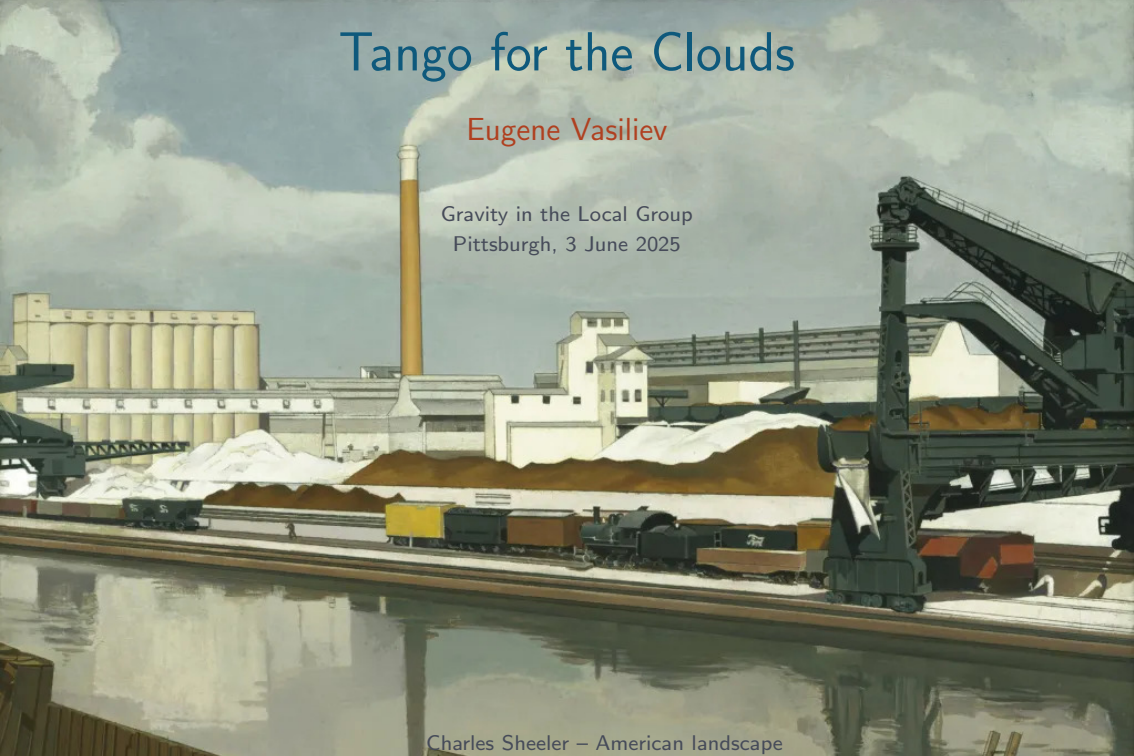
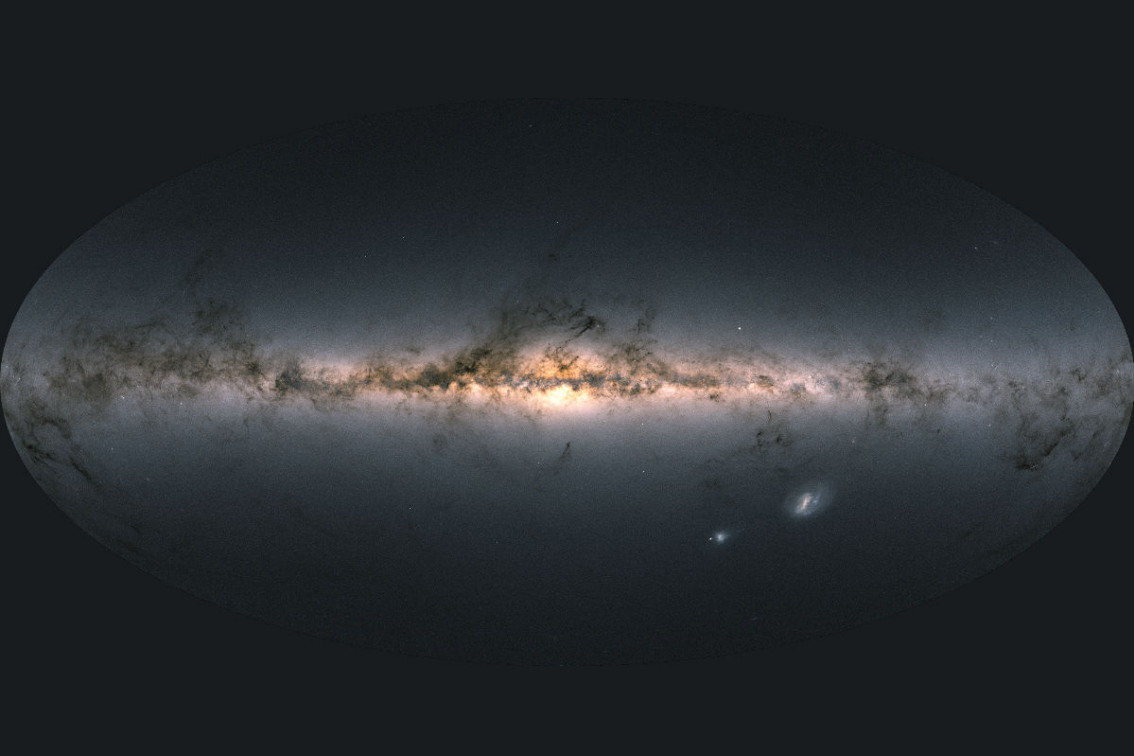
Tango for the Clouds

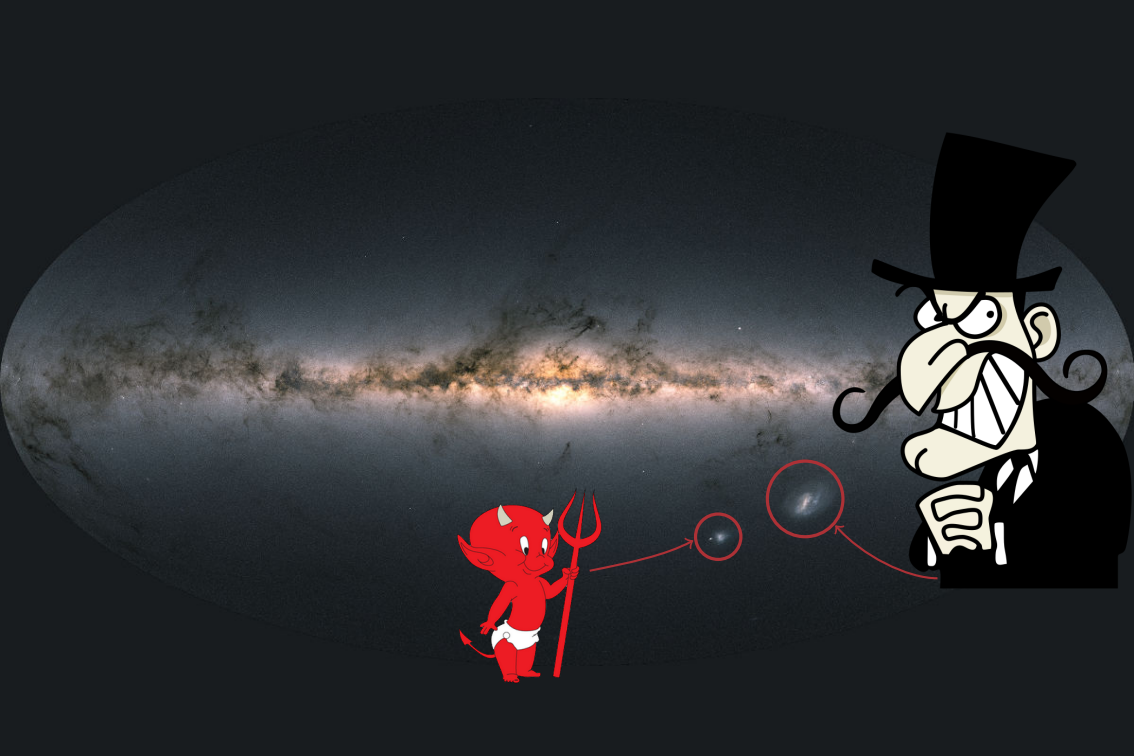
Eugene Vasiliev

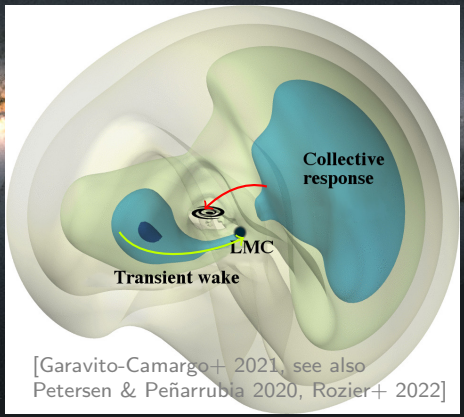
Gravity in the Local Group
Pittsburgh, 3 June 2025



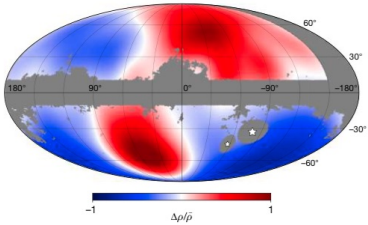
Charles Sheeler – American landscape





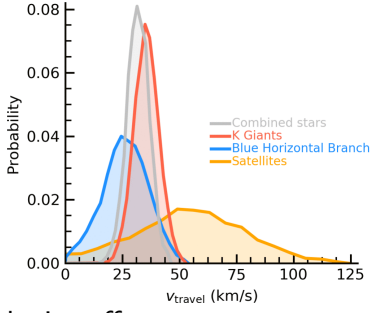


[Garavito-Camargo+ 2021, see also
Petersen & Peñarrubia 2020, Rozier+ 2022]



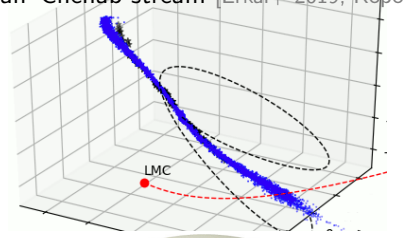
density polarization [Conroy+ 2021]

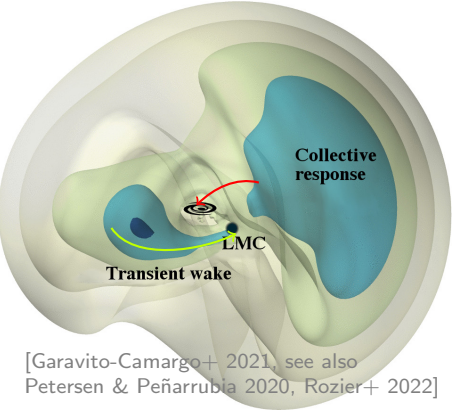
[alternative views: Chandra+ 2023; Amarante+ 2024]



velocity offset [Petersen & Peñarrubia 2021, see also Erkal+ 2021, Yaaqib+ 2024; Byström+ 2024; Chandra+ 2025]

Orphan–Chenab stream [Erkal+ 2019; Koposov+ 2023]





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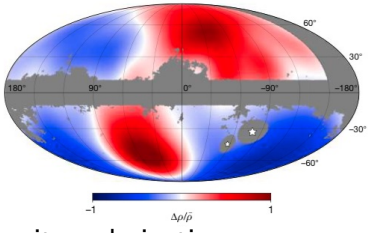

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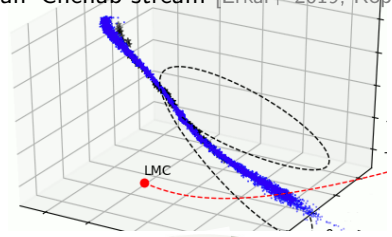

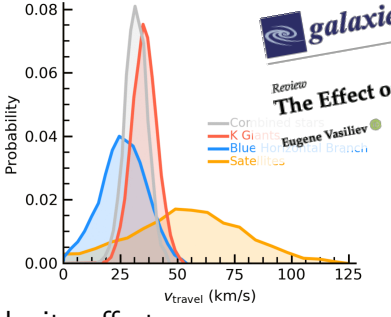

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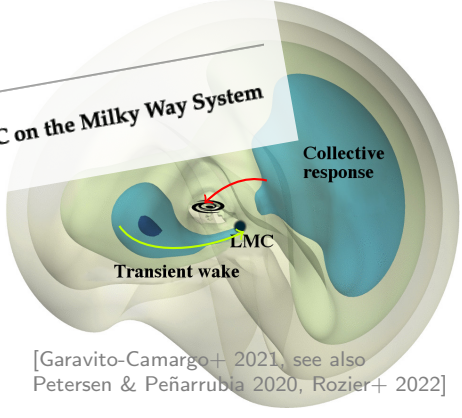


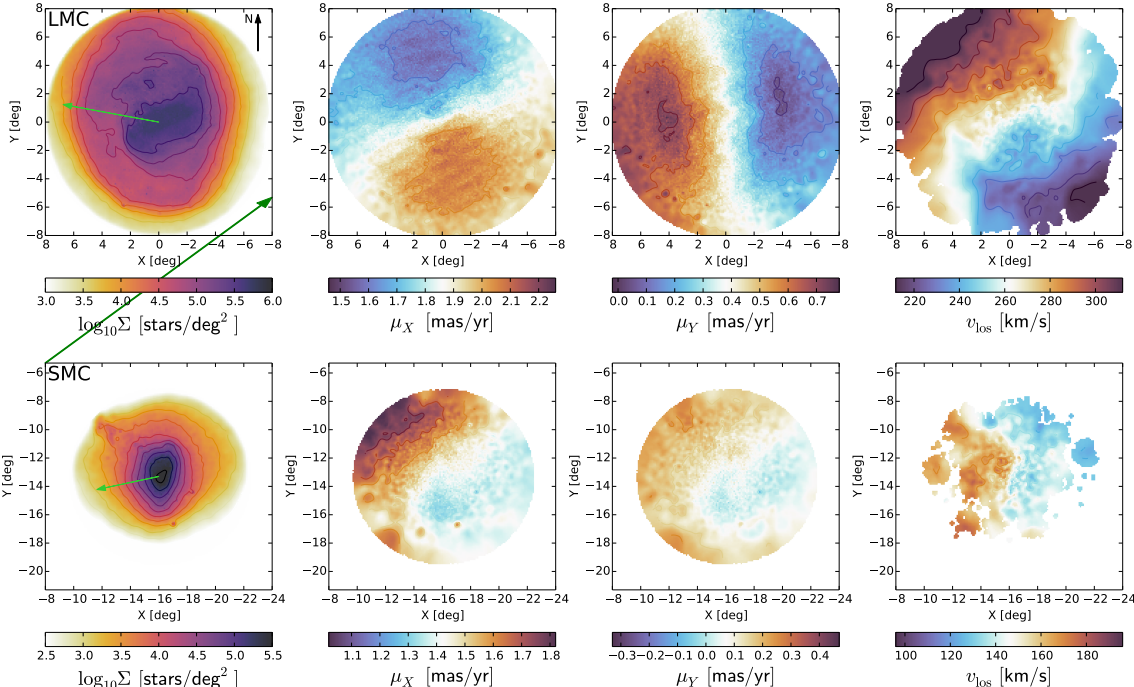
[Garavito-Camargo+ 2021, see also Petersen & Peñarrubia 2020, Rozier+ 2022]

Trivia

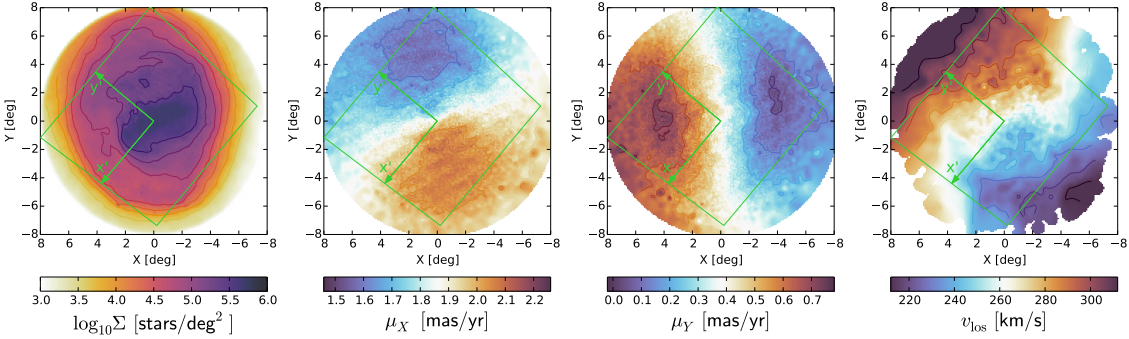
0. LMC orbits the Milky Way; SMC orbits the LMC.
1. LMC has recently ($\sim$100 Myr ago) passed its pericentre around MW.
2. SMC has passed its pericentre around LMC few$\times$100 Myr ago.
3. LMC has a bar and is kinematically perturbed in the outskirts.
4. SMC is irregularly shaped, extended along the line of sight, and obviously in distress (perhaps falling apart due to tidal forces?)

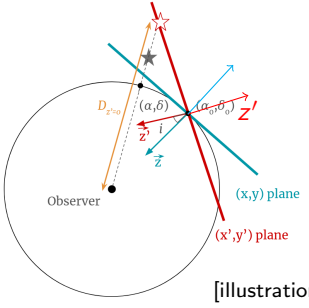
What do observations tell us about their structure and dynamical history?

Observed kinematic maps (from *Gaia* DR3)



Kinematic deprojection of the LMC





thin-disc approximation:
assume that all stars are located in one plane ($z' = 0$);
determine its orientation (inclination i, line-of-nodes Ω)
by minimising the vertical velocity $\overline{v_{z'}}$.

[illustration from Jiménez-Arranz+ 2023]

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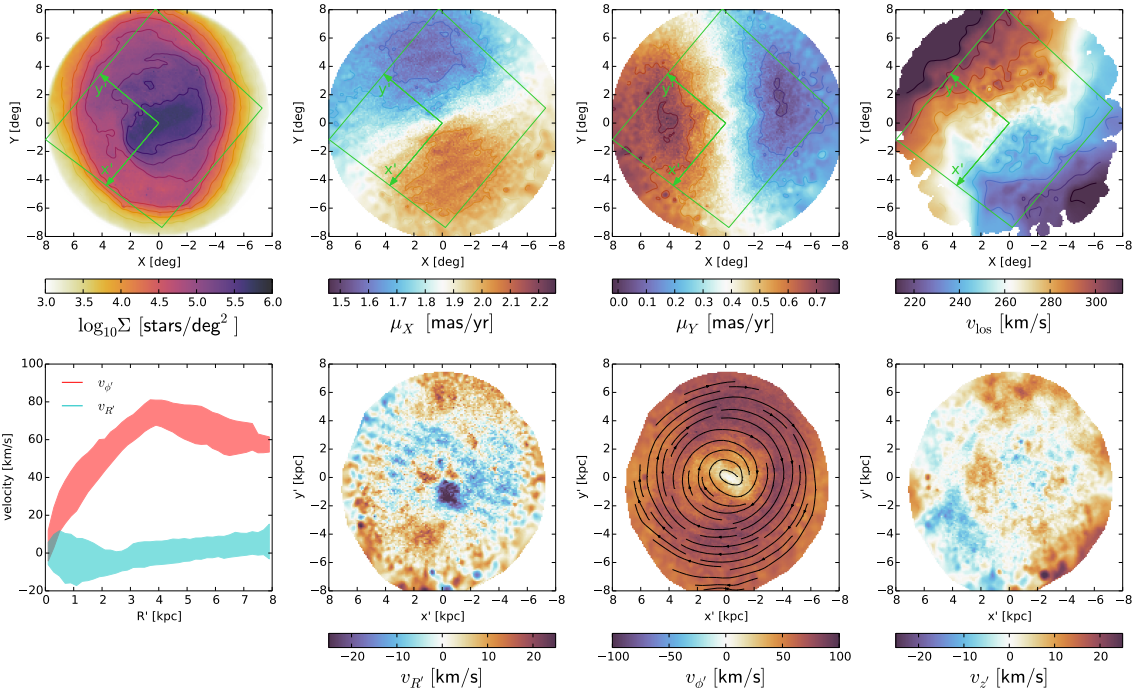

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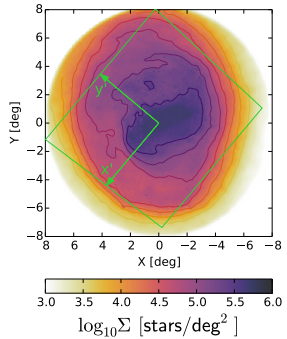
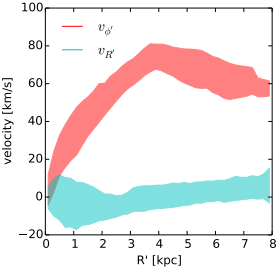
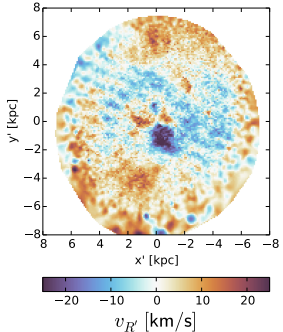
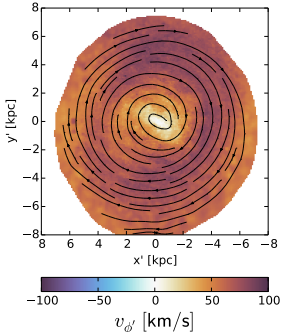


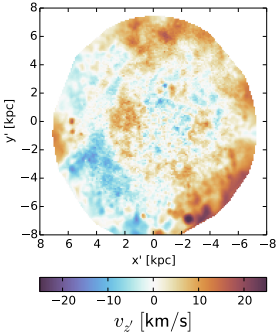
- apparent disc major axis misaligned with the line of nodes
- residual $\overline{v_{z'}} \sim$ a few km/s even in the best orientation
- clear (and asymmetric) quadrupole in $\overline{v_{R'}}$ in the bar region
- $\overline{v_{R'}} > 0$ in the outer parts of the disc (for $i = 27°$)

see also Luri+ 2021; Jiménez-Arranz+ 2024, 2025









Modelling objectives and challenges

Want to infer/constrain:

- orbital history of the LMC around the Milky Way
- orbital history of the SMC around the LMC
- initial & current structure and mass loss history of both Clouds
- origin of the LMC bar and its pattern speed

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For a reliable comparison between models and observations, one needs to match

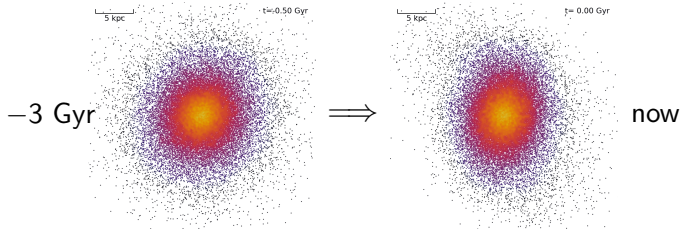
- current location and velocity of both Clouds
- orientaion of the LMC disc and the bar
- kinematic features of the LMC disc: $\overline{v}_\phi(R')$, bar-induced quadrupole in $\overline{v}_{R'}$, velocity dispersions in all three components...
- geometry of the SMC (extended depth along the line of sight)

Modelling approaches (1)

Test-particle simulations [e.g., Belokurov & Erkal 2019, Cullinane+ 2022]:

adopt a fixed potential of the LMC moving on a pre-computed trajectory (orbit rewinding), initialize an LMC disc in equilibrium, integrate particle orbits accounting for the MW tidal field and the SMC flyby.

+ fast (seconds to run)
+ exact control on the orbits, orientation and current potential
− no dynamical consistency between the adopted potential and the actual particle distribution (bar instability cannot be followed; disc plane remains fixed)
− dynamical friction has to be imposed by hand; no deformation of the potential



Modelling approaches (3)

N-body/hydro simulations [e.g., Besla+ 2010, 2012; Jiménez-Arranz+ 2024]

+ most realistic, gravitationally self-consistent
+ dynamical friction and halo deformations occur naturally
  (if the MW is modelled as a live system)
− expensive (hours/days to run)
− difficult to control the present-day state (centre position/velocity, orientation, ...)

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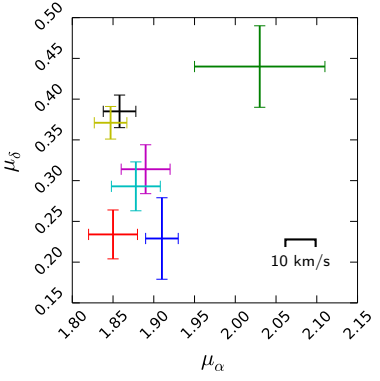

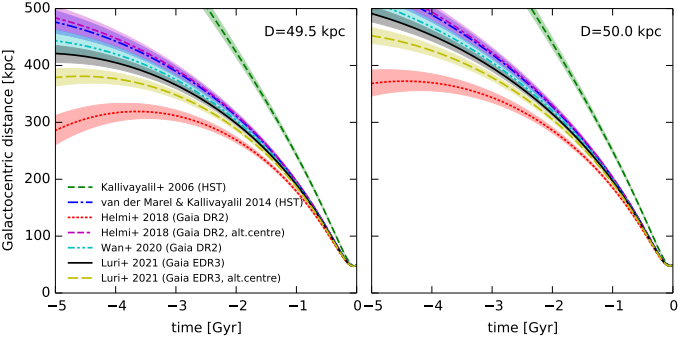

Modelling approaches (3)

+ a workable iterative approach for fitting the orbit of one or two galaxies has been developed [Vasiliev+ 2021, 2023, 2024], but it needs to be generalised to fit all three..

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
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Advance Access publication 2020 November 25

Tango for three: Sagittarius, LMC, and the Milky Way

Eugene Vasiliev [1,2★] Vasily Belokurov [1] and Denis Erkal [3]

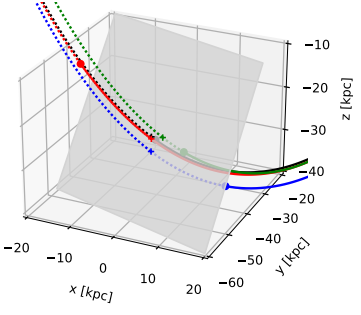
Tango, of course, alludes to the phrase "It takes two to tango", which perfectly describes the way that tidal streams (in particular, Sgr) were analyzed traditionally (just the disrupting satellite and the host galaxy). In this paper, we make the point that it is necessary to bring in the third party – the LMC. However clumsy and unconventional this dance of three galaxies might seem (and we certainly didn't have an easy life fitting the data with all three galaxies moving around!), this is the state of the art we will have to deal with in the upcoming era of precision data.

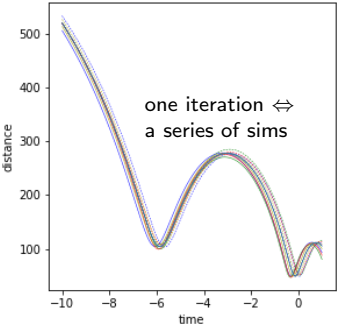
Modelling approaches (3)

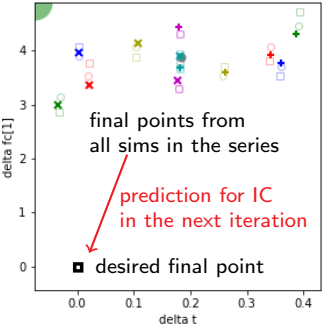
Three key technical developments to reach the desired accuracy of orbit fitting:

- 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).







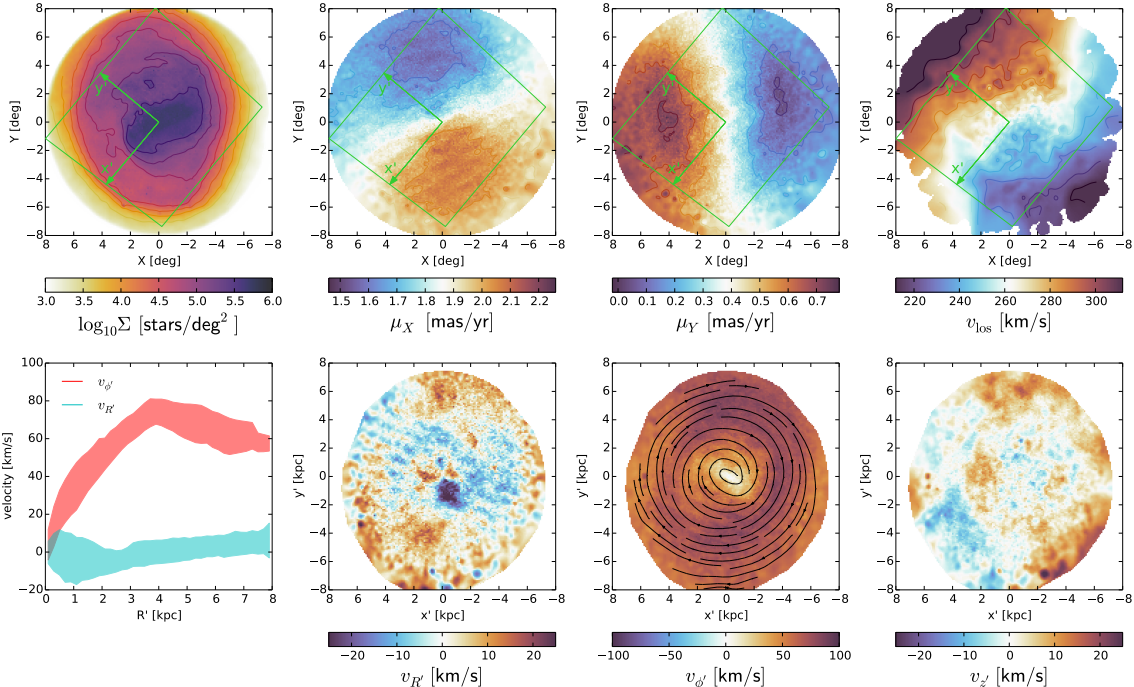
Modelling approaches (2)

"Restricted N-body" simulations [e.g., Vasiliev+ 2021 for the Sagittarius dSph]:

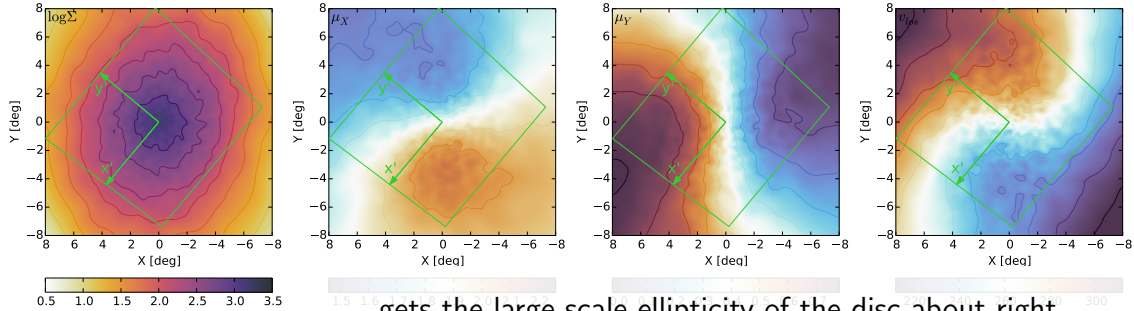
sit between test-particle sims and SCF (self-consistent field) method;
integrate particle trajectories and update the potential once in a while,
using a low-order multipole expansion.

+ semi-fast (seconds/minutes)
+ galaxies follow prescribed orbits, good control on orientation and current potential
+ can describe bar formation and disc warping
− dynamical friction has to be imposed by hand; no deformation of the host halo

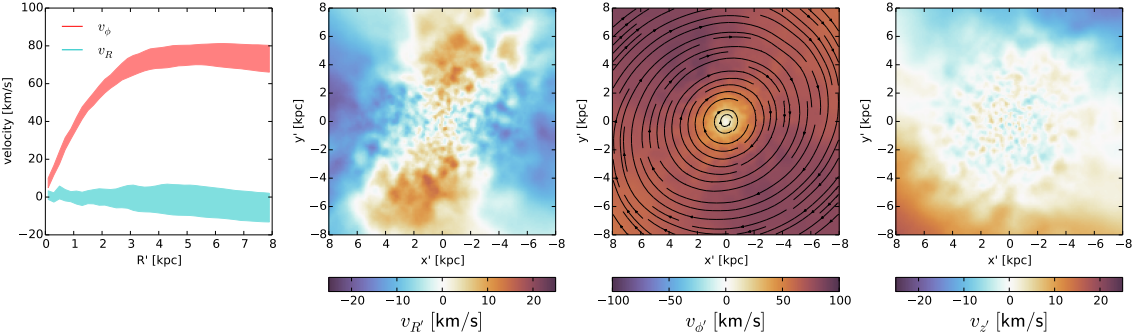
Observational kinematic maps of the LMC



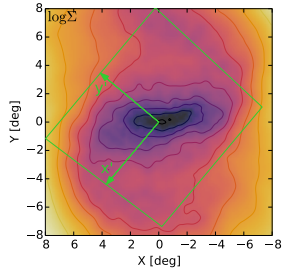
Simulation of LMC passing around MW (no SMC, TP)

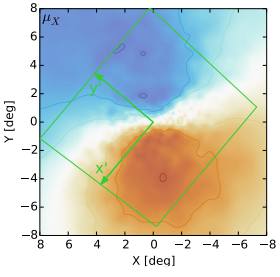


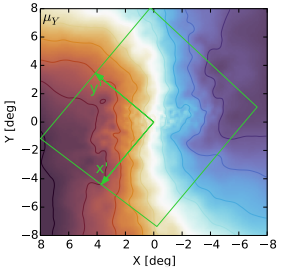
gets the large-scale ellipticity of the disc about right

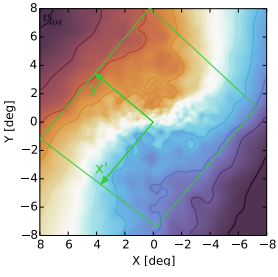


Simulation of LMC passing around MW (no SMC, RNB)

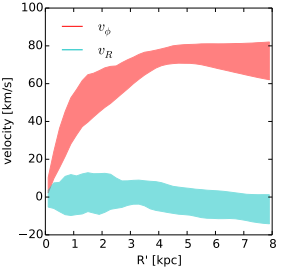


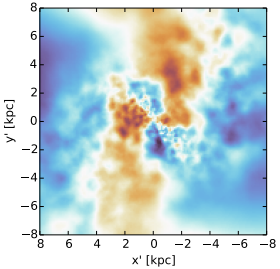


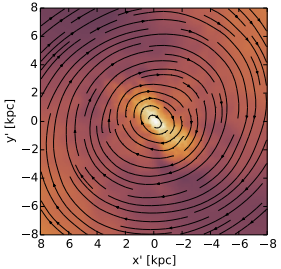


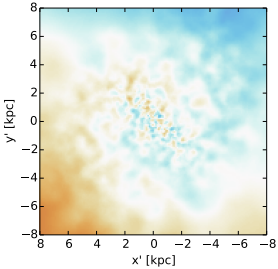


forms a bar (independently of the MW tidal perturbation!); qualitatively matches the quadrupole pattern in $\overline{v}_{R'}$

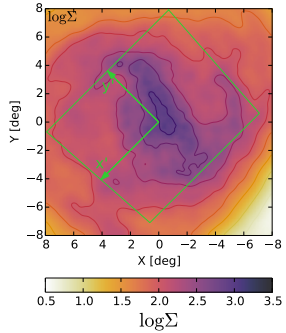


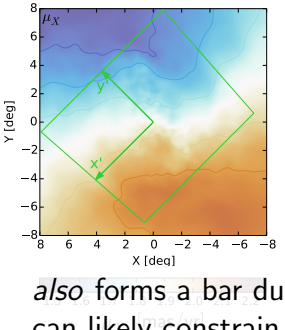


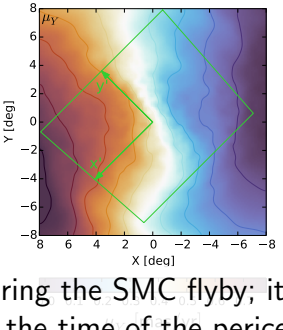


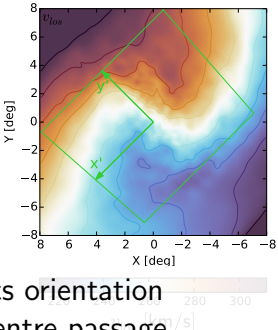


Simulation of LMC perturbed by SMC flyby (no MW, NB)

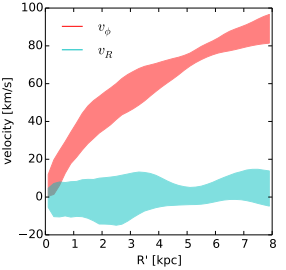


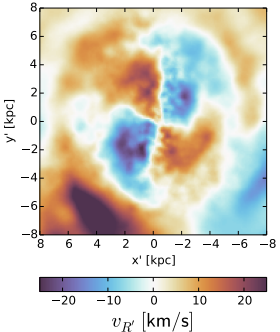


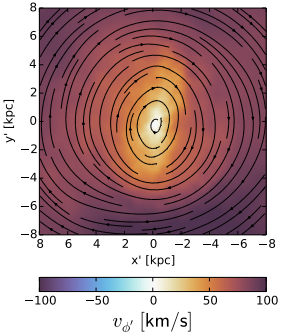


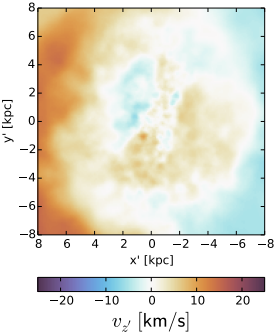


also forms a bar during the SMC flyby; its orientation can likely constrain the time of the pericentre passage





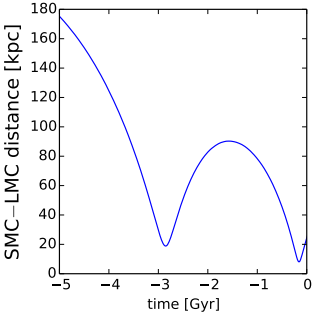




Past orbit and constraints on the masses of all three galaxies

Is SMC even bound to LMC at early times?

or how many pericentre passages around the LMC it has completed?



Past orbit and constraints on the masses of all three galaxies

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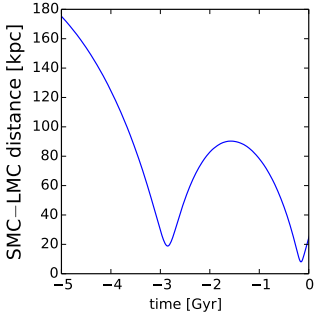
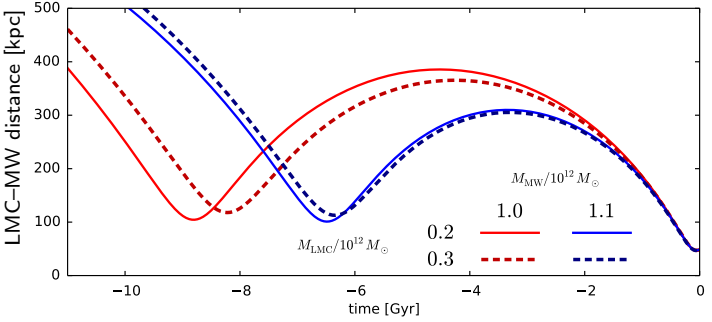
Could it remain bound to the LMC in the second-passage scenario, in which the LMC had another encounter with the MW at a distance $\sim$ 100 kpc?

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

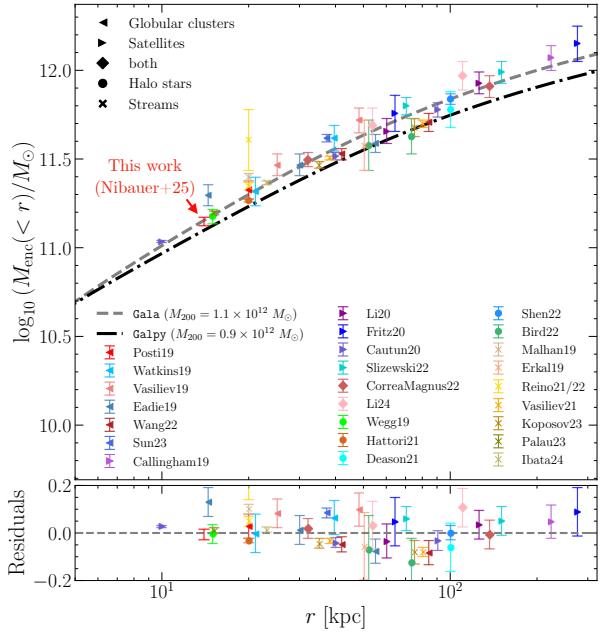
Dear Magellanic Clouds, welcome back!

Eugene Vasiliev





Past orbit and constraints on the masses of all three galaxies



If the second-passage scenario is ruled out, this places interesting constraints on the MW mass.

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Review article

Milky Way dynamics in light of *Gaia*

Jason A.S. Hunt, Eugene Vasiliev *

Outlook

- obtain kinematic maps of MCs from *Gaia*
- develop simulation methods of different levels of complexity/realism
- construct a library of simulations for different choices of initial structure, sampling over uncertainties in present-day position/velocity of both Clouds
- explore the orbital and mass loss history of MCs
- understand the origin and properties of the LMC bar
- test the viability of the second-passage scenario
- use MCs to constrain the Milky Way potential

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